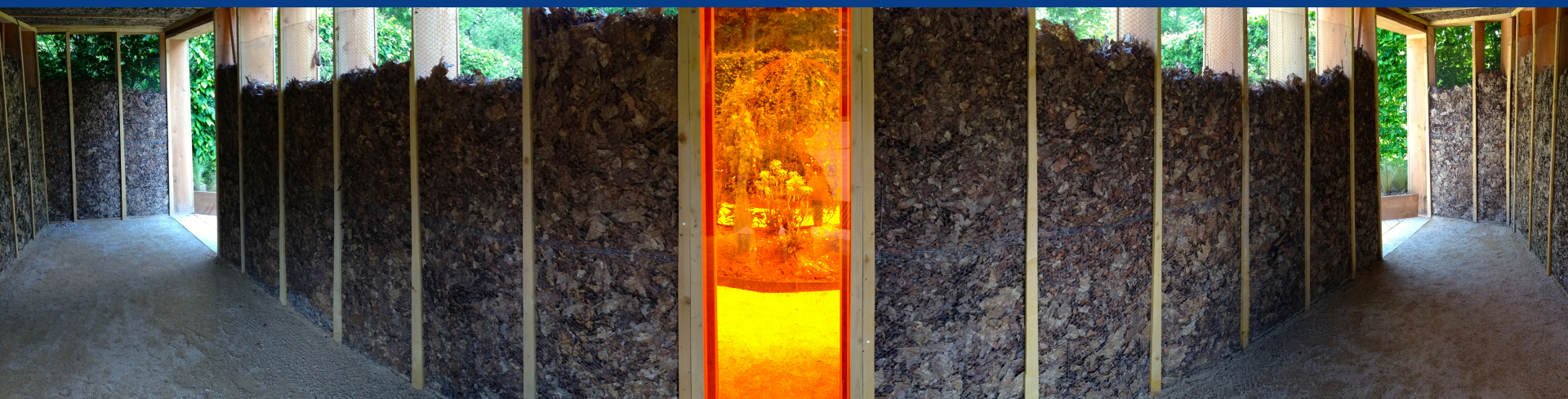




LEARNING TO KNOW THE H(125)

Standard Model of Particle Physics

2

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Standard Model of Particle Physics



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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Standard Model of Particle Physics



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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H - \right. \\
 & W_\nu^+ W_\mu^- - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ W_\mu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^- \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H \\
 & \frac{1}{2}g [W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H) \\
 & W_\mu^- \phi^+] + ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H \\
 & W_\mu^- \phi^+] - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma^\mu \partial_\mu \\
 & ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda) + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_\kappa^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\kappa^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_\kappa^\lambda \\
 & m_\kappa^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_\kappa^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\kappa^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\kappa^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\kappa^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

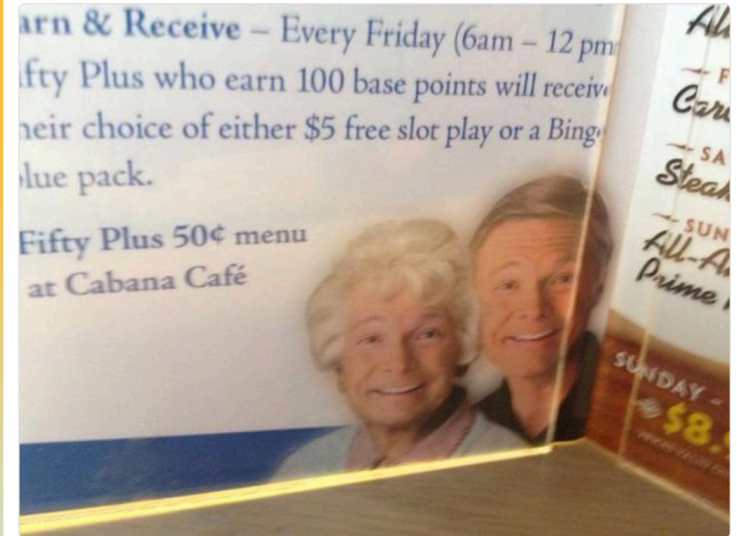


You Had One Job

@_youhadonejob1

Following

Save money by hiring the same actor.



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12:46 PM - 21 May 2017

7

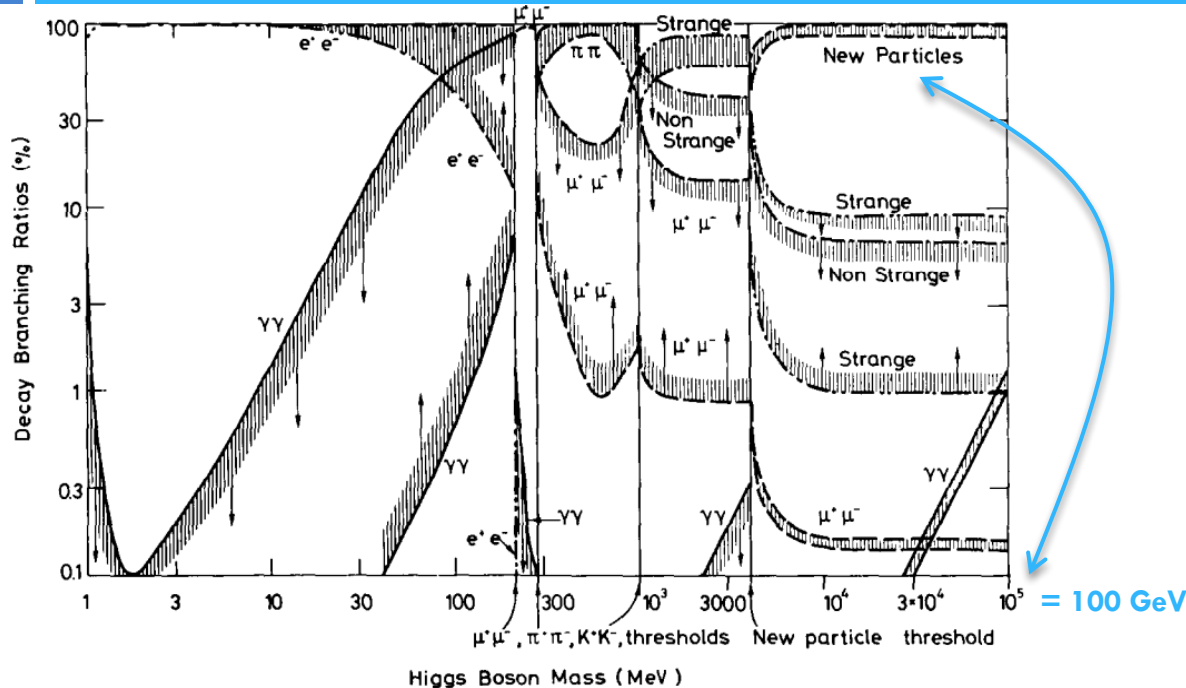
191

626

Phenomenological profile in 1976

5

[NPB 106 (1976) 292]



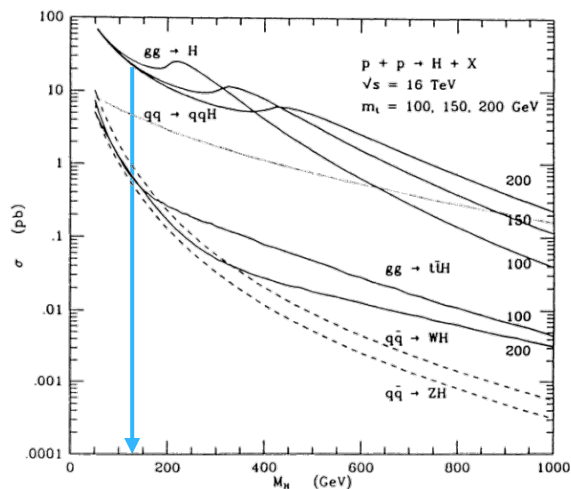
334

J. Ellis et al. / Higgs boson

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A longstanding learning process

[10.5170/CERN-1990-010-V-2]



1990

m_{top} unknown

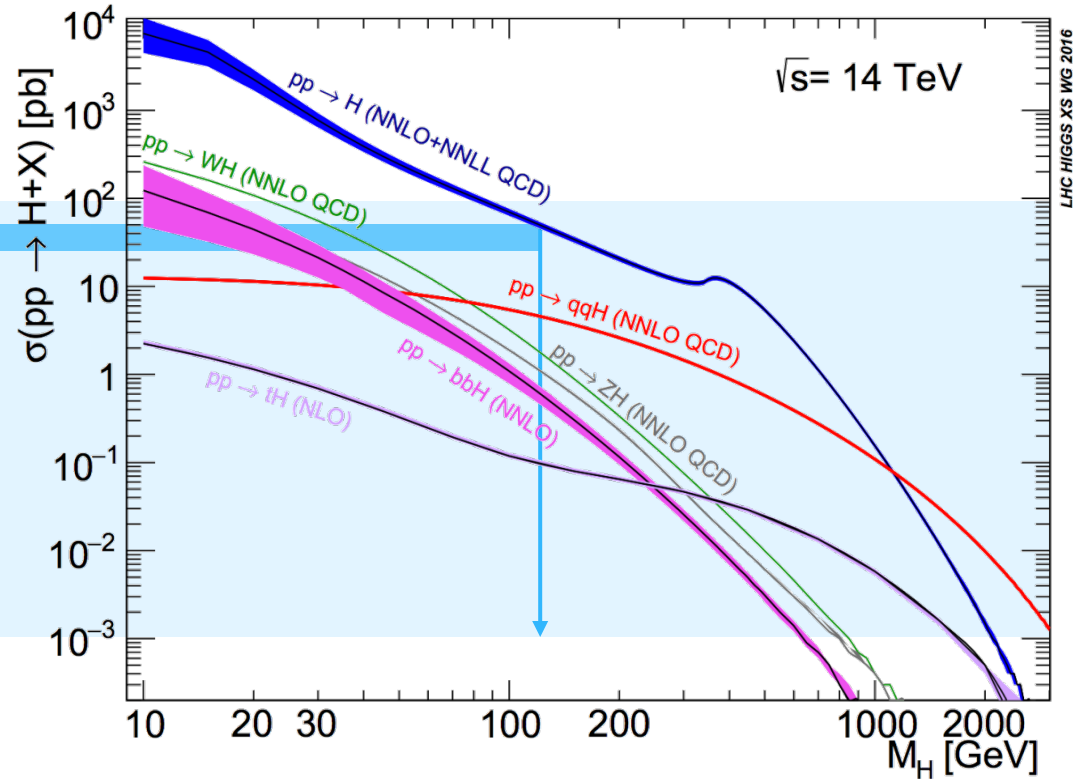
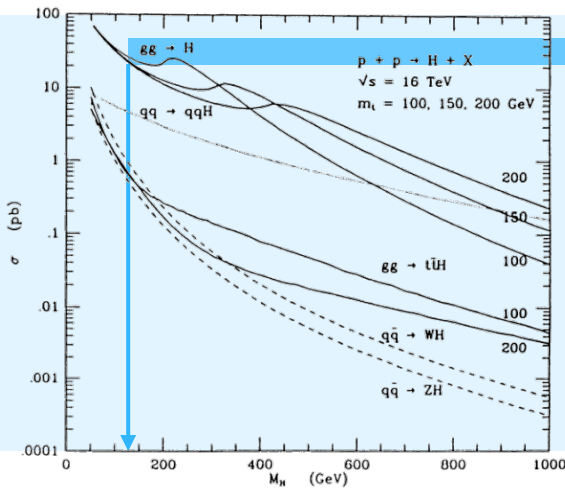
$ggH \sim 25 \text{ pb}$

A longstanding learning process

7

[10.5170/CERN-1990-010-V-2] [arXiv:1610.07922]

Matched vertical scales



1990

m_{top} unknown
 $ggH \sim 25 \text{ pb}$

2016

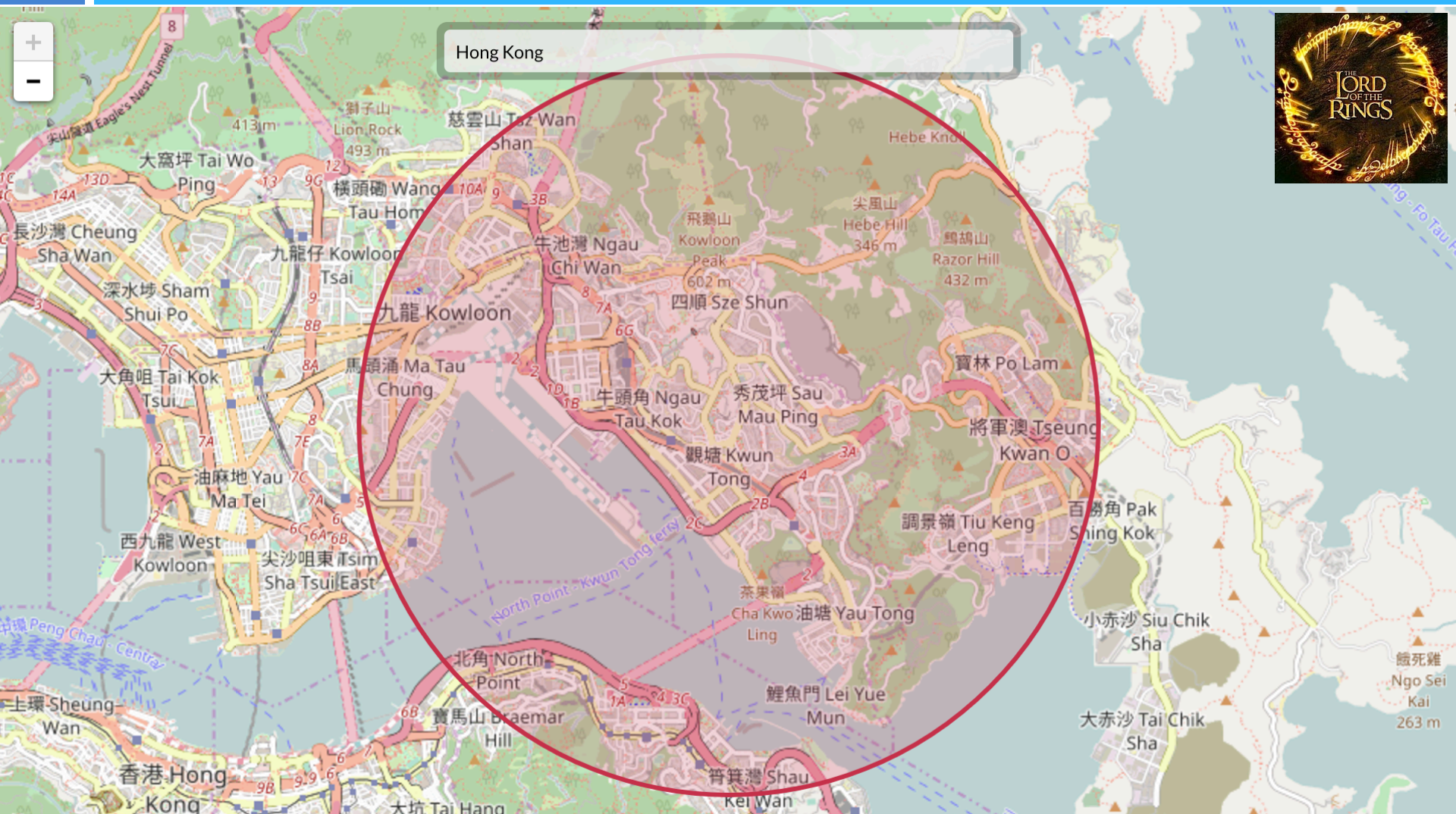
$m_{\text{top}} = 172.5 \pm 1.0 \text{ GeV}$
 ggH ($N^3\text{LO}+N^3\text{LL}$) $\sim 50 \text{ pb}$



LHC – the lord of the rings

8

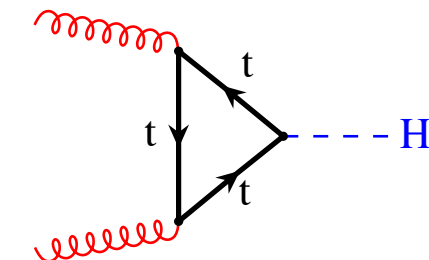
[<http://natronics.github.io/science-hack-day-2014/lhc-map/>]



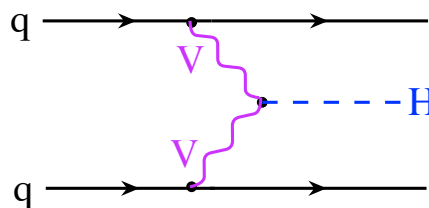
How SM Higgses are born

[<http://cern.ch/go/cWH8>] [<http://cern.ch/go/SnJ8>]

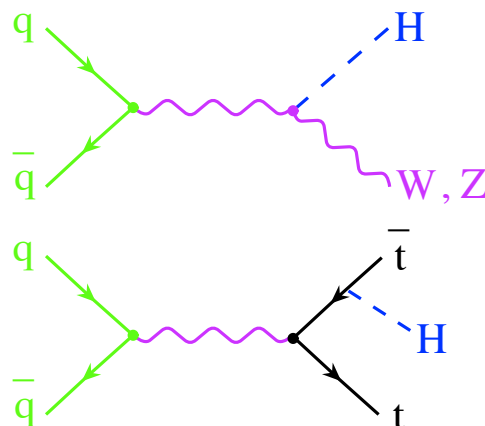
□ **Gluon fusion**



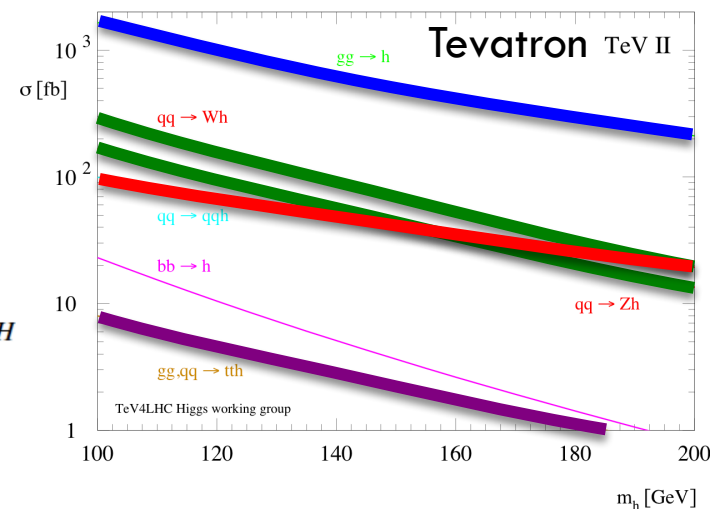
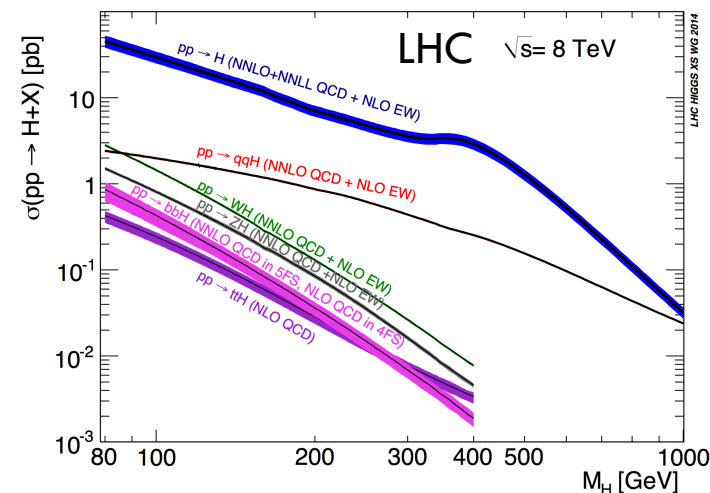
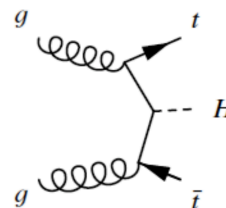
□ **VBF**



□ **WH, ZH**

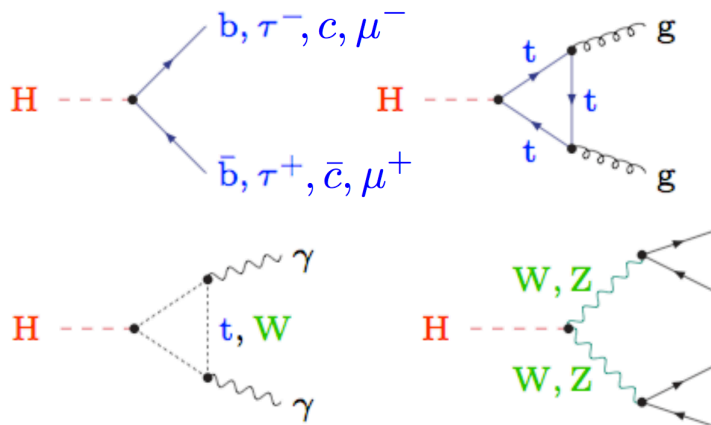


□ **bbH, ttH**

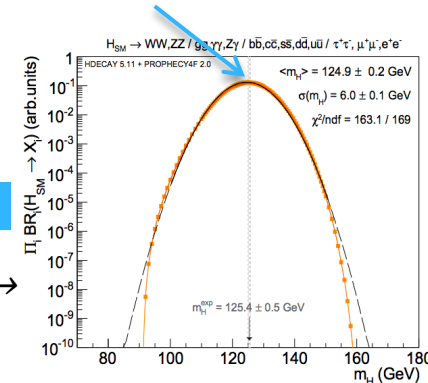
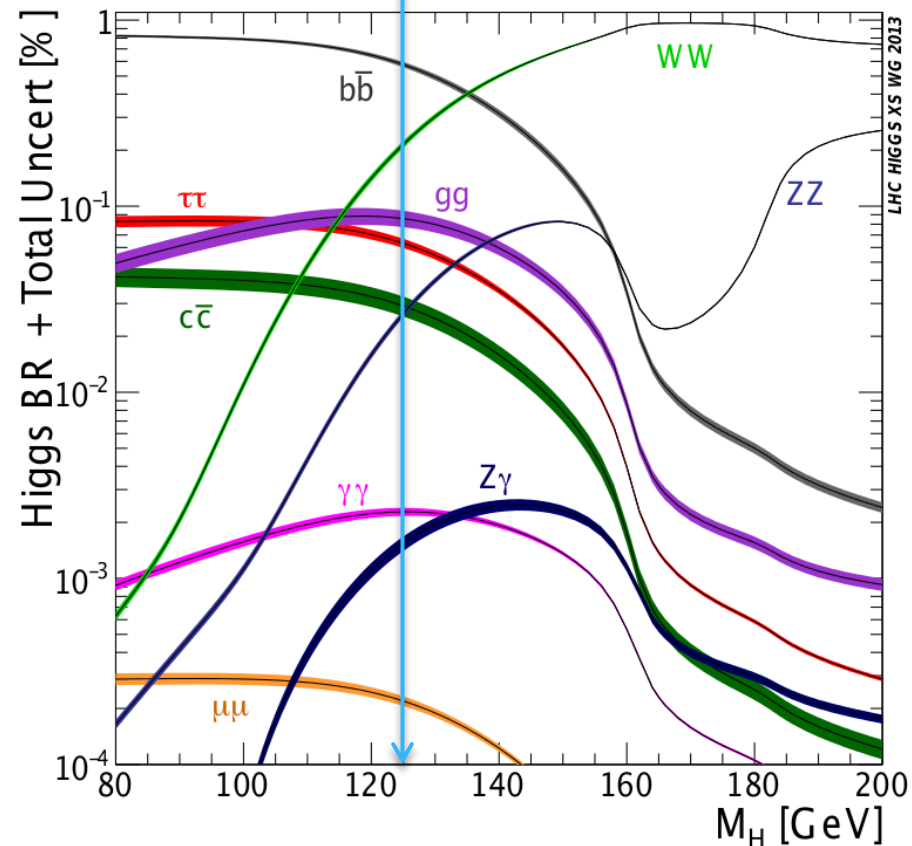


How SM Higgses die

- Couplings and kinematics drive BR ($b\bar{b}$, WW , $\tau\tau$, ZZ).
- Decays with photons ($\gamma\gamma$, $Z\gamma$) through loops.



Near to maximal $\Pi BR_i \rightarrow$



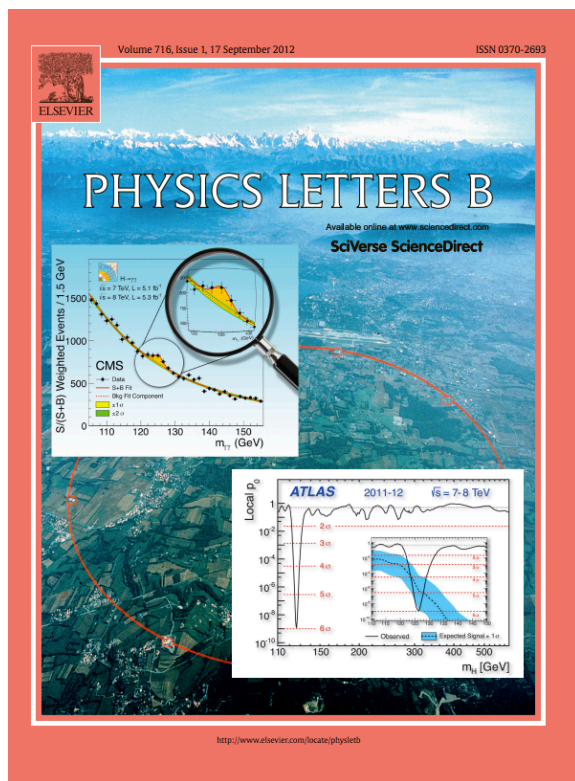




July 4, 2012: looking up to a new boson

13

[<http://cern.ch/go/q8jx>]



2012 2011 2010 2009 2008

Who Should Be TIME's Person of the Year 2012? >

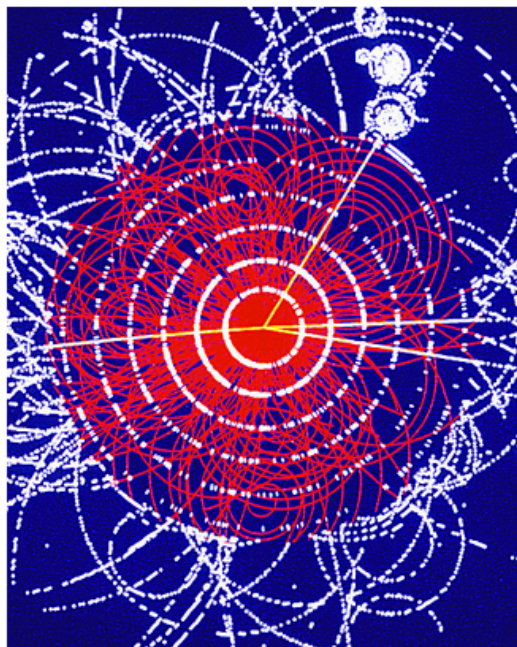
As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

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THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should The Higgs Boson be TIME's Person of the Year 2012?

☐ Definitely ☐ No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

Video

Poll Results

PAST PERSONS OF THE YEAR



2011: The Protester



2010: Facebook's Mark Zuckerberg



2009: Ben Bernanke



2008: Barack Obama

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2012 2011 2010 2009 2008

Who Should Be TIME's Person of the Year 2012? >

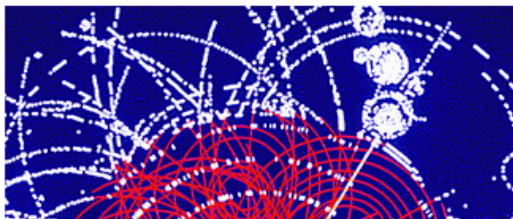
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2010: Facebook's Mark Zuckerberg



last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The

Standard Model of Particle Physics



16

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Standard Theory of Particle Physics



17

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^- - \frac{1}{4}\alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gMW_\mu^+ W_\mu^- H - \frac{1}{2}\frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig s_w (W_\mu^+ \partial_\mu \phi^- - \phi^- \partial_\mu W_\mu^+) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+)) - ig s_w A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g \frac{1}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 (W_\mu^+ W_\mu^-)^2 + (\phi^0)^2 + 2\phi^+ \phi^- - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2}g^2 s_w \frac{1}{c_w} H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \frac{1}{2}(\gamma \partial + m_e^\lambda) A_\mu^\lambda (\gamma \partial + m_e^\lambda) u_j^\lambda - \frac{1}{2}(\gamma \partial + m_u^\lambda) d_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \frac{1}{2}(\gamma \partial + m_d^\lambda) d_j^\lambda (\gamma \partial + m_d^\lambda) u_j^\lambda - \\
 & ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \frac{1}{3}Z_\mu^0 [(\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) d_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{8}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Standard Theory of Particle Physics



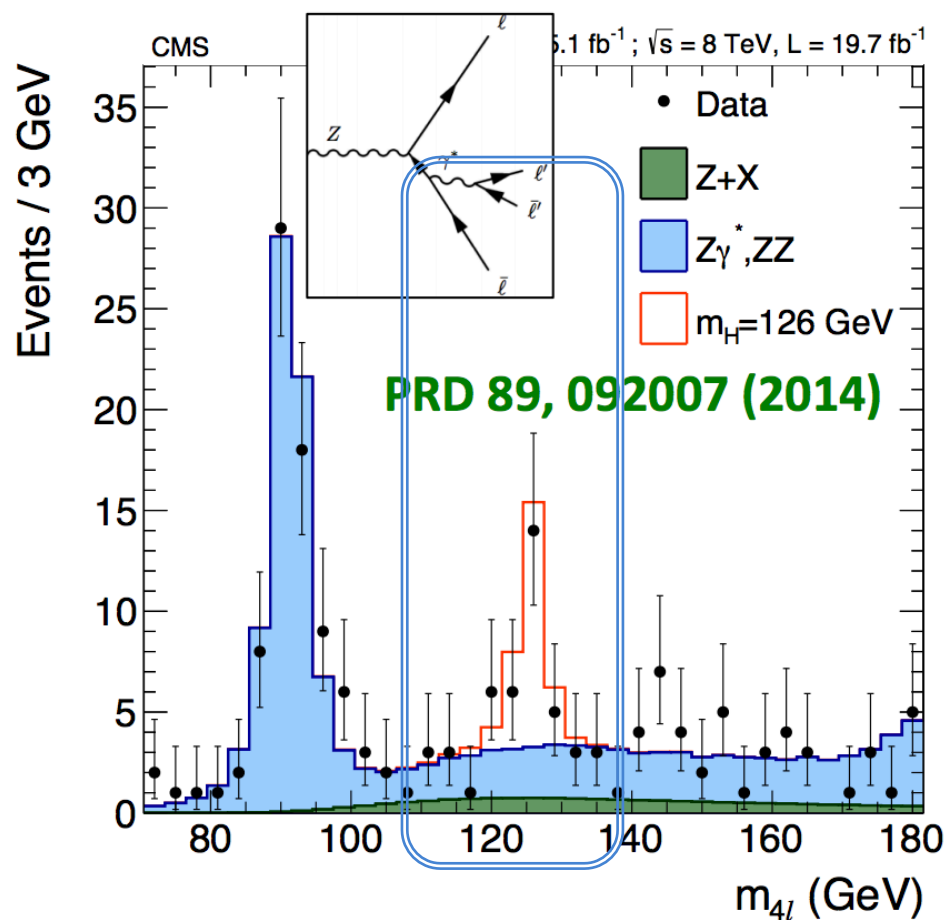
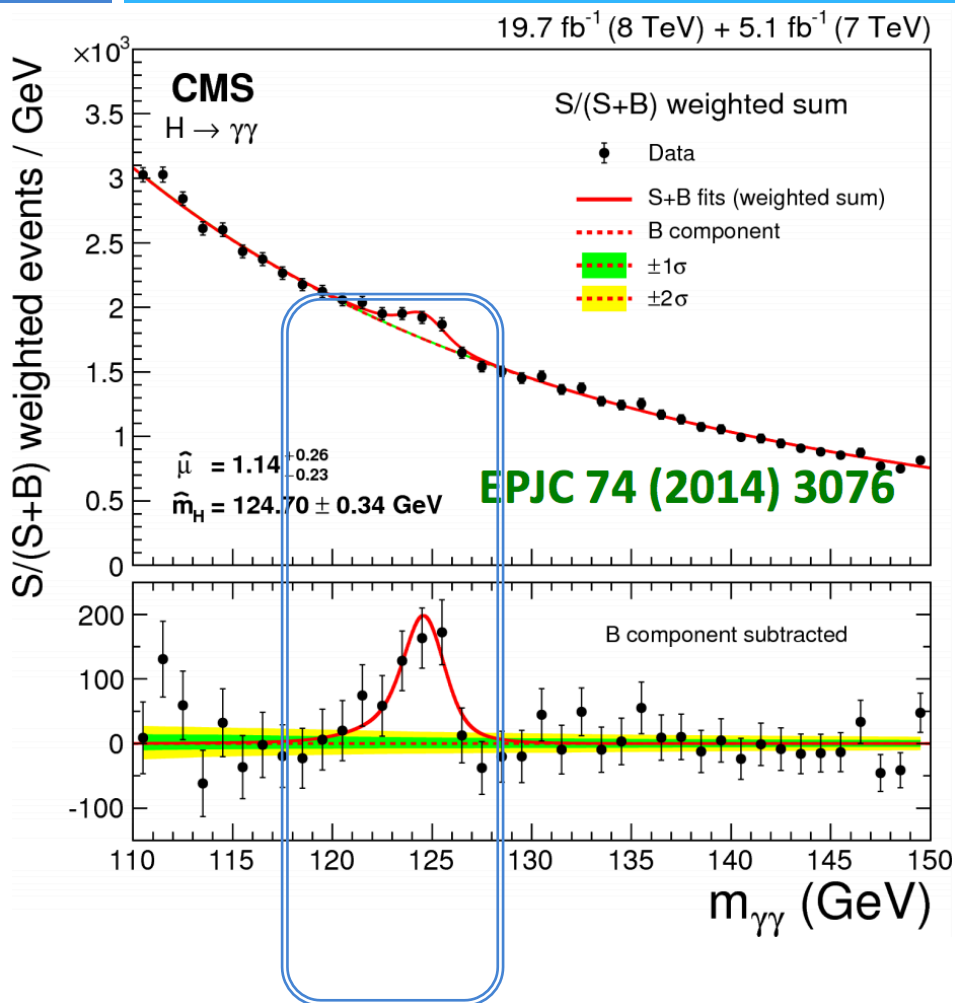
18

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_H^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) - i g s_w [\partial_\mu A_\nu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 - Z_\mu^0 W_\mu^- Z_\mu^0) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^2 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

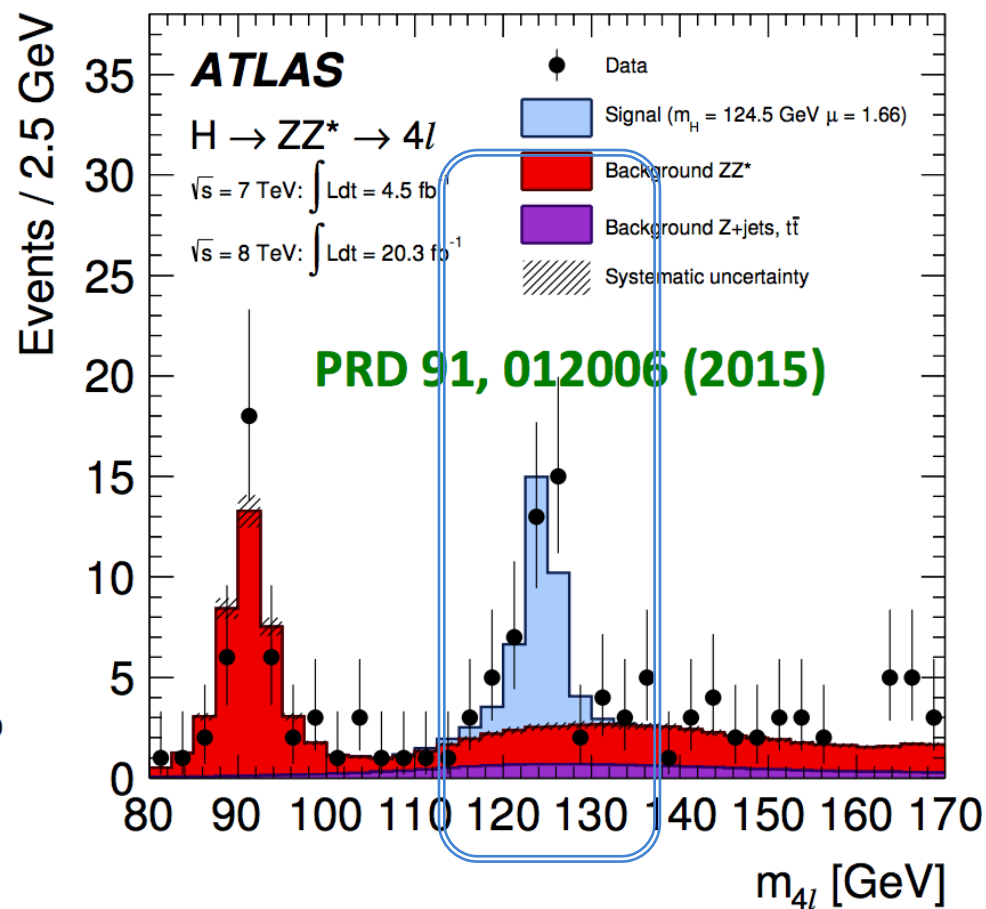
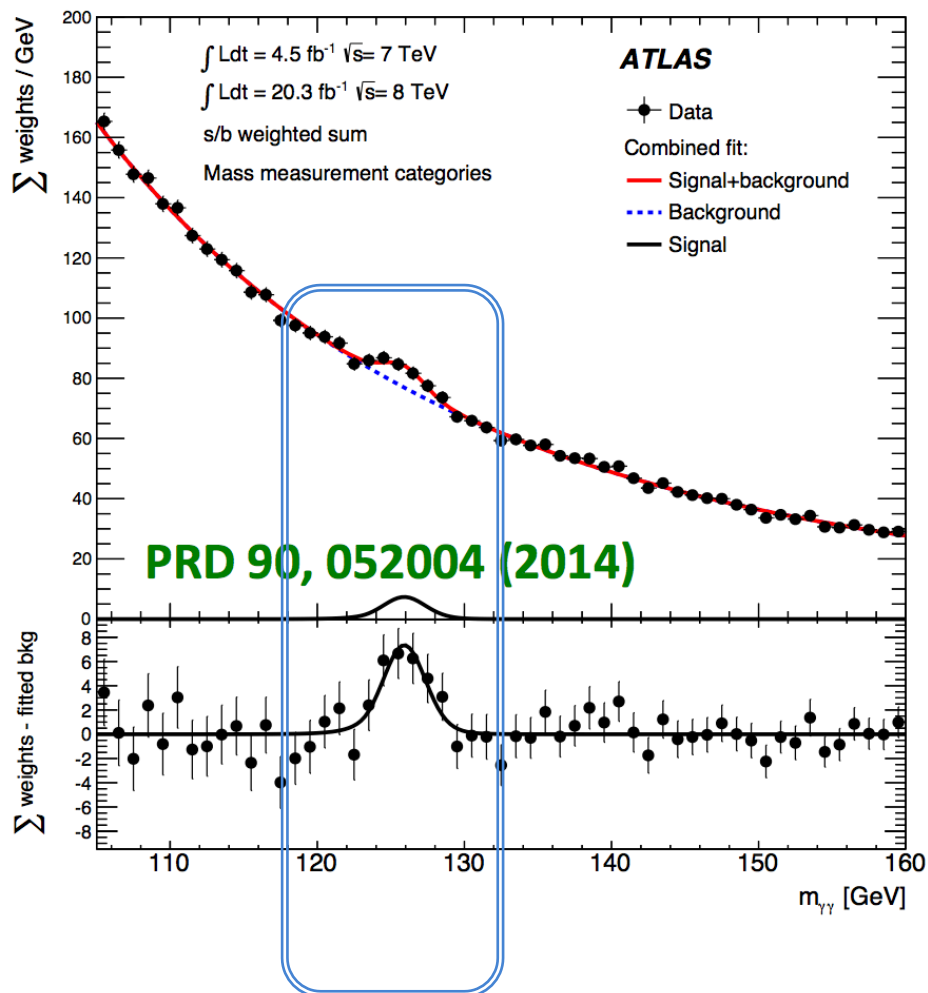
One missing parameter: m_H

Mass peaks: mass measurements



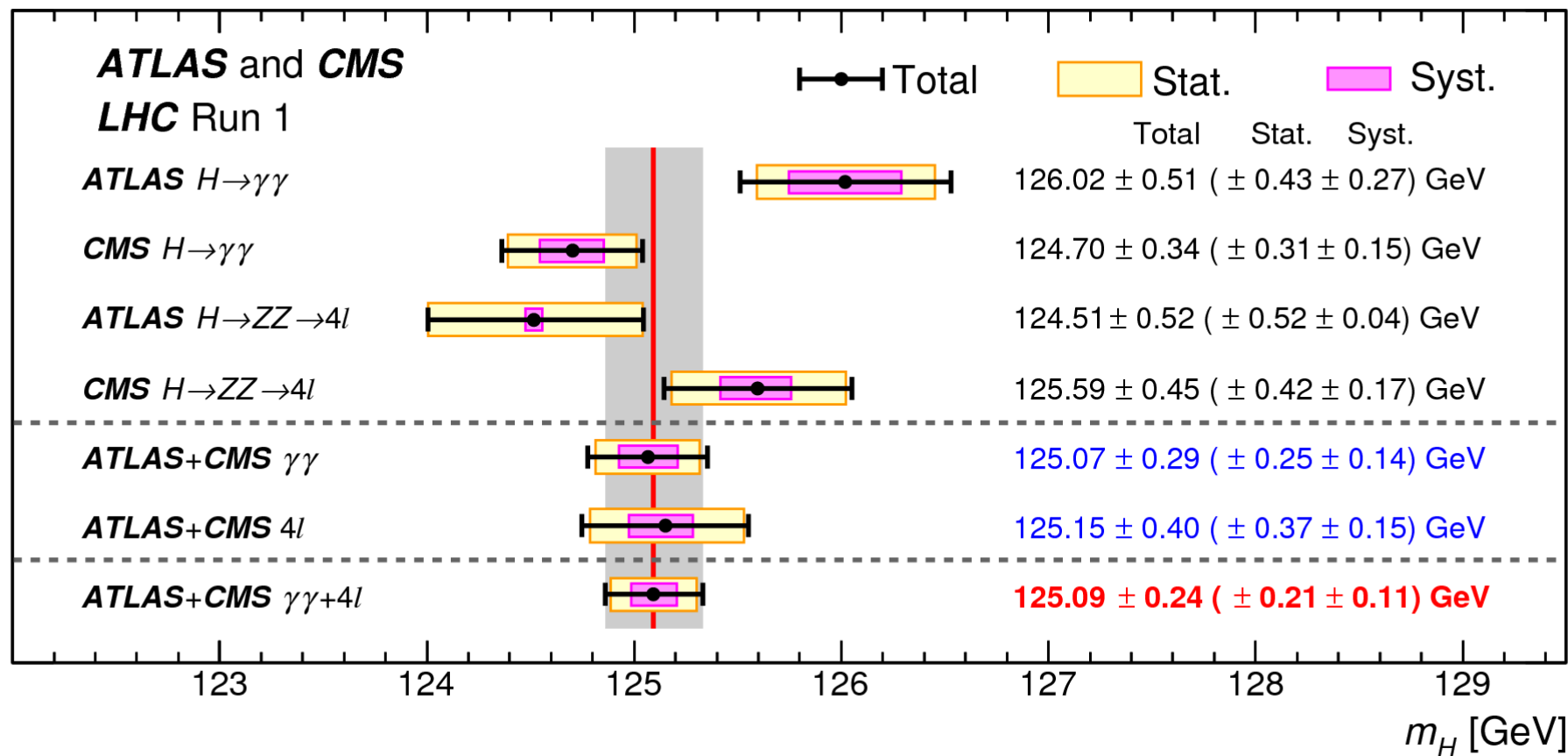
Mass peaks: mass measurements

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Combined LHC mass measurement

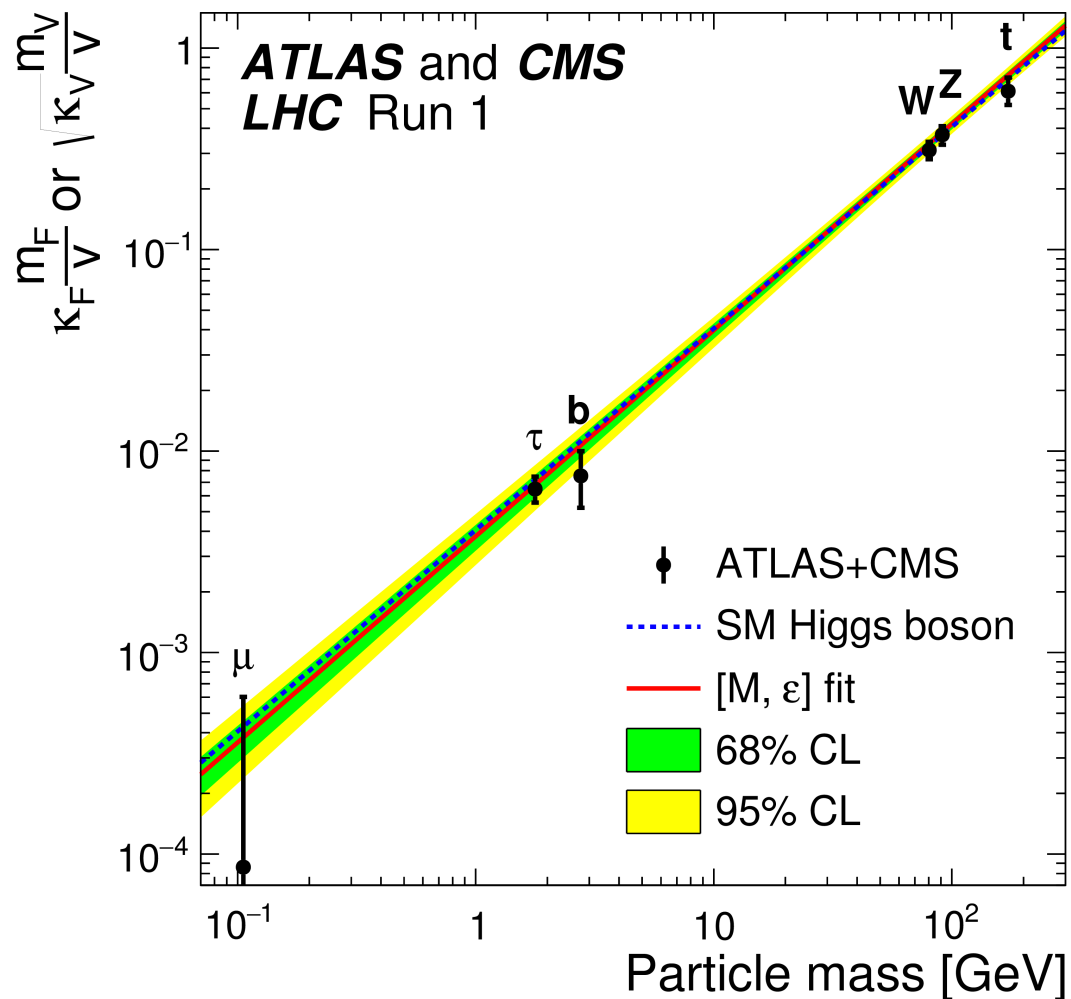
[arXiv:1503.07589]



Run 1 in two plots

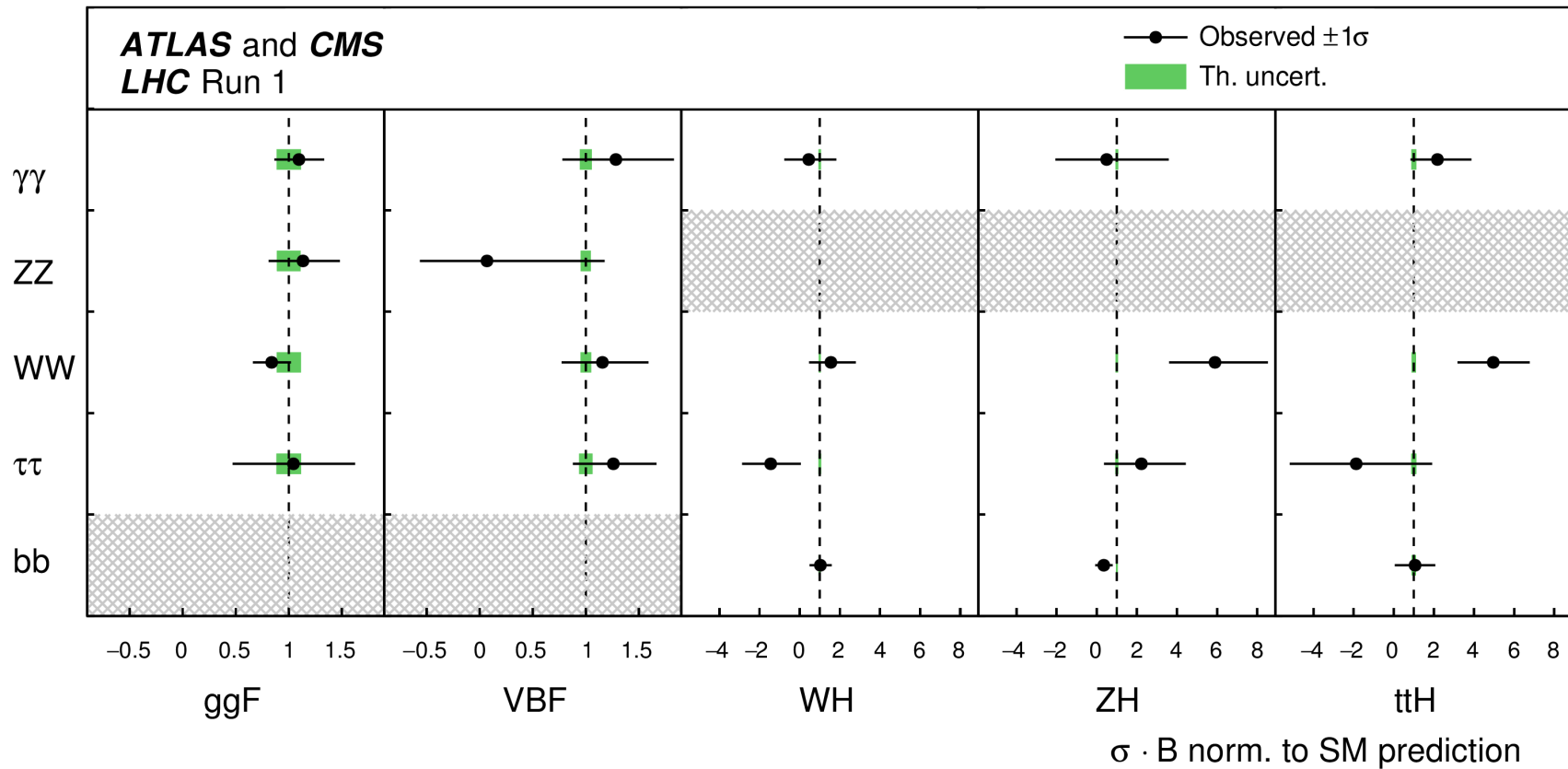
22

[JHEP 08 (2016) 045]



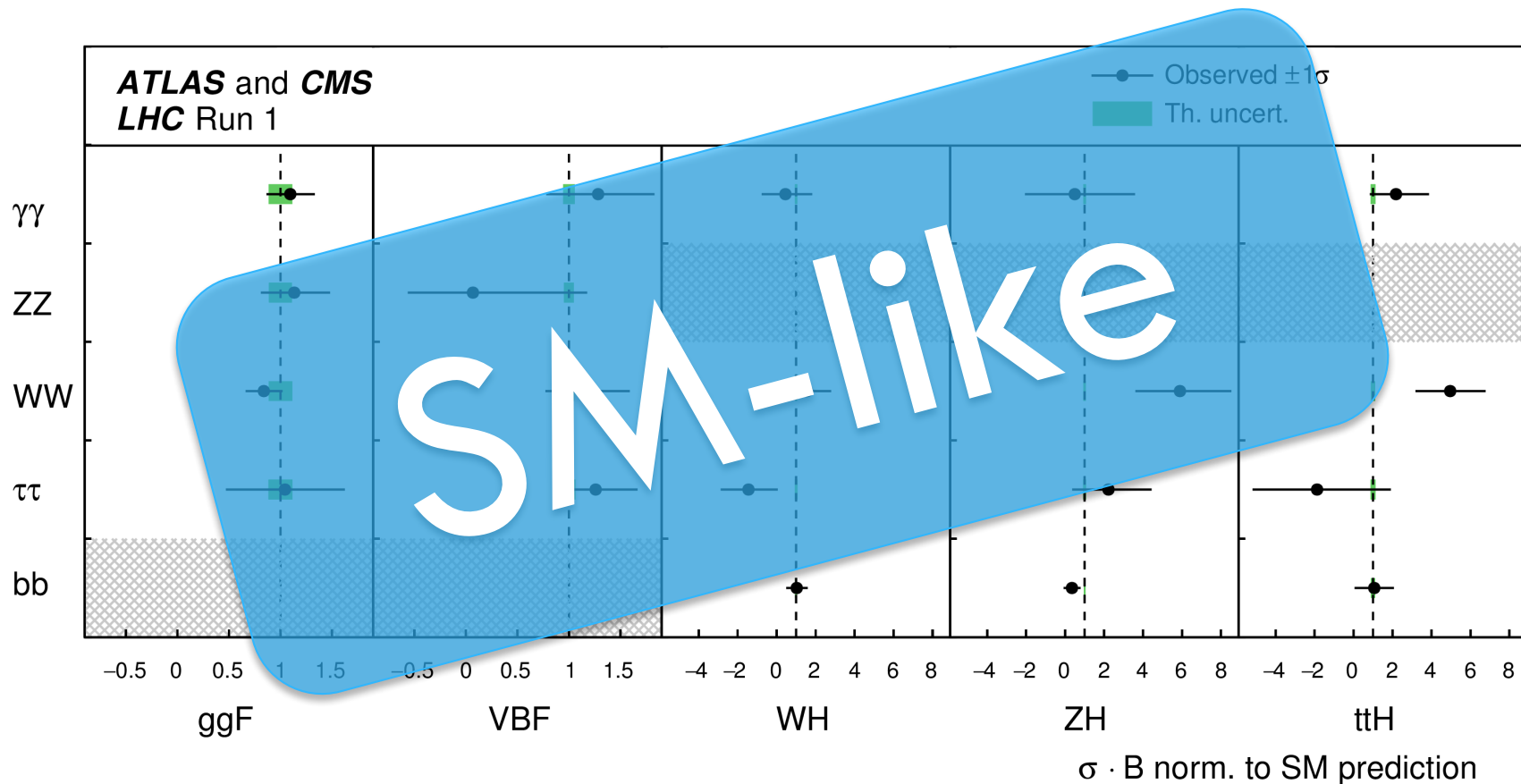
Run 1 in two plots

[JHEP 08 (2016) 045]

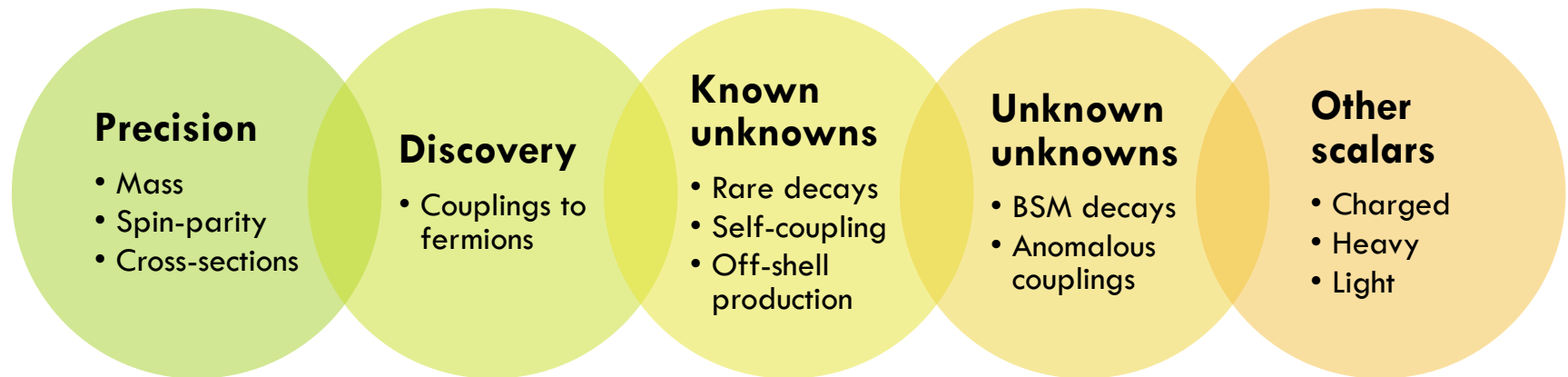


Run 1 in one word

[JHEP 08 (2016) 045]



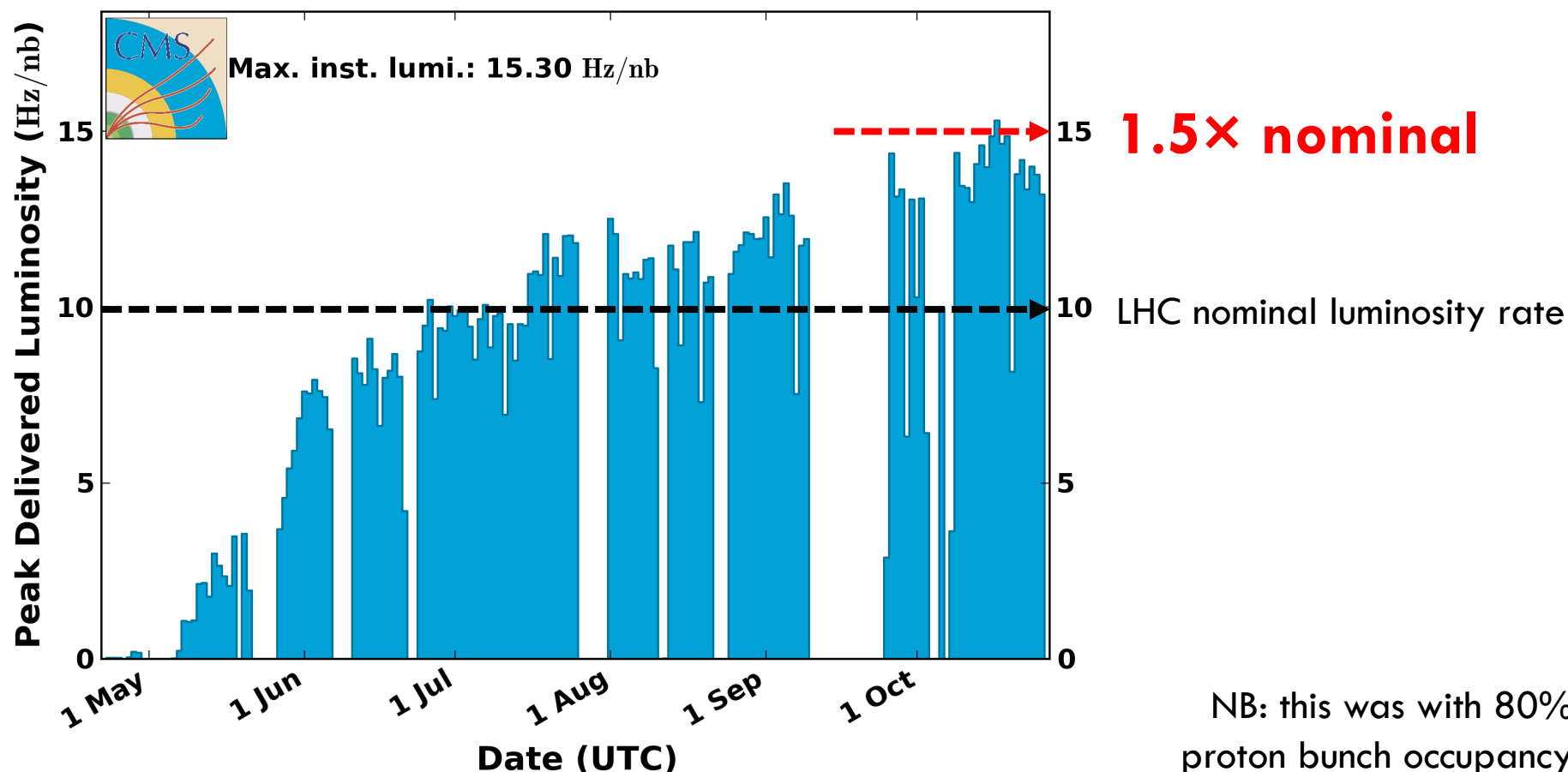
The Higgs Union spectrum after Run 1



LHC in Run 2: 2016

CMS Peak Luminosity Per Day, pp, 2016, $\sqrt{s} = 13$ TeV

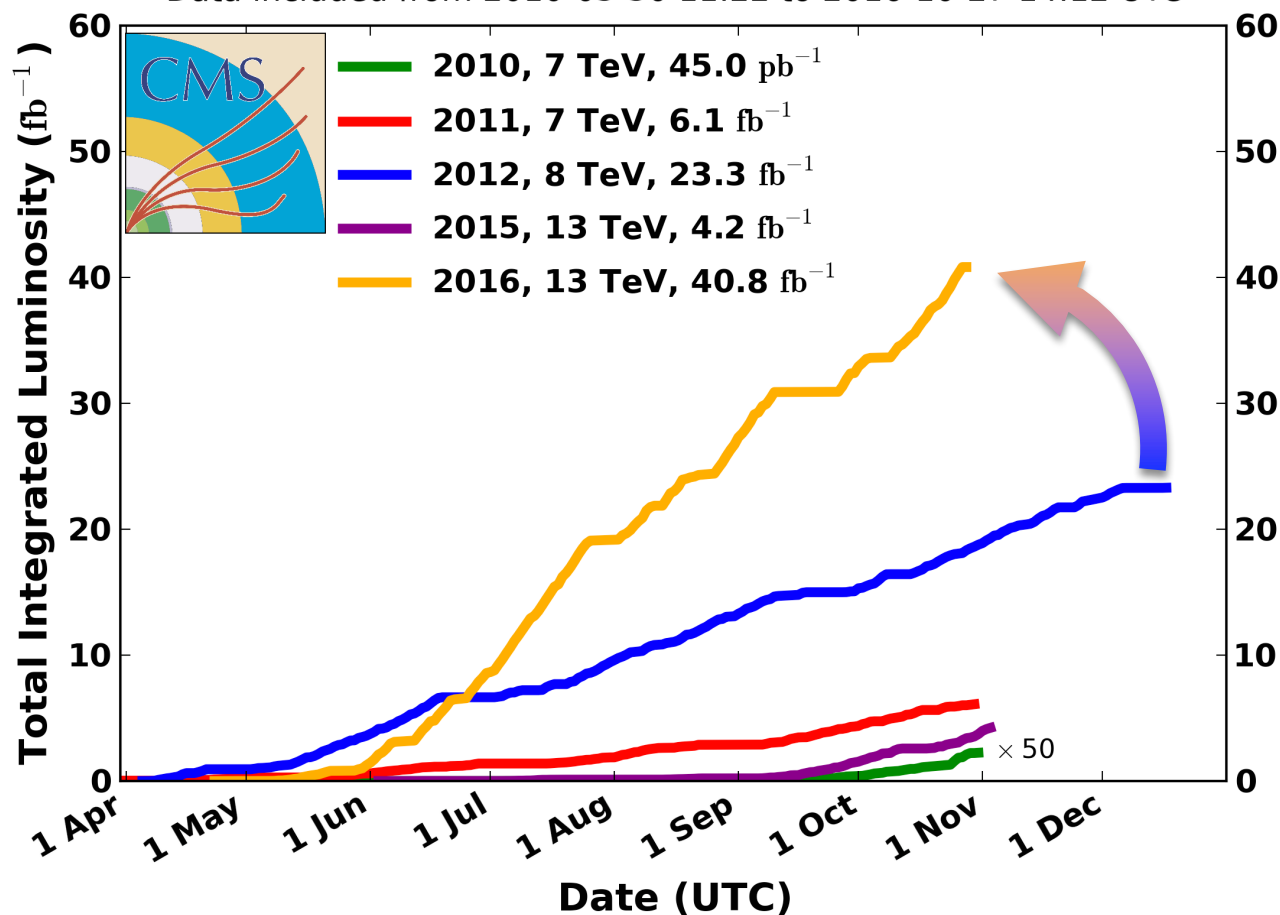
Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC



A large crop of data

CMS Integrated Luminosity, pp

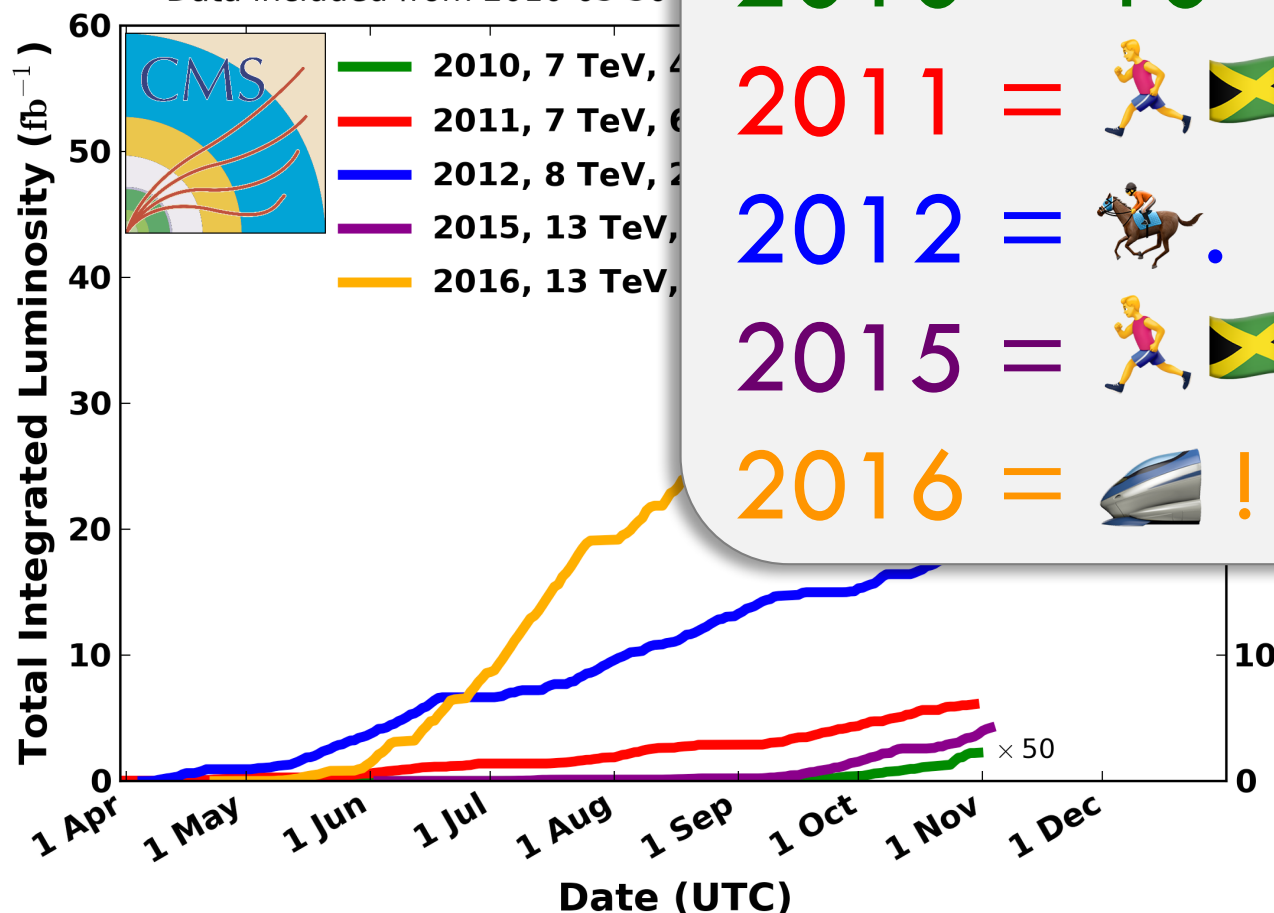
Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC



A fast crop of data

CMS Integrated Luminosity

Data included from 2010-03-30



2010 = 10 ×

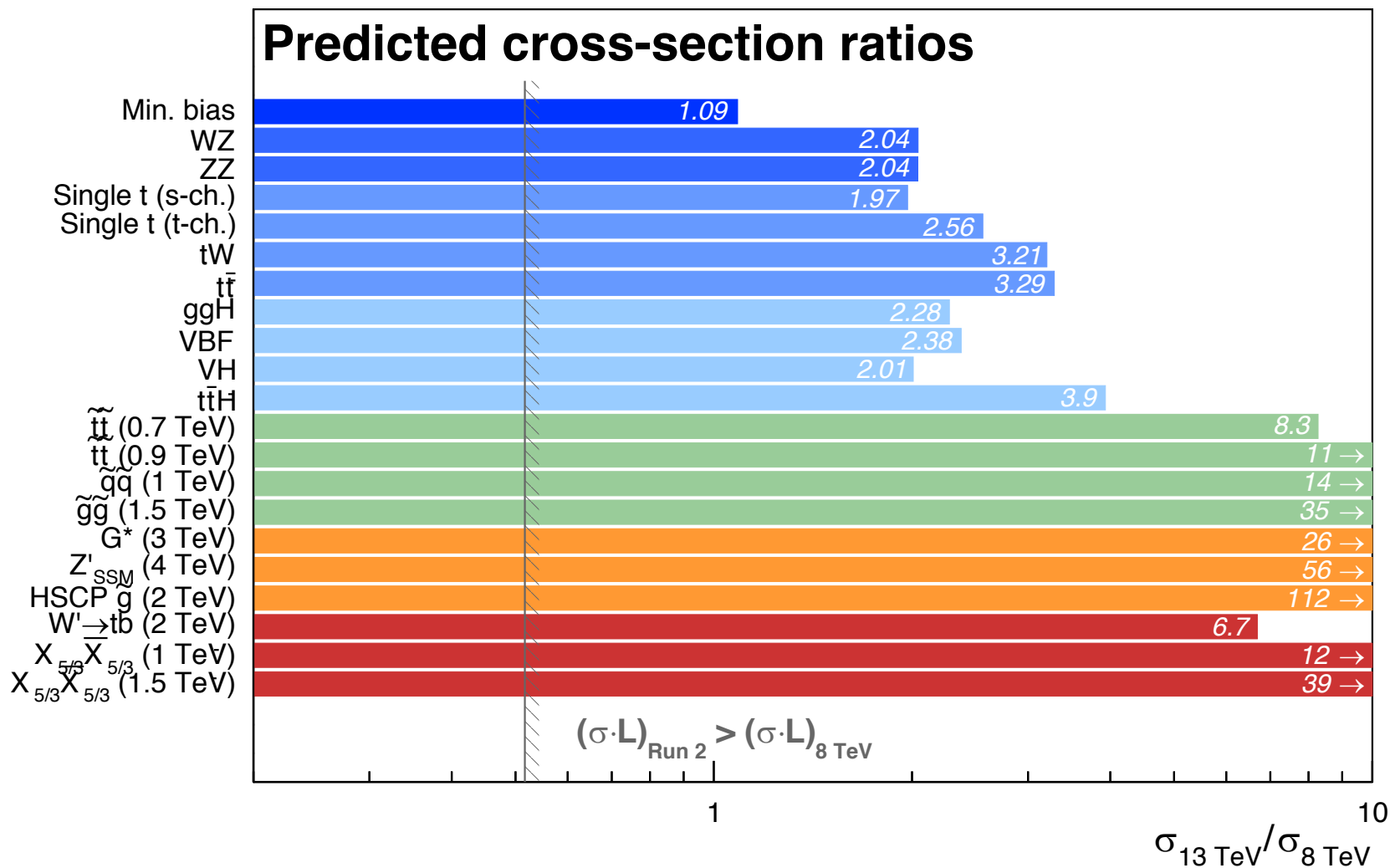
2011 =

2012 =

2015 = again.

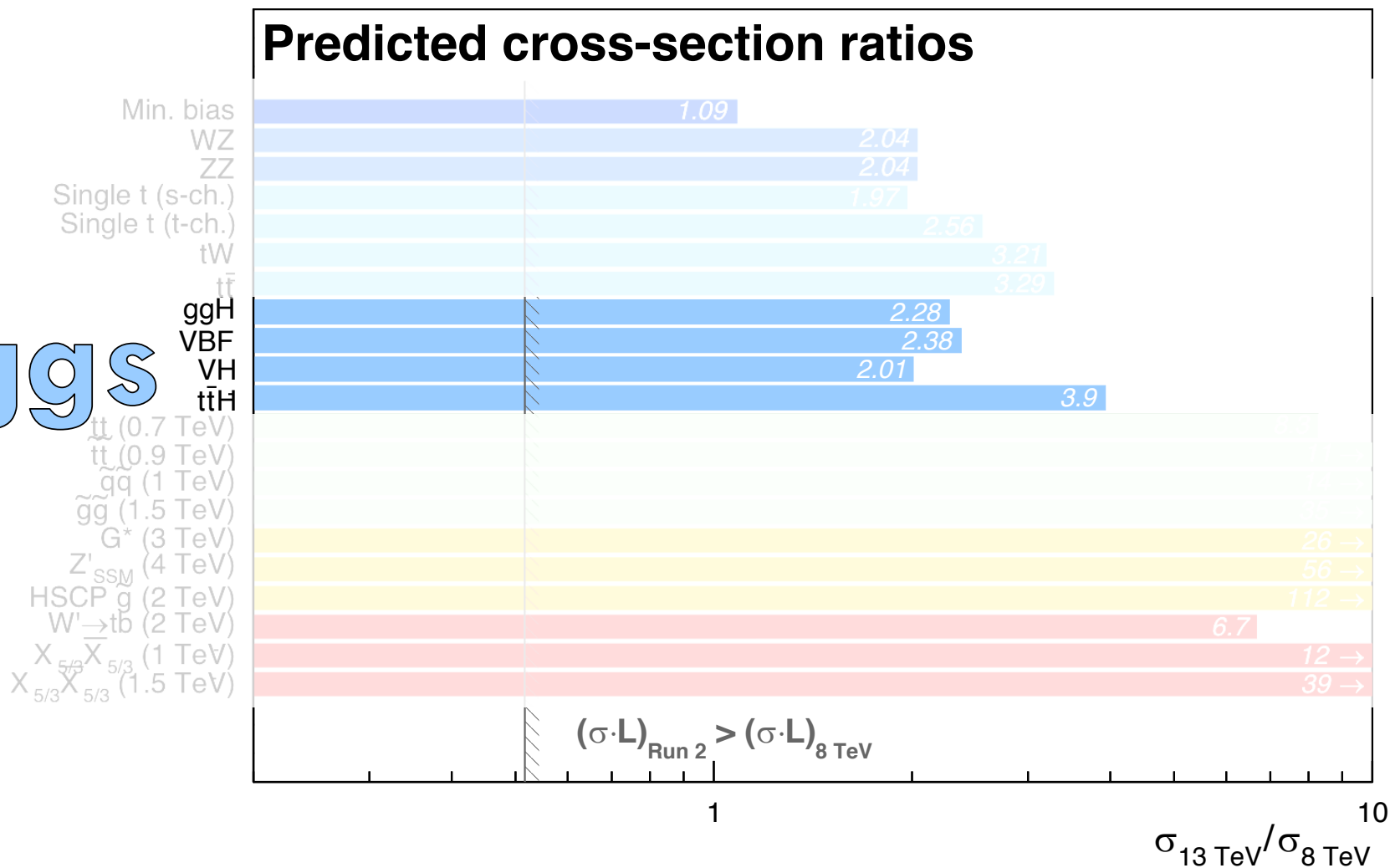
2016 = !

An excellent crop on all fronts



An excellent crop on all fronts

Higgs





Run 2 – one year of Higgs results

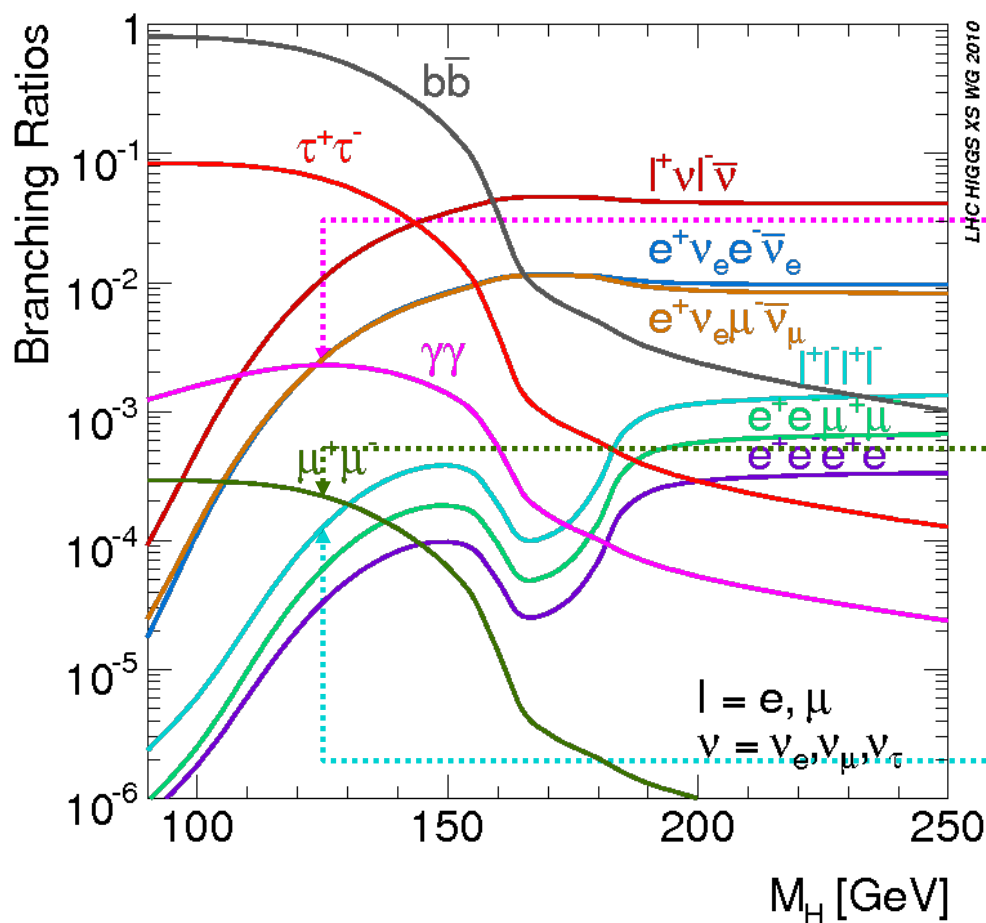
31

[<http://cern.ch/go/6qmZ>]

Full Title	Ref Code	Publication Date
h→γγ, ZZ, WW		
Measurement of fiducial, differential and production cross sections in the $H \rightarrow \gamma\gamma$ decay channel with 13.3 fb ⁻¹ of 13 TeV proton-proton collision data with the ATLAS detector	ATLAS-CONF-2016-067	2016/08/06
Study of the Higgs boson properties and search for high-mass scalar resonances in the $SH \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector	ATLAS-CONF-2016-079	2016/08/04
[NEW] Measurements of the Higgs Boson fiducial and differential cross sections in the 4l decay channel at 13 TeV with the ATLAS detector	ATLAS-CONF-2017-032	2017/05/15
Measurements of the Higgs boson production cross section via Vector Boson Fusion and associated SWH production in the $SWW^{*}(\text{last}) \rightarrow \ell\ell\nu\ell\nu\ell\nu$ decay mode with the ATLAS detector at $\sqrt{s} = 13$ TeV	ATLAS-CONF-2016-112	2016/11/10
h→bb, ττ, μμ		
[NEW] Search for the dimuon decay of the Higgs boson in $pp\bar{p}$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector	Inspire , arXiv , Figures	Submitted: 2017/05/11
Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a $b\bar{b}$ pair in $pp\bar{p}$ collisions at 13 TeV using the ATLAS detector	ATLAS-CONF-2016-091	2016/08/04
Search for Higgs boson production via weak boson fusion and decaying to $b\bar{b}$ in association with a high-energy photon using the ATLAS detector	ATLAS-CONF-2016-063	2016/08/03
"Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"	ATLAS-CONF-2016-080	2016/08/04
ttH		
Measurement of fiducial, differential and production cross sections in the $H \rightarrow \gamma\gamma$ decay channel with 13.3 fb ⁻¹ of 13 TeV proton-proton collision data with the ATLAS detector	ATLAS-CONF-2016-067	2016/08/06
Search for the Associated Production of a Higgs Boson and a Top Quark Pair in Multilepton Final States with the ATLAS Detector	ATLAS-CONF-2016-058	2016/08/03
"Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"	ATLAS-CONF-2016-080	2016/08/04
Combination of the searches for Higgs boson production in association with top quarks in the $\gamma\gamma\gamma$, multilepton, and $b\bar{b}b\bar{b}$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS Detector	ATLAS-CONF-2016-068	2016/08/03
Combination		
Combination of the searches for Higgs boson production in association with top quarks in the $\gamma\gamma\gamma$, multilepton, and $b\bar{b}b\bar{b}$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS Detector	ATLAS-CONF-2016-068	2016/08/03
Combined measurements of the Higgs boson production and decay rates in $H \rightarrow ZZ^{*} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ final states using pp collision data at $\sqrt{s} = 13$ TeV in the ATLAS experiment	ATLAS-CONF-2016-081	2016/08/06
Rare and BSM production or decay		
Search for new phenomena in the $Z(\rightarrow \ell\ell) + E_T^{\text{miss}}$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector	ATLAS-CONF-2016-056	2016/08/03
[NEW] Search for dark matter in association with a Higgs boson decaying to two photons at $\sqrt{s} = 13$ TeV with the ATLAS detector	Inspire , arXiv , Figures	Submitted: 2017/06/13
[NEW] Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ at $\sqrt{s} = 13$ TeV with the ATLAS Detector	ATLAS-CONF-2017-028	2017/04/02
[PUBLISHED] Search for Higgs and ZS Boson Decays to $\phi\eta/\eta\gamma$ with the ATLAS Detector	Phys. Rev. Lett. 117, 111802 , Inspire , arXiv , Figures	(Submitted: 2016/07/12)
[PUBLISHED] Search for the Higgs boson produced in association with a SW boson and decaying to four $b\bar{b}$ -quarks via two spin-zero particles in $pp\bar{p}$ collisions at 13 TeV with the ATLAS detector	Eur. Phys. J. C 76 (2016) 605 , Inspire , arXiv , Figures	(Submitted: 2016/06/27)
Search for long-lived neutral particles decaying into displaced lepton-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector	ATLAS-CONF-2016-042	2016/08/02
[NEW] Search for direct top squark pair production in events with a Higgs or ZS boson, and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp\bar{p}$ collisions with the ATLAS detector	Inspire , arXiv , Figures	Submitted: 2017/06/13

Recent Higgs Physics Preliminary Results		
CMS-PAS-HIG-17-015	Measurement of differential fiducial cross sections for Higgs boson production in the diphoton decay channel in pp collisions at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-17-006	Search for resonant and non-resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-17-003	Search for the associated production of a Higgs boson with a top quark pair in final states with a τ lepton at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-16-041	Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-17-004	Search for Higgs boson production in association with top quarks in multilepton final states at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-17-011	Constraints on anomalous Higgs boson couplings in production and decay $H \rightarrow 4\ell$	March 2017
CMS-PAS-HIG-17-002	Search for pair production of Higgs bosons in the two tau leptons and two bottom quarks final state using proton-proton collisions at $\sqrt{s} = 13$ TeV	March 2017
CMS-PAS-HIG-16-034	Search for new diboson resonances in the dilepton+jets final state at $\sqrt{s} = 13$ TeV with 2016 data	January 2017
CMS-PAS-HIG-16-036	A search for doubly-charged Higgs boson production in three and four lepton final states at $\sqrt{s} = 13$ TeV	January 2017
CMS-HIG-16-018	Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at $\sqrt{s} = 8$ TeV	8 January 2017
CMS-PAS-HIG-16-035	A search for beyond Standard Model light bosons decaying into muon pairs	November 2016
CMS-PAS-HIG-16-038	Search for $\tilde{\chi}_1^0$ production in the $H \rightarrow h\tilde{b}\tilde{b}$ decay channel with 2016 pp collision data at $\sqrt{s} = 13$ TeV	November 2016
CMS-PAS-HIG-16-037	Search for a neutral MSSM Higgs boson decaying into $\tau\tau$ with 12.9 fb ⁻¹ of data at $\sqrt{s} = 13$ TeV	November 2016
CMS-PAS-HIG-16-031	Search for charged Higgs bosons with the $H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ decay channel in the fully hadronic final state at $\sqrt{s} = 13$ TeV	October 2016
CMS-PAS-HIG-15-009	Search for a light pseudo-scalar Higgs boson produced in association with top quarks in pp collisions at $\sqrt{s} = 8$ TeV	October 2016
CMS-PAS-HIG-16-026	Search for non-resonant pair production of Higgs bosons in the $h\bar{h}\bar{b}\bar{b}$ final state with 13 TeV CMS data	August 2016
CMS-PAS-HIG-16-030	Search for $H^{\pm} \rightarrow \tilde{\chi}_1^0 b$ in lepton+jets channel using top quark pair events	August 2016
CMS-PAS-HIG-16-032	Search for $H(h)\bar{H}(\bar{h})\gamma\gamma$ decays at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-024	Search for Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-022	Search for associated production of Higgs bosons and top quarks in multilepton final states at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-020	Updated measurements of Higgs boson production in the diphoton decay channel at $\sqrt{s} = 13$ TeV in pp collisions at CMS.	August 2016
CMS-PAS-HIG-16-023	Search for high mass Higgs to WW with fully leptonic decays using 2015 data	August 2016
CMS-PAS-HIG-16-029	Search for resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state using 2016 data	August 2016
CMS-PAS-HIG-16-027	Search for non-resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state using 2016 data	August 2016
CMS-PAS-HIG-16-025	Search for a narrow heavy resonance decaying to bottom quark-antiquark pairs at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-033	Measurements of properties of the Higgs boson and search for an additional resonance in the four-lepton final state at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-019	Search for $H \rightarrow h\tilde{b}$ in association with a single top quark as a test of Higgs boson couplings at $\sqrt{s} = 13$ TeV	August 2016
CMS-PAS-HIG-16-027	Search for charged Higgs bosons in WZ decays at 13 TeV	August 2016
CMS-PAS-HIG-16-016	Searches for invisible Higgs boson decays with the CMS detector	JHEP 02 (2017) 136 July 2016
CMS-PAS-HIG-15-003	First results on Higgs to WW at $\sqrt{s} = 13$ TeV	June 2016
CMS-PAS-HIG-16-006	Search for a neutral MSSM Higgs boson decaying into $\tau\tau$ at 13 TeV	June 2016
CMS-PAS-HIG-16-003	Search for the standard model Higgs boson produced through vector boson fusion and decaying to $b\bar{b}$ with proton-proton collisions at $\sqrt{s} = 13$ TeV	June 2016
CMS-PAS-HIG-16-005	Search for lepton flavour violating decays of the Higgs boson in the $\mu\mu$ final state at 13 TeV	June 2016
CMS-HIG-14-032	Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width	JHEP 09 (2016) 051 8 May 2016
CMS-PAS-HIG-16-009	Search for invisible decays of a Higgs boson produced via vector boson fusion at $\sqrt{s} = 13$ TeV.	March 2016
CMS-PAS-HIG-16-007	Summary results of high mass BSM Higgs searches using CMS Run-1 data	March 2016
CMS-PAS-HIG-16-011	Search for resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state at $\sqrt{s} = 13$ TeV	March 2016
CMS-PAS-HIG-15-008	Search for $\tilde{\chi}_1^0$ production in multilepton final states at $\sqrt{s} = 13$ TeV	March 2016
CMS-PAS-HIG-16-002	Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 13 TeV	March 2016
CMS-PAS-HIG-15-005	First results on Higgs to $\gamma\gamma$ at 13 TeV	March 2016
CMS-PAS-HIG-16-010	Search for Z to $Z(h) + A(b\bar{b})$ with 2015 data	March 2016
CMS-PAS-HIG-16-014	Search for scalar resonances in the 200-1200 GeV mass range decaying into a Z and a photon in pp collisions at $\sqrt{s} = 8$ TeV	March 2016
CMS-PAS-HIG-16-001	Search for a heavy scalar boson decaying into a pair of Z bosons in the $Z\bar{Z}2\mu$ final state	March 2016
CMS-PAS-HIG-15-004	Studies of Higgs boson production in the four-lepton final state at $\sqrt{s} = 13$ TeV	March 2016
CMS-PAS-HIG-16-004	Search for $\tilde{\chi}_1^0$ production in the $H \rightarrow h\tilde{b}$ decay channel with $\sqrt{s} = 13$ TeV pp collisions at the CMS experiment	March 2016
CMS-PAS-HIG-15-013	Model independent search for Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state	March 2016
CMS-PAS-HIG-16-012	Search for non-resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state	March 2016
CMS-PAS-HIG-16-013	Search for resonant Higgs boson pair production in the $h\bar{h} \rightarrow \gamma\gamma$ final state	March 2016
CMS-PAS-HIG-16-008	Search for invisible Higgs bosons in $pp \rightarrow ZH \rightarrow 2\ell + \cancel{E}_T^{\text{miss}}$ channels at $\sqrt{s} = 13$ TeV	March 2016
CMS-PAS-HIG-14-041	Search for exotic decays of the Higgs boson to a pair of new light bosons with two muon and two b jets in final states	March 2016

More luminosity benefits the lowest BR



$$H \rightarrow \gamma\gamma$$

$$H \rightarrow \mu\mu$$

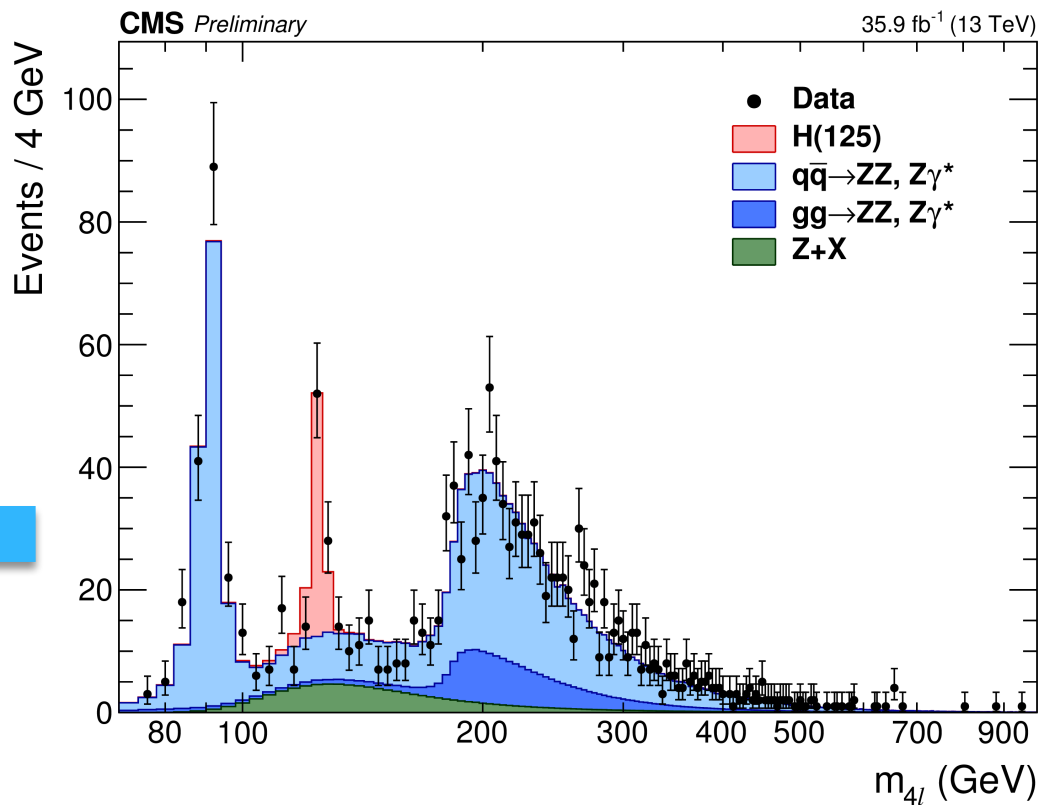
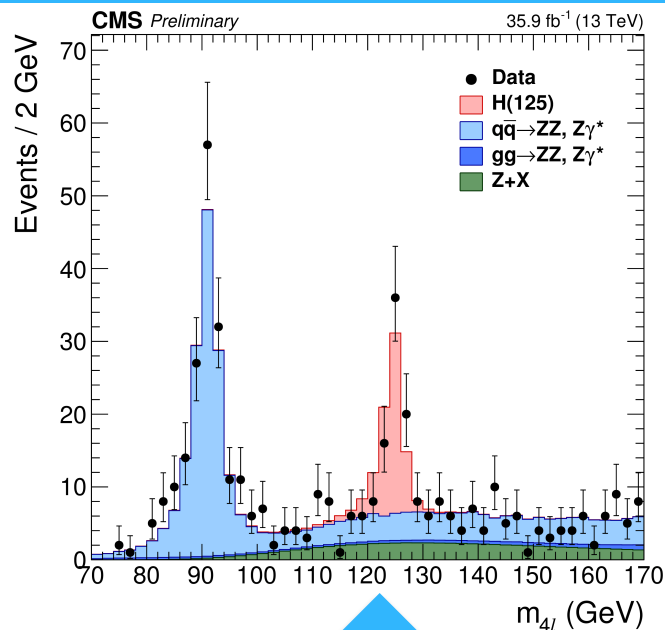
$$H \rightarrow ZZ^* \rightarrow 4\ell$$



$$H \rightarrow ZZ^* \rightarrow 4\ell$$

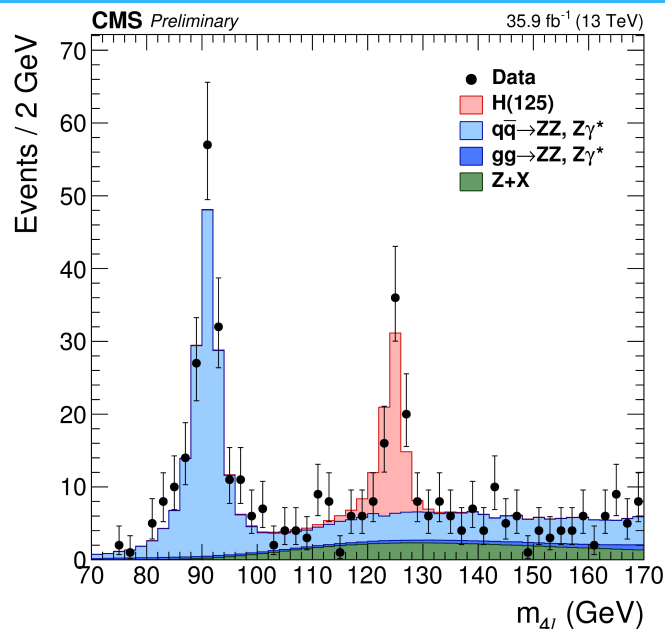
33

[CMS-PAS-HIG-16-041]



$H \rightarrow ZZ^* \rightarrow 4\ell$ mass

[CMS-PAS-HIG-16-041]

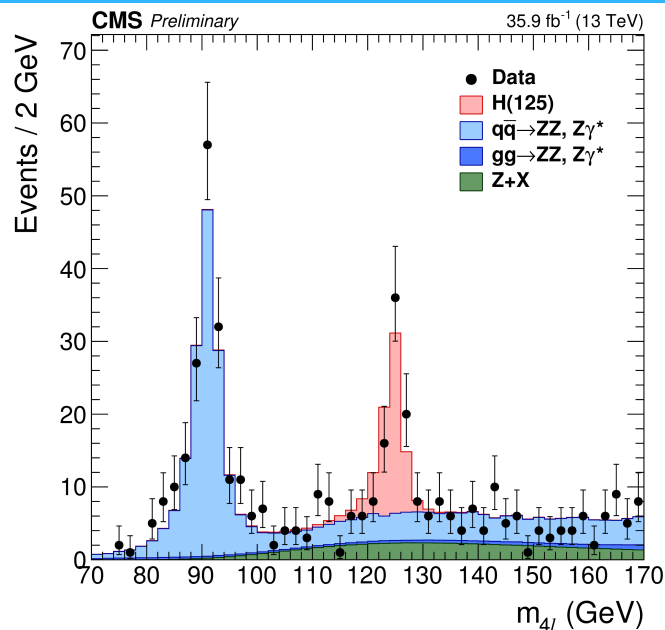


- m_{4l}' : Z_1 mass likelihood based on Higgs signal shape.
- D'_{mass} : Per-event estimated mass resolution.
- $D^{\text{kin}}_{\text{bkg}}$: Background discriminant.

No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4l})$
Expected m_H uncertainty change	+8.1%	+11.2%	+21%
Observed m_H (GeV)	125.28 ± 0.22	125.36 ± 0.24	125.39 ± 0.25
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected m_H uncertainty change	—	+3.2%	+10.7%
Observed m_H (GeV)	125.26 ± 0.21	125.30 ± 0.21	125.34 ± 0.23

$H \rightarrow ZZ^* \rightarrow 4\ell$ mass

[CMS-PAS-HIG-16-041]



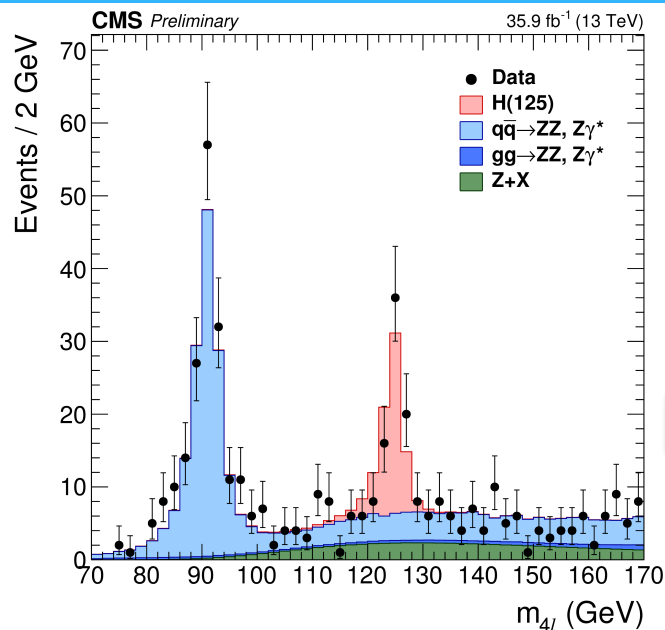
□ Very precise:

- **NB:** 49 MeV ($\sim 20\%$) better than expected.
- $\sim 10\%$ better than ATLAS+CMS Run 1 combination, by chance.

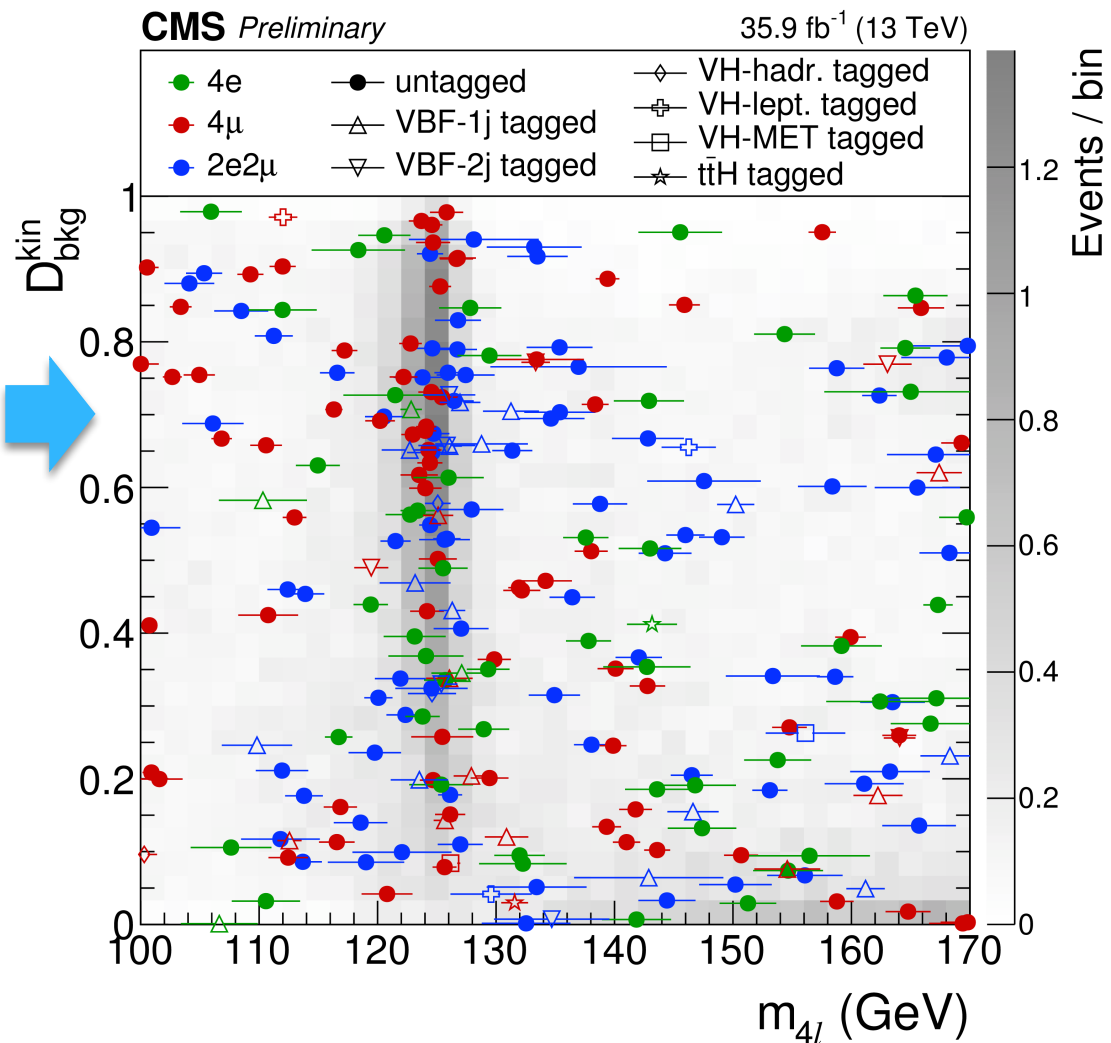
No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4l})$
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With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected m_H uncertainty change	—	+3.2%	+10.7%
Observed m_H (GeV)	125.26 ± 0.21	125.30 ± 0.21	125.34 ± 0.23

$H \rightarrow ZZ^* \rightarrow 4\ell$ production tags

[CMS-PAS-HIG-16-041]



□ Split events using production-specific discriminators.

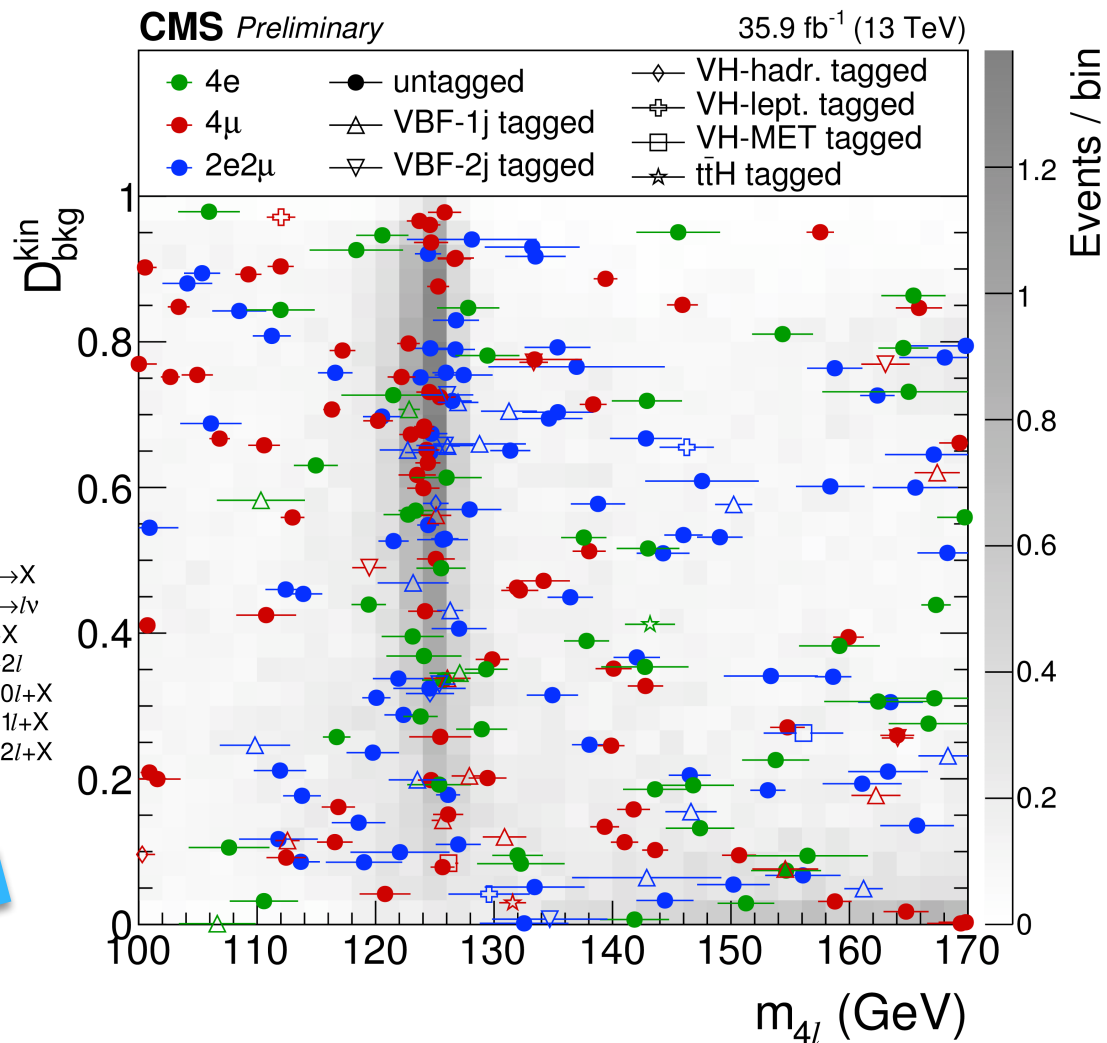
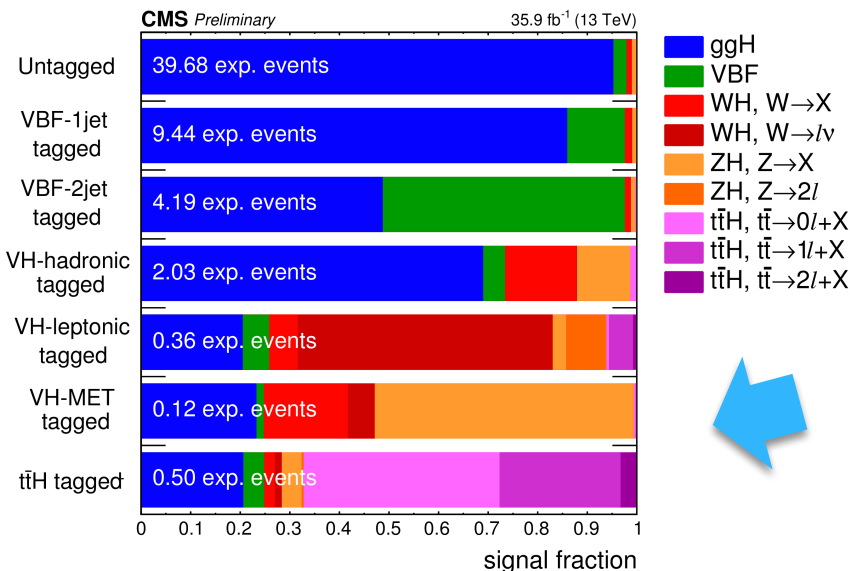


$H \rightarrow ZZ^* \rightarrow 4\ell$ production tags

[CMS-PAS-HIG-16-041]

□ Categorization provides **some** discrimination between production processes, but:

- **ggH** still pervasive.
- Statistics low in most exclusive categories.

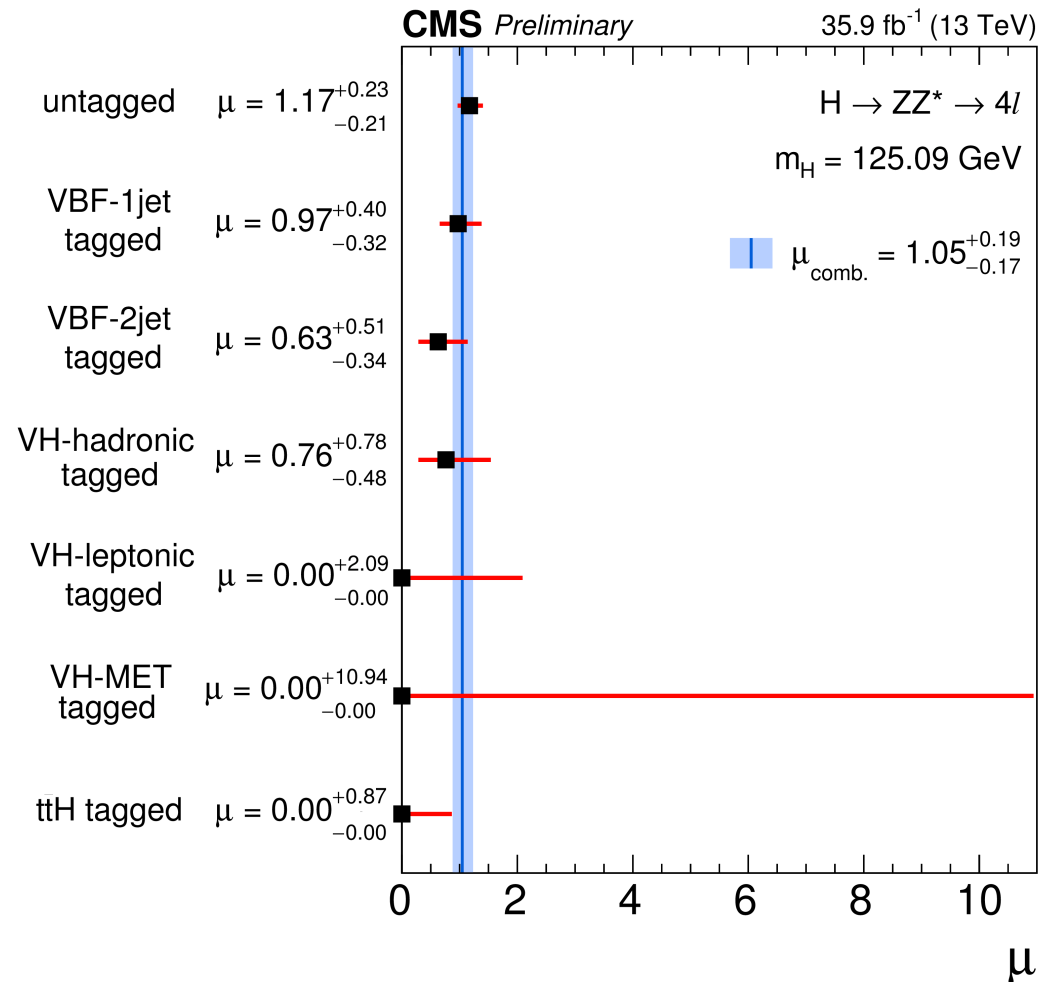
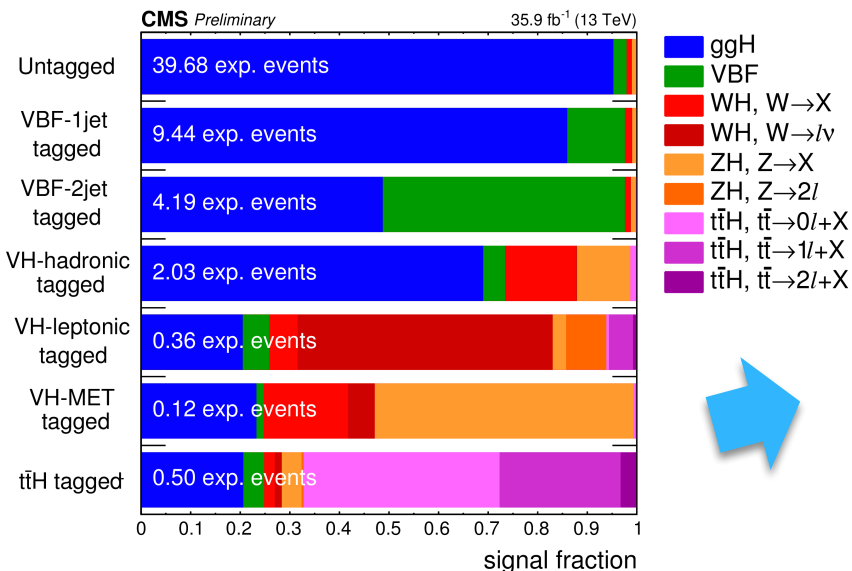




$H \rightarrow ZZ^* \rightarrow 4\ell$ production tags

[CMS-PAS-HIG-16-041]

- Most exclusive categories have low statistics.
- Useful in combinations.
- Set limits on specific processes.

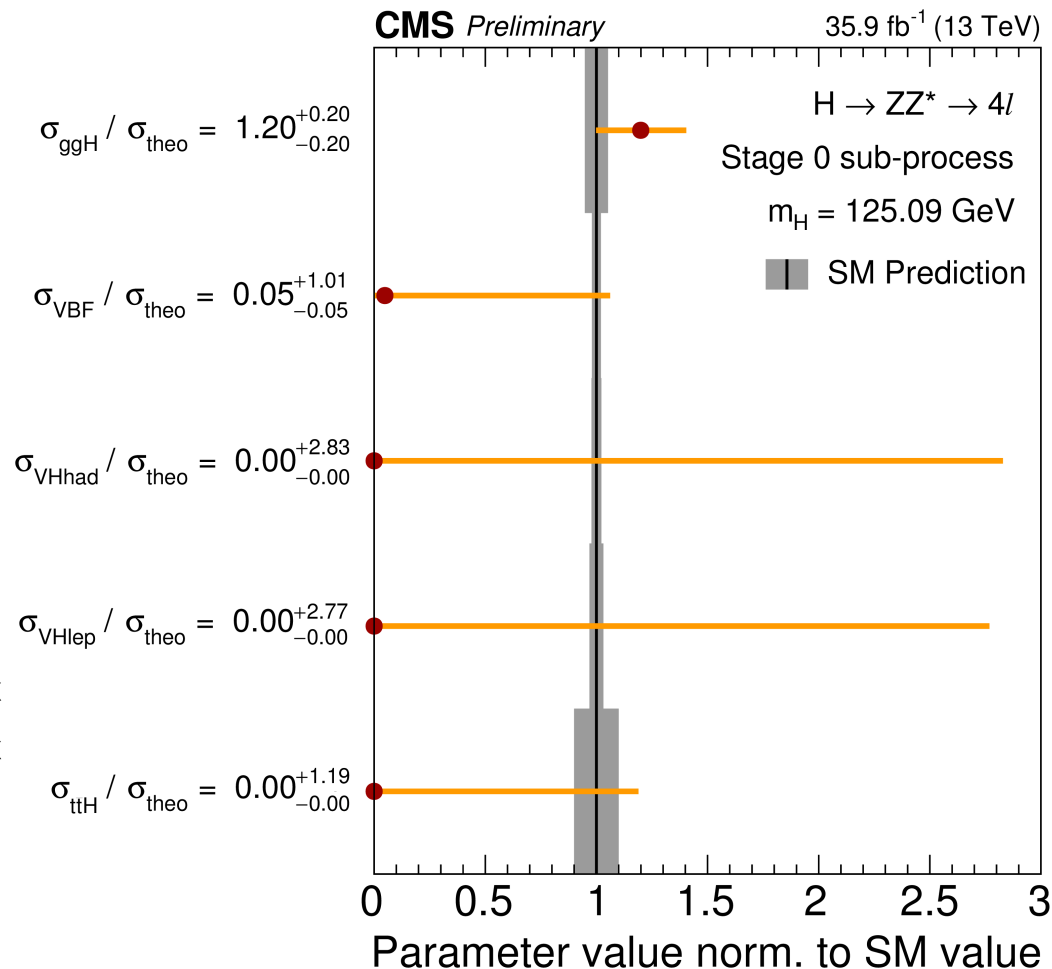
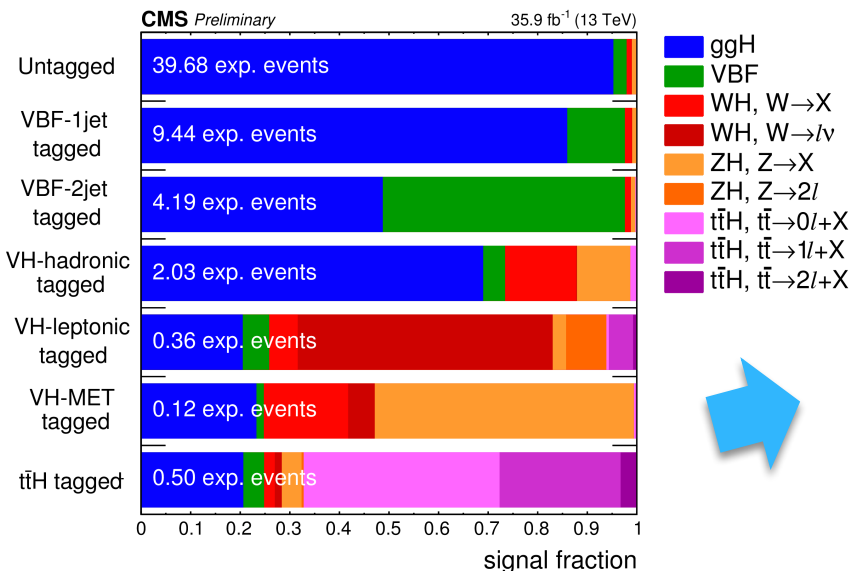




$H \rightarrow ZZ^* \rightarrow 4\ell$ template cross-sections

[CMS-PAS-HIG-16-041]

- Excess in untagged category reduces associated production processes.

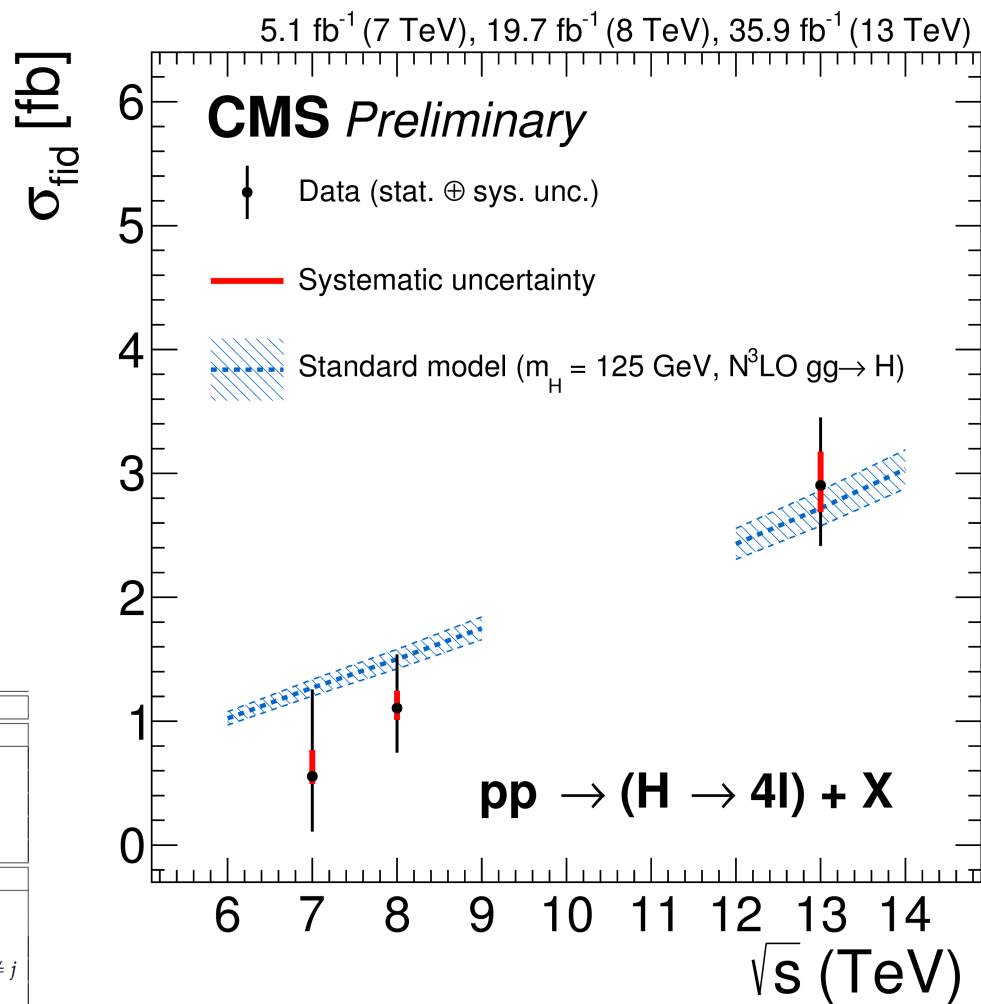


$H \rightarrow ZZ^* \rightarrow 4\ell$ fiducial integral

[CMS-PAS-HIG-16-041]

“finally an excess”

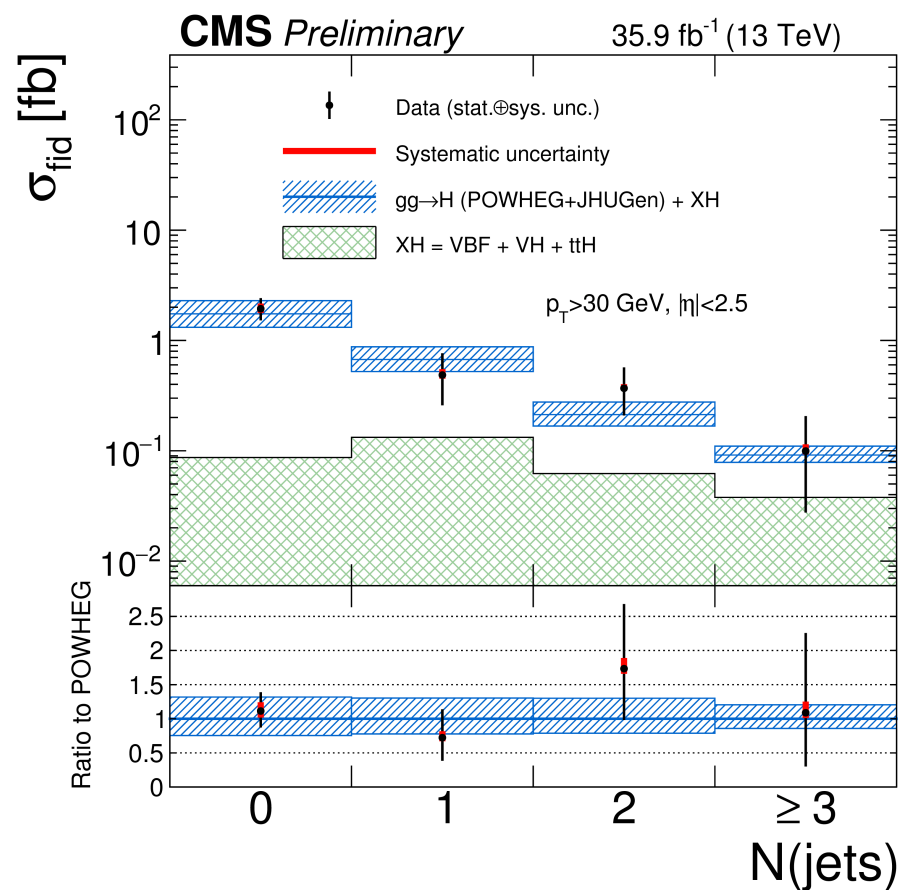
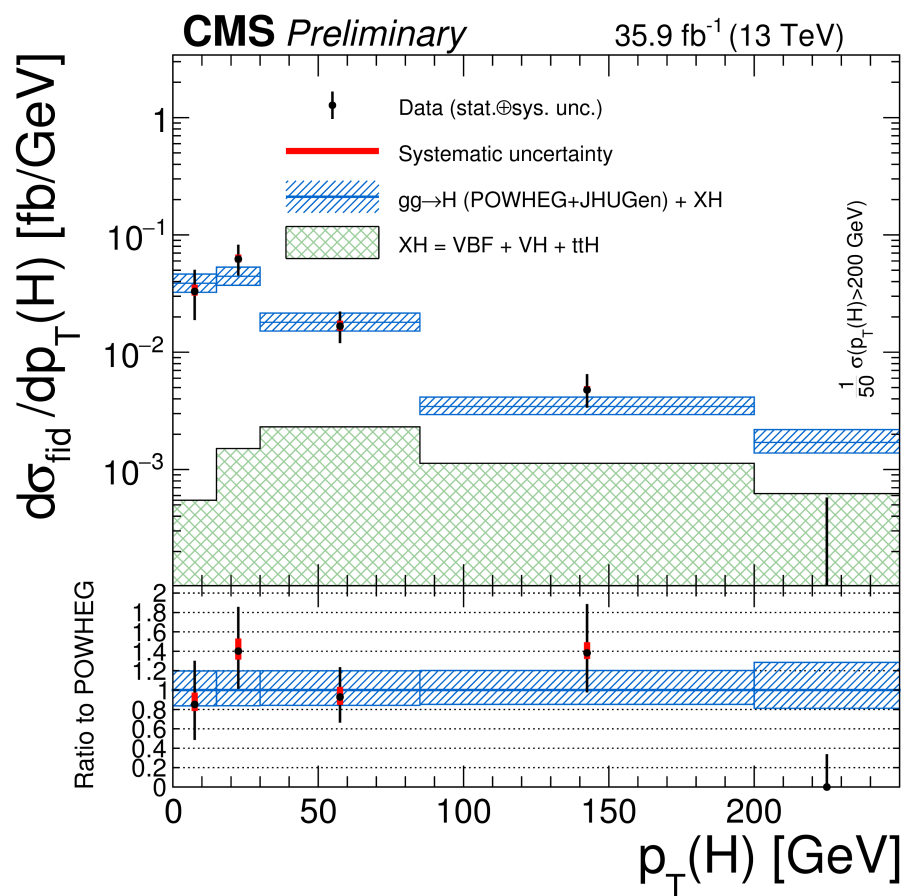
Requirements for the $H \rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$ \eta < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 \text{ GeV} < m_{Z_1} < 120 \text{ GeV}$
Inv. mass of the Z_2 candidate	$12 \text{ GeV} < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell^-} > 4 \text{ GeV}$
Inv. mass of the selected four leptons	$105 \text{ GeV} < m_{4\ell} < 140 \text{ GeV}$



$H \rightarrow ZZ^* \rightarrow 4\ell$ fiducial differential

41

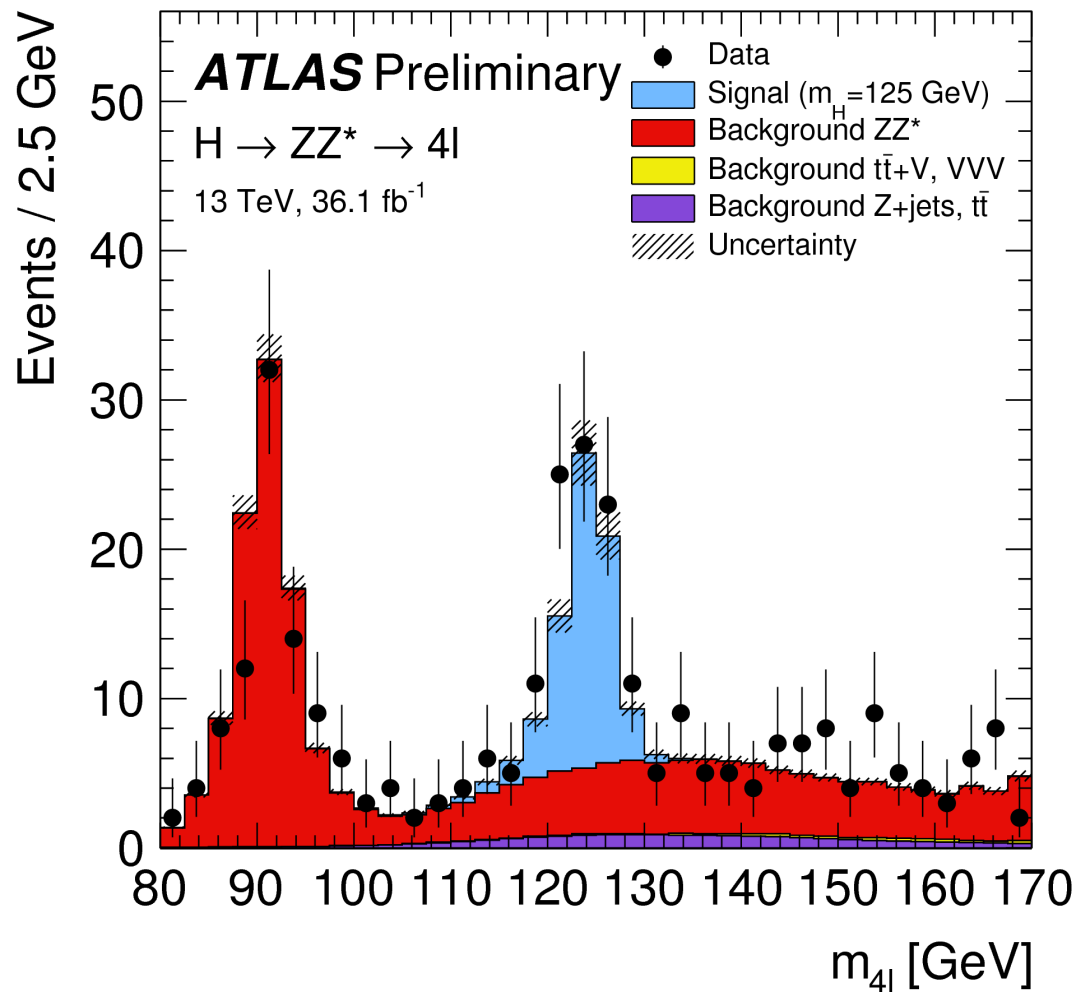
[CMS-PAS-HIG-16-041]



□ No particular deviation, cf. some Run 1 fluctuations.

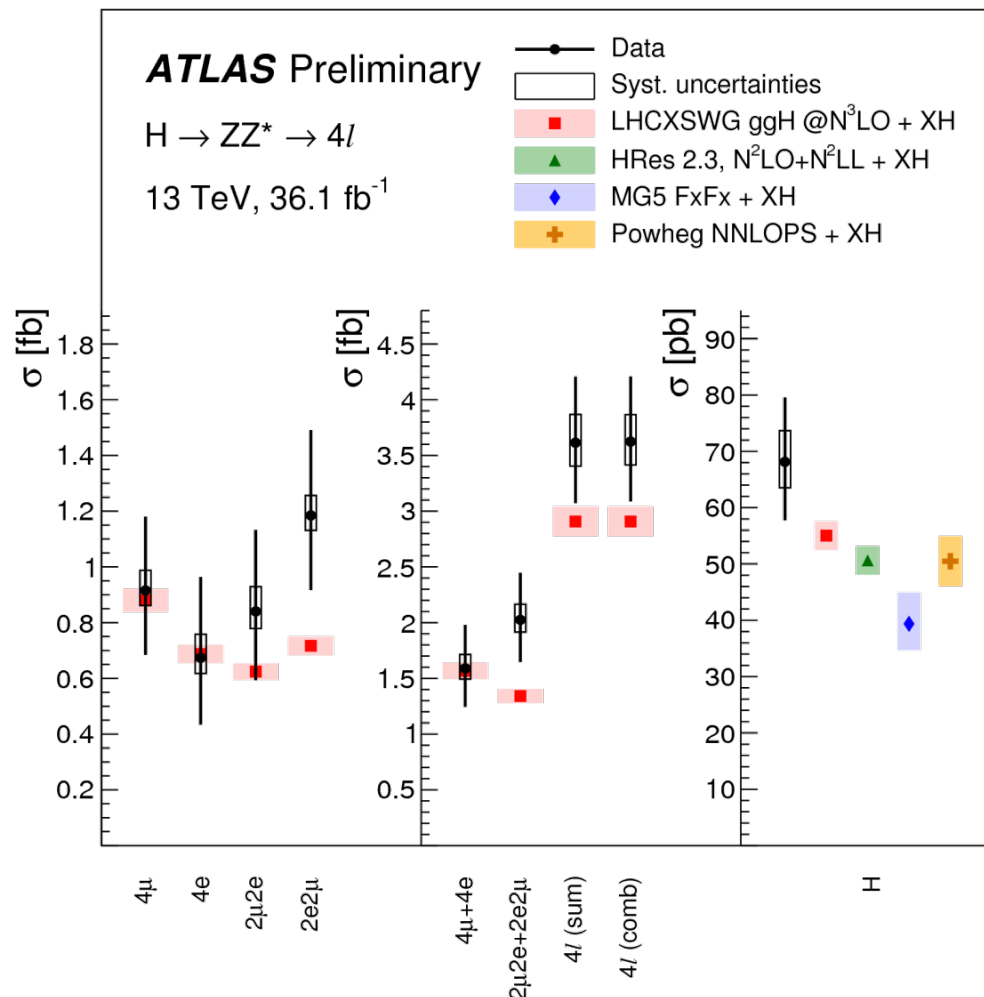
$$H \rightarrow ZZ^* \rightarrow 4\ell$$

[ATLAS-CONF-2017-032]



$H \rightarrow ZZ^* \rightarrow 4\ell$ fiducial integral

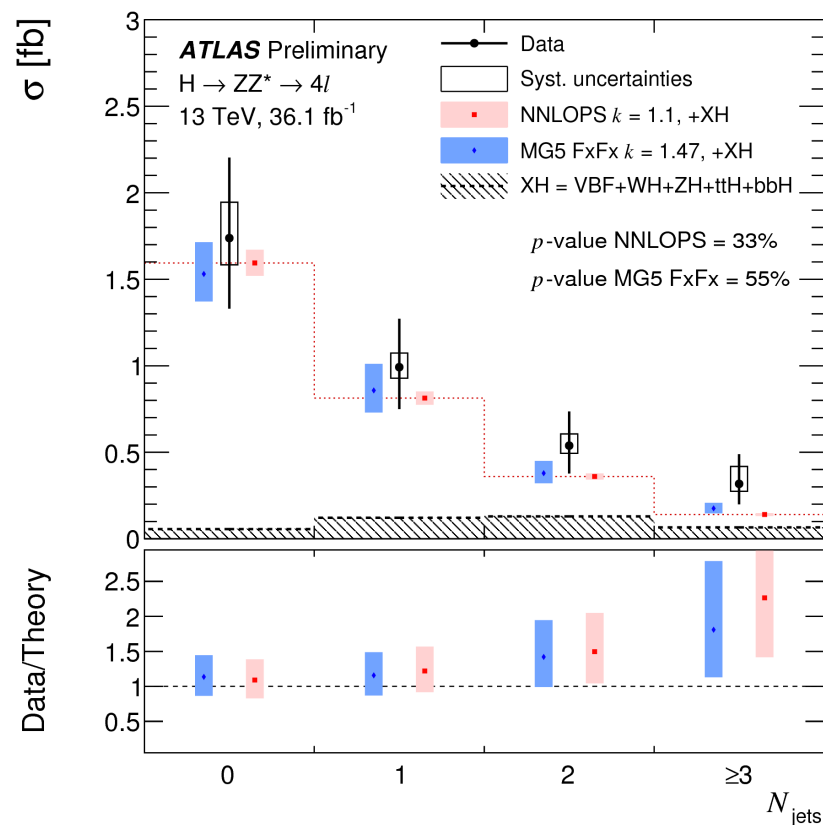
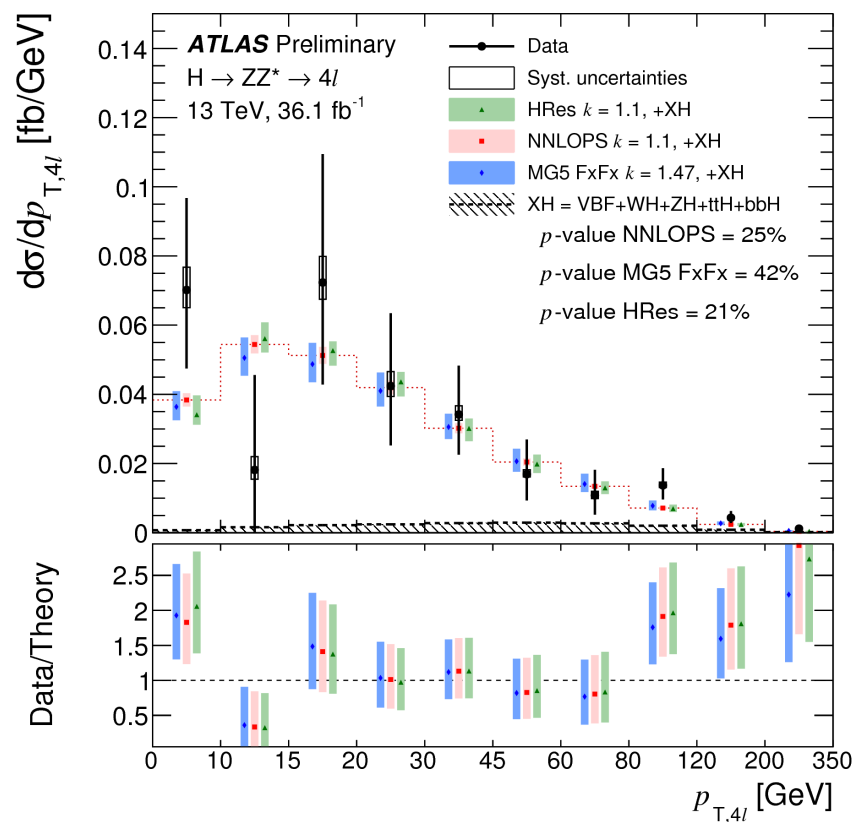
[ATLAS-CONF-2017-032]



□ Cross-sections per decay mode.

$H \rightarrow ZZ^* \rightarrow 4\ell$ fiducial differential

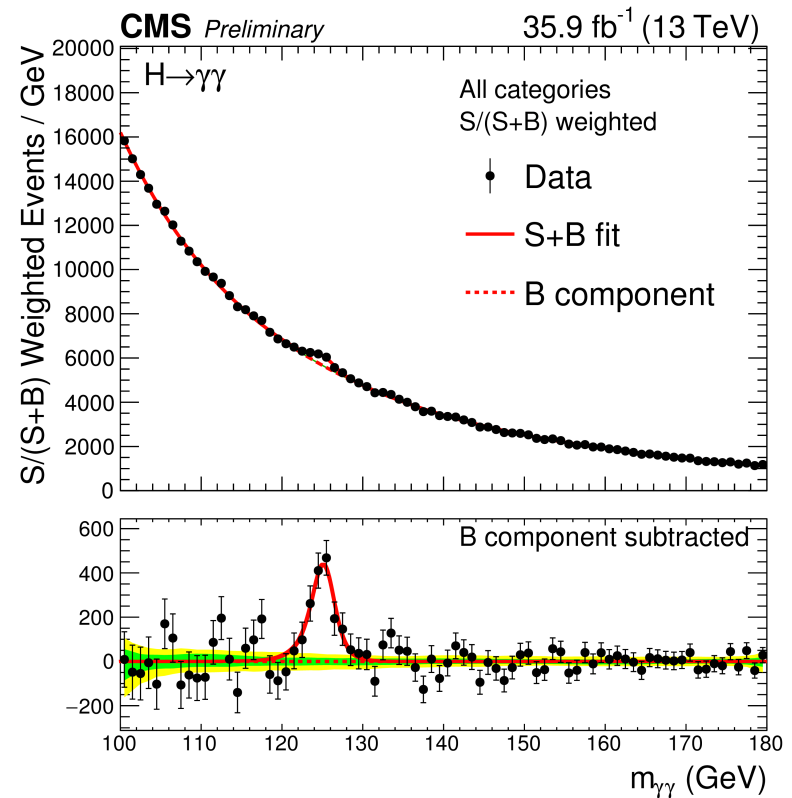
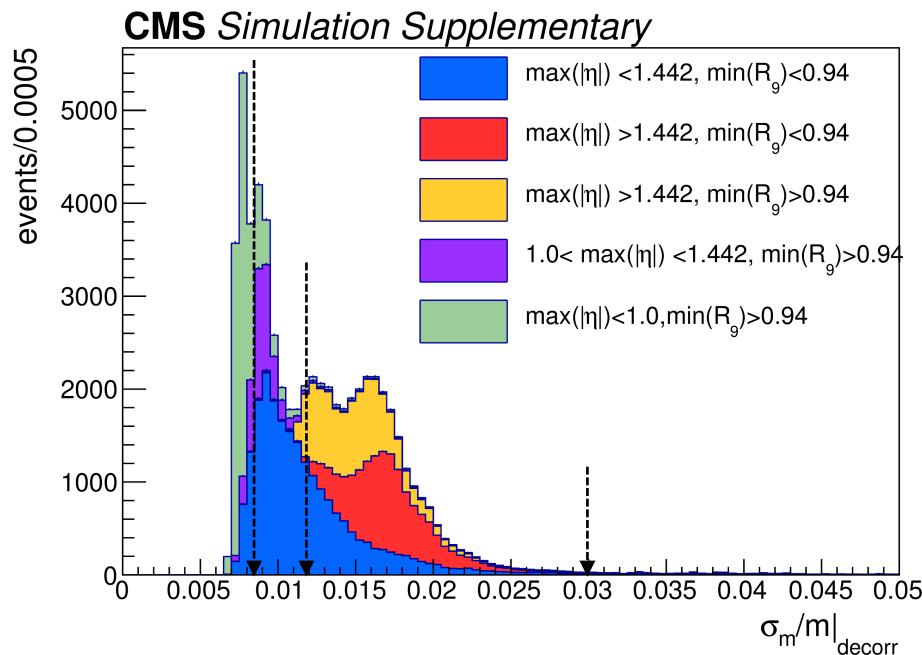
[ATLAS-CONF-2017-032]



□ No particular deviation, cf. some Run 1 fluctuations.

$H \rightarrow \gamma\gamma$ fiducial

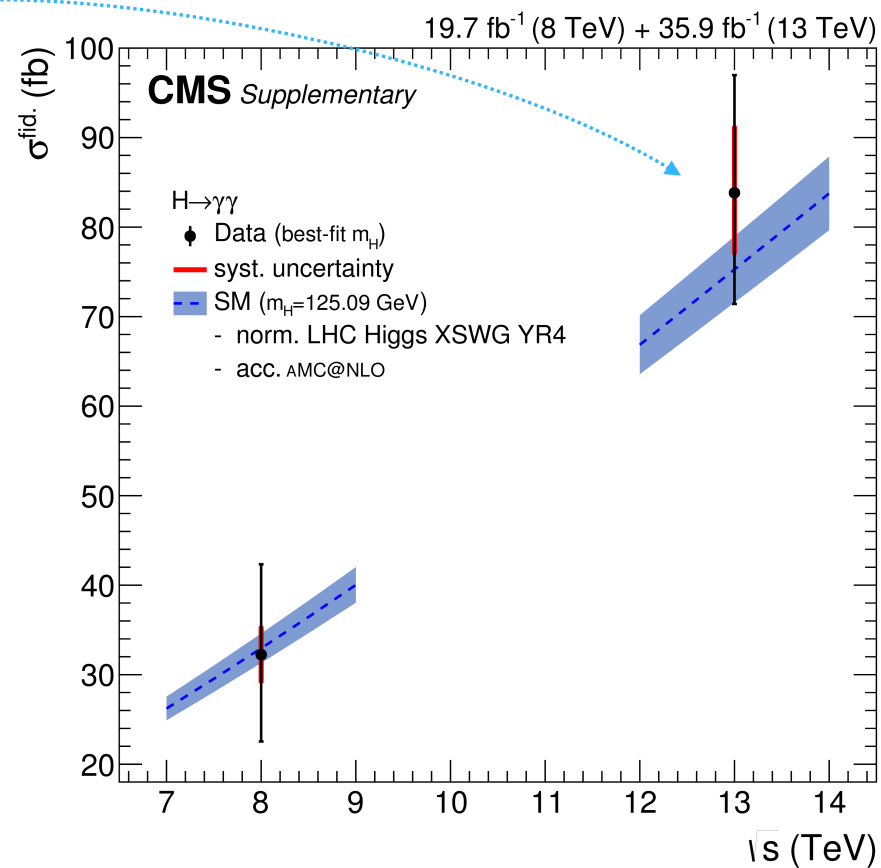
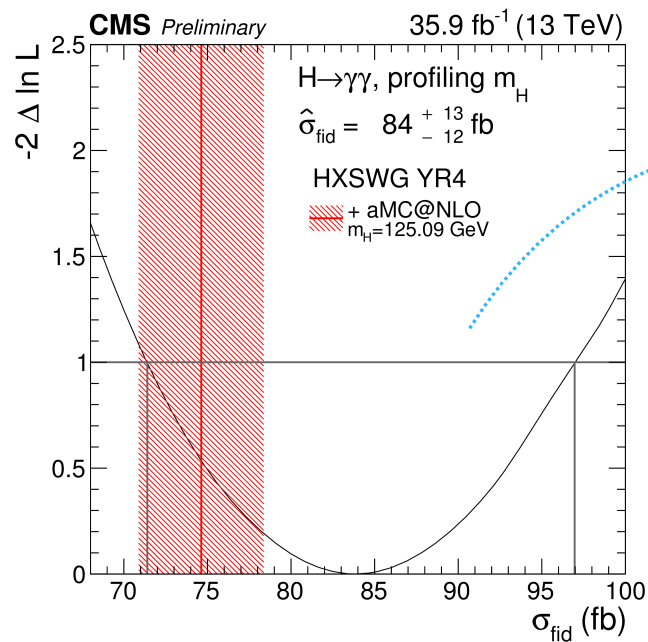
[CMS-PAS-HIG-17-015]



- 3 event categories based on relative mass resolution.

$H \rightarrow \gamma\gamma$ fiducial integral

[CMS-PAS-HIG-17-015]

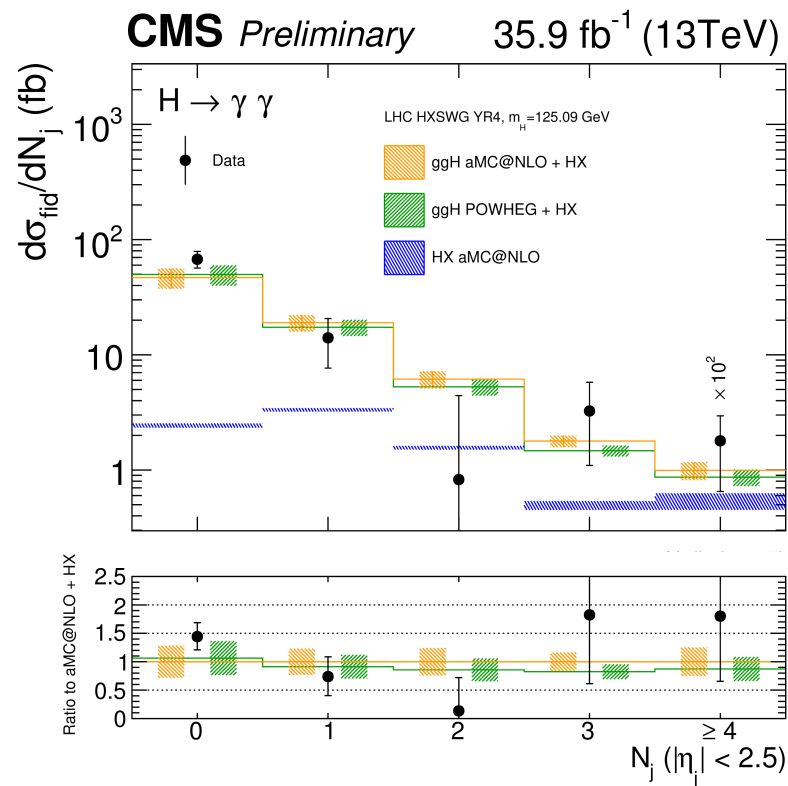
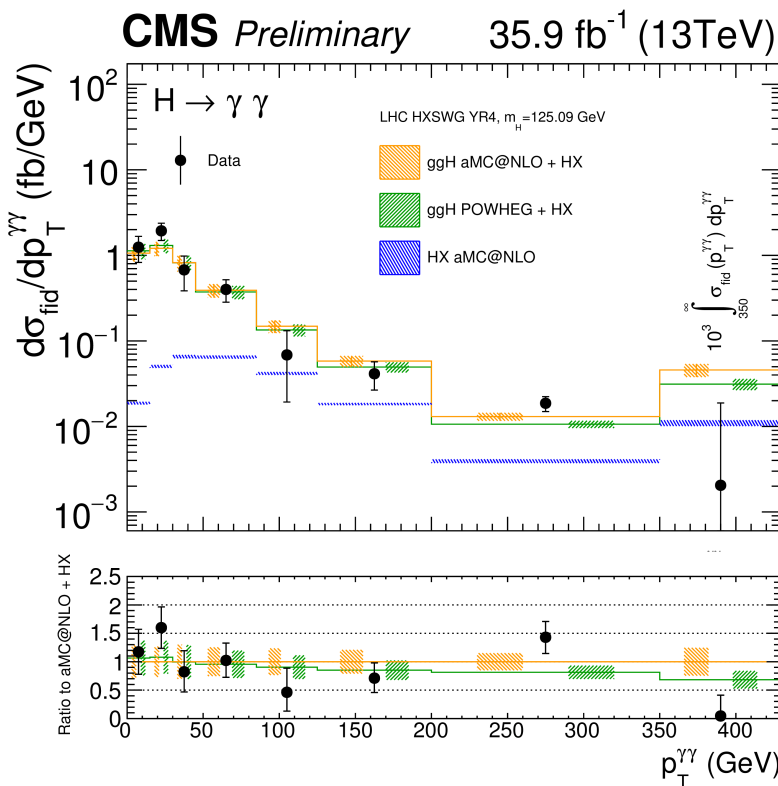


□ Fiducial volume

- $p_T^{1(2)}/m_{\gamma\gamma} > 1/3$ (1/4)
- $|\eta_{\gamma^{1,2}}| < 2.5$
- $E_{\text{iso}} < 10$ GeV within $\Delta R < 0.3$

$H \rightarrow \gamma\gamma$ fiducial differential

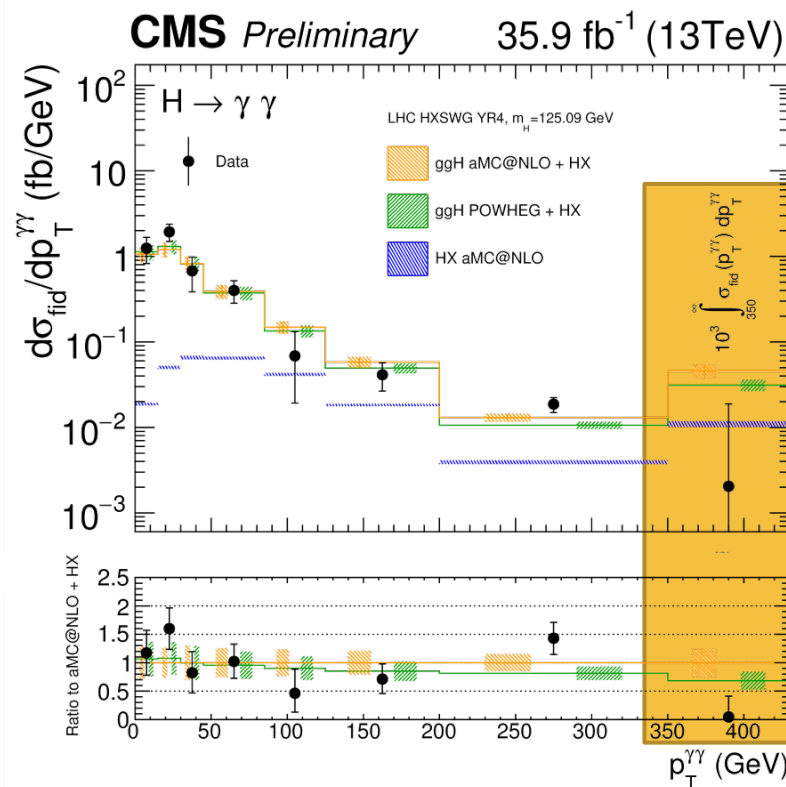
[CMS-PAS-HIG-17-015]



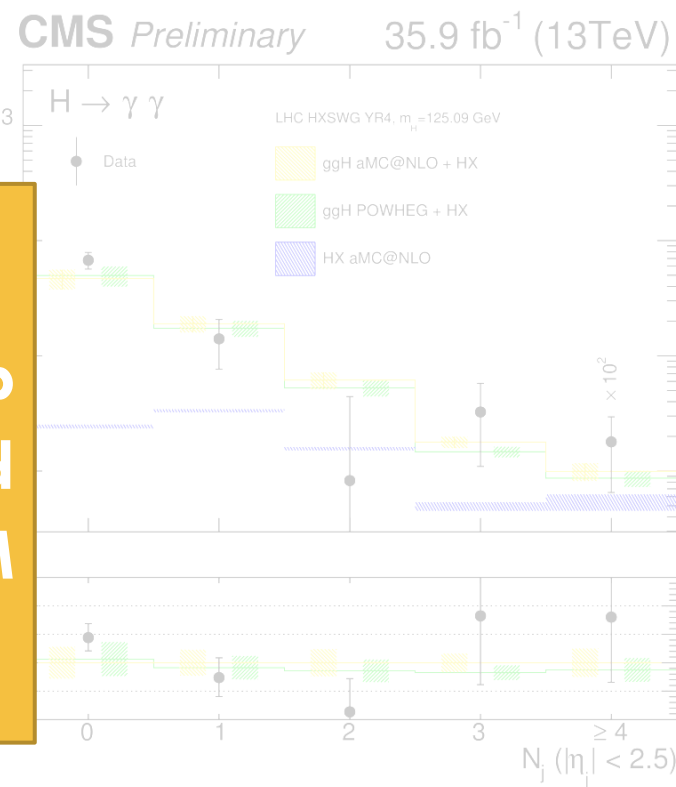
- Unfolding performed by including response matrices in likelihood.
- Nearly no smearing across p_T bins, 10% in N_{jet} .

$H \rightarrow \gamma\gamma$ fiducial differential

[CMS-PAS-HIG-17-015]



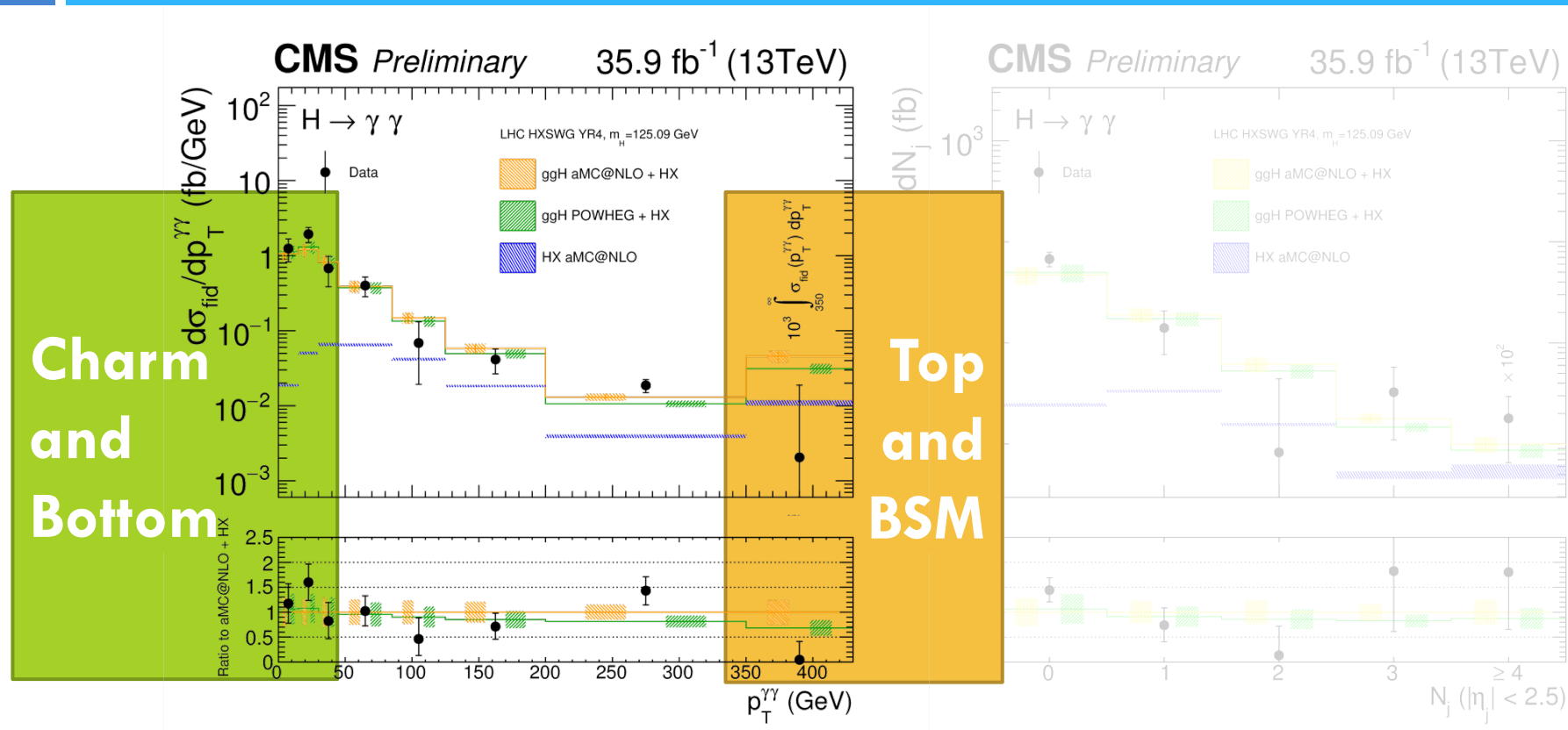
Top
and
BSM



- Unfolding performed by including response matrices in likelihood.
- Nearly no smearing across p_T bins, 10% in N_{jet} .

$H \rightarrow \gamma\gamma$ fiducial differential

[CMS-PAS-HIG-17-015]



- Unfolding performed by including response matrices in likelihood.
- Nearly no smearing across p_T bins, 10% in N_{jet} .

Even more boosted – inclusive $H \rightarrow b\bar{b}$

[arXiv:1609.07483]

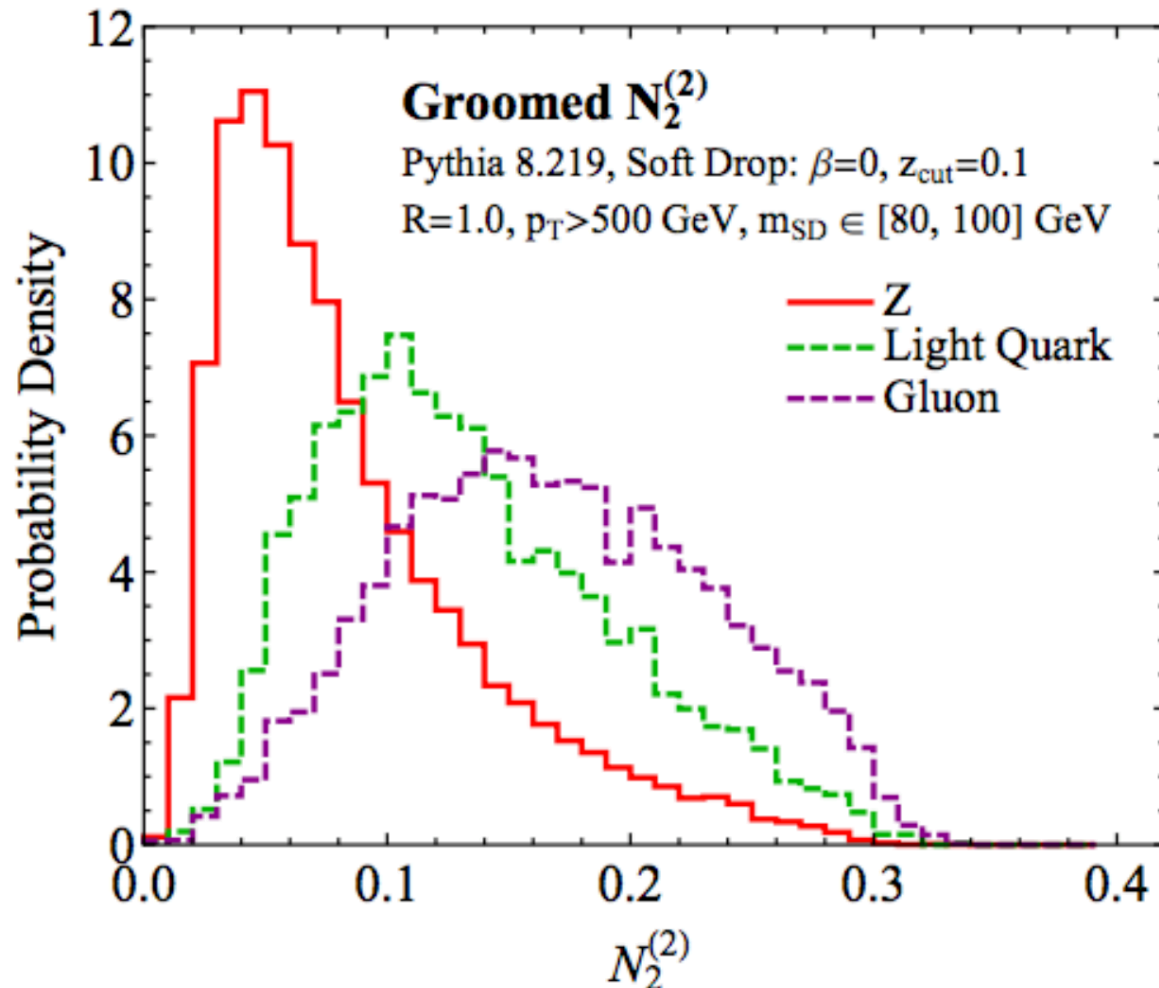
- **“Mission: Impossible”**
 - ▣ Jet substructure identification.
 - ▣ Decorrelation of jet mass and substructure variables.
 - ▣ Double-b tagging in merged jets.
 - ▣ Challenging theoretical accuracy for high- p_T gluon-fusion
- First applied to low mass Z' searches.



Even more boosted – inclusive $H \rightarrow b\bar{b}$

[arXiv:1609.07483]

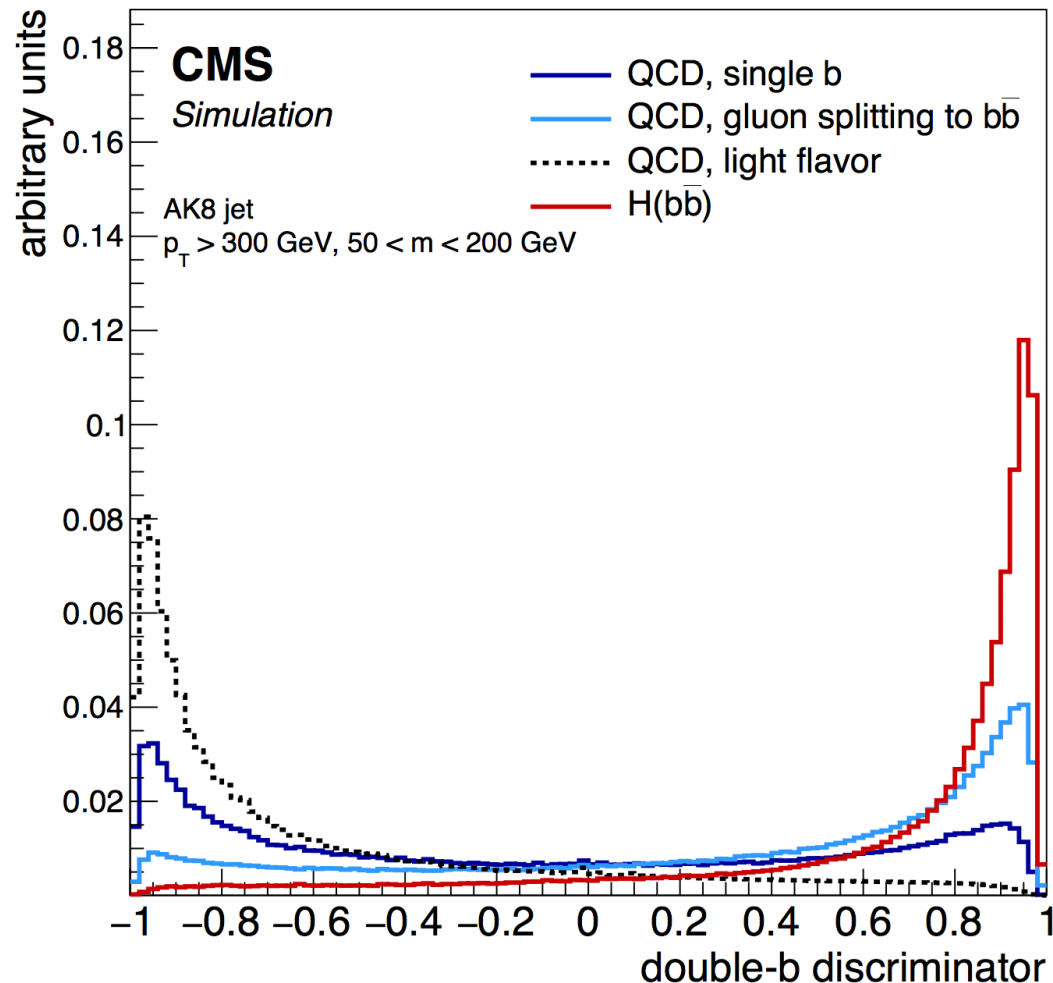
- **“Mission: Impossible”**
 - ▣ **Jet substructure identification.**
 - ▣ **Decorrelation of jet mass and substructure variables.**
 - ▣ **Double-b tagging in merged jets.**
 - ▣ **Challenging theoretical accuracy for high- p_T gluon-fusion**
- **First applied to low mass Z' searches.**



Even more boosted – inclusive $H \rightarrow b\bar{b}$

13 TeV, 2016

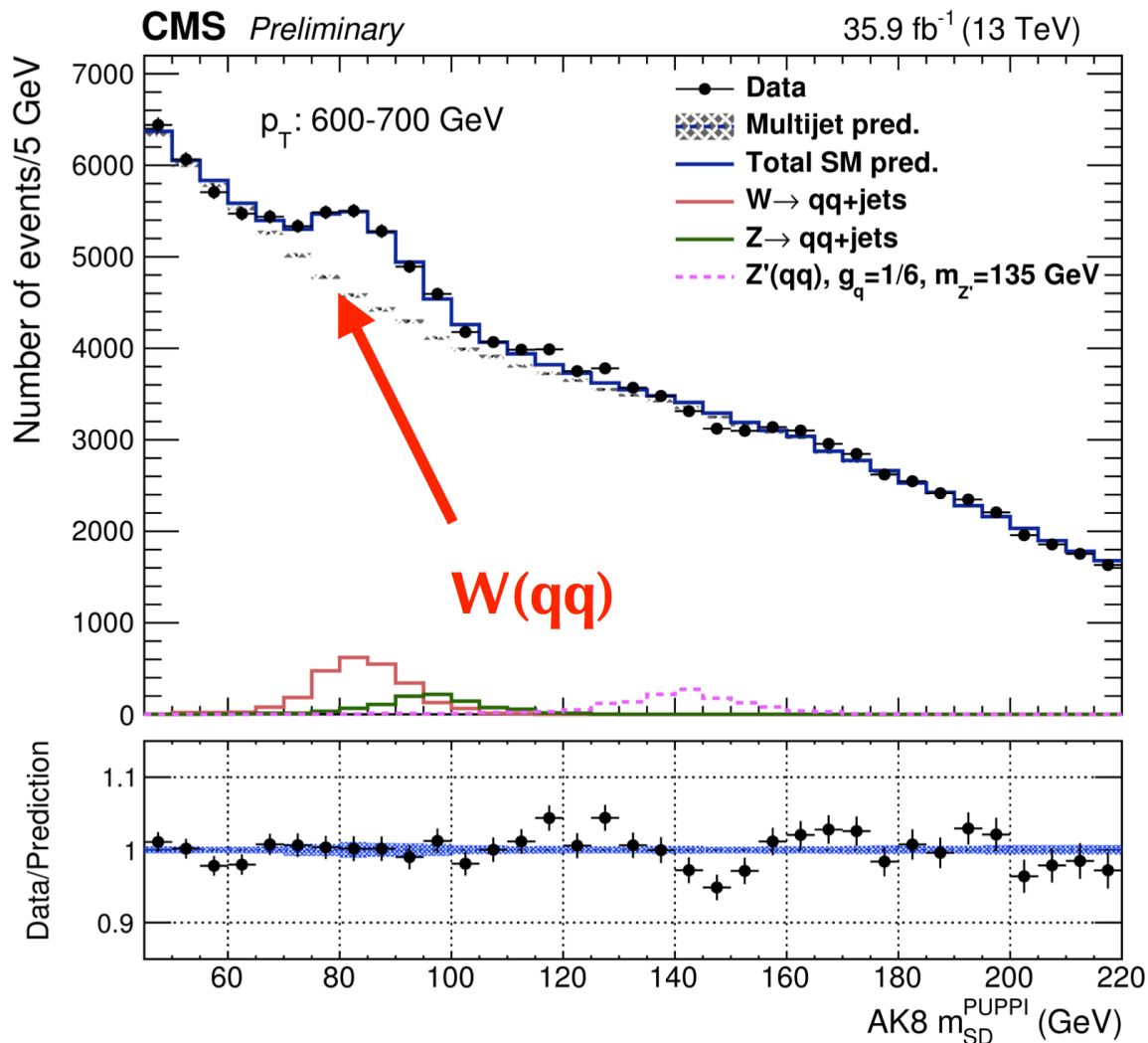
- **“Mission: Impossible”**
 - ▣ Jet substructure identification.
 - ▣ Decorrelation of jet mass and substructure variables.
 - ▣ **Double-b tagging** in merged jets.
 - ▣ Challenging theoretical accuracy for high- p_T gluon-fusion
- First applied to low mass Z' searches.



“Mission: Impossible”

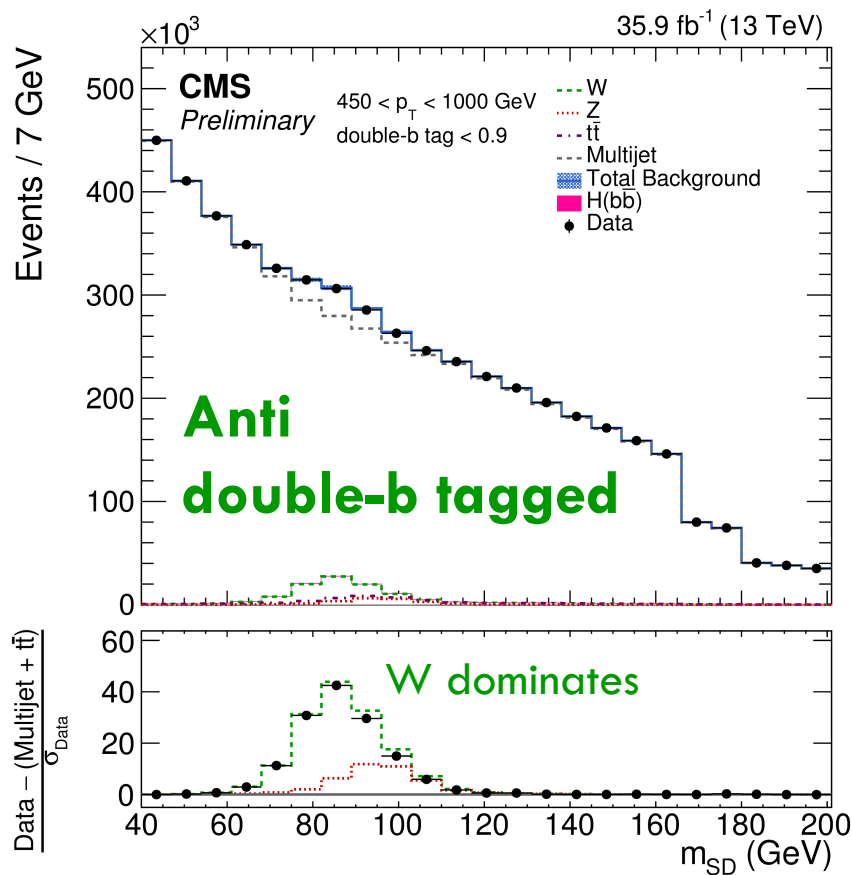
- ▣ Jet substructure identification.
- ▣ Decorrelation of jet mass and substructure variables.
- ▣ Double-b tagging in merged jets.
- ▣ Challenging theoretical accuracy for high- p_T gluon-fusion.

First applied to low mass Z' searches.



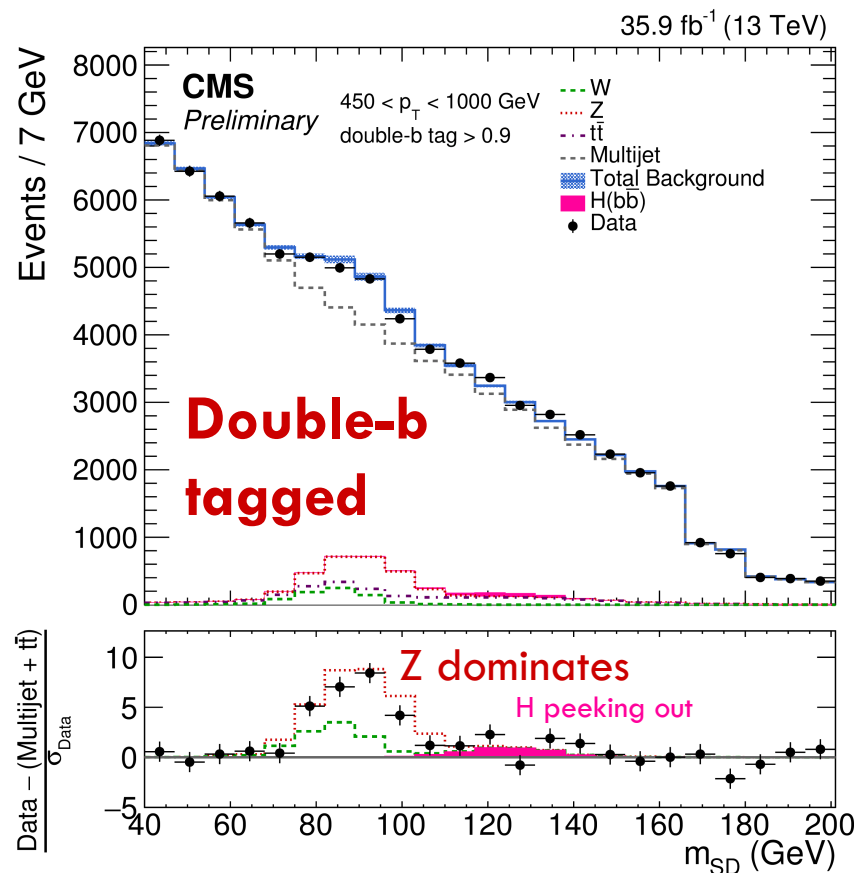
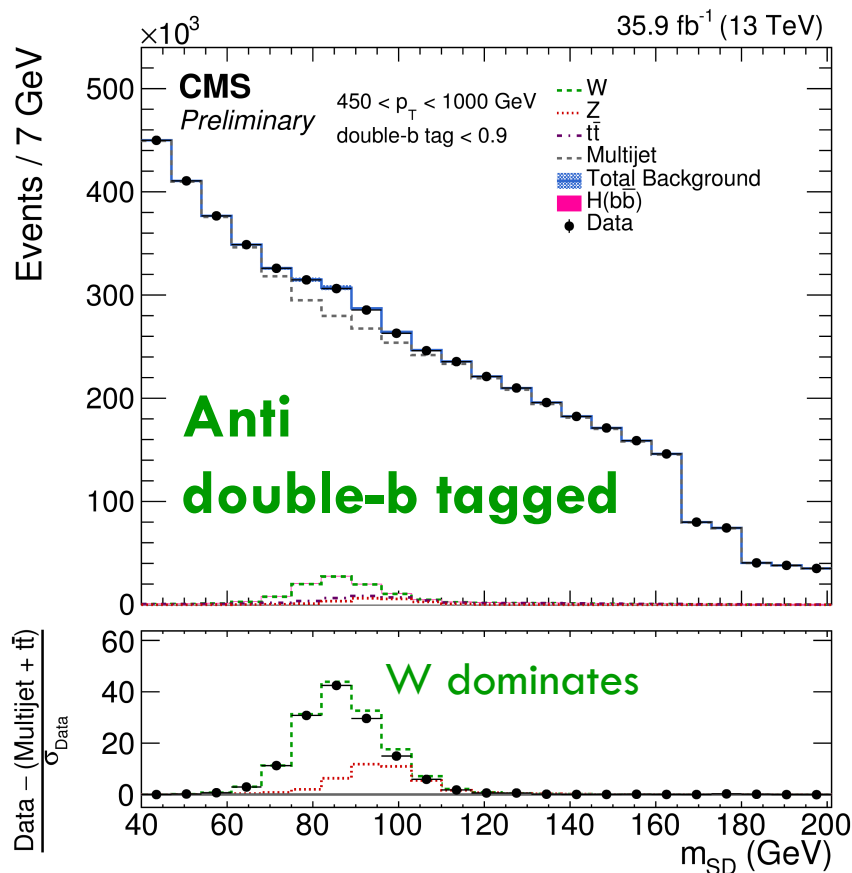
Even more boosted – inclusive $H \rightarrow b\bar{b}$

[CMS-PAS-HIG-17-010]



Even more boosted – inclusive $H \rightarrow b\bar{b}$

[CMS-PAS-HIG-17-010]



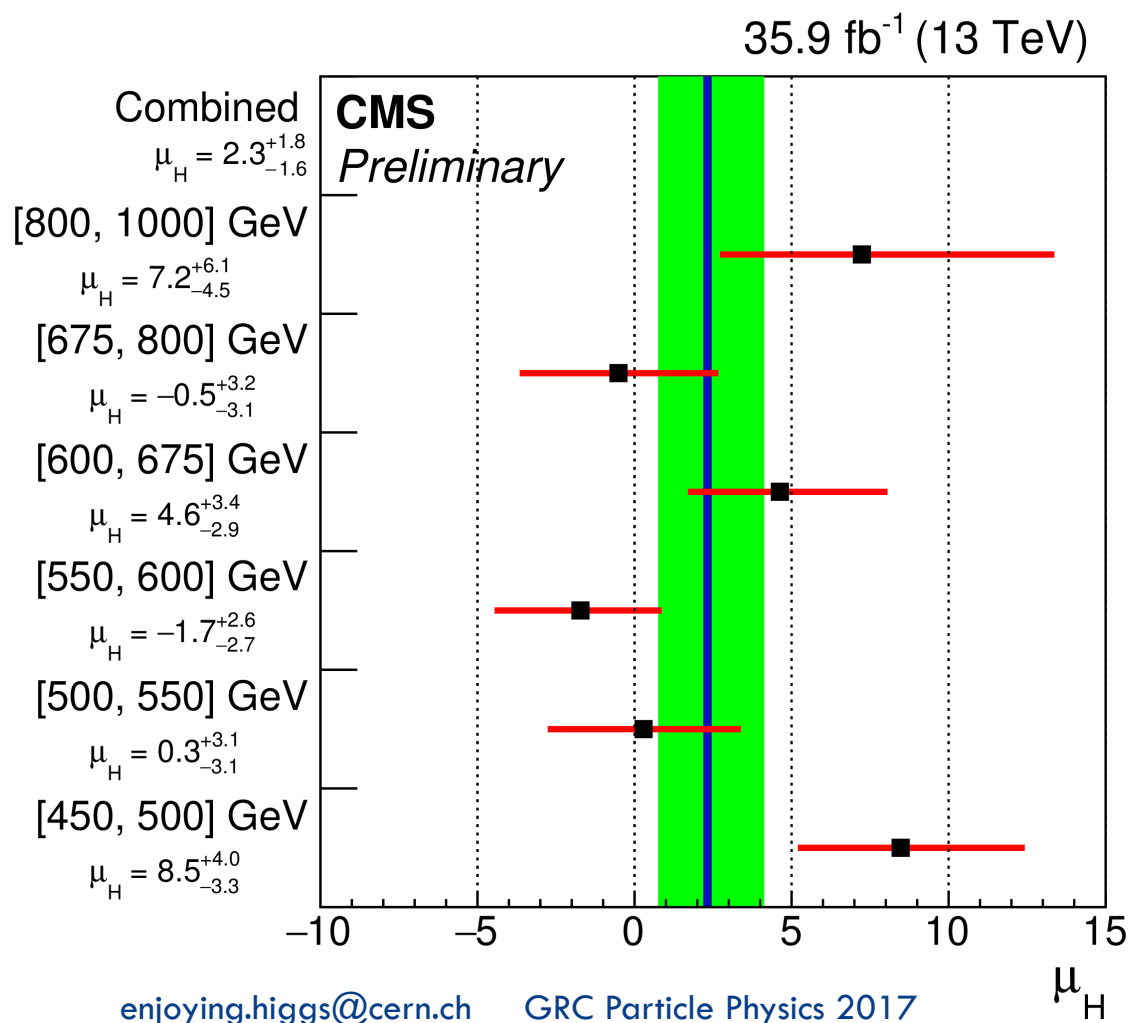
□ Z: 5.1σ (5.8 σ expected)

□ H: 1.5σ (0.7 σ expected)

Even more boosted – inclusive $H \rightarrow b\bar{b}$

[CMS-PAS-HIG-17-010]

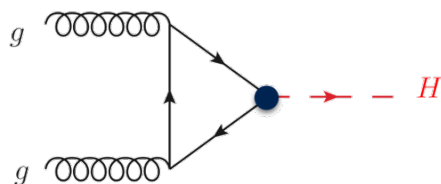
Exploring
brand new
regime:
 $p_T(H) > 450 \text{ GeV}$



The paths to the top-Higgs coupling

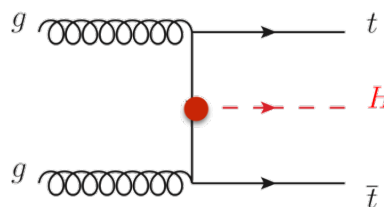
Loop-induced

- ggH : 44 pb



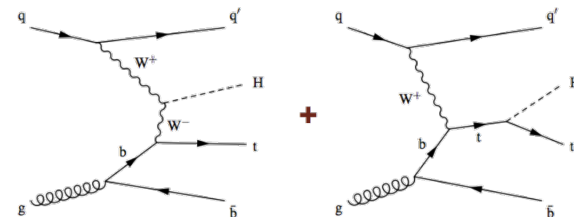
Direct

- $t\bar{t}H$: 0.5 pb



Interference

- tH : 0.08 pb



$\sqrt{s} = 13 \text{ TeV}$
 $m_H = 125 \text{ GeV}$



Paths to ttH : 中道

58

[Middle Path]

$$H \rightarrow b\bar{b}$$

$$H \rightarrow (WW, \tau\tau) \\ \text{multileptons}$$

$$H \rightarrow (4\ell, \gamma\gamma)$$

Paths to ttH : 中道

[Middle Path]

$H \rightarrow b\bar{b}$

$H \rightarrow (WW, \tau\tau)$
multileptons

$H \rightarrow (4\ell, \gamma\gamma)$

Large yield

Low yield

Paths to ttH : 中道

[Middle Path]

$H \rightarrow b\bar{b}$

$H \rightarrow (WW, \tau\tau)$
multileptons

$H \rightarrow (4\ell, \gamma\gamma)$

Theory systematics

Simple background

Large yield

Low yield

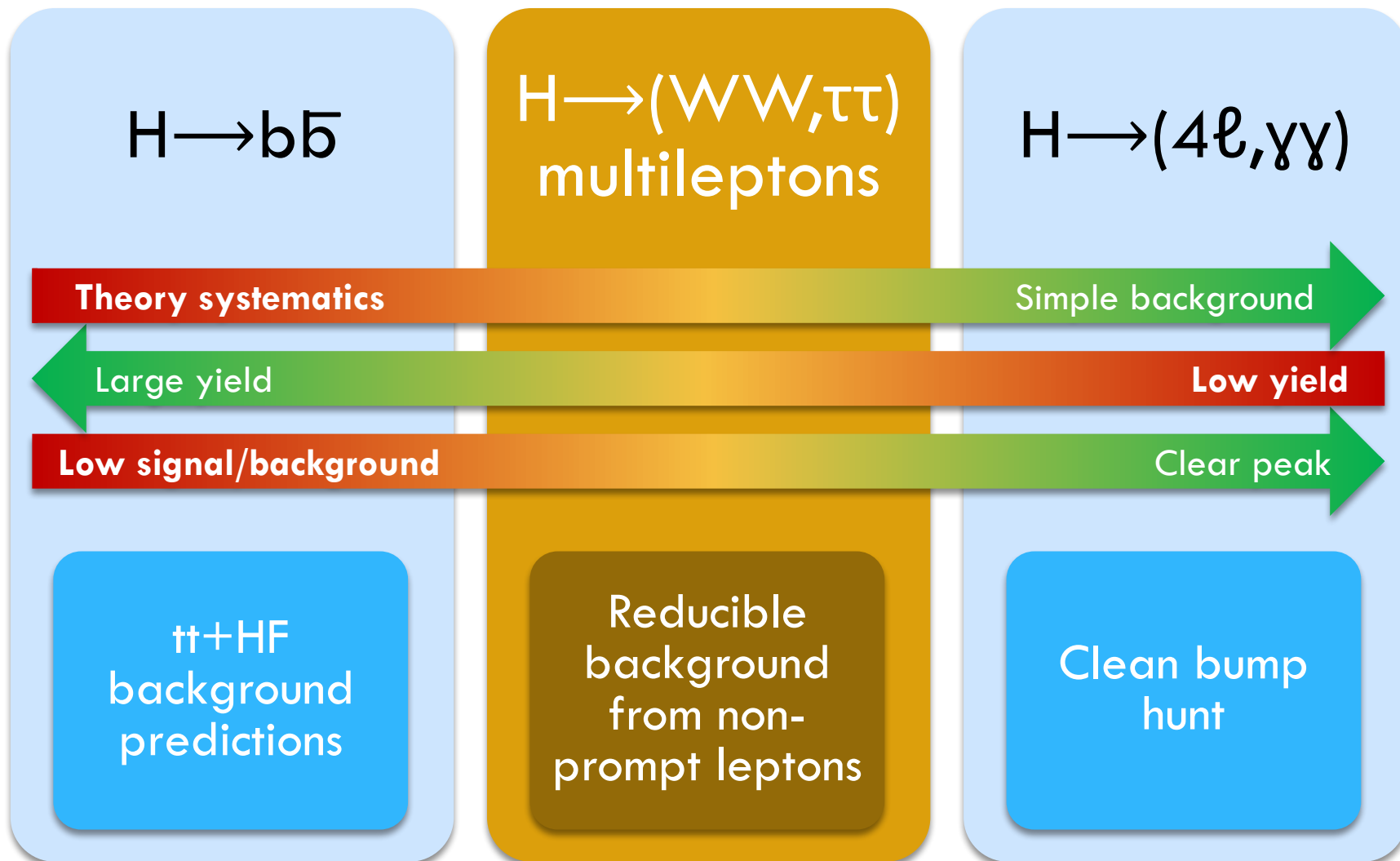
Low signal/background

Clear peak

Paths to $t\bar{t}H$: 中道

61

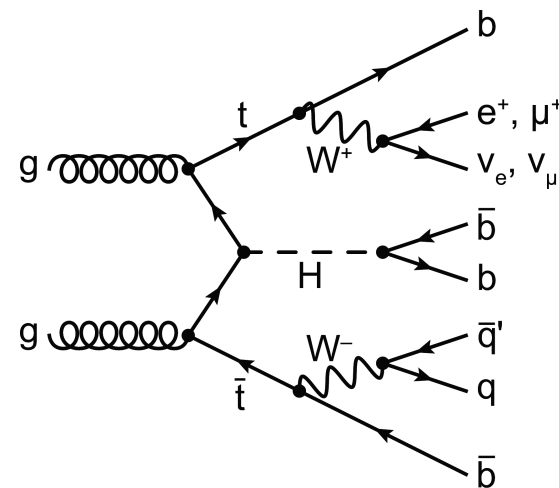
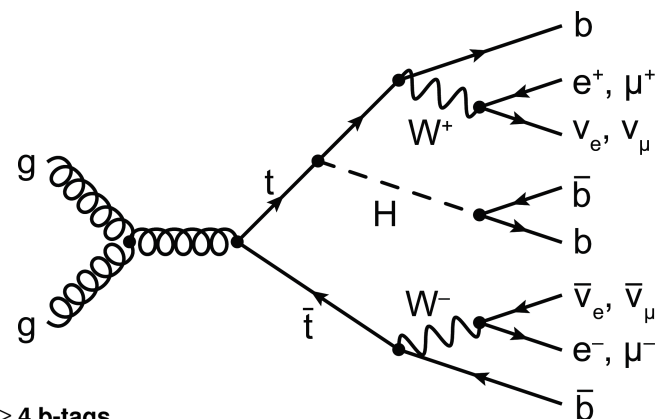
[Middle Path]



Looking for $t\bar{t}H - b\bar{b}$

[CMS-PAS-HIG-16-038]

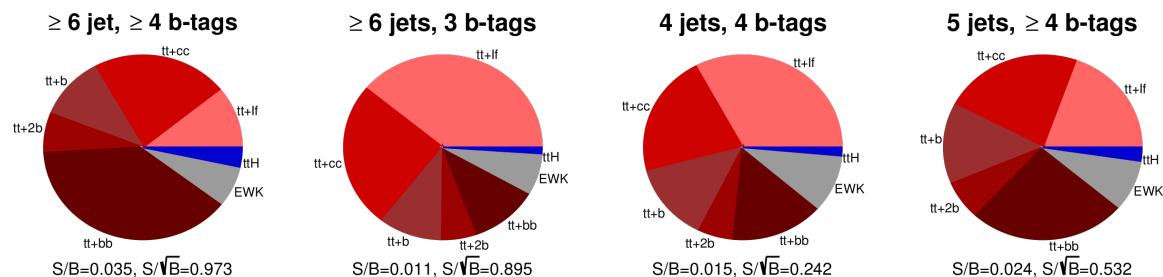
- Large multiplicity of b-tagged jets.
- Complex assignment of jets.



CMS

Simulation

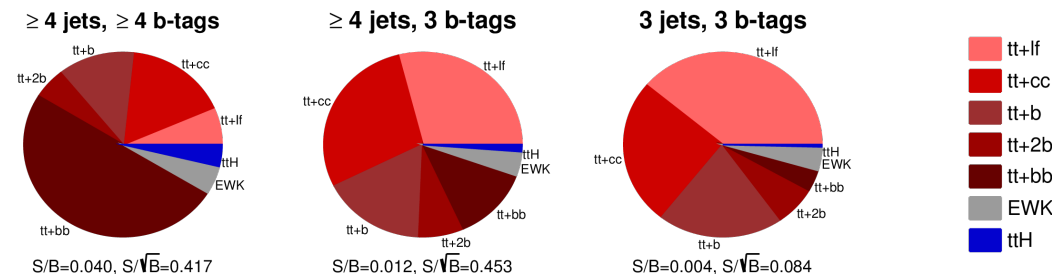
Lepton+Jets Channel



CMS

Simulation

Dilepton Channel

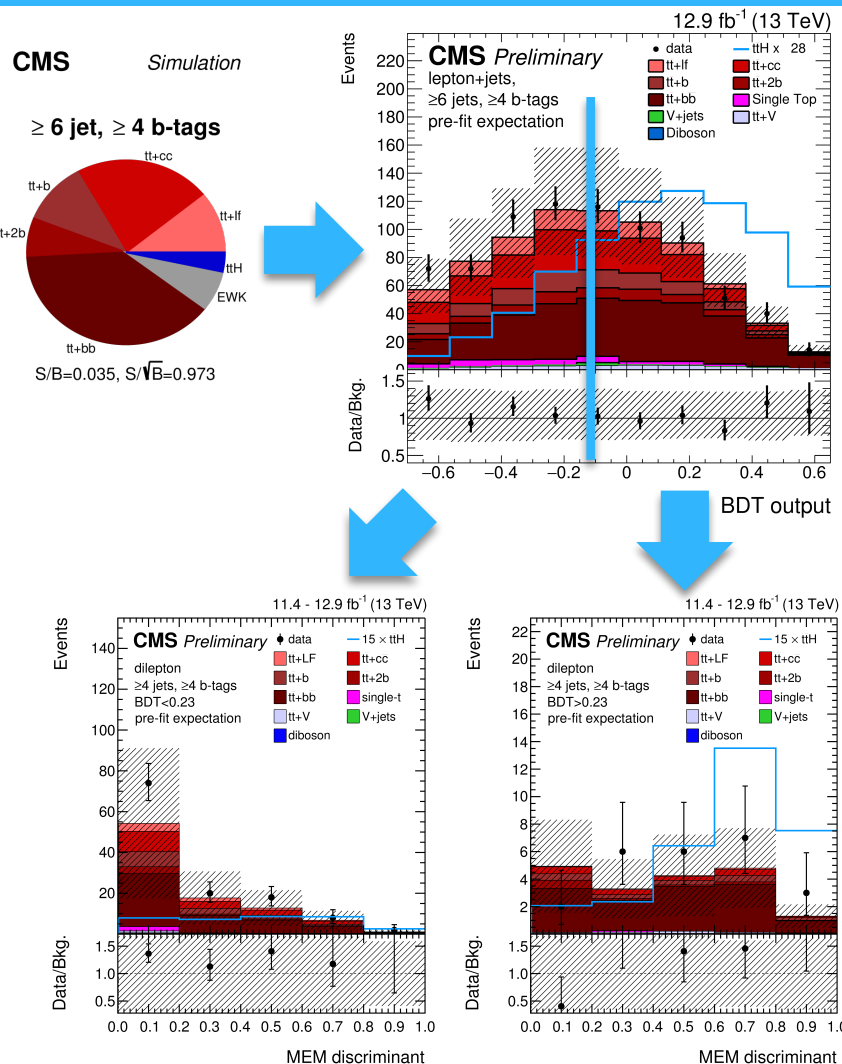


Looking for $t\bar{t}H - b\bar{b}$

63

[CMS-PAS-HIG-16-038]

- Complex assignment of jets:
 - BDT good with missing objects.
 - MEM good with all objects present.



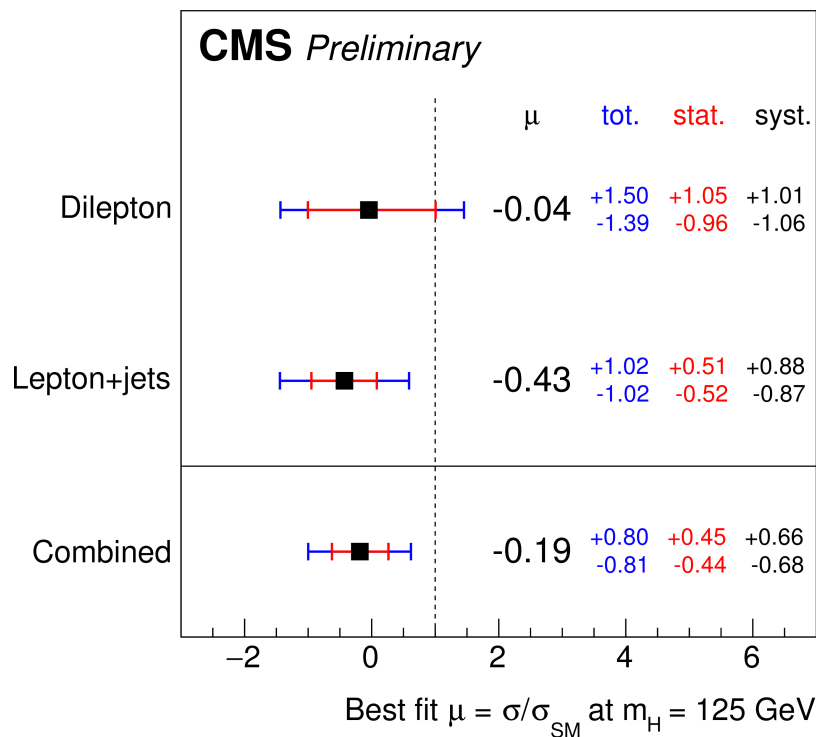
Looking for $t\bar{t}H - b\bar{b}$

64

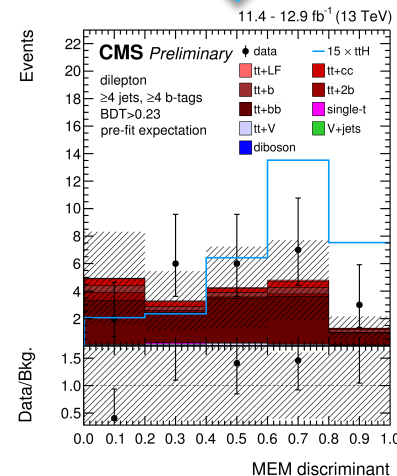
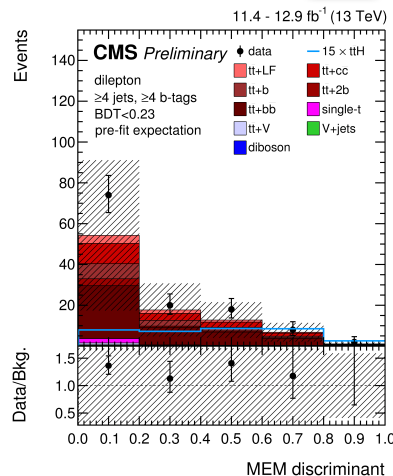
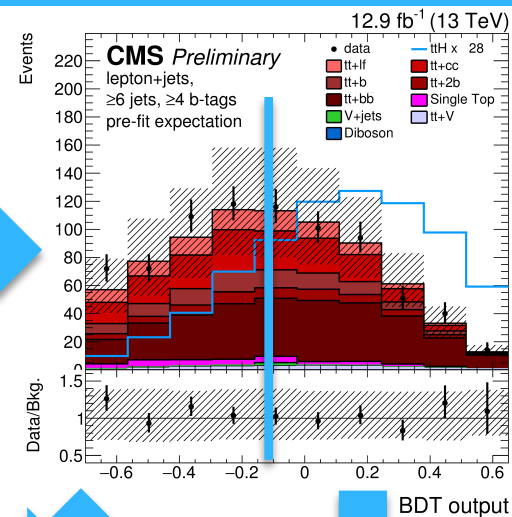
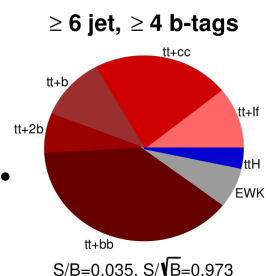
[CMS-PAS-HIG-16-038]

- Complex assignment of jets:
 - BDT good with missing objects.
 - MEM good with all objects present.

11.4 - 12.9 fb^{-1} (13 TeV)



CMS Simulation



Looking for $t\bar{t}H$ – multileptons

[CMS-PAS-HIG-17-004]

□ Categorisation on:

▣ Number of leptons: 2SS, 3, 4.

▣ Lepton charge

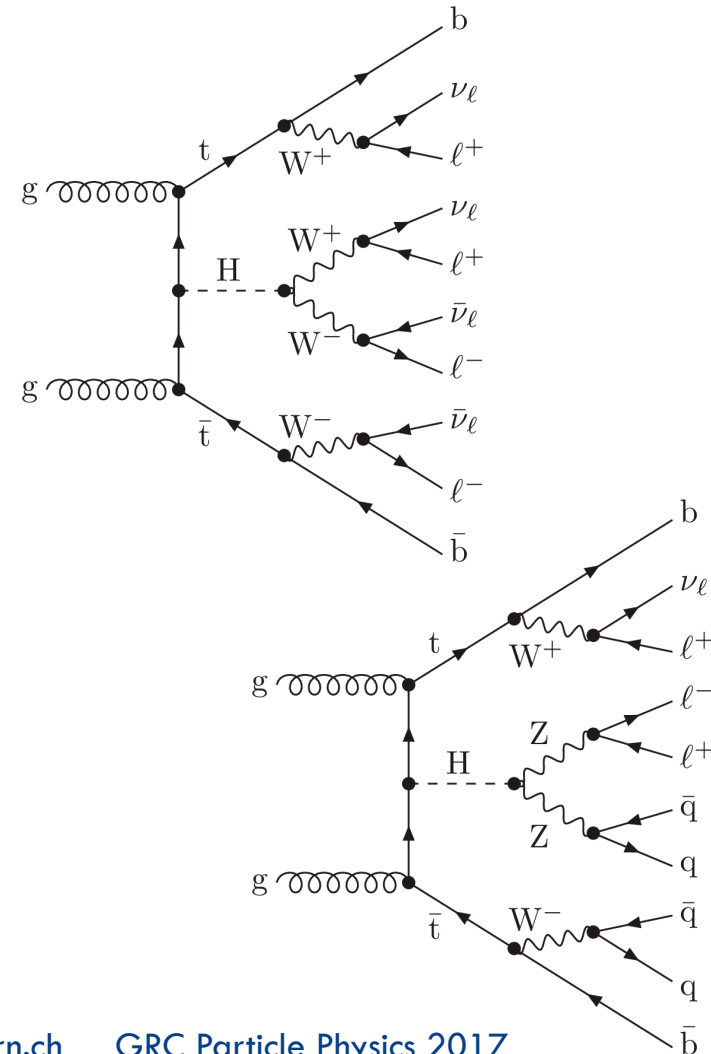
▣ Lepton flavor

▣ B-tagging

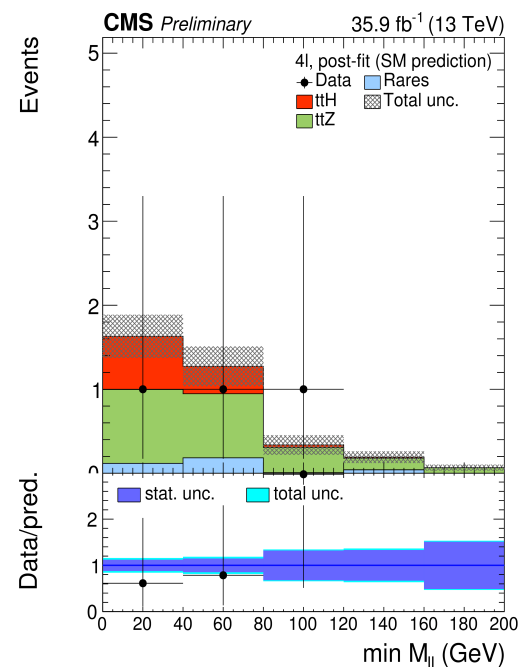
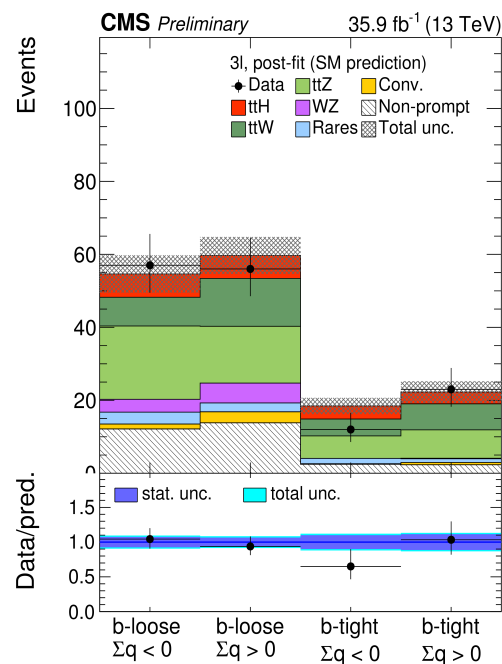
□ Main backgrounds:

▣ $t\bar{t}+W$ (and $t\bar{t}+Z$)

▣ $t\bar{t}+qq$



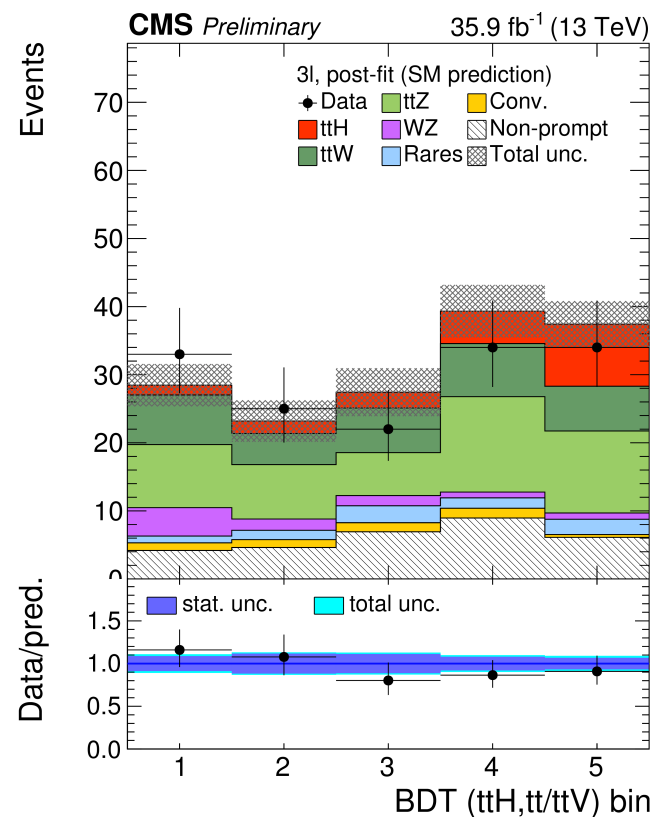
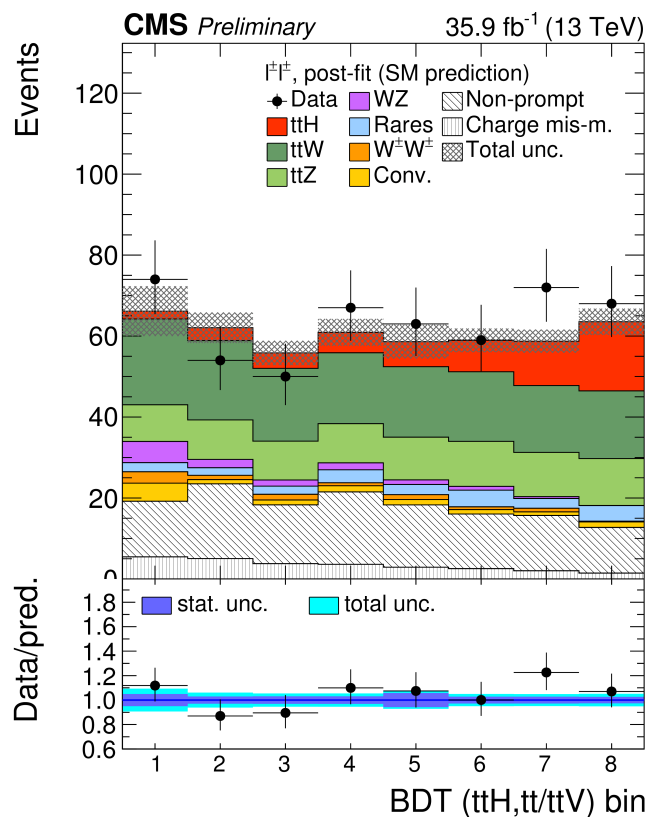
-
- Figure 1 consists of two panels. The top panel is a stacked histogram showing the cross-section of $tt̄$ production as a function of the invariant mass of the $tt̄$ pair. The y-axis is labeled 'Events' and ranges from 0 to 180. The x-axis is labeled 'Invariant mass (GeV)' and ranges from 0 to 180. The histogram is composed of several components: Data (black diamonds), $tt̄$ (red), $tt̄W$ (green), $tt̄Z$ (light green), WZ (purple), Rares (blue), Conv. (yellow), Non-prompt (hatched), Charge mis-m. (dotted), and Total unc. (grey). The bottom panel is a ratio plot showing the ratio of Data to the prediction (Data/pred.) as a function of the invariant mass of the $tt̄$ pair. The y-axis is labeled 'Data/pred.' and ranges from 0.6 to 1.8. The x-axis is labeled 'Invariant mass (GeV)' and ranges from 0 to 180. The ratio plot shows the ratio of Data to the prediction (Data/pred.) as a function of the invariant mass of the $tt̄$ pair. The ratio is shown as a black line with error bars, and the uncertainty is shown as a shaded band (stat. unc. in blue, total unc. in cyan).



Looking for $t\bar{t}H$ – multileptons

[CMS-PAS-HIG-17-004]

- Two MVAs training $t\bar{t}H$ against $t\bar{t}+q\bar{q}$ and $t\bar{t}+V$.
- 2D joint MVA distribution reduced by merging bins of 2D space.



Looking for $t\bar{t}H$ – multileptons

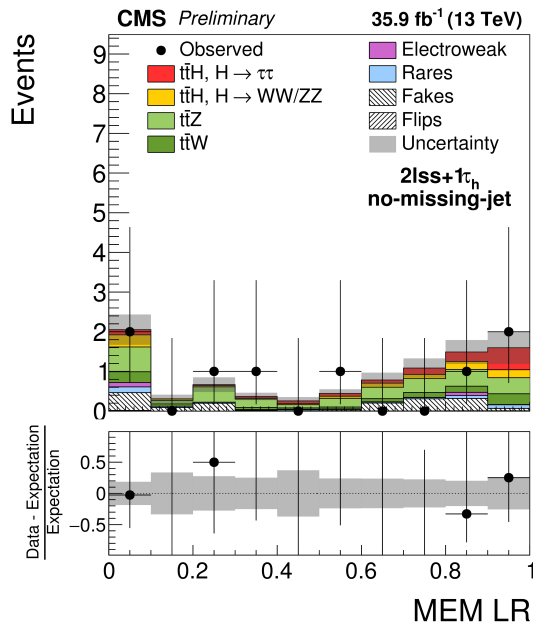
[CMS-PAS-HIG-17-004]

Category	Observed μ fit $\pm 1\sigma$	Expected μ fit $\pm 1\sigma$
Same-sign di-lepton	1.7 (−0.5) (+0.6)	1.0 (−0.5) (+0.5)
Three lepton	1.0 (−0.7) (+0.8)	1.0 (−0.7) (+0.8)
Four lepton	0.9 (−1.6) (+2.3)	1.0 (−1.6) (+2.4)
Combined (2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)
Combined (2015 data) [42]	0.6 (−1.1) (+1.4)	1.0 (−1.1) (+1.3)
Combined (2015+2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)

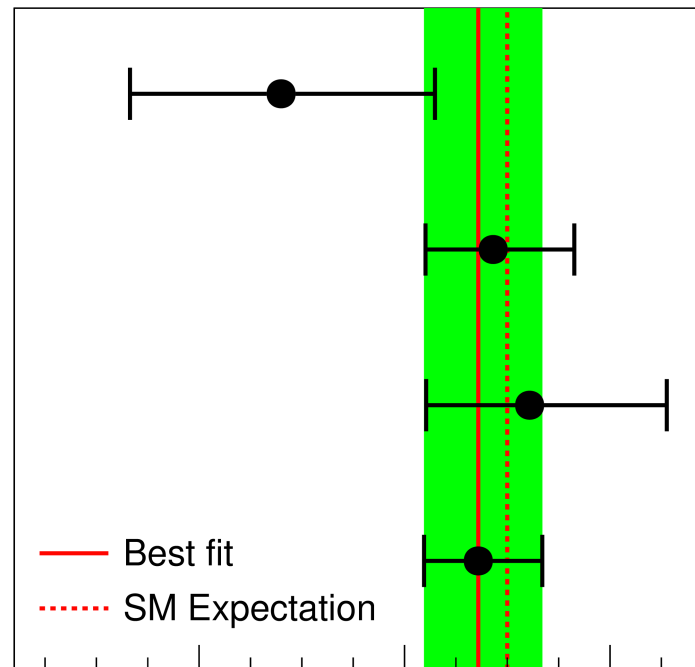
- Clear excess over background-only hypothesis:
 - **Significance: 3.3σ obs. (2.5σ exp.)**

Looking for $t\bar{t}H$ – tau leptons

[CMS-PAS-HIG-17-003]



CMS Preliminary **35.9 fb⁻¹ (13 TeV)**



$$1l+2\tau_h$$

$$\mu = -1.20^{+1.50}_{-1.47}$$

$$2lss+1\tau_h$$

$$\mu = 0.86^{+0.79}_{-0.66}$$

$$3l+1\tau_h$$

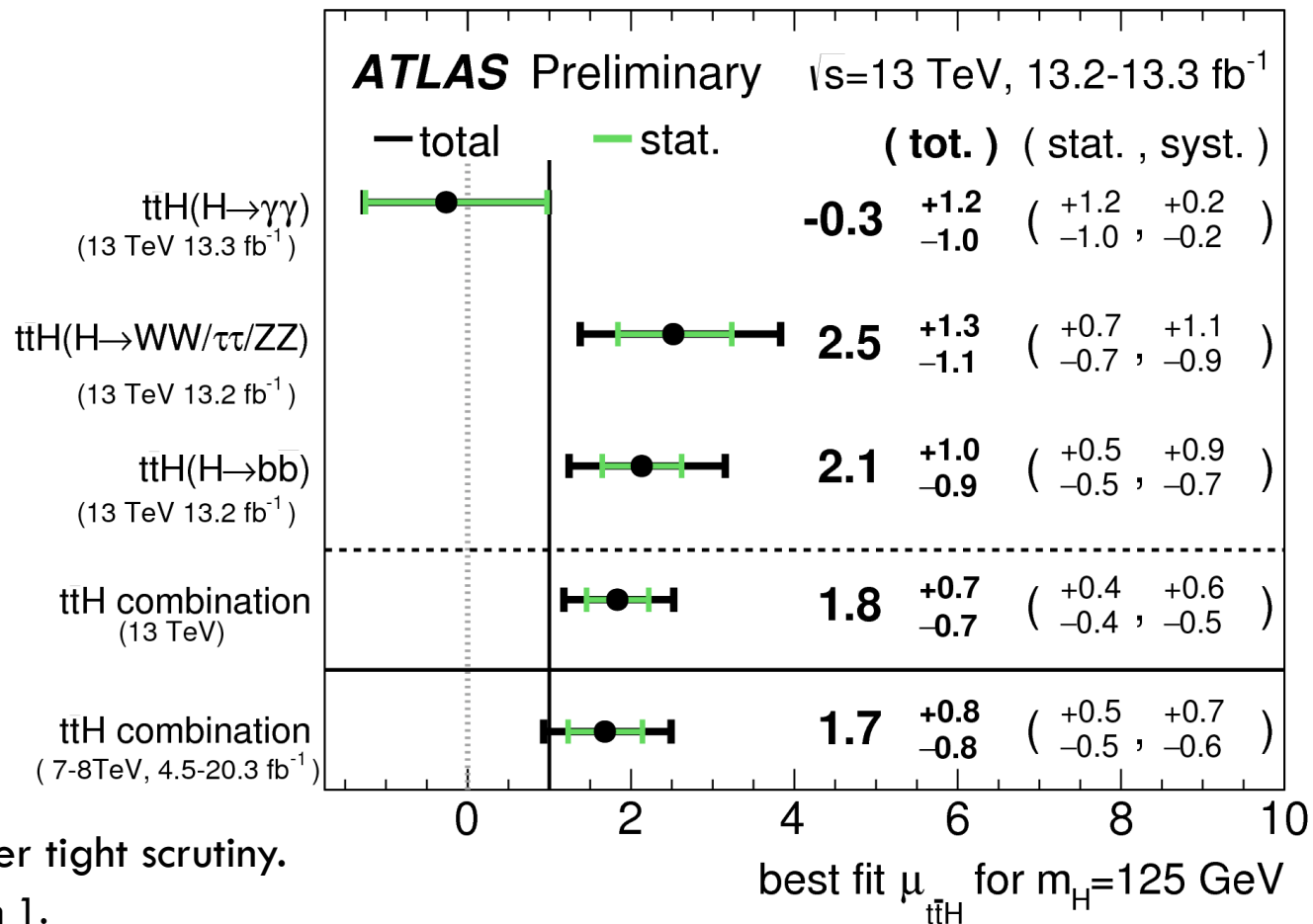
$$\mu = 1.22^{+1.33}_{-1.01}$$

$$\text{Combined}$$

$$\mu = 0.72^{+0.62}_{-0.53}$$

- Very similar analysis, with different background from misidentified hadronic tau lepton decays.

Looking for $t\bar{t}H$

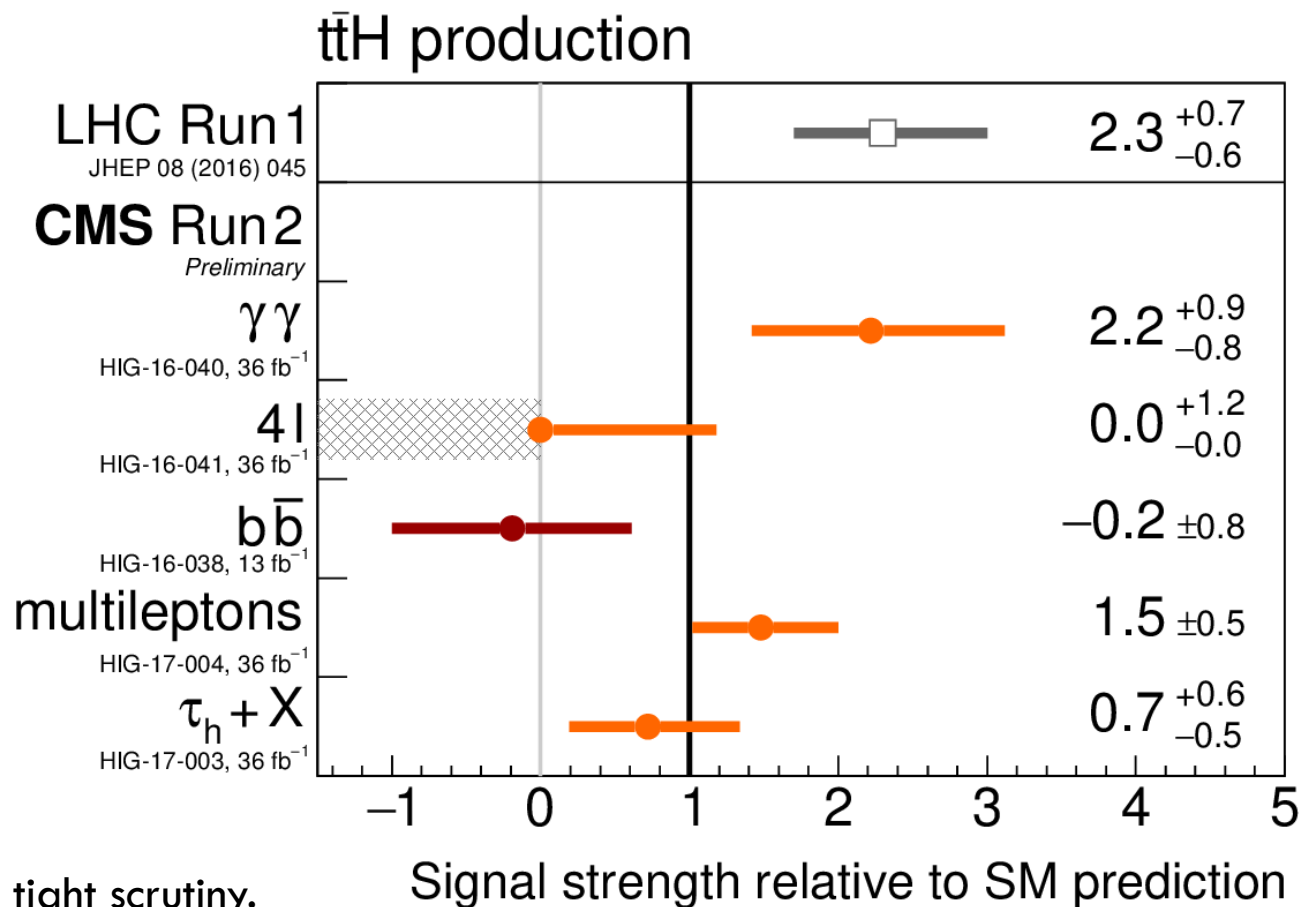


□ top-Higgs coupling under tight scrutiny.

■ Intriguing excess in Run 1.

■ Signal becoming clearer in Run 2.

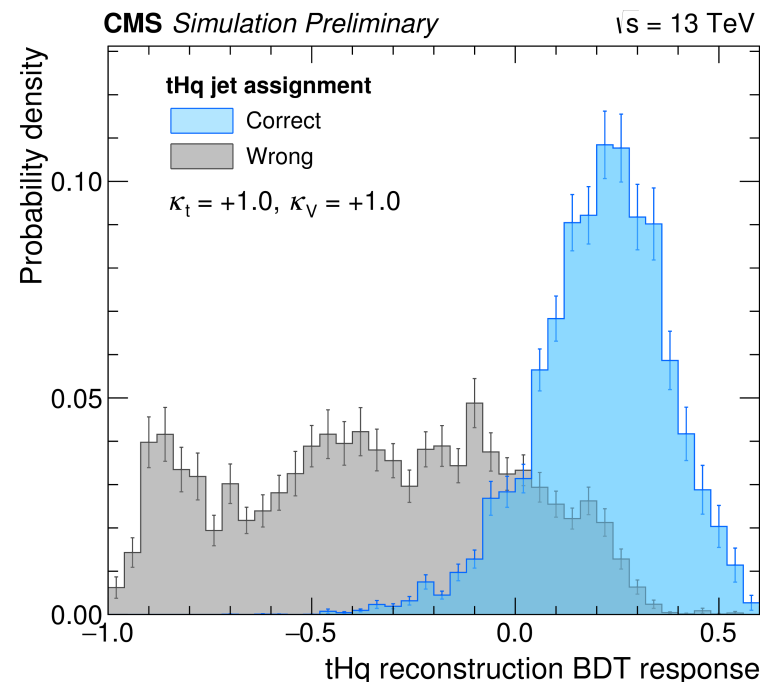
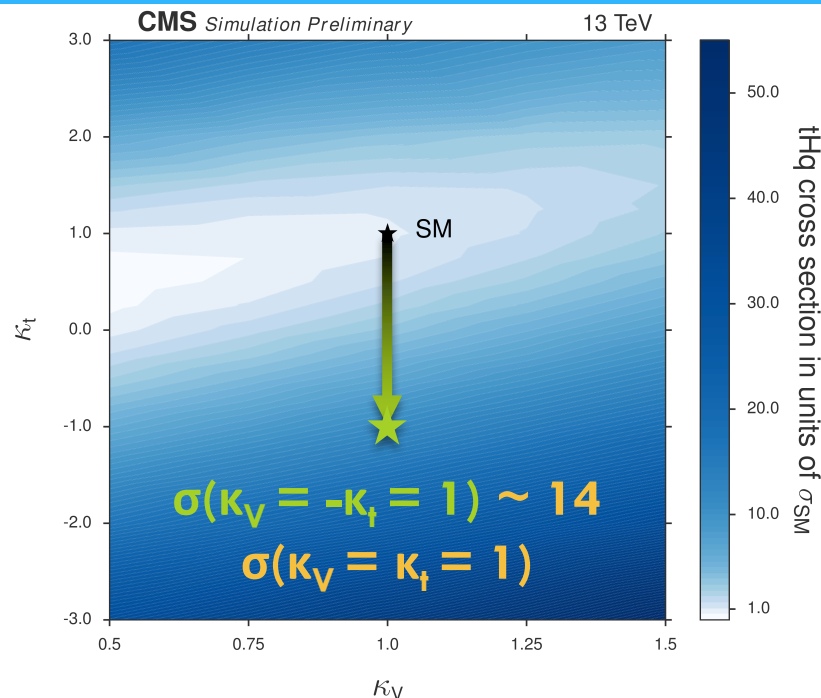
Looking for $t\bar{t}H$



- top-Higgs coupling under tight scrutiny.
 - Intriguing excess in Run 1.
 - Signal becoming clearer in Run 2.

Looking for $tH - b\bar{b}$

[CMS-PAS-HIG-16-019]

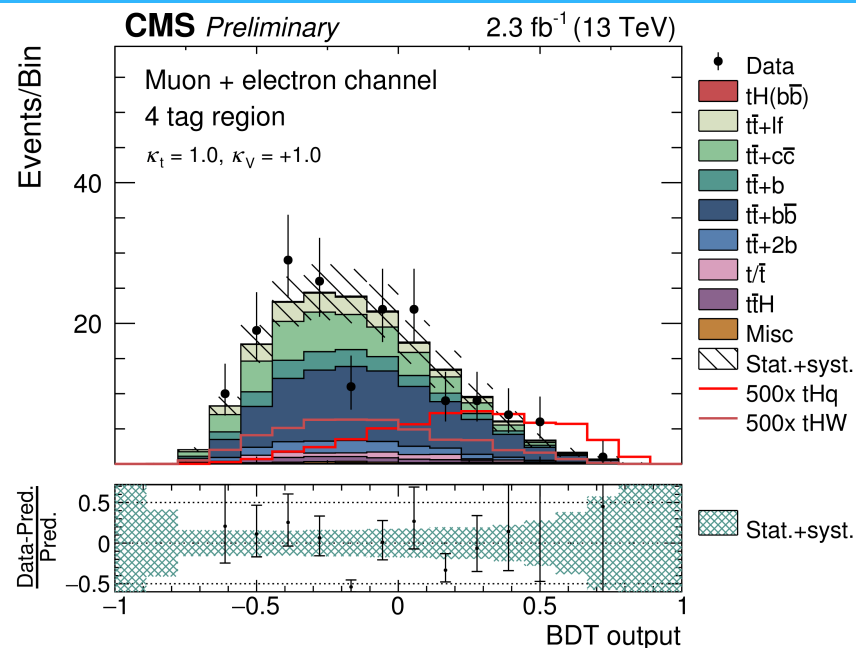
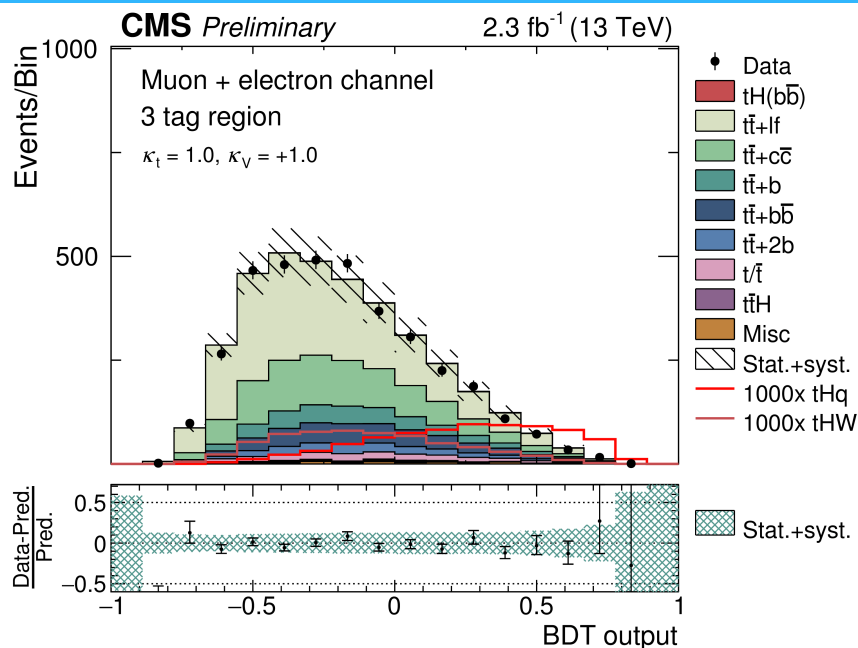


- Large enhancement expected for opposite-sign couplings to W and top.
- MVA trained for correct forward jet assignment.

Looking for $t\bar{t}H - b\bar{b}$

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[CMS-PAS-HIG-16-019]

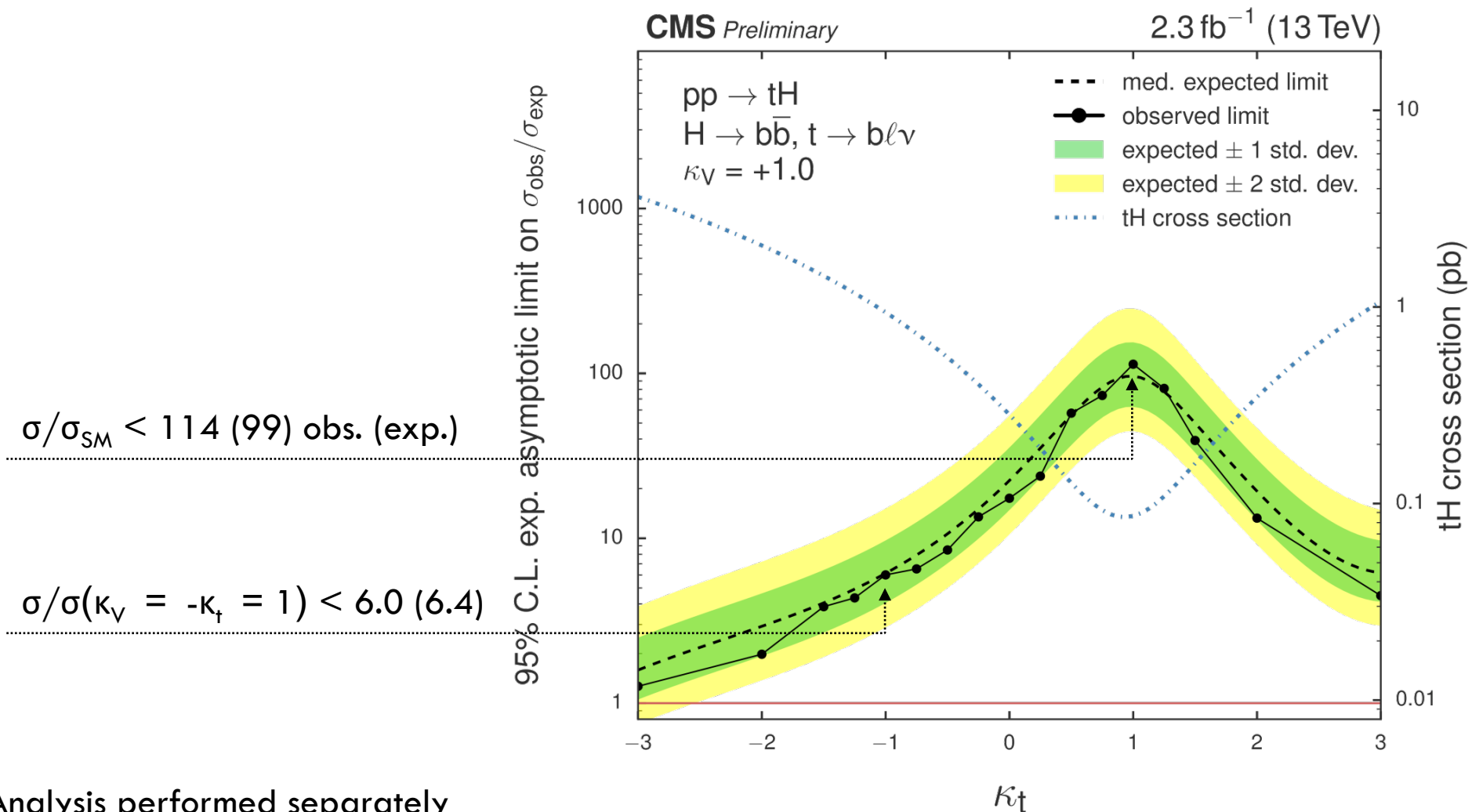


- Categories in number of b-tags.
- Final observable trained against $t\bar{t}+X$ production.

Looking for $tH - b\bar{b}$

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[CMS-PAS-HIG-16-019]



Analysis performed separately
for 3x17 (κ_V, κ_t) hypotheses

HH searches

SM λ_{HHH}

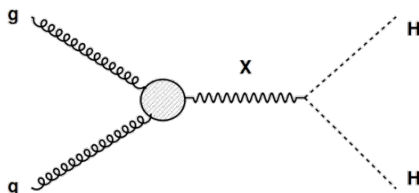
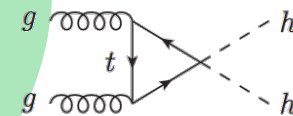
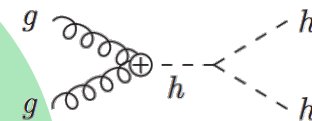
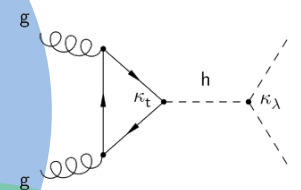
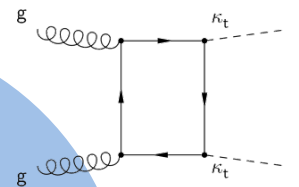
- Destructive interference

Resonant production

- spin-0 radion
- spin-2 graviton

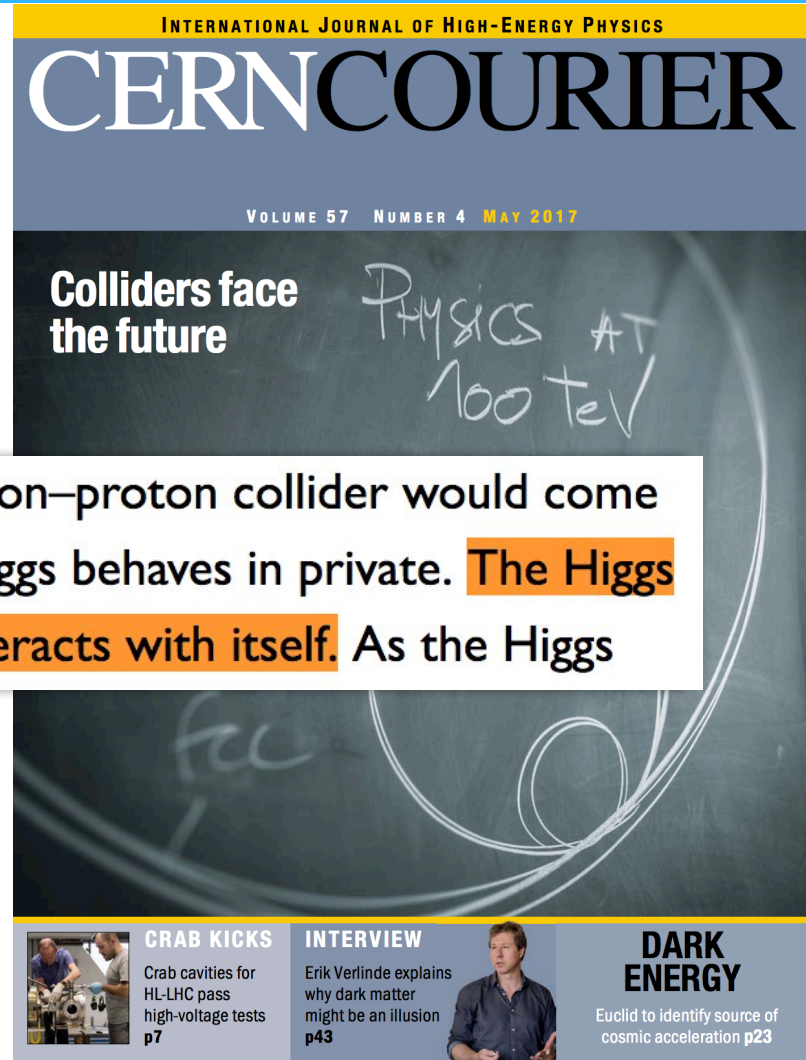
BSM couplings

- Effective Lagrangian





Speaking of λ_{HHH}



One respect in which a 100 TeV proton-proton collider would come to the fore is in revealing how the Higgs behaves in private. **The Higgs is the only particle in the SM that interacts with itself.** As the Higgs

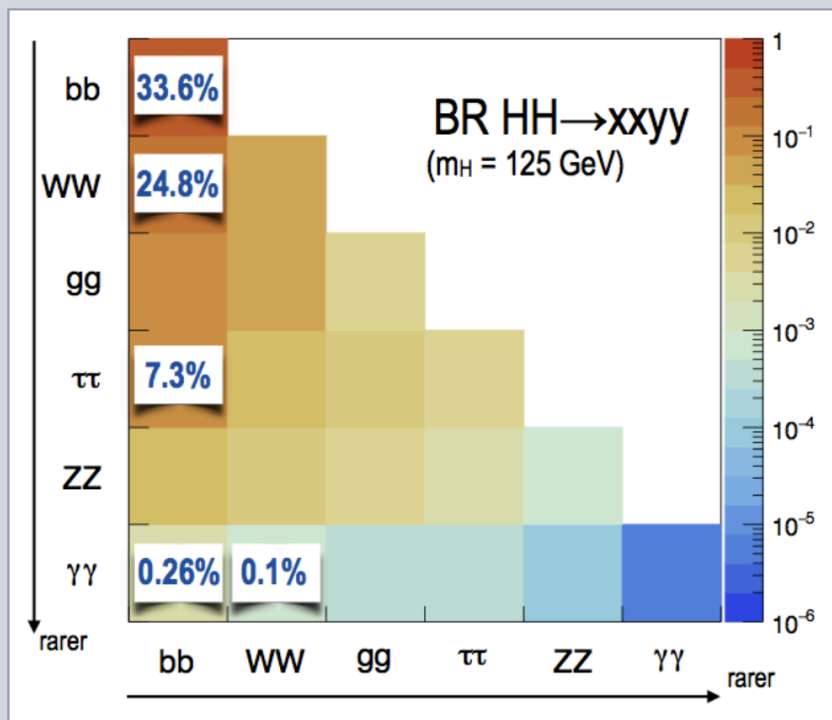
Looking for SM HH

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[T. Du Pree at SM@LHC 2017]

Tradeoff between

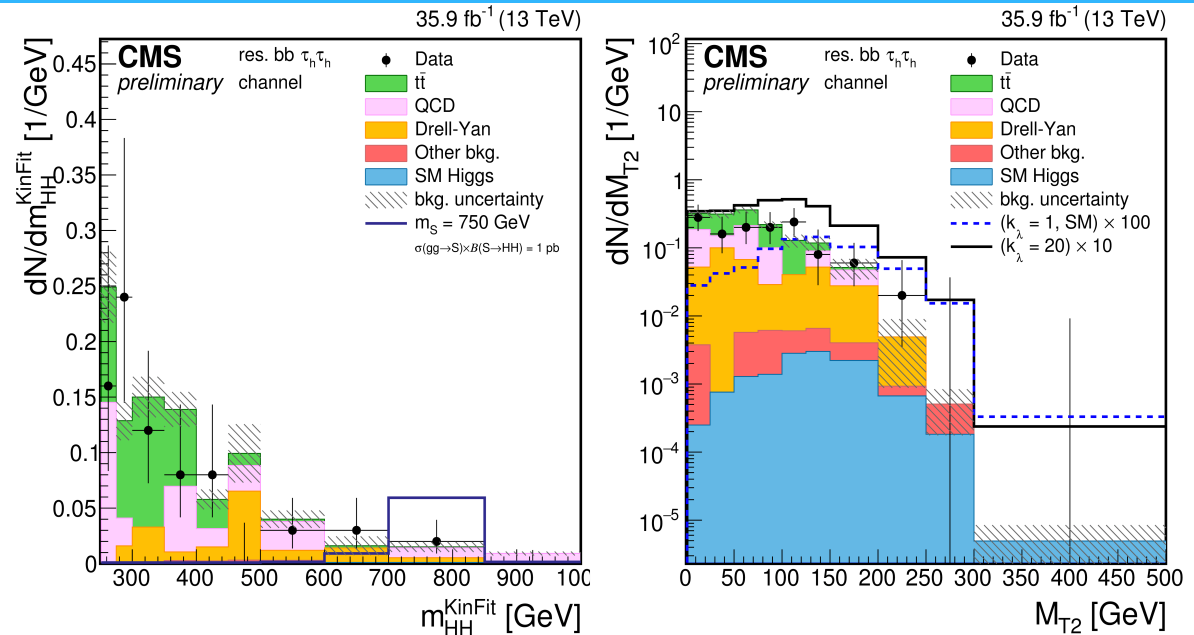
1. Resolution
2. Yield



Looking for $HH - b\bar{b}\tau\tau$

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[CMS-PAS-HIG-17-002]

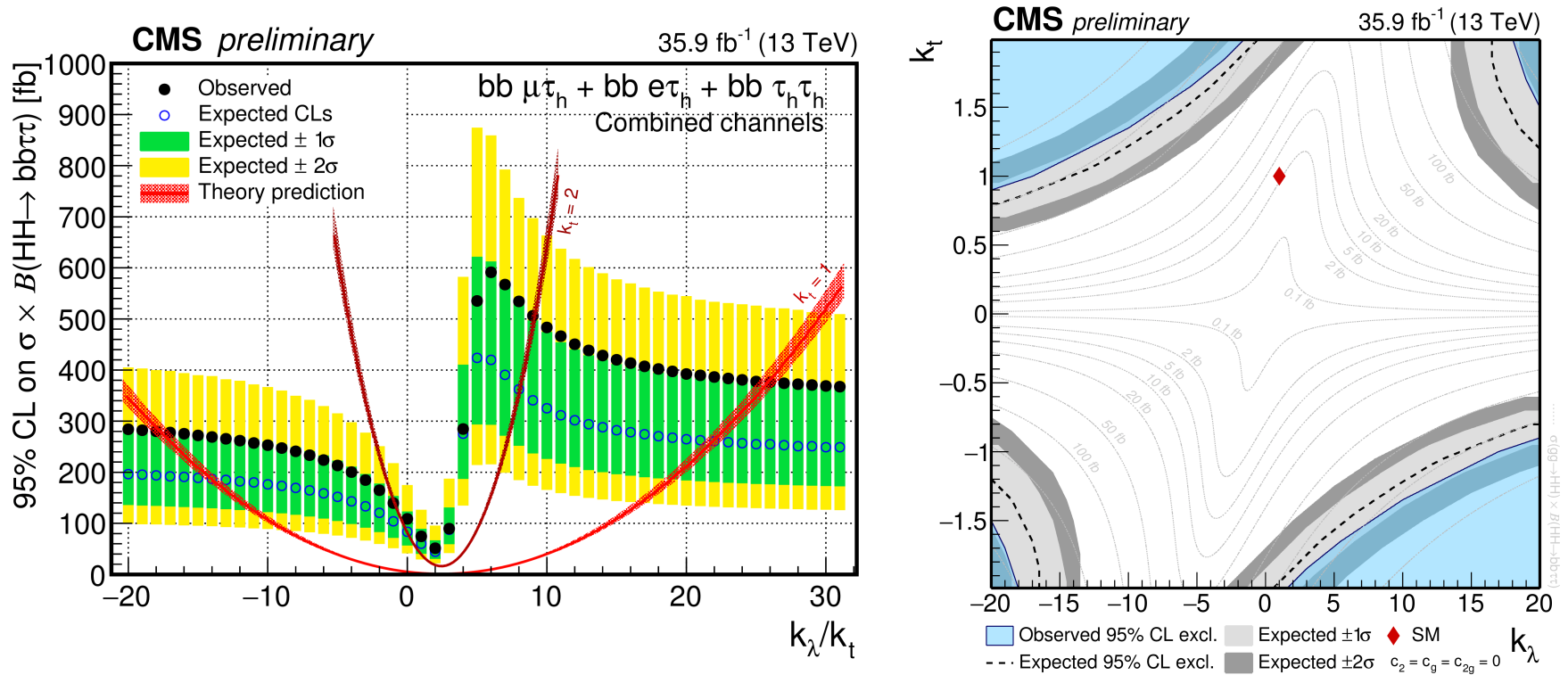


- Multiple b-jet multiplicity categories (2b0j, 1b1j) and tau decay modes ($\tau_e\tau_h$, $\tau_h\tau_h$, $\tau_\mu\tau_h$).
- m_{HH} kinematic fit used for resonant search.
- M_{T2} used for non-resonant search.

Looking for $HH - b\bar{b}\tau\tau$

79

[CMS-PAS-HIG-17-002]

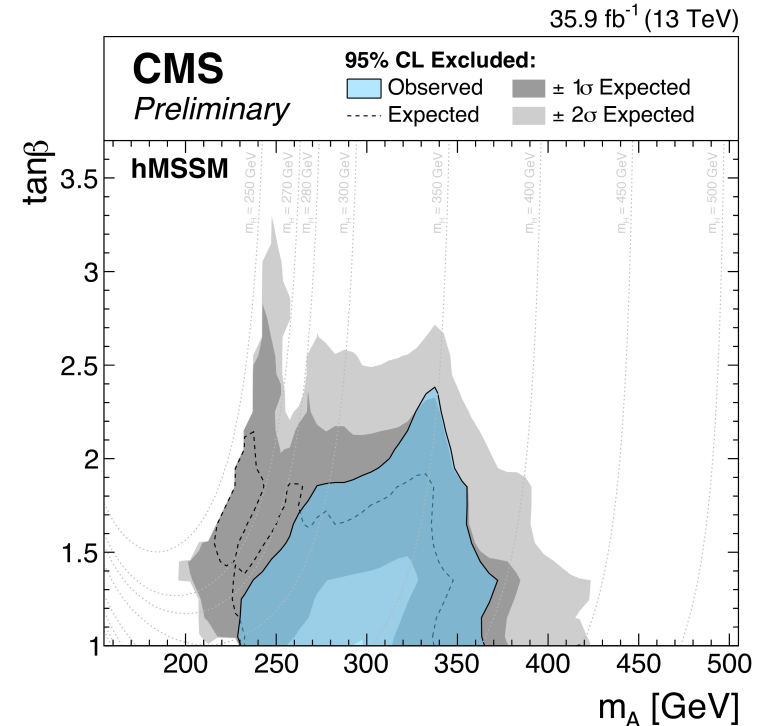
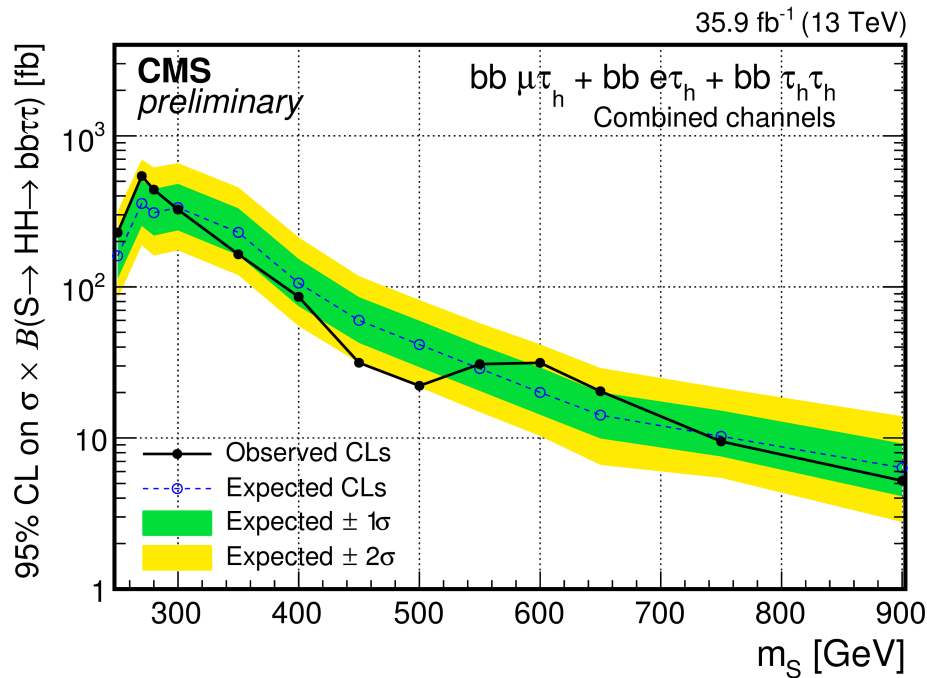


□ Upper limit of $\sim 30\times$ SM expectation.

Looking for $HH - b\bar{b}\tau\tau$

80

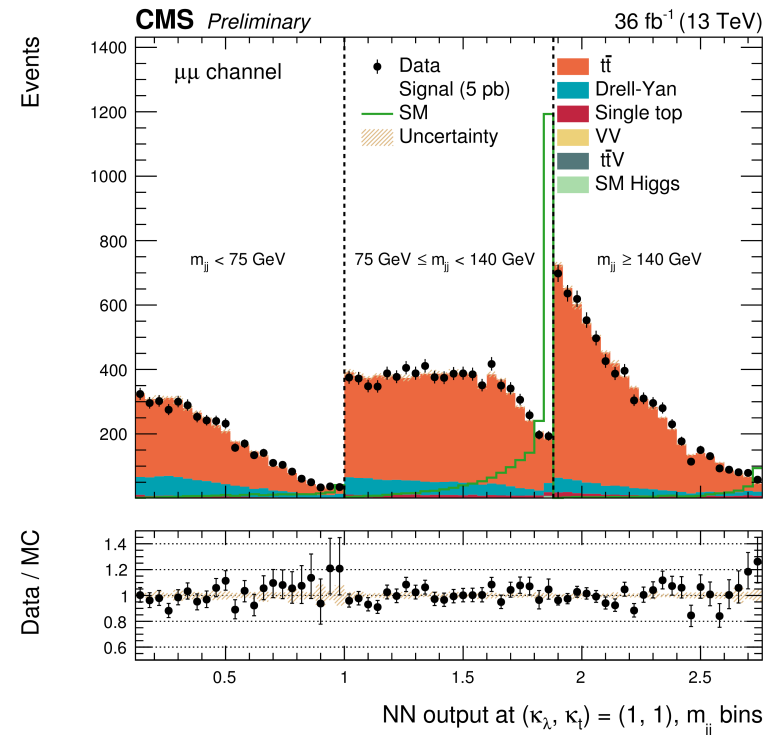
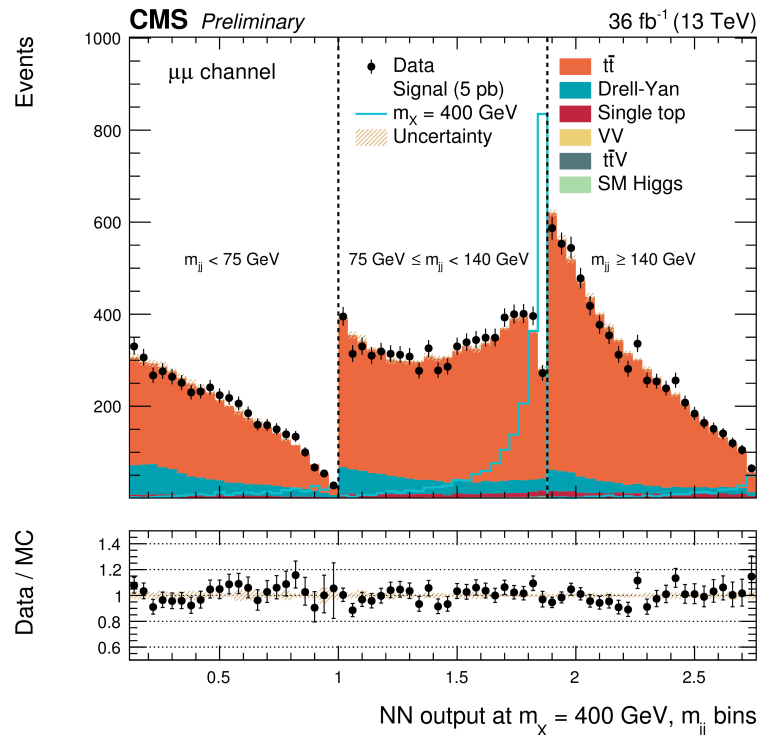
[CMS-PAS-HIG-17-002]



- Limits on heavy scalar and and hMSSM pseudo-scalar.

Looking for HH – $b\bar{b}WW$

[CMS-PAS-HIG-17-006]

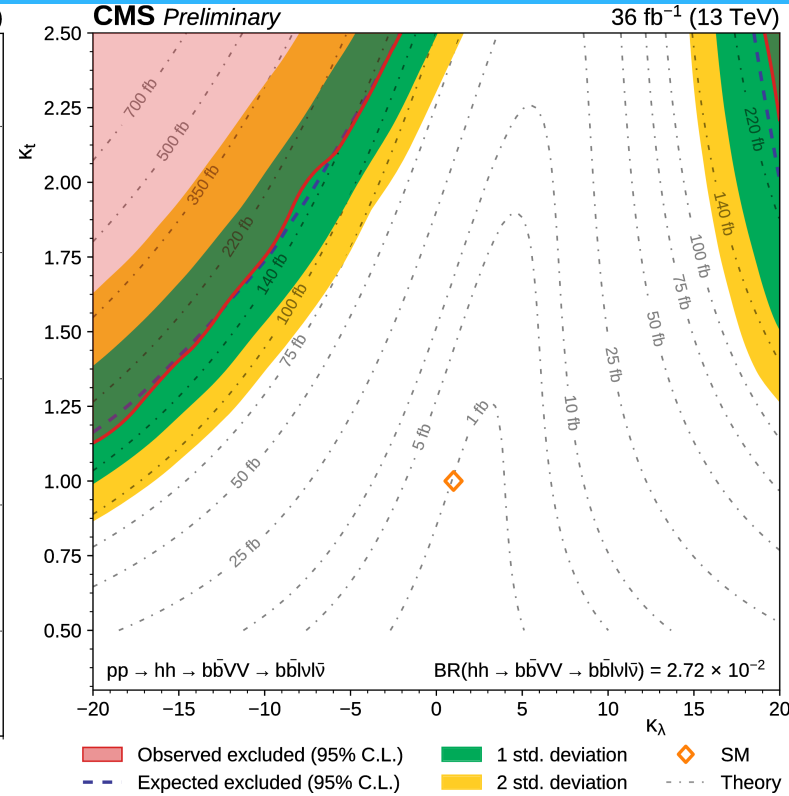
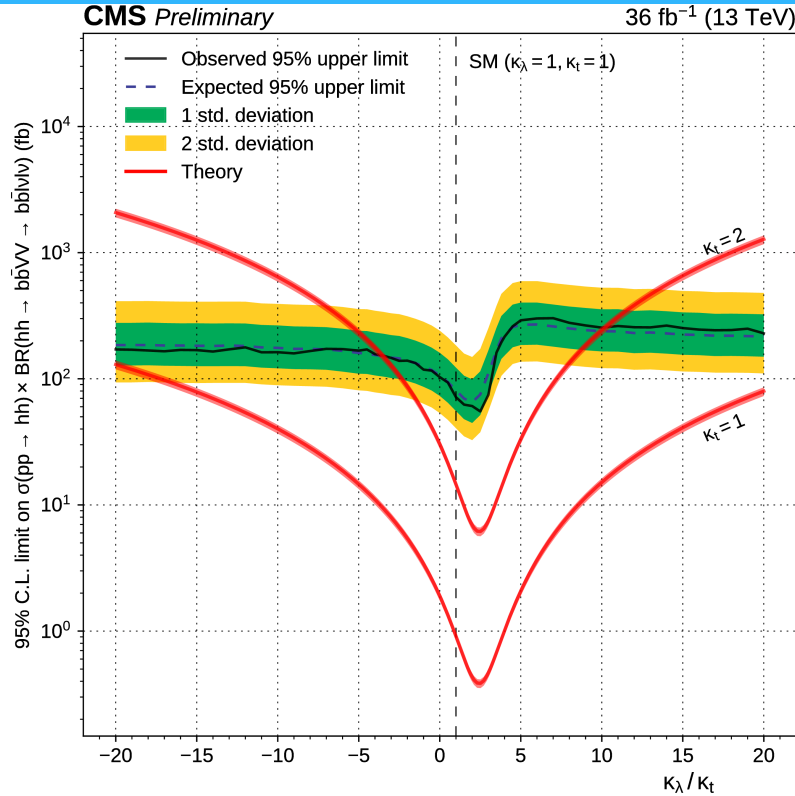


- DNN trained for non-resonant and resonant signals.
- Simultaneous fit to DNN in m_{jj} bins (sidebands and signal region).

Looking HH – $b\bar{b}WW$

82

[CMS-PAS-HIG-17-006]

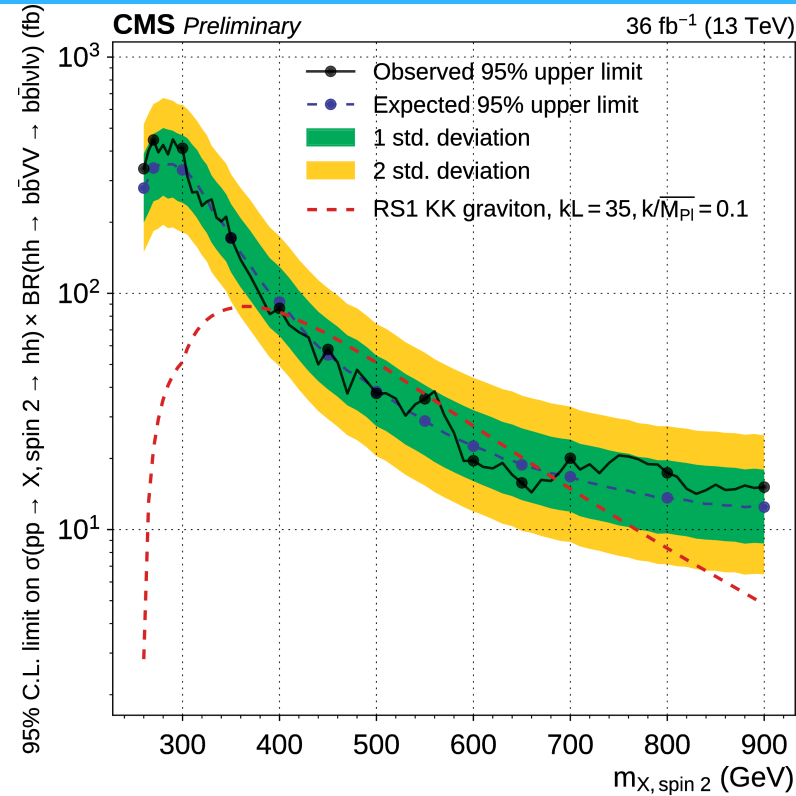
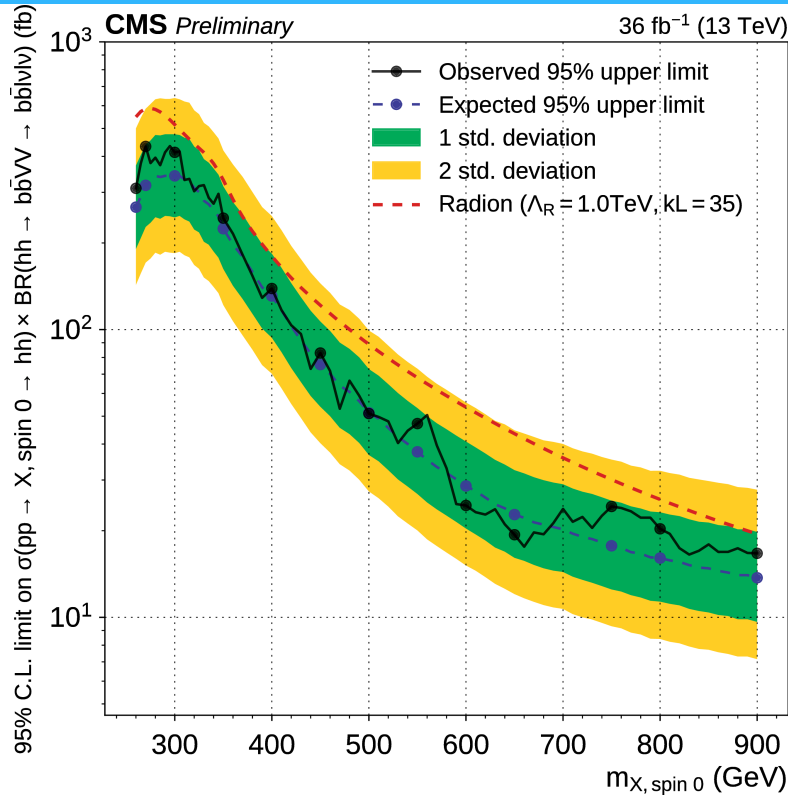


□ Upper limit of $\sim 80\times$ SM expectation.

Looking HH – $b\bar{b}WW$

83

[CMS-PAS-HIG-17-006]



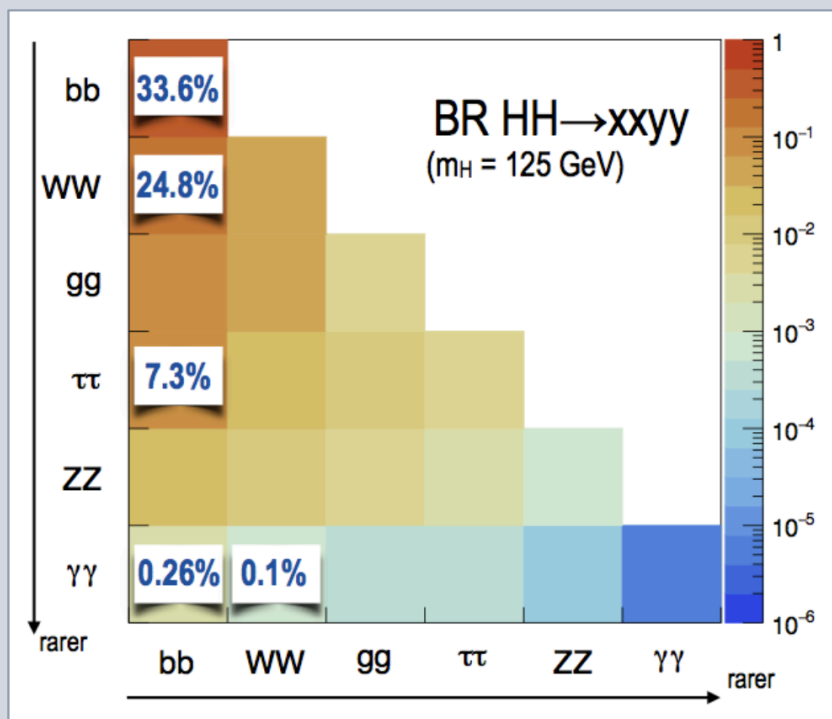
□ Limits on radion and graviton scenarios.

Looking for SM HH

[T. Du Pree at SM@LHC 2017][L. Cadamuro @ Moriond 2017]

Tradeoff between

1. Resolution
2. Yield



Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
	ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbWW	-	79 (89)
bb $\tau\tau$	-	28 (25)
bb $\gamma\gamma$	117 (161)	91 (90)
WW $\gamma\gamma$	747 (386)	-
	2.3-3.2 fb ⁻¹	13.3 fb ⁻¹ 35.9 fb ⁻¹

□: Test of anomalous HH couplings



LHCP 2017 results ~1 month ago

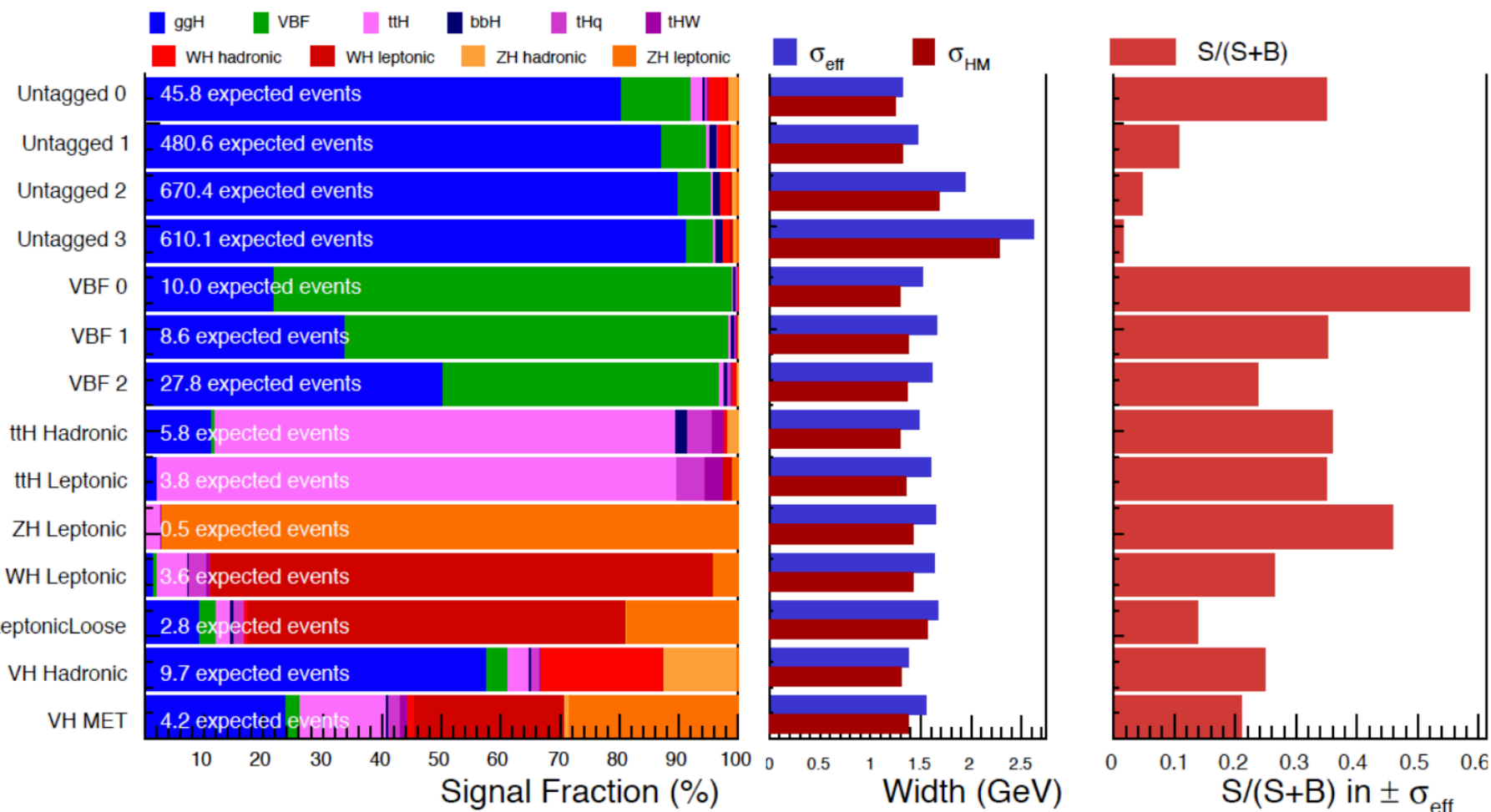
	CMS-HIG-16-041	$H \rightarrow ZZ \rightarrow 4 \text{ lepton}$ <i>properties</i>	35.9 fb ⁻¹
NEW	ATLAS-CONF-2017-32	$H \rightarrow ZZ \rightarrow 4 \text{ lepton}$ <i>properties</i>	36.1 fb ⁻¹
NEW	CMS-HIG-16-040	$H \rightarrow \gamma\gamma$ <i>properties</i>	35.9 fb ⁻¹
	CMS-HIG-17-015	$H \rightarrow \gamma\gamma$ <i>cross sections</i>	35.9 fb ⁻¹
	ATLAS-CONF-2016-067	$H \rightarrow \gamma\gamma$ <i>cross sections</i>	13.3 fb ⁻¹
	ATLAS-CONF-2017-024	$H \rightarrow \gamma\gamma + \text{MET}$ <i>new phenomena</i>	36.1 fb ⁻¹
	ATLAS-CONF-2017-028	$H \rightarrow b\bar{b} + \text{MET}$ <i>dark matter</i>	36.1 fb ⁻¹
NEW	CMS-HIG-16-043	$H \rightarrow \tau\tau$	35.9 fb ⁻¹



$H \rightarrow \gamma\gamma$ production tags

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[CMS-PAS-HIG-16-040]

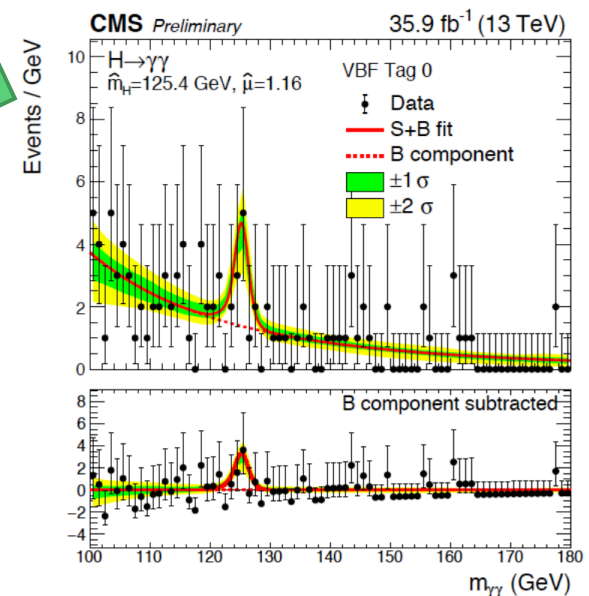
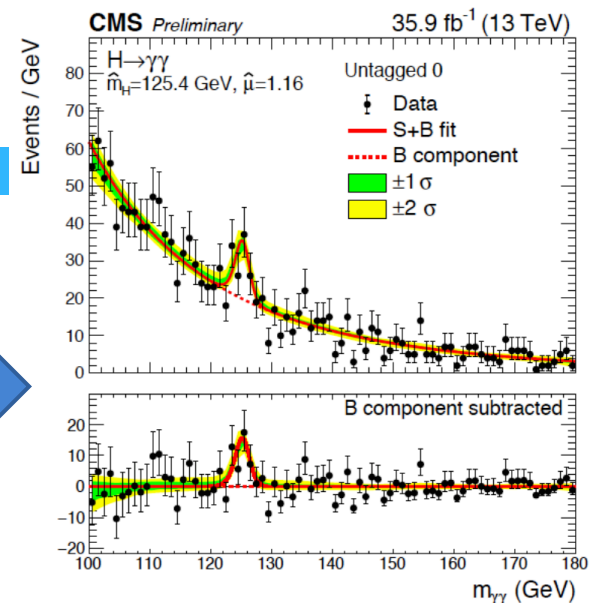
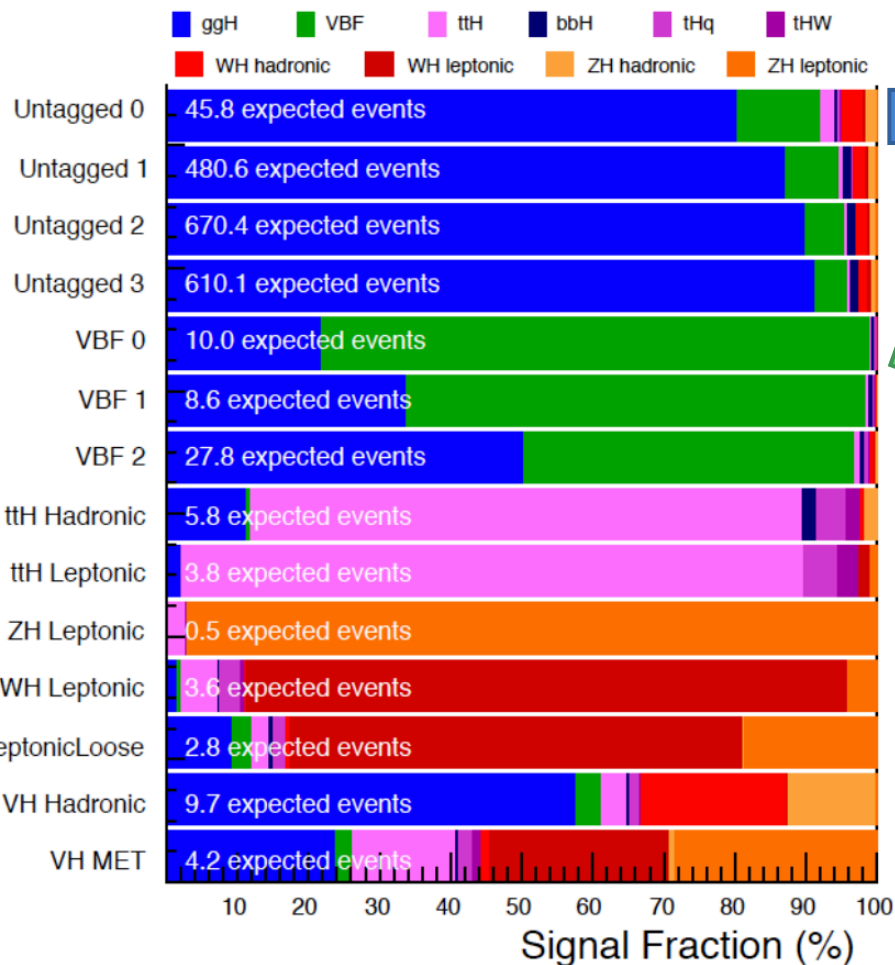
CMS Preliminary $H \rightarrow \gamma\gamma$ 35.9 fb⁻¹ (13 TeV)



87

$H \rightarrow \gamma\gamma$ production tags

[CMS-PAS-HIG-16-040]

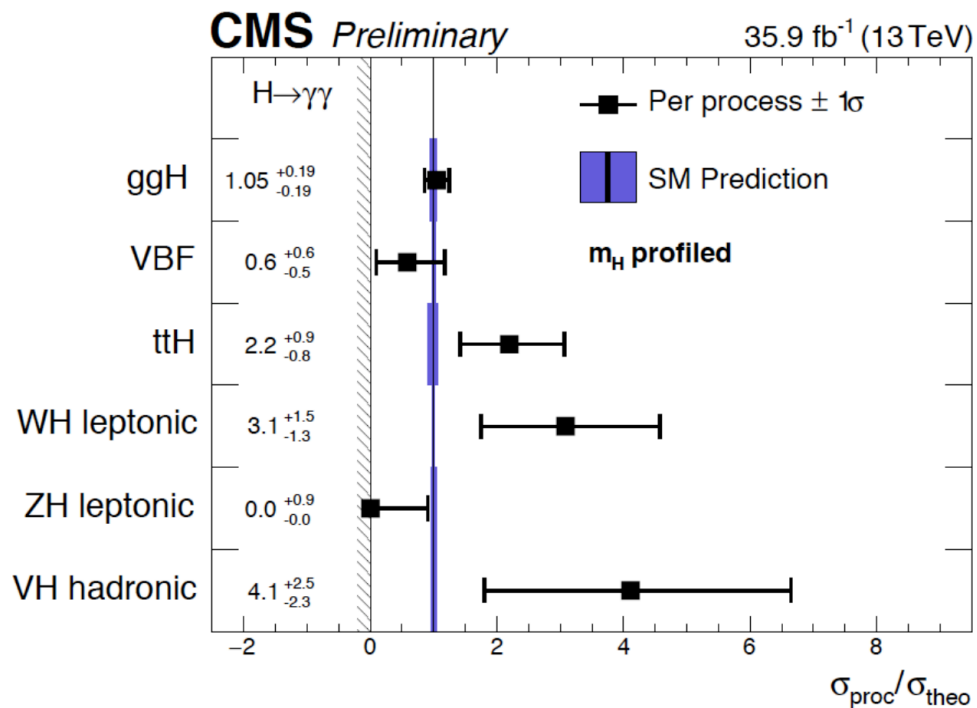
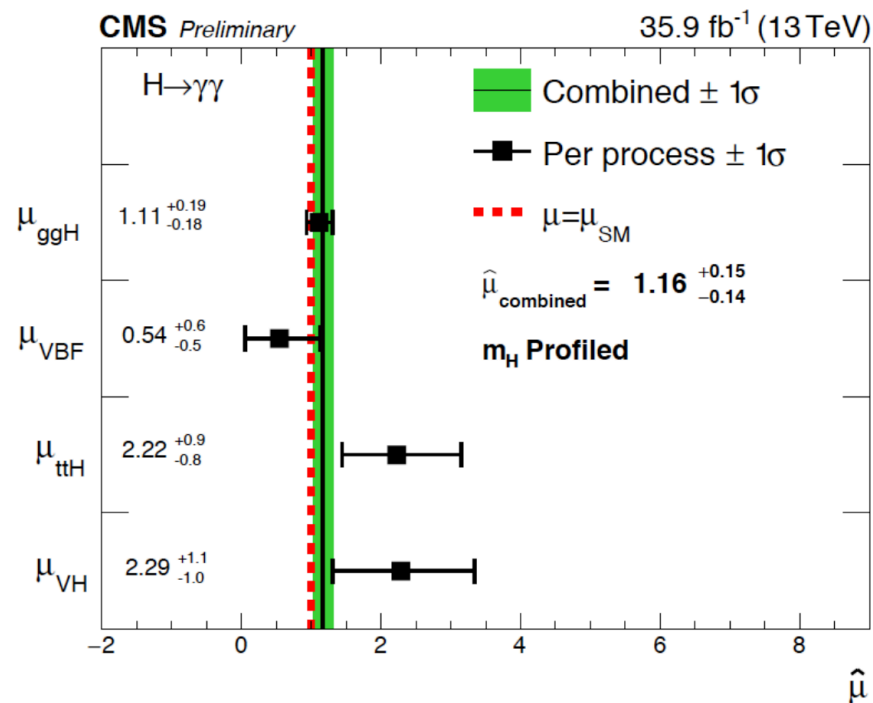
CMS Preliminary $H \rightarrow \gamma\gamma$ 

$H \rightarrow \gamma\gamma$ production tags

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[CMS-PAS-HIG-16-040]

$$\mu = \sigma/\sigma_{\text{SM}} = 1.16_{-0.10}^{+0.11} \text{ (stat.) }_{-0.08}^{+0.09} \text{ (syst.) }_{-0.05}^{+0.06} \text{ (theo.)}$$

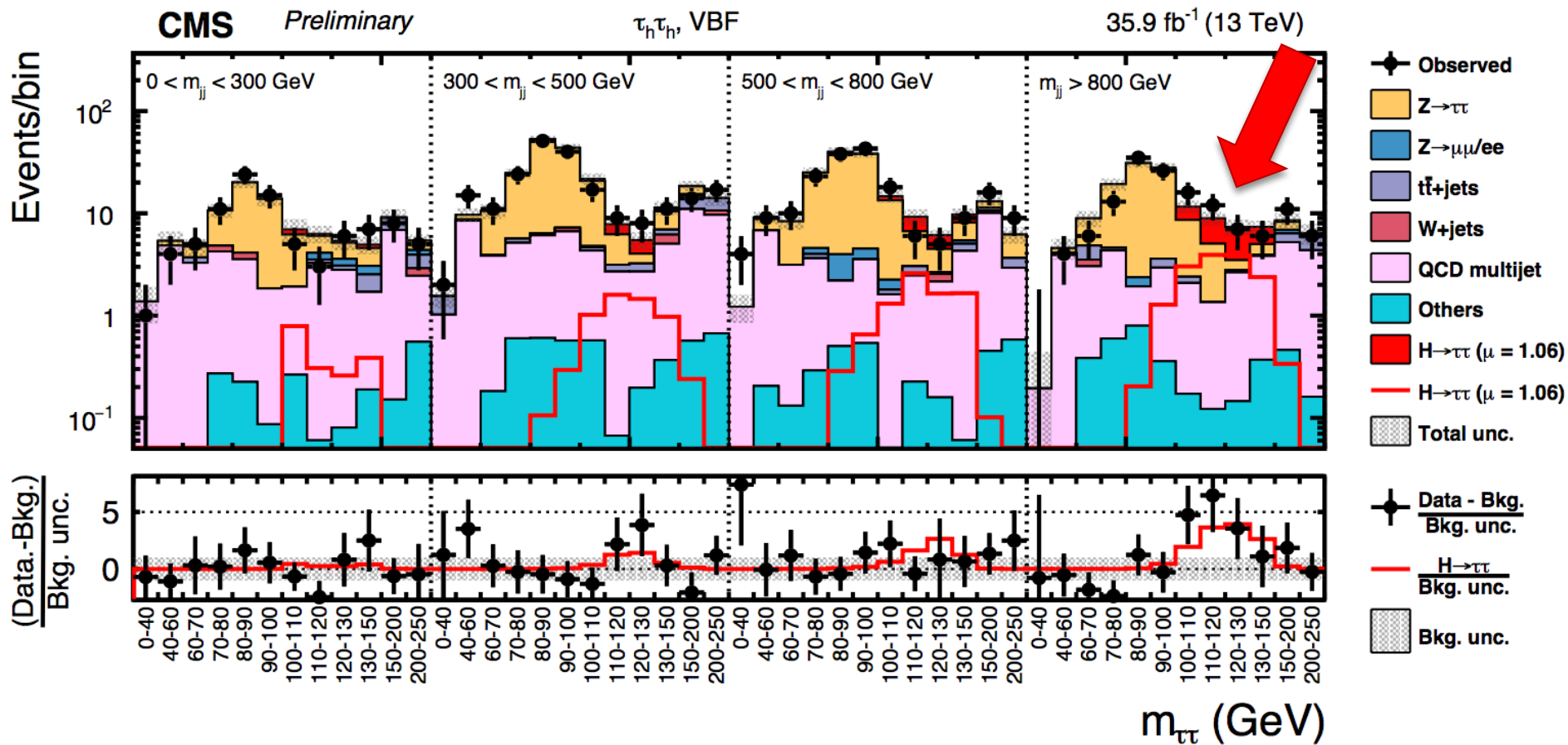


□ Template cross sections factorize theory uncertainty.

Observation of $H \rightarrow \tau\tau$

89

[CMS-PAS-HIG-16-043]

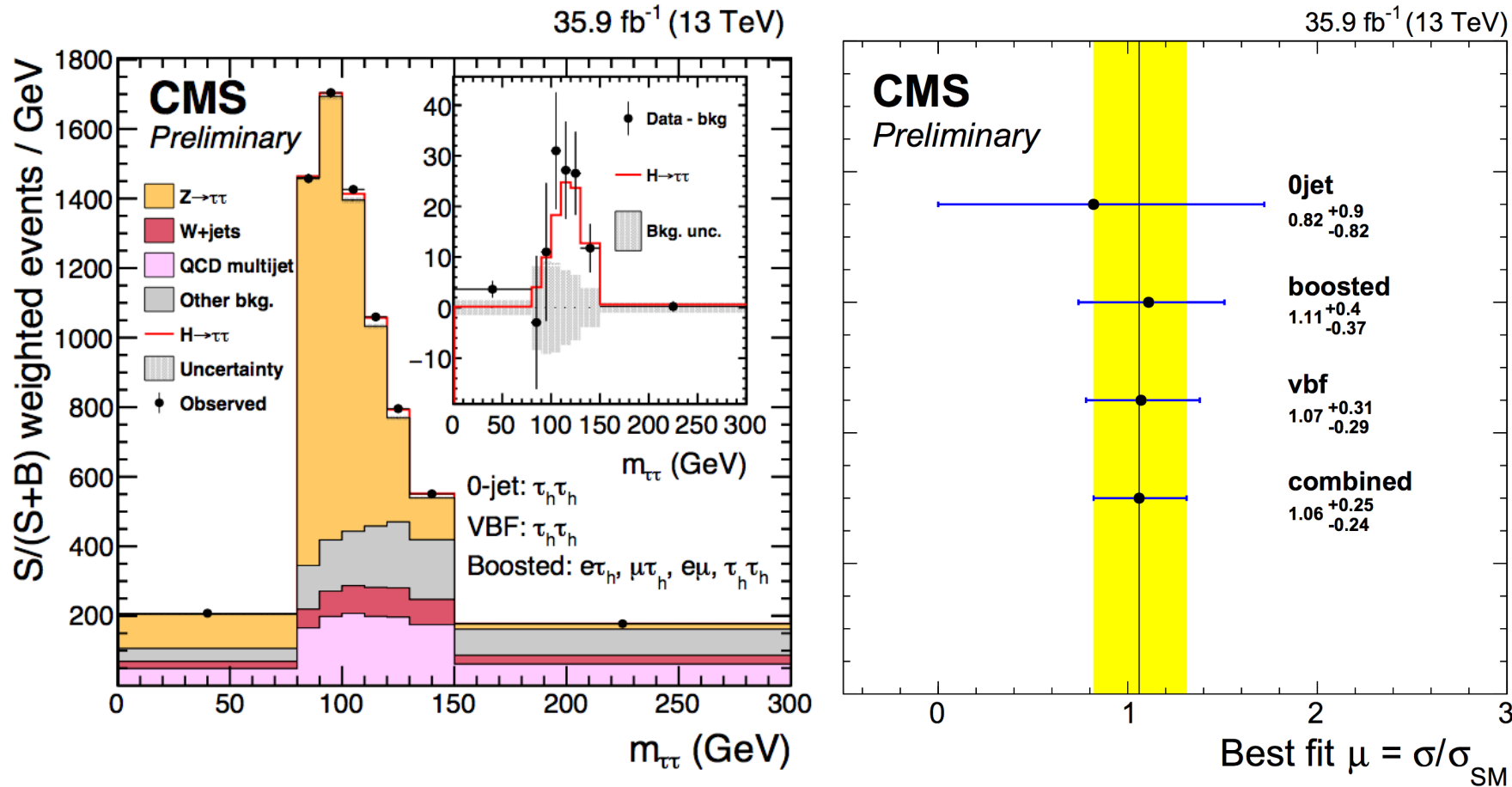


- Exploits 4 final states ($e\mu$, $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$) and 3 categories (0-jet, boosted, and **VBF**)

Observation of $H \rightarrow \tau\tau$

90

[CMS-PAS-HIG-16-043]

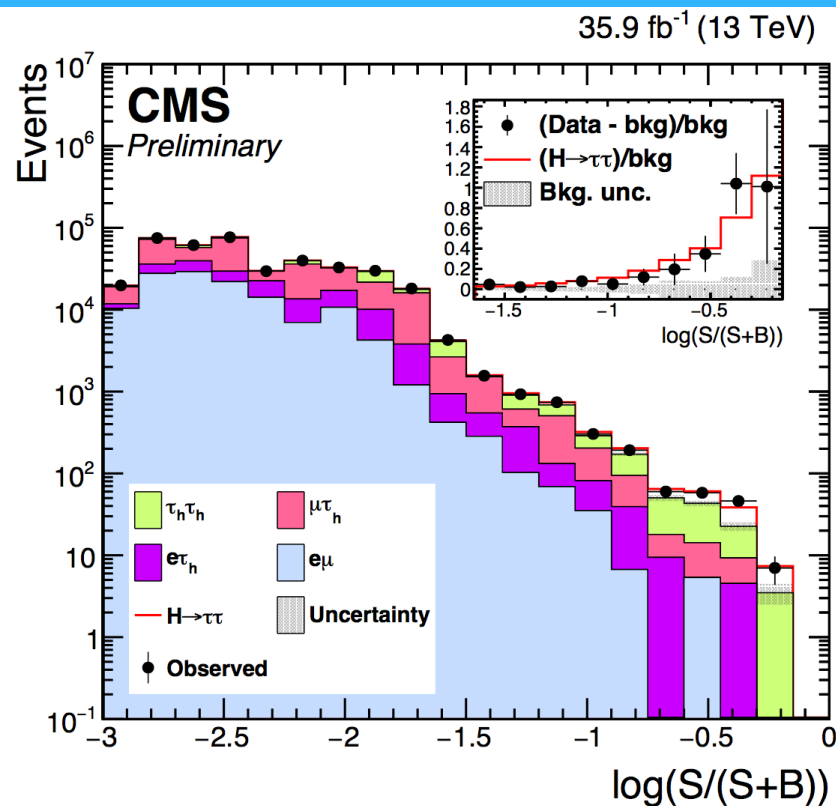
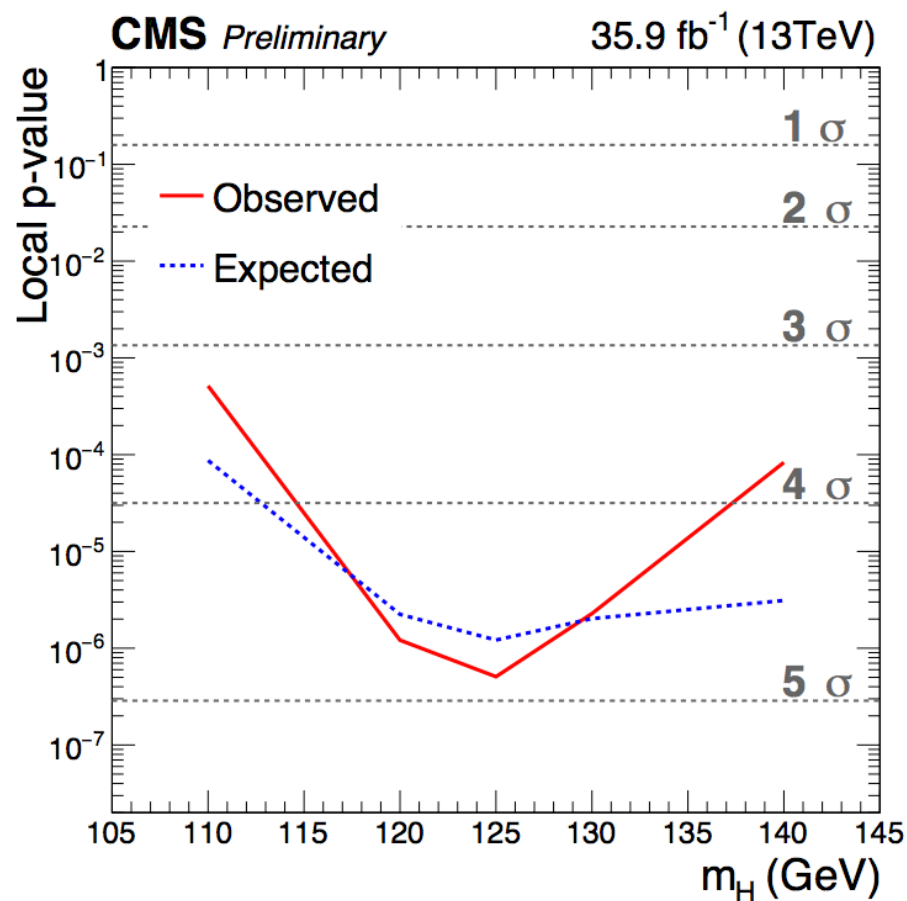


- Exploits 4 final states ($e\mu, \mu\tau_h, e\tau_h, \tau_h\tau_h$) and 3 categories (0-jet, boosted, and VBF)

Observation of $H \rightarrow \tau\tau$

91

[CMS-PAS-HIG-16-043]

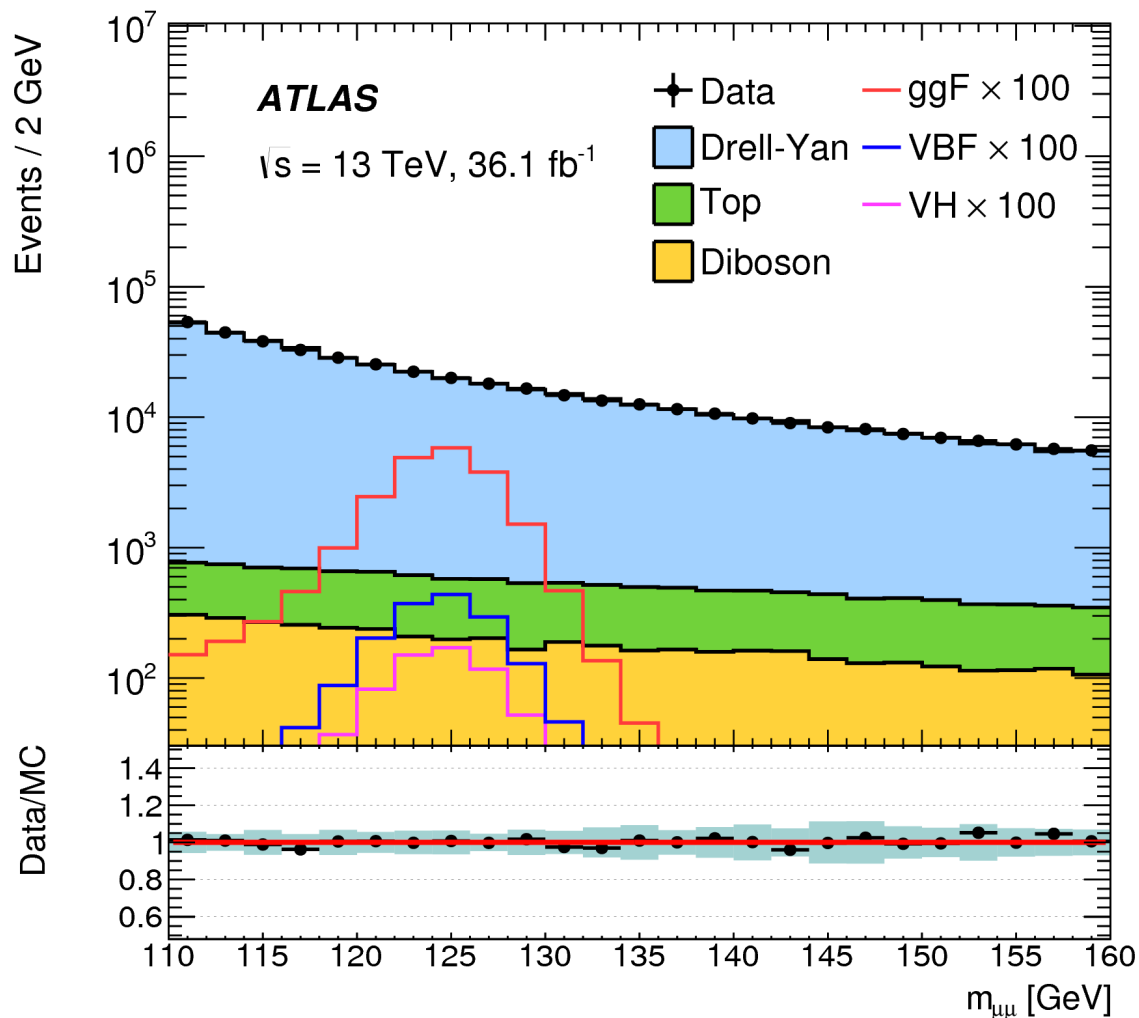


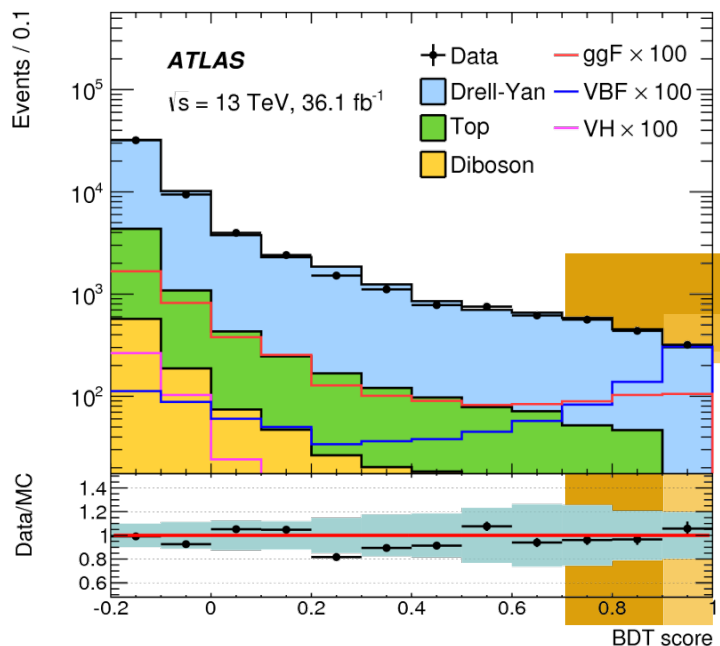
□ **At the 5 σ level.** (4.9 σ obs, 4.7 σ exp.)

Reaching for the 2nd generation

[arXiv:1705.04582]

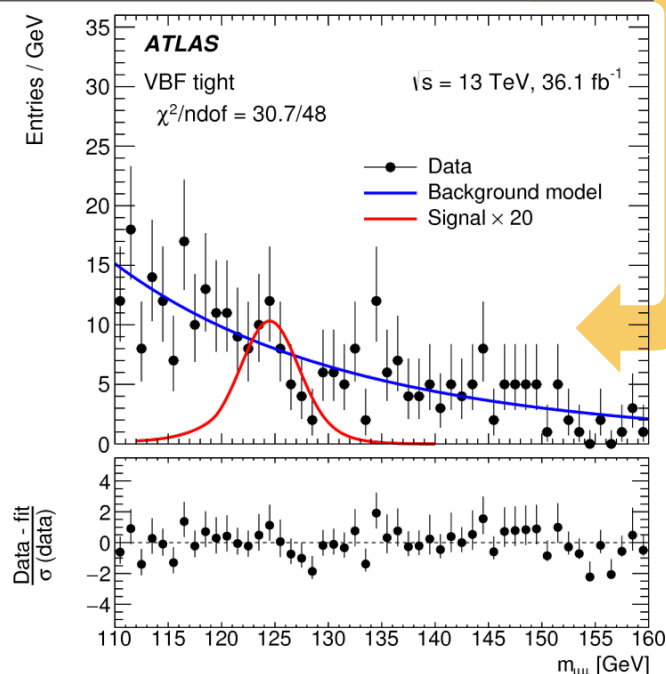
- $H \rightarrow \mu\mu$
- Peak over smooth background.
- Very small S/B.





	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

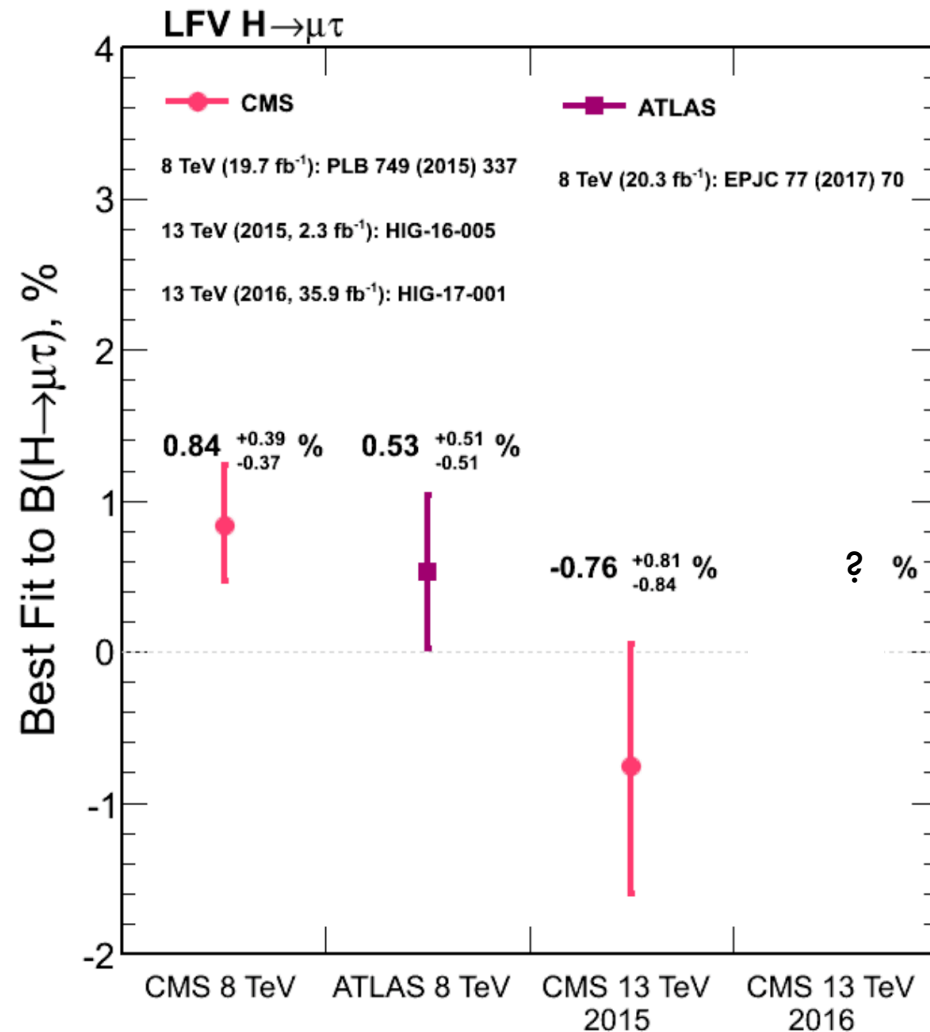
- Multivariate dimuon+dijet discriminant for higher- S/B topology selection.
- $\sigma/\sigma_{SM} < 2.8$ (2.9) obs. (exp.)



A Run 1 (flavour) puzzle

[CMS-PAS-HIG-17-001]

- **Run1: 2σ “hint” in CMS**
 - ▣ Not disproven by ATLAS data.
- **Run2: CMS first result negative but inconclusive.**

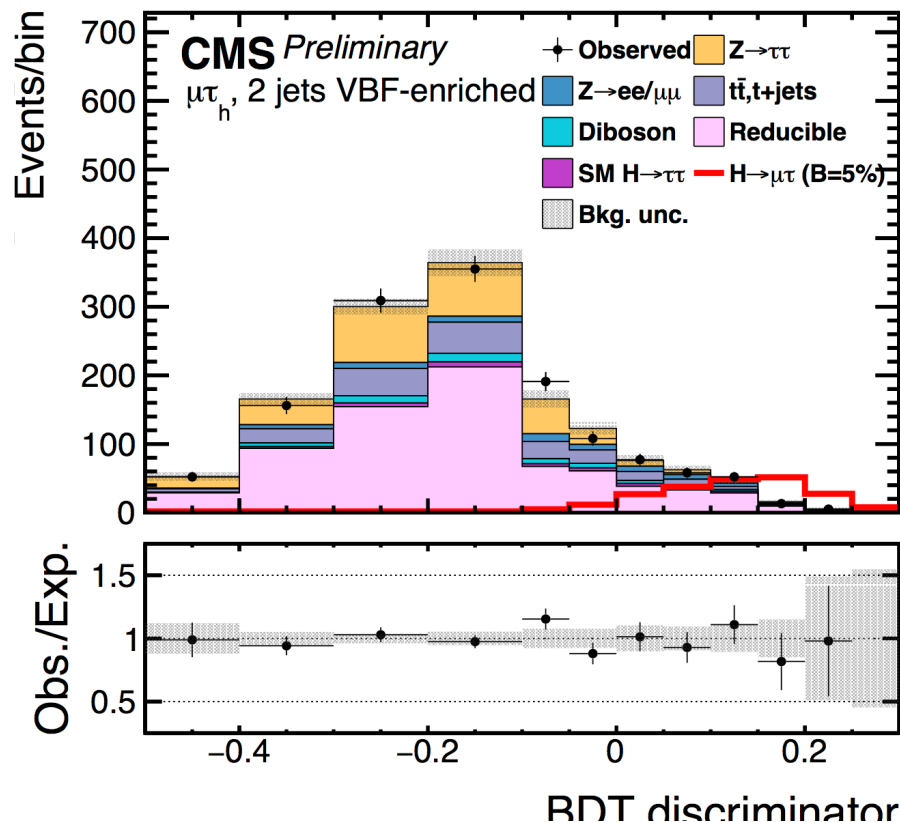


Search for LFV decays

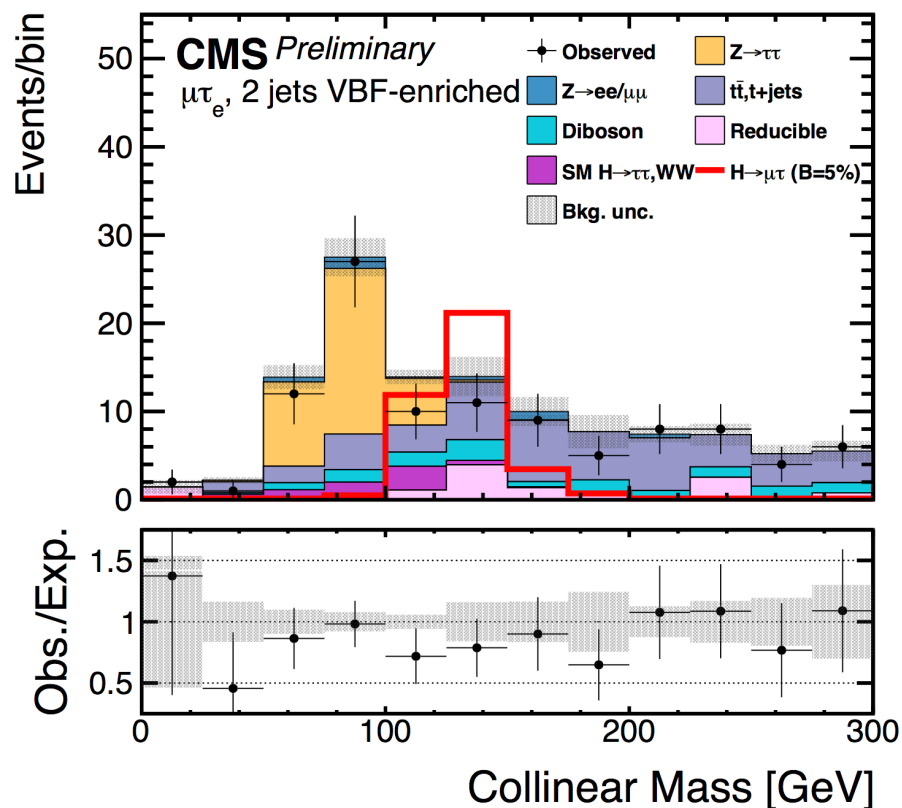
95

[CMS-PAS-HIG-17-001]

2016, 35.9 fb⁻¹ (13 TeV)



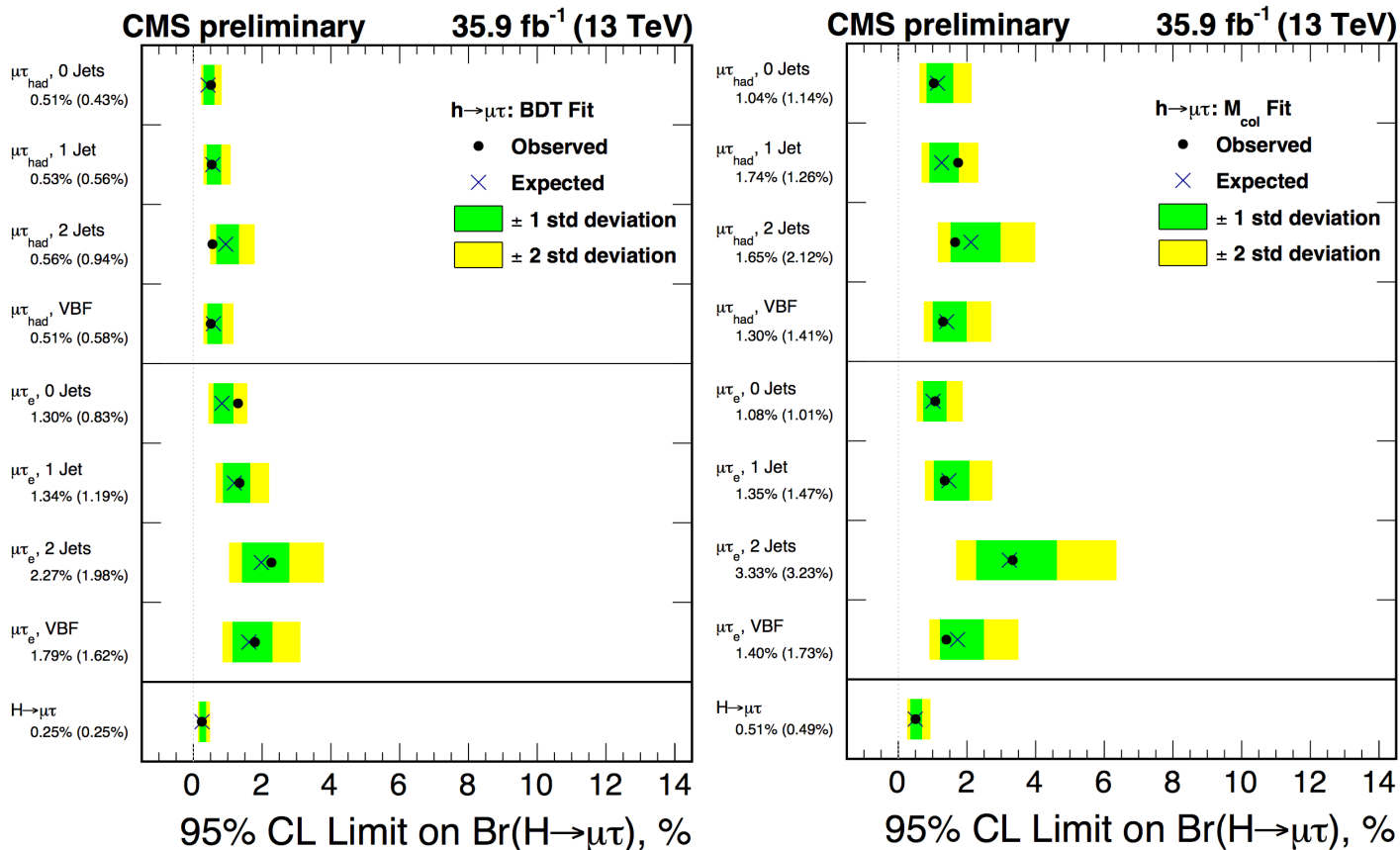
2016, 35.9 fb⁻¹ (13 TeV)



□ BDT extraction and collinear mass cross-check.

Search for LFV decays

[CMS-PAS-HIG-17-001]

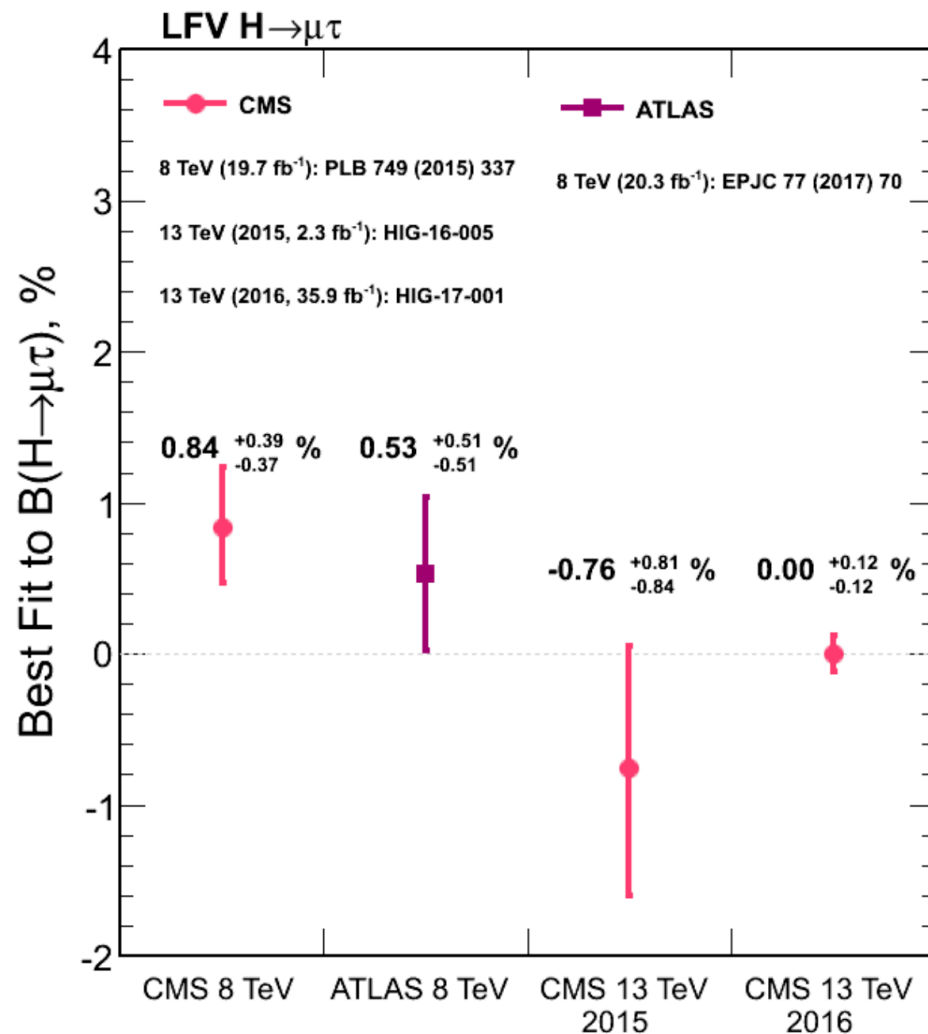


□ BDT extraction and collinear mass cross-check.

A Run 1 (flavour) puzzle

[CMS-PAS-HIG-17-001]

- **Null result.**
- **SM wins again.**



Standard Theory of Particle Physics



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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^- - \frac{1}{4} \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g \frac{M}{c_w} [(\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} \frac{1}{c_w} [Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+)] - i g s_w A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g \frac{1}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 (W_\mu^+ W_\mu^-)^2 + (\phi^0)^2 + 2\phi^+ \phi^- - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2} g^2 s_w \frac{1}{c_w} H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \frac{1}{2} (\gamma \partial + m_e^\lambda) A_\mu^\lambda (\gamma \partial + m_e^\lambda) u_j^\lambda - \frac{1}{2} (\gamma \partial + m_u^\lambda) d_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \frac{1}{2} (\gamma \partial + m_d^\lambda) d_j^\lambda (\gamma \partial + m_d^\lambda) u_j^\lambda - \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \frac{1}{3} Z_\mu^0 [(\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) d_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \gamma^5) u_j^\lambda) + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c} [Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w W_\mu^- \phi^+] + i g s_w W_\mu^+ \phi^- + \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H \\
 & W_\mu^- \phi^+] - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Valid up to $\sim$ Planck scale ?

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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c} [Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c} Z_\mu^0 H (W^+ \phi^- - W^- \phi^+) + \frac{1}{2} g^2 s_w^2 A_\mu \phi^0 (W^+ \phi^- + W^- \phi^+) + \frac{1}{2} i g^2 s_w^2 A_\mu H (W^+ \phi^- - W^- \phi^+) - \\
 & g^2 \frac{s_w^2}{c_w} (2c_w^2 - 1) Z_\mu^0 \\
 & i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e \\
 & 1 - \gamma^5) u_j^\lambda] + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{2}{3} s_w^2 - \gamma^5) d_j^\lambda) + \frac{e g}{2\sqrt{2}} W_\mu^+ [(\nu^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (u_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{e g}{2\sqrt{2}} W_\mu^- [(e^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_\lambda^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\lambda^2}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{i g}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Valid up to $\sim$ Planck scale ?

But: dark matter, matter-antimatter, etc.

The Next Standard Model



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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (g_\mu^a \gamma^\mu g_\mu^a) g_\mu^a + \tilde{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \tilde{G}^a G^b g_\mu^c - \\
 & \partial_\mu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2} M^2 \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - \\
 & A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\mu^+ W_\mu^- + \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\mu^+ W_\mu^- + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^- - Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\mu W_\mu^- - A_\mu A_\mu W_\mu^+ W_\mu^-) + g^2 s_w c_w [A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - 2A_\mu Z_\mu^0 W_\mu^+ W_\mu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] + \frac{1}{2} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{2M}{g^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} [Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+)] - i g \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^4 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_\nu^\lambda) e^\lambda - \bar{e}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_\lambda^j) u_j^\lambda - d_j^\lambda (\gamma \partial + m_\lambda^j) d_j^\lambda + \\
 & i g s_w A_\mu [- (\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{2}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{1}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda j} d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda j}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_\lambda^j}{M} [- \phi^- (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\lambda^j}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [- m_\lambda^j C_{\lambda j}^\dagger (1 - \gamma^5) d_j^\lambda + m_\lambda^j (\bar{u}_j^\lambda C_{\lambda j} (1 + \gamma^5) d_j^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^- [m_\lambda^j (\bar{d}_j^\lambda C_{\lambda j}^\dagger (1 + \gamma^5) u_j^\lambda) - \\
 & m_\lambda^j (\bar{d}_j^\lambda C_{\lambda j}^\dagger (1 - \gamma^5) u_j^\lambda)] - \frac{g}{2} \frac{m_\lambda^j}{M} H (\bar{u}_j^\lambda d_j^\lambda) + \frac{g}{2} \frac{m_\lambda^j}{M} H (\bar{d}_j^\lambda u_j^\lambda) + \frac{g}{2} \frac{m_\lambda^j}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_\lambda^j}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^- X^+ - \partial_\mu \bar{X}^+ X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2s_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

The Next Standard Model



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[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2} i g_s^2 (g_\mu^\tau \gamma^\mu q_\mu^\tau) g_\mu^\mu + \tilde{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \tilde{G}^a G^b g_\mu^c - \\
 & \partial_\mu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - \\
 & A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\mu^+ W_\mu^- + \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\mu^+ W_\mu^- - \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^- - Z_\mu^0 Z_\mu^0 W_\mu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\mu W_\mu^- - A_\mu A_\mu W_\mu^+ W_\mu^-) + g^2 s_w c_w [A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - 2A_\mu Z_\mu^0 W_\mu^+ W_\mu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] + \frac{1}{2} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{2M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} [Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+)] - i g \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 s_w (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^4 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_\nu^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - d_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & i g s_w A_\mu [- (\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{2}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{1}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{2g}{\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\mu} d_j^\lambda)] + \frac{2ig}{\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\mu}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}M} [- \phi^- (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [- m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\mu}^\dagger (1 - \gamma^5) d_j^\lambda) + m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\mu} (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\mu}^\dagger (1 + \gamma^5) u_j^\lambda) - \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\mu}^\dagger (1 - \gamma^5) d_j^\lambda)] - \frac{g}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + \\
 & i g s_w A_\mu (\partial_\mu \bar{X}^- X^+ - \partial_\mu \bar{X}^+ X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2s_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



Something
else



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Ways to find something else

Ways to find something else



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“Always two there are, no more, no less.
A master and an apprentice.”

– Yoda

Ways to find something else



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“Always two there are, no more, no less.
Direct searches and precision
measurements.”

Ways to find something else



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“Always two there are, no more, no less.
Direct searches and precision
measurements.”

Ways to find something else



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“Always two there are, no more, no less.

Direct searches will be presented later by measurements.” **J.-B. de Vivie**

Ways to find something else



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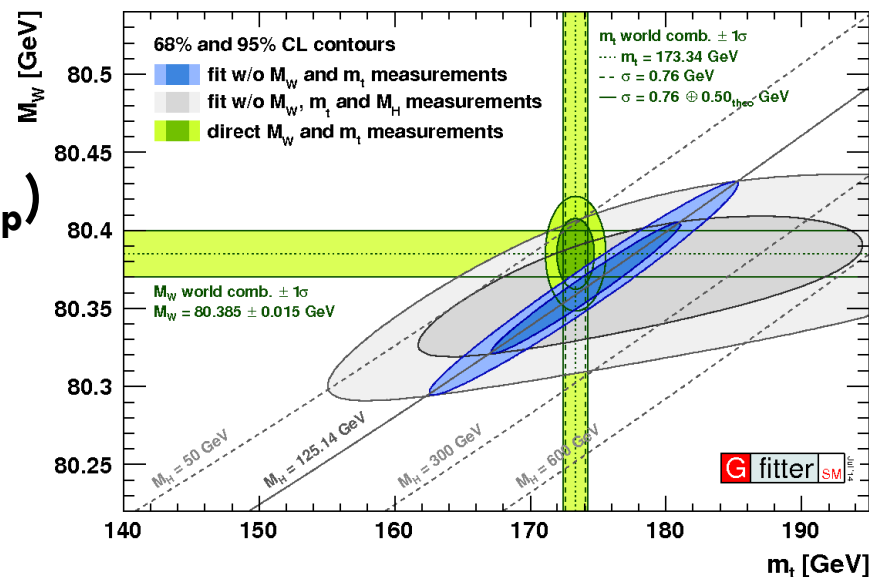
“Always two there are, no more, no less.
Direct searches and **precision
measurements.**”

H(125) – looking for “something else”

- Mass
 - ▣ Exp. Uncertainties
 - ▣ SM consistency: (m_H , m_W , m_{top})
- Spin
 - ▣ $J=1$ and $J=2$ disfavored.
- Charge
 - ▣ Zero. (That was easy.)
- Parity
 - ▣ Amplitude decomposition $\rightarrow$ EFT
- Scalar couplings
 - ▣ $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

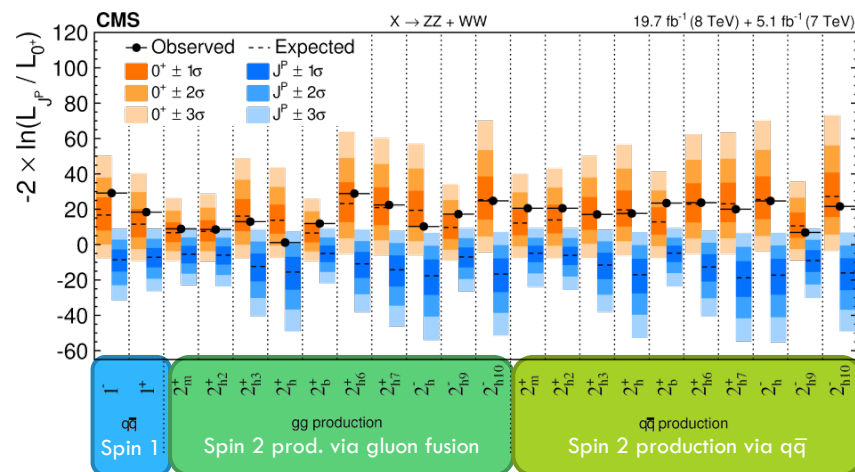
Handles on deviations

- **Mass**
 - ▣ **Exp. Uncertainties**
 - ▣ **SM consistency: (m_H , m_W , m_{top})**
- Spin
 - ▣ J=1 and J=2 disfavored.
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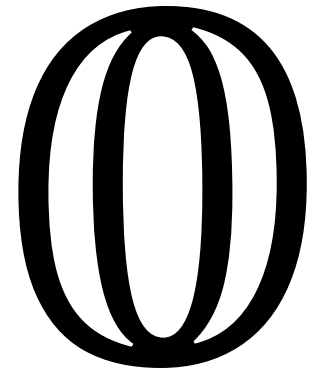
Handles on deviations

- Mass
 - ▣ Exp. Uncertainties
 - ▣ SM consistency: (m_H , m_W , m_{top})
- Spin
 - ▣ **J=1 and J=2 disfavored.**
- Charge
 - ▣ Zero. (That was easy.)
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 - ▣ Amplitude decomposition $\leftarrow$ EFT
- Scalar couplings
 - ▣ $\kappa \rightarrow \kappa(q) \rightarrow f(q) \leftarrow$ EFT



Handles on deviations

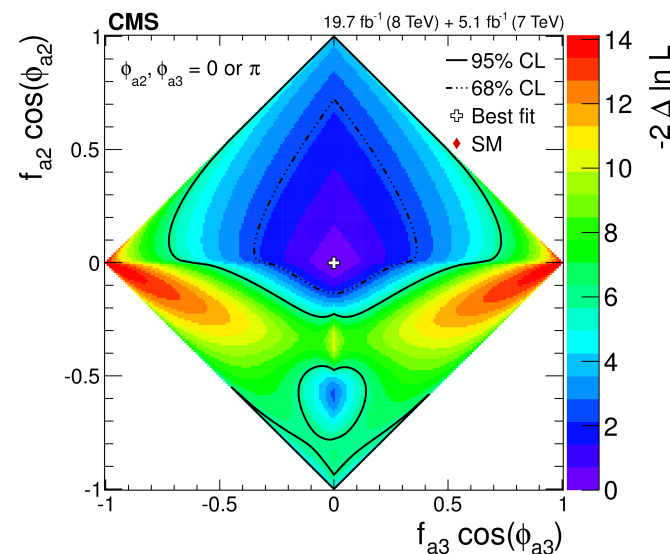
- Mass
 - ▣ Exp. Uncertainties
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- **Charge**
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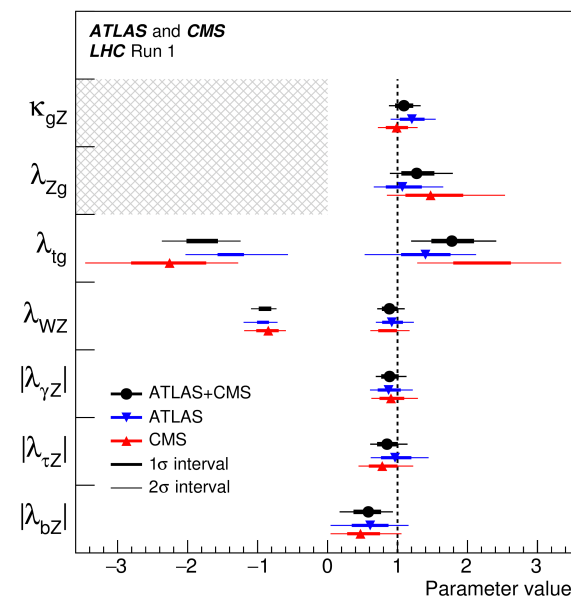
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$$\begin{aligned}
 A(X_{J=0} \rightarrow V_1 V_2) &\sim v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\
 &+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\
 &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
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 \end{aligned}$$



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$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1 \text{ TeV}}{f} \right)^2$$

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Supplementing the Standard Theory

Concrete BSM

- SUSY: MSSM, NMSSM, etc.
- Possibly:
 - ▣ Light new physics.
 - ▣ Other states.
 - ▣ Non-decoupled.
- Specific benchmarks.
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- Add higher-dimensional operators.
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Not all EFT are born the same

Top-down EFT

- Full theory known:
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A taxonomy of dim-6 SMEFT operators

[Trott et al. JHEP 04 (2014) 159]

Class	N_{op}	CP -even			CP -odd		
		n_g	1	3	n_g	1	3
1 : X^3	4	2	2	2	2	2	2
2 : H^6	1	1	1	1	0	0	0
3 : $H^4 D^2$	2	2	2	2	0	0	0
4 : $X^2 H^2$	8	4	4	4	4	4	4
5 : $\psi^2 H^3 + \text{h.c.}$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6 : $\psi^2 XH + \text{h.c.}$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7 : $\psi^2 H^2 D$	8	$\frac{1}{2}n_g(9n_g + 7)$	8	51	$\frac{1}{2}n_g(9n_g - 7)$	1	30
8 : $(\overline{LL})(\overline{LL})$	5	$\frac{1}{4}n_g^2(7n_g^2 + 13)$	5	171	$\frac{7}{4}n_g^2(n_g - 1)(n_g + 1)$	0	126
8 : $(\overline{RR})(\overline{RR})$	7	$\frac{1}{8}n_g(21n_g^3 + 2n_g^2 + 31n_g + 2)$	7	255	$\frac{1}{8}n_g(21n_g + 2)(n_g - 1)(n_g + 1)$	0	195
8 : $(\overline{LL})(\overline{RR})$	8	$4n_g^2(n_g^2 + 1)$	8	360	$4n_g^2(n_g - 1)(n_g + 1)$	0	288
8 : $(\overline{LR})(\overline{RL})$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\overline{LR})(\overline{LR})$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3 + 2n_g^2 + 89n_g + 2)$	25	1191	$\frac{1}{8}n_g(107n_g^3 + 2n_g^2 - 67n_g - 2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4 + 2n_g^3 + 213n_g^2 + 30n_g + 72)$	53	1350	$\frac{1}{8}(107n_g^4 + 2n_g^3 + 57n_g^2 - 30n_g + 48)$	23	1149

Table 2. Number of CP -even and CP -odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4 + 2n_g^3 + 135n_g^2 + 60)/4$, which is 76 for $n_g = 1$ and 2499 for $n_g = 3$.

SM-EFT questions

- From 2499 dim-6 operators to ~ 60 operators.
 - **Symmetries** guide the culling:
 - Flavour, $\sim$ custodial, CP.
 - Each assumption needs **testing** measurements/observables.

- But to go down from ~ 60 :
 - Guidance from **experimental sensitivity**.
 - Use **complementary information**:
 - LEP, Tevatron, etc experimental constraints.
 - α TGC/ α QGC, top quark, EDM searches, etc.

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SM-EFT cuts across

colliders (ee, eh),

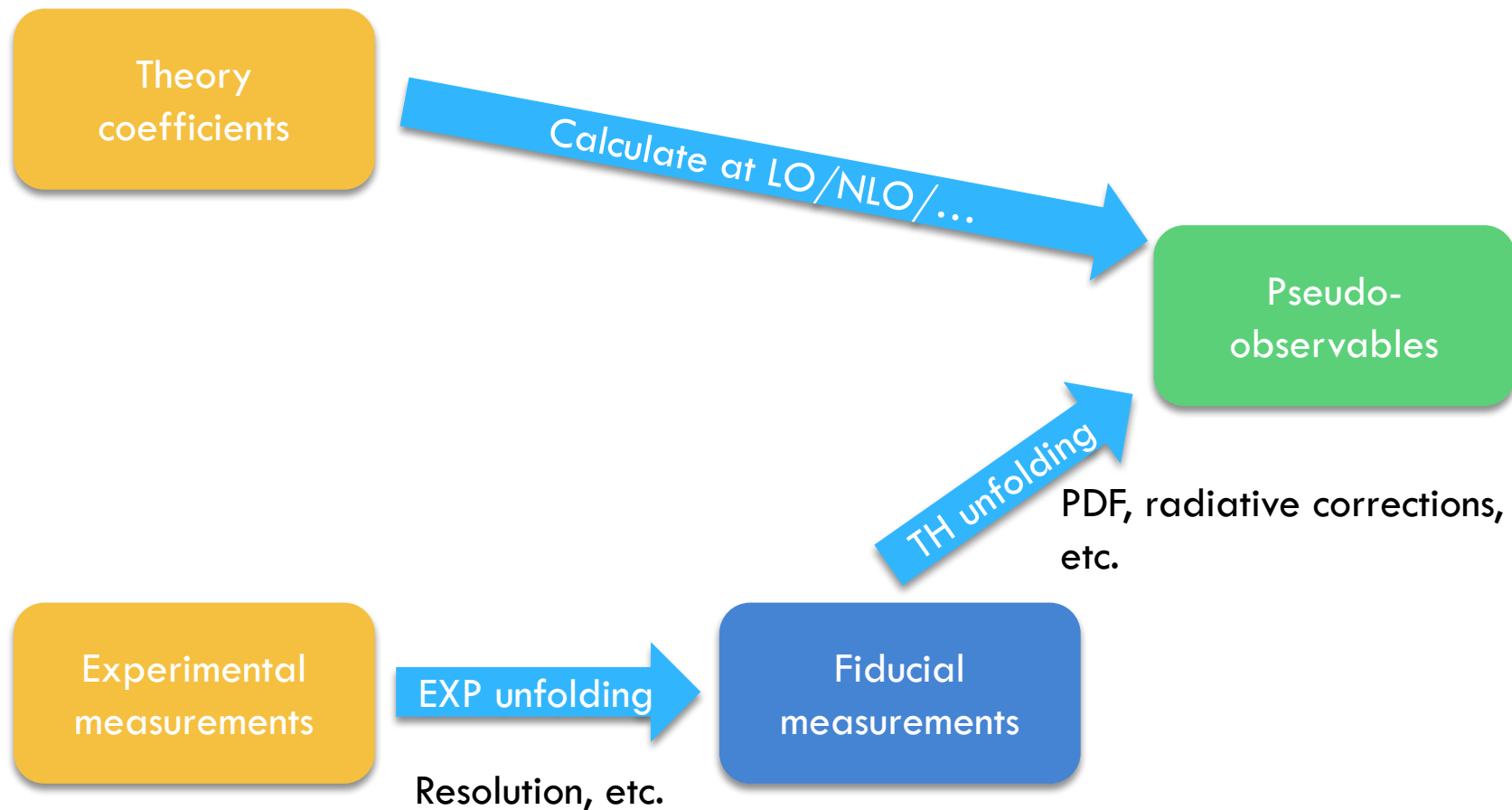
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sectors (multi-bosons, top),

and searches (LFV, EDM)...

- Use complementary information
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With some LEP inspiration



The easy PO – on-shell $h(125) \rightarrow 4\ell$

[<https://goo.gl/JcWEuc>] [arXiv:1504.04018]

Multi-body modes

e.g. $h \rightarrow 4\ell, \ell\ell\gamma, \dots$



Form factors $\rightarrow f_i(\mathbf{s})$ [E.g.: $s = m_{\ell\ell}^2$]



Momentum expansion of the $f.f.$ around leading poles

$$\text{E.g.: } f_i^{\text{SM+NP}} = \frac{\kappa_i}{\mathbf{s} - m_Z^2 + im_Z\Gamma_Z} + \frac{\epsilon_i}{m_Z^2} + \mathcal{O}(\mathbf{s}/m_Z^4)$$

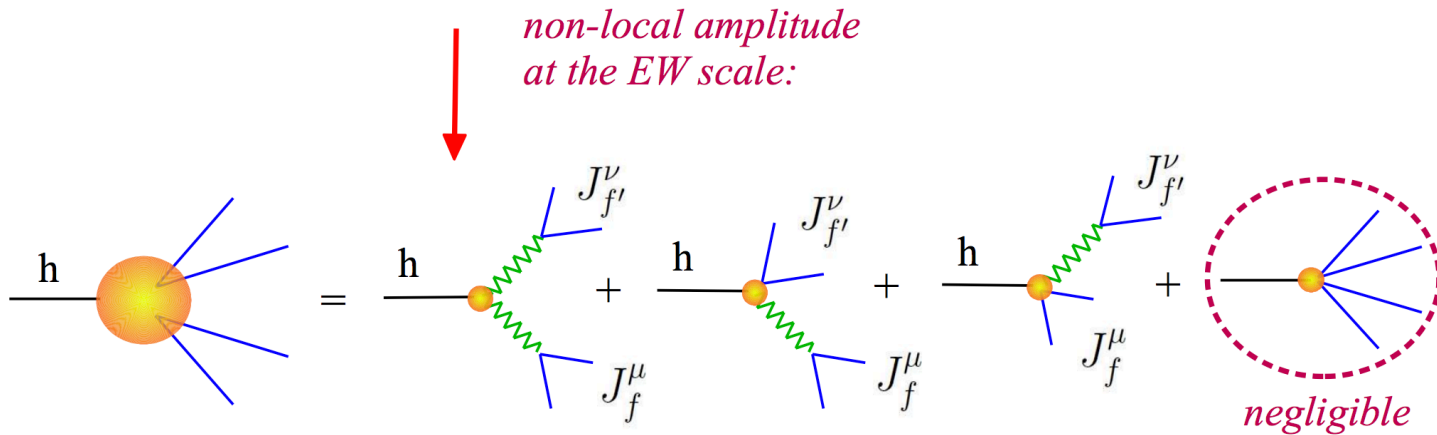
Two-body (on-shell) decays

[no polarization properties of the final state accessible]

e.g. $h \rightarrow \gamma\gamma, \mu\mu, \tau\tau, b\bar{b}$

The easy PO – on-shell $h(125) \rightarrow 4\ell$

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$$\mathcal{A} = i \frac{2m_Z^2}{v_F} \sum_{e=e_L, e_R} \sum_{\mu=\mu_L, \mu_R} (\bar{e} \gamma_\alpha e) (\bar{\mu} \gamma_\beta \mu) \times$$

$$\left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2} \frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2} \frac{g_Z^e}{P_Z(q_1^2)} \right) g^{\alpha\beta} + \right.$$

$$+ \left(\epsilon_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \kappa_{Z\gamma} \epsilon_{Z\gamma}^{\text{SM-1L}} \left(\frac{e Q_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{e Q_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma} \epsilon_{\gamma\gamma}^{\text{SM-1L}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{q_1 \cdot q_2 g^{\alpha\beta} - q_2^\alpha q_1^\beta}{m_Z^2} +$$

$$\left. + \left(\epsilon_{ZZ}^{\text{CP}} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}} \left(\frac{e Q_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{e Q_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\text{CP}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\epsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8 \times 10^{-3}$$

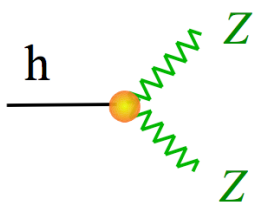
$$\epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7 \times 10^{-3}$$

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

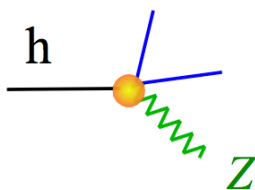
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Double Z-pole



Single Z-pole

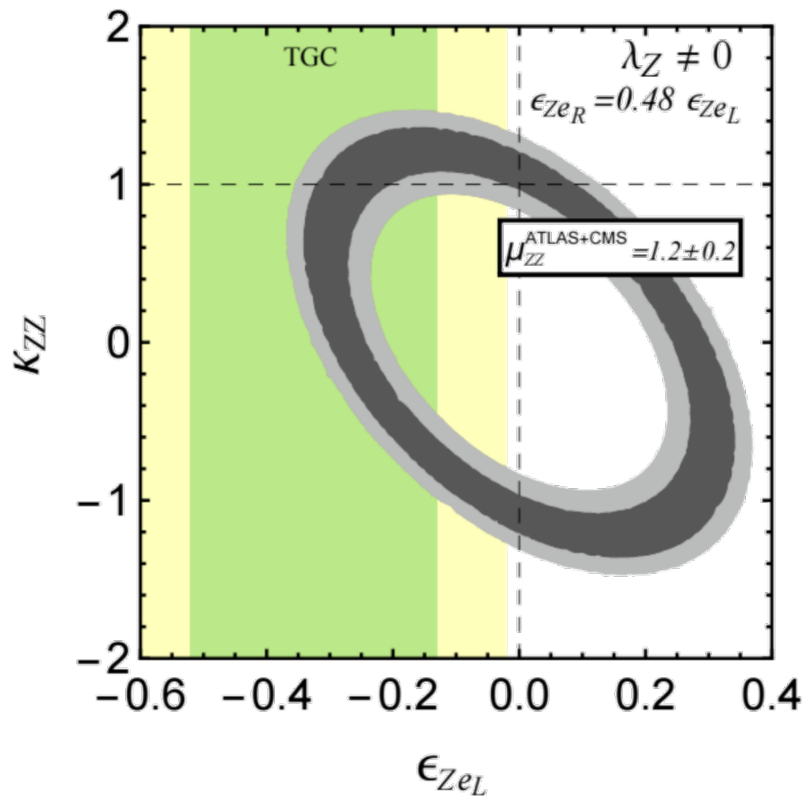


$$\mathcal{A} = i \frac{2m_Z^2}{v_F} \sum_{e=e_L, e_R} \sum_{\mu=\mu_L, \mu_R} (\bar{e} \gamma_\alpha e) (\bar{\mu} \gamma_\beta \mu) \times$$

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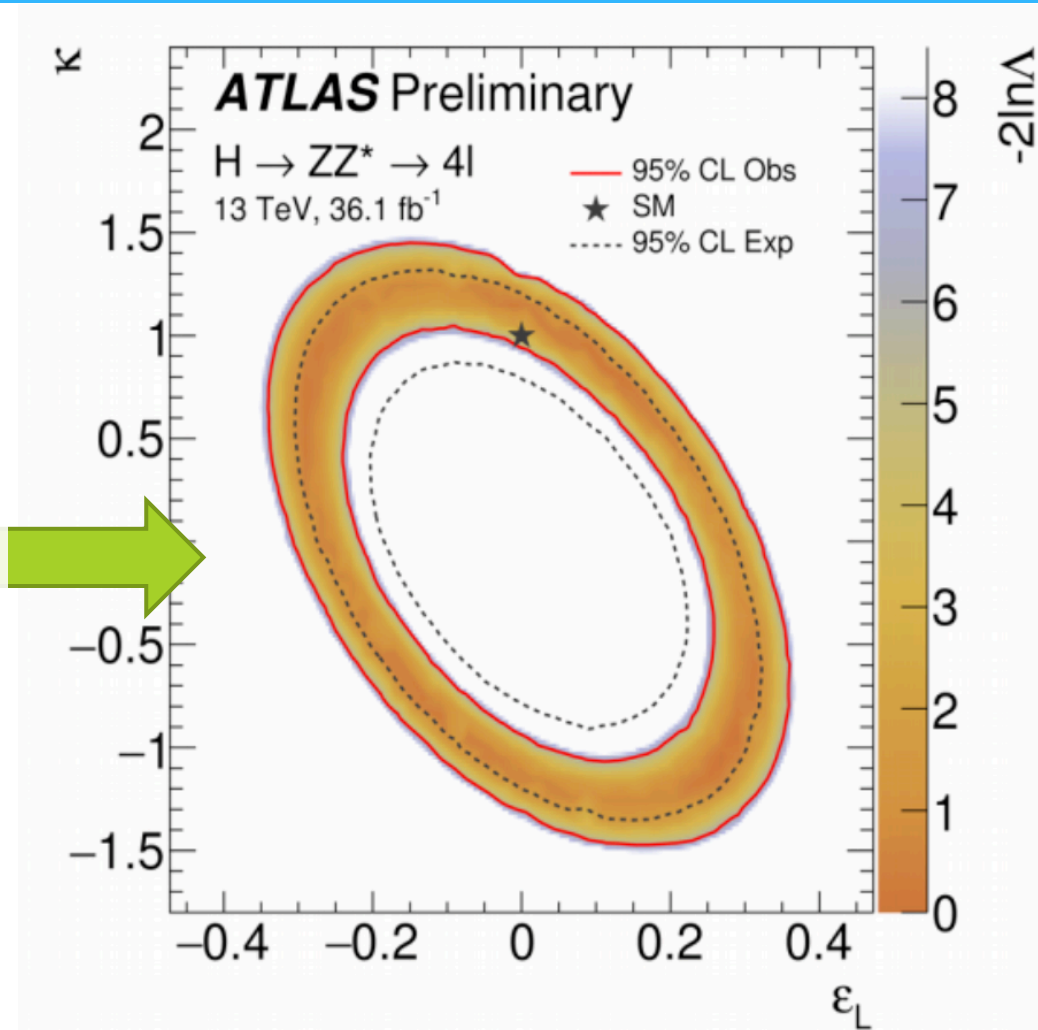
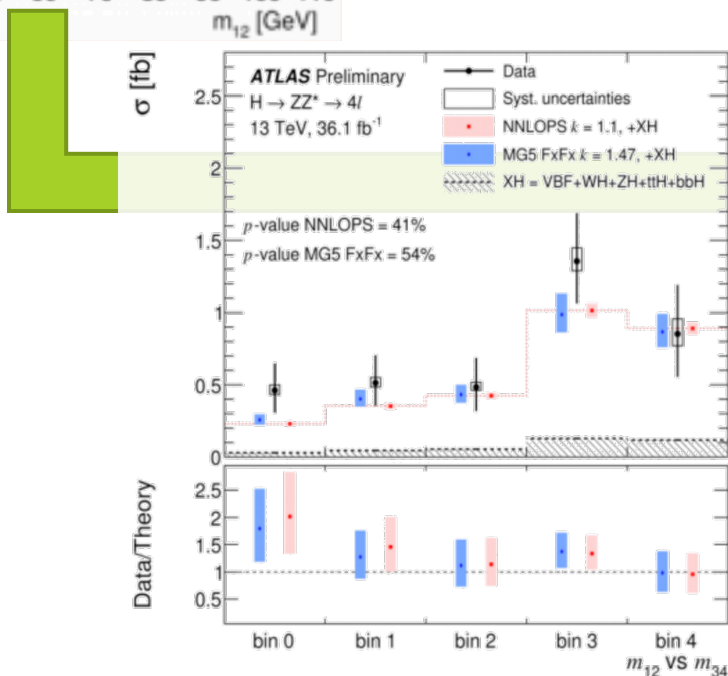
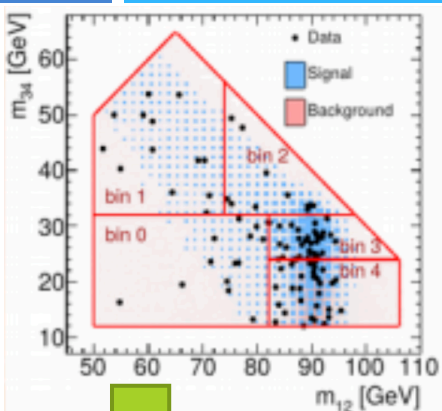


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The easy PO – on-shell $h(125) \rightarrow 4\ell$

129

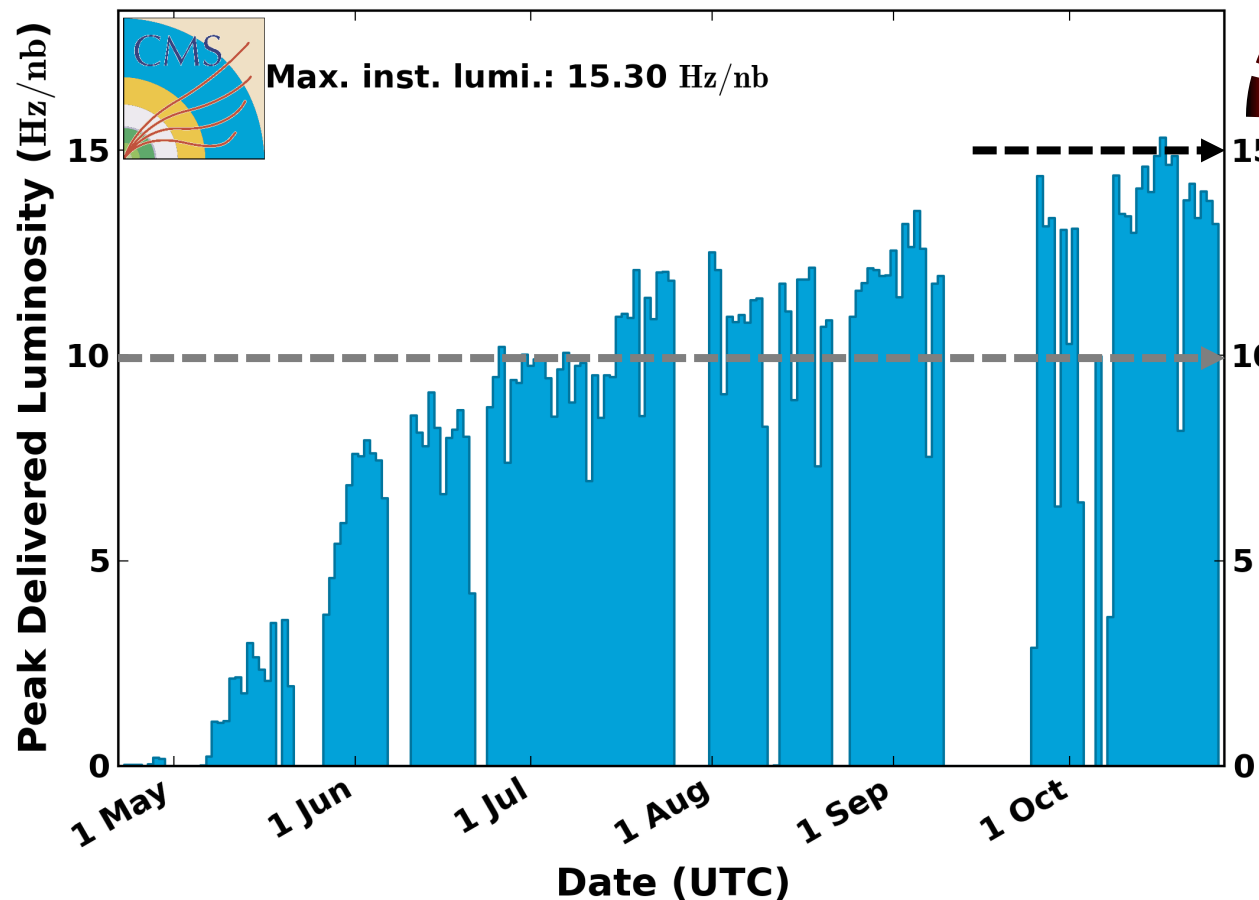
[ATLAS-CONF-2017-032]



And for 2017...

CMS Peak Luminosity Per Day, pp, 2016, $\sqrt{s} = 13$ TeV

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC



2017:
2× nominal

2016:
1.5× nominal

LHC nominal luminosity rate

It is not *like* a new detector, it is a new detector.



131

CMS pixel tracker transplant: everything went well so far

by *Achintya Rao*

Posted by [Stefania Pandolfi](#) on
13 Mar 2017. Last updated 14
Mar 2017, 15.23.

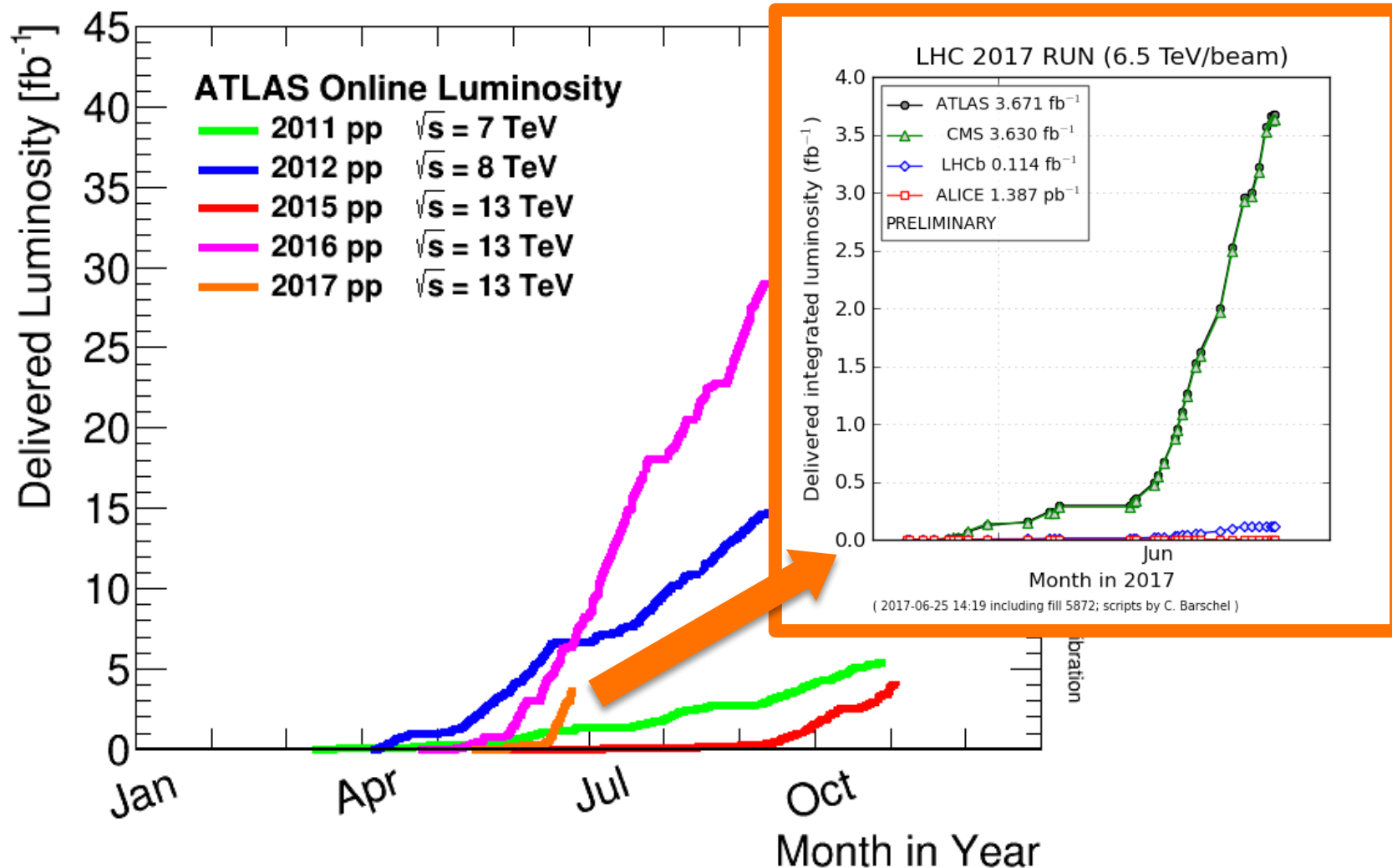
[Voir en français](#)

This content is archived on the
[CERN Document Server](#)



Delicate surgery: The new Pixel Tracker being installed at the heart of the CMS detector. (Photo: Max Brice/CERN)

2017 data-taking is in full swing



On the shoulders of giants

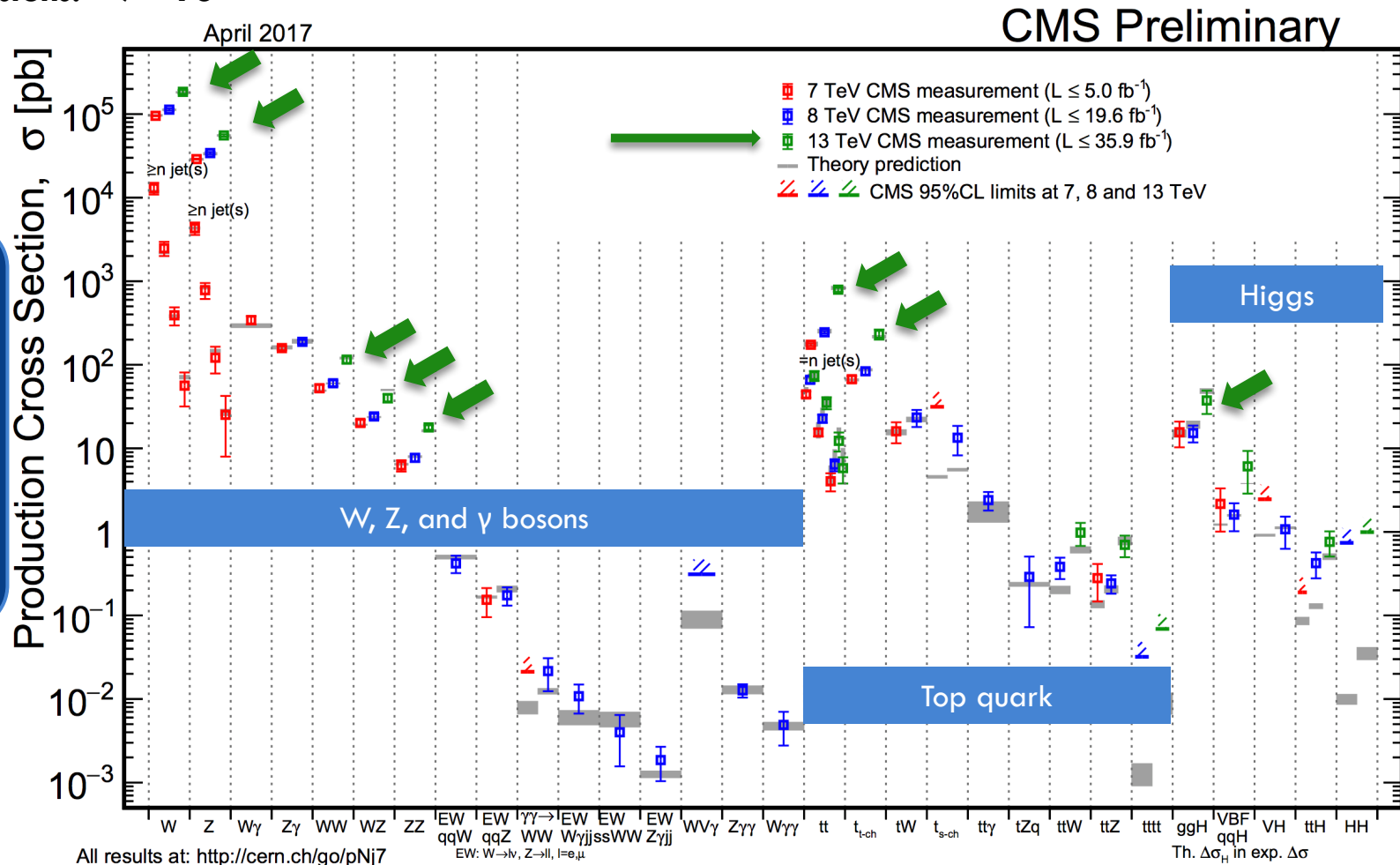
detector makers & theory calculators

133

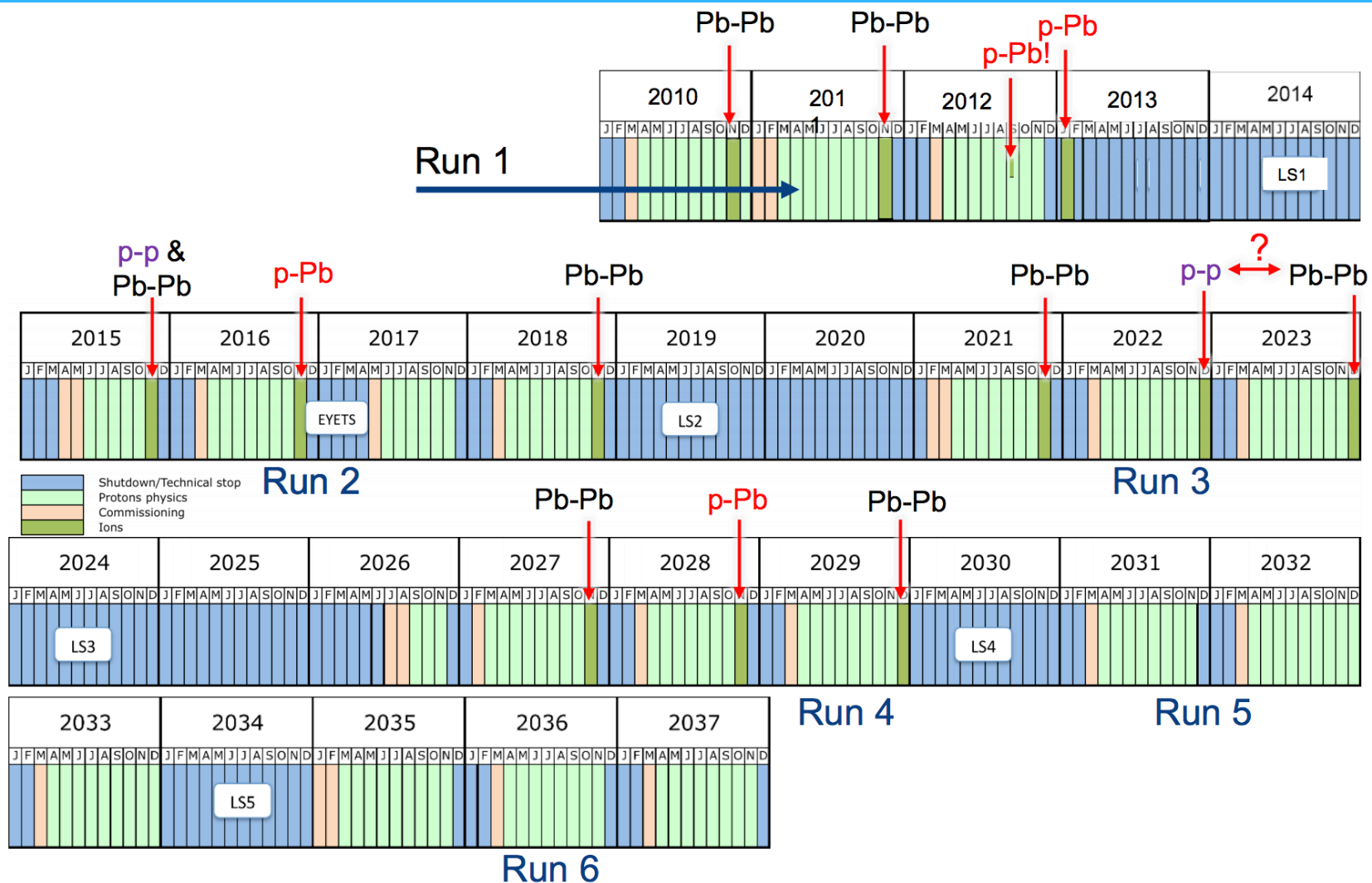
"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [<http://cern.ch/go/lf9C>] [<http://cern.ch/go/KD8D>]

Inelastic collisions: $\sim 7 \times 10^{10}$

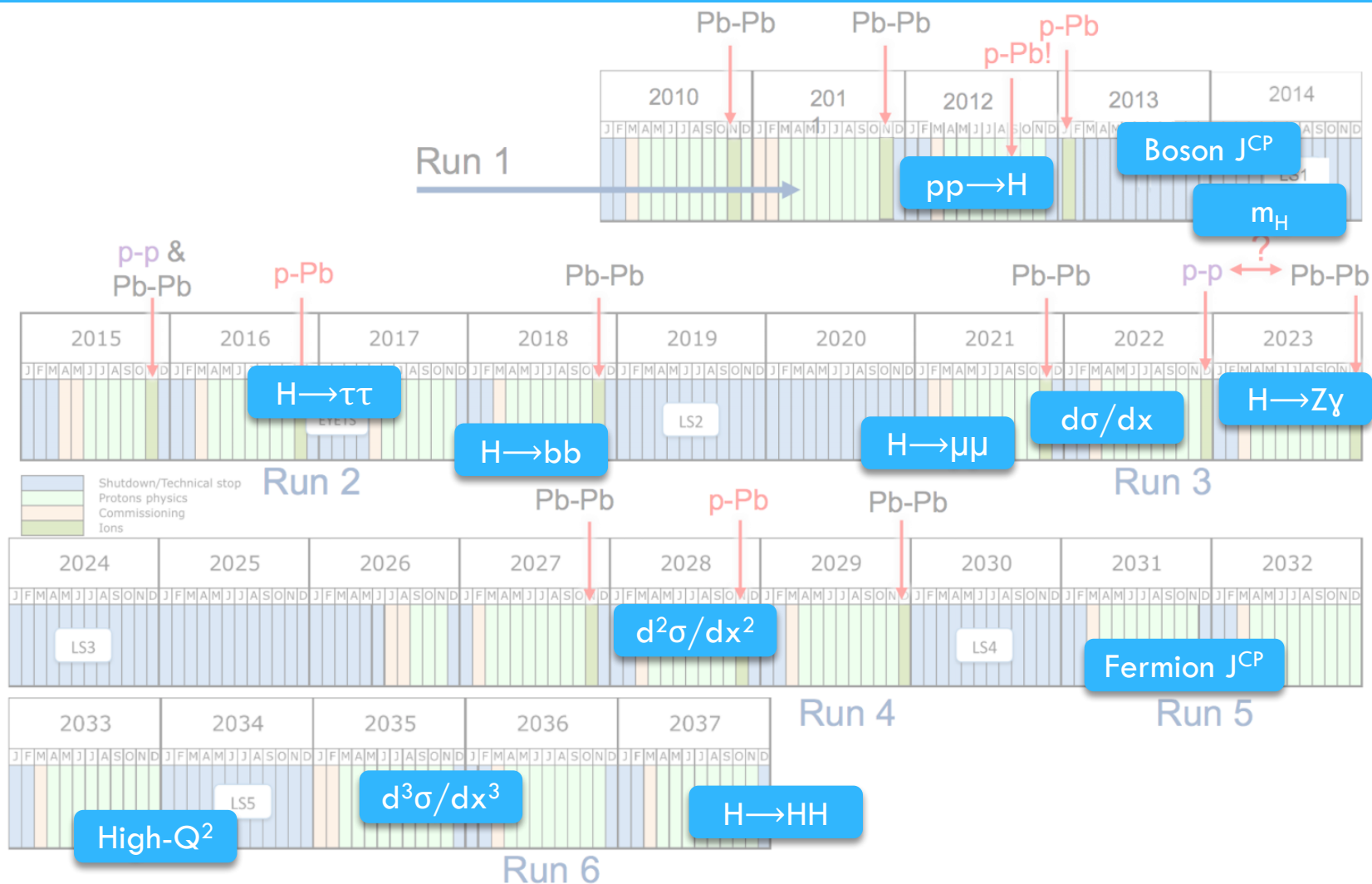
Eight orders of magnitude of EWK, top, and Higgs Physics



Deeper into the rabbit hole



Deeper into the rabbit hole



Summary



Summary

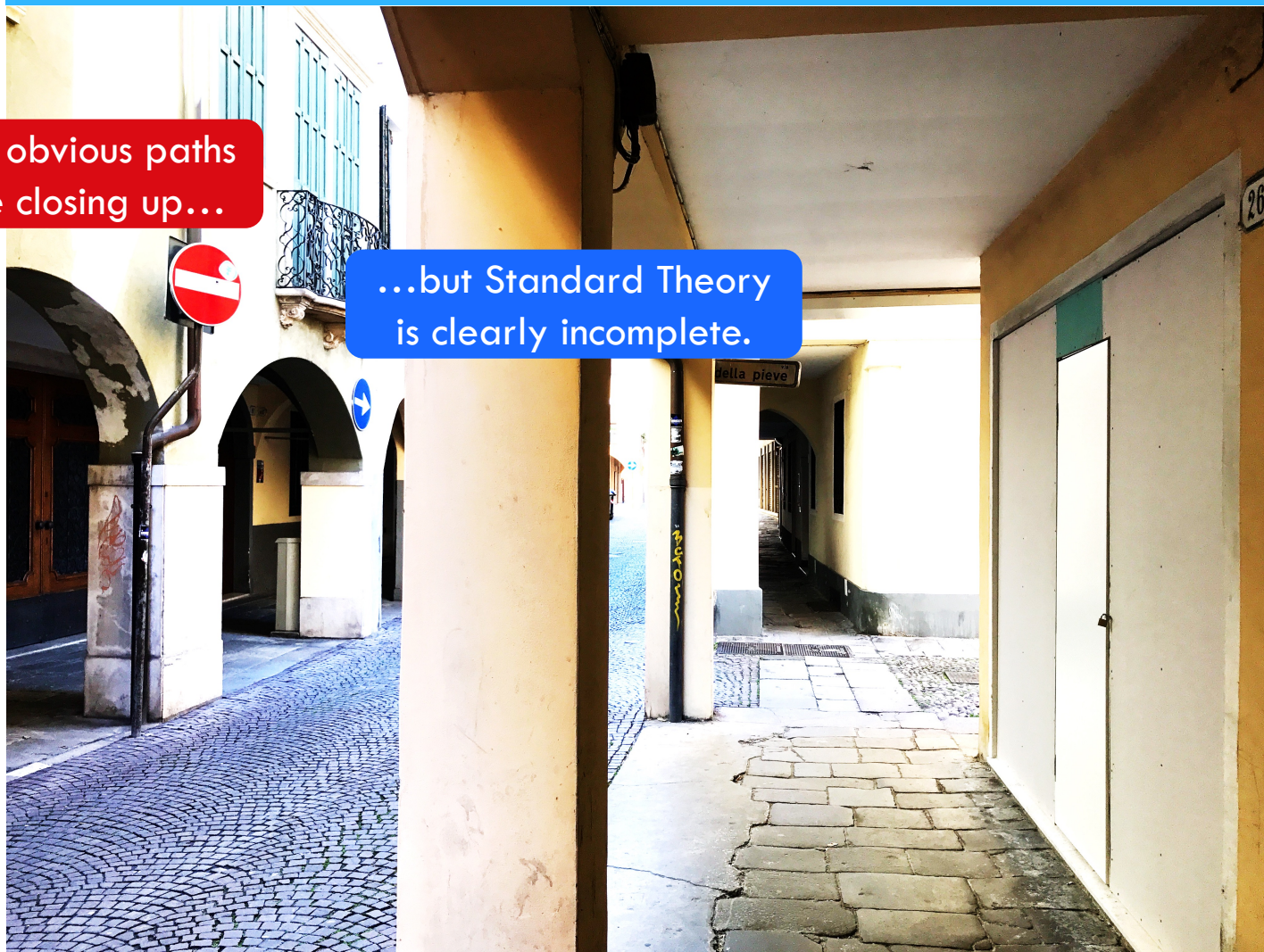
The obvious paths
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Summary

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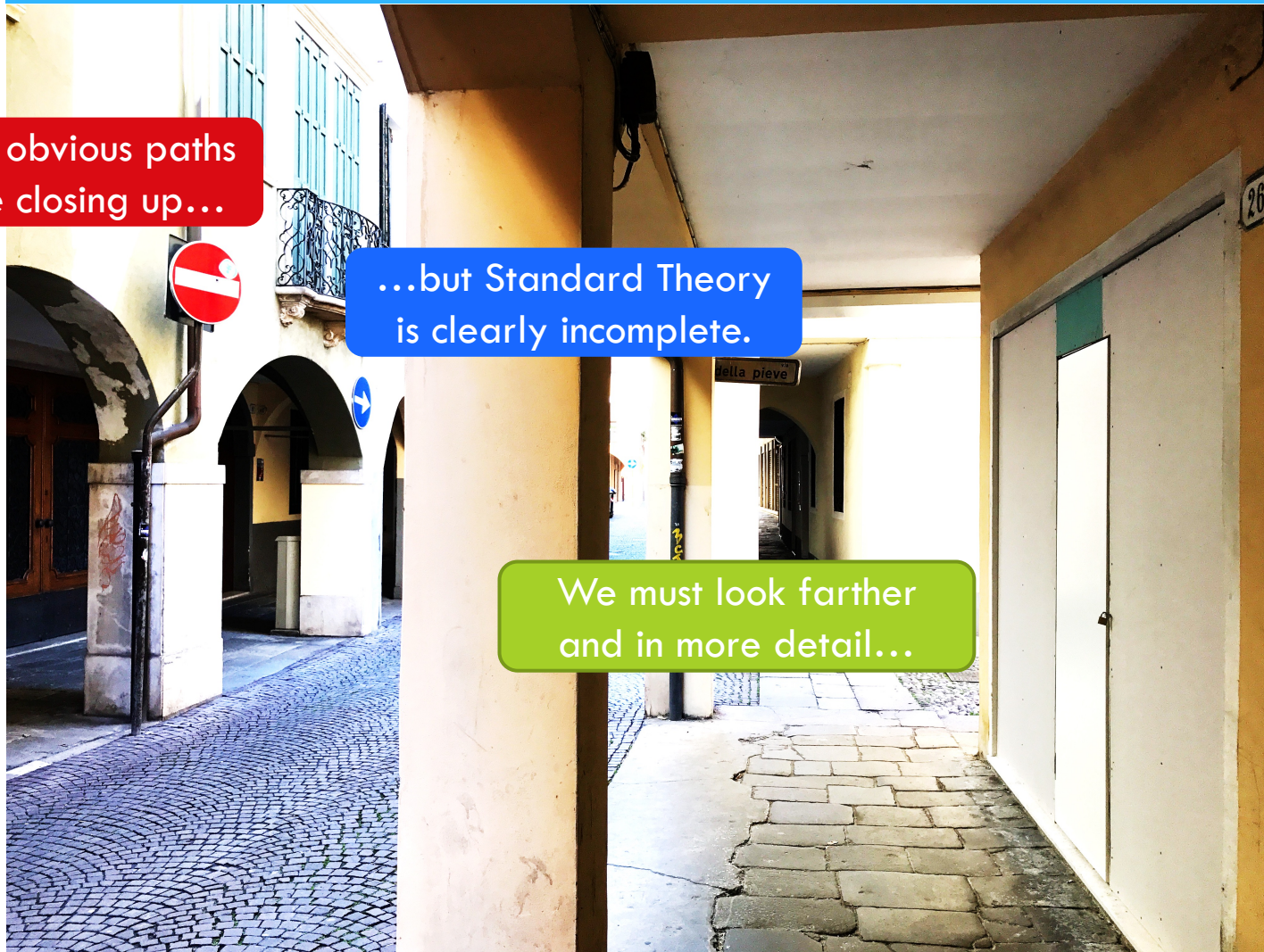


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...to get to the Next Standard Model.

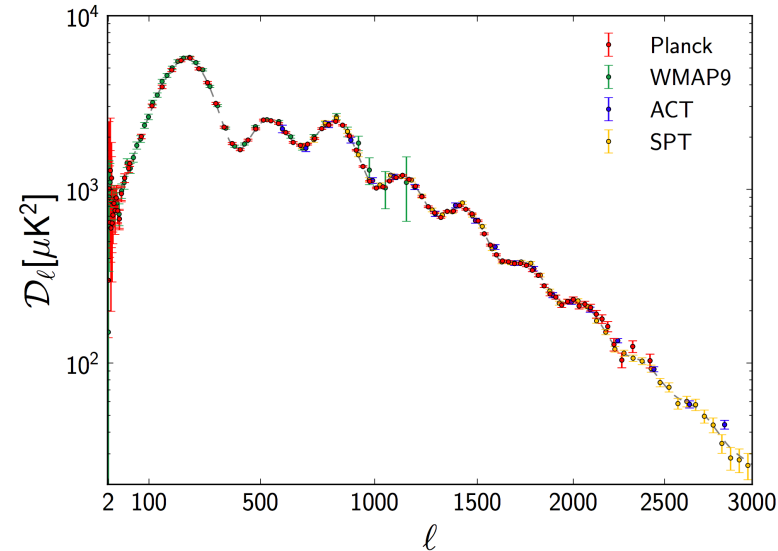


The beautiful boring Universe today

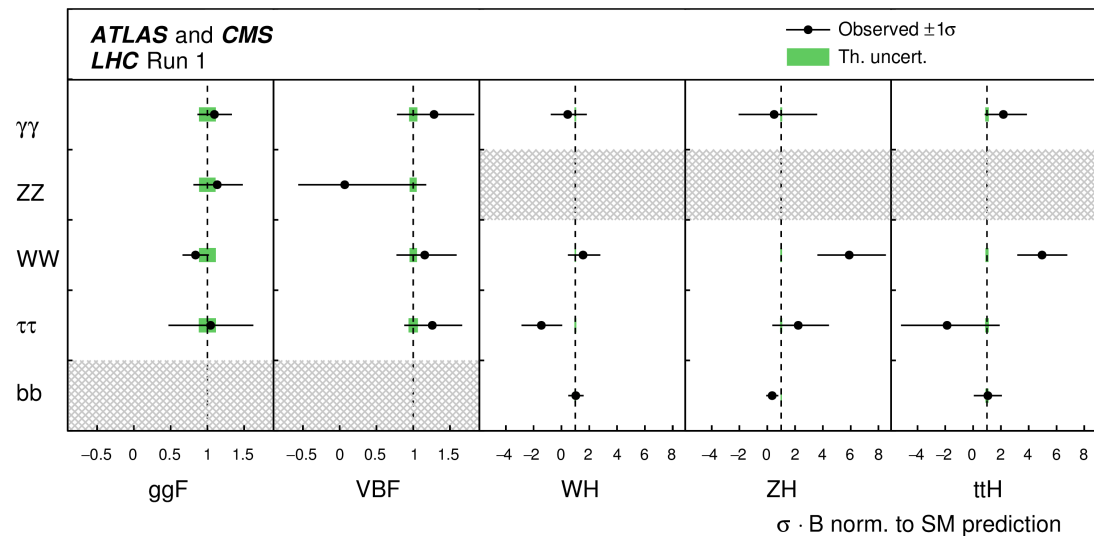
143

[arXiv:1303.5062] [JHEP 08 (2016) 045]

- **Up above:**
(Simple) 6-parameter Λ CDM.



- **Down below:**
(Not-as-simple) ~ 20 -parameter Standard Model of Particle Physics.



Looking forward to surprises at higher energy: PeV neutrinos, more data at LHC 13 TeV, ...

“...and references therein.”

- Experiments' pages on Higgs results:
 - ATLAS: <http://cern.ch/go/7IDT>
 - CMS: <http://cern.ch/go/6qmZ>

145 Three pillars



146

The good, the bad, and the ugly



The good, the bad, and the ugly

New poles



The good, the bad, and the ugly

Old poles

New poles



The good, the bad, and the ugly

Old poles

New poles

Tails



The good, the bad, and the ugly

Old poles

Precision measurements

New poles

Searches

Tails



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$$Q^2 \sim m_X^2$$

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Measurements

Of what?

Parameterized how?

Interpreted how?

By who?

Tails

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Take 1: descriptive

[arXiv:1306.6352]

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Take 1: descriptive

[arXiv:1306.6352]

Theory parameters

$$\frac{g_{hbb}}{g_{h_{\text{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\text{SM}}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Take 1: descriptive

Experimental measurements

$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Take 1: descriptive

[arXiv:1306.6352]

Stuff in
between

$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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We can
measure
these!

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Take 2: actionable

[arXiv:1306.6352]

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Take 2: actionable

What we
want to learn
something
about

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Take 2: actionable

[arXiv:1306.6352]

What can
surely be
measured

$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Take 2: actionable

[arXiv:1306.6352]

What
needs to be
calculated

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Between a rock and a hard place

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Between a rock and a hard place

Same theory, but
change calculation:

- Better accuracy
($LO \rightarrow NLO \rightarrow \dots$)
- $\neq$ assumptions,
- $\neq$ algorithm.

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Between a rock and a hard place

Same theory,
change
calculation:
**Numerical
values change...**

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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these $\sim$ evolving_function(these)

$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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Director's take in English

[arXiv:1306.6352]

Experimentalists
measure these,
theorists calculate and
improve these as many
times as needed,
together we learn more
and better about these.

$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

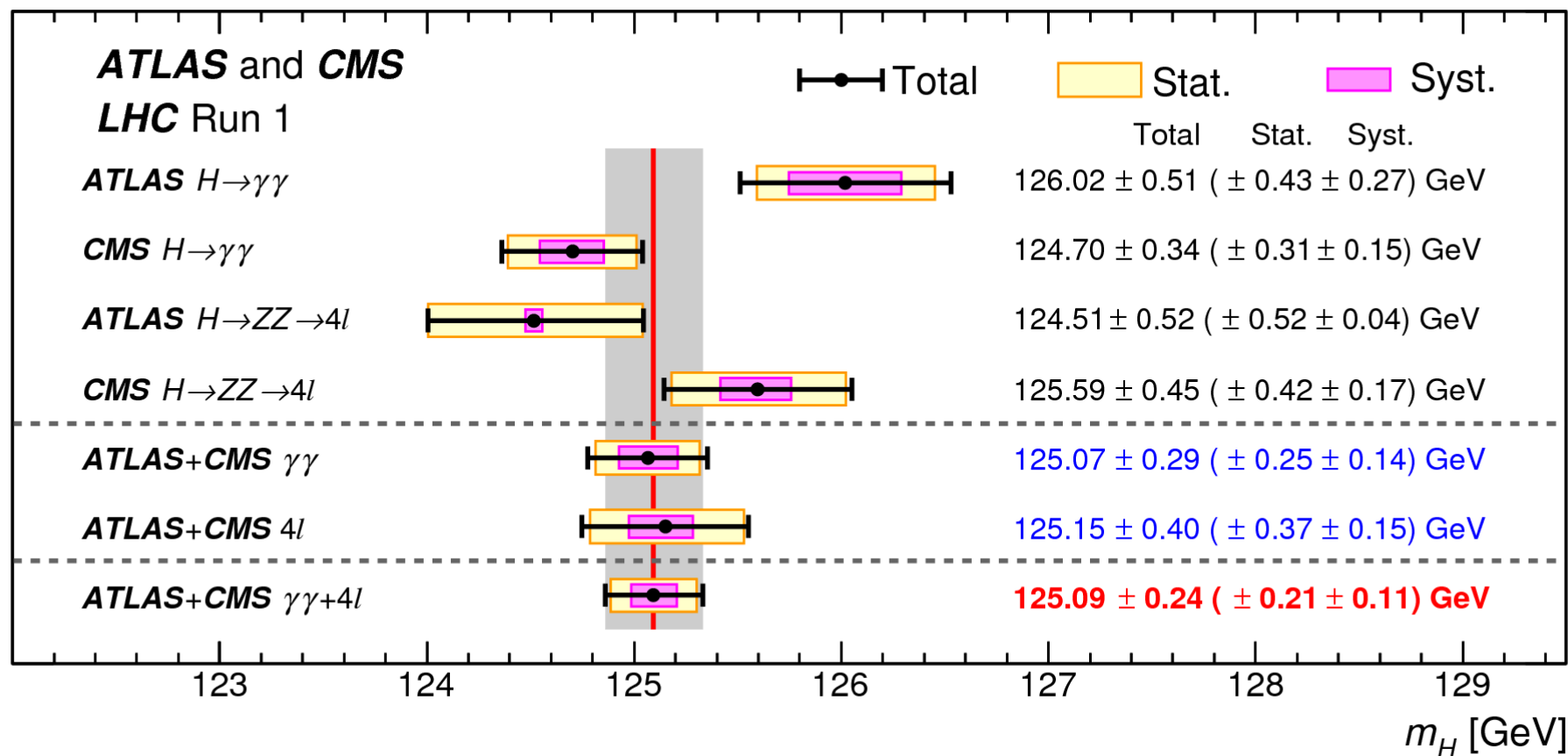
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176 m_H combination

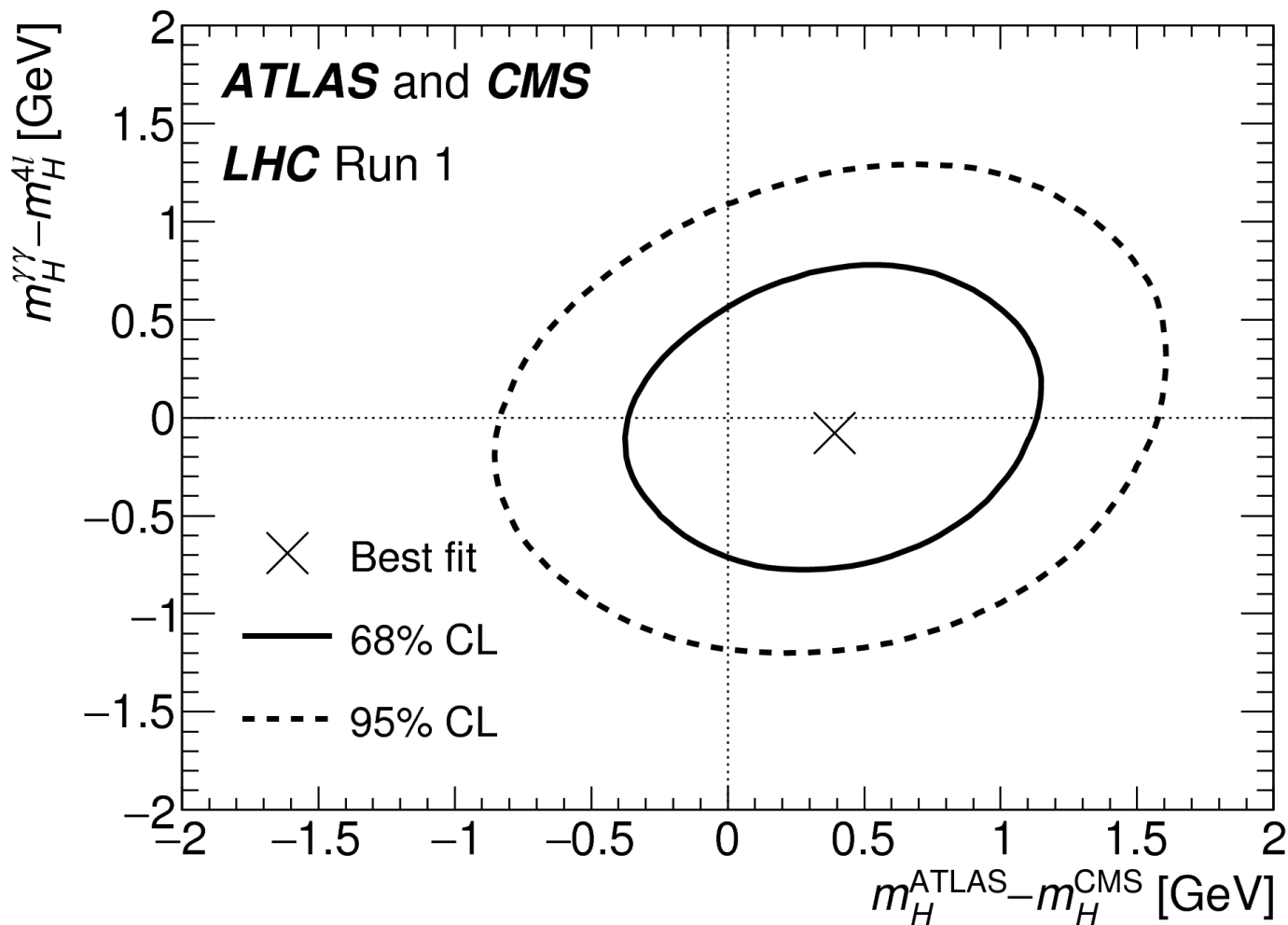
Combined LHC mass measurement

[arXiv:1503.07589]



Combined LHC mass measurement

[arXiv:1503.07589]

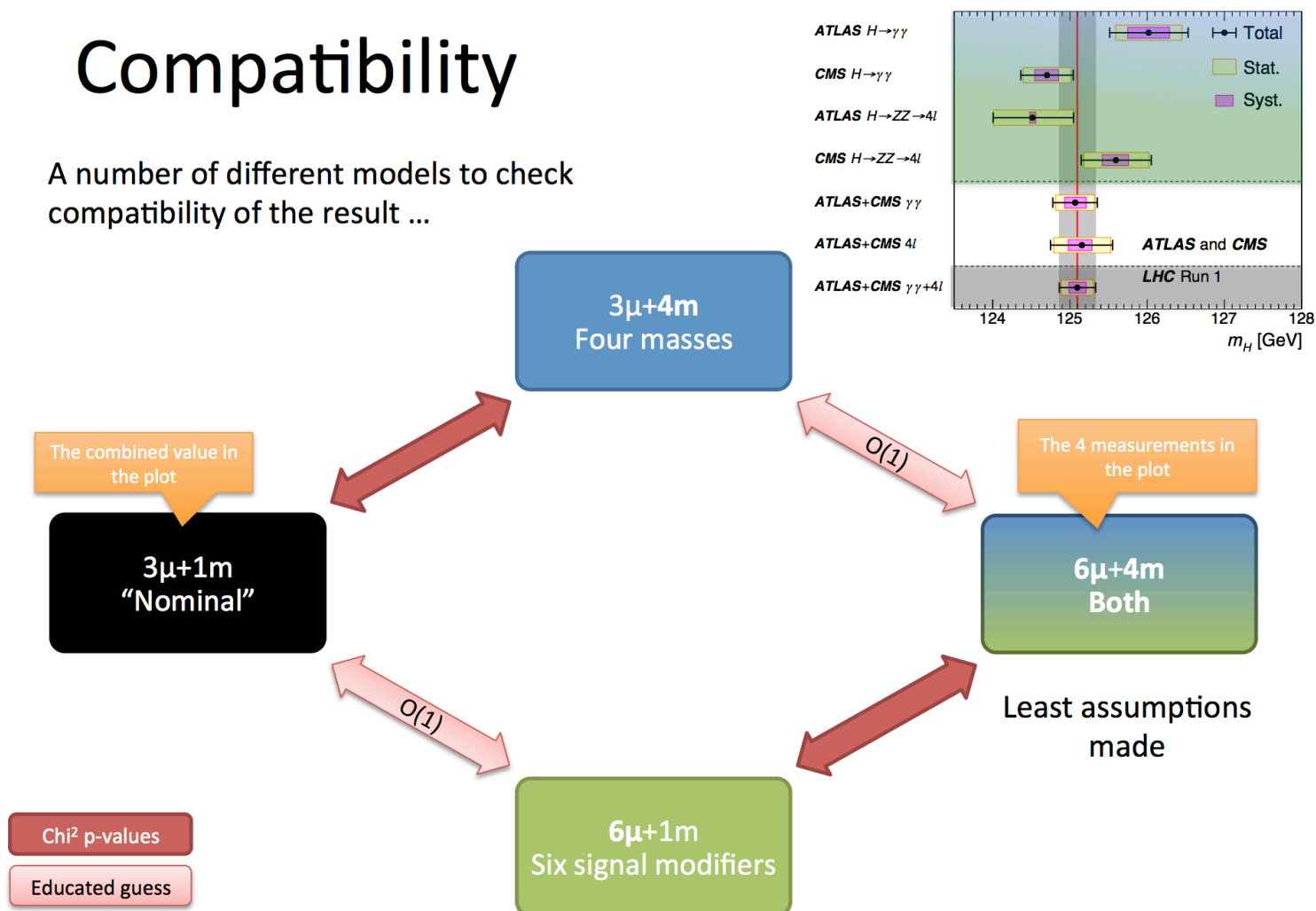


Combined LHC mass measurement

[arXiv:1503.07589]

Compatibility

A number of different models to check compatibility of the result ...

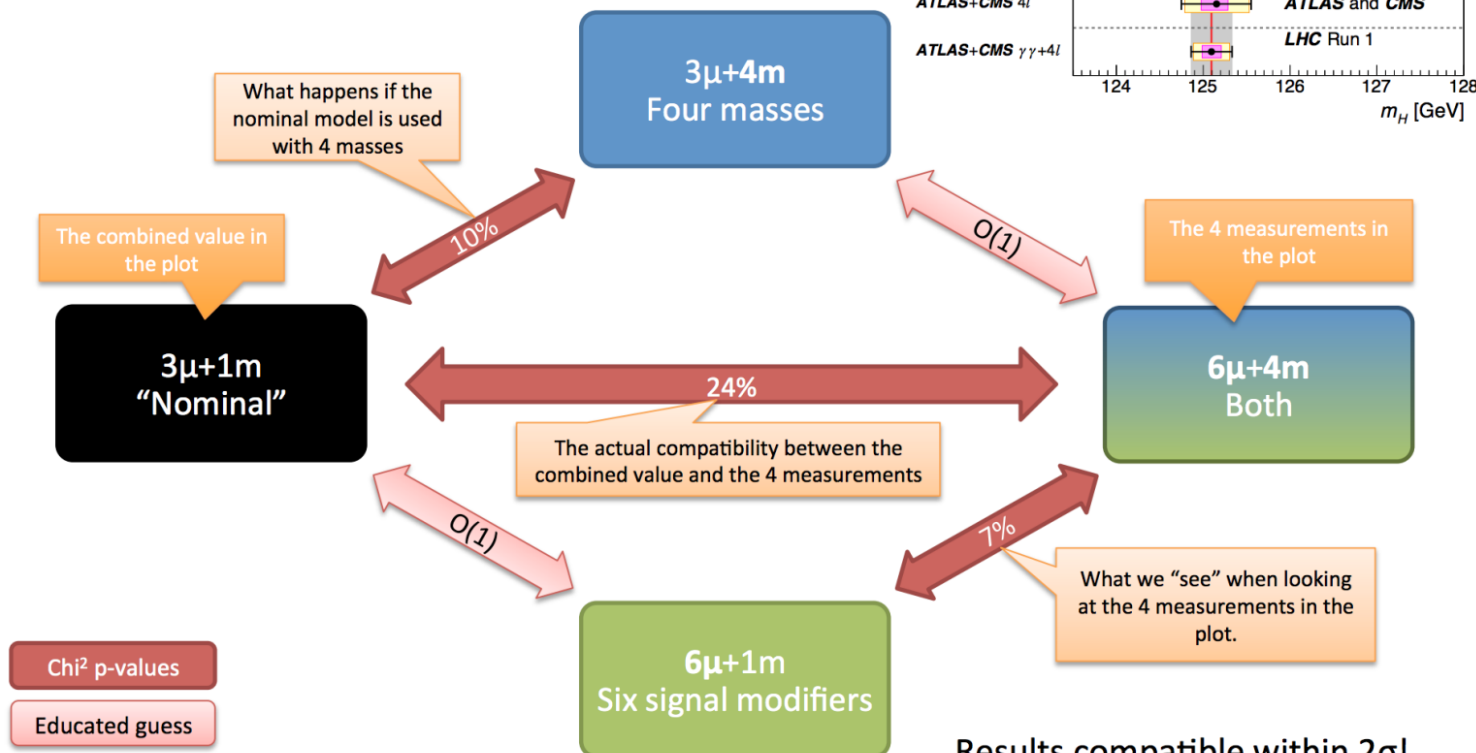


Combined LHC mass measurement

[arXiv:1503.07589]

Compatibility

A number of different models to check compatibility of the result ...



Results compatible within 2σ !

Combined LHC mass measurement

[arXiv:1503.07589]

$$m_H = 125.09 \pm 0.21 \text{ (stat)}$$

$$\pm 0.11 \text{ (scale)}$$

$$\pm 0.02 \text{ (other)}$$

$$\pm 0.01 \text{ (theory*)}$$

**Stat. uncertainty
dominates overall.**

**Energy scale syst. can
be improved.**

Run 2 will reduce
uncertainty !

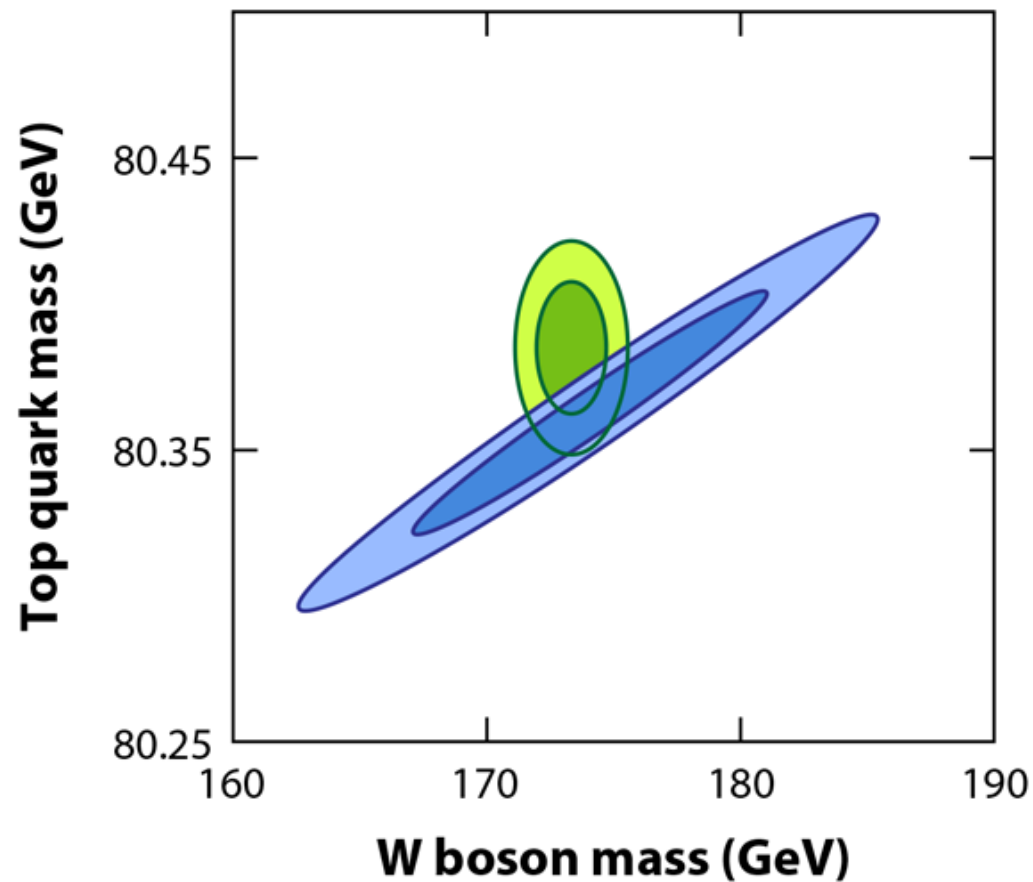
GeV

ATLAS+CMS m_H in PRL

182

[PRL 114 (2015) 191803] [<http://physics.aps.org/articles/v8/45>]

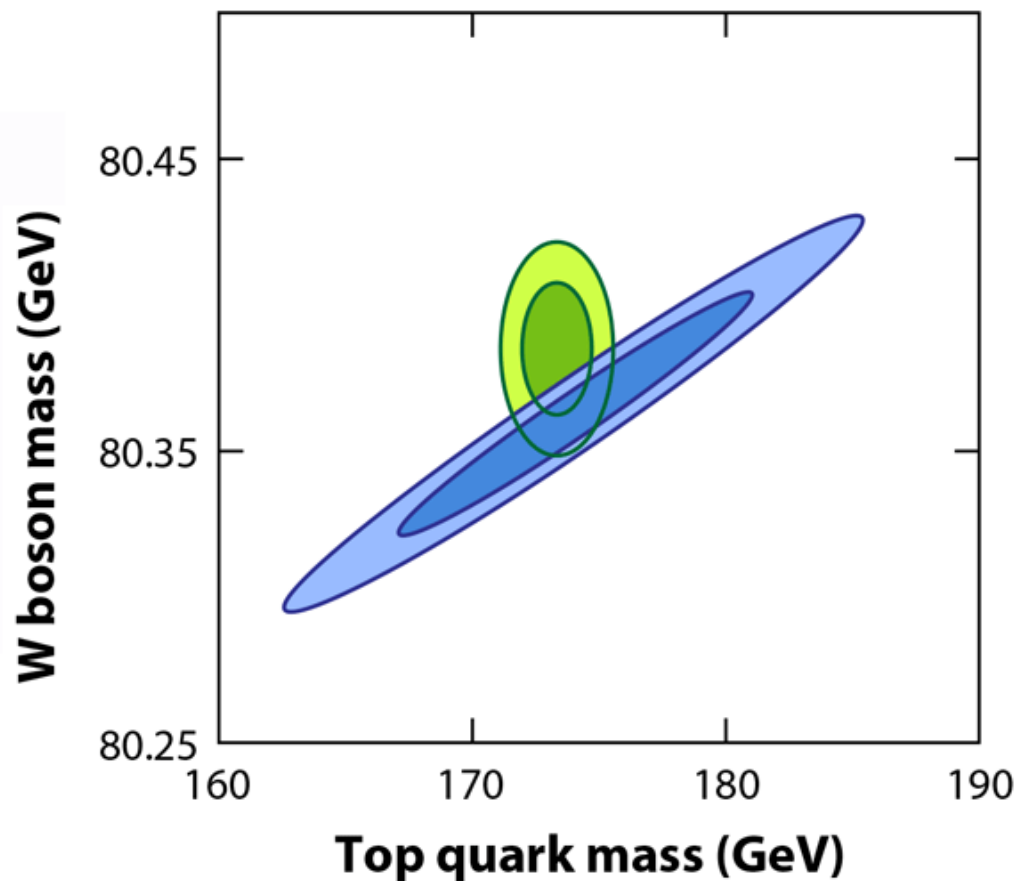
- First ATLAS+CMS publication.
 - ▣ 0.2% precision.
- PRL Viewpoint by Chris Quigg: *“With LHC Run 2 [we] can look forward to a new round of exploration, searches for new phenomena, and refined measurements. Combined analyses [...], such as the measurement of the Higgs boson mass discussed here, will help make the most of the data. **We still have much to learn about the Higgs boson, the electroweak theory, and beyond.**”*



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[PRL 114 (2015) 191803] [<http://physics.aps.org/articles/v8/45>]

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For the record

- ~5 kiloauthors.
- Found that there are two:
 - Archana Sharma
(both in CMS)
 - Andrea Bocci
 - Muhammad Ahmad
 - F. M. Giorgi
(one in CMS, one in ATLAS)



Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015



CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of contributors to a single research article.

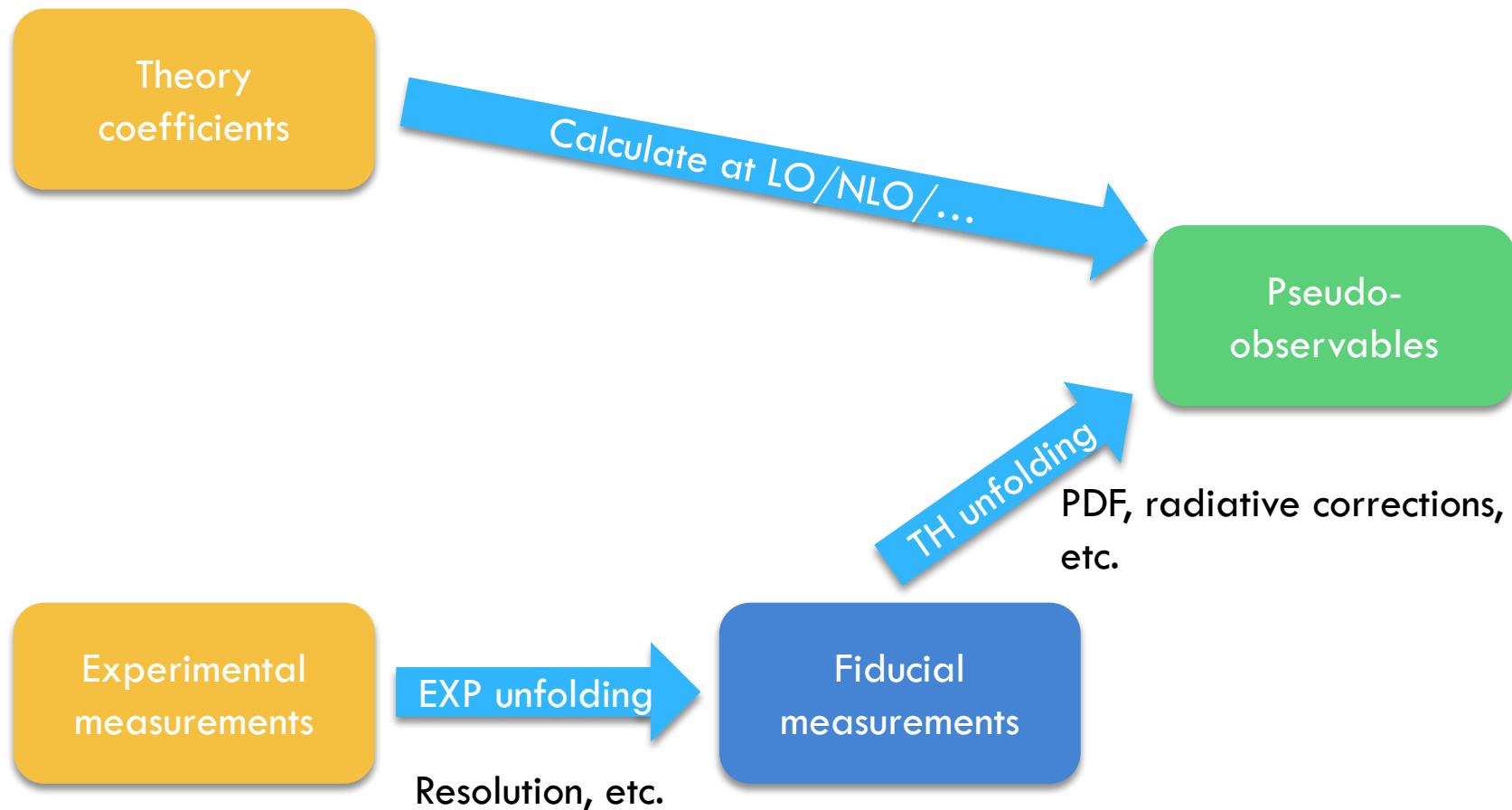
185

Pseudo-observables

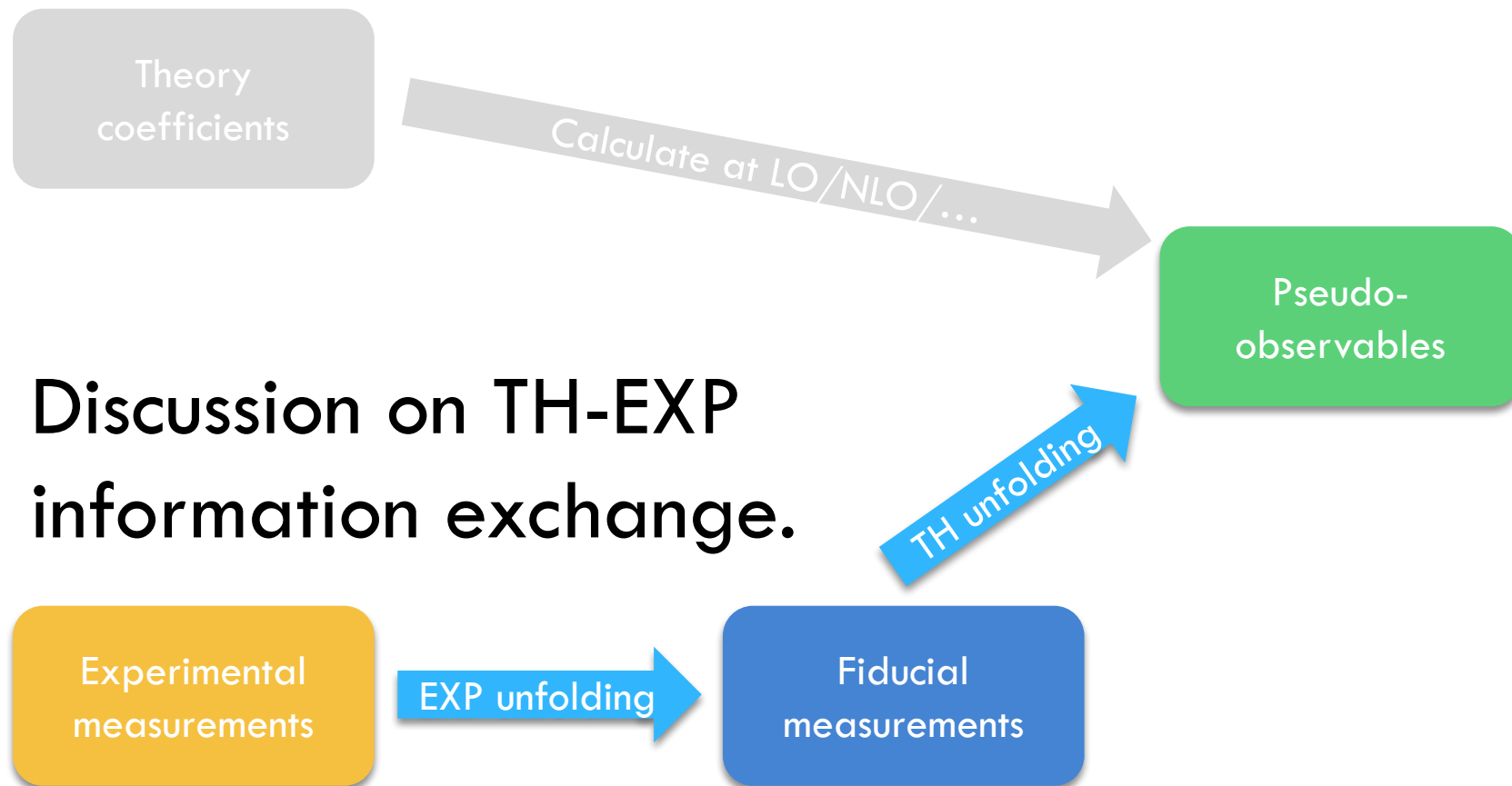
The need for the middle way

- **EFT** is all-encompassing, calculable, and evolving.
 - ▣ **But** too costly to redo all analyses if/when higher order calculations become available.
- **Fiducial cross-section** could be produced differentially for many quantities.
 - ▣ **But** no physical interpretation of every single bin by itself.
- **The middle way: pseudo-observables (PO).**
 - ▣ LEP-inspired scheme where theory and experiment intersect at clearly-defined points.

With some LEP inspiration



With some LEP inspiration



With some LEP inspiration

Theory
coefficients

Calculate at LO/NLO/...

Pseudo-
observables

Discussion on EFT.

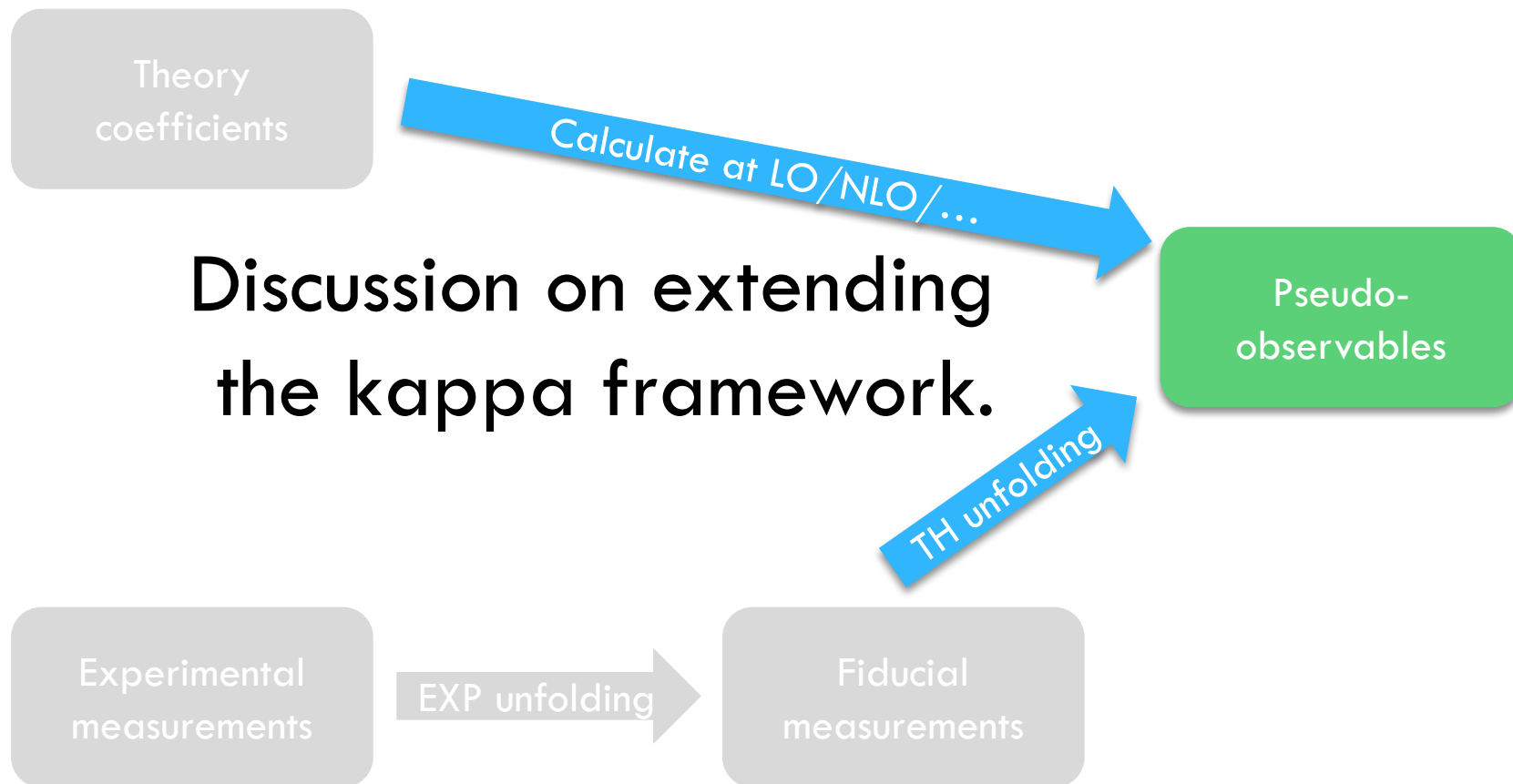
Experimental
measurements

EXP unfolding

Fiducial
measurements

TH unfolding

With some LEP inspiration



From kappas that fit little stuff...



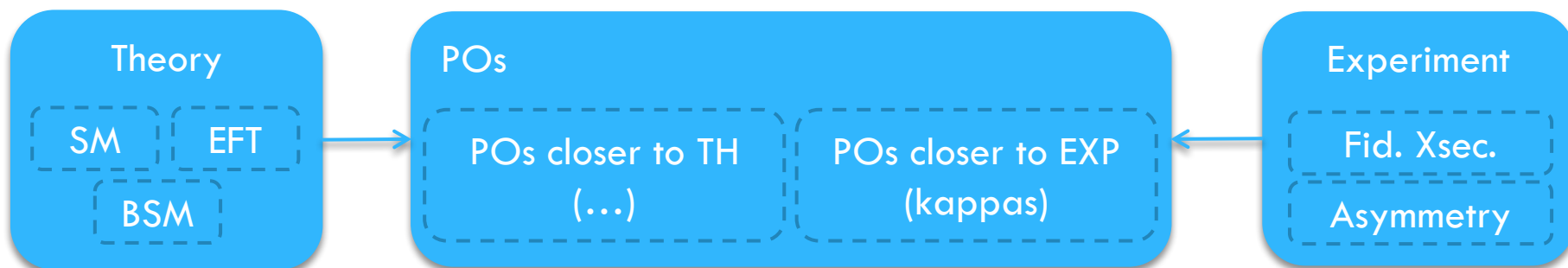
...to kappas that fit more stuff.



Kappas might have been our first POs

- Kappas **must be extended** to:
 - ▣ Differential quantities.
 - ▣ Remove some assumptions.
 - ▣ Cover smooth deviations from the SM.

- With better/more POs, kappas may remain as part of the PO framework:



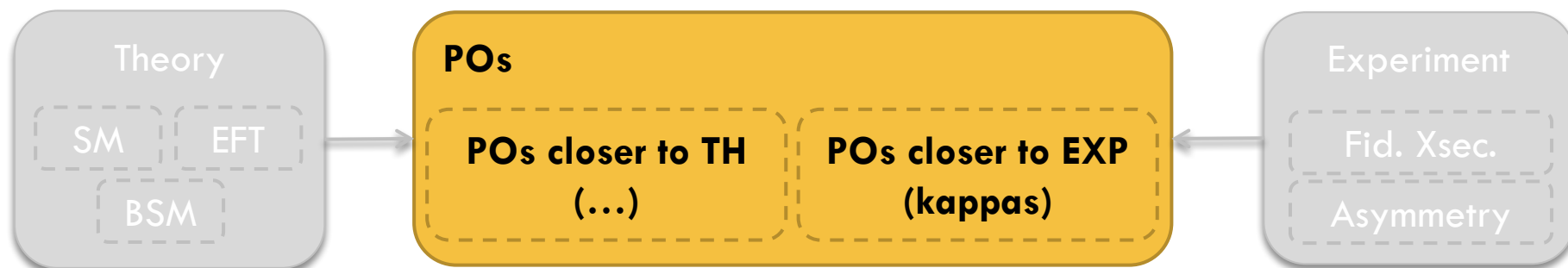
Inspiration for building PO

- If we assume that:

$$\text{Next SM} \sim |\text{dim-4} + \text{dim-6} + \text{dim-8} + \dots|^2$$

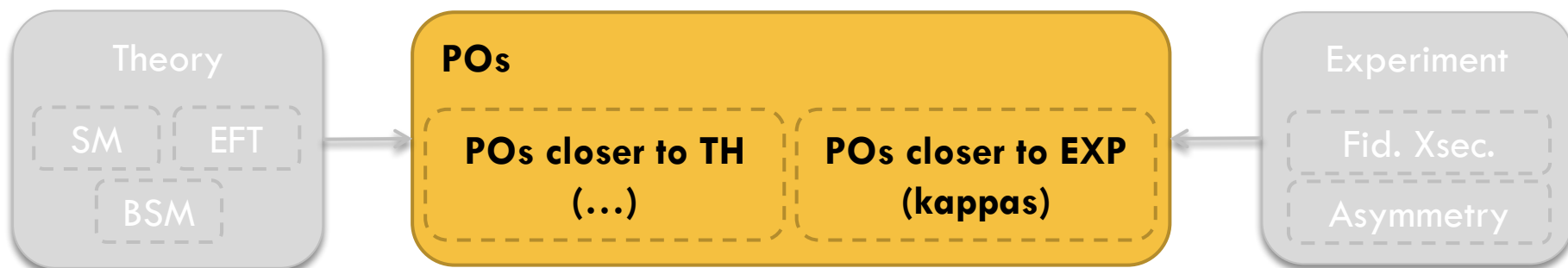
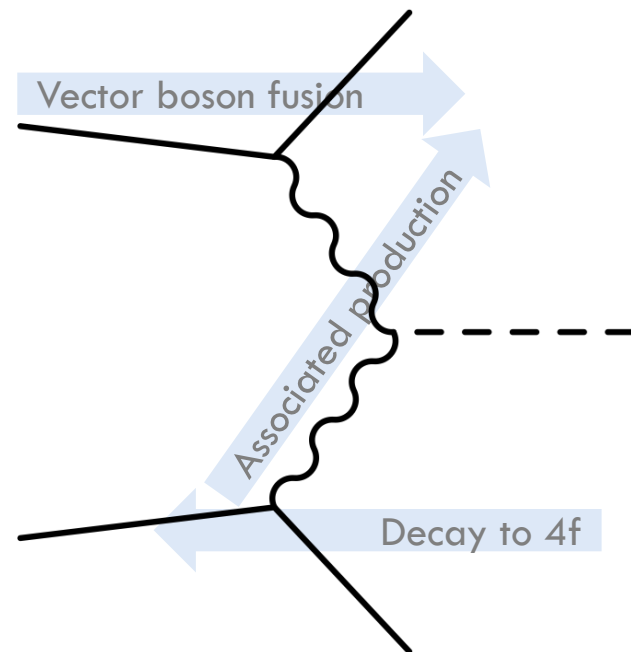
- Then POs can be motivated to parametrize:

$$\delta(\text{PO}_i) \sim (\text{Data} - \text{d4}^2) = \text{d4} \times \text{d6} + \text{d6}^2 + \text{d4} \times \text{d8} + \dots$$

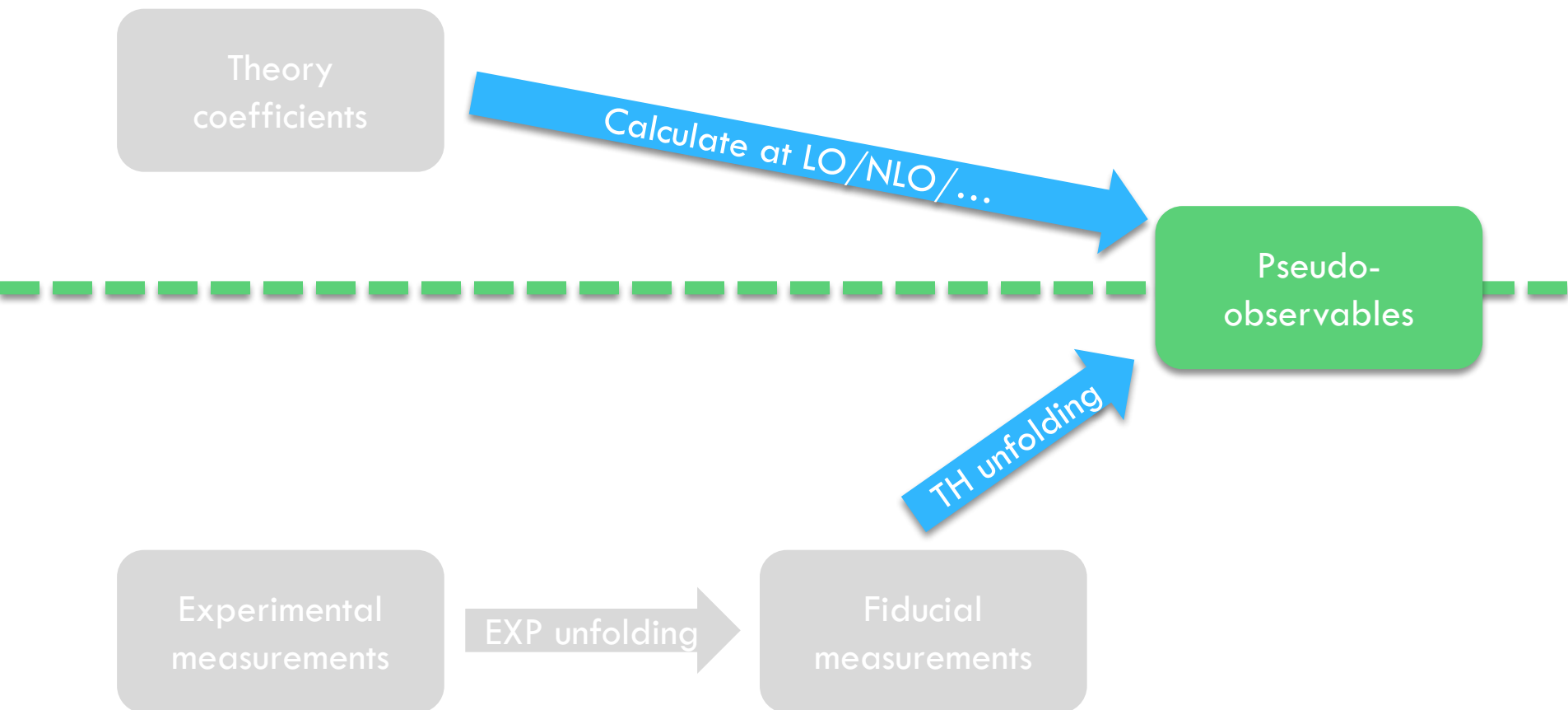


Inspiration for building PO

- Many practical issues to be solved.
- Many conceptual issues to be tackled.
- Many discussions to be held.



The middle way in action



The middle way in action

Theorists refine calculations and interpret against PO.

Theory
coefficients

Calculate at LO/NLO/...

Pseudo-
observables

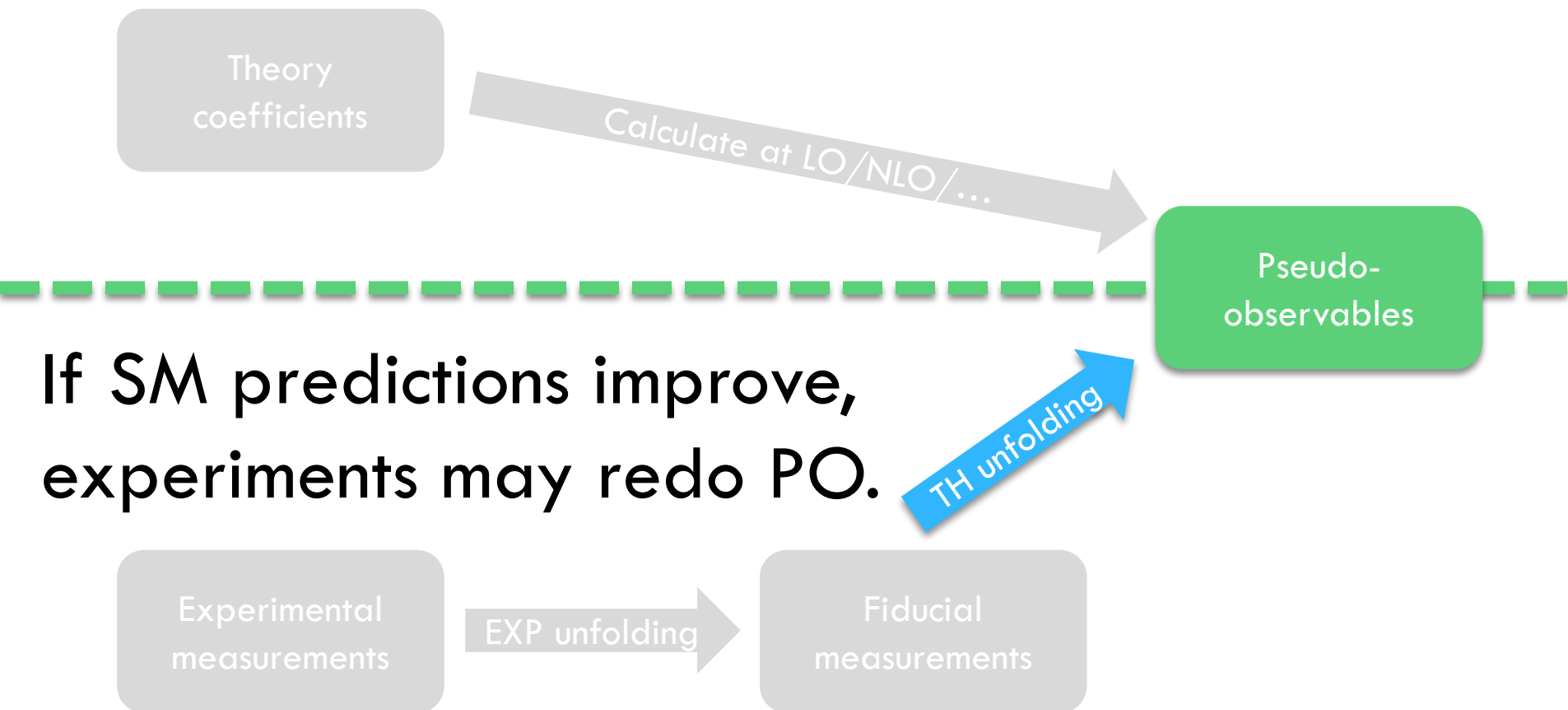
Experimental
measurements

EXP unfolding

Fiducial
measurements

TH unfolding

The middle way in action



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Nobel expectations

Do not open unless you take bets.



Let's go back a few years

200 [<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

CERN home > LHC 2008 > Nobel Expectations



Nobel expectations for new physics at the LHC

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What do leading figures in particle physics expect from the LHC?

2008 Nobel expectations for the LHC

[<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

David Gross: "a super world"

I expect new discoveries that will give us clues about the unification of the forces, and maybe solve some of the many mysteries that the Standard Model (SM) leaves open.

I personally expect supersymmetry to be discovered at the LHC; and that enormous discovery, if it happens, will open up a new world — a super world.

2008 Nobel expectations for the LHC

[<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

George Smoot: "the nature of dark matter"

I am looking forward to hearing about the Higgs, because I'd like to see the Standard Model completed and understood. I'm also hoping that the LHC will begin to unveil extra dimensions, and that will have huge applications across the board.

But what I am really looking forward to is **supersymmetry or something that shows what dark matter is made of**, so I have really high hopes, perhaps too high hopes.

2008 Nobel expectations for the LHC

[<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

Martinus Veltman: "the unexpected"

What I expect from the LHC? That's a big problem.

What **I would like to see is the unexpected**. If it gives me what the Standard Model predicted flat out — the Higgs with a low mass — that would be dull. I would like something more exciting than that.

2008 Nobel expectations for the LHC

[<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

Gerardus 't Hooft: "a Higgs, or more"

The first thing we expect – we hope to see – is the Higgs. I am practically certain that the Higgs exists. My friends here say it is almost certain that if it exists, the LHC will find it.

So we're all prepared and we're very curious because there's little known about the Higgs except some interaction signs.

There could be more than one Higgs, several Higgs, and there could be a composite Higgs, but most of us think it should be an elementary particle...

My real dream is that the Higgs comes up with a set of particles that nobody has yet predicted and doesn't look in any way like the particles that all of us expect today. That would be the nicest of all possibilities. We would then really have work to do to figure out how to interpret those results.

See also arXiv:1609.01725

2008 Nobel expectations for the LHC

[<http://lhc2008.web.cern.ch/LHC2008/nobel/index.html>]

Carlo Rubbia: "Nature will tell"

I think Nature is smarter than physicists. **We should have the courage to say: "Let Nature tell us what is going on."**

Our experience of the past has demonstrated that in the world of the infinitely small, it is extremely silly to make predictions as to where the next physics discovery will come from and what it will be.

In a variety of ways, this world will always surprise us all. **The next breakthrough might come from beta decay, or from underground experiments, or from accelerators.**

We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science.

The LEP era – lower limit

[arXiv:1705.04951]

“I am very sorry, I said, your interpretation may well be right, but the evidence is not conclusive. **This is not a golden event with neutrinos, because of the lack of missing momentum. It would be different if you could increase LEP energy by say 30 GeV. In that case you would produce the Higgs and the Z0 with some momentum and neutrinos could be identified by missing momentum in addition to missing energy.** In the present conditions, neutrinos can be identified only statistically, but in one year of running you will not be able to go from a suggestion to discovery. The significance of the event as Higgs production was slightly below 3σ , but to go 5σ , the discovery limit, would require running for four to five years, or something like that.”

Luciano Maiani

