Particle Physics Today, Tomorrow and Beyond

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Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

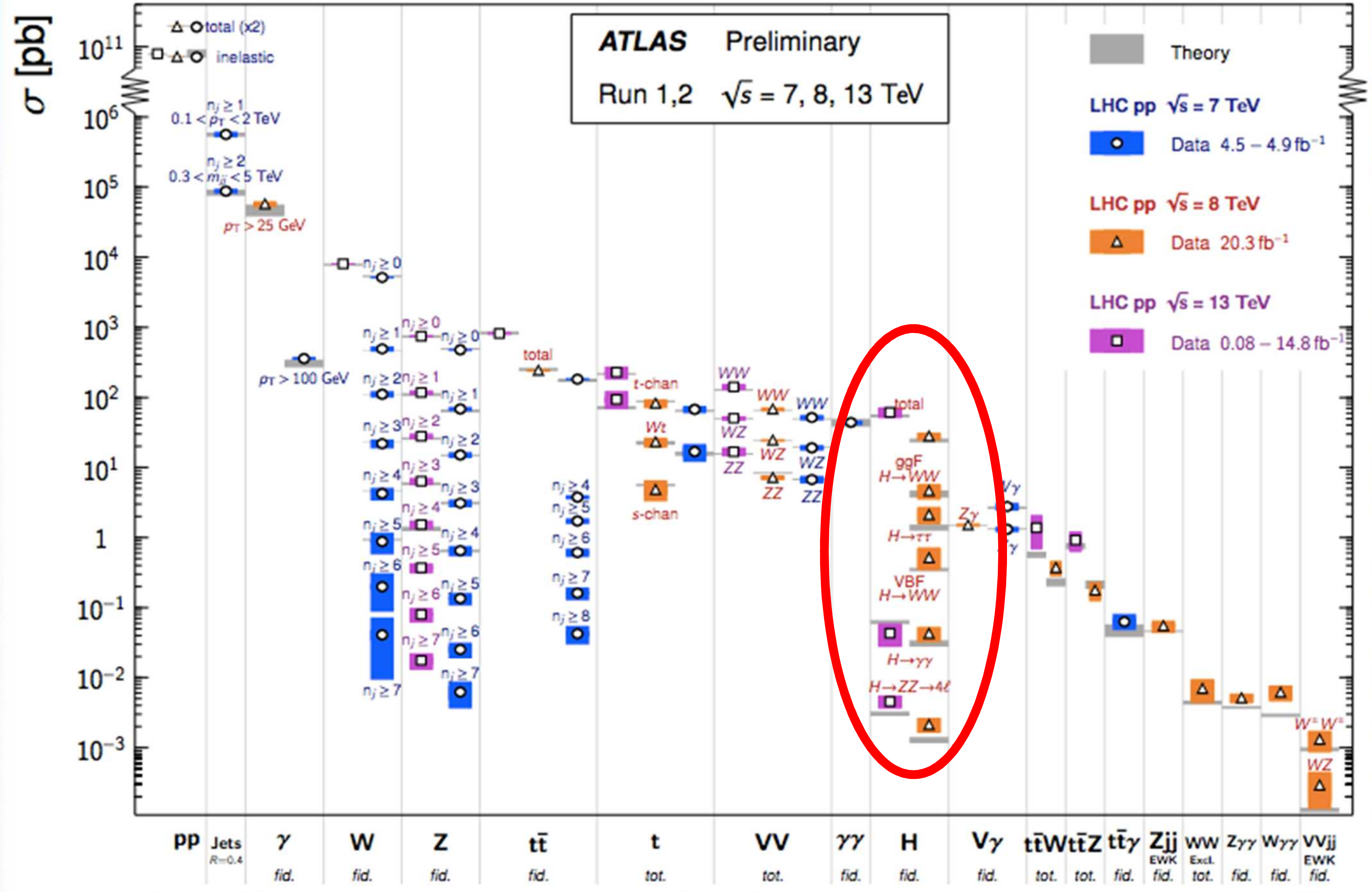
L_L E_R	$\begin{pmatrix}\nu_e\\e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\\mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\\tau^-\end{pmatrix}_L$ e_R^-, μ_R^-, τ_R^-	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
Q_L U_R D_R	$\begin{pmatrix}u\\d\end{pmatrix}_L, \begin{pmatrix}c\\s\end{pmatrix}_L, \begin{pmatrix}t\\b\end{pmatrix}_L$ u_R, c_R, t_R d_R, s_R, b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

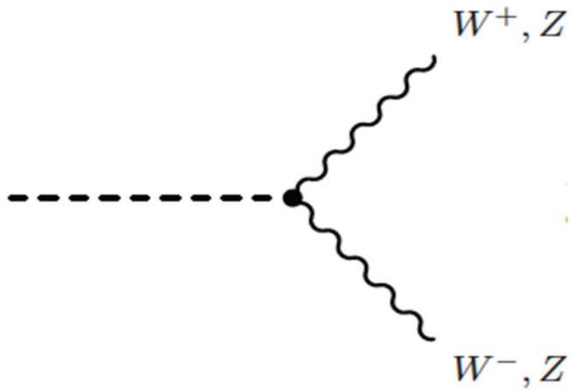
$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions}\\ &+ i\bar{\psi}\not{D}\psi + h.c. && \text{matter fermions}\\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions}\\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential}\end{aligned}$$

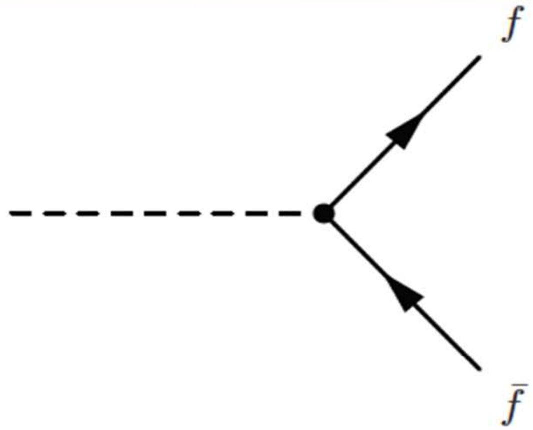
Untested before 2012

Physics Measurements @ LHC



Higgs Boson Couplings





$g_2 M_W \,, \quad g_2 \frac{M_Z}{c_W}$

$\frac{m_f}{v} = \frac{g_2\, m_f}{2 M_W}$

$$\Gamma(H \to f\bar{f}) \quad = \quad N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

Weinberg 1967

$$\Gamma(H \to VV) \quad = \quad \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

Higgs 1966

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

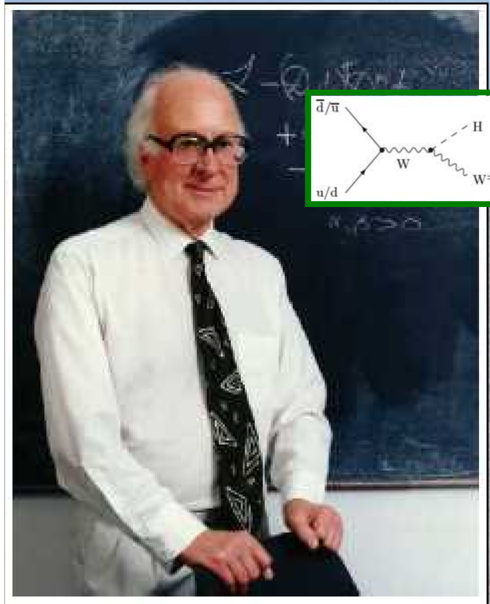
Received 7 November 1975

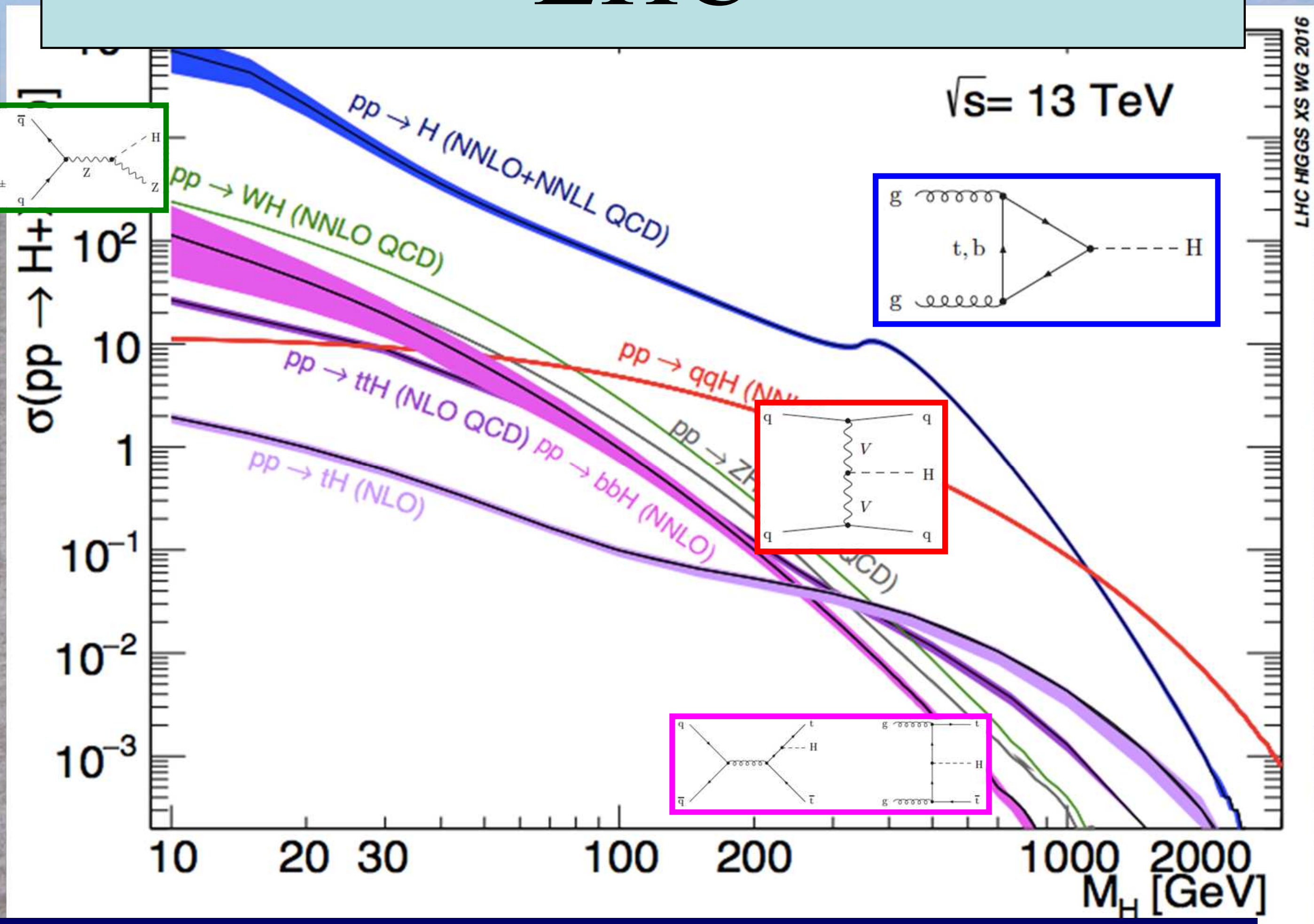
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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 la recherche du Higgs perdu …

Higgs Production at the LHC





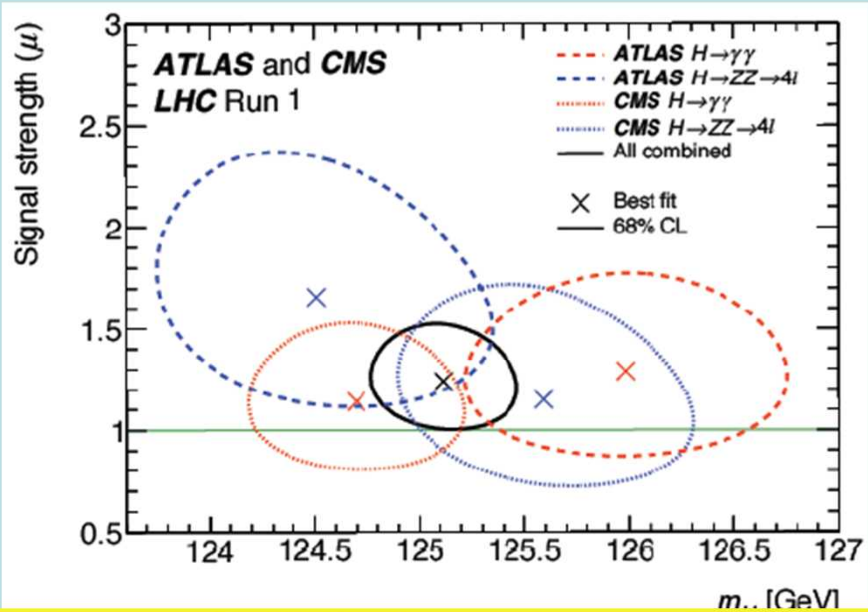
LHC Higgs Cross-Section Working Group (LHXSWG)

Many production modes measurable if M_h ~ 125 GeV

Large Hadron Collider at CERN

Higgs Mass Measurements

- ATLAS + CMS ZZ^* and γγ final states



- Run 1: $125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$
- Run 2: $125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})$ GeV (CMS ZZ^*)
- Makes precision tests possible
- **Crucial for stability of electroweak vacuum**

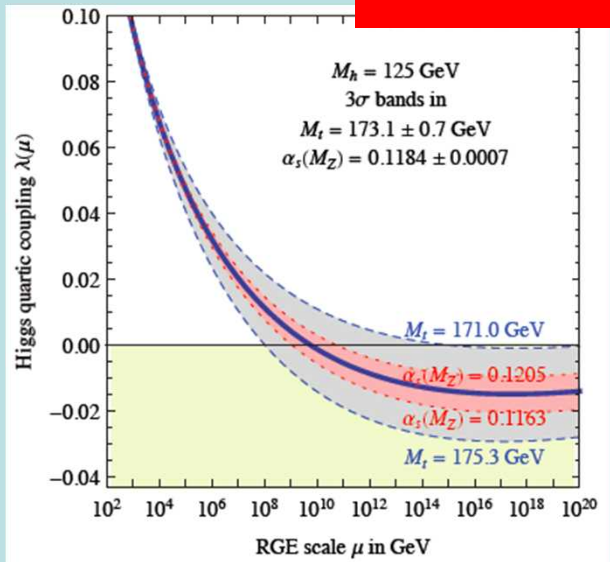
Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4}\log\frac{Q}{v}$$

Instability @ $10^{9.4\pm1.1}$ GeV

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

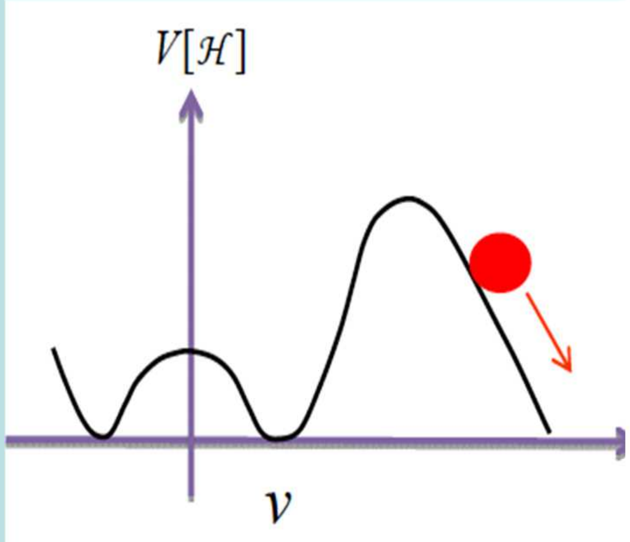


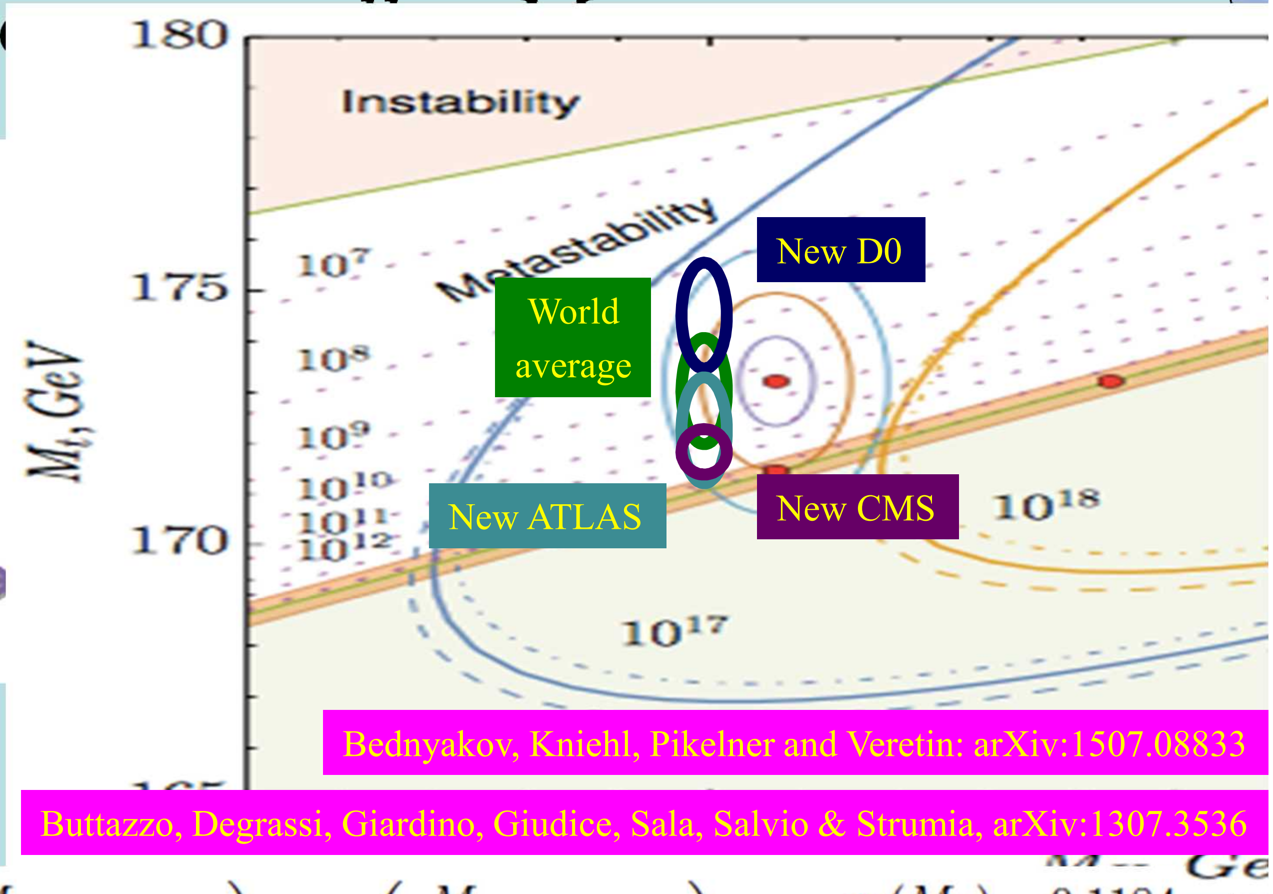
- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive t





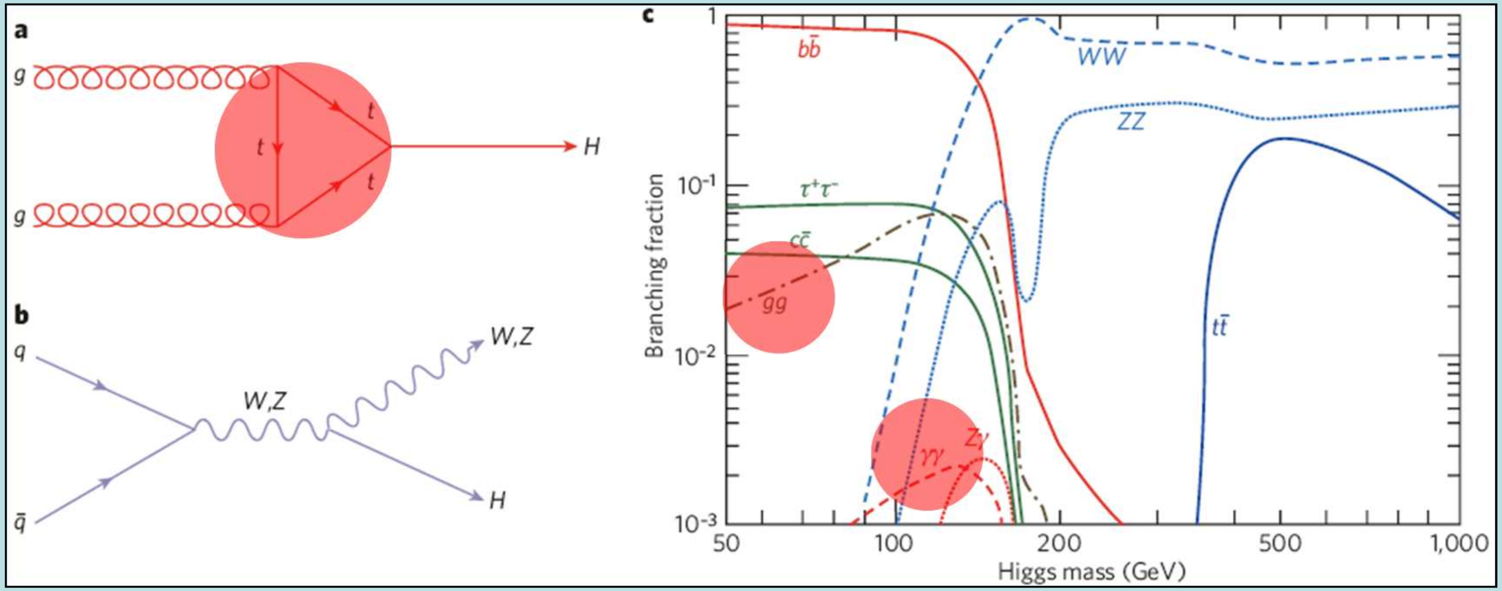
- Instability scale

$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 9.4 \pm 1.1$

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)

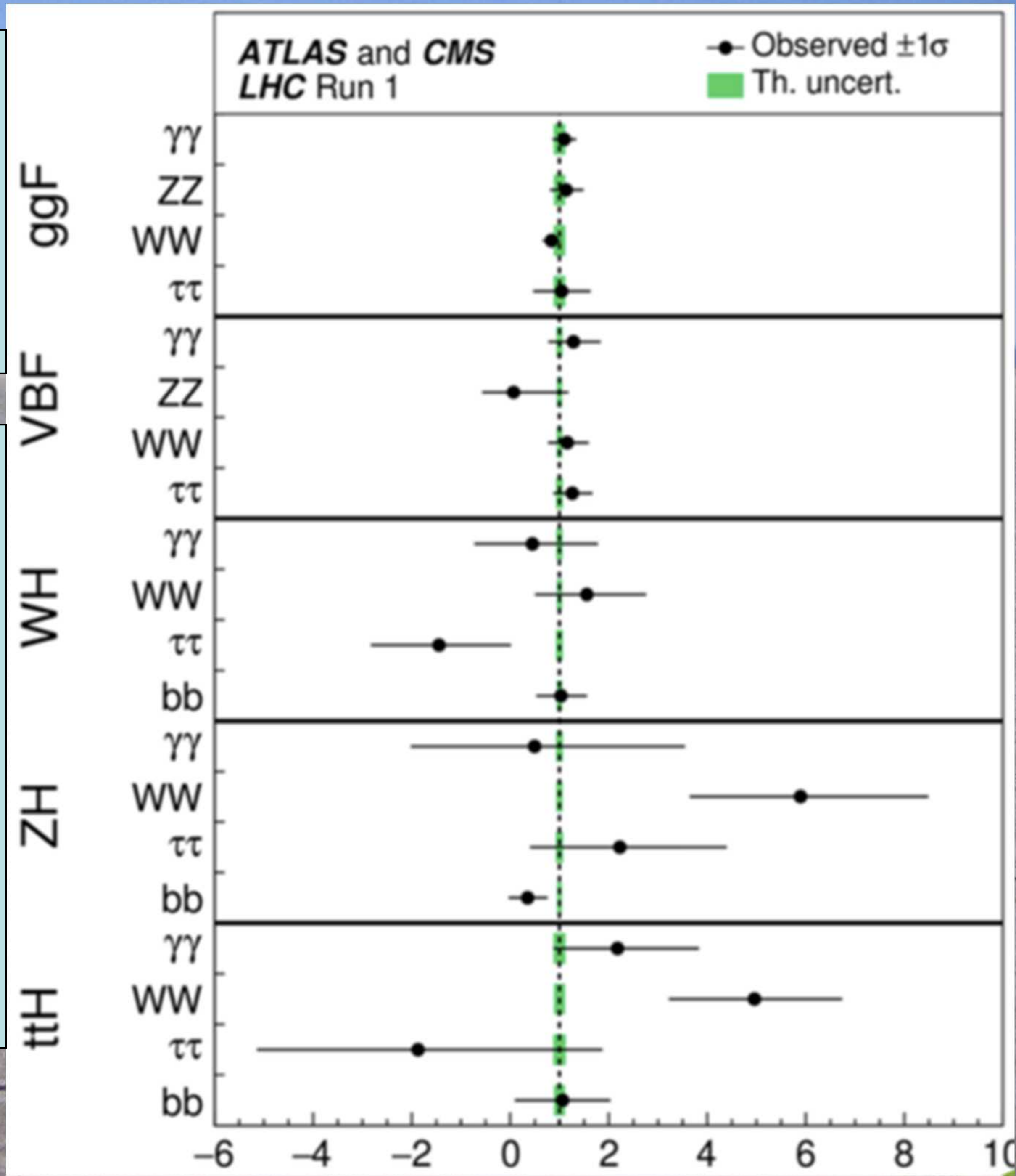


- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if $M_h \sim 125$ GeV

Production Measurements in Run 1

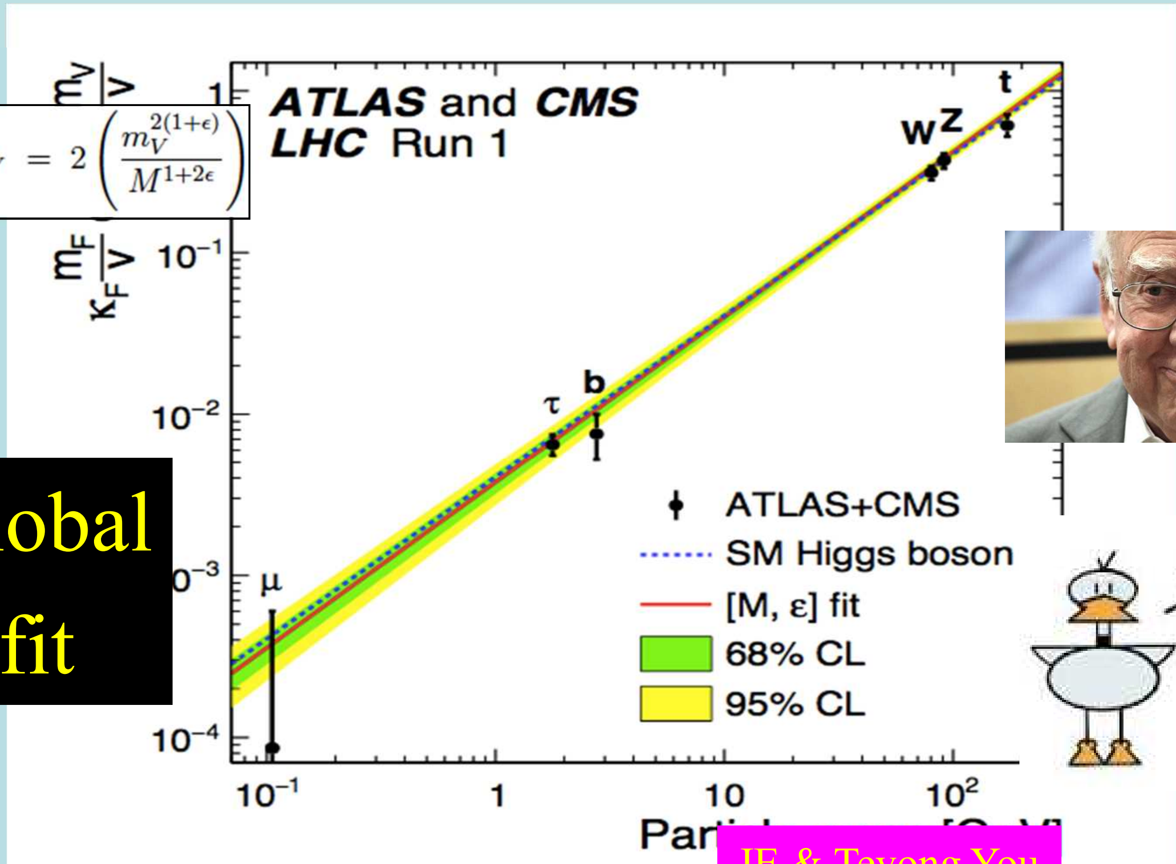
- Open questions:
  - H➔bb?
    - 2.6σ @ LHC
    - 2.8σ @ FNAL
  - H➔➚μ?
  - ttH production?
  - tH production?



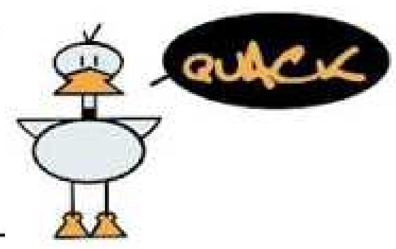
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

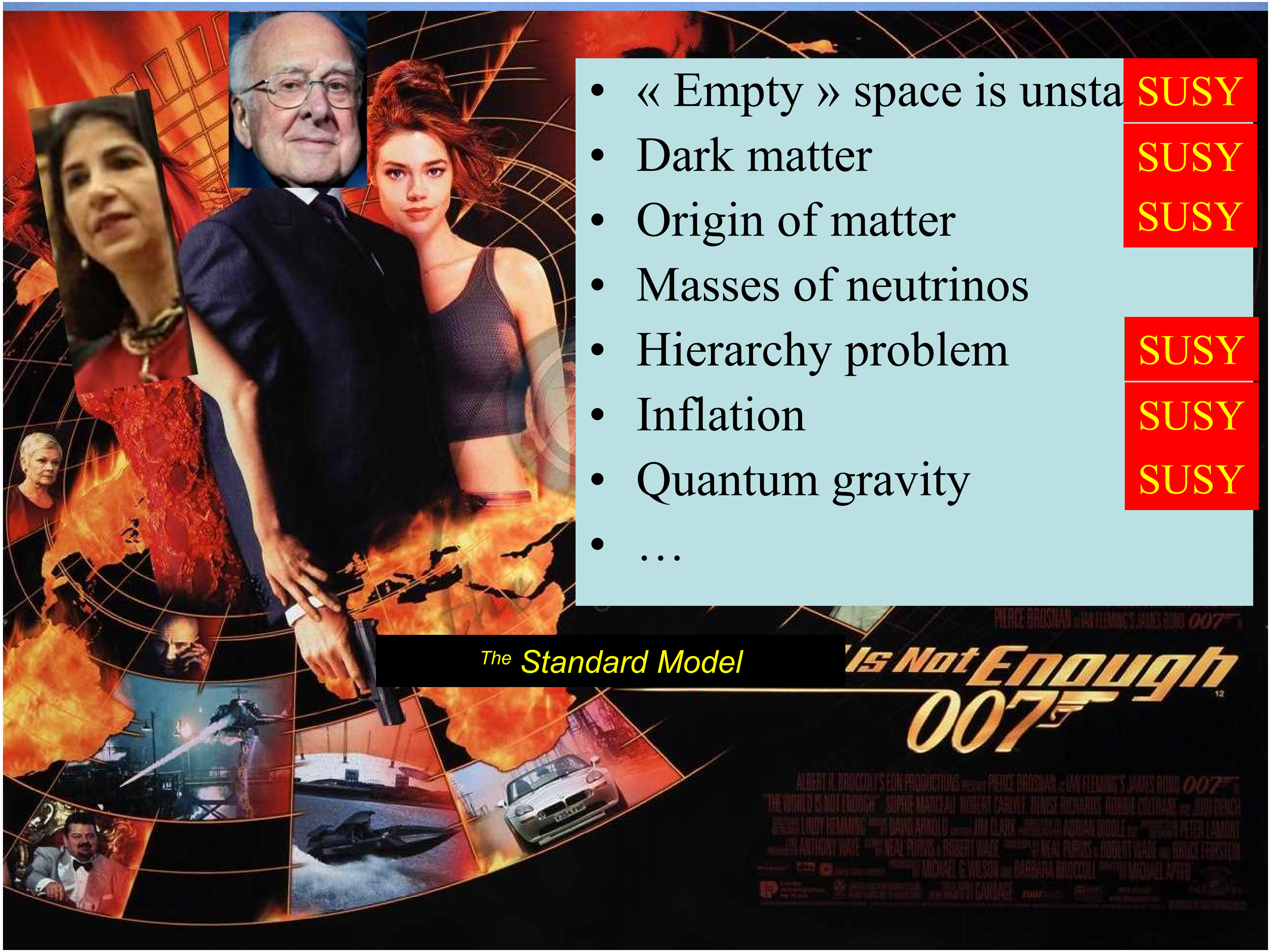


Global fit



JE & Tevong You

- **Blue** dashed line = Standard Model



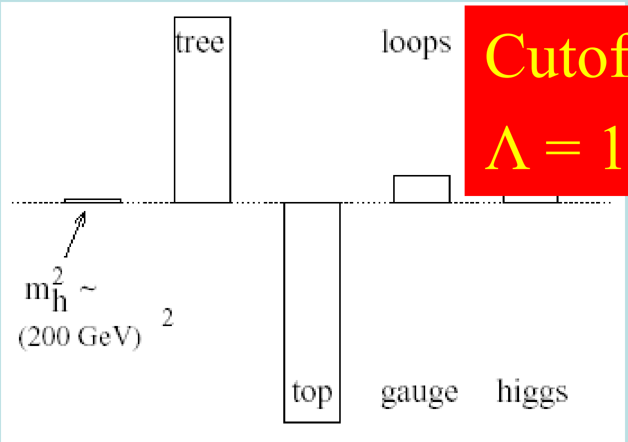
• « Empty » space is unsta
• Dark matter
• Origin of matter
• Masses of neutrinos
• Hierarchy problem
• Inflation
• Quantum gravity
• …
SUSY
SUSY
SUSY
SUSY
SUSY
SUSY
The Standard Model
Is Not Enough
007

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff

$\Lambda = 10$ TeV

Cut-off $\Lambda \sim 1$ TeV with **Supersymmetry?**

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- New ‘technicolour’ force?

- Heavy scalar resonance?
- **Problems with precision electroweak data**
- Pseudo-Nambu-Goldstone boson?

Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

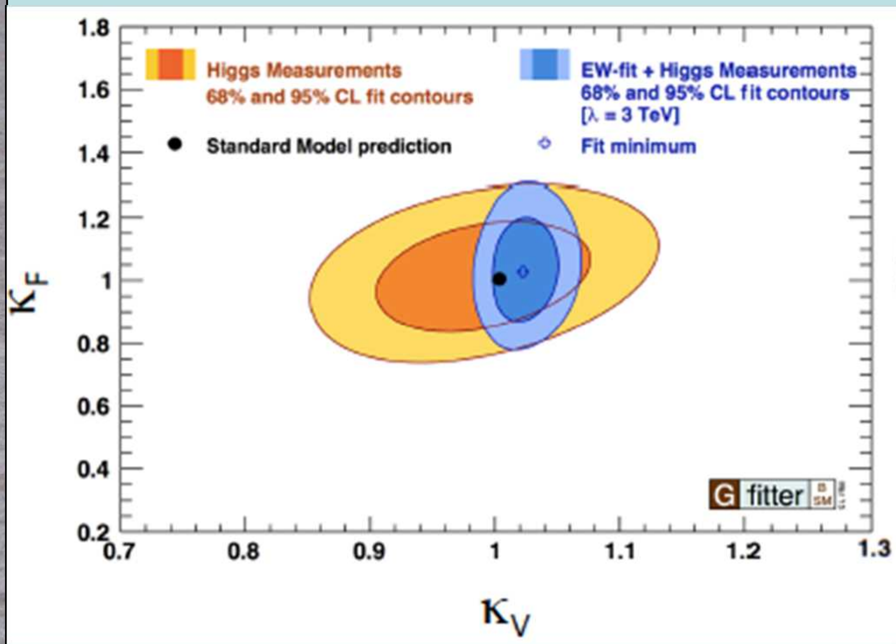
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i\bar{\psi}_L^i\Sigma\left(1 + c\frac{h}{v} + \ldots\right)\psi_R^i + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

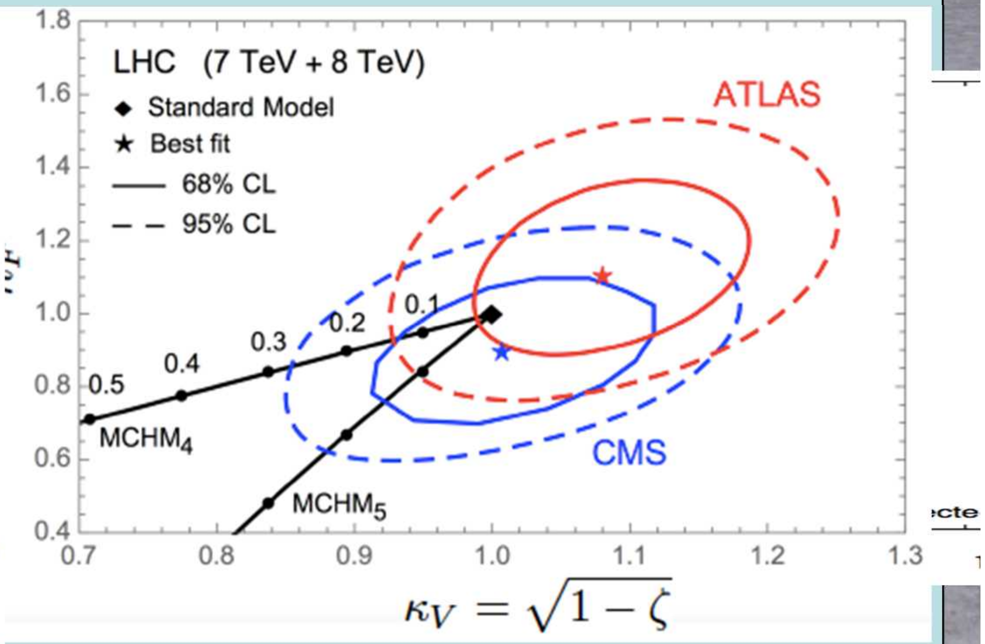
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \qquad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients ***a = c = 1*** in Standard Model

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$





- Consistency between Higgs and EW measurements
- **Must tune composite models to look like SM**

Assuming H(125) is SM-like: Model-independent search for new physics

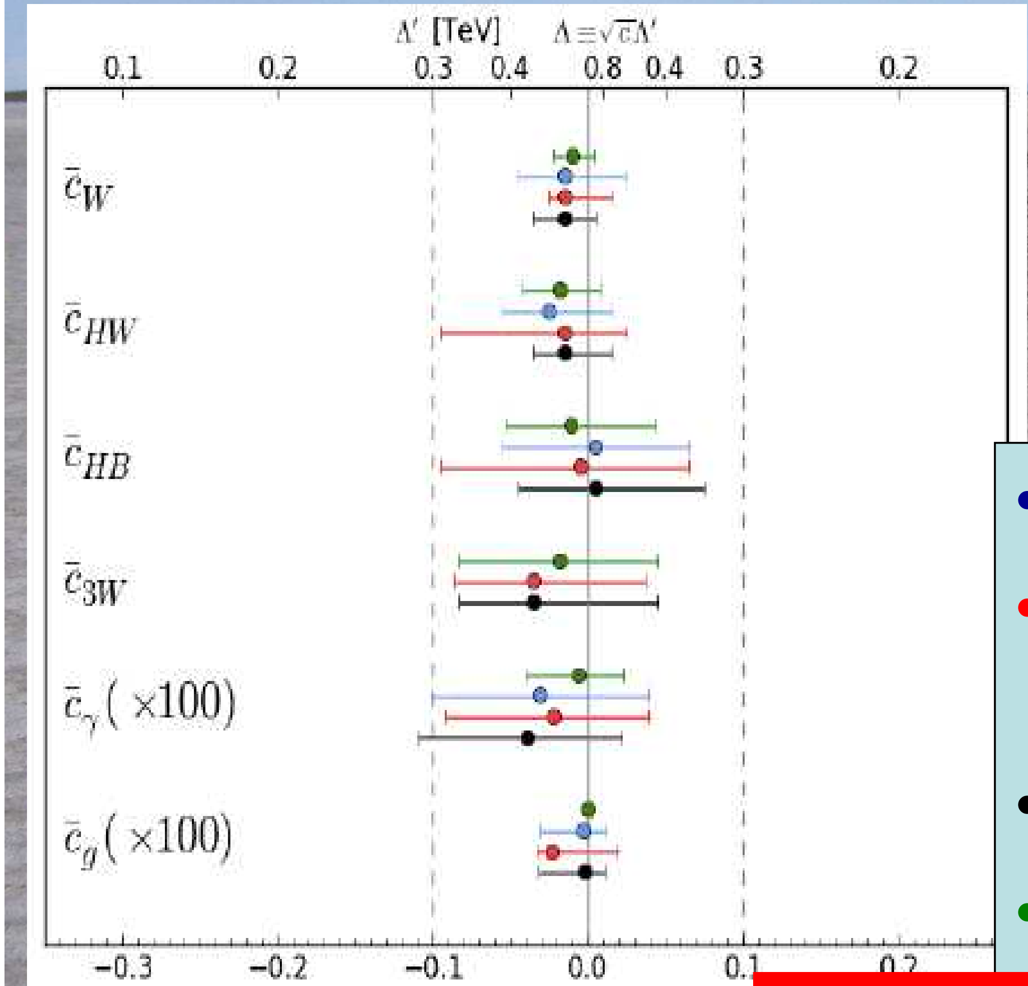
Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6: $\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

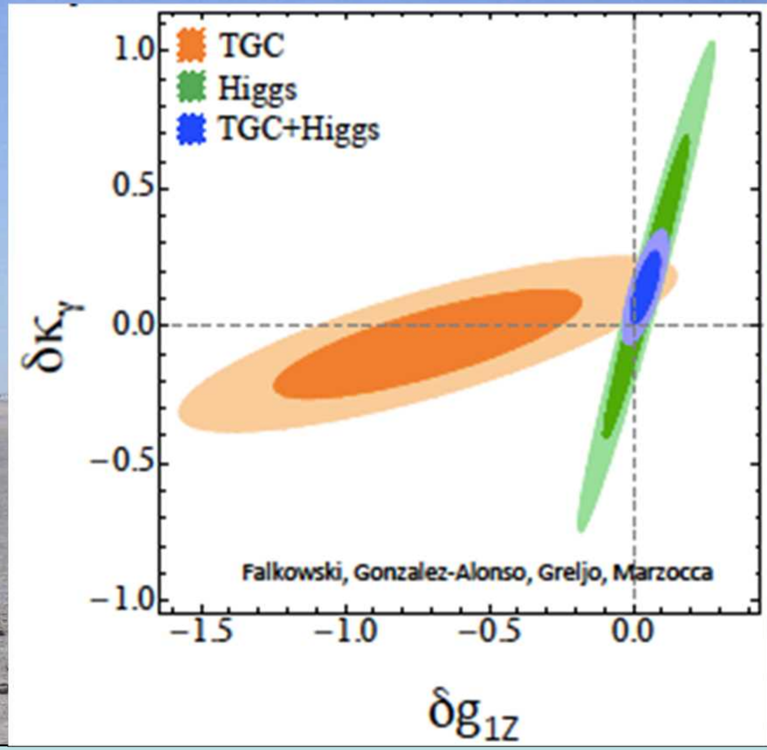
$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu[\Phi^\dagger\Phi]\partial_\mu[\Phi^\dagger\Phi] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ & \frac{2ig\,\bar{c}_{HW}}{m_W^2}[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}[D^\mu\Phi^\dagger D^\nu\Phi]B_{\mu\nu} \\
+\ & \frac{ig\,\bar{c}_W}{m_W^2}[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi]D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2m_W^2}[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi]\partial^\nu B_{\mu\nu} \\
+\ & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R
\end{aligned}$$

- Constrain with precision EW, Higgs data, TGCs ...

Global Fits including LHC Dta



JE, Sanz & Tevong You, arXiv:1410.7703



- **Higgs production**
- **LHC Triple-gauge couplings**
- **Global combination**
- **Individual operators**

Preferred framework for analyzing Run 2

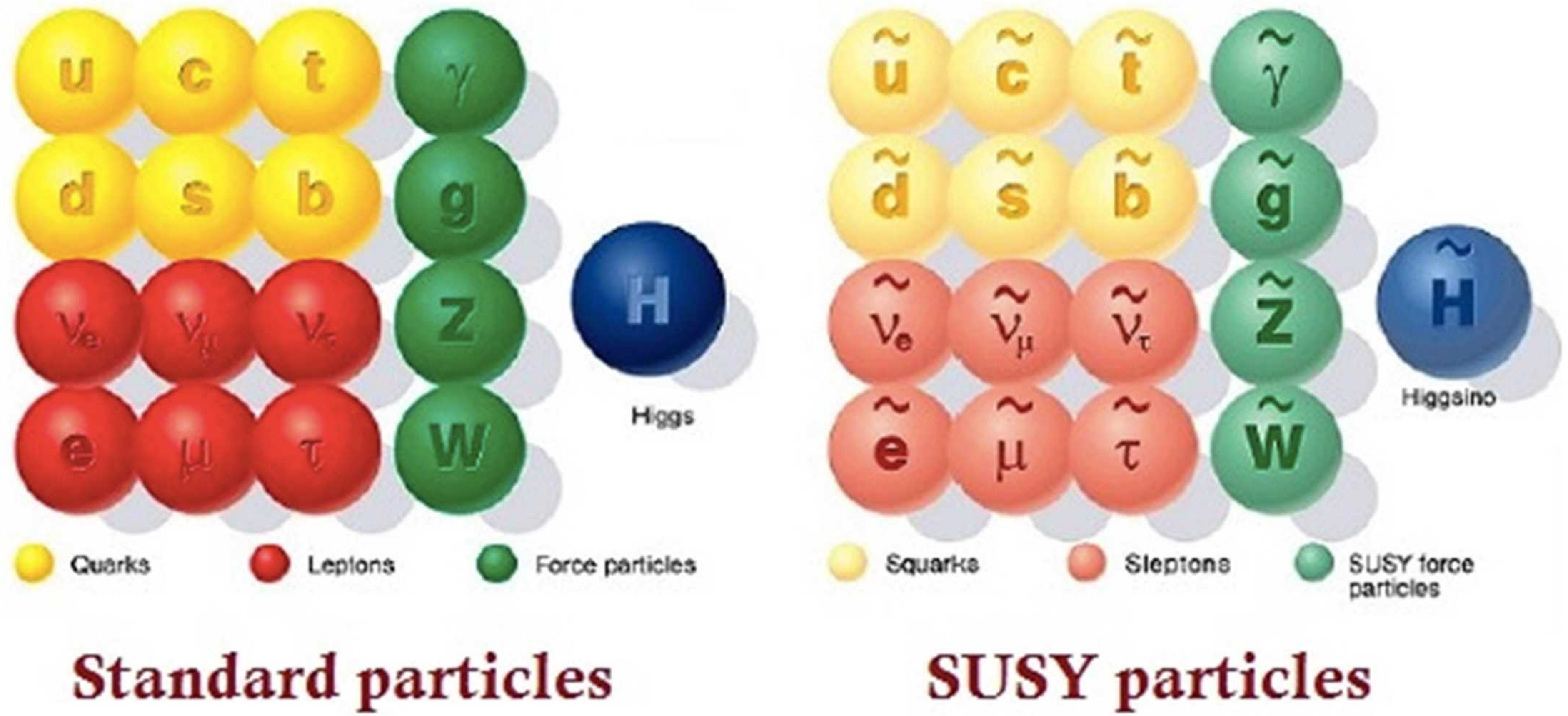
What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

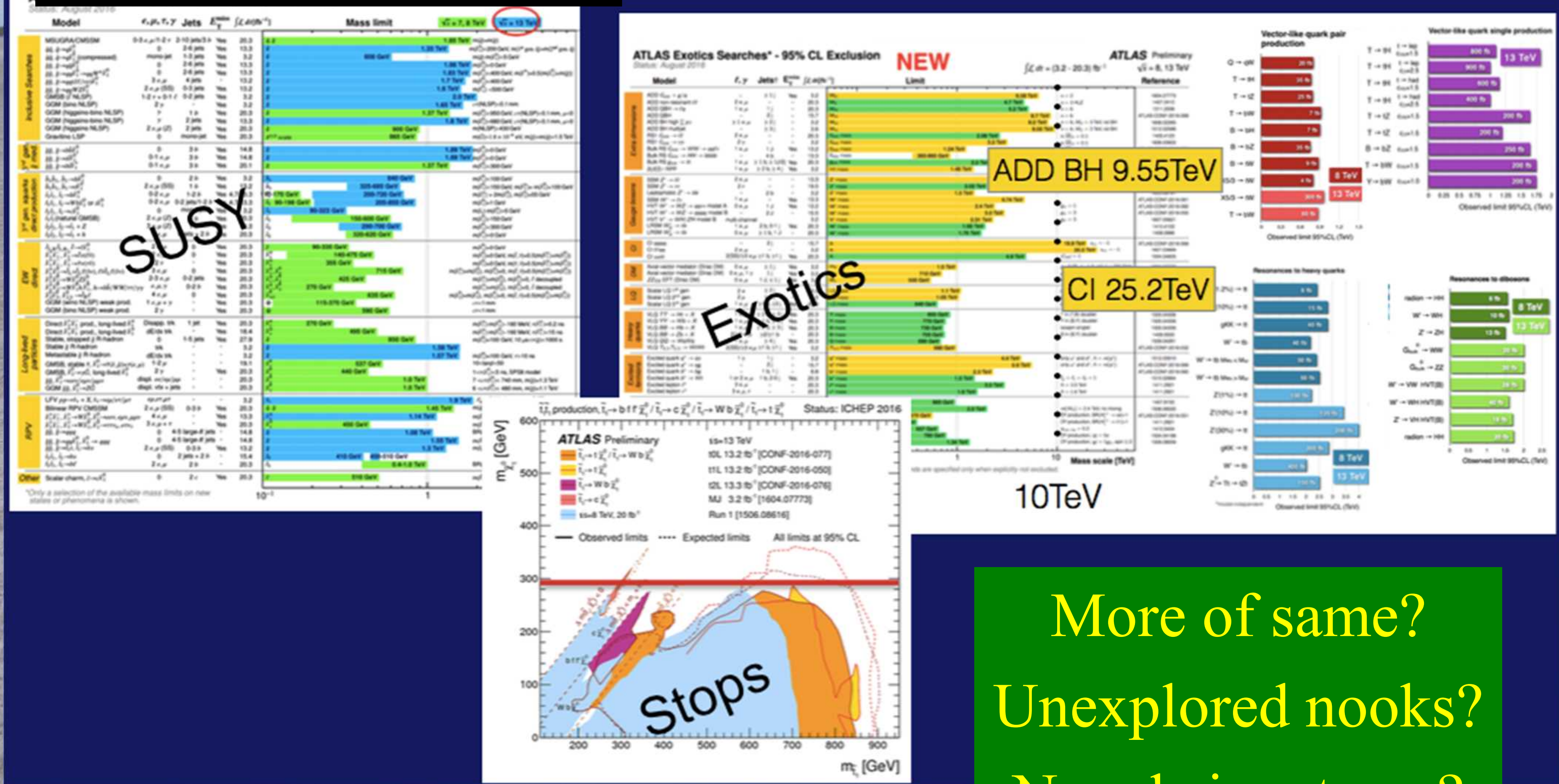
Minimal Supersymmetric Extension of the Standard Model



Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?

Unexplored nooks?

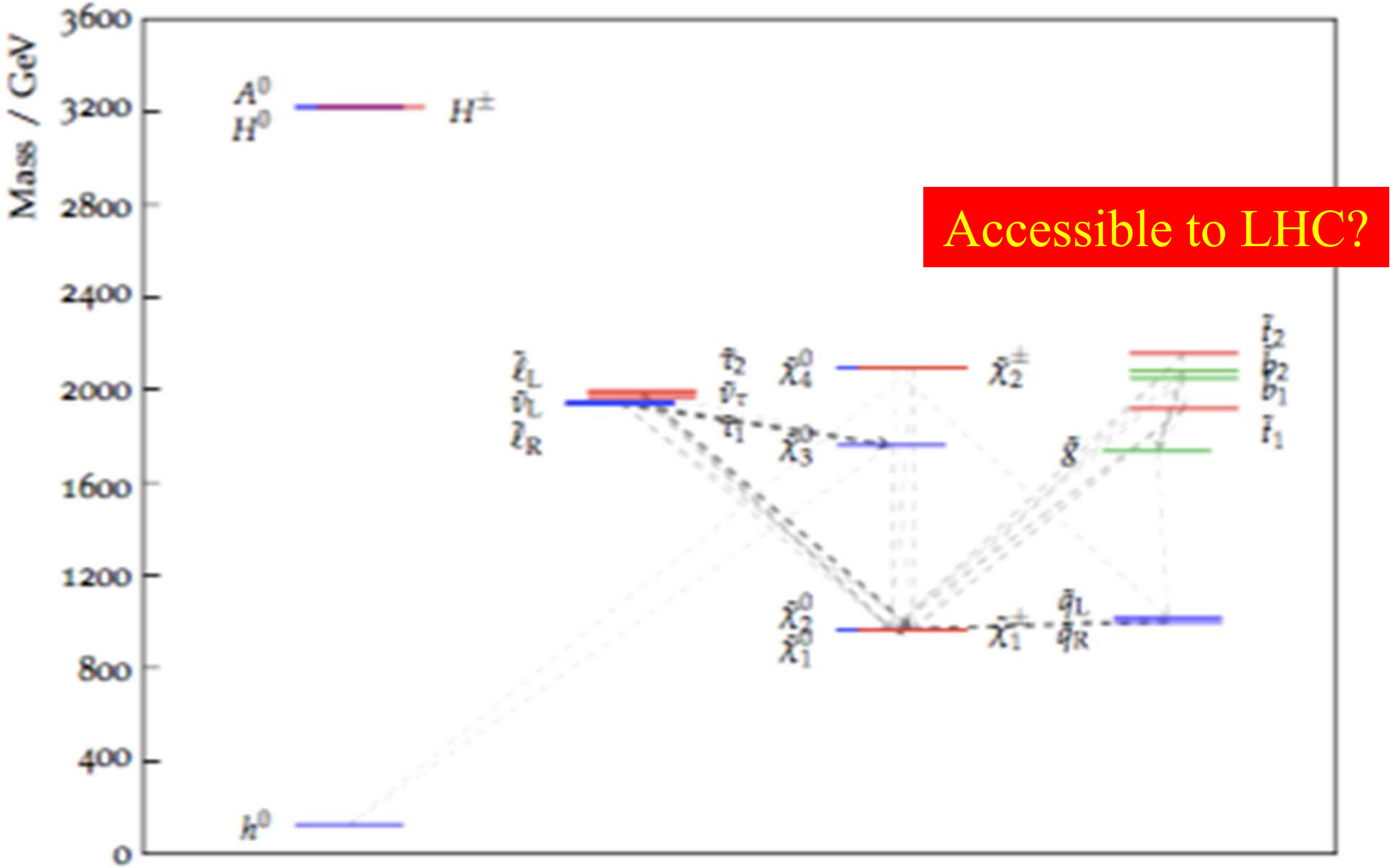
Novel signatures?

Inputs to Global Fits for New Physics

	Observable	Source Th./Ex.	Constraint
Electroweak observables	M_W [GeV]	[88] / [57,58]	$80.379 \pm 0.012 \pm 0.010_{\rm MSSM}$
	$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[59] / [60]	$(30.2 \pm 8.8 \pm 2.0_{\rm MSSM}) \times 10^{-10}$
Flavour observables: Interpretation requires lattice inputs	$R_{\mu\mu}$	[61–63]	2D likelihood, MFV
	$\tau(B_s \to \mu^+\mu^-)$	[63]	$2.04 \pm 0.44(\rm stat.) \pm 0.05(\rm syst.)$ ps
	$\mathrm{BR}_{b\to s\gamma}^{\rm EXP/SM}$	[65]/ [66]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
	$\mathrm{BR}_{B_u\to\tau\nu}^{\rm EXP/SM}$	[66,67]	$0.883 \pm 0.58_{\rm EXP} \pm 0.096_{\rm SM}$
	$BR_{B\to X_s\ell\ell}^{\rm EXP/SM}$	[68]/ [66]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
	$\Delta M_{B_s}^{\rm EXP/SM}$	[34,69] / [66]	$0.968 \pm 0.001_{\rm EXP} \pm 0.078_{\rm SM}$
	$\frac{\Delta M_{B_s}^{\rm EXP/SM}}{\Delta M_{B_d}^{\rm EXP/SM}}$	[34,69] / [66]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
	$BR_{K\to\mu\nu}^{\rm EXP/SM}$	[34,70] / [71]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
	$BR_{K\to\pi\nu\bar\nu}^{\rm EXP/SM}$	[72]/ [73]	$2.01 \pm 1.30_{\rm EXP} \pm 0.18_{\rm SM}$
Dark Matter	σ_p^{SI}	[3,5,6]	Combined likelihood in the $(m_{\tilde\chi_1^0}, \sigma_p^{SI})$ plane
	σ_p^{SD}	[4]	Likelihood in the $(m_{\tilde\chi_1^0}, \sigma_p^{SD})$ plane
LHC observables	$\tilde g \to q\bar q\tilde\chi_1^0, b\bar b\tilde\chi_1^0, t\bar t\tilde\chi_1^0$	[16,17]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi_1^0})$ plane
	$\tilde q \to q\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi_1^0})$ plane
	$\tilde b \to b\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi_1^0})$, plane
	$\tilde t_1 \to t\tilde\chi_1^0, c\tilde\chi_1^0, b\tilde\chi_1^\pm$	[16]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi_1^0})$, plane
	$\tilde\chi_1^\pm \to \nu\ell^\pm\tilde\chi_1^0, \nu\tau^\pm\tilde\chi_1^0, W^\pm\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_1^\pm}, m_{\tilde\chi_1^0})$ plane
	$\tilde\chi_2^0 \to \ell^+\ell^-\tilde\chi_1^0, \tau^+\tau^-\tilde\chi_1^0, Z\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_2^0}, m_{\tilde\chi_1^0})$ plane
	Heavy stable charged particles	[74]	Fast simulation based on [74, 75]
	$H/A \to \tau^+\tau^-$	[28,29,76,77]	Likelihood in the $(M_A, \tan\beta)$ plane

Best-Fit Sparticle Spectrum

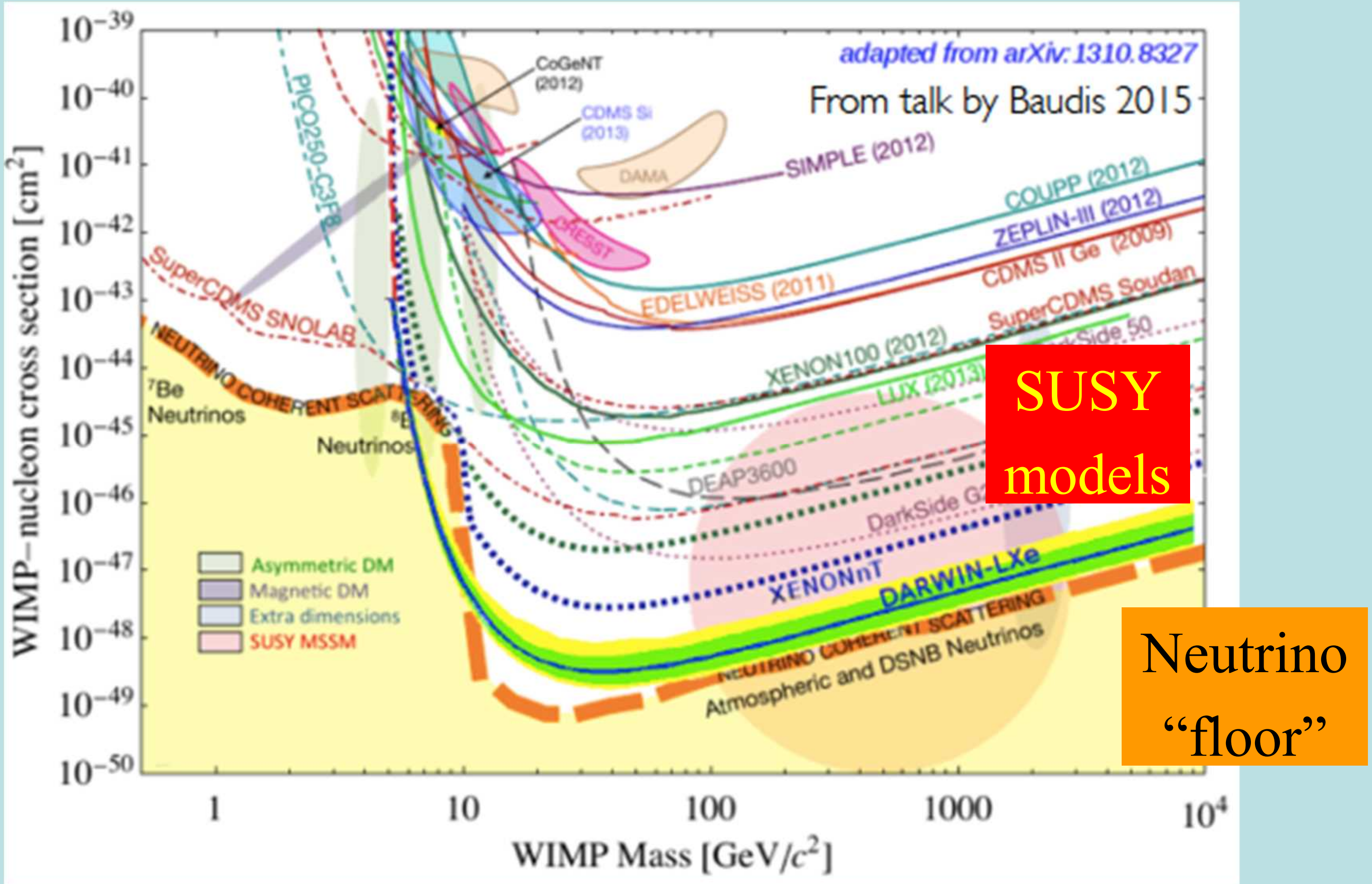
Phenomenological MSSM



Bagnaschi, Sakurai, JE et al*: to appear*

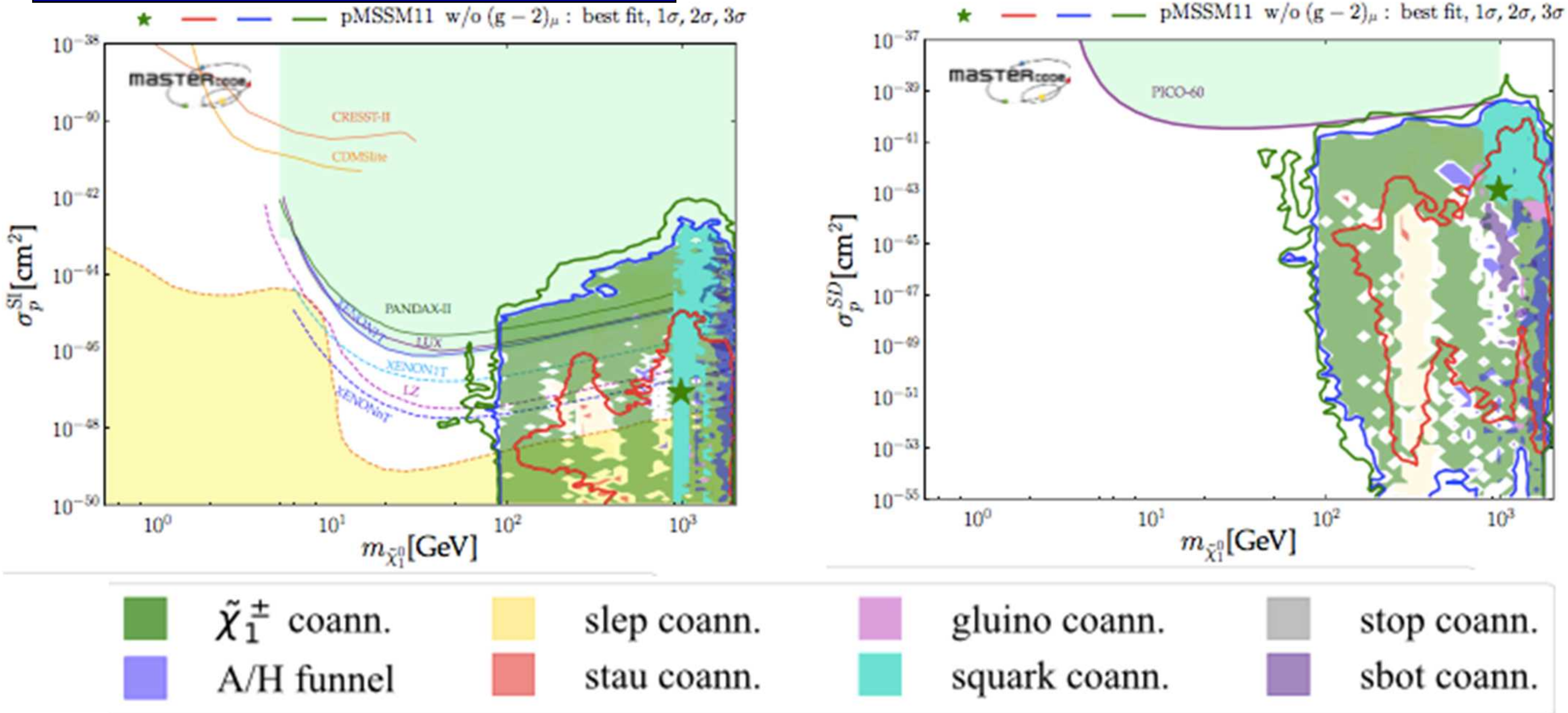
Direct Dark Matter Searches

- Compilation of present and future sensitivities



Direct Dark Matter Searches

Phenomenological MSSM



Spin-independent scattering cross-section

close to PandaX upper limit?

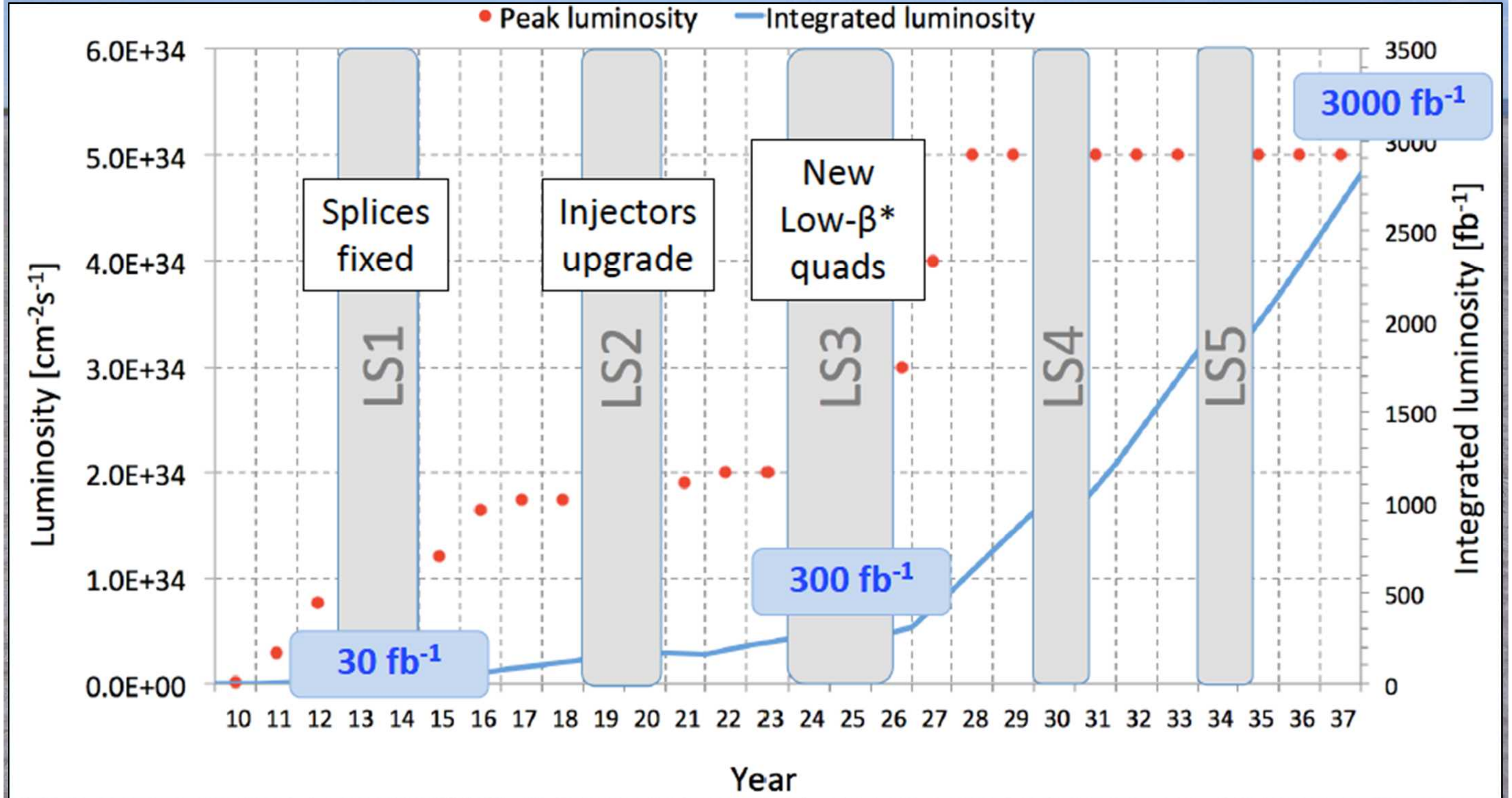
Spin-dependent scattering:

Strongest limit from

PICO experiment

Bagnaschi, Sakurai, …, JE et al: *in preparation*

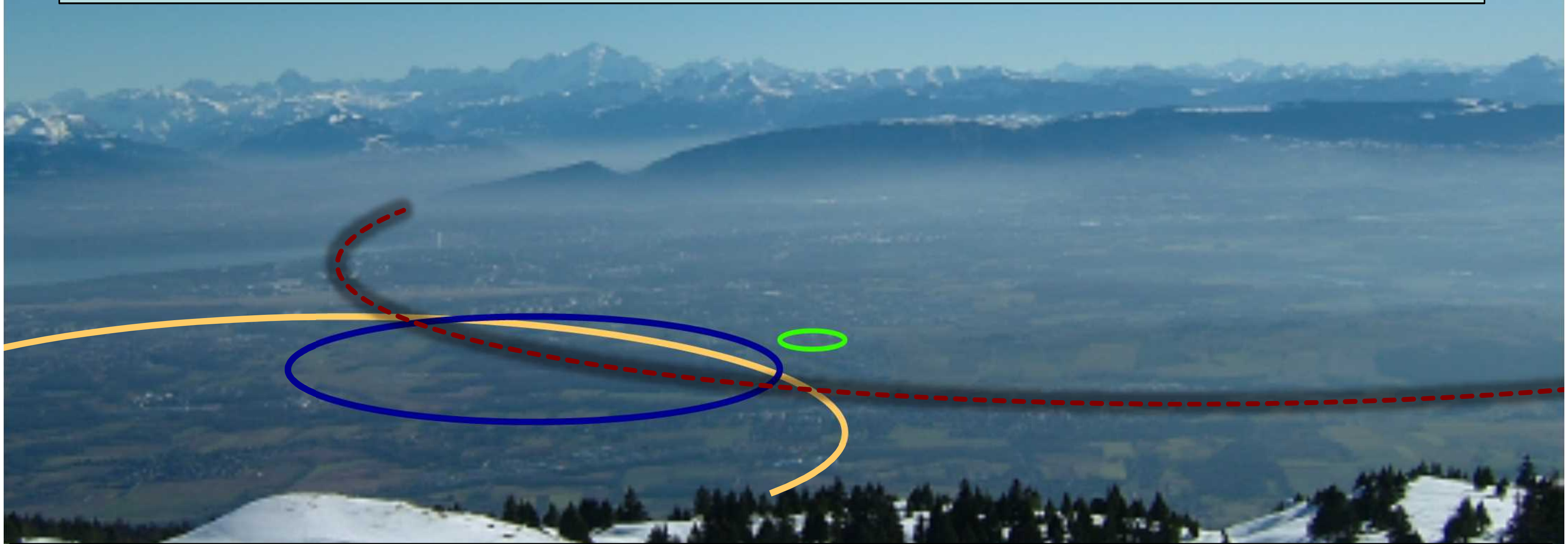
The LHC in Future Years



CEPC-SPPC

Preliminary Conceptual Design Report

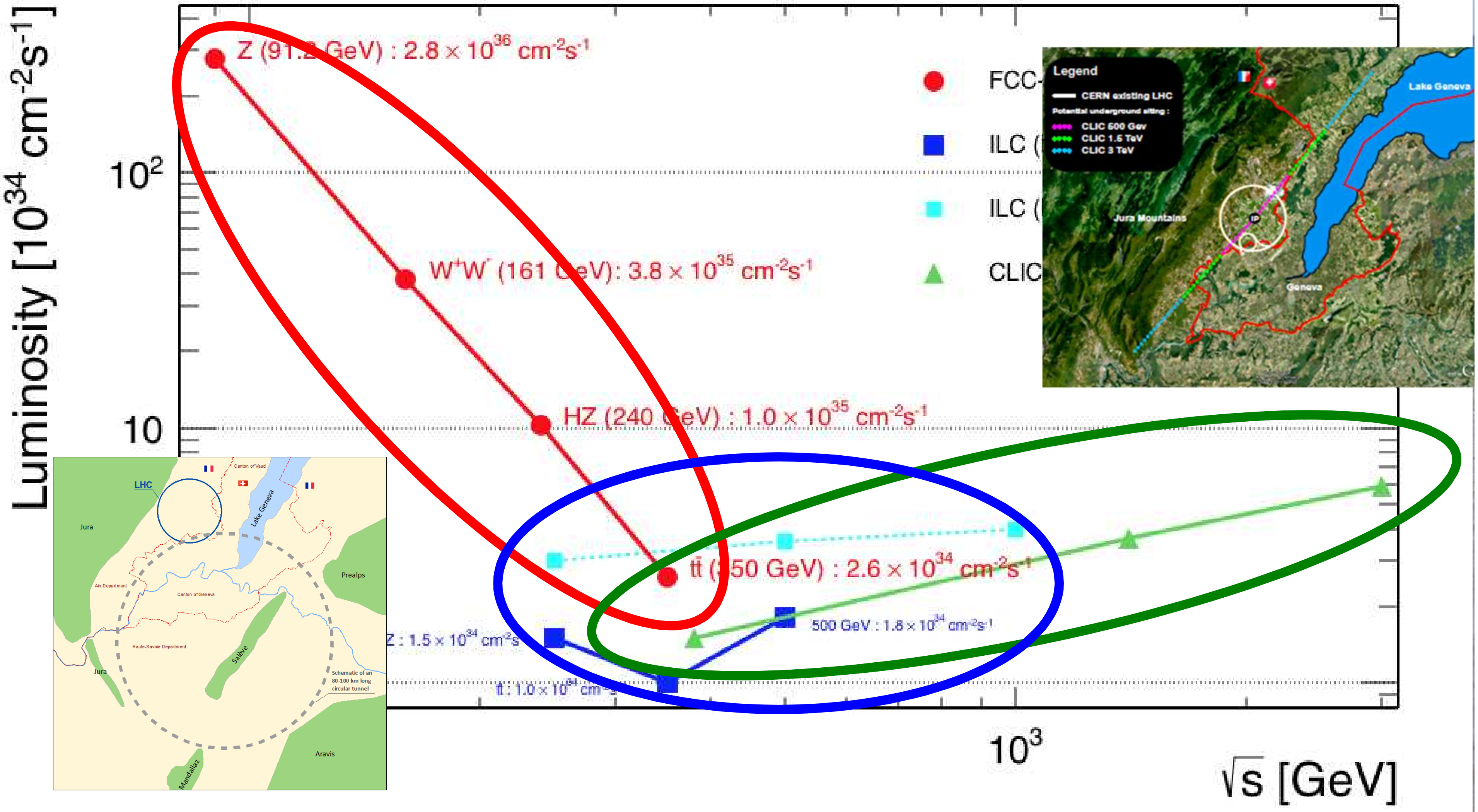
Future Circular Colliders



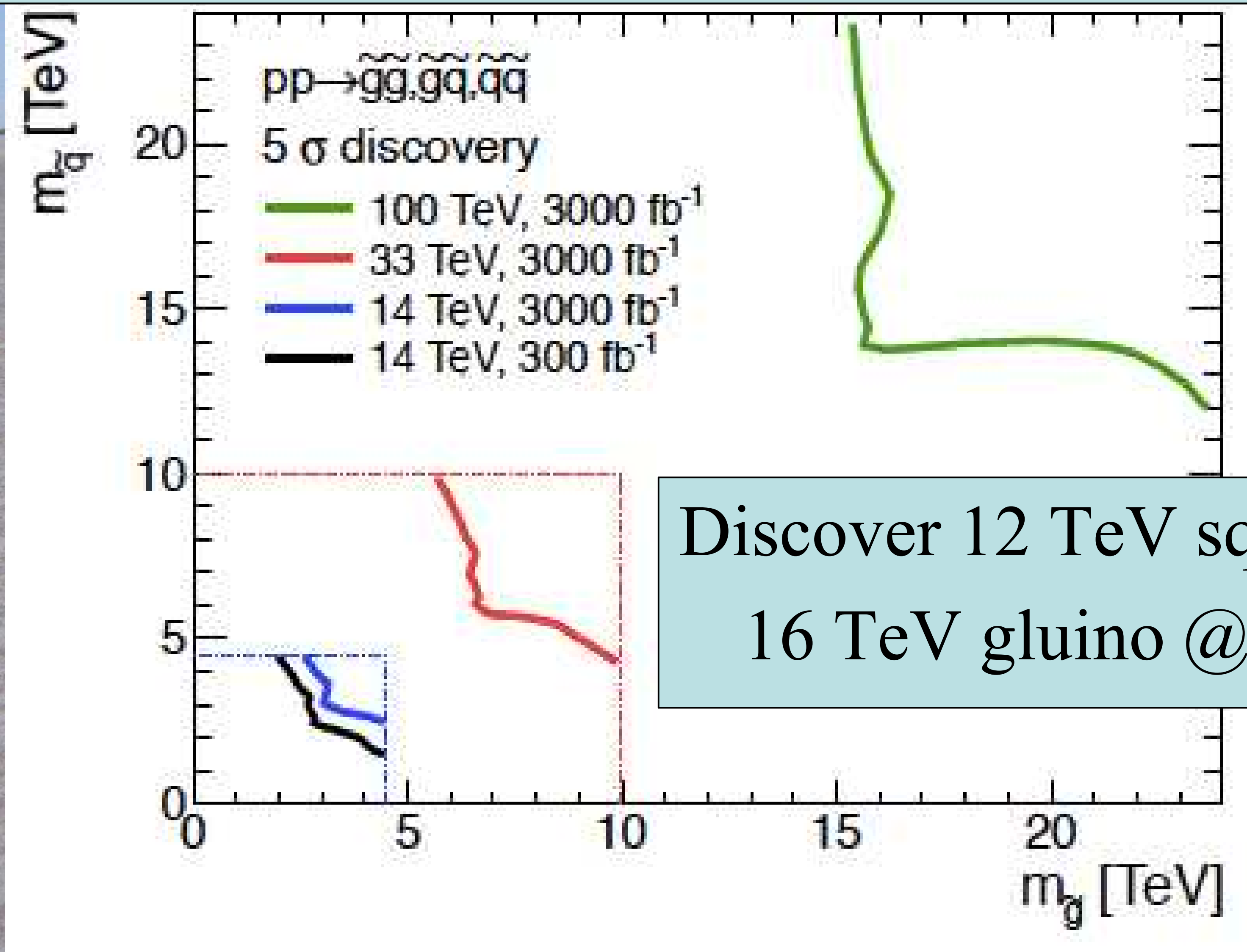
The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Projected e^+e^- Colliders: Luminosity vs Energy



Squark-Gluino Plane



Discover 12 TeV squark,

16 TeV gluino @ 5σ

Summary

- The discovery of the Higgs boson at the LHC is a big challenge for theoretical physics!
- The LHC may yet discover physics beyond the SM at ~ 13 TeV
- If it **does**, priority will be to study it
- If it does **not**, natural to focus on the Higgs
- In either case, a large circular collider offers the best prospects