"וְעֵילָם נָשָׂא אַשְׁפָּה..."

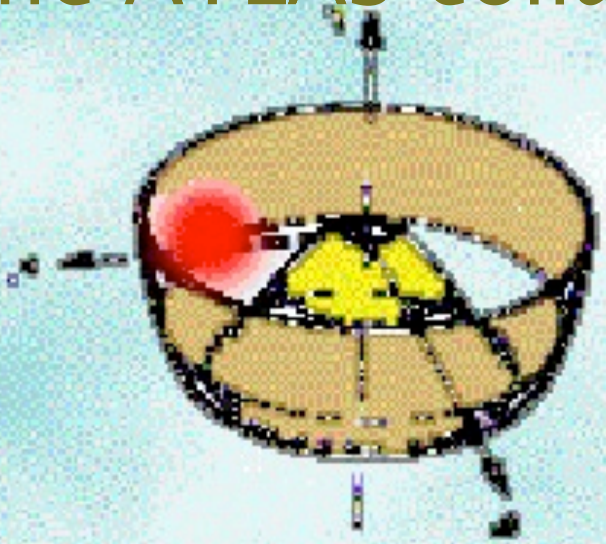
ישעיה כב

Eilam Gross

Weizmann & CERN

Hunting the Higgs

On behalf of the ATLAS collaboration



ATLAS EXPERIMENT

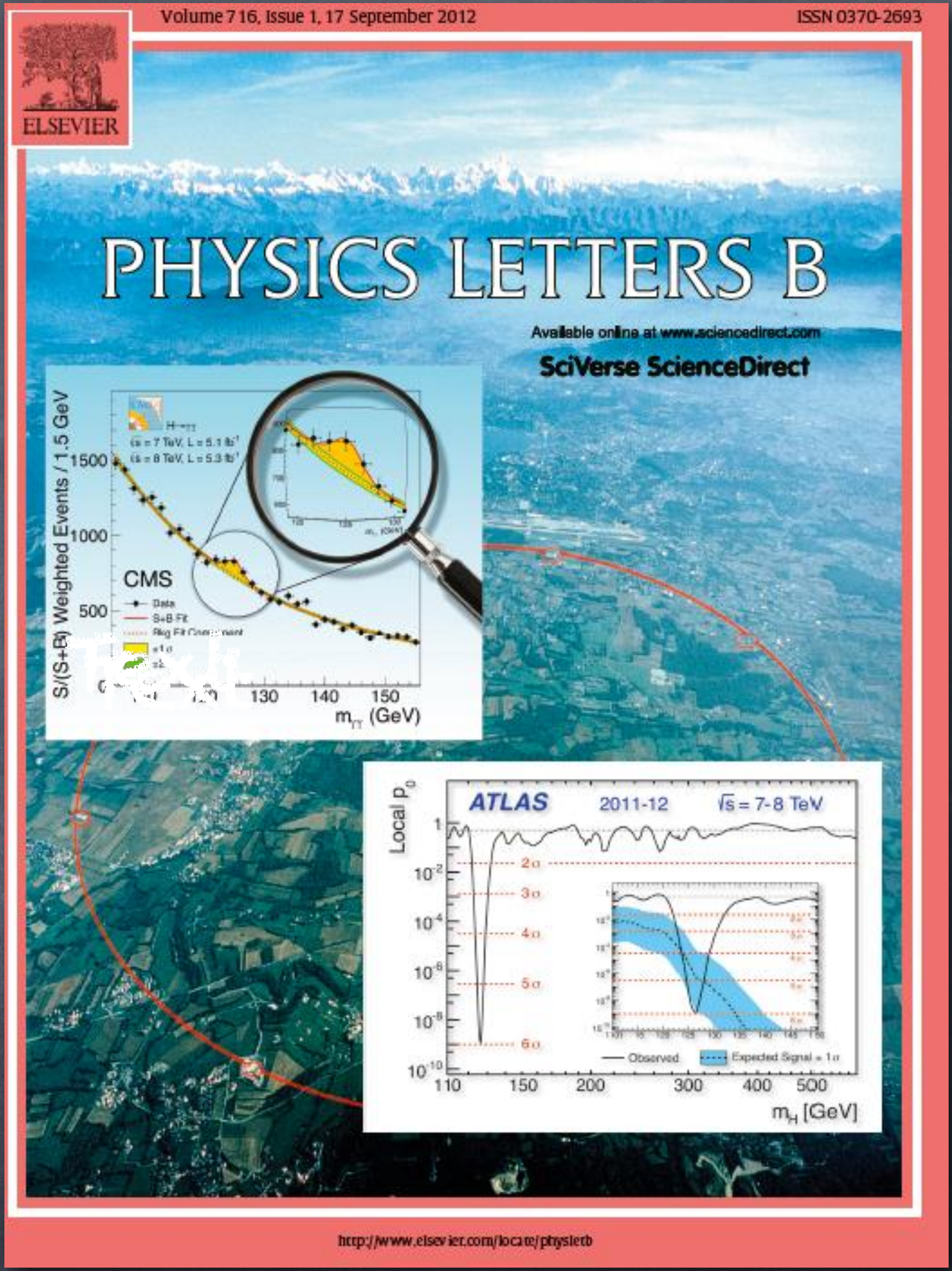
Technion

May 2013

"And Eilam bare the quiver..."

Jesaia 22

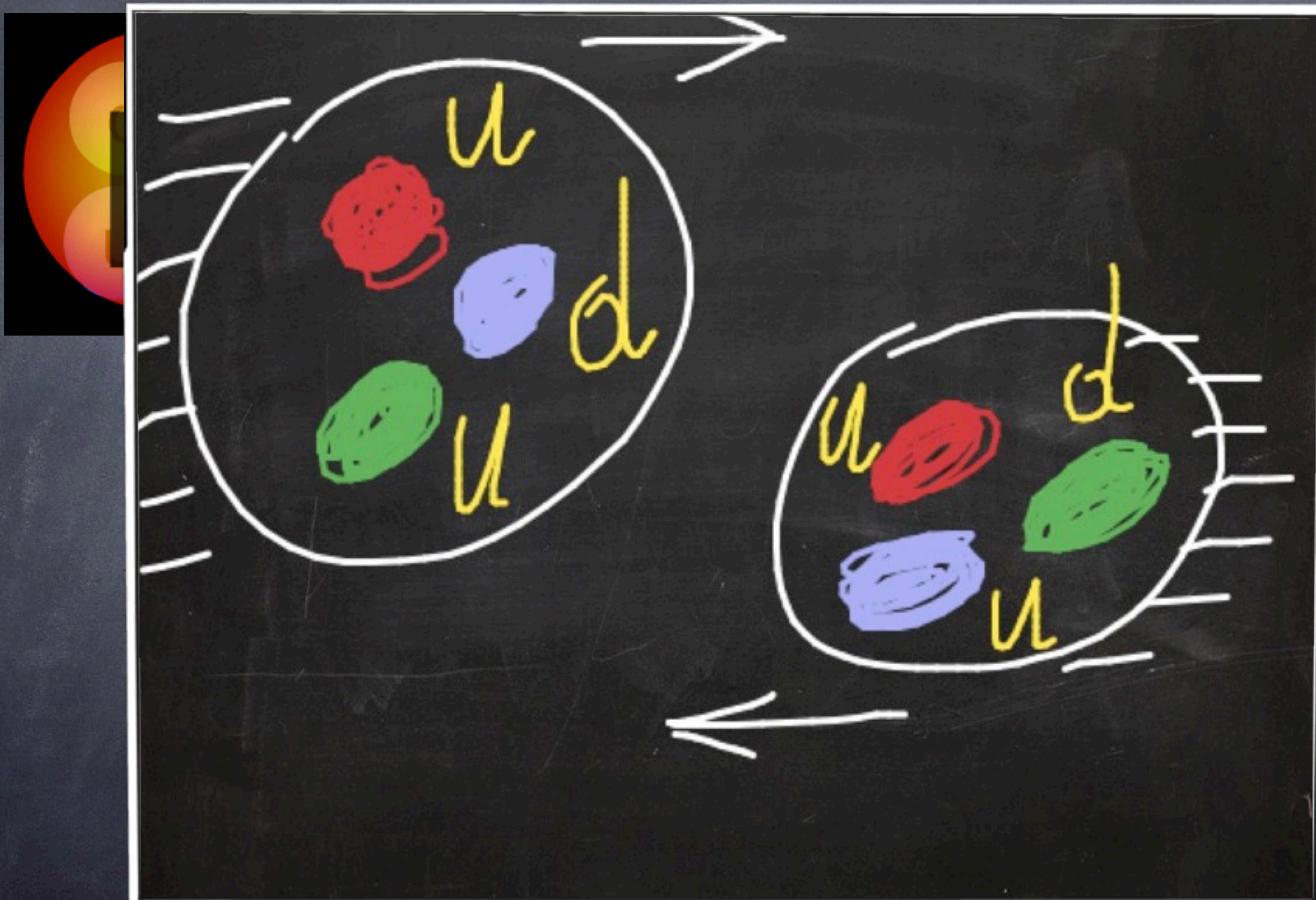
17 september 2012

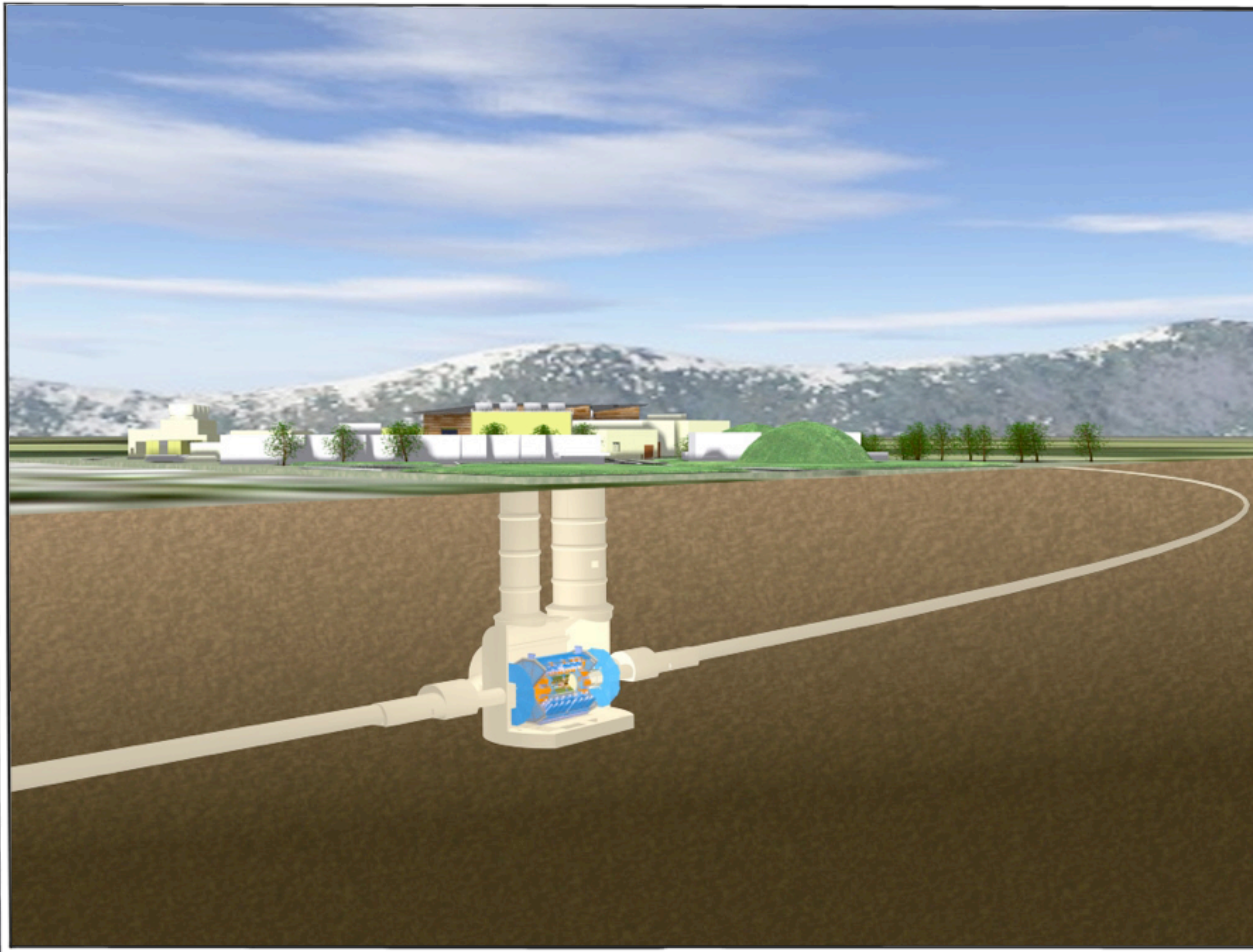



On Behalf of the ATLAS Collaboration
C
D

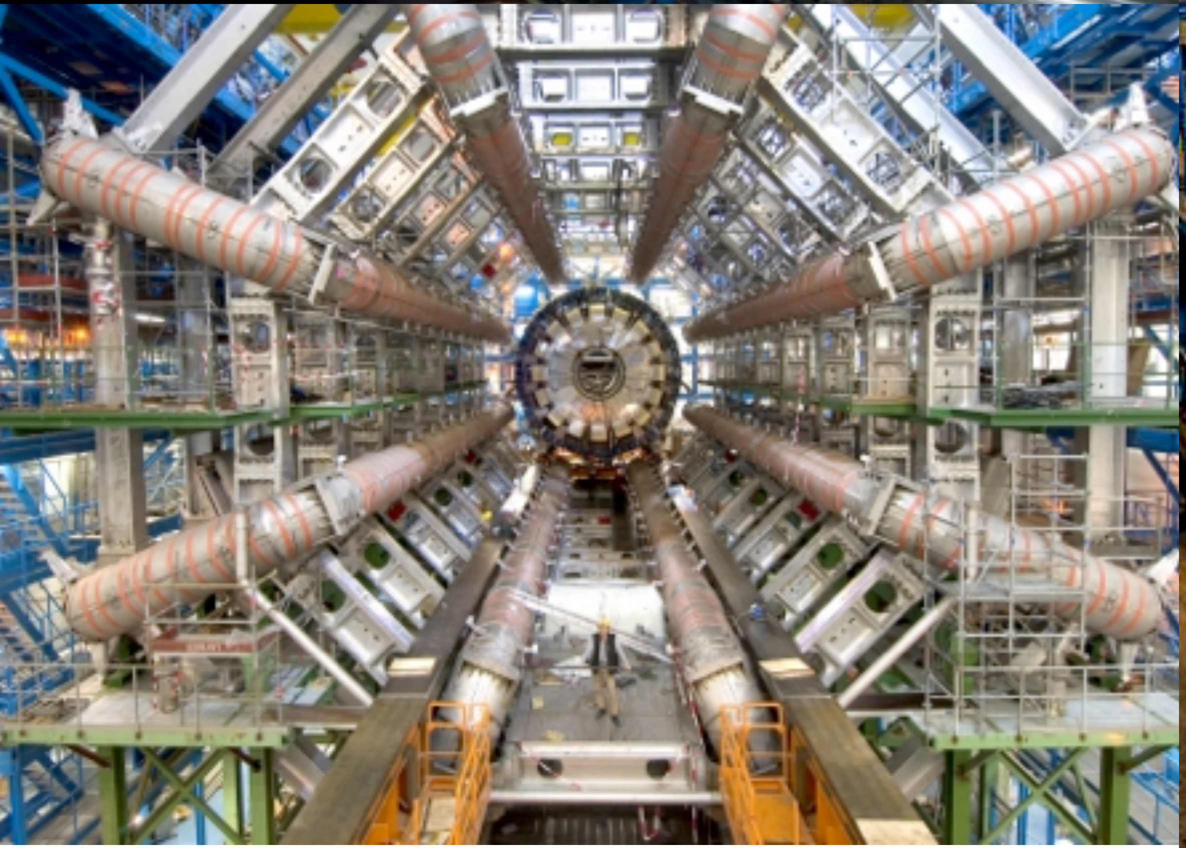
Seeing The Higgs Boson - How To?

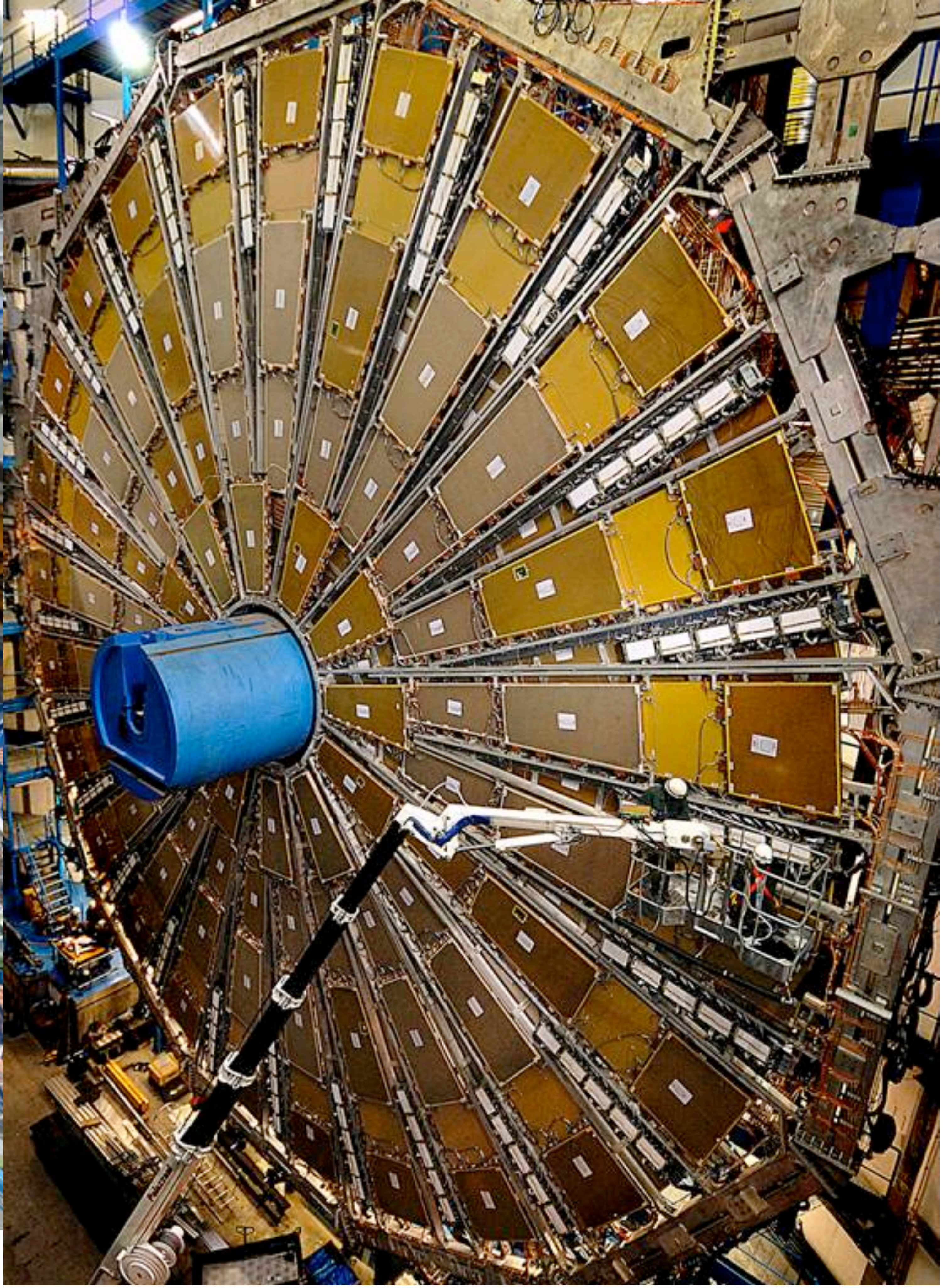
Proton-Proton Collisions



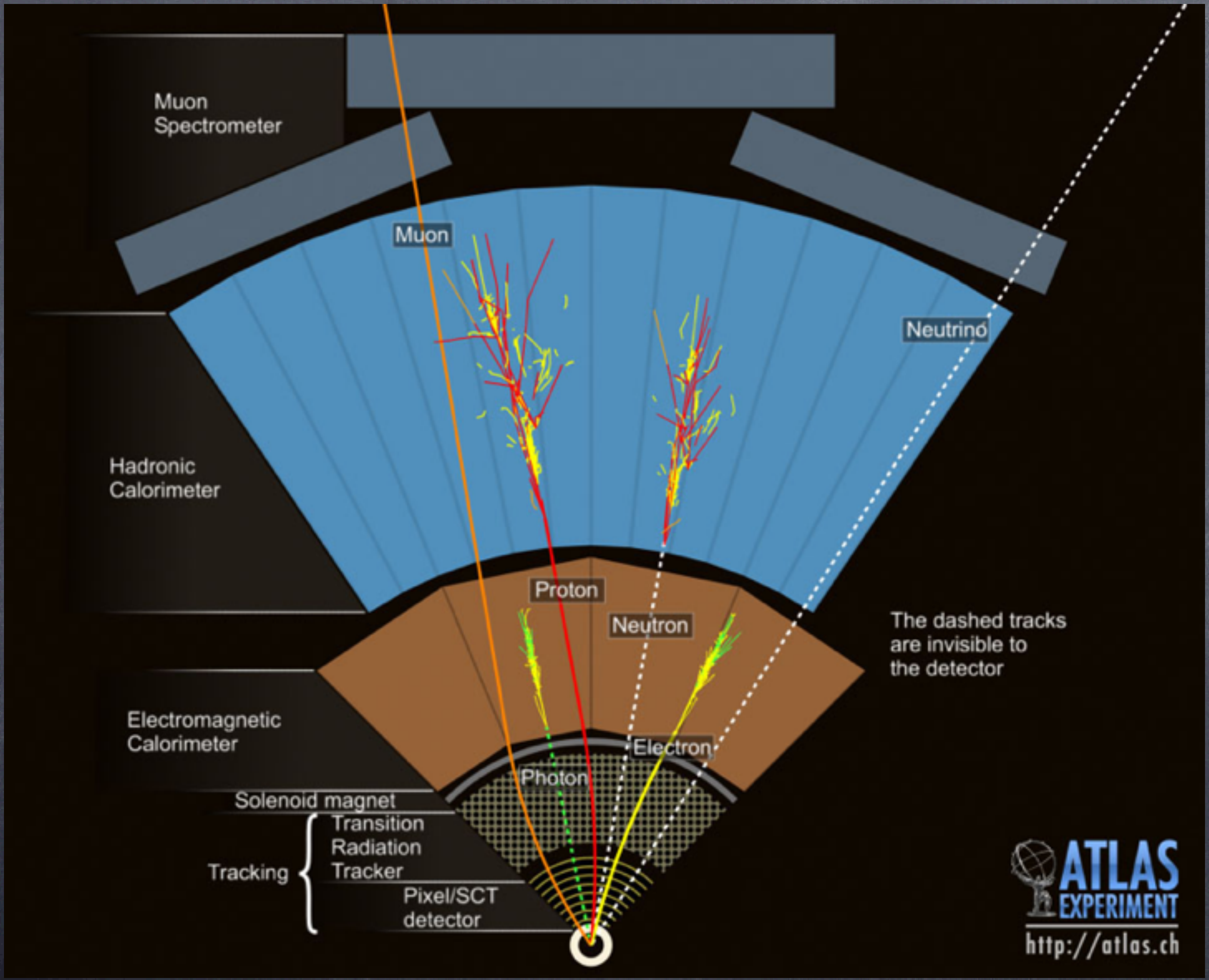



SUX 1





Seeing Particles



Thanks to the LHC Team

Proton Runs 2010-12

Not currently active

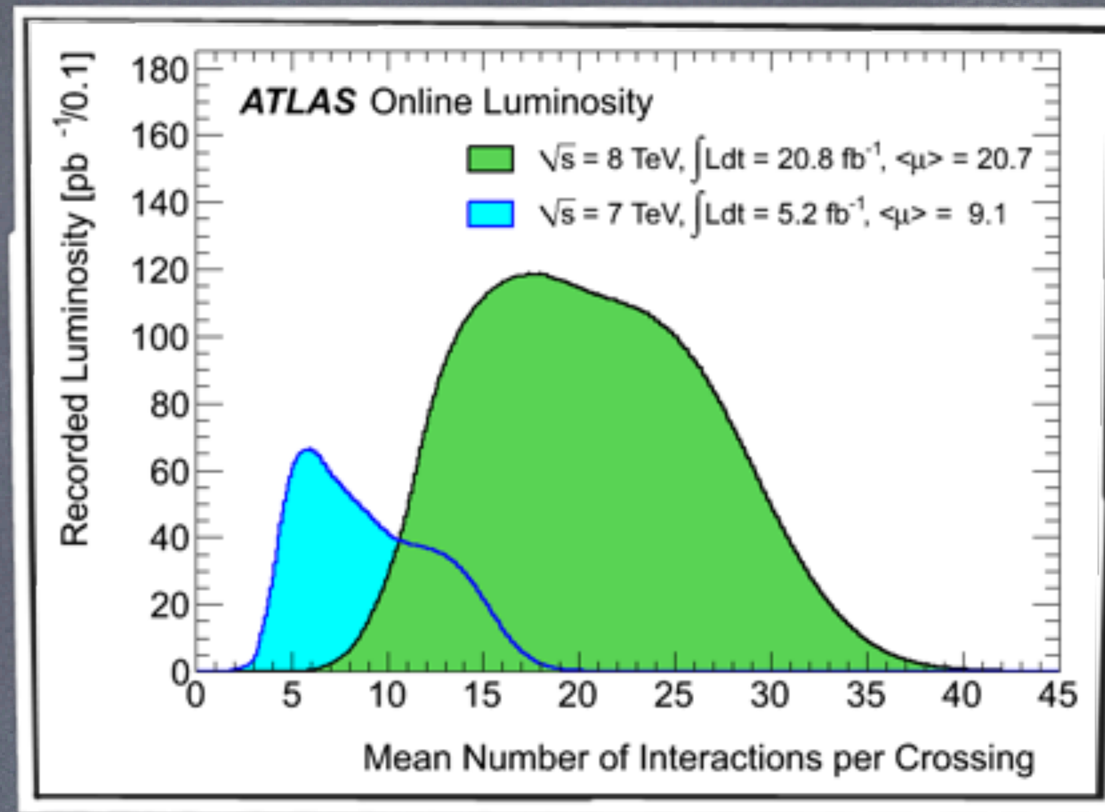
Highest luminosity = $7.73 \cdot 10^{33}$ $cm^{-2}s^{-1}$

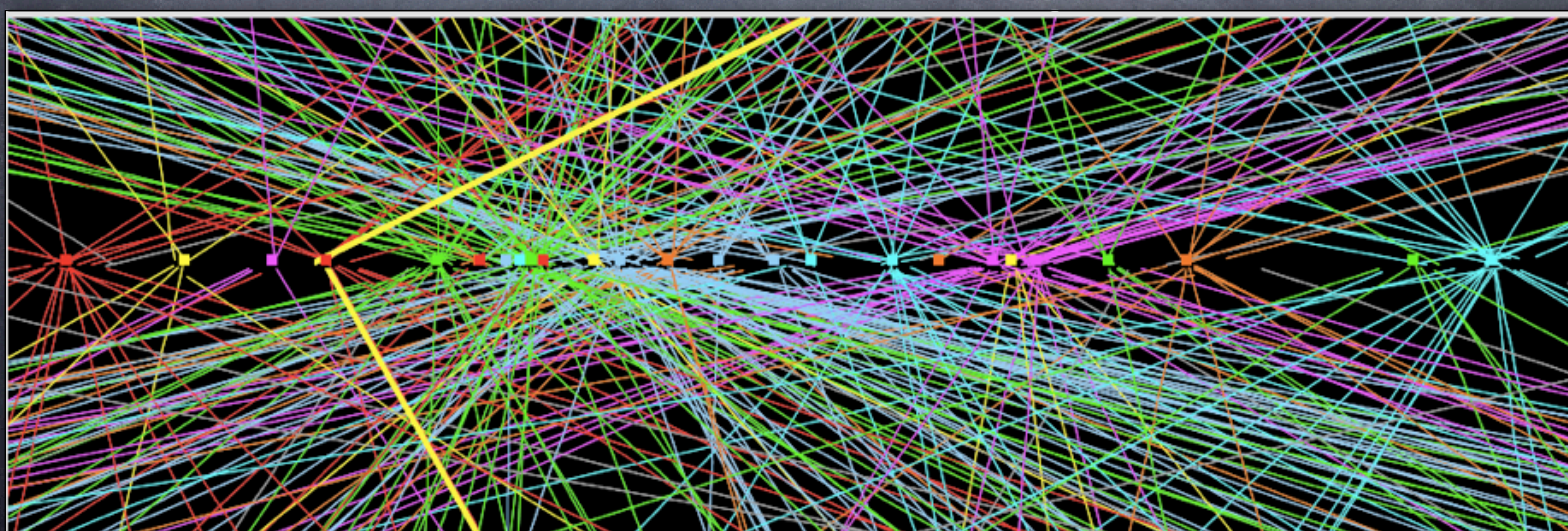
Total Collisions = $1.80 \cdot 10^{15}$ = 1 800 000 000 000 000

Recorded luminosity = 27.03 fb^{-1}

A dream comes true: 27 fb^{-1} by 2012

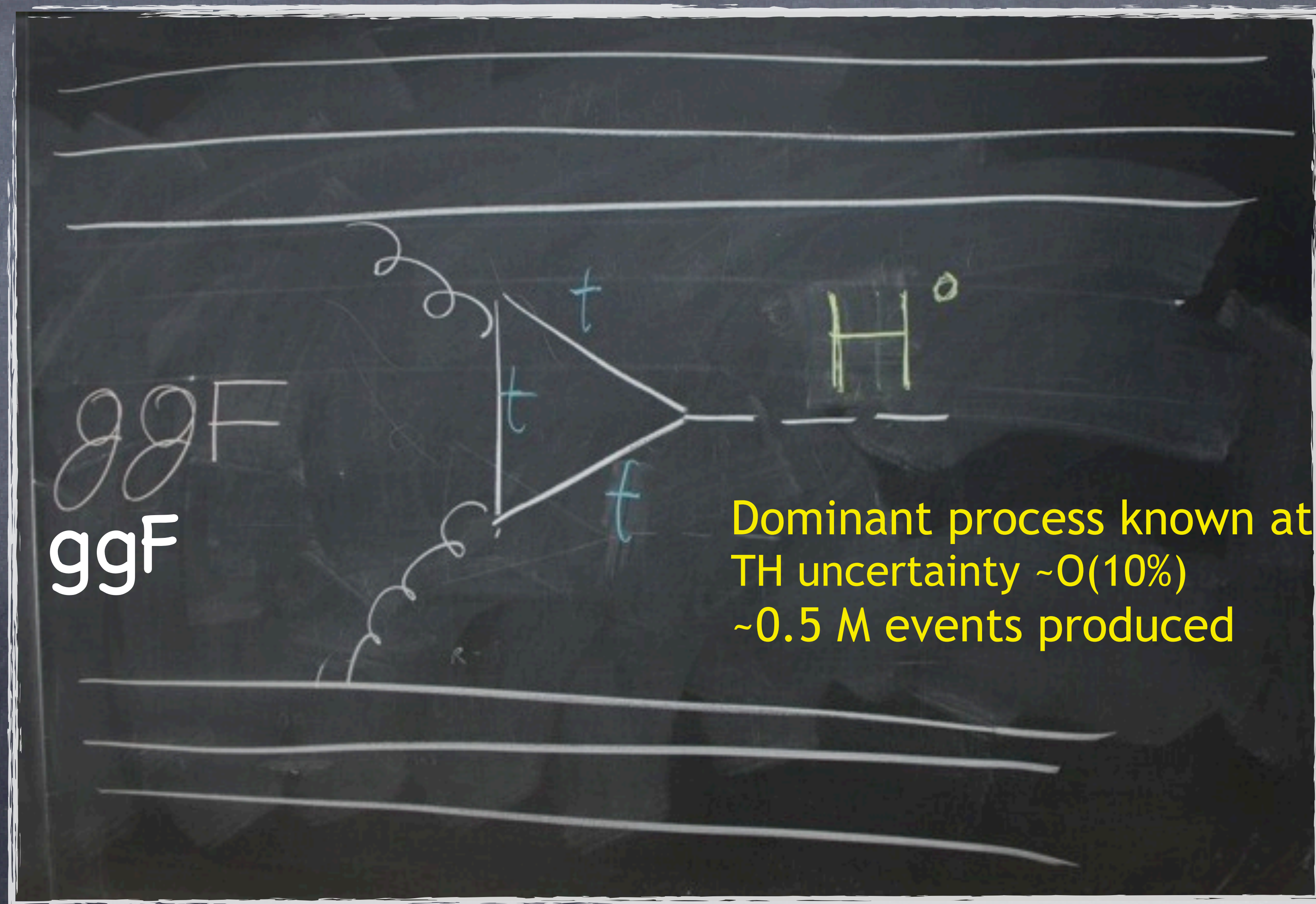
27 fb^{-1} at the price of large pile-up





Higgs Production @ the LHC

- Higgs hardly couples to u & d quarks (which make protons)
- To produce a Higgs Boson in P-P collisions 4 processes are used: ggF, VBF, Associate Production and ttH



Dominant process known at NNLO
TH uncertainty ~O(10%)
~0.5 M events produced

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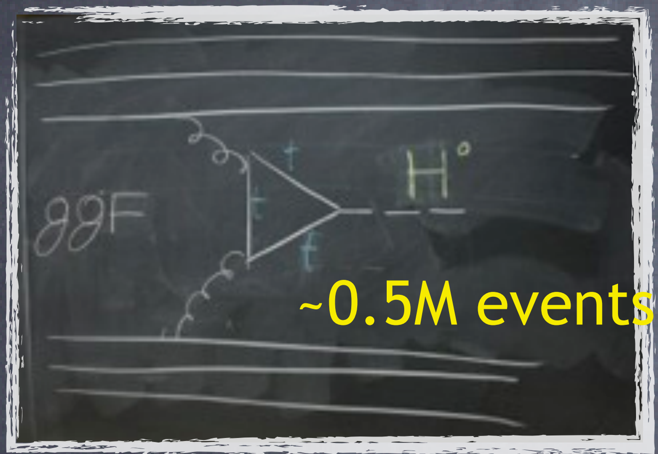

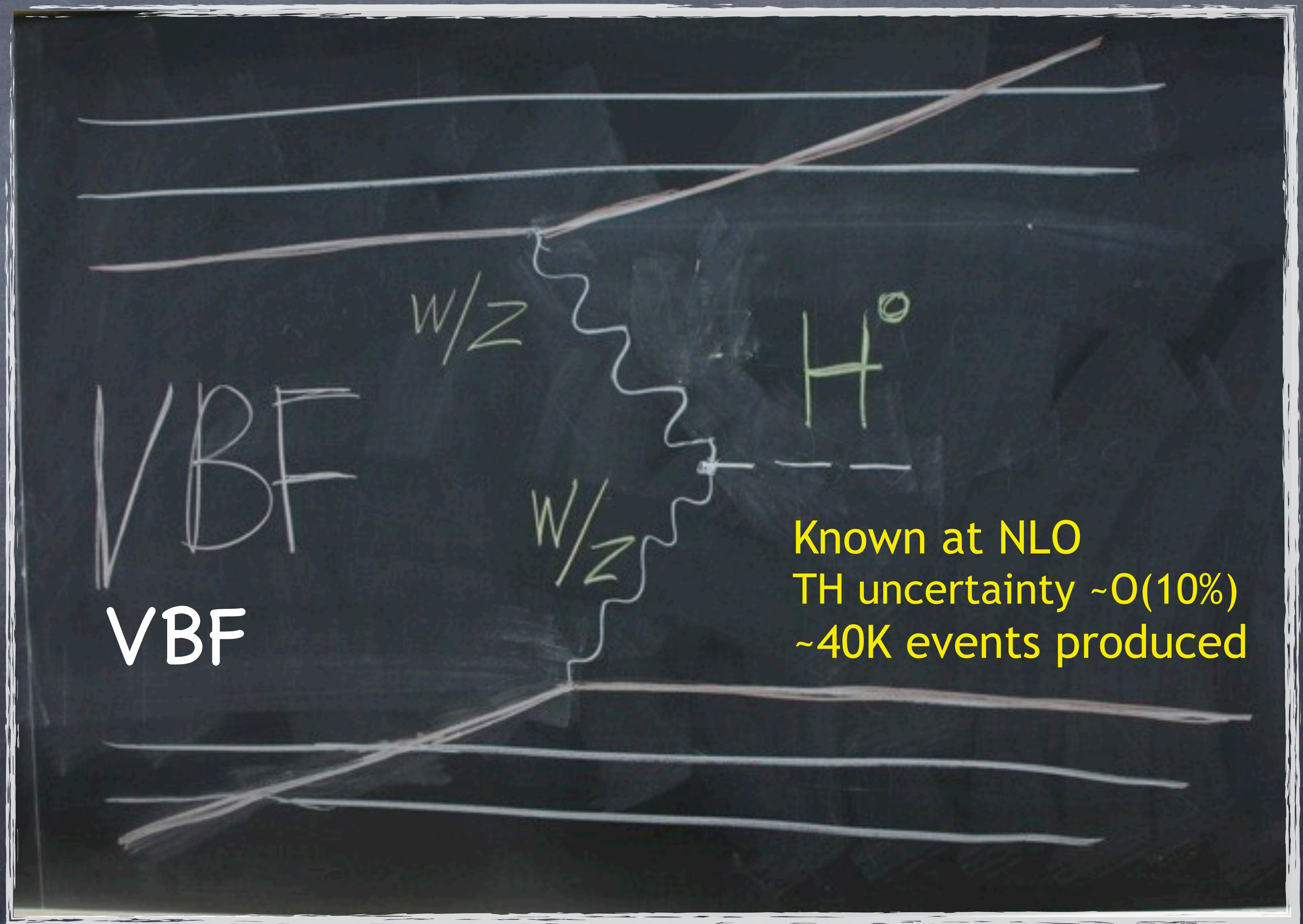

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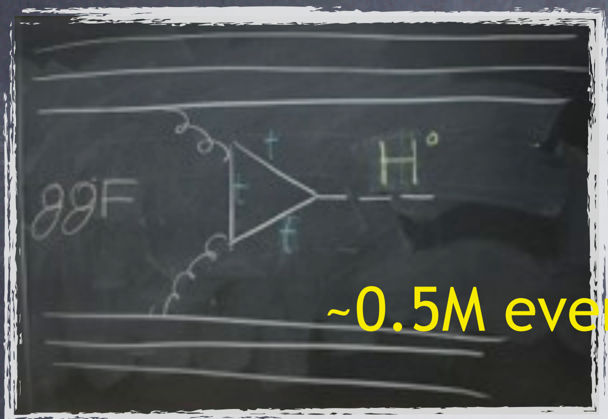

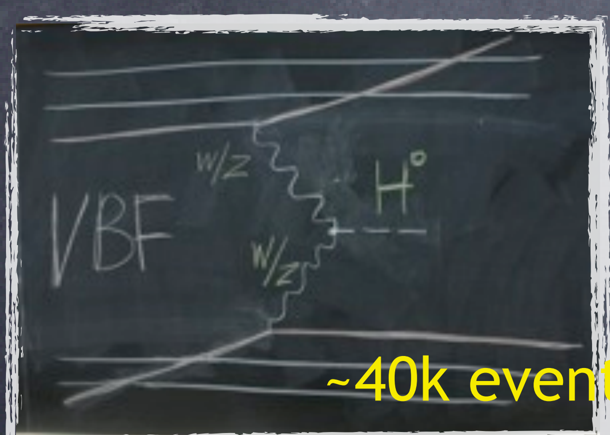

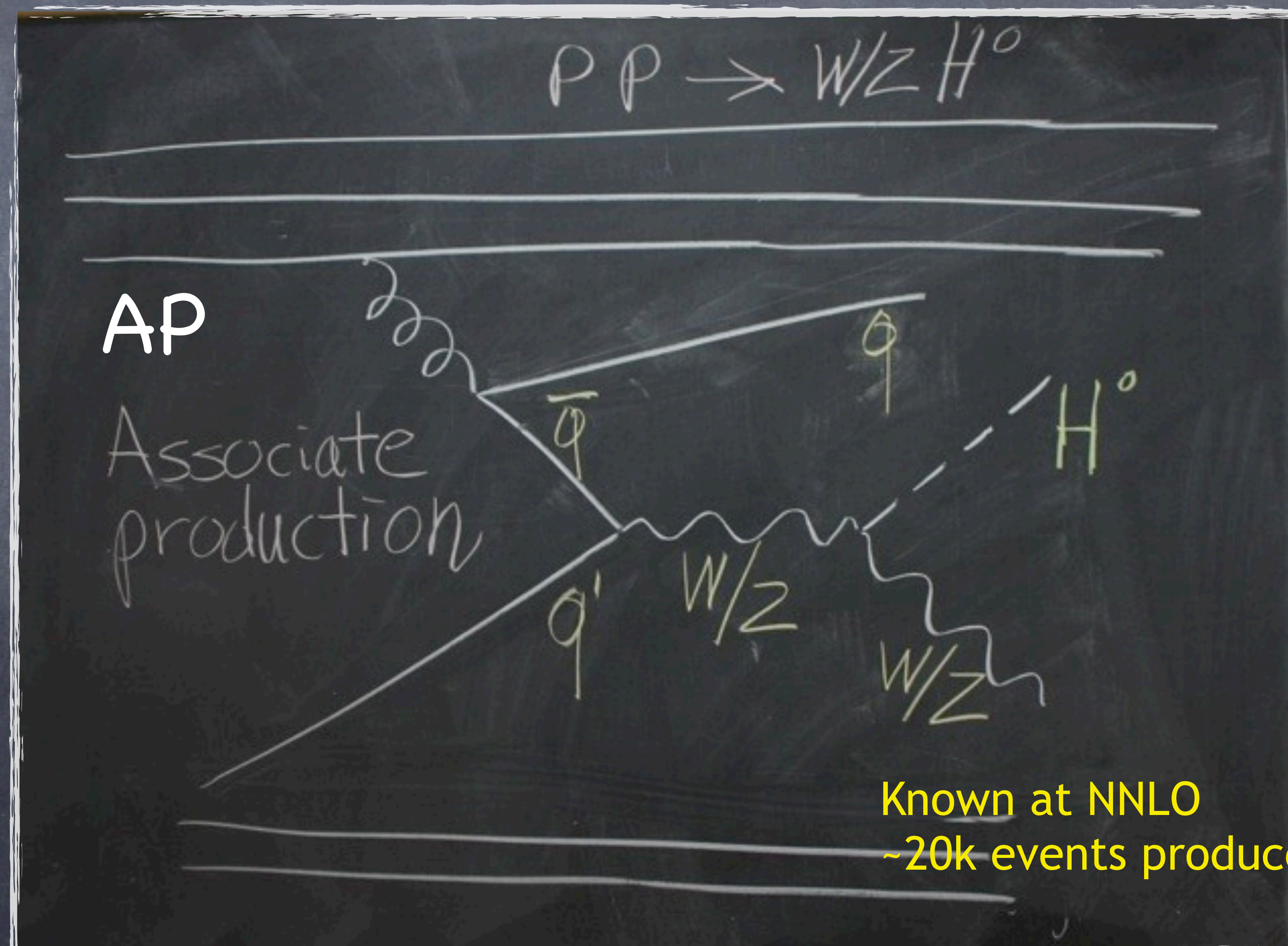

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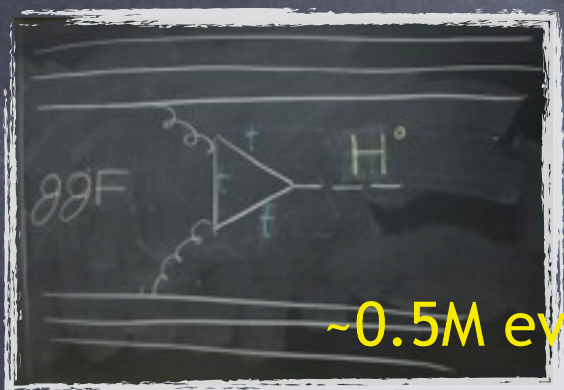
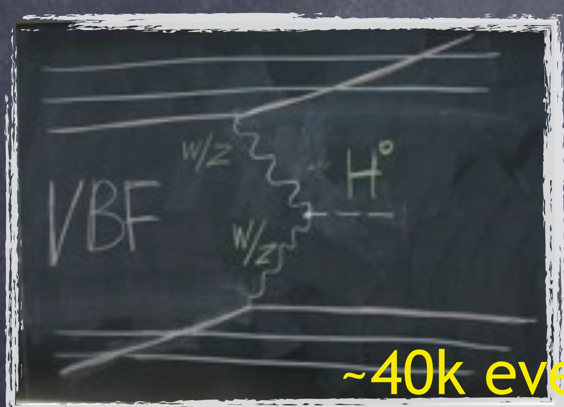
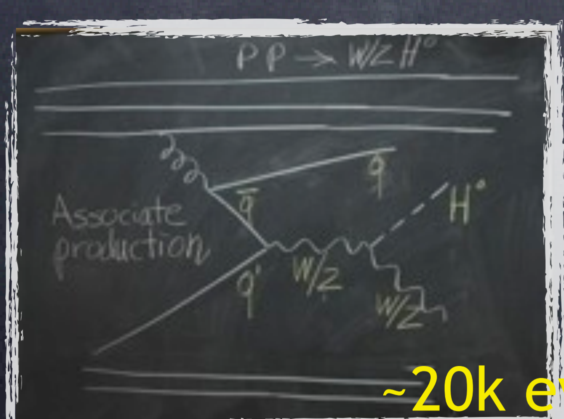


~0.5M events

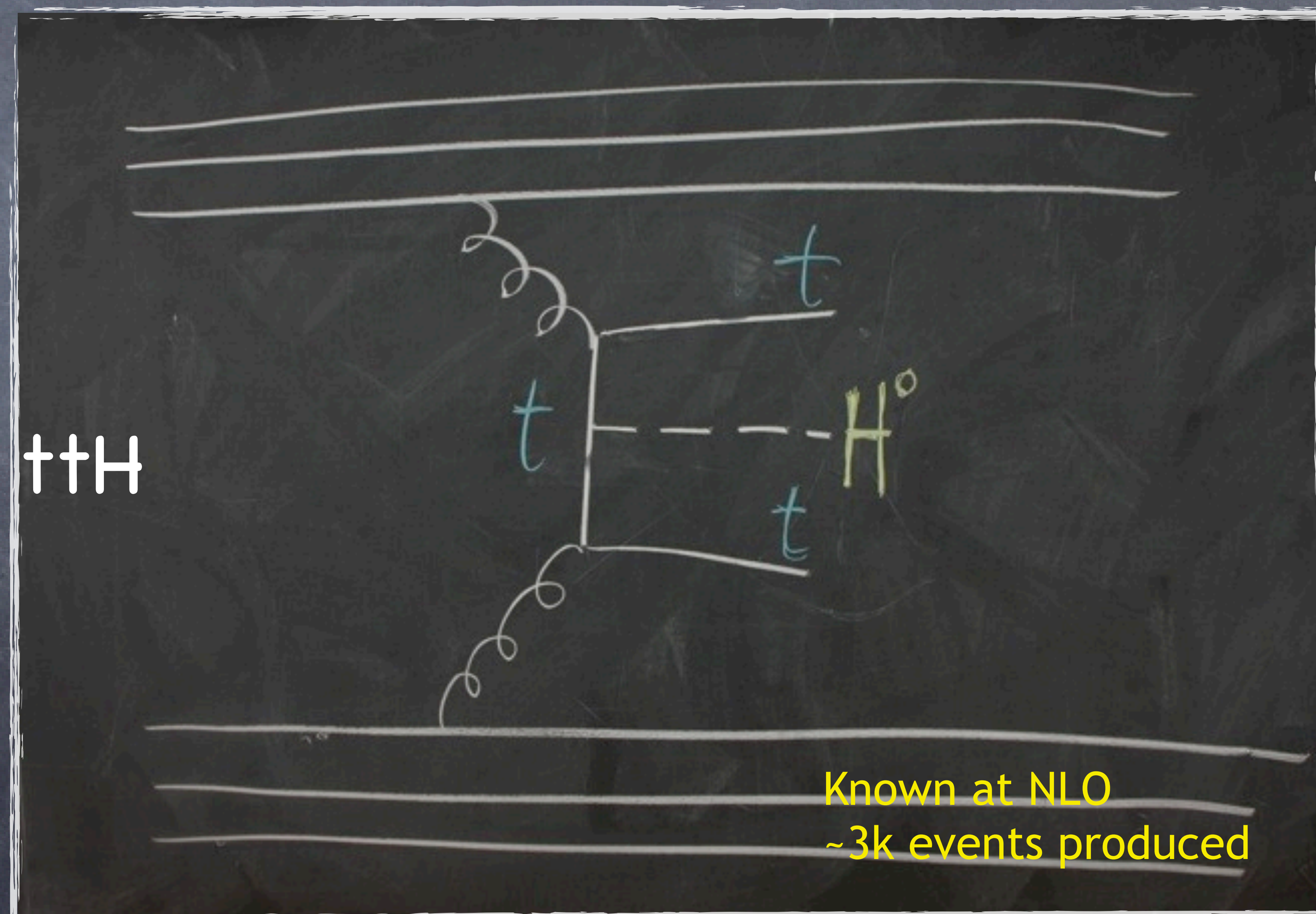


~40k events



~20k events

ttH



Known at NLO

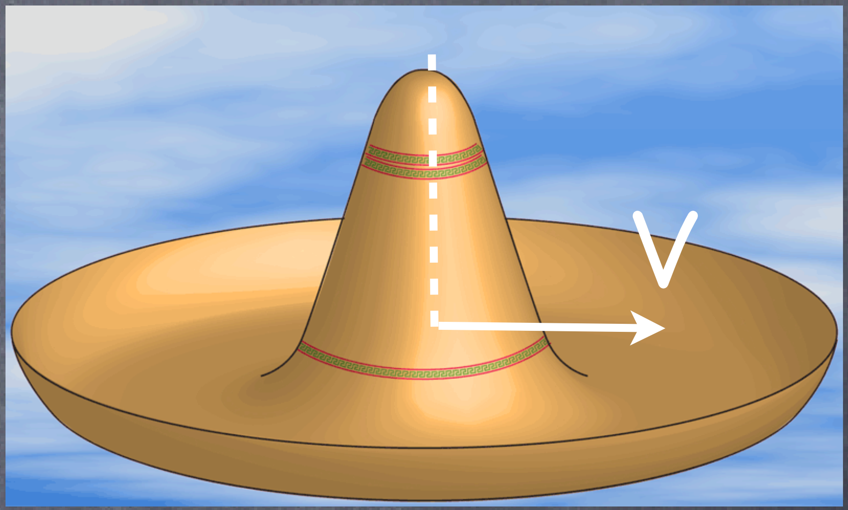
~3k events produced

How Elementary Particles Acquire Mass

- A mass term is given by $m\bar{\psi}_L \psi_R$
- Only left handed fields carry weak charge.
- Via SSB the Higgs field "charges" the vacuum with a weak charge and the symmetry is preserved ("hidden")

$$g_{H\psi} H_L \bar{\psi}_L \psi_R -> g_{H\psi} \langle H_L \rangle \bar{\psi}_L \psi_R = g_{H\psi} \mathrm{v} \bar{\psi}_L \psi_R$$

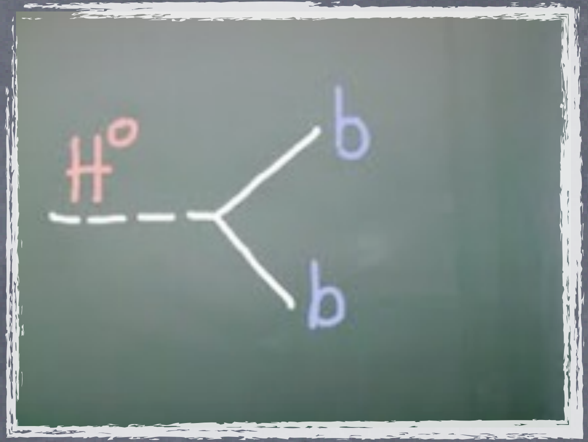
$$m_\psi = g_{H\psi} \mathrm{v}, \qquad g_{H\psi} = \frac{m_\psi}{\mathrm{v}}$$

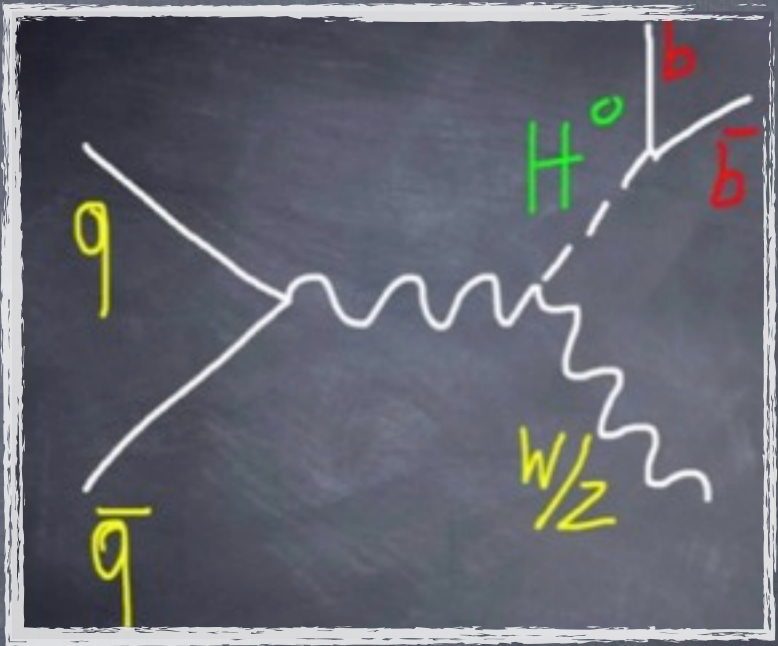


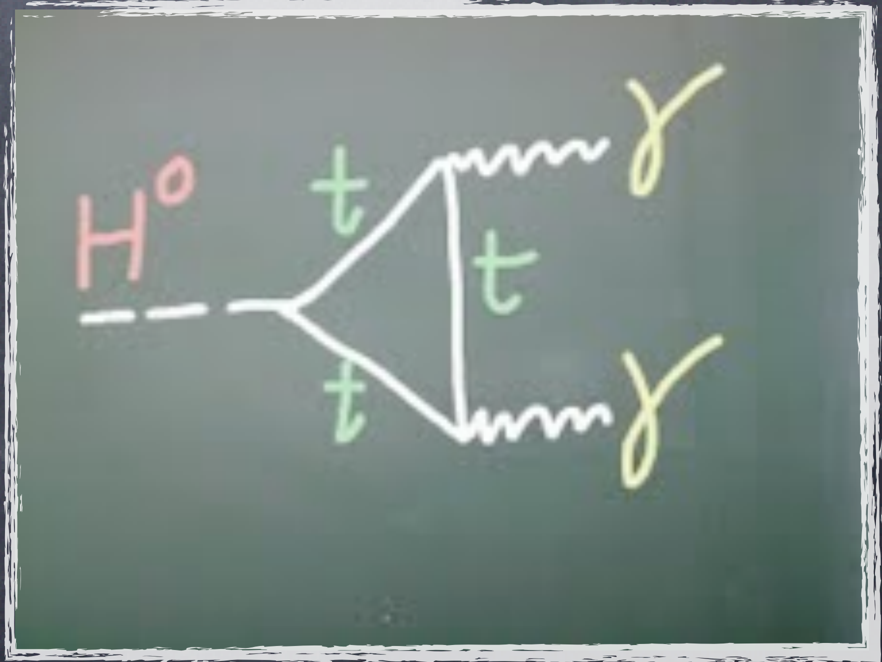
- The coupling of the Higgs to particles is proportional to the particles' mass
- The Higgs Boson will therefore decay with a higher probability to the heaviest particle kinematically available

Higgs Decay Modes

- The Higgs Boson couples stronger to the heaviest kinematically available particles pair
- A light Higgs (mH~125 GeV) decays to ττ and mainly to a pair of bottom Quarks (bb)
- But H->bb is hard to detect or trigger on (only via its association with a W or a Z)
- Leptons (electrons or muons) and photons are easy to trigger on and detect.
- Though BR(H->gamma gamma)~10^{-3}, H->gamma gamma is the favorite experimental channel for a Higgs with mH~110-130







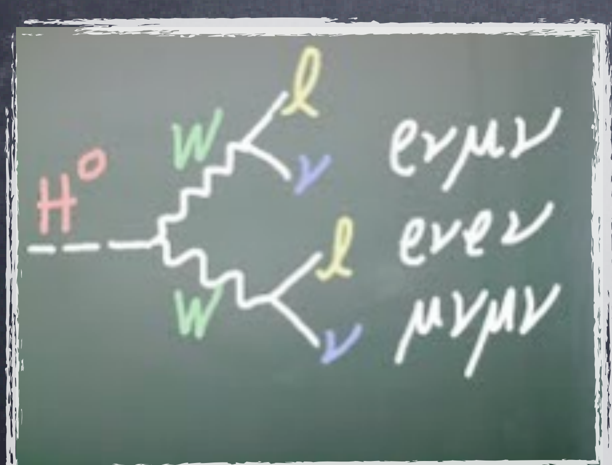
Higgs Decay Modes

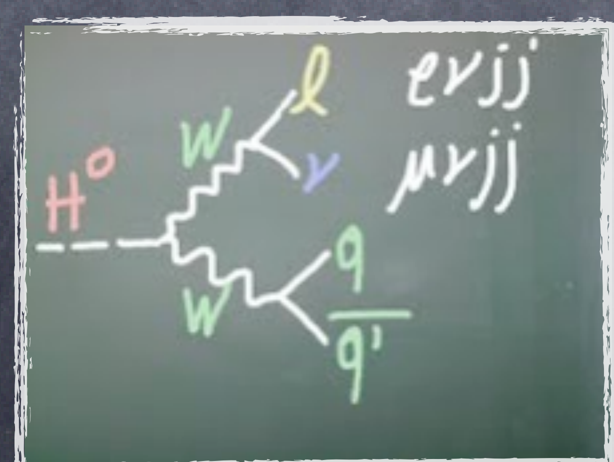
- Once the Z and W channels are open (mH>120) it decays to ZZ* and WW*

- The Higgs decay modes are classified according to the decays of the daughter bosons, thus the main decay modes are

- the golden channel 4l=4 leptons

- and other WW or ZZ channels





m_H=125 GeV Channels Weight

$$w_i \simeq \frac{\left(s_i/\sqrt{s_i+b_i}\right)^2}{\sum_i \left(s_i/\sqrt{s_i+b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

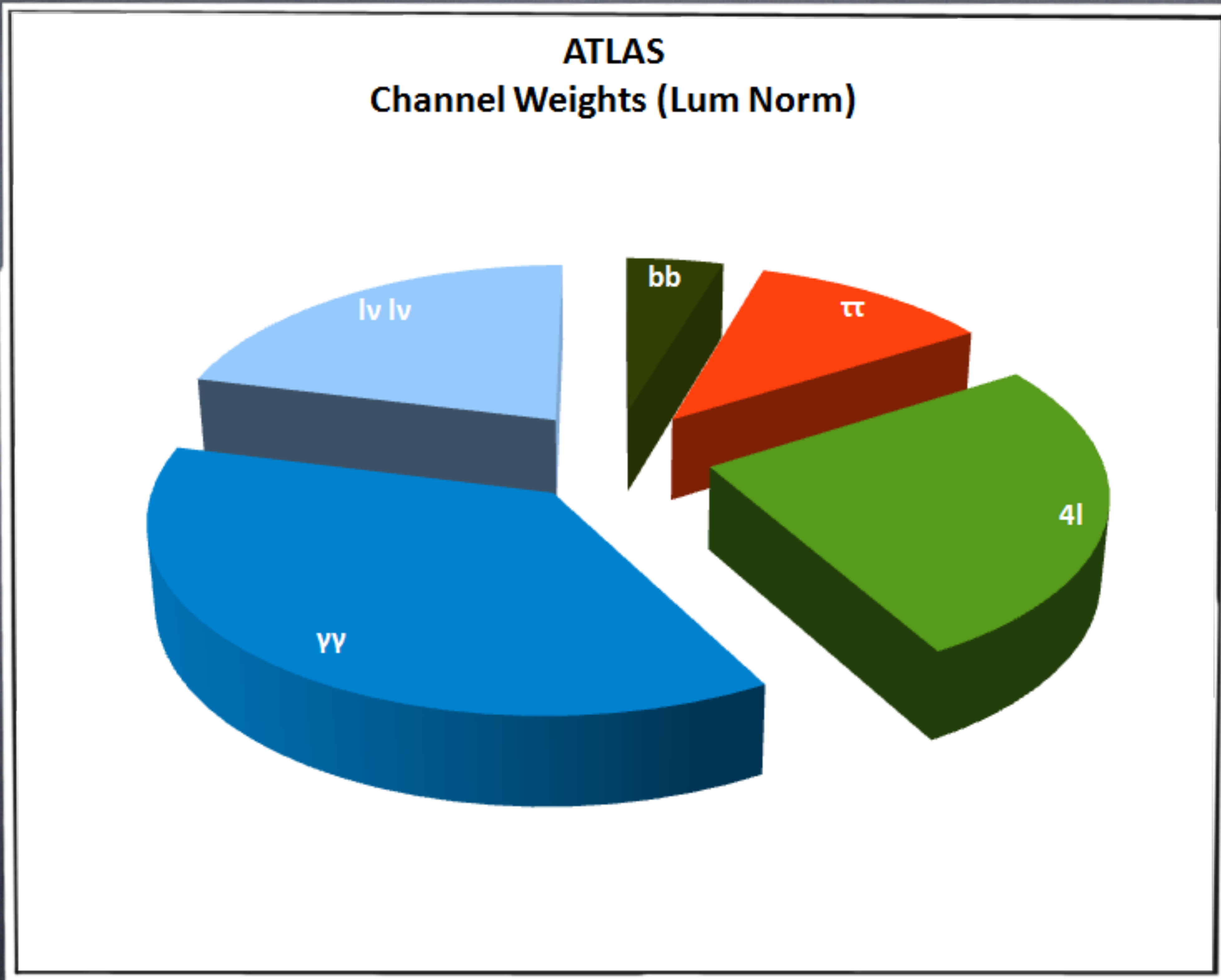
H-> $\gamma\ \gamma$

H->4l

H->WW->lvlv

VH-> Vbb,

H-> $\tau\ \tau$



H->γγ the "grey" became gold

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

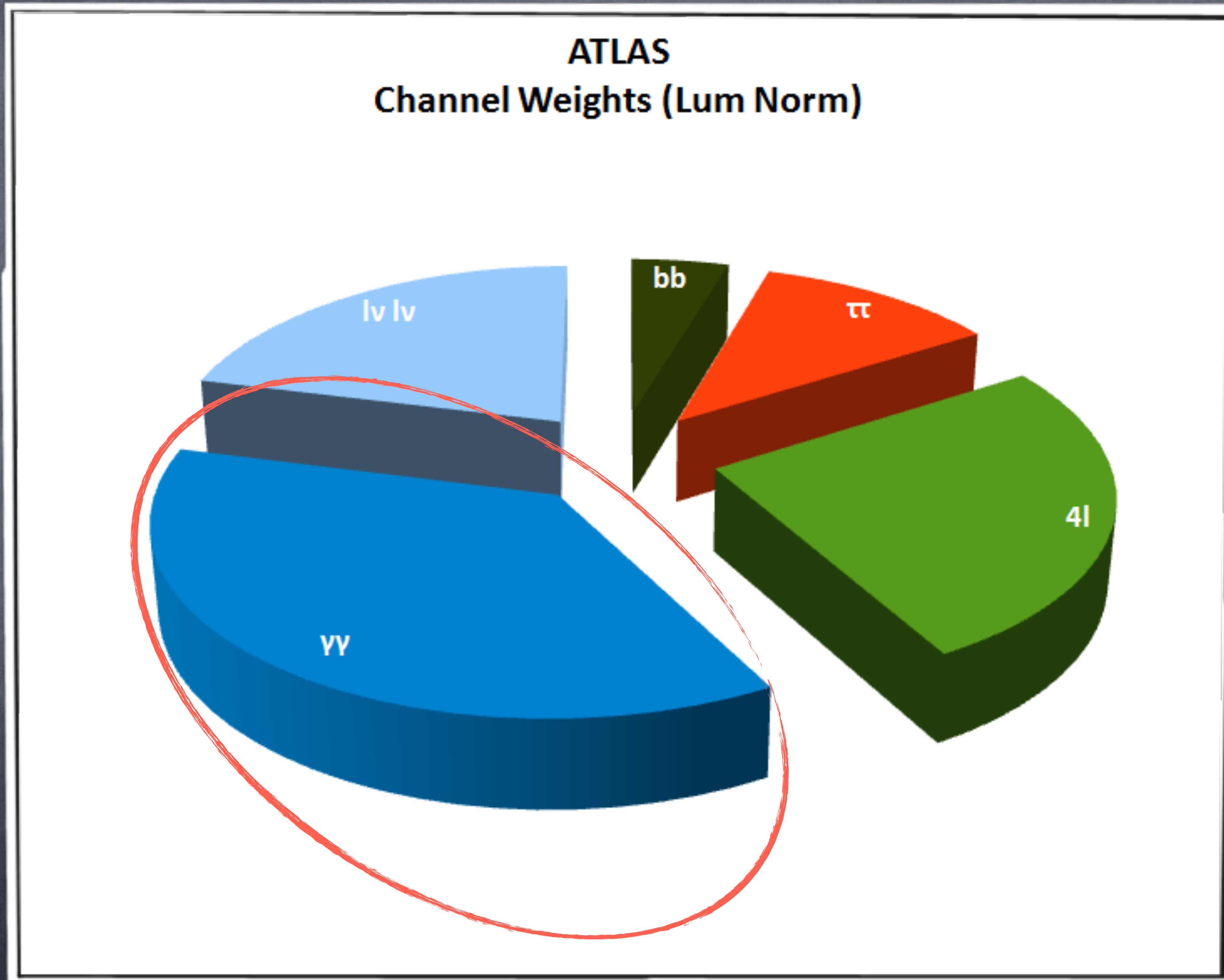
H-> γ γ

H->4l

H->WW->lvlv

VH-> Vbb,

H-> τ τ



H->γγ

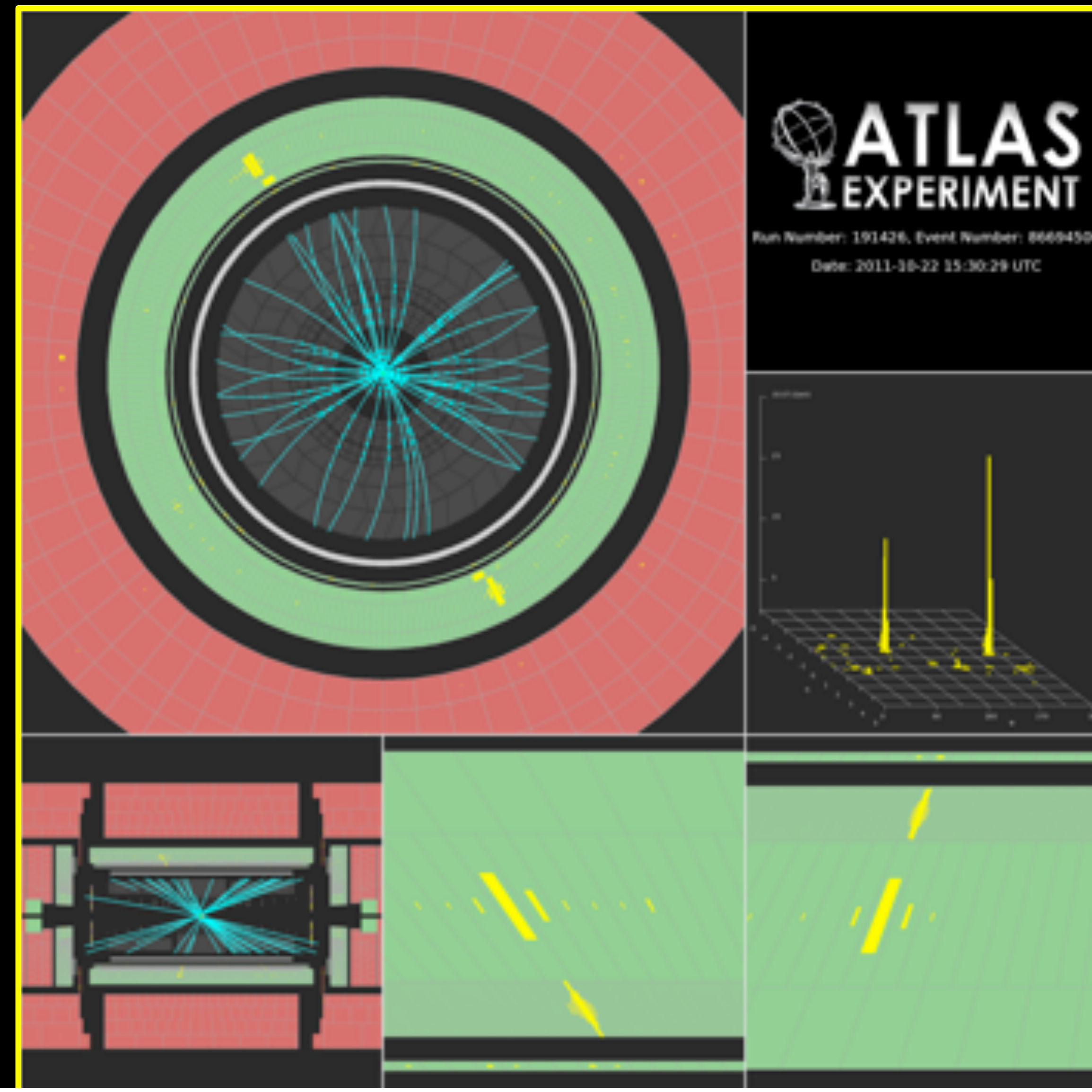
Clean signature: 2 energetic isolated photons->narrow mass peak

E^T (γ1, γ2) > 40, 30 GeV

A narrow peak is searched for over a large, smooth background.

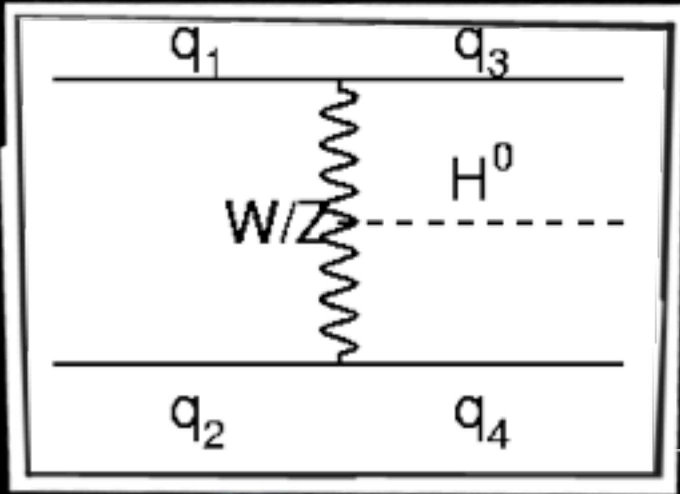
σxBR~50fb

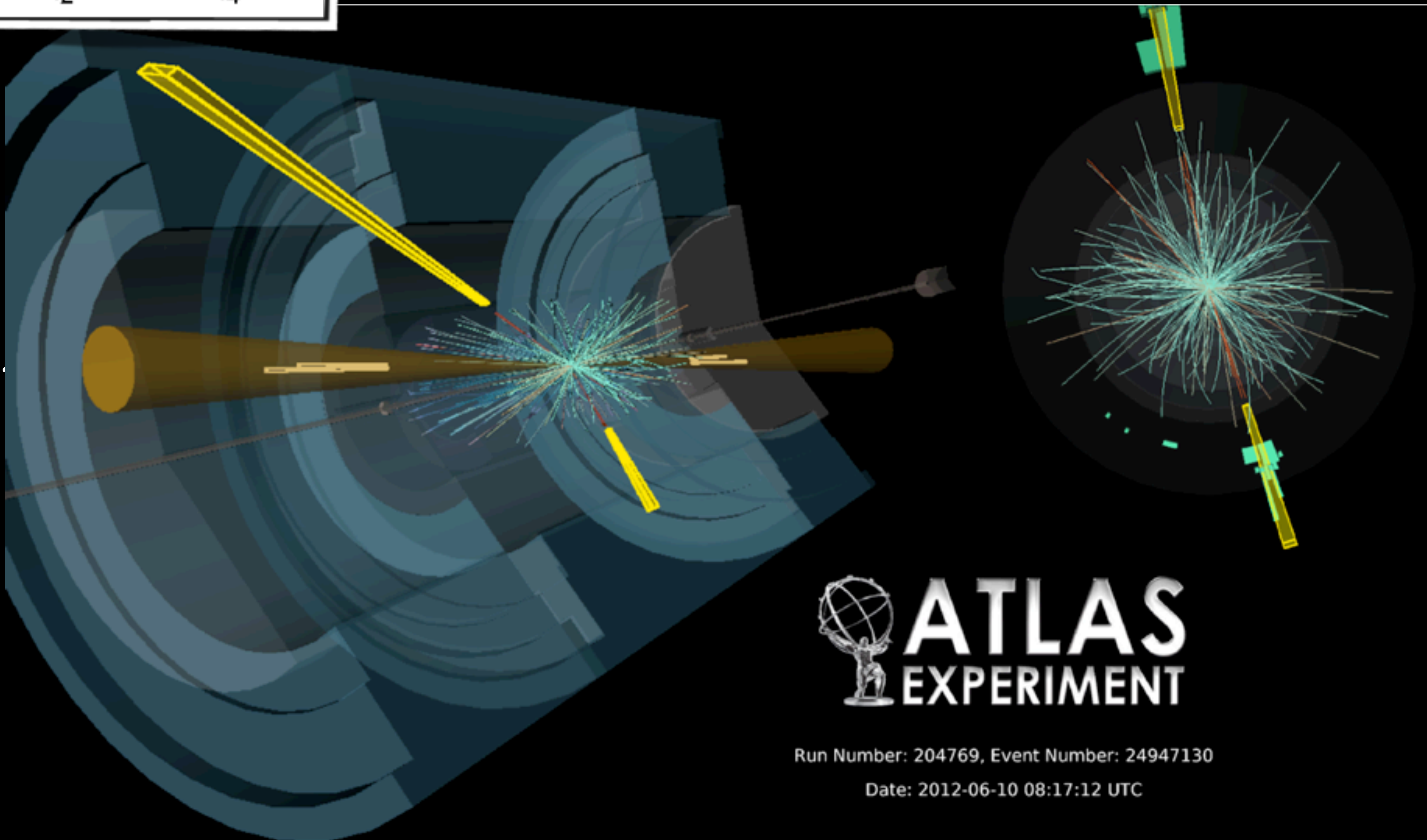
@ mH=125



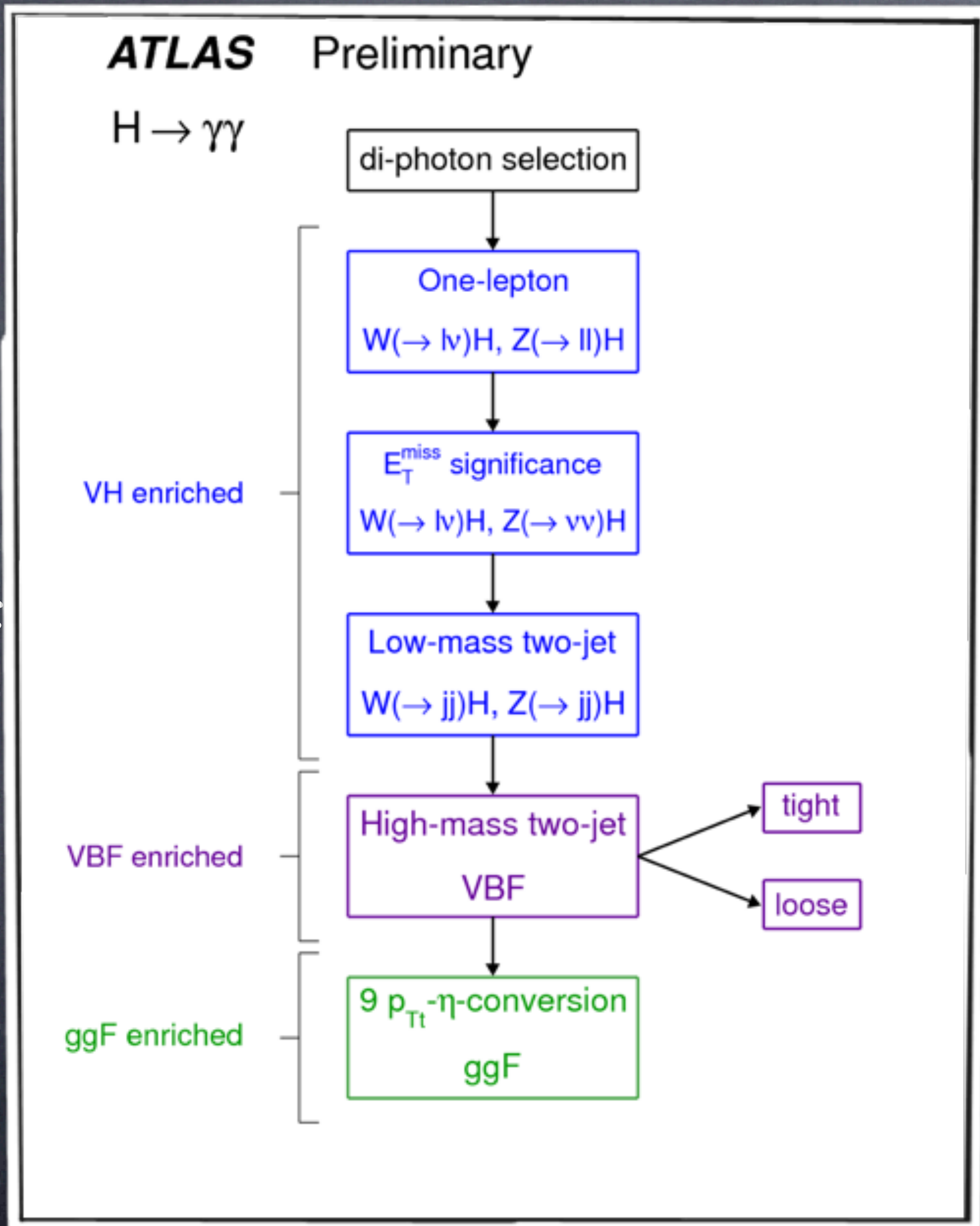
Prod	Luminosity	BG	Signal @8TeV (126.5 GeV)	s/b
ggF, VBF, VH	4.9+20.7 fb^{-1}	γγ,jj,γj	~2-100 (total ~355)	2%-57%

VBF candidate



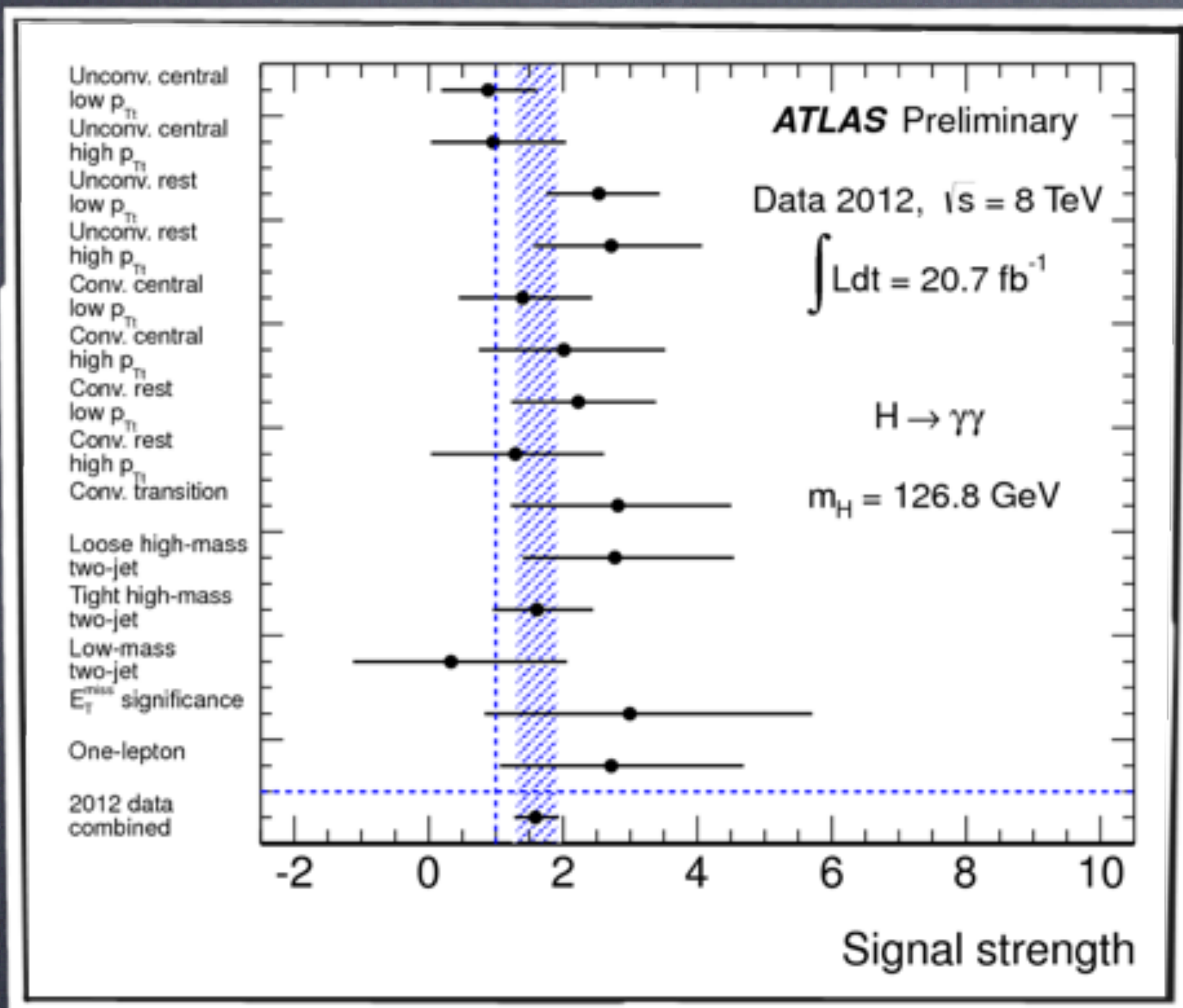


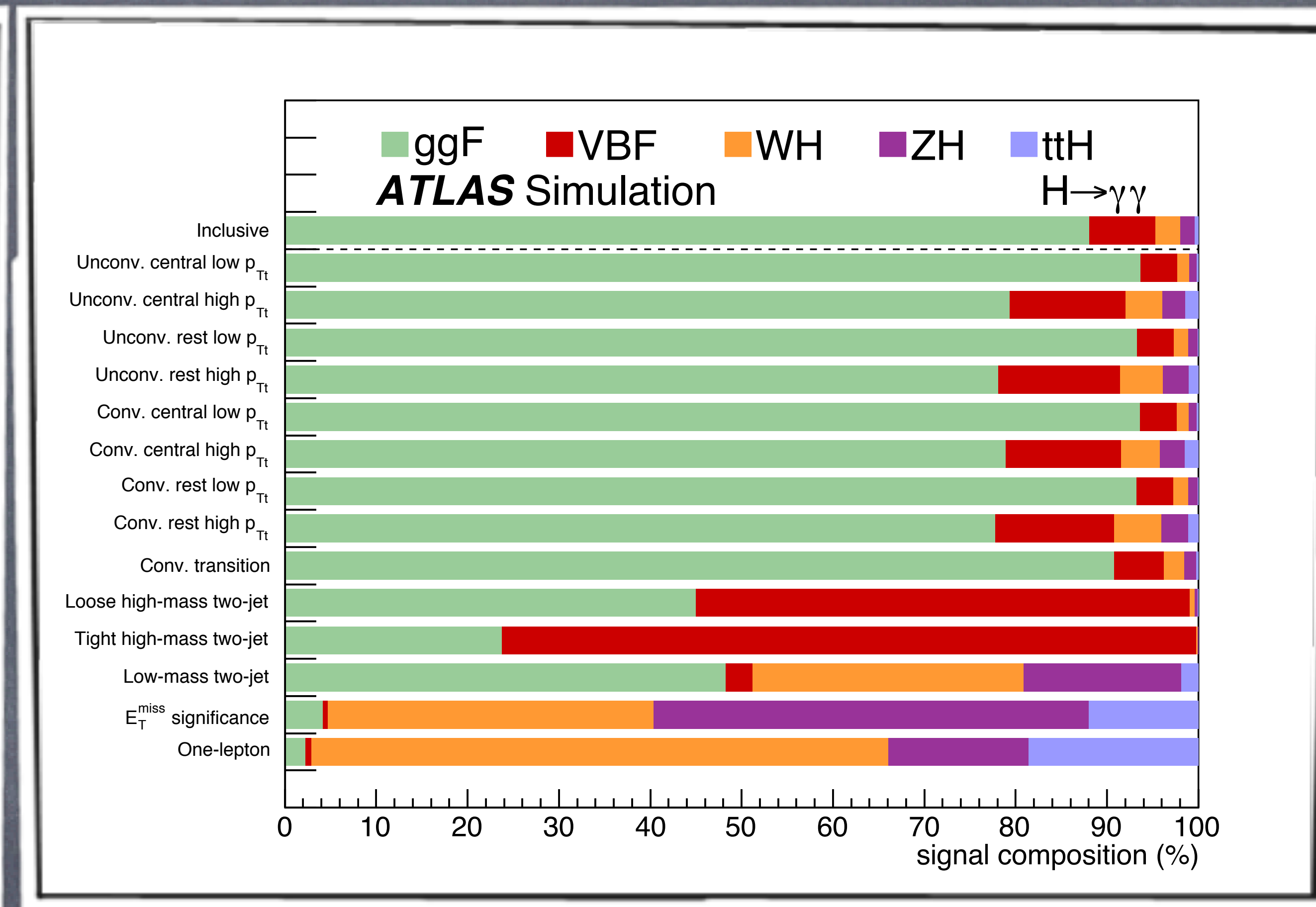
H->γγ Categories



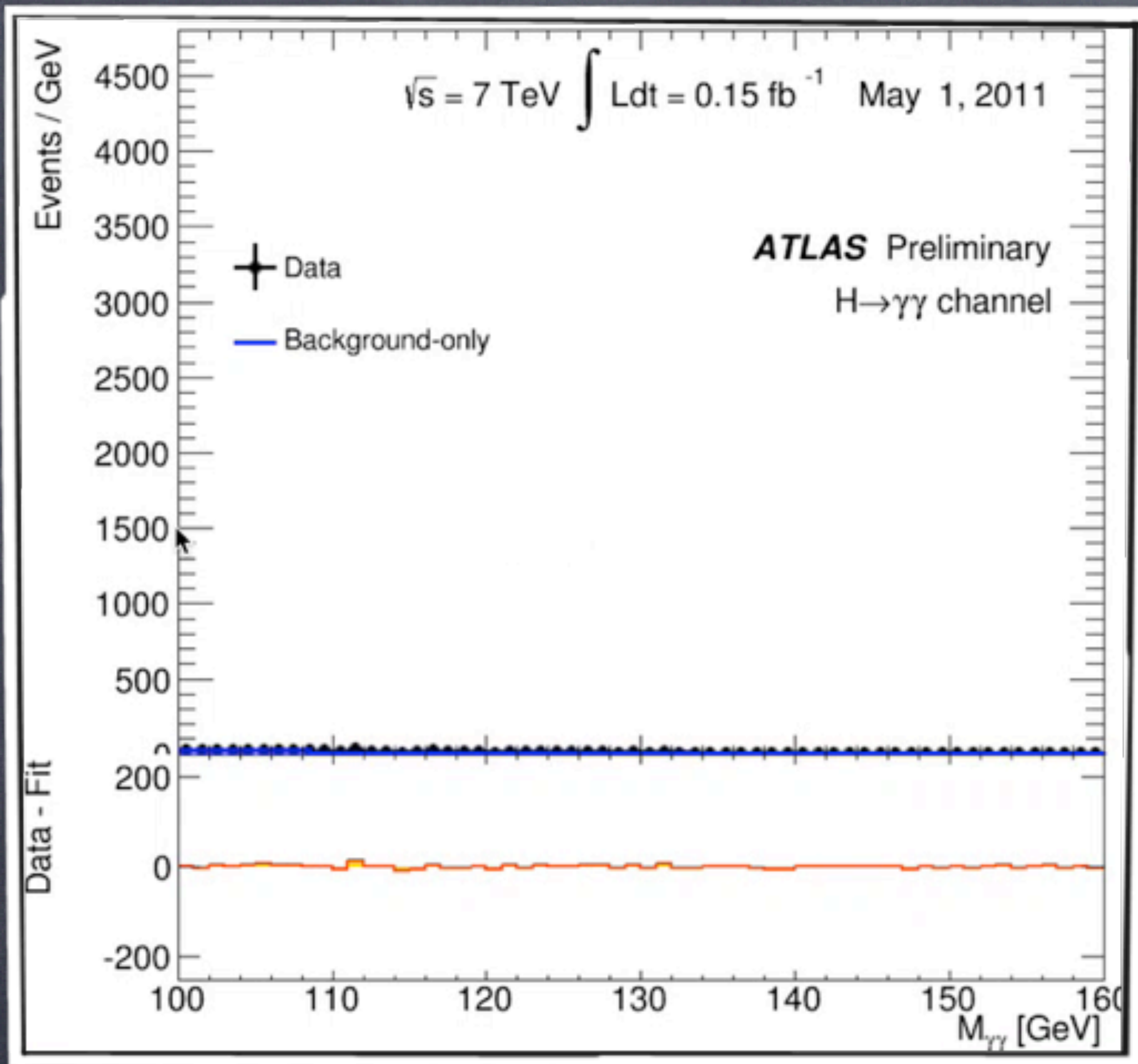
Tight BDT ≥ 0.74

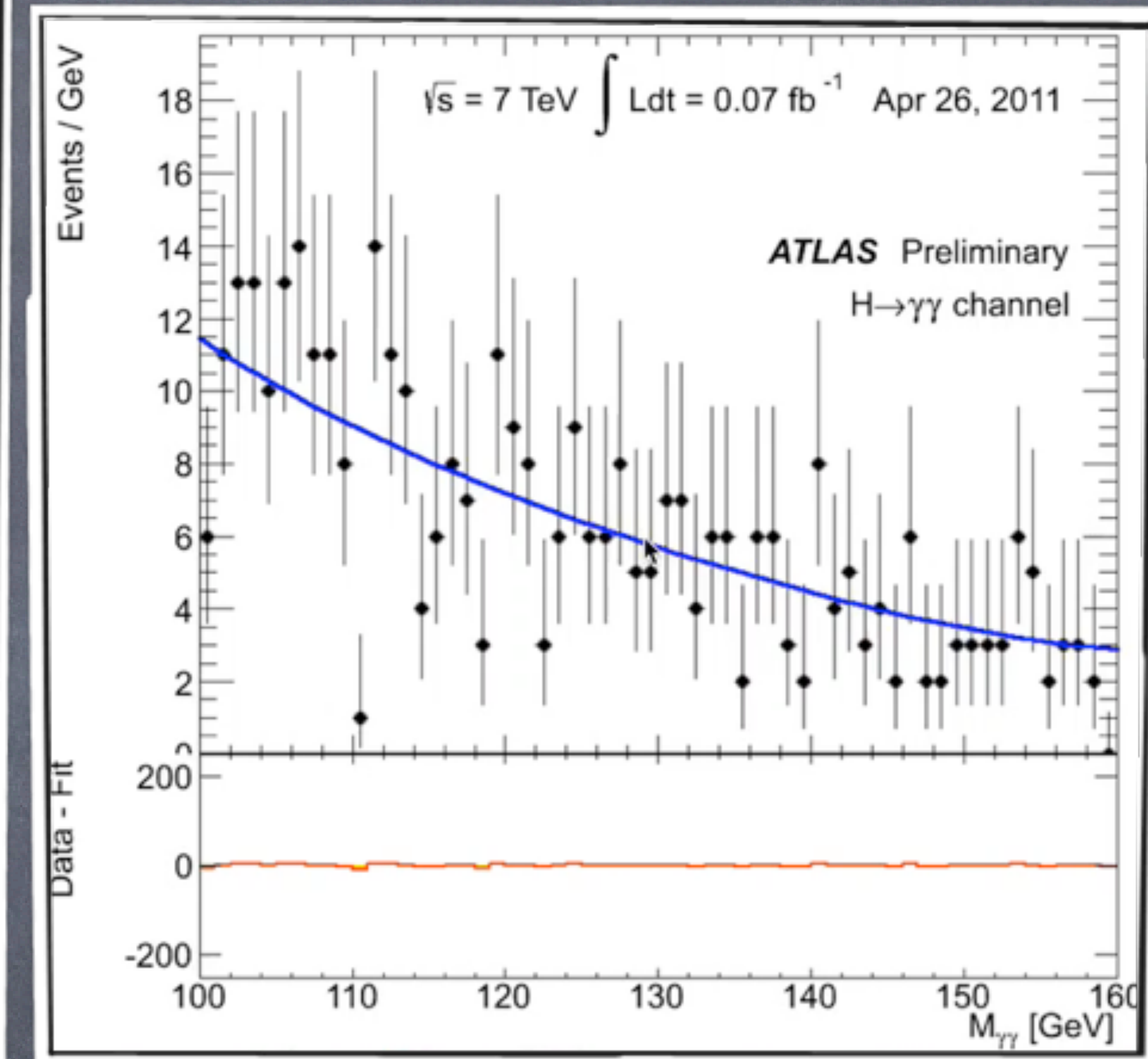
Loose 0.44 < BDT < 0.74


ATLAS Preliminary
Data 2012, √s = 8 TeV
∫Ldt = 20.7 fb⁻¹
H → γγ
m_H = 126.8 GeV
Unconv. central low p_Tt
Unconv. central high p_Tt
Unconv. rest low p_Tt
Unconv. rest high p_Tt
Conv. central low p_Tt
Conv. central high p_Tt
Conv. rest low p_Tt
Conv. rest high p_Tt
Conv. transition
Loose high-mass two-jet
Tight high-mass two-jet
Low-mass two-jet
E_T^miss significance
One-lepton
2012 data combined
Signal strength


ggF
VBF
WH
ZH
ttH
ATLAS Simulation
H→γγ
Inclusive
Unconv. central low p_Tt
Unconv. central high p_Tt
Unconv. rest low p_Tt
Unconv. rest high p_Tt
Conv. central low p_Tt
Conv. central high p_Tt
Conv. rest low p_Tt
Conv. rest high p_Tt
Conv. transition
Loose high-mass two-jet
Tight high-mass two-jet
Low-mass two-jet
E_T^miss significance
One-lepton
signal composition (%)

Birth of a New Particle ($\gamma\gamma$)

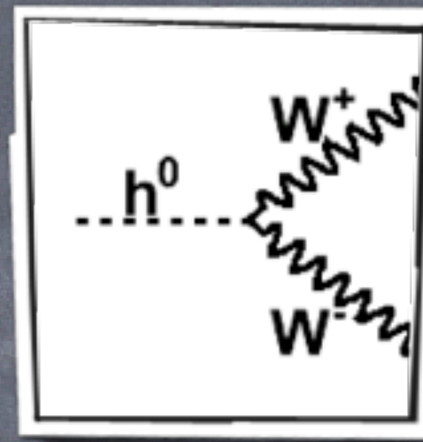




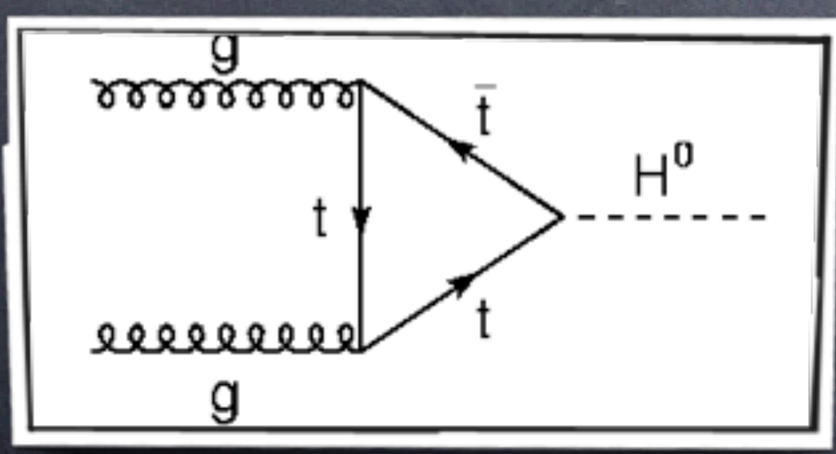
$$n_s^{\,i} = \sum_{\text{Production mode k}} \mu^k \sigma_{SM}^{\;k} \times Br^i \times Lumi^i$$

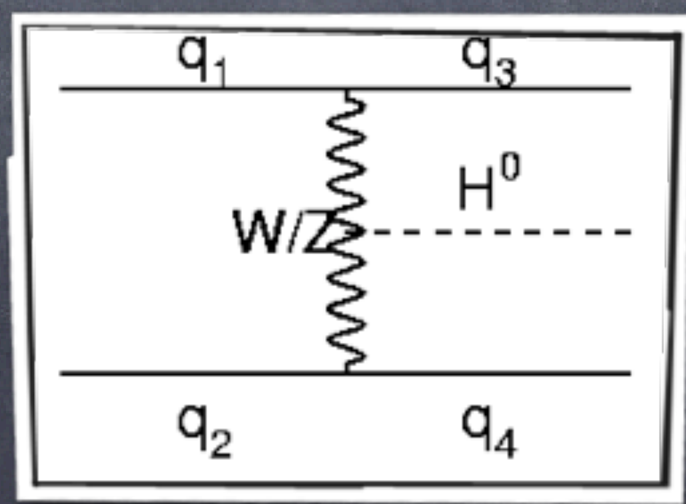
$$\mu^k = \frac{\sigma^k}{\sigma_{SM}^k}$$

$i = \gamma\gamma, 4\ell, WW$ Decay Mode



$k = ggF, VBF$ Production Mode





Discovery p_0

$$q_0 = -2\log\frac{max_{\{b\}}L(b)}{max_{\{\mu,b\}}L(\mu s(m_H)+b)}$$

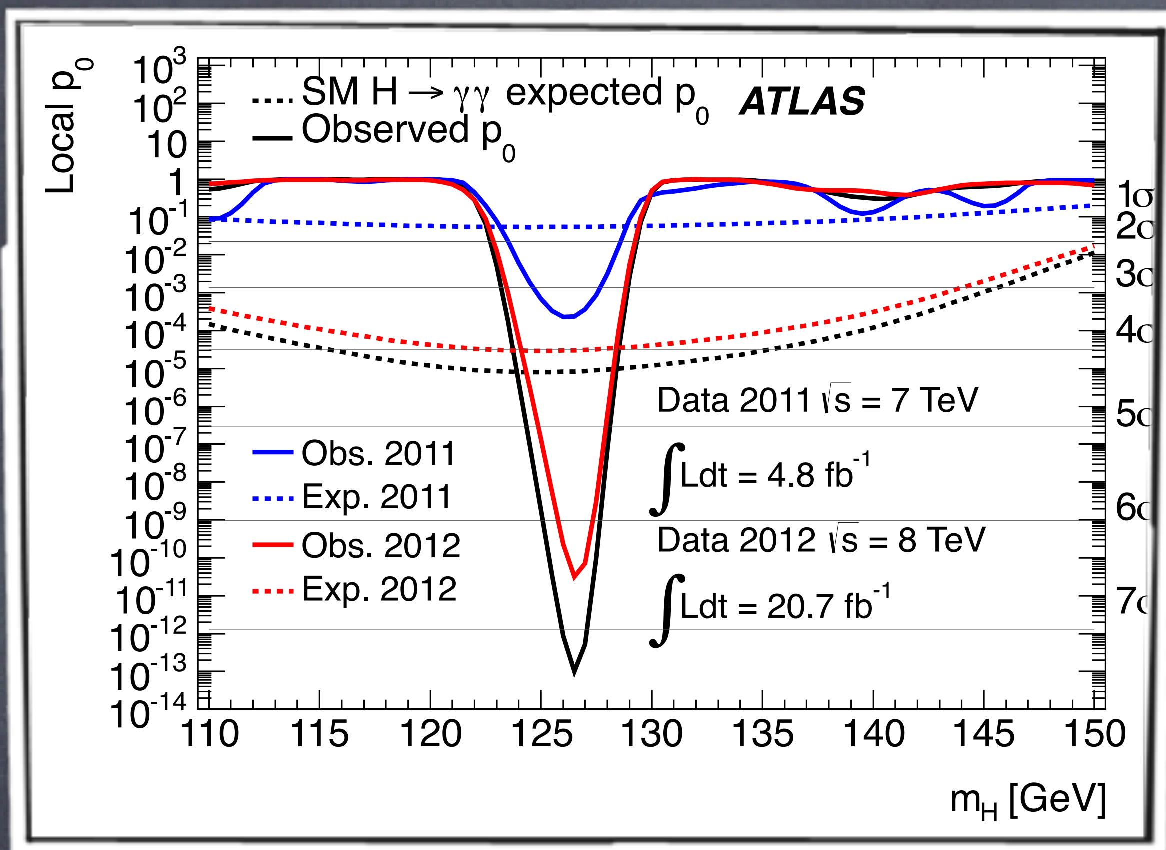
->p_0 measures the compatibility of the data with the NO-HIGGS hypothesis.

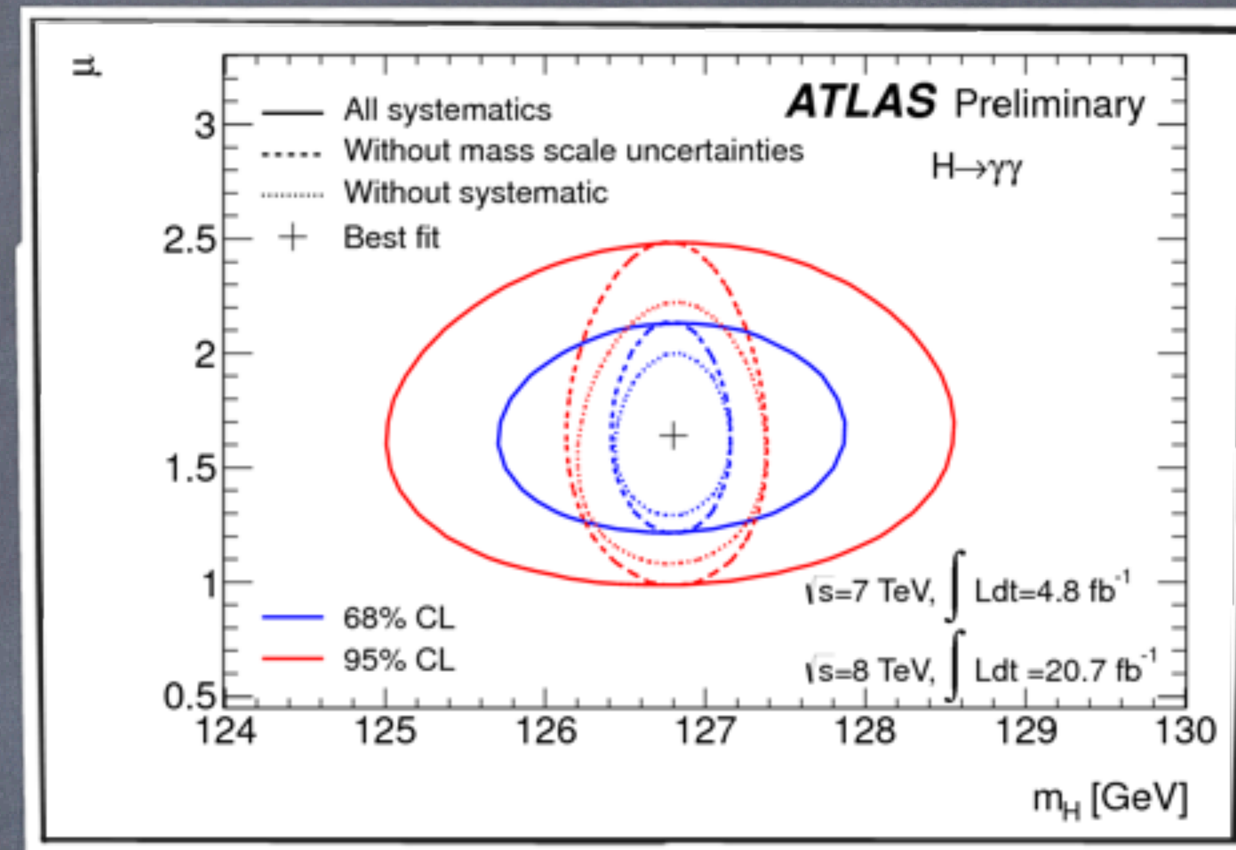
$$p_0 = Prob(q_0 > q_0^{obs} \mid H_0)$$

->If p_0=0.025 the NO-HIGGS hypothesis is rejected at the 2σ level (coin is head ~3 times consequently)

->If $p_0=2.8\cdot 10^{-7}$ the NO-HIGGS hypothesis is rejected at the 5σ level (coin is head about ~21 times consequently)

γγ p_0 and mass





Observed local significance

7.4 σ (@ 126.5 GeV)

expected 4.1 σ

Best masss fit

$$m_{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst) GeV$$

$$\mu = 1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$$

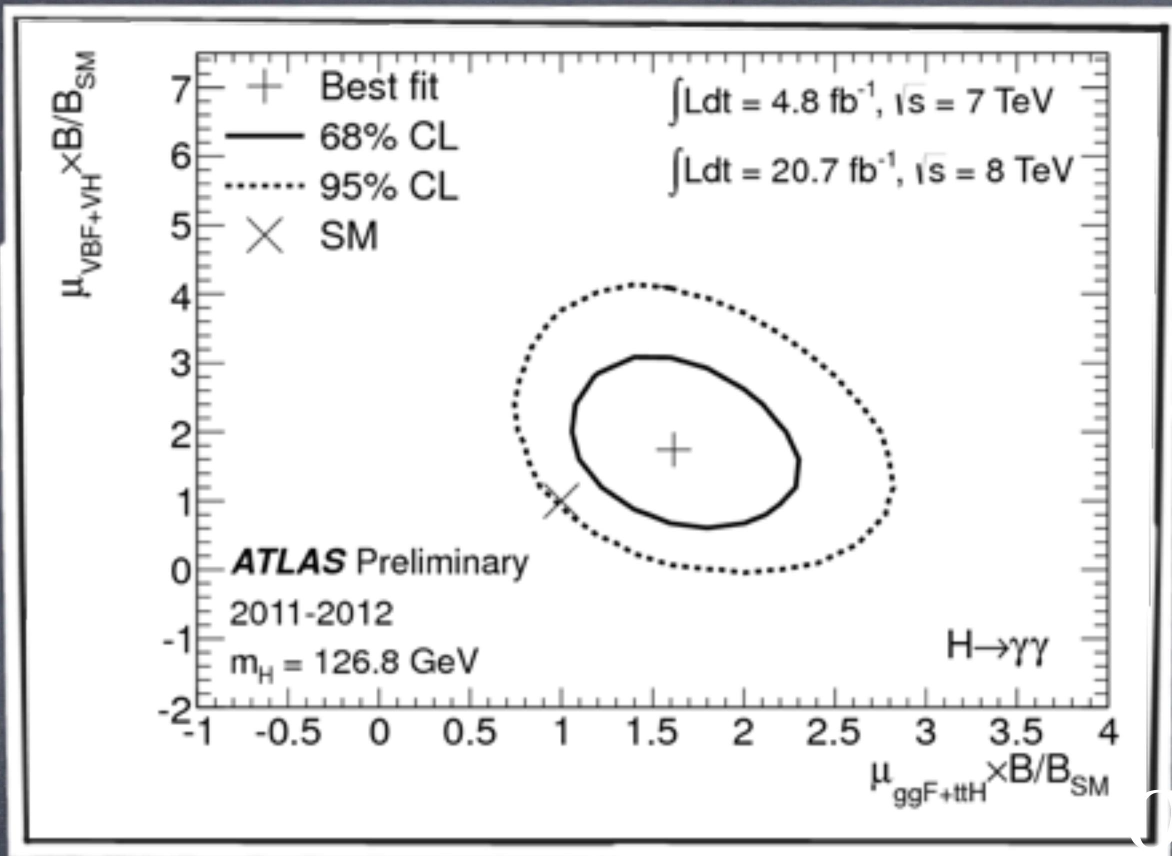
2.3 σ from SM Higgs+BG

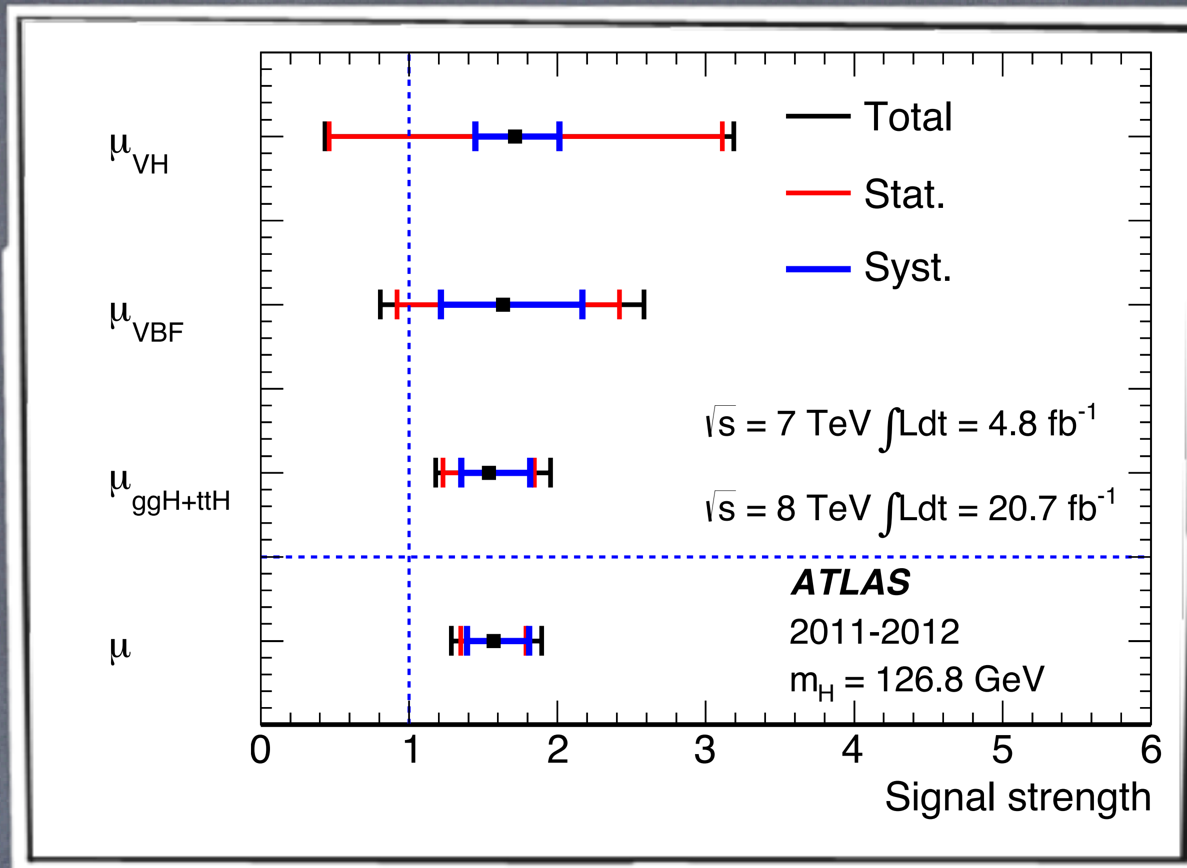
Dominant systematics

Photon Energy Scale

γγ Coupling Studies

$$\psi_s \propto \sum_{i\in\{ggF,VBF,VH,ttH\}} \mu_i(\sigma^i_{SM} Br_{\gamma\gamma}) L\varepsilon_i A_i \psi^i_s$$



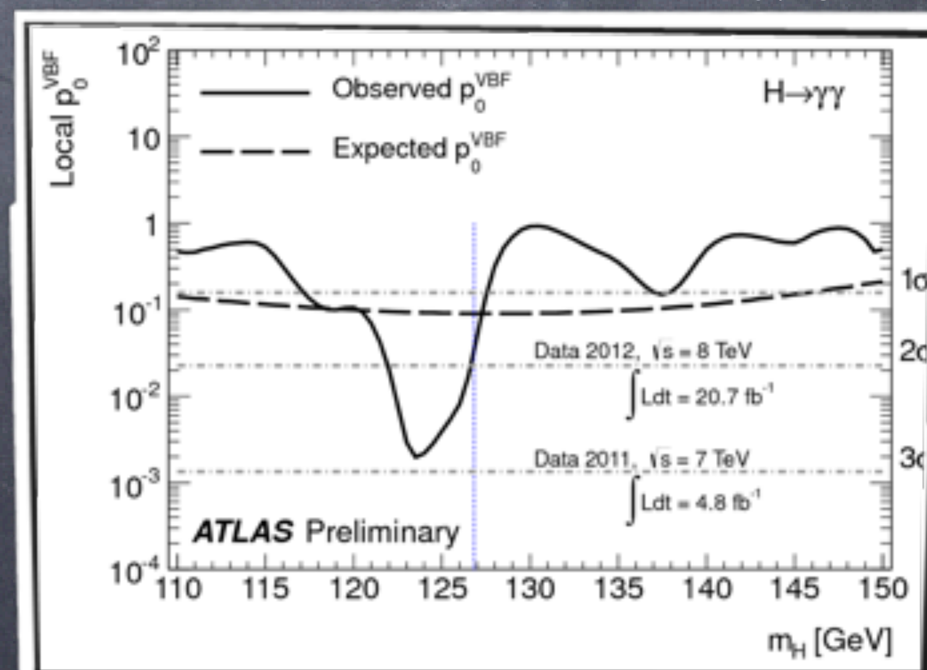


Agreement with SM at 2σ level

$$\mu = 1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$$

The ggF, WH, ZH and ttH processes are considered as background here and their respective signal strengths are treated as nuisance parameters.

Excess for VBF production @126.8 GeV @~ 2σ level



The Golden Channel H->ZZ->4l

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

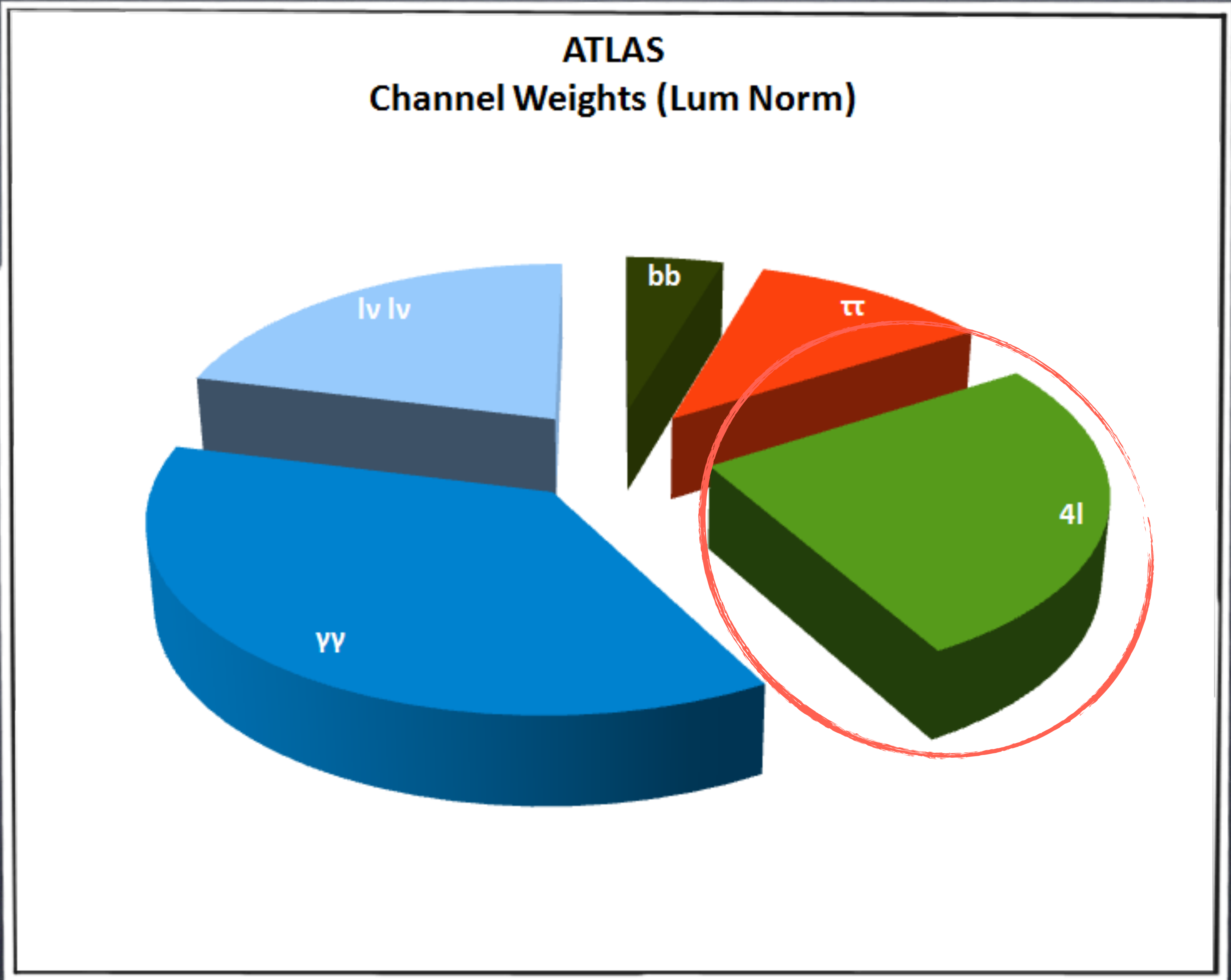
  H-> $\gamma\ \gamma$

  H->4l

  H->WW->lvlv

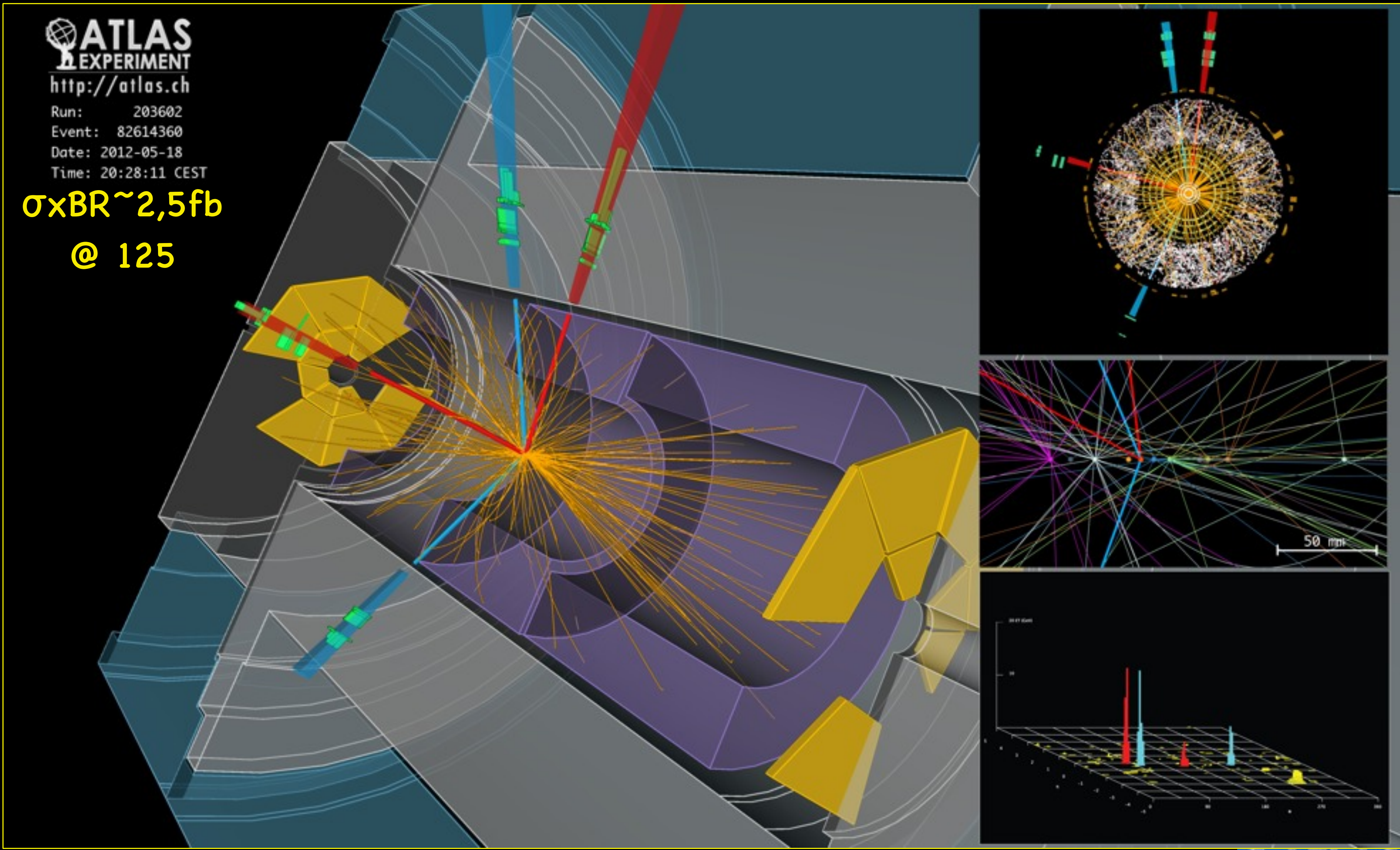
  VH-> Vbb,

  H-> $\tau\ \tau$



4 leptons

4e candidate with mass = 124.5 GeV

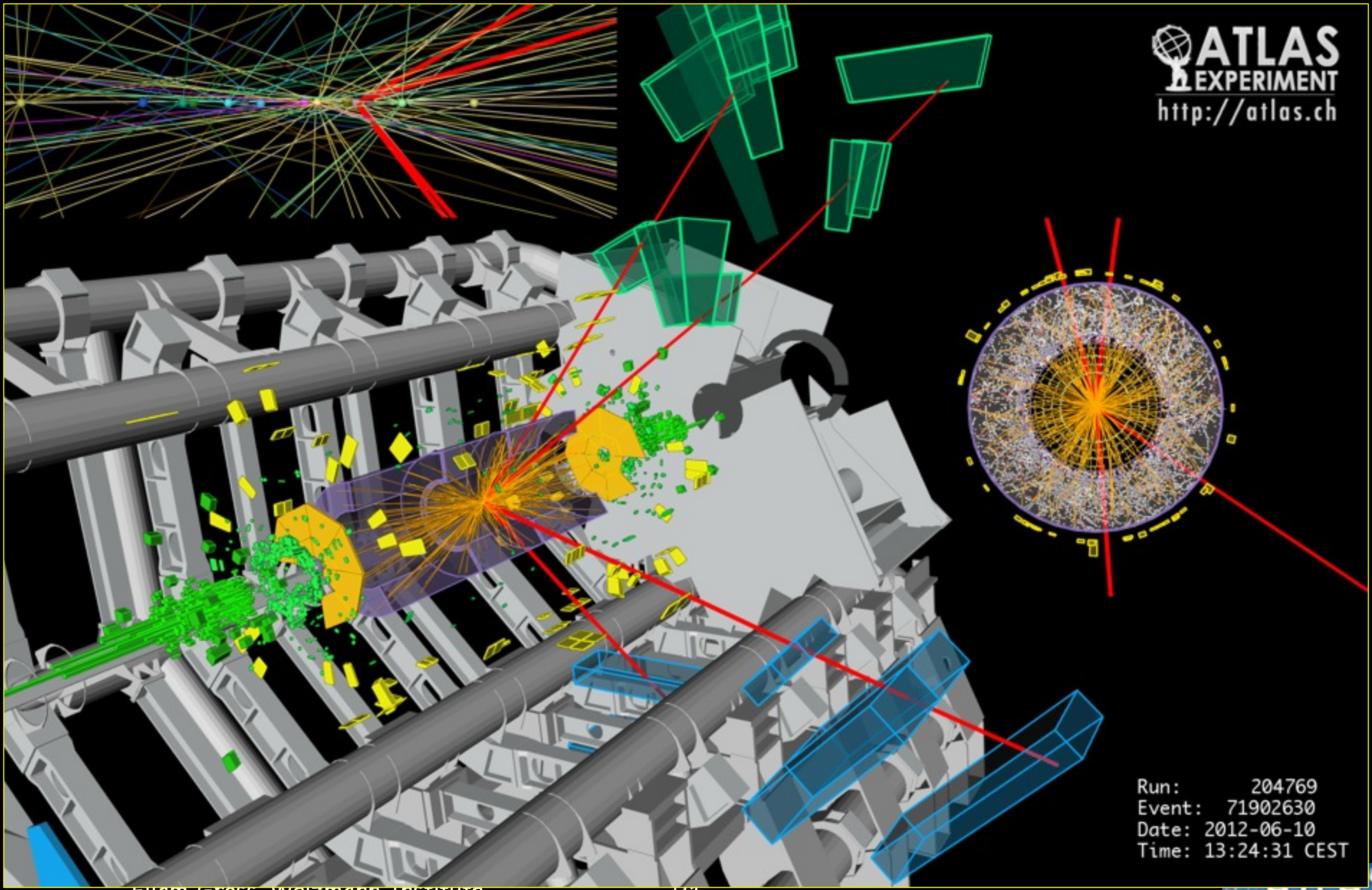


σxBR~2,5fb

@ 125

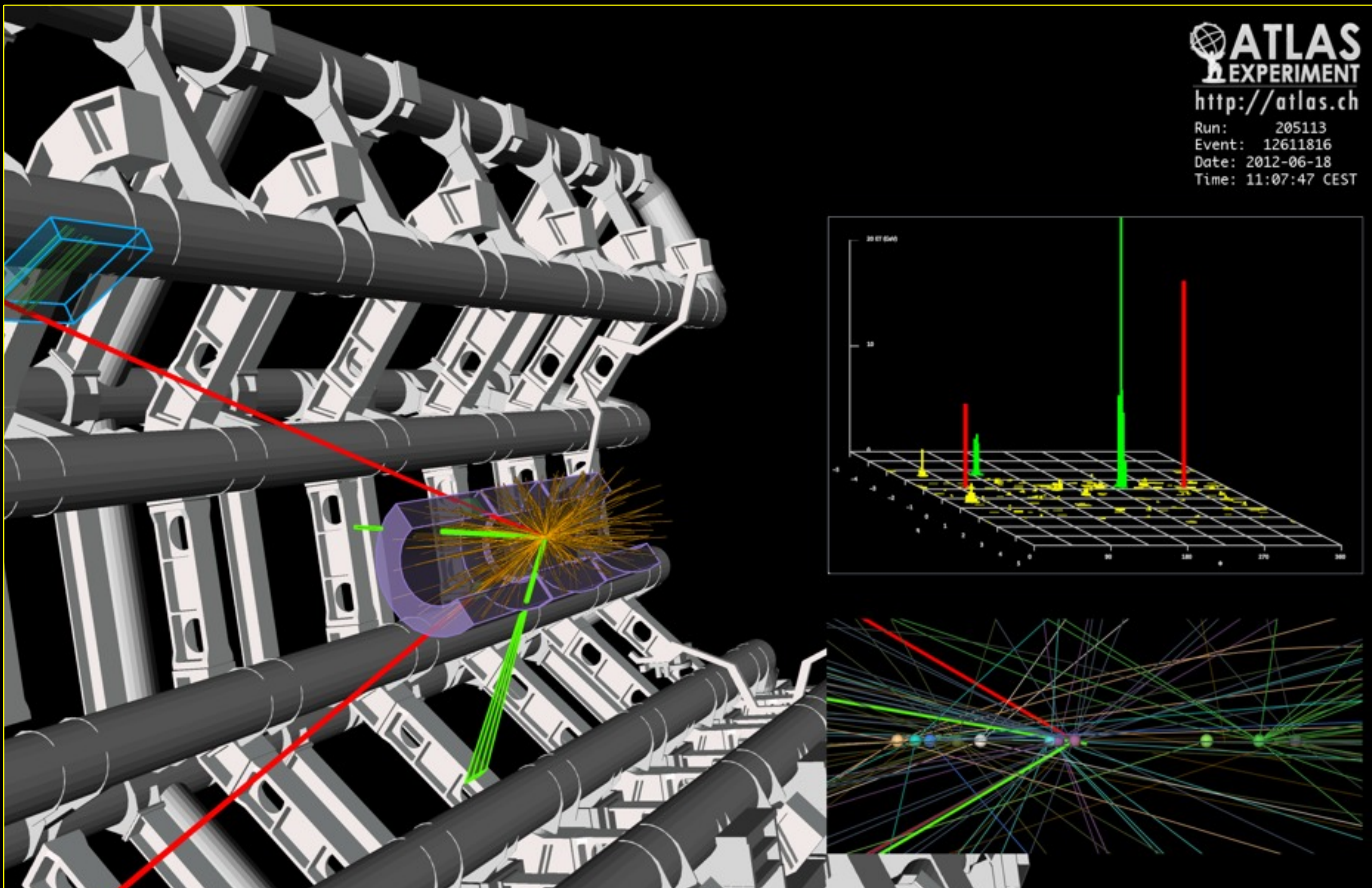
4 leptons

4μ candidate with mass = 124.1 GeV



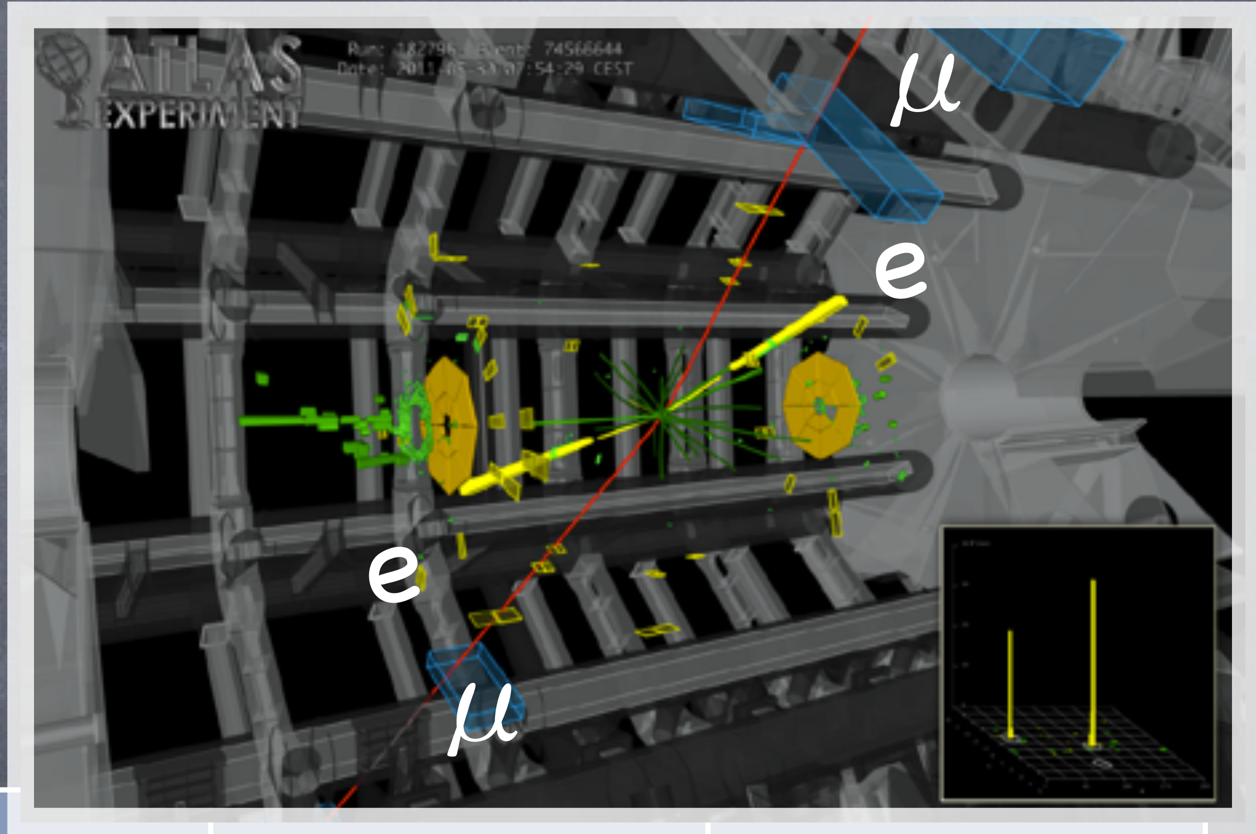
4 leptons

2e2μ candidate with mass = 122.7 GeV



The Golden Channel: H->ZZ->4l

- CLEAN but very low rate (σ ~2-5fb), yet robust
- All information is available, one can fully reconstruct the kinematics and the masses (m_{2l}, m_{4l})
- Signature: Two pairs of same flavor opposite charged isolated leptons, one or both compatible with Z ->narrow peak
- Main backgrounds:
  - ZZ* (irreducible)
    Zbb, Z+jets, tt
  - Suppress backgrounds with isolation and impact parameters cuts on two softest leptons

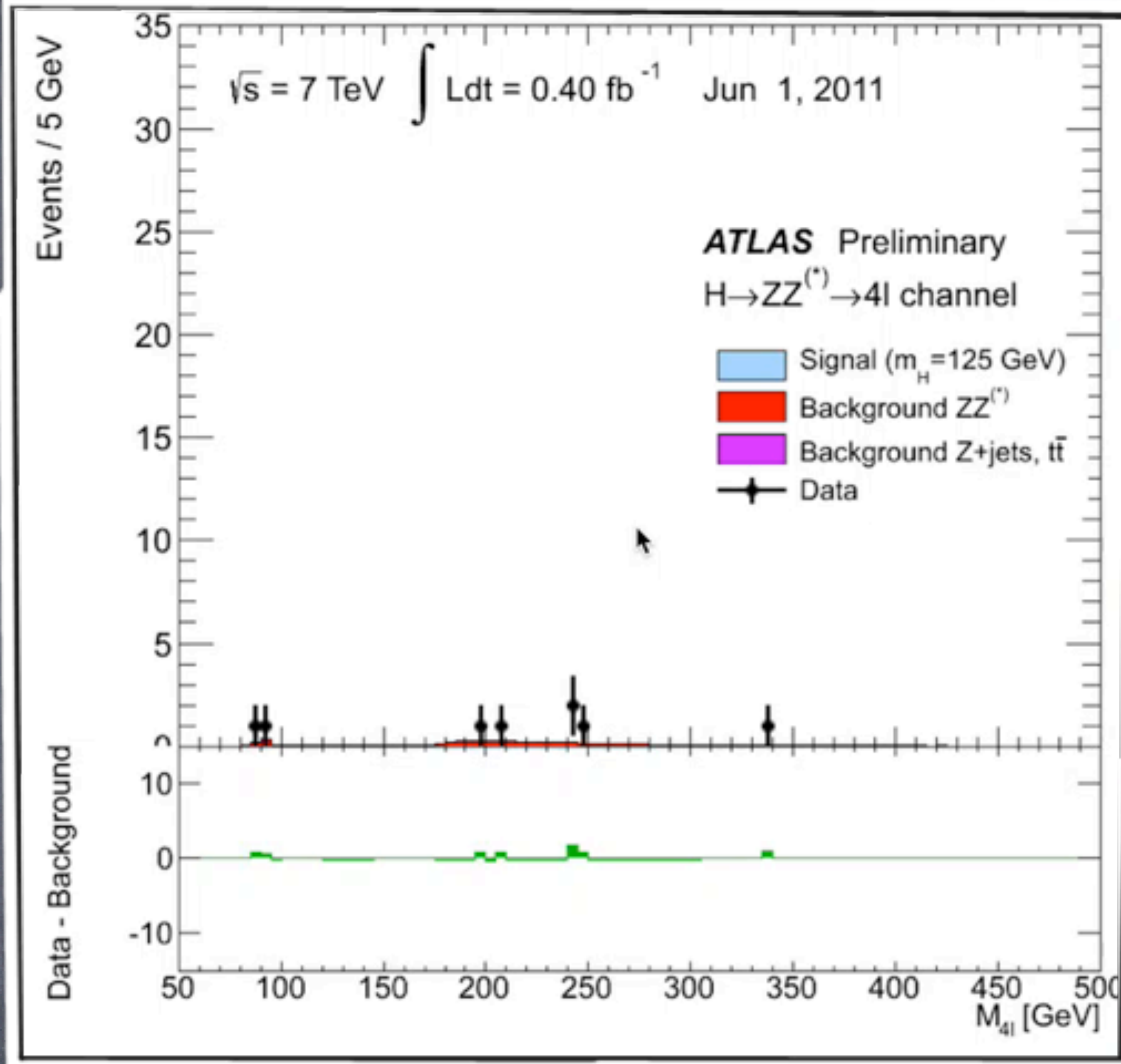


Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
Inclusive	4.6+20.7 fb^{-1}	ZZ*,Zbb, Z+jets, top	~16	~1.3

4 ℓ

- The resolution of the reconstructed Higgs boson mass is dominated by detector resolution at low mH values and by the Higgs boson width at high mH.
- Candidates account:

Expected from BG	@mH=125 ±5 GeV	Observed
11.1±1.3	15.9±2.1	32

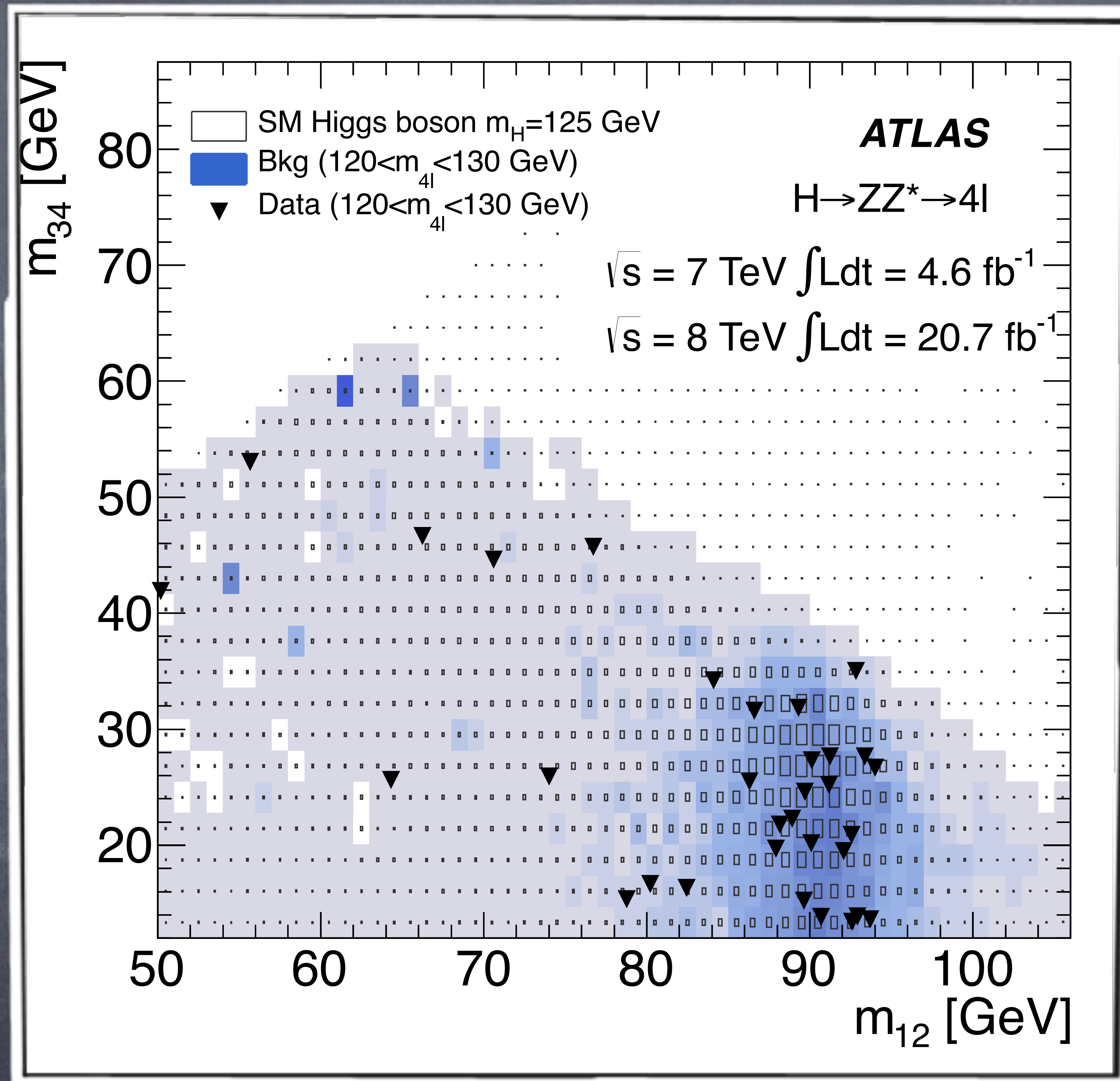


In region m4l>160 GeV: 376 events observed, 348±26 expected from bknd (mainly ZZ)

The Golden Channel: H->ZZ->4l

FSR γ candidate (ET>1 GeV) added if 66<M12 (μμ) [GeV]<89 ~4% of events

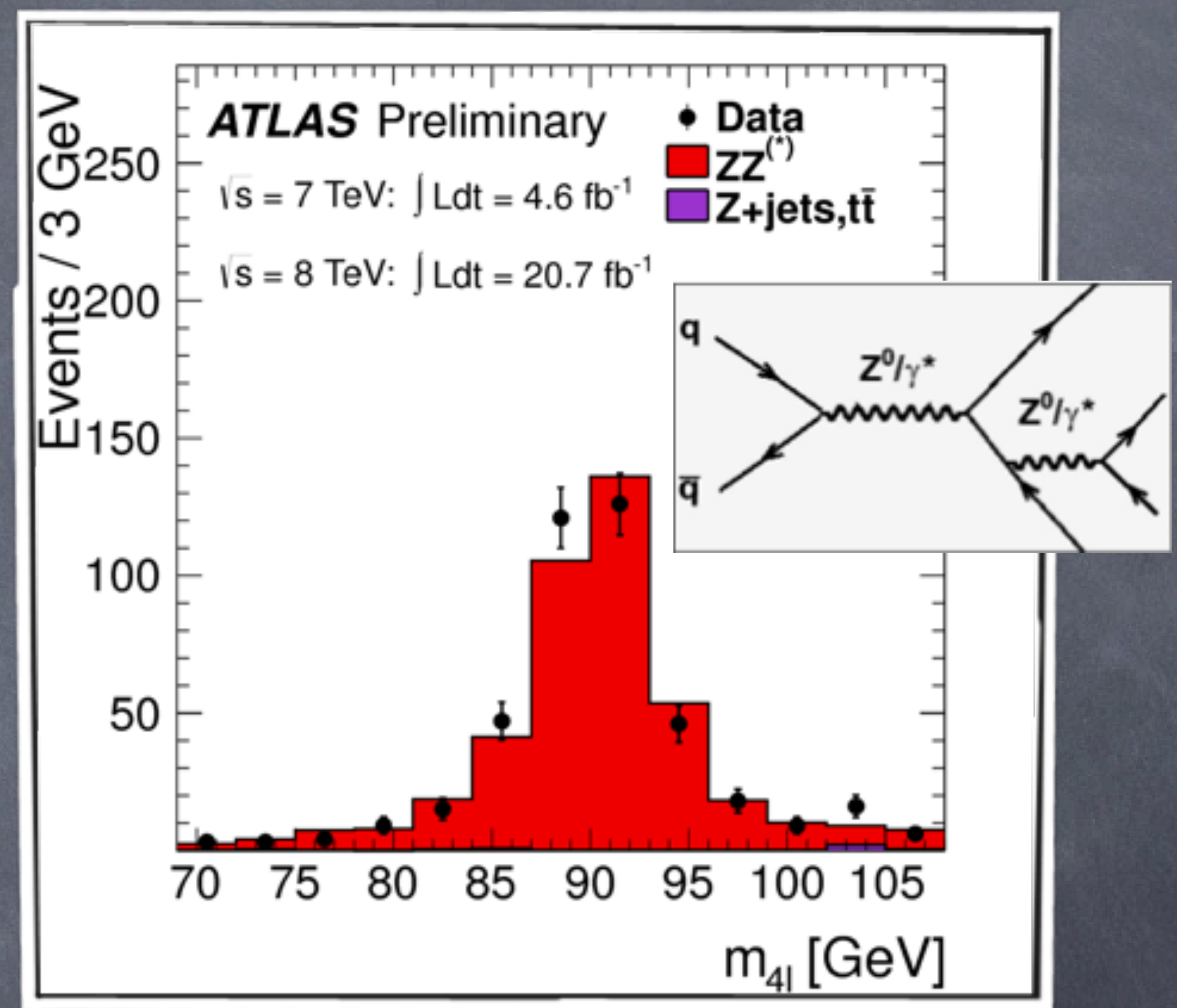
Mass resolution 1.3/1.9% for 4m/4e @125 GeV using Z-mass constraint on leading lepton pair



Friday, July 19, 13

Validating 4 ℓ analysis method

- Demonstrating the single-resonant peak
  pp-> Z-> 4leptons
- To improve the acceptance the requirements on m12, m34 and the leptons pT were relaxed

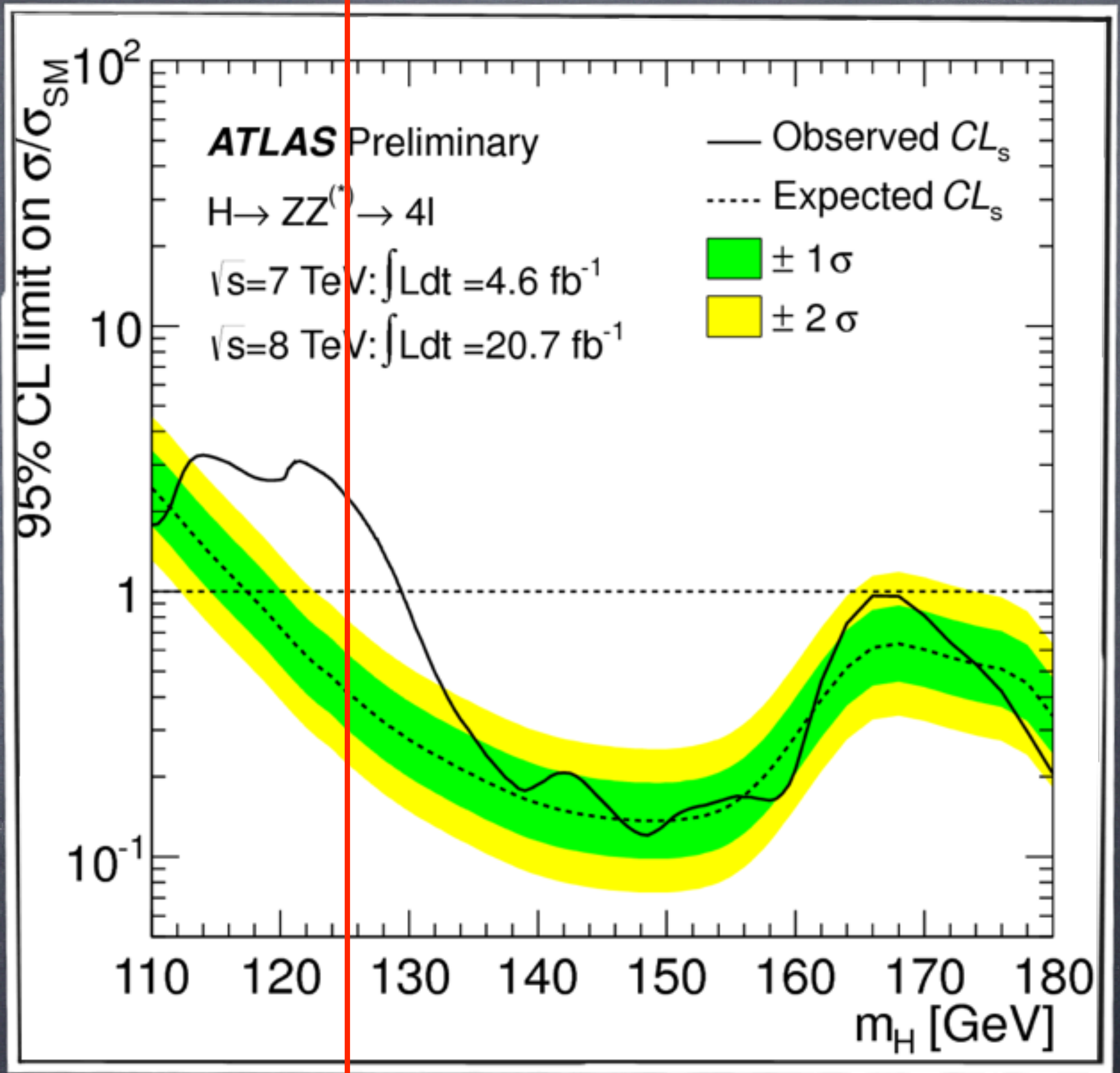


Exclusion

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

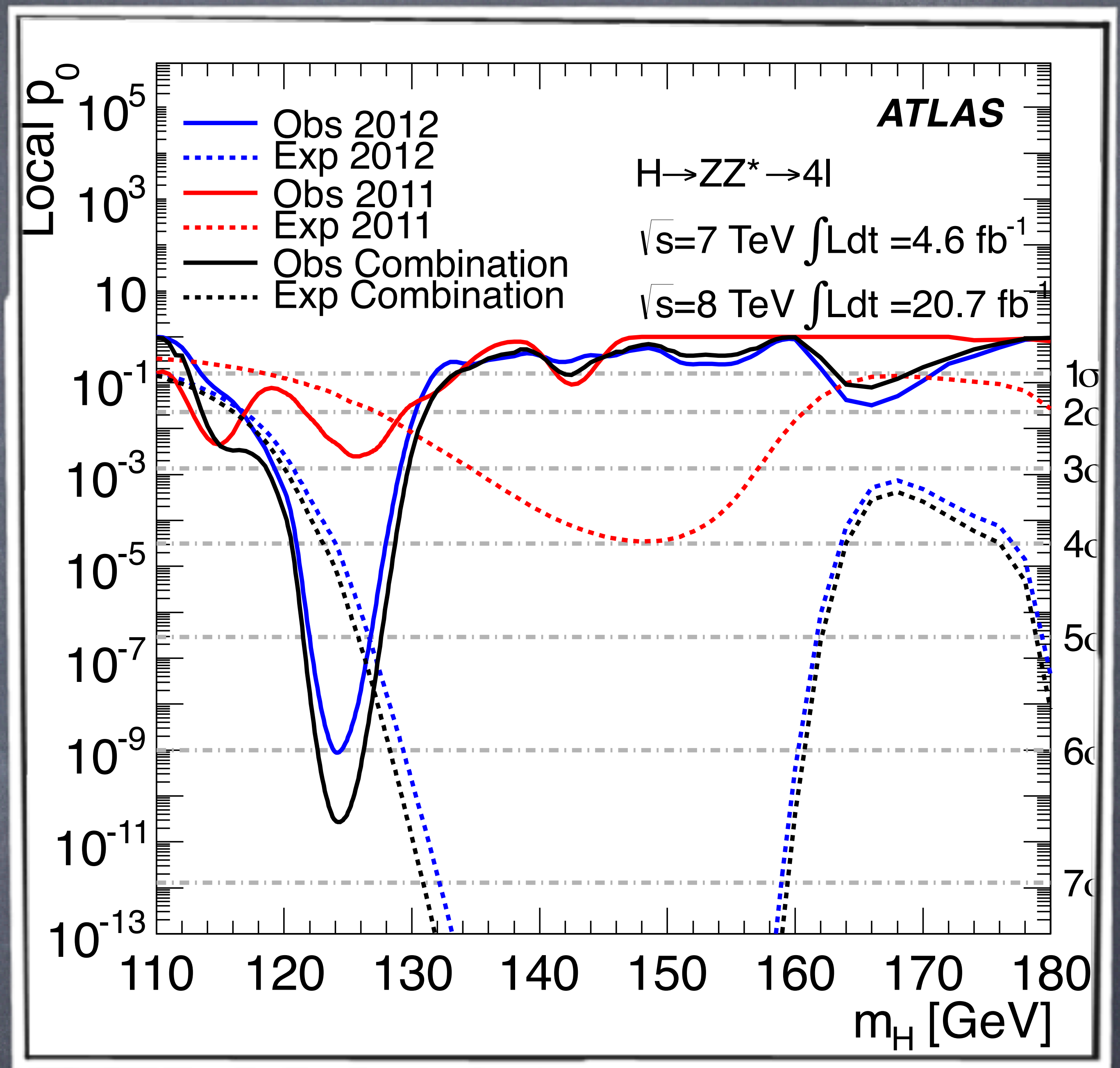
- If we exclude μ <1, then we exclude $\sigma < \sigma_{SM}$

  i.e SM Higgs is excluded at the 95% Confidence Level



4 ℓ discovery excess is confirmed

	2011	2012	Combined
Mass	125.6 GeV	124.1 GeV	124.3 GeV
Exp	1.8 σ	4.0 σ	4.4 σ
Obs	2.8 σ	6.0 σ	6.6 σ



4 ℓ discovery excess is confirmed

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Mass (p0)	125.6 GeV	124.1 GeV	124.3 GeV
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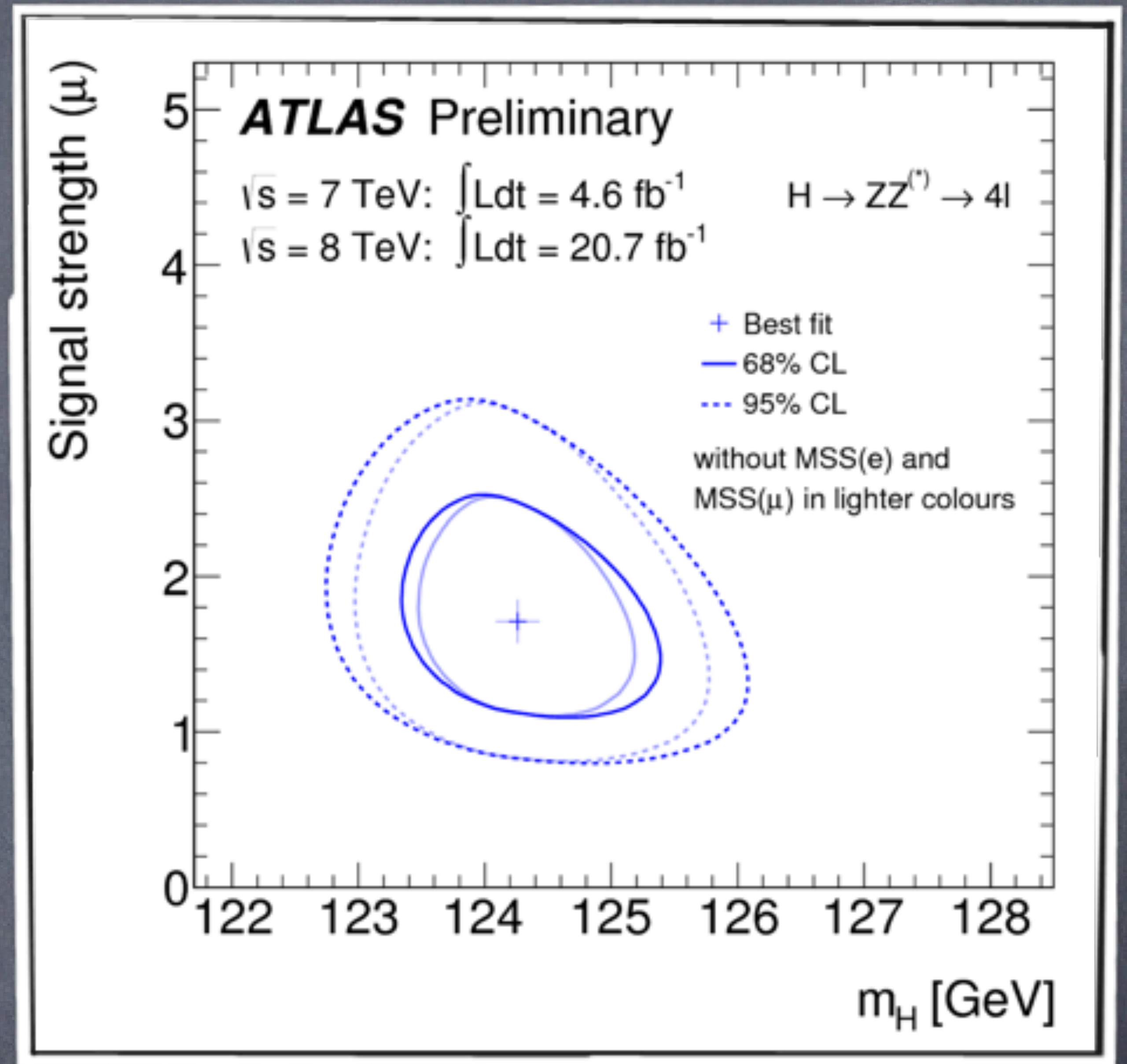


$$\hat{\mu} = 1.3 \pm 0.4$$

$$m_H = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)$$

H->WW

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

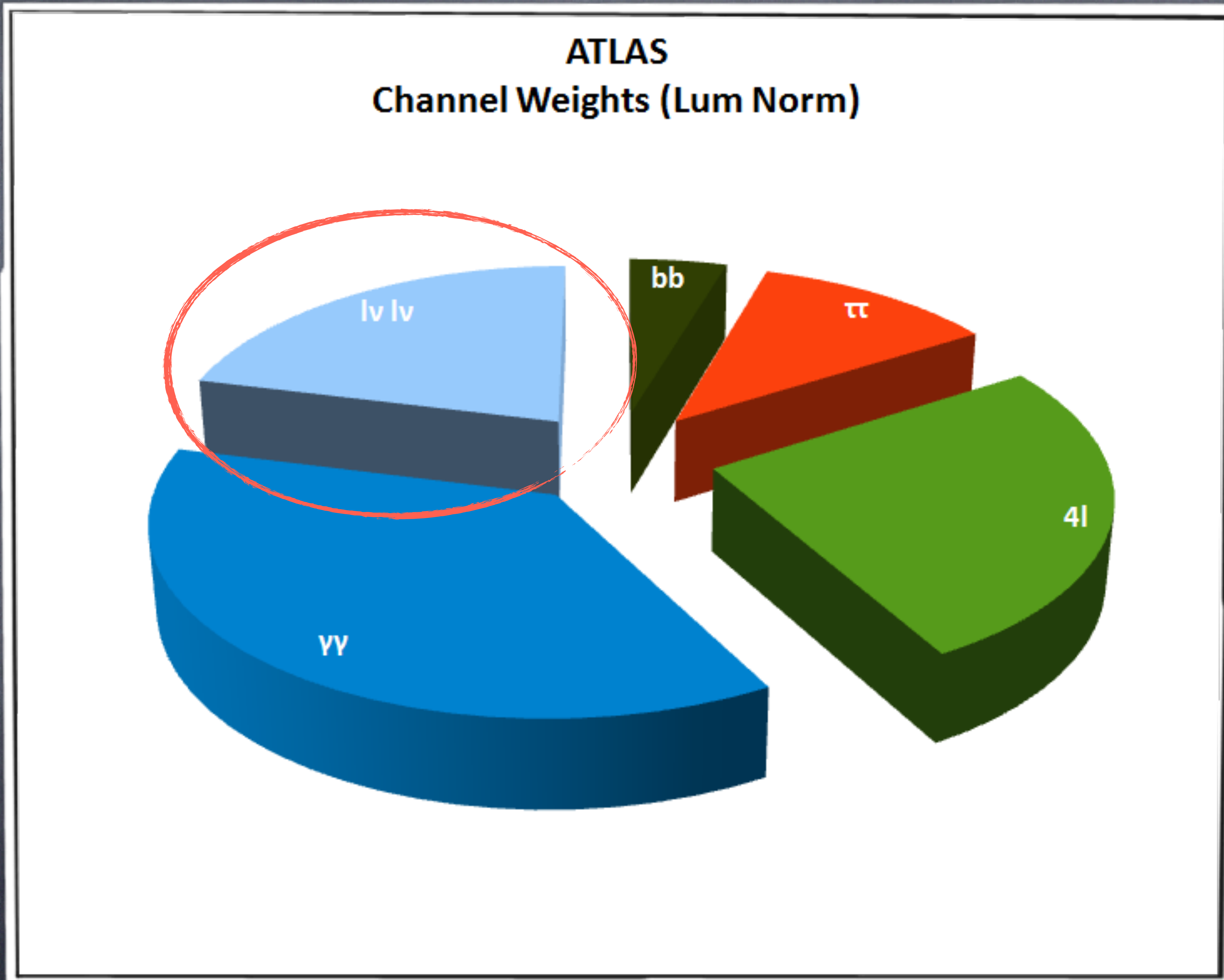
- Probing mH=125 GeV
- Probing channels:

  H-> $\gamma\ \gamma$

  H->4l

  H->WW->lvlv

  VH-> Vbb, H-> $\tau\ \tau$

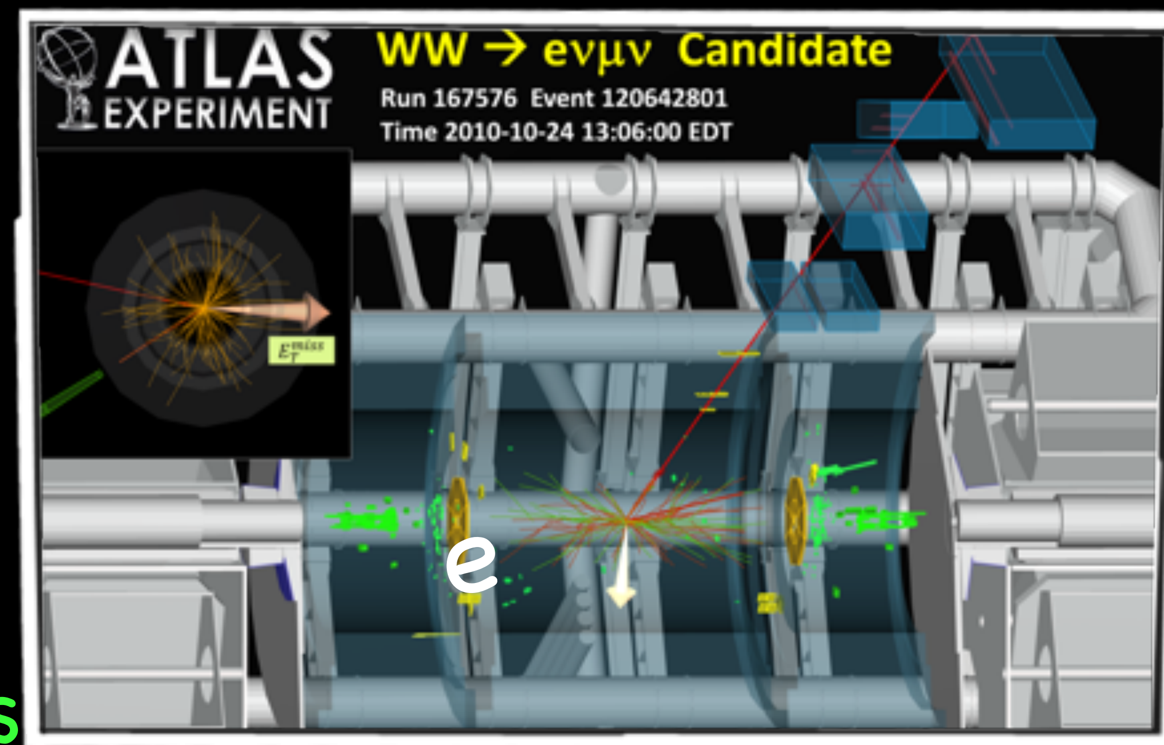


H->WW->eνμν, eνeν,μνμν

σxBR~200 fb
@ 125

- The cannel is challenging 2 neutrinos- no mass reconstruction ->mT

μ

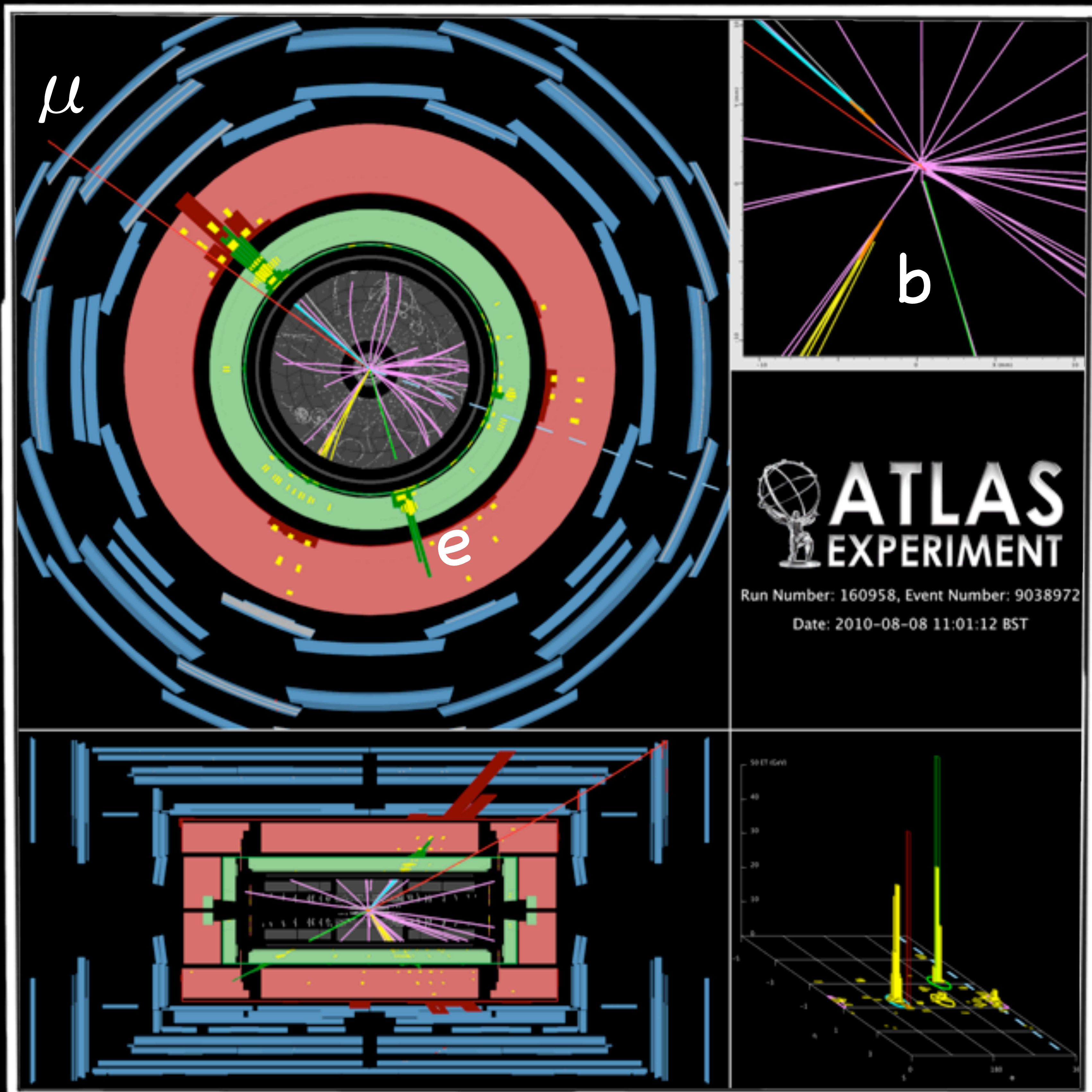


- Signature: 2 high p_T opposite sign isolated leptons with large E_T^{miss}->Understanding of E_T^{miss} is crucial

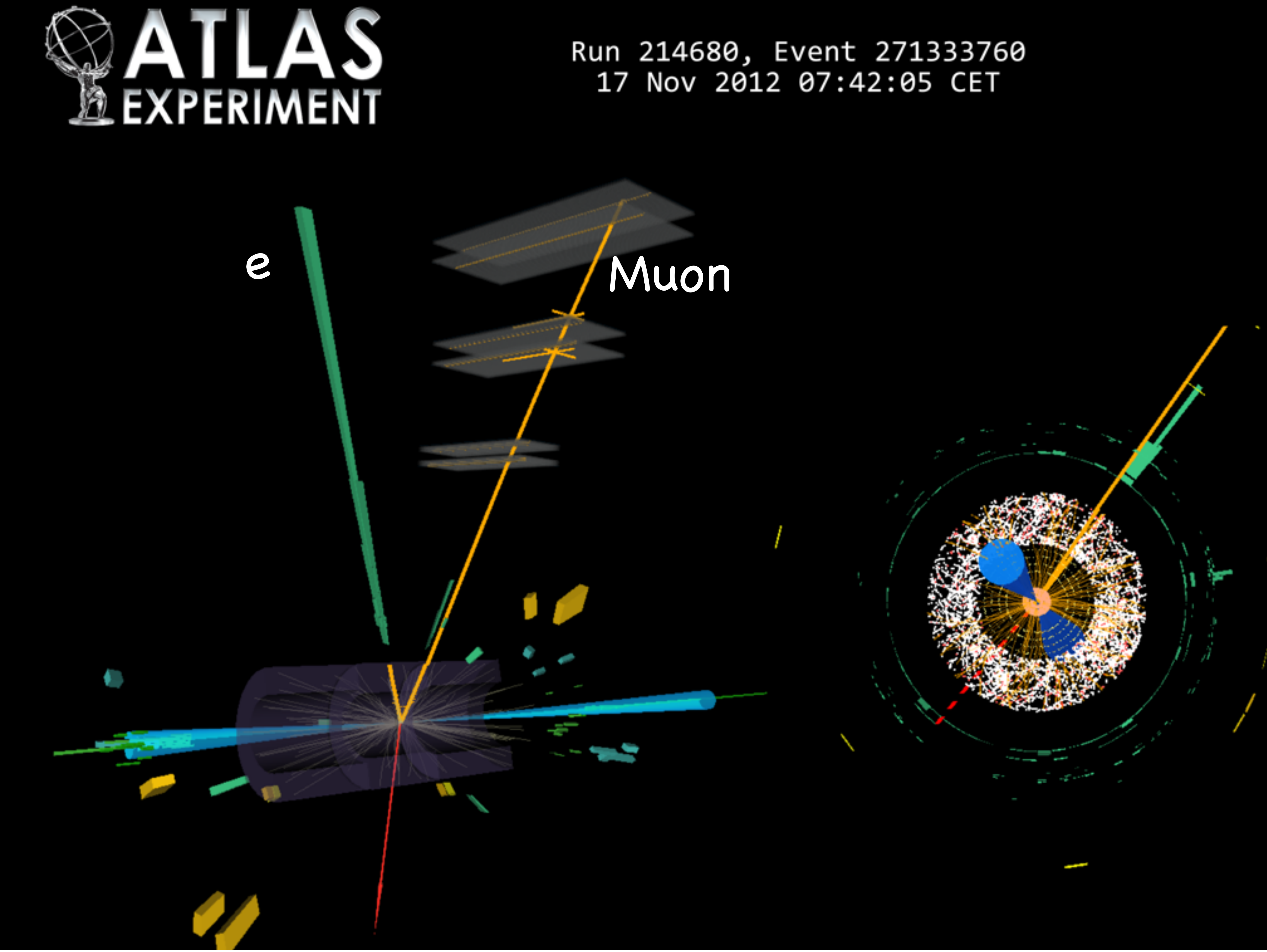
- Analysis 0,1,2 jets, DF, SF

Signal	s/b	Prod	Luminosity	BG
~250	~5%-40%	ggF,VBF	4.6+20.7 fb^{-1}	WW, W+jets, top

H->WW->e ν μ ν



- top BG, Rejected by b-tag veto
- WW can be reduced by exploiting the Higgs spin, require small $\Delta\Phi_{ll}$


ATLAS EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
e
Muon

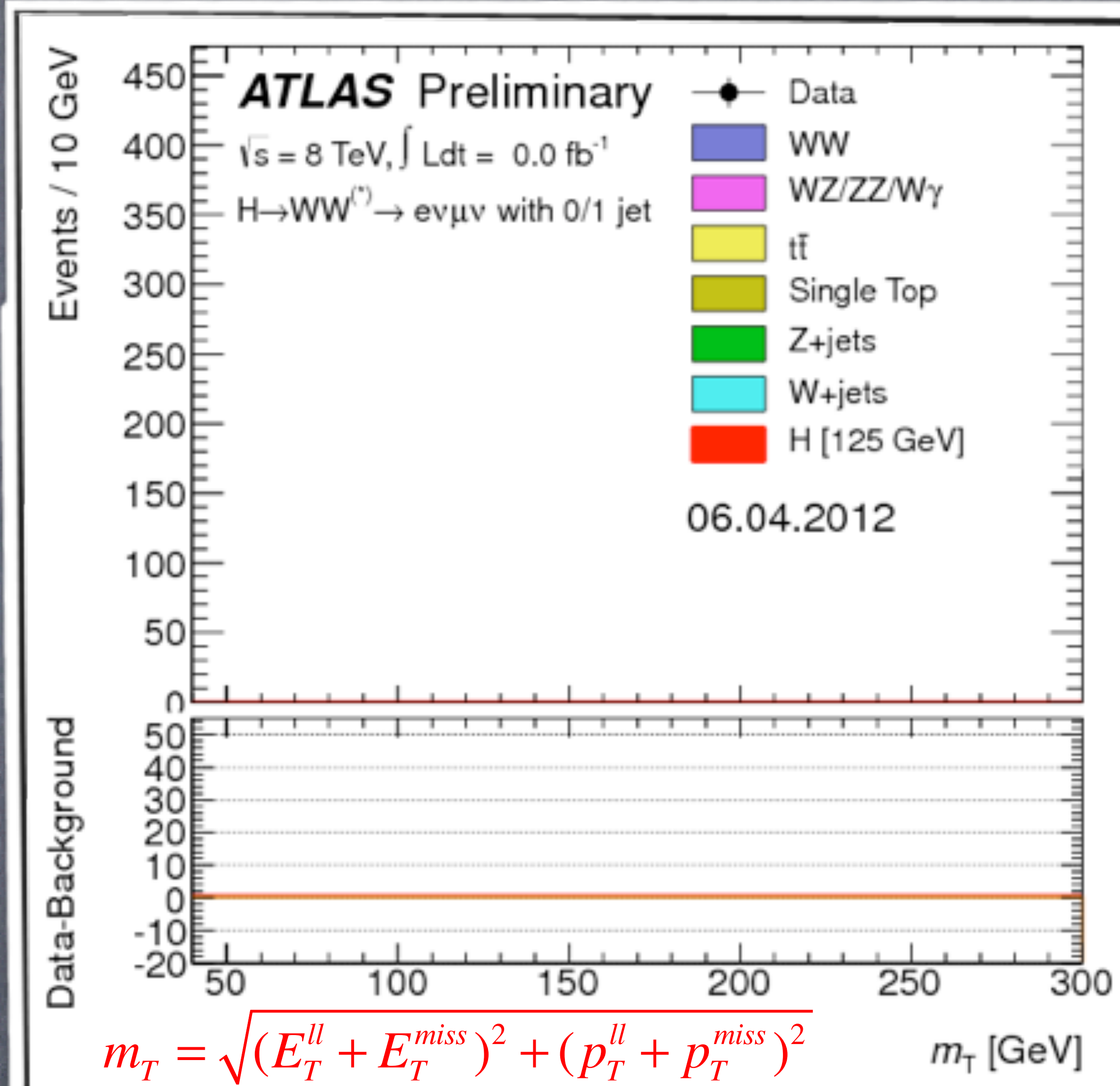
WW Results

Event Yields

Numbers quoted for 0.75 mH < mT < mH   w/mH =125 GeV
(mT < 1.2 mH for 2-jet ch)

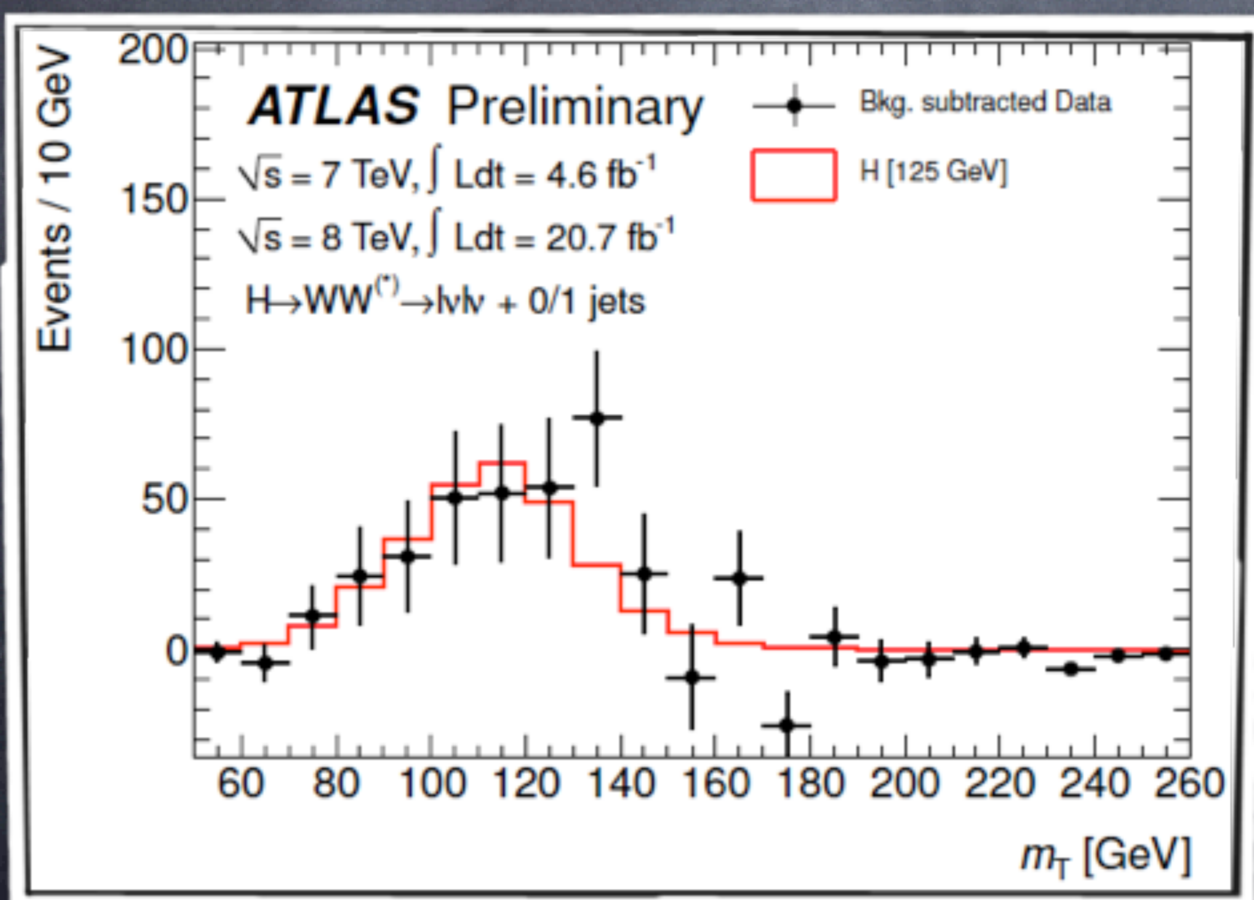
8 TeV	Signal Expectation	Total Bkg	Data
0 jet	97 ± 20	739 ± 39	831
1 jet	40 ± 13	261 ± 28	309
2 jet	10.6 ± 1.4	36 ± 4	55

7 TeV	Signal Expectation	Total Bkg	Data
0 jet	25 ± 5	161 ± 11	154
1 jet	7 ± 2	47 ± 6	62
2 jet	1.4 ± 0.2	4.6 ± 0.8	2



H->WW->e ν μ ν

Excess after BG subtraction

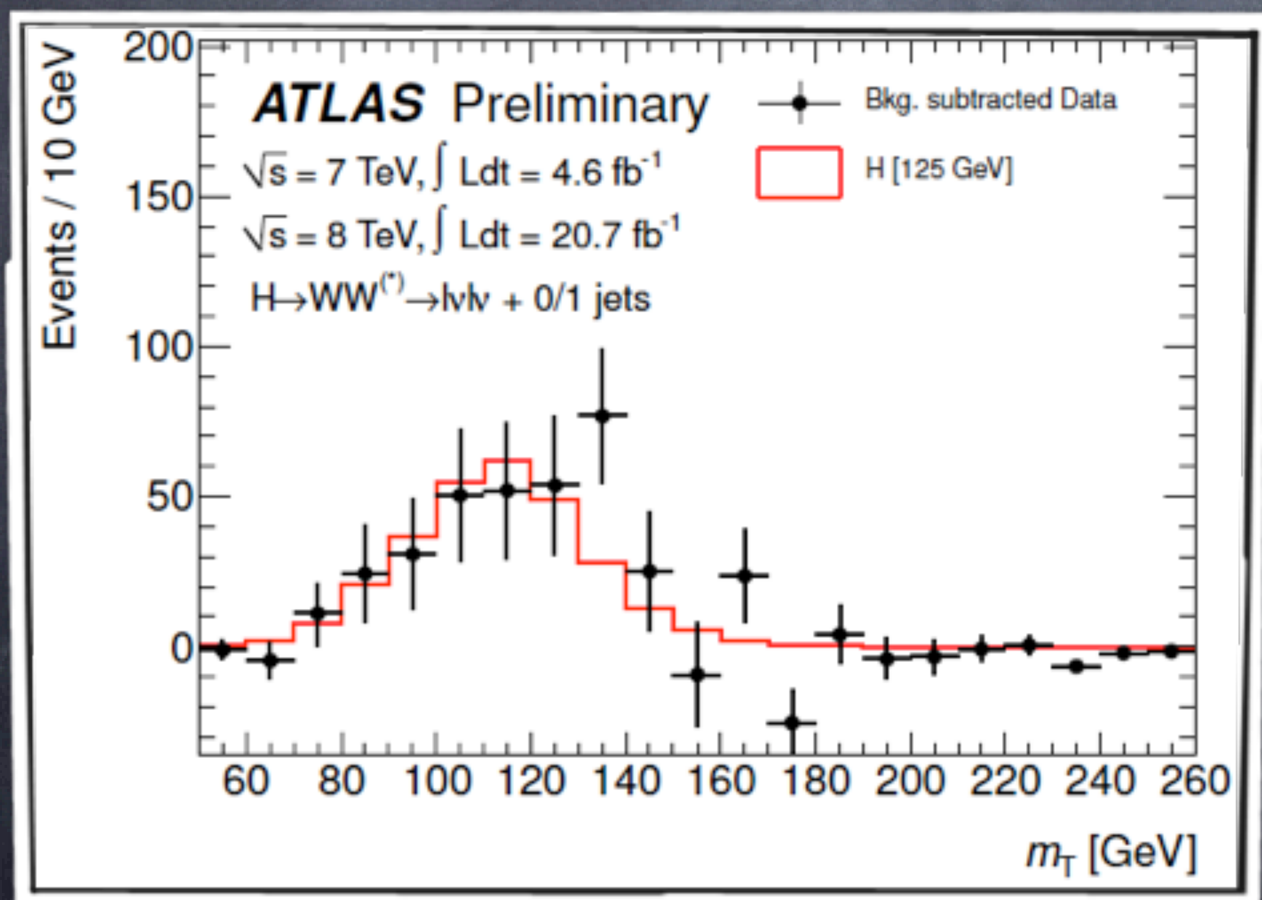


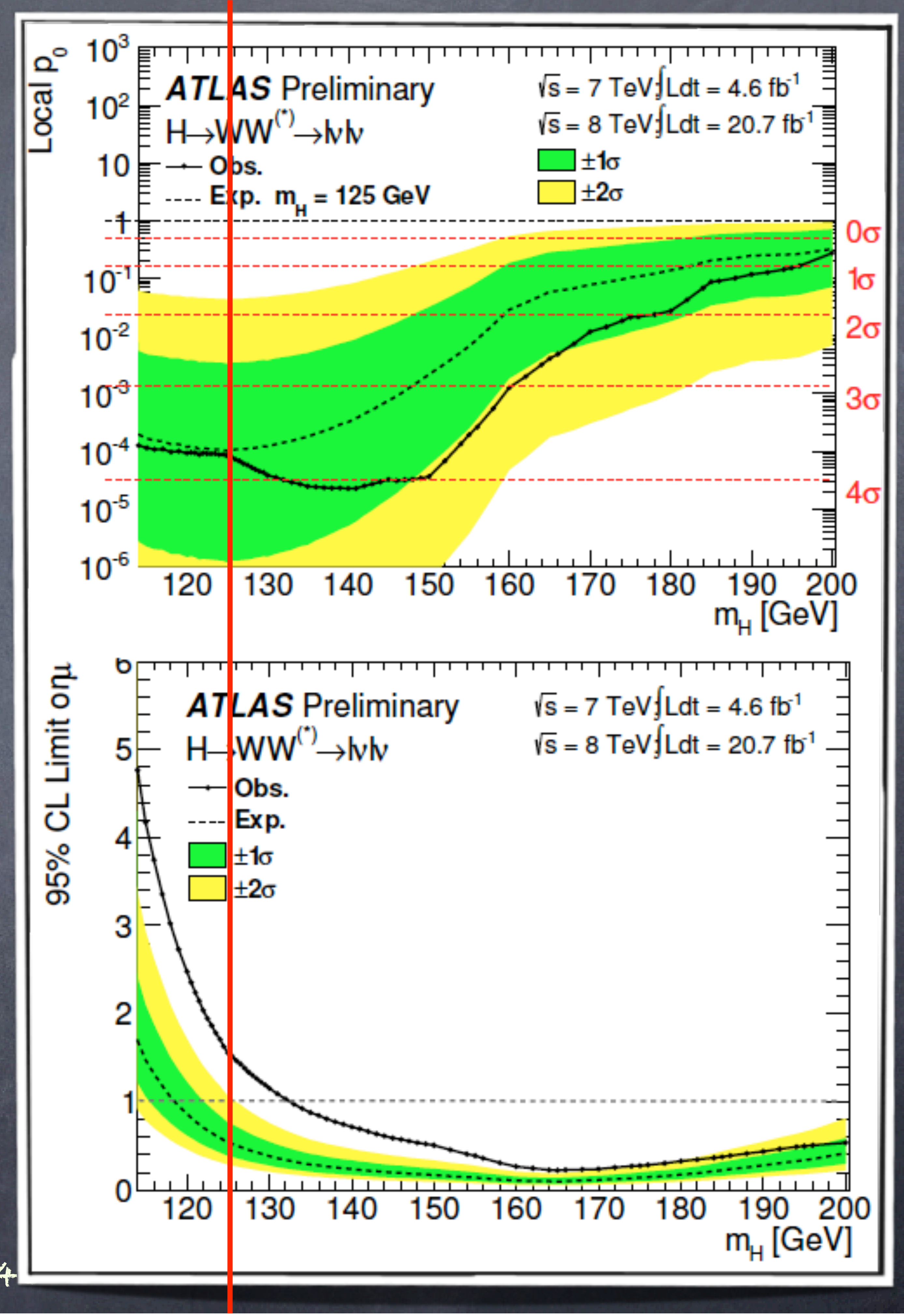
H->WW->$e\nu\ \mu\ \nu$

- Observed excess @ 125 GeV: 3.8 σ

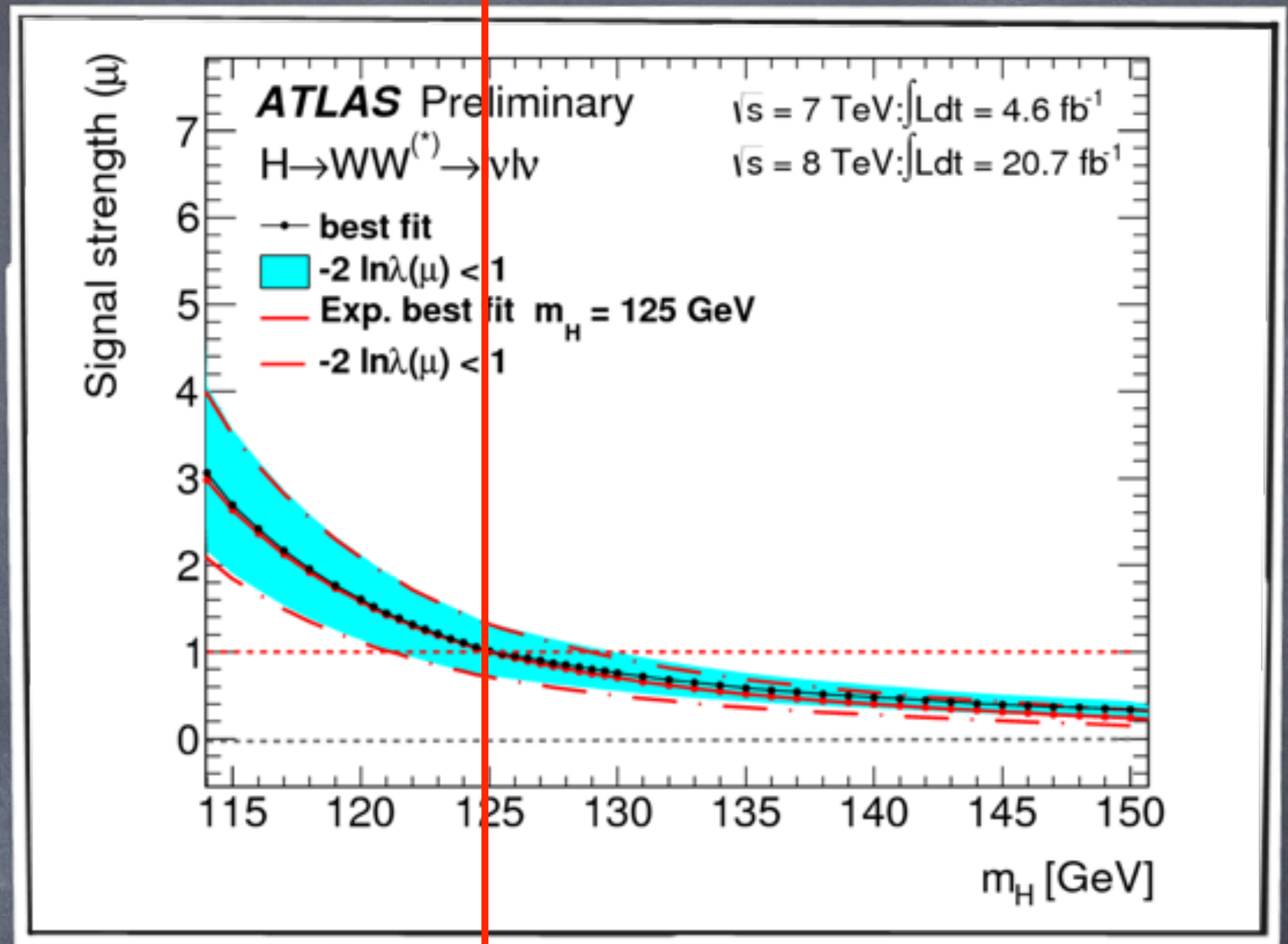
  Expected significance @ 125 GeV is 3.7 σ

Excess after BG subtraction





H->WW->$e\nu\mu\nu$



$$\hat{\mu}(125GeV) = 1.01 \pm 0.31$$

- Consistent with SM Higgs Boson

μ_{obs} = 1.01 ± 0.21 (stat.) ± 0.19 (theo. syst.) ± 0.12 (expt. syst.) ± 0.04 (lumi.)

The Fermionic Channels

$$w_i \simeq \frac{\left(s_i / \sqrt{s_i + b_i}\right)^2}{\sum_i \left(s_i / \sqrt{s_i + b_i}\right)^2}$$

- Probing mH=125 GeV
- Probing channels:

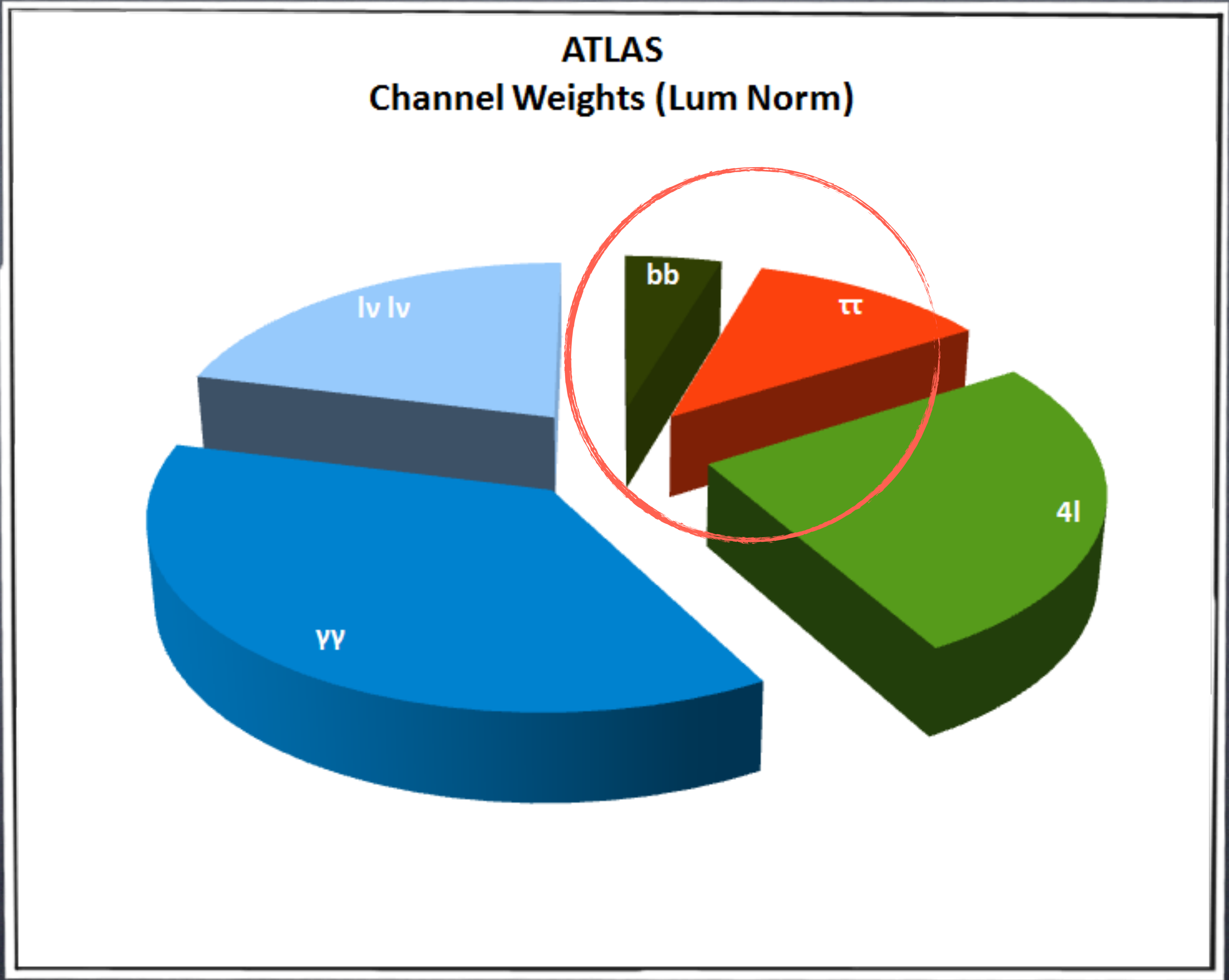
H-> $\gamma\ \gamma$

H->4l

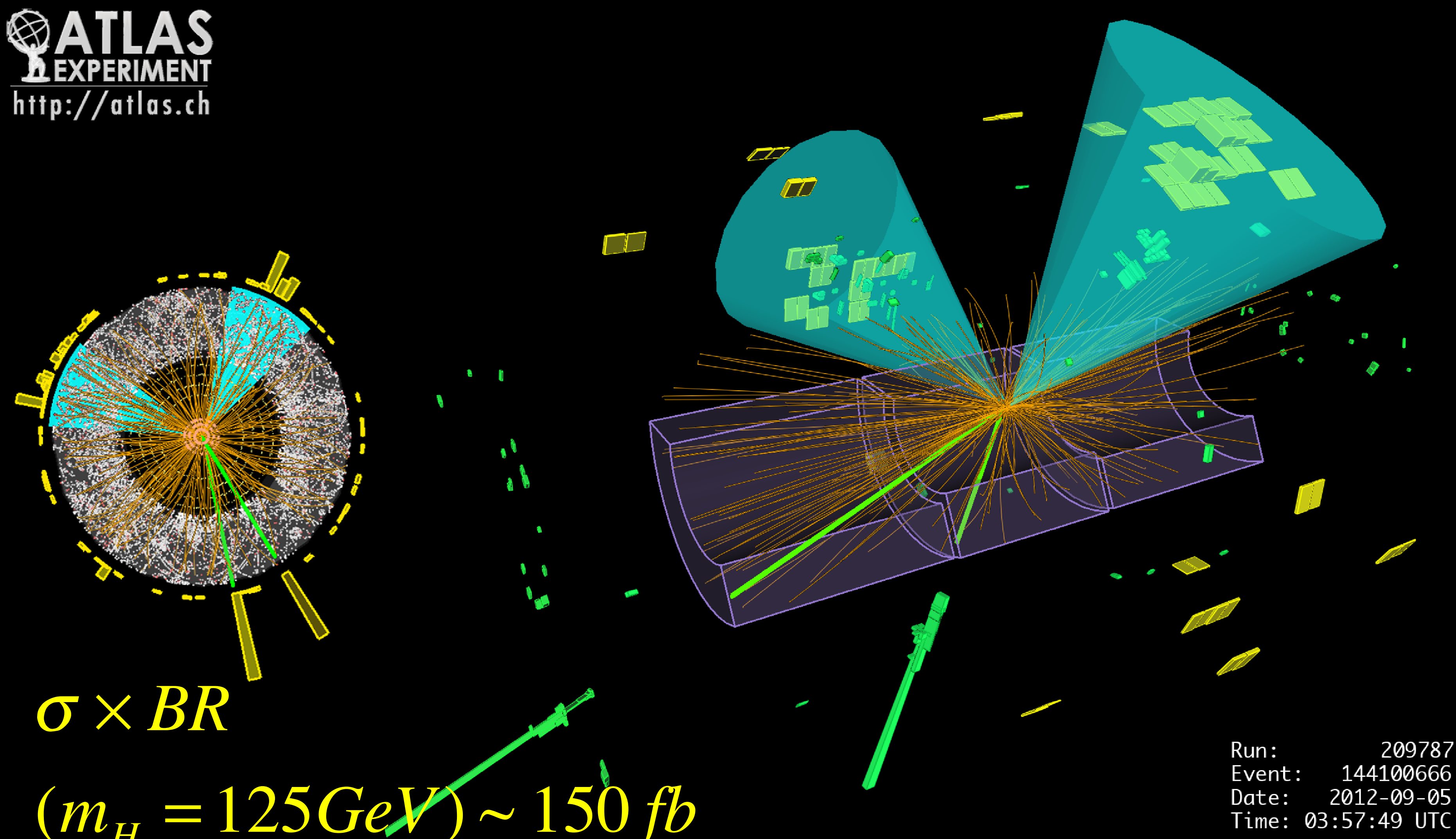
H->WW->lvlv

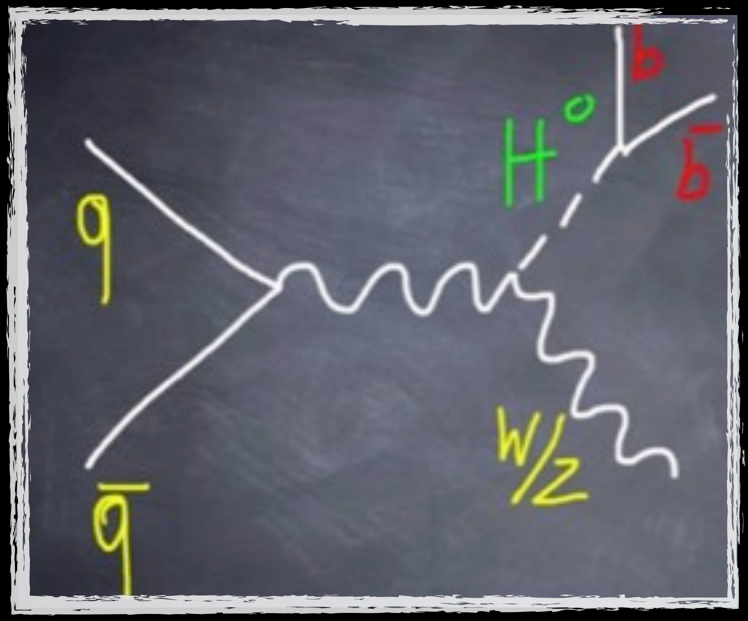
VH-> Vbb,

H-> $\tau\ \tau$



H->bb: W/ZH->W/Zbb



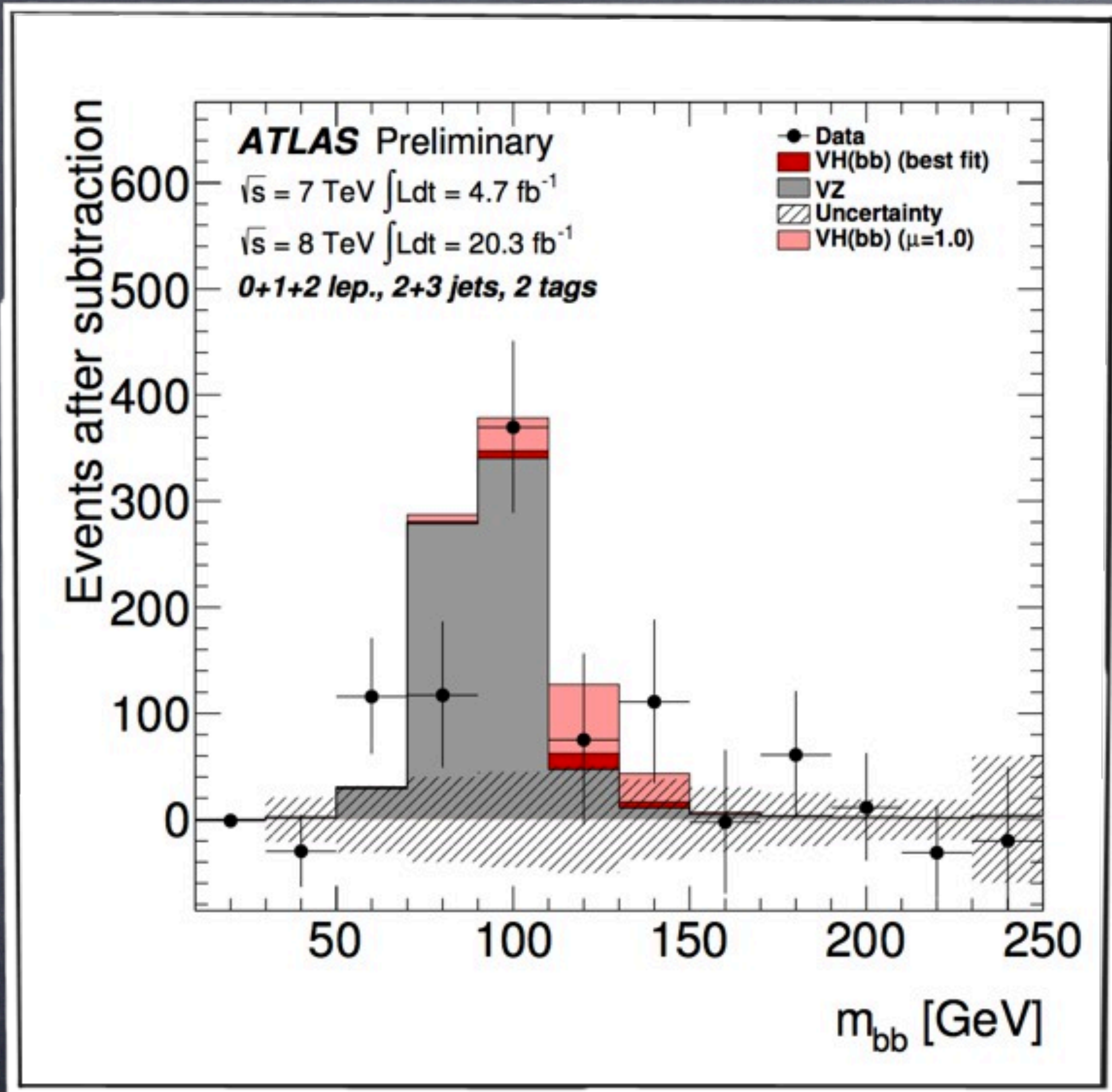


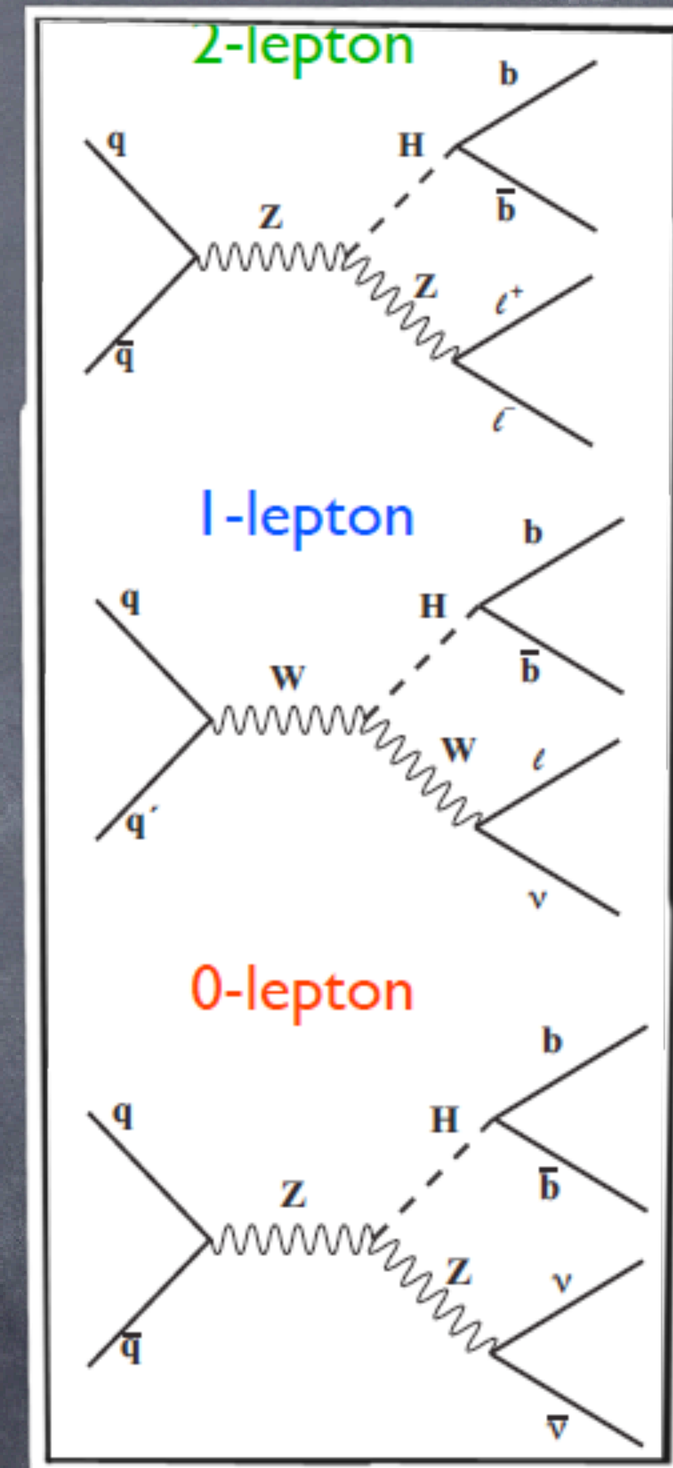
$\sigma \times BR$

$(m_H = 125 GeV) \sim 150\, fb$

Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
VH	4.9+20 fb^{-1}	W/Zbb, top	~65	~1-10%

Fresh from the Oven





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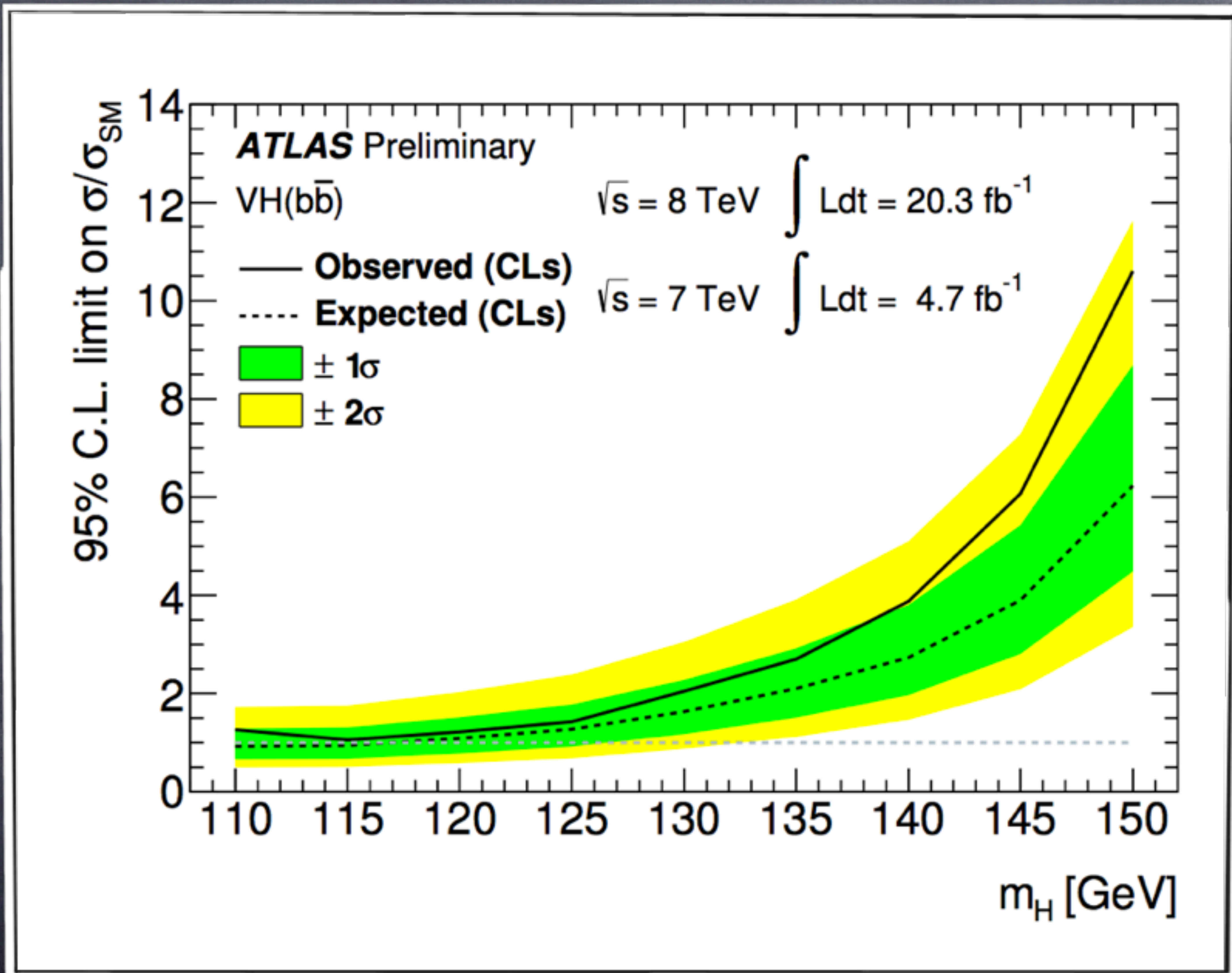
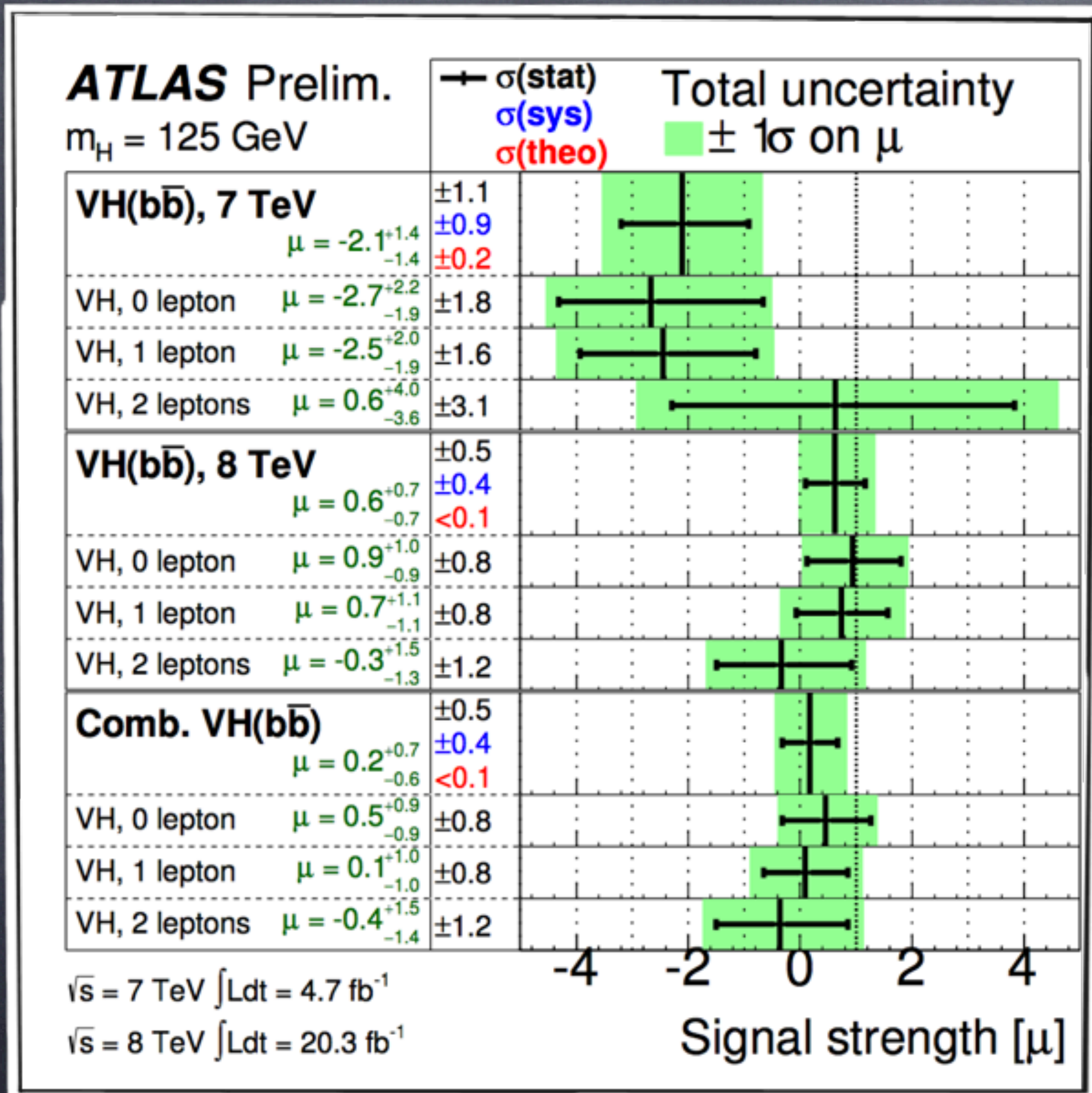
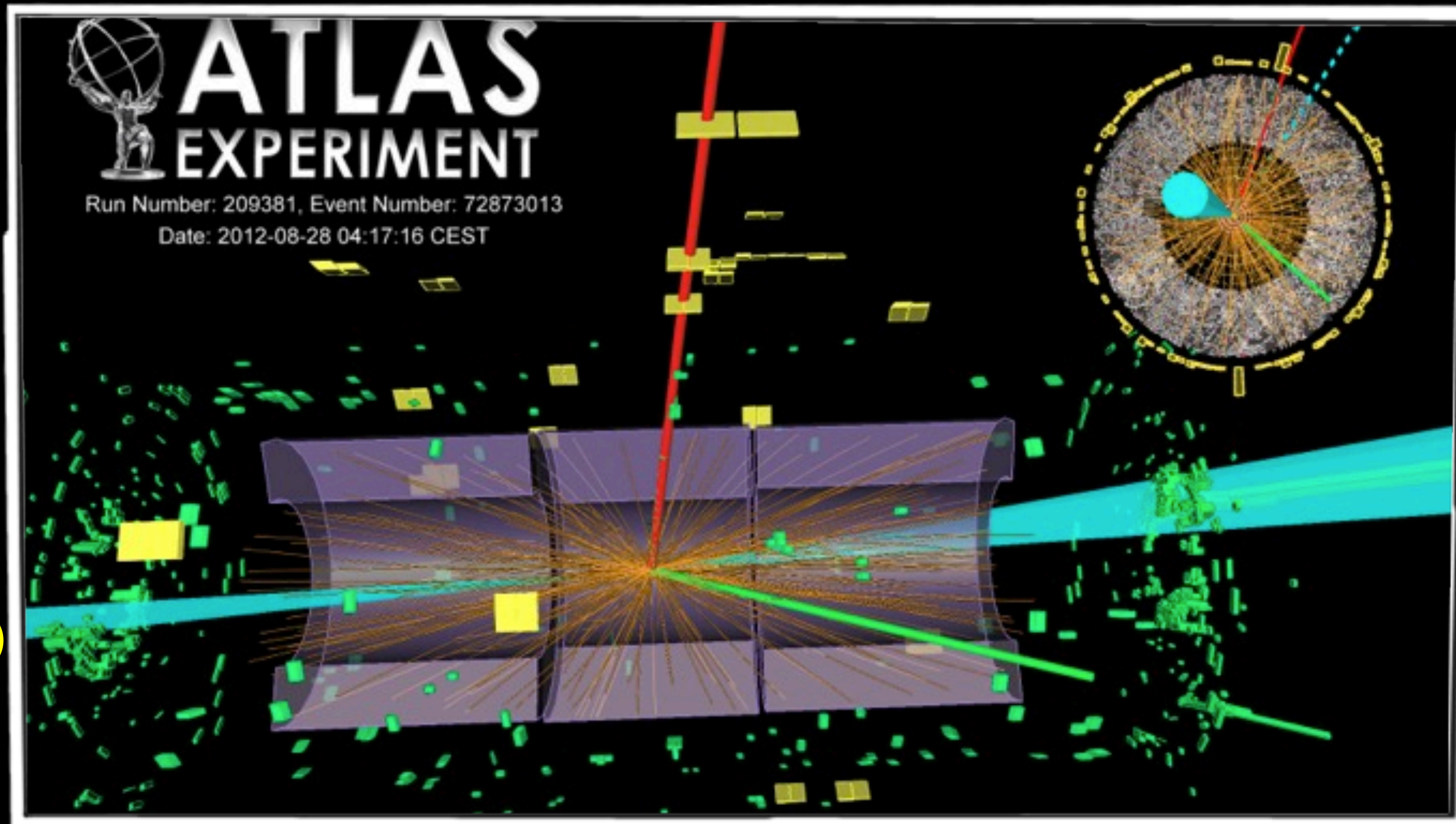


Fresh from the Oven



H->ττ



$\sigma \times BR$
$(m_H = 125 GeV)$
$\sim 1.3 pb$

Prod	Luminosity	BG	Signal (126.5 GeV)	s/b
ggF,VH,VBF	4.9+13 fb^{-1}	Z+jets, W+jets, QCD, top	~330	~0.3-10%

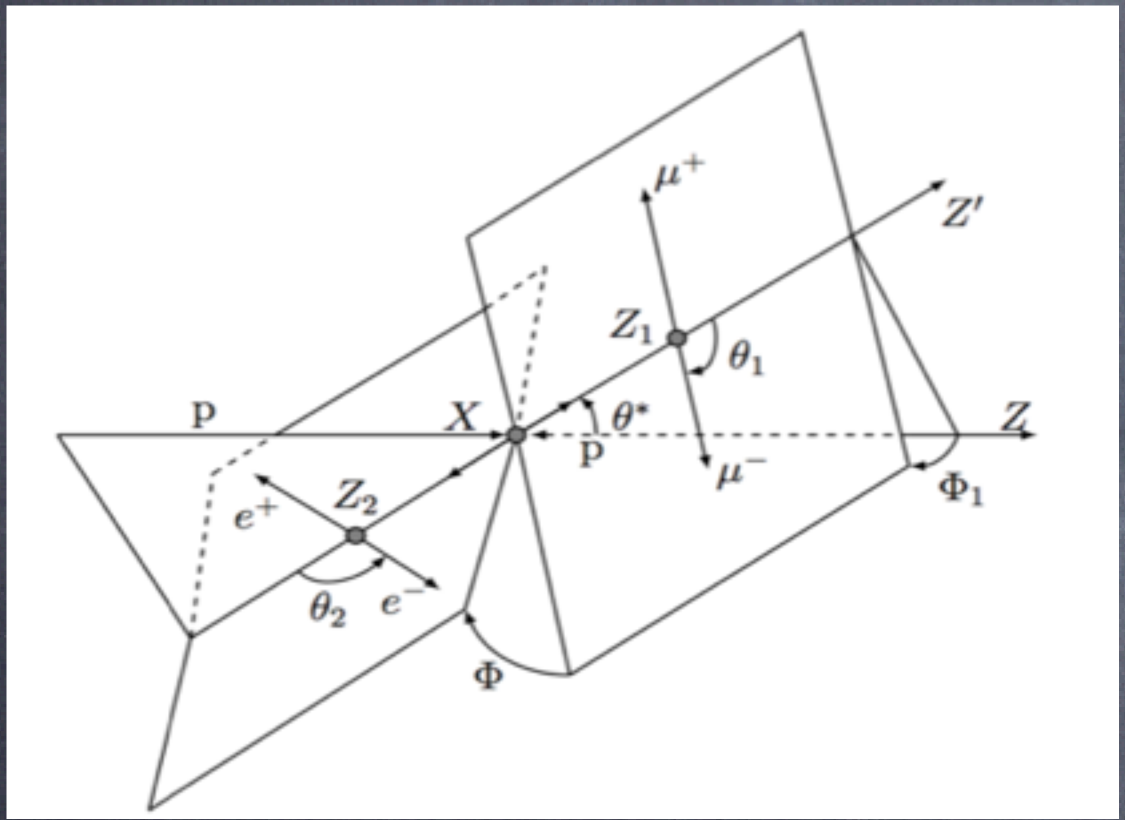
Spin

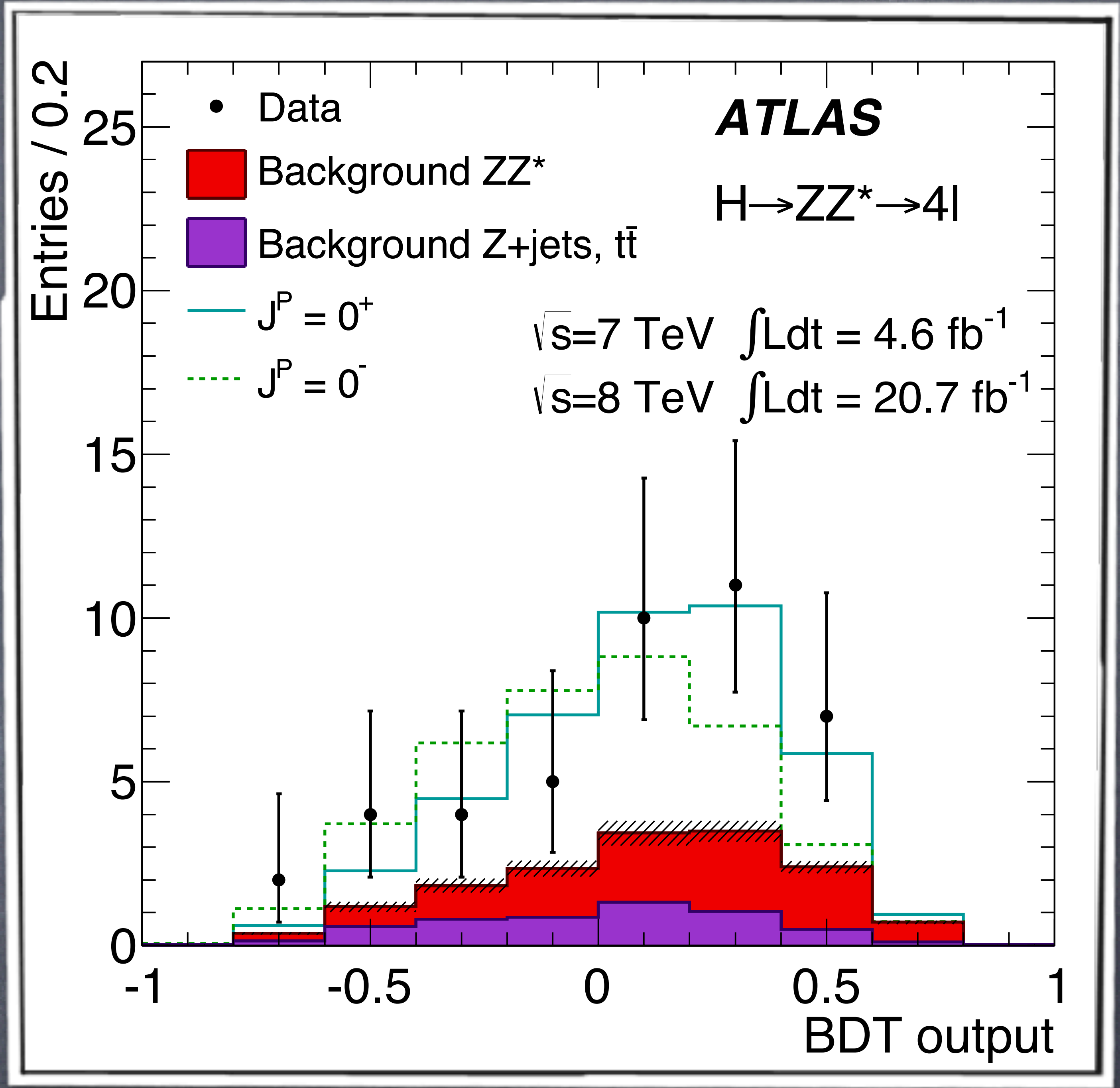
- Three primary spin analyses
- H->WW, H->$\gamma\gamma$, H->4l
- H->WW,
  -2D BDT, one axis trained for each spin 0+ and 2+ vs background
- H->$\gamma\gamma$
  Fit to cos θ*
- H->4l
  BDT and MELA analyses
  sensitive to parity
- Results fully based on toys using ratio of profiled likelihoods as test statitic with the CLs method

$$Q = \ln \frac{L(0^+, \hat{\mu}(0^+))}{L(J^P, \hat{\mu}(J^P))}$$

4 ℓ Spin & CP

$$H_1 = 0^-$$
$$H_0 = 0^+$$



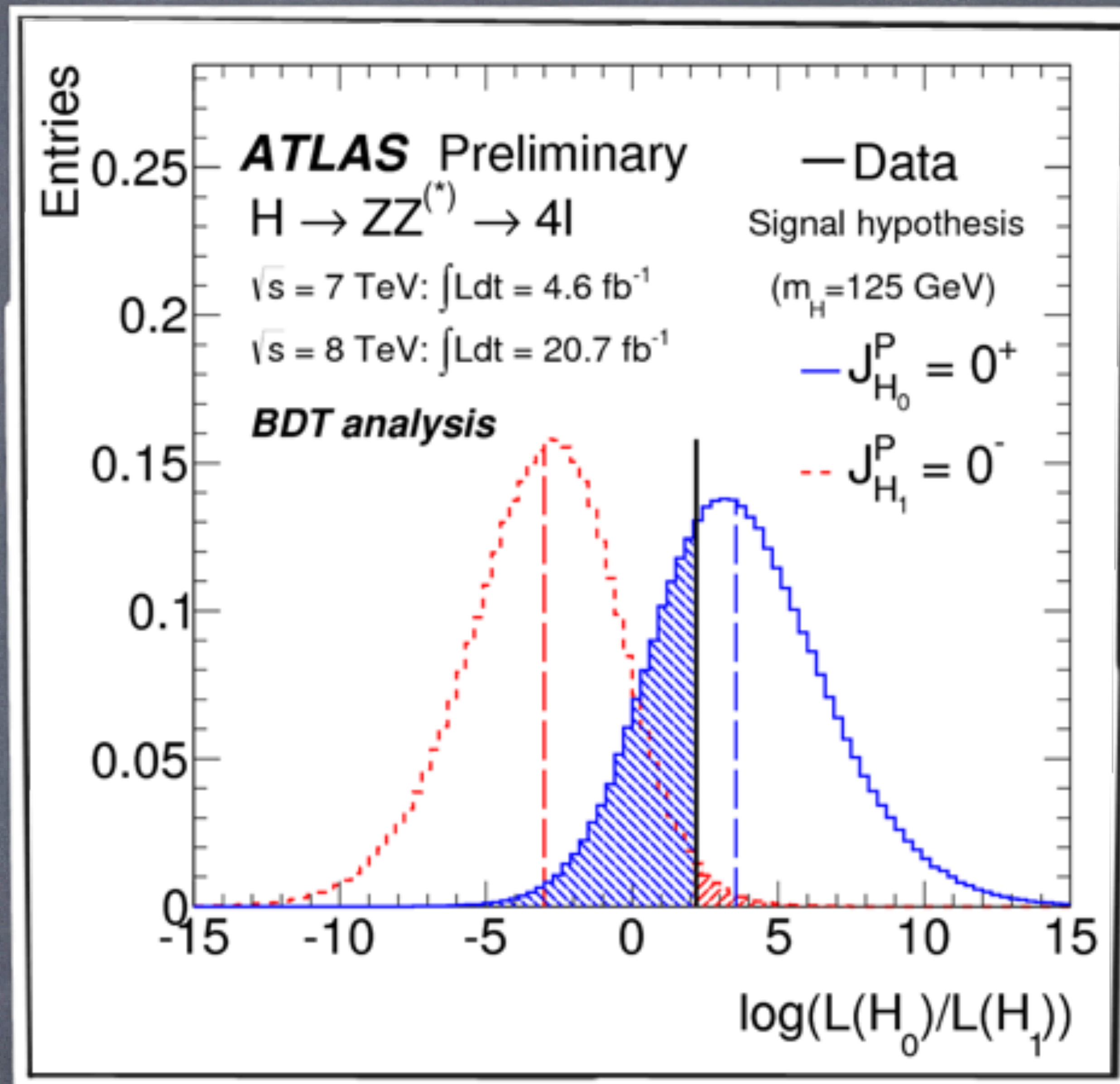


Use the distributions of
5 production and decay angles, m12 and m34 fed into BDT or MELA (Matrix Element) discriminant.

4 ℓ Spin & CP, test $J^P=0^-$

$$H_1 = 0^-$$
$$H_0 = 0^+$$

$$q = \log\frac{L(H_0)}{L(H_1)}$$



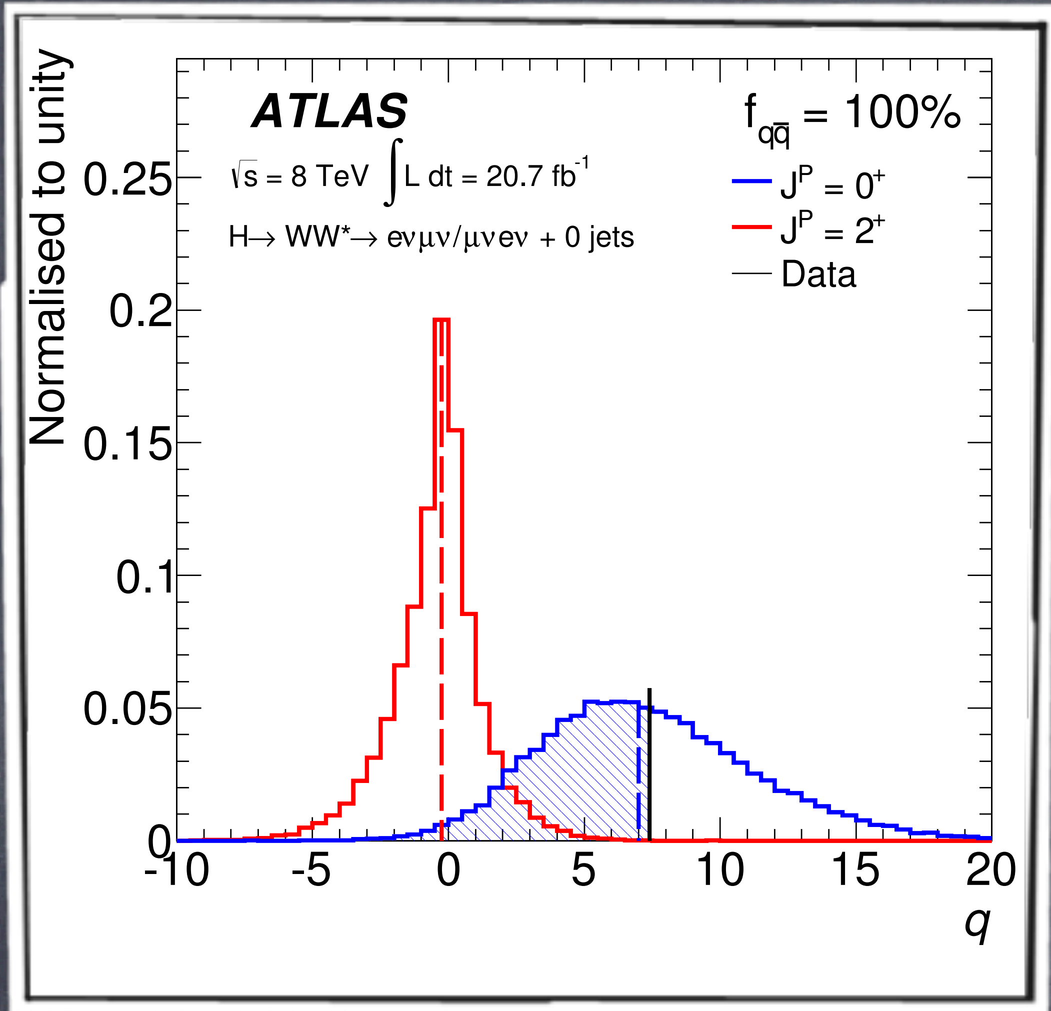
$$p_{H_1} = \text{Prob(more } H_1\text{-like} \mid H_1)$$
$$p_{H_1}(\exp \mid H_0) = 0.37\%,$$
$$p_{H_1}(obs) = 1.5\%$$
$$p_{H_0}(obs) = 31\%$$
$$p_{H_1}^{CL_s}(obs) = 2.2\%$$

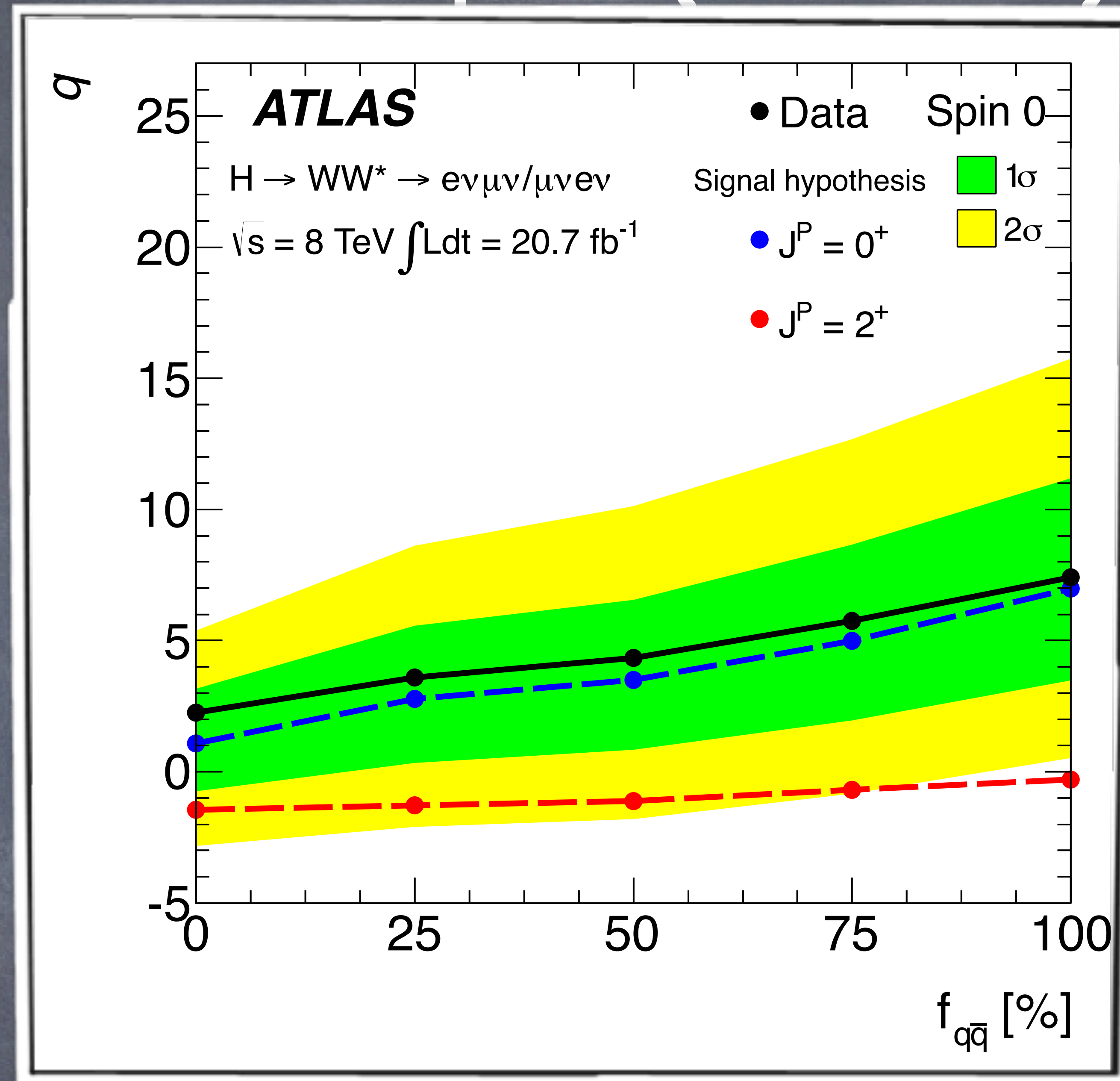
Which means

$J^P=0^-$ is excluded at the 97.8% CL in favour of $J^P=0^+$

Likewise $J^P=1^+,1^-,2^{+m}$ are excluded at the 99.8%,99.4%,83.2% (BDT)

WW Spin (results)





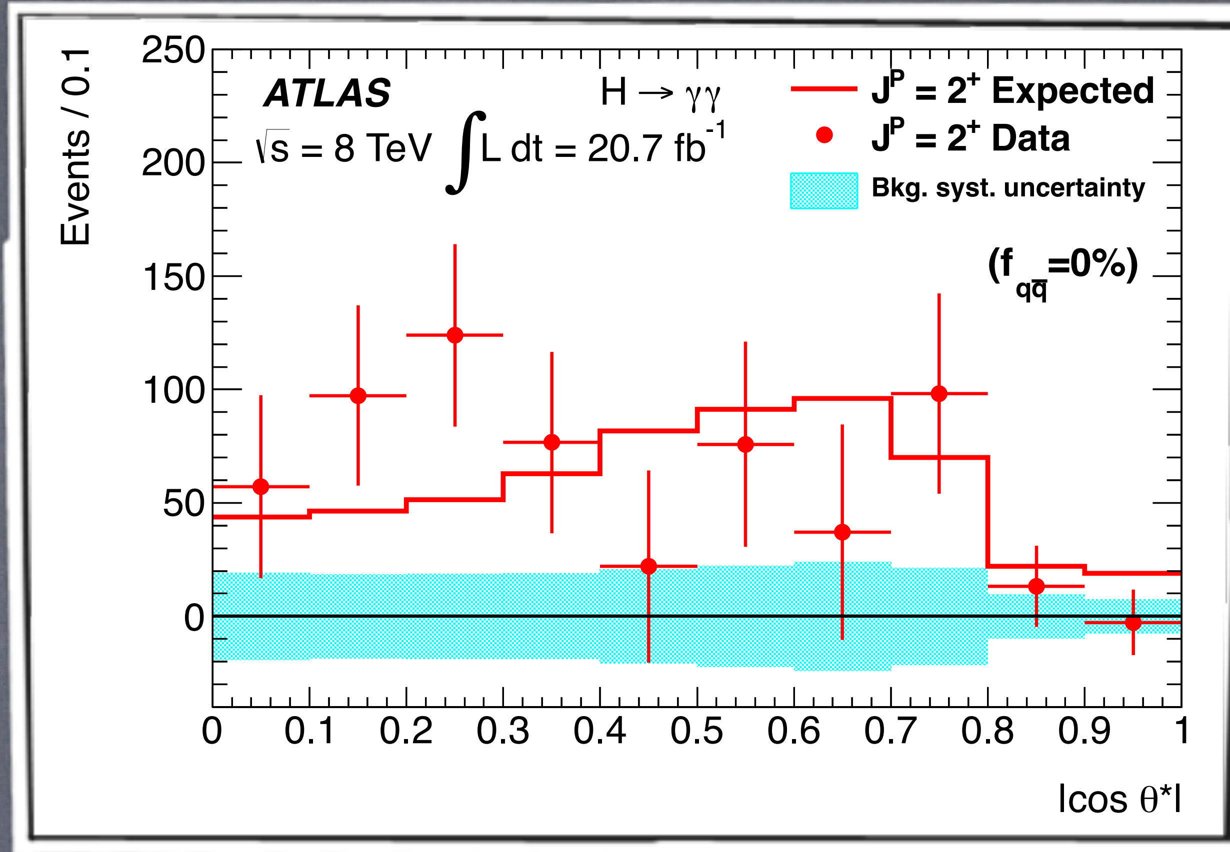
- 2^+ is excluded at the 95% CL (fqq=0%) 99% CL (fqq=100%)
- Thats a compelling evidence for spin 0^+

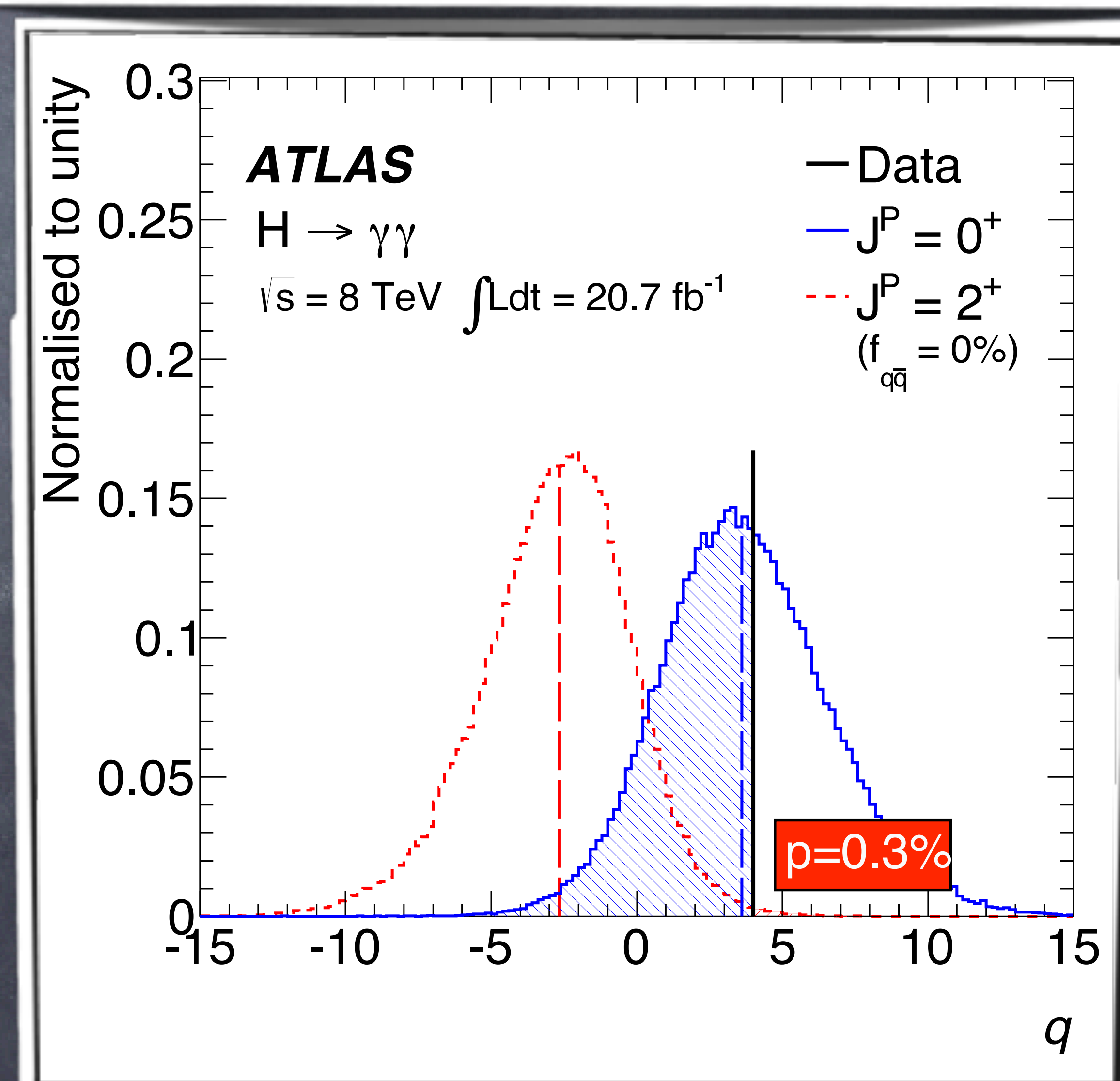
γγ Spin

- Using the angular distribution of the photons in the helicity ref frame (Collins-Soper)
- Spin 0 hypothesis
  dN/dcos θ *~flat (before cuts)
- Spin 2 hypothesis
  dN/dcos θ *~1+6cos² θ *

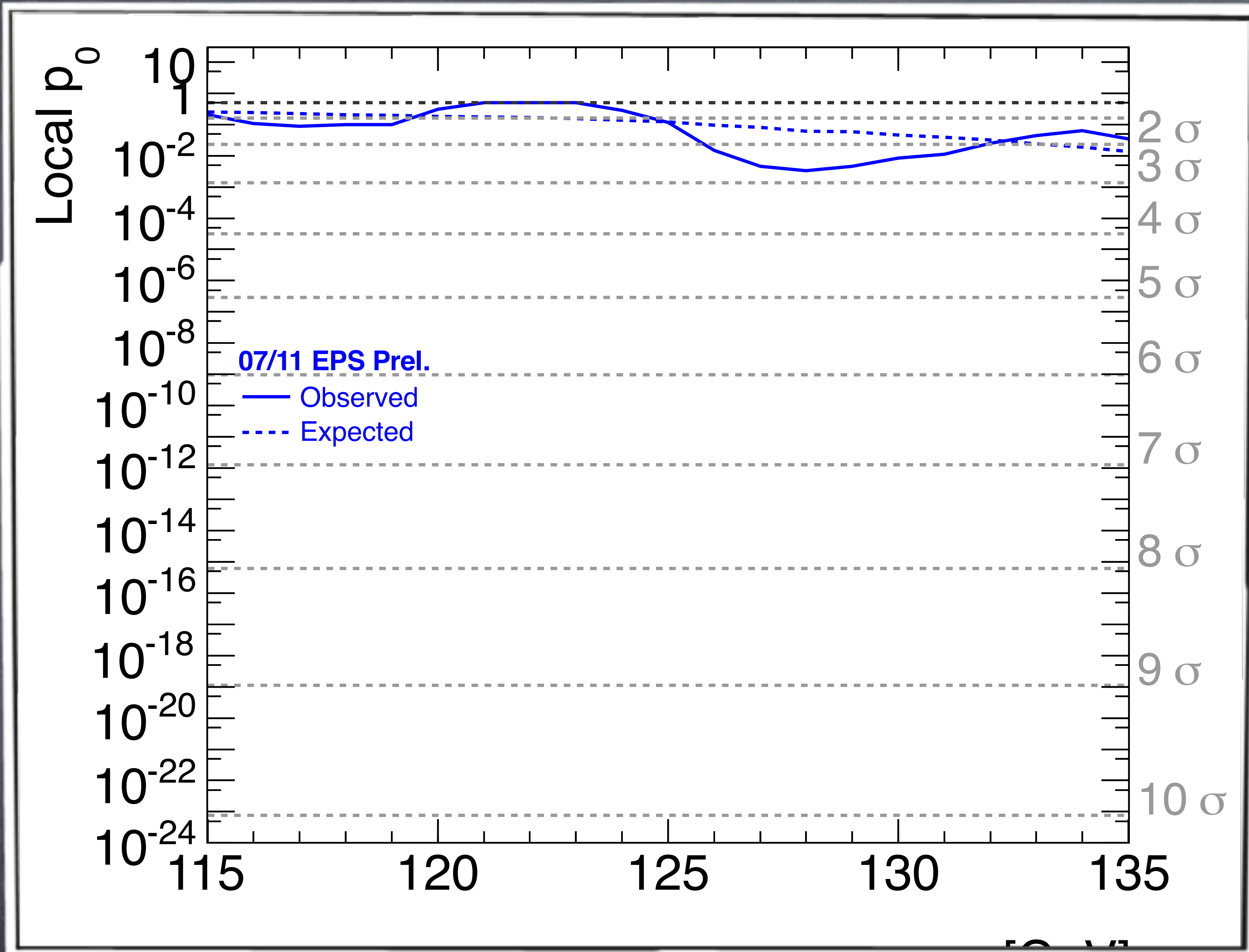
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma 1}-\eta_{\gamma 2})}{\sqrt{1+(pT^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2pT^{\gamma 1}pT^{\gamma 2}}{m^2_{\gamma\gamma}}$$

- Spin 2 is excluded at the CLs=99.3% CL (100% gg)





Combining Results



Local p_0
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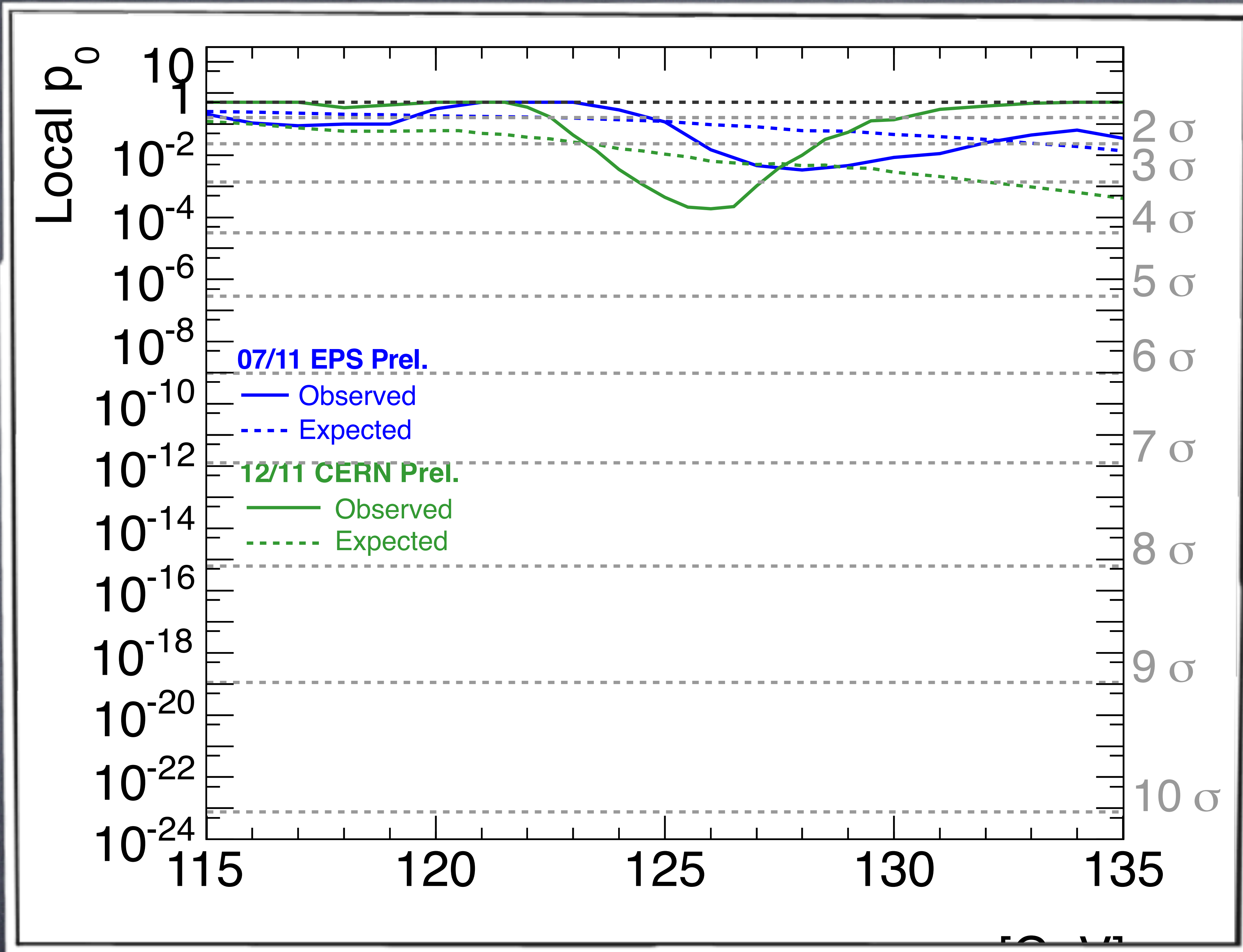
10^{-24}
115
120
125
130
135
07/11 EPS Prel.
Observed
Expected
2 σ
3 σ
4 σ
5 σ
6 σ
7 σ
8 σ
9 σ
10 σ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2 σ
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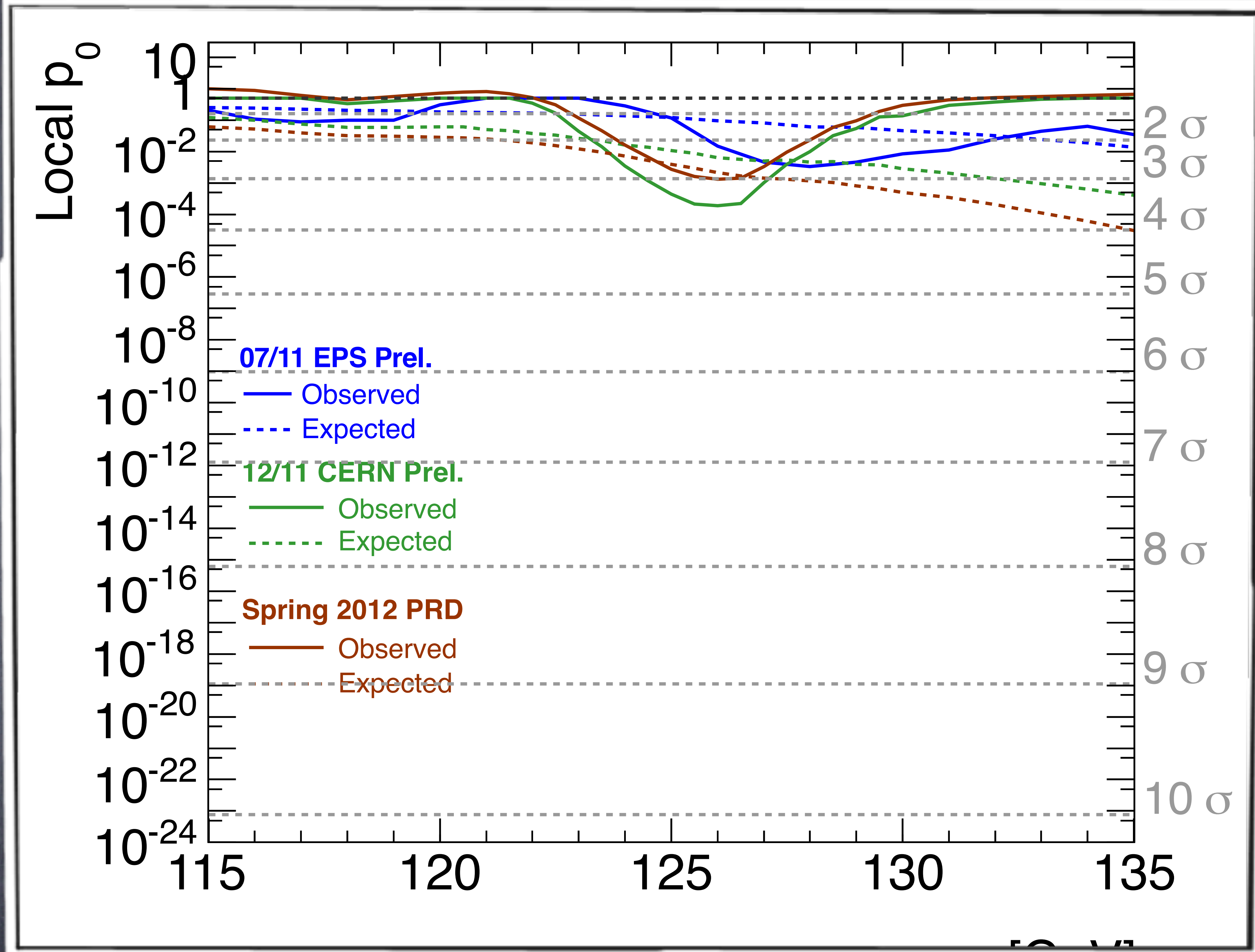
10 σ
07/11 EPS Prel.
Observed
Expected
12/11 CERN Prel.
Observed
Expected



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07/11 EPS Prel.
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12/11 CERN Prel.
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Spring 2012 PRD
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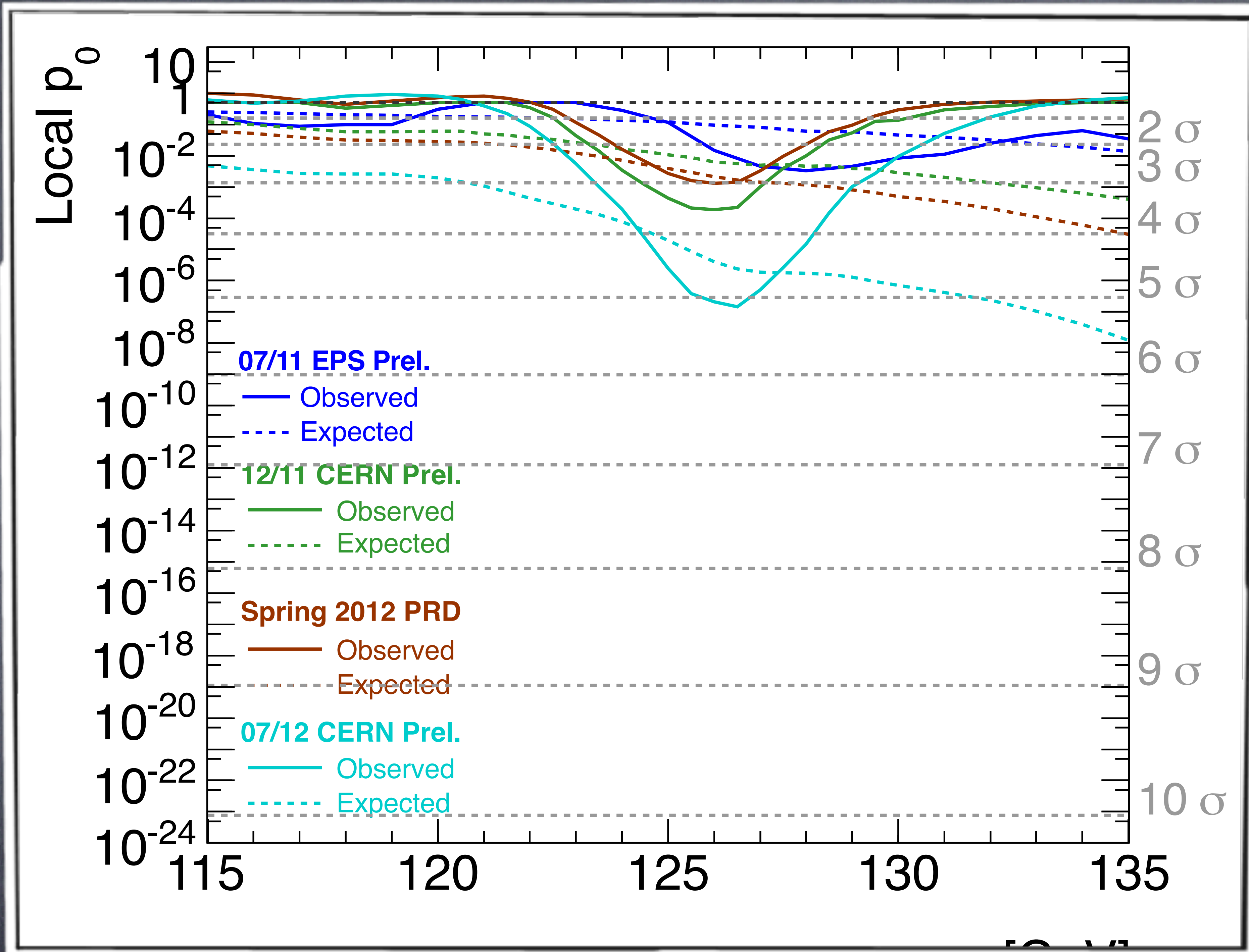
Expected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07/11 EPS Prel.
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12/11 CERN Prel.
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Spring 2012 PRD
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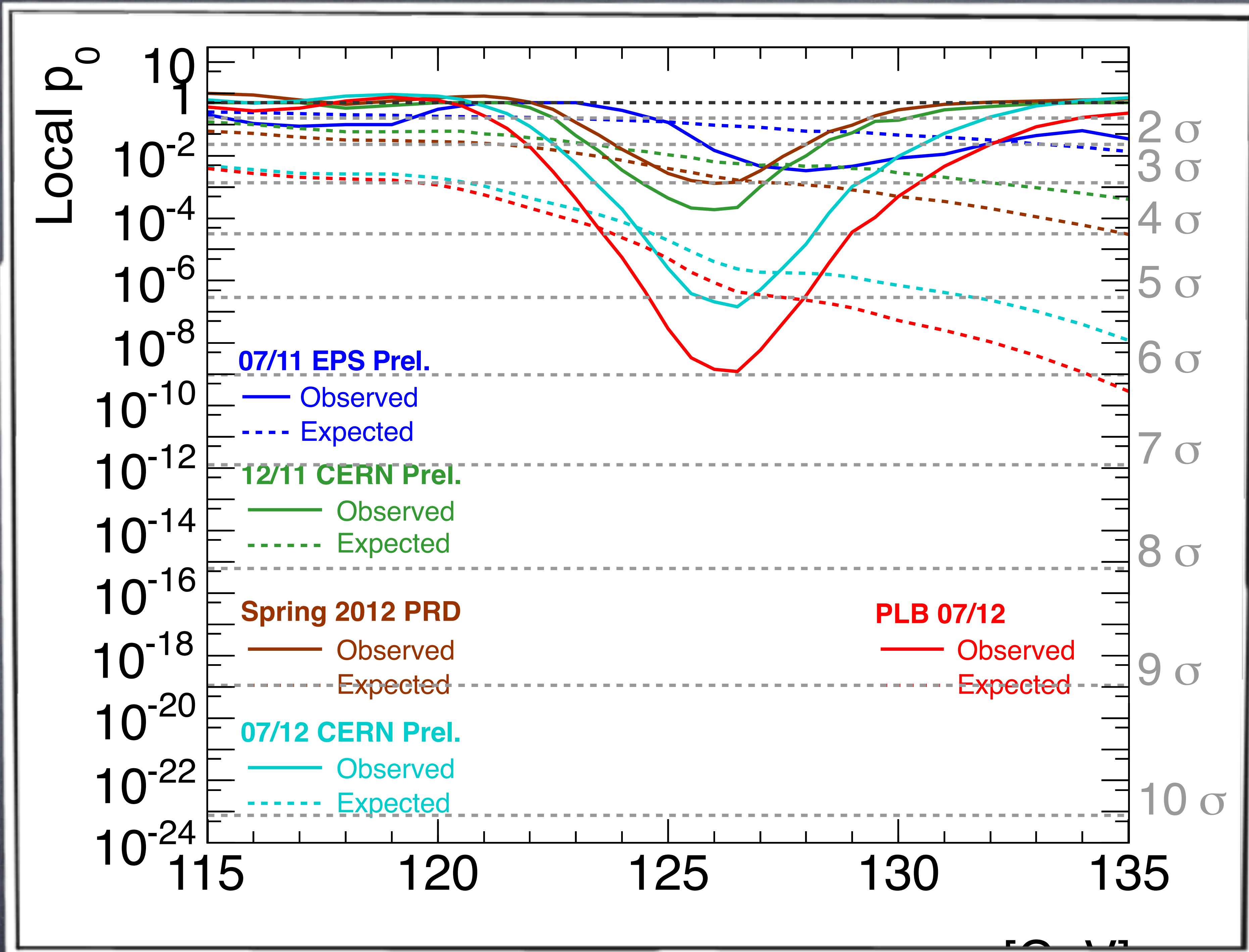
07/12 CERN Prel.
Observed
Expected



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07/12 CERN Prel.
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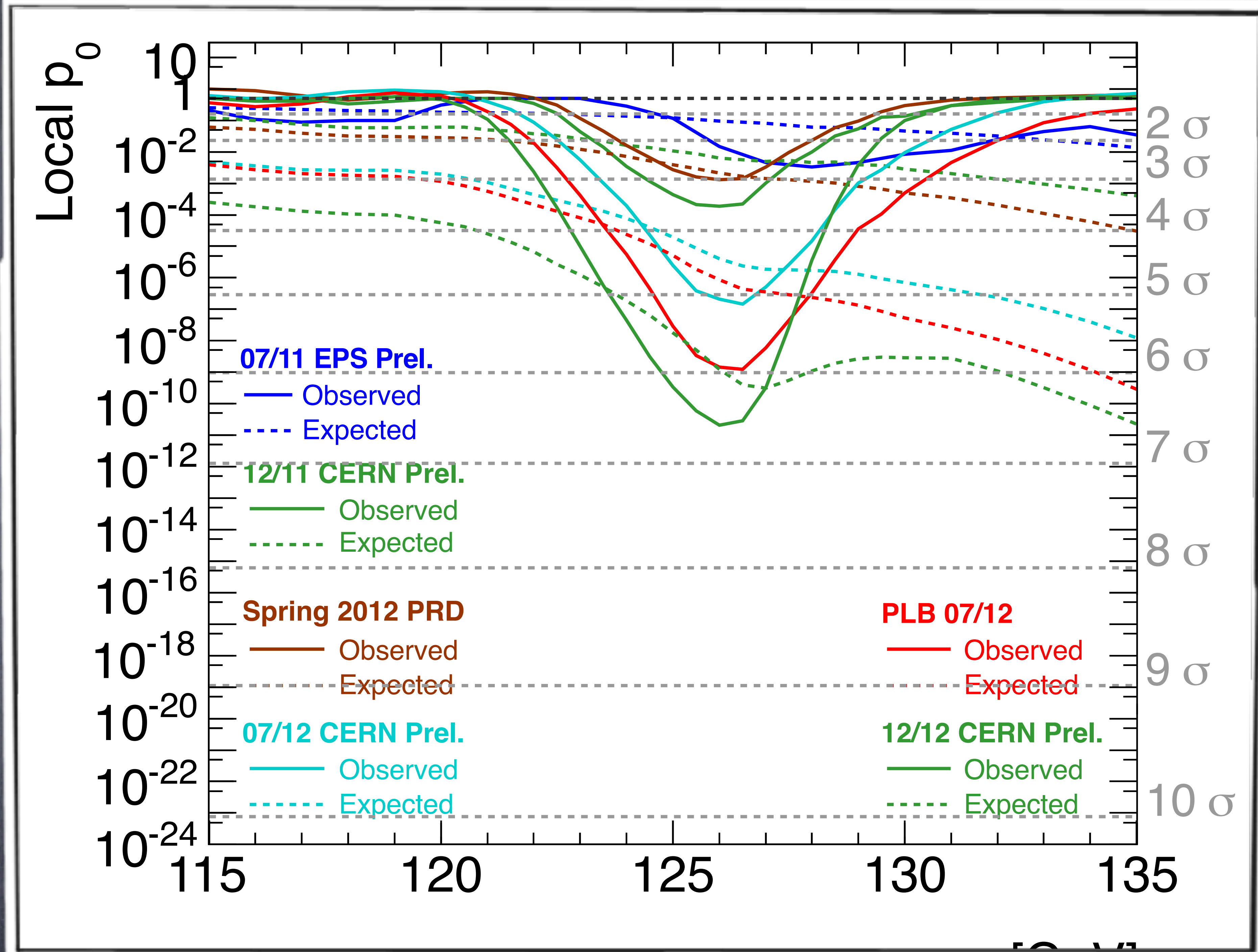
PLB 07/12
Observed
Expected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Observed
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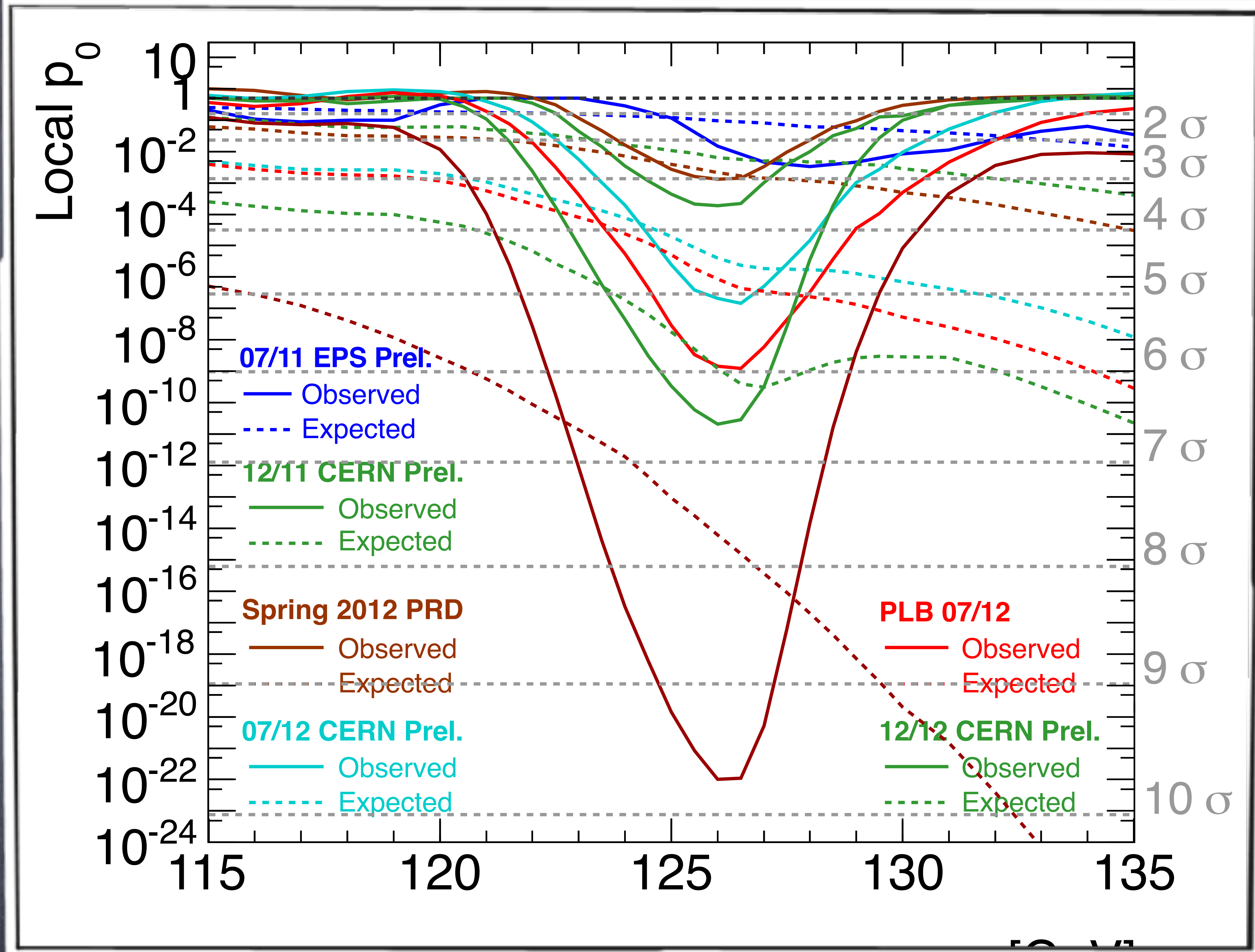
Local p_0
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Expected
Spring 2012 PRD
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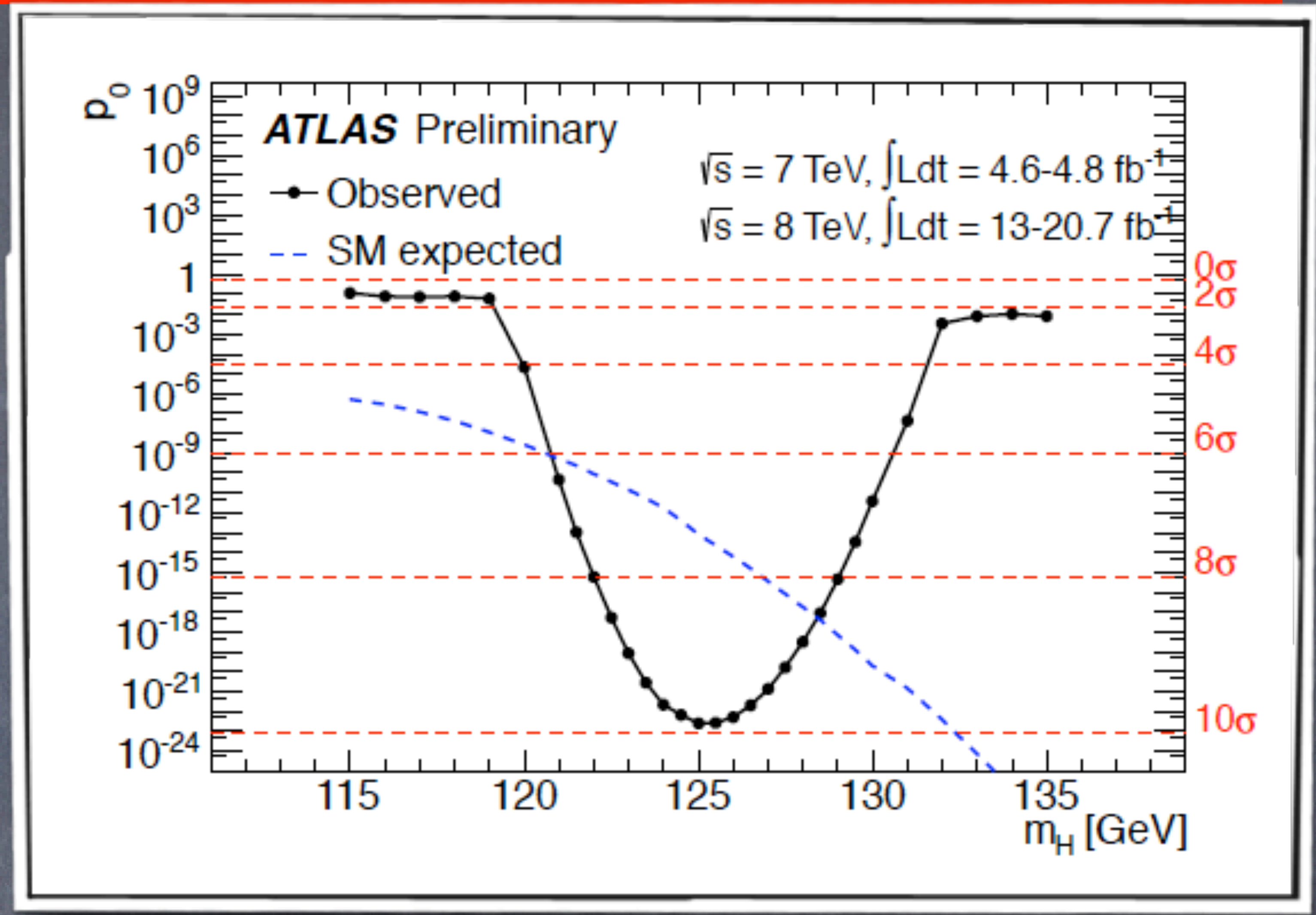
Expected
07/12 CERN Prel.
Observed
Expected
PLB 07/12
Observed
Expected
12/12 CERN Prel.
Observed
Expected

This is the End of the Beginning

- The MSS are taken into account with a modified asymptotic approximation
- **10 σ**

  When was July 4th?



ATLAS EXPERIMENT

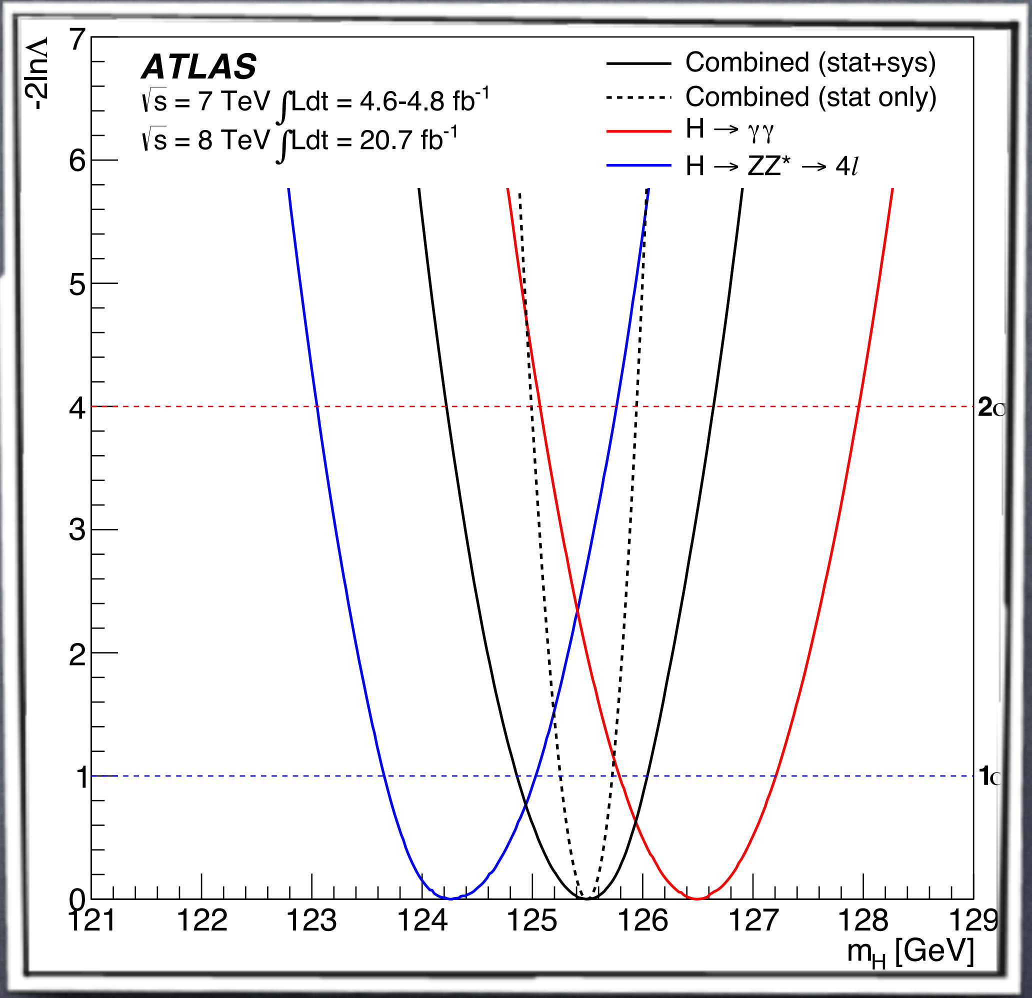
Combining 4 ℓ and γγ

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H,\hat{\mu}_{\gamma\gamma},\hat{\mu}_{4\ell},\hat{\theta})}$$

Here, the signal strengths are left free in the fit

$$m_{4l} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)$$

$$m_{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst)GeV$$

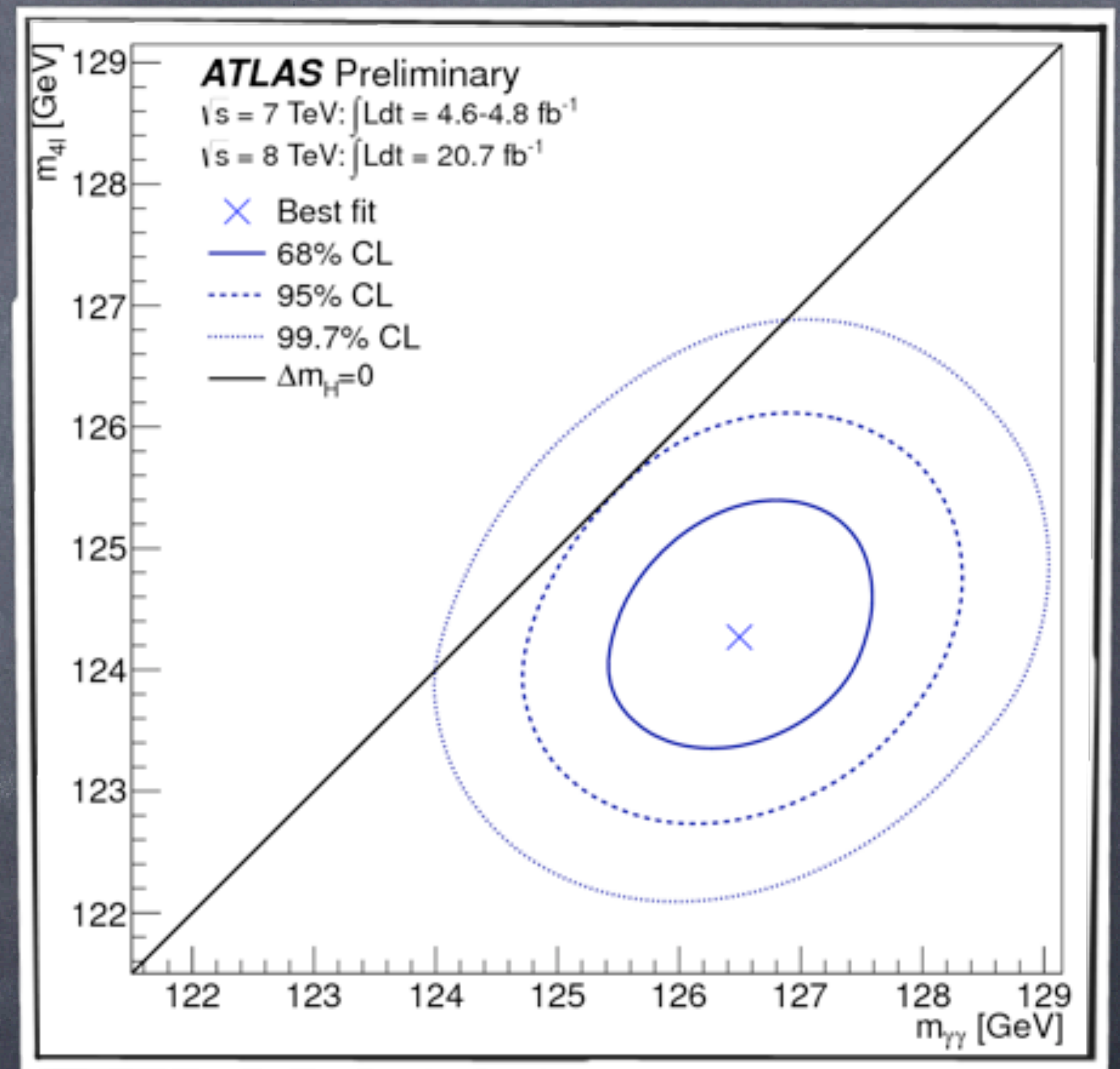


$$m_H = 125.5 \pm 0.2\ (stat)^{+0.5}_{-0.6}\ (syst)\ \text{GeV}$$

Consistency of 4 ℓ and $\gamma\gamma$ mass measurenst

$$\Lambda(m_H^{\gamma\gamma}, m_H^{4l}) = \frac{L\left(m_H^{\gamma\gamma}, m_H^{4l}, \hat{\hat{\theta}}(m_H^{\gamma\gamma}, m_H^{4l})\right)}{L\left(\hat{m}_H^{\gamma\gamma}, \hat{m}_H^{4l}, \hat{\theta}\right)}$$

- The two mass measurements are almost uncorrelated
- Largest correlation is the overall e/γ energy scale (from Z->ee calibration) affecting mostly the $\gamma\gamma$ channel, pulling it down by 350 MeV



ATLAS EXPERIMENT

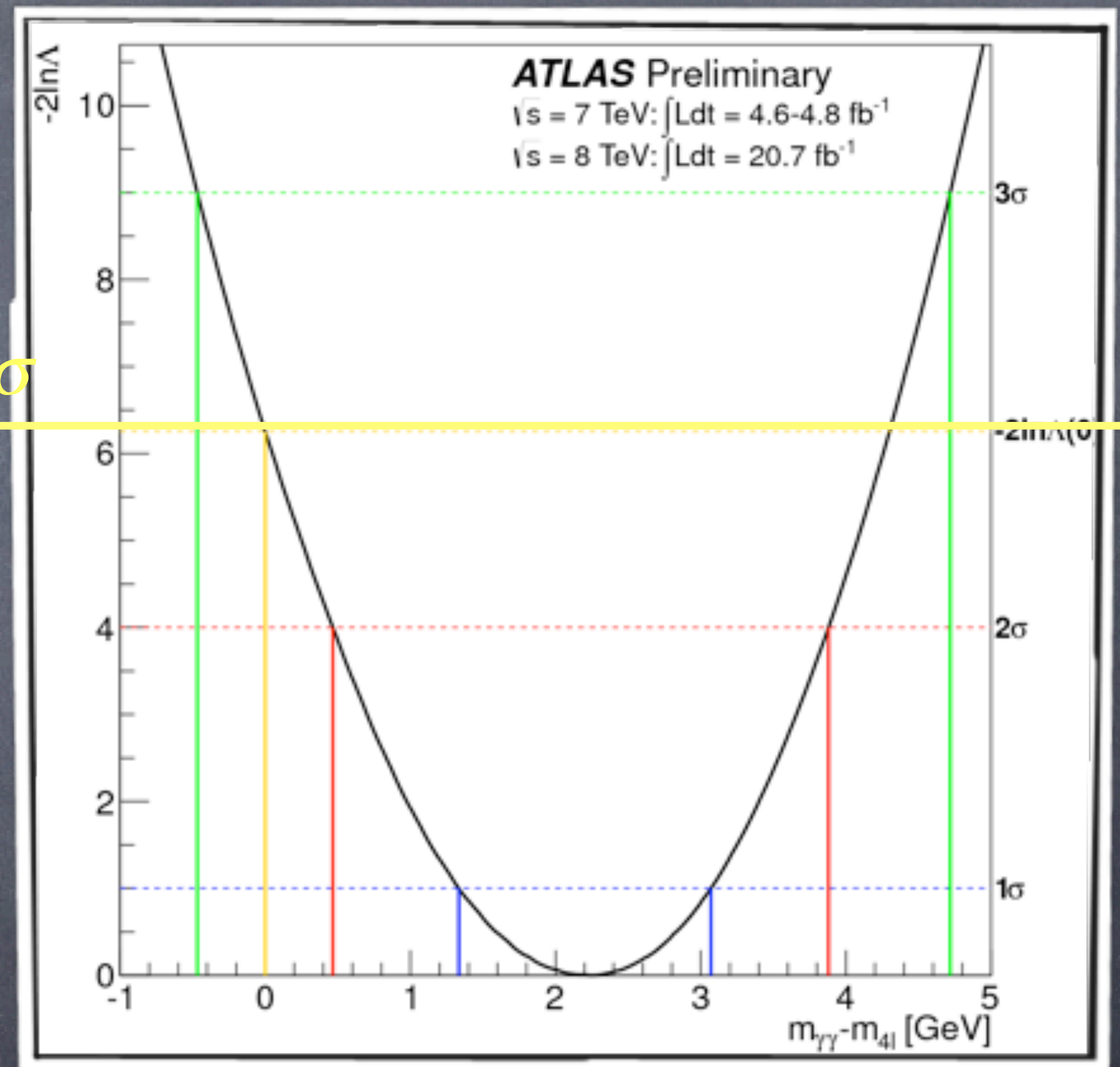
Consistency of 4 ℓ and $\gamma\gamma$ mass measuremenst

$$\Lambda(\Delta m_H) = \frac{L(\Delta m_H\,,\, \hat{\hat{\mu}}_{\gamma\gamma}(\Delta m_H)\,,\, \hat{\hat{\mu}}_{4\ell}(\Delta m_H)\,,\, \hat{\hat{m}}_H(\Delta m_H)\,,\, \hat{\hat{\theta}}(\Delta m_H))}{L(\hat{\Delta m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{m}_H, \hat{\theta})}$$

- Test the $\Delta m_H=0$ hypothesis
- The (2-sided) probability for a single Higgs Boson to produce a value of the test statistic disfavoring the $\Delta m_H=0$ hypothesis more than the observed is 1.2% (2.5 σ)

$$q = -2\log\Lambda(\Delta m_H)$$

$$\sqrt{q(\Delta m_H = 0)} = 2.5\sigma$$

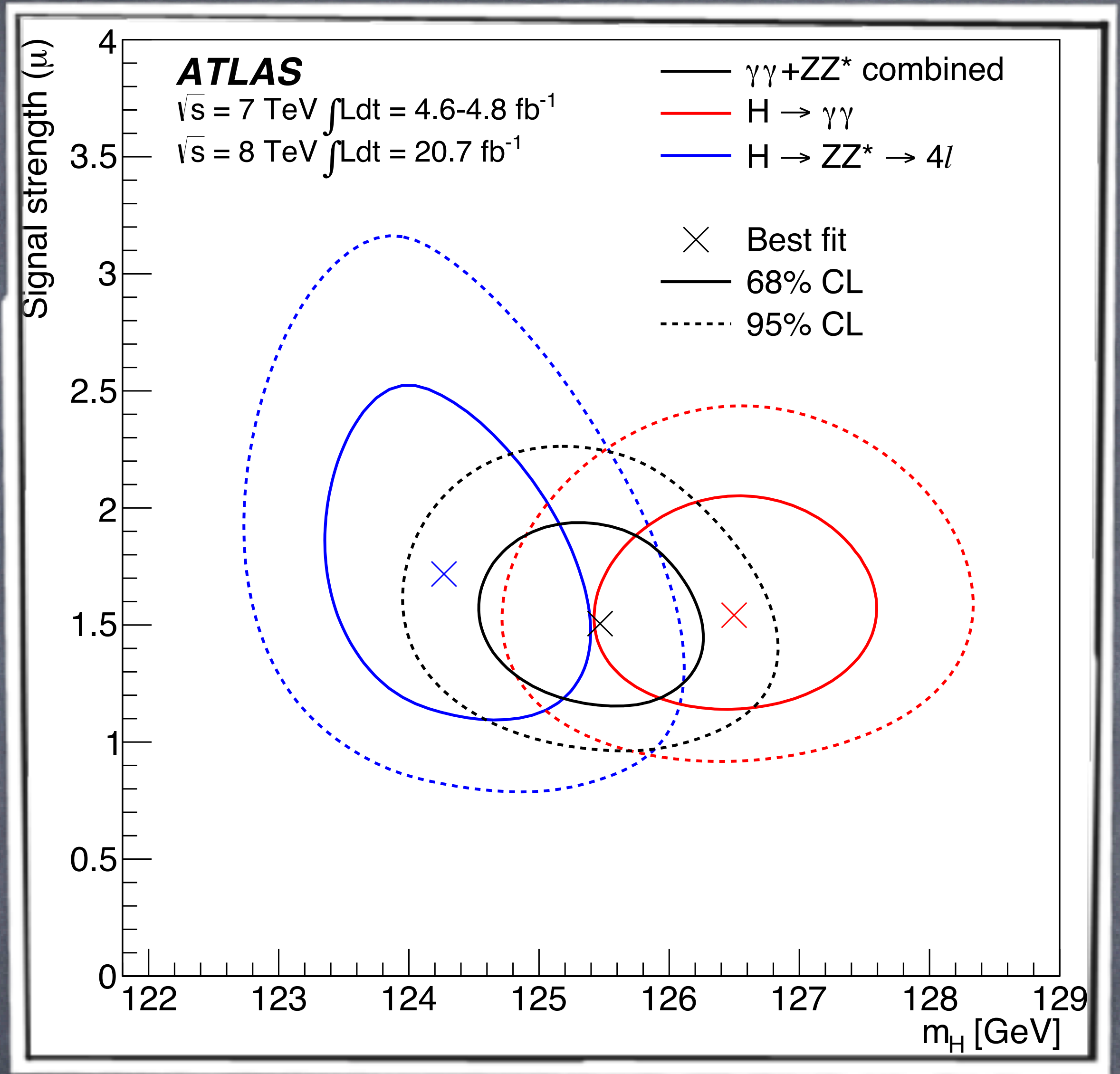


- Using toy experiments similar results are achieved (2.4 σ)
- Using rectangular pdf for ESS, the mass difference significance is reduced to <2 σ (p-value=8%)

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

Combining 4 ℓ and γγ

- Let $q = -2\log\Lambda(\mu, m_H; \theta)$ (2 parameters of interest)



$$\hat{\mu} = 1.43 \pm 0.16\ (stat) \pm 0.14\ (syst)$$

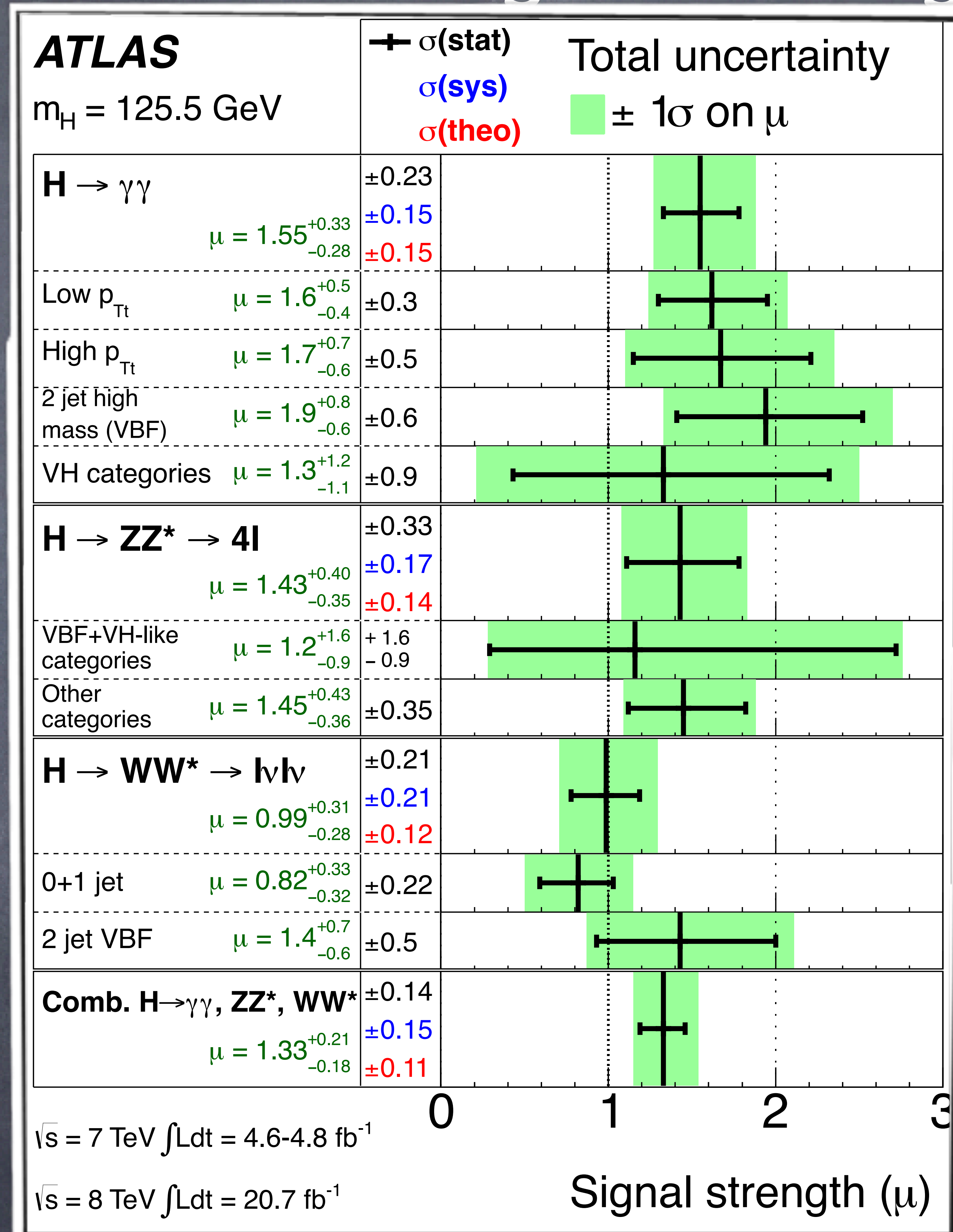
$$m_H = 125.5 \pm 0.2\ (stat)^{+0.5}_{-0.6}\ (syst)\ \text{GeV}$$

Significance and Production Signal Strength

$$\Lambda(\mu; m_H) = \frac{L(\mu, \hat{\hat{\theta}}(\mu); m_H)}{L(\hat{\mu}, \hat{\theta}; m_H)}$$

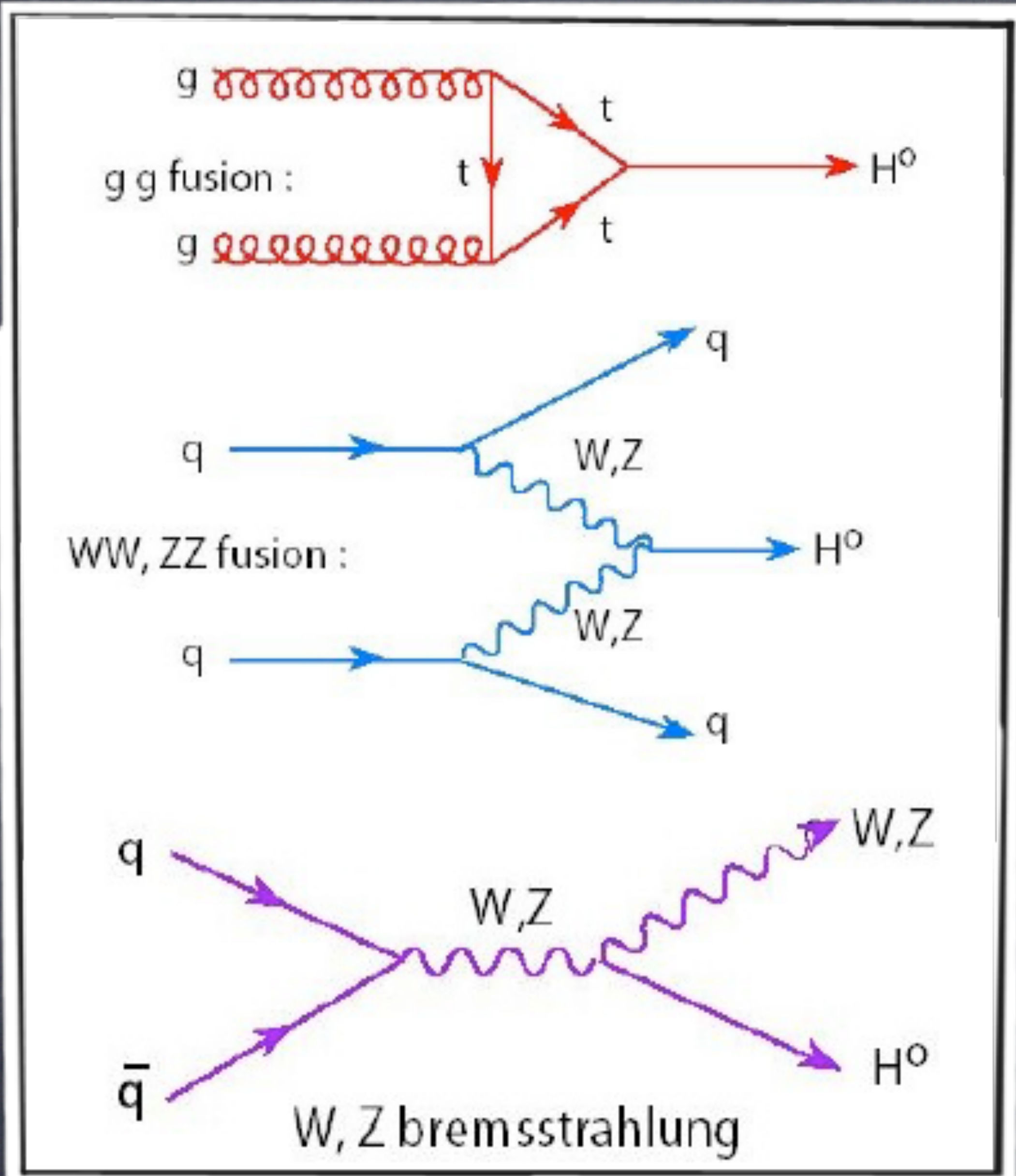
$\gamma\gamma$	$\mu = 1.55 \pm 0.3$
ZZ	$\mu = 1.43 \pm 0.4$
WW	$\mu = 1.0 \pm 0.3$
Combined	$\mu = 1.33 \pm 0.2$

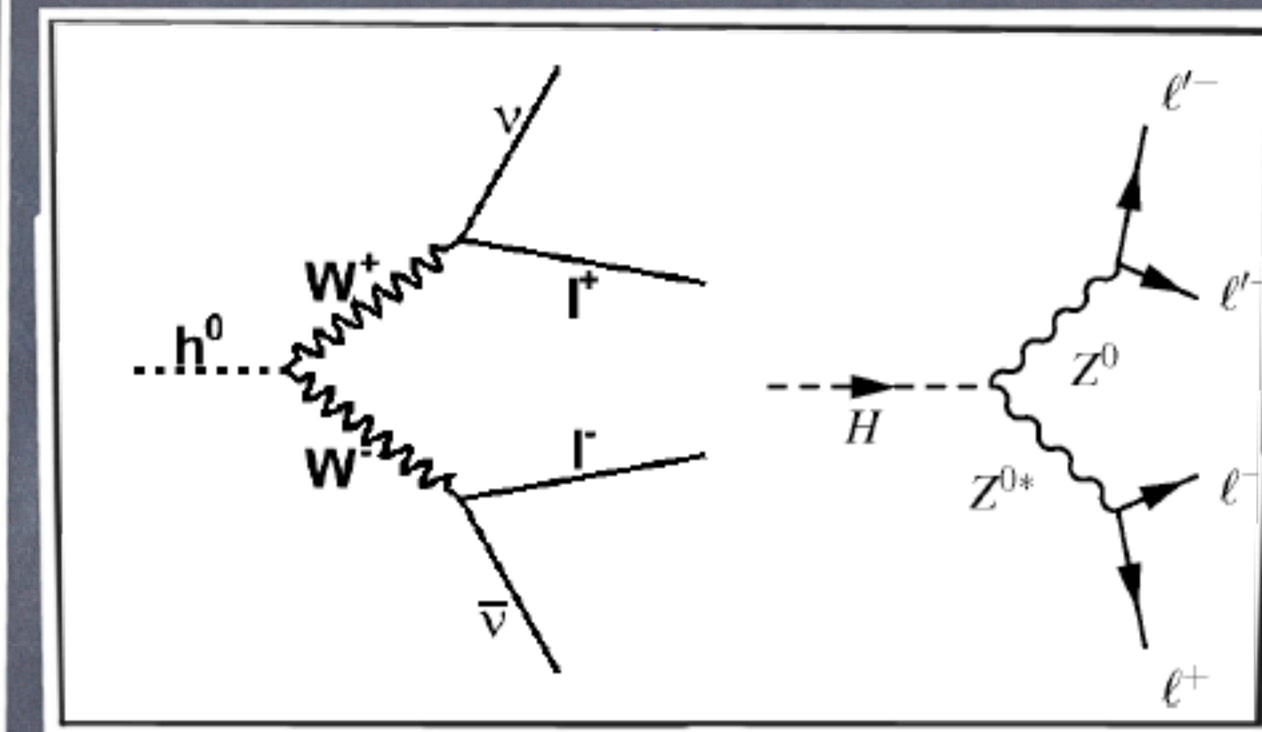
- Changing the mass value between 124.5-126.5 GeV changes the best fitted signal strength by 4%

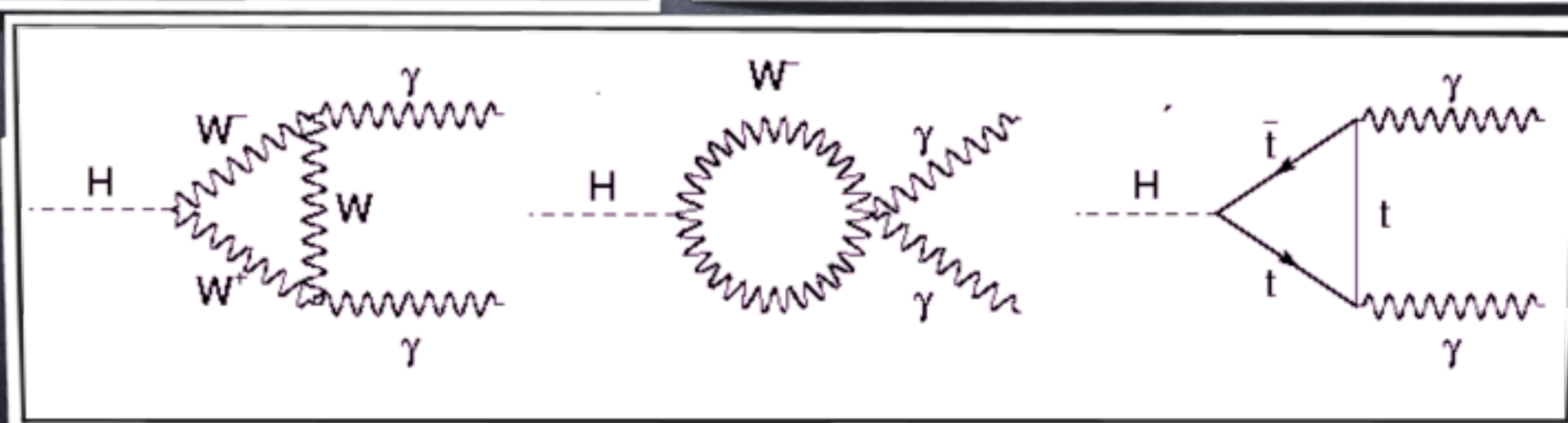


Analysis of Higgs Couplings

- A lot of information is contained in the various production and decay modes of the Higgs allowing us to perform various tests
 (direct and indirect via loops)







The Model Notations

$$n^i = n_s^i + n_b^i$$

$n_s^{\,i}$
i=γγ,4l.lνlν,...
number of events in Channel i

μ^k
Production Modes
k=ggF,VBF,VH,ttH
Production Mode k Strength

$A \times \varepsilon$
Acceptance x Efficiency

Decay Rates
BR^i
Deacay Channel i BR

$$n_s^{\,i} = \mu\left(\sum_{\text{Production mode k}} \mu^k \sigma_{SM}{}^k \times A^{ki} \times \varepsilon^{ki}\right) \times \mu^i Br^i \times Lumi^i$$

μ
Global Sugnal Strength

$\sigma^k{}_{SM}$
Production Mode k cross section

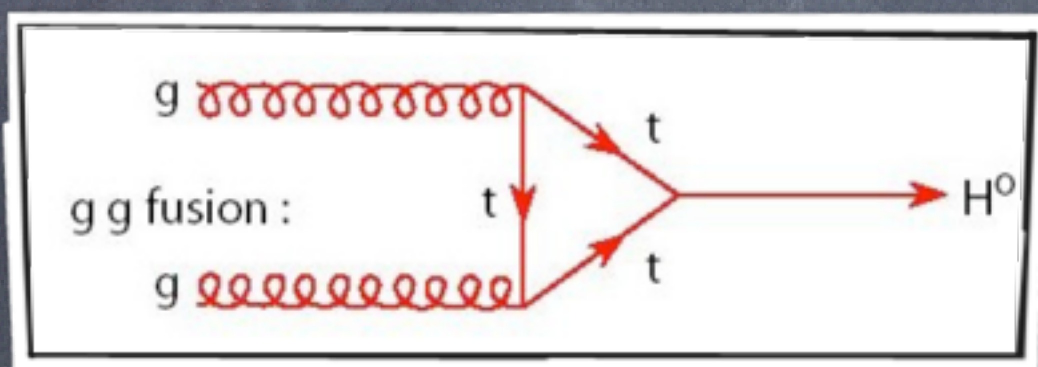
μ^i
i=γγ,4l.lνlν,...
Decay Channel i Strength

$Lumi^i$
Analayzed Luminosuty for Channel i

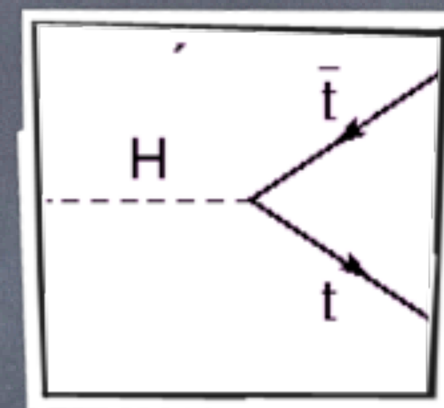
ATLAS EXPERIMENT

Analysis of Higgs Couplings

- The wealth of couplings and possibilities led to defining some benchmarks by the LHC Higgs Cross Section group
- For each coupling g_i, define $k_i = g_i/g_i^{SM}$, so if the coupligs are SM like we find that ki=1



$$k_g^2(k_b, k_t, k_H)$$

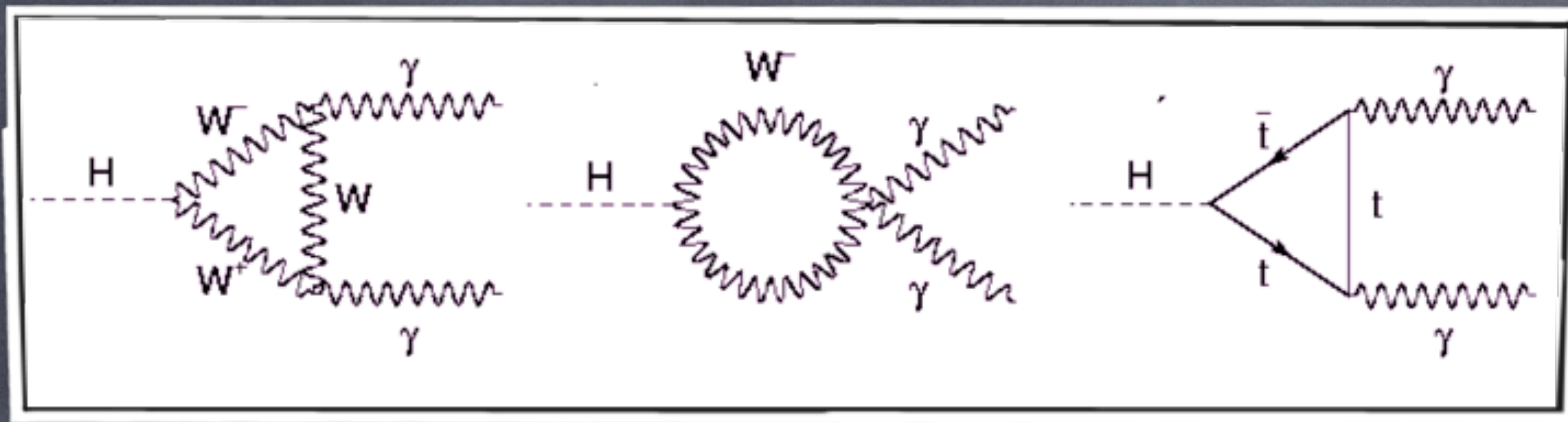


$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = k_t^2$$

$$\frac{\Gamma_{WW}}{\Gamma_{WW}^{SM}} = k_W^2$$

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

Analysis of Higgs Couplings



$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2 \qquad \frac{\Gamma_H}{\Gamma_H^{SM}} = k_H^2(k_i, m_H)$$

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{k_g^2 \cdot k_\gamma^2}{k_H^2}$$

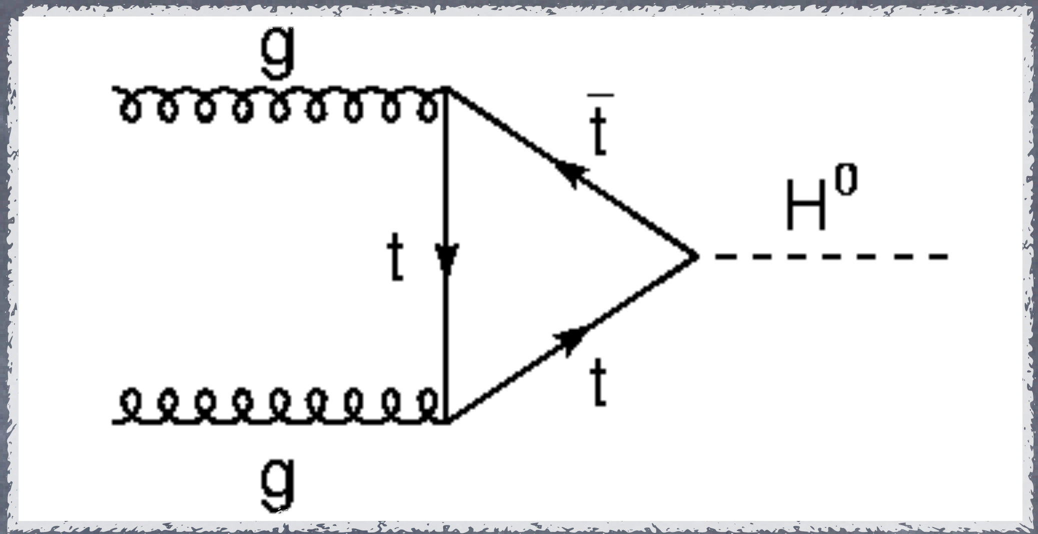
When fitting the couplings to the data, the data might prefer a non-plausible negative k_t to compensate for the non-plausible observed high γγ rate

Test Production Modes

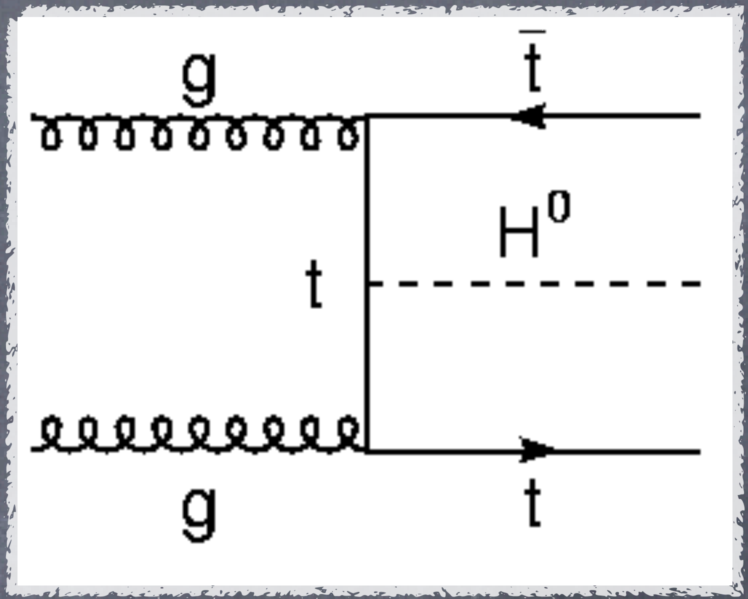
$$n \sim \mu_{ggF} \times \frac{BR^{\gamma\gamma}}{BR^{\gamma\gamma}_{SM}}$$

$\mu_{ggF} \times k^2_t$

Through top loop
Sensitive to
fermion couplings

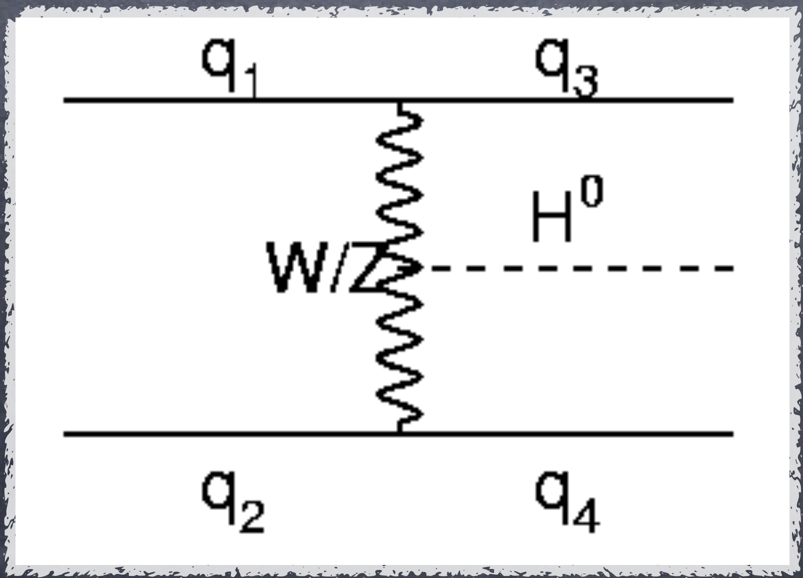


$\mu_{ttH} \times k^2_t$

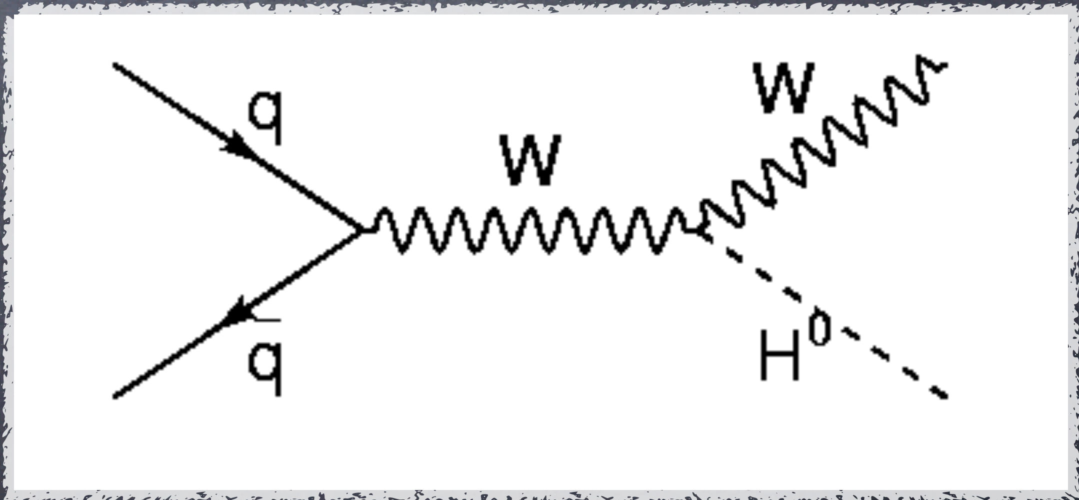


$\mu_{VBF} \times k^2_V$

HVV coupling
Test custodial
symmetry



$\mu_{VH} \times k^2_V$



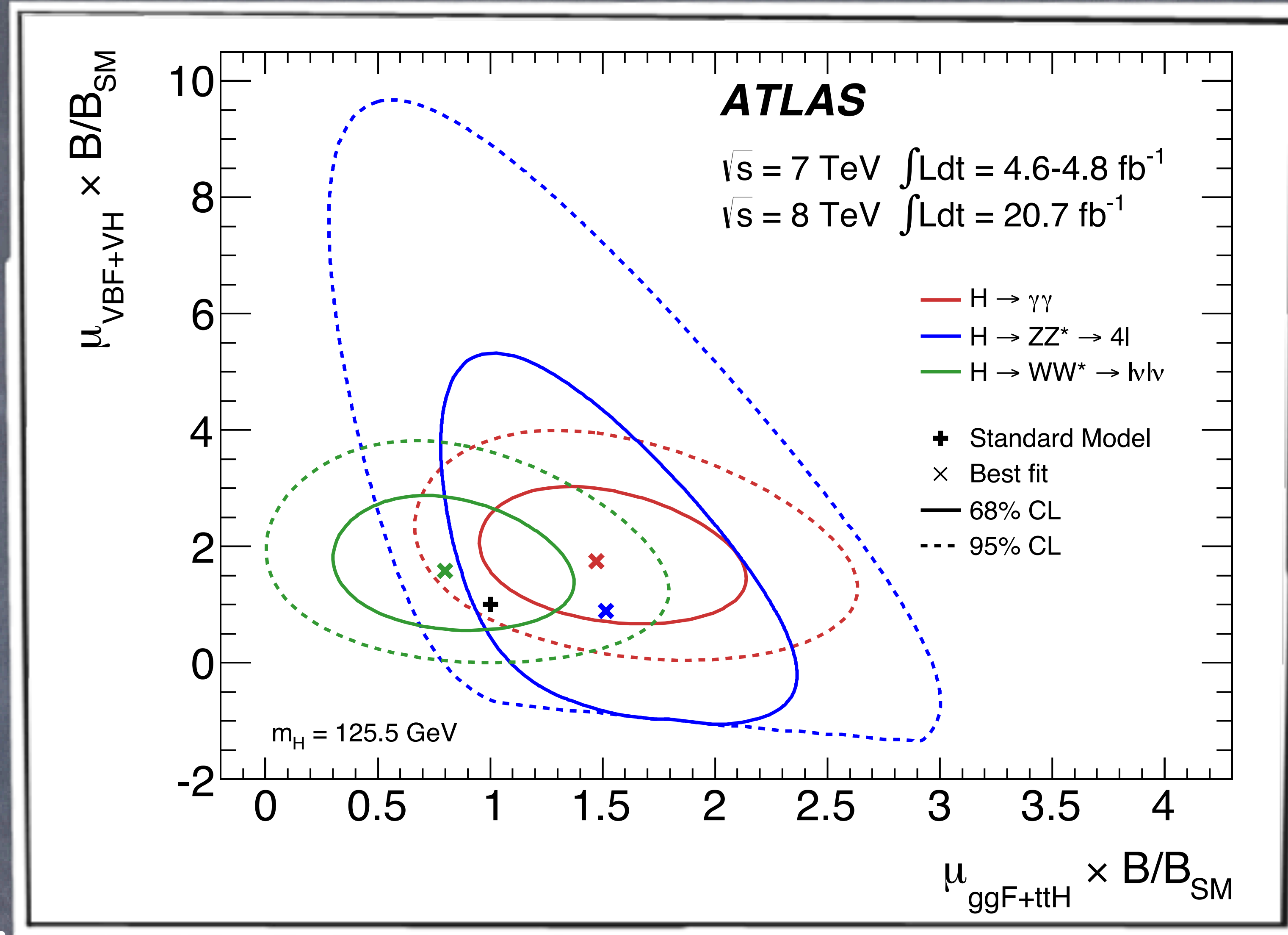
Probing VBF

$$n \sim \mu_{ggF} \times \frac{BR^{\gamma\gamma}}{BR^{\gamma\gamma}_{SM}}$$

To simplify assume

$$\mu_{ggF} = \mu_{ttH} \equiv \mu_{ggF+ttH}$$

$$\mu_{VBF} = \mu_{VH} \equiv \mu_{VBF+VH}$$



Cannot combine,
BRs do not factor out

Probing VBF

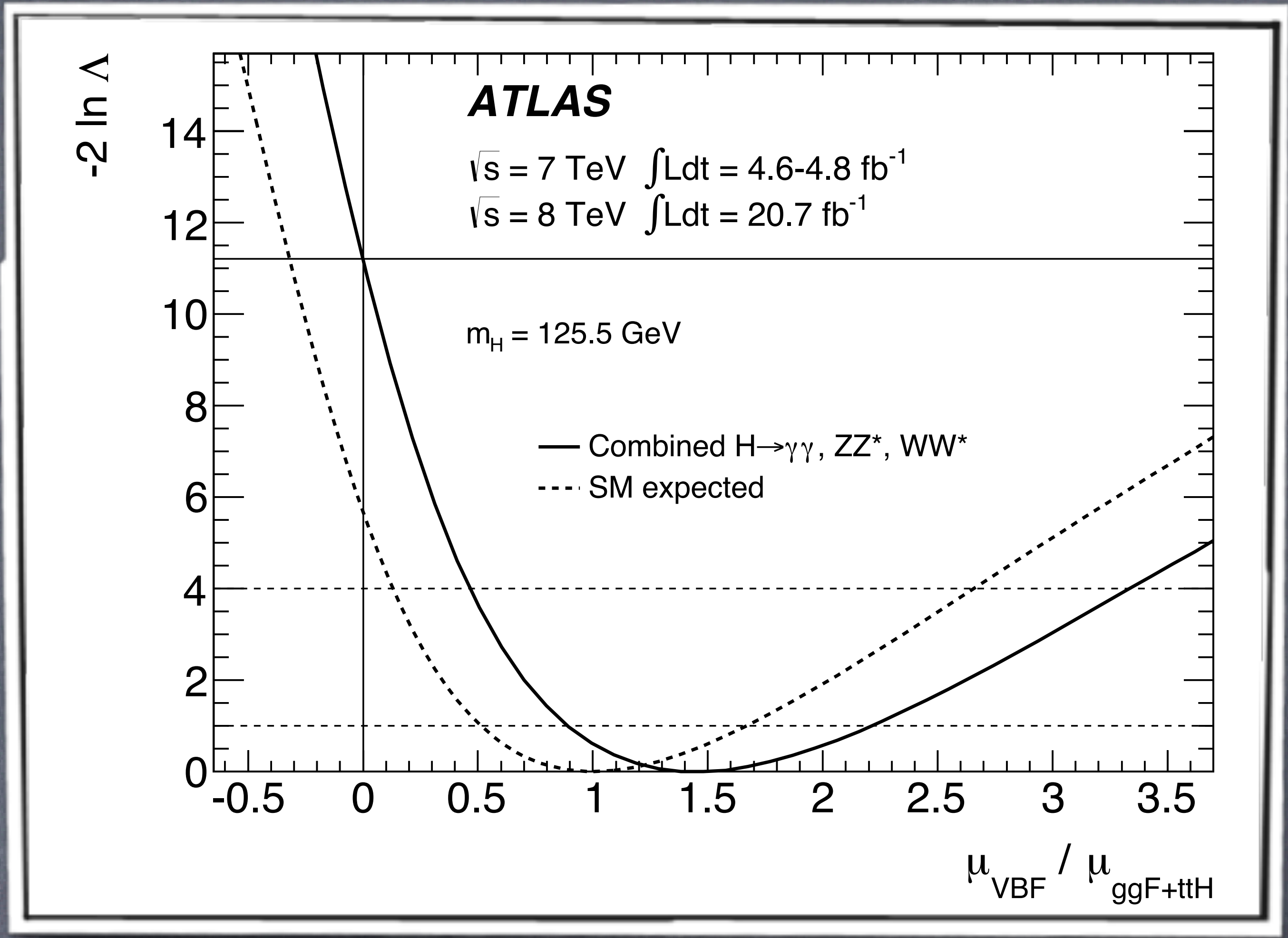
Factor out the BR by fitting ratios (same channel) and performed a combined fit

$$\frac{\mu_{VBF+VH} \times \dfrac{BR^{\gamma\gamma}}{BR^{\gamma\gamma}_{SM}}}{\mu_{ggF+ttH} \times \dfrac{BR^{\gamma\gamma}}{BR^{\gamma\gamma}_{SM}}} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}
\end{aligned}$$

Evidence for VBF

$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(stat)^{+0.6}_{-0.4}(sys)$$



μ_{VBF}=0 is excluded at

3.3 σ (p-value=0.04%)

Evidence for VBF

$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(stat)^{+0.6}_{-0.4}(sys)$$

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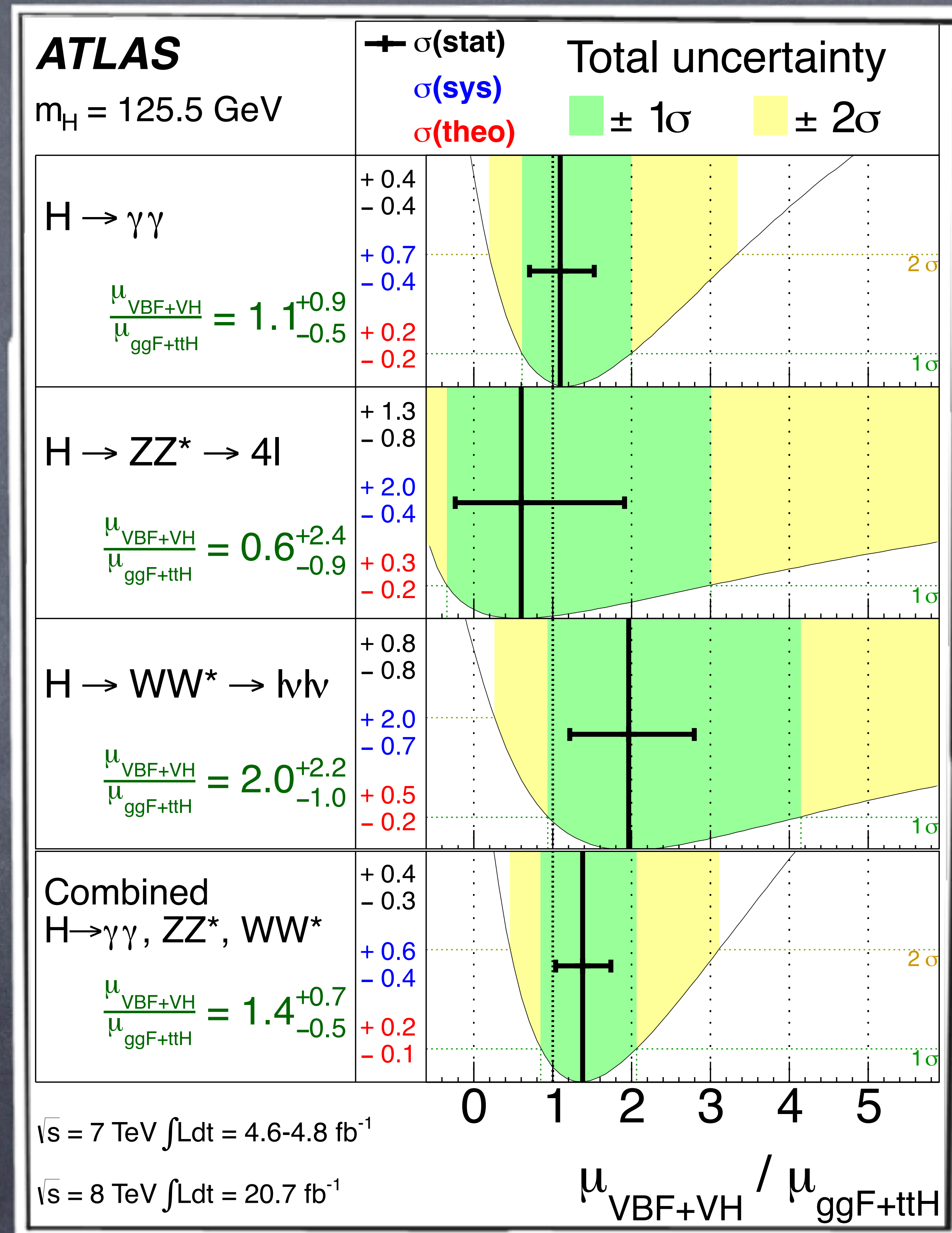


Measuring Couplings: The Model

$$n \sim \mu_{ggF} \times \frac{BR^{\gamma\gamma}}{BR^{\gamma\gamma}_{SM}} \sim \mu_{ggF} \times \frac{\Gamma^{\gamma\gamma}}{\Gamma^{H}} \times \frac{\Gamma^{H}_{SM}}{\Gamma^{\gamma\gamma}_{SM}} \sim \mu_{ggF} \times \frac{g^2_{H\gamma\gamma}}{g^2_{H\gamma\gamma,SM}} \times \frac{\Gamma^{H}_{SM}}{\Gamma^{\gamma\gamma}_{SM}}$$

$$k_\gamma \equiv \frac{g^{H\gamma\gamma}}{g^{H\gamma\gamma}_{SM}}, \qquad k_H{}^2 \equiv \frac{\Gamma^H}{\Gamma^H_{SM}}$$

$$n \sim \mu_{ggF} \times k_\gamma{}^2 \times \frac{1}{k_H{}^2}$$

- To test the compatibility with the SM
  - Make assumptions (MODEL) e.g. universal F and V couplings k_F & k_V
  - Choose parameters of interest, e.g. k_F and k_V
  - Fit the paraeters of interest while profiling the others

Analysis of Higgs Couplings

Make assumptions to test various couplings in the context of a SM Higgs

Simplest assumption, the universal coupling:

$\mu = k^2$

Common scale factor

Free parameter: $\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$ VBF WH ZH			κ^2		

Analysis of Higgs Couplings

Make assumptions to test various couplings in the context of a SM Higgs

- **κ = sqrt(μ):** Universal scaling of couplings to all particles
- **κ_V vs. κ_F:** Spin, vector bosons vs. fermions
- **κ_W vs. κ_Z:** Custodial symmetry, W vs. Z boson
- **κ_q vs. κ_l:** Fermion flavor, quarks vs. leptons
- **κ_u vs. κ_d:** Fermion type, up vs. down

Probing Vector and Fermion Couplings

Probe different couplings for fermions vs bosons

Three variants:

Fermion versus Vector Coupling Models	
Model	Free Parameters
SM Particles Only	$\kappa_F (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_g)$ $\kappa_V (= \kappa_W = \kappa_Z)$
Free Total Width	$\lambda_{FV} = \frac{\kappa_F}{\kappa_V} \leftarrow$ POI $\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$
Free Total Width + Free $\gamma\gamma$ loop	$\lambda_{FV} = \frac{\kappa_F}{\kappa_V} \leftarrow$ POI $\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$ $\kappa_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$

Higgs width and H->$\gamma\gamma$ constrained to SM (only SM particles contribute to loop)

Higgs width left unconstrained

+ k_γ coupling left unconstrained

Probing Vector and Fermion Couplings

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

$$k_H^2 = 0.75 k_F^2 + 0.25 k_V^2$$

k_H Constrains k_F if no invisib decays are considered

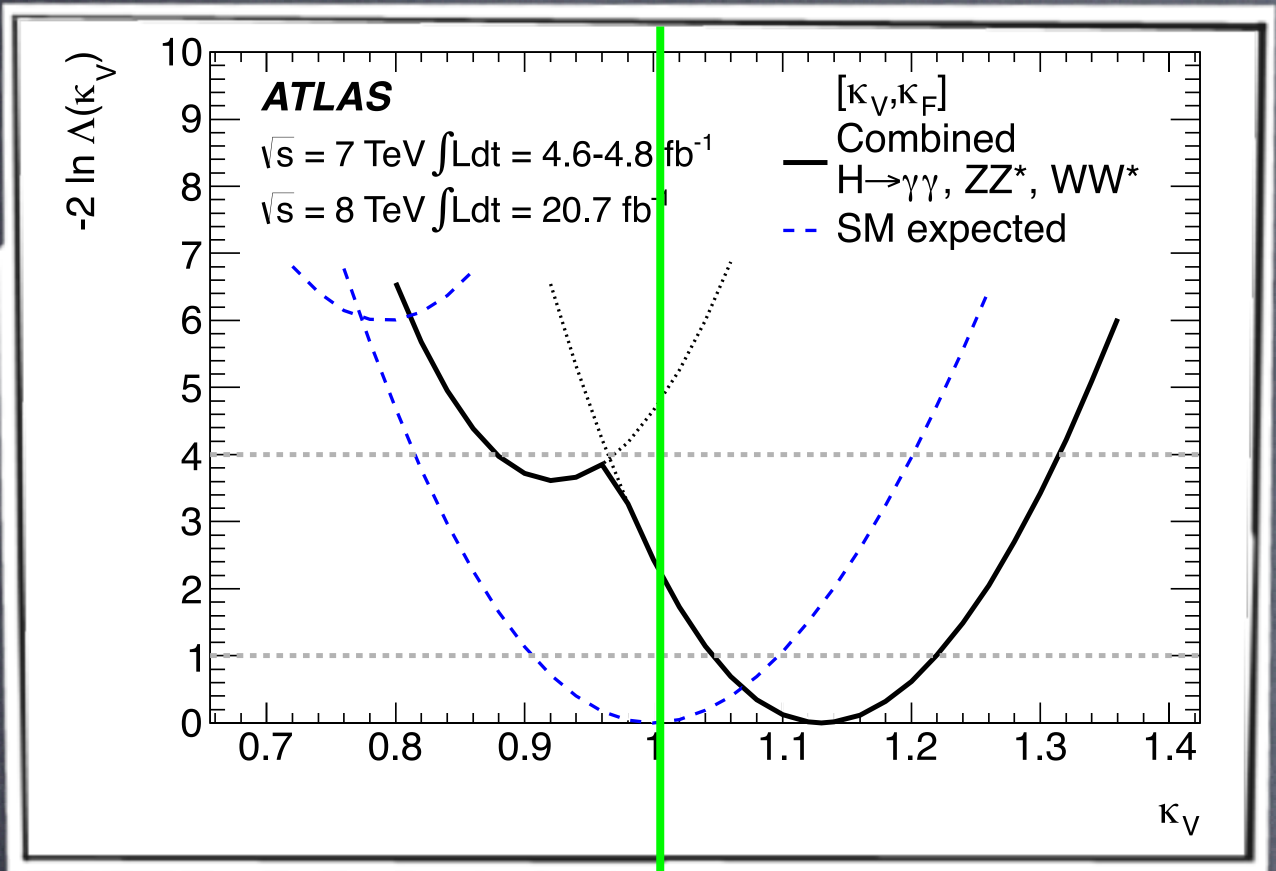
$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$

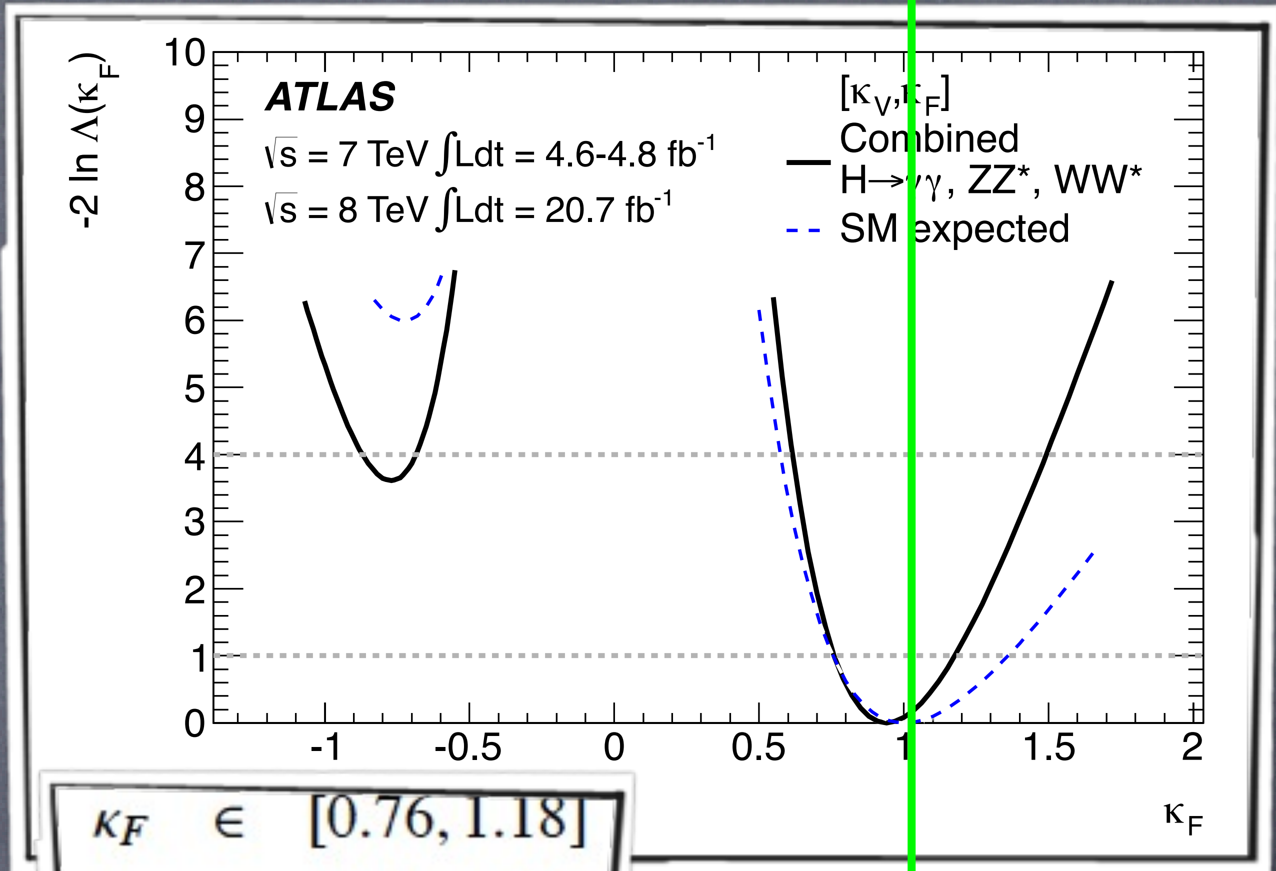
Note the negative interference which might favour negative k_F in the fit

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$
$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2},$$

Probing Vector and Fermion Couplings

Non SM minimum is compatible at the 1 sigma level





$\kappa_F \in [0.76, 1.18]$

$\kappa_V \in [1.05, 1.22]$

High sensitivity to k_F through the gg loop and the Higgs width. k_F is largely deviating from zero

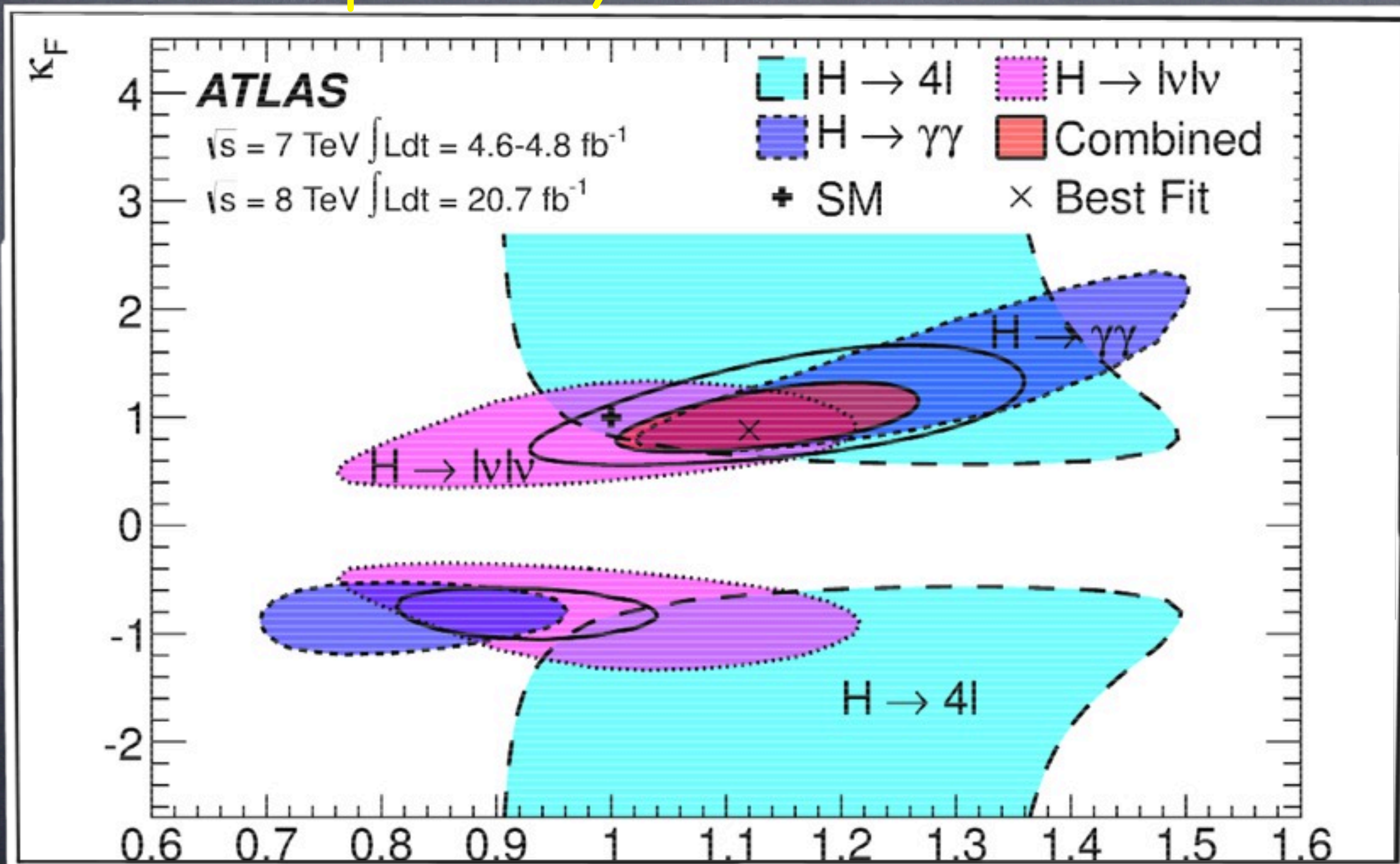
The logical game:

The high $\gamma\gamma$ rate pulls k_W (=k_V) up and keeps k_t positive

Probing Vector and Fermion Couplings

Non SM minimum is compatible at the 1 sigma level

2D compatibility with SM is 12%



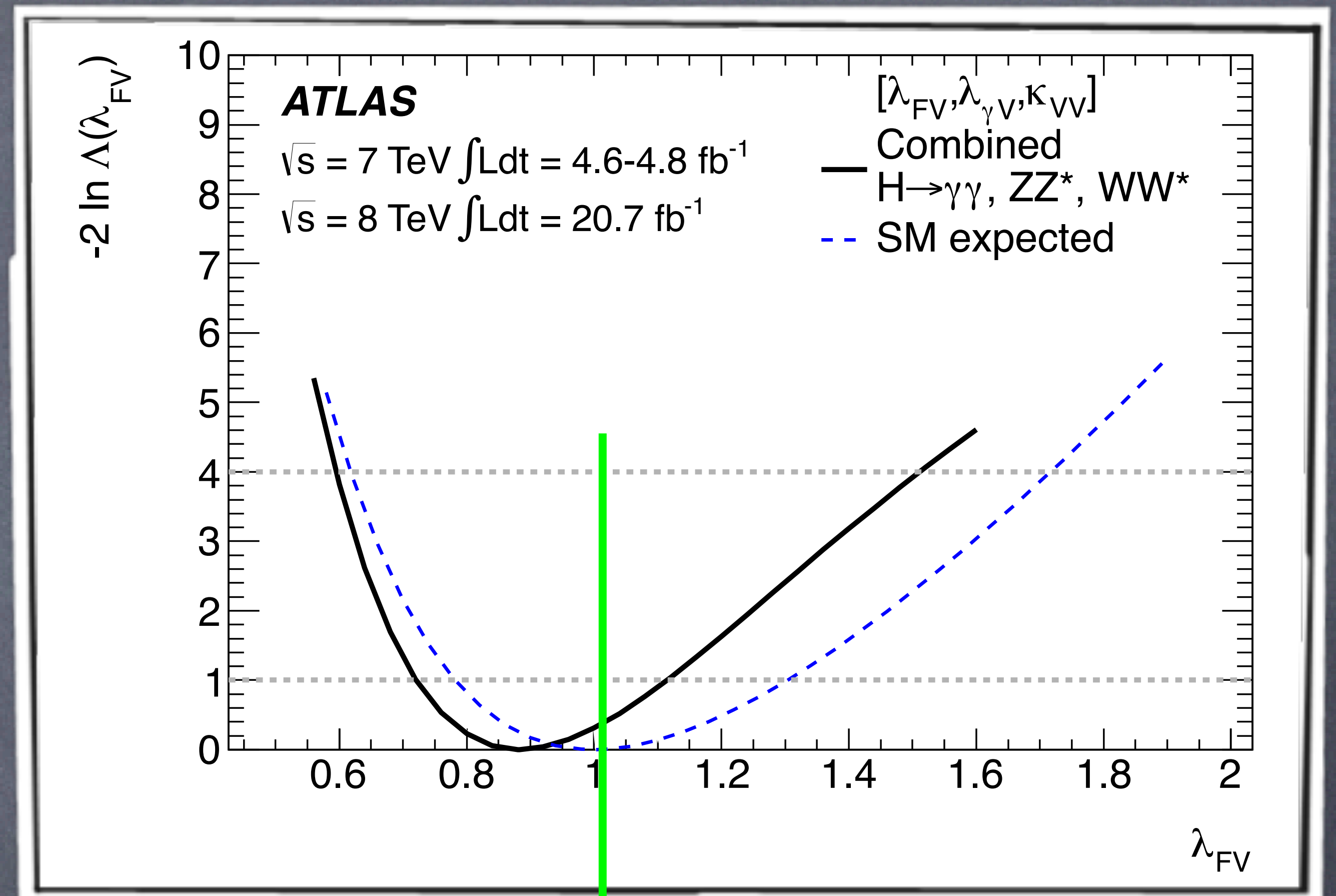
Probing Vector and Fermion Couplings

The total width constrained to SM width, strongly constrains the k_F and k_g, here we relex this constraint.

Only ratios can be probed

Parameters of interest

$$\lambda_{FV} \in [0.70, 1.01]$$



$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1) \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \kappa_{VV}^2 \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \kappa_{VV}^2 \cdot \lambda_{FV}^2 \quad ,
\end{aligned}$$

Probing Custodial Symmetry

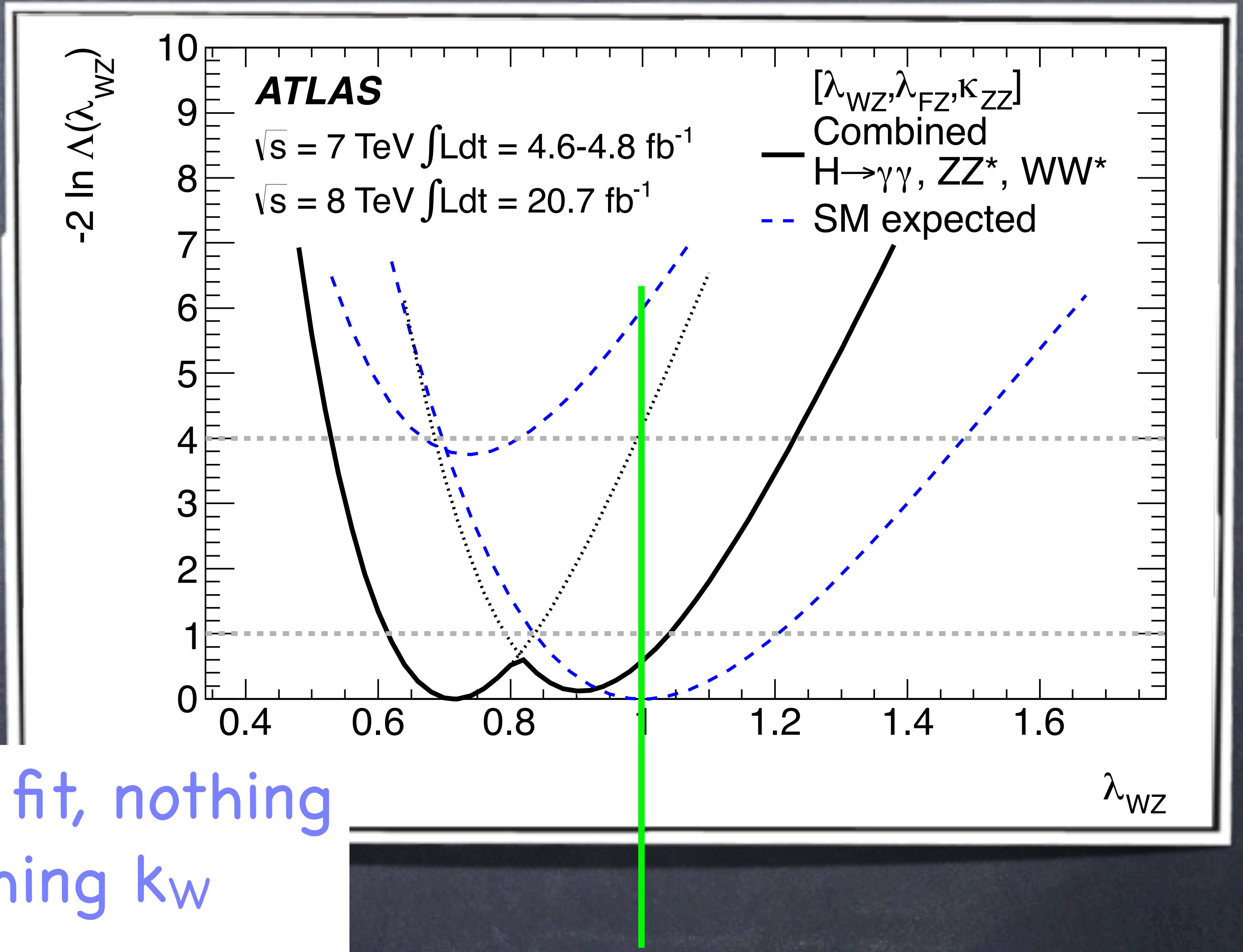
k_γ affects kW, decouple also k_γ add another p.o.i.

λ_{WZ} is the p.o.i and the other parameters are profiled

$$\lambda_{\gamma Z} = \frac{k_\gamma}{k_Z} \quad \lambda_{FZ} = \frac{k_F}{k_Z} \quad \lambda_{WZ} = \frac{k_W}{k_Z} \quad k_{ZZ} = \frac{k_Z^2}{k_H}$$

$$\lambda_{WZ} = 0.82 \pm 0.15$$

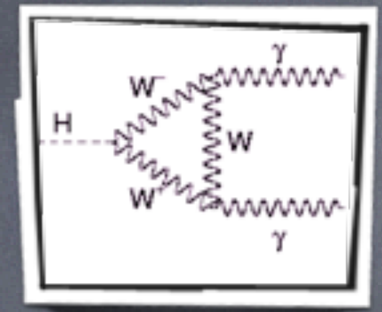
4D compatibility with SM is 20%

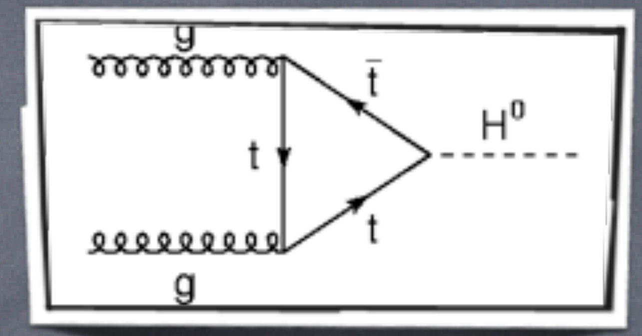


The measured value of λ_{WZ} is in agreement with the custodial symmetry within 2σ regardless of the inclusion of the γγ channel as indirect constraint on kW.

W and Z are decoupled in the fit, nothing prevents k_t to go negative pushing k_W down, keeping the high γγ rate

Probing New Physics in the Loops

The gg and $\gamma\gamma$ loops 



might contain non SM part.

There might also be undetected decay modes.

The total width might contain inv. or inv,undetected decay modes.

Some models were constructed to test the additional possible physics hidden in the loops .

k_γ and k_g were tested under the assumptions of

~SM Higgs width, and without this assumption

All couplings but k_γ and k_g were set to SM (=1)

Probing New Physics

Assuming total width unaffected, k_γ and k_g are left free in the fits

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

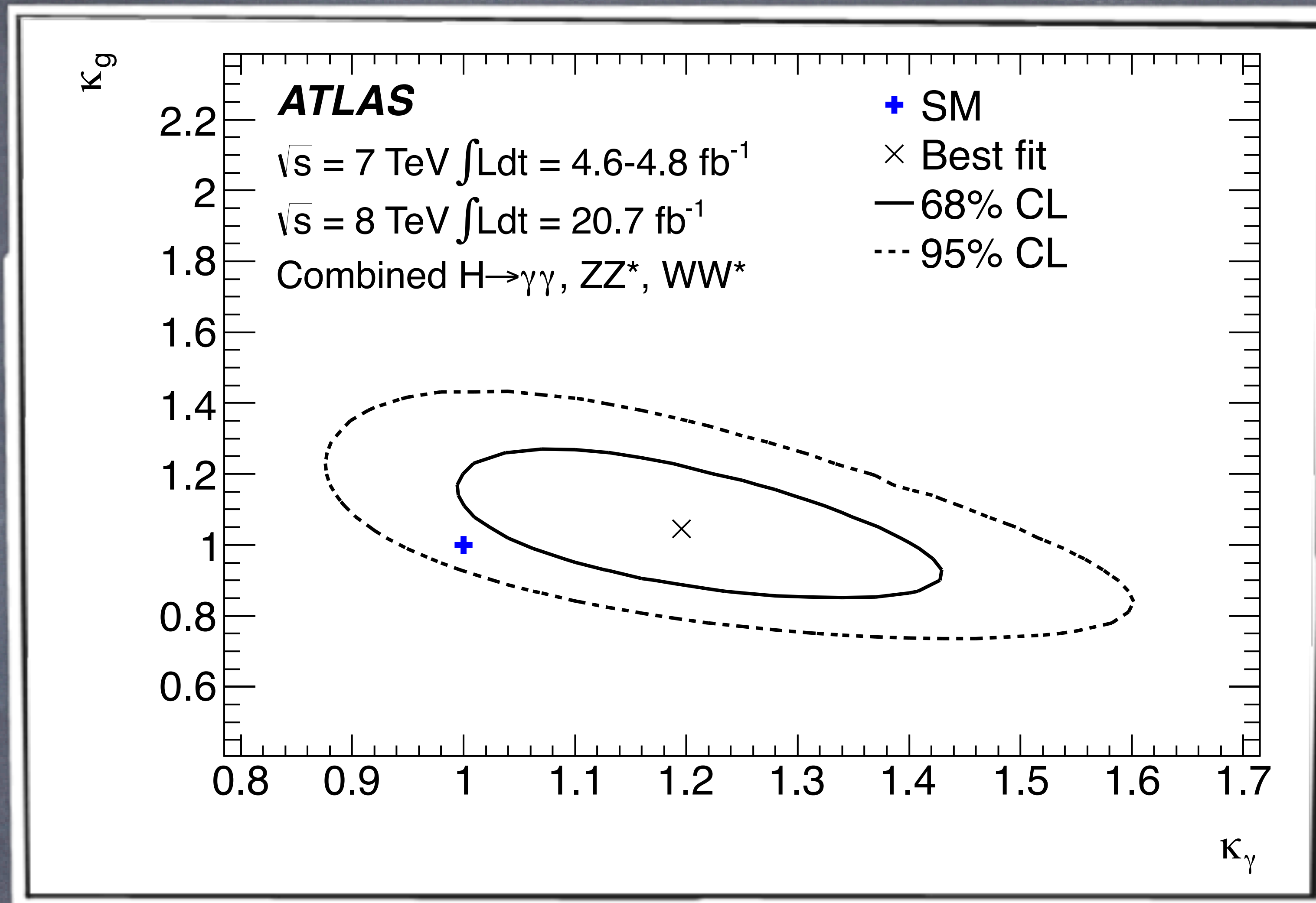
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

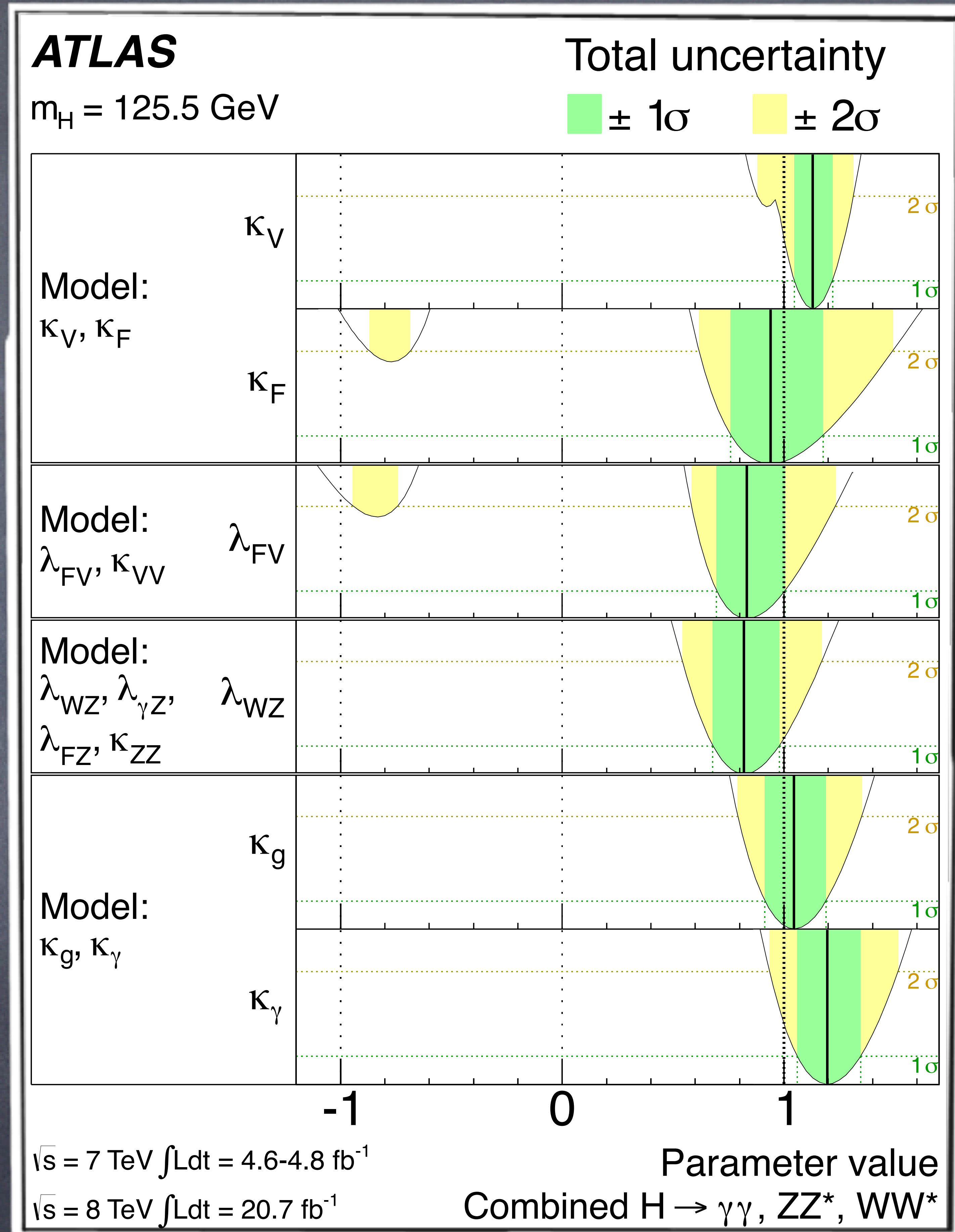
Probing New Physics



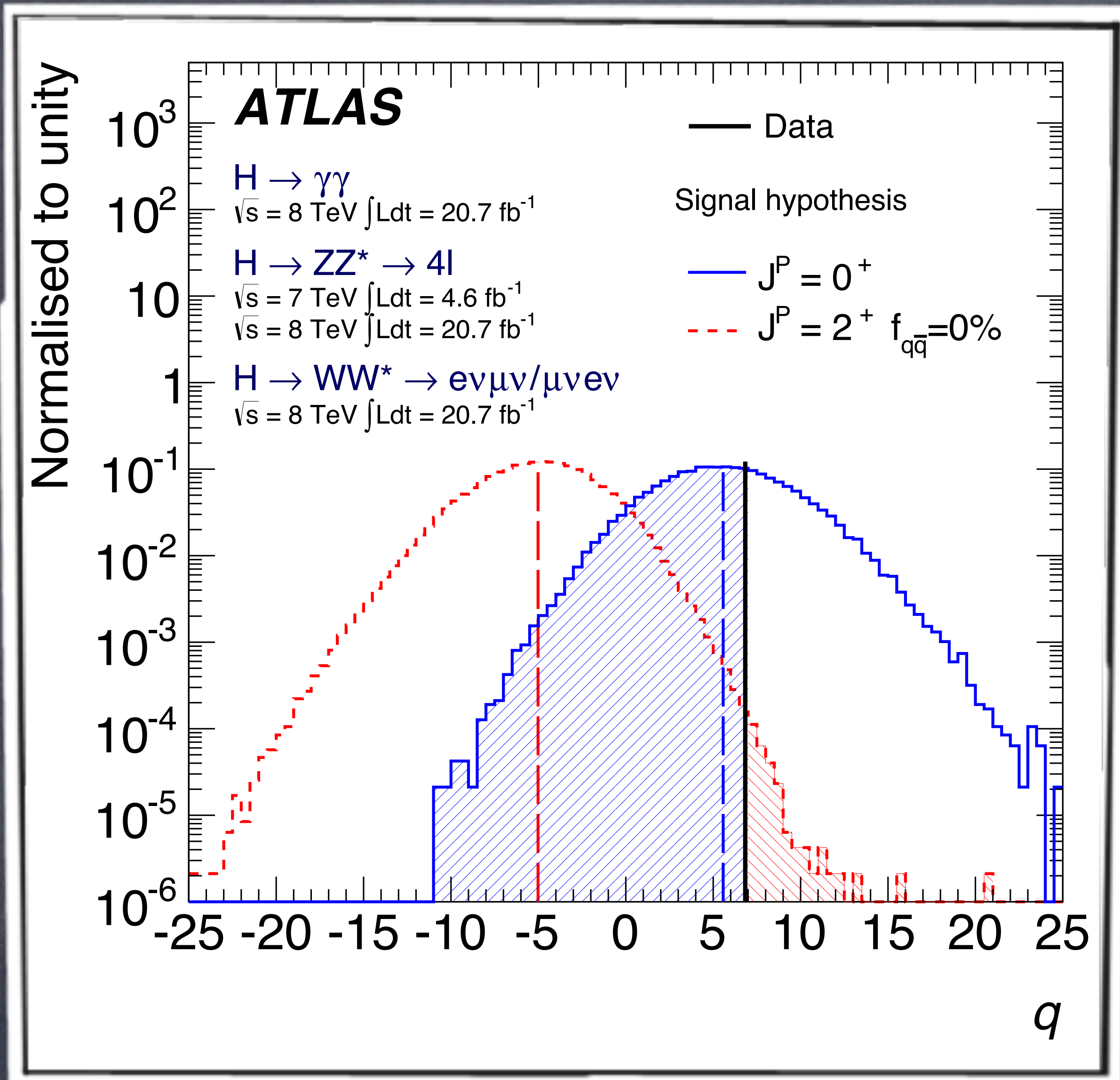
$$\kappa_g = 1.04 \pm 0.14$$
$$\kappa_\gamma = 1.20 \pm 0.15$$

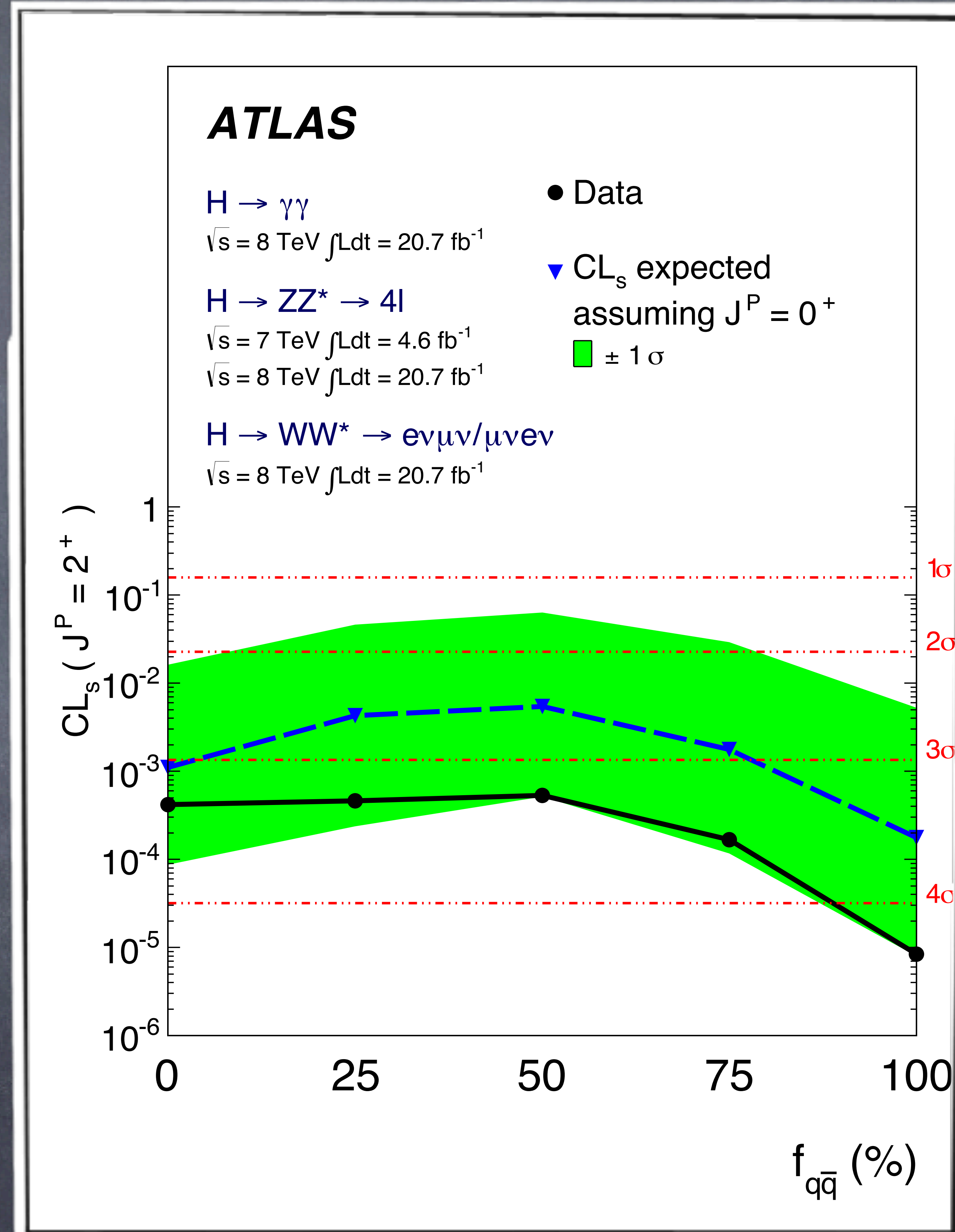
2D compatibility with SM is 14%

All tested model are (beautifully) compatible with the SM (~10%)



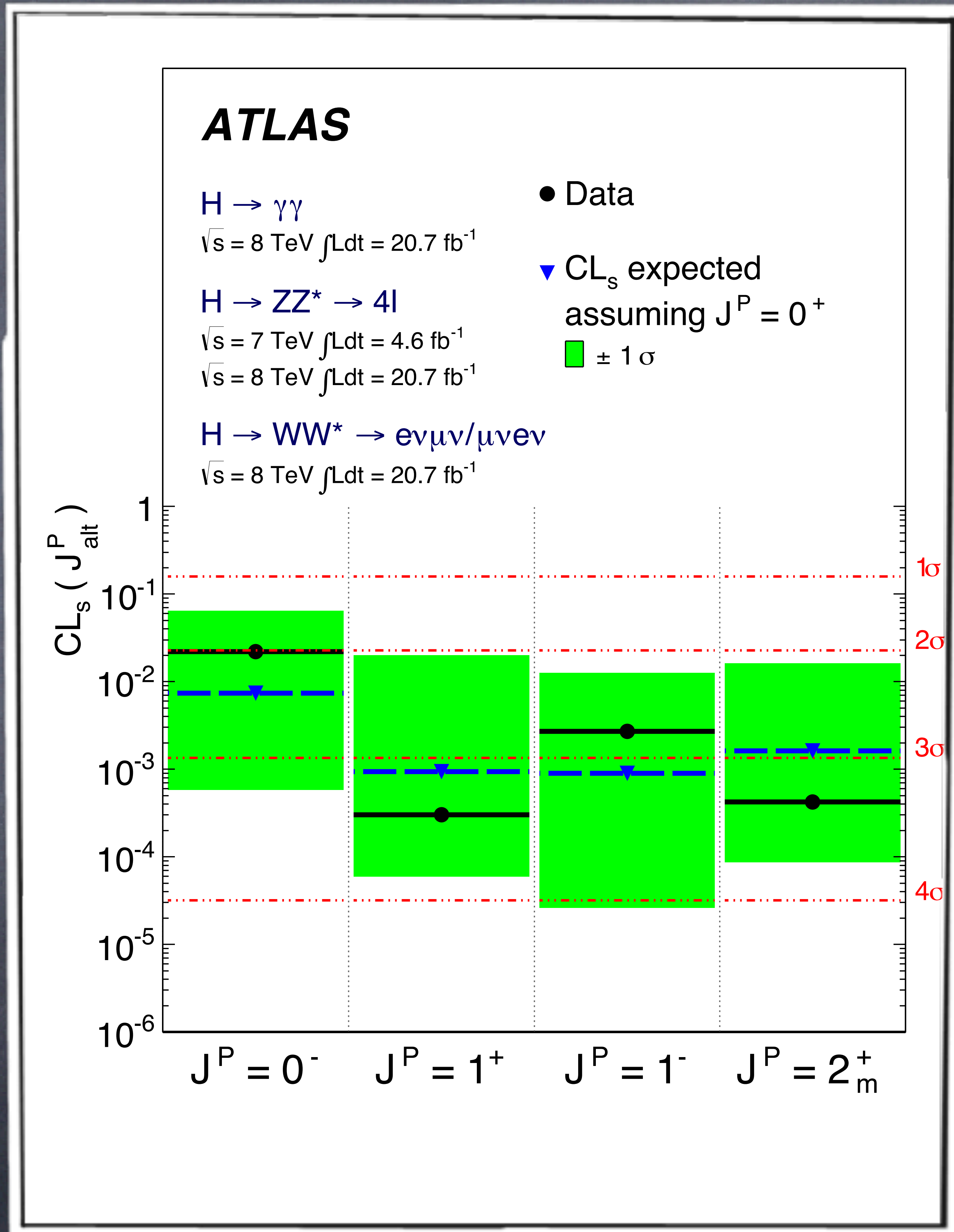
Spin Combination





The observed exclusion of $J^P=2^+$ hypothesis in favour of the SM $J^P=0^+$ hypothesis exceeds 99.9% for all values of fqq

Spin Combination



Conclusions

Higgs-Like Boson?

SM-Like Higgs Boson

CERN Press Release: New results indicate that particle discovered at CERN is a Higgs boson

Inbox x

Rolf Heuer <rolf.heuer@cern.ch> 3:29 AM (6 hours ago)

to cern-personnel

La version française sera disponible ultérieurement ici: http://press.web.cern.ch/fr/press-releases

New results indicate that particle discovered at CERN is a Higgs boson

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

Friday, July 19, 13

A Phenomenological Profile of the Higgs Boson

1976

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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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.

Thank You

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