LHC RESULTS
AND PHYSICS BEYOND SM

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Cortona, 31 Maggio

WHAT WE KNOW

SM is a gauge theory based on $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$\mathcal{L}_{Kinetic} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}W^b_{\mu\nu}W^{b\mu\nu} + i\sum_{j=1}^{3}\left(\bar{\Psi}^j_L \; \not{D}\Psi^j_L + \bar{\Psi}^j_R \; \not{D}\Psi^j_R\right)$$

$$\Psi_{L,R} = (3,2)_{\frac{1}{6}} \oplus (3,1)_{\frac{2}{3}} \oplus (3,1)_{-\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}} \oplus (1,1)_{-1}$$

(3 couplings)

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(3 couplings)

Unbroken gauge symmetry forbids mass terms:
vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q$$

Mass terms can be written,

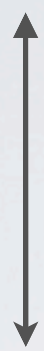
$$\mathcal{L}_{mass} = \sum_{i,j=1}^{3}\left[\bar{u}^i_L M^u_{i,j} u_R + \bar{d}^i_L M^d_{i,j} d_R + \bar{e}^i_L M^e_{i,j} e_R\right] + h.c.$$

$$+m^2_W W^2 + \frac{1}{2}m^2_Z Z^2$$

O(20) parameters

Mass for gauge bosons implies new degrees of freedom

$m_1 = 0$



$m_1 \neq 0$

The extra degrees of freedom are Goldstone Bosons

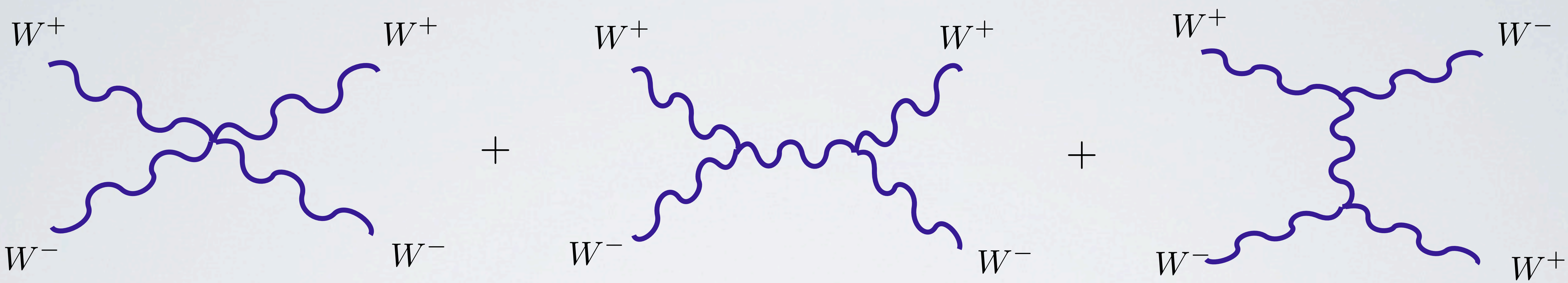
$$SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

They become longitudinal polarizations of W & Z

Important hint:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1 \quad \longrightarrow \quad \text{Custodial Symmetry } SU(2)_c$$

In principle the Higgs scalar is not necessary for EWSB



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{v^2}(s+t)$$

Interactions become strongly coupled around TeV.
Perturbativity is violated at

$$\Lambda \sim 3\,\mathrm{TeV}$$

In the SM electro-weak symmetry is broken through a scalar doublet with Y=1/2

$$V(H) = \lambda \left(|H|^2 - v^2 \right)^2$$

$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\, GeV$$

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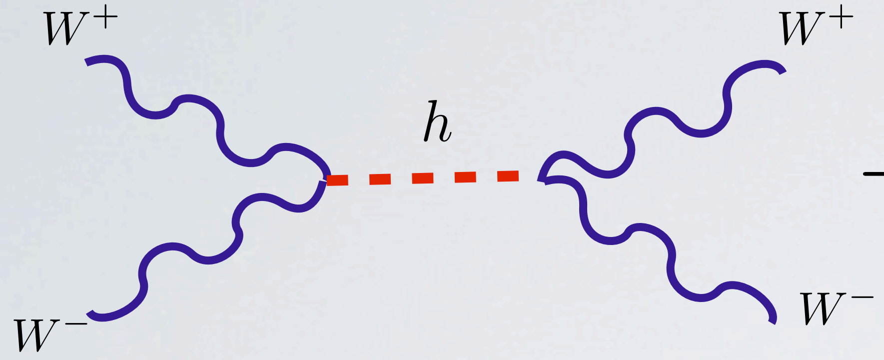
VEV breaks symmetry. The Goldstone Bosons in $U(x)$ are eaten giving mass to W & Z. Higgs sector respects custodial symmetry

$$\frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \longrightarrow \rho \approx 1$$

If SM is correct only unknown is the quartic/mass

$$m_h = \sqrt{\lambda}\, v$$

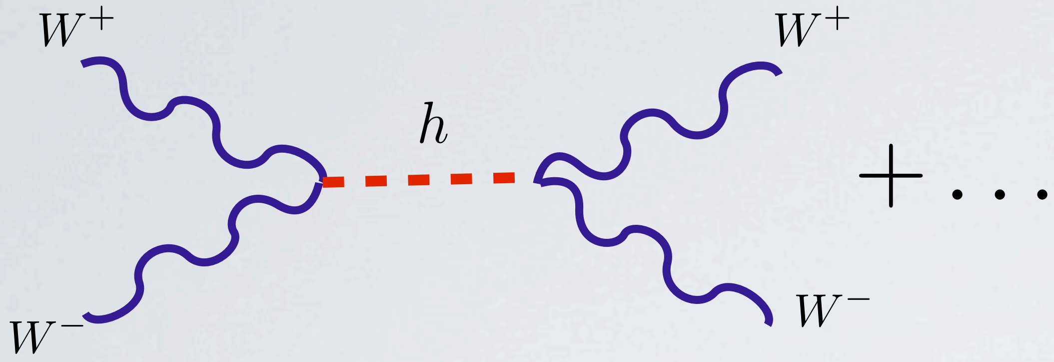
In the SM:



$$+\ldots \qquad A(W_L^+W_L^- \to W_L^+W_L^-) \simeq \frac{1}{v^2}\left[s - \frac{s^2}{s-m_h^2} + (s\to t)\right]$$

Amplitude does not grow so SM can be valid up to the Planck scale.

In the SM:



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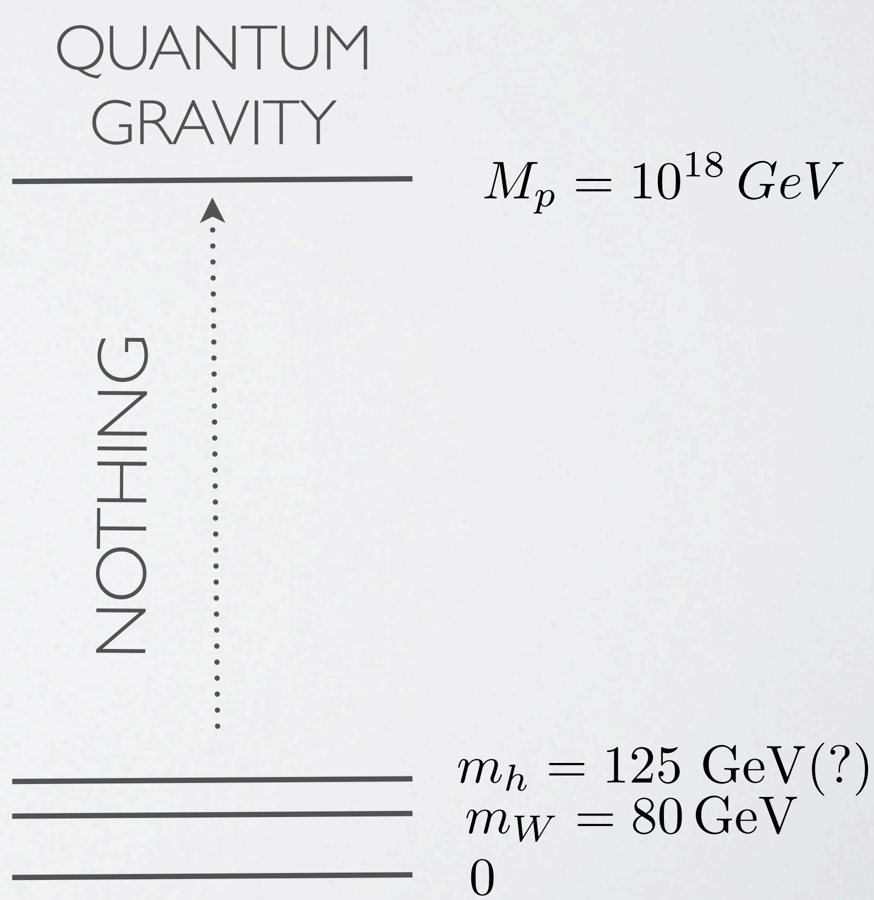
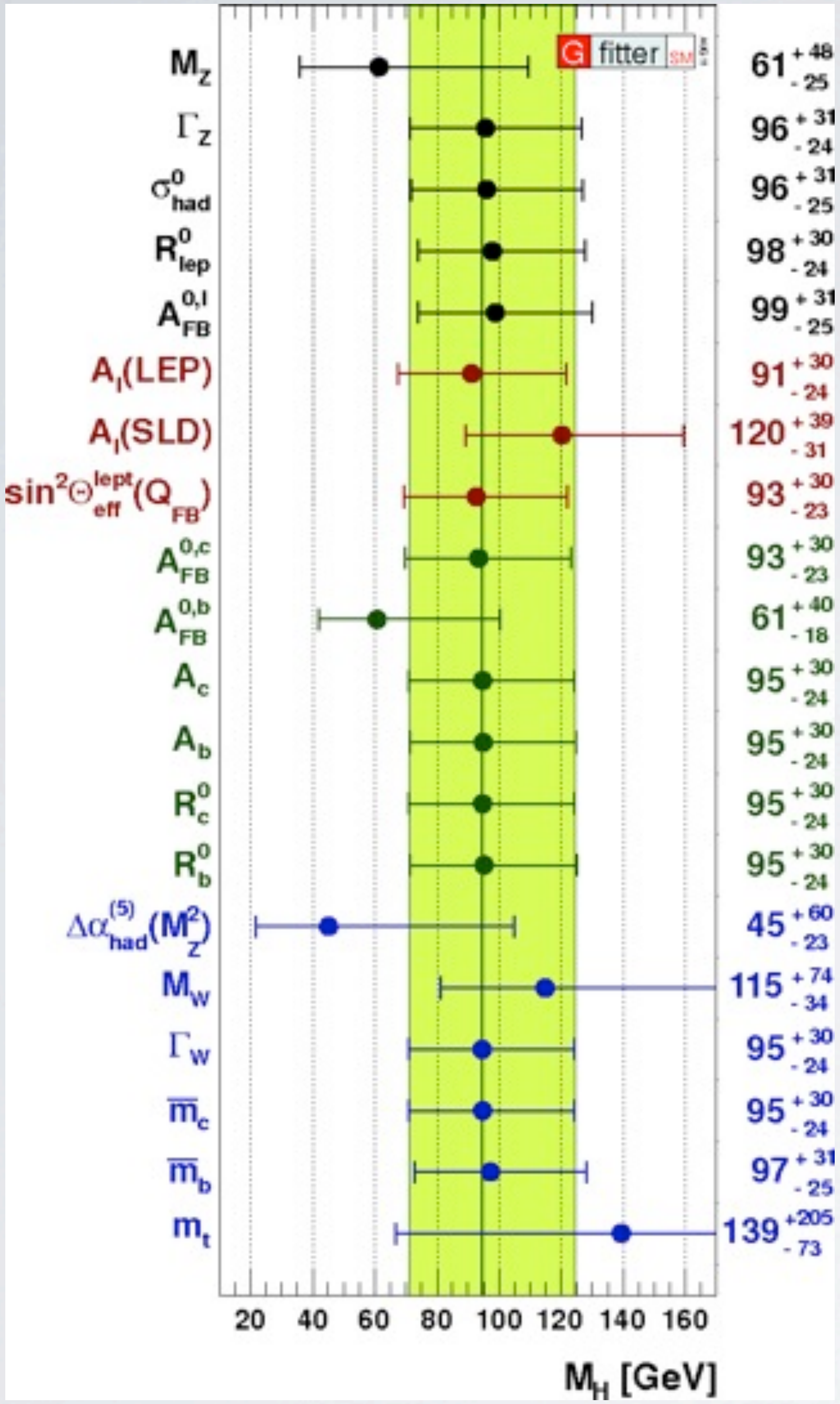
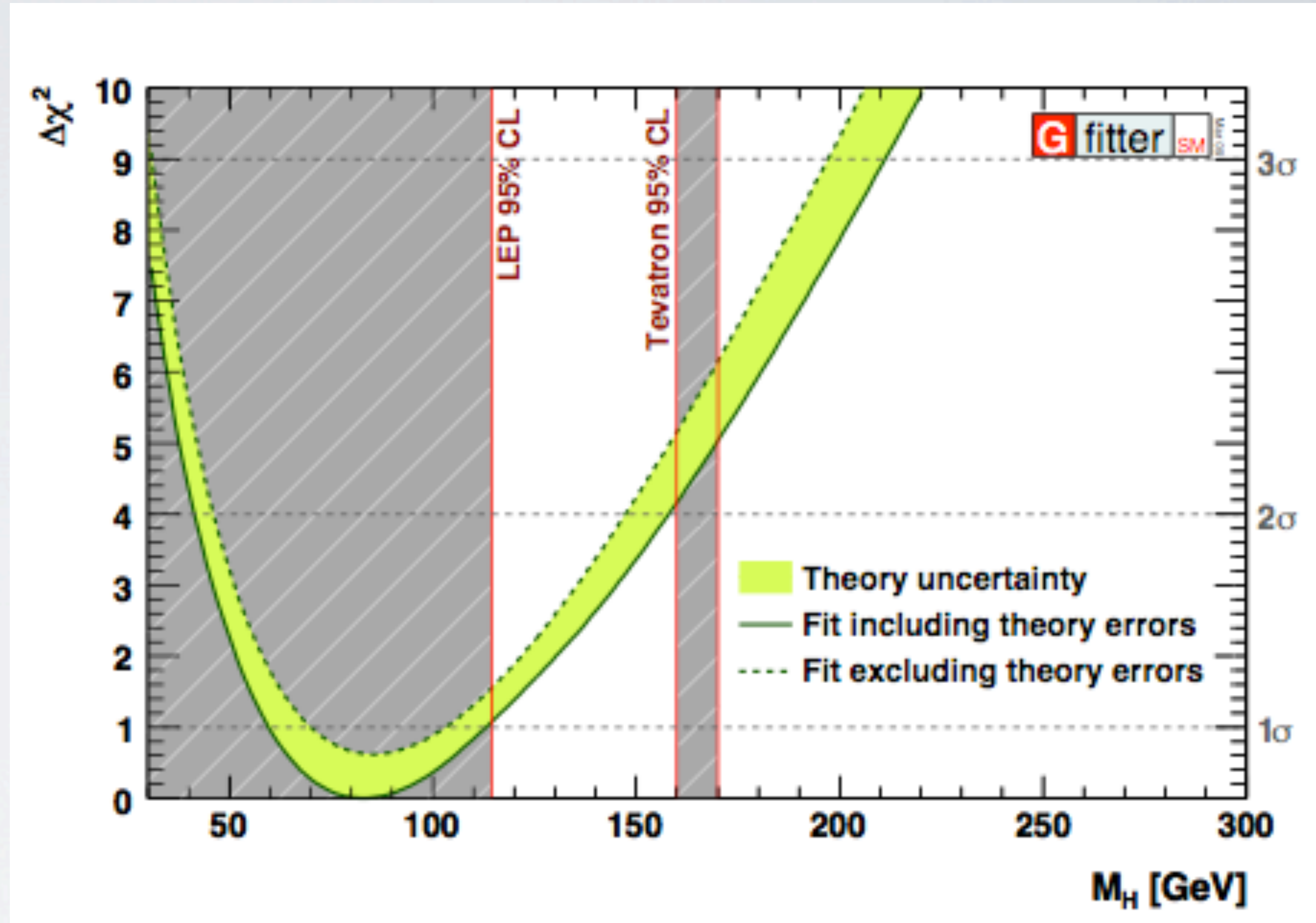
Amplitude does not grow so SM can be valid up to the Planck scale.

- Hierarchy problem
- Dark Matter
- Origin of Yukawas, CP
- Explains nothing







Indirect tests: $m_h < 150 \text{ GeV}$

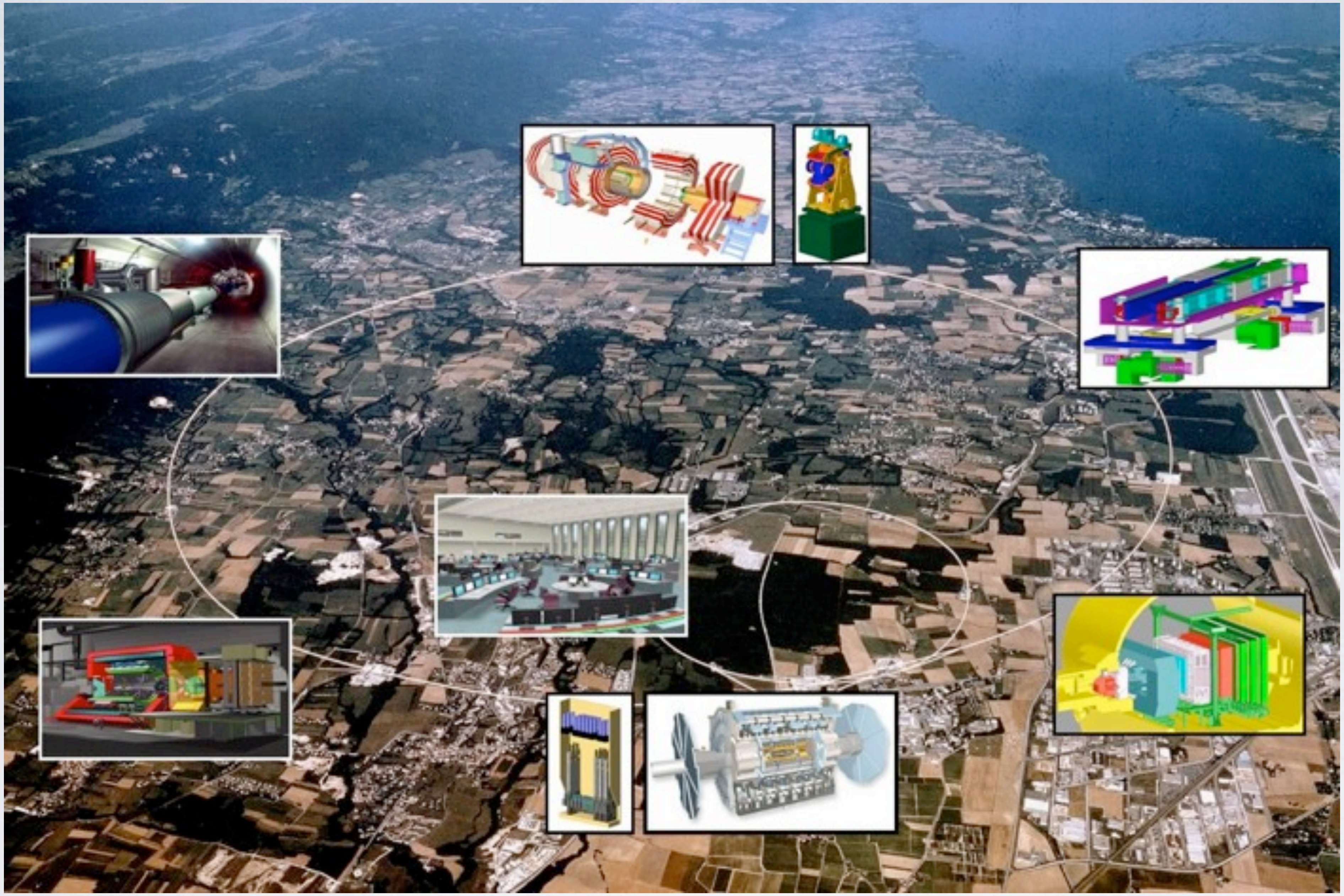
Direct search: $m_h > 114 \text{ GeV}$

2011 LHC: HIGGS

(+ Moriond Update)

Atlas and CMS presented results based of 5/fb luminosity.

Main goal of LHC:
discover the force that breaks electro-weak symmetry

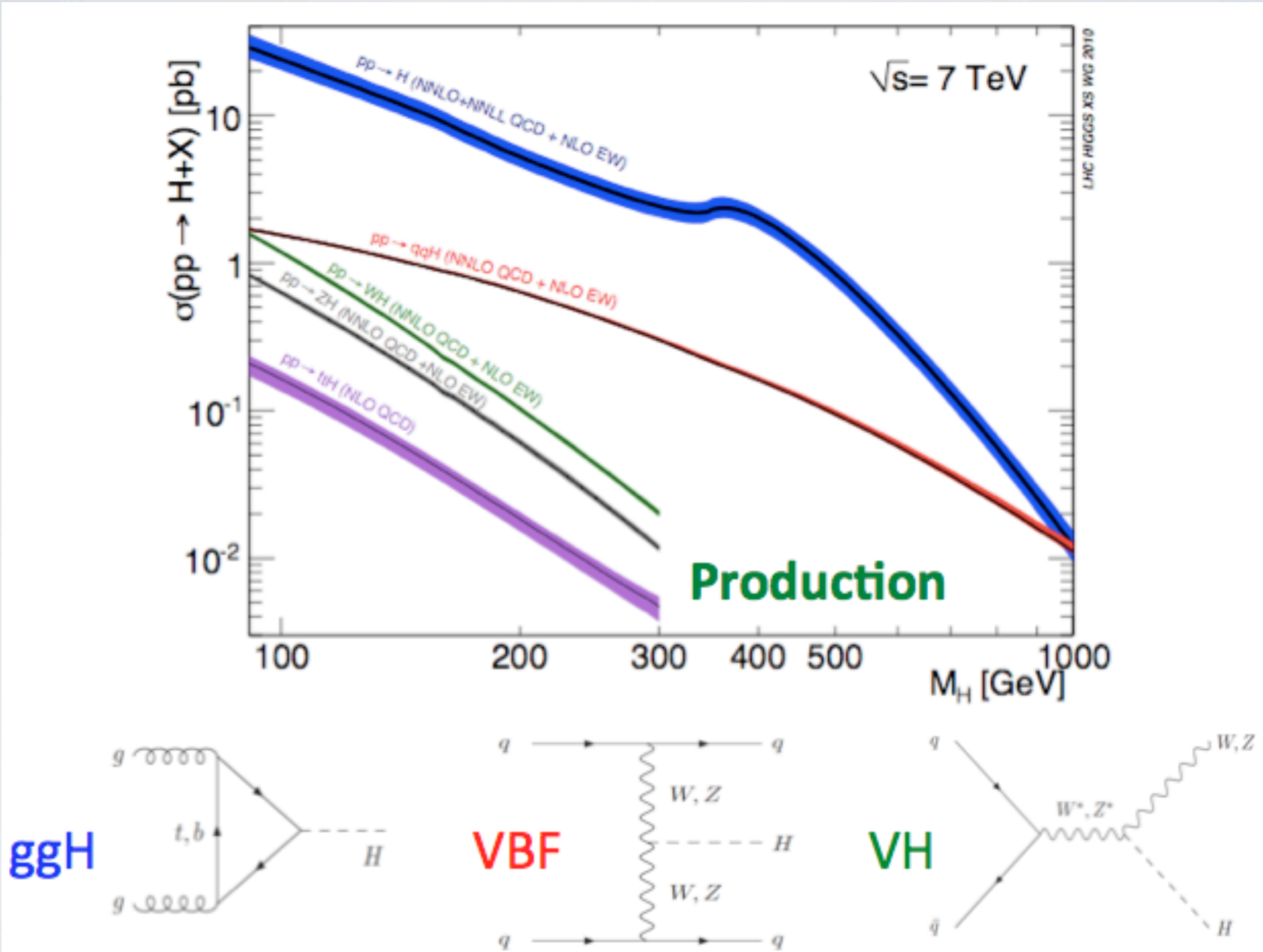


$$pp \to u, d, c, s, t, b, w, z, g, \gamma,$$
$$h(?) + \text{new physics}$$

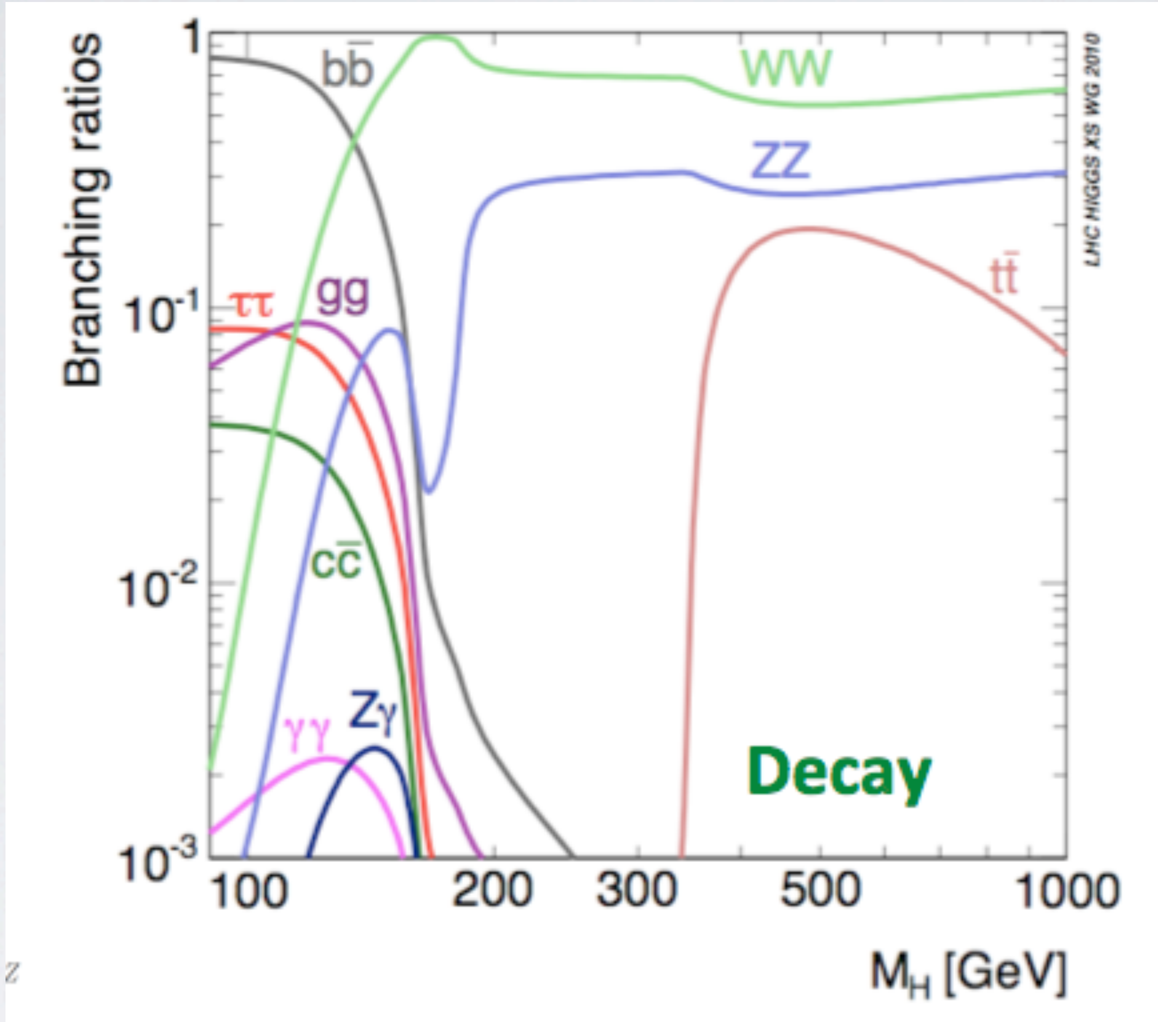
$2011: \; E = 7 \text{ TeV}$

$2012: \; E = 8 \text{ TeV}$

Higgs production at LHC:



Higgs decay:



Higgs @ 125 GeV:

$\mathrm{BR}(h \to b\bar{b}) = 58\%$

$\mathrm{BR}(h \to WW^*) = 21.6\%$

$\mathrm{BR}(h \to \tau^+\tau^-) = 6.4\%$

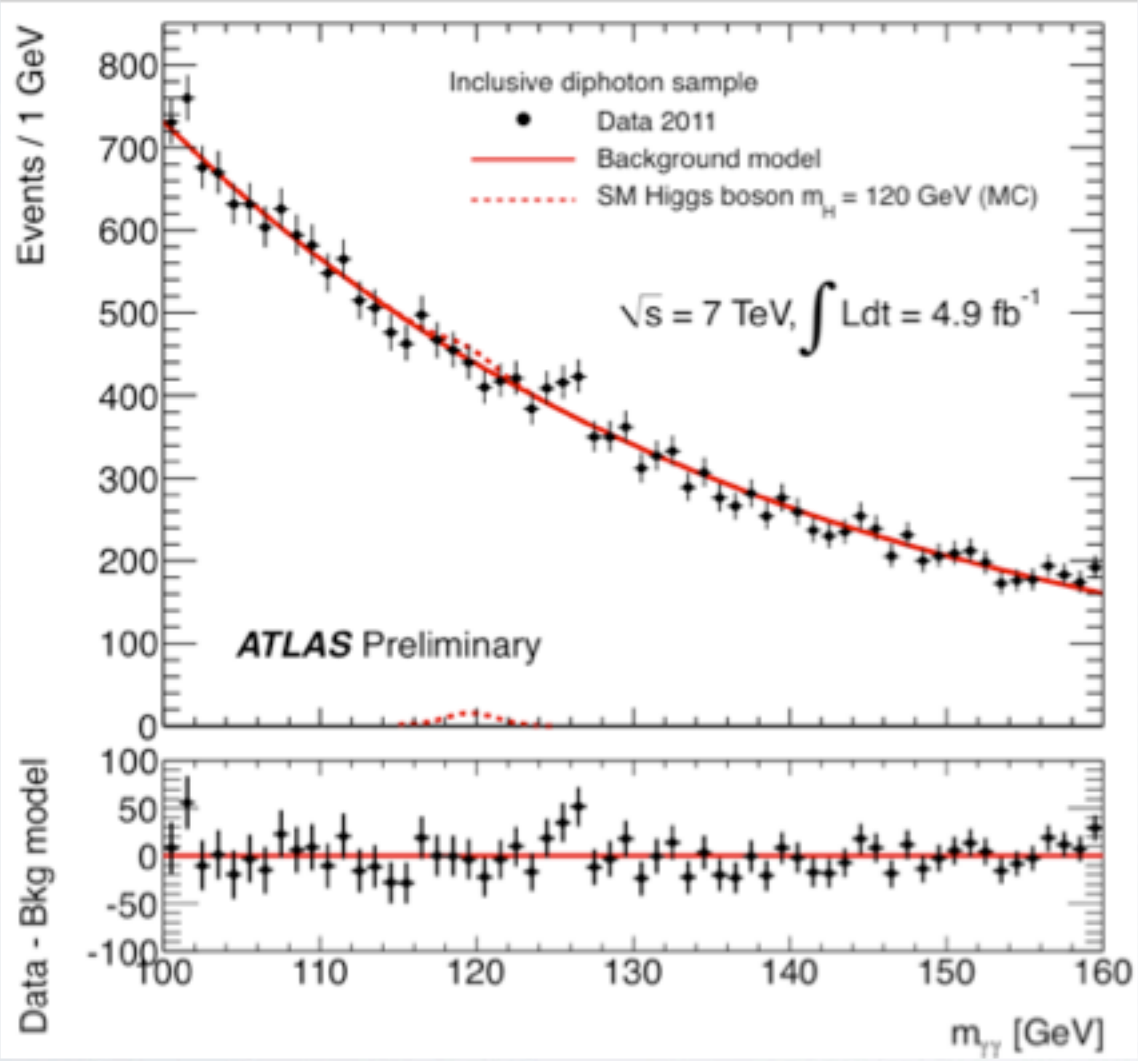
$\mathrm{BR}(h \to ZZ^*) = 2.7\%$

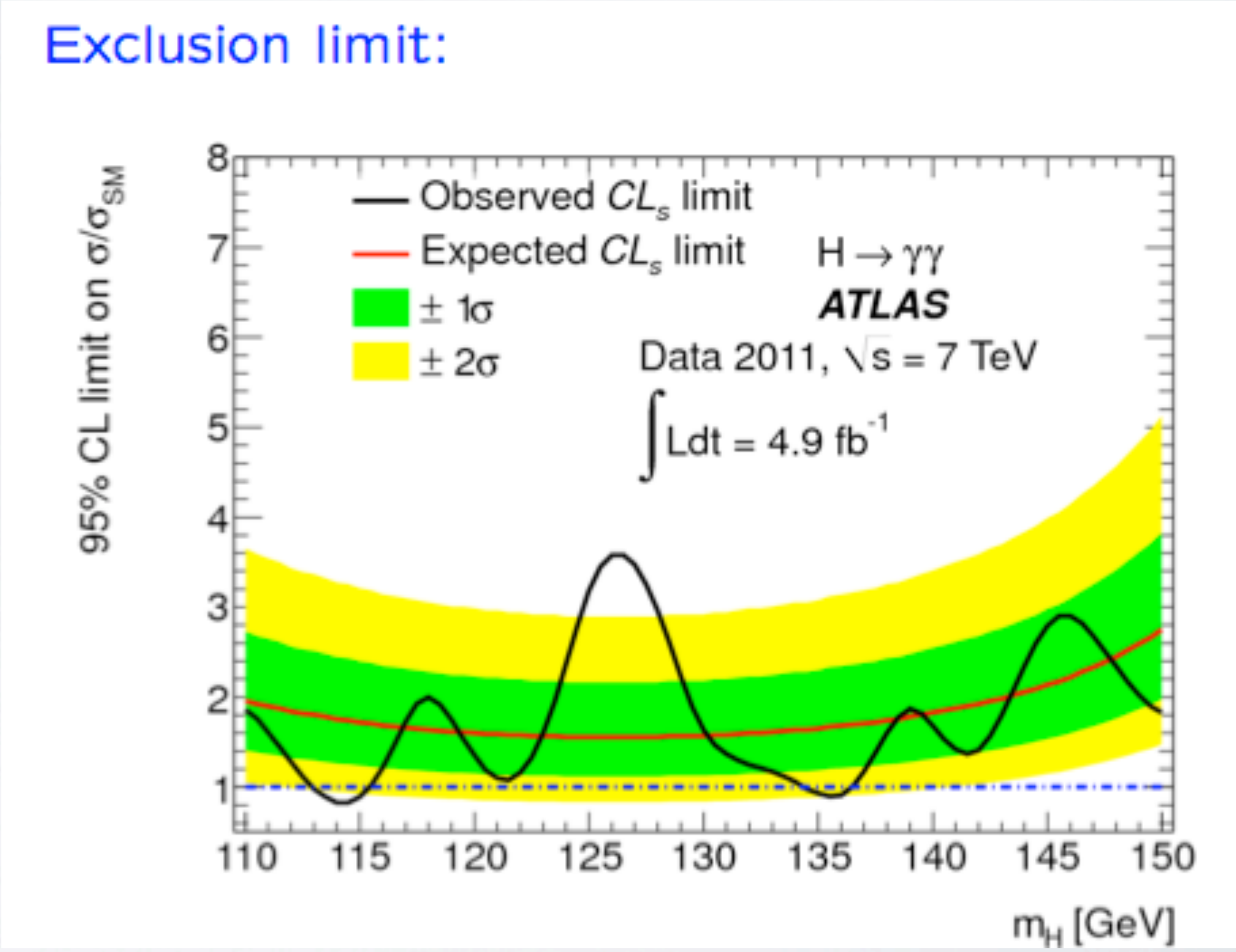
$\mathrm{BR}(h \to gg) = 8.5\%$

$\mathrm{BR}(h \to \gamma\gamma) = 0.22\%$

$H \to \gamma\gamma$

Atlas:

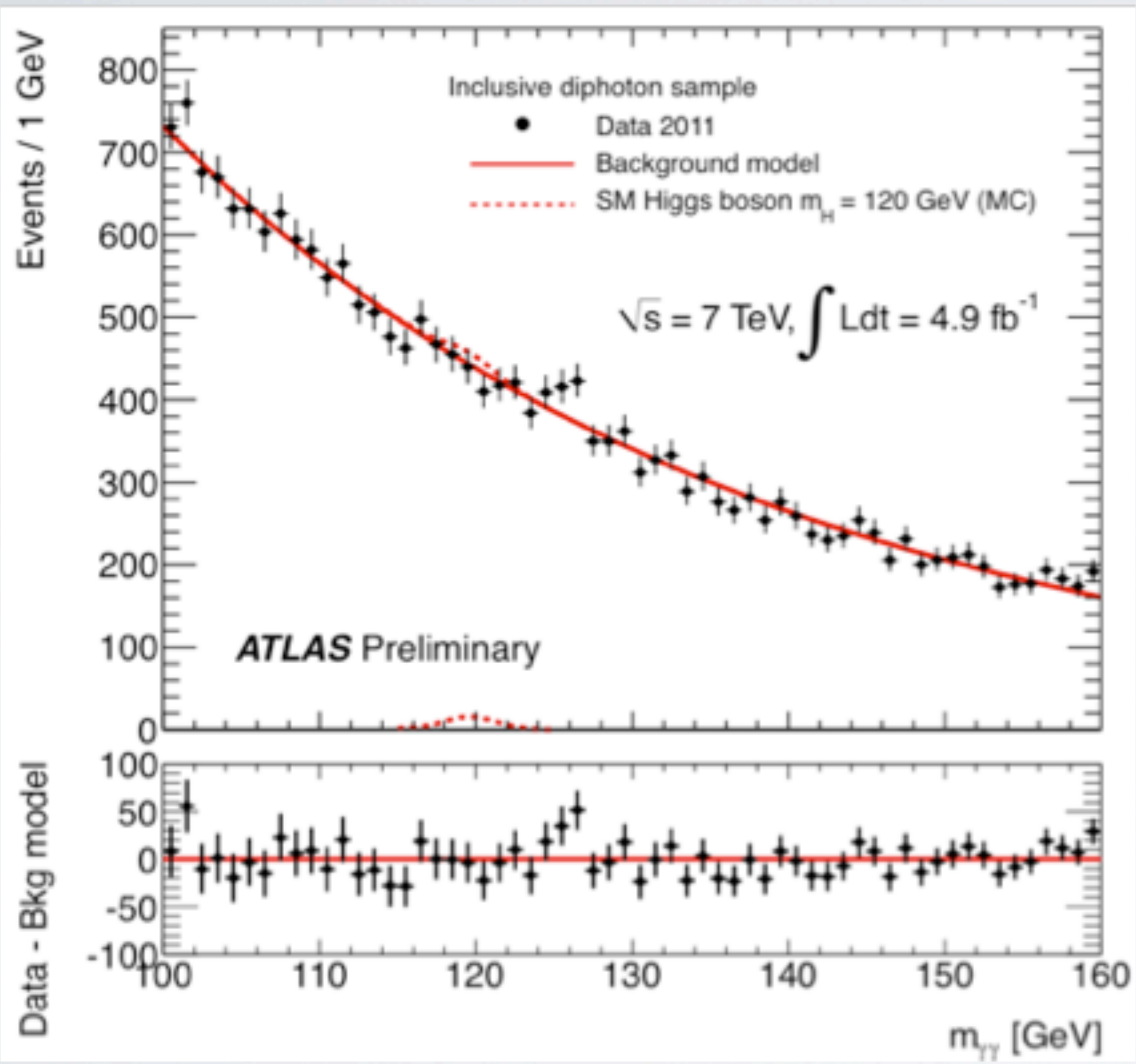


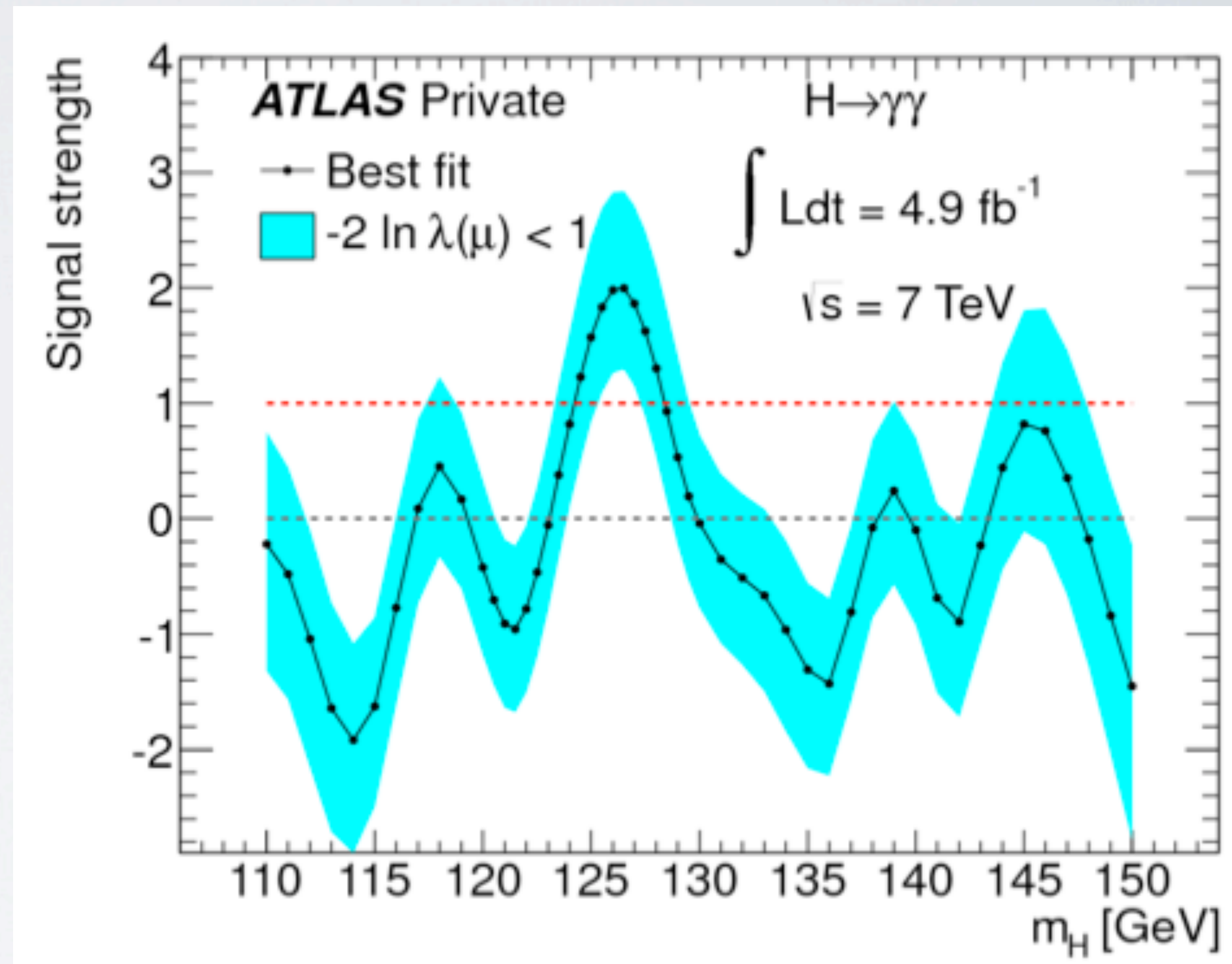


Excess @ 126 GeV; local significance 2.8 SD.

$H \to \gamma\gamma$

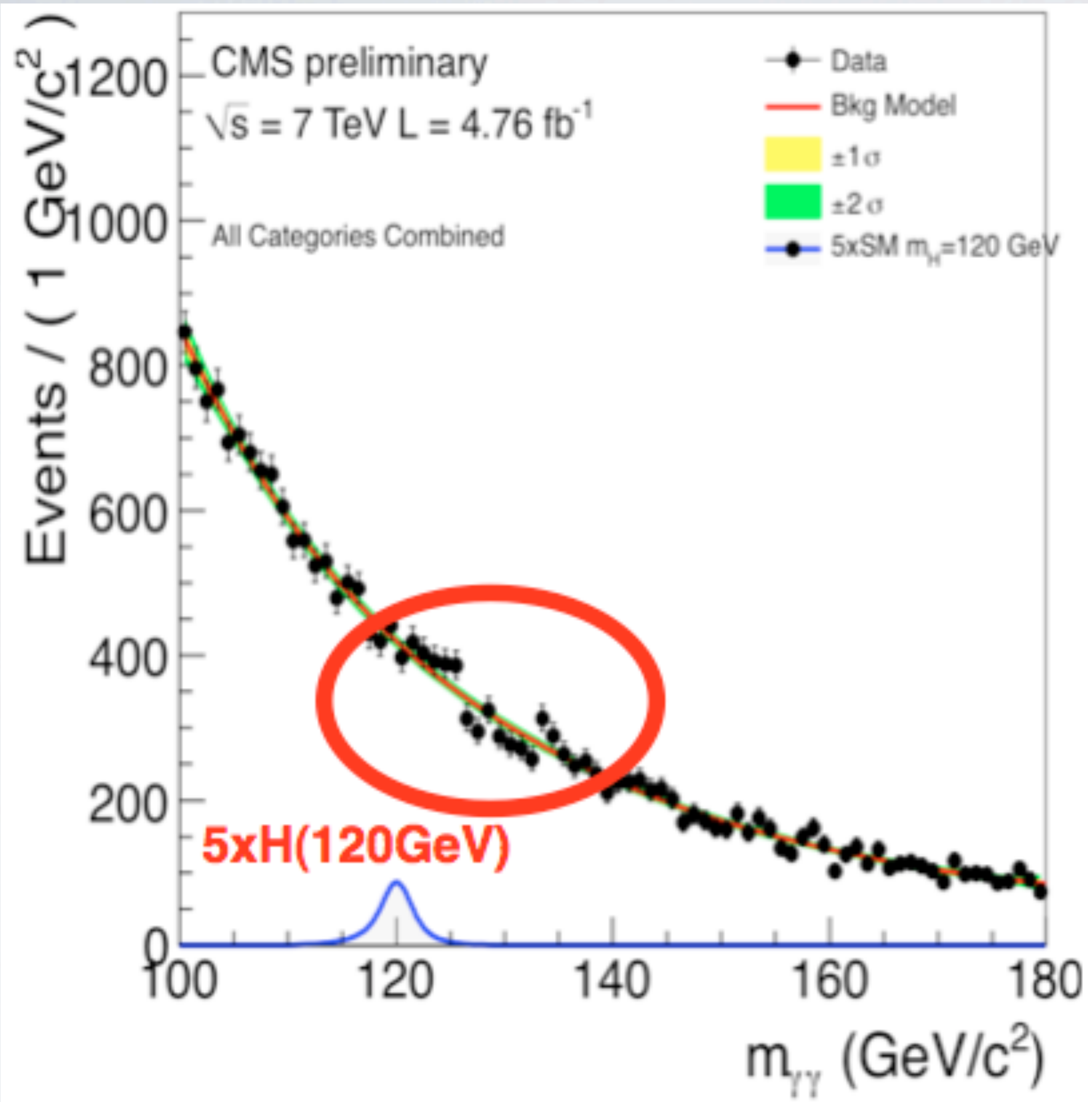
Atlas:

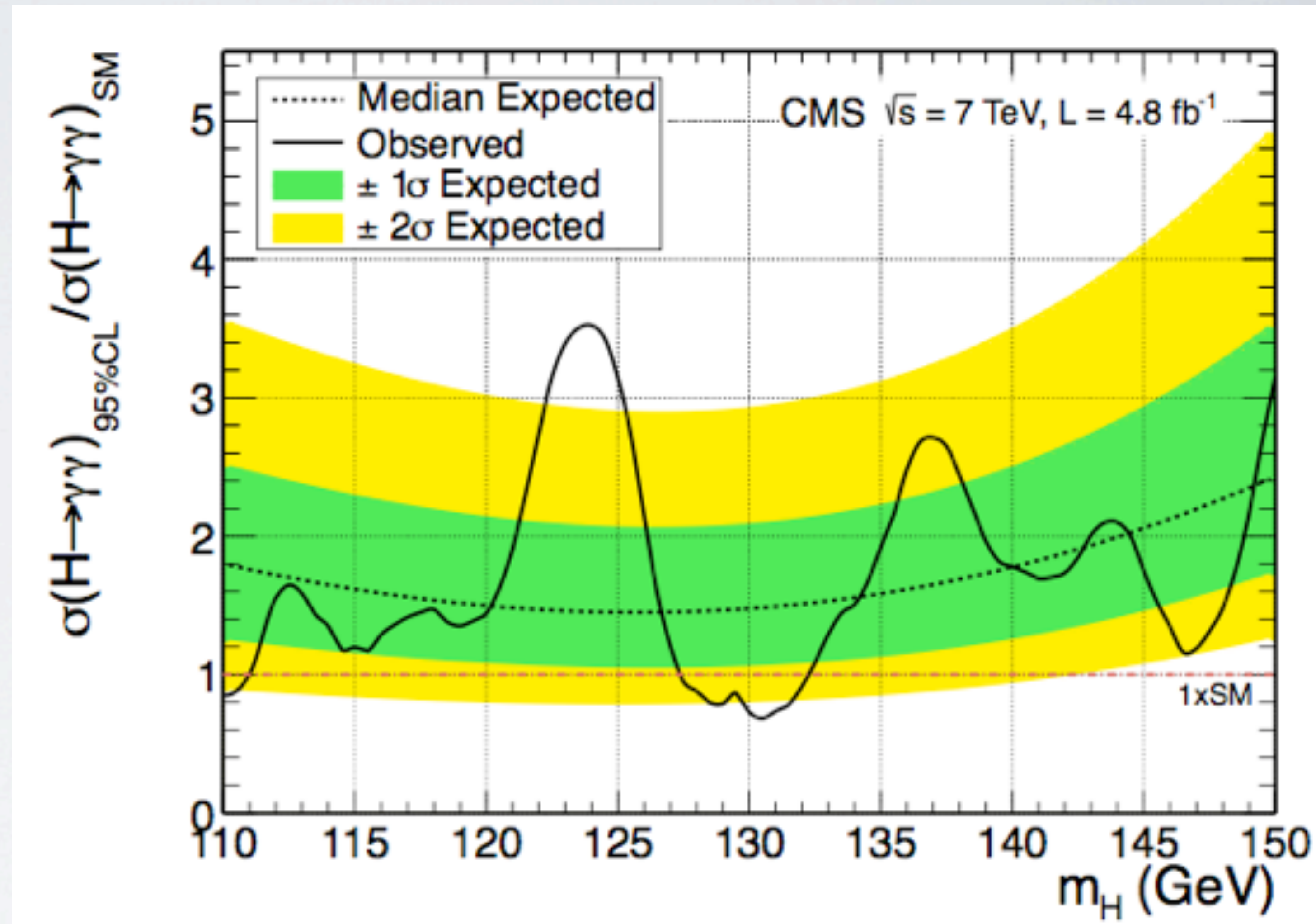




Excess @ 126 GeV; local significance 2.8 SD.

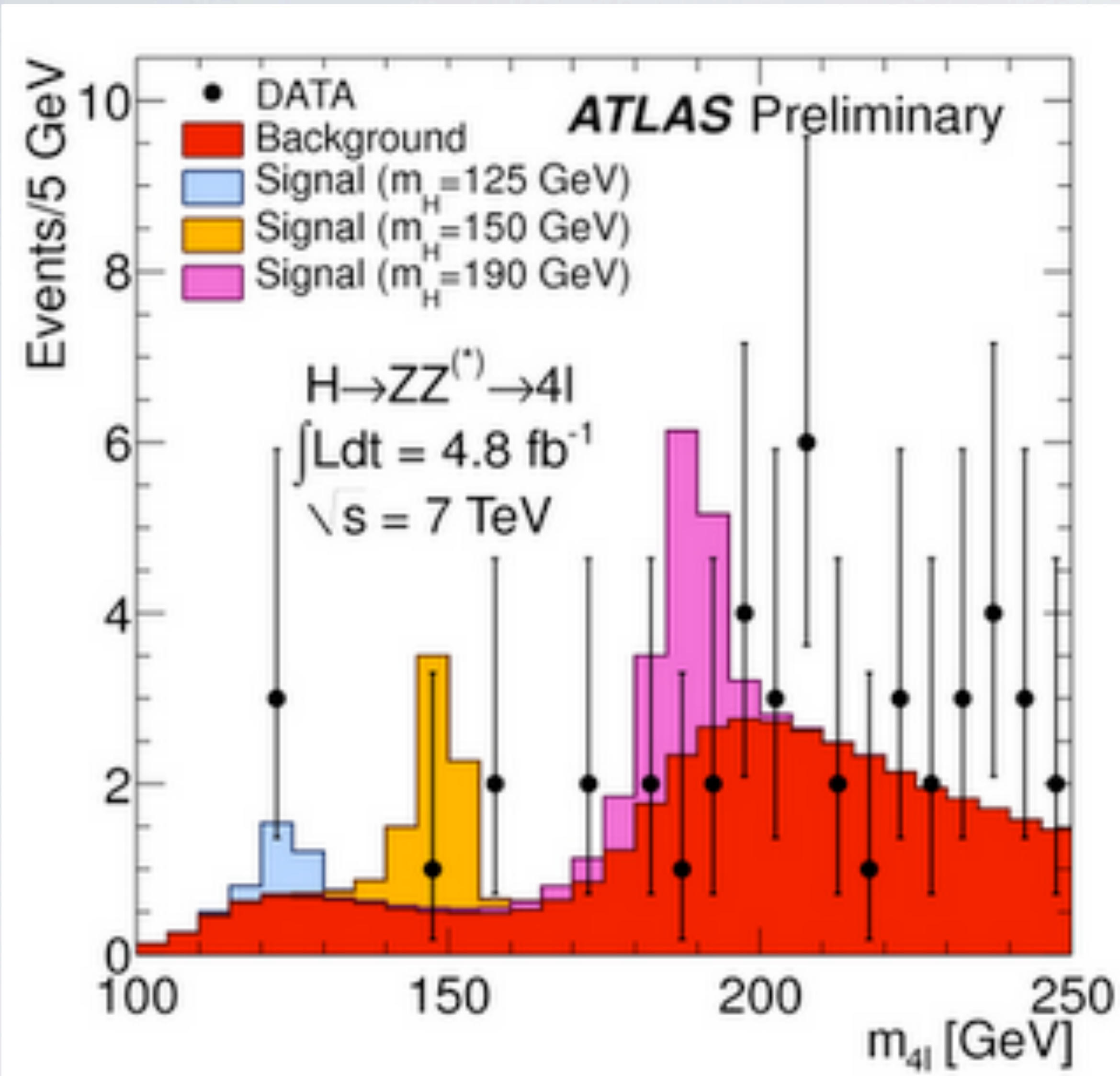
CMS:

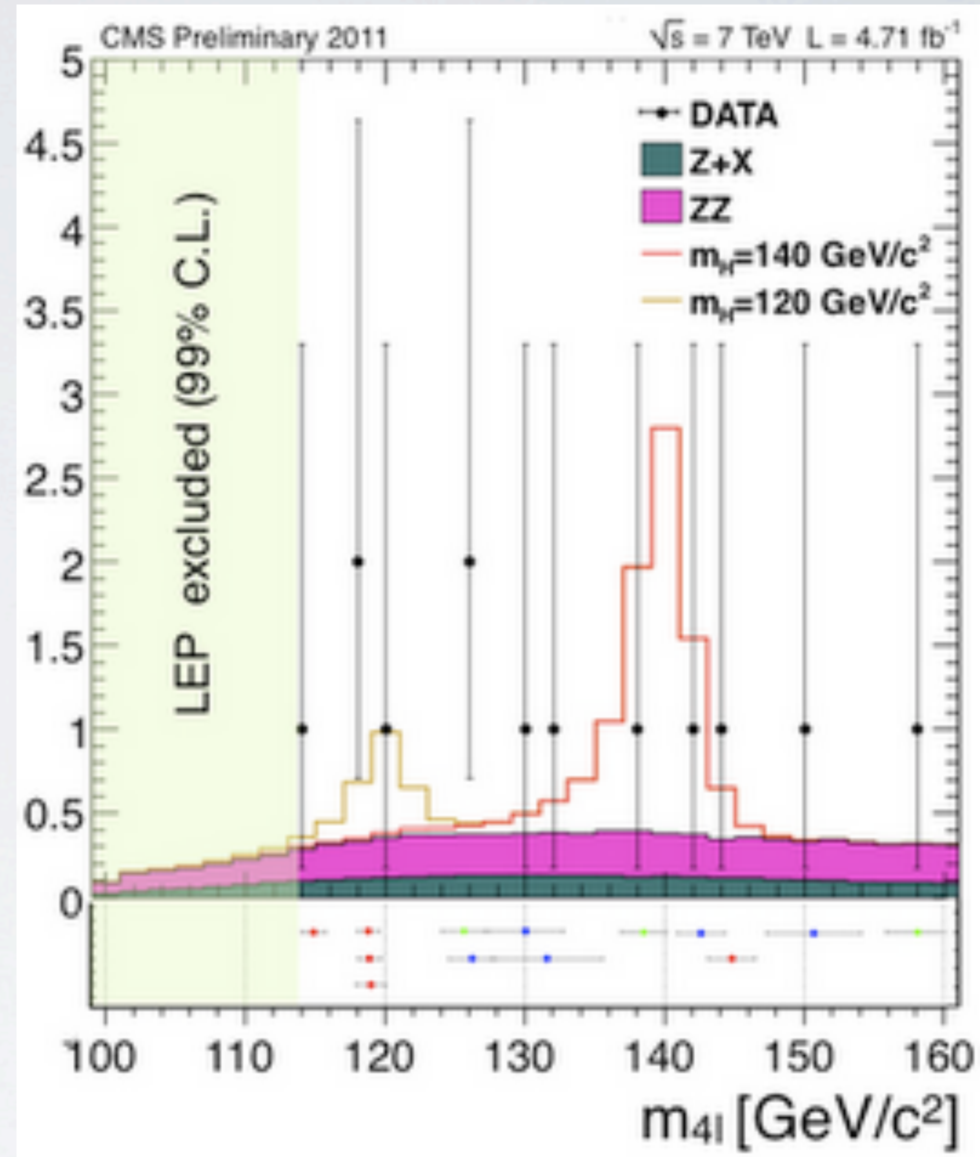




Excess @ 124.5 GeV:
local significance 2.9 SD, 1.6 SD globally

$H \to ZZ^* \to 4l$

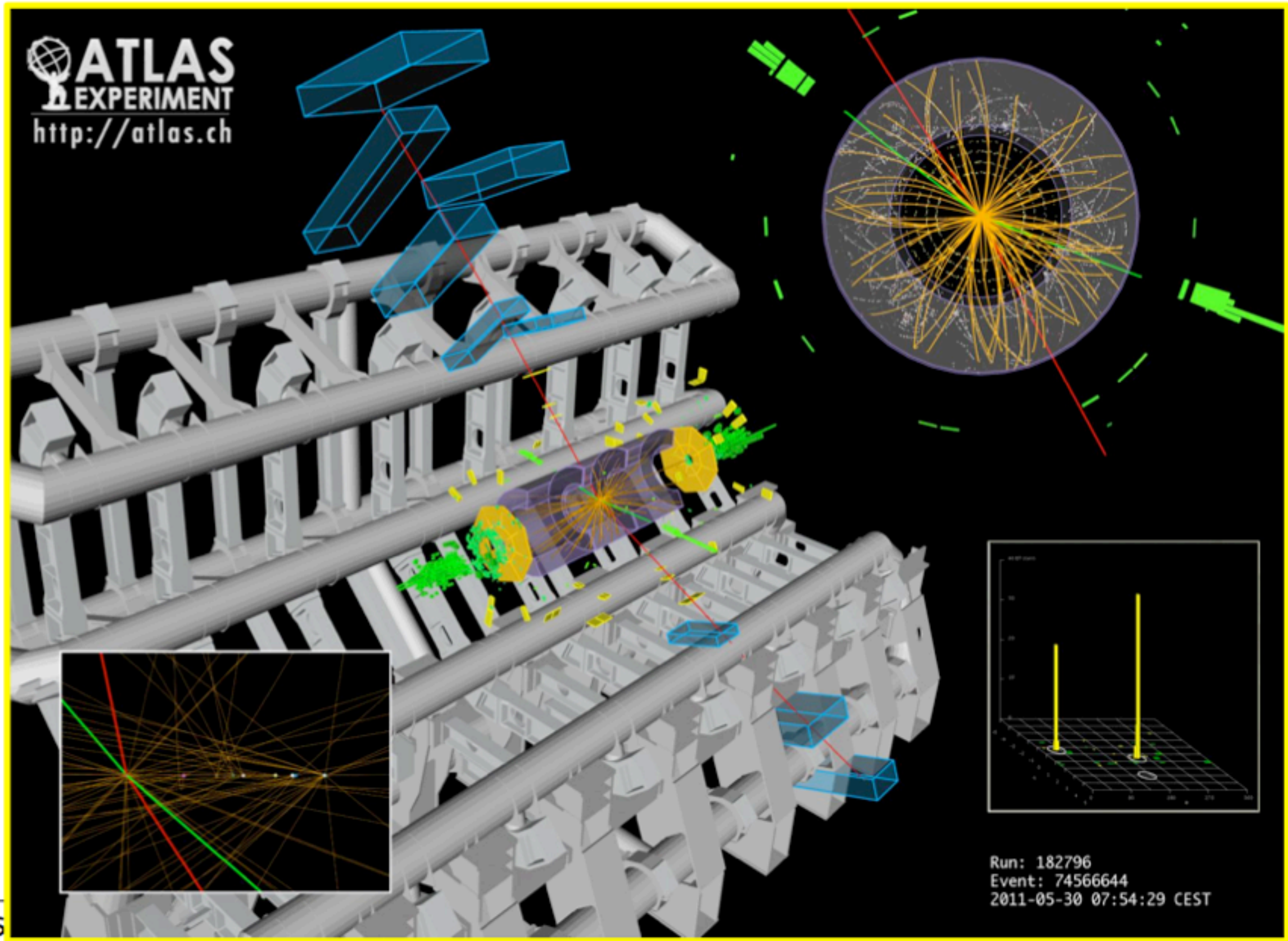




Atlas has 3 events at 124-125 GeV: 2.1 SD
CMS has 2 events at 125 GeV but also 3 at 119-120 GeV.

2e2μ candidate with $m_{2e2\mu}$= 124.3 GeV

p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV

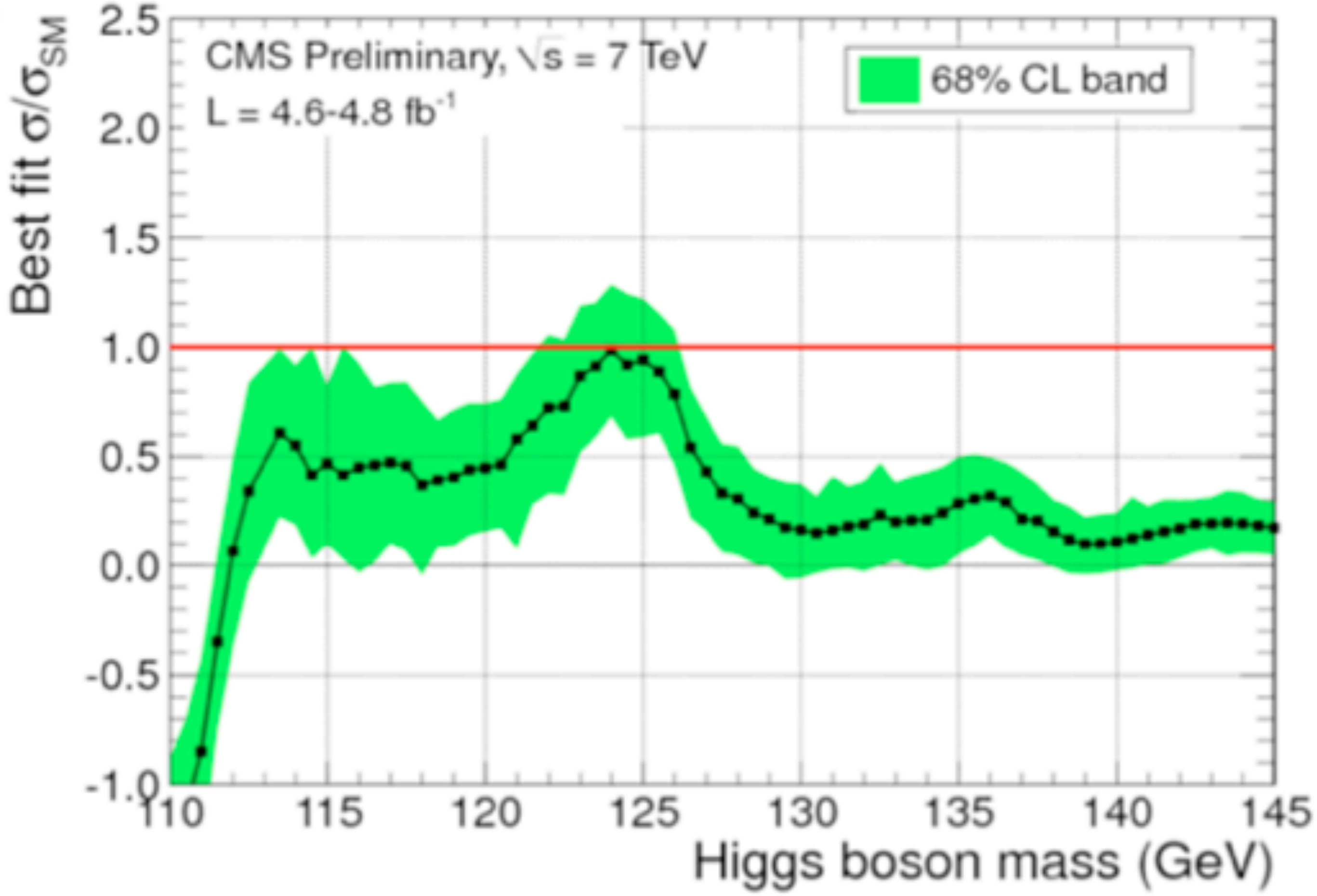


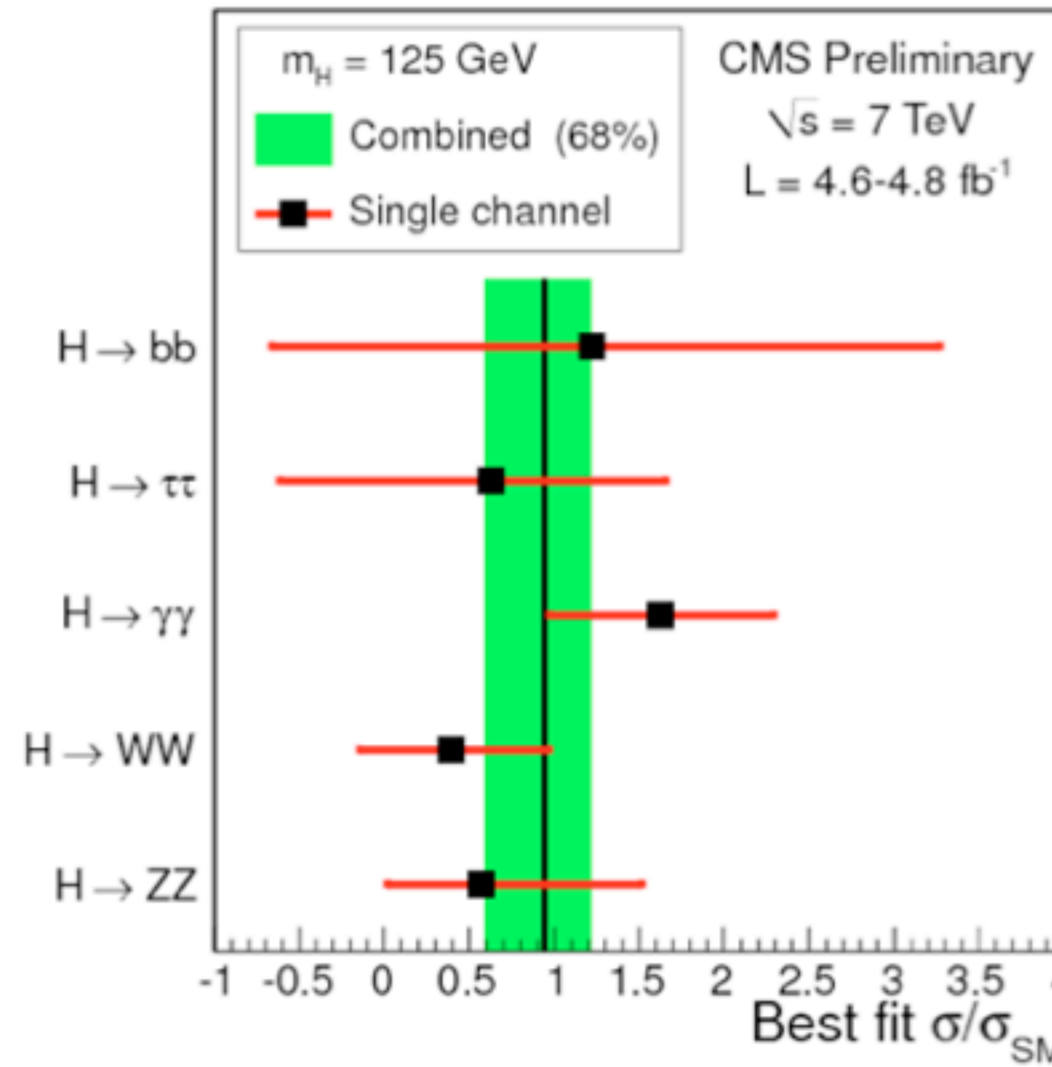
Thursday, May 31, 2012

Fitted signal strength σ/σ_{SM}

NEW

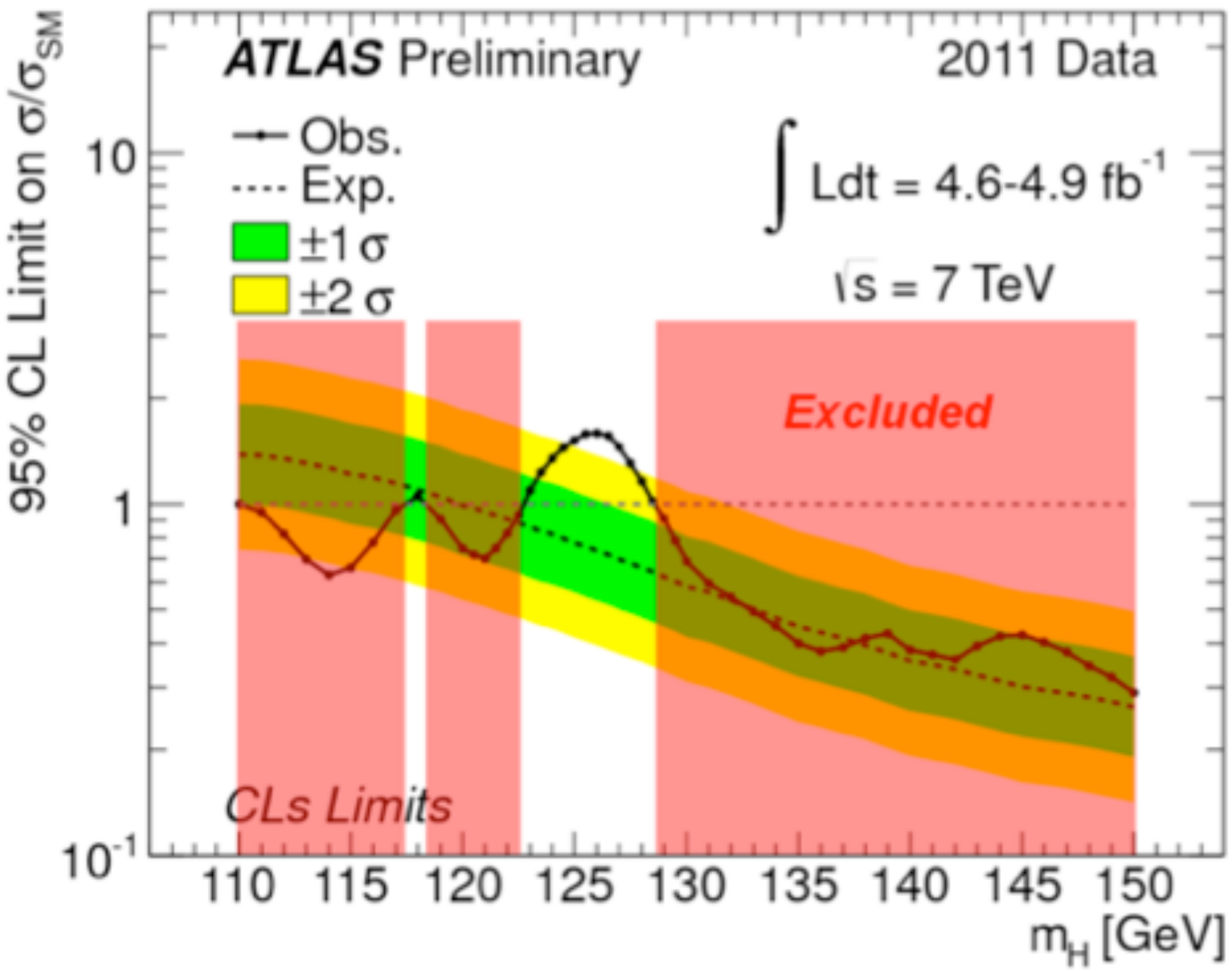
Comparison of channels for M_H=125 GeV



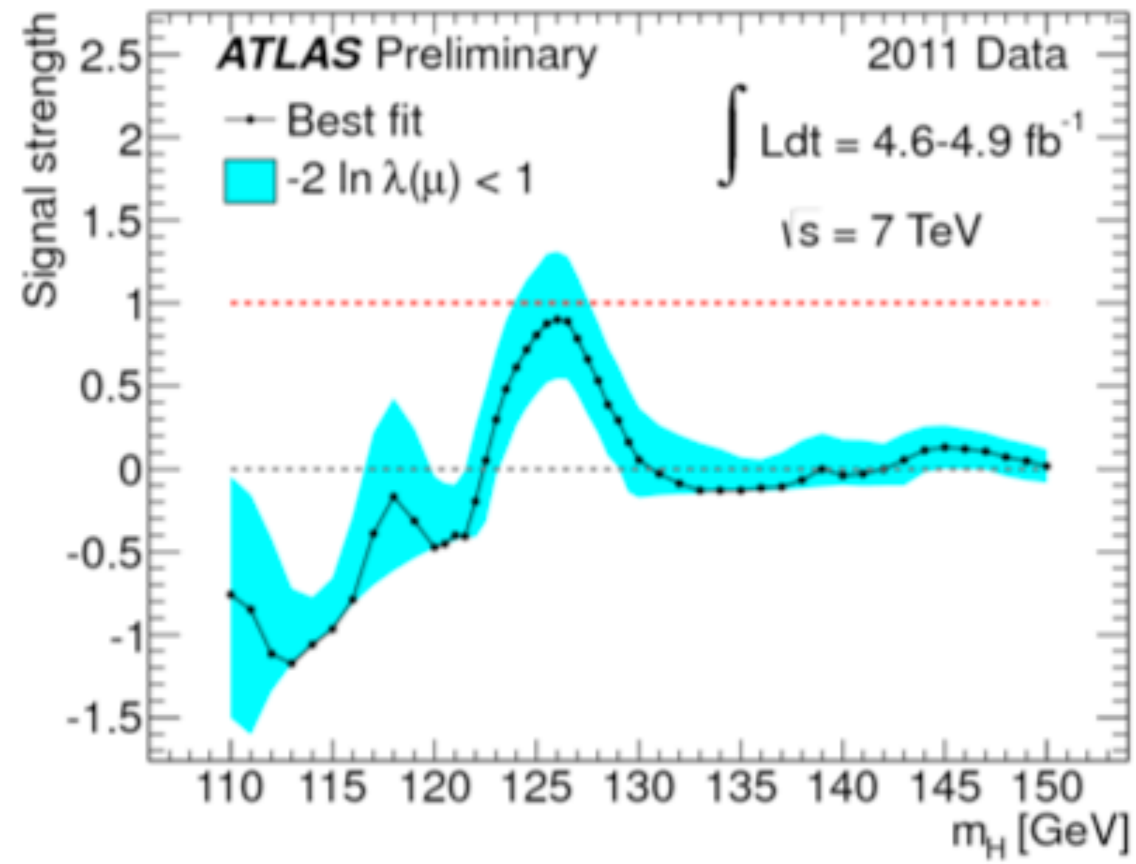


- The fitted σ of the excess near 125 GeV is consistent with the SM scalar boson expectation
- At low mass several channels show some excess
  - At 125 GeV all sensitive channels show an excess consistent with signal expectations

Breakdown of an observed excess

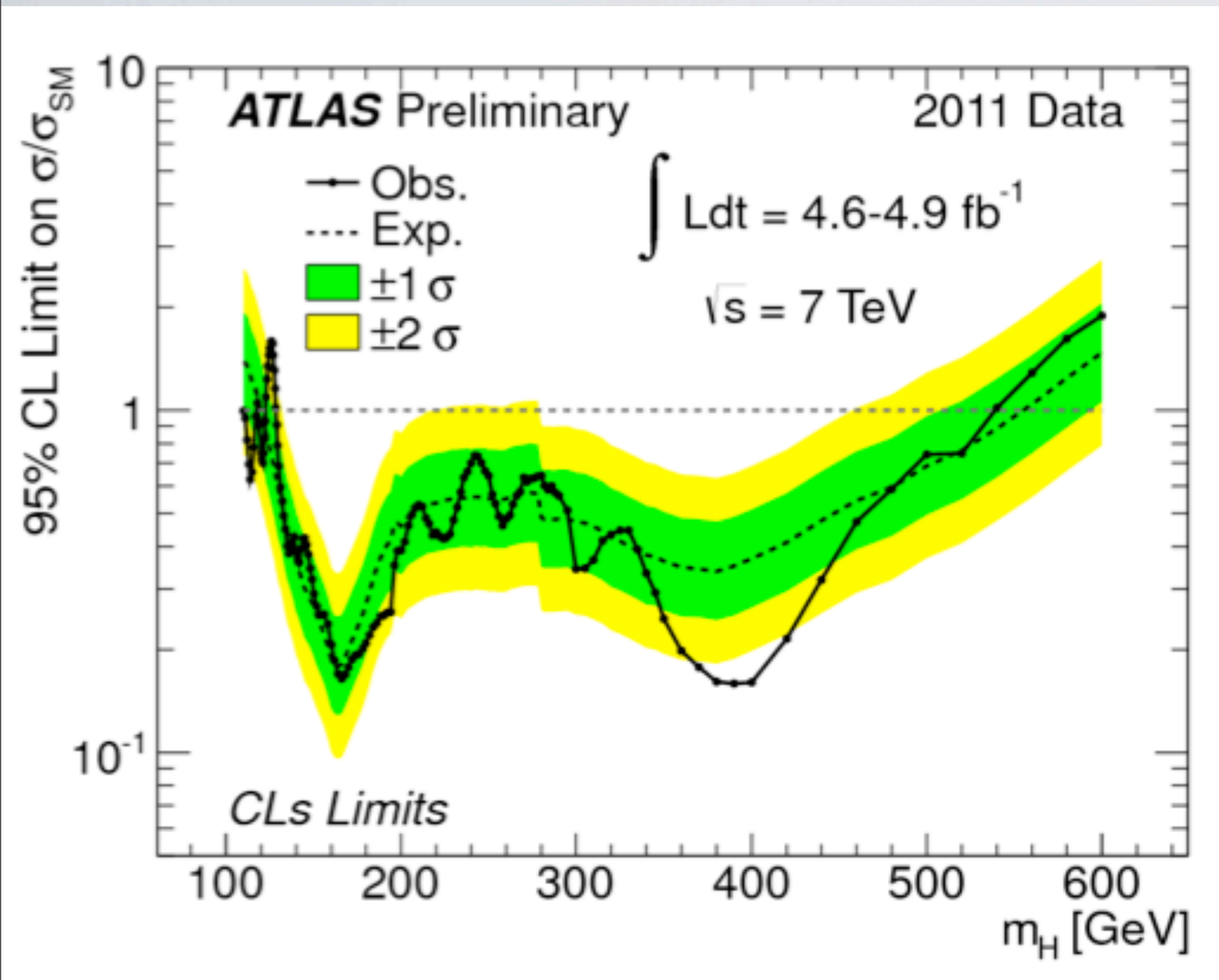


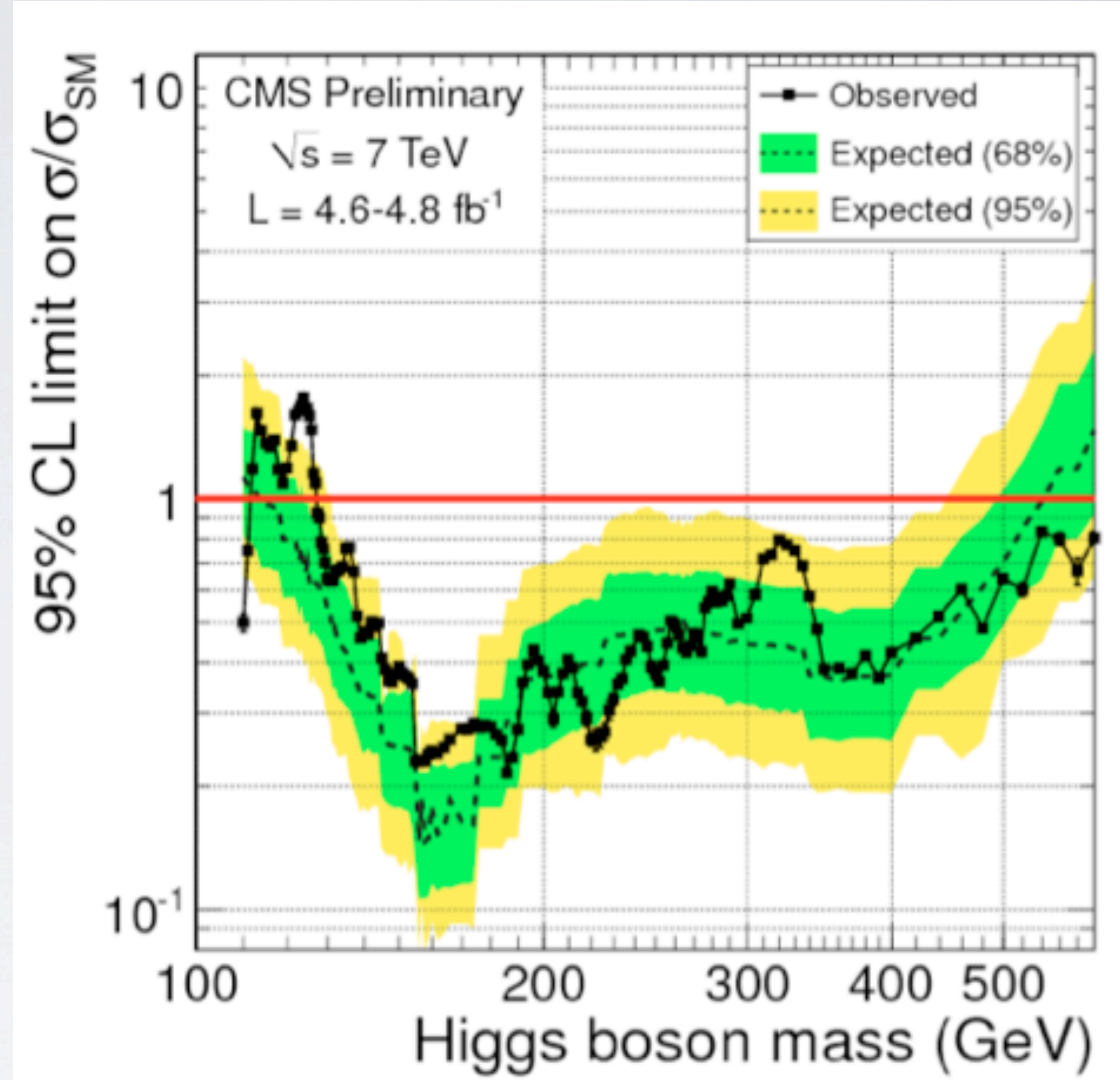
Best fit signal strength $\mu = \sigma/\sigma_{SM}$:



Excess of events observed at 126 GeV:

- Observed local significance 2.5σ (expected 2.9σ).
- Best-fit signal strength at 126 GeV: $\hat{\mu} = 0.9^{+0.4}_{-0.3}$.
- Global probability of such a background fluctation anywhere in the full explored mass range (110-600 GeV): 30%;
  in the mass range (110-146 GeV): 10%.





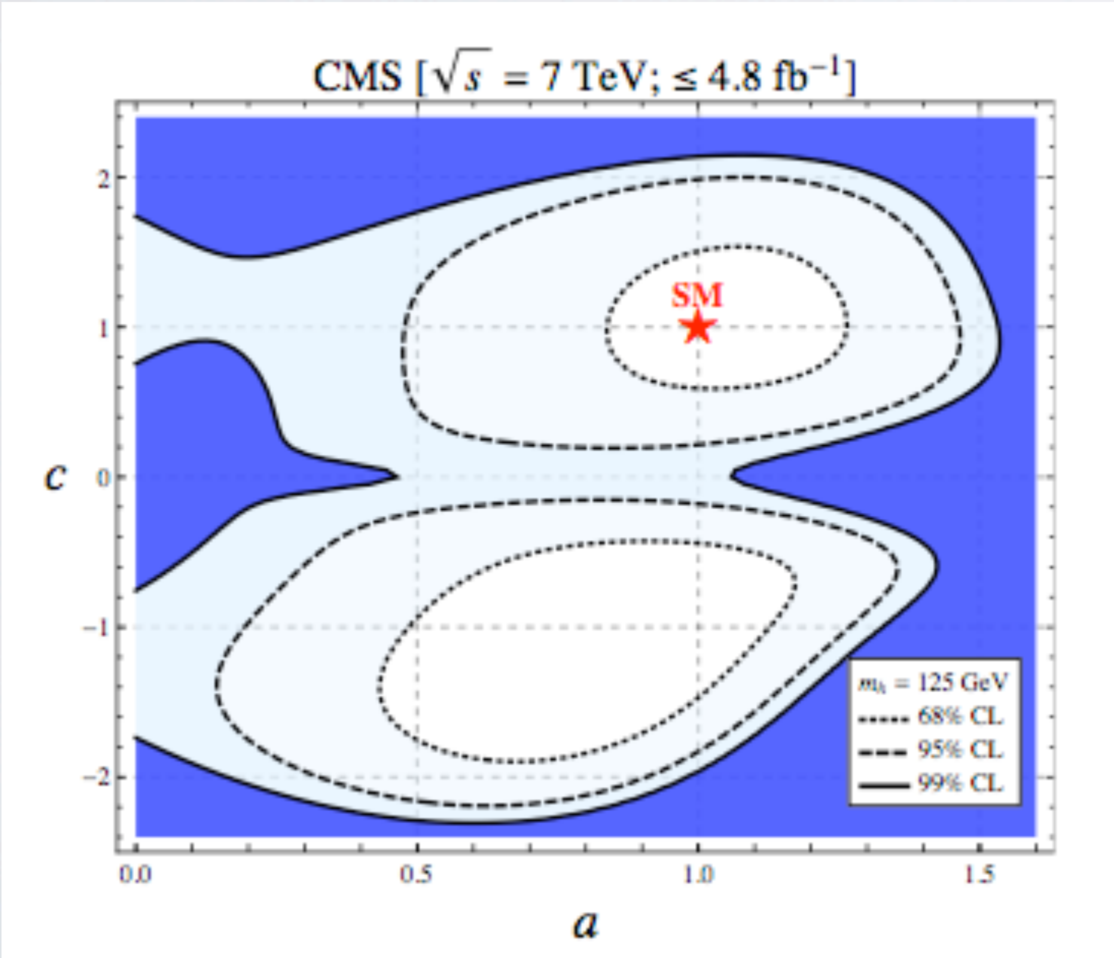
If Higgs exists it must be at 125 GeV!

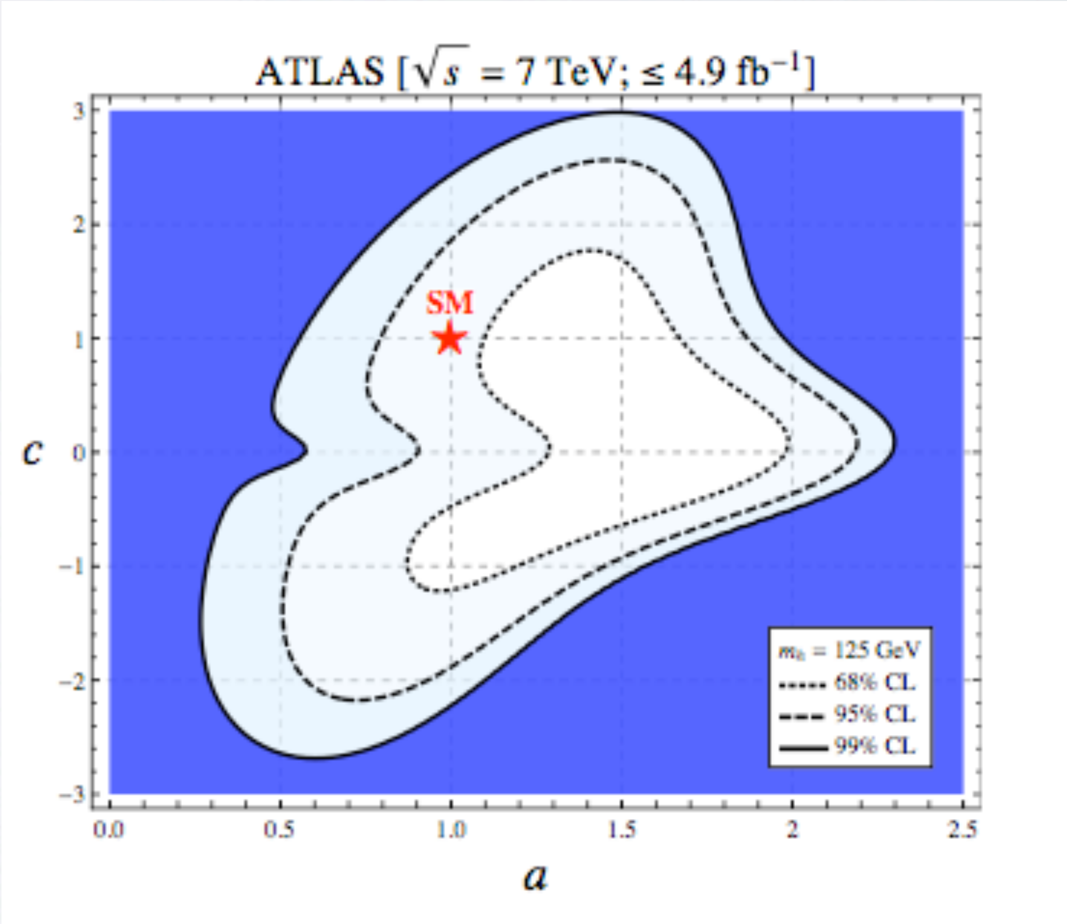
IMPLICATIONS

SM HIGGS?

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\dots\right]$$
$$- m_i \bar{\psi}_{Li}\Sigma\left(1 + c\frac{h}{v} + \dots\right)\psi_{Ri} + h.c.$$

$$\mathrm{SM:} \quad \mathrm{a = b = c = 1}$$

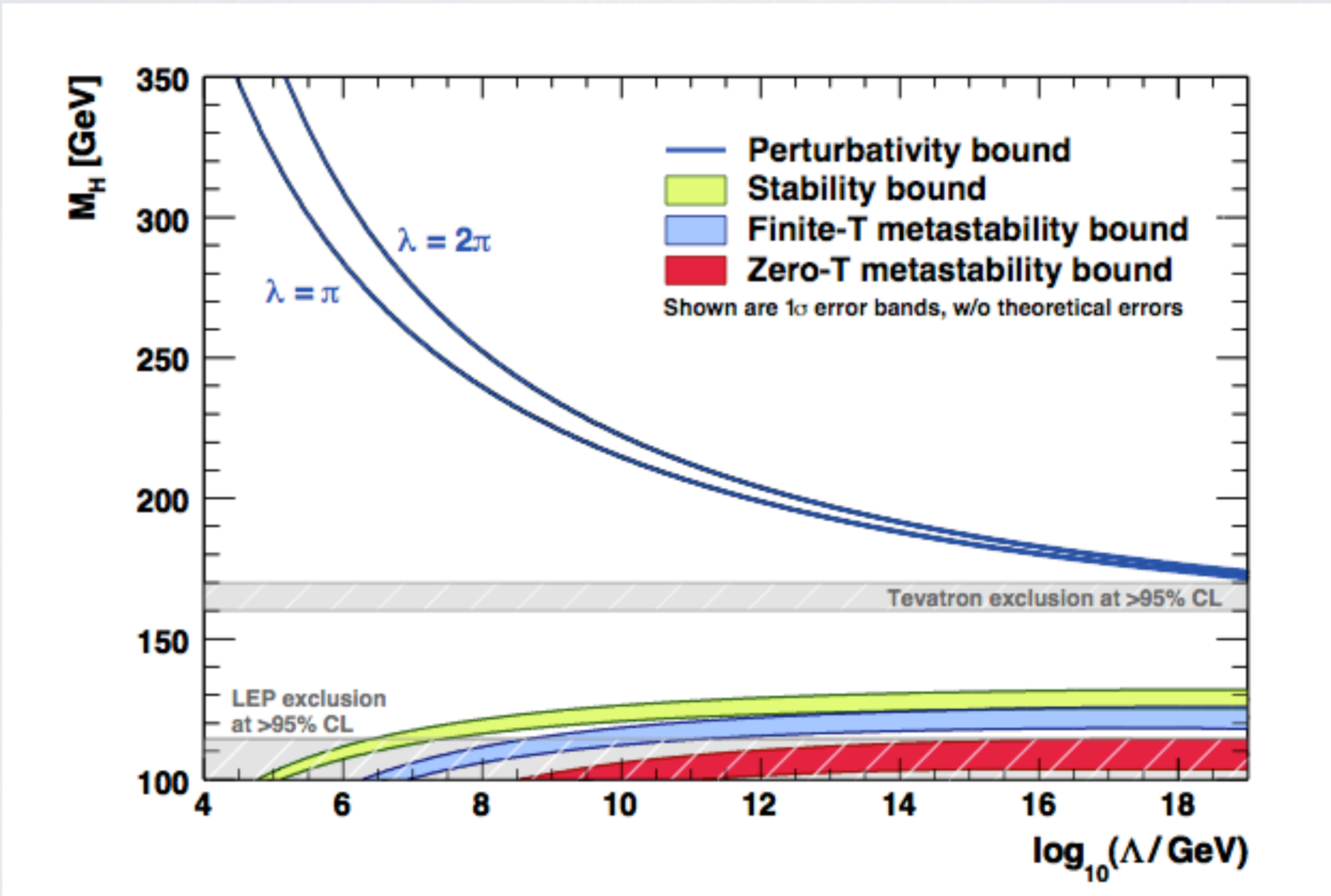




Azatov, Contino, Galloway '12

Can SM be the whole story?

$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

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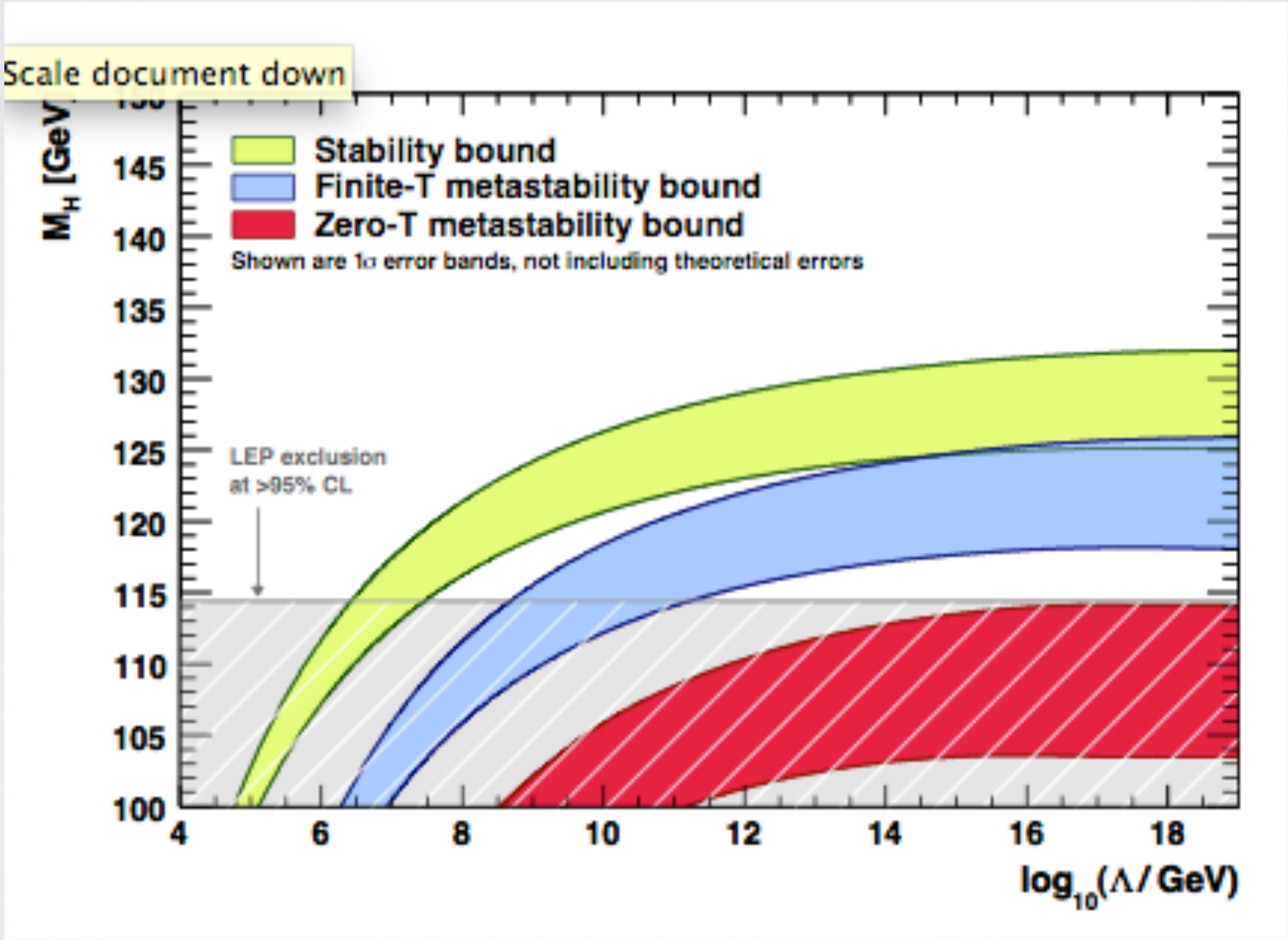


Giudice et al.
1112.3022

Stability:

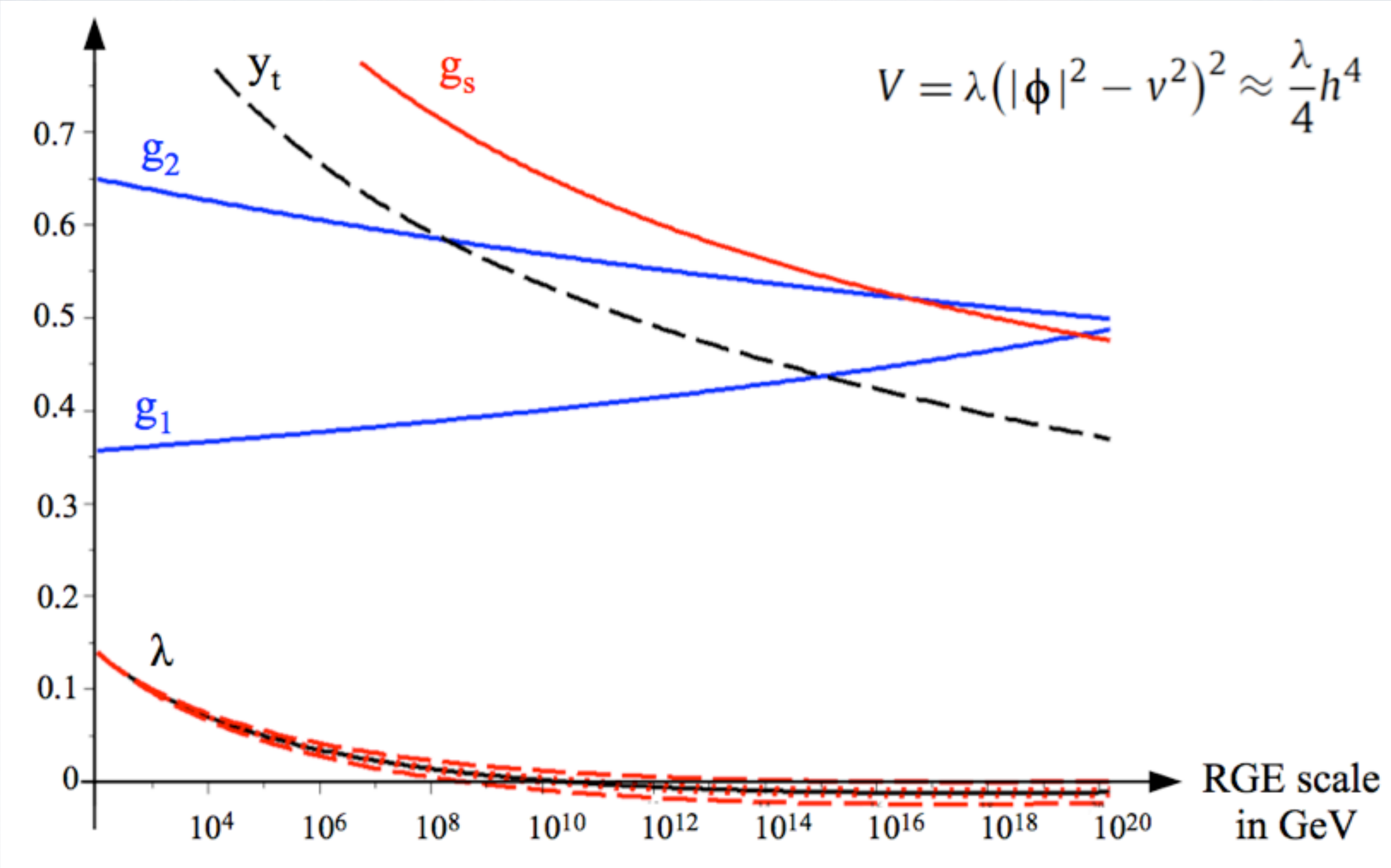
$$m_h > 130\,\mathrm{GeV} + 1.8\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.5\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\ \mathrm{GeV}$$

Metastability:

$$m_h > 111\,\mathrm{GeV} + 2.8\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.9\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\,\mathrm{GeV}$$

Thermal Stability:

$$m_h > 121.7\,\mathrm{GeV} + 2\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.6\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\,\mathrm{GeV}$$



126 GeV Higgs only marginally compatible with $\lambda(m_p) = 0$

NEW PHYSICS

NATURALNESS

Higgs mass only relevant operator in SM:

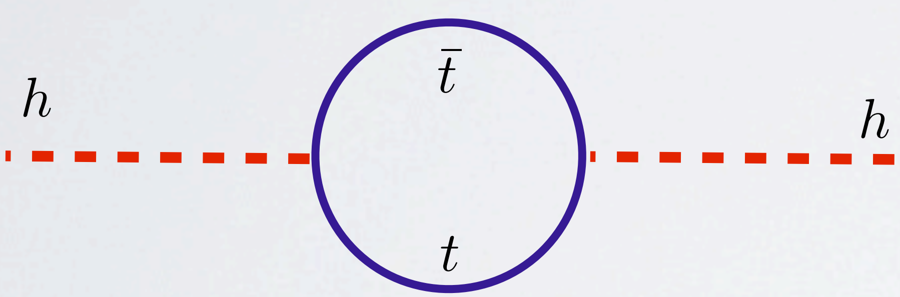
$$[\phi^2] \approx 2 \xrightarrow{\text{naive coefficient}} \Lambda^2$$

NATURALNESS

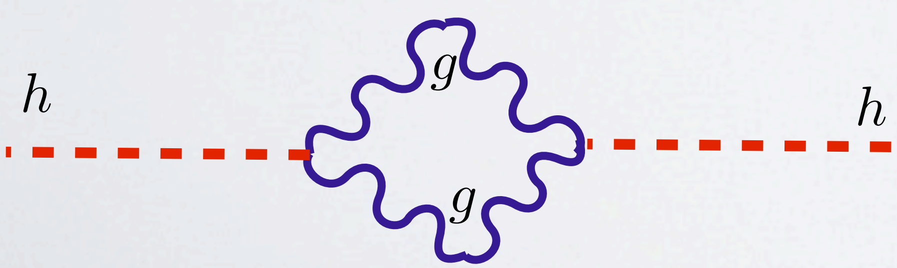
Higgs mass only relevant operator in SM:

$[\phi^2] \approx 2$ —naive coefficient→ Λ^2

Perturbatively:



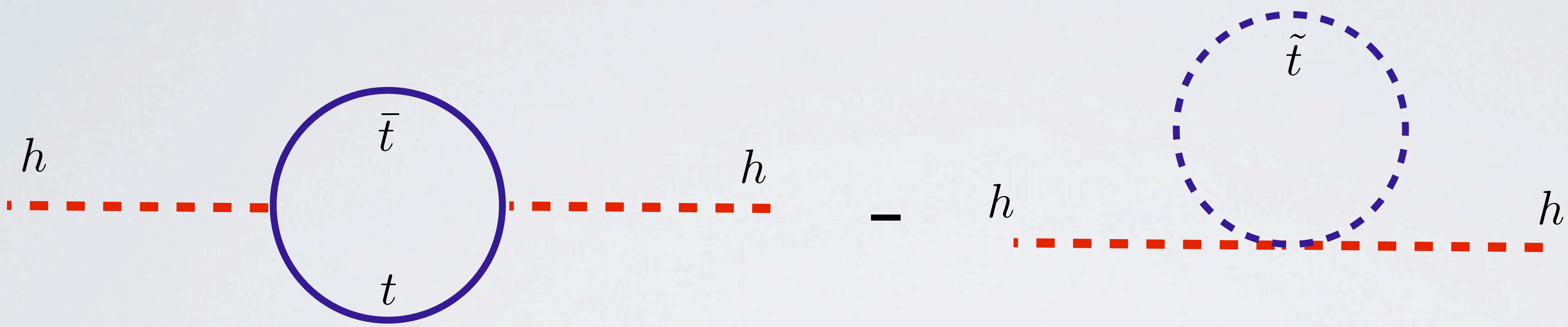
$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2 \longrightarrow \Lambda_t \sim 3\, m_h$$



$$\delta m_h^2 = \frac{9g^2 + 3g'^2}{32\pi^2}\Lambda_g^2 \longrightarrow \Lambda_g \sim 9\, m_h$$

Two paradigms:

- Weak Coupling: Supersymmetry



$\sim 100\,\mathrm{GeV}$

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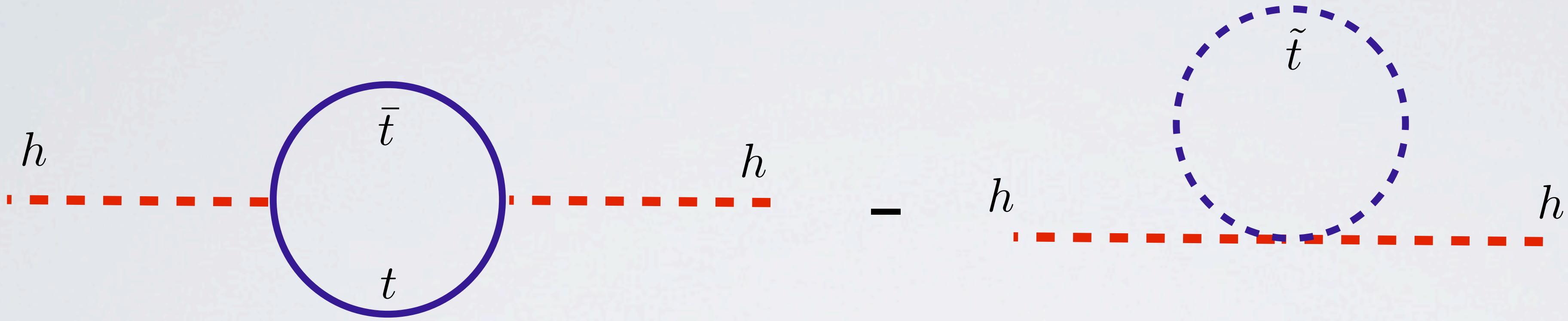
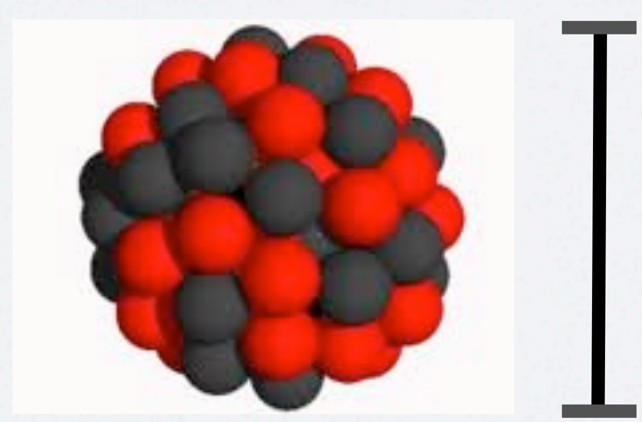


$\sim\ 100\,\mathrm{GeV}$

- Strong Coupling:
  Technicolor, Composite Higgs, Higgsless, Extra-dimensions ...



$$\sim \frac{1}{\mathrm{TeV}}$$

SUSY

MSSM tree level:

$$m_h < M_z \cos 2\beta \qquad\qquad @\,\mathrm{LEP}: \quad m_h > 114\,\mathrm{GeV}$$

SUSY

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$$m_h < M_z \cos 2\beta \qquad\qquad @\,\mathrm{LEP}: \quad m_h > 114\,\mathrm{GeV}$$

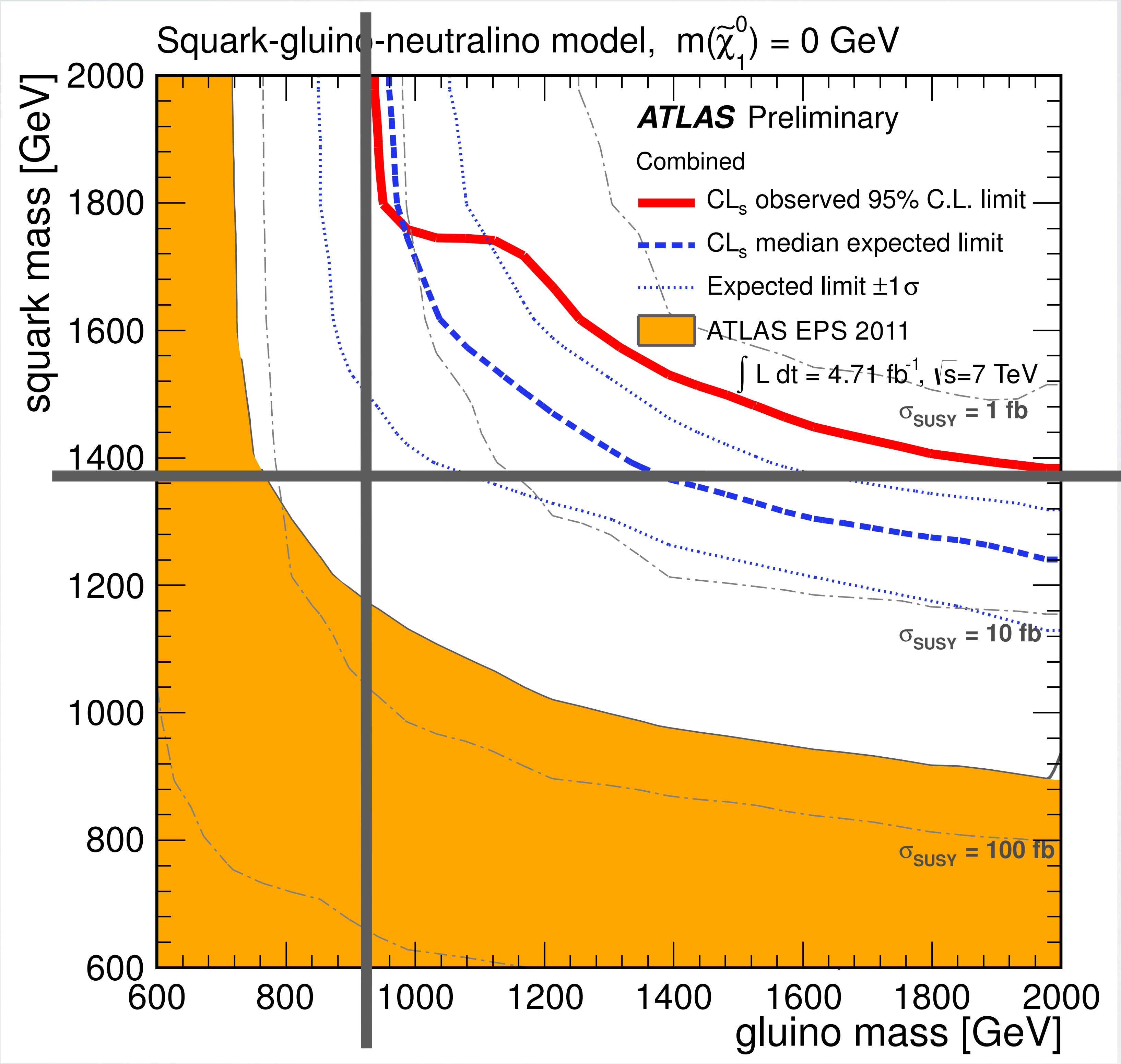
Radiative corrections

$$\Delta m_h^2 \approx \frac{3\, m_t^4}{\pi^2\, v^2} \log \frac{m_{\tilde{t}}}{m_t}$$

Possible, but

$$\mathrm{TUNING} \approx \frac{\Delta m_{H_u}^2}{m_Z^2} > \frac{3 y_t^2}{4\pi^2} \frac{m_{\tilde{t}}^2}{m_t^2} \log \frac{m_{\tilde{t}}}{m_t}$$

CMSSM bounds:



~1400 GeV

~930 GeV

Still ways out:

Large A-terms

Natural SUSY

R-parity Violation

NMSSM

Split SUSY

Compressed Spectrum

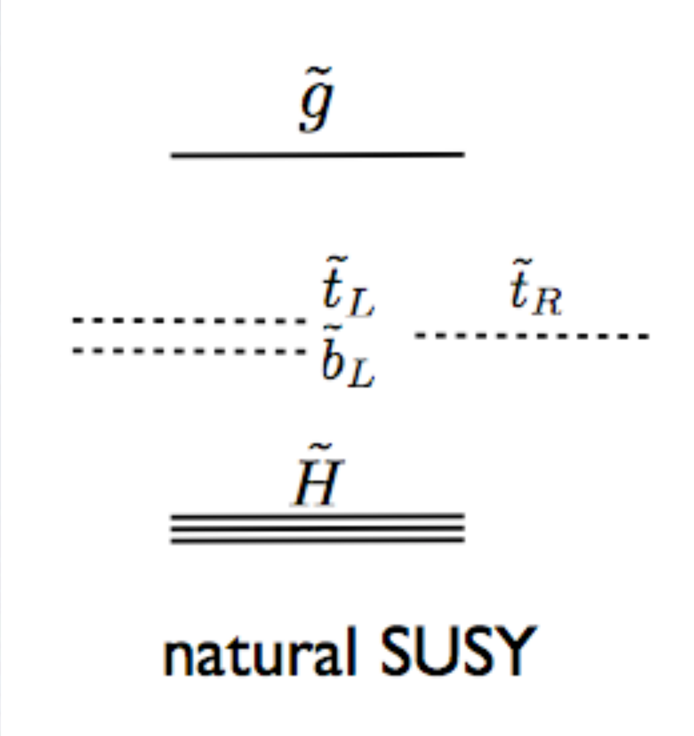
Partial SUSY

Tuning

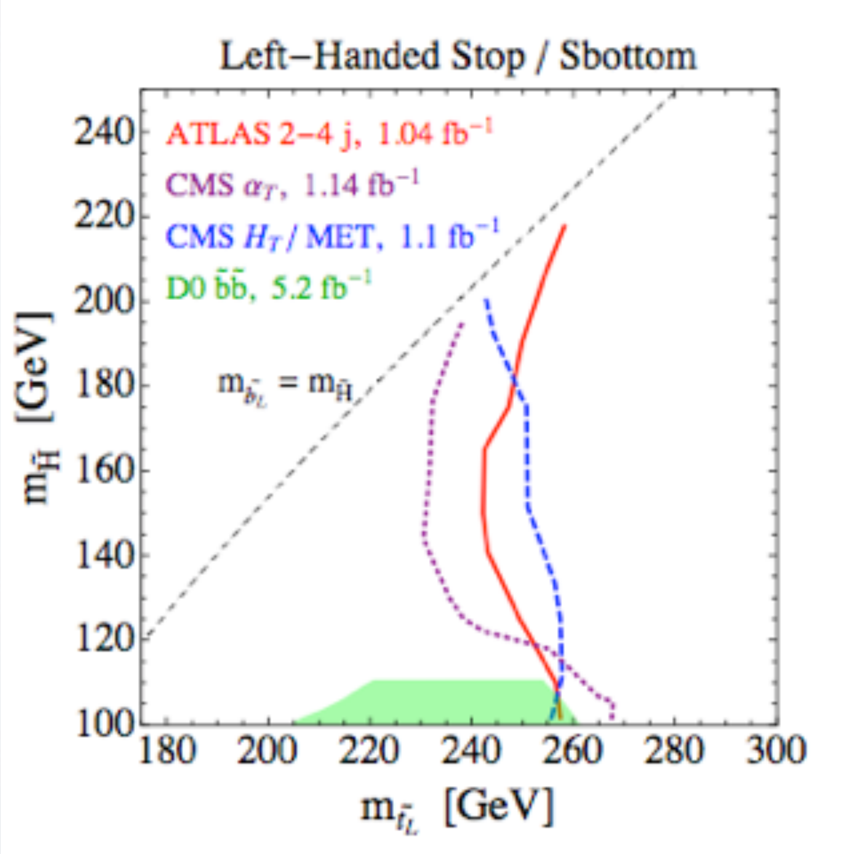
PMSSM

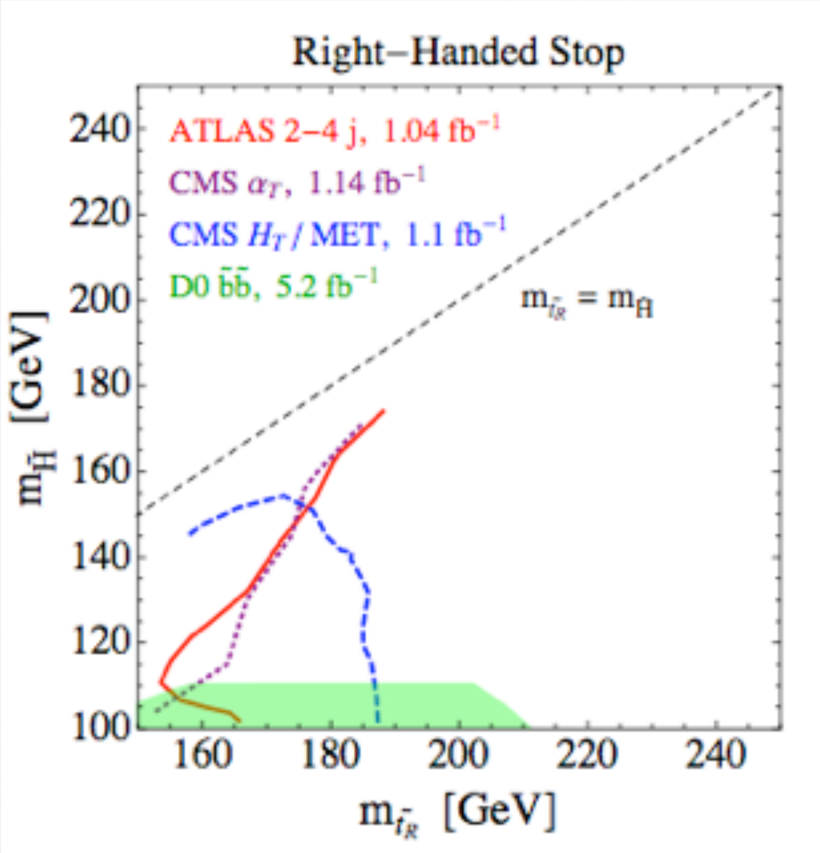
None terribly convincing...

Natural SUSY:



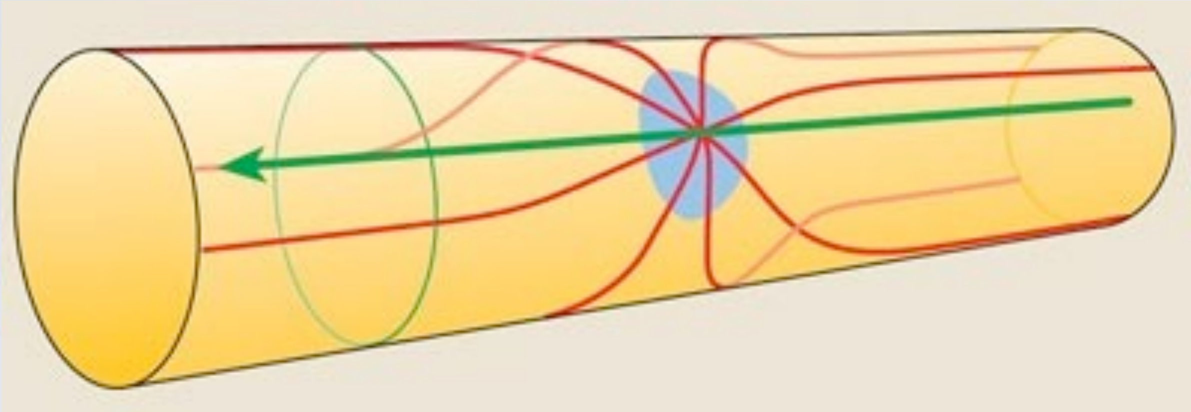
Stops can still be light!





STRONG DYNAMICS

- Large Extra-Dimensions:



$$m_p^2 = m_D^{D-2}\, V_{D-4}$$

$$= m_D^2\, N_{eff}$$

Always problematic for flavor physics and precision tests.

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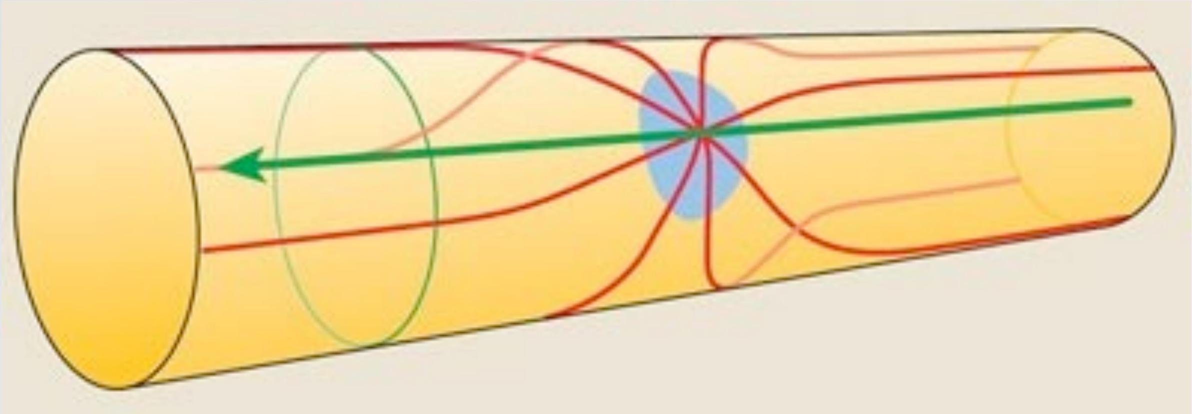

$$m_p^2 = m_D^{D-2}\, V_{D-4}$$

$$= m_D^2\, N_{eff}$$

Always problematic for flavor physics and precision tests.

Strong gravity at the TeV scale:

$$\frac{4}{m_T^4}\left(T_{\mu\nu}T^{\mu\nu} - \frac{T^\mu_\mu T^\nu_\nu}{D-2}\right) \longrightarrow \quad m_D \;\; \text{in multi} - \text{TeV range}$$

- Technicolor (Higgsless)

$$\langle \bar{\Psi}^i_L \Psi^j_R \rangle \sim v^3 \delta^{ij} \longrightarrow \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}$$

Longitudinal polarizations of W & Z are composite states.

- Technicolor (Higgsless)

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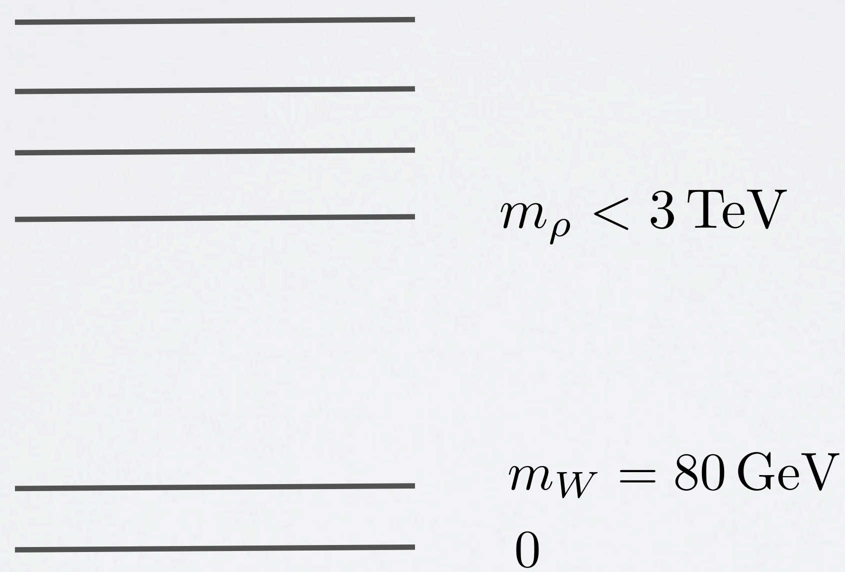
Longitudinal polarizations of W & Z are composite states.

No Higgs scalar but techni-resonances (spin 0, 1/2, 1 etc.).



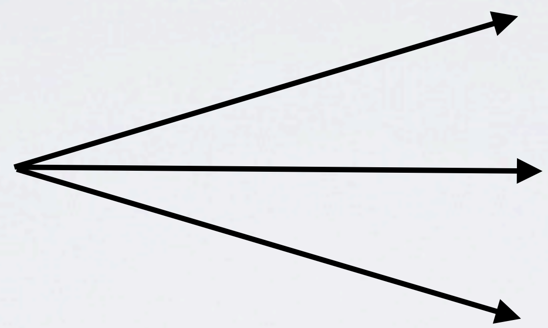
Clearly ruled out if Higgs confirmed.

- Composite Higgs:

Georgi, Kaplan '80s

Higgs doublet could be a light remnant of strong dynamics.

Strong sector:
resonances +
Higgs bound state



spin 1

spin 1/2

spin 0.... $2_{\frac{1}{2}}$

Two parameters:

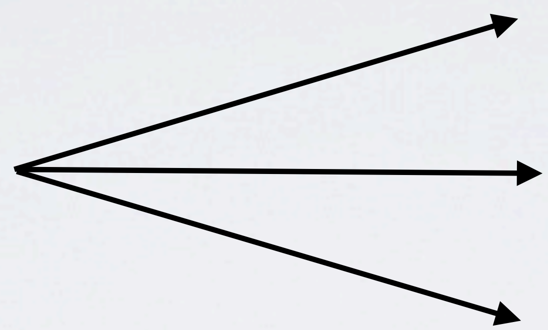
m_ρ g_ρ

- Composite Higgs:

Georgi, Kaplan ‘80s

Higgs doublet could be a light remnant of strong dynamics.

Strong sector:
resonances +
Higgs bound state



spin 1

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Two parameters:

m_ρ g_ρ

- Relieves hierarchy problem

$$\delta m_h^2 \sim \frac{3\,\lambda_t^2}{4\pi^2} m_\rho^2$$

Particularly compelling if Higgs is a Goldstone Boson:
Massless at leading order.

Ex: $\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$

Agashe , Contino, Pomarol, '04

Or: $\frac{SO(6)}{SO(5)}$ $\frac{SO(6)}{SO(4) \otimes U(1)}$ $+ \ldots$

Mrazek, Pomarol, Rattazzi, MR, Serra, Wulzer '11

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Low energy lagrangian

$$\mathcal{L} = f^2\, D_\mu \Sigma^i D^\mu \Sigma^i + \ldots \xrightarrow{SU(2)_L \otimes SU(2)_R} \rho \approx 1$$

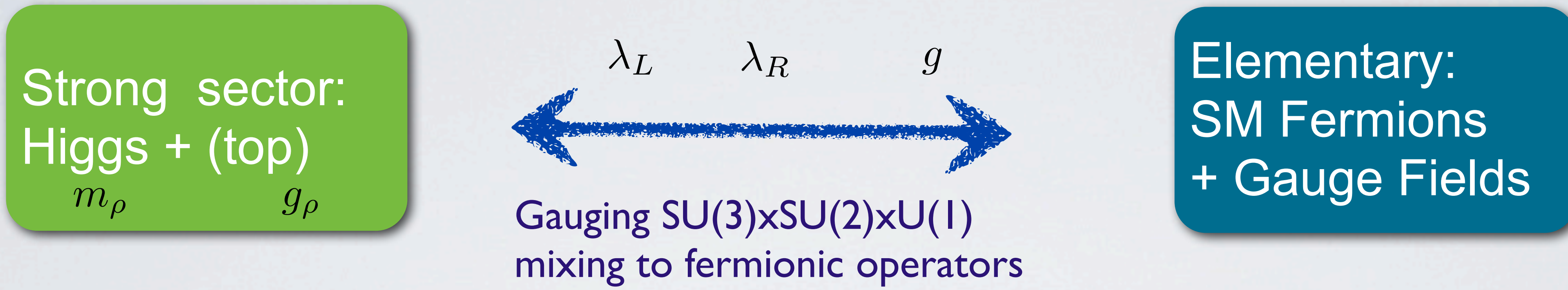
$$m_\rho = g_\rho f$$

General picture:

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

General picture:



They talk through linear couplings:

$$\mathcal{L}_{gauge} = g\, A_\mu J^\mu$$

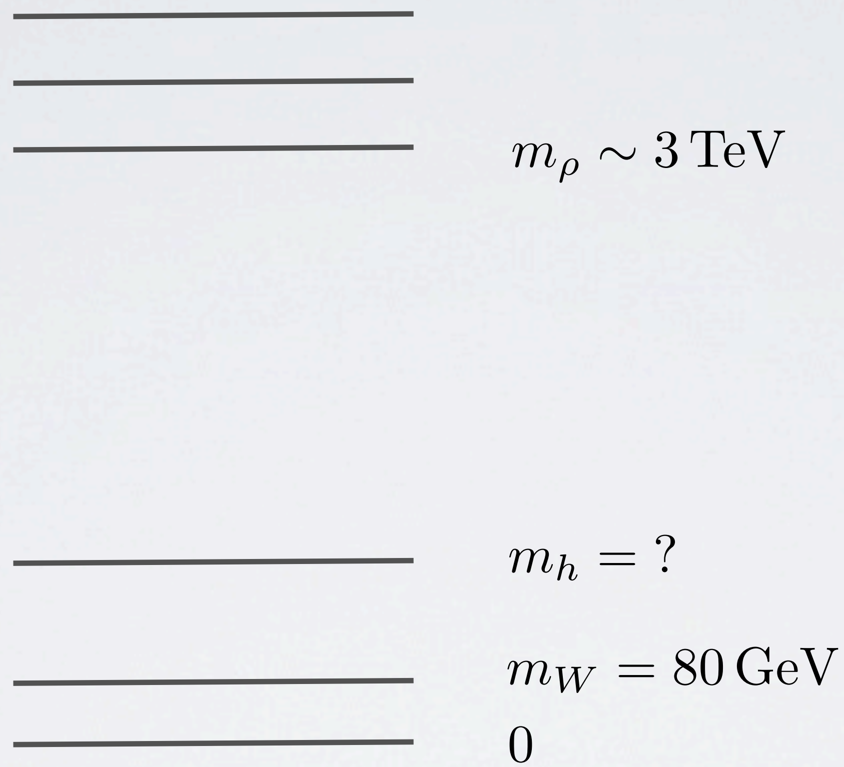
$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \quad \xrightarrow{\tan\varphi \sim \frac{\lambda}{g_\rho}} \quad y \sim \frac{\lambda_L \lambda_R}{g_\rho}$$

Potential generated at 1-loop:

$$V(H) \propto \frac{m_\rho^4}{g_\rho^2} \frac{\lambda_{L,R}^2}{16\pi^2} \hat{V}\left(\frac{H}{f}\right)$$

Main difference from techni-color is that f is not linked to v. Increasing f CH approximates SM.

Spectrum:



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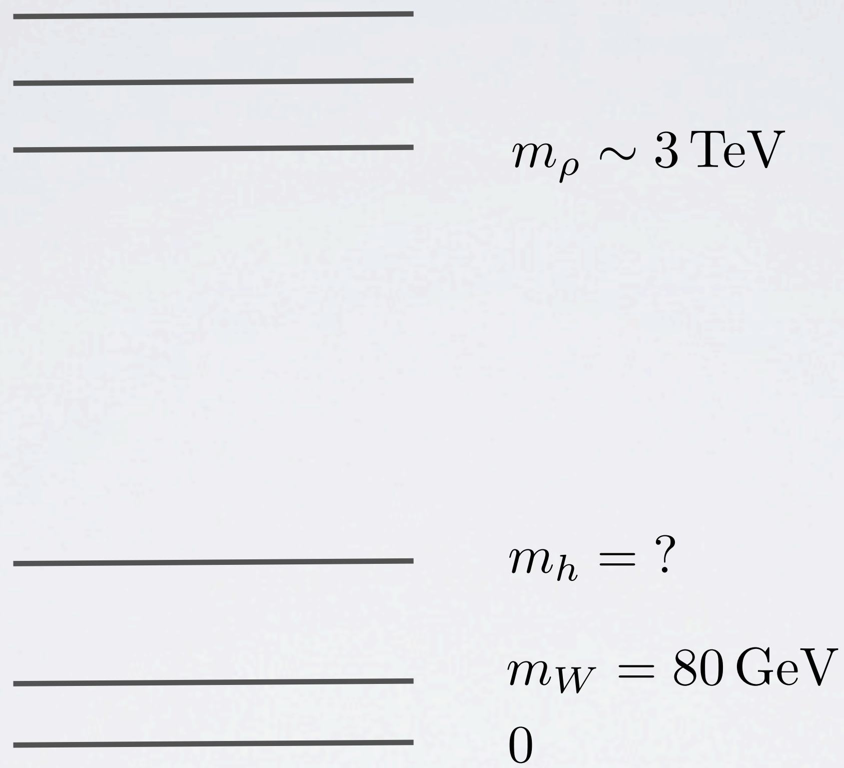


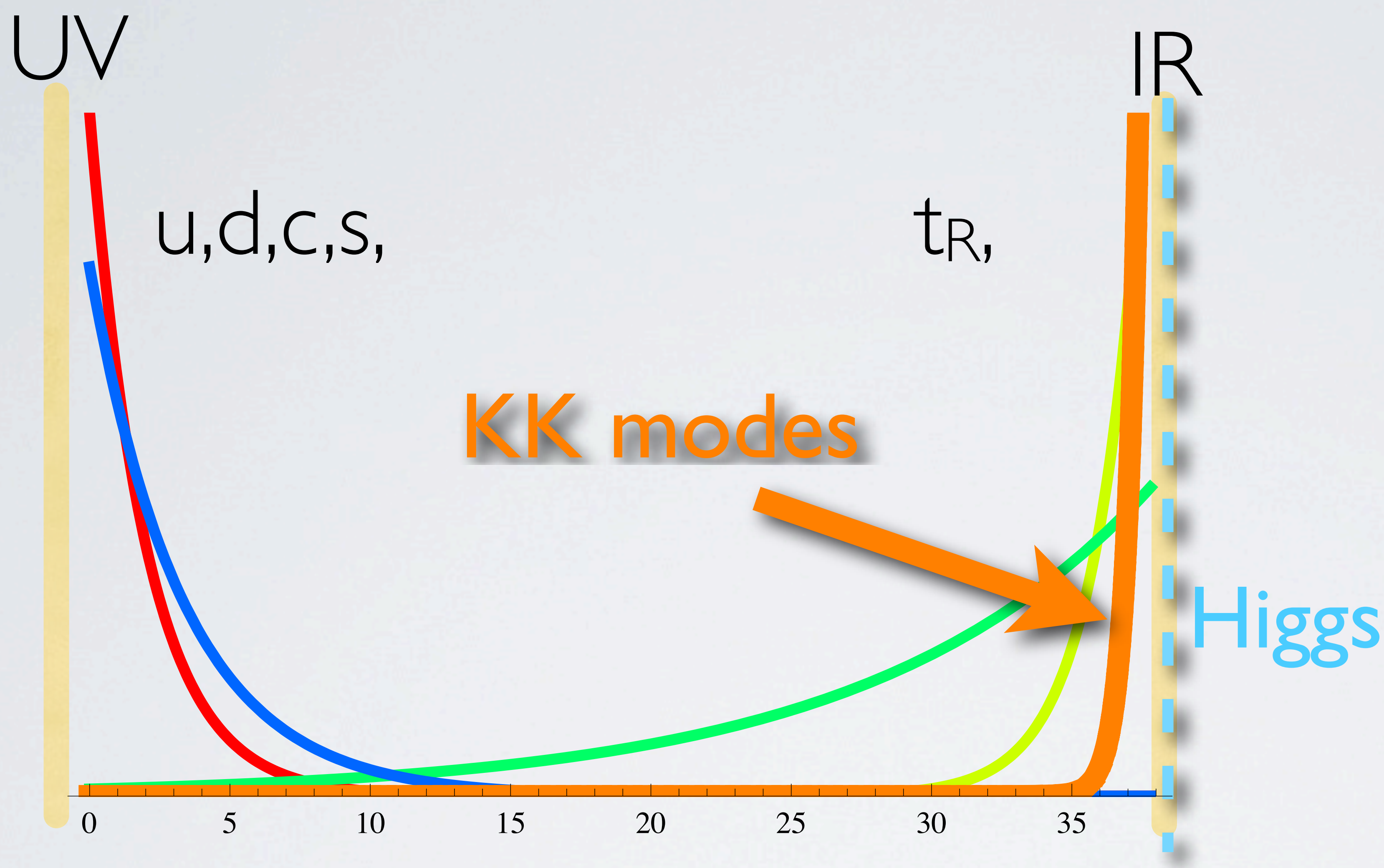
Higgs is angle,

$0 < h < 2\pi f$ →

Tuning

$$\xi = \frac{v^2}{f^2}$$

Realized in Randall-Sundrum scenario



(Randall-Sundrum '99)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

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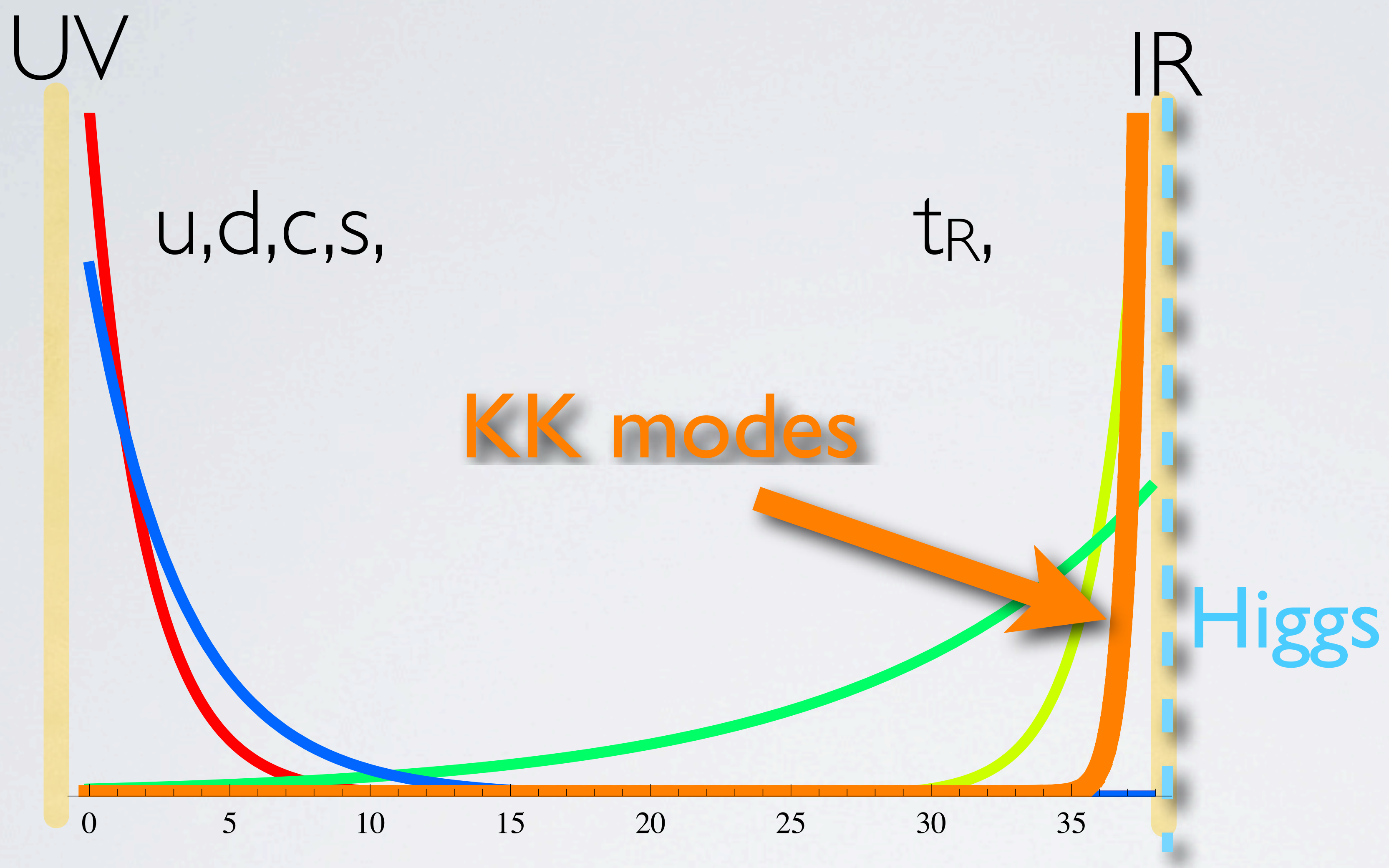

(Randall-Sundrum '99)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

Connected through AdS/CFT to strongly coupled CFTs

Arkani-Hamed, Porrati, Randall '01

Rattazzi, Zaffaroni '01

Modified couplings:

$$a,\ b,\ c = 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right)$$

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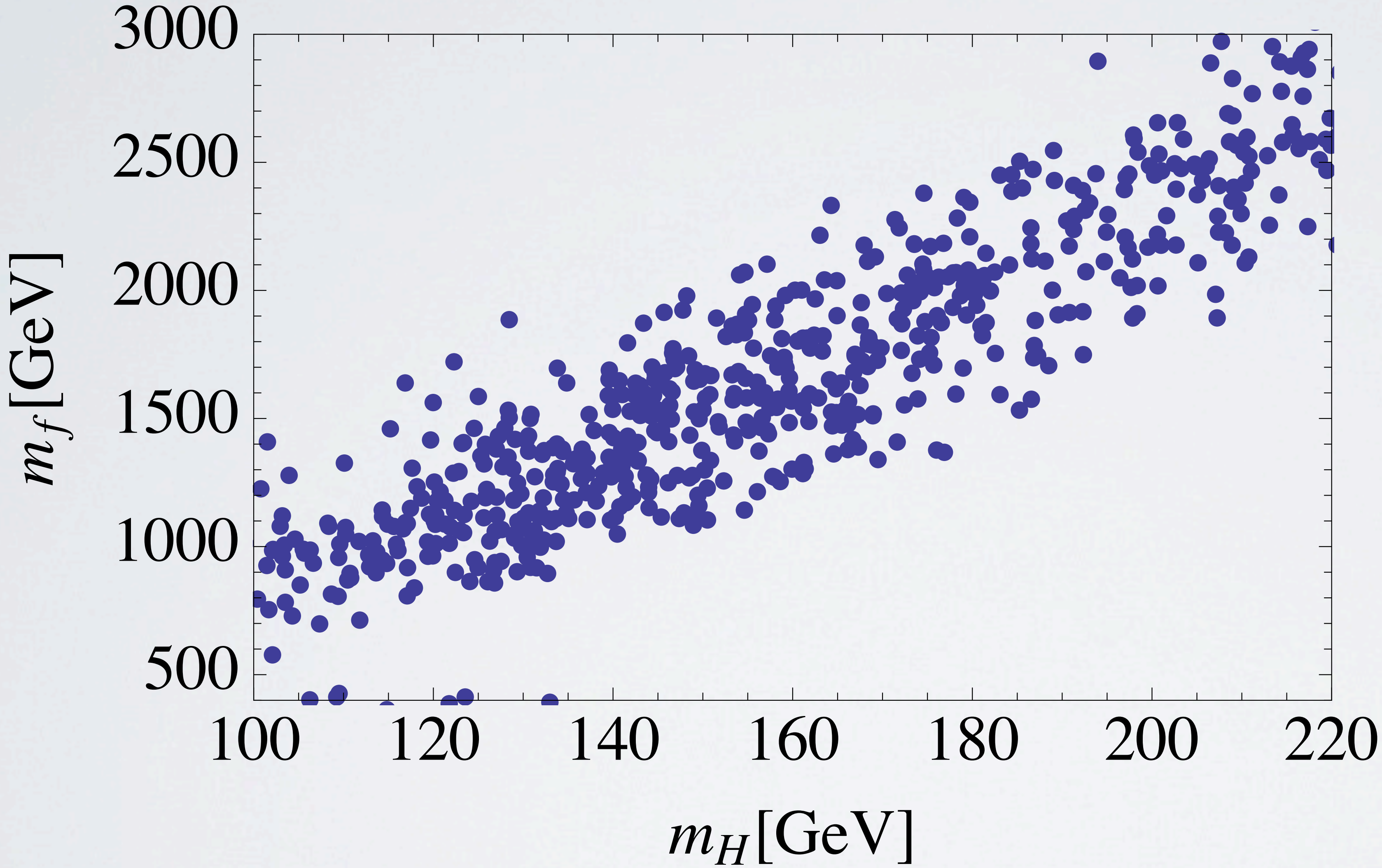


$$f = 800\,\mathrm{GeV}$$

MR, Tesi '12

Light Higgs wants light partners.

Most sensitive experimental searches (1-slide snapshot)

- Looking for pair production

[CMS L=1.14 fb-1] PAS-EXO-11-050 — $T\bar{T} \to WbW\bar{b} \to b\bar{b}\, l^+ l^- \not{E}_T$ — $m_T > 422\,\text{GeV}$

[CMS L=0.80 fb-1] PAS-EXO-11-051 — $T\bar{T} \to WbW\bar{b} \to b\,3j\, l^\pm \not{E}_T$ — $m_T > 450\,\text{GeV}$

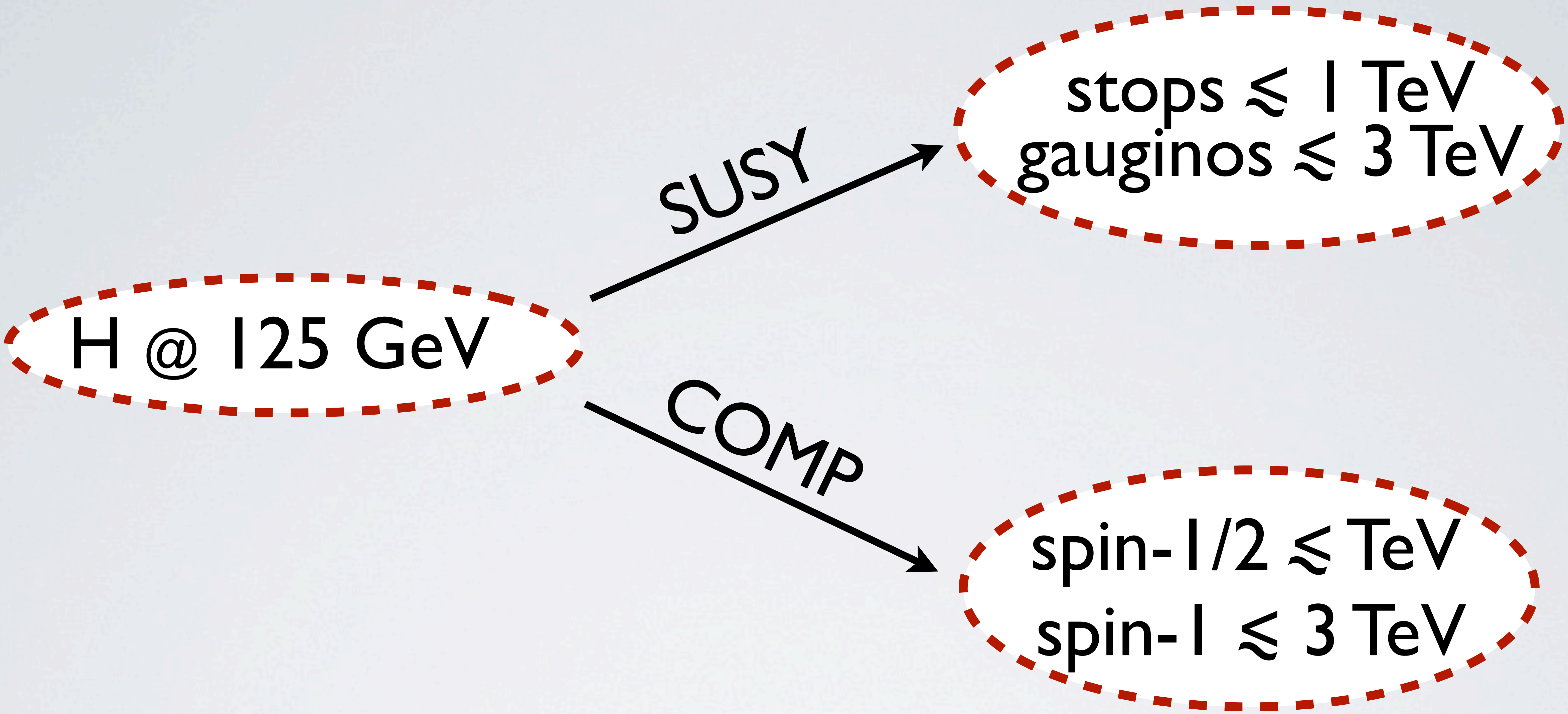
[CMS L=191 pb-1] PAS-EXO-11-005 — $T\bar{T} \to tZ\,\bar{t}Z \to (l^+ l^-) l^\pm\, jj$ — $m_T > 417\,\text{GeV}$

[CMS L=1.14 fb-1] PAS-EXO-11-036 — $B\bar{B} \to WtW\bar{t} \to l^\pm l^\pm\, b\,3j\, \not{E}_T$, $\to lll\, b\,1j\, \not{E}_T$ — $m_B > 495\,\text{GeV}$

- Looking for single production

[D0 L=5.4 fb-1] arXiv:1010.1466 — $Q\bar{q} \to Wq\bar{q} \to l^\pm jj\, \not{E}_T$, $\to Zq\bar{q} \to (l^+ l^-) jj$

Notice: All analyses assume 100% BR to the considered channel



If naturalness is a good guide new states must be around the corner and maybe seen in 2012.

OUTLOOK

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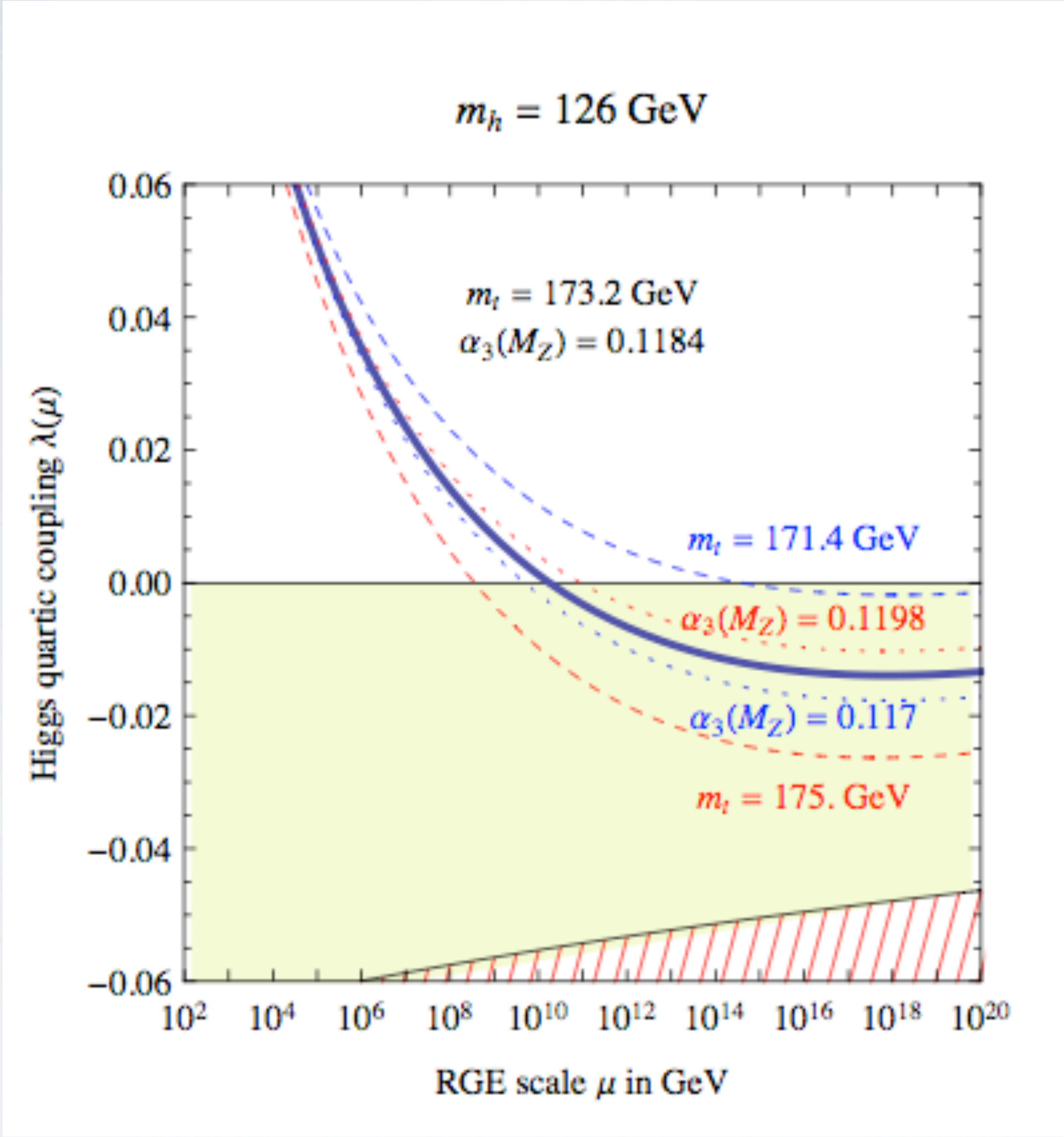
- If Higgs @ 125 GeV is confirmed with couplings compatible with SM, room for new physics getting narrow. Universe might be tuned.


UNEXPECTED RD



126 GeV Higgs only marginally compatible with $\lambda(m_p) = 0$

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2}\right)\right)$$