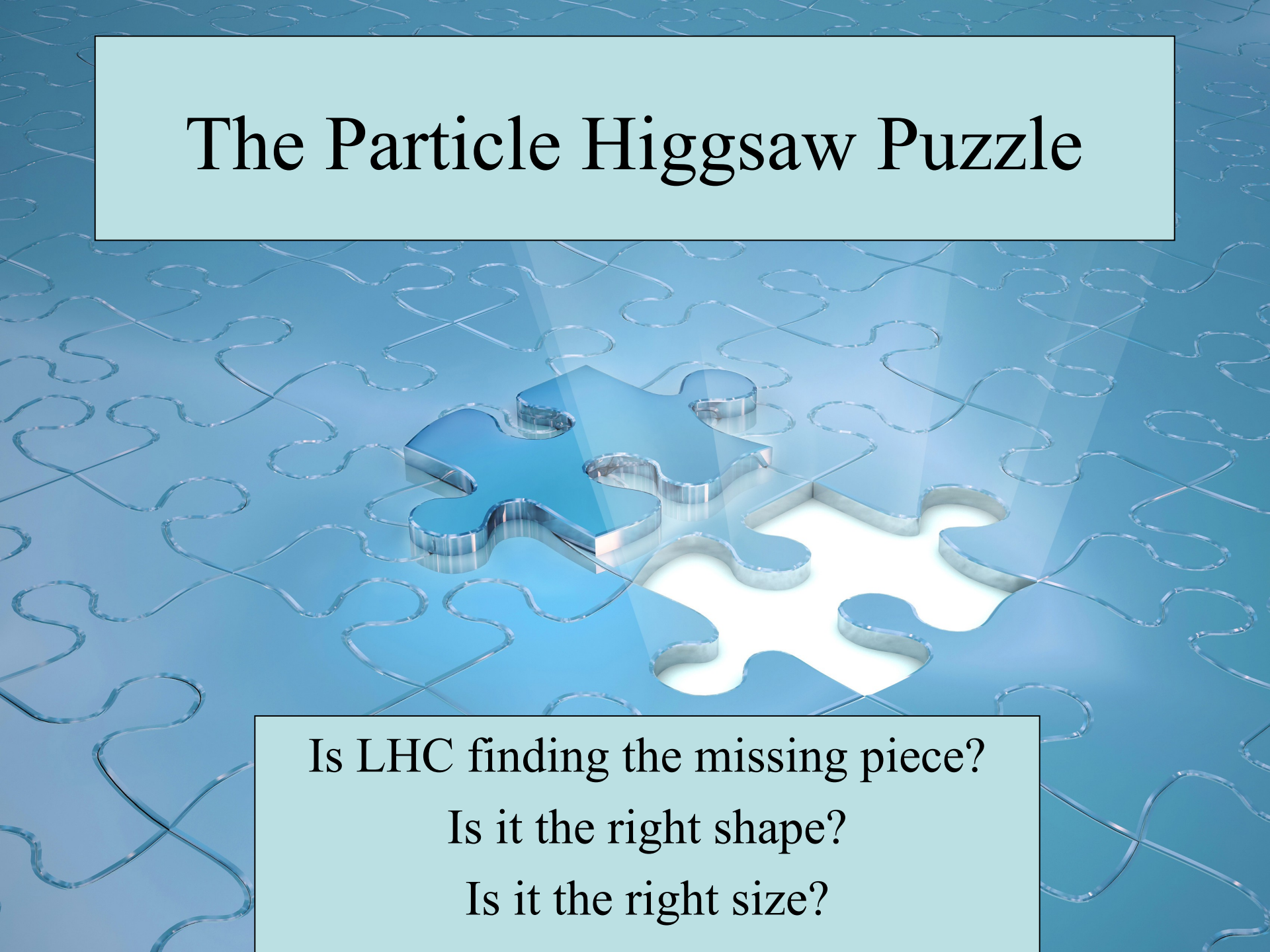
Programme of Lectures

- The road to the Higgs discovery
- Characterizing the new particle
- What else?
  - Supersymmetry?
  - Future accelerators?
  - Cosmological inflation?

JE “Higgs Physics”: arXiv:1312.5672

The Particle Higgsaw Puzzle



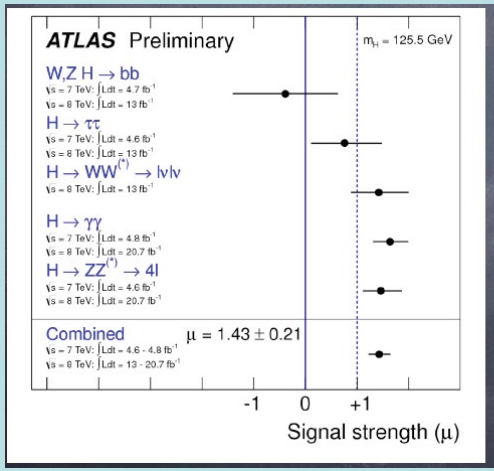
Is LHC finding the missing piece?

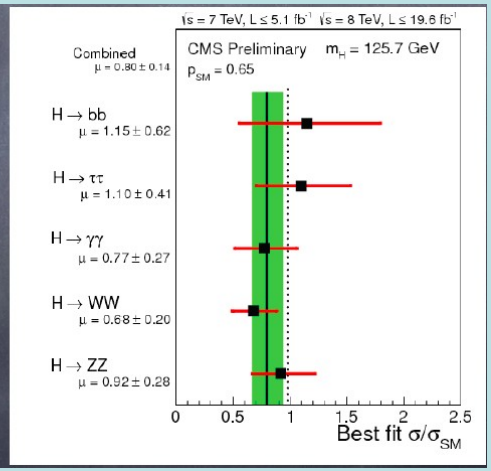
Is it the right shape?

Is it the right size?

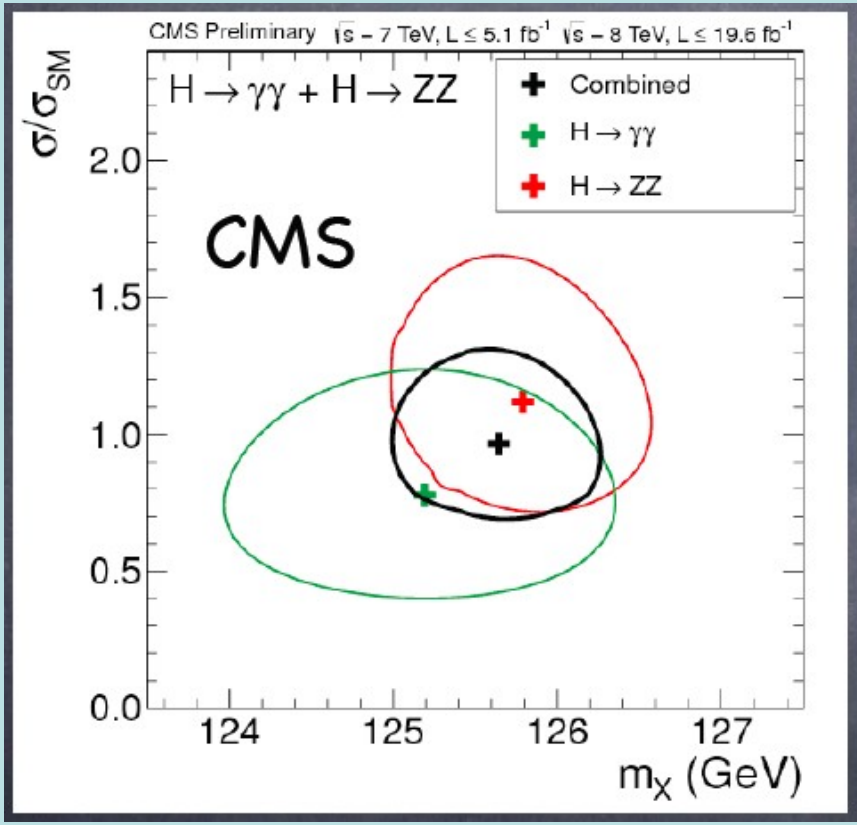
From Discovery to Measurement

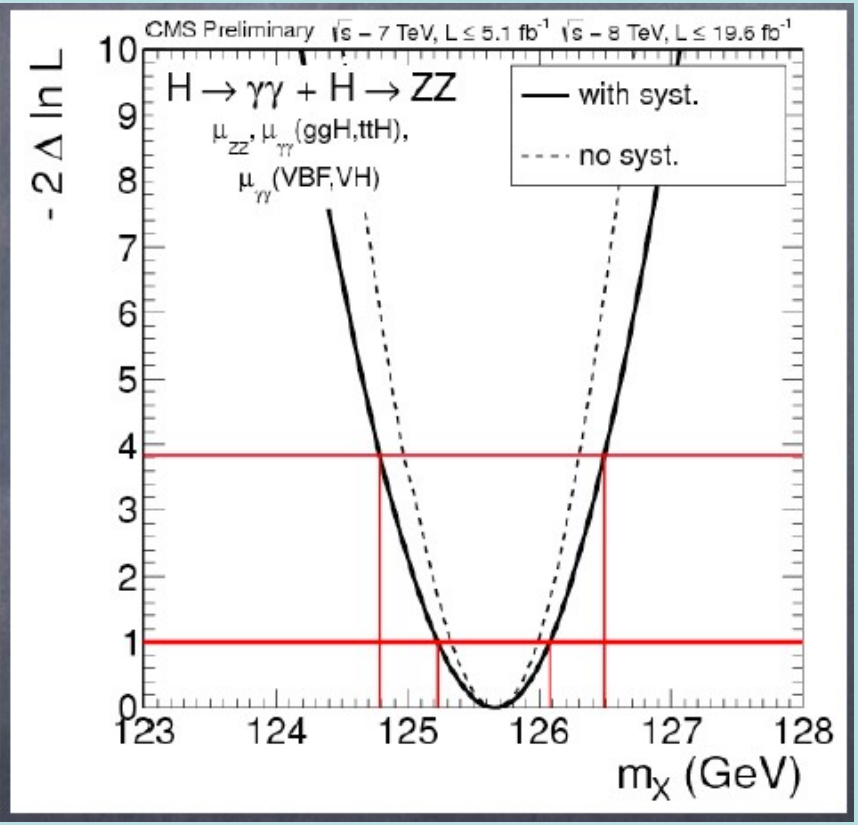
- Mass measurements:
  125.6 ± 0.3 GeV
- Signal strengths ~ SM
  in many channels
- Frontiers:
  - VBF significance 2σ in several channels, 3σ combined
  - Decay to ττ recently established, limits on μμ
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling
    (search for ttbar + H/W, Zγ)





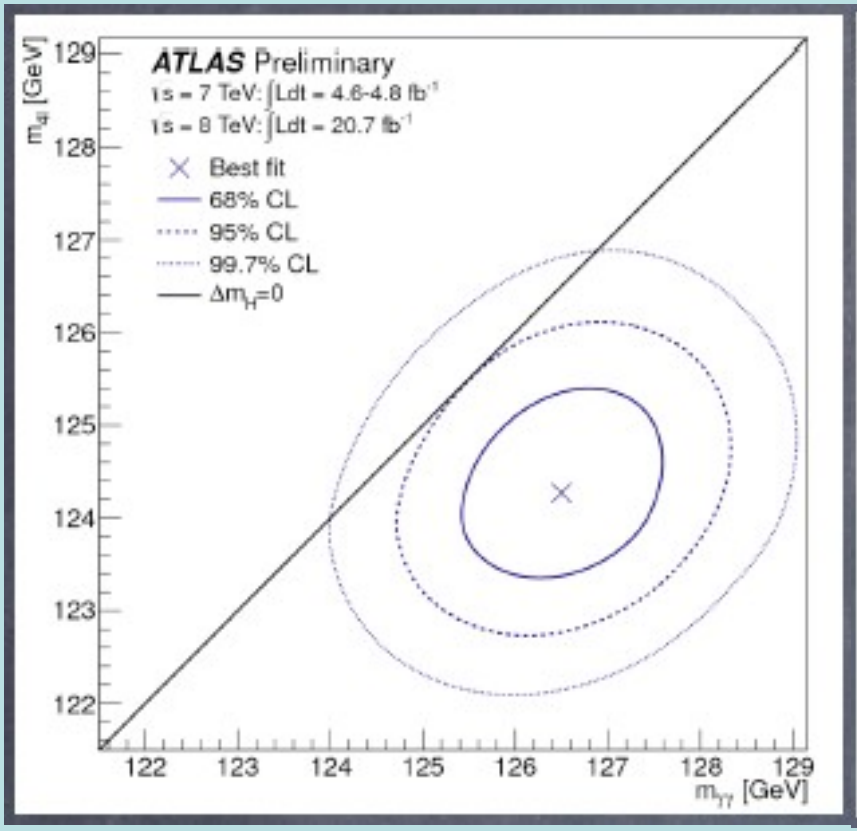
Higgs Mass Measurements

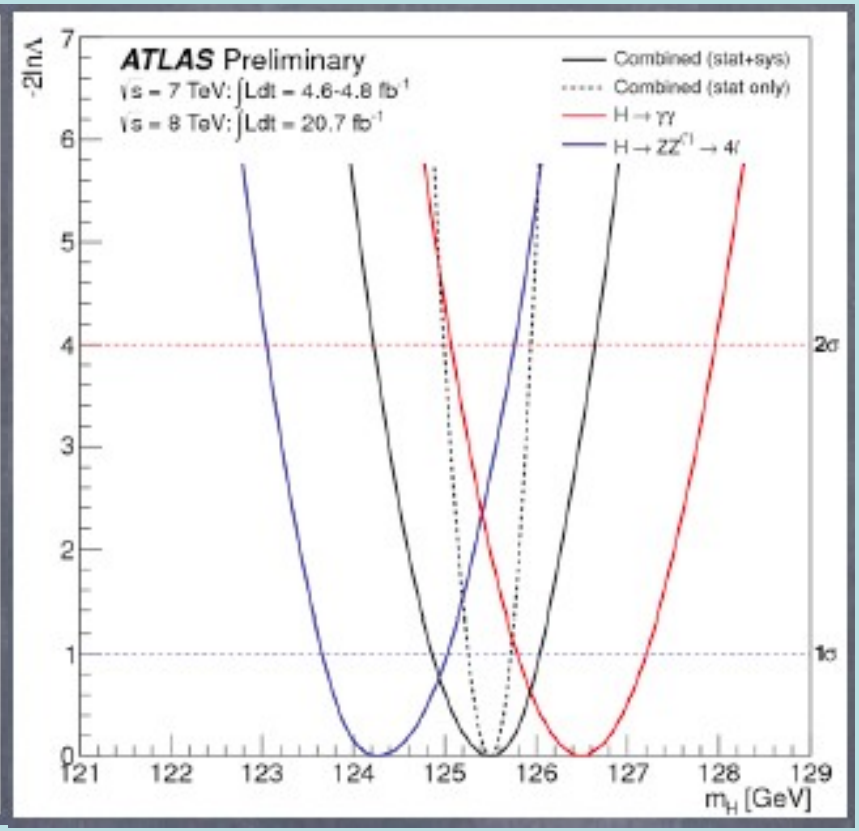




- CMS $\gamma\gamma$ and ZZ* measurements consistent

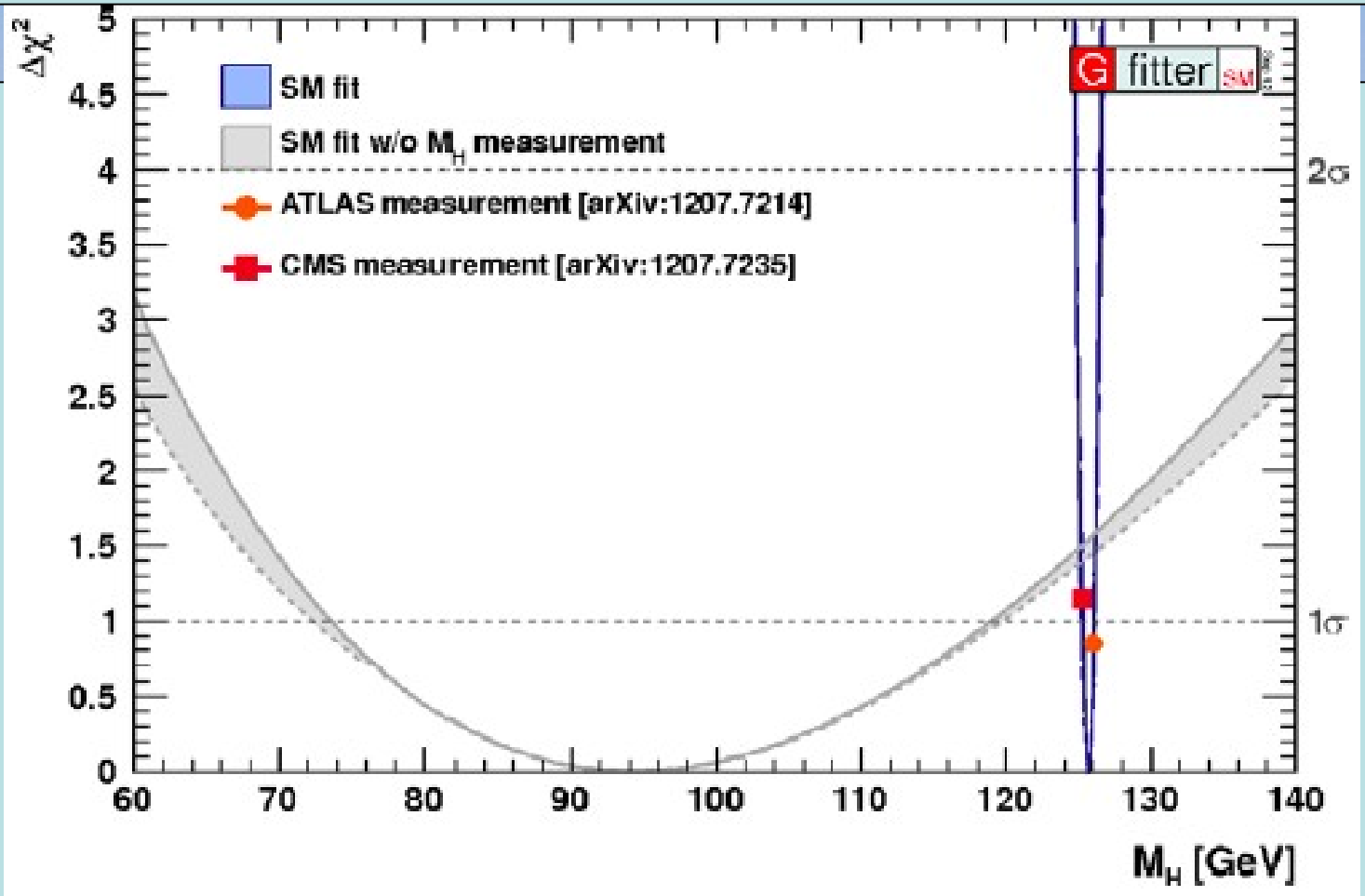
Higgs Mass Measurements





- Tension in ATLAS γγ and ZZ* measurements

Comparison with Electroweak Fit



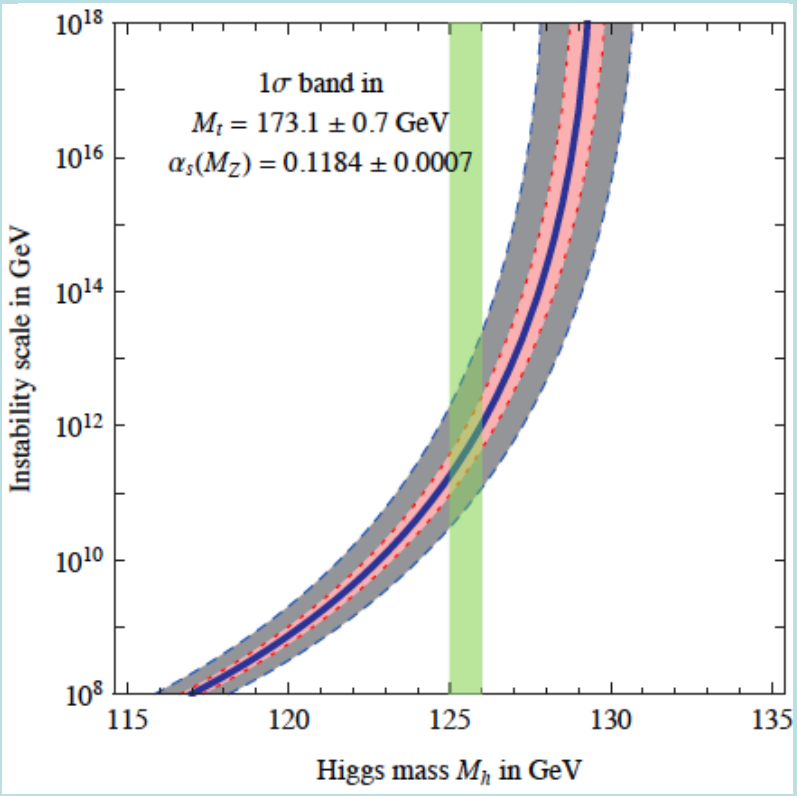
Quite consistent: $\Delta\chi^2 \sim 1.5$

Theoretical Constraints on Higgs Mass

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

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

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

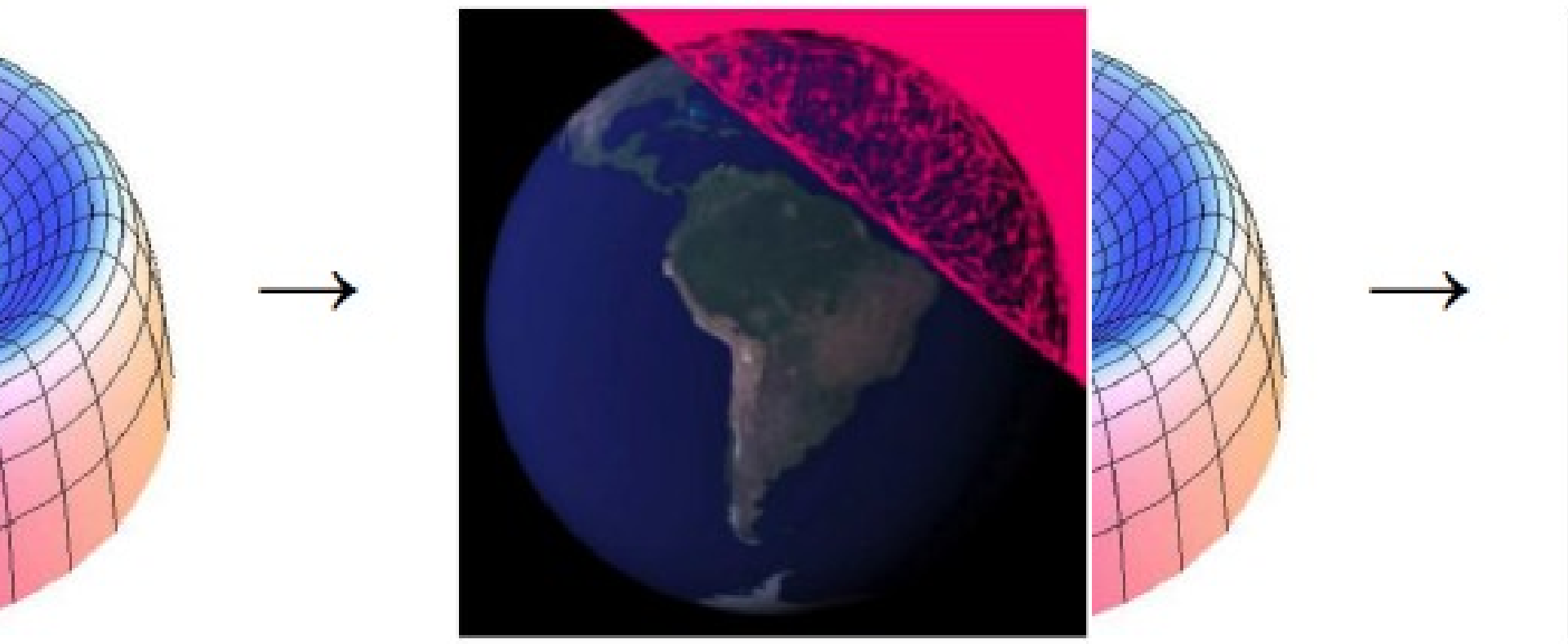


- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

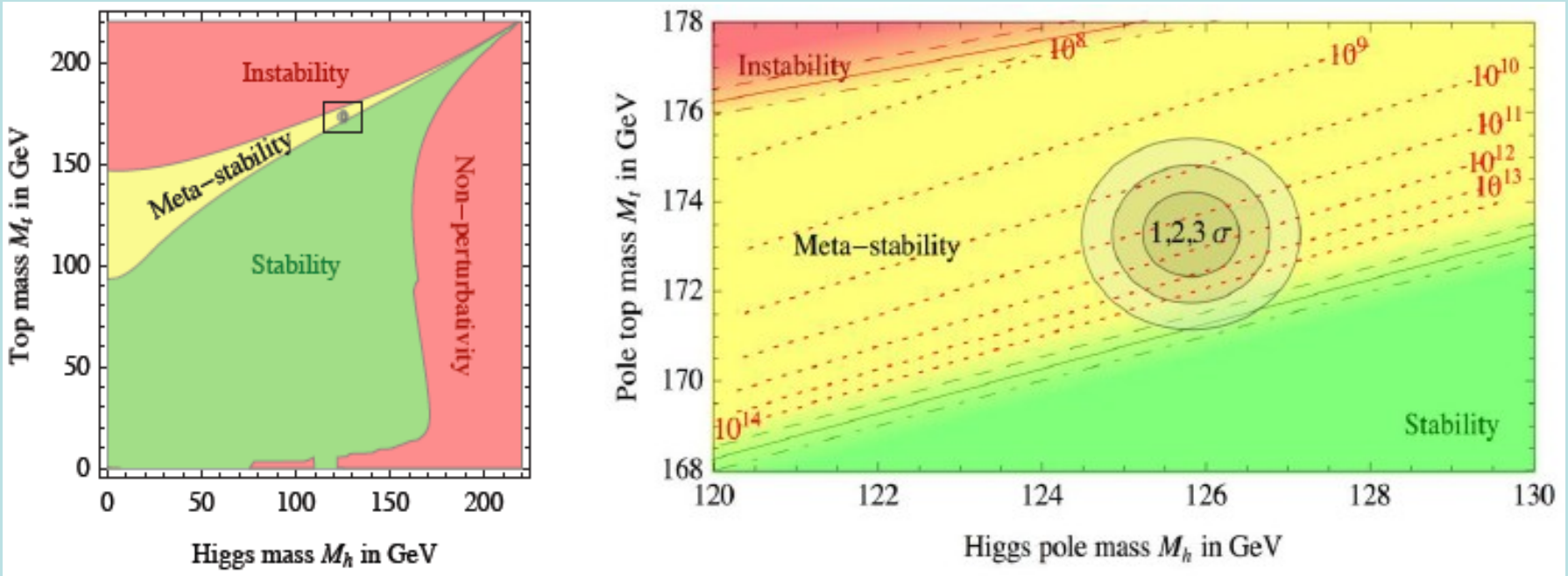
- Due to radiative corrections due to top quark



- Lifetime >> age of the Universe

Vacuum Instability in the Standard Model

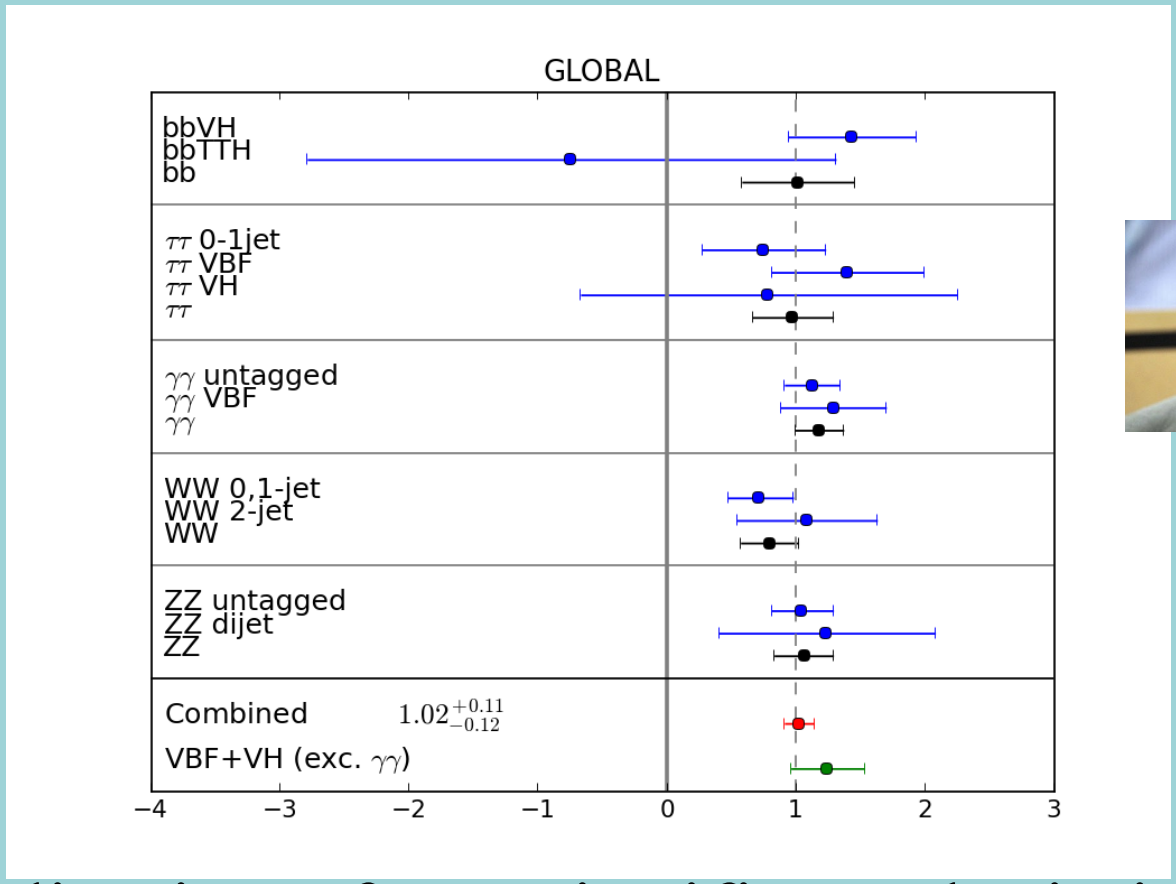
- Very sensitive to m_t as well as M_H



- Present vacuum probably metastable with lifetime >> age of the Universe

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

Couplings resemble Higgs of Standard Model



- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

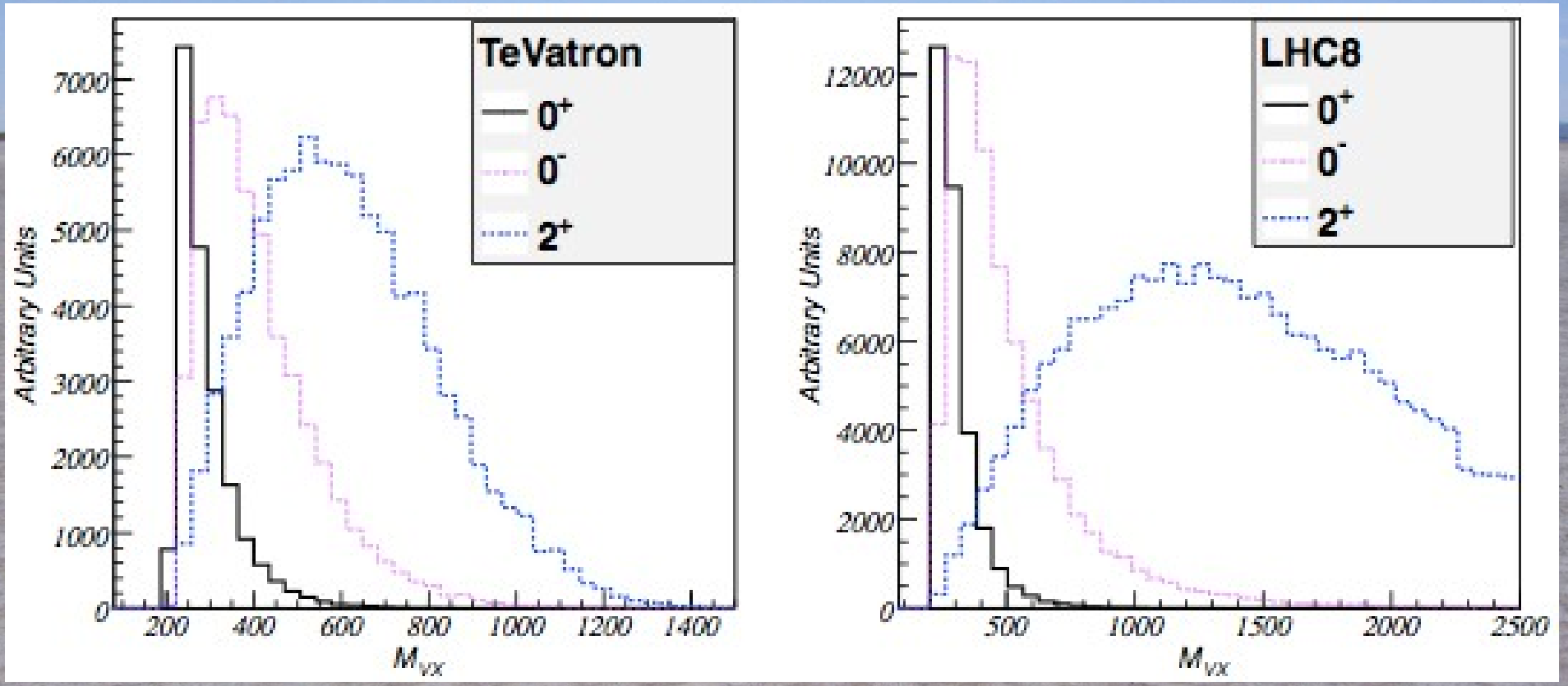
What is it ?

- Does it have spin 0 or 2?
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

What is the Spin of the 'Higgs'?

- Decays into $\gamma\gamma$, so cannot have spin 1
- **Spin 0 or 2?**
- Selections of WW and ZZ events are based on spin 0 hypothesis
- Can diagnose spin via
  - production in association with W or Z
  - angular distribution of $\gamma\gamma$
  - angular correlations of leptons in WW, ZZ decays

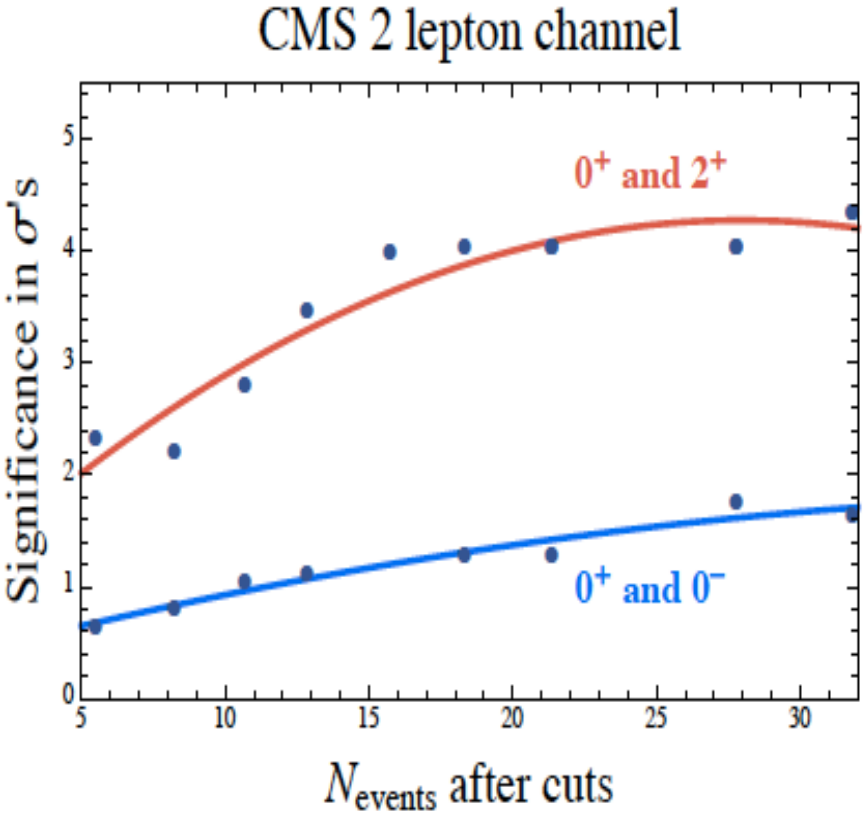
Does the ‘Higgs’ have Spin Zero ?

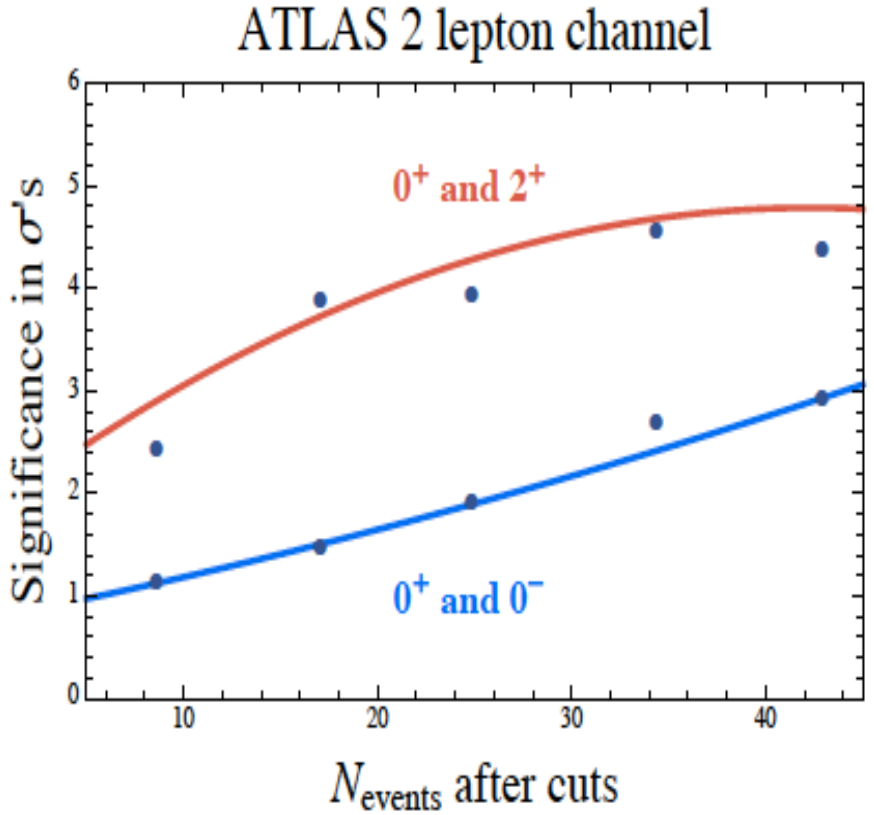


Vector boson + ‘Higgs’ combined invariant mass very different for spins 0 and 2

JE, Hwang. Sanz & You: arXiv:1208.6002

Spin Discriminating Power

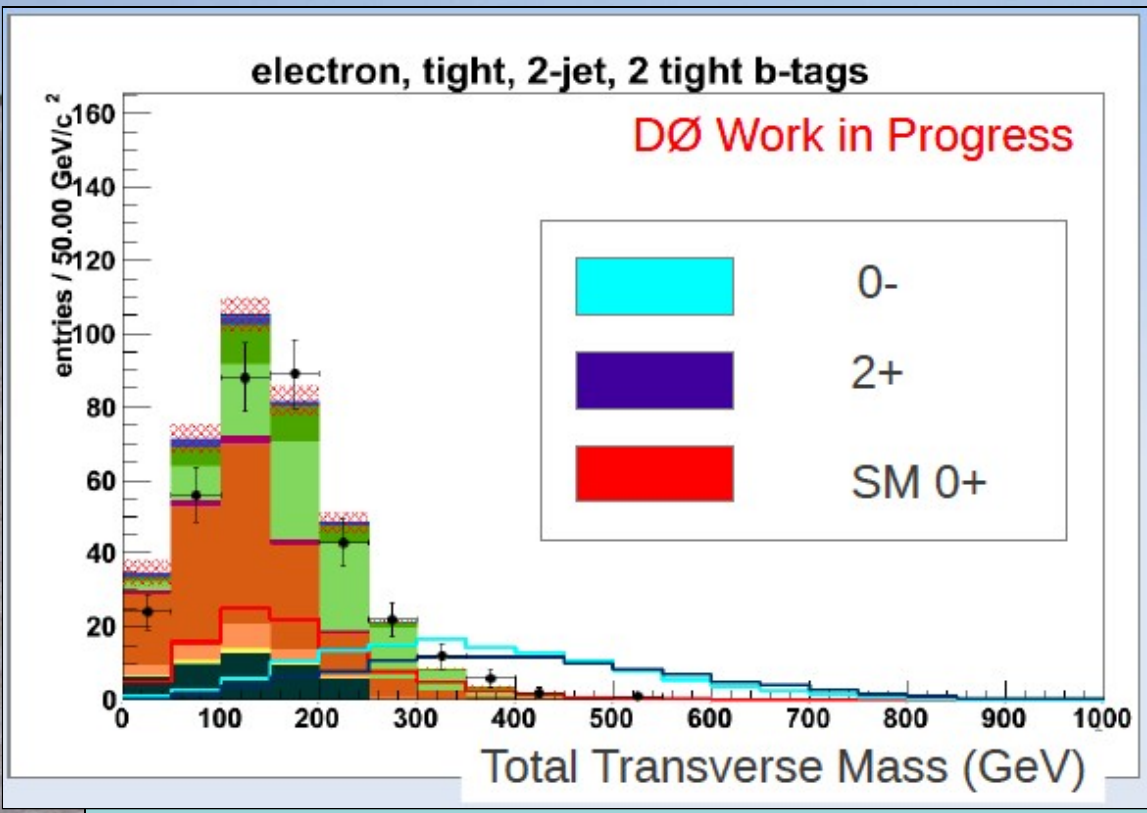




Available TeVatron data, 2012 LHC data should be able to distinguish spins 0 and 2

JE, Hwang. Sanz & You: arXiv:1208.6002

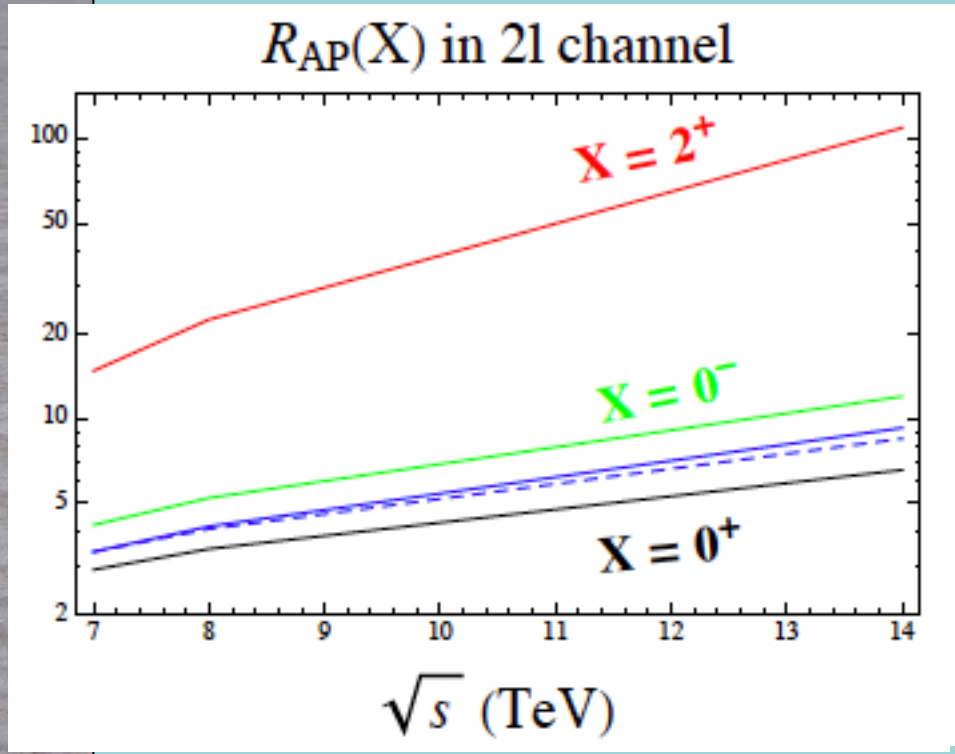
The ‘Higgs’ probably a Scalar

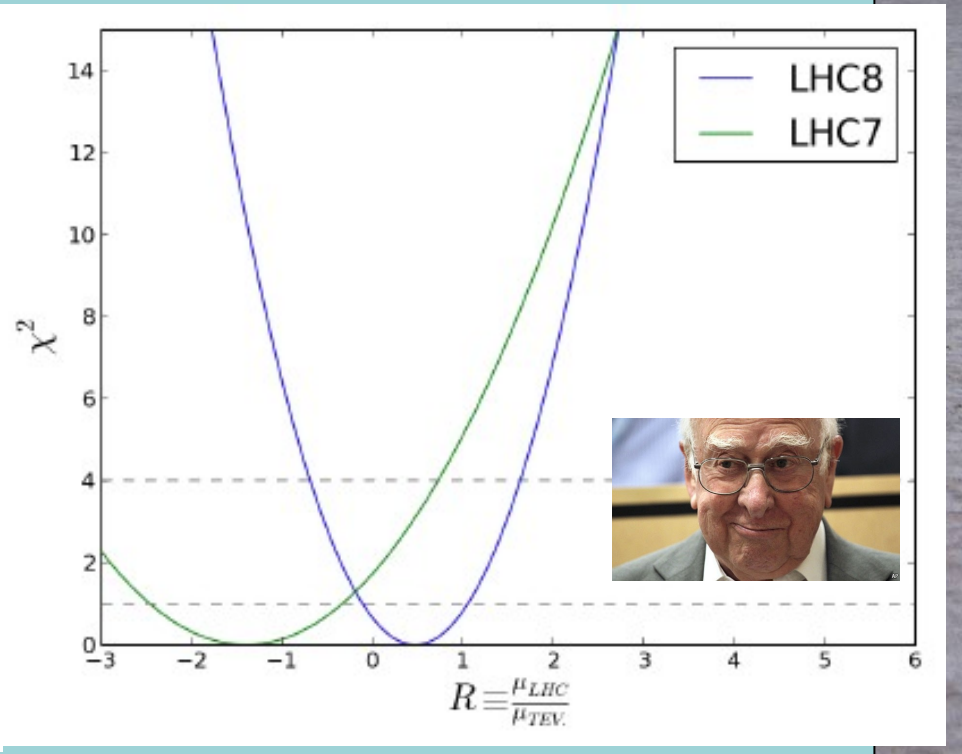


The ‘Higgs’ probably a Scalar

JE. Sanz & You: arXiv:1303.0208

- Associated production cross section increases more rapidly with energy for 0^-, spin 2





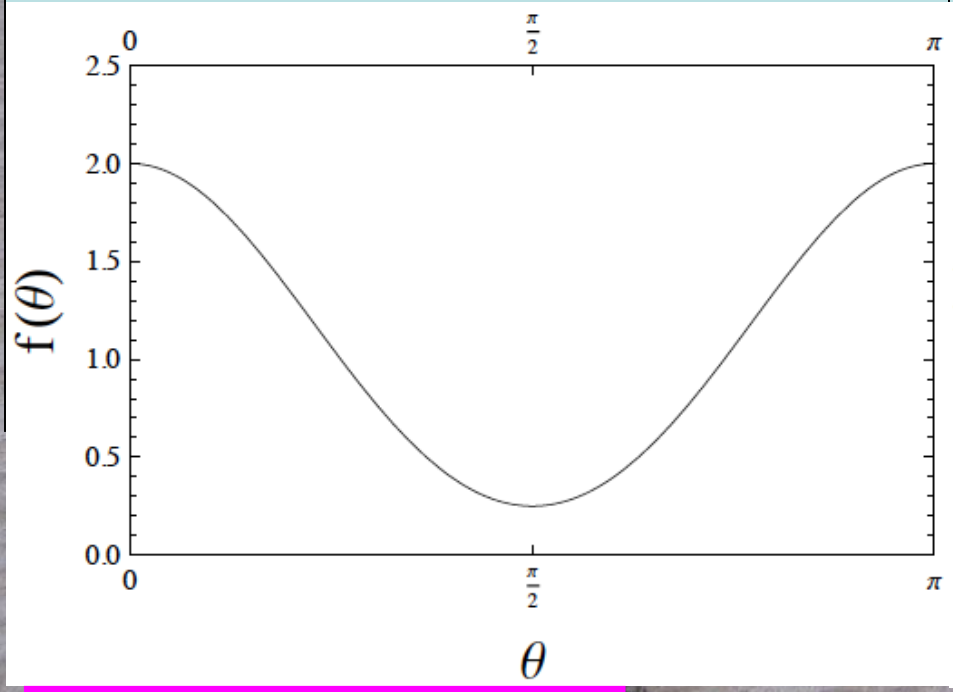
Does the 'Higgs' have Spin Zero ?

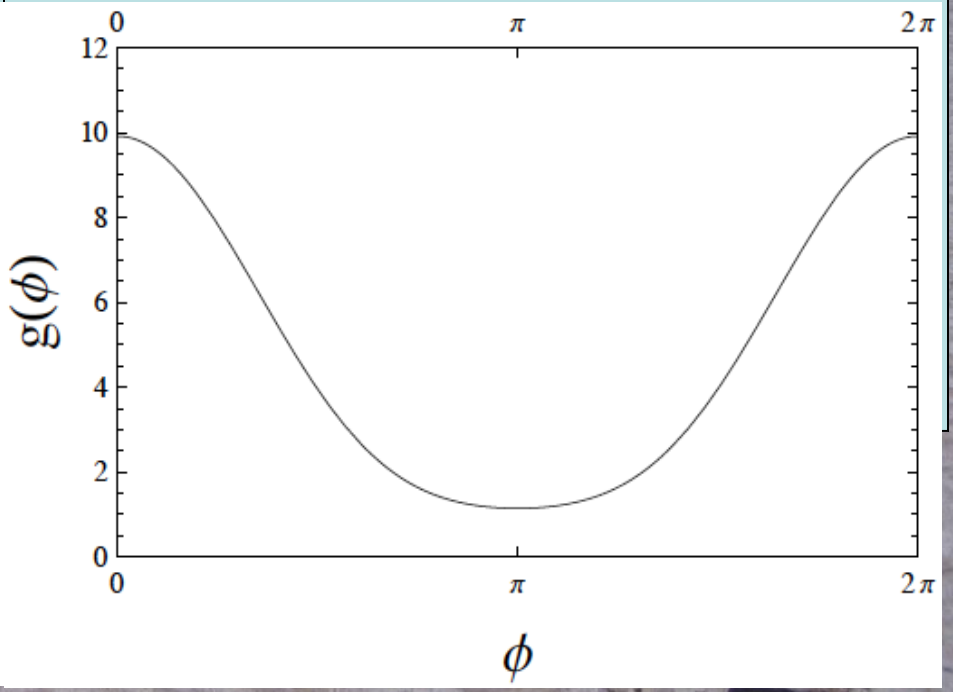
- Polar angle distribution: $X_2 \rightarrow \gamma\gamma$

  (flat for X_0)

- Azimuthal angle distribution: $X_0 \rightarrow WW$

  (flat for X_2)





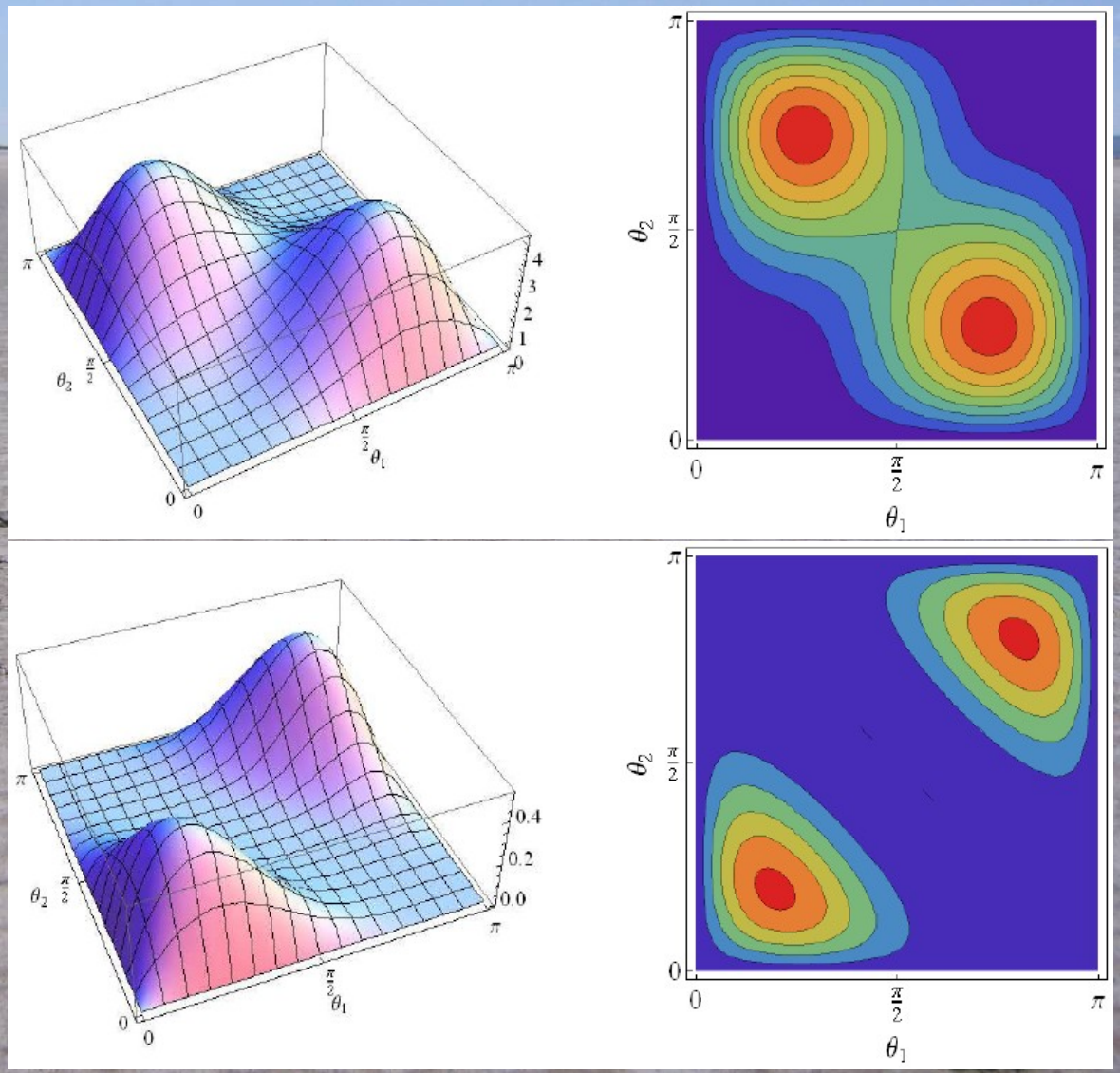
JE, Hwang: arXiv:1202.6660

Does the 'Higgs' have Spin Zero ?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$

(for $\varphi = \pi$)

JE, Hwang: arXiv:1202.6660

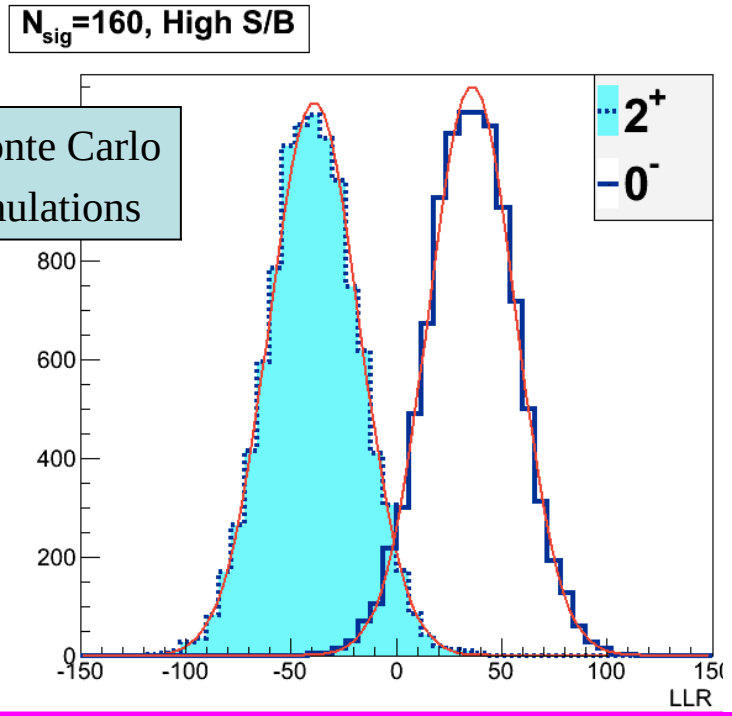


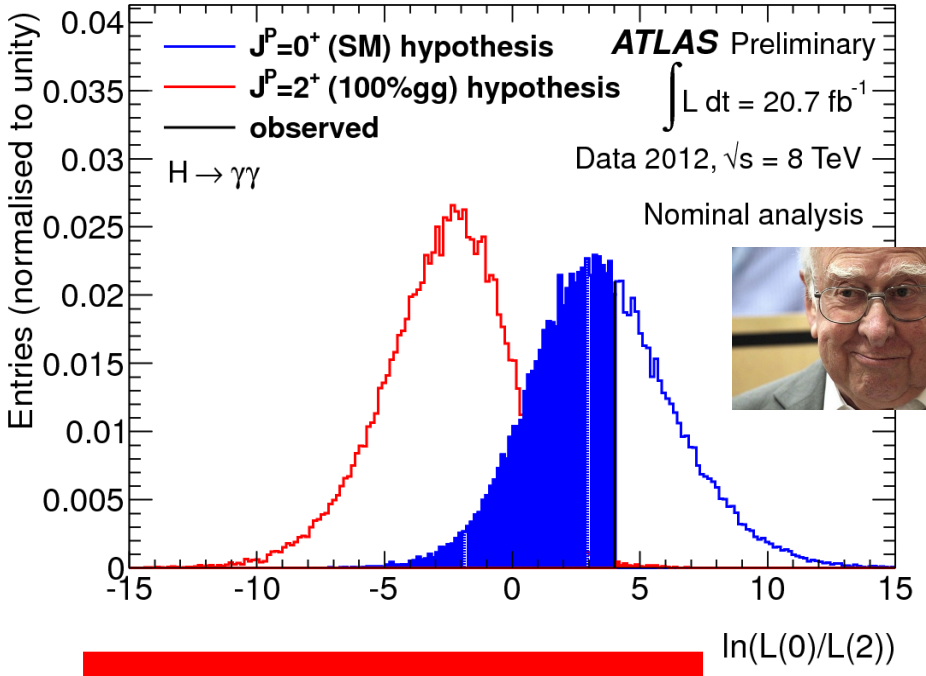
Does the 'Higgs' have Spin Two ?

- Discriminate spin 2 vs spin 0 via angular distribution of decays into γγ

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations

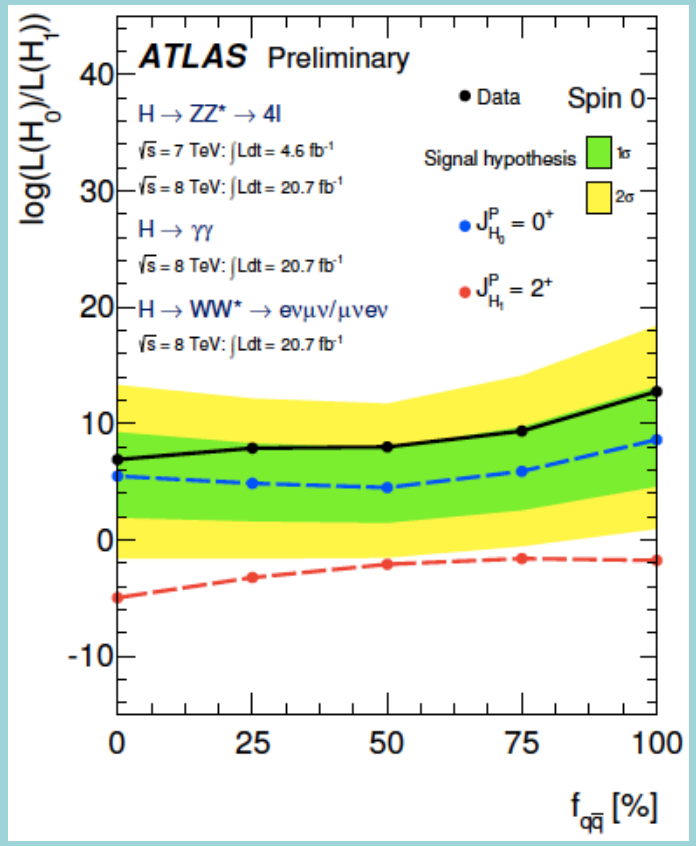


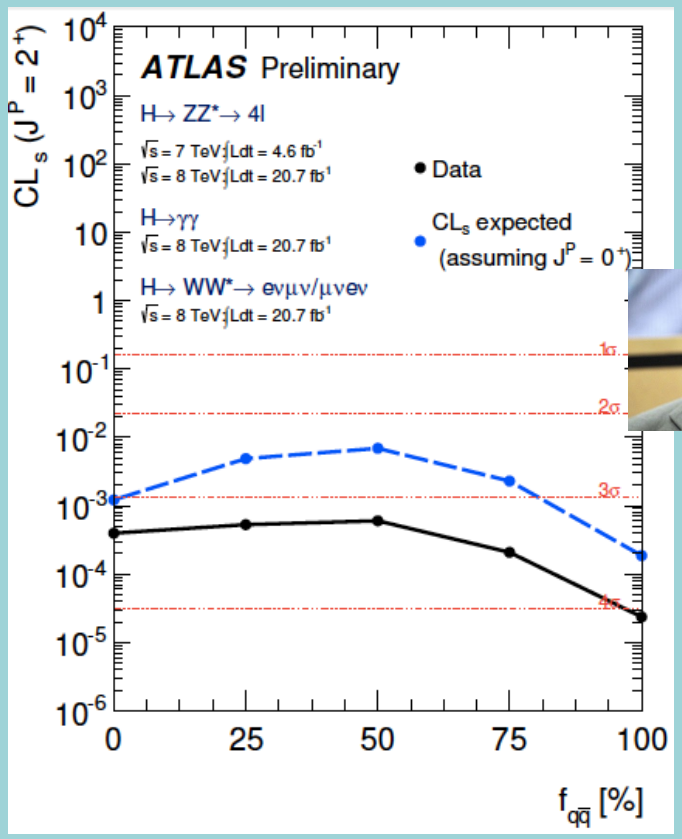


JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

2^+ disfavoured @ 99%

The ‘Higgs’ Spin is probably 0

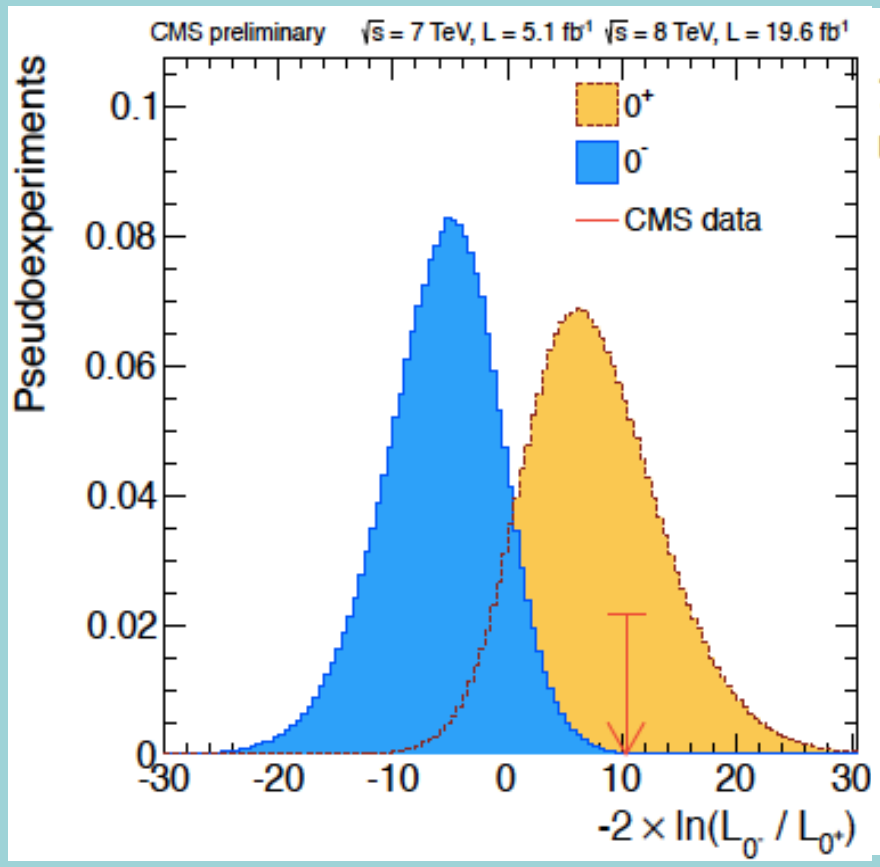


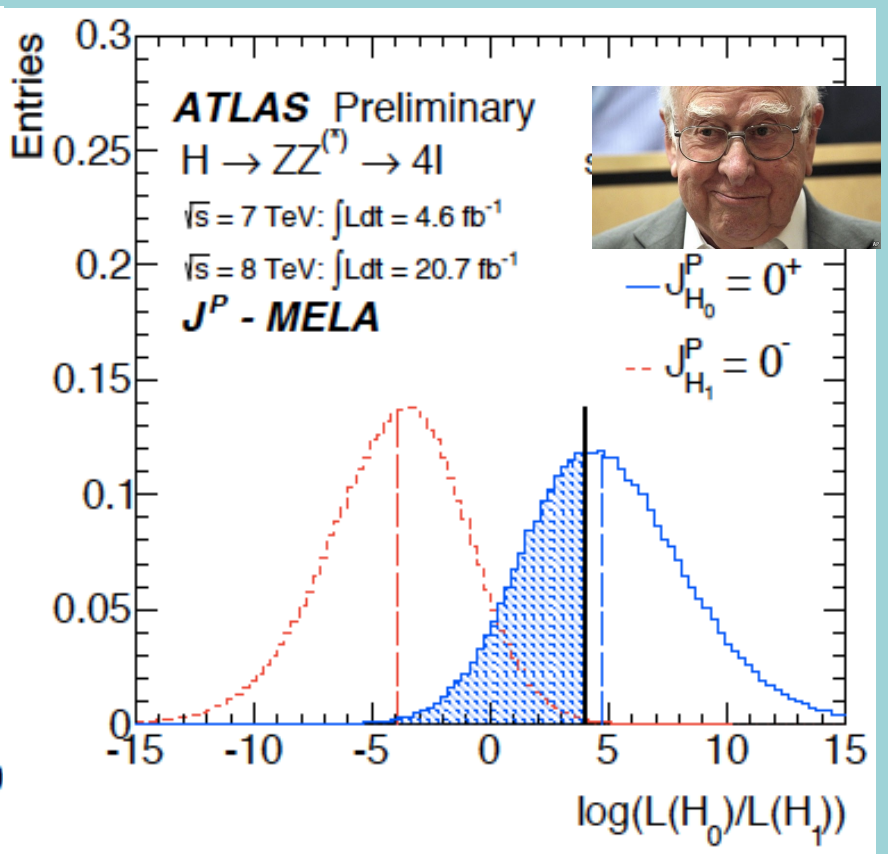


What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 very unlikely**
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

The ‘Higgs’ is probably a scalar





- Pseudoscalar 0^- disfavoured at > 99% CL

What is it ?

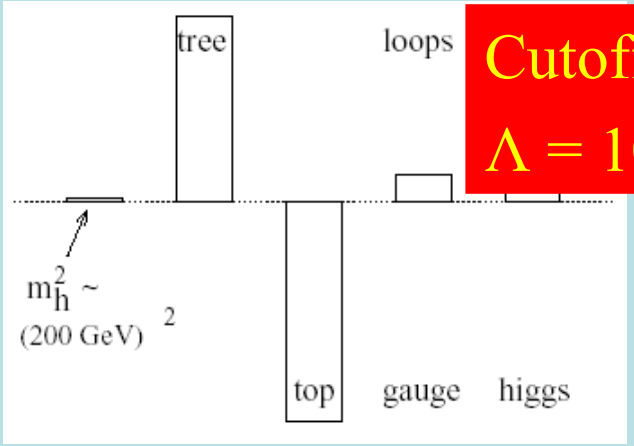
- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



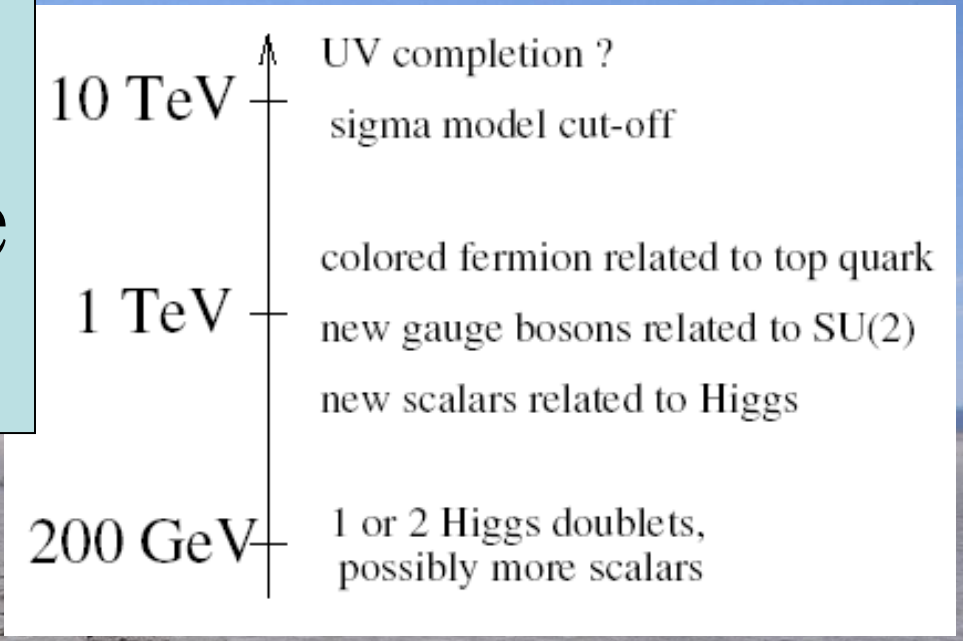
Cutoff
Λ = 10 TeV

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

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

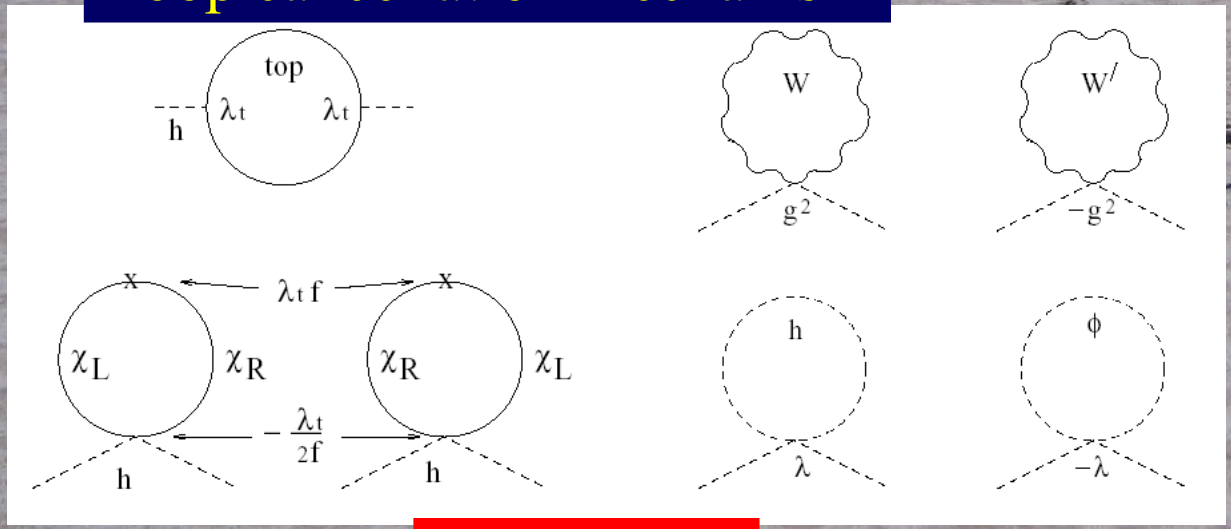
New technicolour force?
-Heavy scalar resonance?
-Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

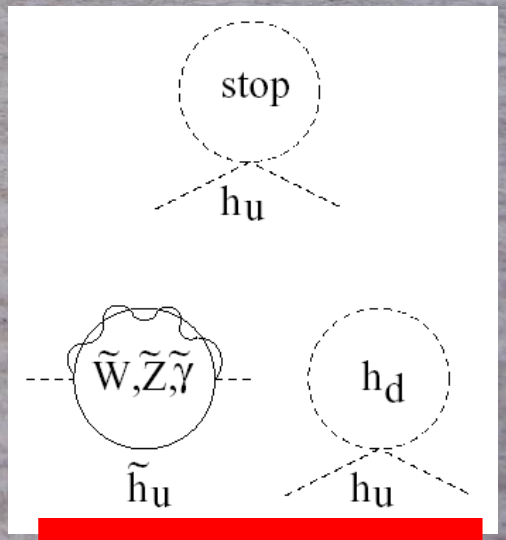


'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

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:

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

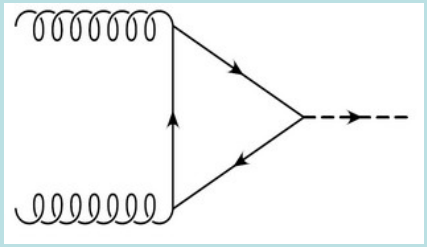
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \qquad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

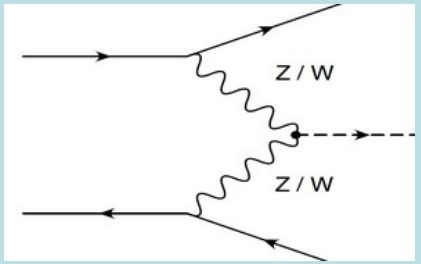
- Coefficients ***a = c = 1*** in Standard Model

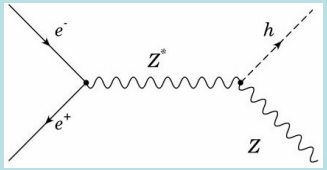
Phenomenological Framework

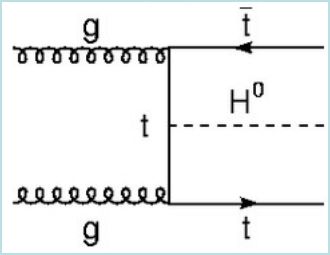
- *a* parametrizes couplings of *h* to massive gauge bosons
- *c* parametrizes couplings of *h* to fermions:
  - Standard Model: $a = c = 1$
  - Composite Higgs MCHM4: $a = c = \sqrt{1-\xi}$ $\xi \equiv (v/f)^2$
  - Composite Higgs MCHM5: $a = \sqrt{1-\xi}, \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$
  - Pseudo-Dilaton: $a = c = \frac{v}{V}$

Re-interpreting SM Higgs Searches

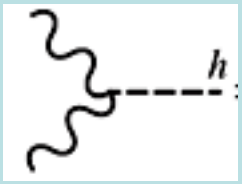


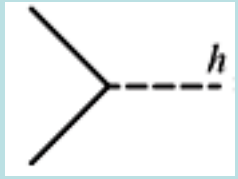


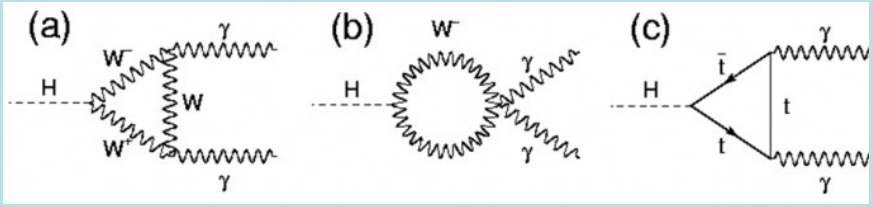




$$R_{gg} = \frac{(-\frac{v}{V} b_s + c F_t)^2}{F_t^2} \quad , \quad R_{\rm VBF} = a^2 \quad , \quad R_{\rm ap} = a^2 \quad , \quad R_{\rm hs} = c^2$$







$$R_{VV} = a^2 \quad , \quad R_{\bar{f}f} = c^2 \quad ,$$

$$R_{\gamma\gamma} = \frac{(-\frac{v}{V} b_{em} - \frac{8}{3} c F_t + a F_w)^2}{(-\frac{8}{3} F_t + F_w)^2}$$

- **Only $R_{\gamma\gamma}$ is sensitive to relative sign of *a*, *c***

Re-Interpreting SM Higgs Searches

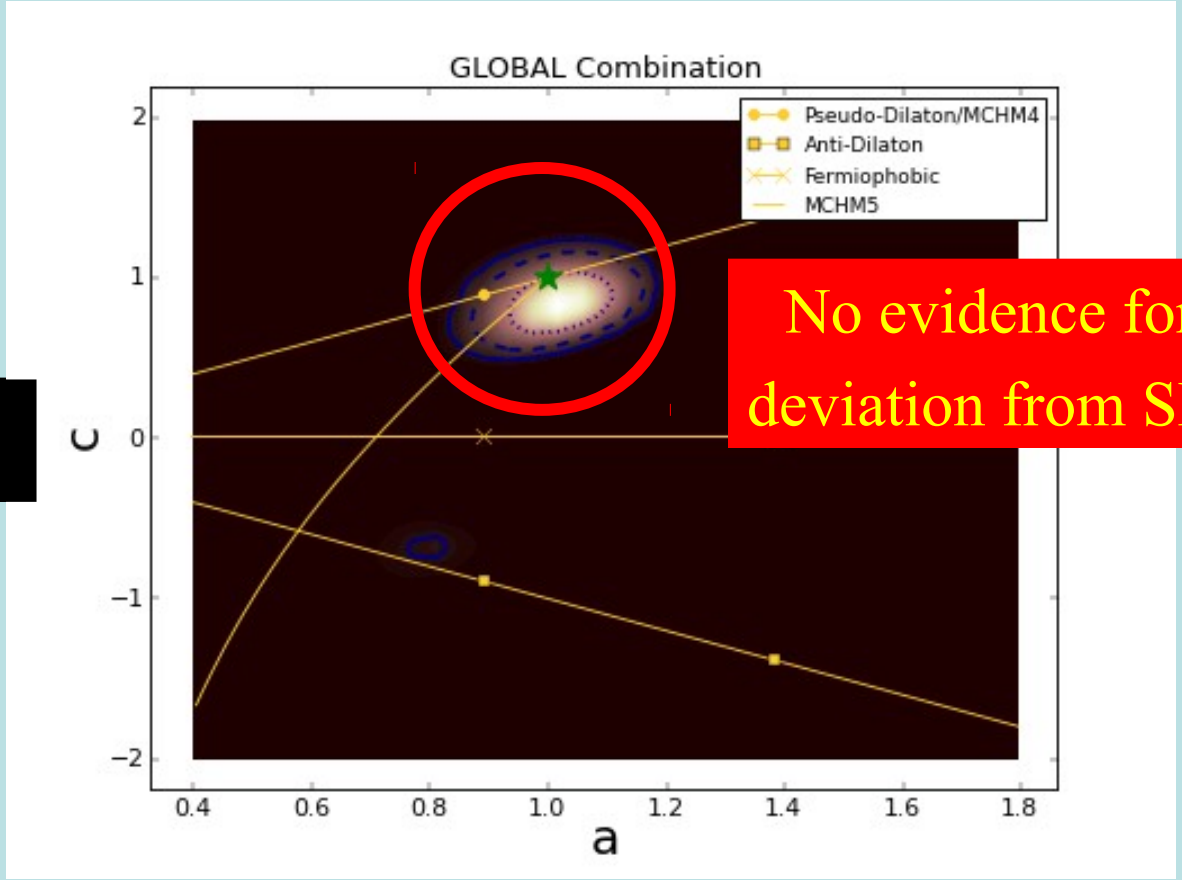
- Sensitivities of different experimental search (sub)channels:

channel	Production sensitive to		Decay sensitive to	
	a	c	a	c
$\gamma\gamma$	✓	✓	✓	✓
$\gamma\gamma$ VBF	✓	×	✓	✓
WW	✓	✓	✓	×
WW 2-jet	✓	×	✓	×
WW 0,1-jet	×	✓	✓	×
$b\bar{b}$ (VH)	✓	×	×	✓
$b\bar{b}$ ($\bar{t}tH$)	×	✓	×	✓
ZZ	✓	✓	✓	×
$\tau\tau$	✓	✓	×	✓
$\tau\tau$ (VBF, VH)	✓	×	×	✓

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by a, to fermions by c

Global



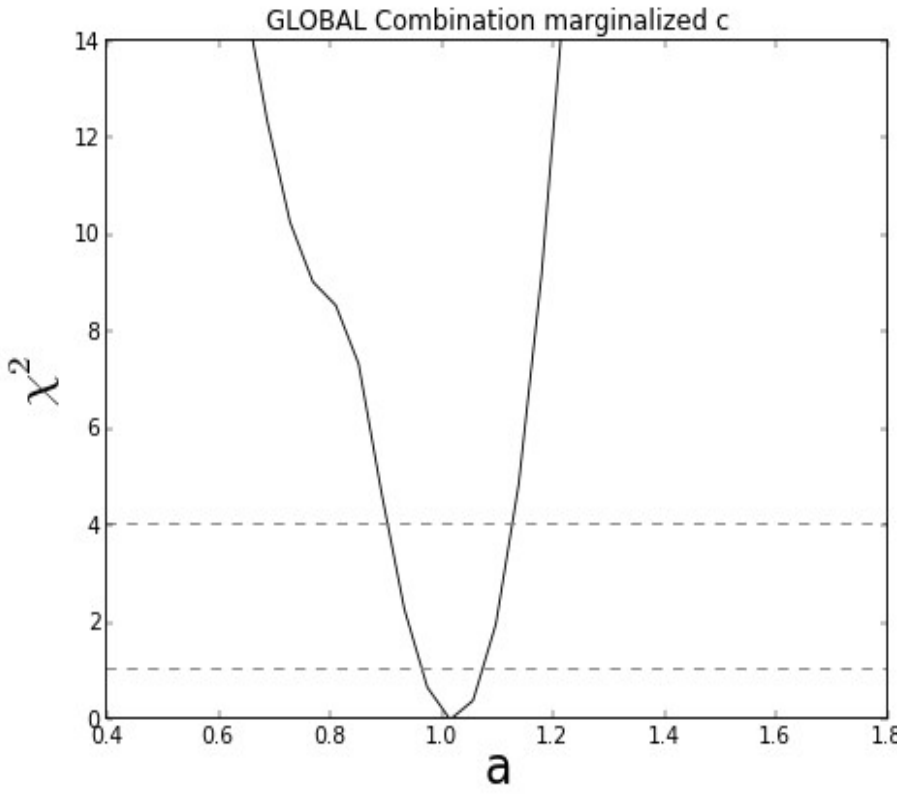
No evidence for deviation from SM

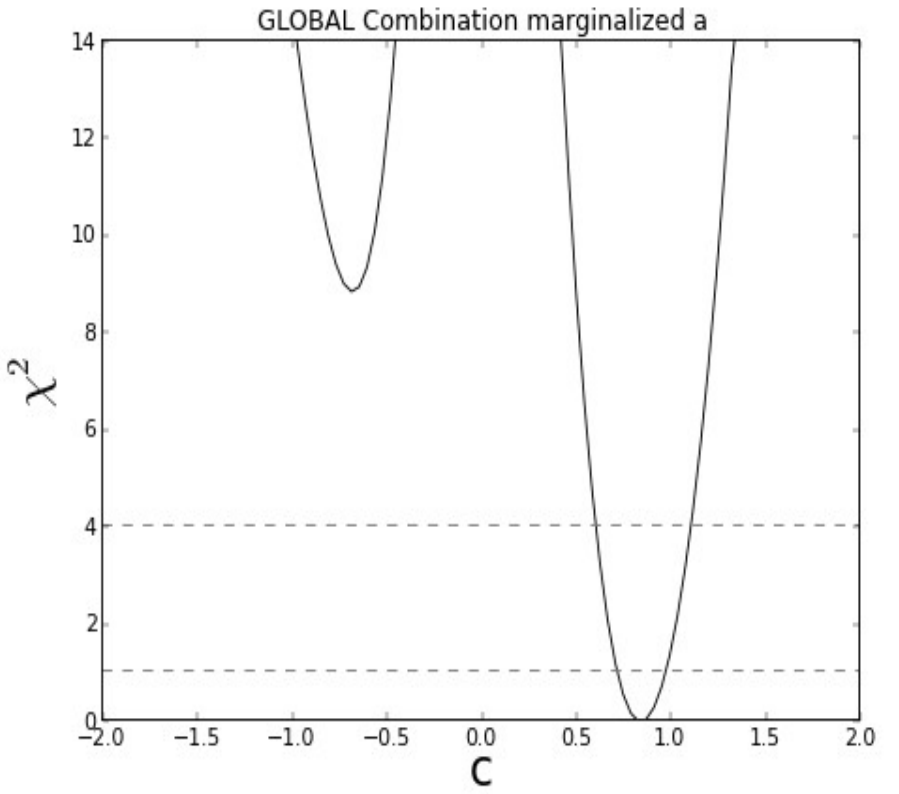
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by a, to fermions by c





- 'Wrong' sign of c disfavoured

JE & Tevong You, arXiv:1303.3879

What is it ?

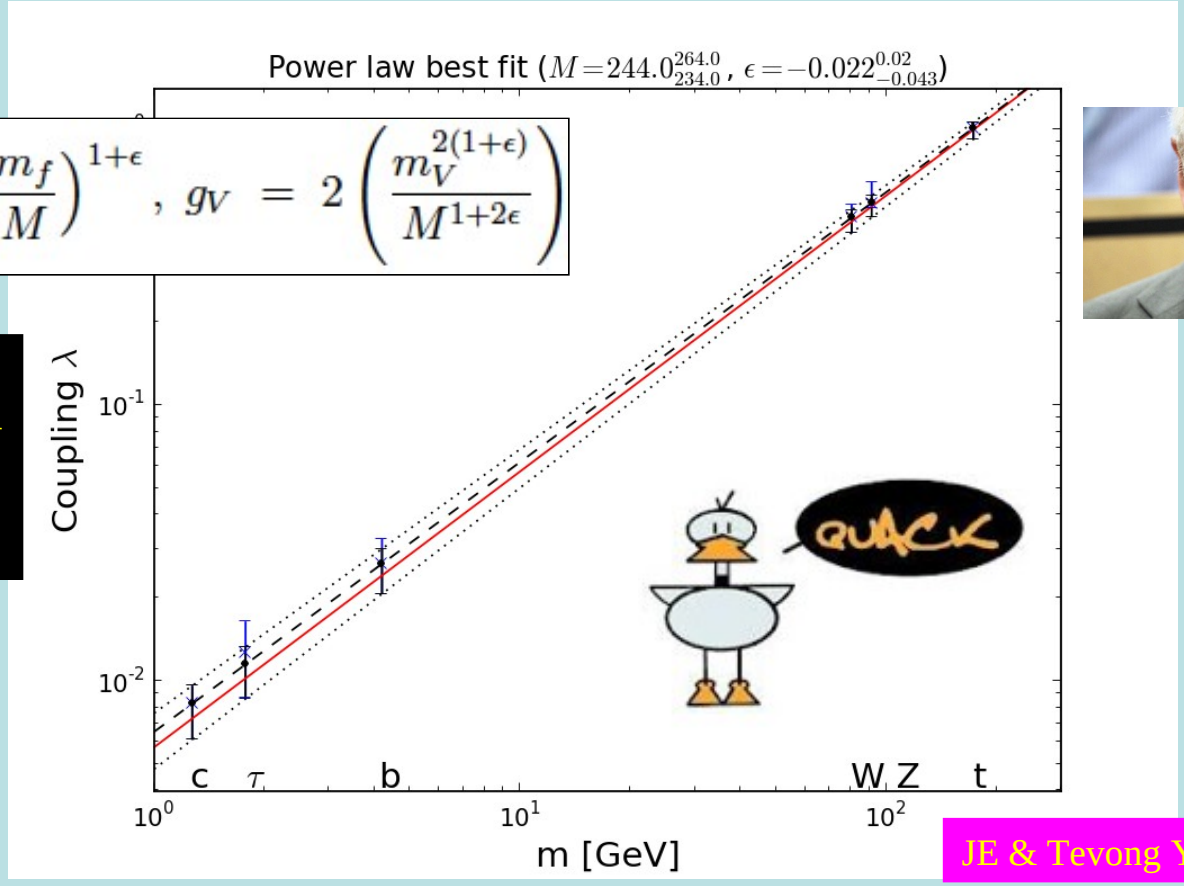
- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

It Walks and Quacks like a Higgs

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

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

Global fit



JE & Tevong You, arXiv:1303.3879

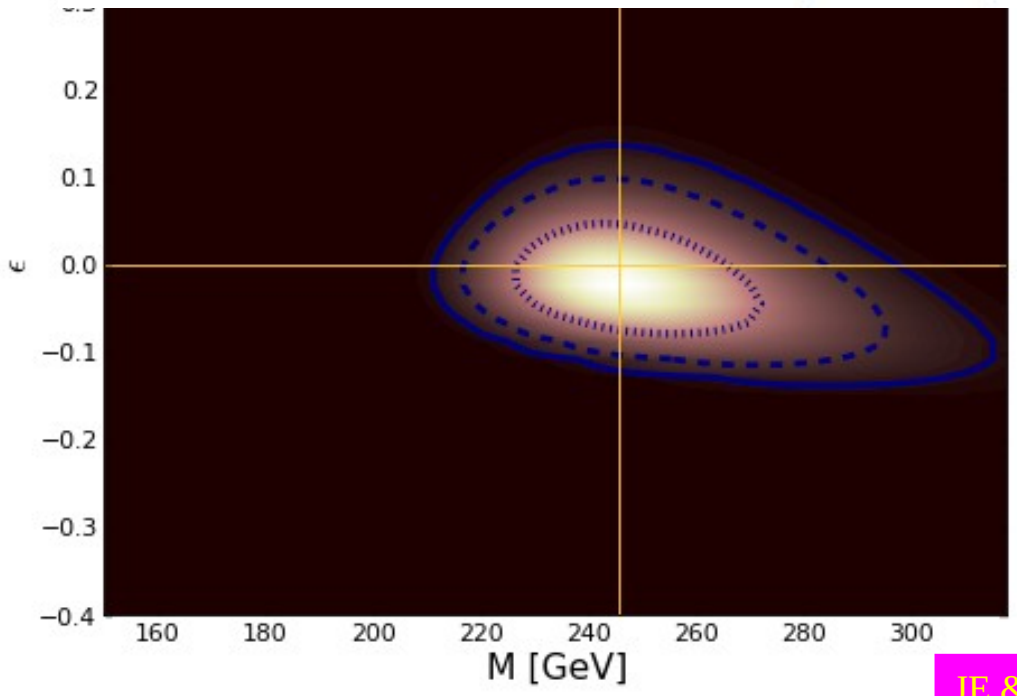
- **Red line = SM**, dashed line = best fit

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

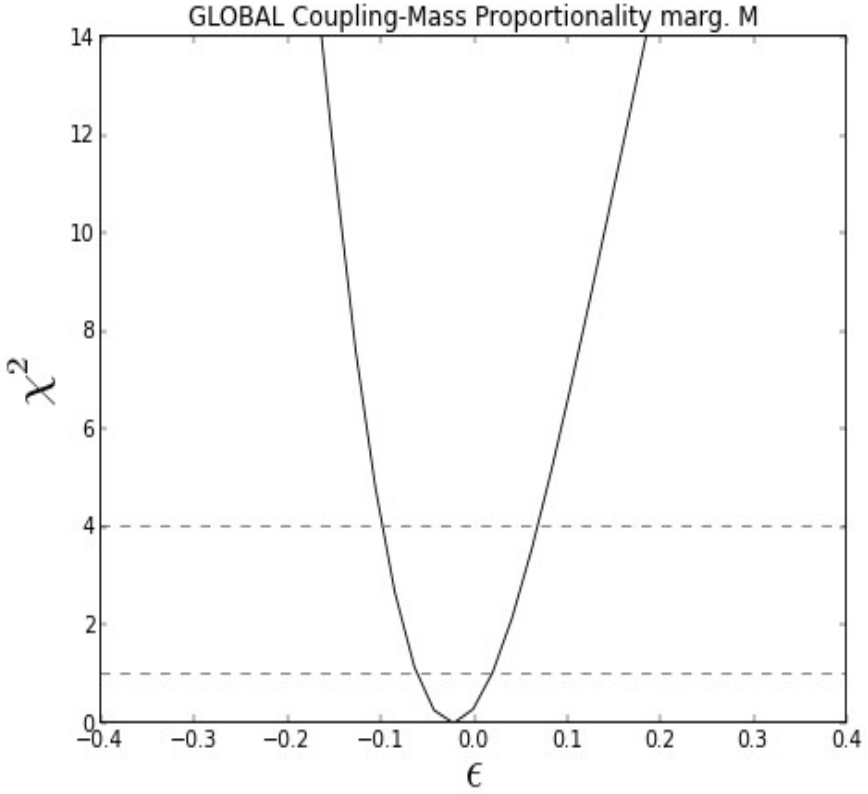


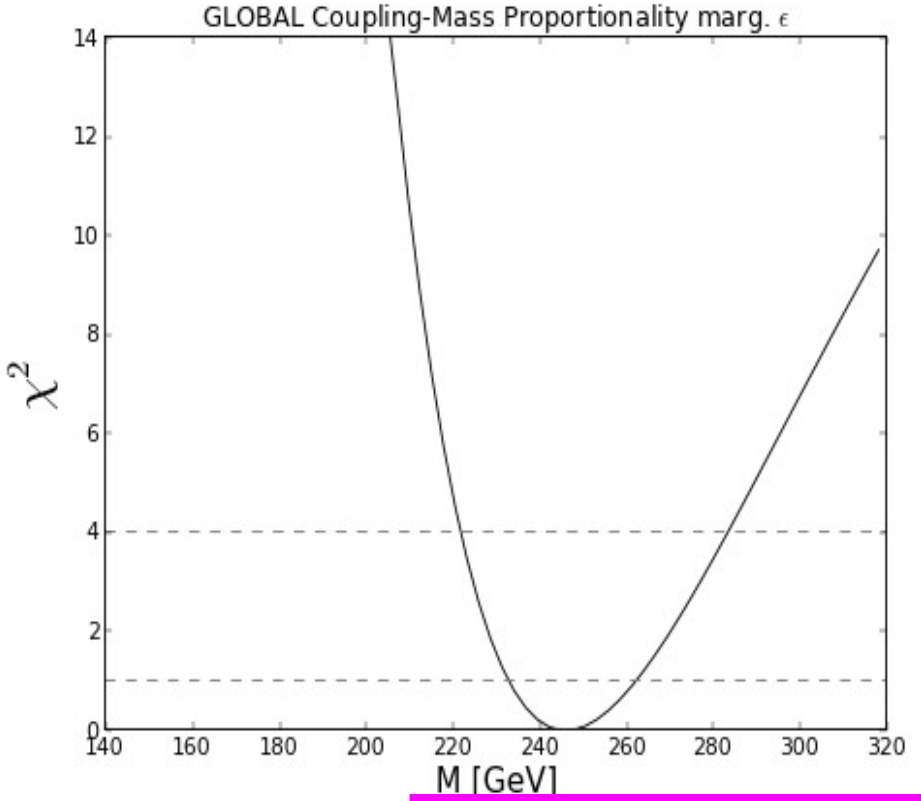
JE & Tevong You, arX:1303.3879

- Standard Model Higgs: ε = 0, M = v

It Walks and Quacks like a Higgs

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





JE & Tevong You, arXiv:1303.3879

$\varepsilon = -0.022^{+0.042}_{-0.021}$ $M = 244^{+20}_{-10}$ GeV

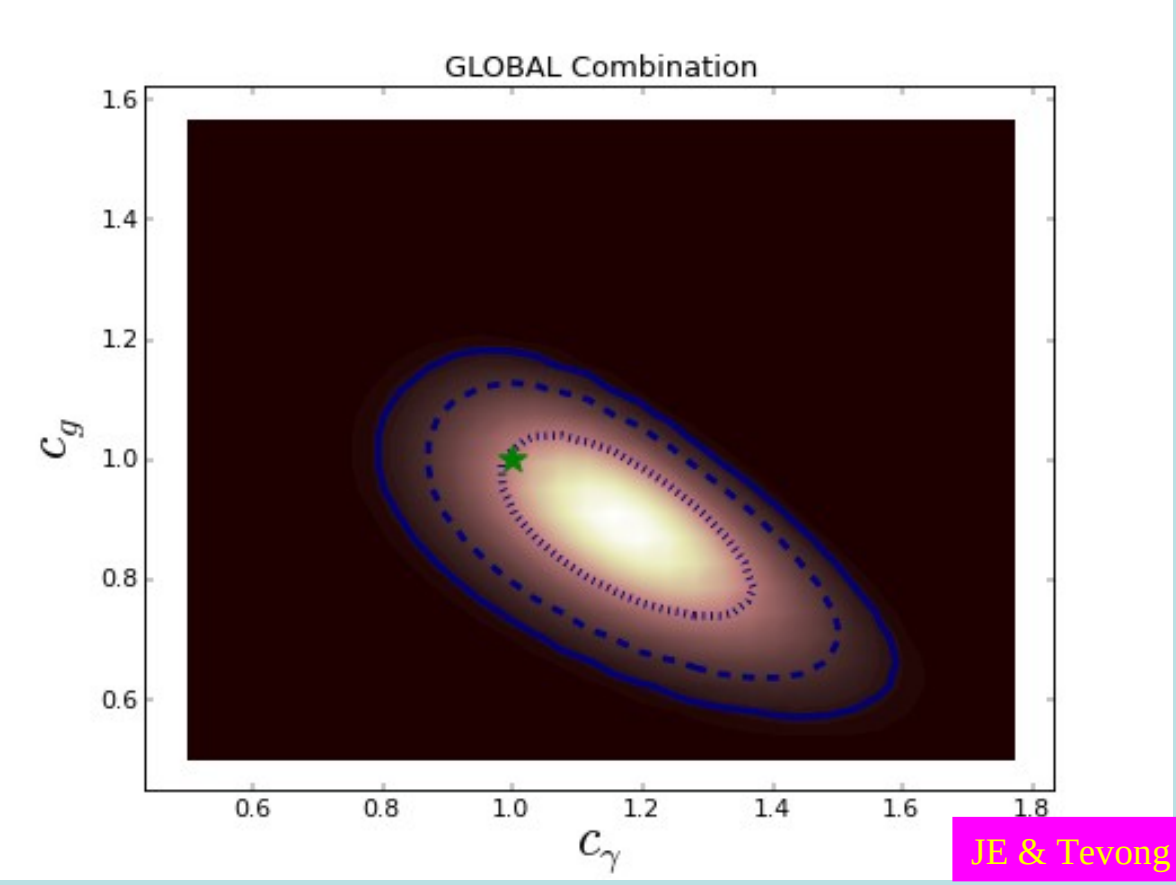
What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - **Some *prima facie* evidence that it does**
- Quantum (loop) corrections?

- What are its self-couplings?

Loop Corrections ?

- ATLAS sees excess in γγ, CMS sees deficit

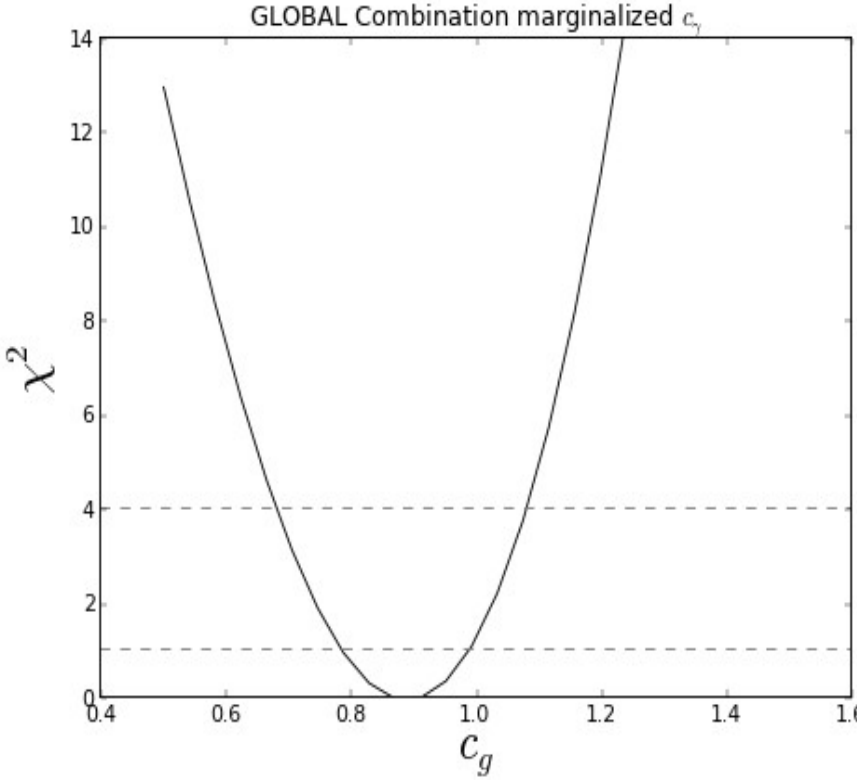


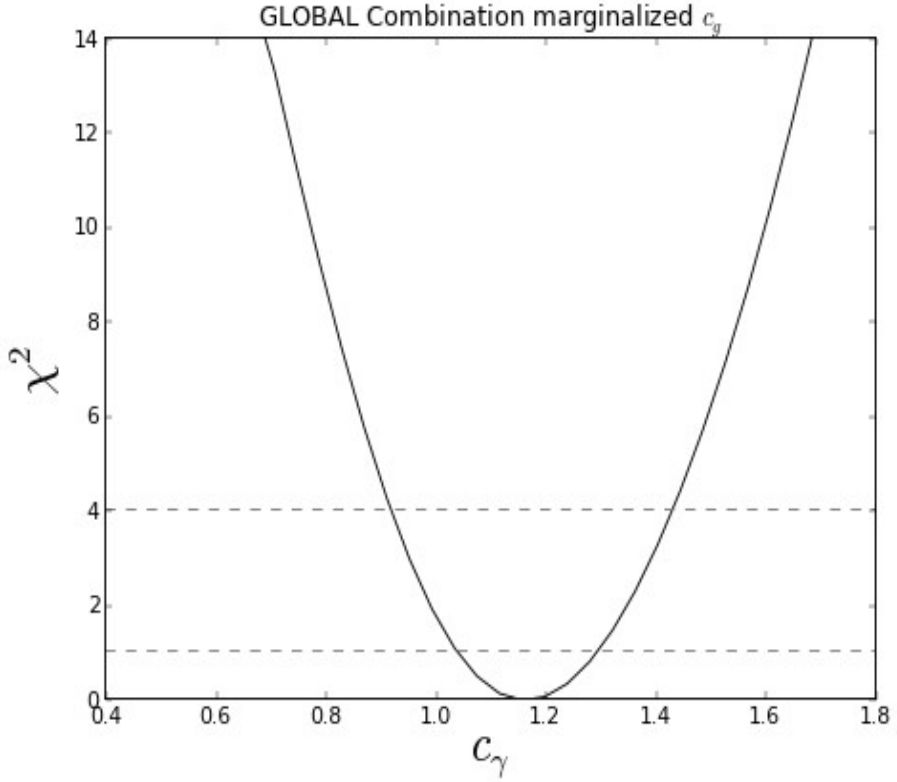
JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

Loop Corrections ?

- Gluon-gluon coupling ~ 1 σ low?





JE & Tevong You, arXiv:1303.3879

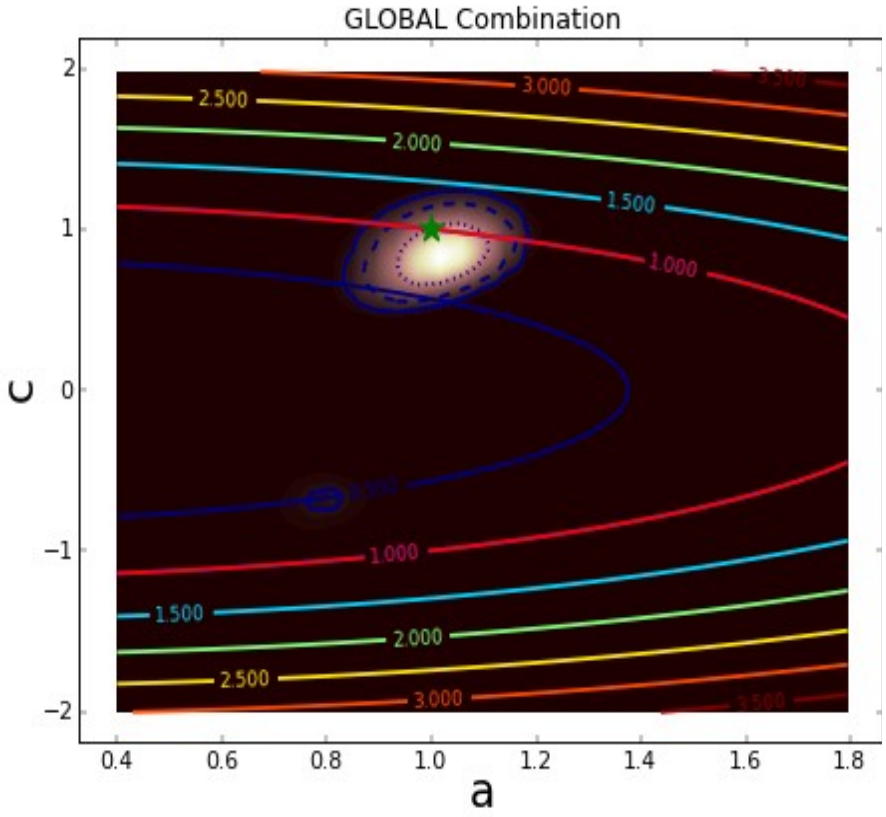
- γγ coupling ~ 1 σ high?

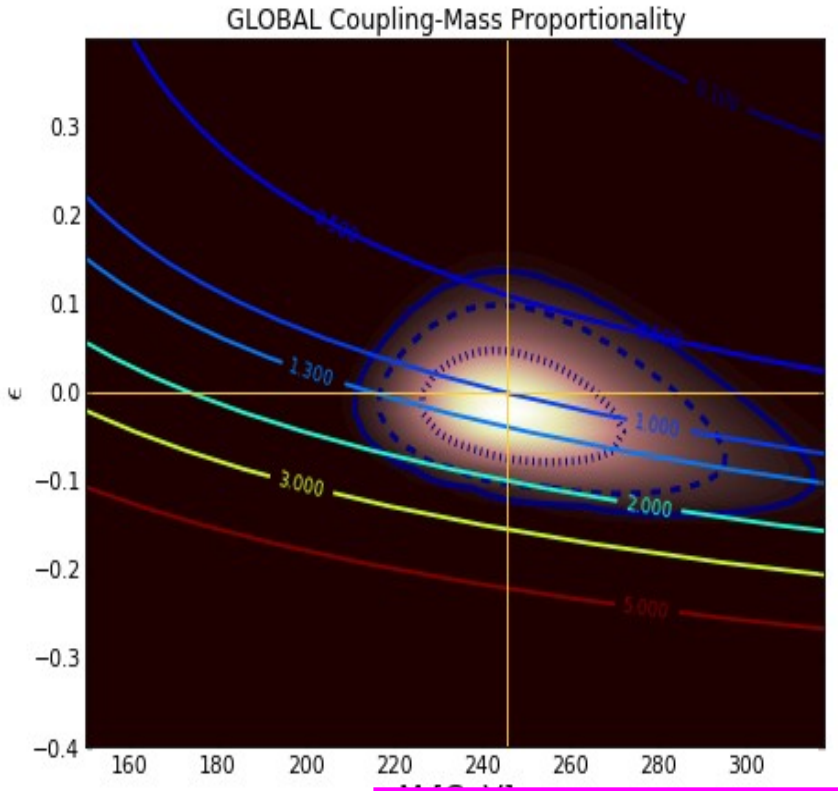
Beyond any Reasonable Doubt

- Does it have spin 0 or 2?
  - **Simple spin 2 couplings excluded**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **$\gamma\gamma$ coupling $\gtrsim$ Standard Model?**
- What are its self-couplings? **Hi-lumi LHC or …?**

What is its Decay Rate ?

- Compared with the Standard Model prediction



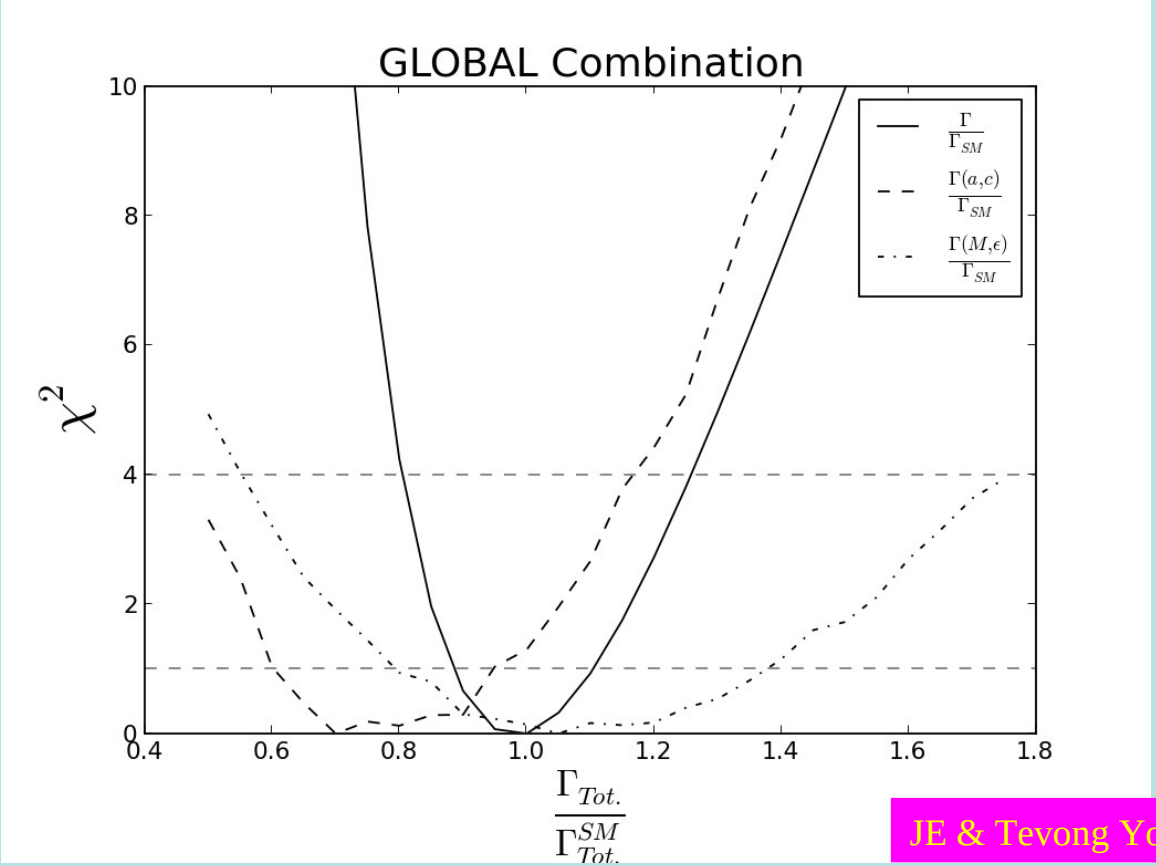


JE & Tevong You, arXiv:1303.3879

- Assuming no non-Standard Model modes

What is its Decay Rate ?

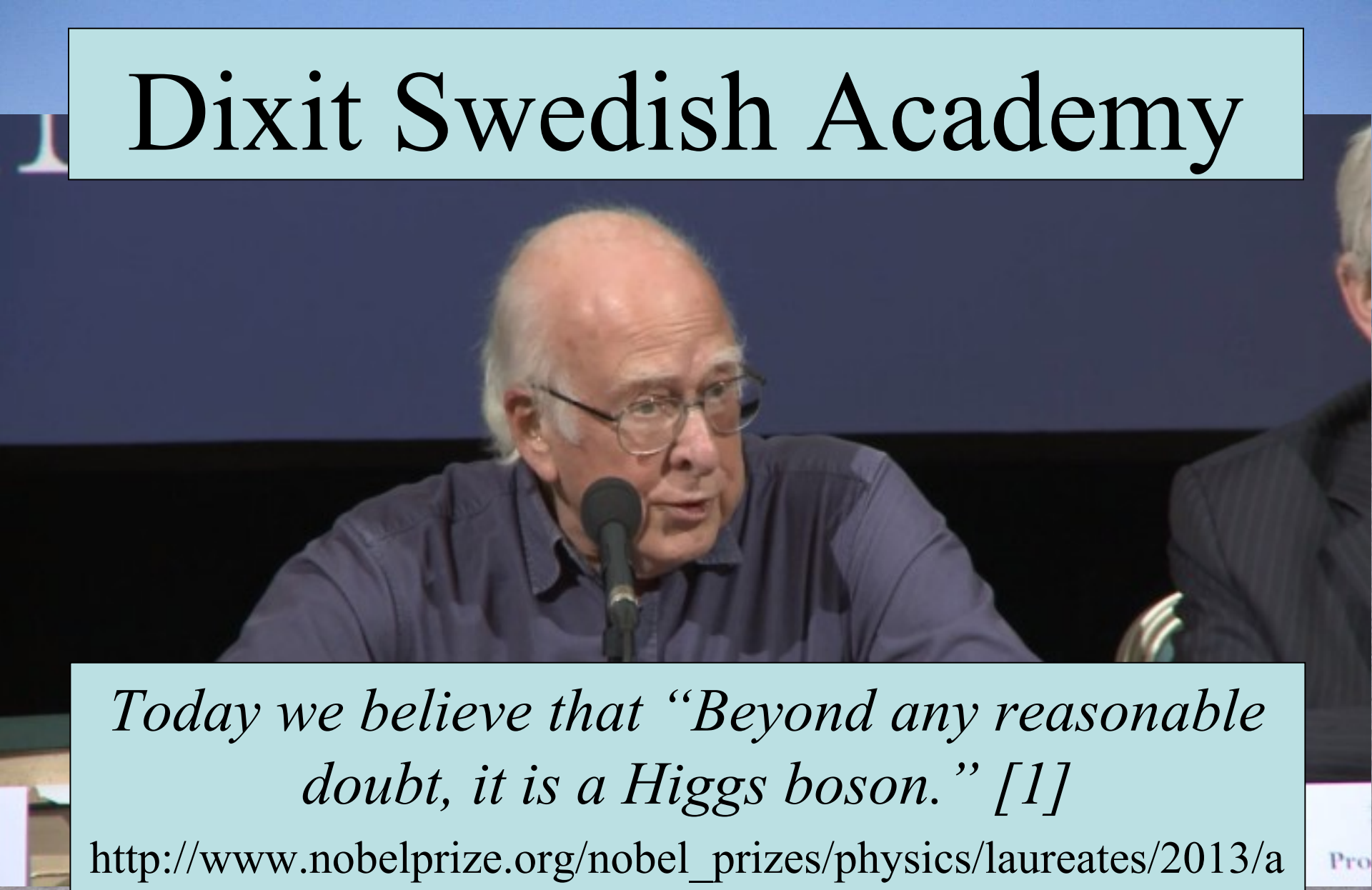
- Compared with the Standard Model prediction



JE & Tevong You, arXiv:1303.3879

- Assuming no non-Standard Model modes

Dixit Swedish Academy

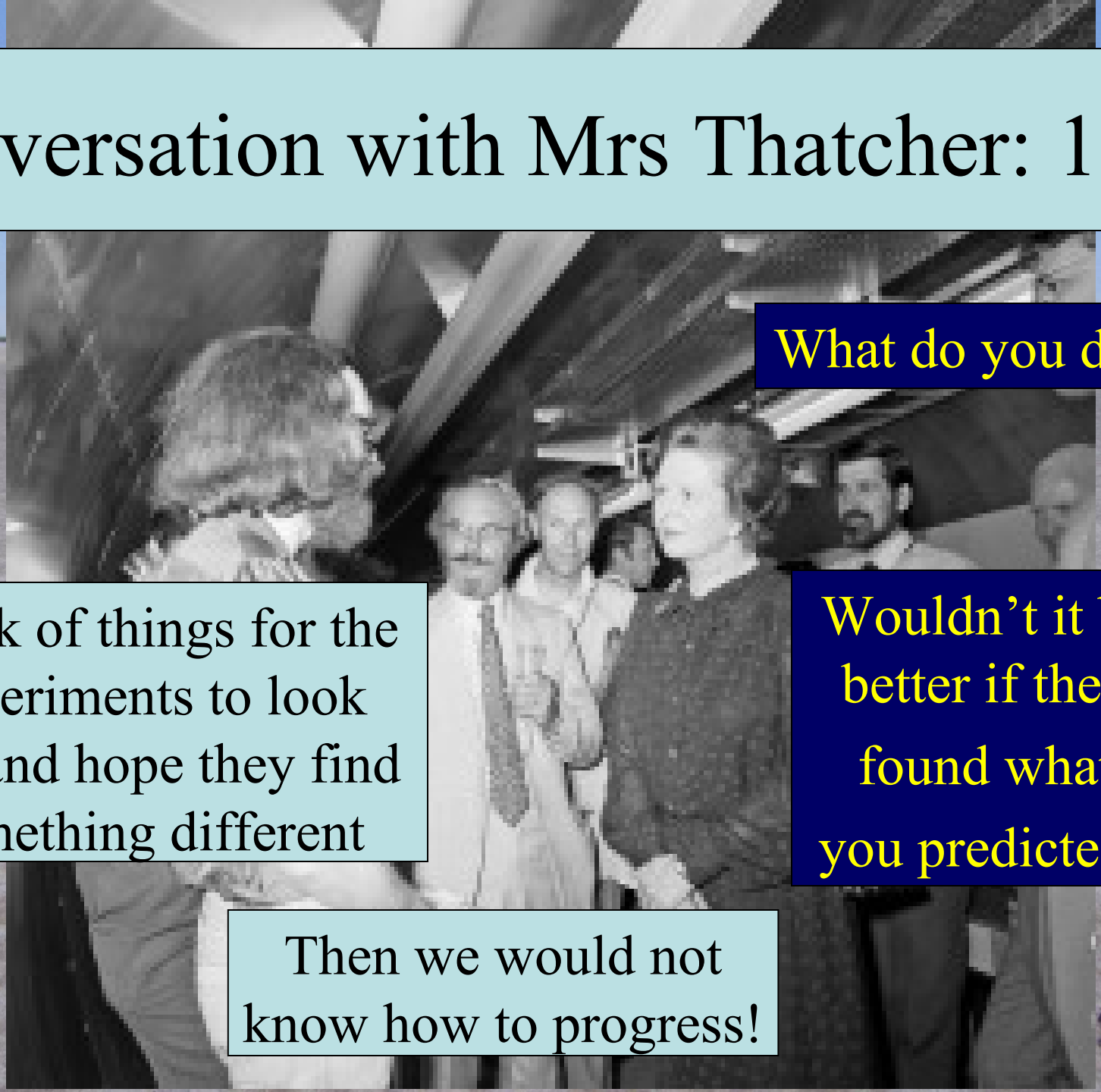


Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

•[1] = JE & Tevong You, arXiv:1303.3879

Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not know how to progress!