Programme of Lectures

- Motivations and introduction
- What we know now
- The future?
  - Supersymmetric Higgses
  - Higgs factories

The Particle Higgsaw Puzzle

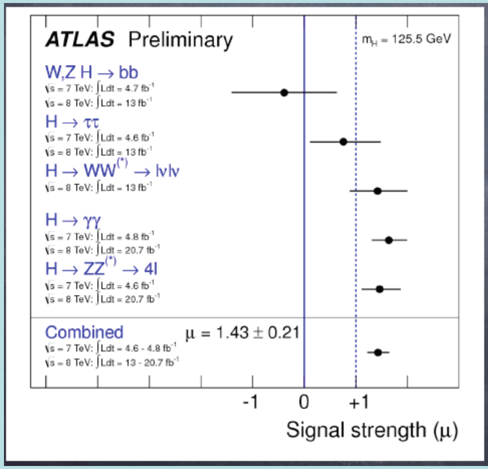
Is LHC finding the missing piece?

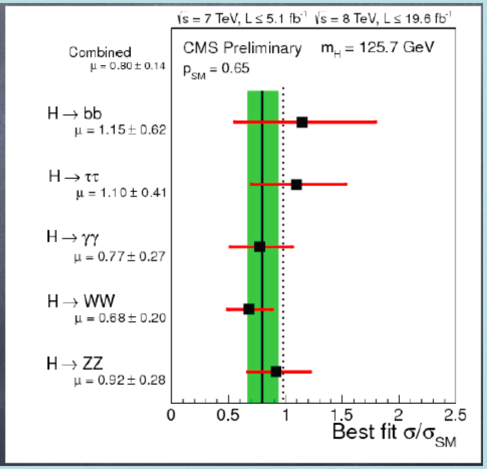
Is it the right shape?

Is it the right size?

From Discovery to Measurement

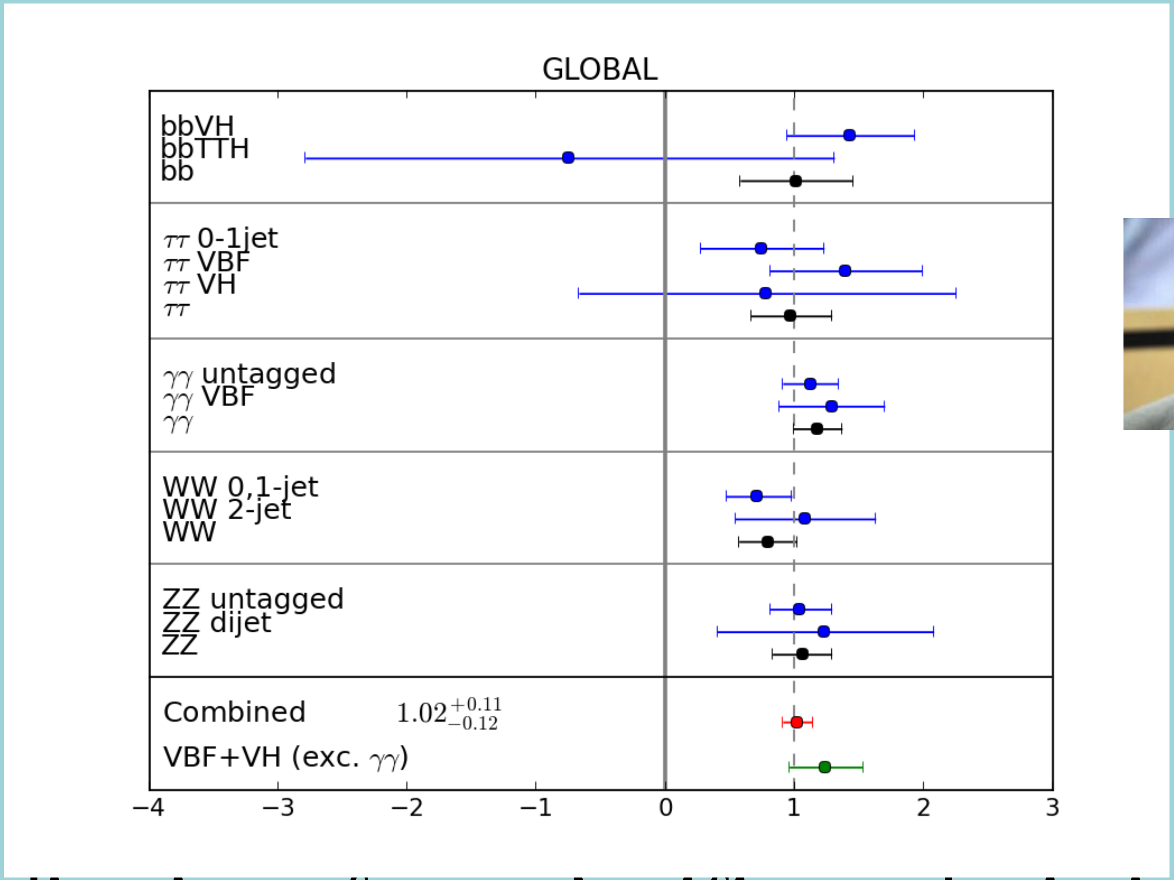
- Mass measurements: 125.6 ± 0.3 GeV
- Signal strengths ~ SM in many channels





- Frontiers:
  - VBF significance 2σ in several channels, 3σ combined
  - Decay to ττ emerging, limits on ττ (μτ, eτ)
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling
    (search for ttbar + H/W, Zγ)

Couplings resemble Higgs of Standard Model

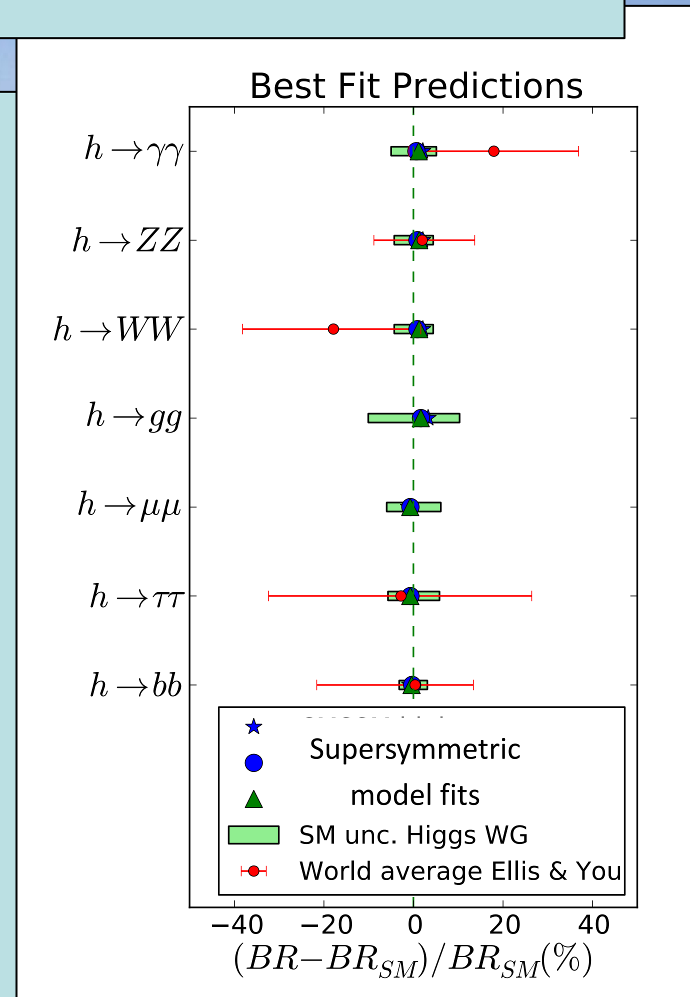


- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

Some Questions

- What is it?
  - –Higgs or …?
- What else is there?
  - –Supersymmetry …?
- What next?
  - –A Higgs factory or …?

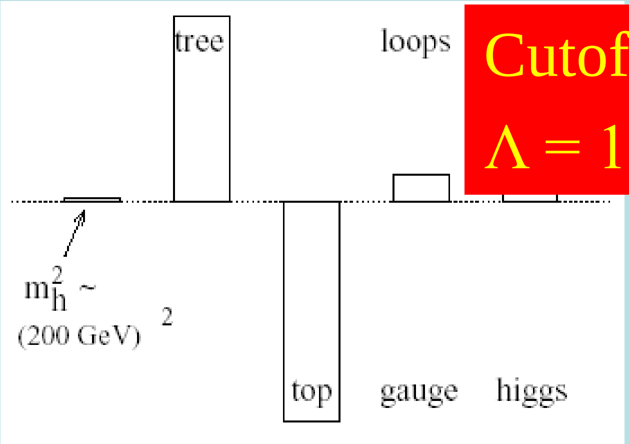


Elementary Higgs or Composite?

- Higgs field:

  <0|H|0> ≠ 0

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off Λ ~ 1 TeV with Supersymmetry?

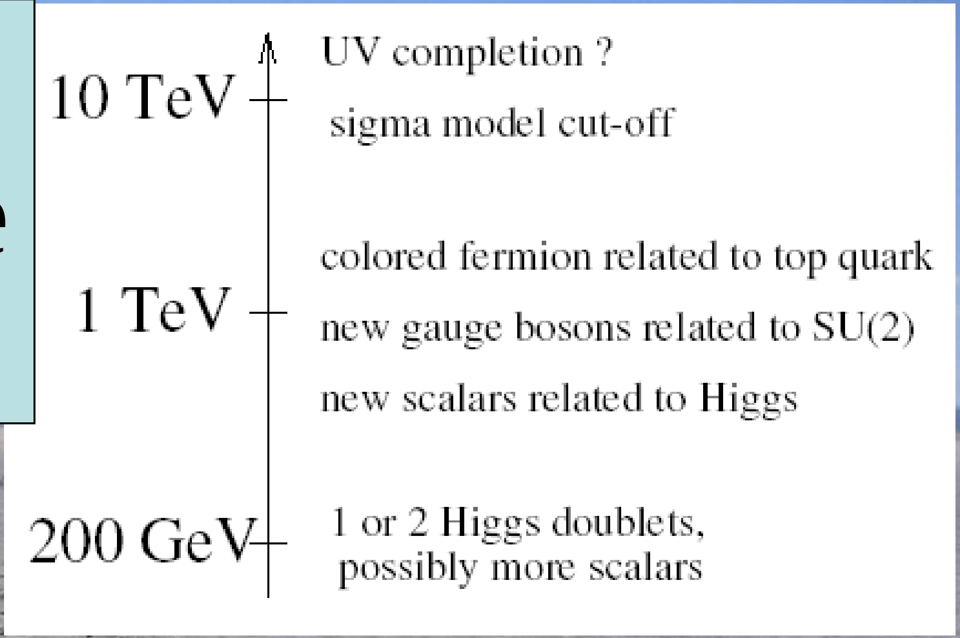
- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

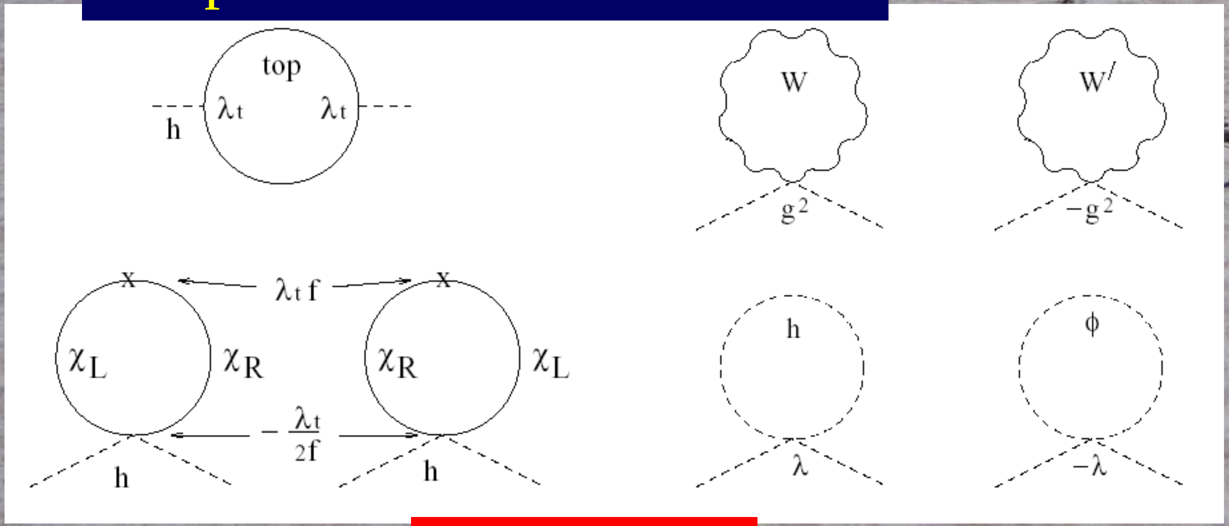
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

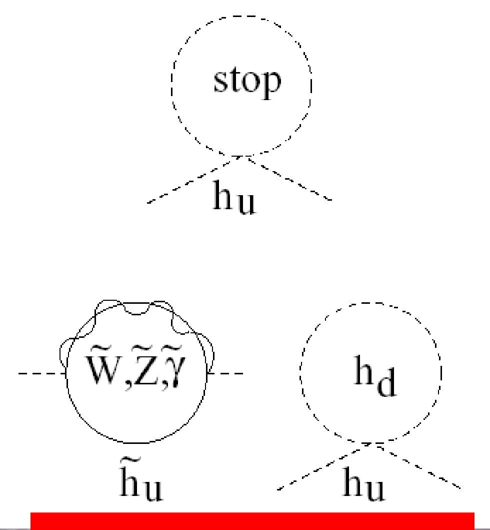
‘Little Higgs’ models
(breakdown of larger symmetry)



Loop cancellation mechanism



Little Higgs



Supersymmetry

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 γγ, 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 γγ
  - angular correlations of leptons in WW, ZZ decays

Does the 'Higgs' have Spin Two ?

- Would have graviton-like couplings: $\mathcal{L}_{int} = -\frac{c_i}{M_{eff}} G^{\mu\nu} T^i_{\mu\nu}$
- Coefficients somewhat model-dependent
- Warped compactification: $ds^2 = w^2(z)\left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$
- Expect equal couplings for photons, gluons

$$\Gamma(X \to gg) = 8\,\Gamma(X \to \gamma\gamma) \qquad c_{g,\gamma} \simeq 1/\int_{z_{UV}}^{z_{IR}} w(z)dz$$

- Larger coefficients for W, Z, b, t

$$c_b \simeq c_t \gtrsim c_W \simeq c_Z = \mathcal{O}(35) \times (c_g = c_\gamma > c_u, c_d)$$

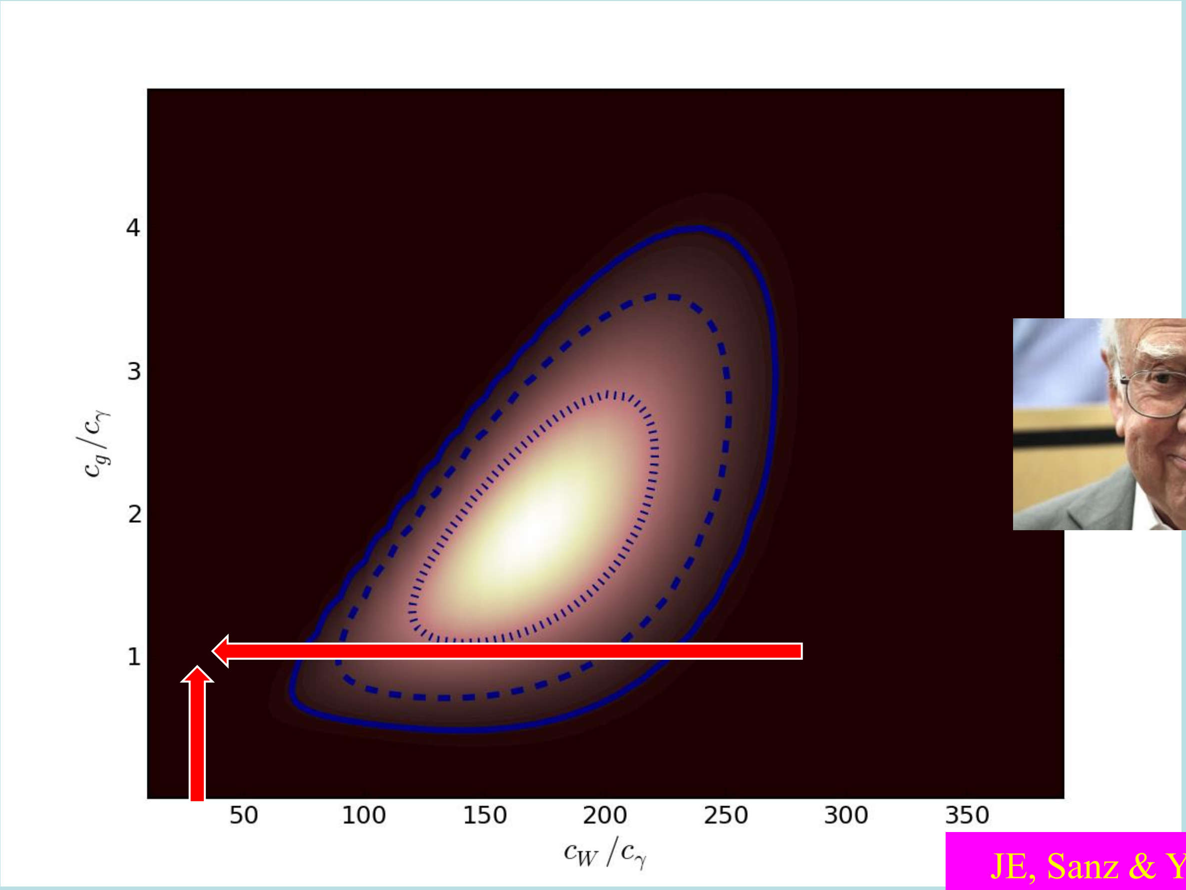
- Smaller coefficients for u, d, s, c

JE, Sanz & You, arXiv:1211.3068

(Also expect vector mass < tensor mass **X LHC**)

Does the 'Higgs' have Spin Two ?

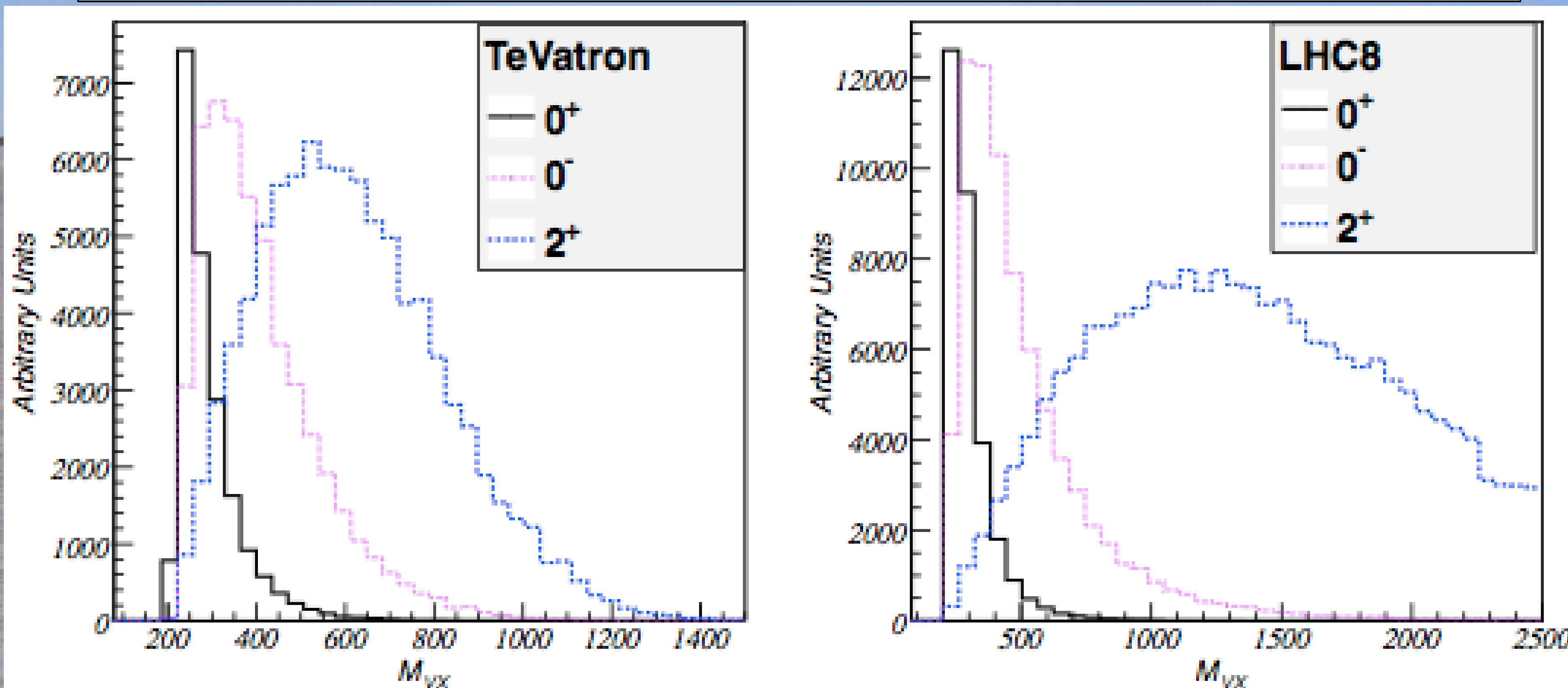
- Fit of vector-boson couplings to spin-two model



JE, Sanz & You, arXiv:1211.3068

- **Prediction of AdS-type graviton-like model disfavoured by > 3 σ**

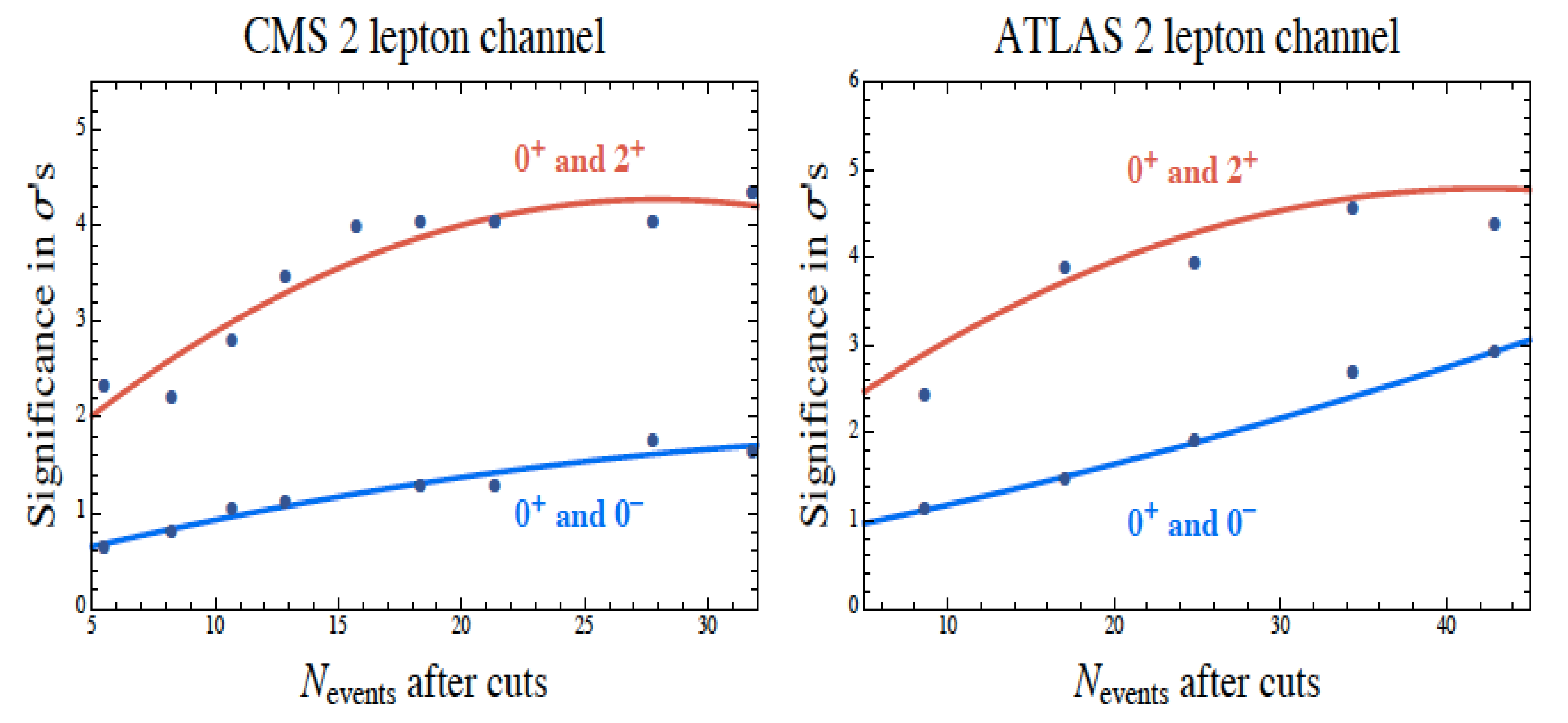
Does the ‘Higgs’ have Spin Zero ?



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

JE, Hwang. Sanz & You: arXiv:1208.6002

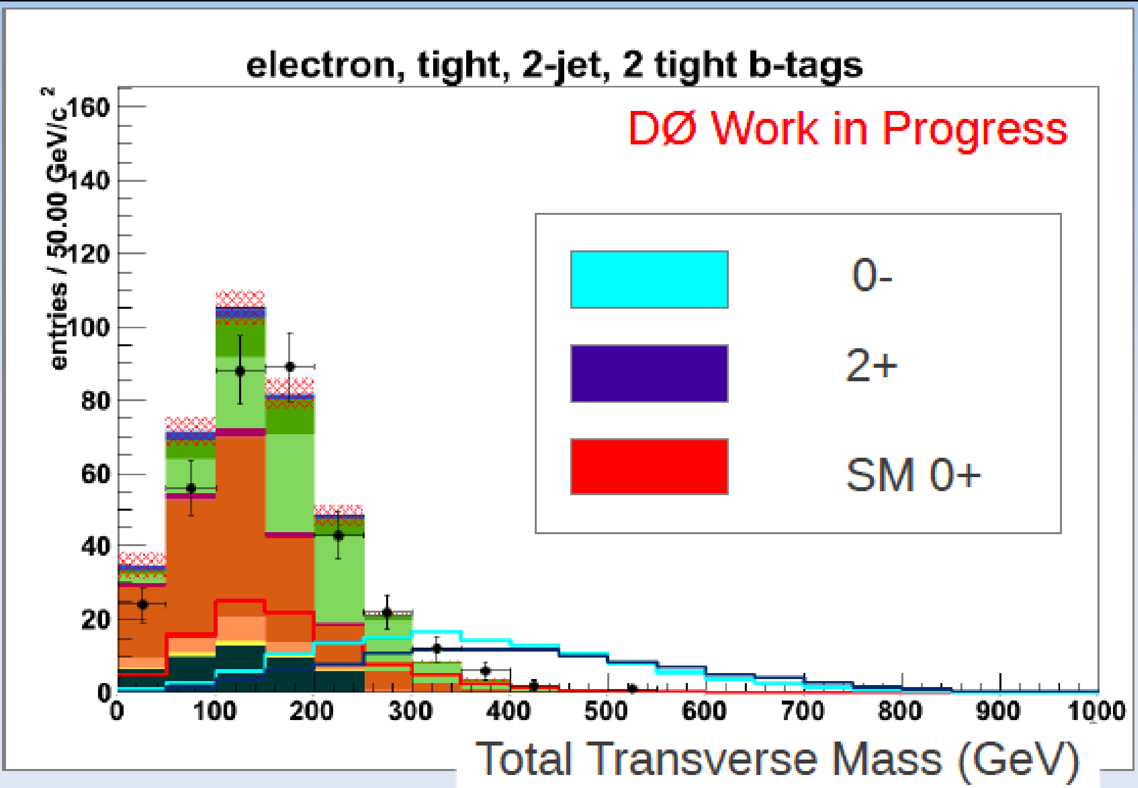
Spin Discriminating Power



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

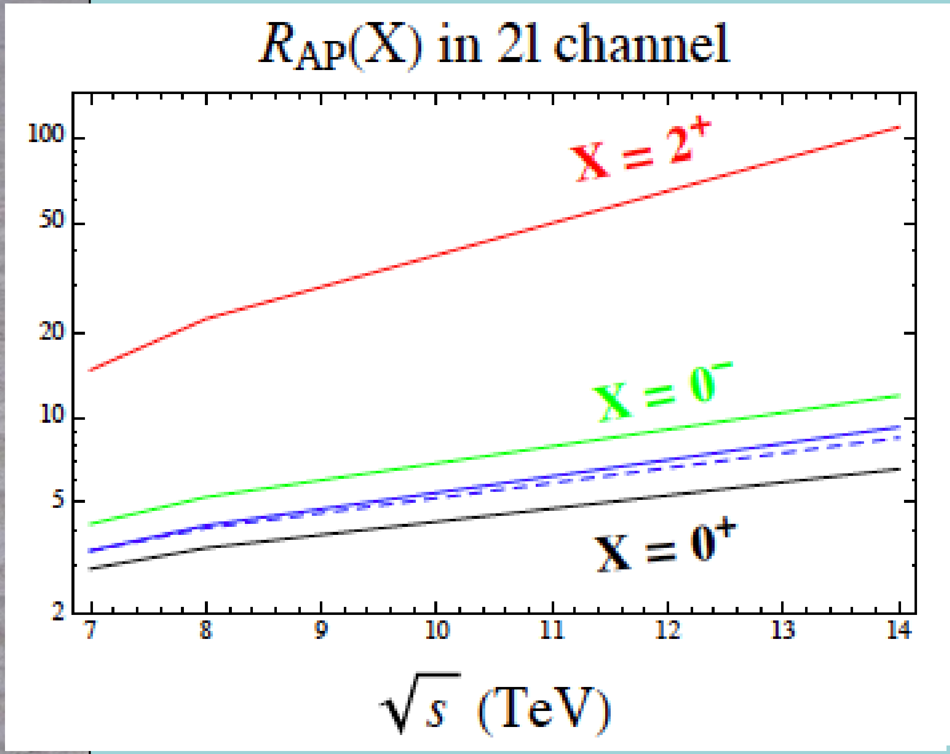


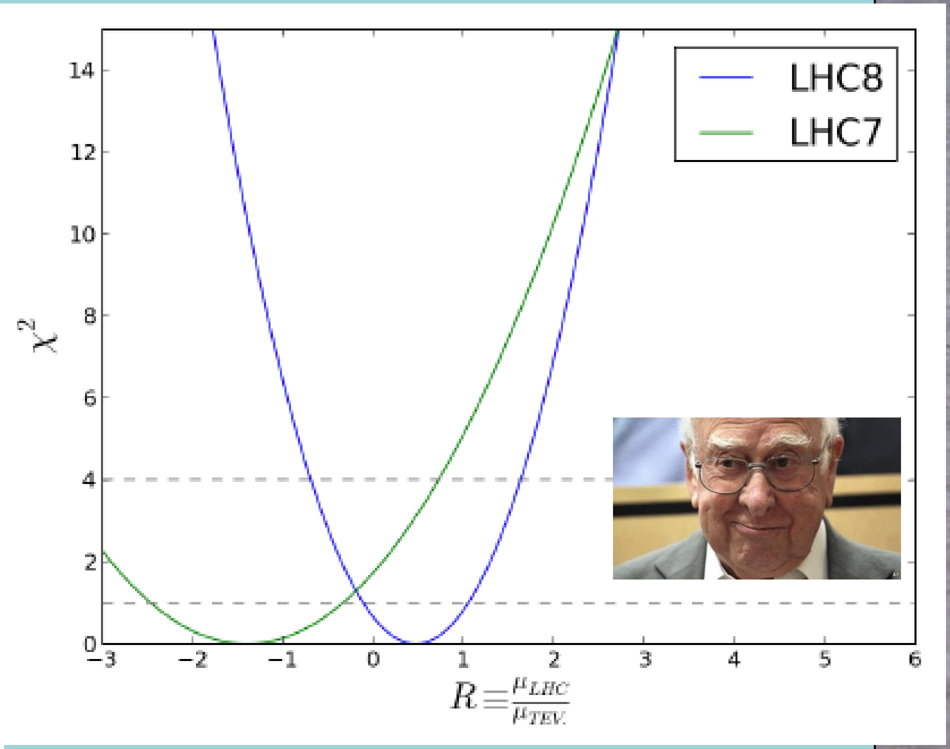
- Pseudoscalar, graviton-like spin-2 disfavoured

The ‘Higgs’ probably a Scalar

JE. Sanz & You: arXiv:1303.0208

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



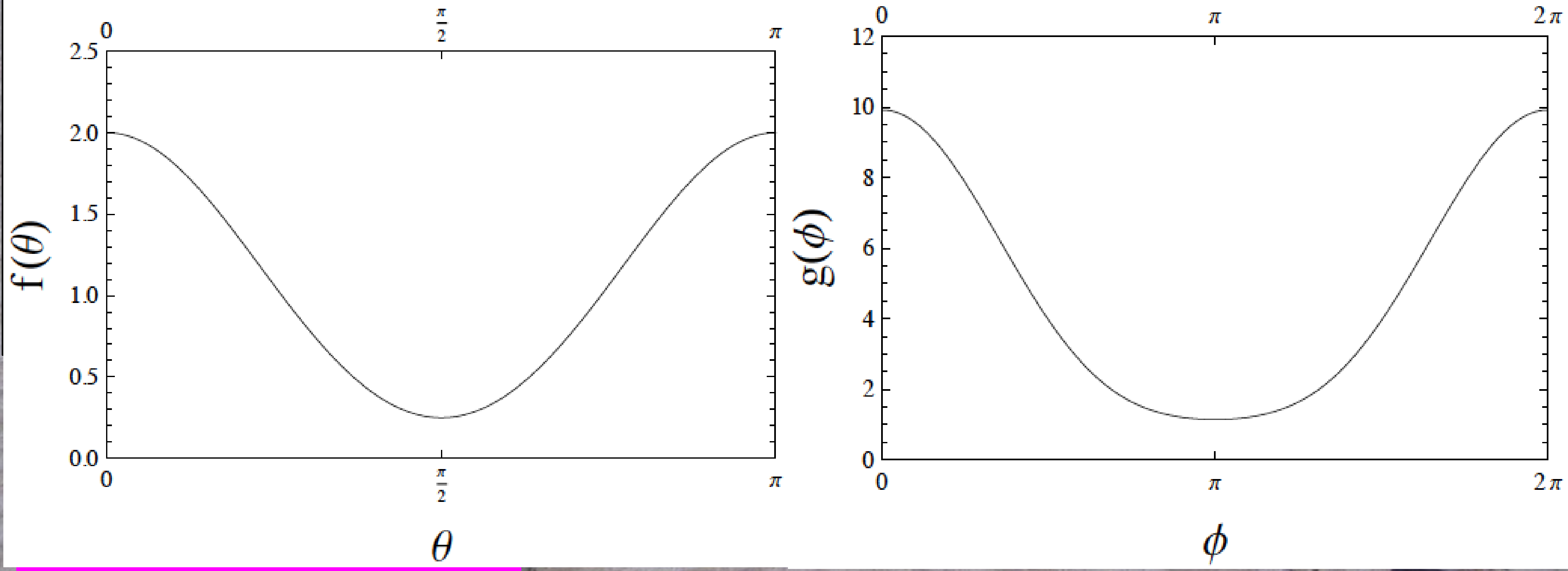


- Pseudoscalar, graviton-like spin-2 disfavoured

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)



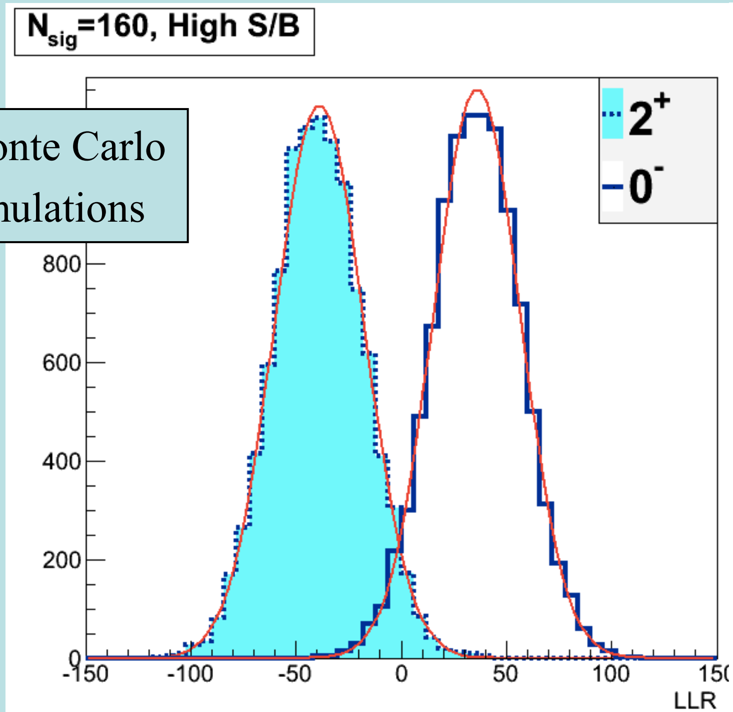
JE, Hwang: arXiv:1202.6660

Does the ‘Higgs’ have Spin Two ?

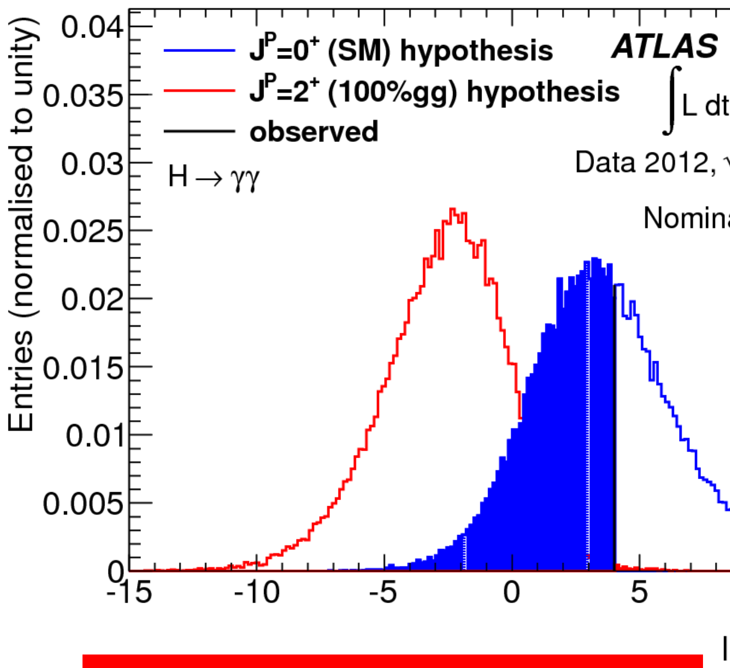
- Discriminate spin 2 vs spin 0 via angular distribution of decays into γγ

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations



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

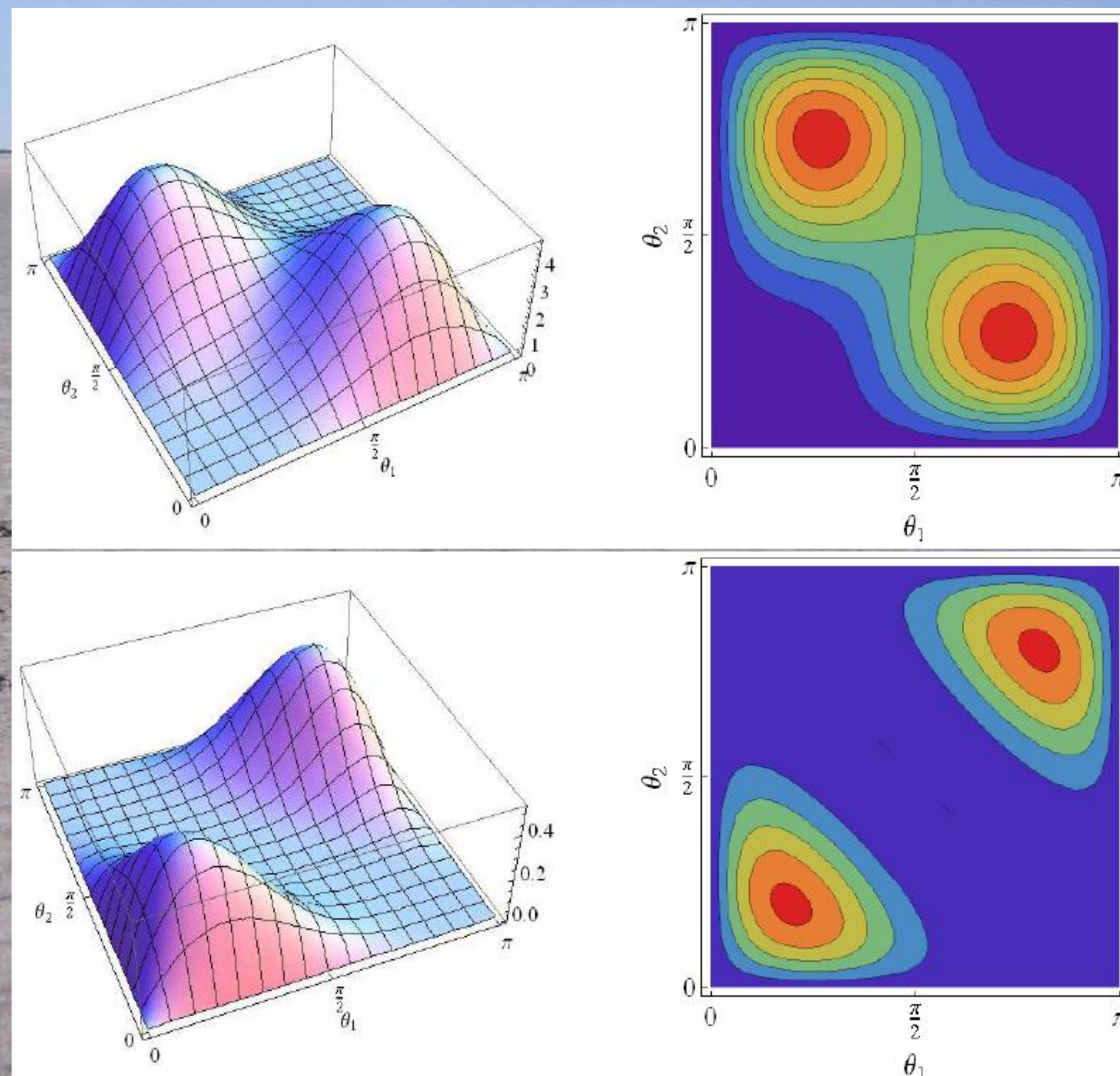


2$^+$ disfavoured @ 99%

Does the ‘Higgs’ have Spin Zero ?

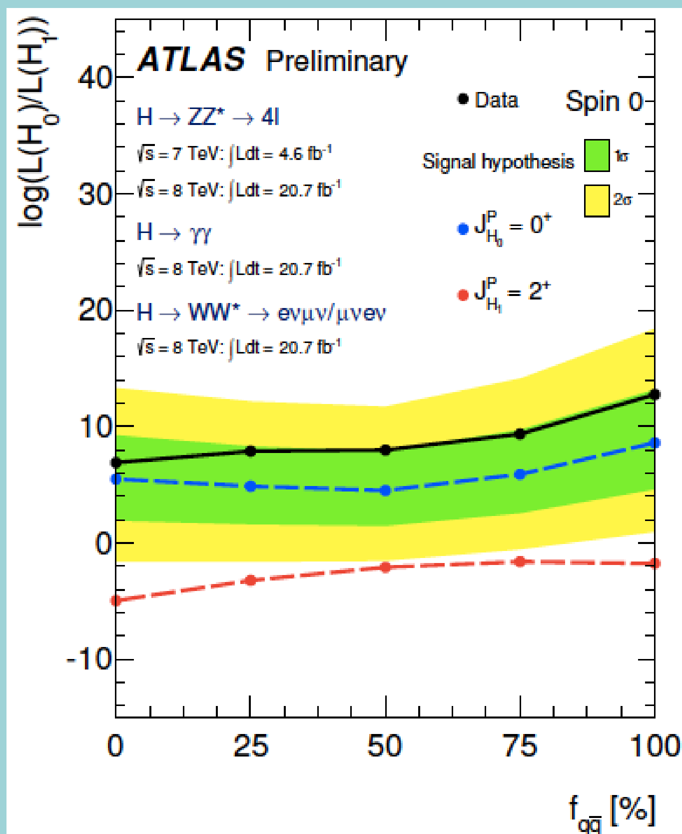
- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$

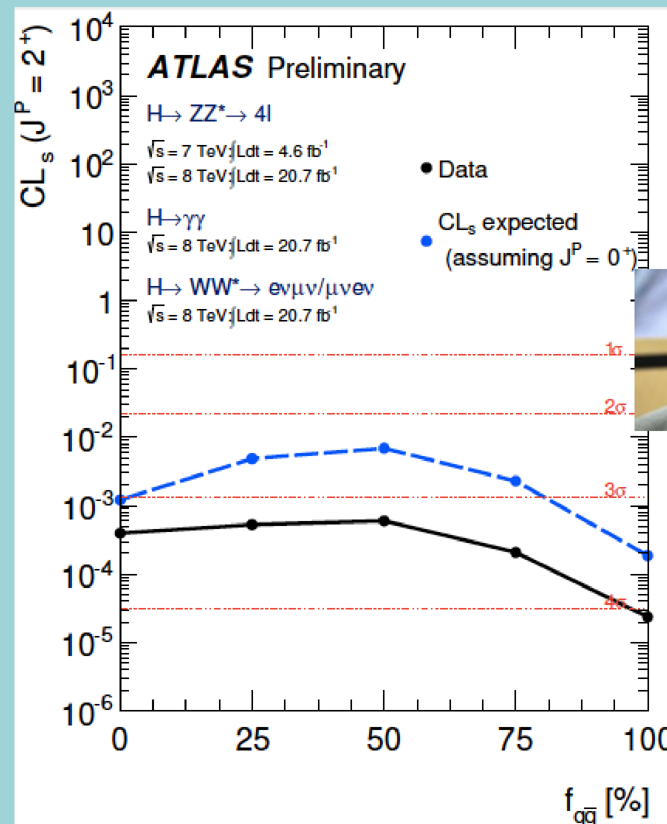
  (for $\varphi = \pi$)



JE, Hwang: arXiv:1202.6660

The ‘Higgs’ Spin is probably 0



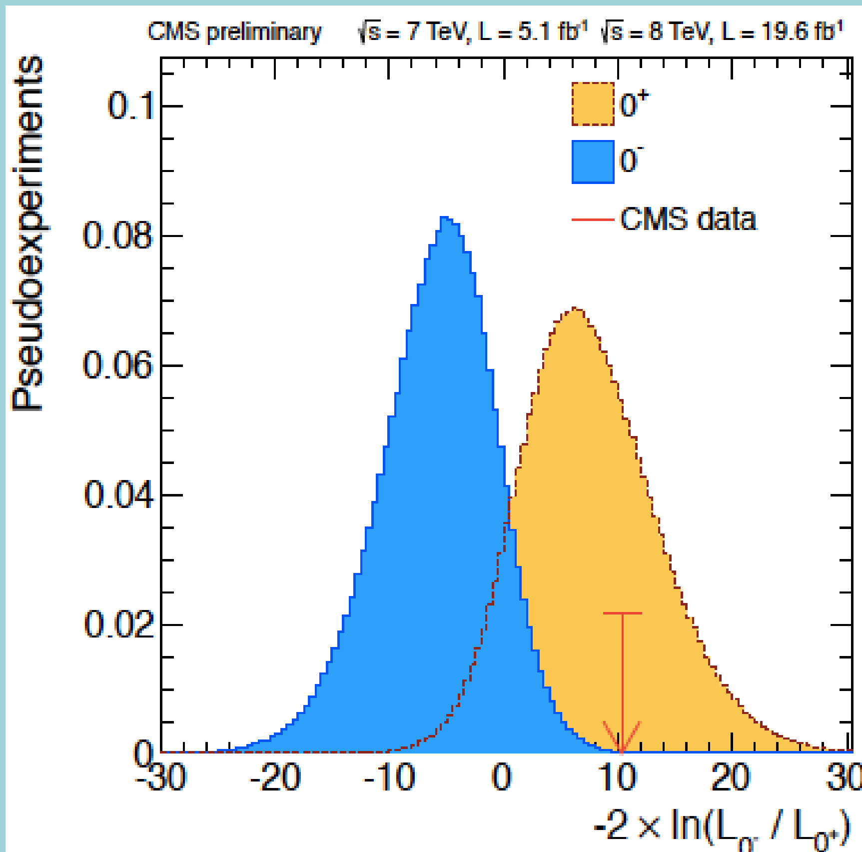


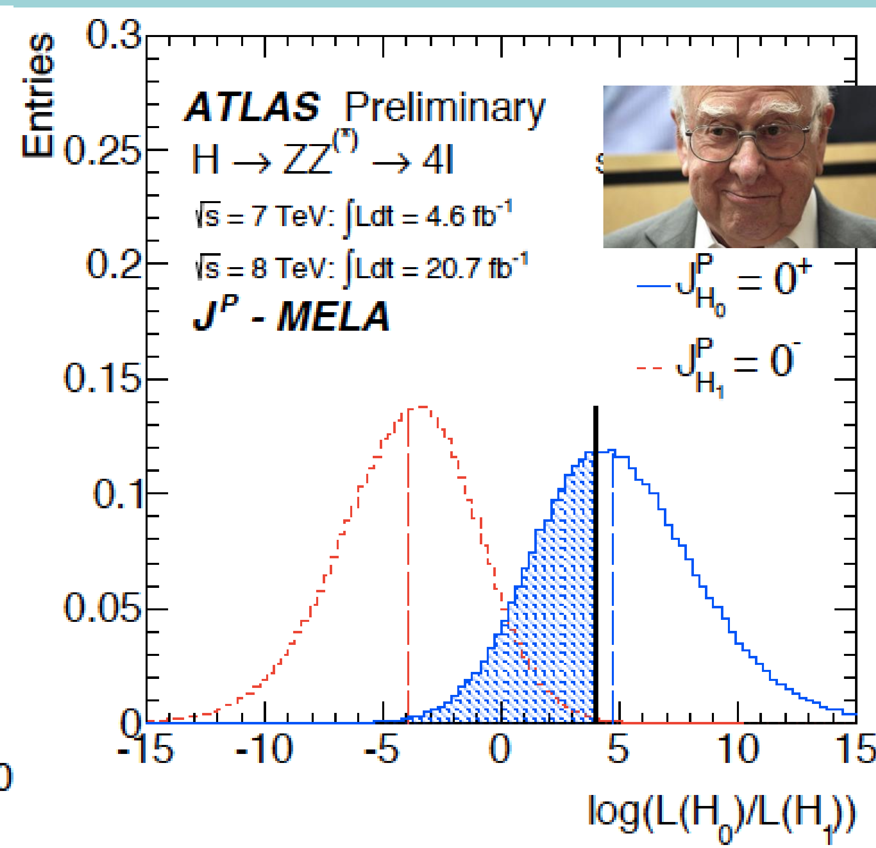
- Graviton-like spin-2 disfavoured at 99.9% CL

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?

Phenomenological Framework

- Assume custodial symmetry:

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

- Parameterize gauge bosons by 2 × 2 matrix Σ:

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

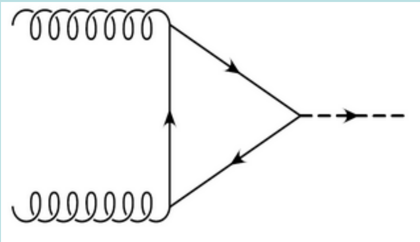
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \quad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

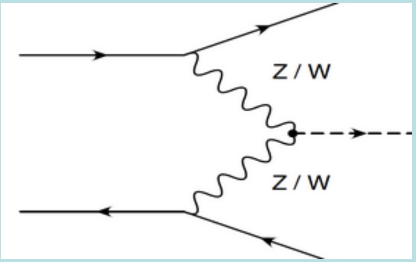
- Coefficients ***a = c = 1*** in Standard Model

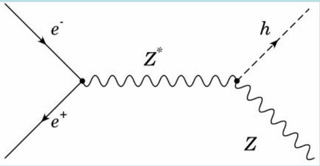
Phenomenological Framework

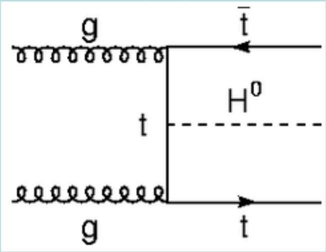
- *a* parametrizes couplings of *h* to massive gauge bosons
- *c* parametrizes couplings of *h* to fermions:
  - Standard Model: $a = c = 1$
  - Composite Higgs MCHM4: $a = c = \sqrt{1-\xi}$ $\xi \equiv (v/f)^2$
  - Composite Higgs MCHM5: $a = \sqrt{1-\xi}, \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$
  -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

Re-interpreting SM Higgs Searches

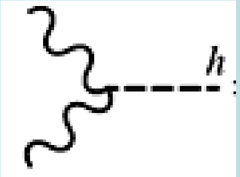


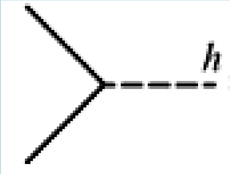


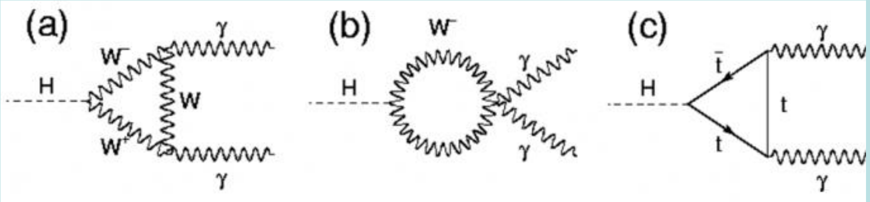




$$R_{gg} = \frac{(-\frac{v}{V} b_s + cF_t)^2}{F_t^2} \quad , \quad R_{\mathrm{VBF}} = a^2 \quad , \quad R_{\mathrm{ap}} = a^2 \quad , \quad R_{\mathrm{hs}} = c^2$$







$$R_{VV} = a^2 \quad , \quad R_{\bar{f}f} = c^2 \quad , \quad R_{\gamma\gamma} = \frac{(-\frac{v}{V} b_{em} - \frac{8}{3} cF_t + aF_w)^2}{(-\frac{8}{3} F_t + F_w)^2}$$

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

Re-Interpreting SM Higgs Searches

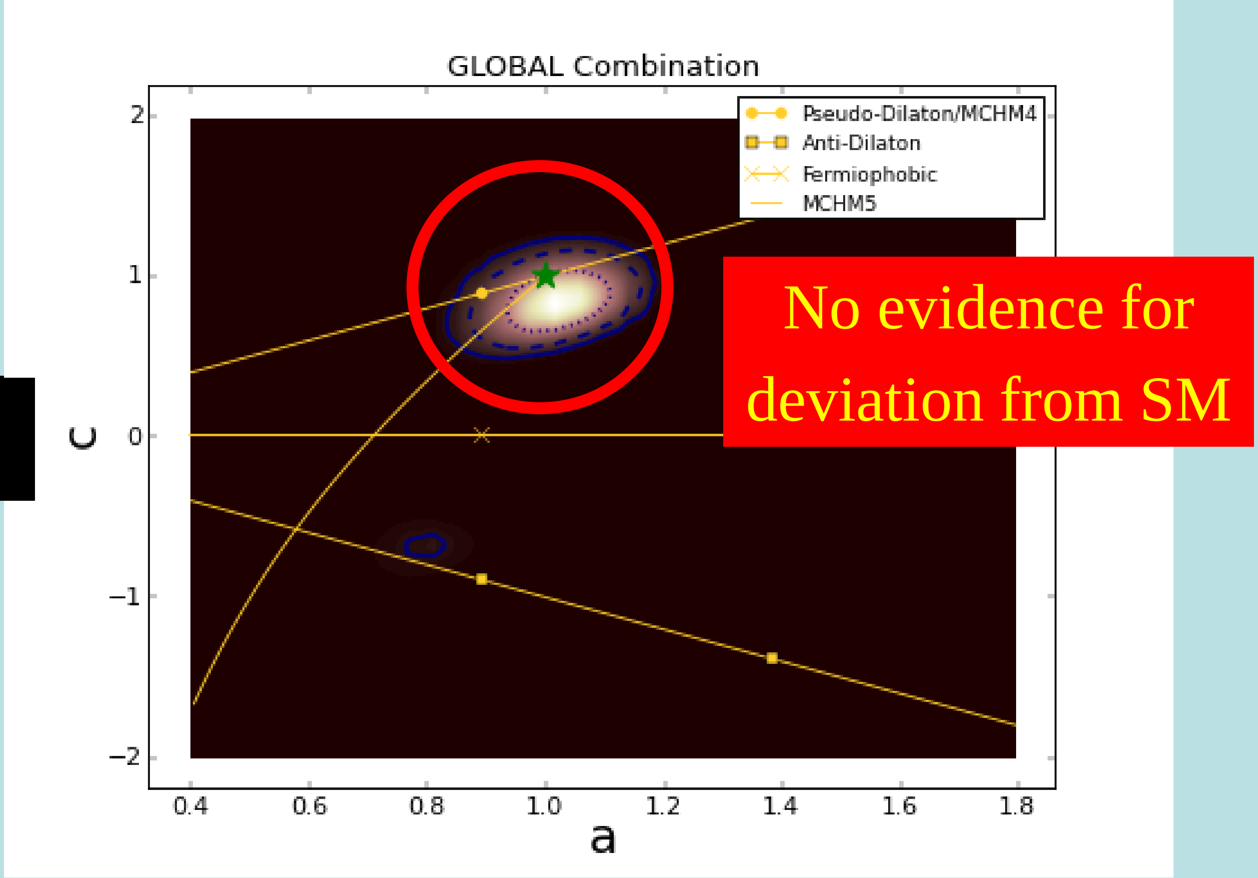
- Sensitivities of different experimental search (sub)channels:

channel	Production sensitive to a	Production sensitive to c	Decay sensitive to a	Decay sensitive to 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

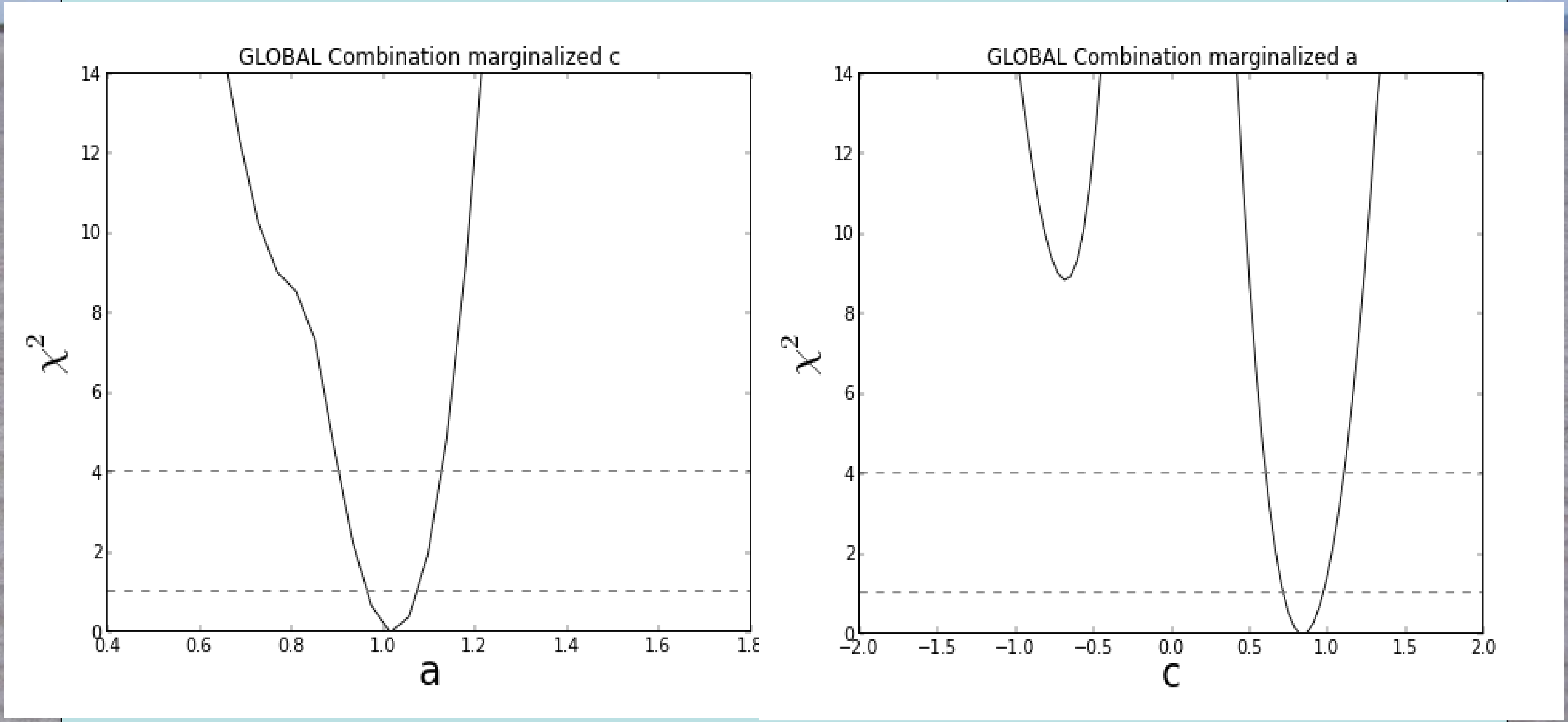


- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

Global Analysis of Higgs-like Models

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

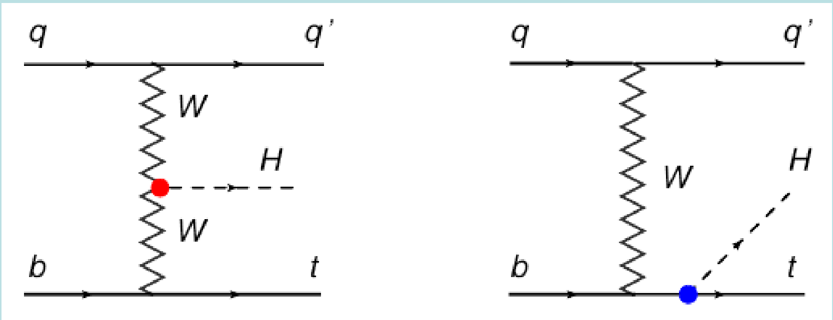


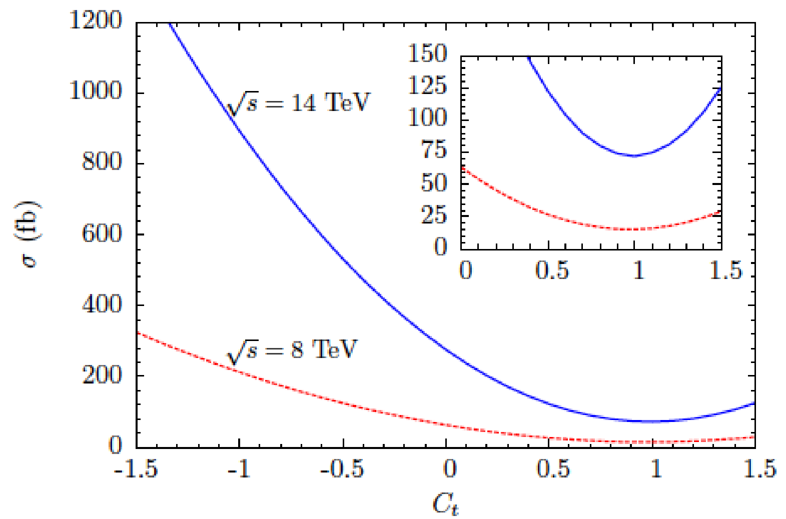
- 'Wrong' sign of *c* disfavoured

JE & Tevong You, arXiv:1303.3879

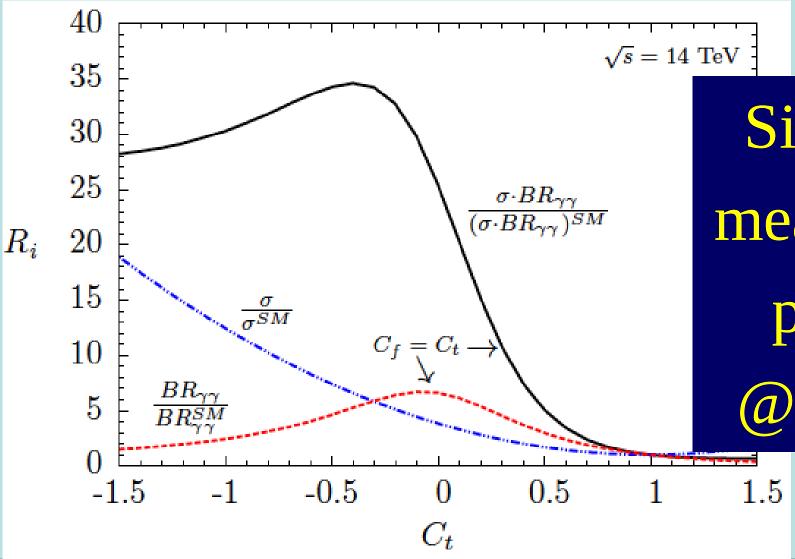
Single Higgs + Top Production

- Sensitive to sign of H-t coupling

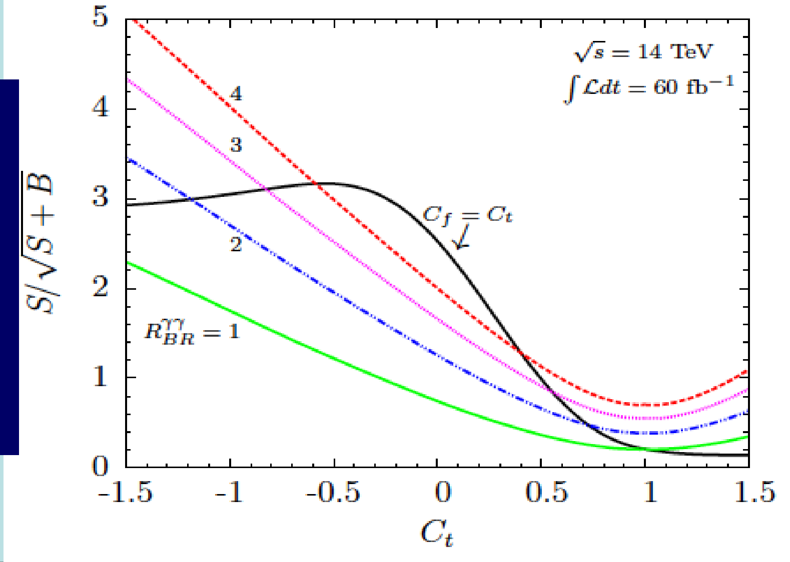




- Sign fixed by renormalizability



Significant measurement possible @ LHC14?



What is it ?

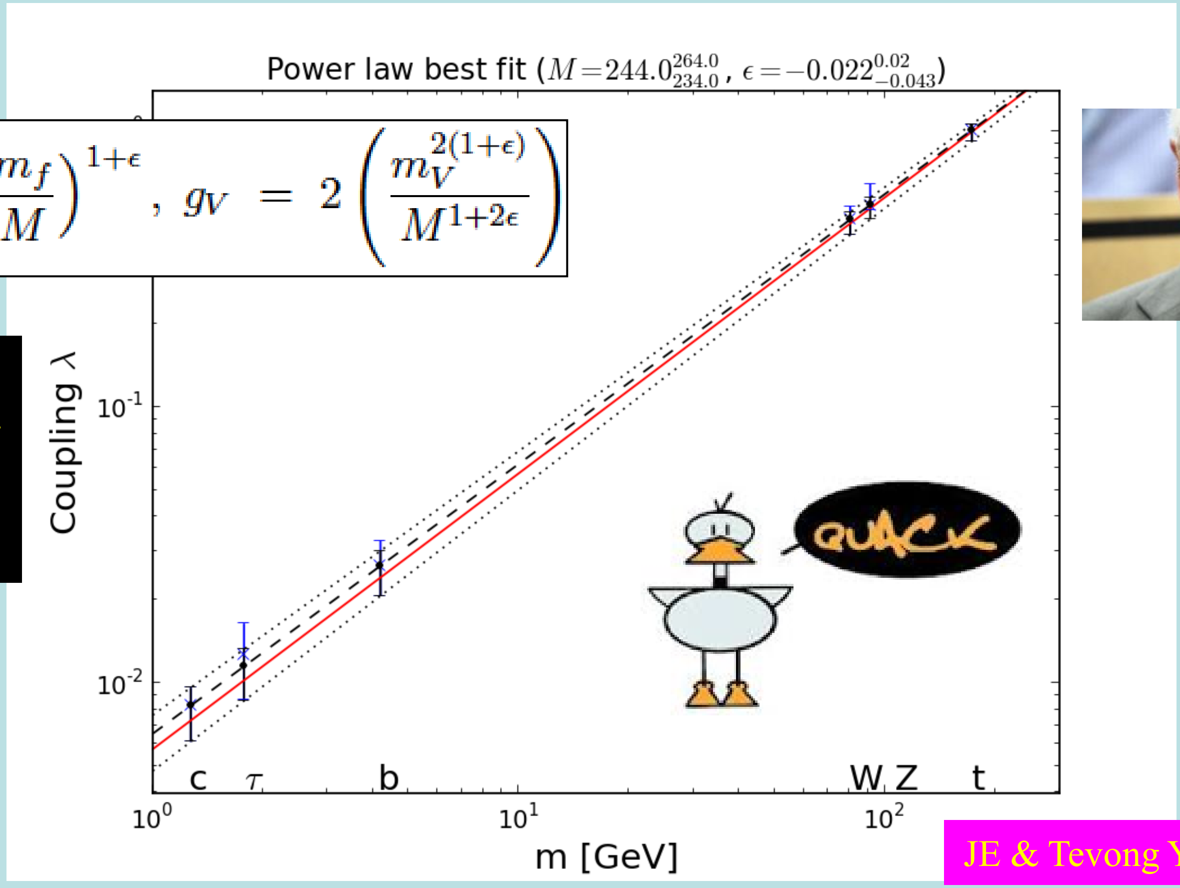
- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
- Quantum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

It Walks and Quacks like a Higgs

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

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

Global fit



JE & Tevong You, arXiv:1303.3879

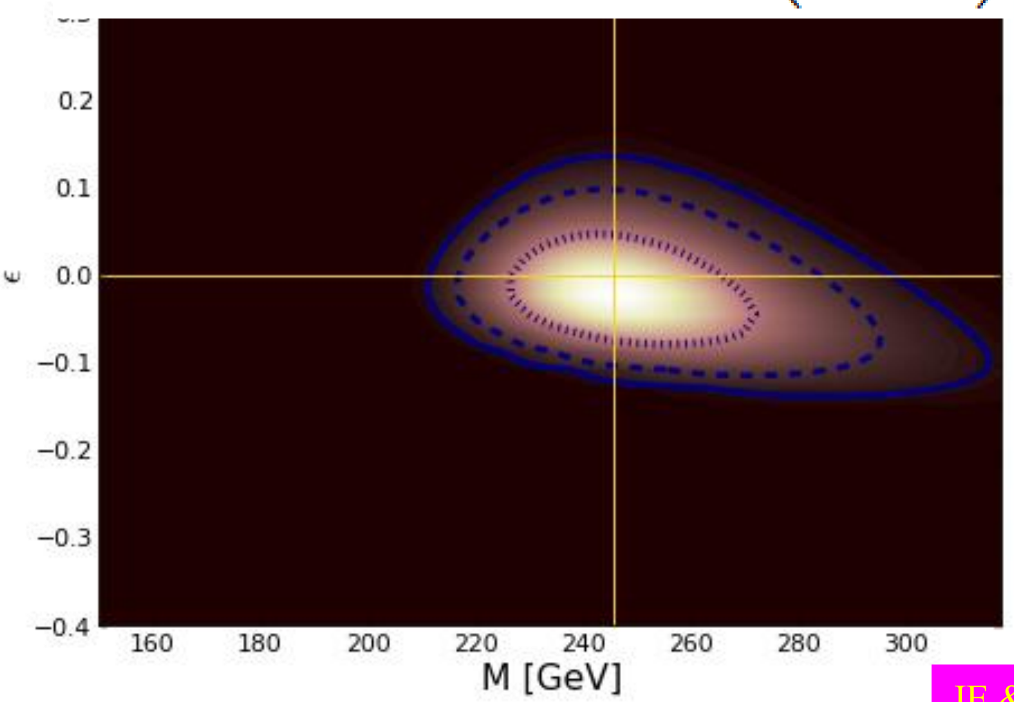
- **Red line = SM**, dashed line = best fit

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

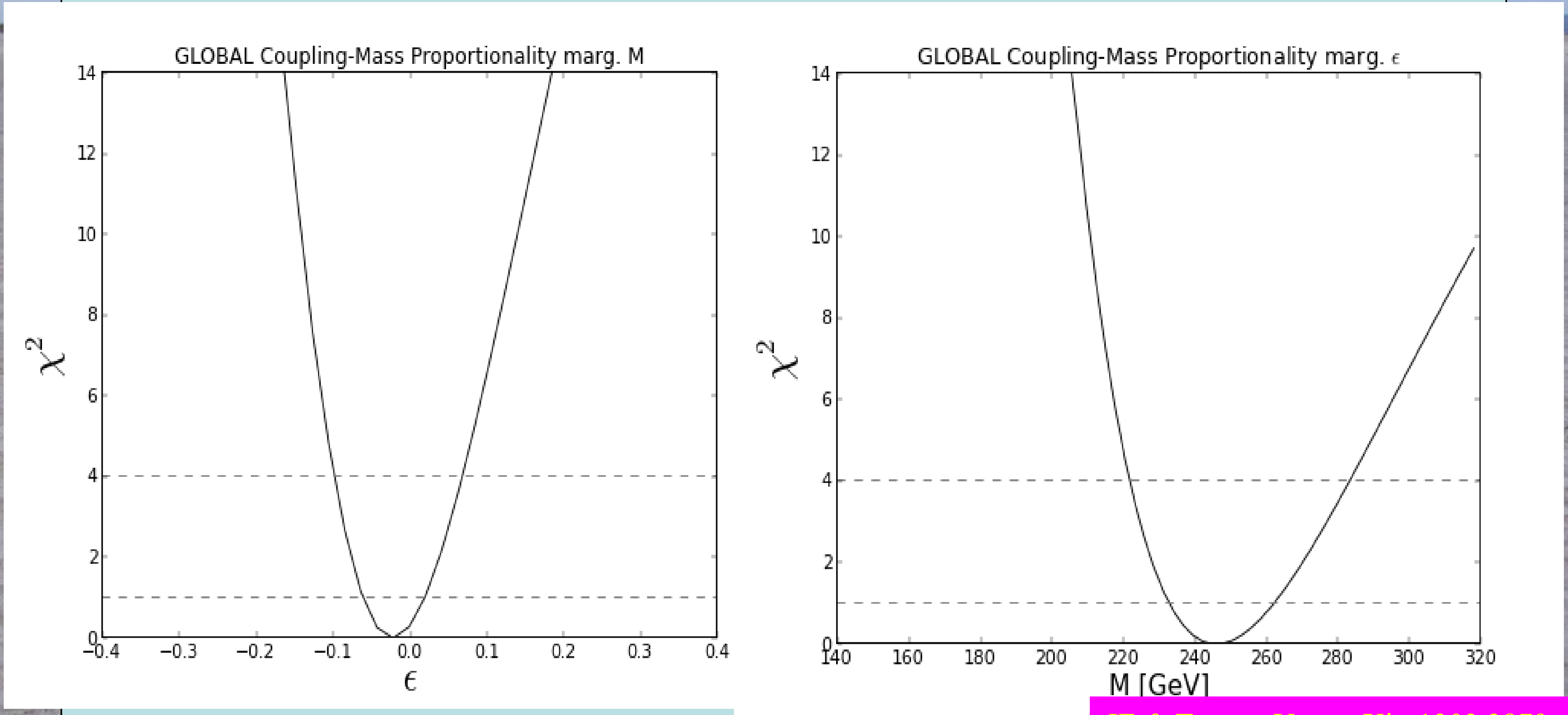


JE & Tevong You, arX:1303.3879

- 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

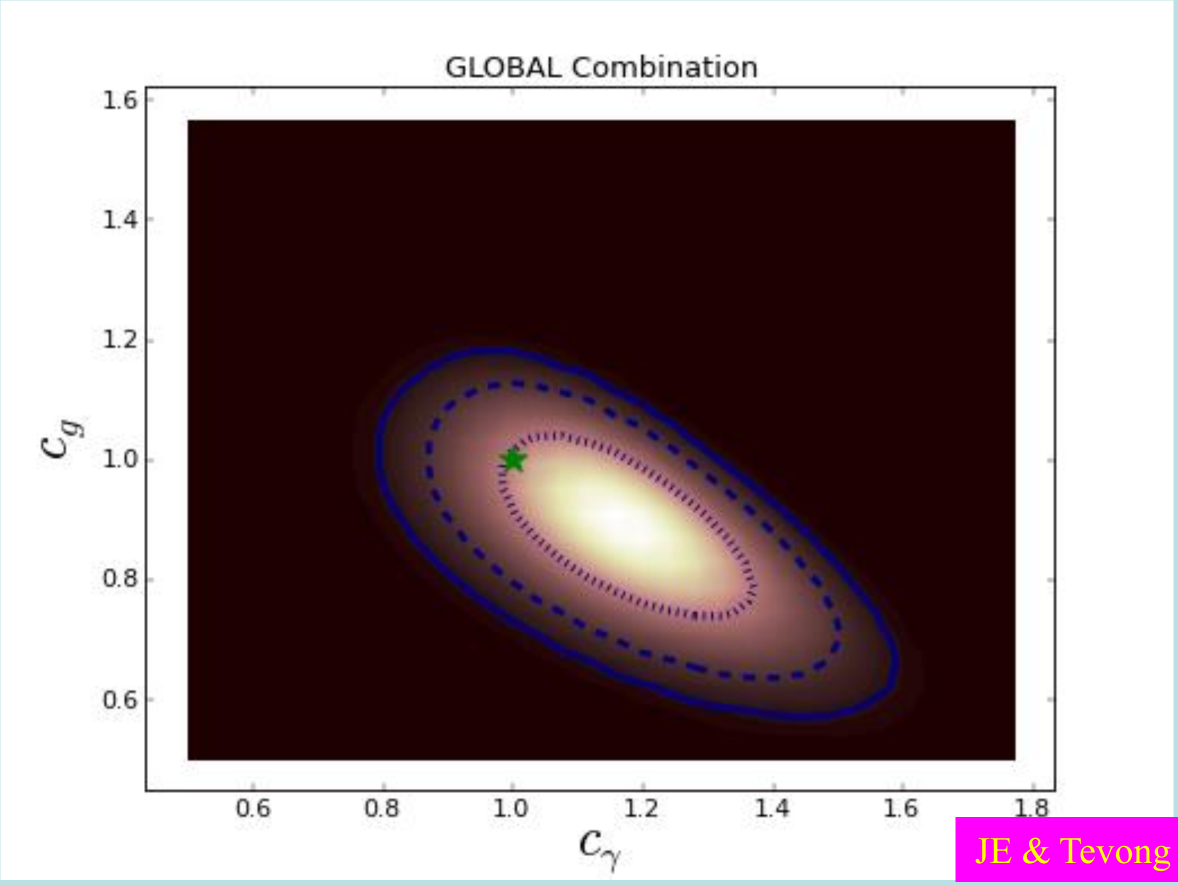
$\varepsilon = -0.022^{+0.042}_{-0.021}$ $M = 244^{+20}_{-10}$ GeV

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

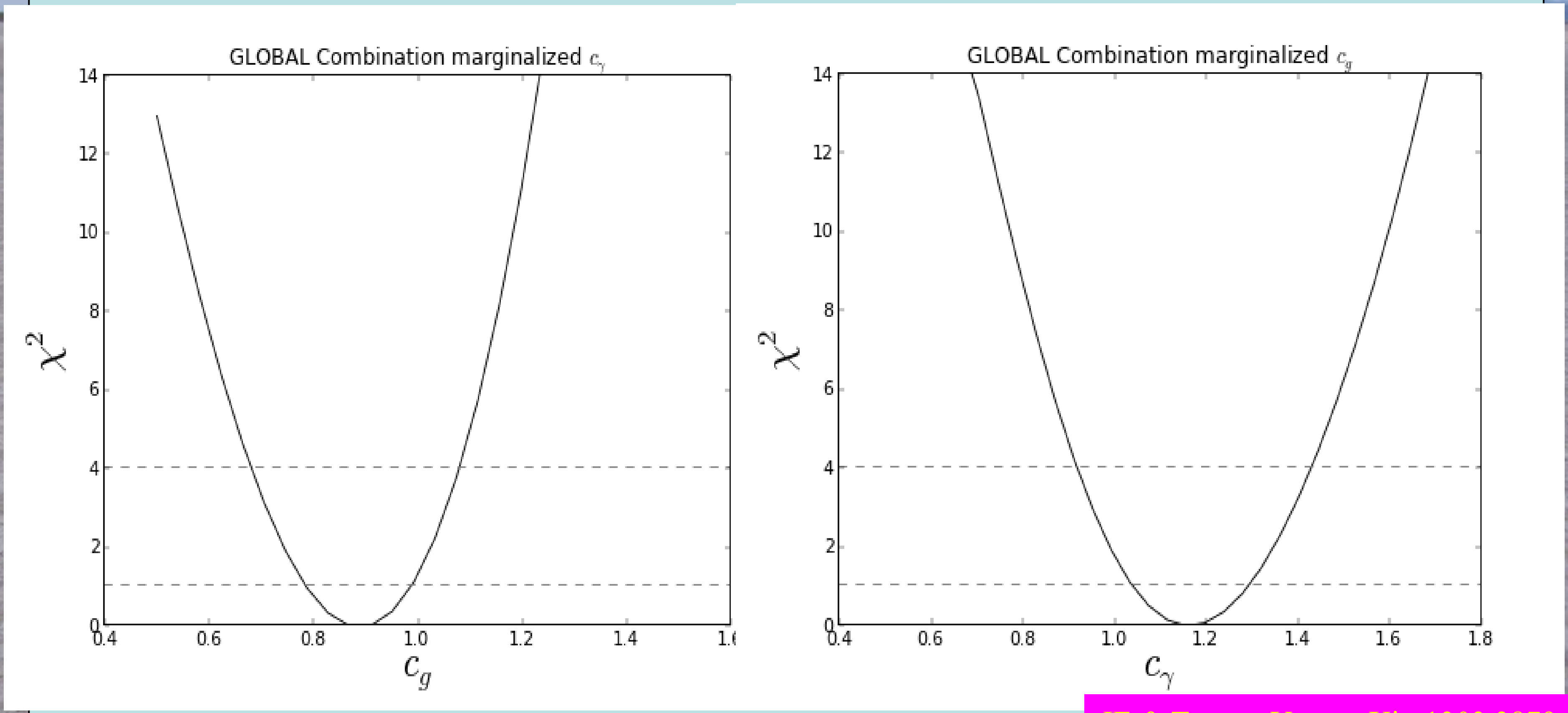


JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

Loop Corrections ?

- Gluon-gluon coupling ~ 1 σ low?



JE & Tevong You, arXiv:1303.3879

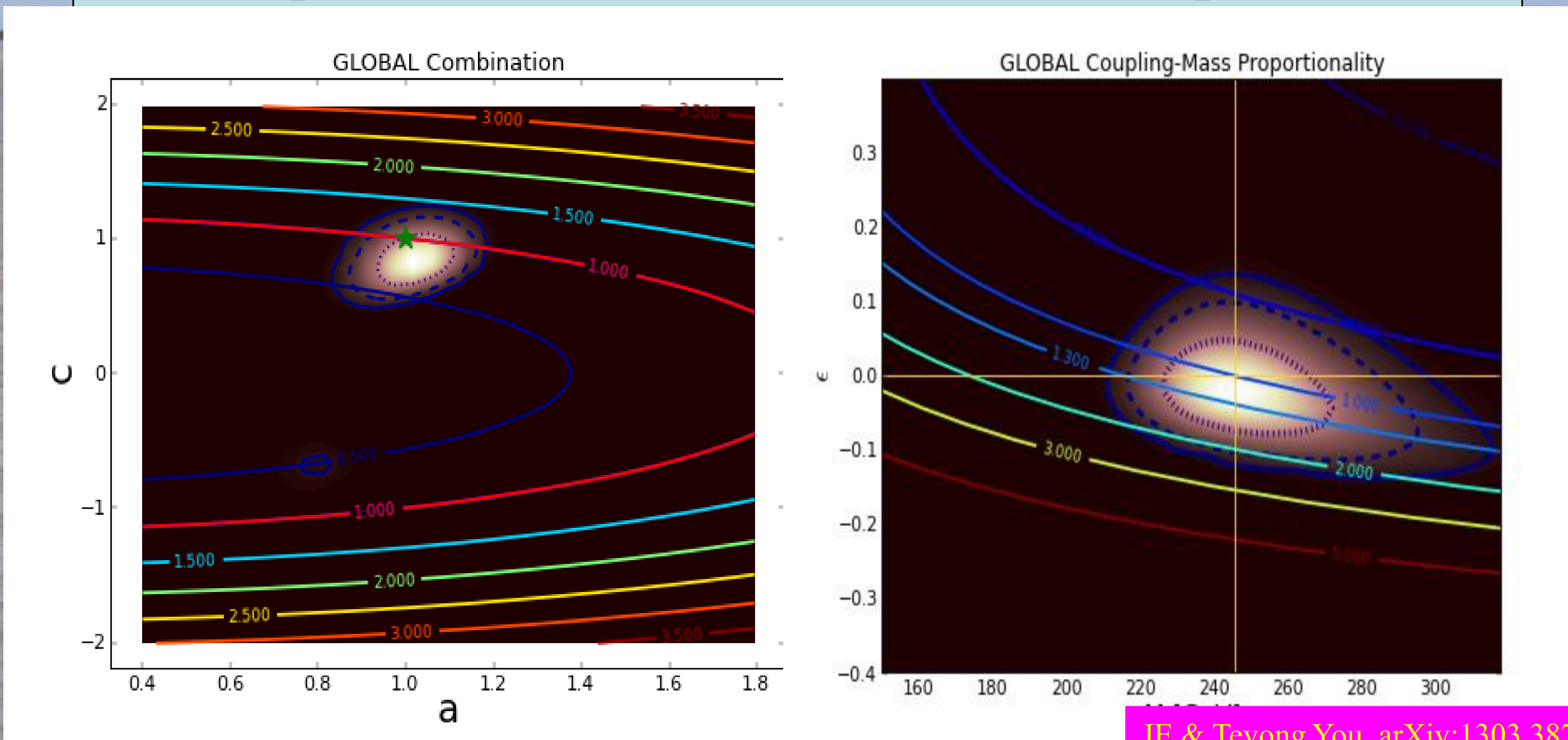
- γγ coupling ~ 1 σ high?

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?
  - **γγ coupling >~ Standard Model?**
- What are its self-couplings? **Hi-lumi LHC or …?**

What is its Decay Rate ?

- Compared with the Standard Model prediction

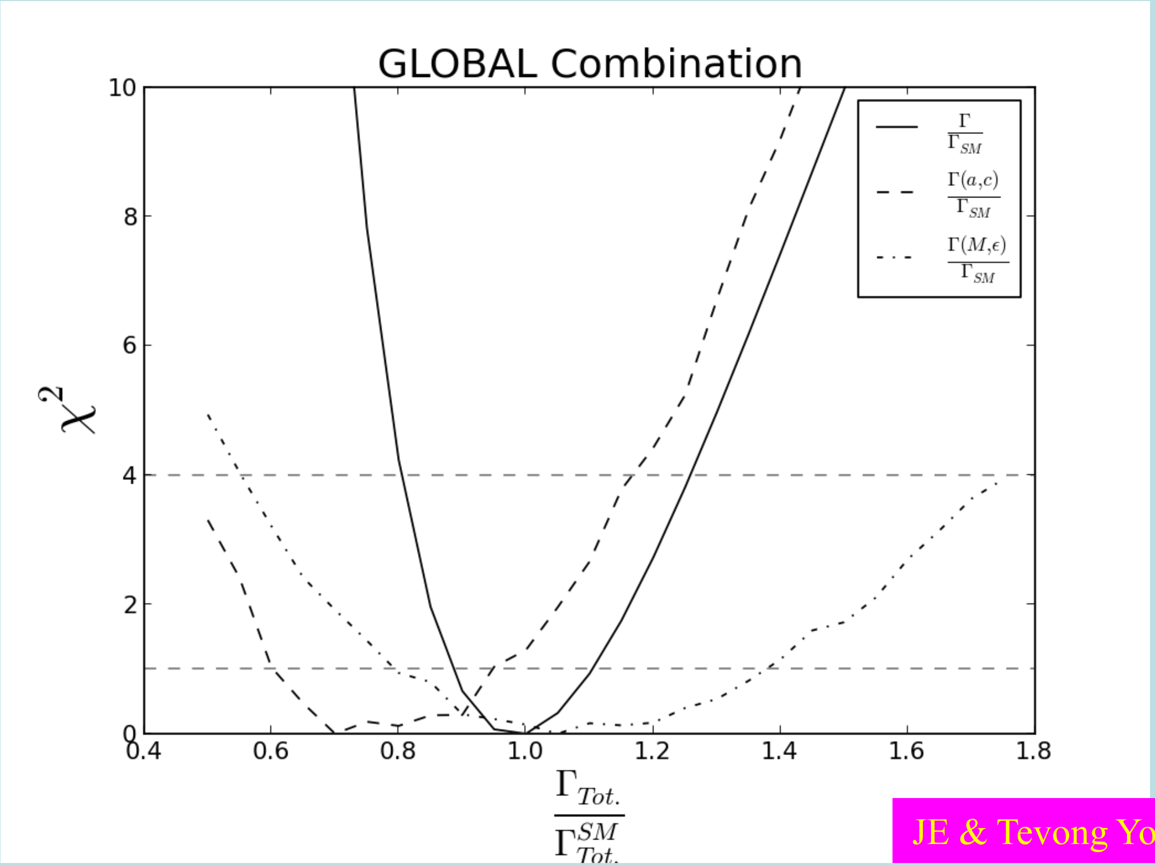


JE & Tevong You, arXiv:1303.3879

- Assuming no non-Standard Model modes

What is its Decay Rate ?

- Compared with the Standard Model prediction

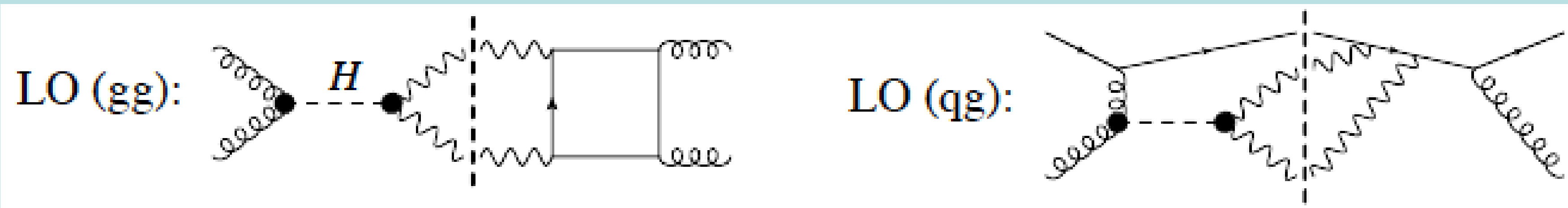


JE & Tevong You, arXiv:1303.3879

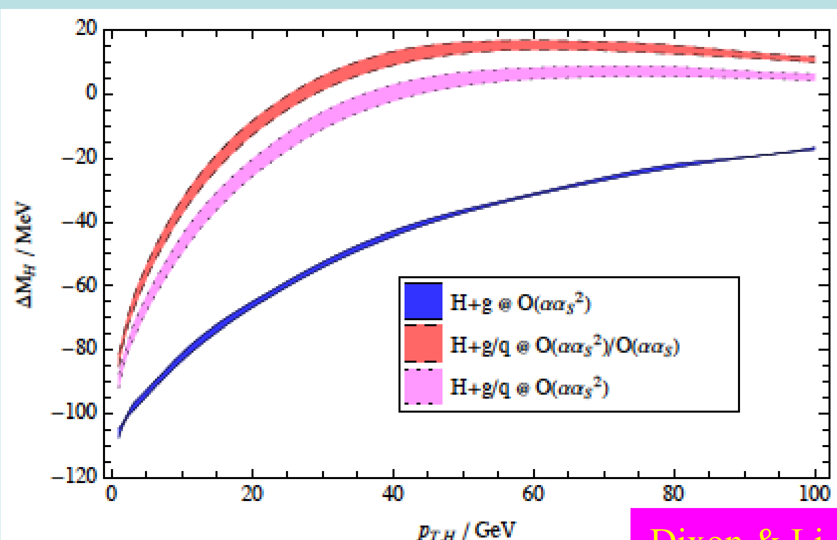
- Assuming no non-Standard Model modes

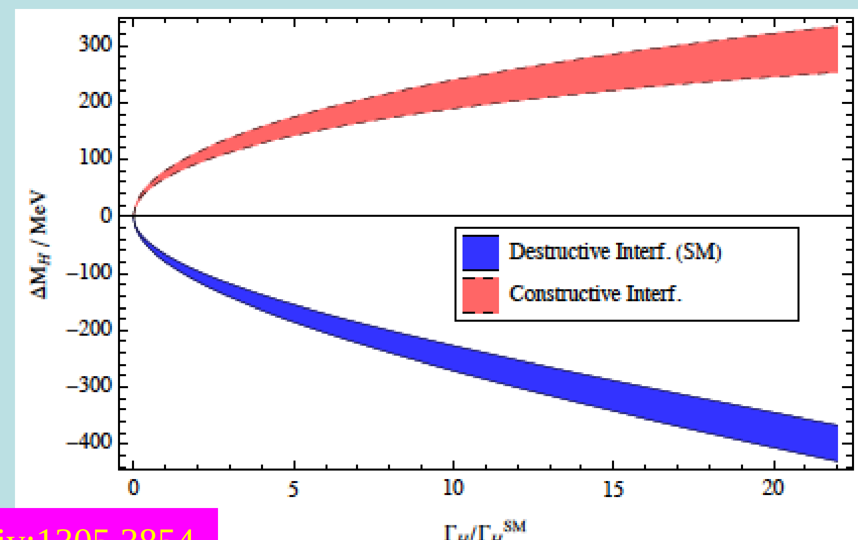
Mass Shift sensitive to Γ_H

- Apparent $m_{\gamma\gamma} \neq m_{ZZ*}$ due to interference with QCD



  - Depends on kinematics
  - Sensitive to sign and magnitude of Higgs couplings



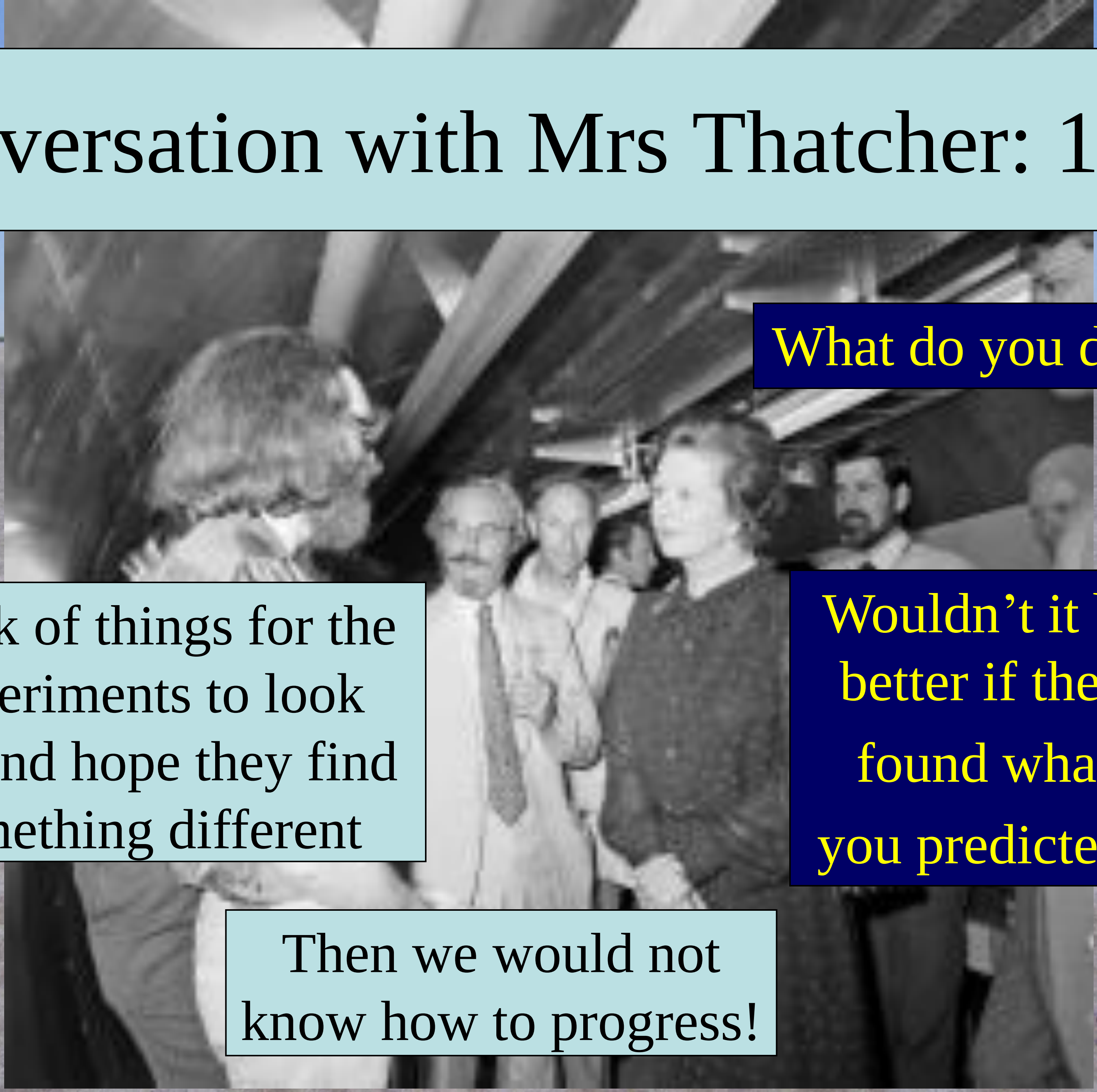


Dixon & Li, arXiv:1305.3854

The Story so Far

- **A new chapter in particle physics is open**
- The new particle is a scalar
- Couplings ~ Standard Model Higgs
- Severe constraint on composite models
- **Elementary scalar a challenge for theorists**
- Fits naturally within supersymmetry
  - Mass, couplings
- But no sign of supersymmetric particles
- **On to HE, HL-LHC and beyond**

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!