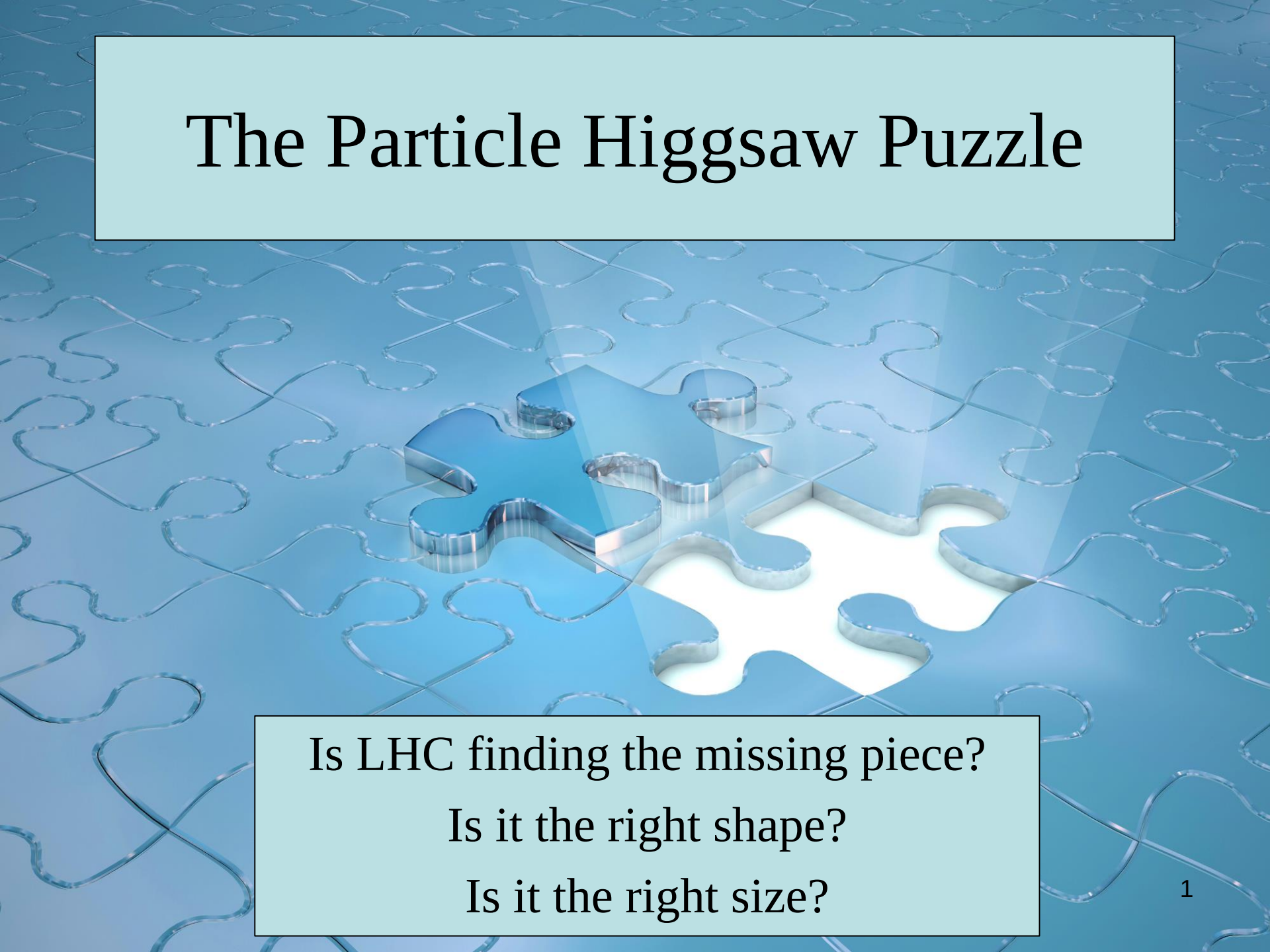
The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

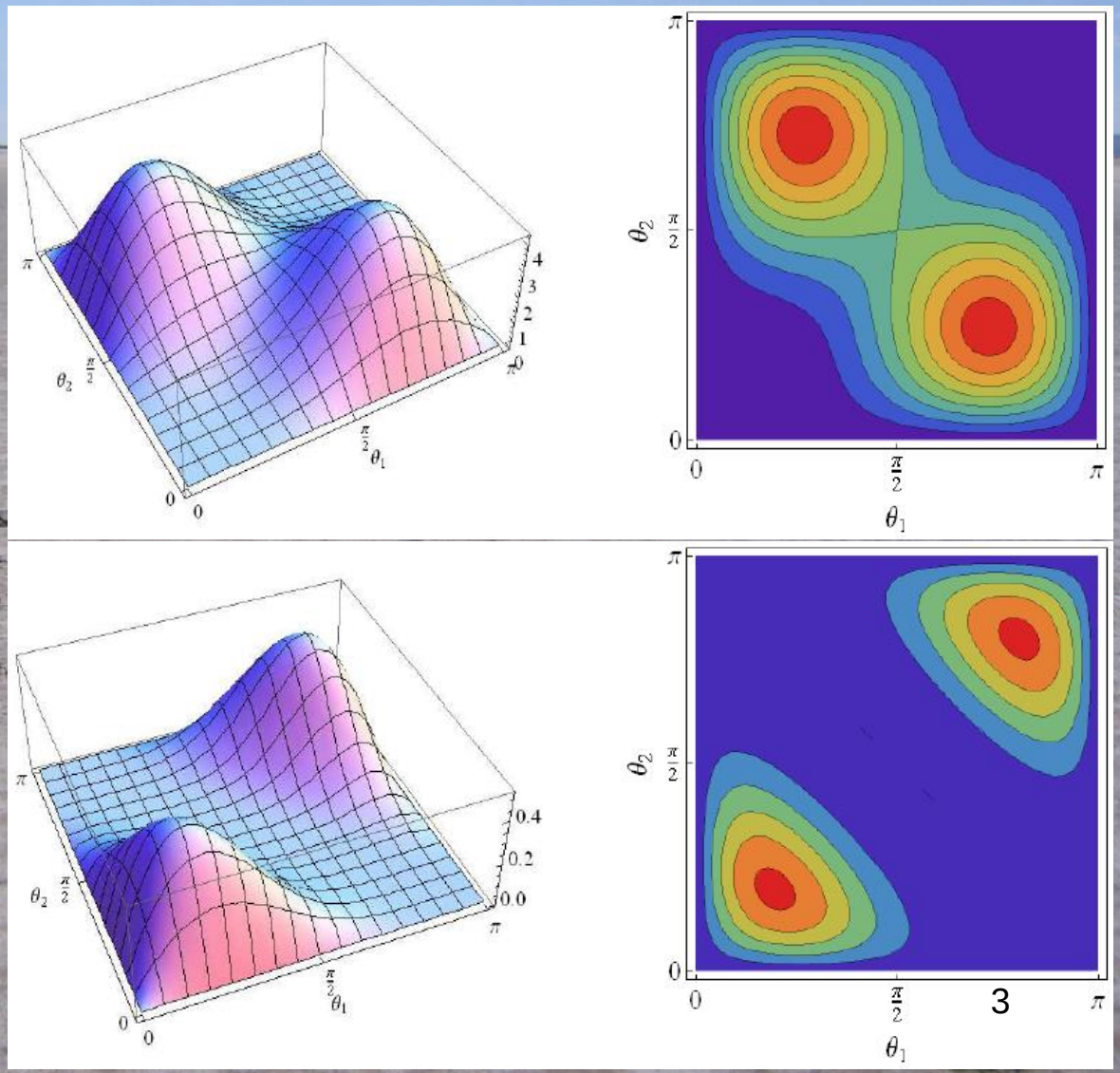
What is it ?

- 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- and other couplings?

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 $\varphi = \pi$)



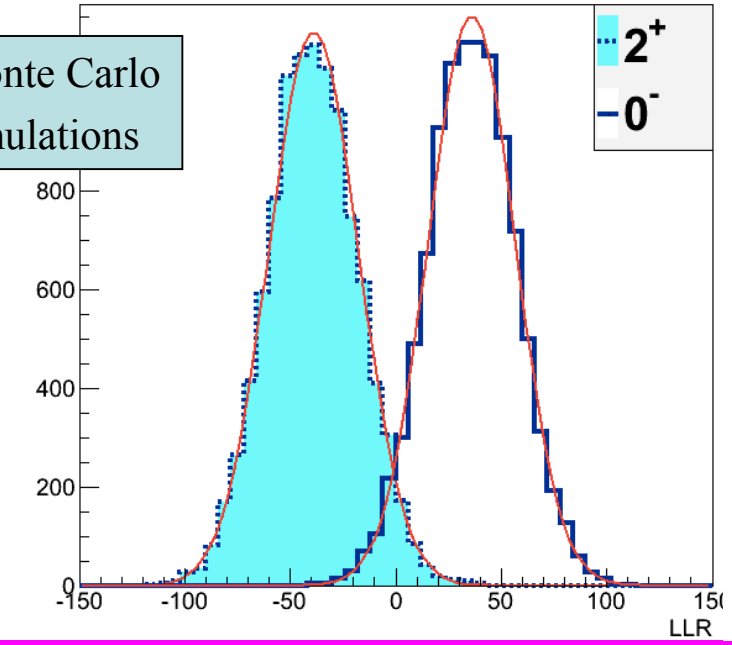
JE, Hwang: arXiv:1202.6660

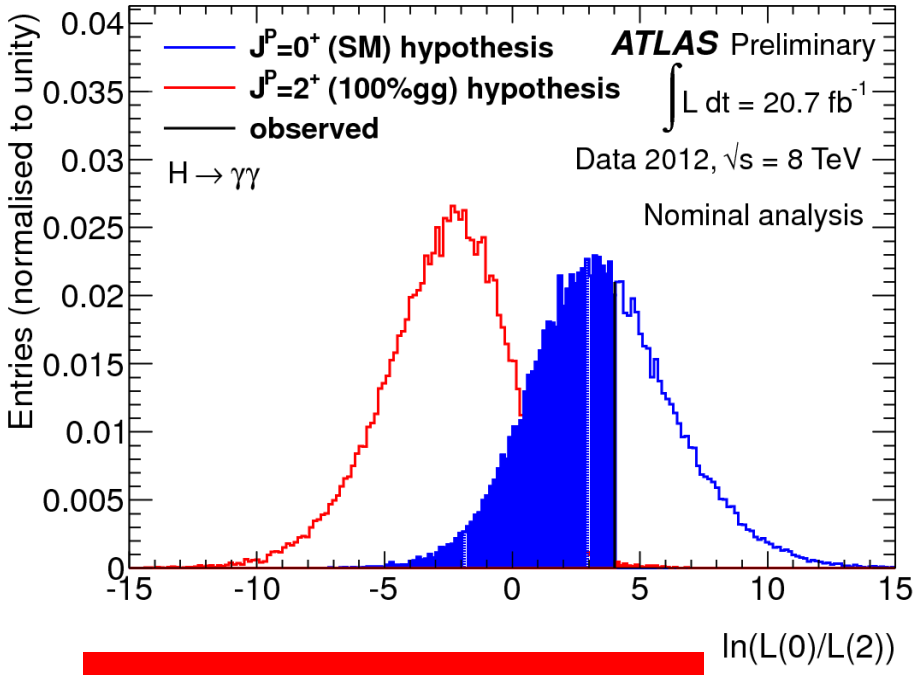
Does the 'Higgs' have Spin Two ?

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

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations

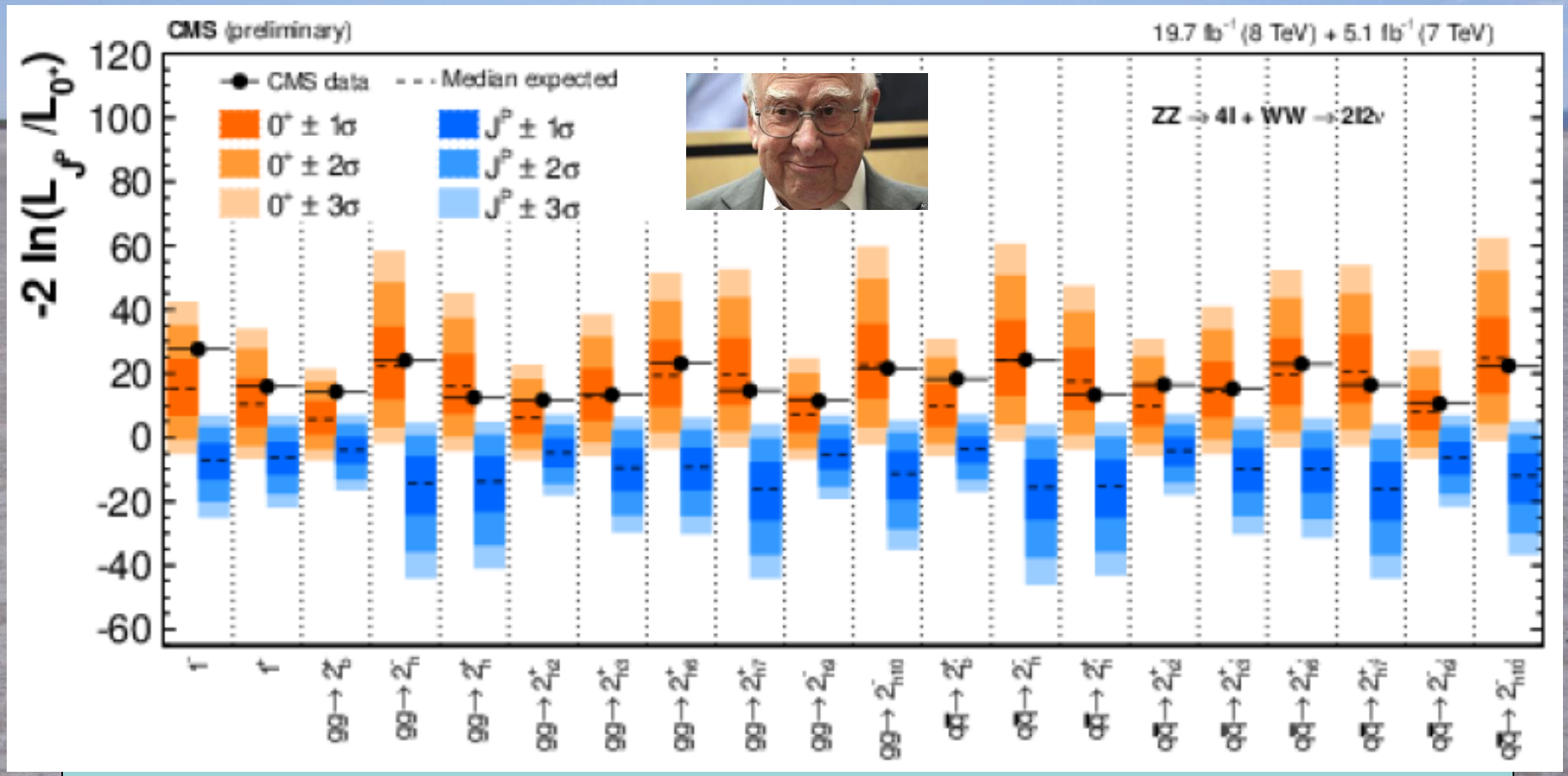




JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

2^+ disfavoured @ 99%

The ‘Higgs’ has Spin 0



- Alternative spin-parity hypotheses disfavoured

What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
- Does it couple to particle masses?
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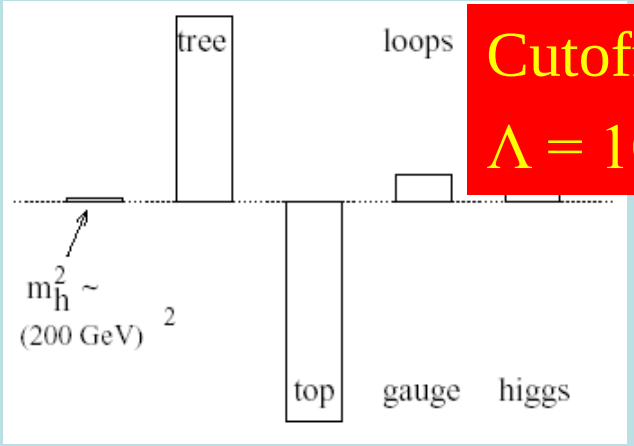
- What are its self- and other couplings?

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff
Λ = 10 TeV

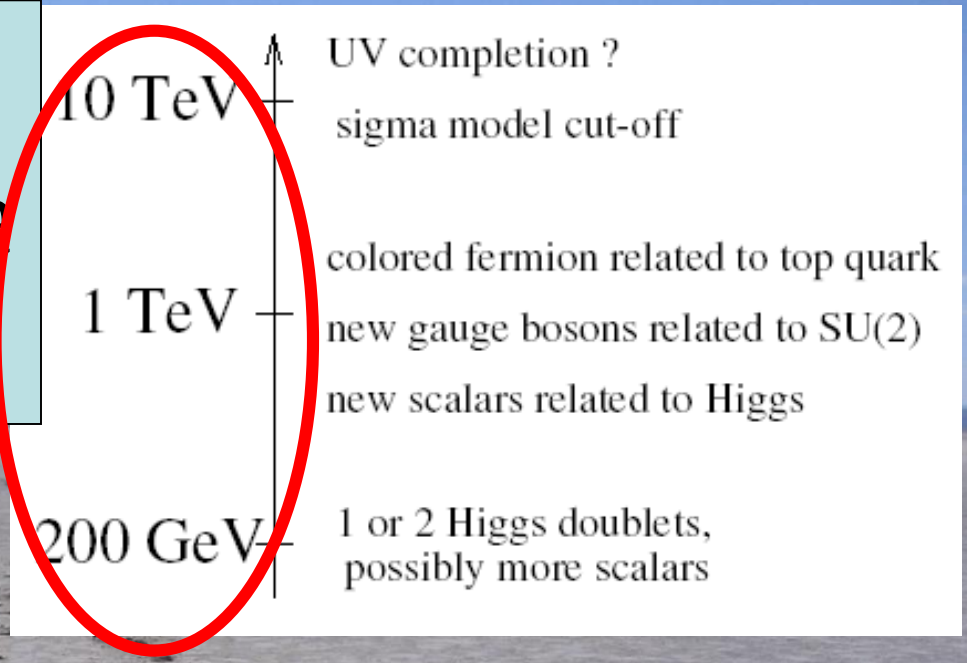
Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

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

New technicolour force?

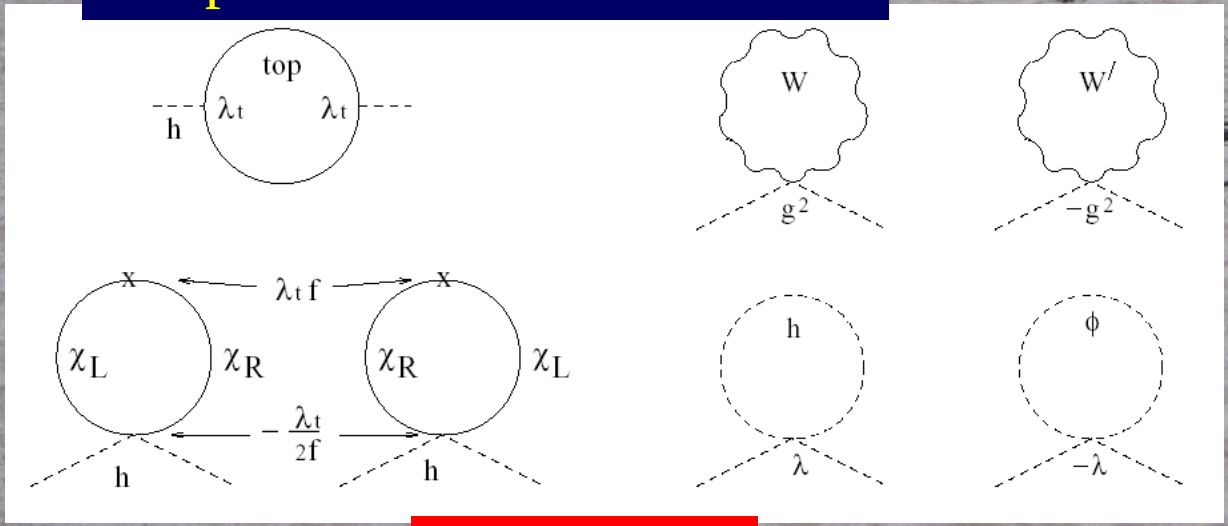
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

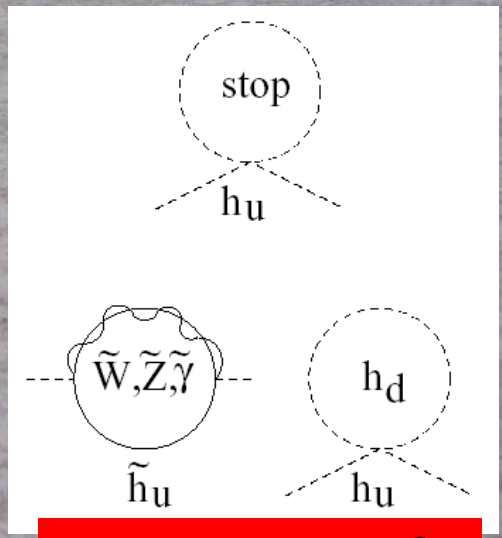
Higgs as a Pseudo-Goldstone Boson



'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

Examples of Higgs as Pseudo-Goldstone Boson

- Sample models:
- Dependences of couplings on model parameters:
- **To be measured!**
- Translation to experimental parameters:

$a = \kappa_V$, $c = \kappa_F$

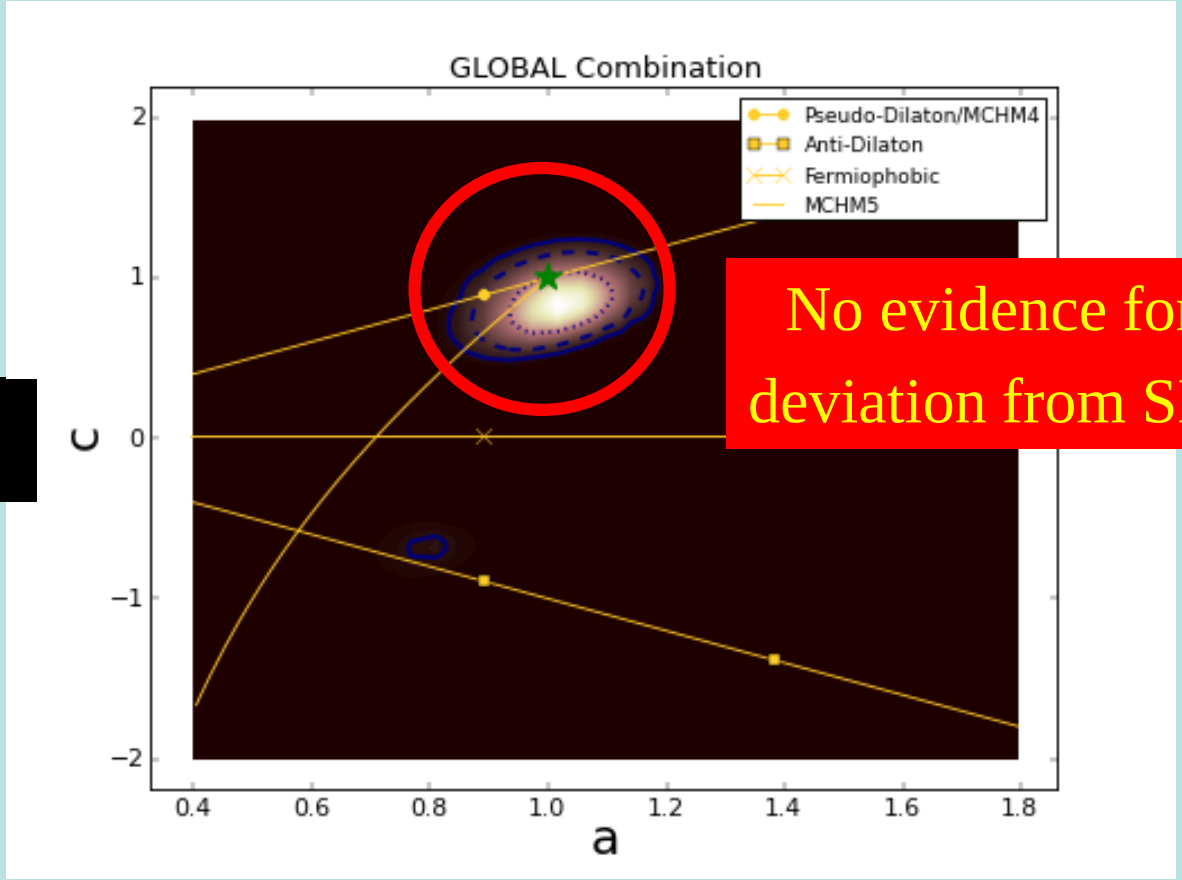
Model	Symmetry Pattern	Goldstones
SM	SO(4)/SO(3)	W_L, Z_L
—	SU(3)/SU(2)×U(1)	W_L, Z_L, h
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, h
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, h, a
MCTHM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^{\pm}, a$

Parameters	SILH	MCHM4	MCHM5
a	$1 - c_H\xi/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
b	$1 - 2c_H\xi$	$1 - 2\xi$	$1 - 2\xi$
b_3	$-\frac{4}{3}\xi$	$-\frac{4}{3}\xi\sqrt{1-\xi}$	$-\frac{4}{3}\xi\sqrt{1-\xi}$
c	$1 - (c_H/2 + c_y)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_2	$-(c_H + 3c_y)\xi/2$	$-\xi/2$	-2ξ
d_3	$1 + (c_6 - 3c_H/2)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
d_4	$1 + (6c_6 - 25c_H/3)\xi$	$1 - 7\xi/3$	$\frac{1-28\xi(1-\xi)/3}{1-\xi}$

Global Analysis of Higgs-like Models

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

Global



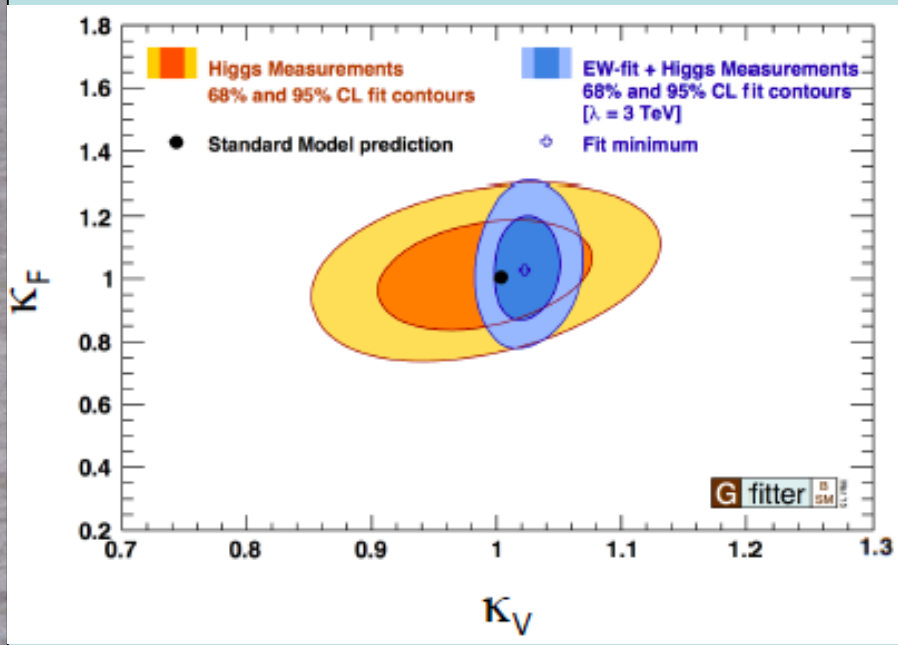
No evidence for deviation from SM

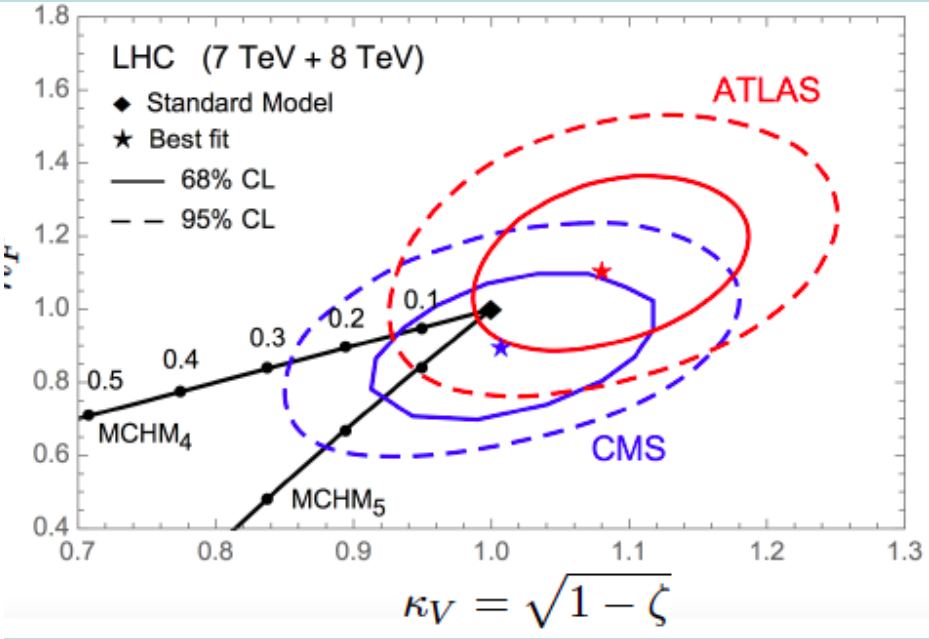
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

Global Analysis of Higgs-like Models

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





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

What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
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  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
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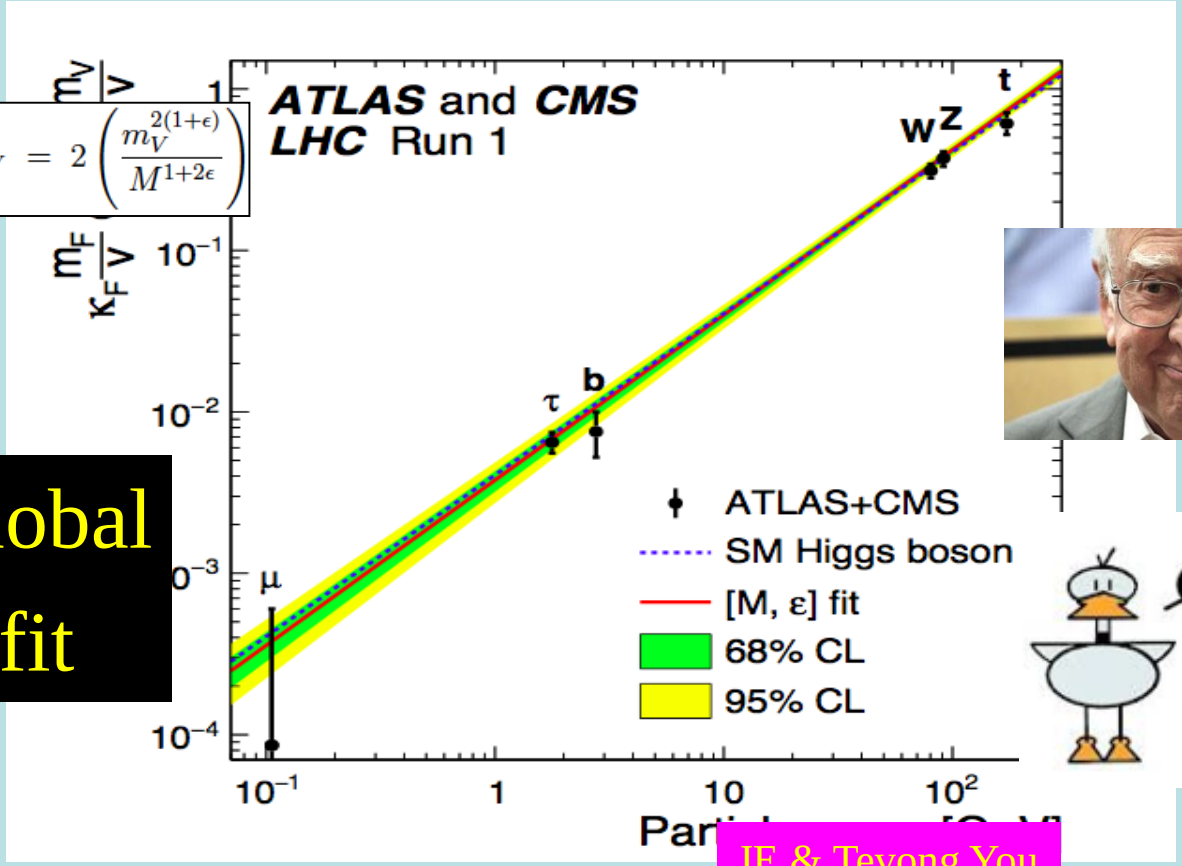
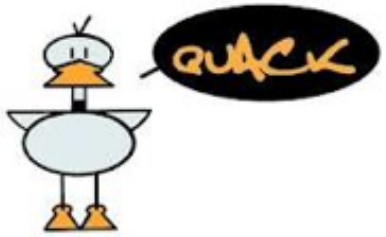
It Walks and Quacks like a Higgs

- 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

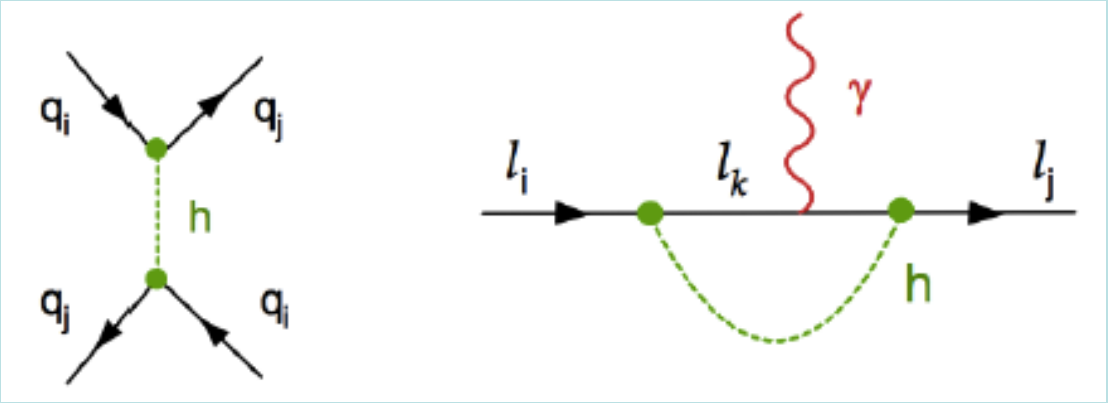


JE & Tevong You

- **Blue** dashed line = Standard Model

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



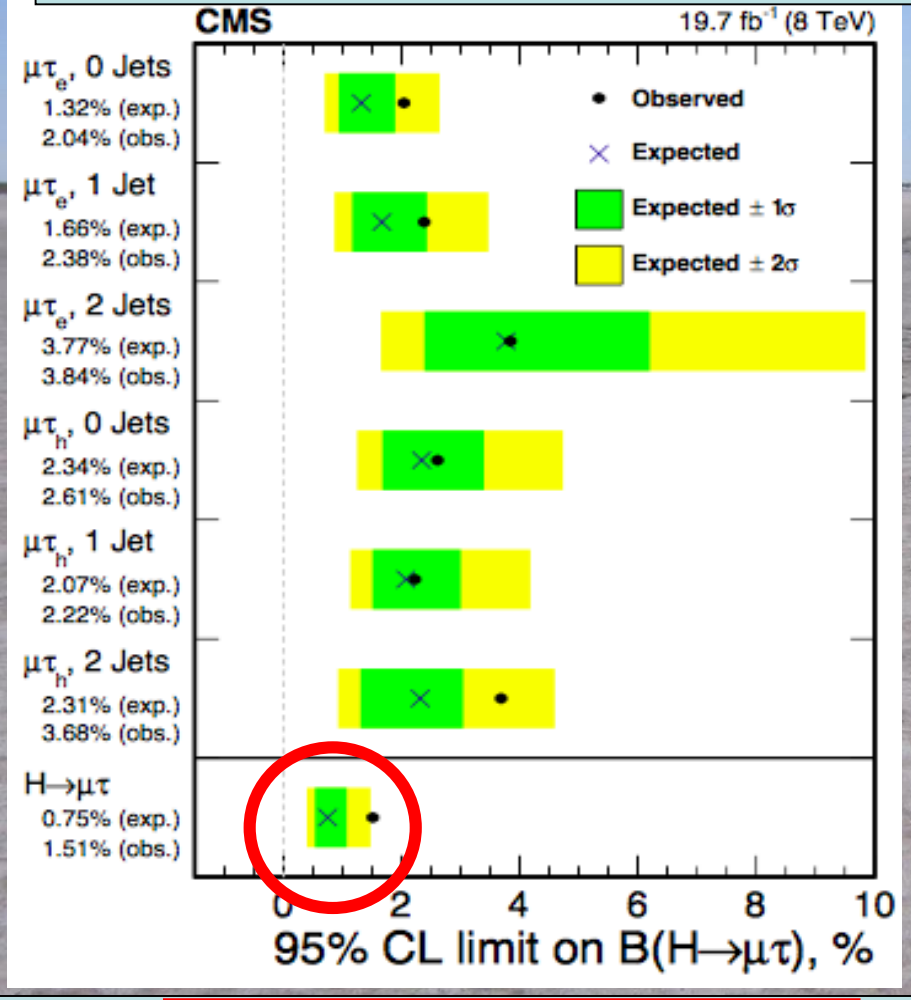
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

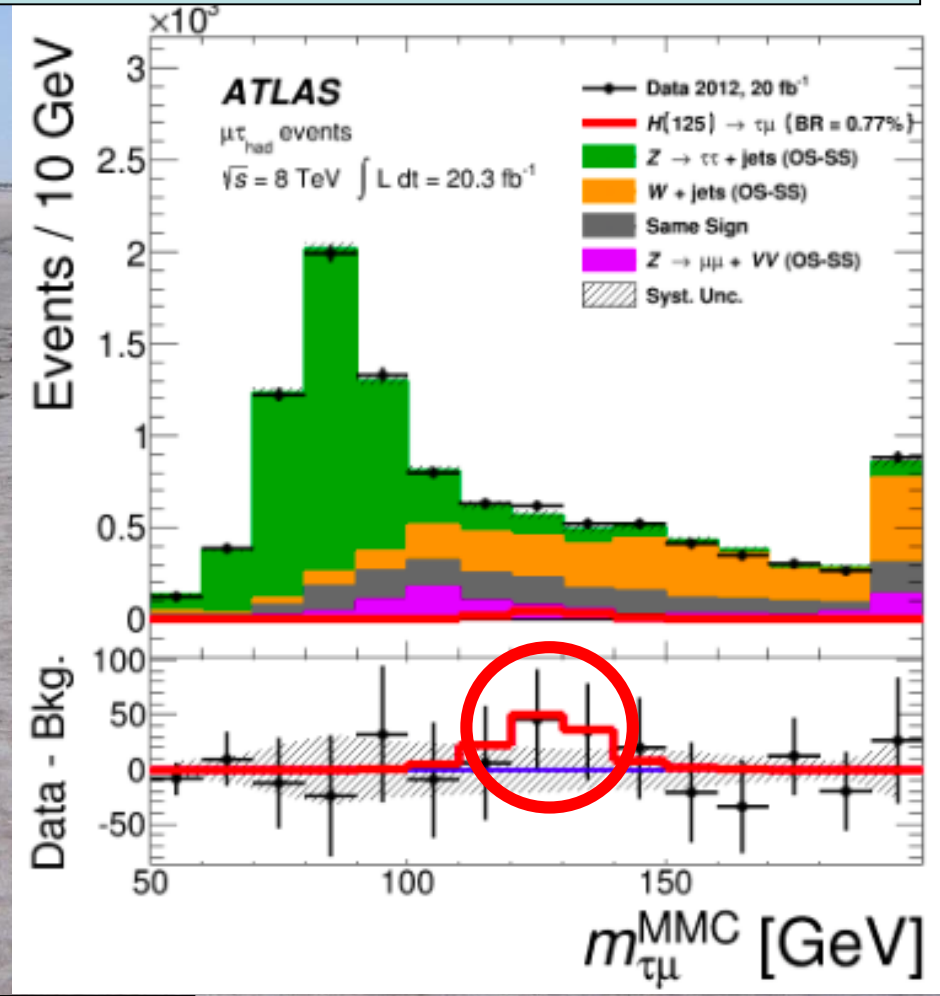
BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Coupling?



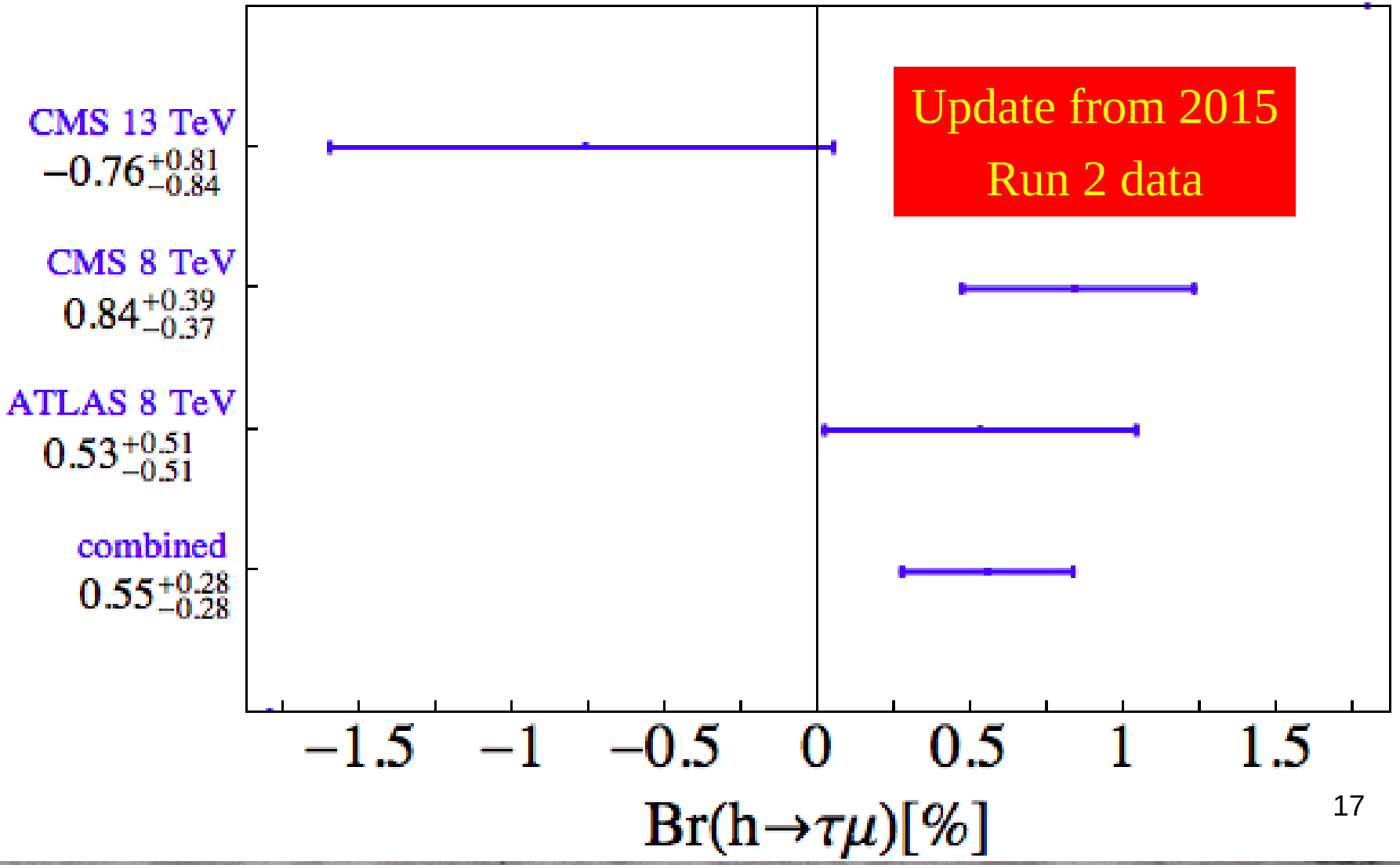


$$\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

$$\mathrm{Br}(H \to \mu\tau) = (0.77 \pm 0.62)\%$$

Also: BR(eτ) < 0.69%, BR(eμ) < 0.036%

Flavour-Changing Higgs Coupling?



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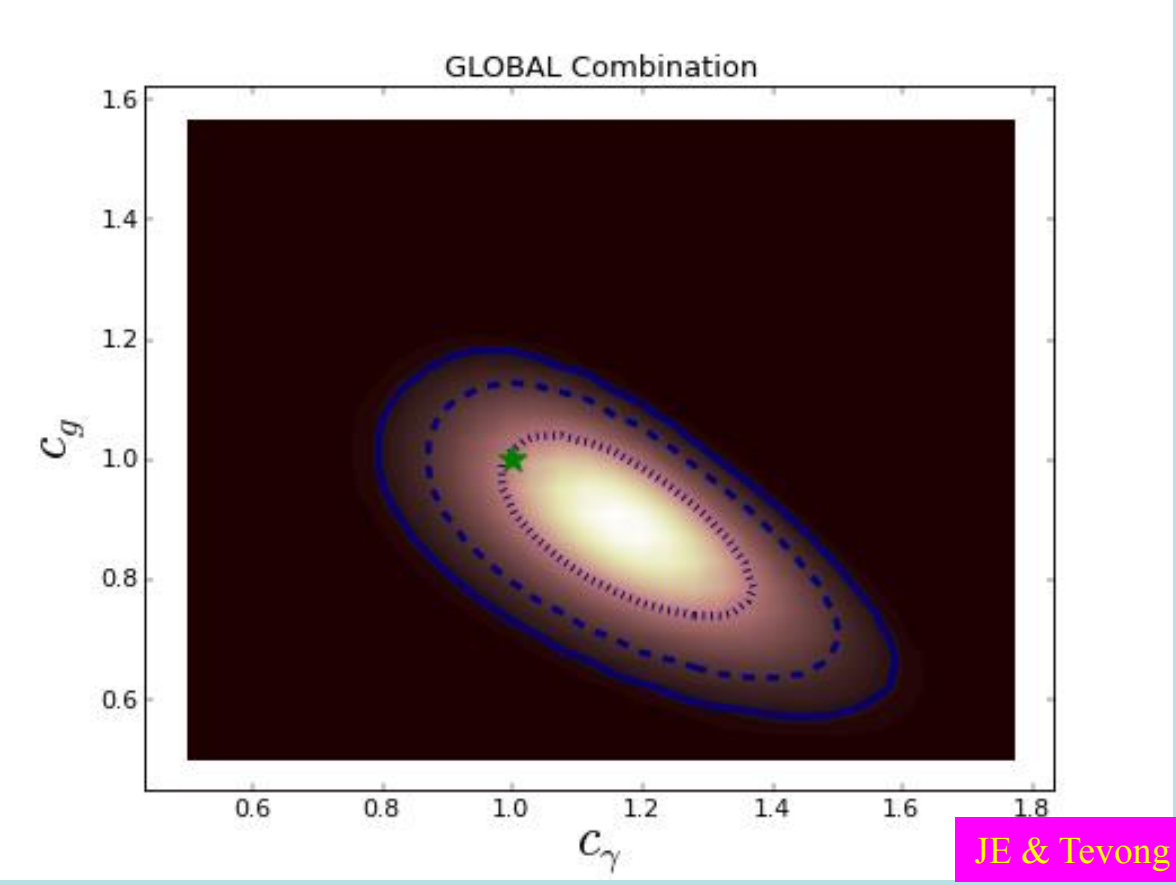
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?
- What are its self- and other couplings?

Loop Corrections ?

- Combination of data on γγ, gluon-gluon couplings



JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

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- Quantum (loop) corrections?
  - **γγ, gg couplings ~ Standard Model**
- What are its self- and other couplings?

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.81 \pm 0.16$

$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)

$\gamma\gamma = 1.17^{+0.19}_{-0.17}$

$b\bar{b} = 0.85 \pm 0.29$

$\mu^+\mu^- < 7.0$, CL = 95%

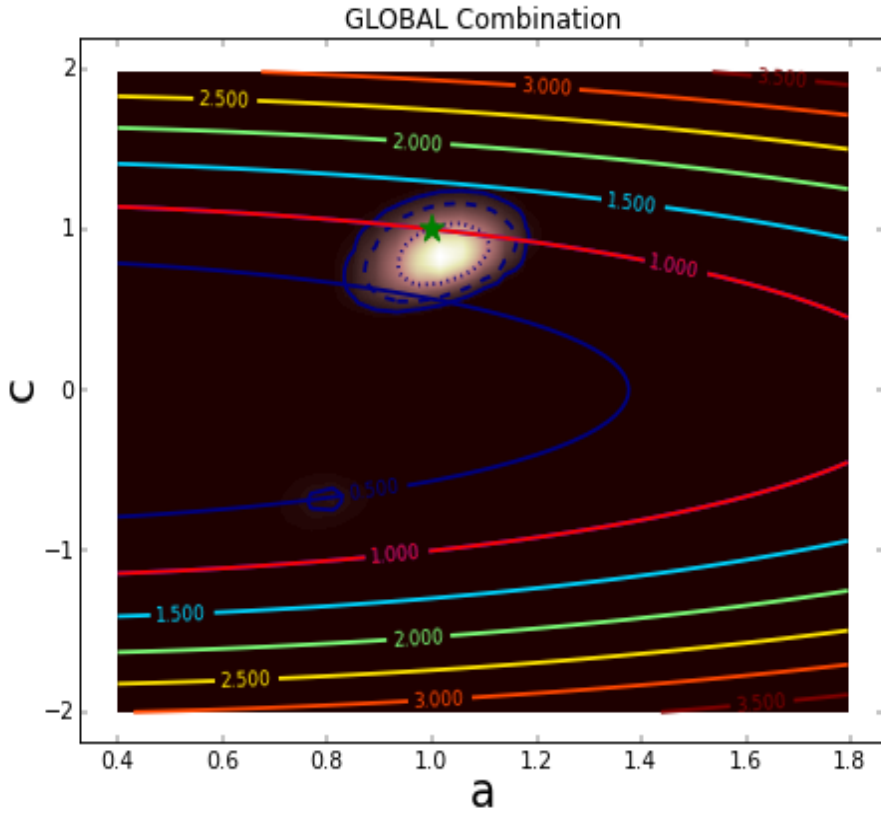
$\tau^+\tau^- = 0.79 \pm 0.26$

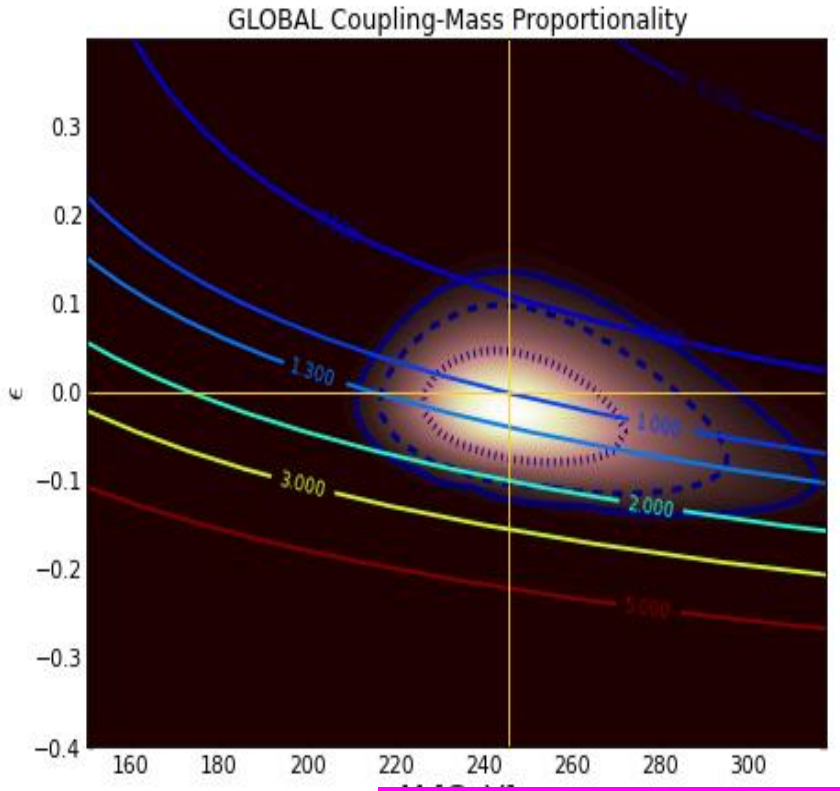
$Z\gamma < 9.5$, CL = 95%

$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

What is its Decay Rate ?

- Compared with the Standard Model prediction



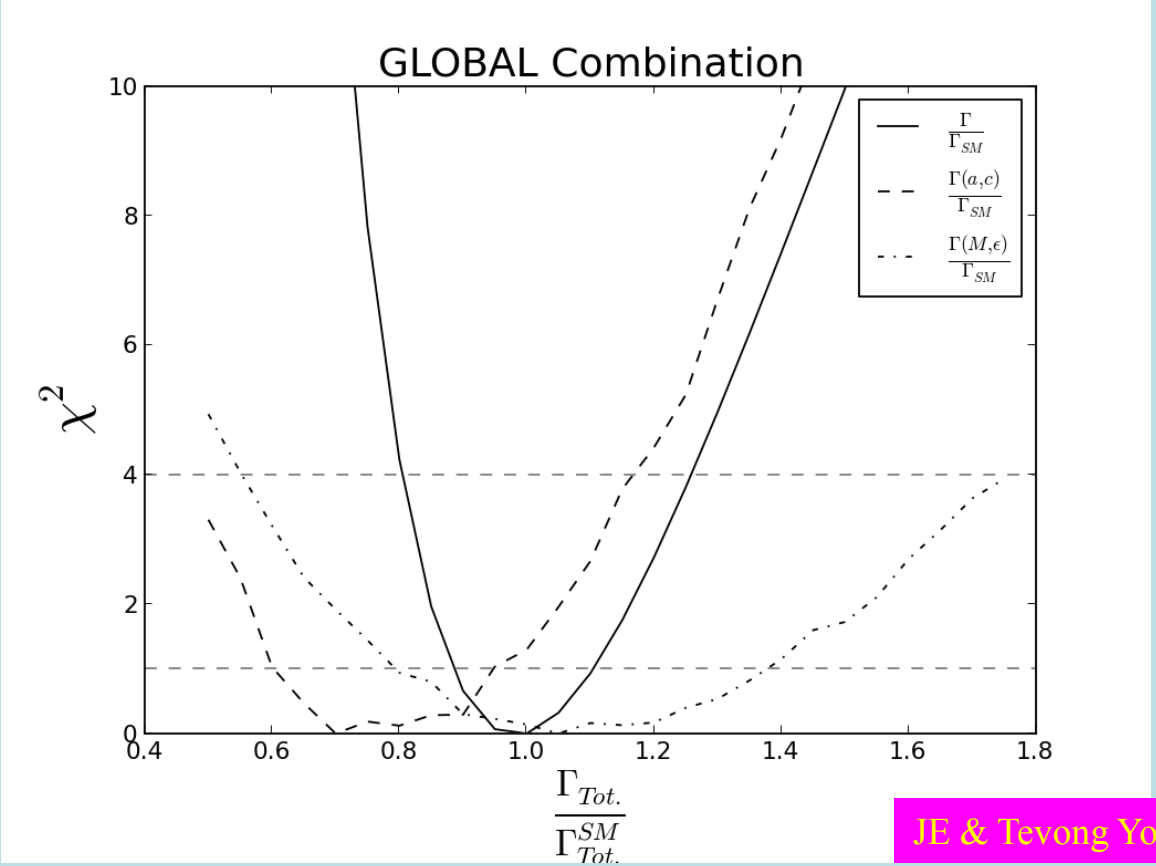


JE & Tevong You, arXiv:1303.3879

- Assuming no non-Standard Model modes

What is its Decay Rate ?

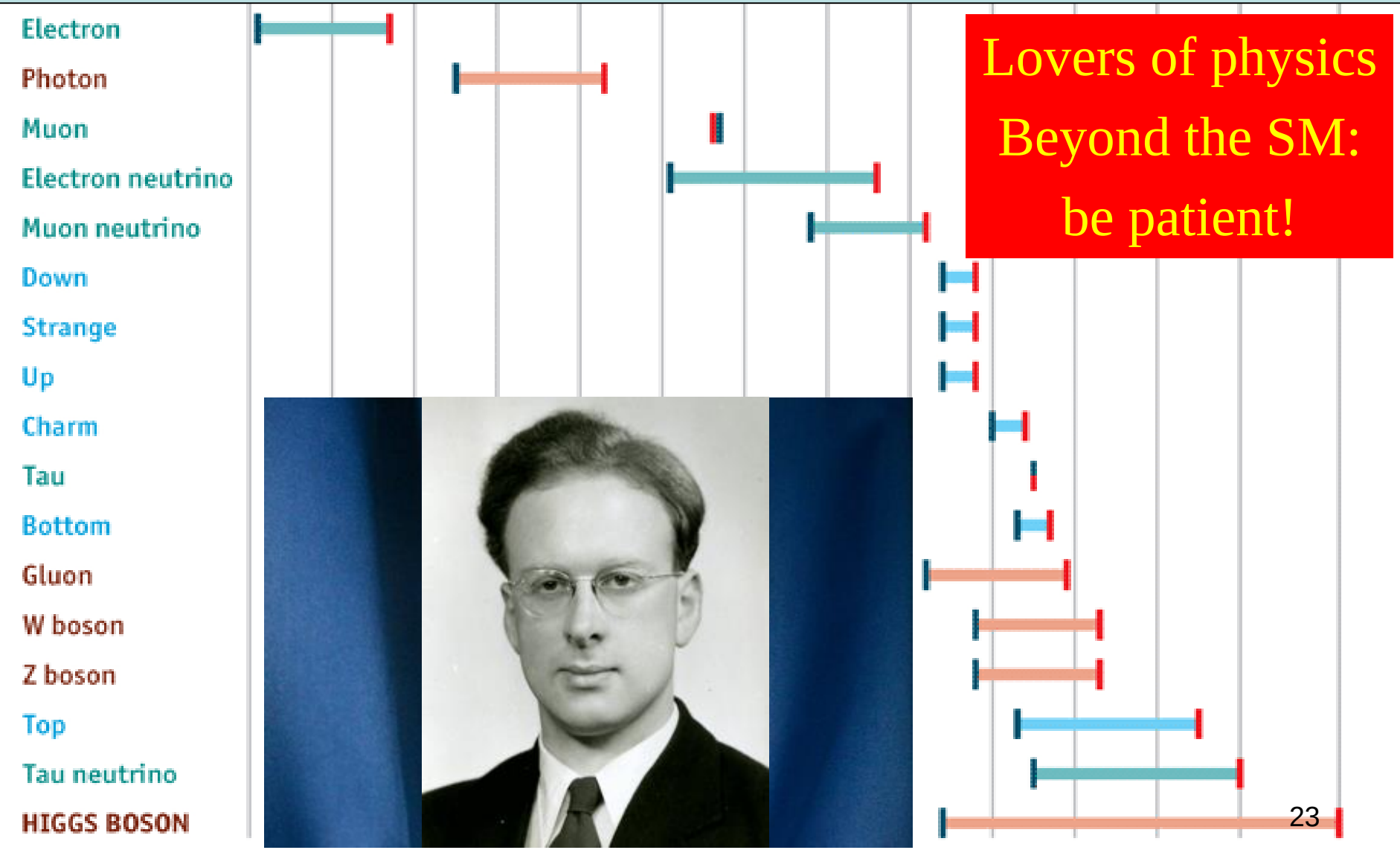
- Compared with the Standard Model prediction



JE & Tevong You, arXiv:1303.3879

- Assuming no non-Standard Model modes

Standard Model Particles:
Years from Proposal to Discovery



Lovers of physics Beyond the SM: be patient!

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

Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

- Operators constrained by SU(2) × U(1) symmetry:

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

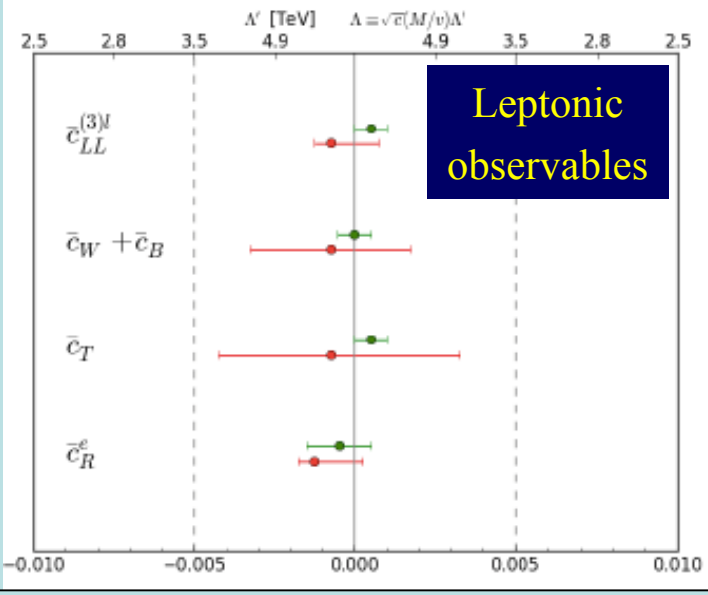
- Constrain with precision EW, Higgs data, TGCs...

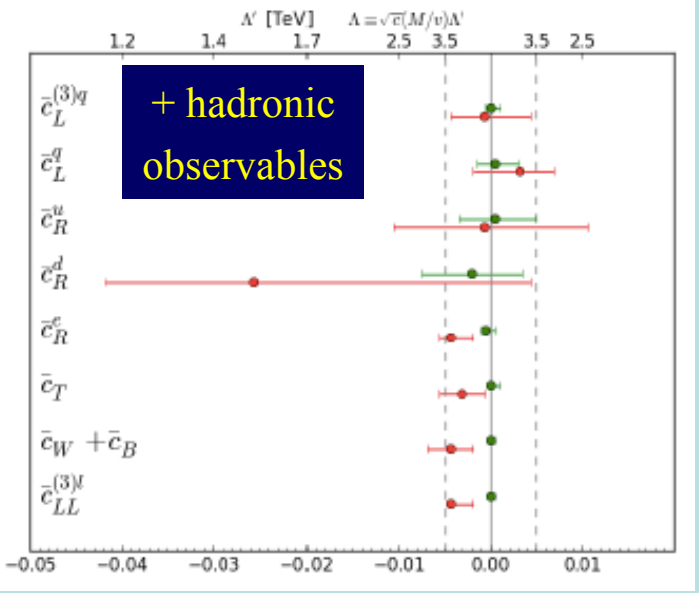
Electroweak Precision Data

- Operators affecting oblique parameters

$$\mathcal{L}_{\text{dim-6}} \subset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$$

- Also other electroweak tests
- Constraints from LEP et al. data





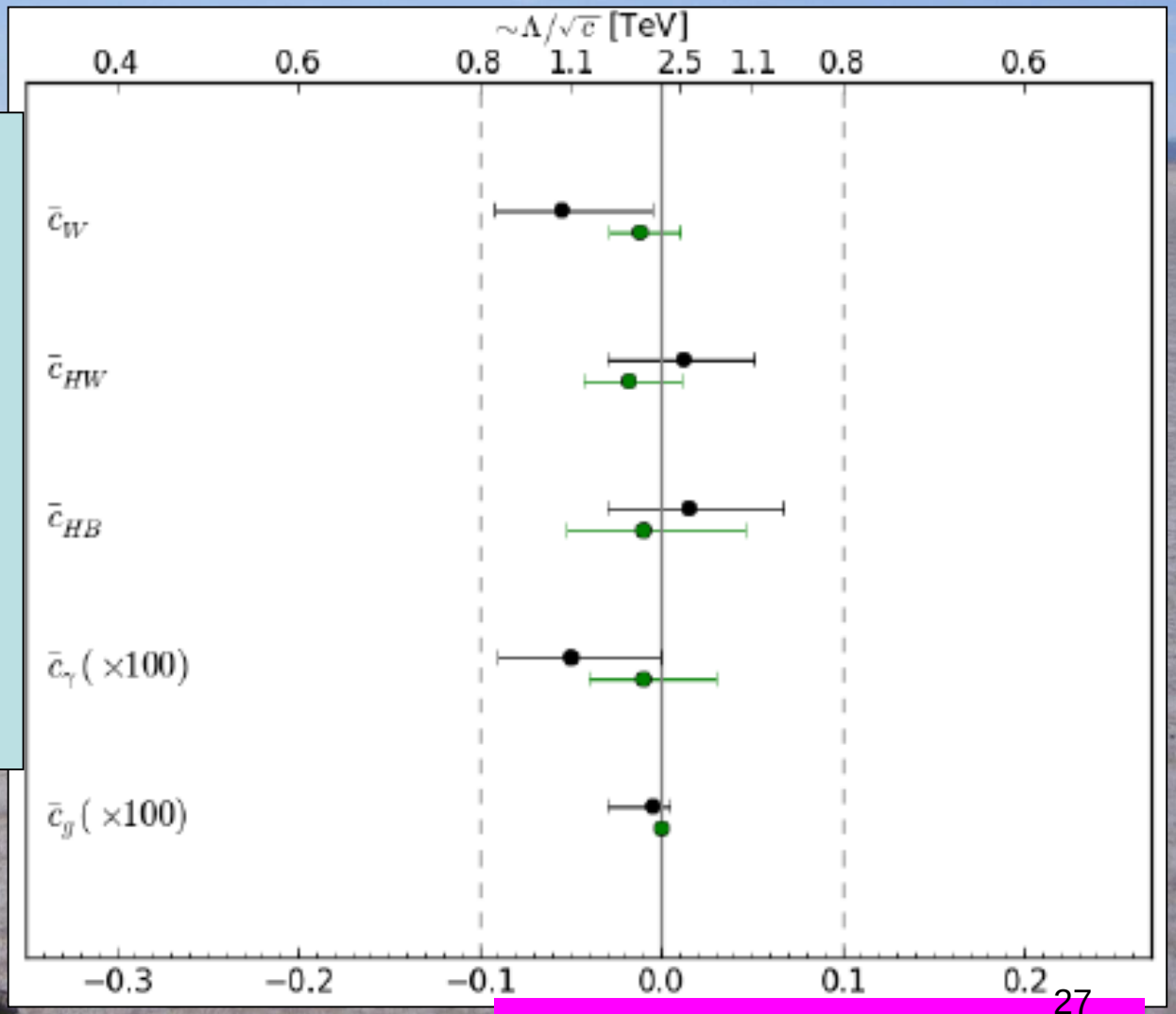
Fits to individual dimension-6 operators

Global fit to dimension-6 operators

JE, Sanz & Tevong You, arXiv:1410.7703

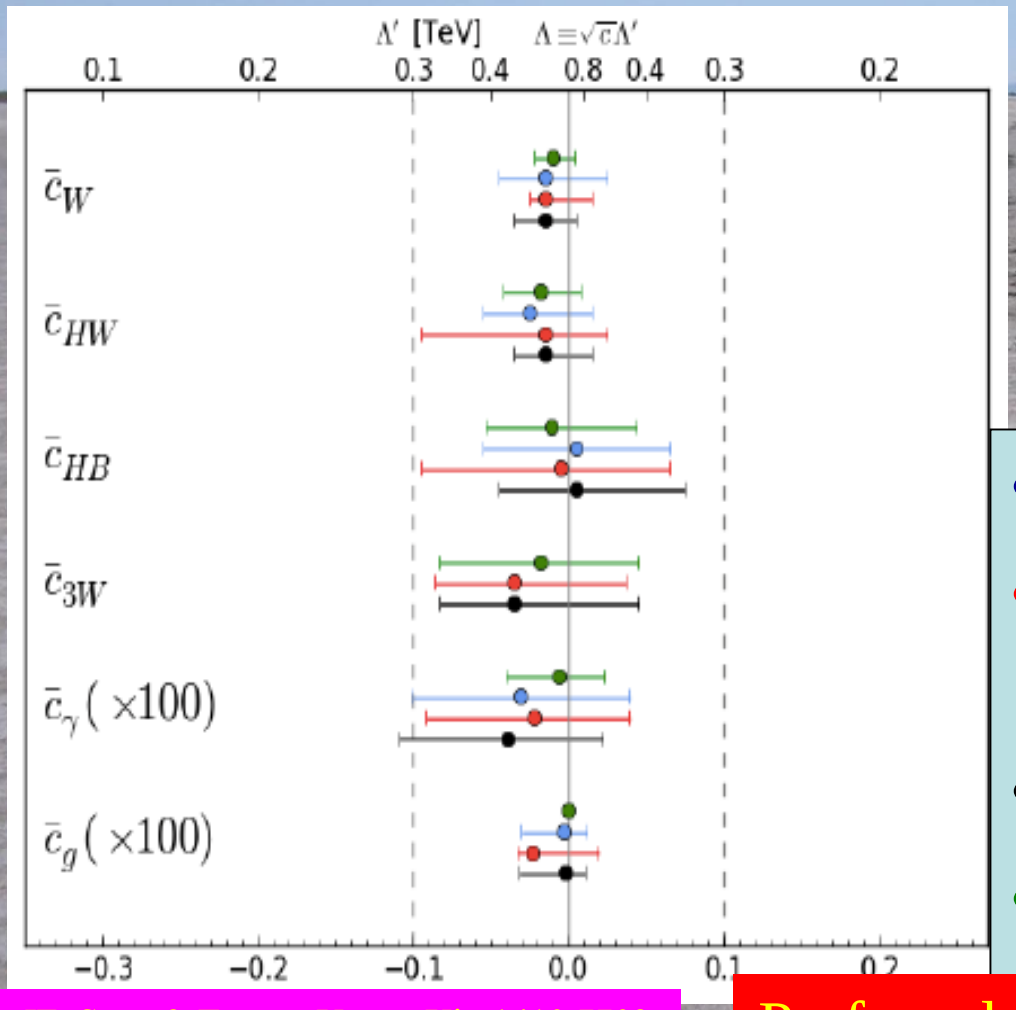
Fits including Higgs Production

- Using signal strengths & VH kinematics in global fit
- **Single-parameter fits**



JE, Sanz & Tevong You, arXiv:1404.3667

Global Fits including LHC TGCs



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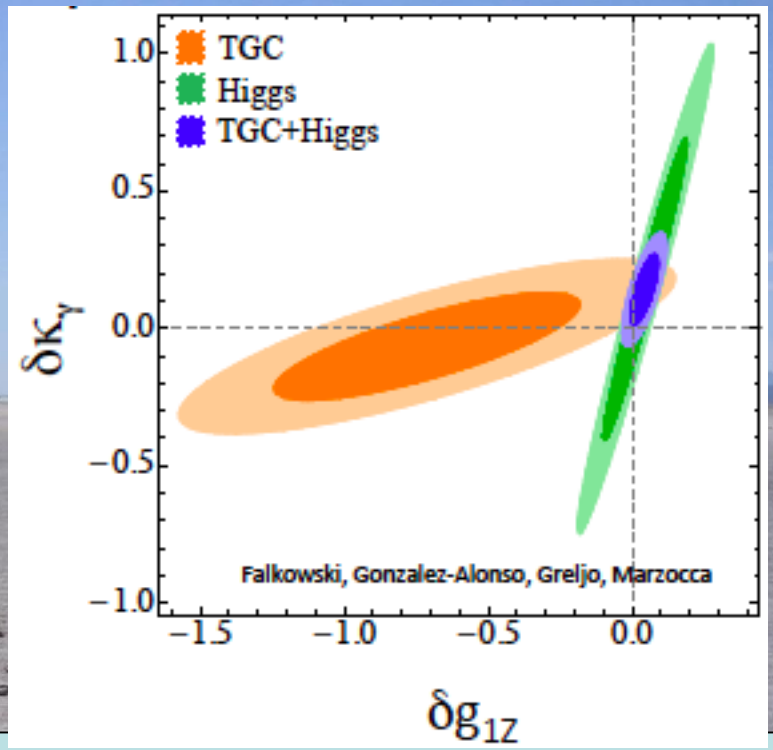
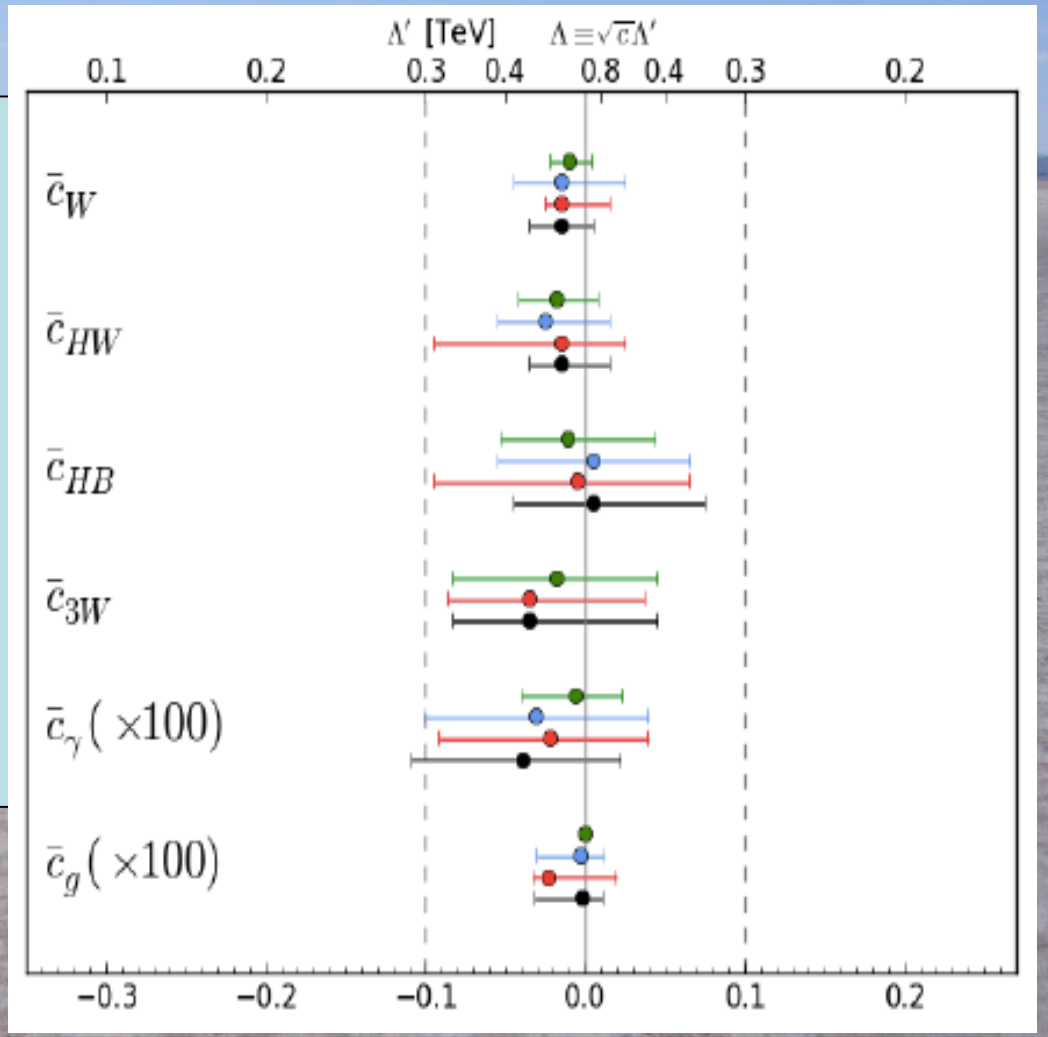


- **Associated production**
- **LHC Triple-gauge couplings**
- Global combination
- **Individual operators**

Preferred framework for analyzing Run 2

Including LHC Triple-Gauge Couplings

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



JE, Sanz & Tevong You, arXiv:1410.7703

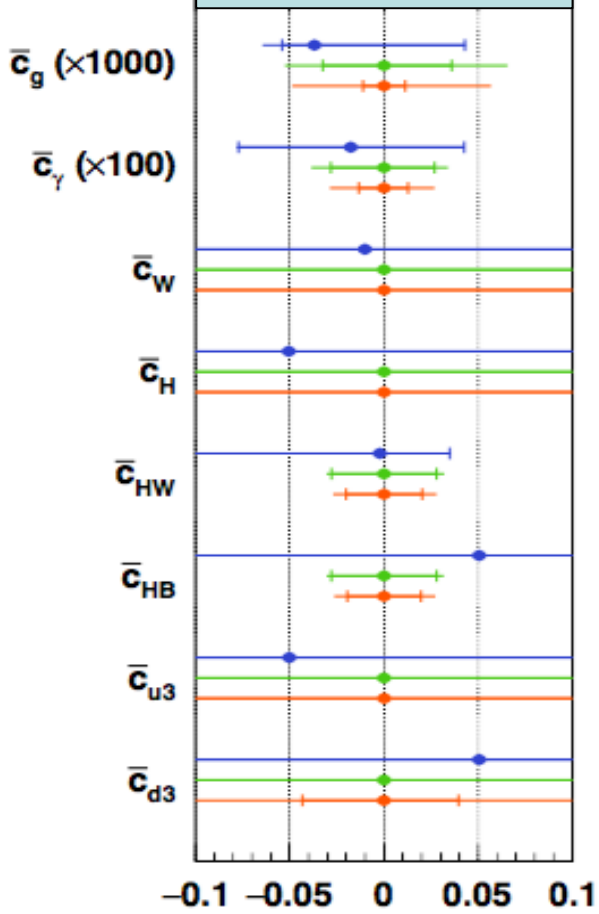
Constraints on Dimension-6 Operators

Operators

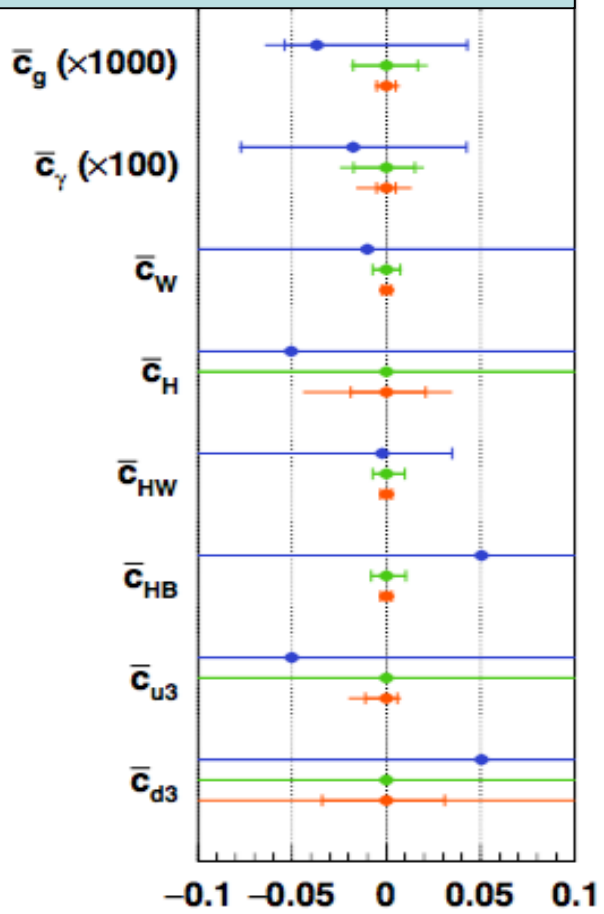
Bosonic CP-even

O_H	$\frac{1}{2v^2}\left[\partial_\mu (H^\dagger H)\right]^2$
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)^2$
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu}$
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right) \partial_\nu B_{\mu\nu}$
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Constraints from rates



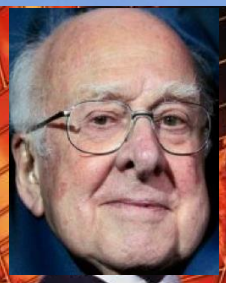
Constraints including kinematics



Current **300/fb** **3000/fb**

No BSM? Beware Historical Hubris

- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"* - Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980



- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

The Standard Model

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

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

Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets
  (cancel anomalies, form of SUSY couplings)
- 8 – 3 = 5 physical Higgs bosons
  Scalars h, H; pseudoscalar A; charged $H^{\pm}$
- Lightest Higgs < MZ at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}} M^2_{\mathrm{A}} \cos^2 2\beta}\right]$$

- Important radiative corrections to mass:

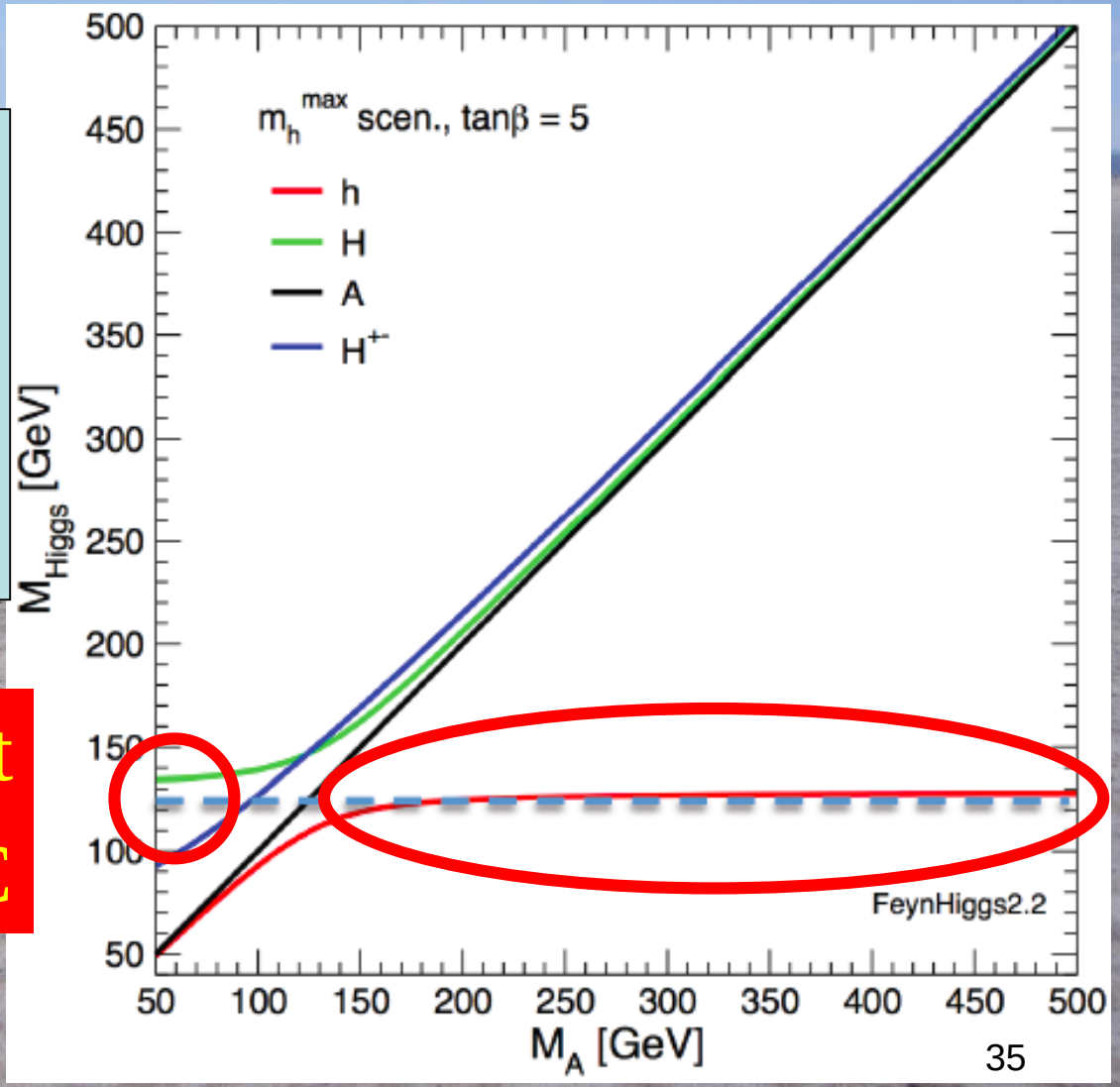
$$G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right)\Big|_{\mathrm{TH}} \sim 1.5\ \mathrm{GeV}$$

MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC



More Supersymmetry, not less?

JE, Quevillon & Sanz: arXiv:1607.05541

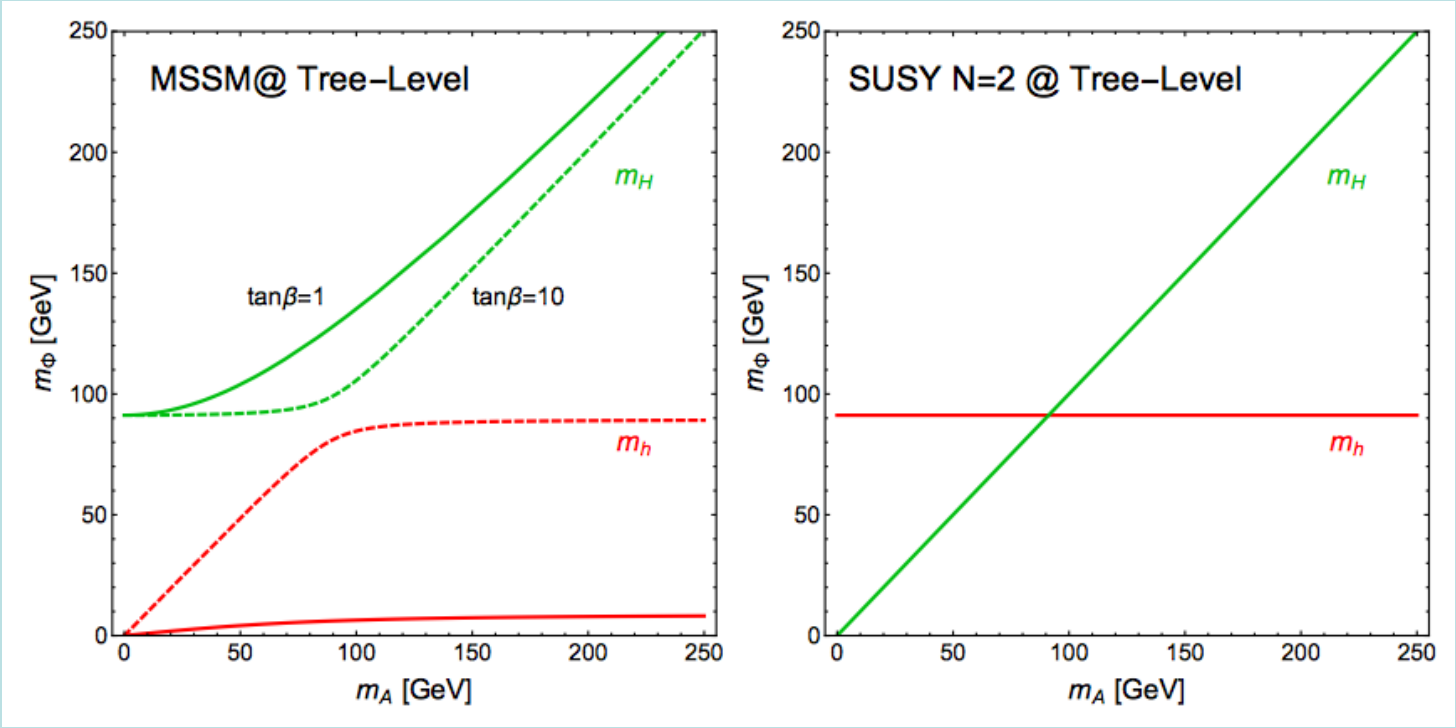
- 750 GeV ☹ ➔re-examined vector-like fermions
- Appear in many extensions of the Standard Model
  - Five-dimensional models
  - String compactifications
  - GUTs
- Could accommodate N=2 supersymmetry
- **Double up on supersymmetry?**
- N=2 gauge sector?
- **Higgs sector also vector-like, could be N=2**

Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

- Higgs sector as portal to N=2 world at TeV scale?
- Tree-level neutral Higgses:

$$\mathcal{M}^{2,N2}_{\rm tree} = \begin{pmatrix} m_Z^2\cos^2\beta + m_A^2\sin^2\beta & -(m_A^2 - m_Z^2)\cos\beta\sin\beta \\ -(m_A^2 - m_Z^2)\cos\beta\sin\beta & m_Z^2\sin^2\beta + m_A^2\cos^2\beta \end{pmatrix} \qquad m_h^{N2} = m_Z; \quad m_H^{N2} = m_A$$

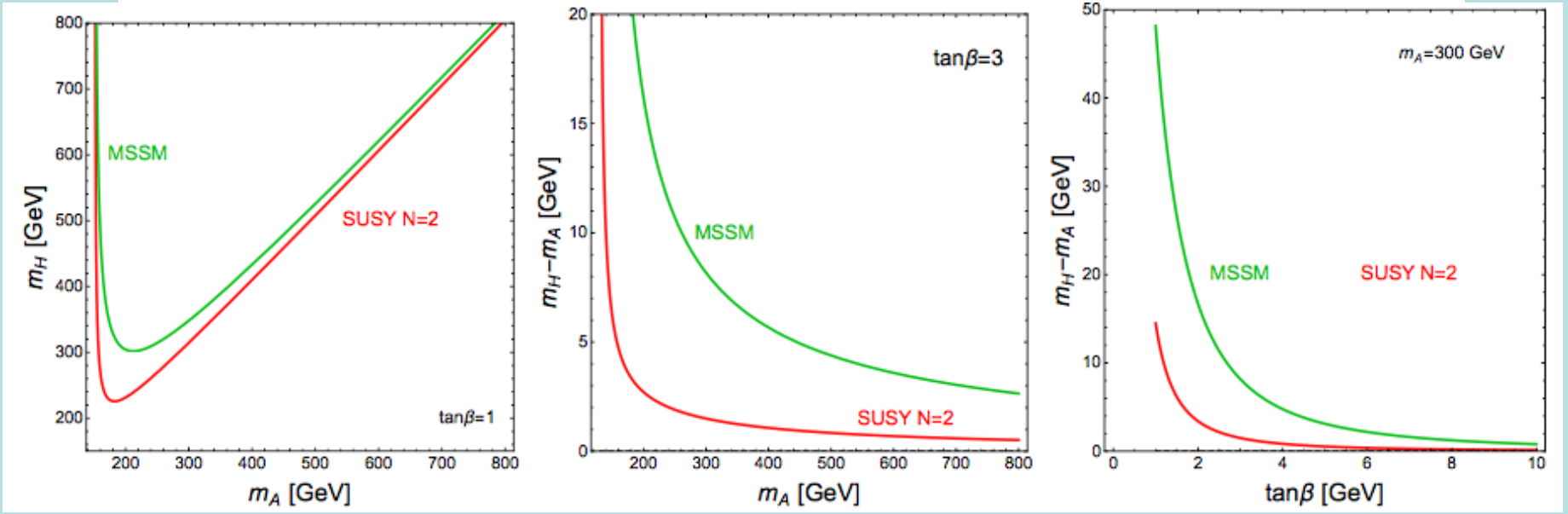


Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

- Include 1-loop radiative corrections from stops
- Require lighter scalar neutral Higgs @ 125 GeV

$$\epsilon_{N2} = \Delta\mathcal{M}^{2,N2}_{22} = \frac{2(m_A^2 - m_h^2)(m_h^2 - m_Z^2)}{\cos 2\beta\,(m_Z^2 - m_A^2) + m_A^2 - 2m_h^2 + m_Z^2}$$

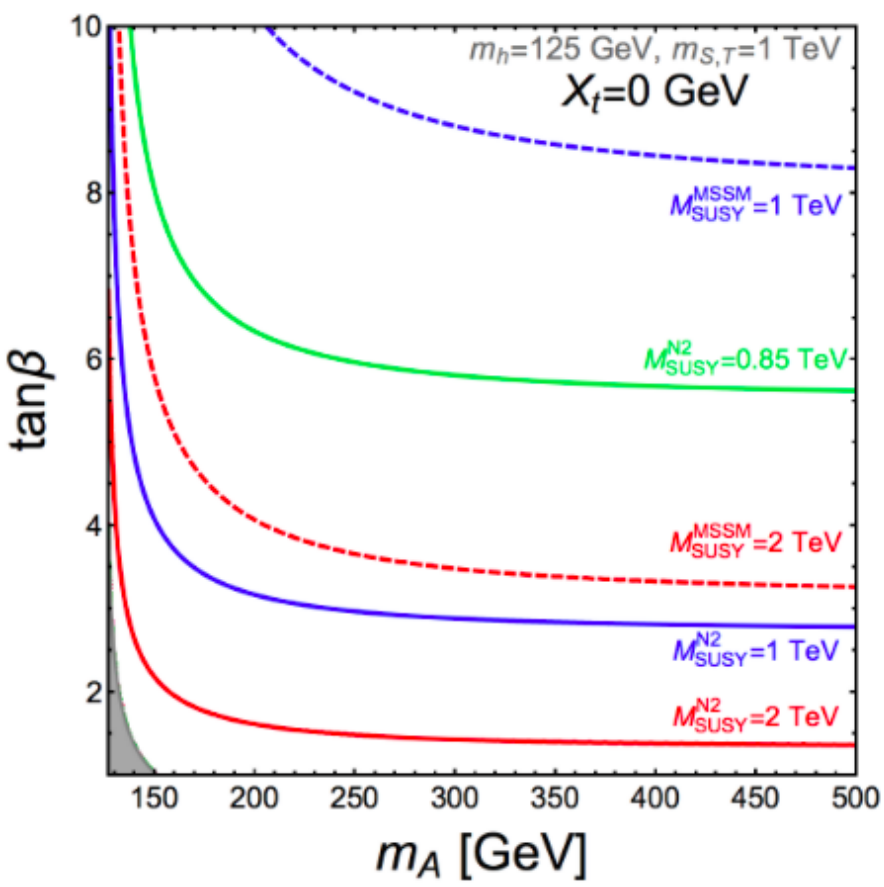


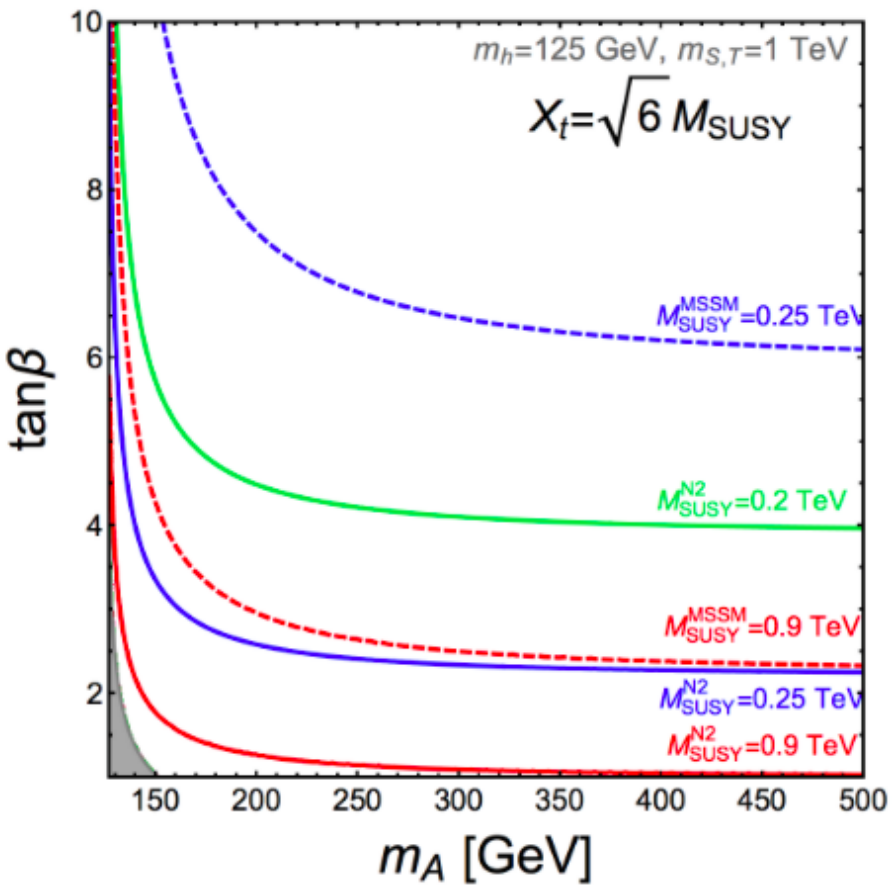
- H can be lighter than in MSSM, $m_H - m_A$ smaller

Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

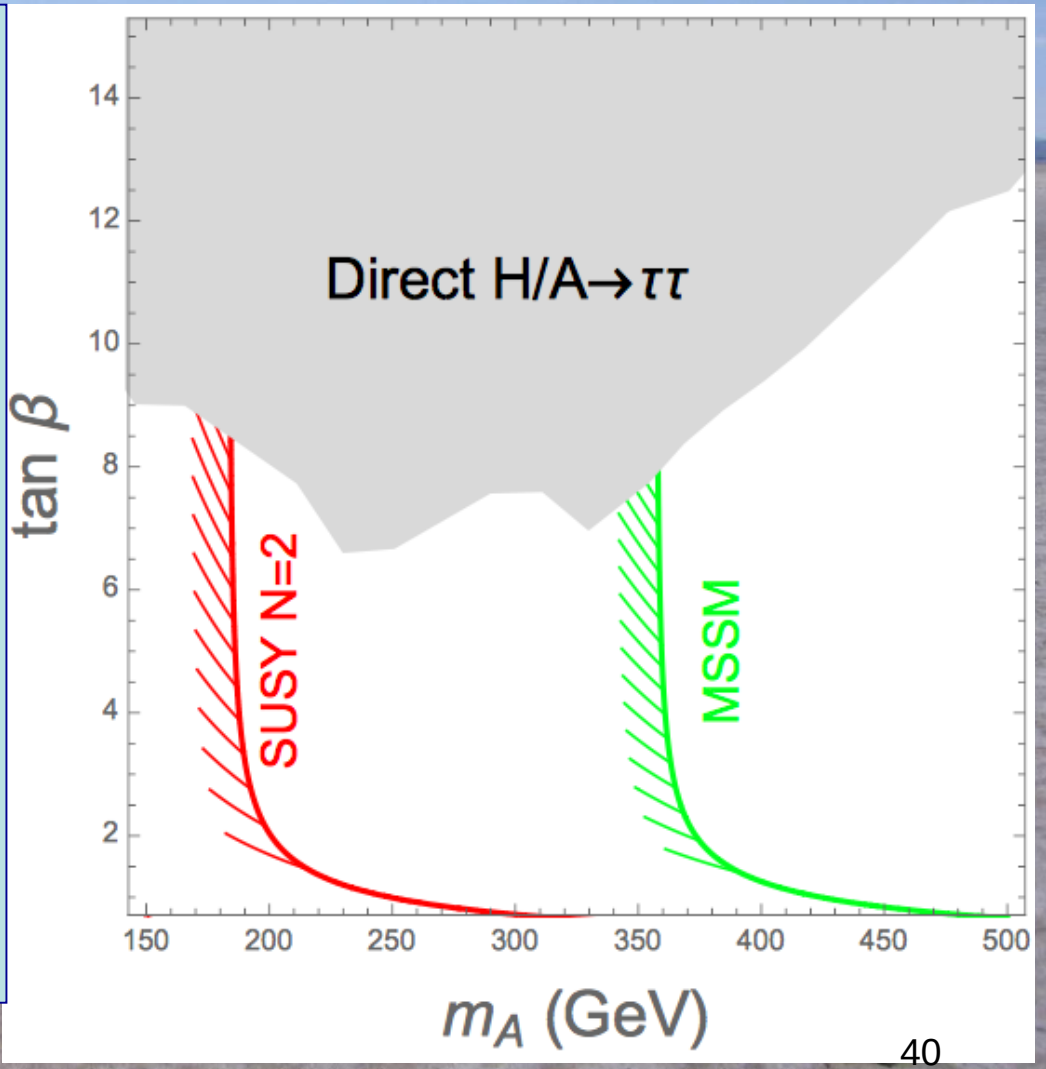
- **M_{SUSY} smaller than MSSM for same $m_{h,A}$, tan β**





Doubling up on Supersymmetry

- Including LHC constraints
- m_A can be smaller than in MSSM for all tan β
- Supersymmetry and SUSY Higgses may be closer than suggested by MSSM



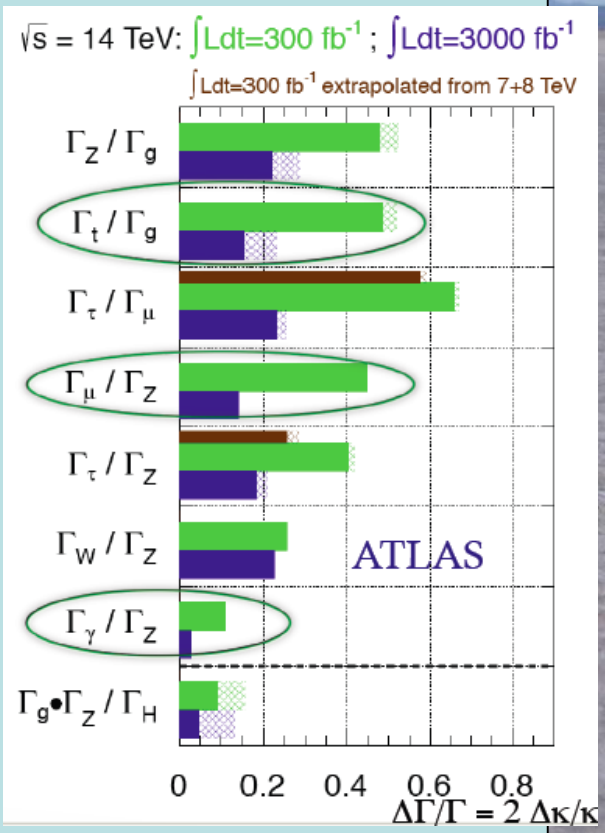
JE, Quevillon & Sanz: arXiv:1607.05541

What Next: A Higgs Factory?

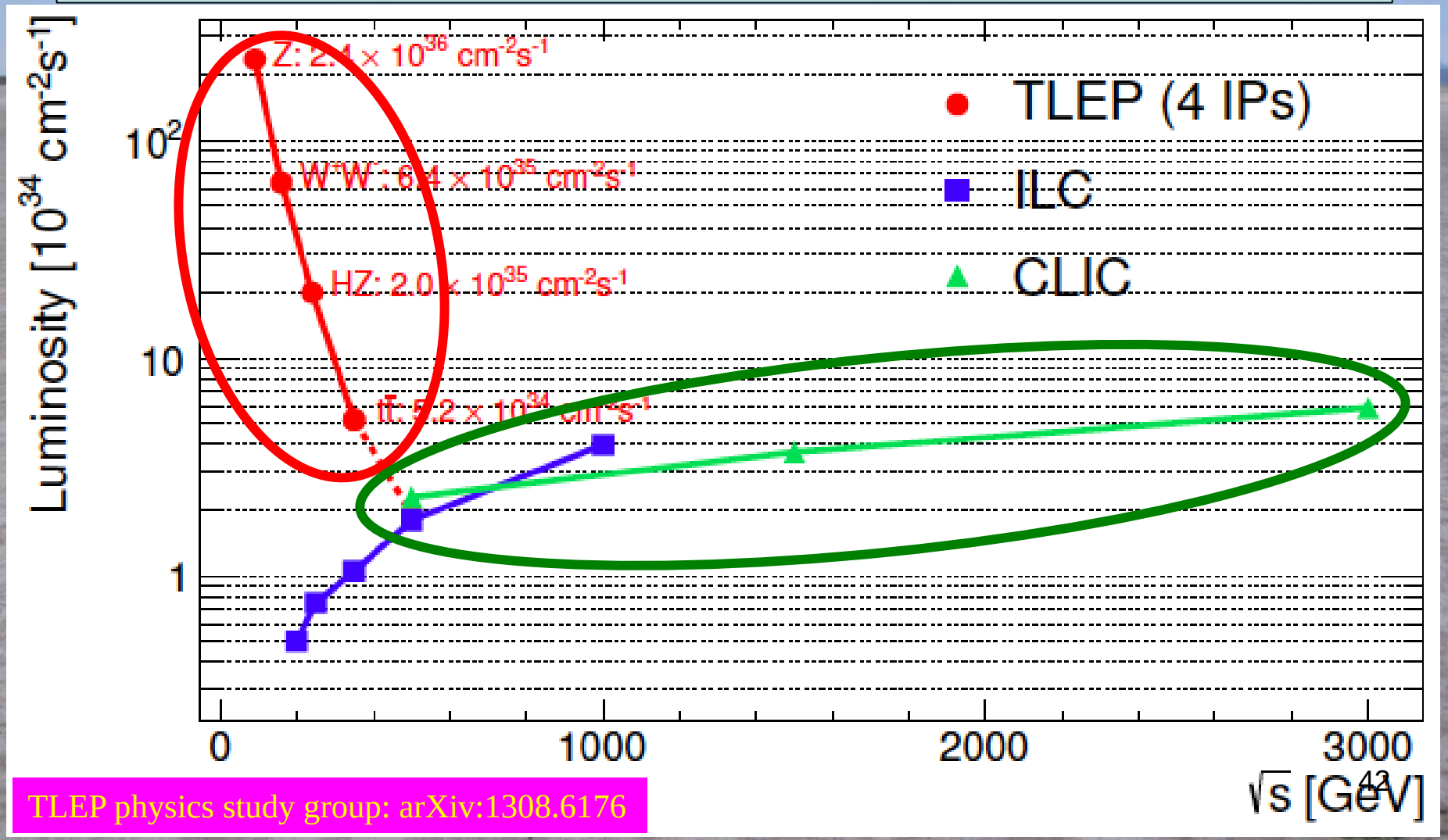
To study the 'Higgs' in detail:

- The LHC
  - Consider LHC upgrades in this perspective
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV

    (Larger cross section at higher energies)
- **A circular e^+e^- collider?**
- An ep collider?
- A $\gamma\gamma$ collider? A muon collider?
- **Wait for results from LHC @ 13/14 TeV**

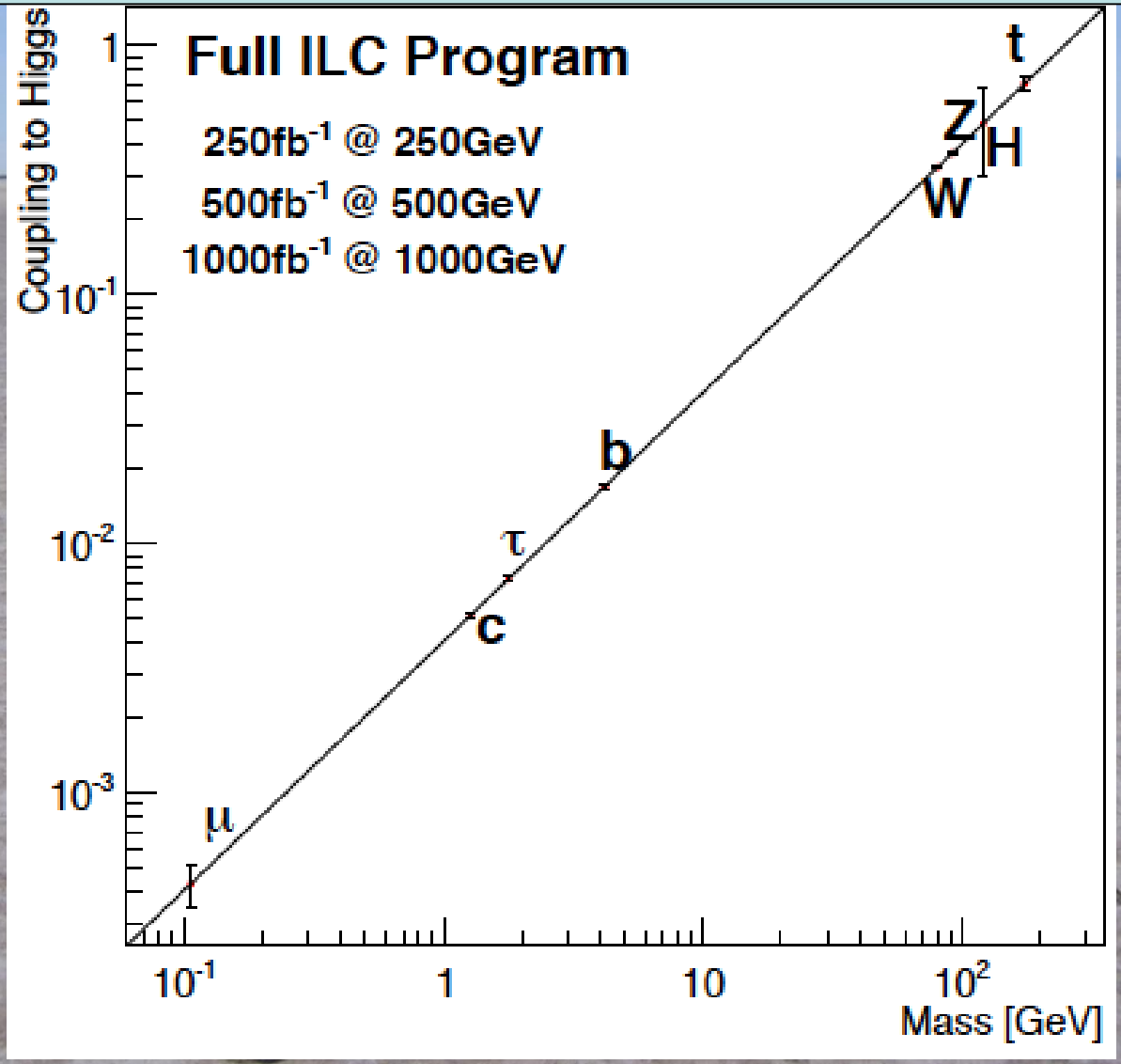


Projected e^+e^- Colliders: Luminosity vs Energy

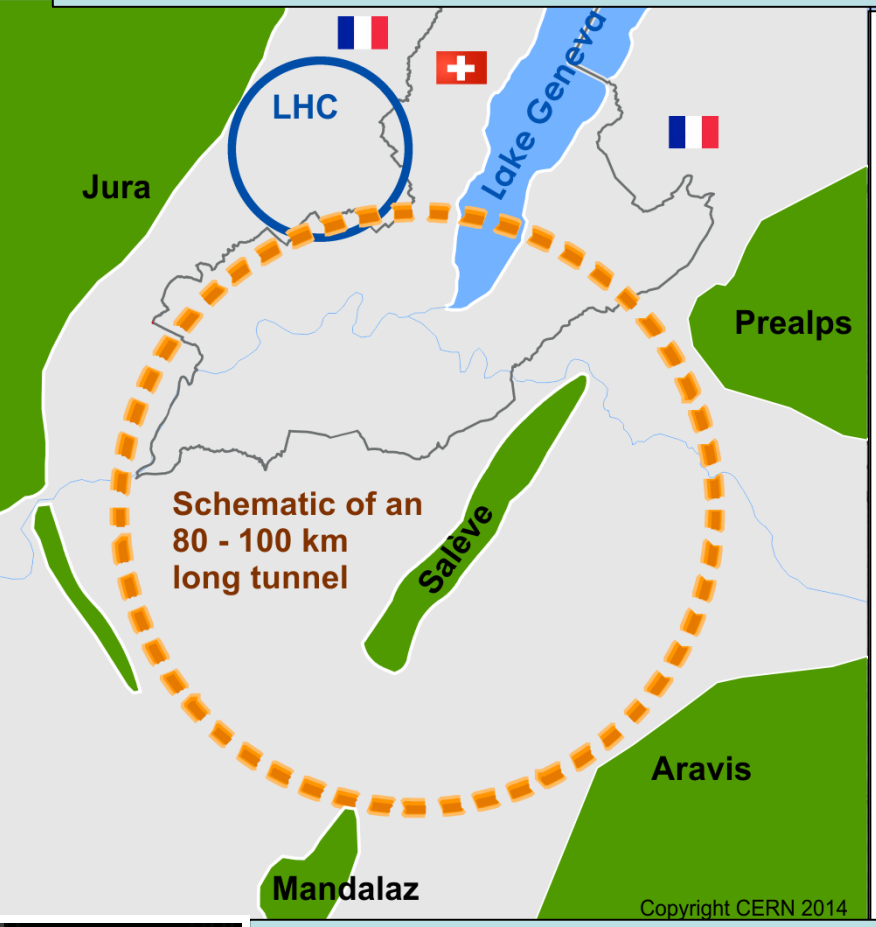


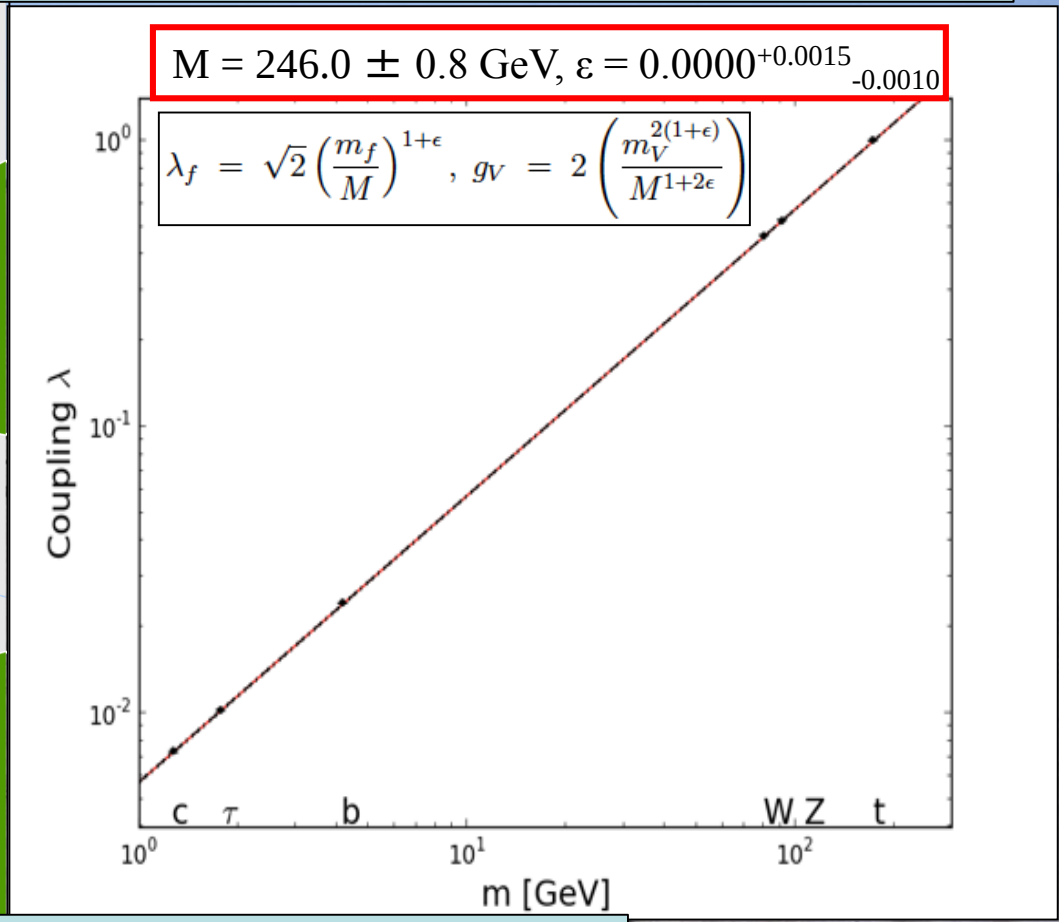
TLEP physics study group: arXiv:1308.6176

Coupling Measurements @ ILC



Future Circular e^+e^- Collider?

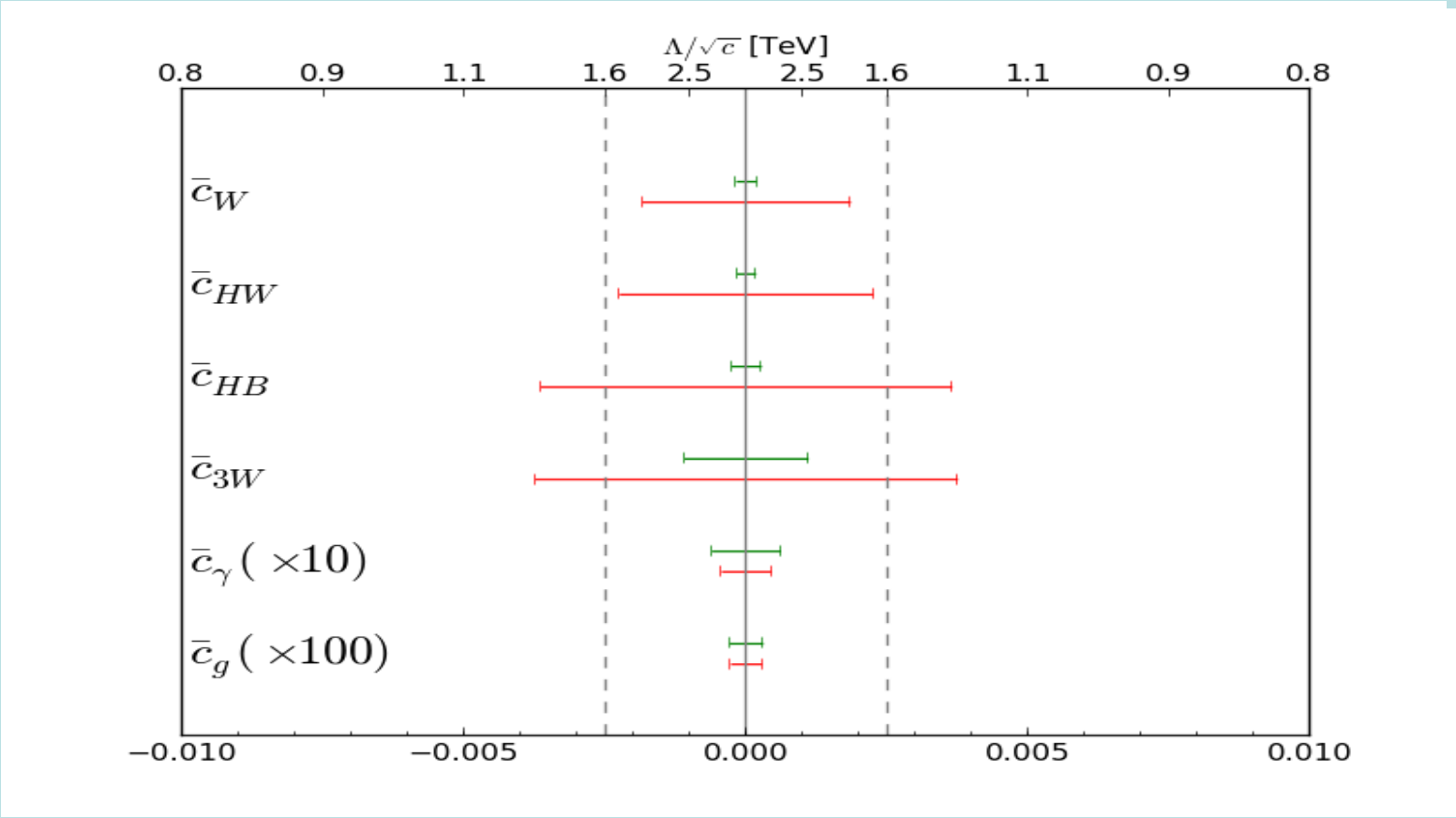




Not just Higgs physics:

Also Tera-Z, Oku-W, Mega-t

FCC-ee Higgs & TGC Measurements



- LHC constraints

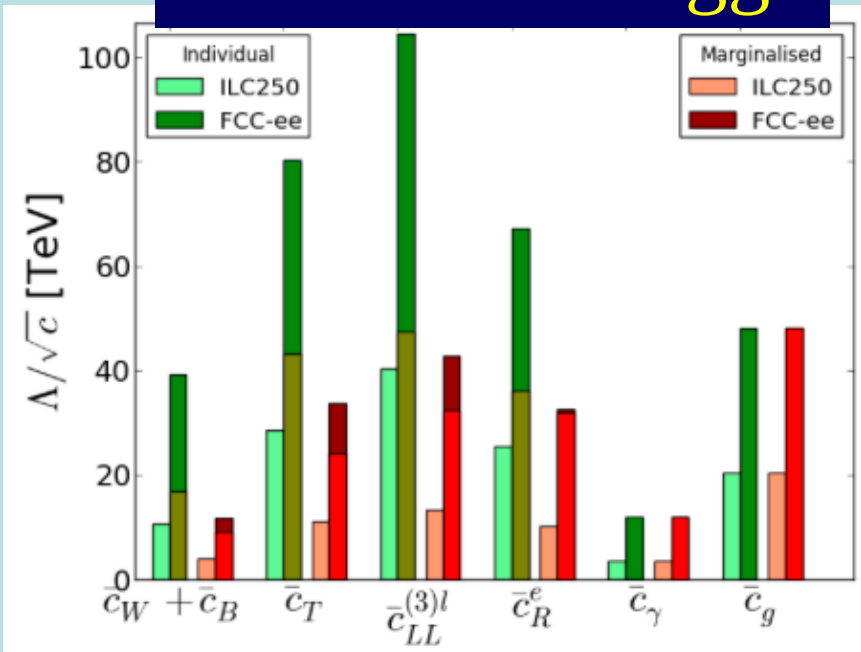
JE & Tevong You, arXiv:1510.04561

- **FCC-ee** constraints: see $\Lambda \sim 10$ TeV?

JE & Tevong You, arXiv:1510.04561

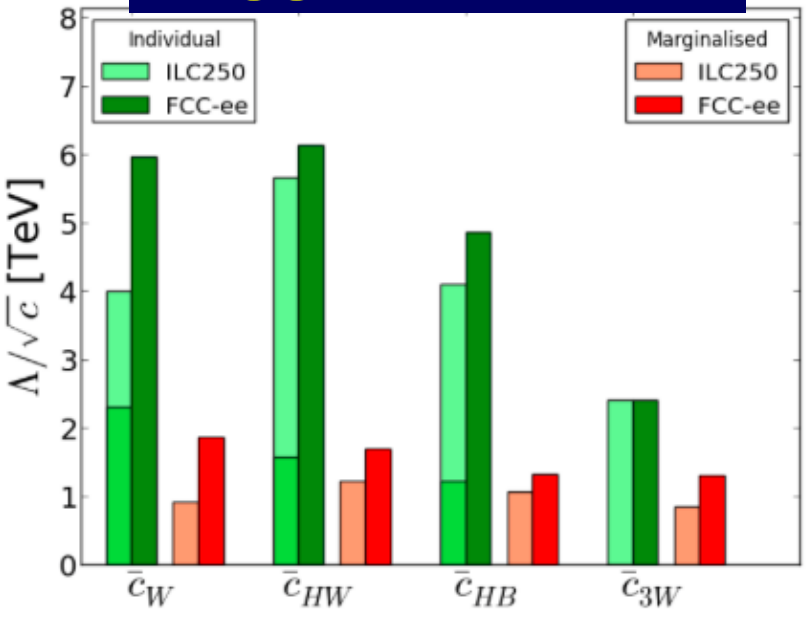
FCC-ee Higgs & TGC Measurements

EWPTs and Higgs



- Shadings:
  - With/without theoretical EWPT uncertainties

Higgs and TGCs



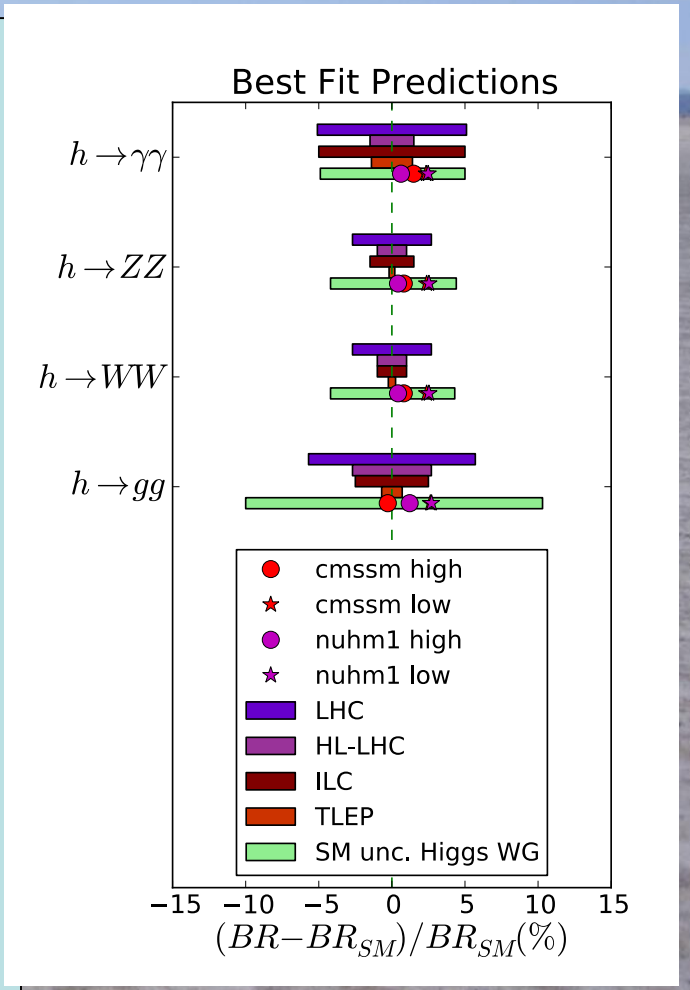
- Shadings of green:
  - Effect of including TGCs at ILC

Should extend to include prospective FCC-hh measurements of TGCs, …

Impact of Higgs Measurements

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - **LHC**
  - **HL-LHC**
  - **ILC**
  - **TLEP (= FCC-ee)**

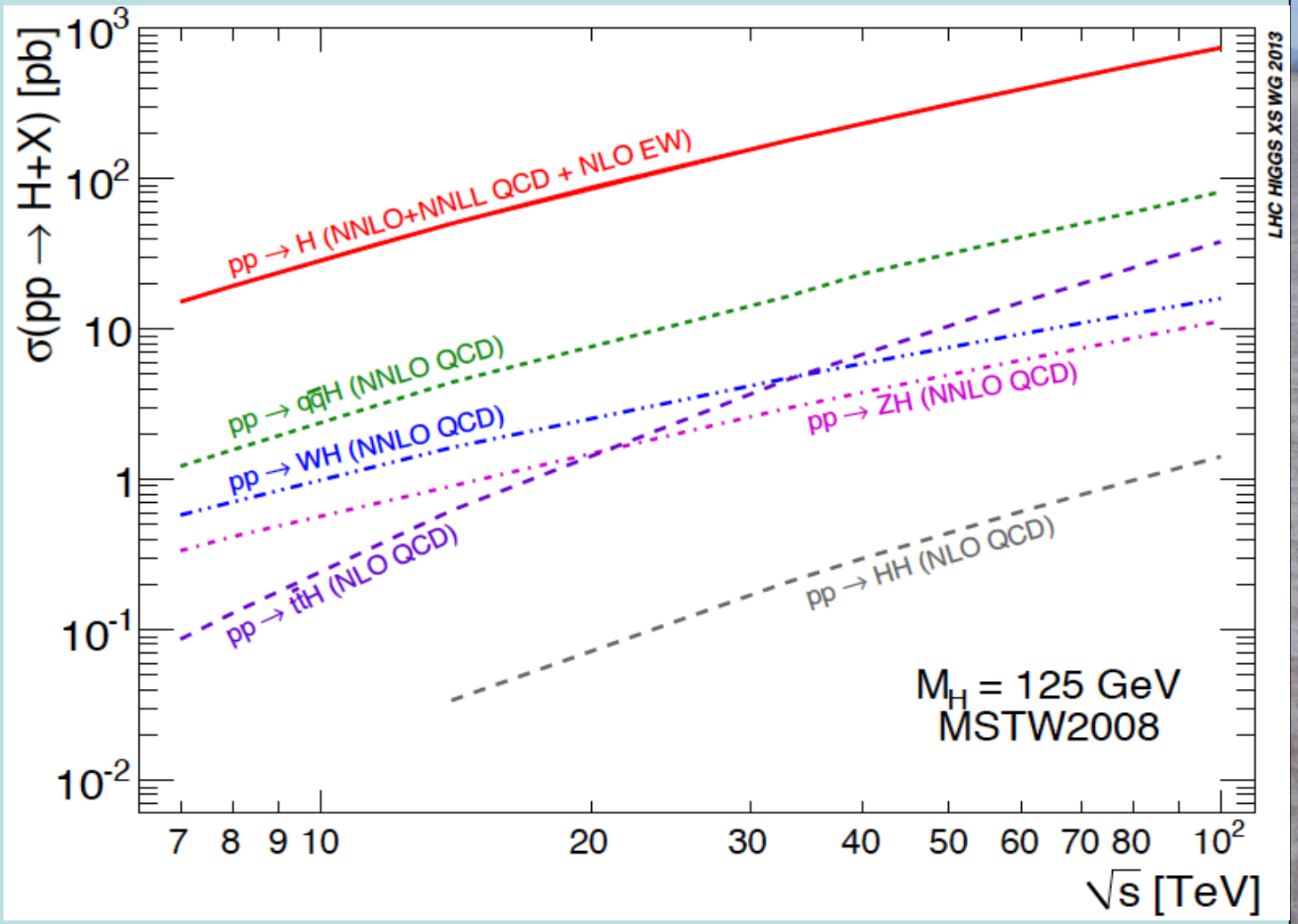
  (Able to distinguish from SM)



Buchmueller, JE et al: arXiv:1505.04702

Higgs Cross Sections

- At the LHC and beyond:



Summary

- Beyond any reasonable doubt, the LHC has discovered a (the) Higgs boson
- A big challenge for theoretical physics!
- The LHC may discover physics beyond the SM when it restarts at ~ 13 TeV
- If it **does**, priority will be to study it
- If it does **not**, natural to focus on the Higgs
- In this case, future circular colliders may offer the best prospects