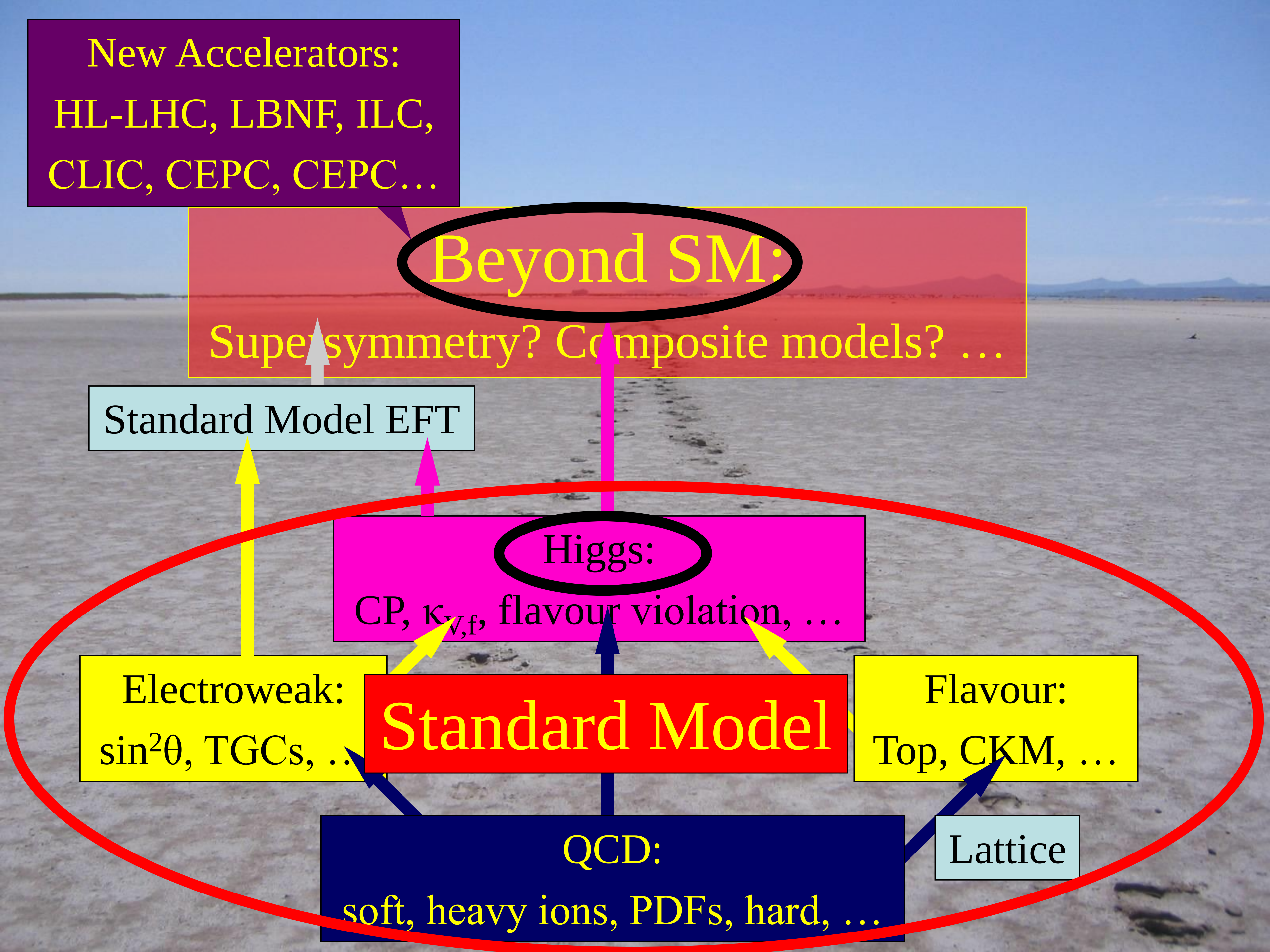
What will we see through the Higgs Portal?

Proposal, discovery, measurement, interpretation, what next?

John Ellis

KING'S College LONDON


New Accelerators:
HL-LHC, LBNF, ILC,
CLIC, CEPC, CEPC…
Beyond SM:
Supersymmetry? Composite models? …
Standard Model EFT
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Standard Model
Flavour:
Top, CKM, …
QCD:
soft, heavy ions, PDFs, hard, …
Lattice

The Standard Model Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}$$

✓ Experiment: accuracy < %

$$\mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^{L\mu}\phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R +$$

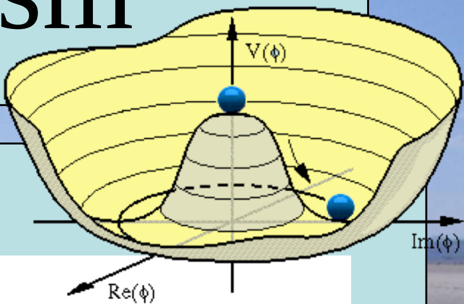
No direct evidence until July 4, 2012

$$D^L_\mu = \partial_\mu - igW^a_\mu T^a - iYg'B_\mu \quad , \quad D^R_\mu = \partial_\mu - iYg'B_\mu$$

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \quad .$$

1964

Abelian Higgs Mechanism



- Lagrangian

$$\mathcal{L} = \left(D_\mu \phi\right)^+ \left(D^\mu \phi\right) - V(|\phi|) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad D_\mu = \partial_\mu - ieA_\mu$$

- Gauge transformation

$$\phi'(x) = e^{i\alpha(x)}\,\phi(x) = e^{i\alpha(x)}\, e^{i\theta(x)} \eta(x)$$

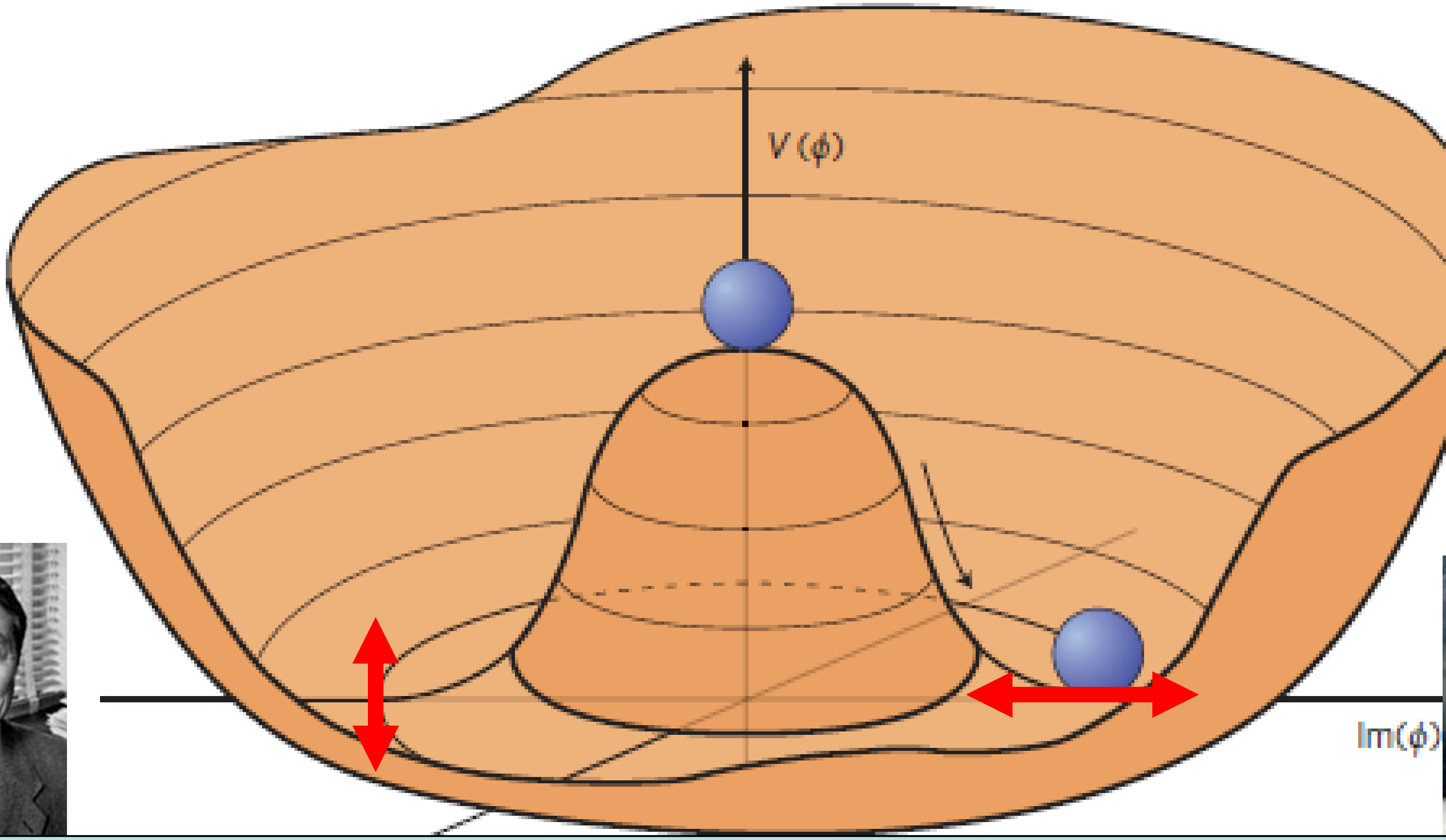
$$A'_\mu(x) = A_\mu(x) + \frac{1}{e} \partial_\mu \alpha(x)$$

- Choose $\alpha(x) = -\theta(x)$: $\quad \phi'(x) = \eta(x)$
- Rewrite Lagrangian: $\mathcal{L} = |(\partial - ieA'_\mu)\eta|^2 - V(\eta) - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$

$$\mathcal{L} = |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}} H)|^2 - \tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - V$$

$$= \underbrace{-\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + v^2 e^2 A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2}[(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots$$

Nambu **EB, H, GHK** **and Higgs**



Spontaneous symmetry breaking: massless Nambu-Goldstone boson **'eaten' by massless gauge boson**

Accompanied by massive particle

Masses for SM Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + i g \epsilon_{ijk} W^j_\mu W^k_\nu$ $\quad F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

- Expanding around vacuum: $\phi = < 0|\phi|0 > + \hat{\phi}$

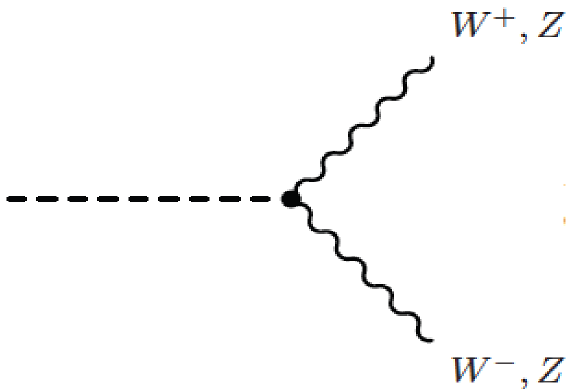
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\, W^+_\mu\, W^{\mu -} - g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu 3}$$

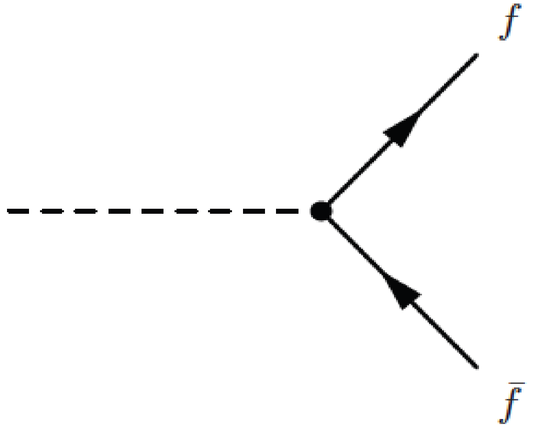
- Boson masses: 

$$m_{W^\pm} = \frac{g v}{2} \qquad Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}} \; : \; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v \; ; \quad A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}} \; : \; m_A = 0$$

1966, 1967

Higgs Boson Couplings





$$g_2 M_W \ , \quad g_2 \frac{M_Z}{c_W}$$

$$\frac{m_f}{v} = \frac{g_2\, m_f}{2 M_W}$$

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}} m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}} F(r) \left(\frac{1}{2}\right)_Z , \quad r = \frac{M_V}{M_H}$$

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975

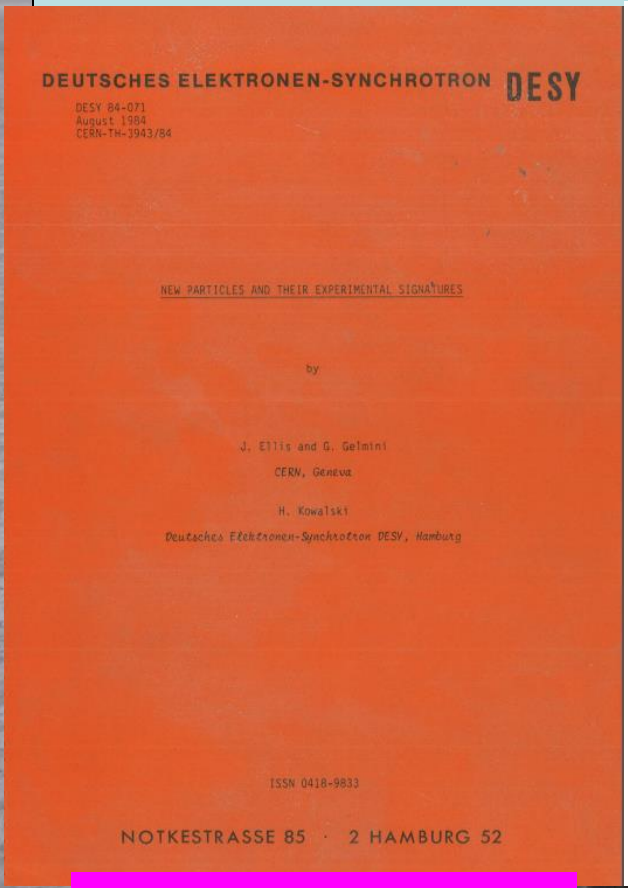
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

1984

A Preview of the Higgs Boson @ LHC

- Prepared for LHC Lausanne workshop 1984


DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 84-071
August 1984
CERN-TH-3943/84

NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES

by

J. Ellis and G. Gelmini
CERN, Geneva

H. Kowalski
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

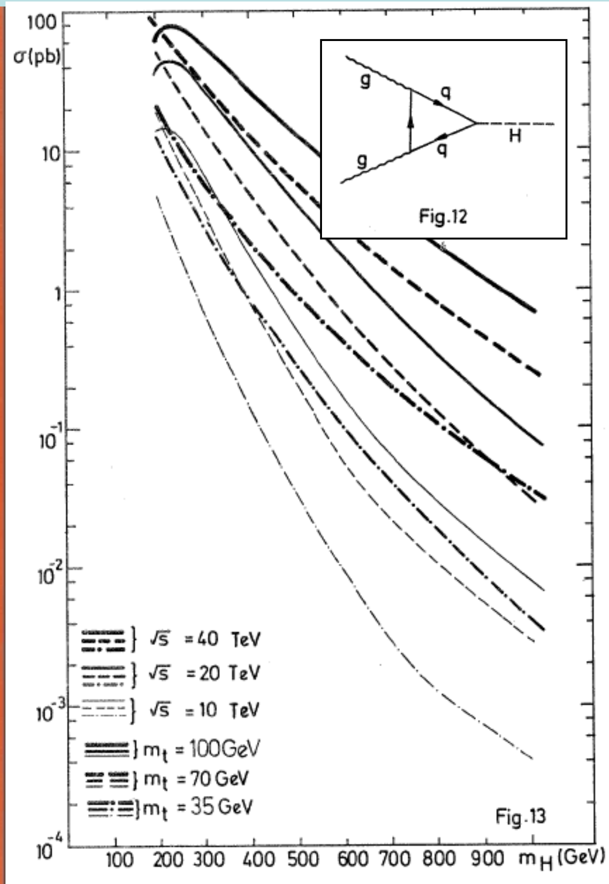


Fig.13

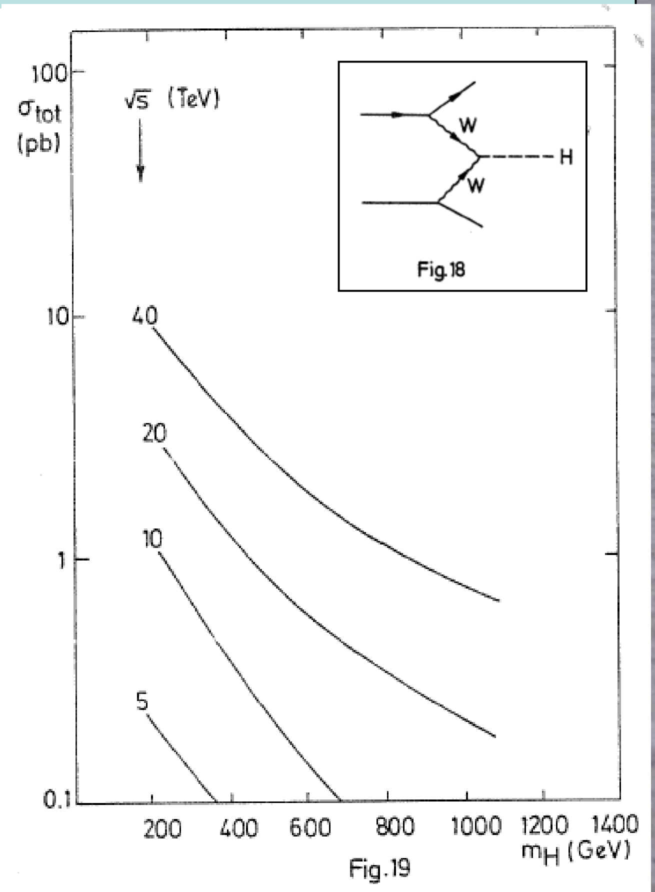


Fig.19

JE, Gelmini & Kowalski, 1984

2011

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

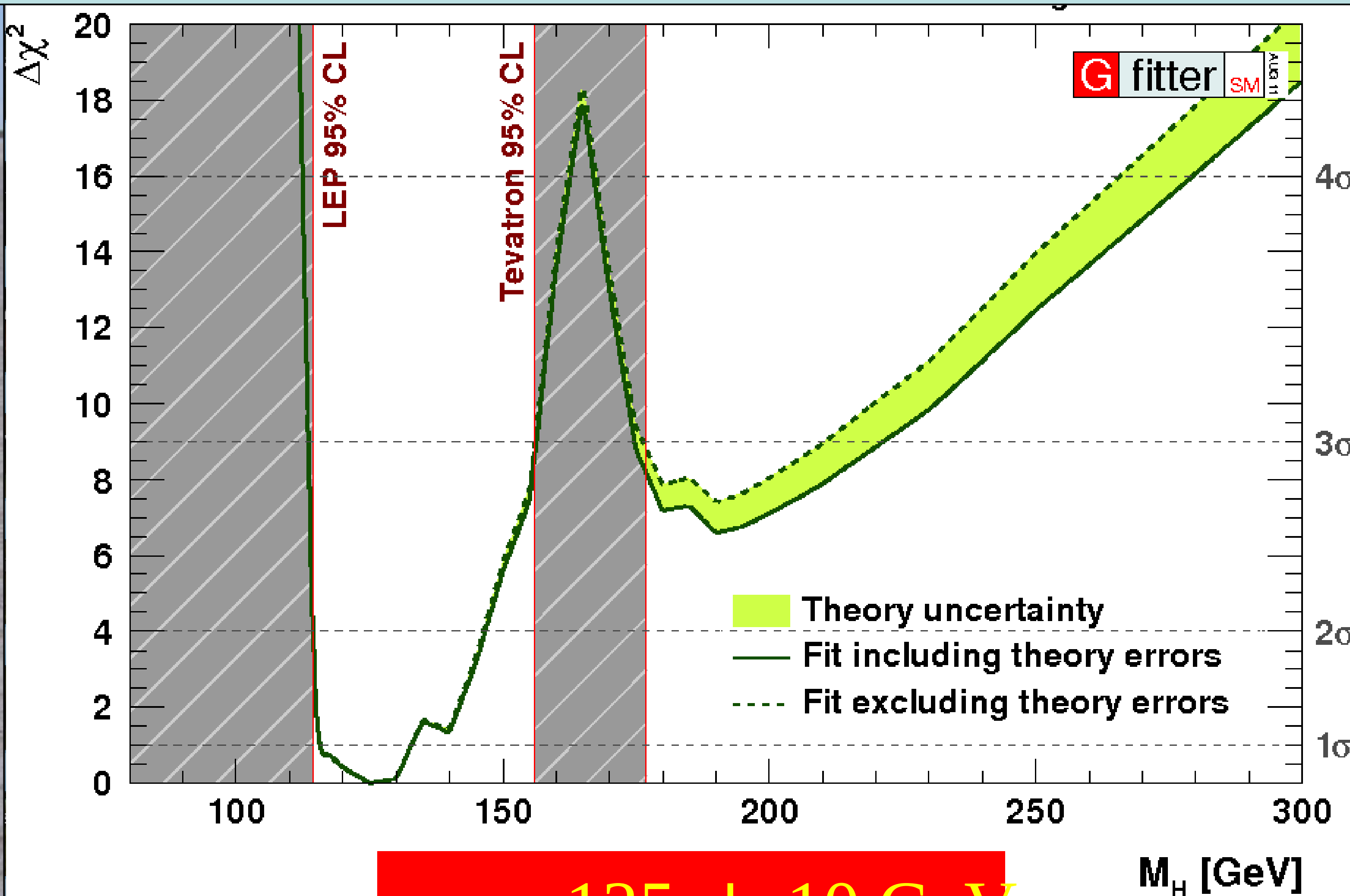
$$\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}\mathrm{G}_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+...\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H \sim 100 \pm 30$ GeV**
- Compare with lower limit from direct search at LEP:

$m_H > 114$ GeV

and exclusion around **(160, 170 GeV)** at TeVatron

2011: Combining Information from Previous Direct Searches and Indirect Data

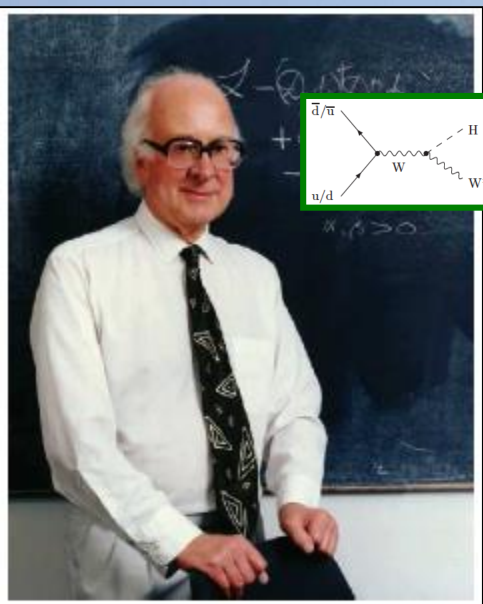


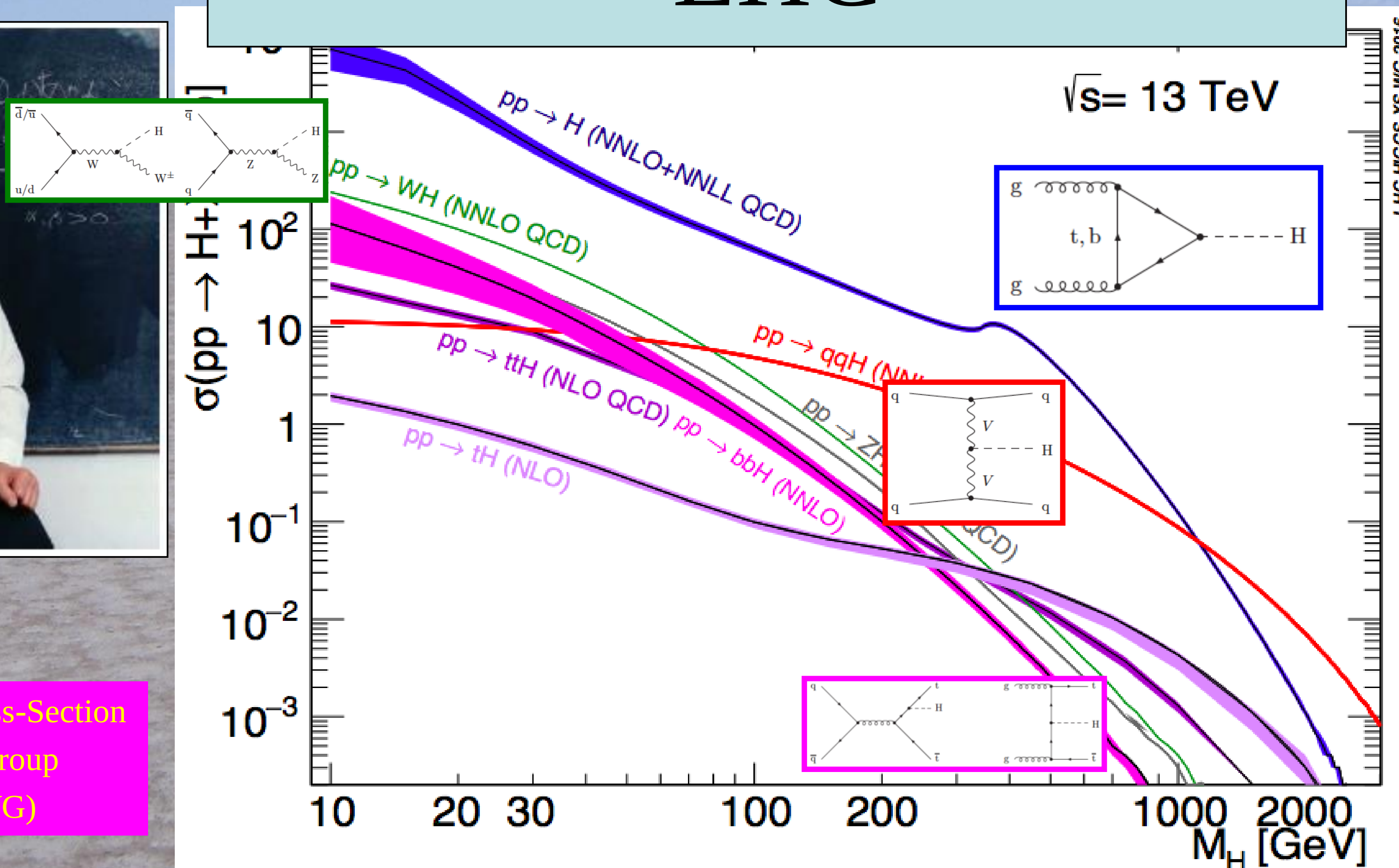
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du
Higgs perdu …

Higgs Production at the LHC



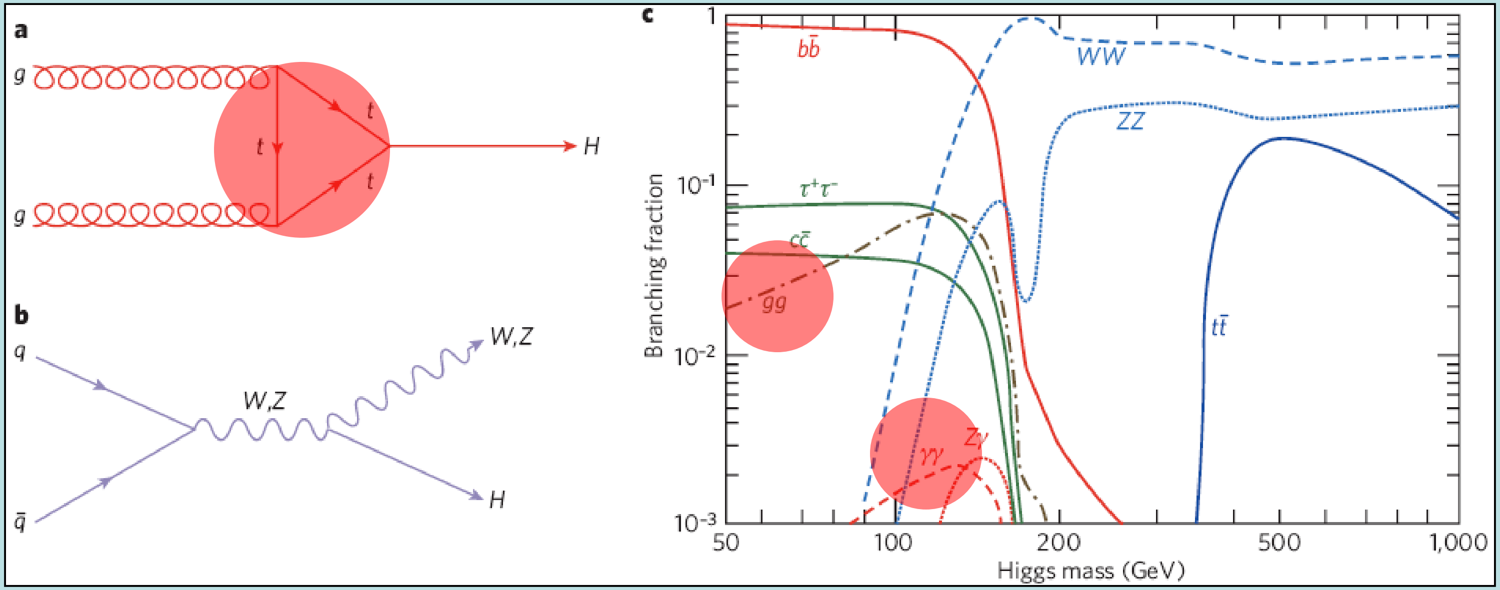


LHC Higgs Cross-Section Working Group (LHXSWG)

Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

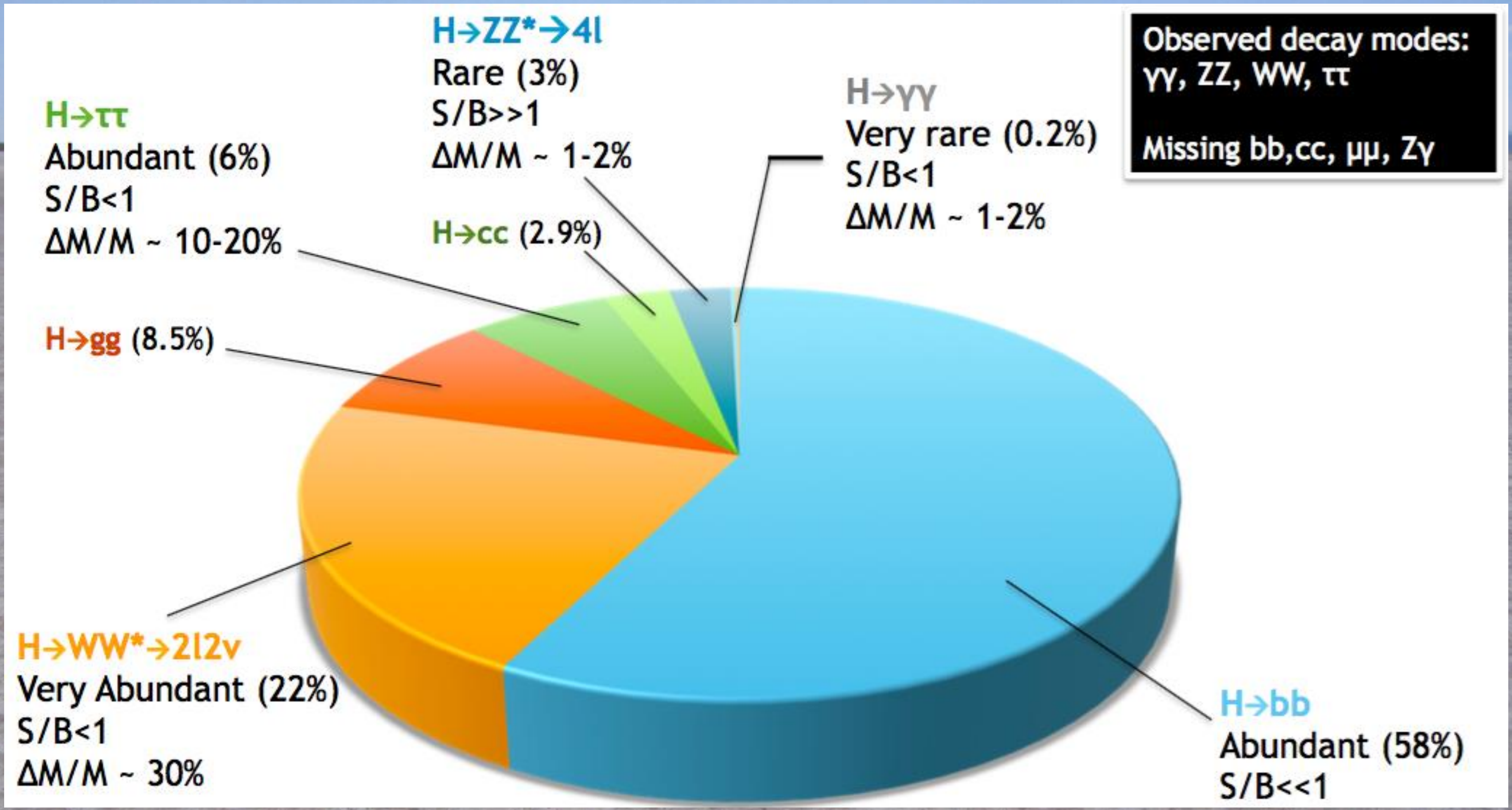
- Couplings proportional to masses (?)



- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

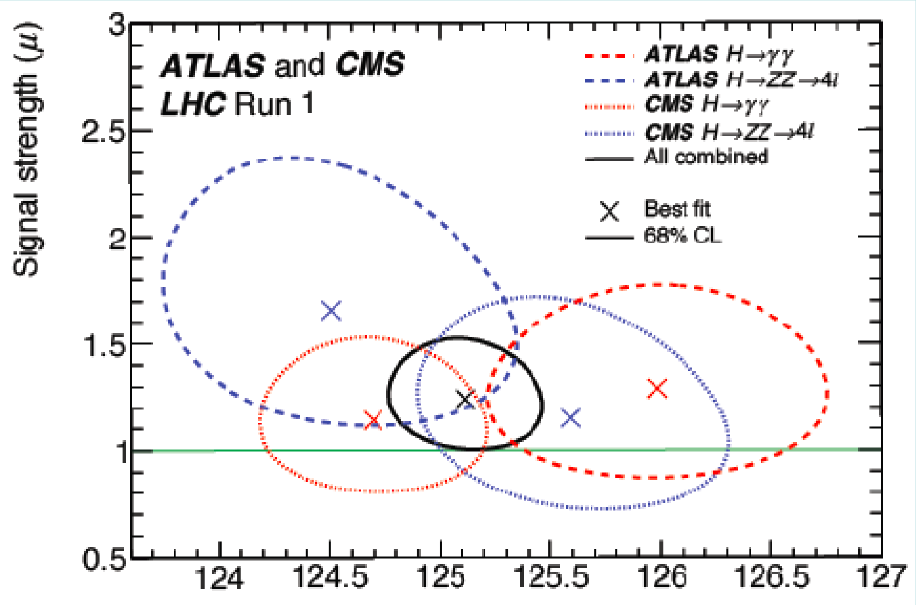
What we Expect



What do we know?

Higgs Mass Measurements

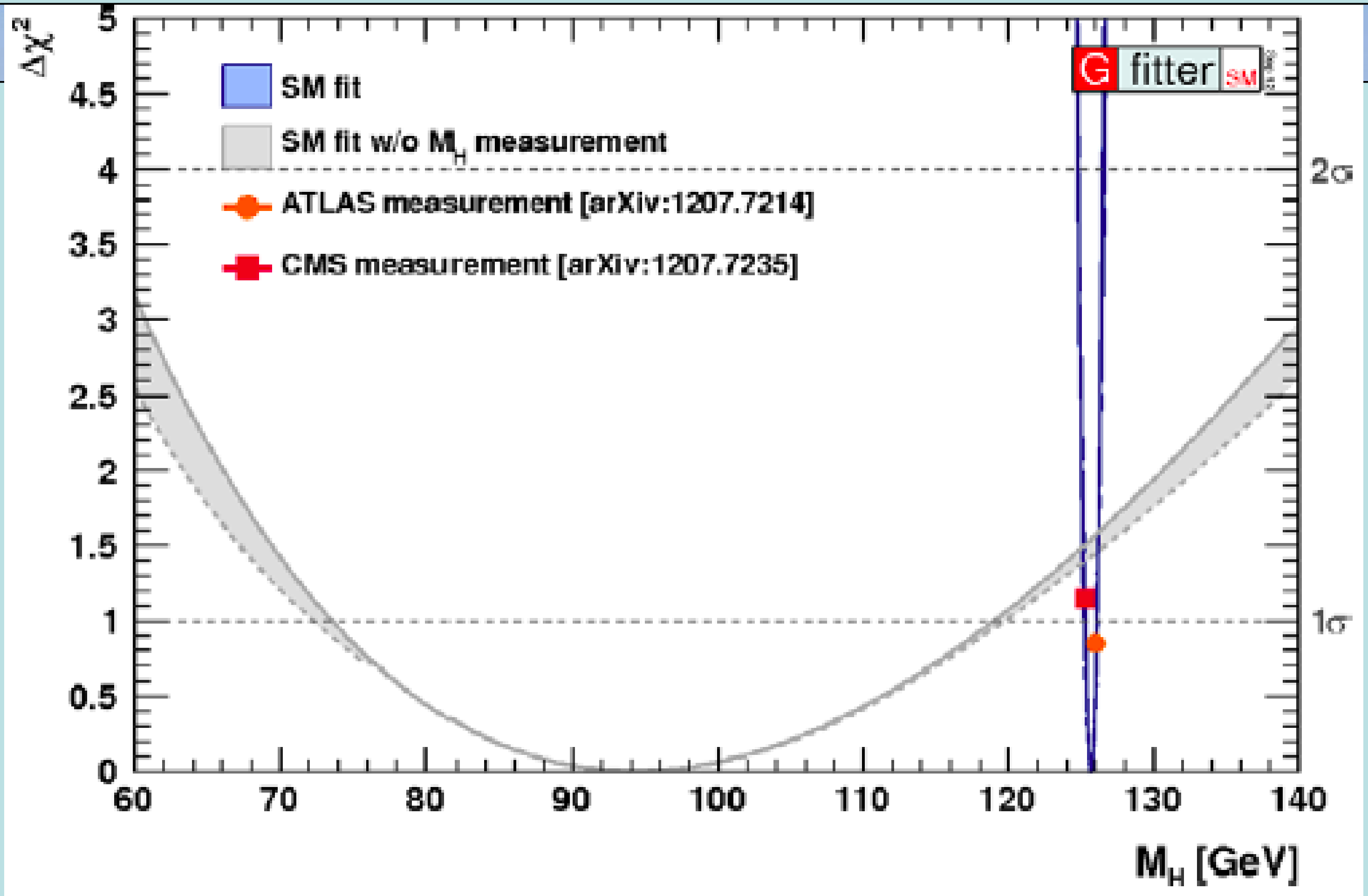
- ATLAS + CMS ZZ* and γγ final states



125.09 ± 0.21 (stat) ± 0.11 (syst)

- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

Comparison with Electroweak Fit



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

Theoretical Constraints on Higgs Mass

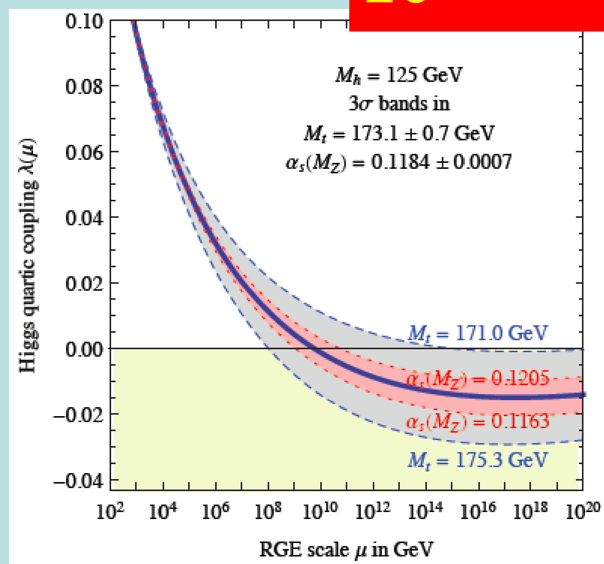
- Large M_h → large self-coupling → blow up at

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

$\lambda(Q) =$

Instability @ $10^{11.1 \pm 1.3}$ GeV

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

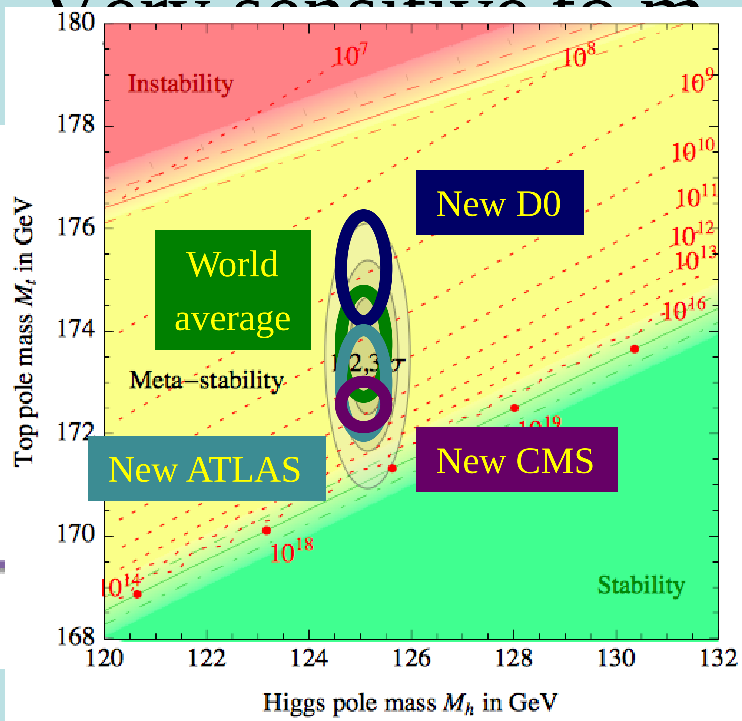


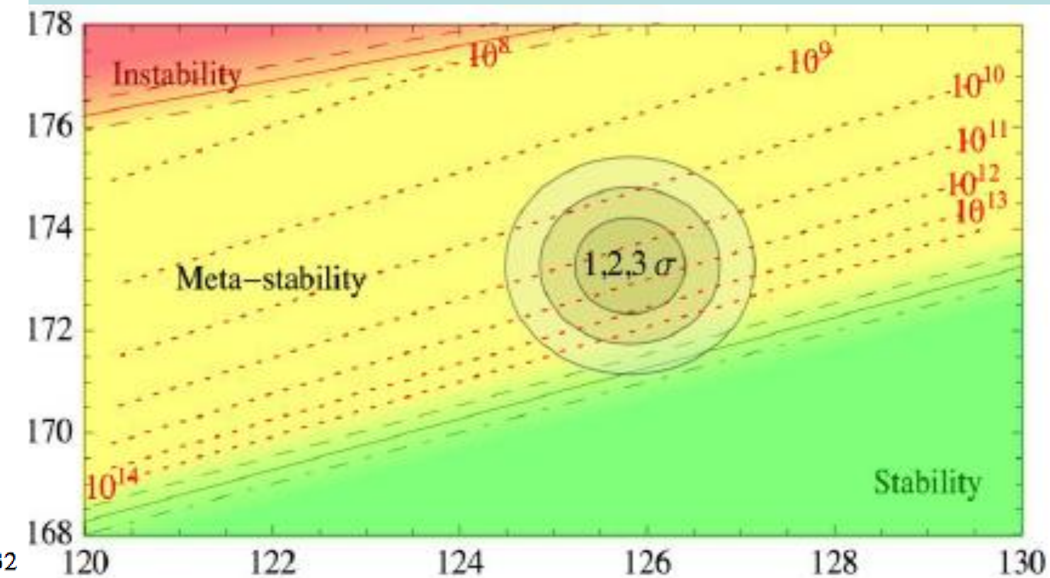
- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H





Bednyakov, Kniehl, Pikelner and Veretin: arXiv:1507.08833

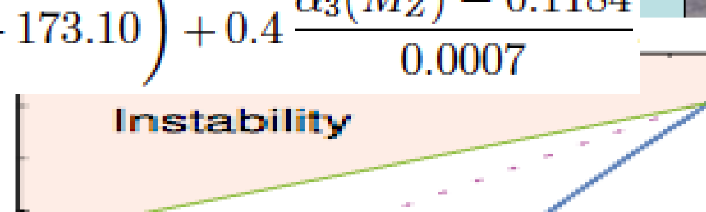
- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

m_t = 173.3 ± 1.0 GeV →

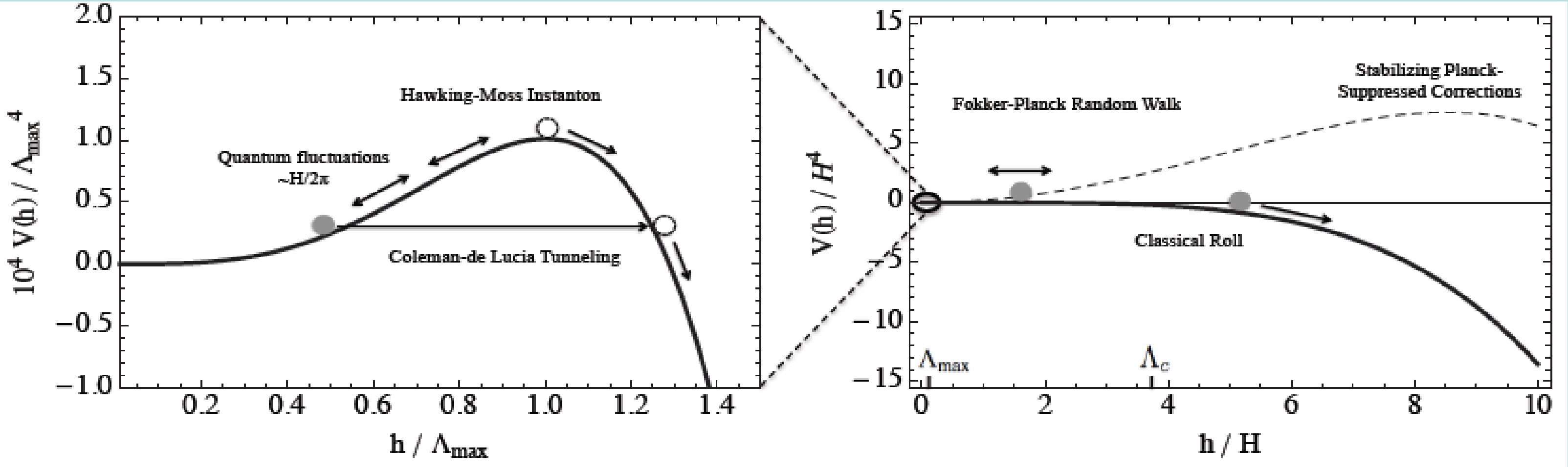
1.3



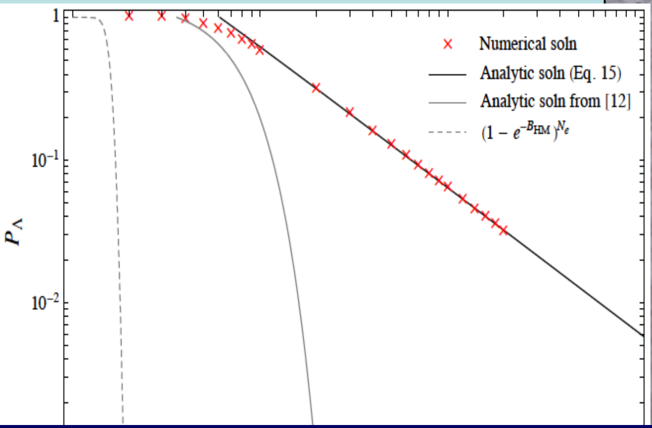
Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so
  - If not, OK if more inflation



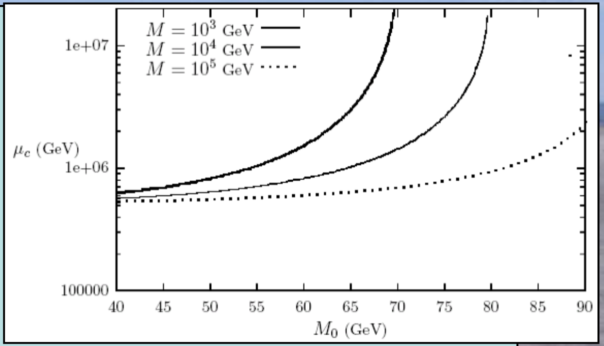
Stabilize vacuum with some physics beyond the SM?

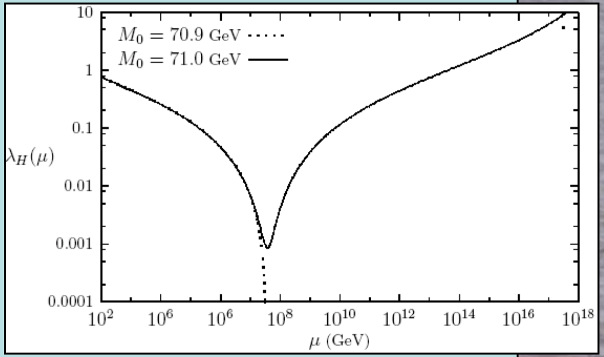
How to Stabilize a Light Higgs Boson?

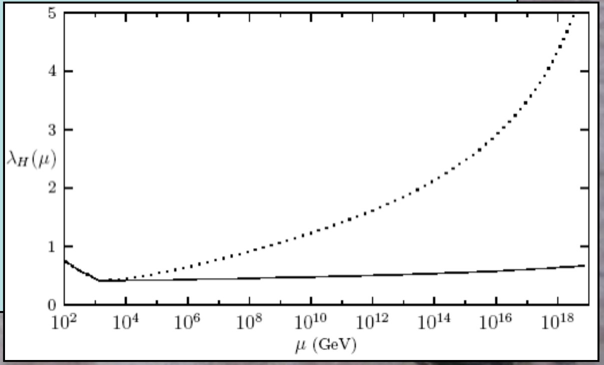
- Top quark destabilizes potential: introduce stop-like scalar:

$$\mathcal{L} \supset \; M^2|\phi|^2 + \frac{M_0}{v^2}|H|^2\,|\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like **Supersymmetry!**



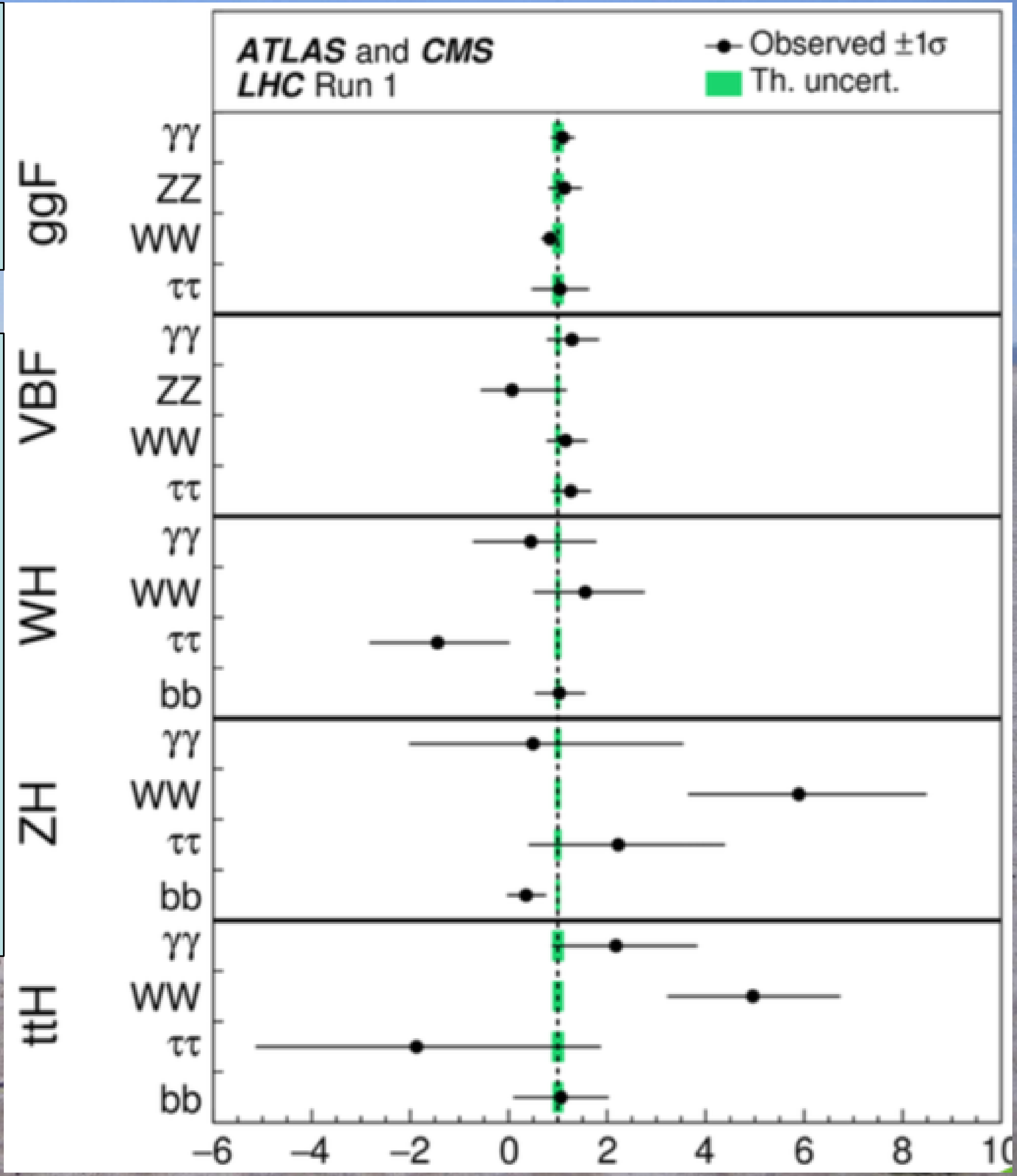




JE + D. Ross

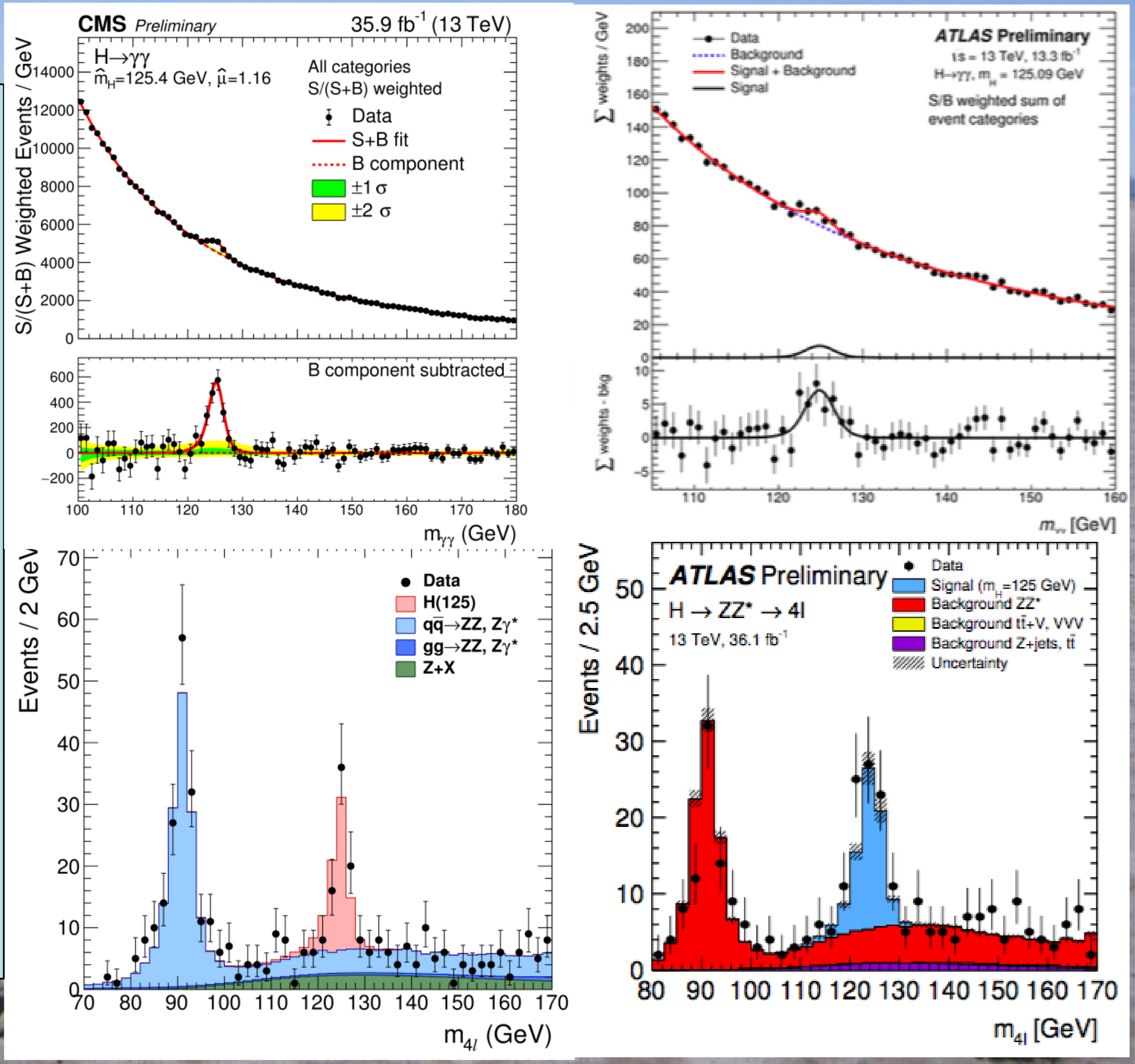
Measurements in Run 1

- Open questions:
  - H➔bb?
    - 2.6σ @ LHC
    - 2.8σ @ FNAL
  - H➔➚μ?
  - ttH production?
  - tH production?



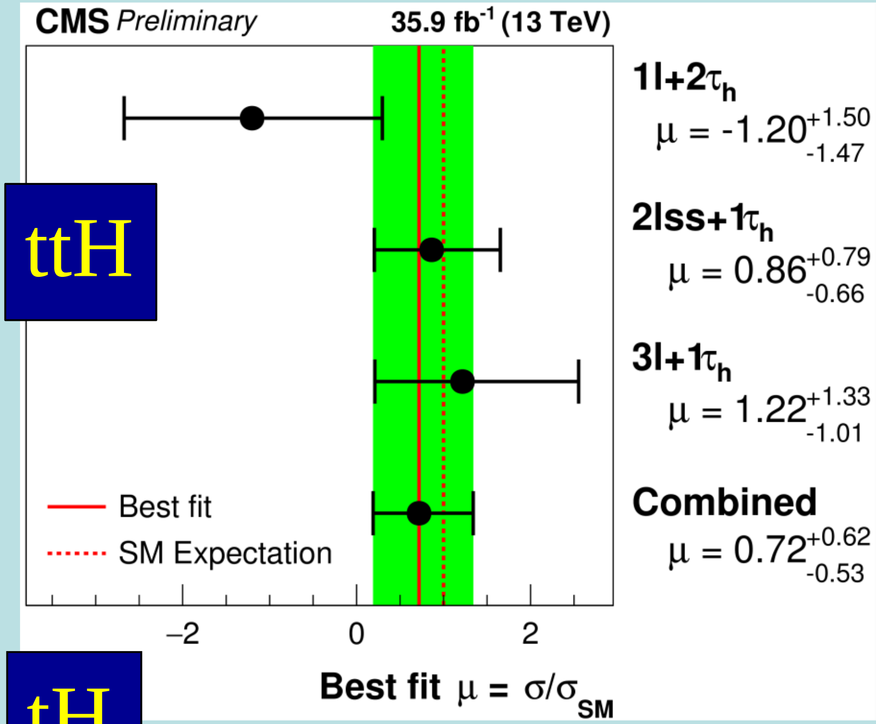
Measurements in Run 2

- Measurements in γγ and ZZ* final states
- 10σ significance
- Cross-section agrees with theory
- Searching for ttH, H➔μμ and tH



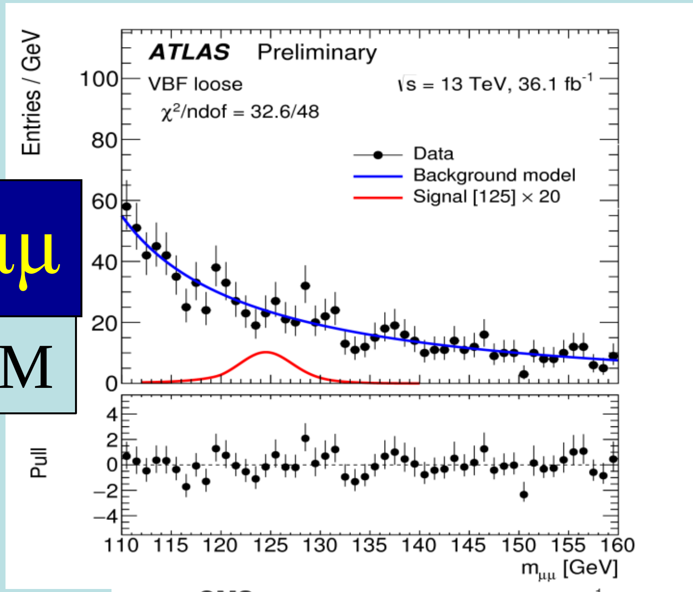
The Next Frontiers

ttH

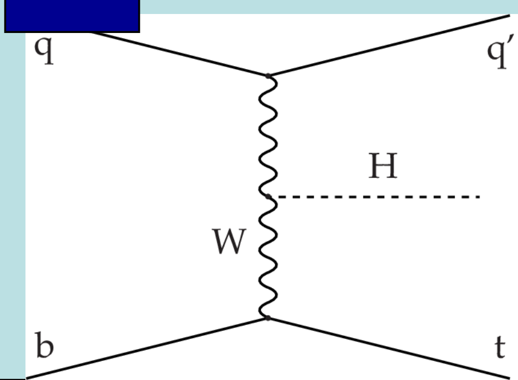


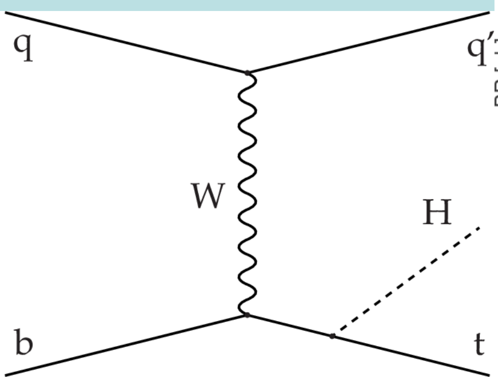
H→μμ

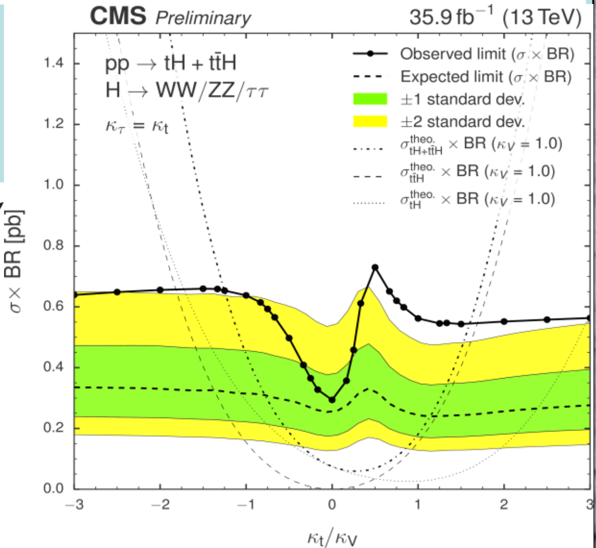
< 2.8 SM



tH







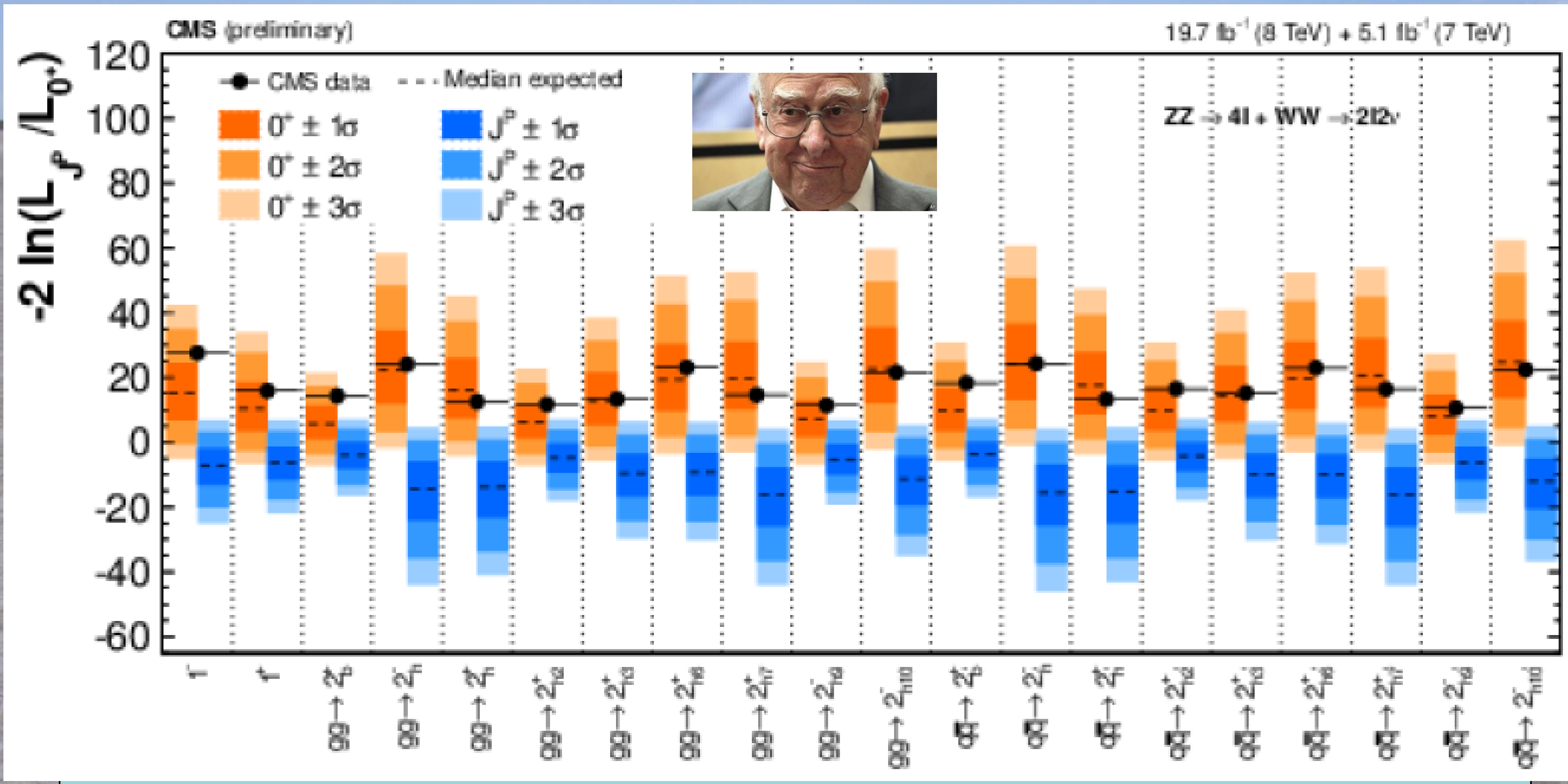
The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

The ‘Higgs’ has Spin 0

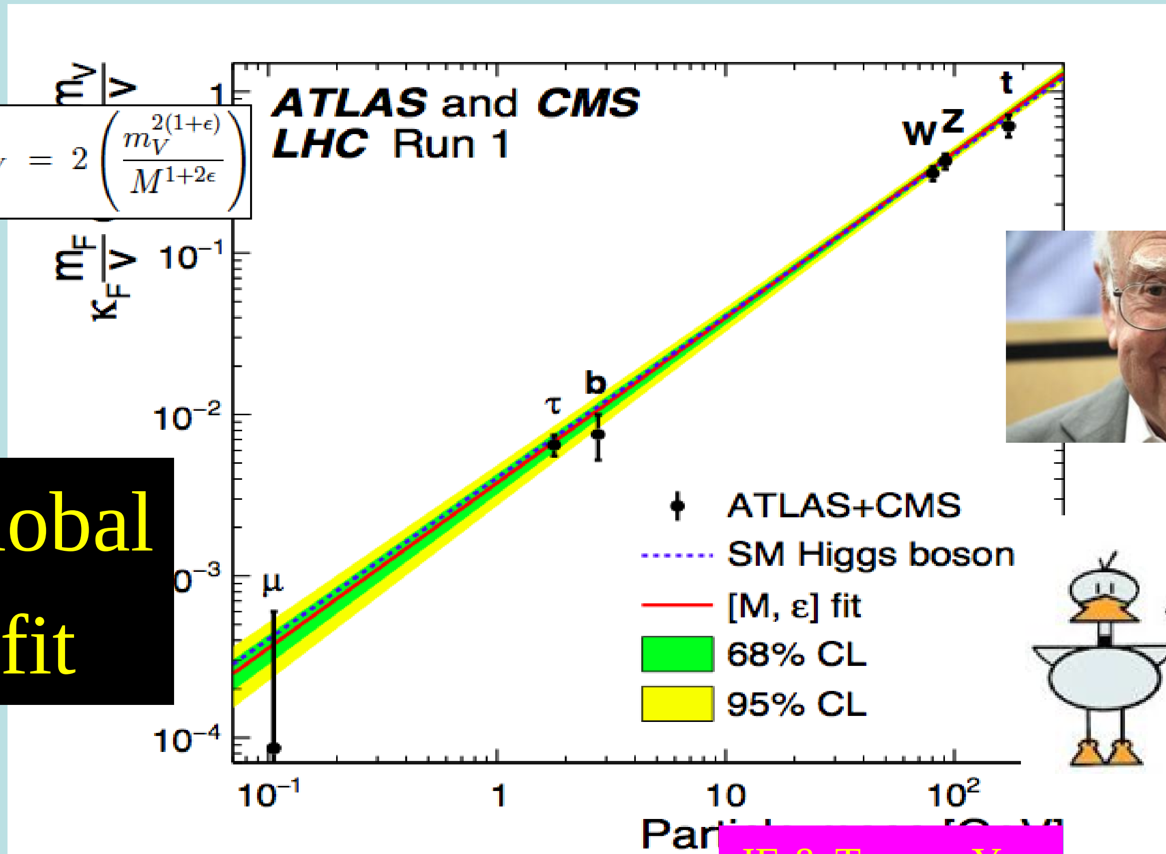


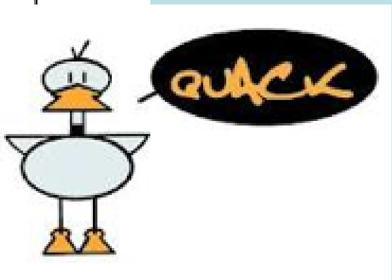
- Alternative spin-parity hypotheses disfavoured

It Walks and Quacks like a Higgs

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

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





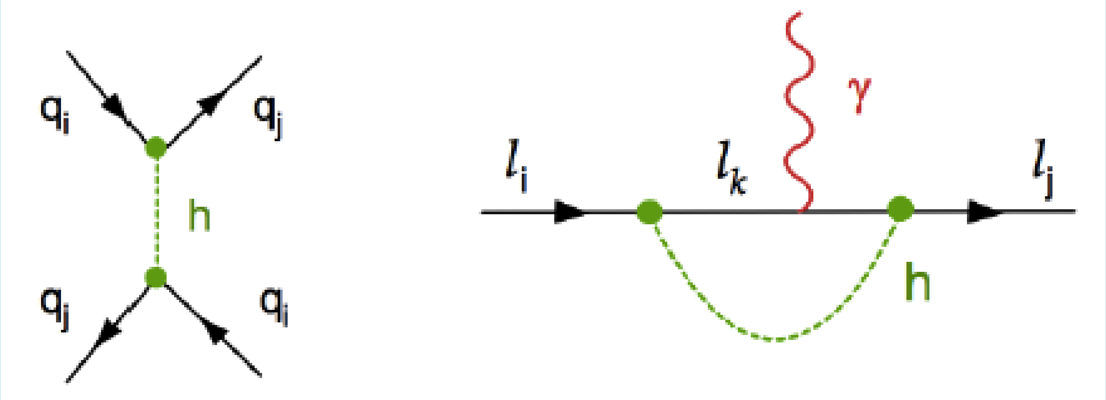
Global fit

JE & Tevong You

- **Blue** dashed line = Standard Model

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



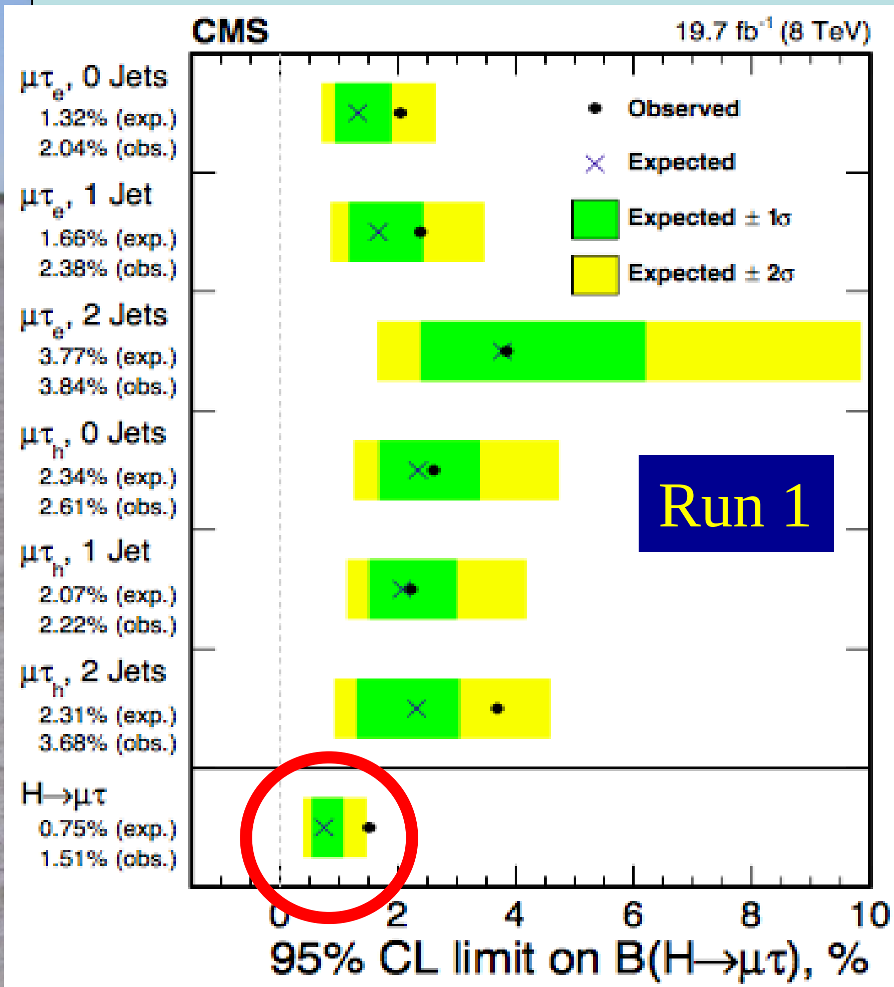
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

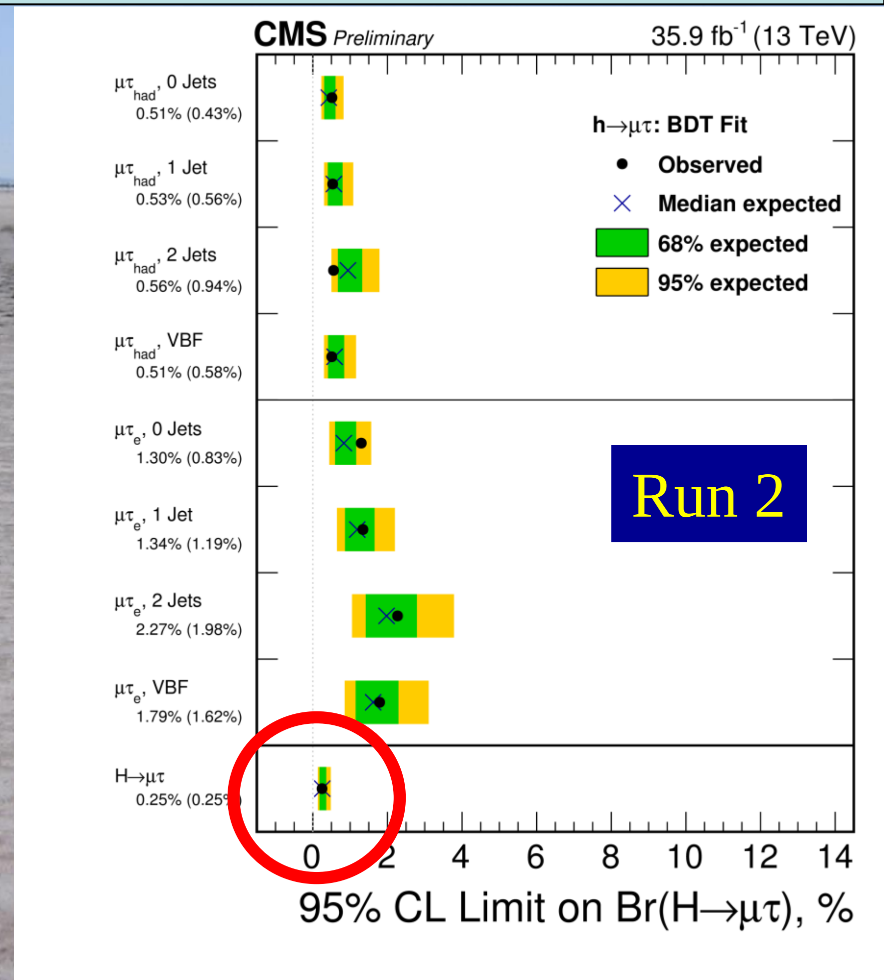
BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Coupling?





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

Also: BR(eτ) < 0.69%, BR(eμ) < 0.036%

$\mathcal{B}(\mathrm{H} \to \mu\tau) < 0.25\%$

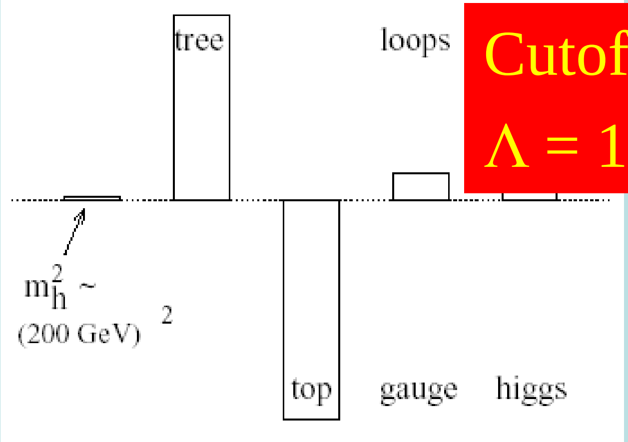
Also: BR(eτ) < 0.61%

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff

$\Lambda = 10$ TeV

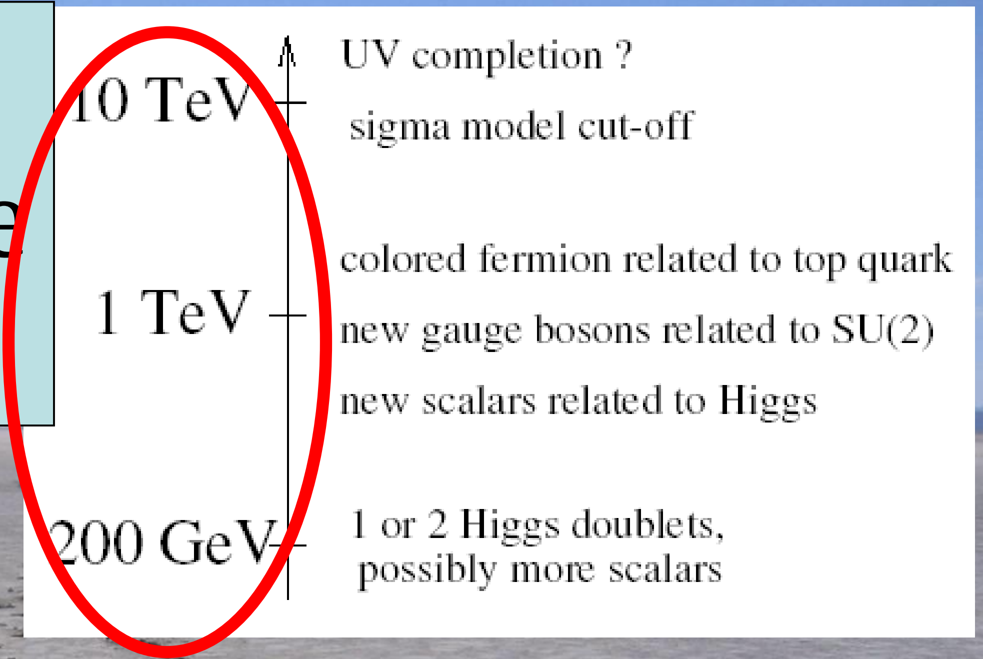
Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

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

New technicolour force?

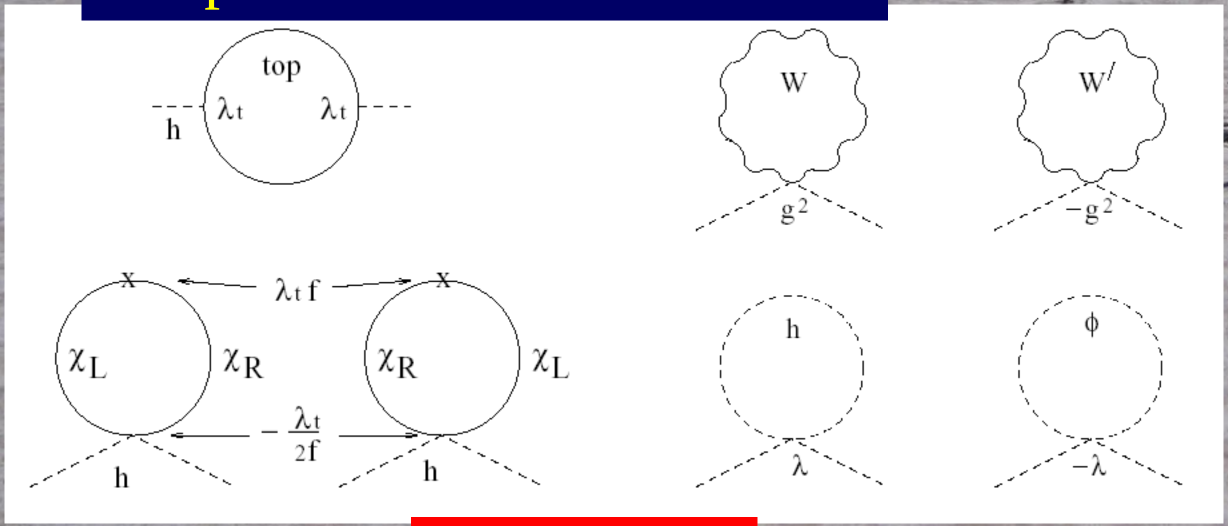
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

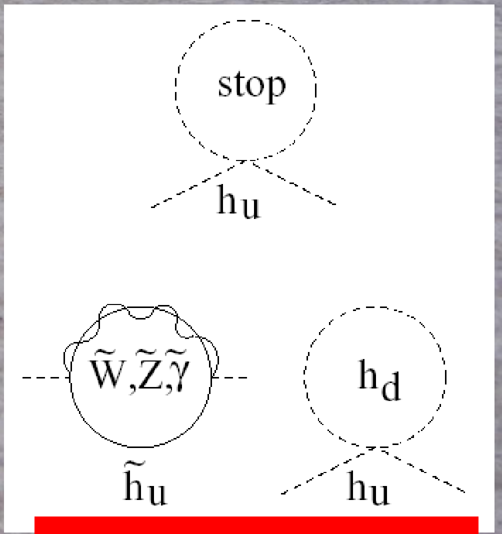


‘Little Higgs’ models
(breakdown of larger symmetry)

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:

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

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

- 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:

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

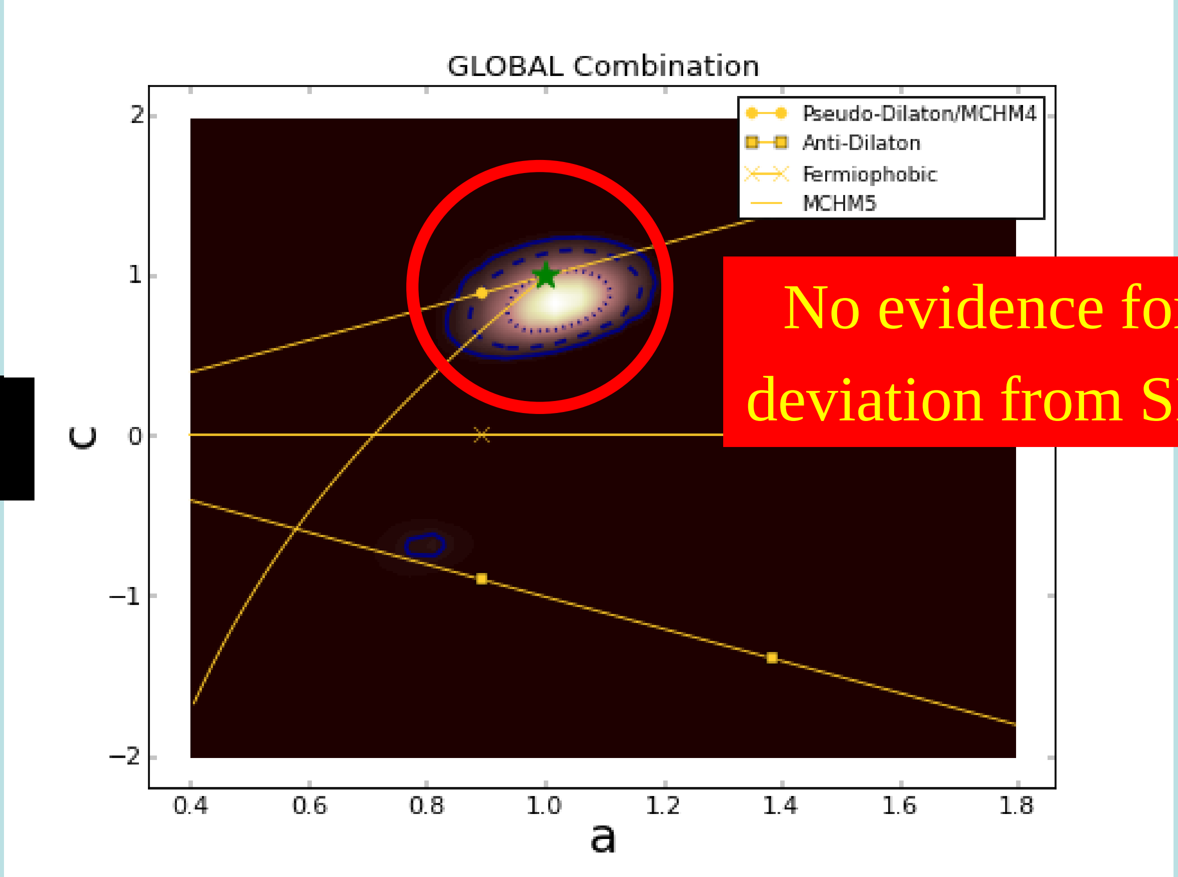
Model	Symmetry Pattern	Goldstones
SM	SO(4)/SO(3)	W_L, Z_L
—	SU(3)/SU(2)×U(1)	W_L, Z_L, h
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, h
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, h, a
MCTHM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^{\pm}, a$

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



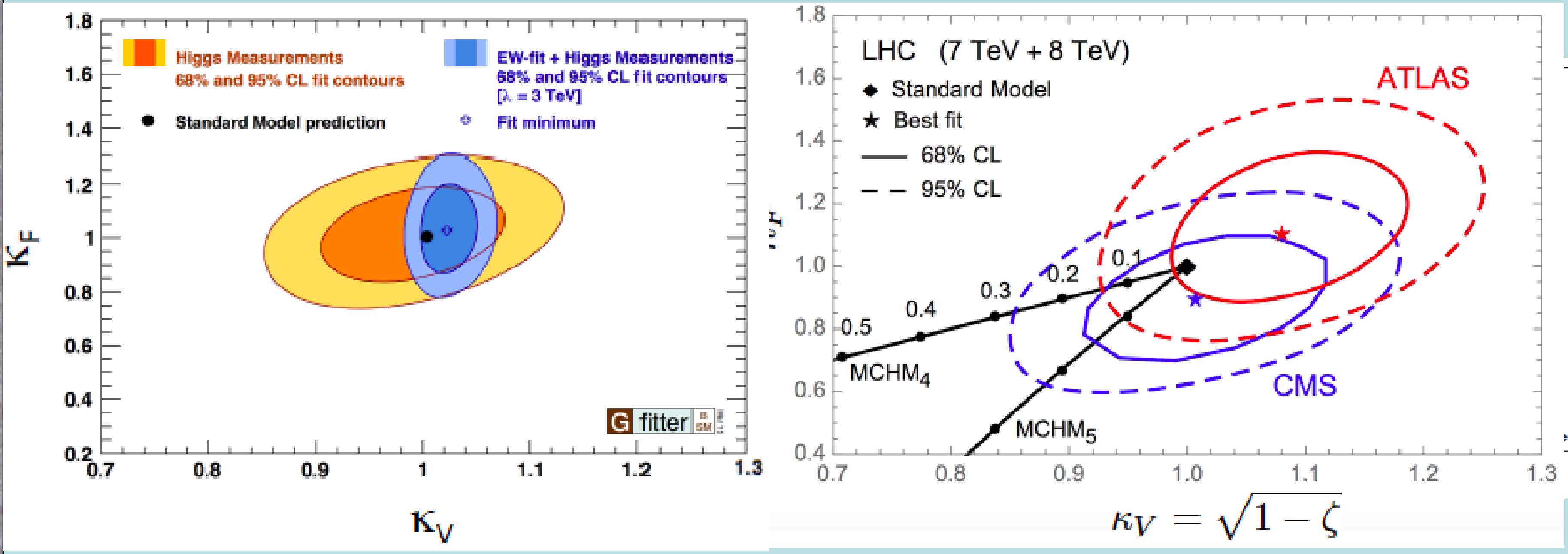
No evidence for deviation from SM

- 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**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar 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, 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 $= 2.5^{+0.9}_{-0.8}$

Assuming H(125) is SM-like: Model-independent search for new physics

Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

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

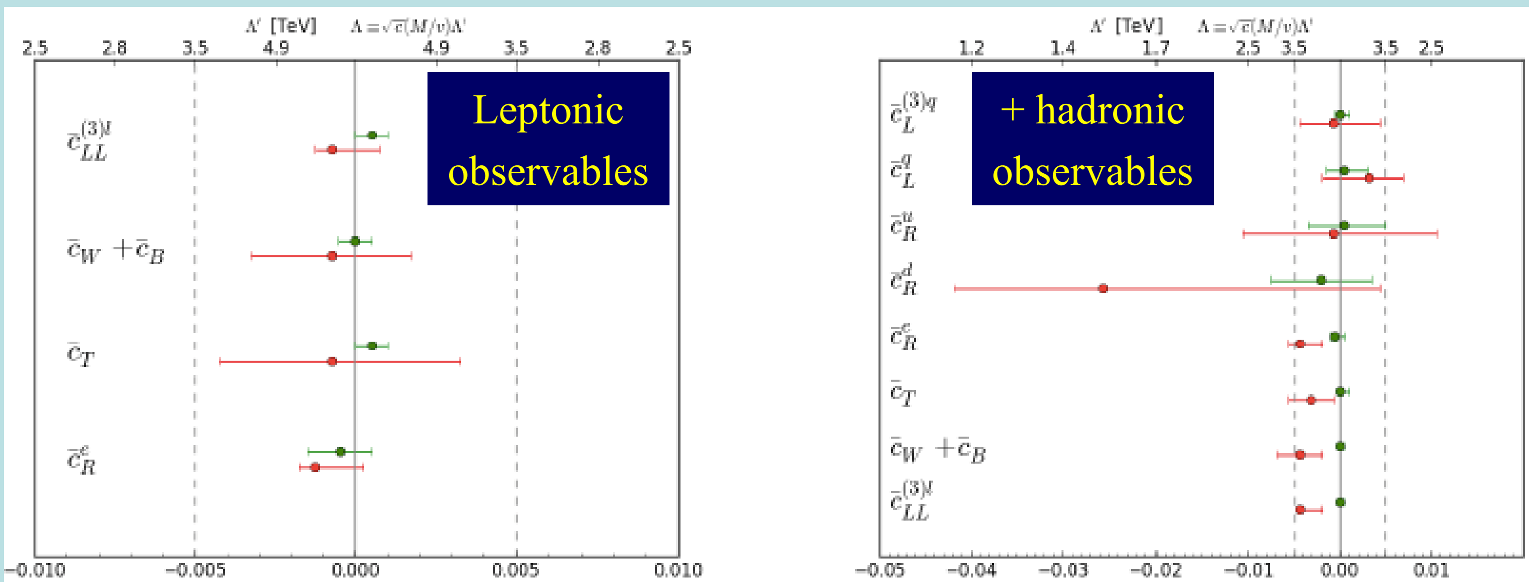
- Constrain with precision EW, Higgs data, TGCs …

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



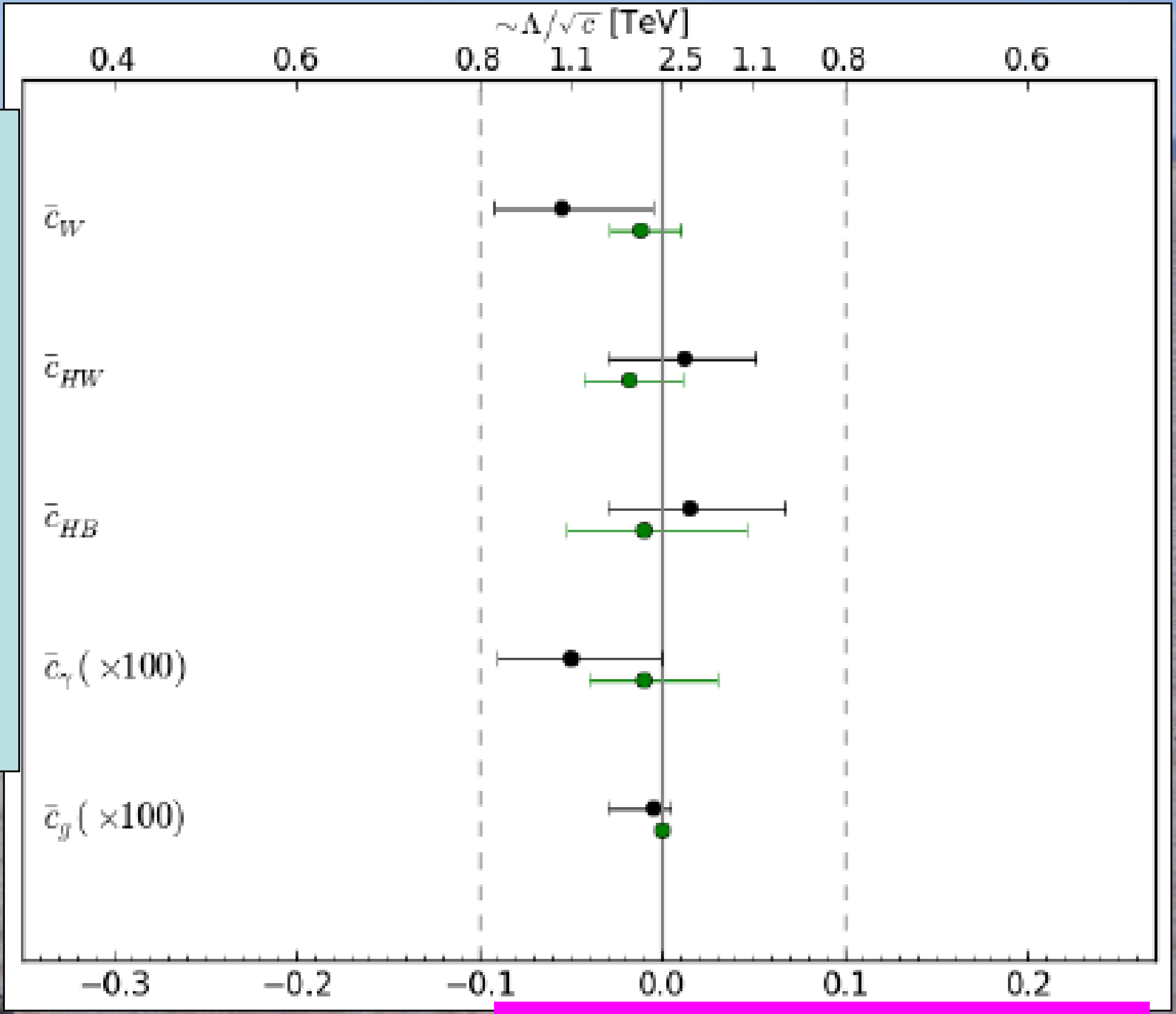
Fits to individual dimension-6 operators

Global fit to dimension-6 operators

JE, Sanz & Tevong You, arXiv:1410.7703

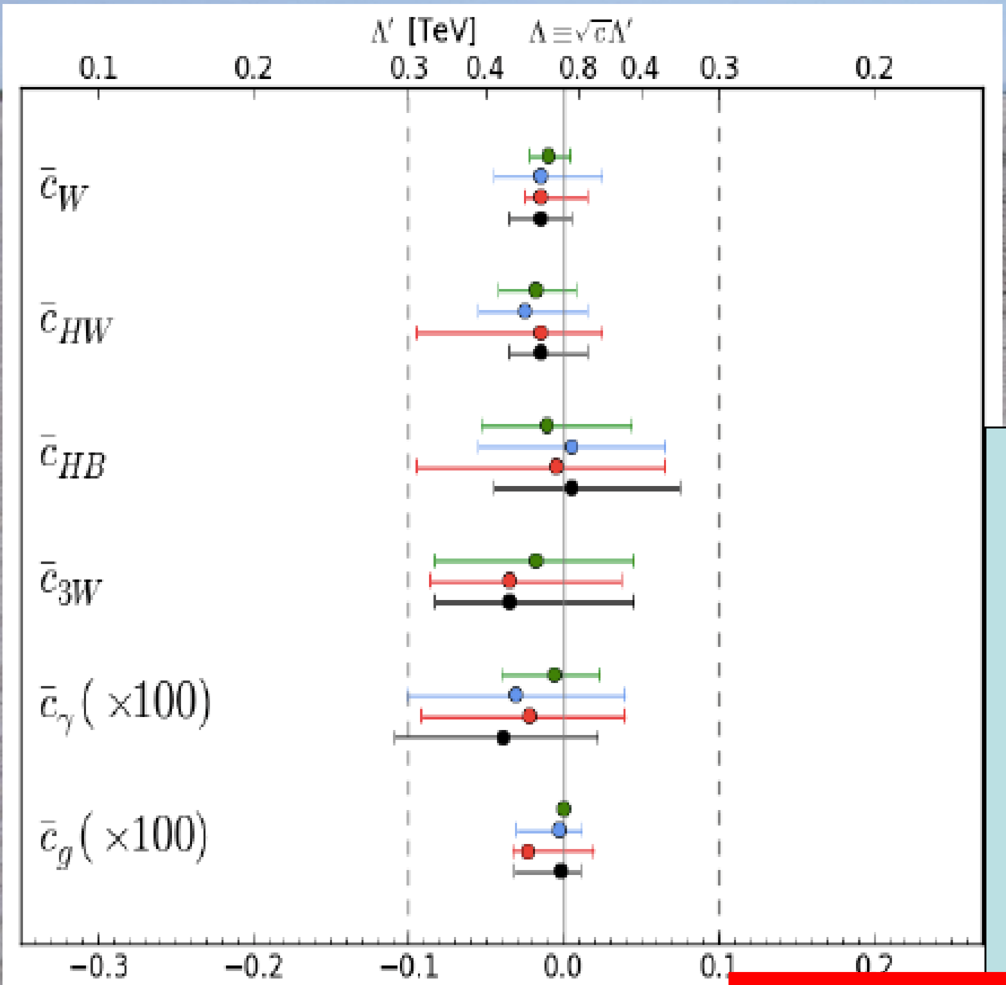
Fits including Higgs Production

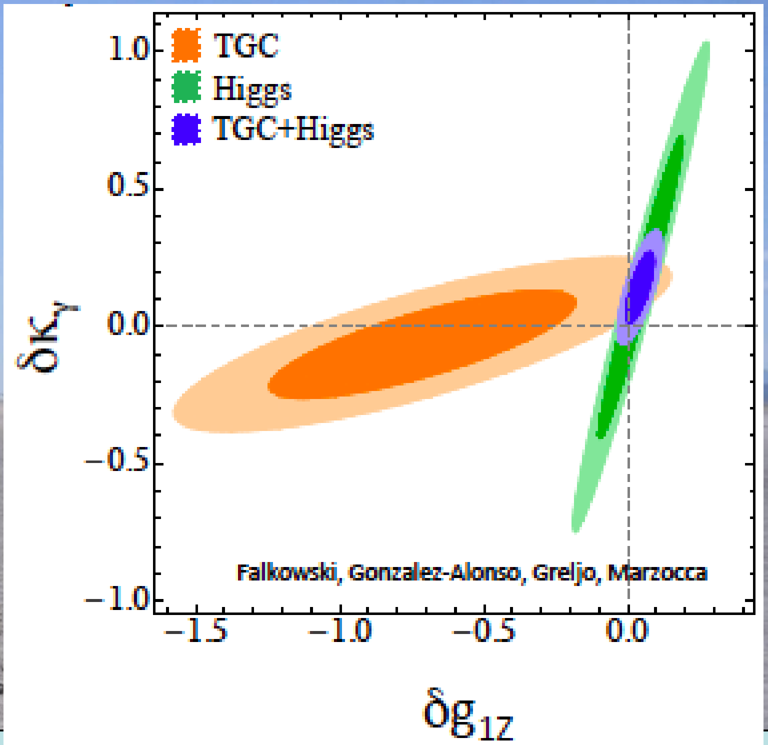
- Using signal strengths & VH kinematics in global fit
- **Single-parameter fits**



JE, Sanz & Tevong You, arXiv:1404.3667

Global Fits including LHC TGCs





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

JE, Sanz & Tevong You, arXiv:1410.7703

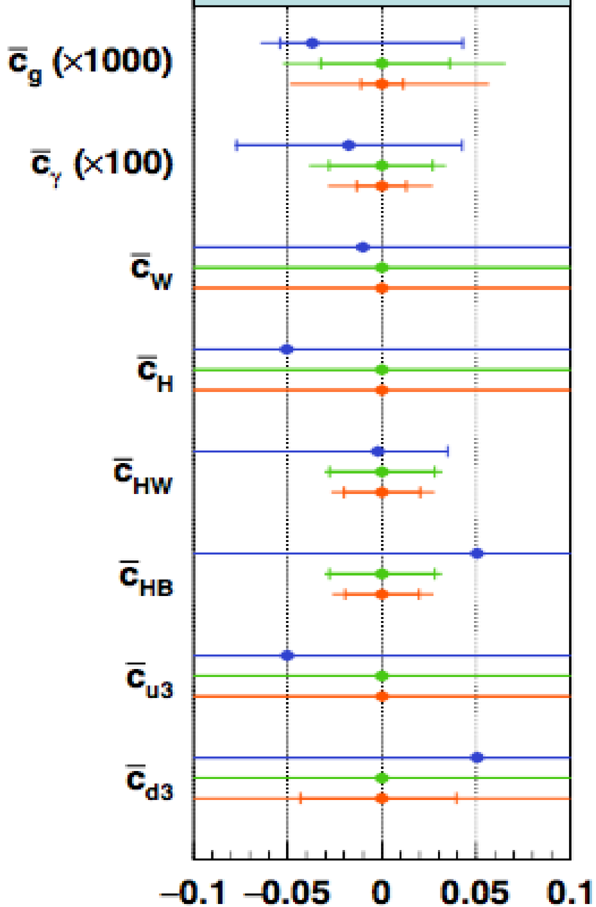
Preferred framework for analyzing Run 2

Present & Future Constraints on D=6 Operators

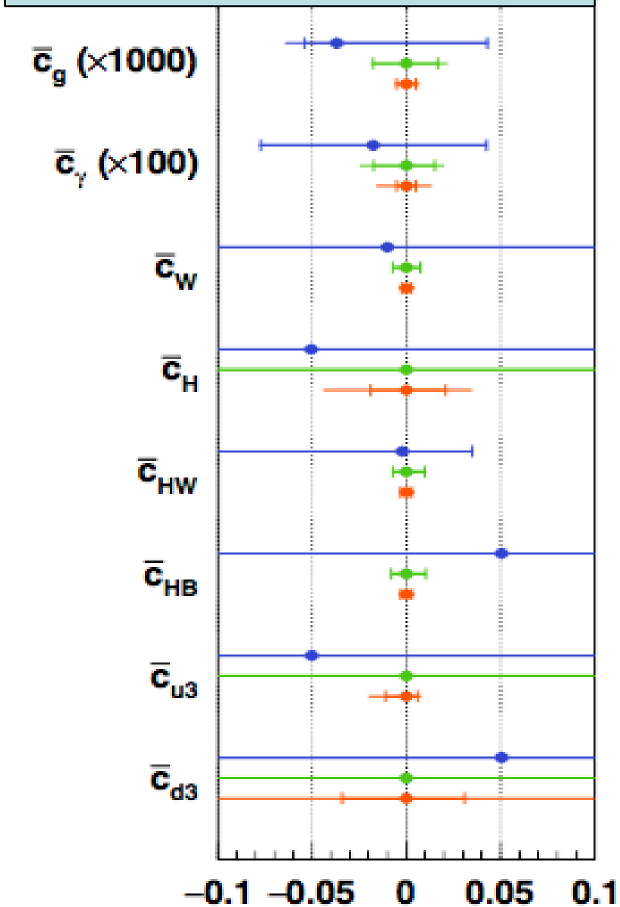
Operators

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}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

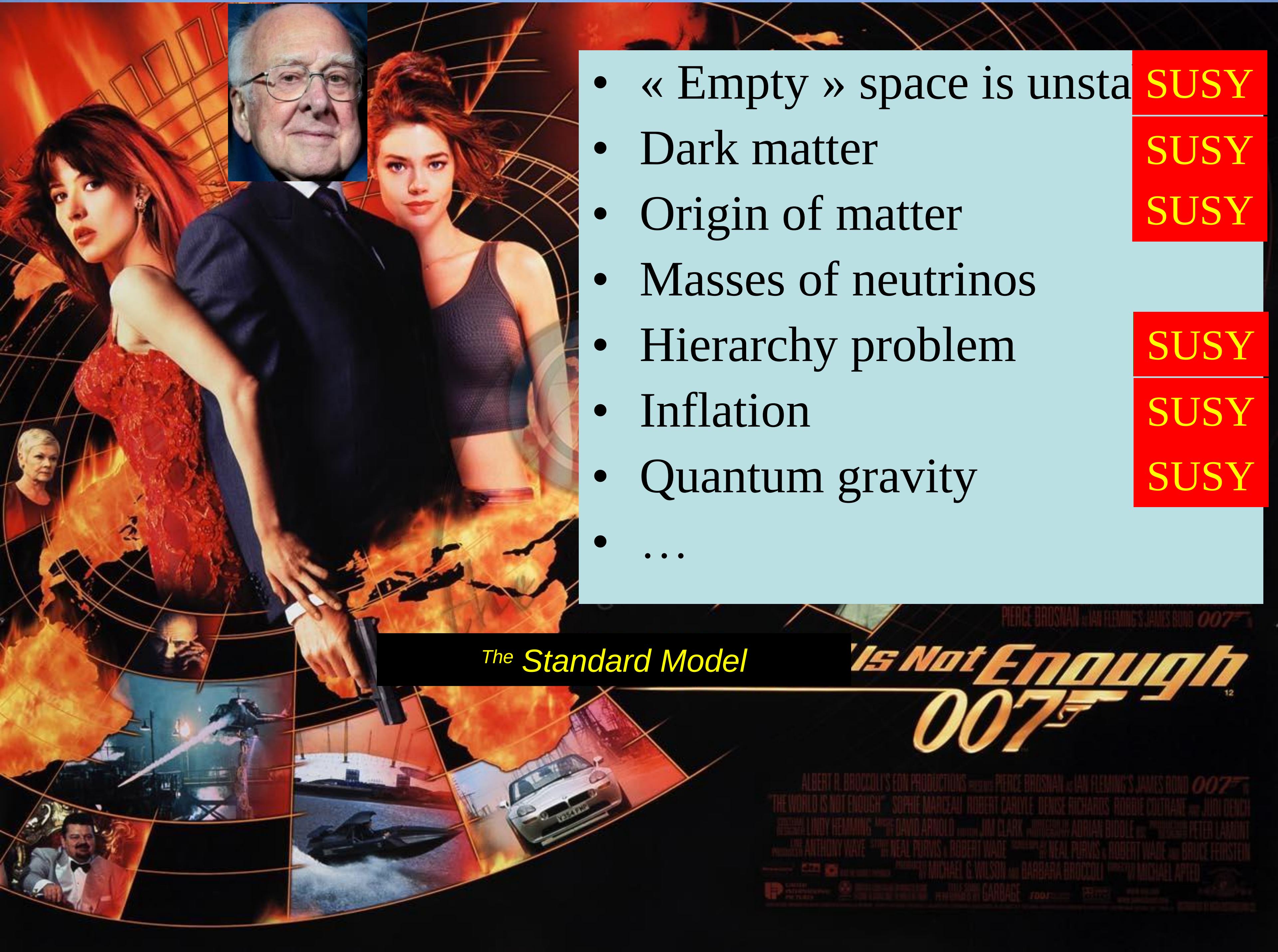
Constraints from rates



Constraints including kinematics



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



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

What lies beyond the Standard Model?

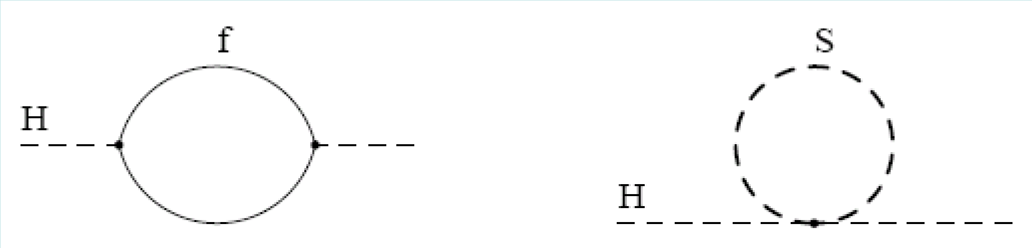
Supersymmetry

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**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

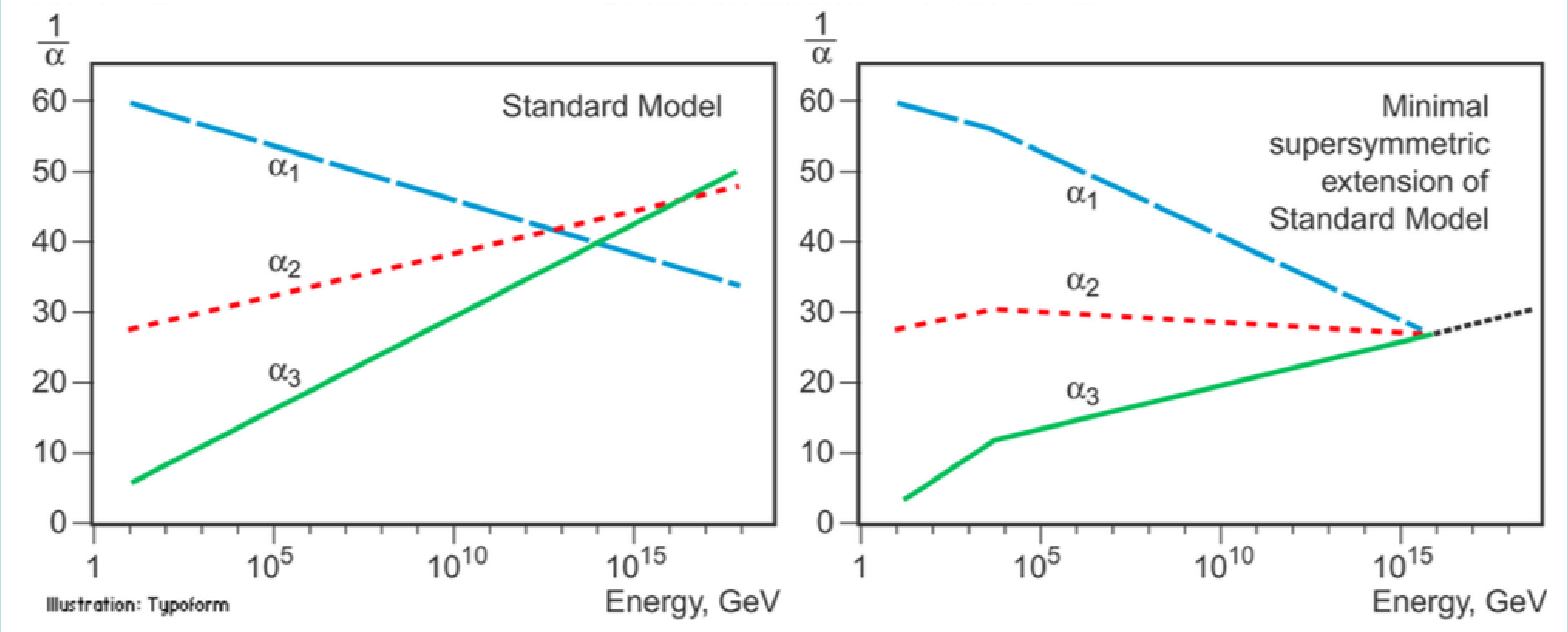
$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

Unification of Gauge Couplings



- **Impressive!**
- **Over-ambitious? Hubristic?**

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:

$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right)$$

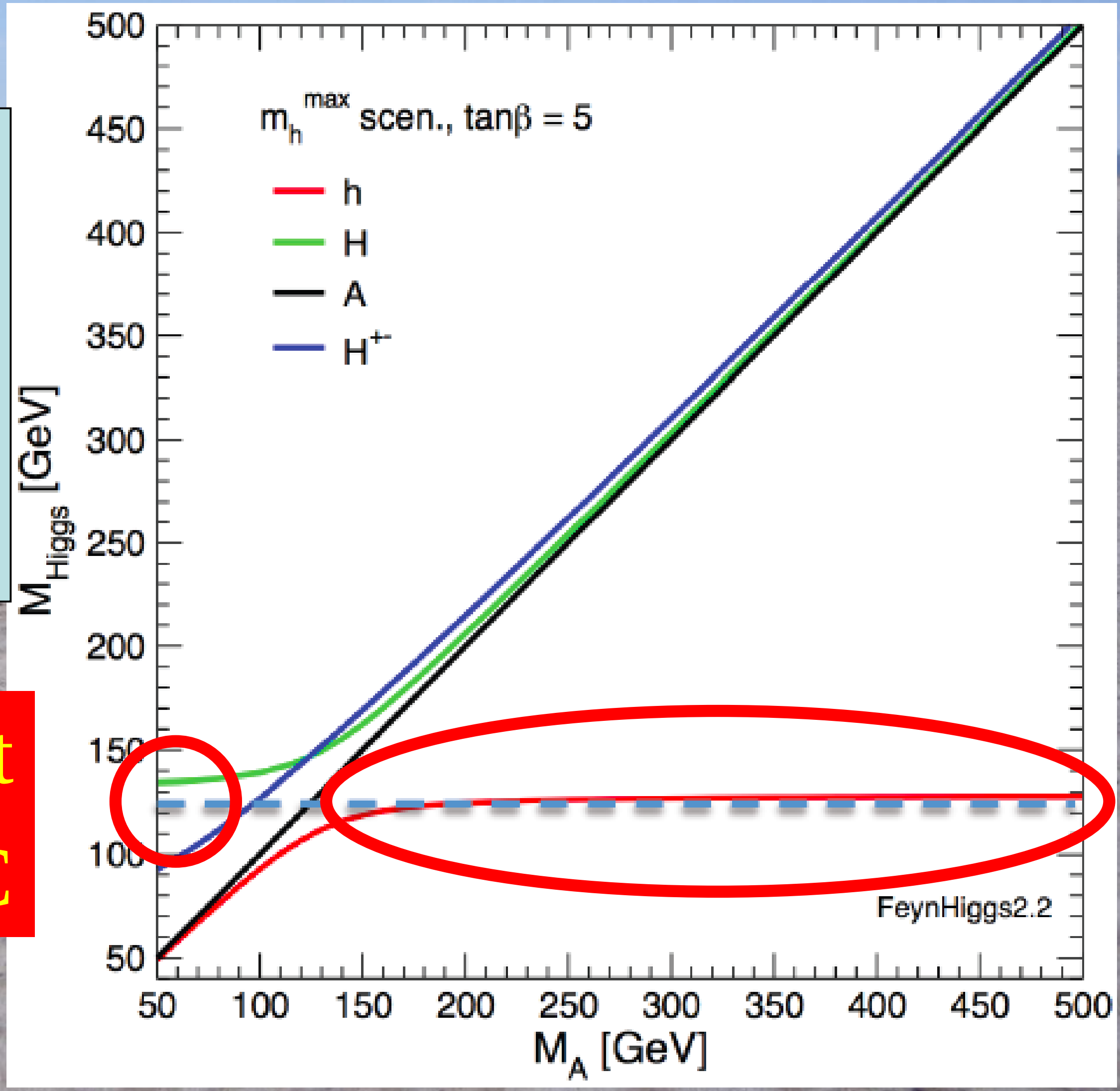
$\Delta M_H|_{TH} \sim 1.5$ GeV

MSSM Higgs Masses & Couplings

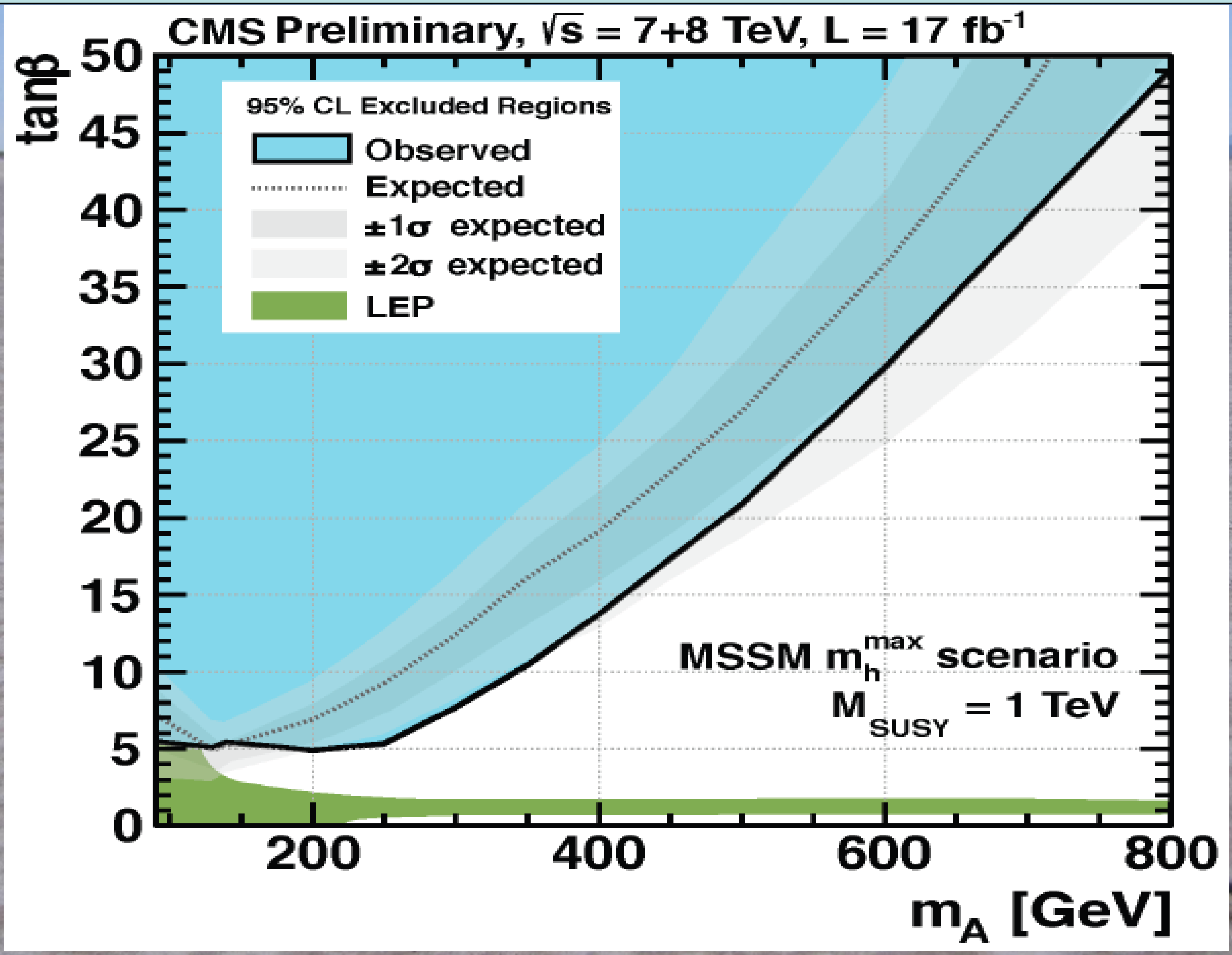
Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC



Limits on Heavy MSSM Higgses

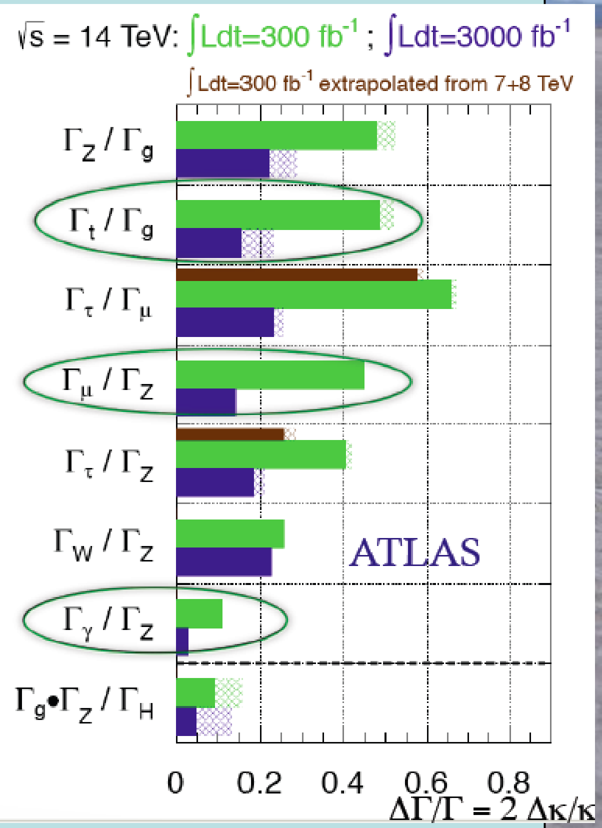


What Next: A Higgs Factory?

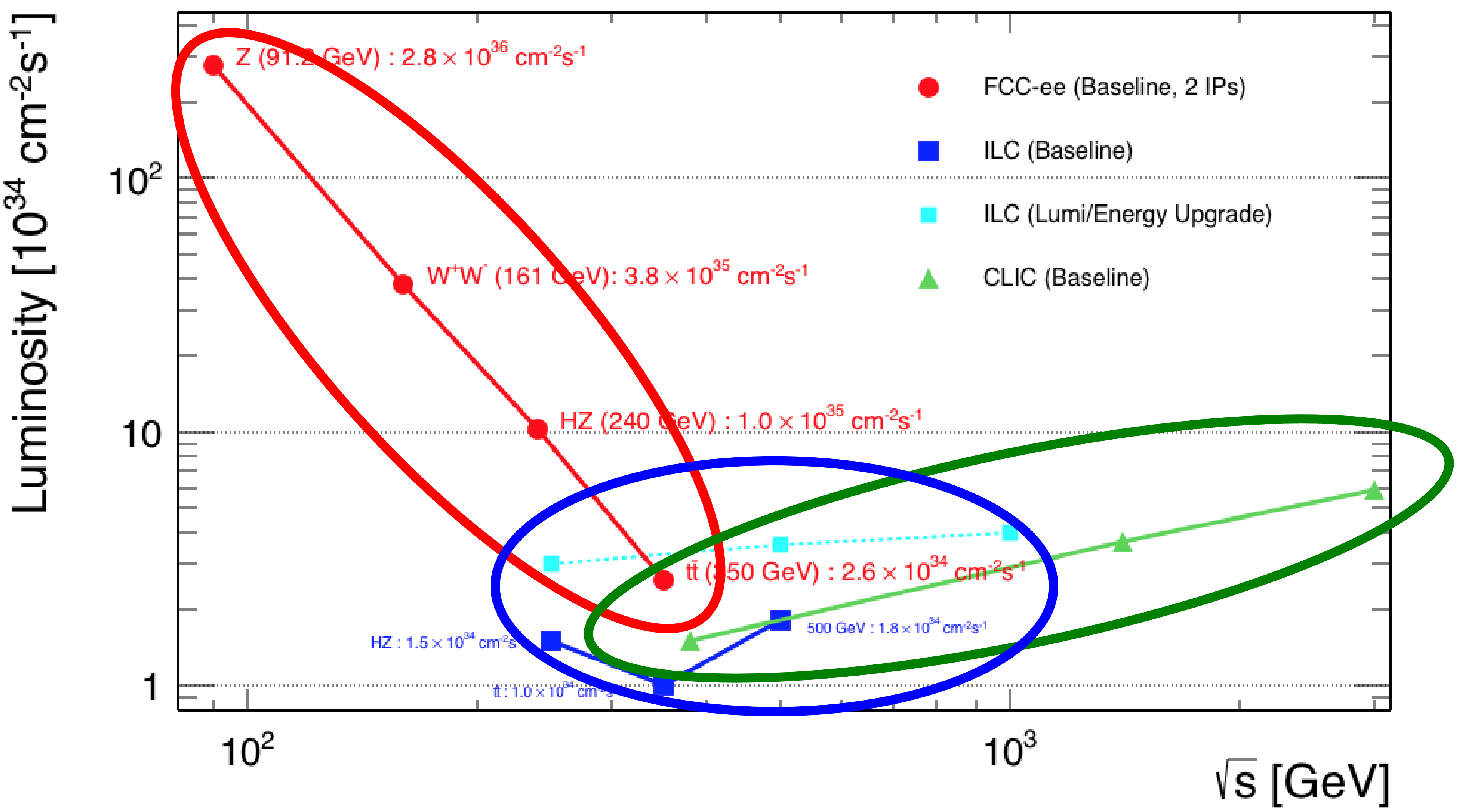
To study the 'Higgs' in detail:

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

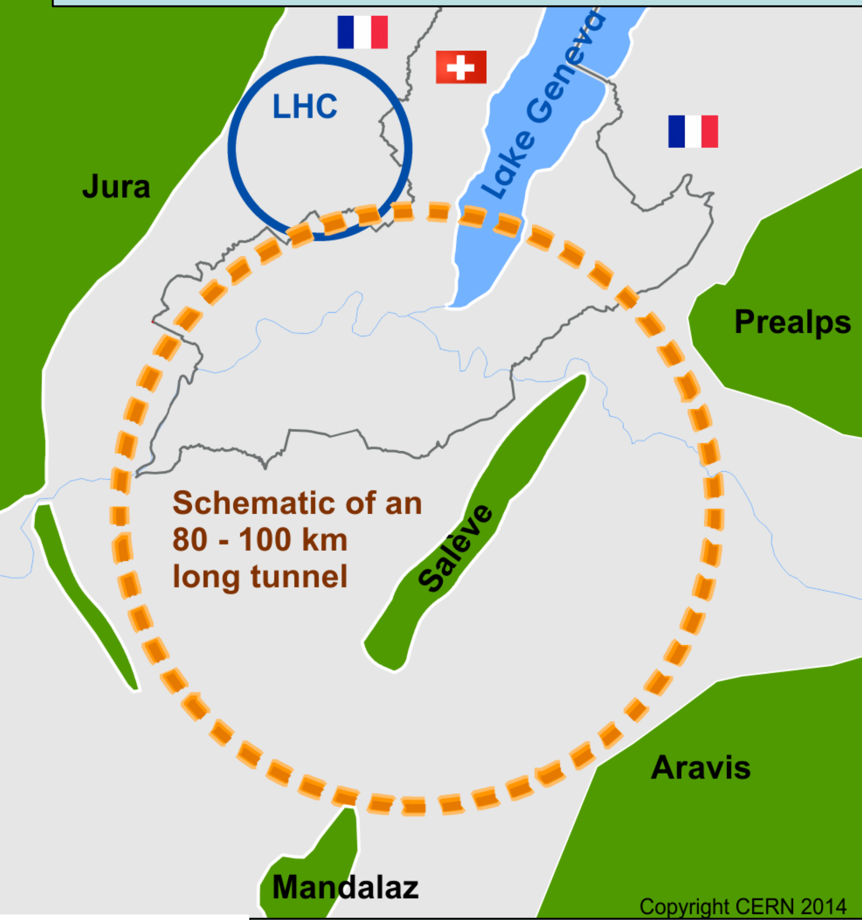
    (Larger cross section at higher energies)
- **A circular e^+e^- collider?**
- An ep collider?
- A γγ collider? A muon collider?
- **Wait for results from LHC @ 13/14 TeV**

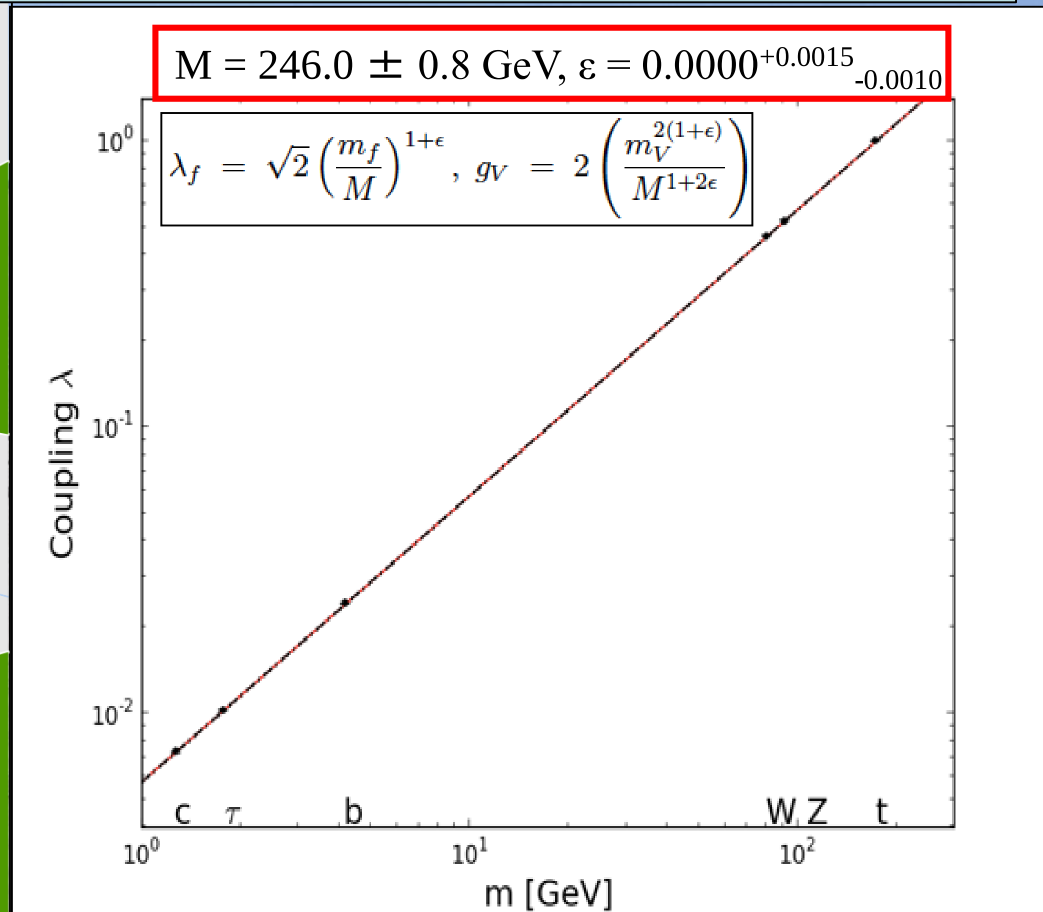


Projected e⁺e⁻ Colliders: Luminosity vs Energy



Future Circular e^+e^- Collider?





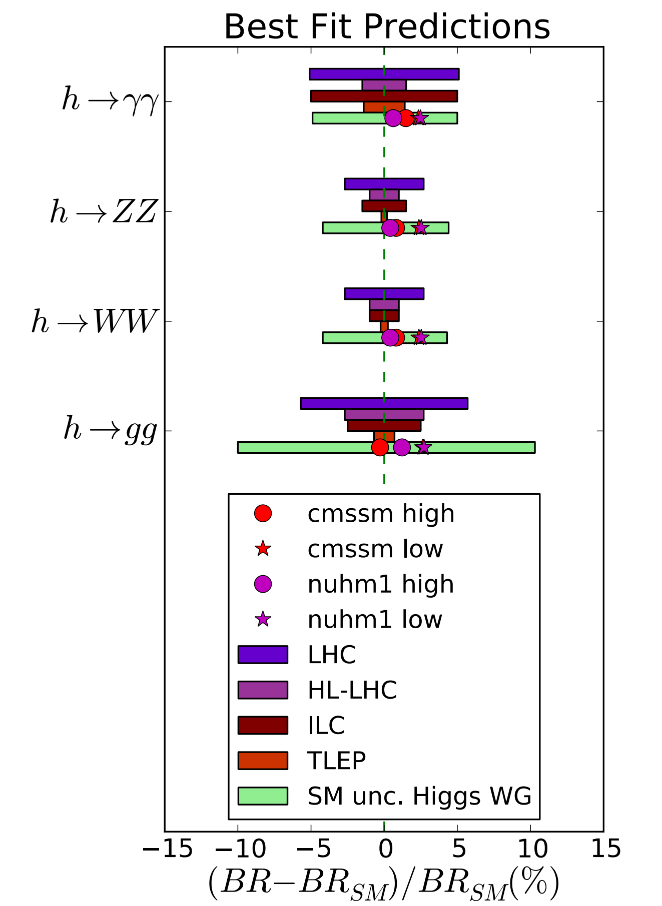
Not just Higgs physics:

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

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)

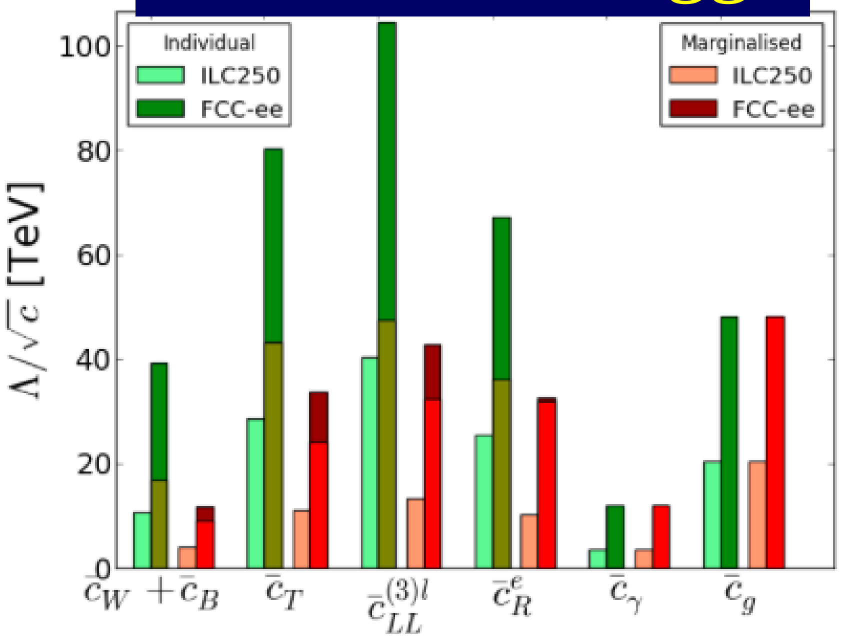


Buchmueller, JE et al: arXiv:1505.04702

JE & Tevong You, arXiv:1510.04561

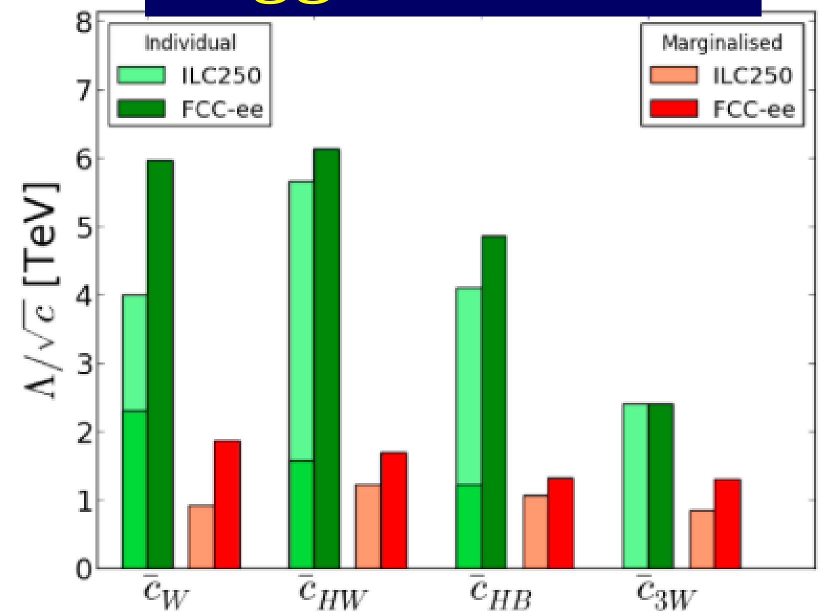
FCC-ee Higgs & TGC Measurements

EWPTs and Higgs



- Shadings:
  - With/without theoretical EWPT uncertainties

Higgs and TGCs



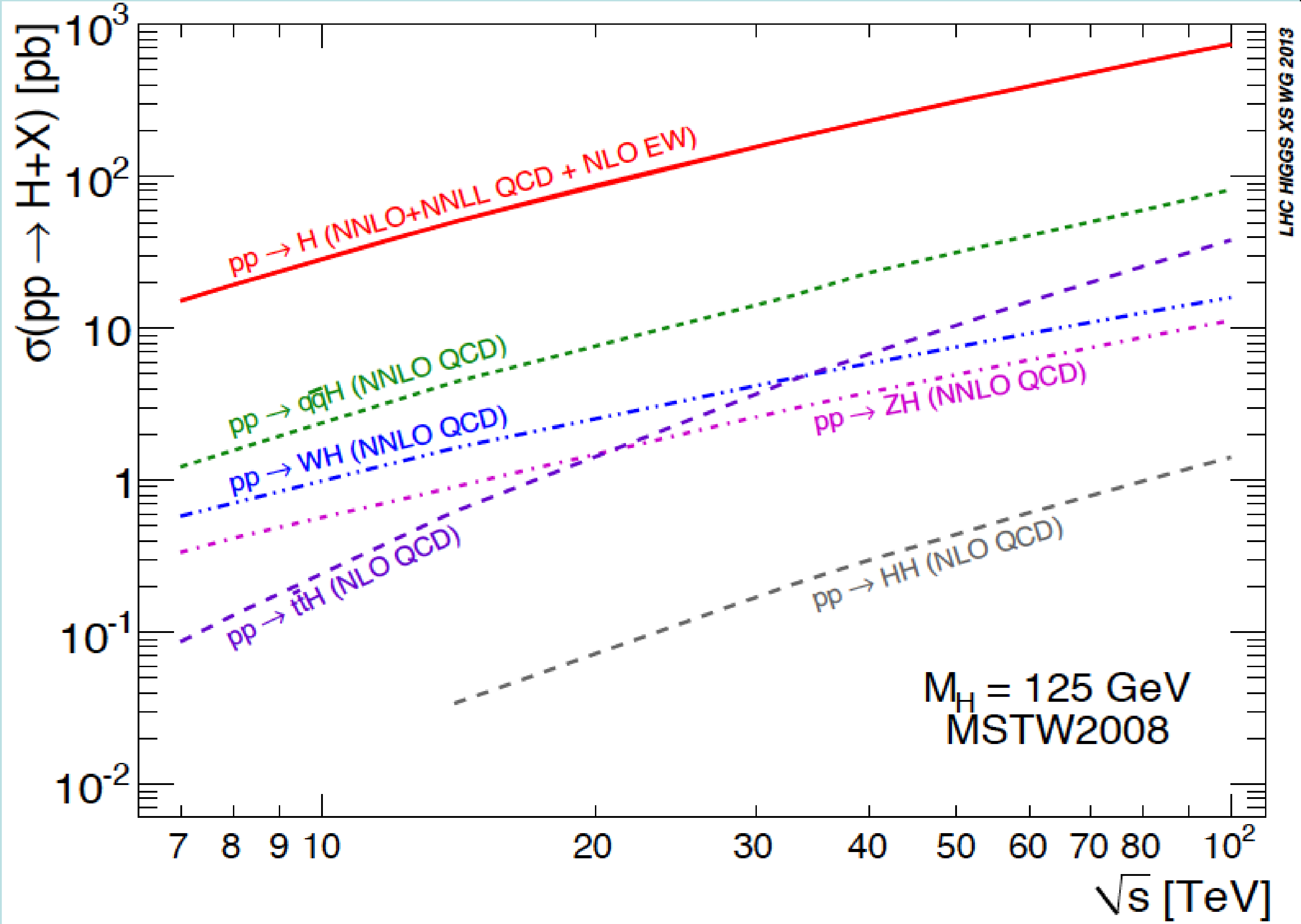
- Shadings of green:
  - Effect of including TGCs at ILC

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

Higgs Cross Sections

Benedikt

- 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, TLEP offers the best prospects
  - and also other high-precision physics