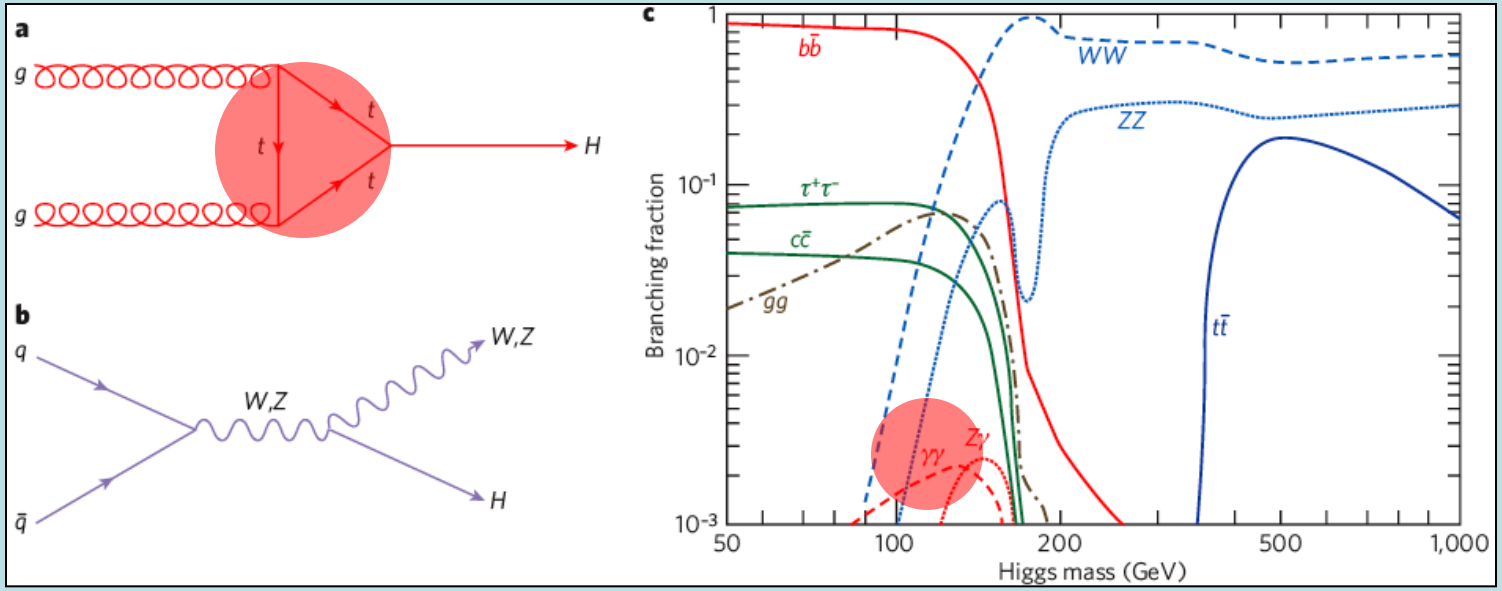
Physics Overview

4th TLEP workshop (EuCARD-AccNet)

John Ellis
King's College London
(& CERN)

Higgs Decay Branching Ratios

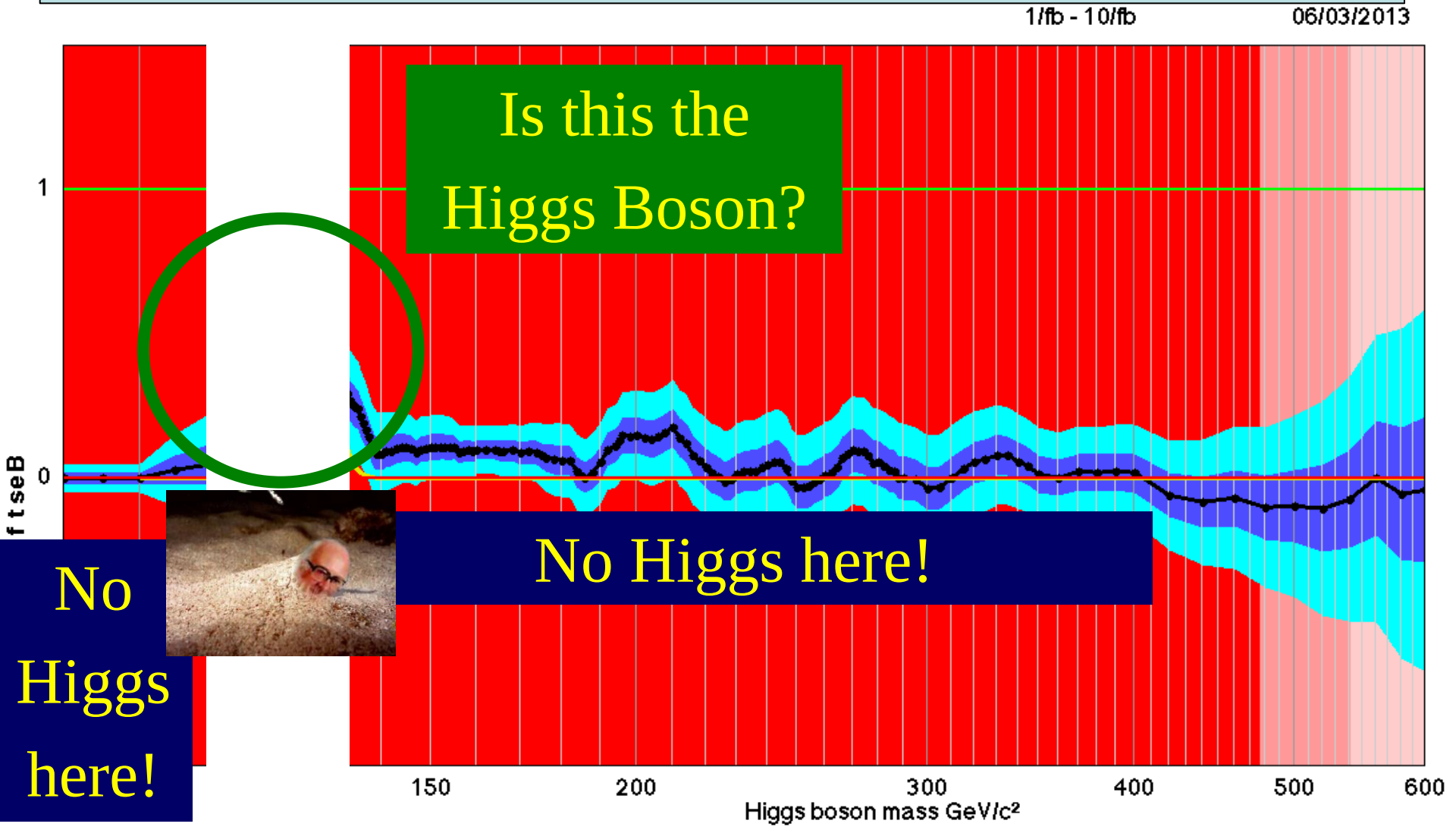
- Couplings proportional to masses (?)



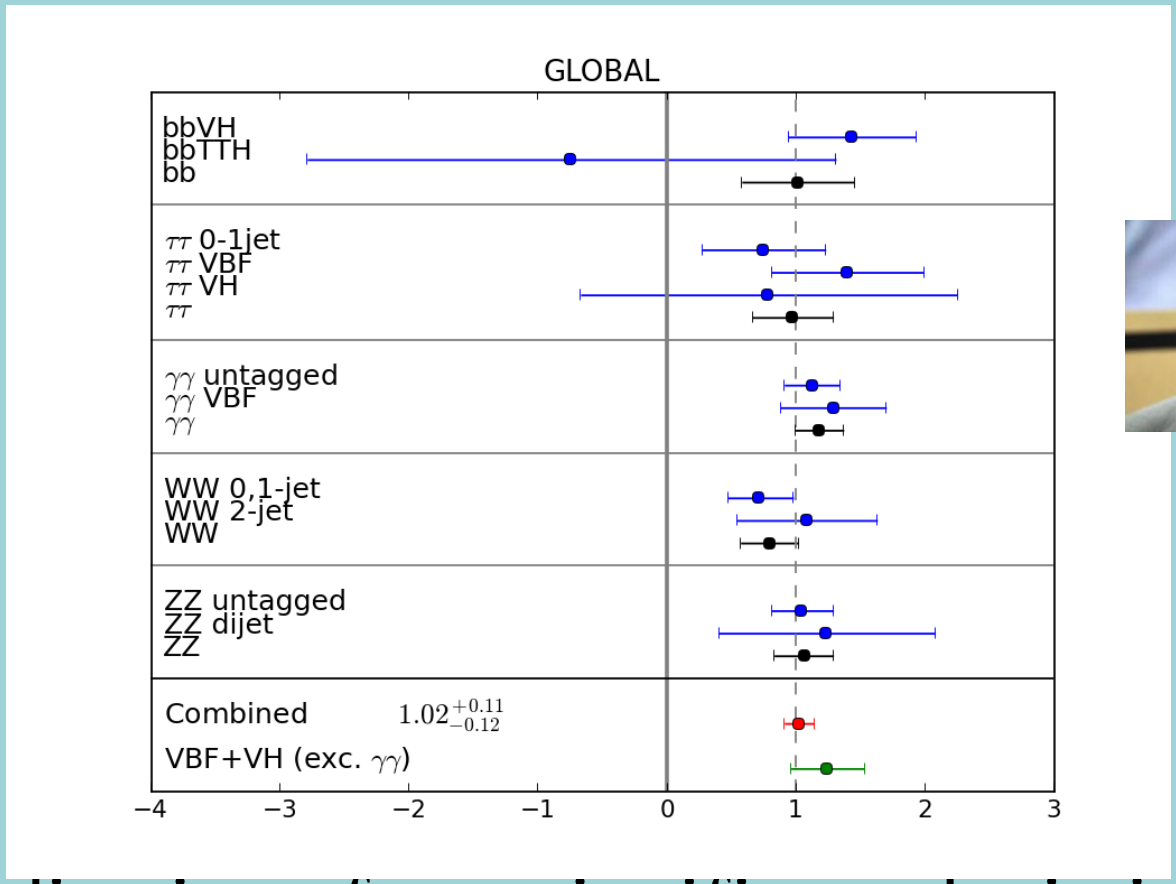
- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

Unofficial Combination of Higgs Search Data from March 6th



Couplings resemble Higgs of Standard Model



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

JE & Tevong You, arXiv:1303.3879

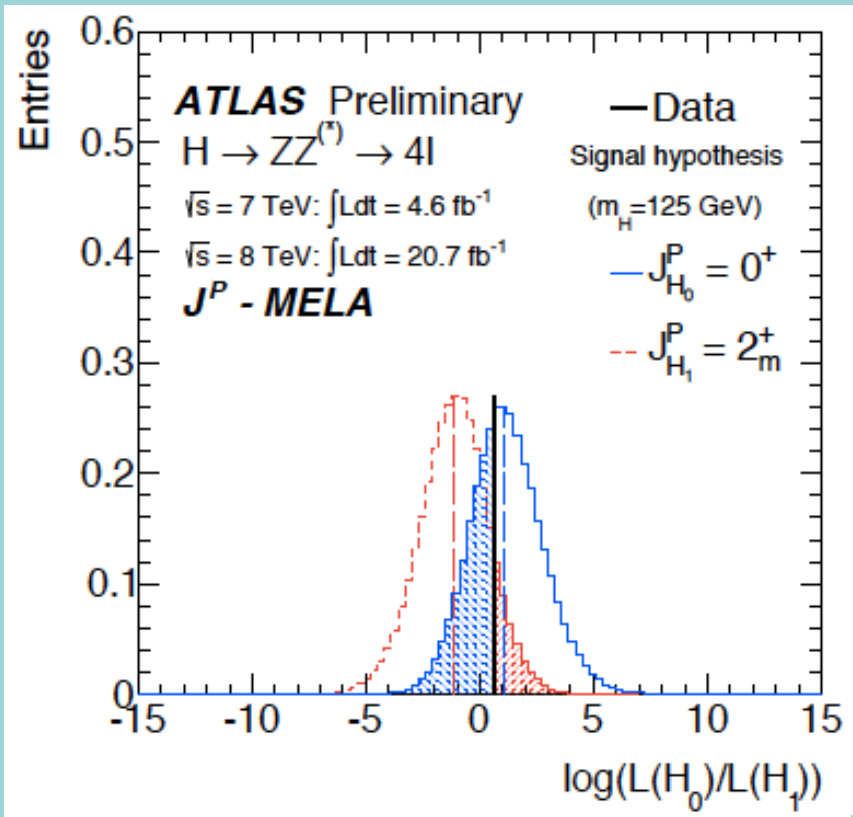
Some Questions

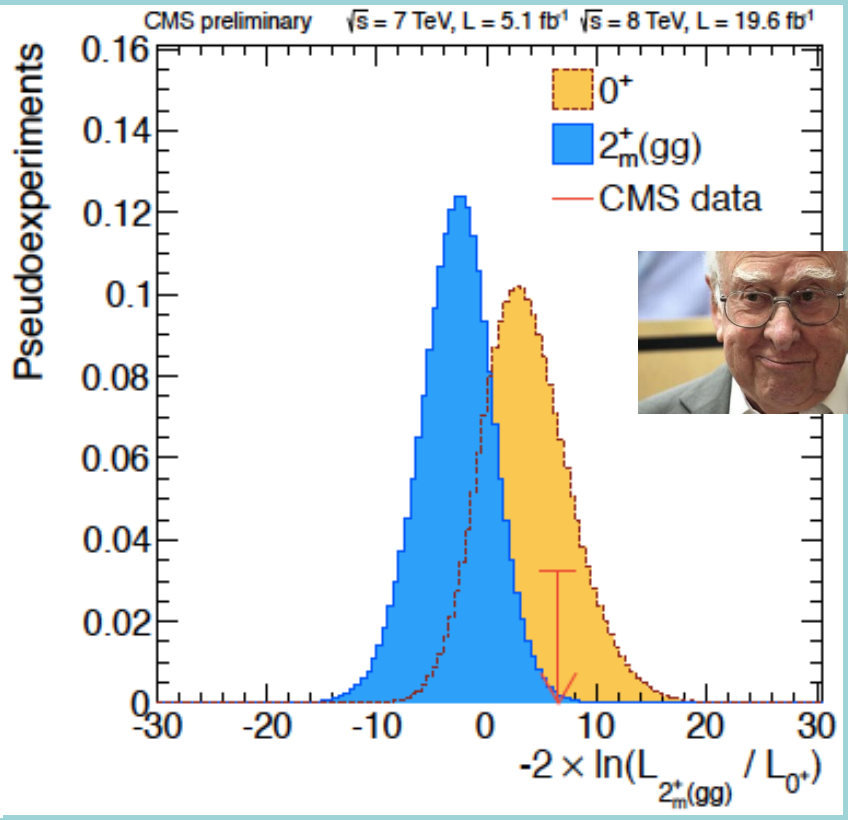
- What is it?
  - –Higgs or …?
- What else is there?
  - –Supersymmetry or …?
- What next?
  - –A Higgs factory or …?

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?

The ‘Higgs’ Spin is probably 0



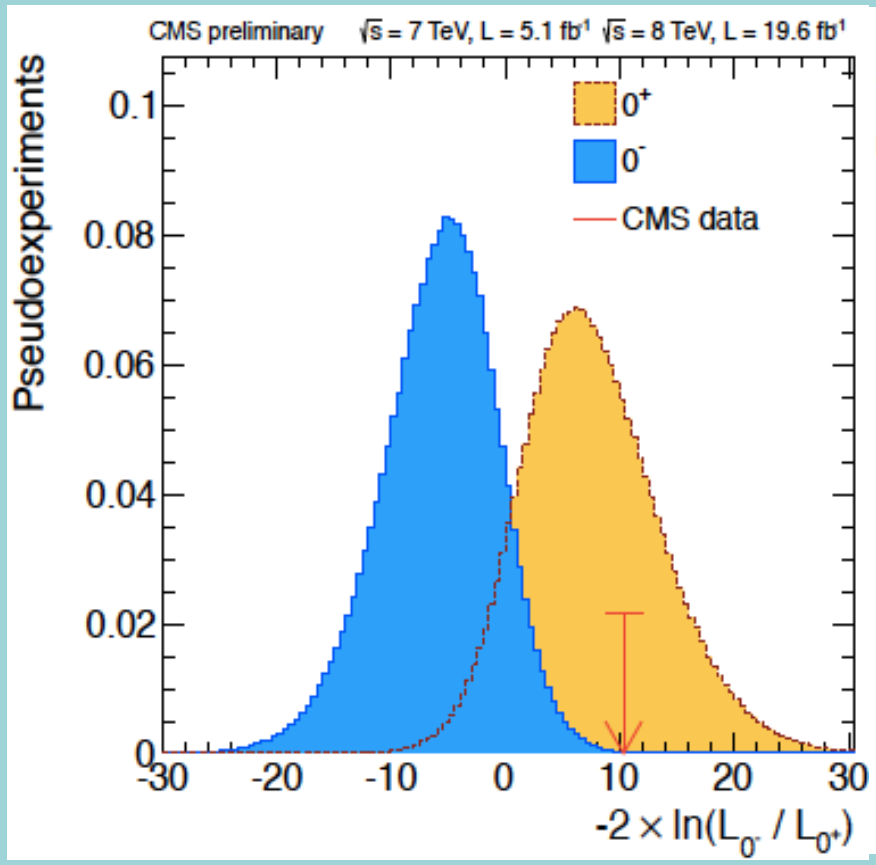


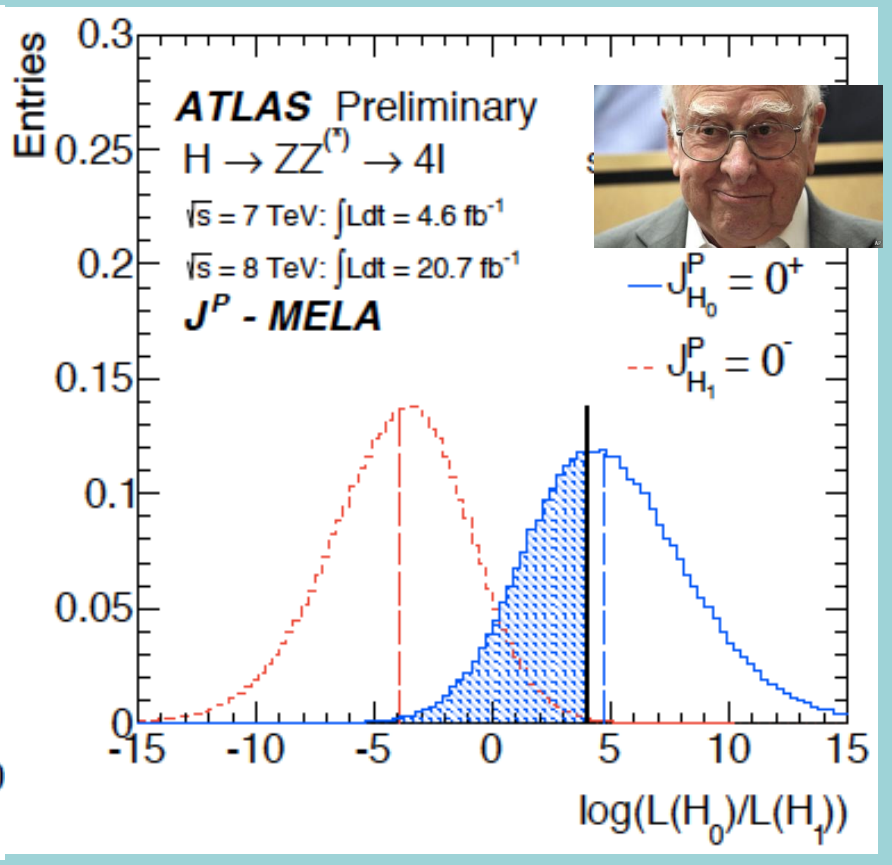
- Graviton-like spin-2 disfavoured at 98.5% CL

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?

General Analysis of 'unHiggs' Models

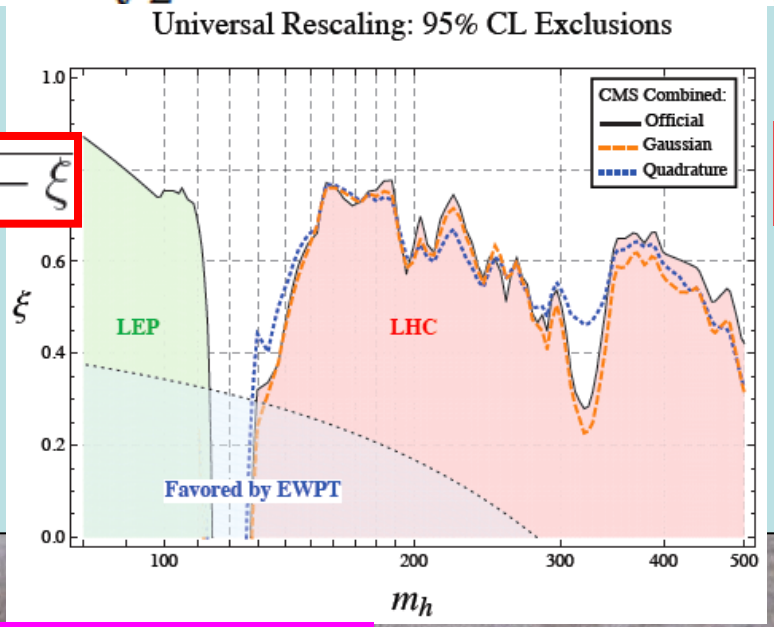
- Parametrization of effective Lagrangian:

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

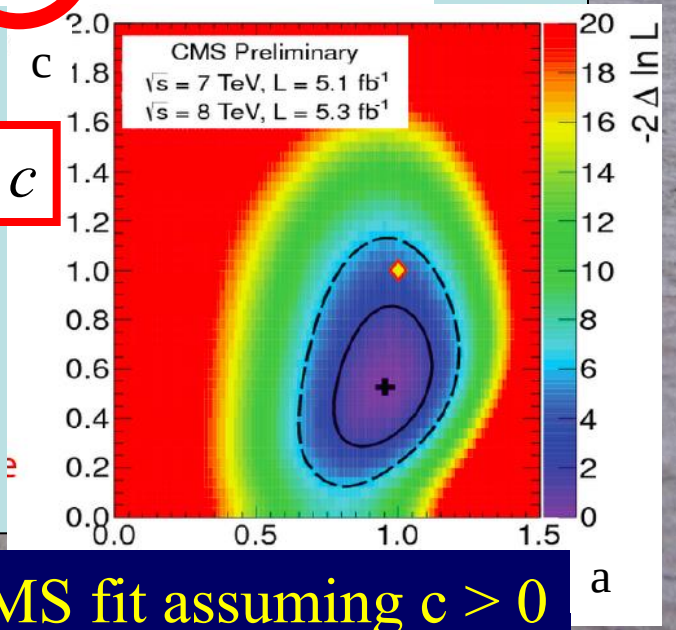
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\frac{h}{v} + c_{2u}\frac{h^2}{v^2} + \cdots\right)$$

- Fits

$a = c = \sqrt{1-\xi}$



$a \neq c$



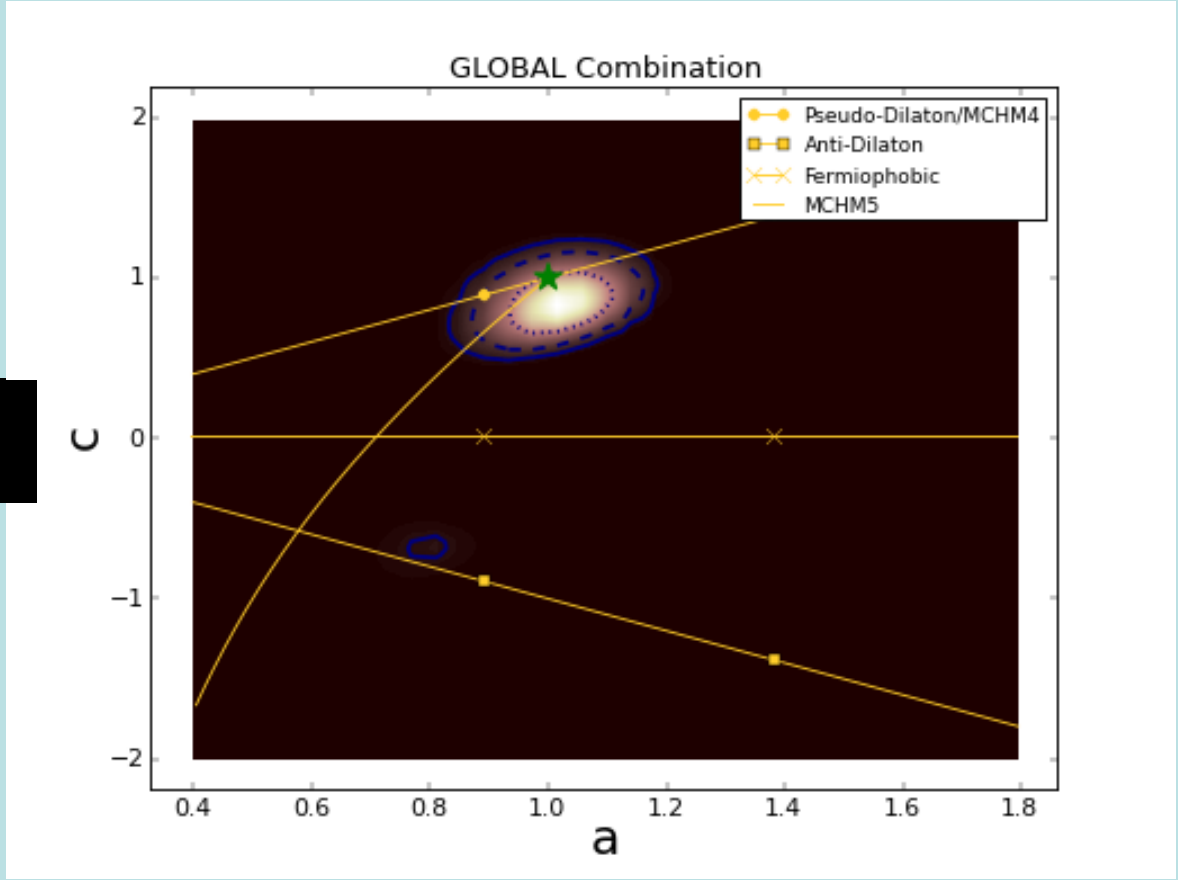
CMS fit assuming c > 0

Azatov, Contino, Galloway: arXiv:1202.3415

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

What is it ?

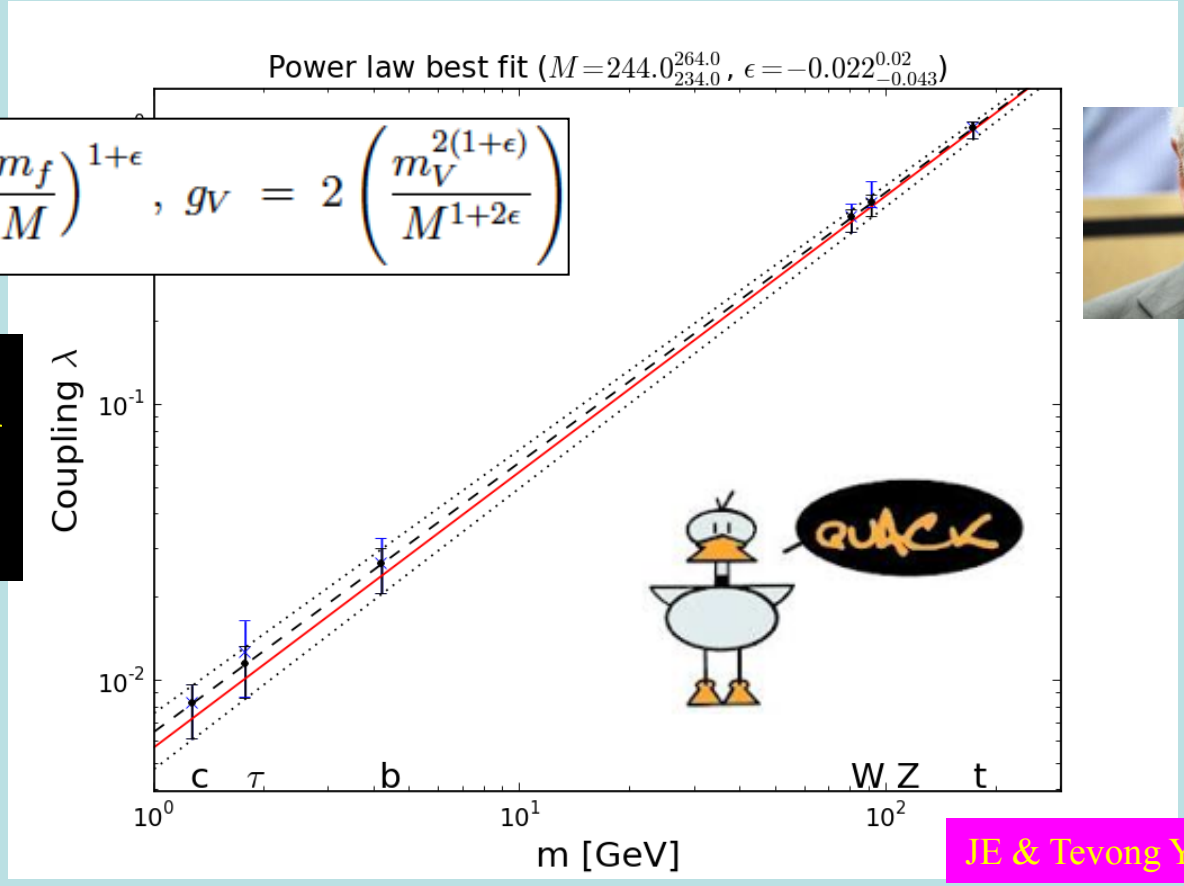
- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
- Quantum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

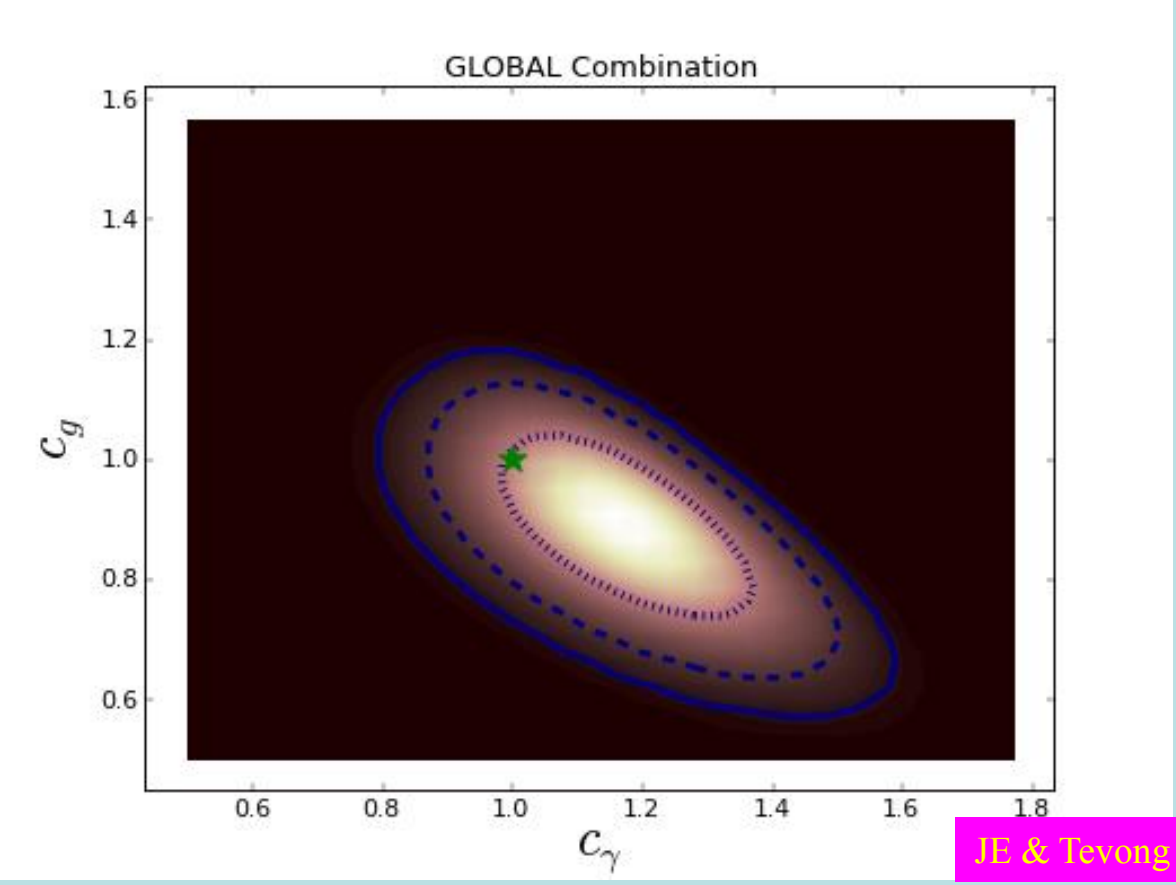
- **Red line = SM**, dashed line = best fit

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 $\gamma\gamma$, CMS sees deficit



JE & Tevong You, arXiv:1303.3879

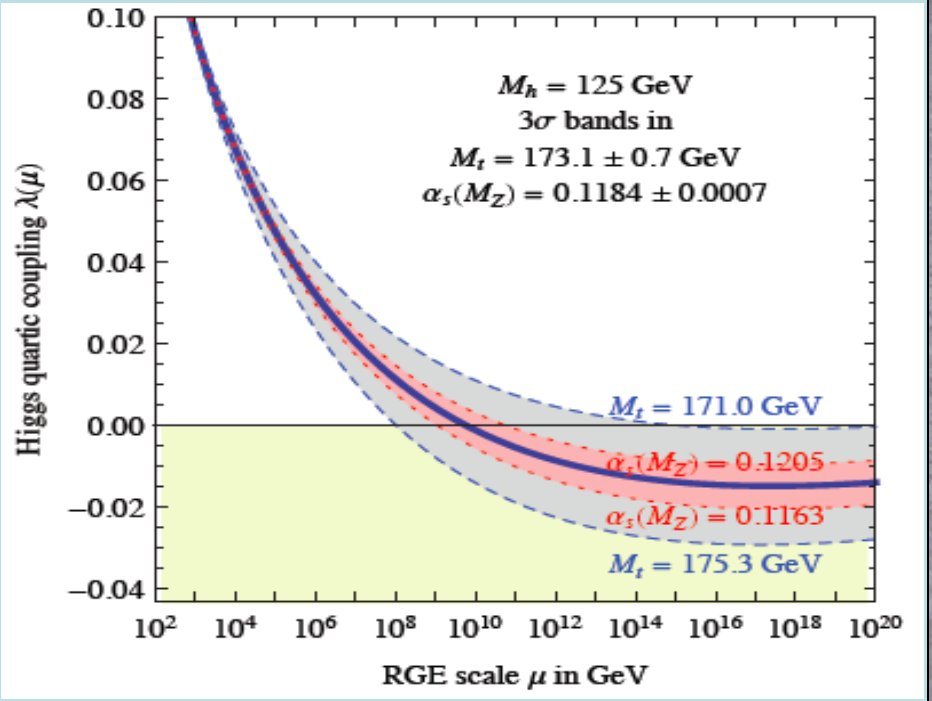
- Loop diagrams ~ Standard Model?

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?
  - **$\gamma\gamma$ coupling > Standard Model?**
- What are its self-couplings?

Theoretical Constraints on Higgs Mass

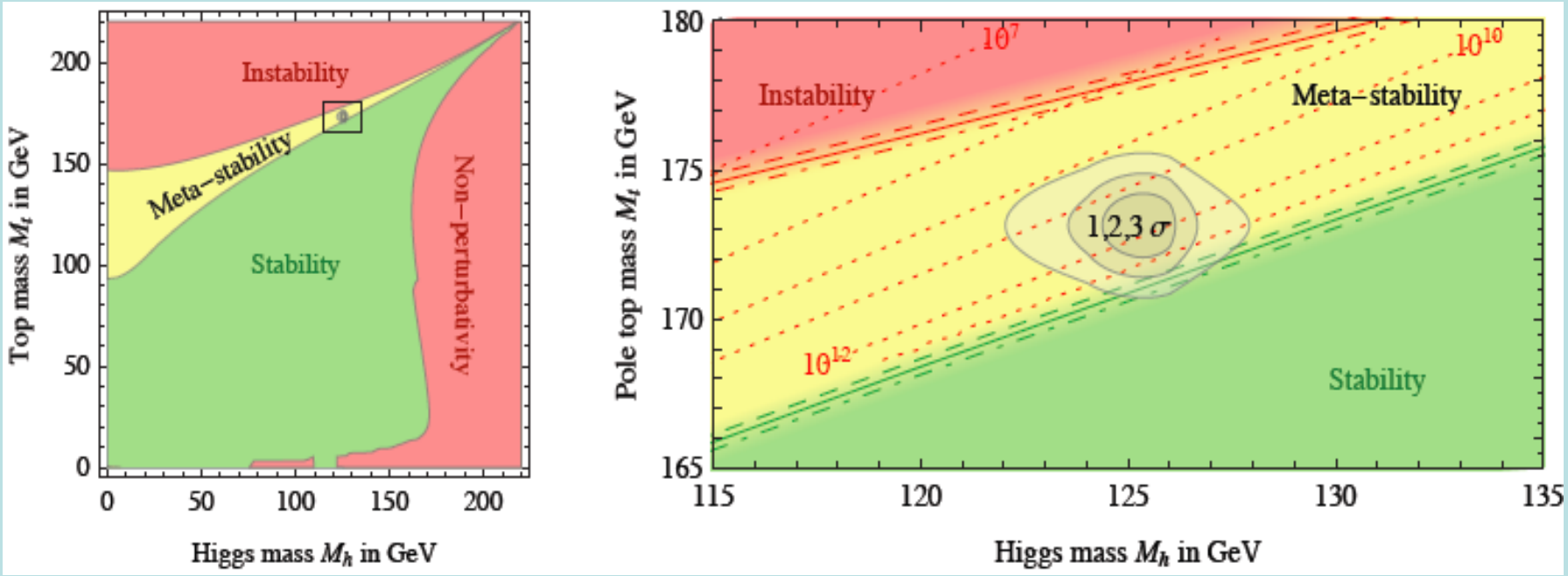
- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**



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



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

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

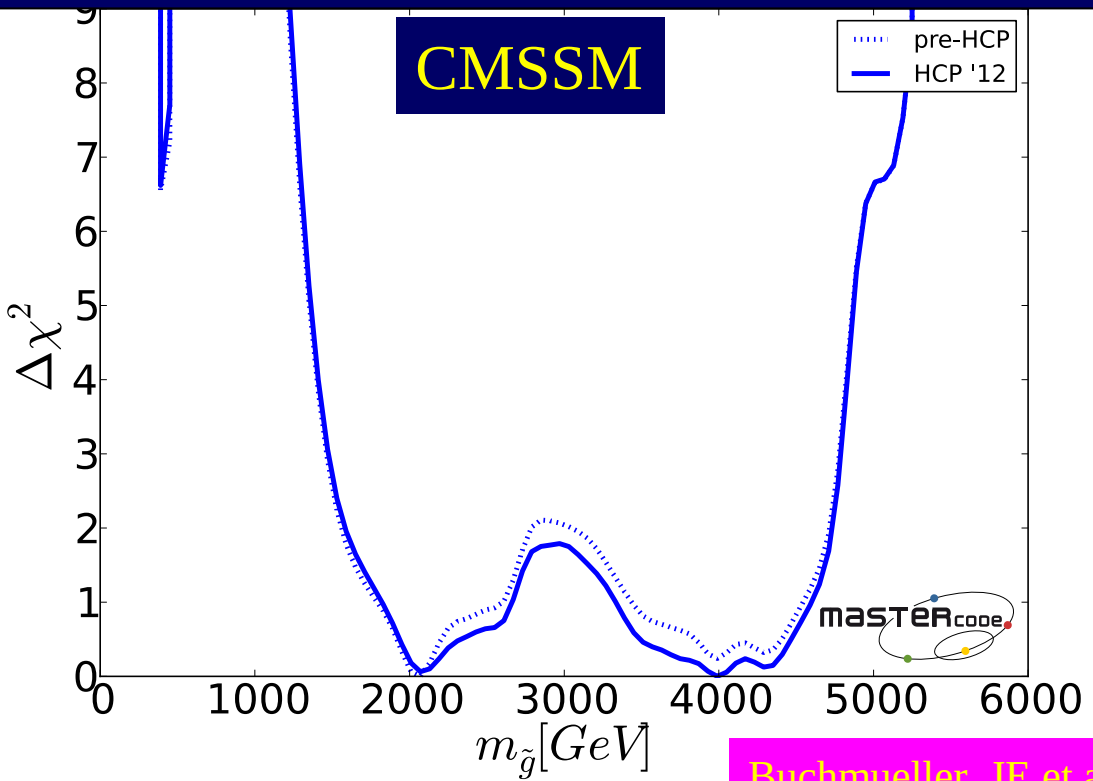
What else is there?

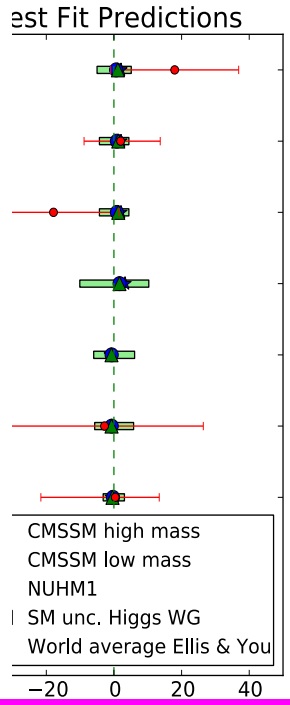
Supersymmetry

Gluino mass

CMSSM

- Successf
  - Should
- Successf
  - Should





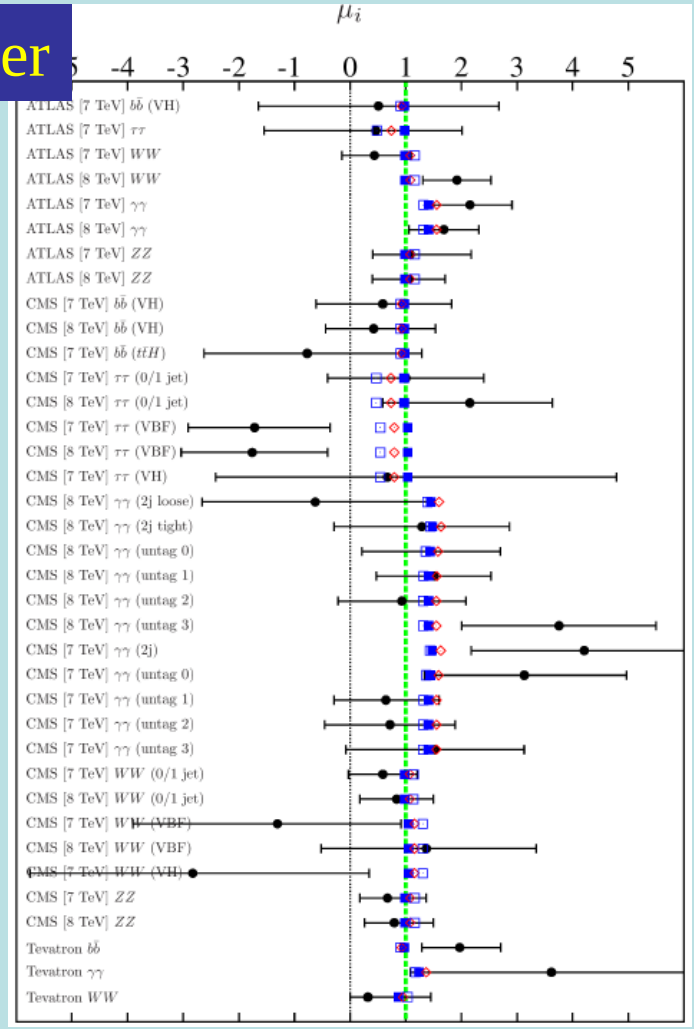
Buchmueller, JE et al: arXiv:1207.3715

Bechtle et al., arXiv:1211.1955

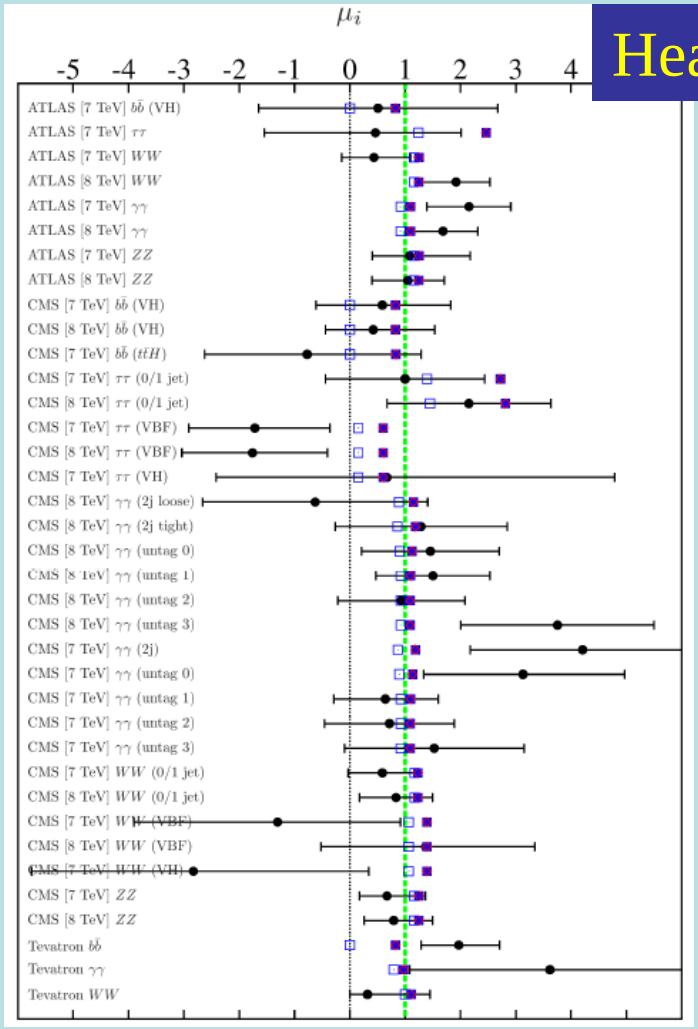
Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

Lighter



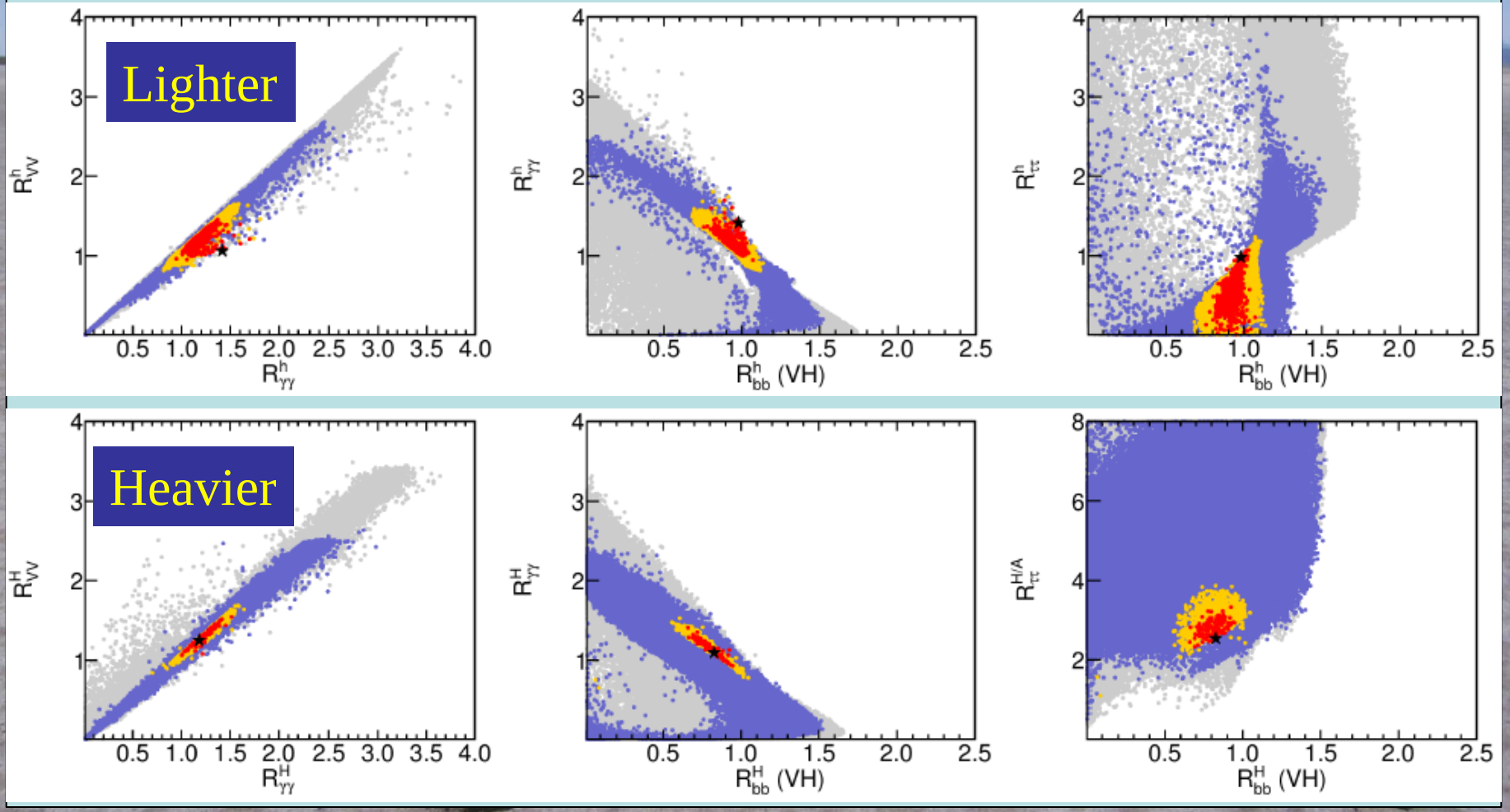
Heavier



Bechtle et al., arXiv:1211.1955

Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

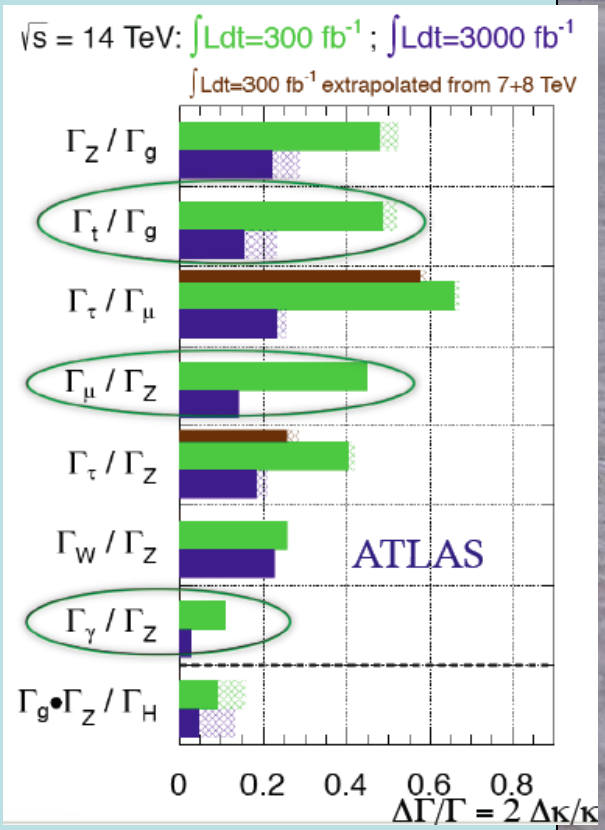


What Next: A Higgs Factory?

To study the 'Higgs' in detail:

- The LHC
  - Rethink 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: TLEP, …
  - A photon-photon collider: SAPPHiRE
- A muon collider



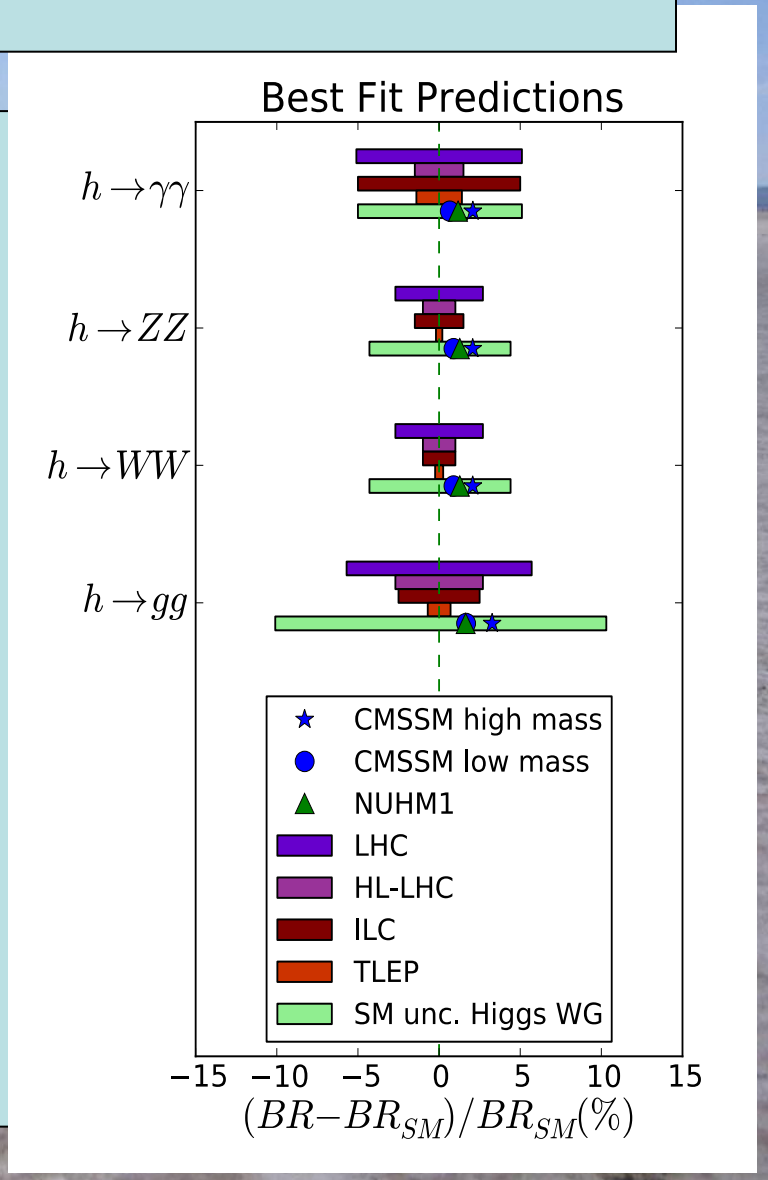
Higgs Factory Summary

Best precision

Accelerator →Physical quantity ↓	LHC 300fb^{-1} /exp	HL-LHC 3000fb^{-1} /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2021	2030	2035	2045	2035	2035
N_H	1.7 x 10^7	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) (1.4 10^5 Hvv)	4 10^5ZH	2 10^6 ZH
m_H (MeV)	100	50	35	35	26	7
$\Delta\Gamma_H/\Gamma_H$	--	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30	<10	--	--	14%	7%

Impact of Higgs Factory?

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



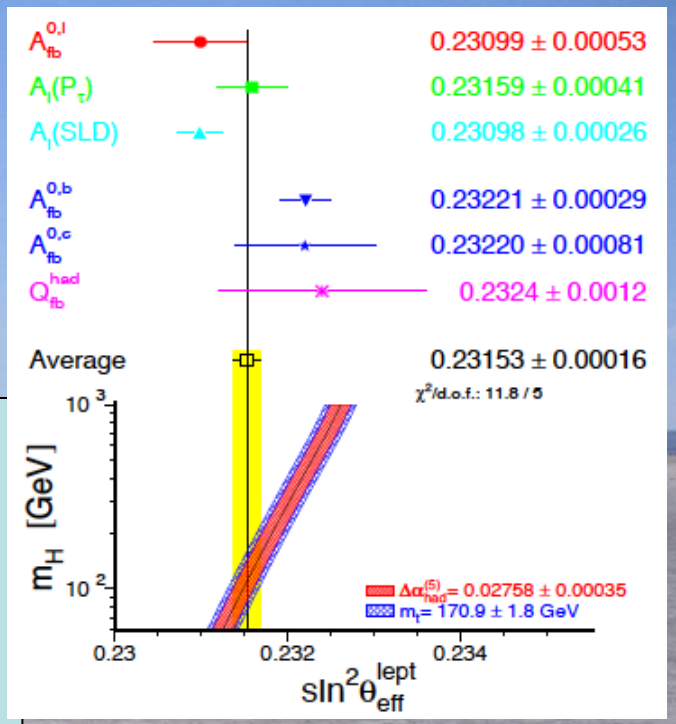
Impact of TeraZ & GigaW

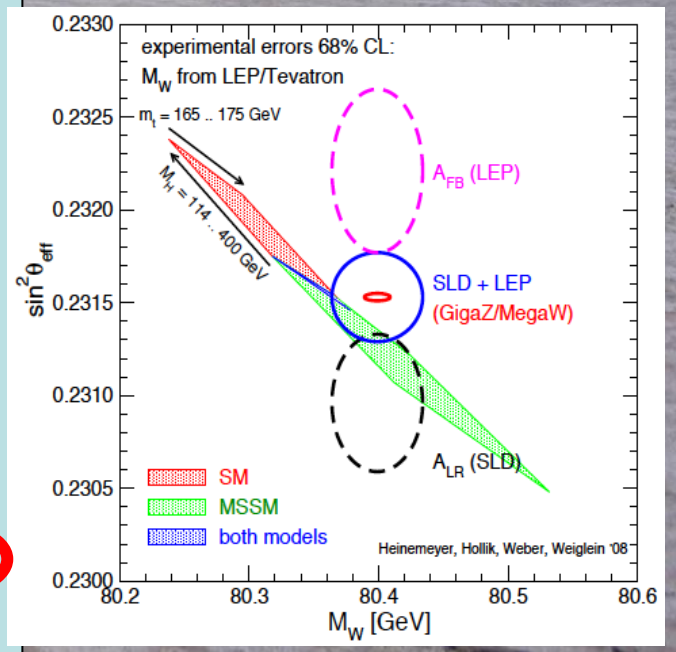
- No serious studies yet: refer back to GigaZ studies Heinemeyer & Weiglein, arXiv:1007.5232
- Issues in LEP/SLC data at Z peak
- Big improvement possible at GigaZ

observable	central exp. value	$\sigma \equiv \sigma^{\text{today}}$	σ^{LHC}	σ^{ILC}
M_W [GeV]	80.399	0.023	0.015	0.007
$\sin^2\theta_{\text{eff}}$	0.23153	0.00016	0.00020–0.00014	0.000013
m_t [GeV]	173.3	1.1	1.0	0.1

- **BUT** $\delta\alpha_{\text{em}}$, δM_Z, higher-order EW …

	$\delta m_t = 1$ GeV	$\delta m_t = 0.1$ GeV	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2\theta_{\text{eff}}$ $[10^{-5}]$	3	0.3	1.8	1.4
ΔM_W [MeV]	6	1	1	2.5





Precision at TeraZ/GigaW?

- Estimates using M_H, M_Z, α_{em}, m_t, α_s:

  $M_W = 80.361 \pm 0.006 \pm 0.004$ GeV

  (parametric) (higher-order EW)

  $\sin^2\theta_{eff} = 0.23152 \pm 0.00005 \pm 0.00005$

  (parametric) (higher-order EW)

Ferroglia & Sirlin, arXiv:1211.1864

- GigaZ/MegaW aim at

  $\delta M_W = 7$ MeV, $\delta \sin^2\theta_{eff} = 10^{-5}$

- What can be done with TeraZ/GigaW?
- **Much theoretical work also needed!**

Summary

- Beyond any reasonable doubt, the LHC has discovered a (the) Higgs boson
- 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
- A severe test also for theoretical physics