INTERPRETAZIONE TEORICA DEI RISULTATI SPERIMENTALI SUL BOSONE DI HIGGS

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VI Workshop Italiano sulla fisica p-p a LHC - Genova, 8-10 Maggio 2013

PART 1

What data say on the new boson

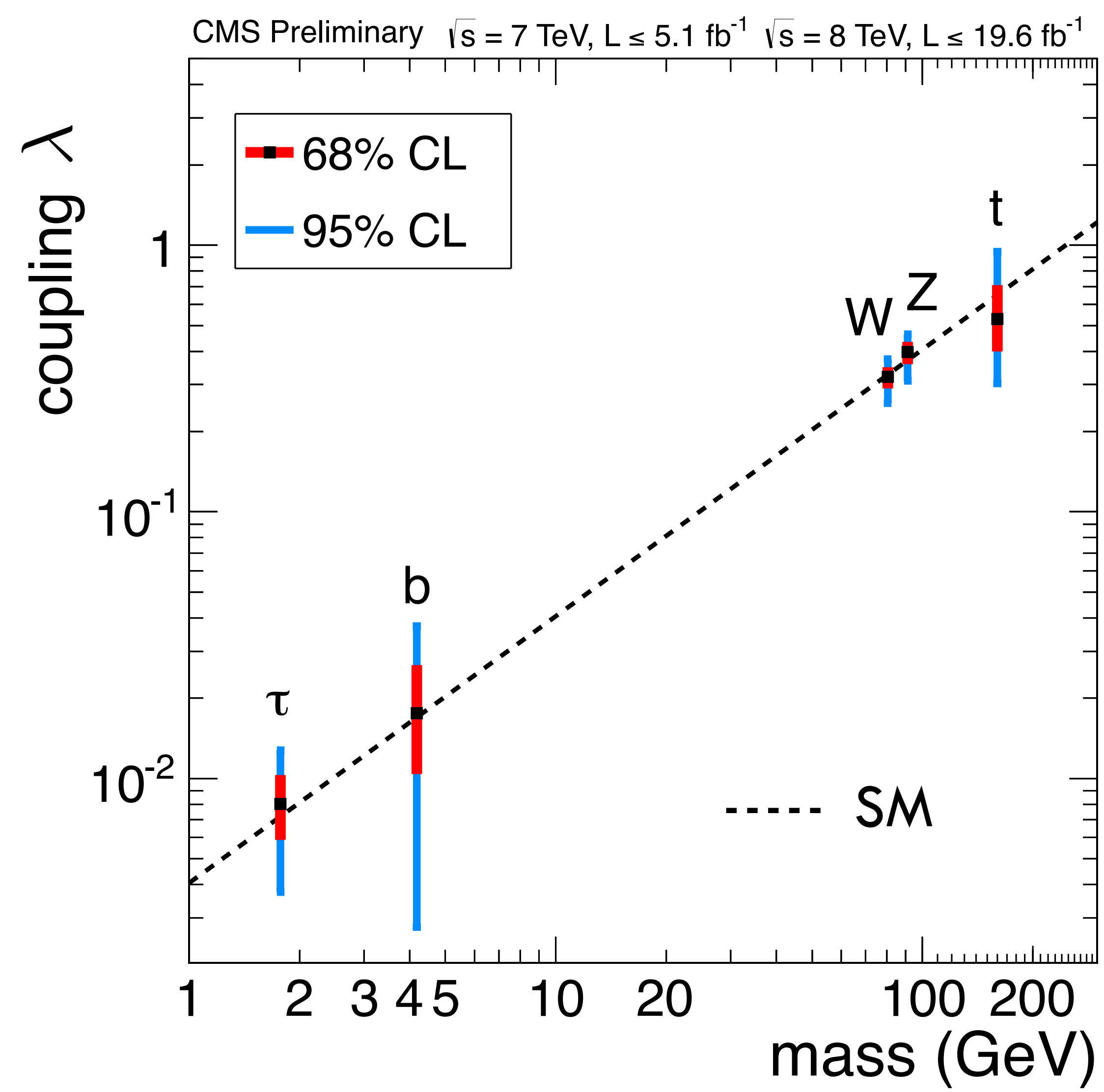
“It has to do with the EWSB”

Already first data gave evidence of:

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

True in the SM:

$$\lambda_\psi = \frac{m_\psi}{v}\,, \qquad \lambda_V = \frac{m_V}{v}$$



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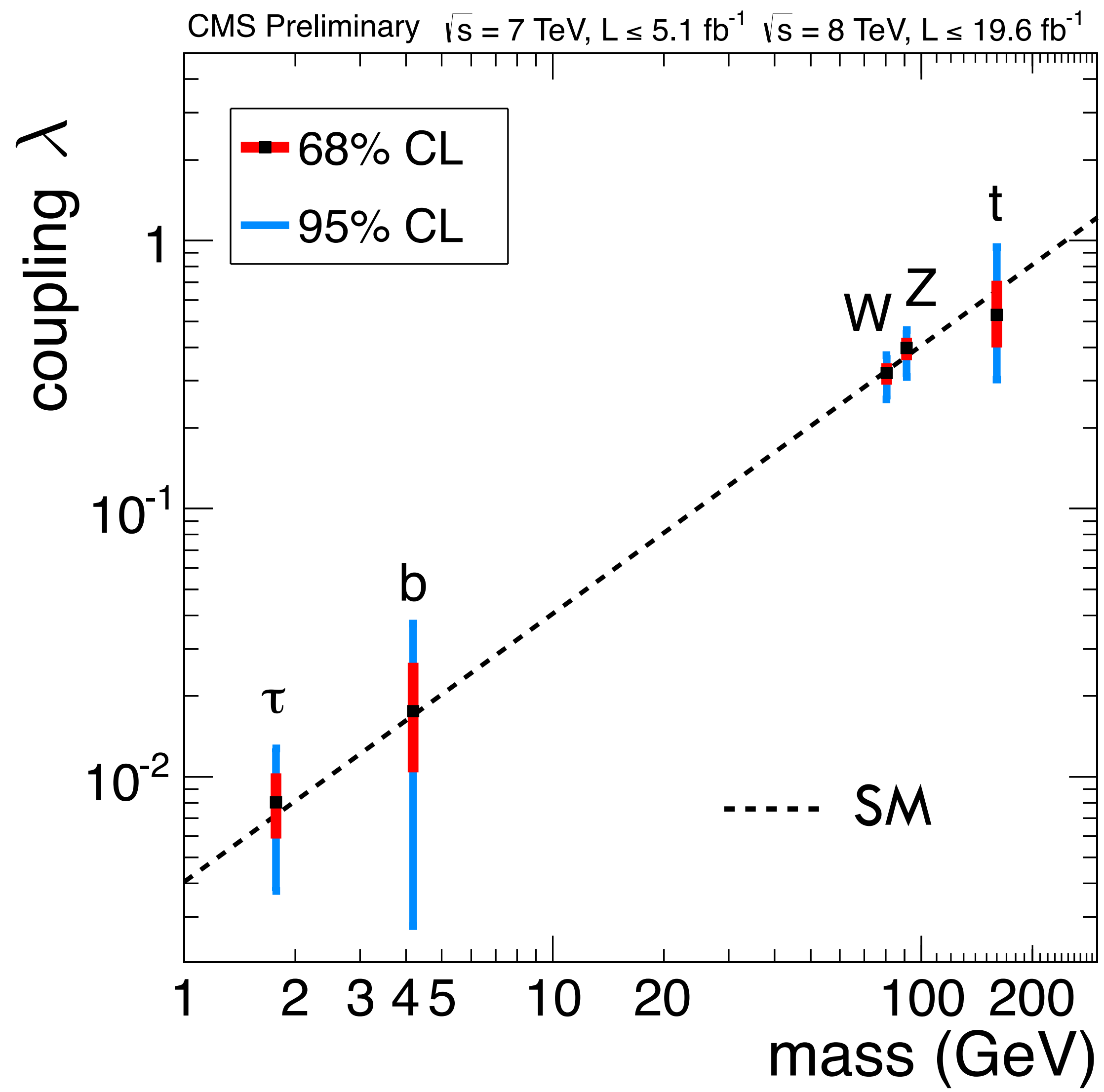

True in the SM:

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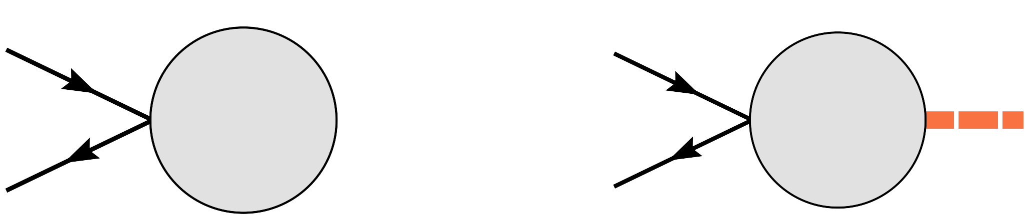
Scaling coupling ∝ mass follows naturally if the new boson is part of the sector that breaks the EW symmetry

It does *not* necessarily imply that the new boson is part of an $SU(2)_L$ doublet

For a non-doublet one naively expects: $$\frac{\lambda - \lambda^{SM}}{\lambda^{SM}} = O(1)$$

Ex: composite NG boson in TC



“It looks like a doublet”

New data show an agreement with the SM prediction within ~20%-30%:

The new boson does not look an impostor at all, it closely resembles the SM Higgs

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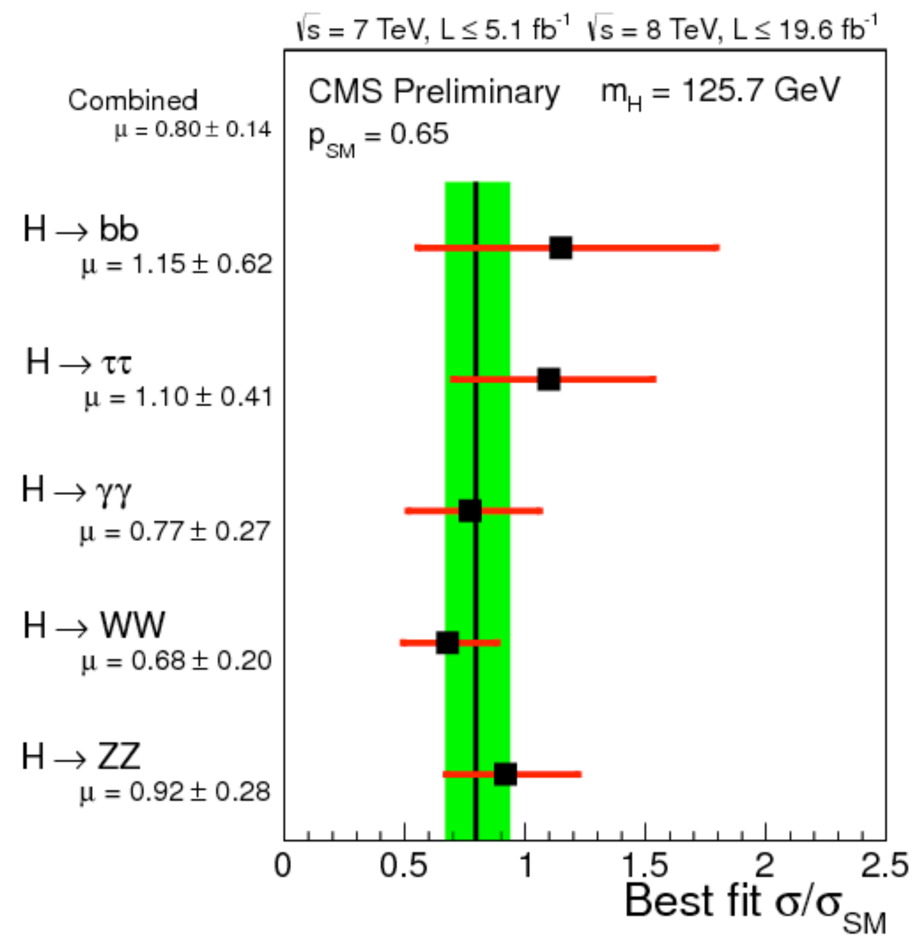

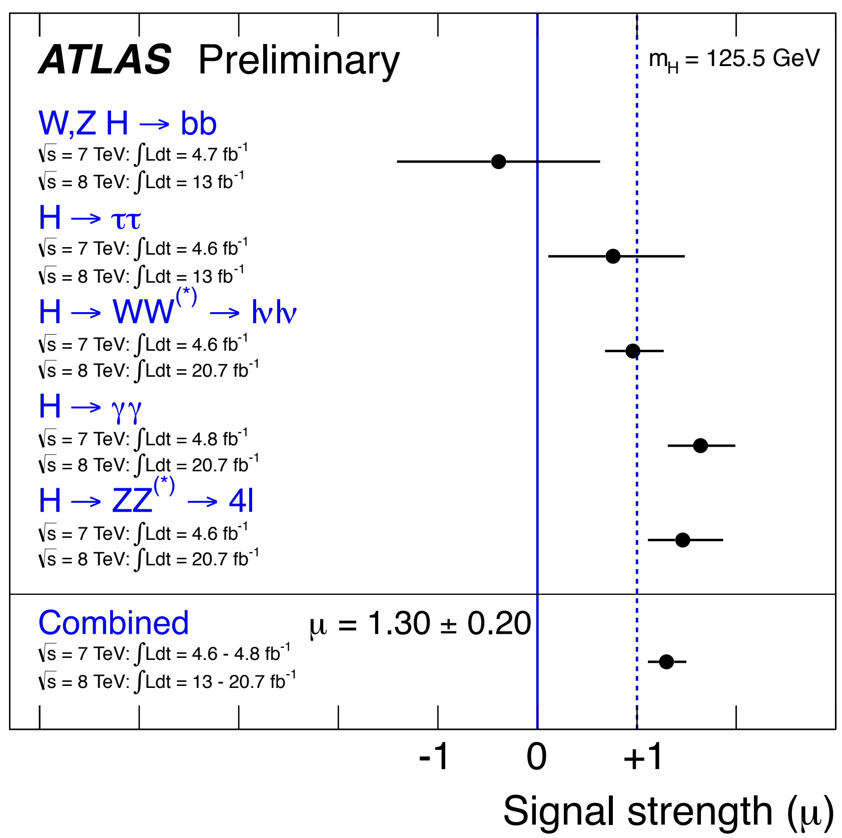

ATLAS $\mu = 1.30 \pm 0.20$

CMS $\mu = 0.80 \pm 0.14$

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Experimental evidence based on many detailed analyses:

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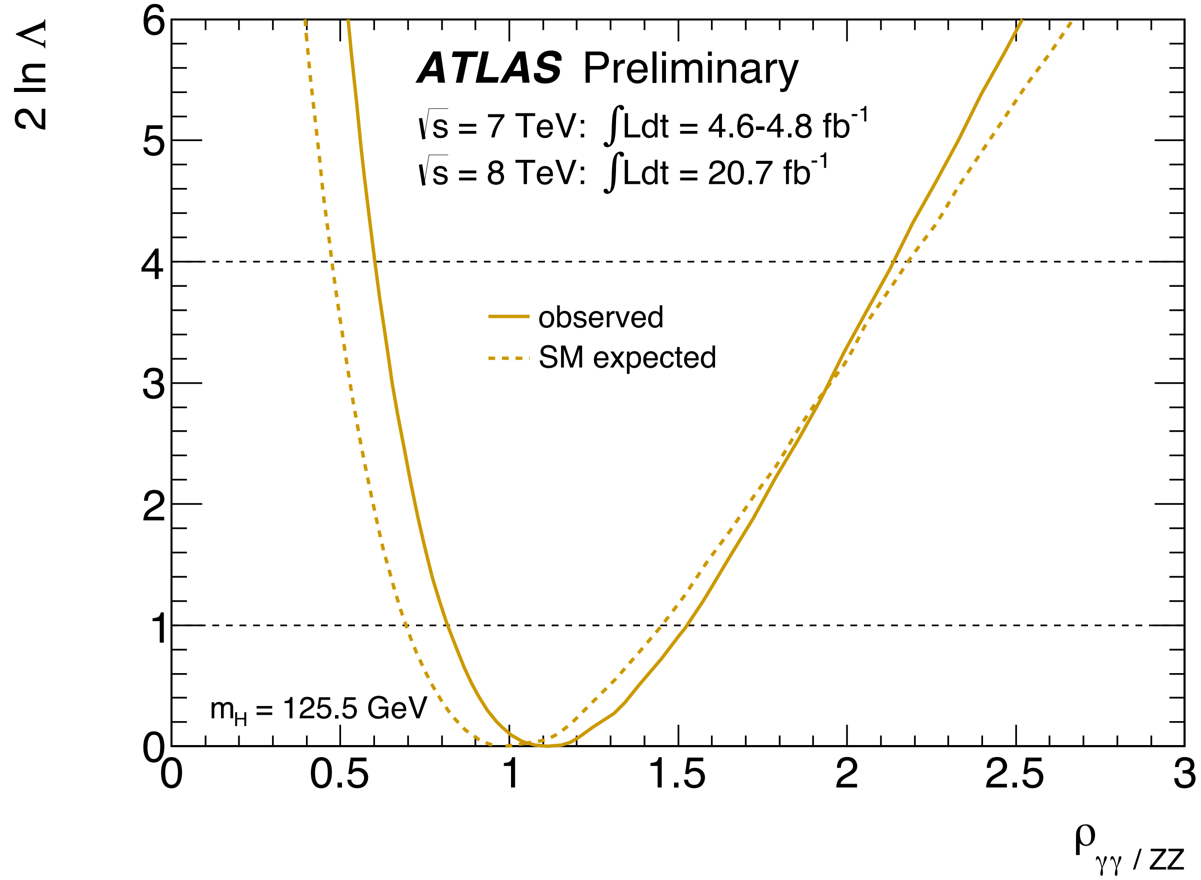
- Decay rates



Dependence on BRs isolated by taking ratios of decays with same production mode

$$\rho_{XX/YY} \equiv \frac{\sigma \times BR(h \to XX)}{\sigma \times BR(h \to YY)} \Big/ \frac{\sigma \times BR(h \to XX)}{\sigma \times BR(h \to YY)}\Big|_{SM}$$

ATLAS

$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

$$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$$

$$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$

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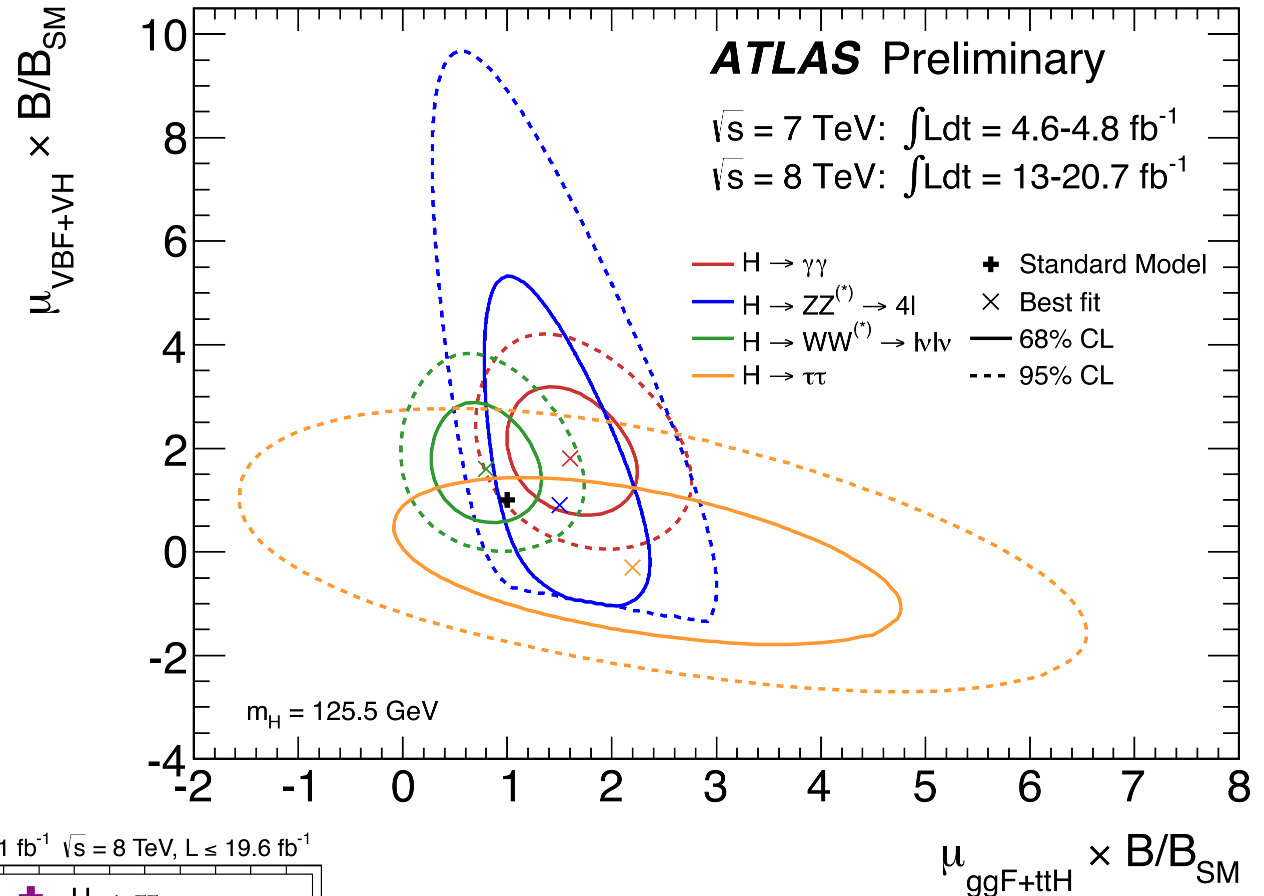

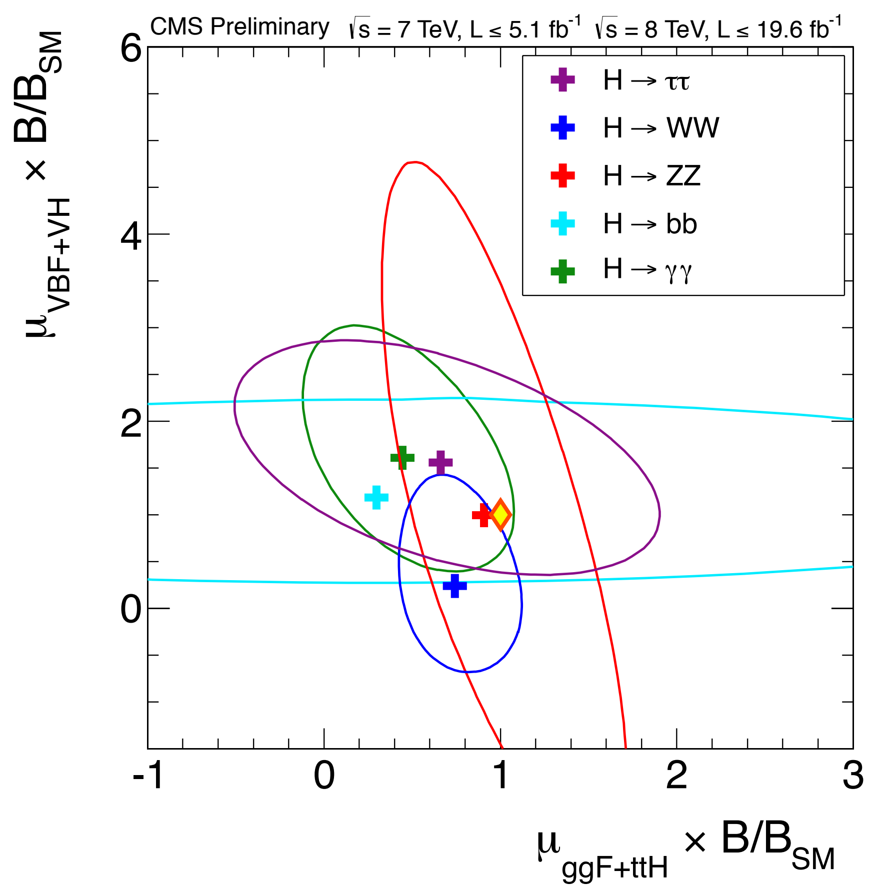

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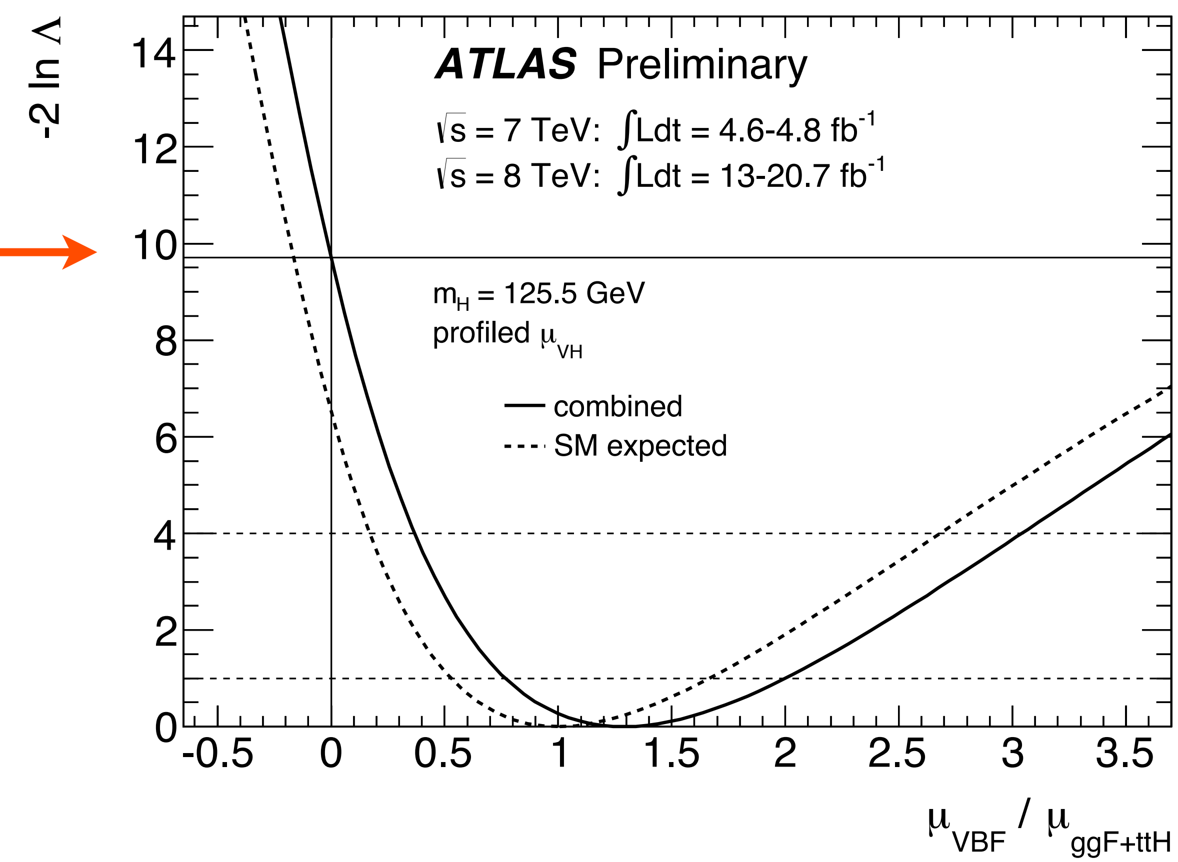
Dependence on production isolated by taking ratios of production modes channel by channel

3σ evidence of VBF



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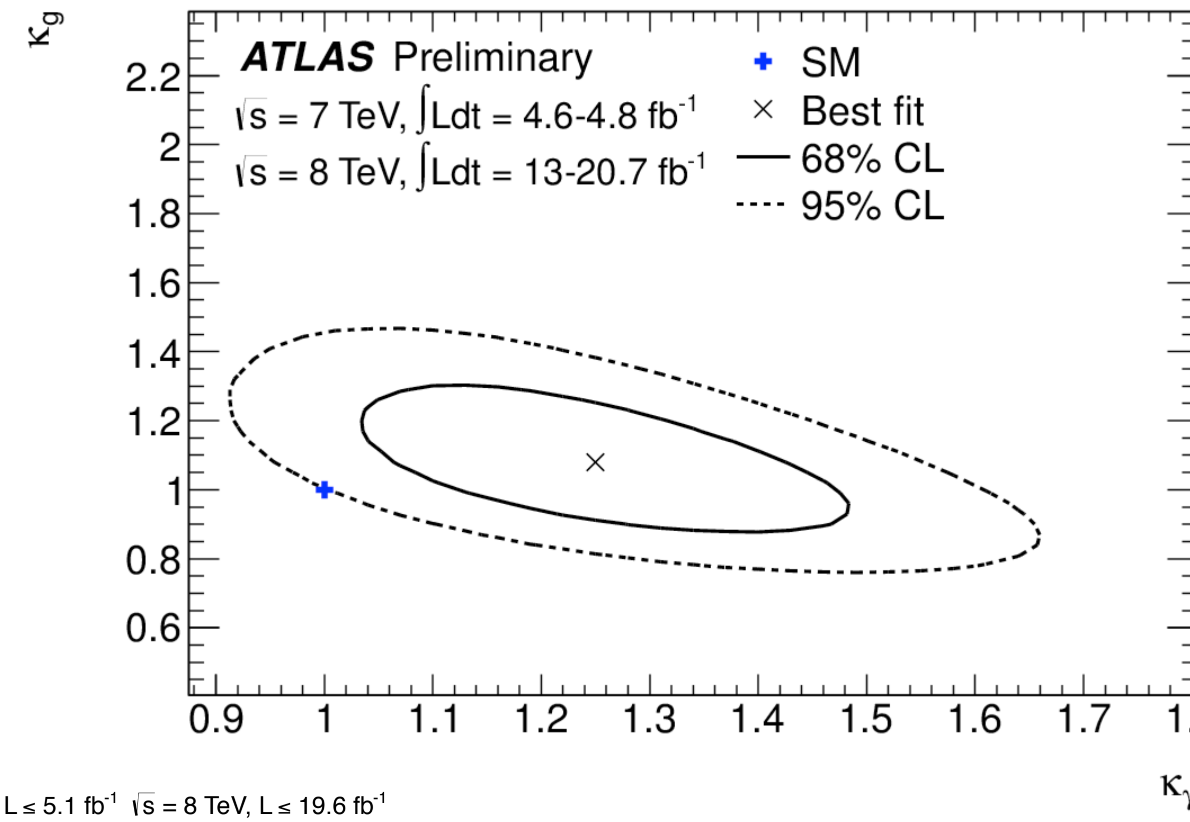
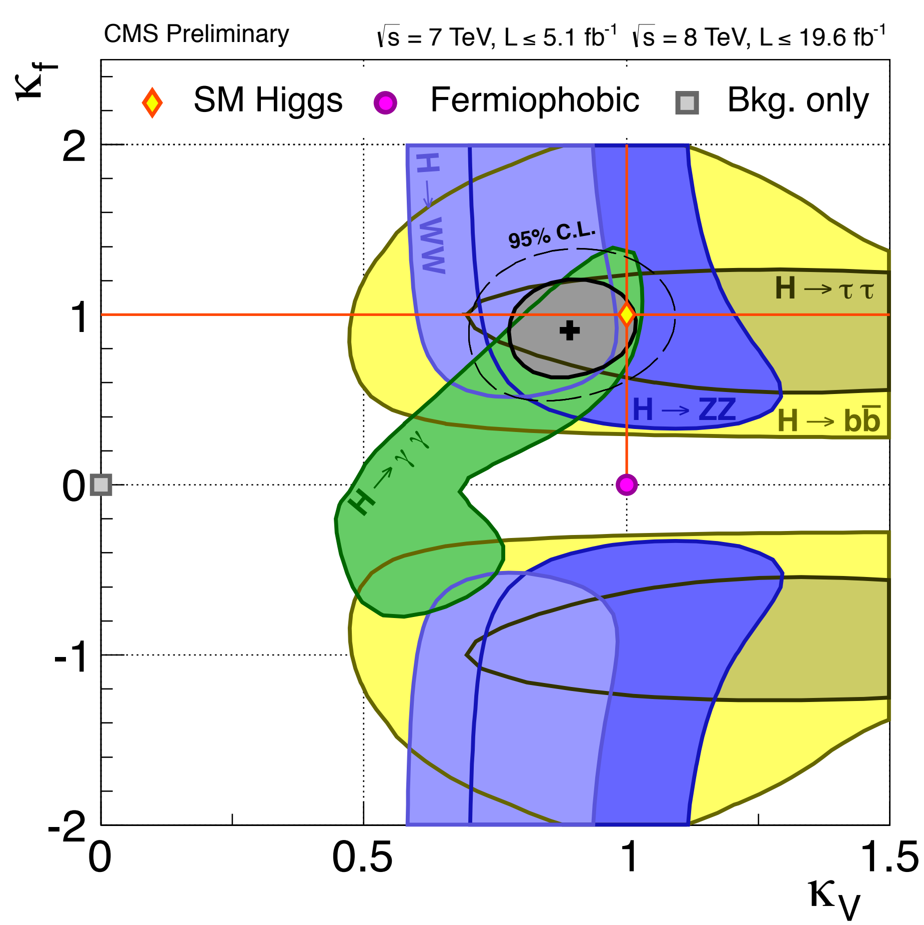
Experimental evidence based on many detailed analyses:

- Overall compatibility with SM
- Decay rates
- Production rates
- Global fit on couplings





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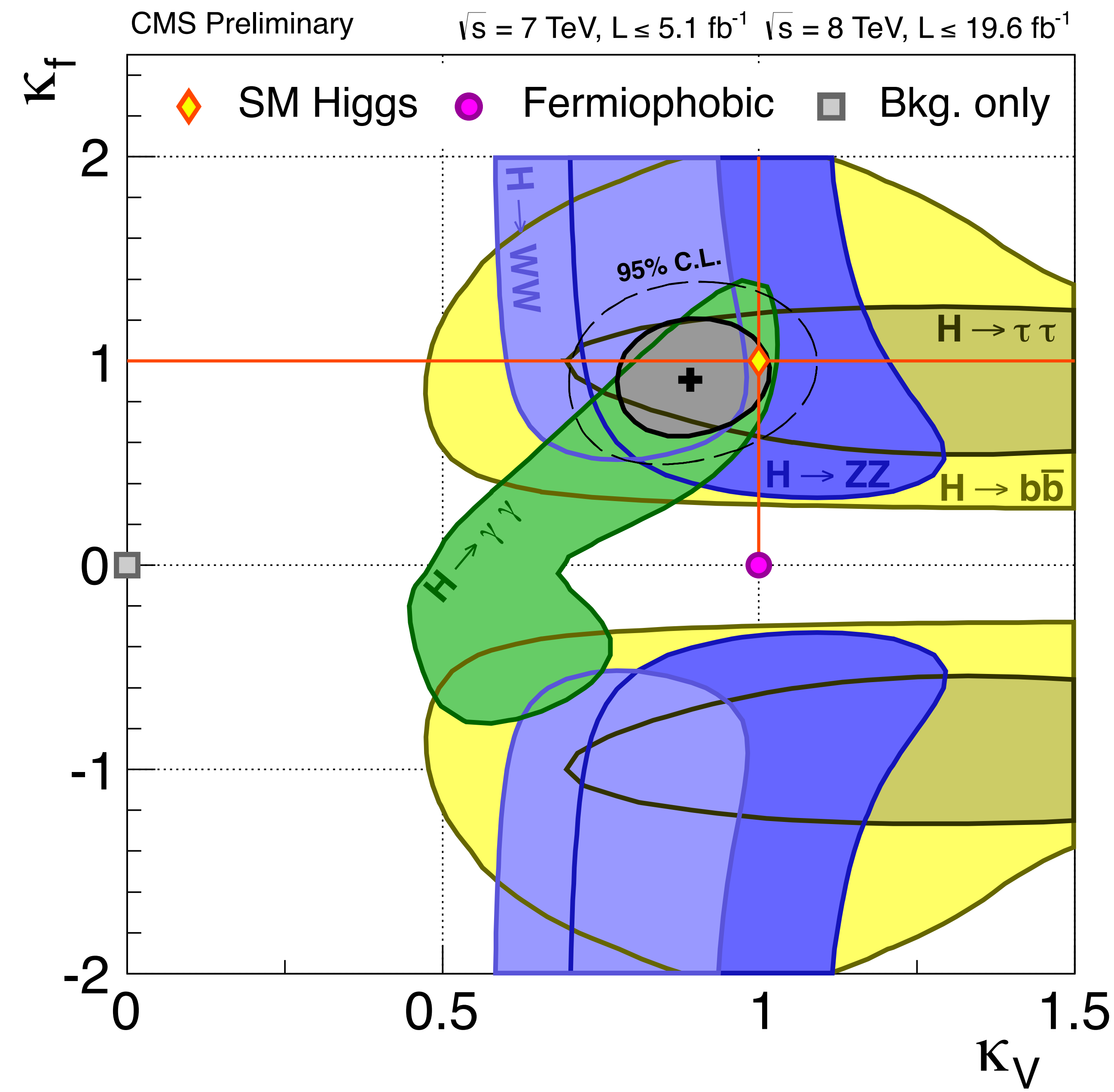

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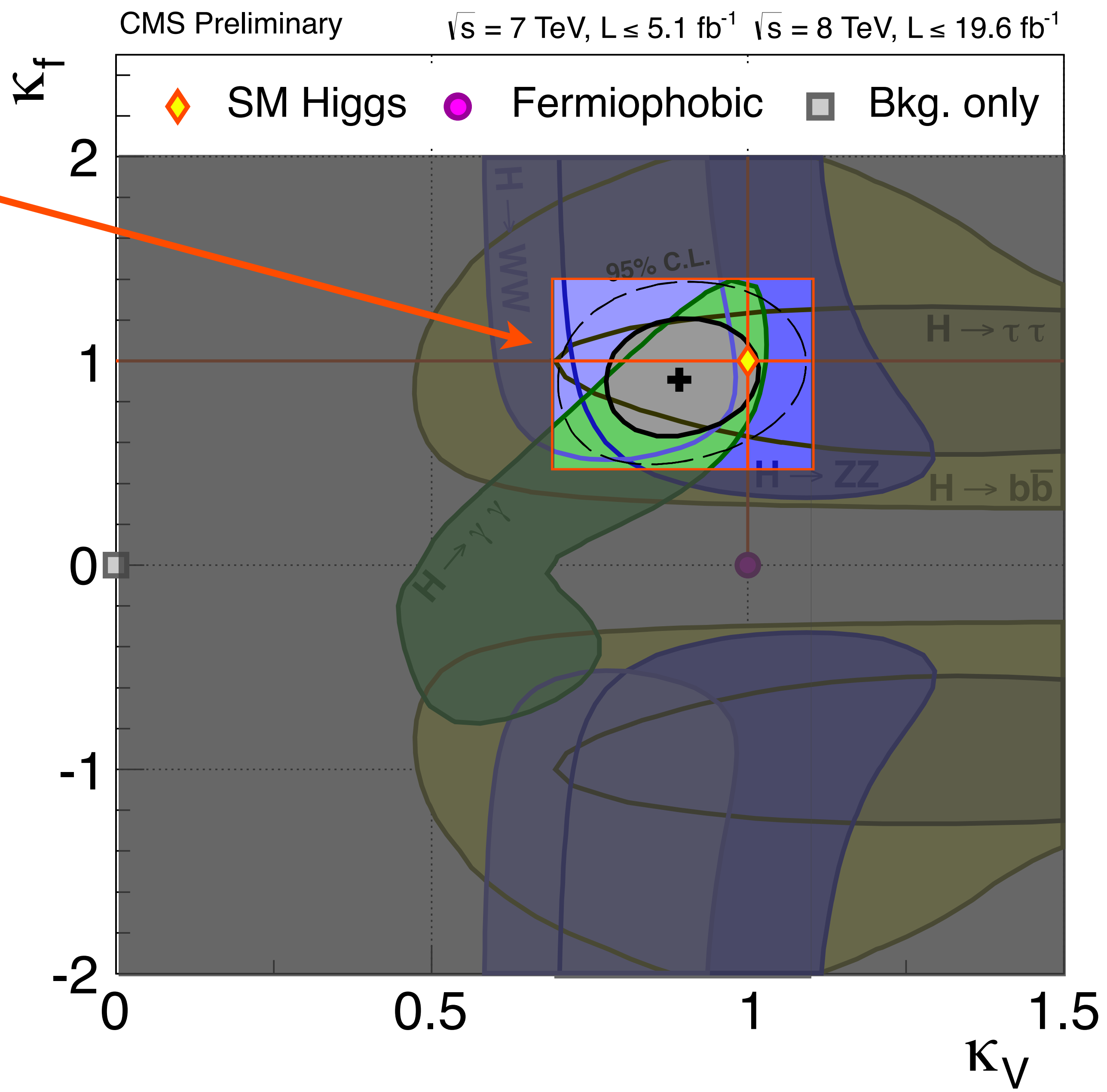
The focus now is on a region of the parameter space around the SM point



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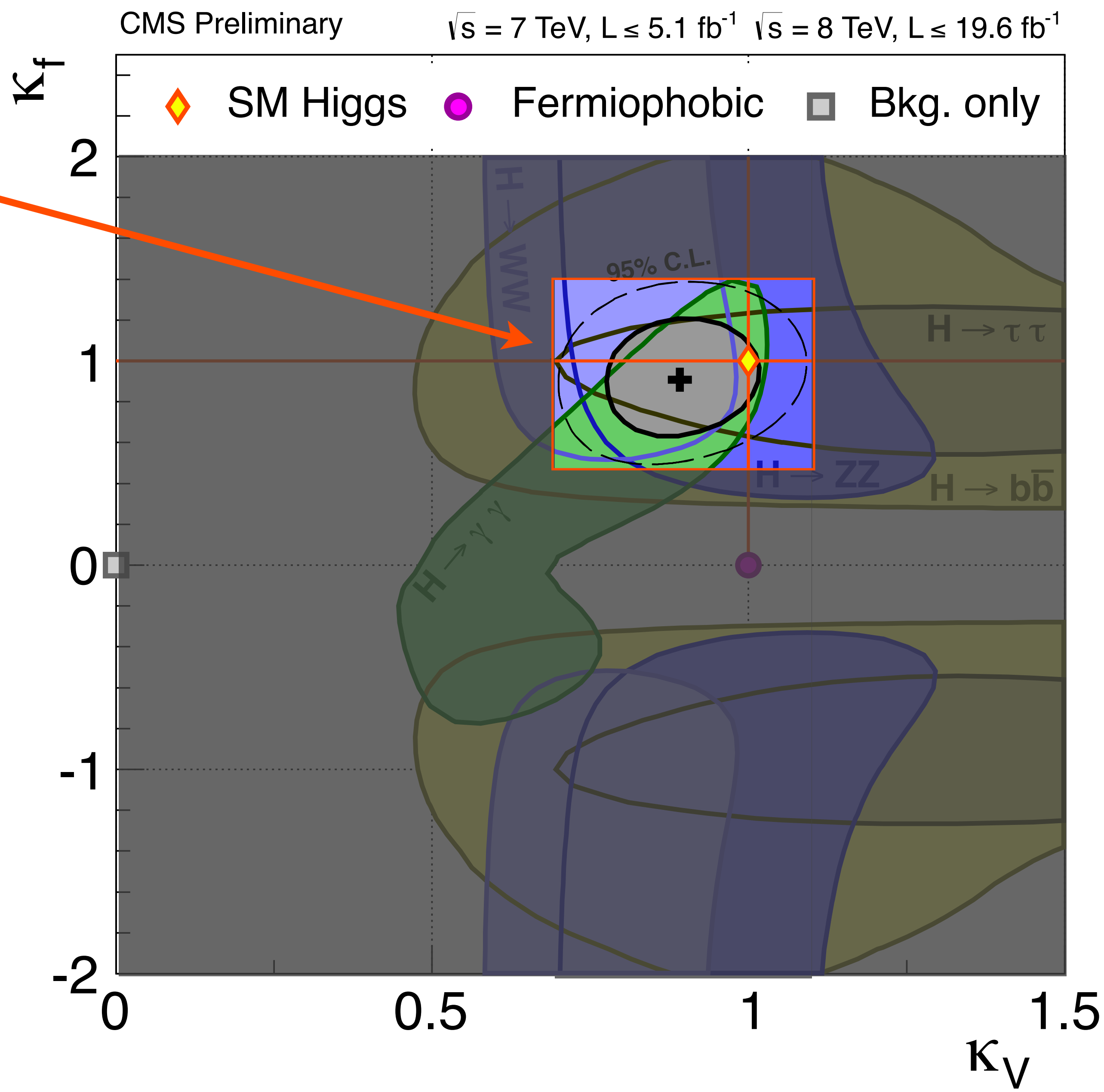
This is a *natural* region to live if:

1. The new boson is part of an $SU(2)_L$ doublet

2. There is a gap between the NP scale and m_H



$$\frac{\delta c}{c_{SM}} \sim \frac{g_H^2 v^2}{M^2}$$

g_H = Higgs coupling strength

$$\frac{\delta c}{c_{SM}} \lesssim 0.2 \quad \Rightarrow \quad M \gtrsim g_H \times 550\,\mathrm{GeV}$$

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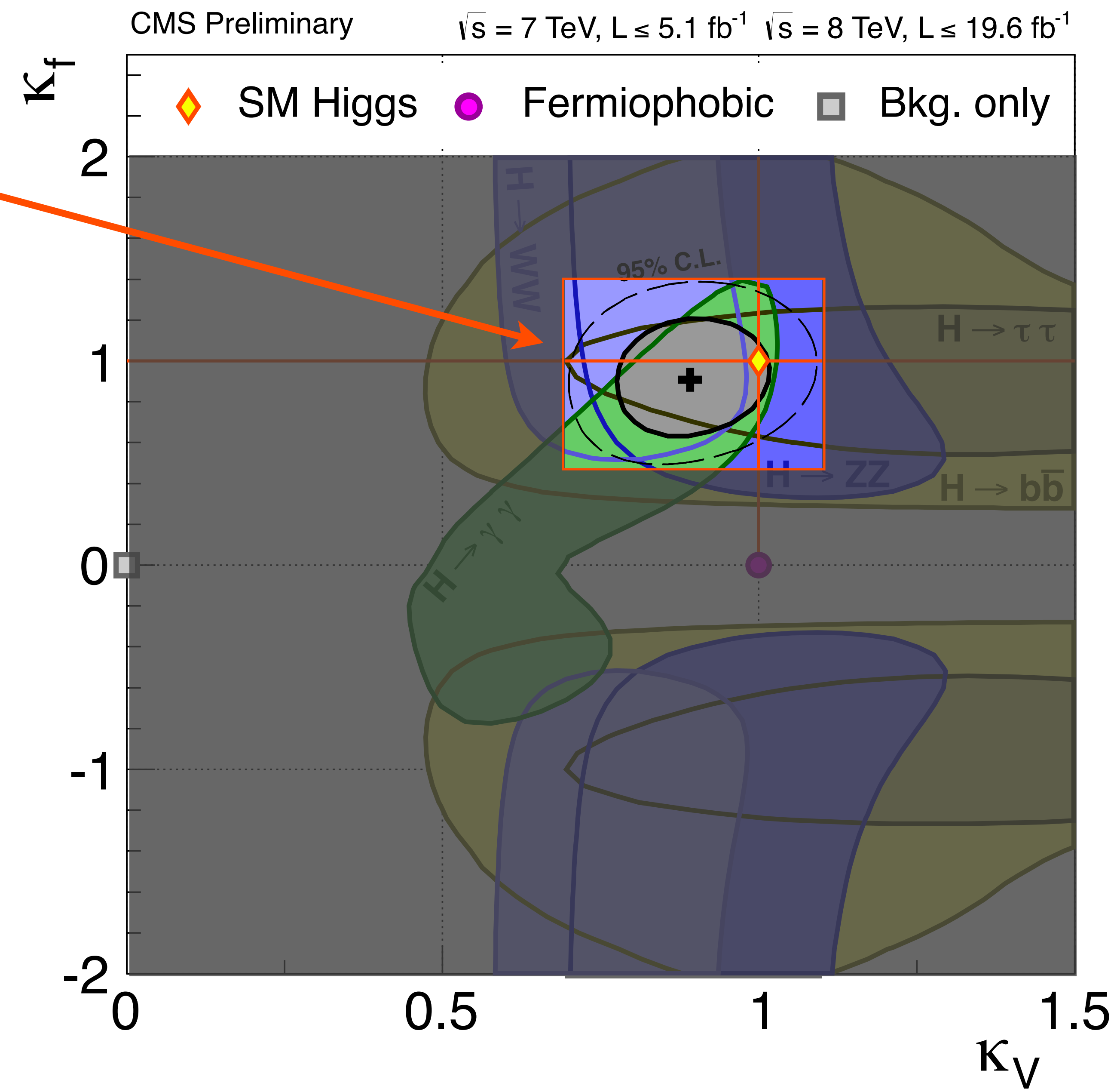

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Notice: the SM point is the only one in which the low-energy theory is *renormalizable and weakly coupled up to high energies*

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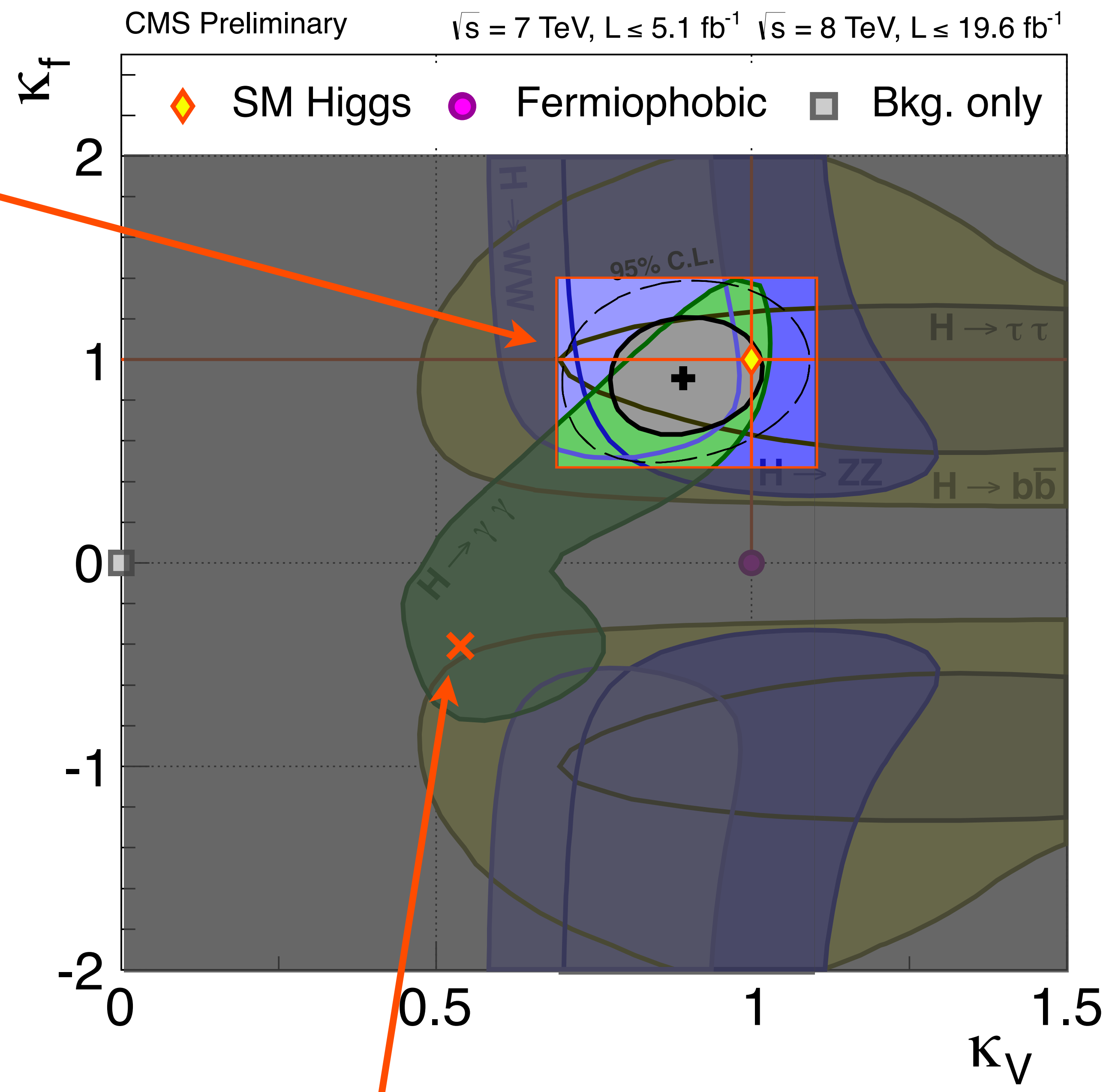

living in any other point requires either light NP or strong dynamics

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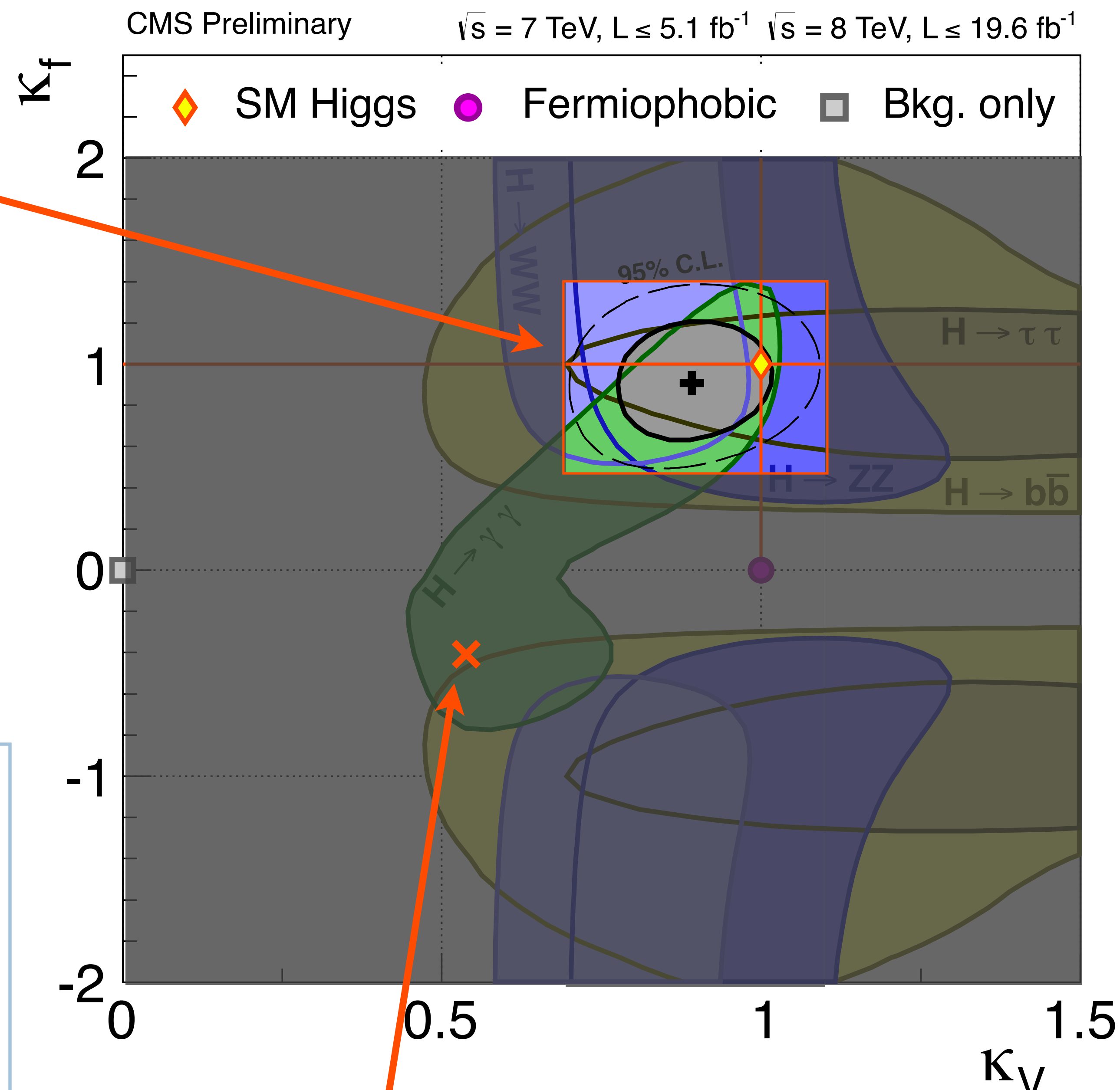
Conclusion:

Theories w/o a Higgs boson or with strong dynamics at low scale are now excluded

Ex: TC and CH with $M \approx 4\pi v$



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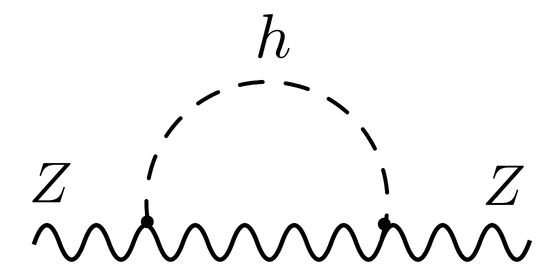
“Didn’t we know already from LEP ?”

Not quite so:

1. evidence was indirect (through loops)
2. only hZZ coupling and m_H constrained



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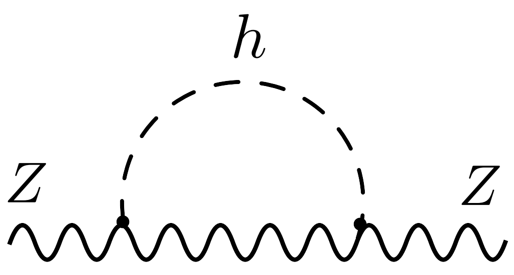


In fact:

Most recent EW fit much more stringent than before due to:

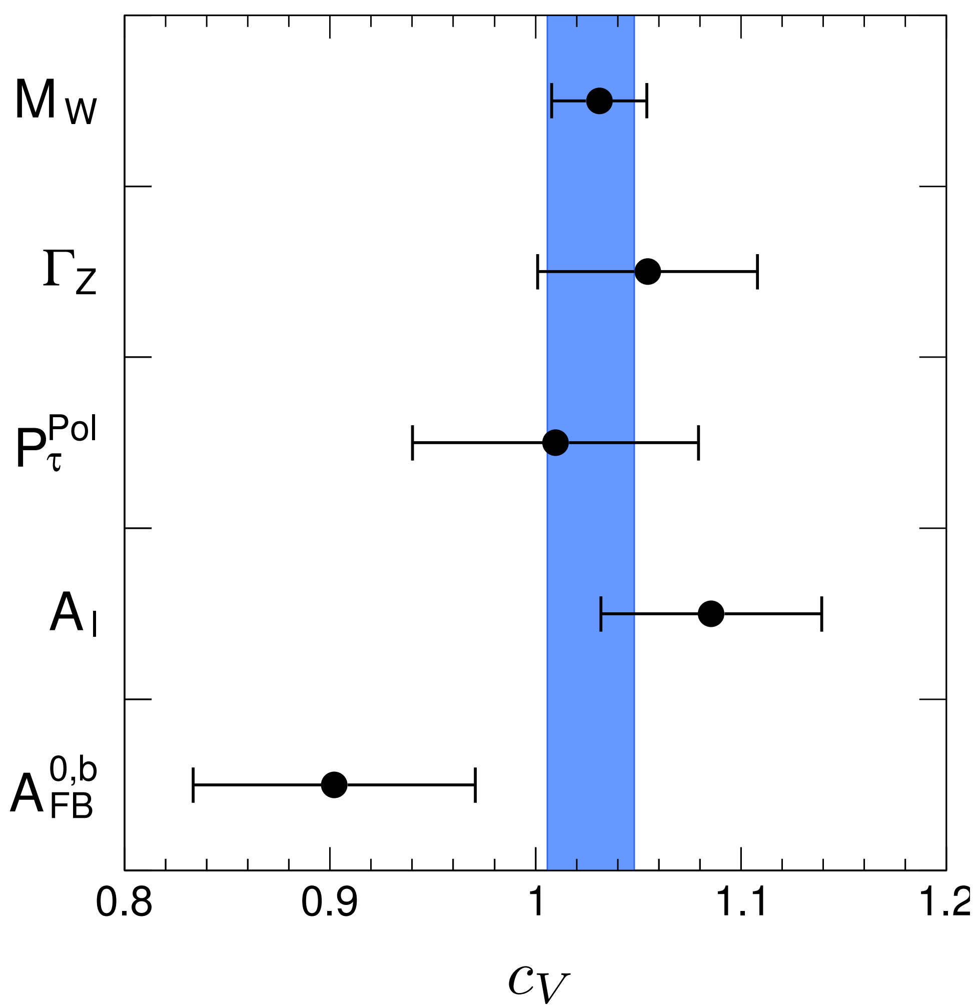
– mH now precisely known

– new m_W from Tevatron

Precision on c_V at the level of ~5% !

[Assuming no extra contribution to EWPO from new particles]

courtesy of S. Mishima



M. Ciuchini, E. Franco, L. Silvestrini, S. Mishima, to appear

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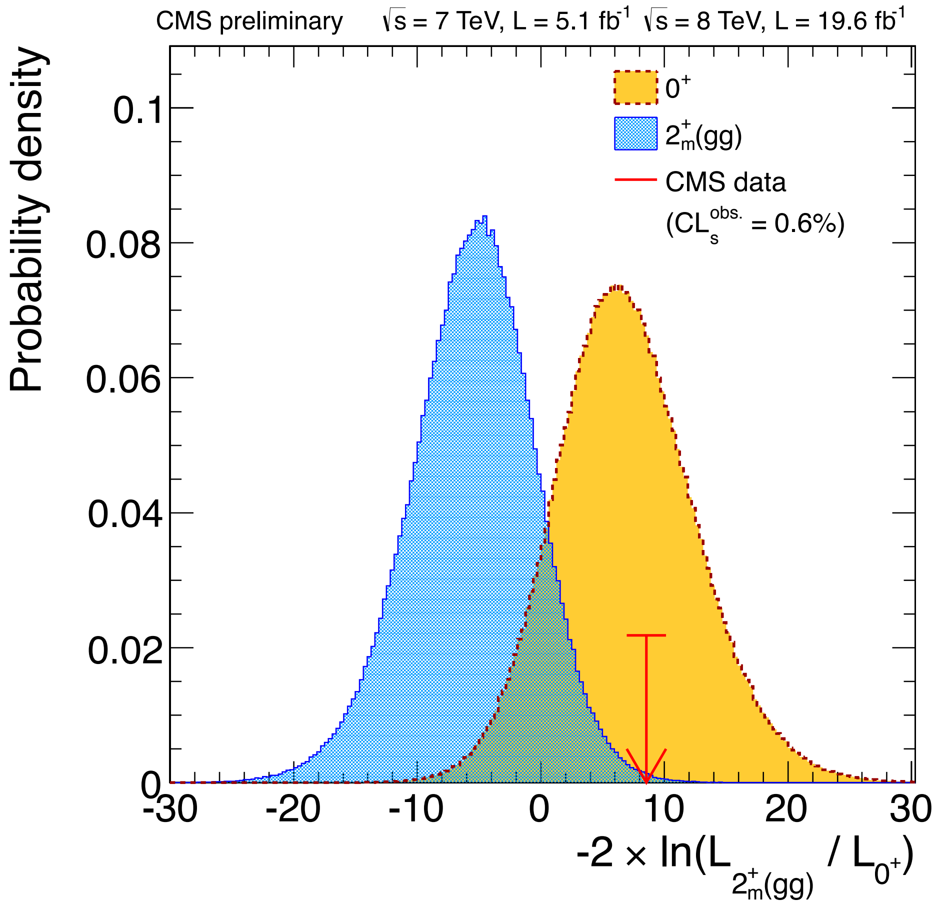

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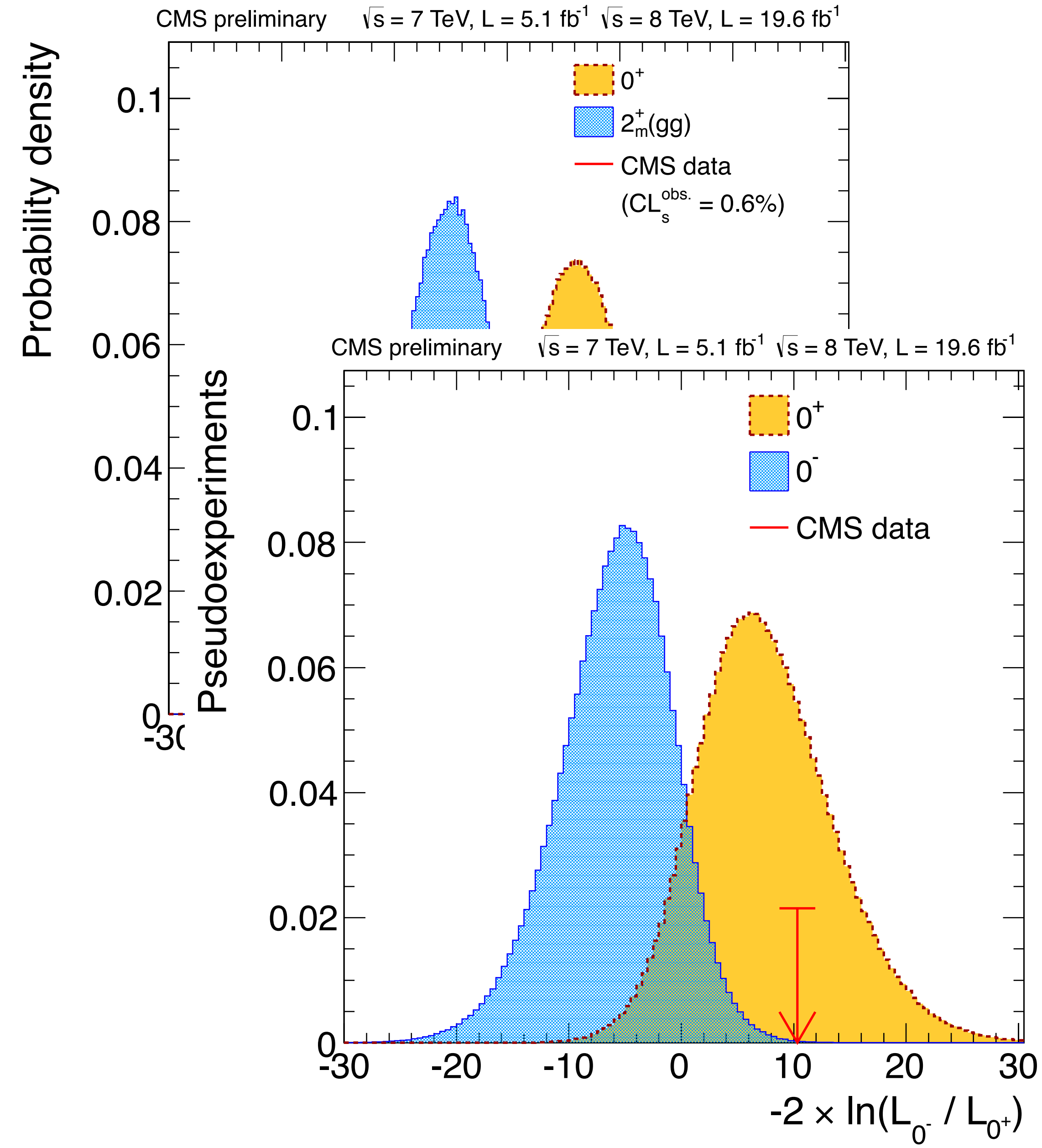

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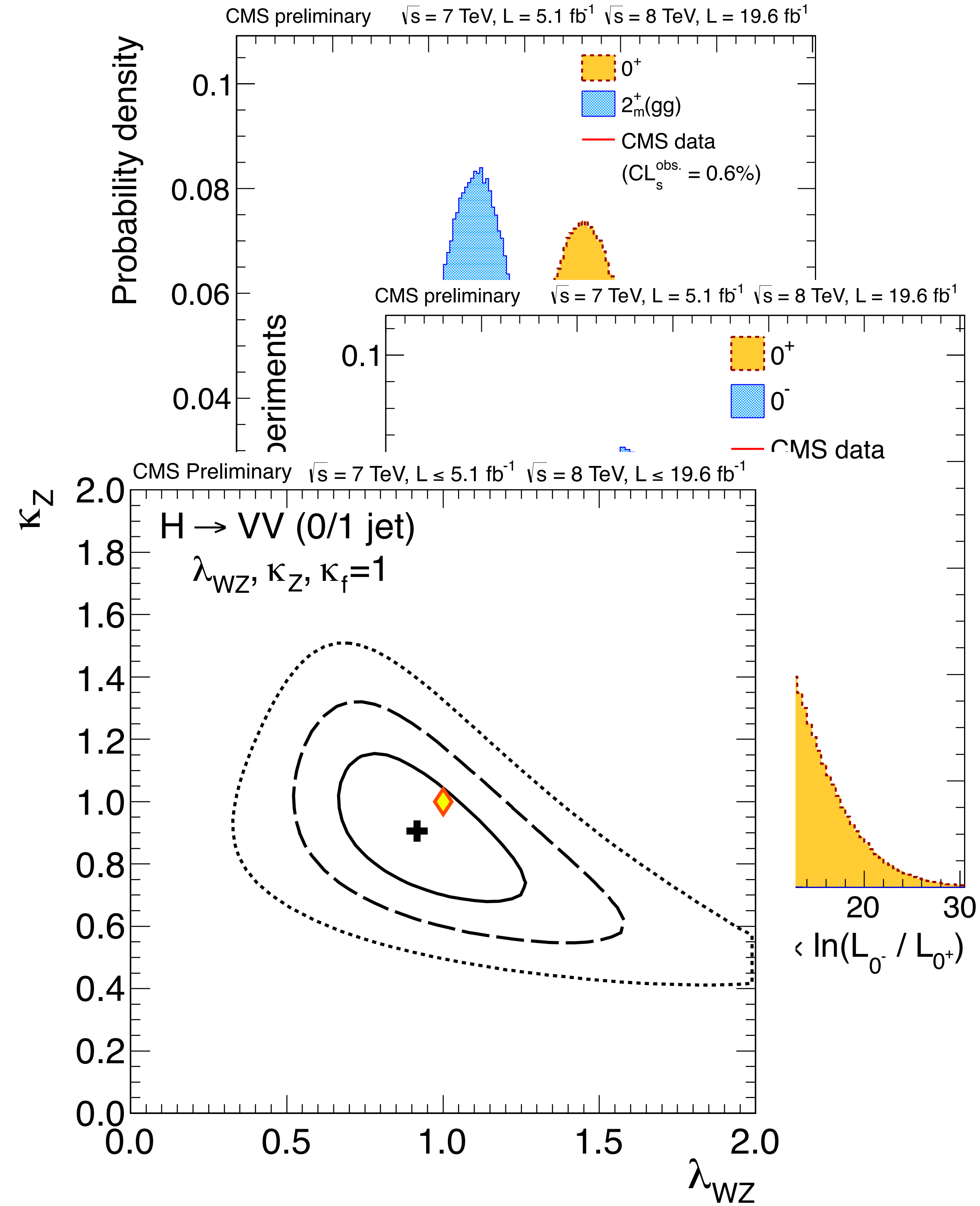
Ex: custodial symmetry ✓

$$\frac{m_W}{m_Z \cos\theta_W} = 1 \quad \Rightarrow \quad \lambda_{WZ} = \frac{c_W}{c_Z} = 1$$



CMS only ZZ,WW $\lambda_{WZ} \in [0.60, 1.40]$ @ 95%

CMS all channels $\lambda_{WZ} \in [0.62, 1.19]$ @ 95%

ATLAS all channels $\lambda_{WZ} \in [0.55, 1.13]$ @ 95%

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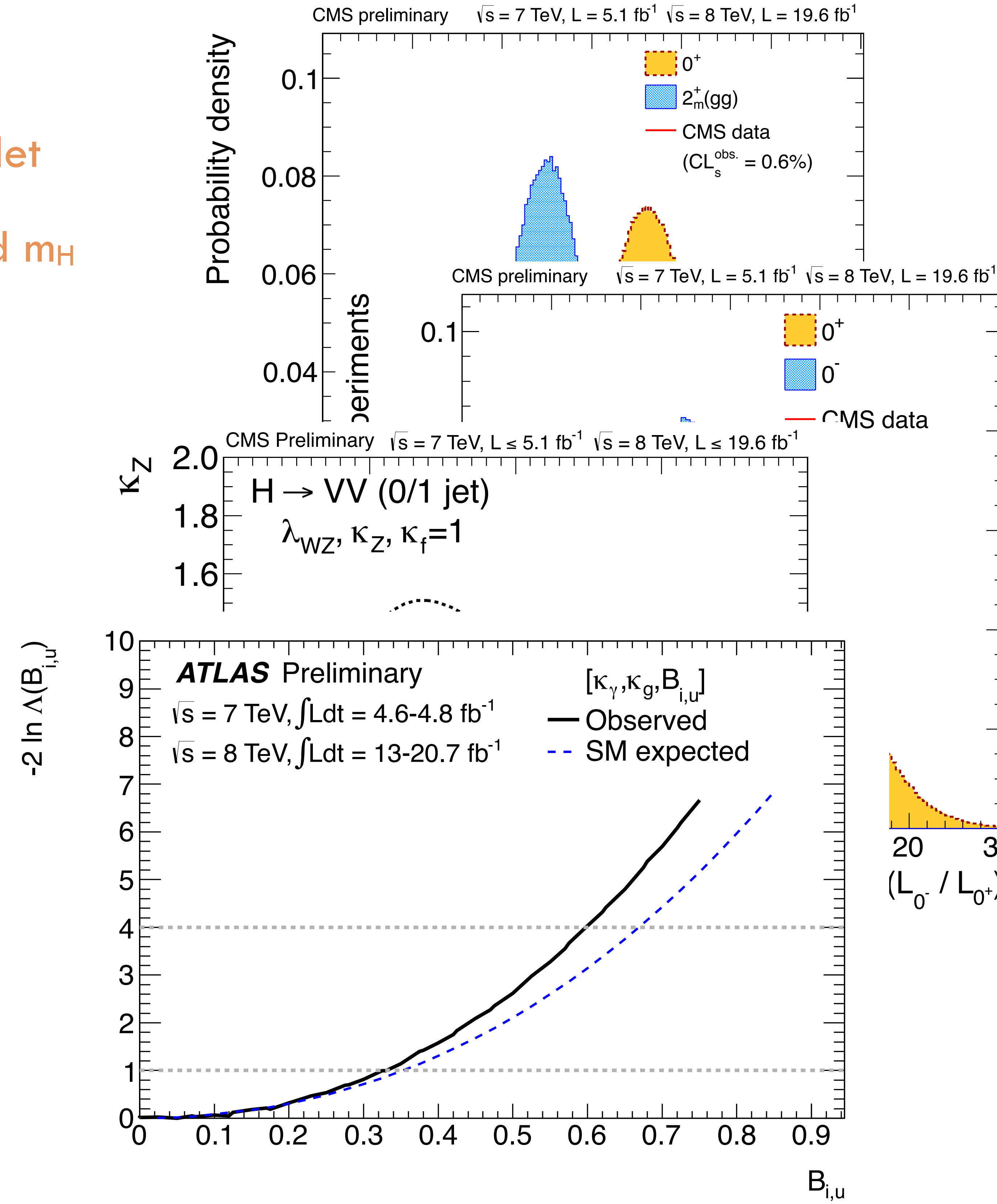
- There are no new light states to which the Higgs boson can decay

  Ex: Invisible width=0 ✓



ATLAS $BR_{\text{inv}} \leq 0.6$ @ 95%

CMS $BR_{\text{inv}} \leq 0.52$ @ 95%

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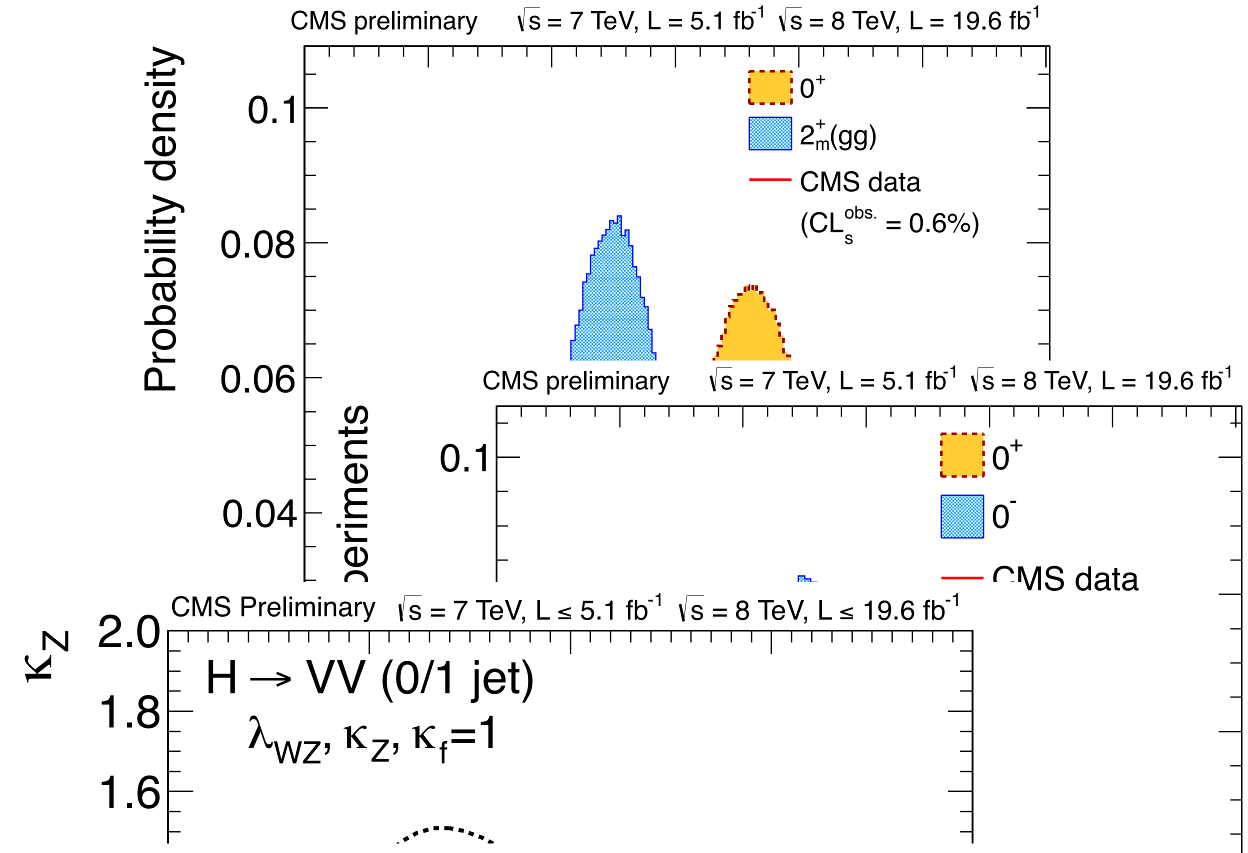

All these independent tests important to confirm the picture but their success comes less of a surprise given the fits on couplings

Ex: there's no reason why a $J^P=0^-$ boson should have SM coupling strength

$$|D_\mu H|^2 \quad \text{vs} \quad \frac{\tilde{c}_{WW}}{M^2} W_{\mu\nu}\tilde{W}^{\mu\nu} H^\dagger H$$

PART 2

Implications on BSM models

SUSY (MSSM and beyond)

- Shifts to tree-level couplings due to mixing with heavier Higgs

$$c_V = \sin(\beta - \alpha) \qquad c_t = \frac{\cos\alpha}{\sin\beta} \qquad c_b = -\frac{\sin\alpha}{\cos\beta}$$

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}\, H_u^0 \\ \mathrm{Re}\, H_d^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_u}{v_d}$$

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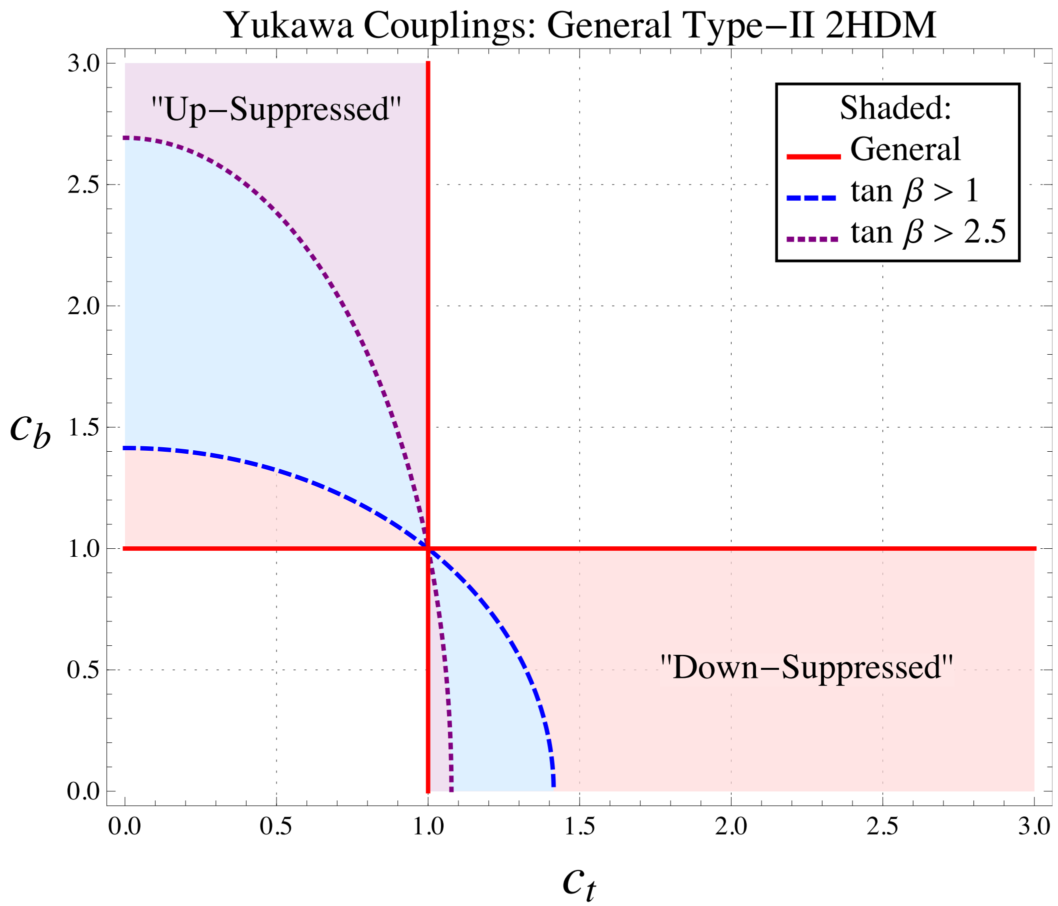
Only two regions in the (c_t, c_b) plane accessible in a *generic* Type-II 2HDM

Down-Suppressed region almost *not accessible* in the MSSM for $\tan\beta > 1$



see: Azatov, Chang, Craig, Galloway PRD 86 (2012) 075033

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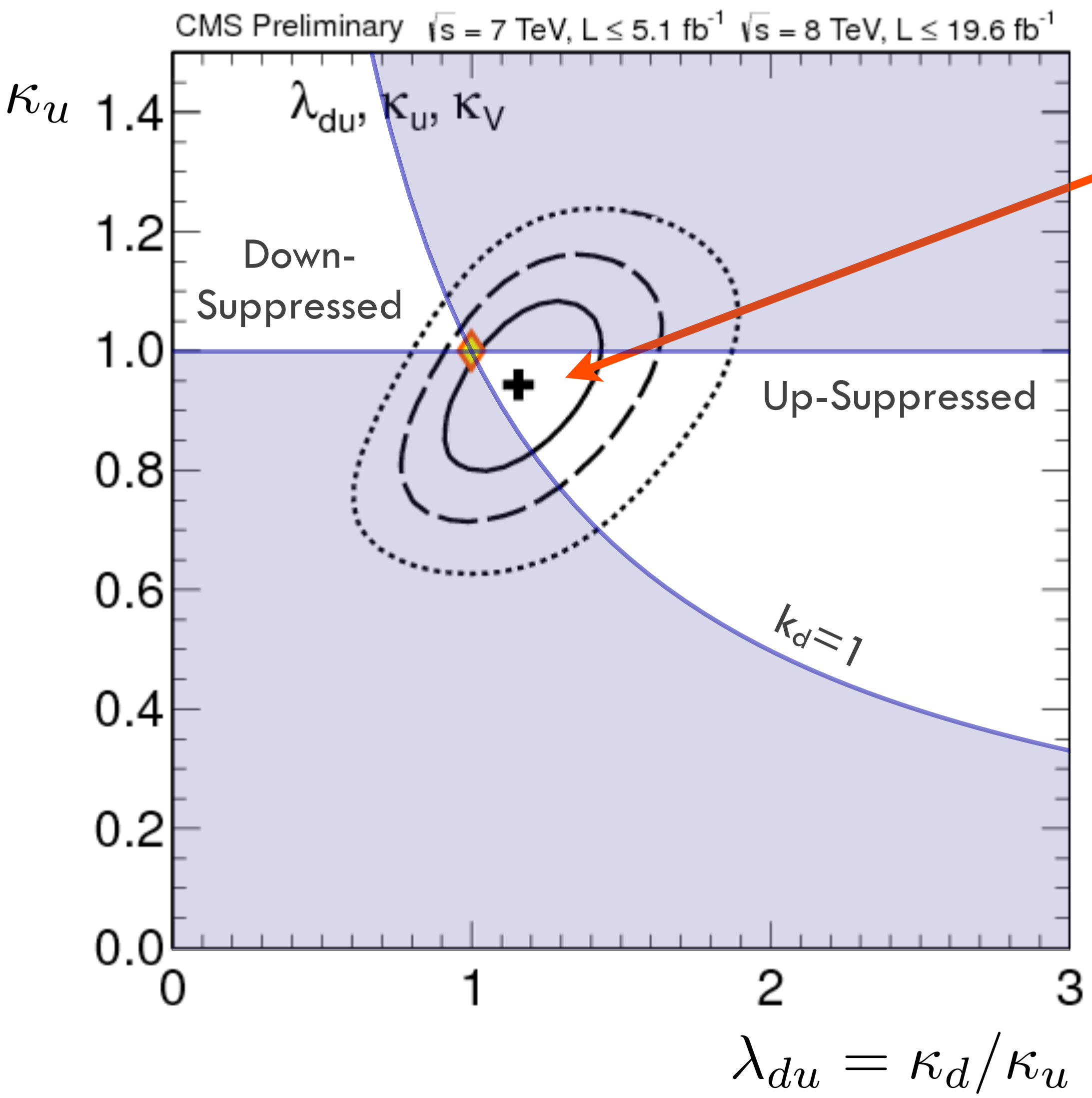

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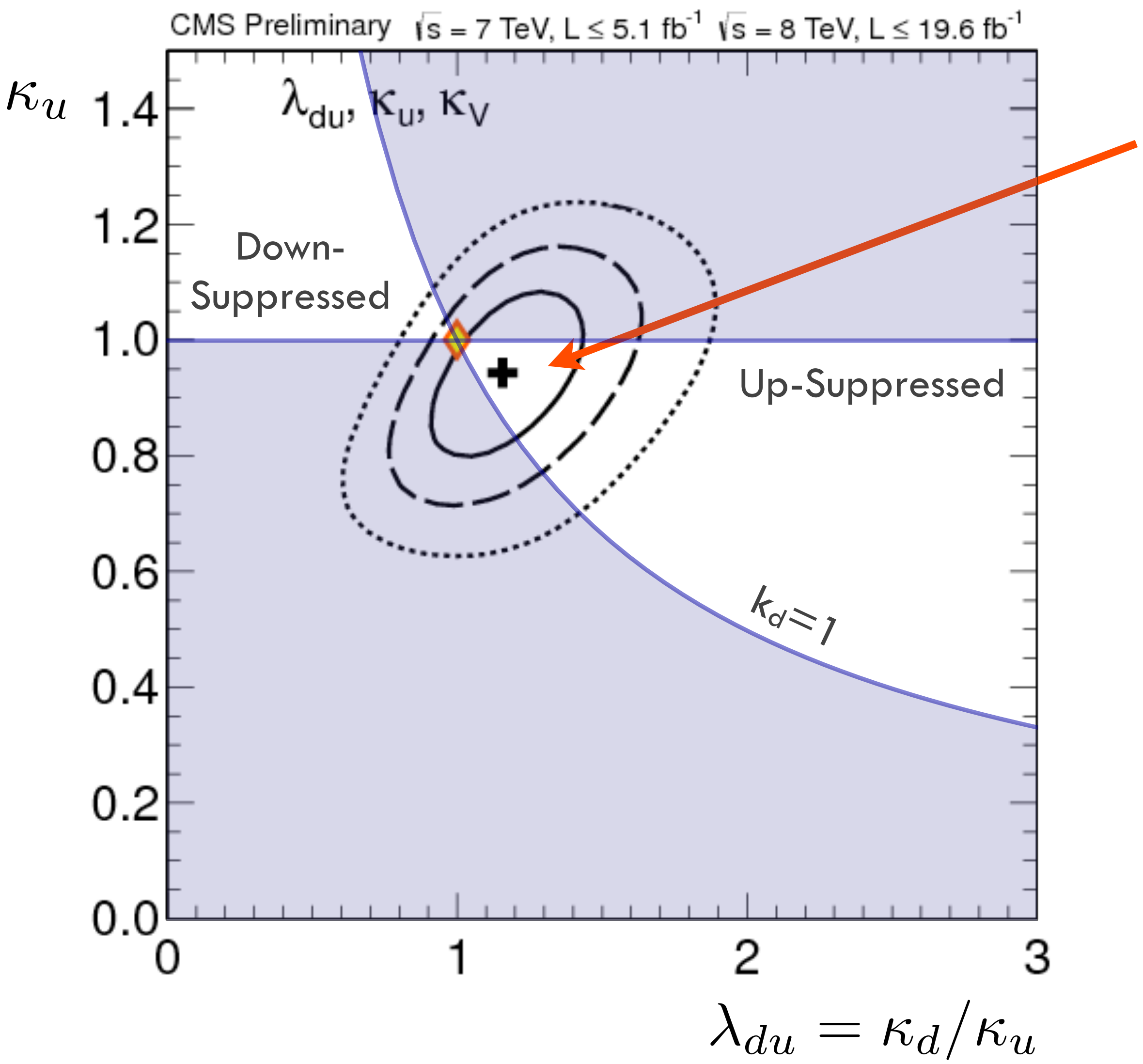

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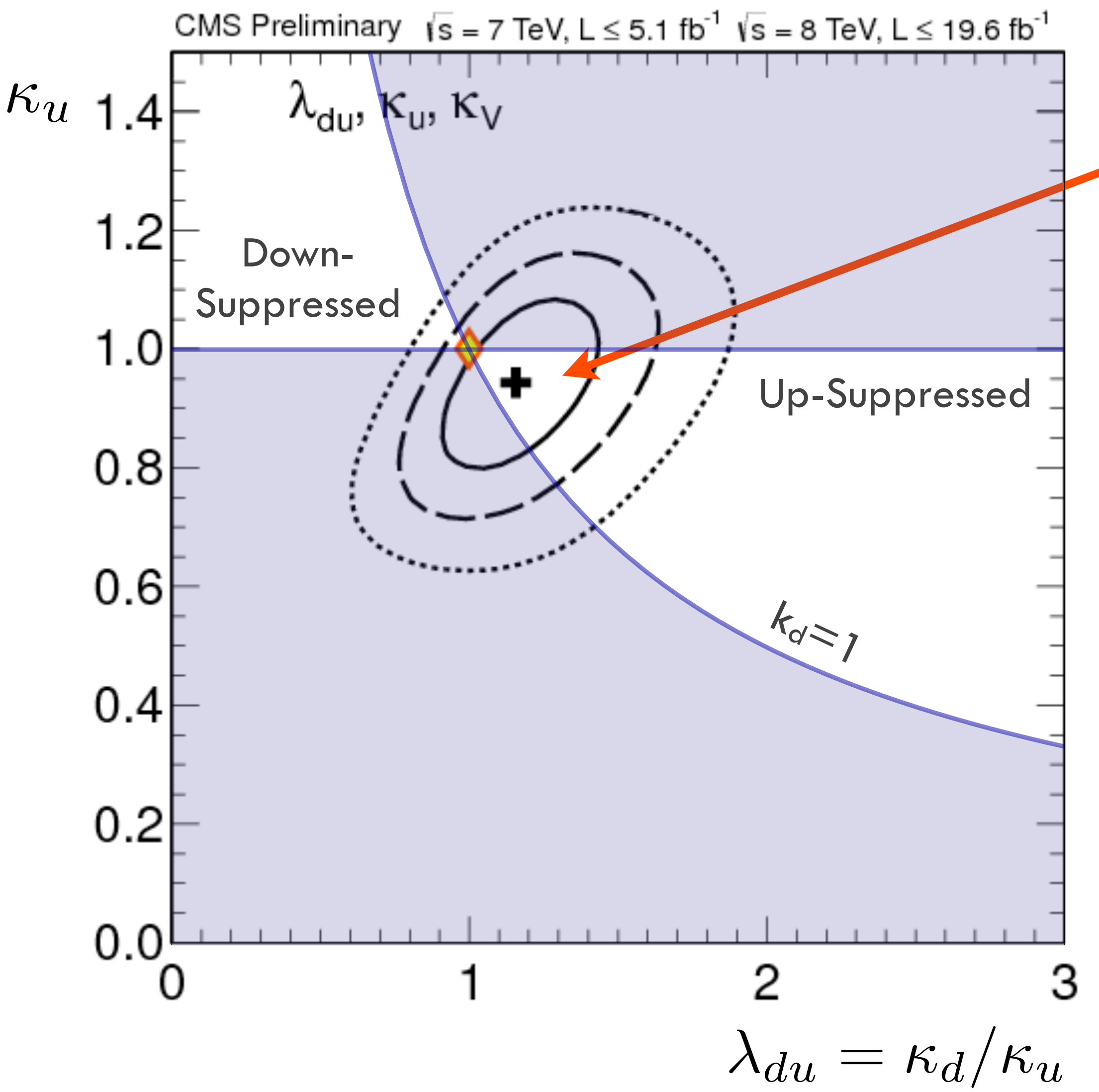

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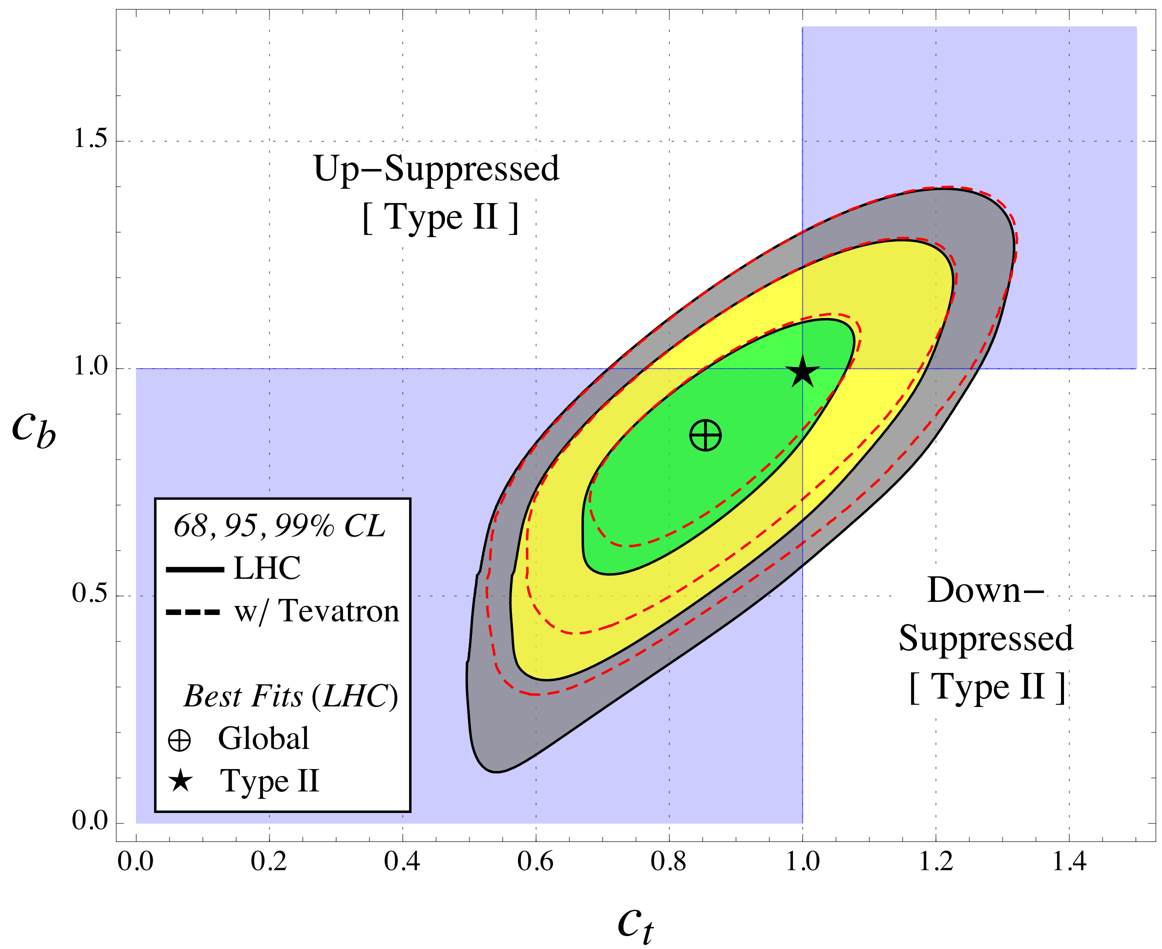
For the impatient ones here is a theorist's combination of ATLAS+CMS+Tevatron:



from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

SUSY (MSSM and beyond)

- Implications on the masses of the heavier Higgses

In the decoupling limit: $\alpha \to \beta - \pi/2$

$$c_V = 1 - \Delta^2 \frac{1}{\tan^2\beta} + O(\Delta^3) \qquad c_t = 1 - \Delta \frac{1}{\tan^2\beta} + O(\Delta^2) \qquad \Delta = O\left(\frac{m_Z^2}{m_H^2}\right)$$

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c_b most sensitive probe of spectrum of Heavy Higgses

$$\frac{\delta c_b}{c_b} > 0.1 \quad \Rightarrow \quad m_H > 300 - 400\,\mathrm{GeV}$$

Lighter masses (up to m_H ~200 GeV) however simple to obtain in explicit models (ex: NMSSM) with mild tuning of Δ

see for example: Barbieri et al. arXiv:1304.3670

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Notice:

masses of Heavy Higgses are *not* linked to naturalness of m_h anyway

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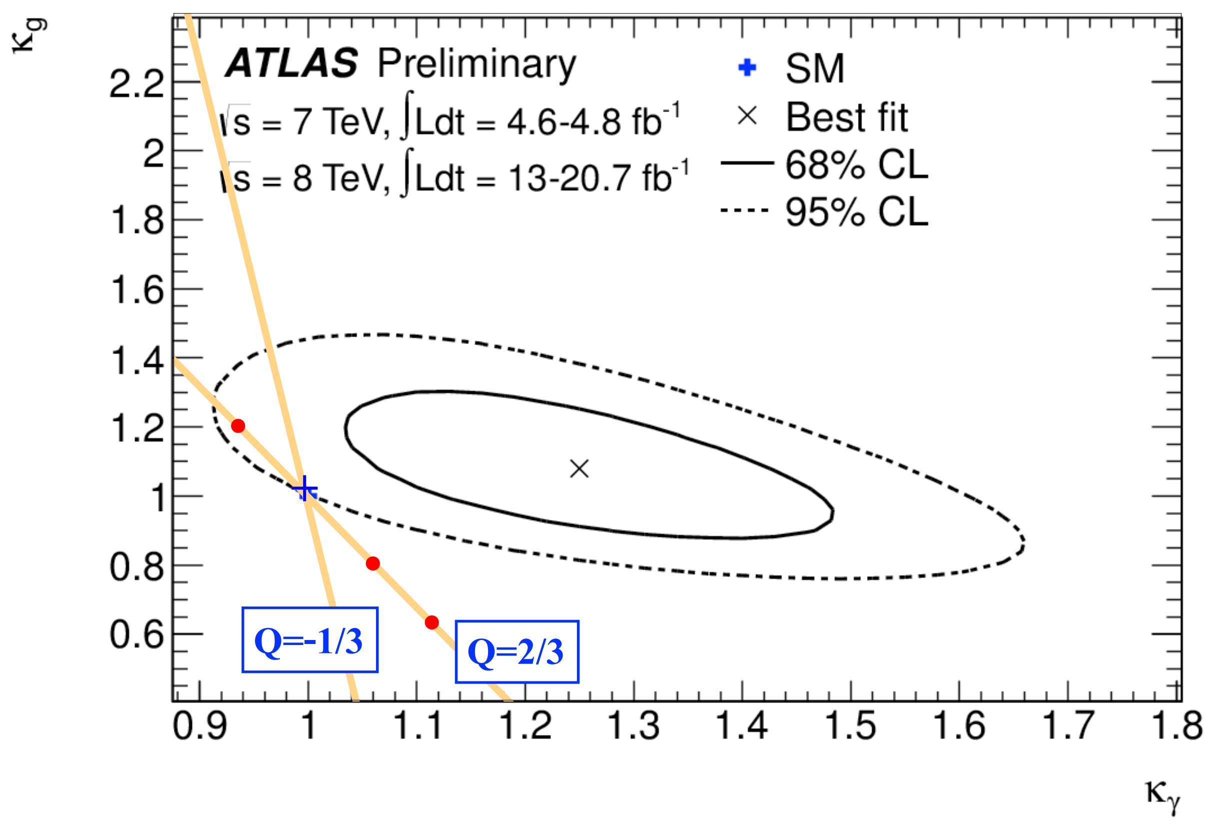

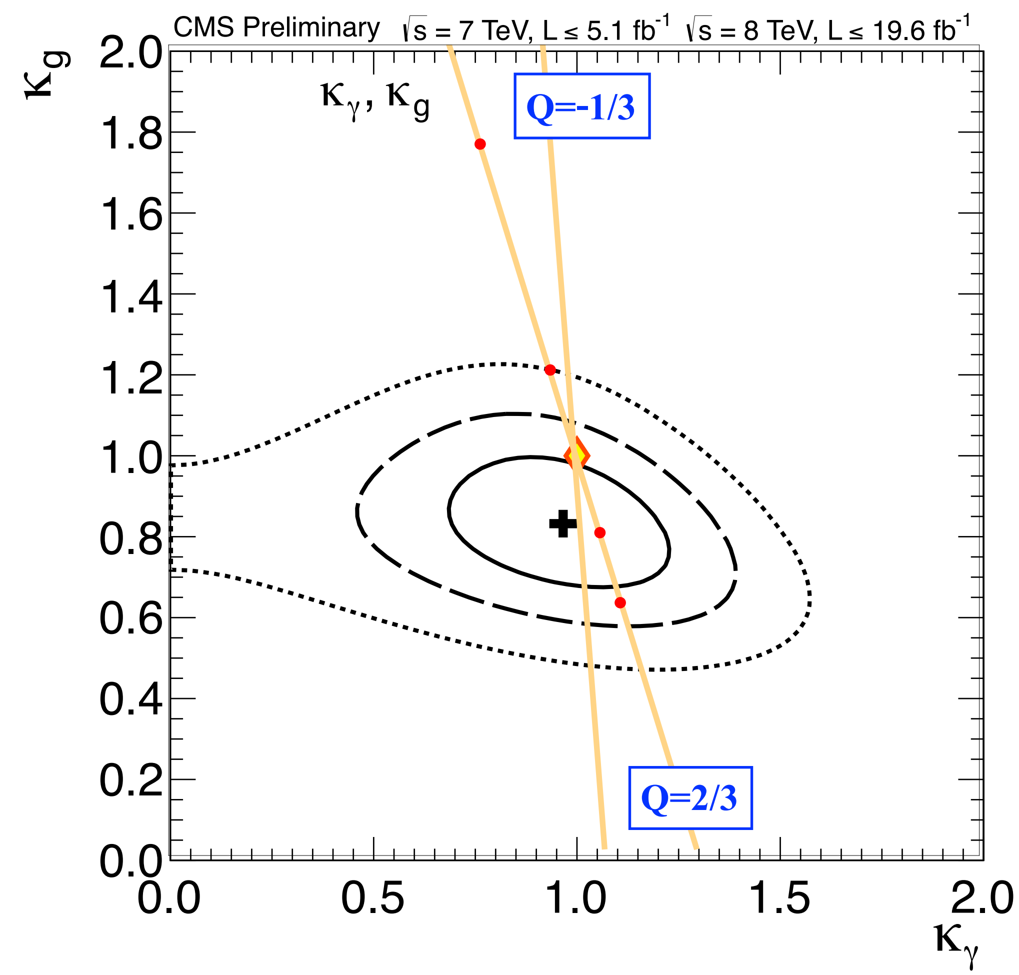

Small mixing: ➡ $\Gamma(gg \to h)$ enhanced

$\Gamma(h \to \gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg \to h)$ suppressed

$\Gamma(h \to \gamma\gamma)$ enhanced

SUSY (MSSM and beyond)

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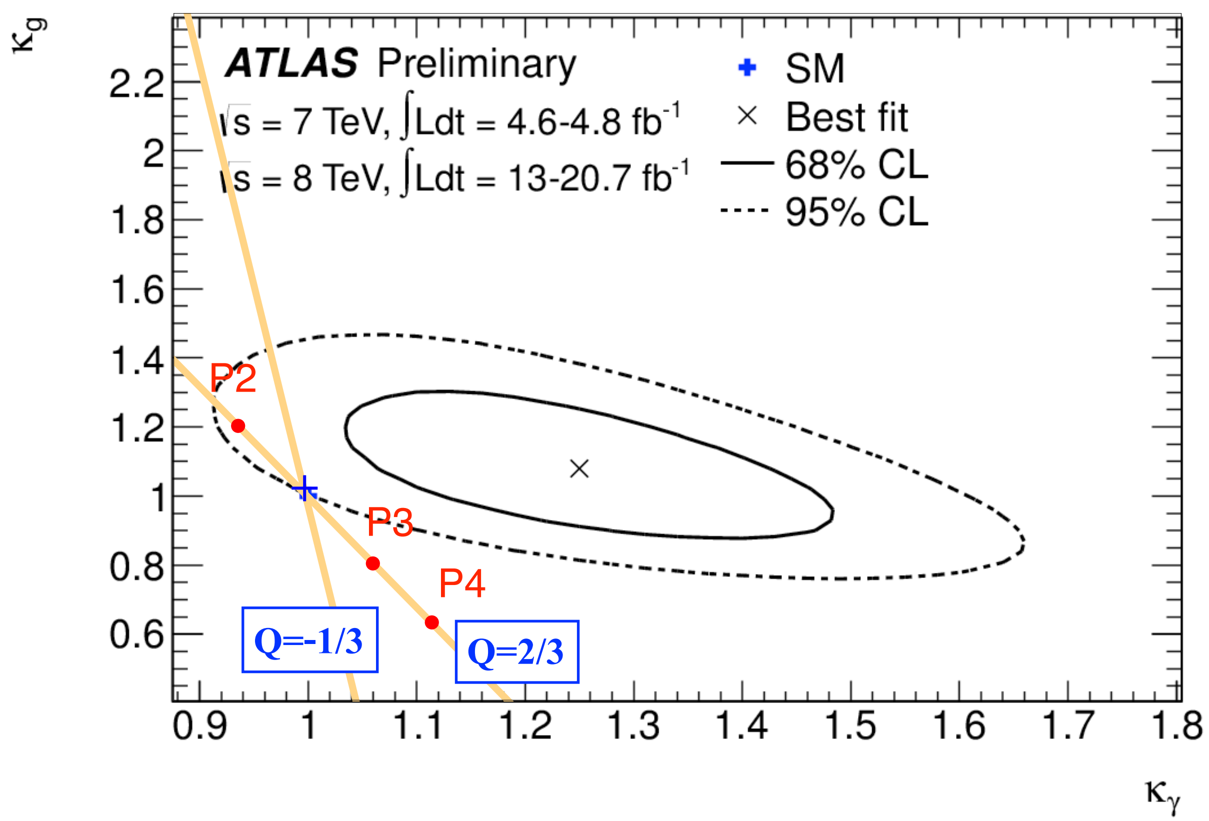
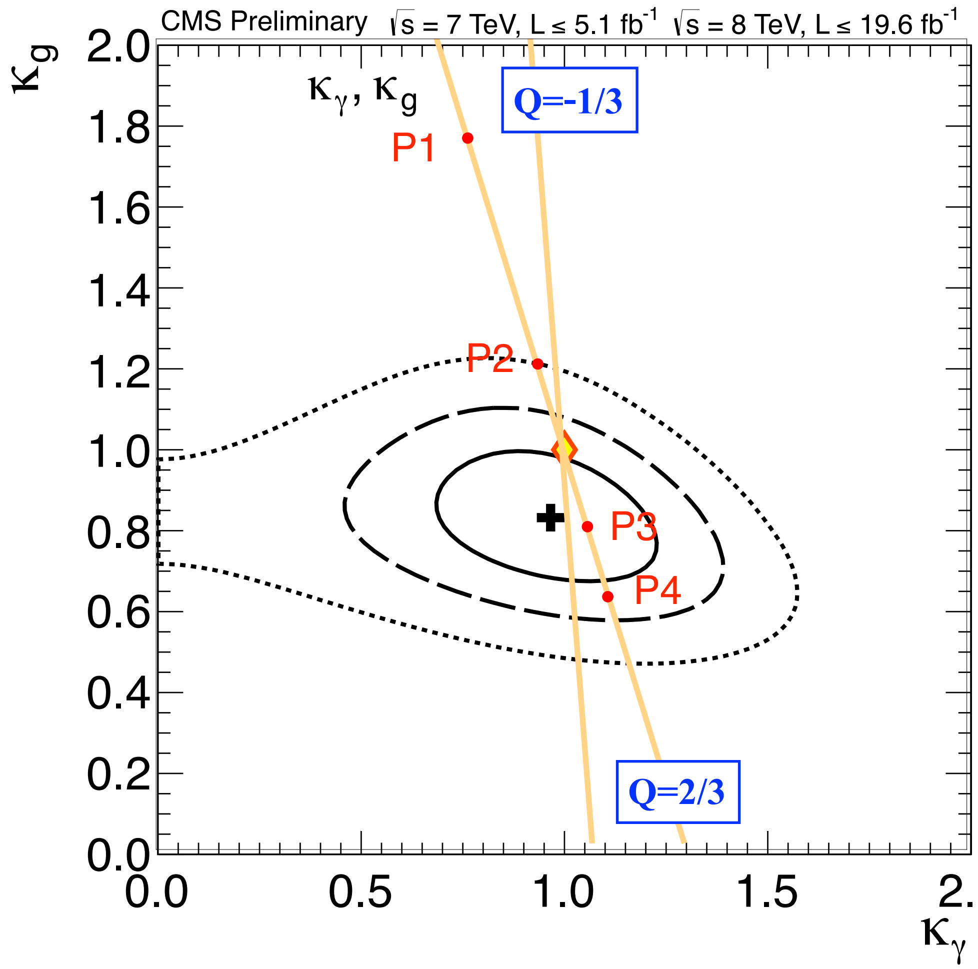




Small mixing: ➡ $\Gamma(gg \to h)$ enhanced

$\Gamma(h \to \gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg \to h)$ suppressed

$\Gamma(h \to \gamma\gamma)$ enhanced

P1: $m_{\tilde{t}_1} = 100\,\mathrm{GeV},\ m_{\tilde{t}_2} = 300\,\mathrm{GeV},\ \theta_t = 0$

P2: $m_{\tilde{t}_1} = 200\,\mathrm{GeV},\ m_{\tilde{t}_2} = 500\,\mathrm{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1000\,\mathrm{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1500\,\mathrm{GeV},\ \theta_t = \pi/4$

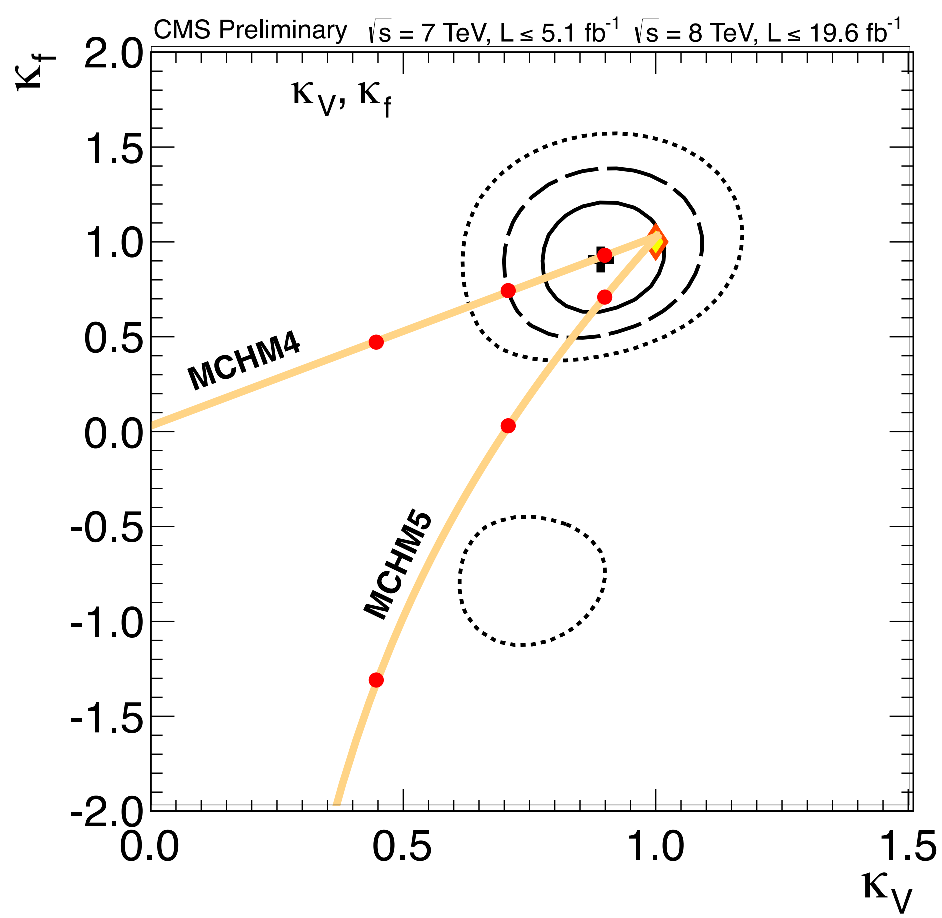
Composite Higgs theories

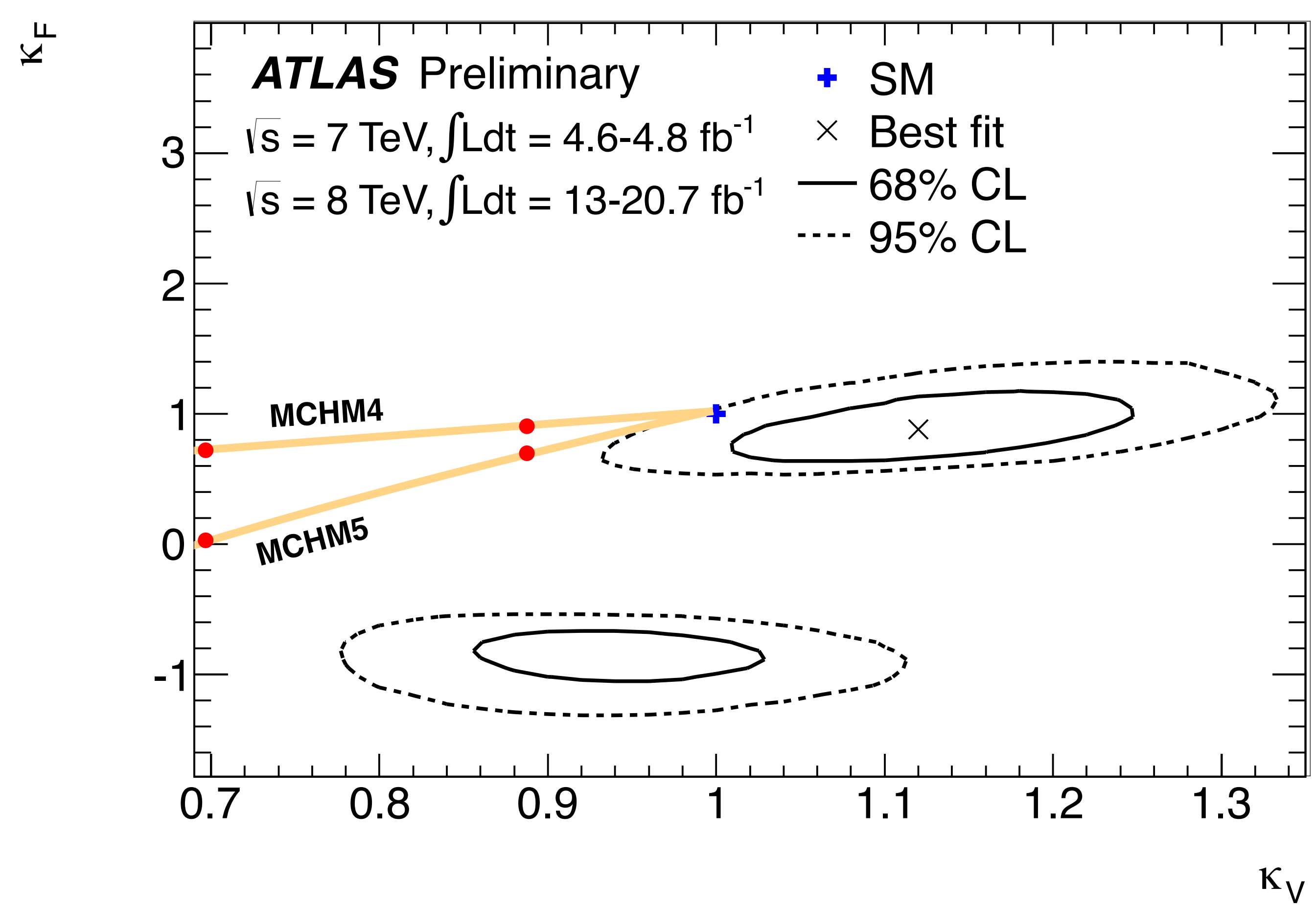
- Leading effects in tree-level couplings and Zγ rate

$$c_V, c_u, c_d = 1 + O\left(\frac{v^2}{f^2}\right) \qquad \frac{\Gamma(h \to Z\gamma)}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right)$$

f = Higgs decay constant

$$m_{\text{new}} = g_* f \lesssim 4\pi f$$





Red points at $(v/f)^2 = 0.2,\ 0.5,\ 0.8$

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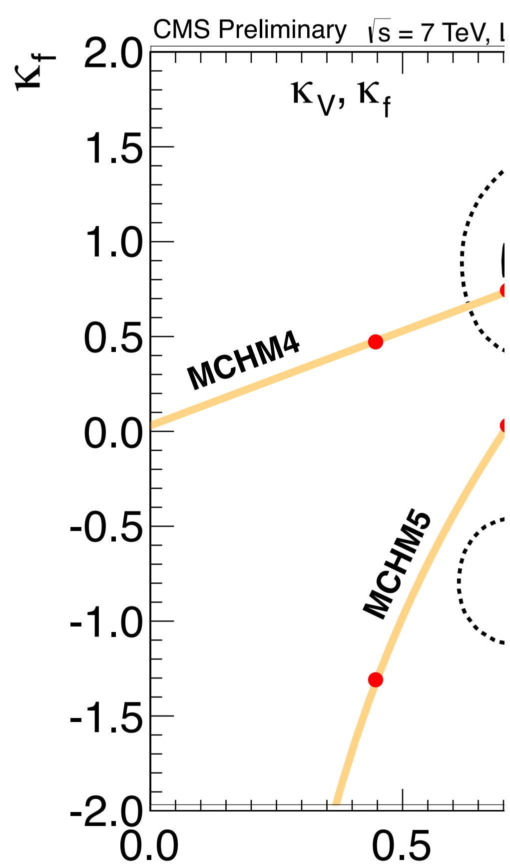

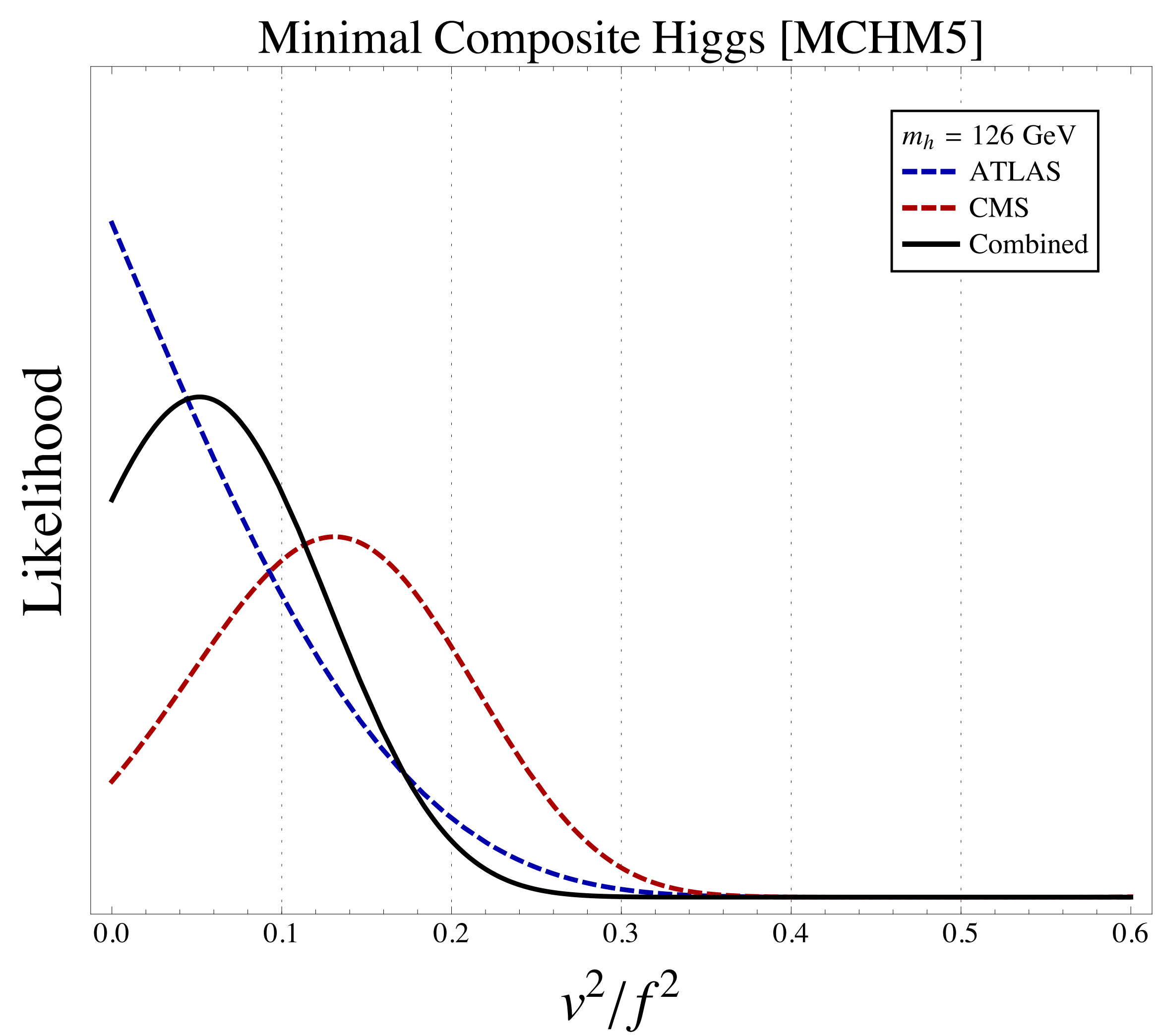

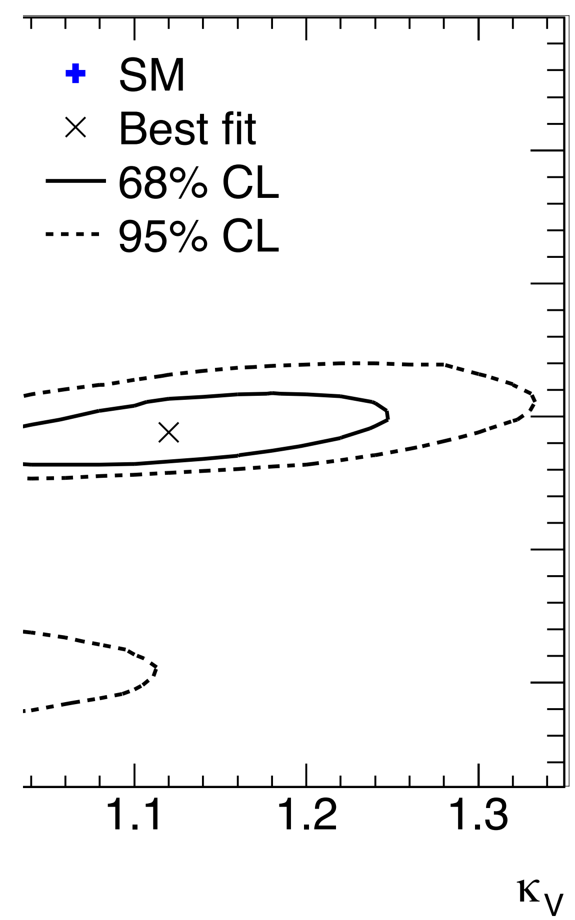

$(v/f)^2 < 0.22$ at 95% ➡ $m_{\text{new}} \gtrsim 1.6\,\text{TeV}\left(\frac{g_*}{3}\right)$

Composite Higgs theories

- Corrections to $\gamma\gamma$ and gg couplings suppressed by Goldstone symmetry

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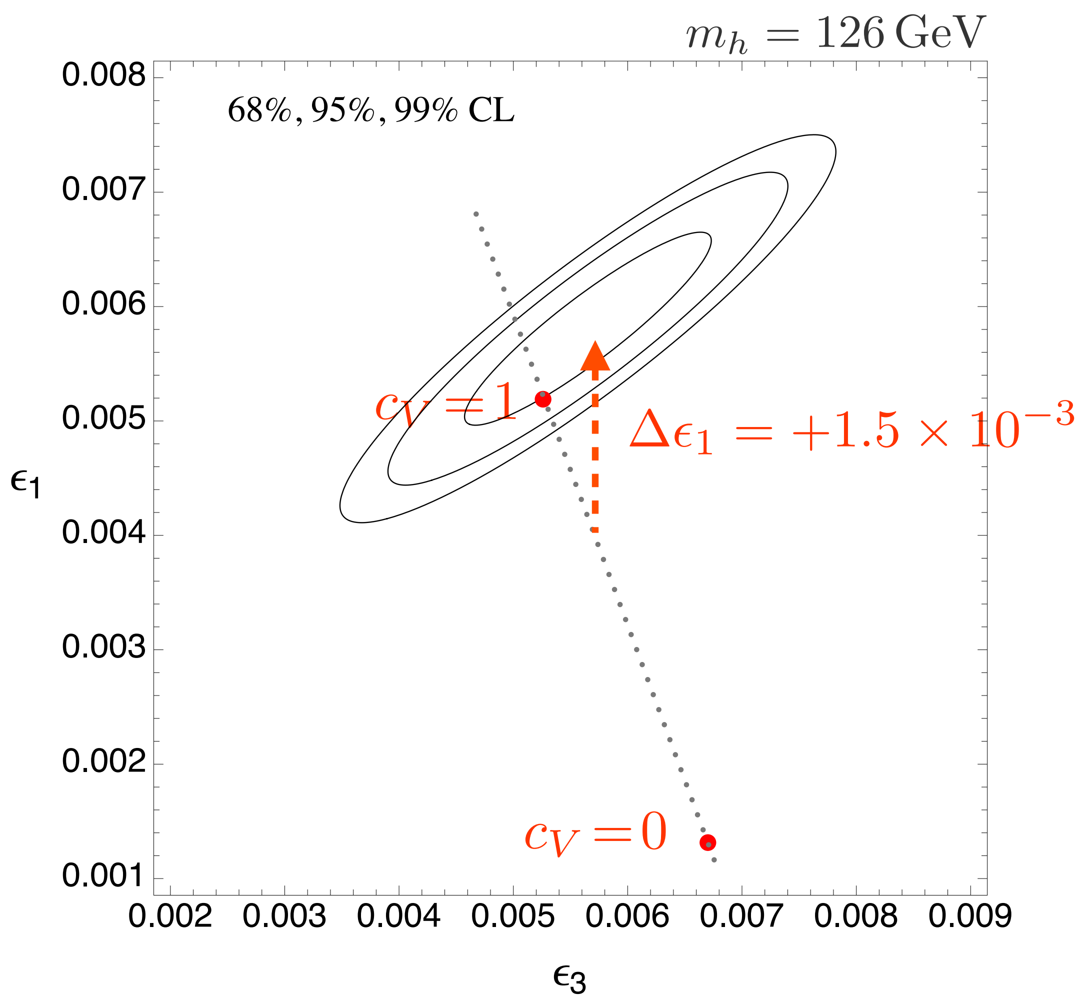
New Physics contribution (e.g. $\Delta\epsilon_1 > 0$) required to accommodate shifts of order $\Delta c_V \sim O(10\%)$ or larger

New resonances (e.g. top partners) must not be too heavy



Outlook

- Era of Higgs precision physics has started. Use the Higgs Effective Lagrangian to perform calculations and look for NP effects

see recent review: RC, Ghezzi, Grojean, Muehlleitner, Spira arXiv:1303.3876

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← LEP bounds

$(\bar{c}_W + \bar{c}_B) \lesssim \text{a few} \times 10^{-3}$

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← CP odd

$$\frac{\delta(d\Gamma/d\Omega)}{(d\Gamma/d\Omega)_{SM}} \lesssim O\left(\frac{m_W^2}{M^2}\times\frac{16\pi^2}{g^2}\right)$$

Take advantage of different angular distributions of final fermions

Outlook

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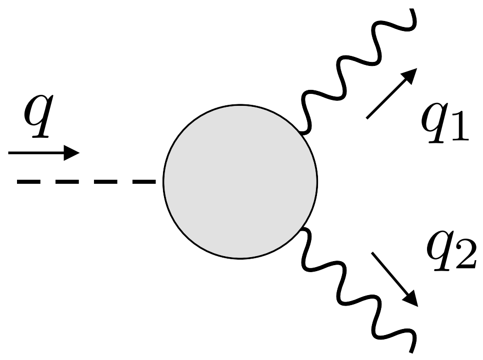

$$A(h\to ZZ) = v^{-1}\epsilon_1^\mu\epsilon_2^\nu\left(a_1 m_H^2\,\eta_{\mu\nu} + a_2\, q_\mu q_\nu + a_3\,\epsilon_{\mu\nu\rho\sigma}q_1^\rho q_2^\sigma\right)$$

$$a_1 = \frac{m_Z^2}{m_h^2} + (\bar{c}_W + \bar{c}_{HW}) + (\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$$

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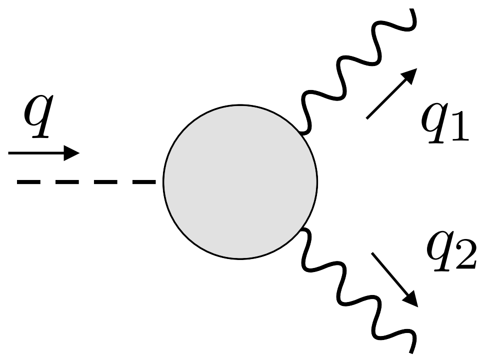

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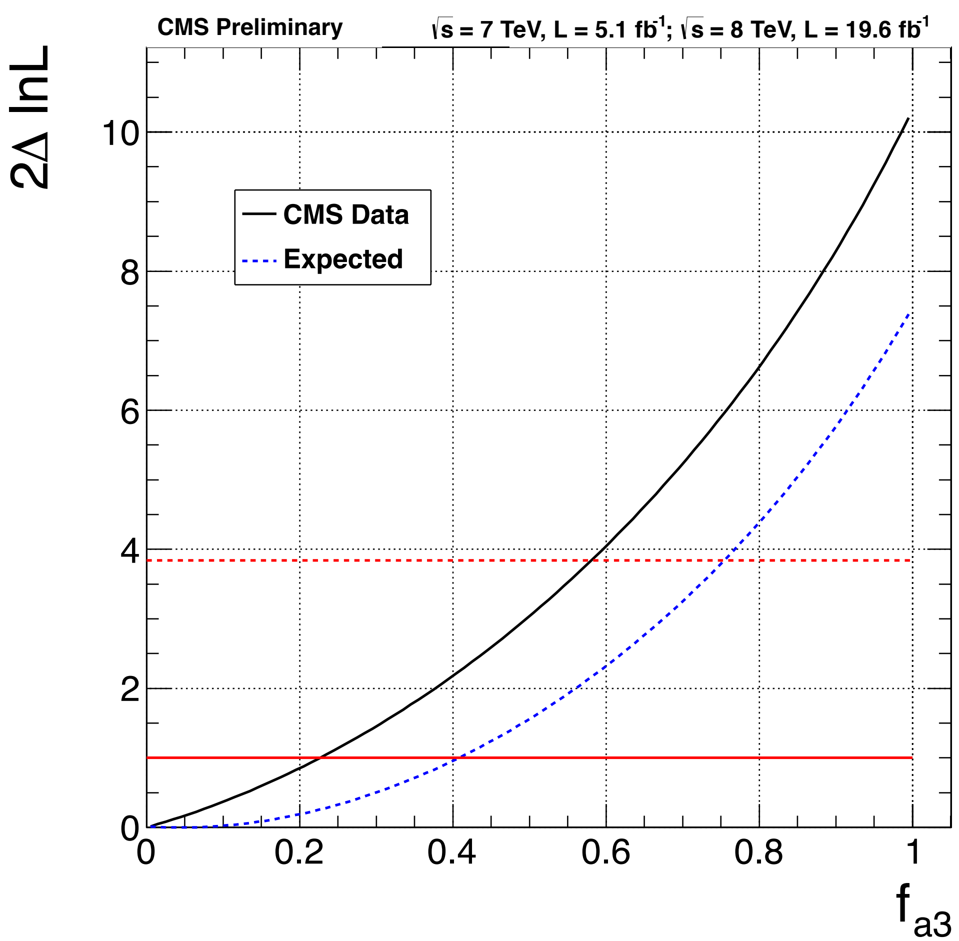

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- Key observables/processes for SUSY:

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  - $\gamma\gamma$, and gg rates

  - production of Heavy Higgses

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- Key observables/processes for Composite Higgs theories:

  - tree-level couplings

  - $Z\gamma$ rate

  - double Higgs production via gluon fusion ($gg \to hh$)

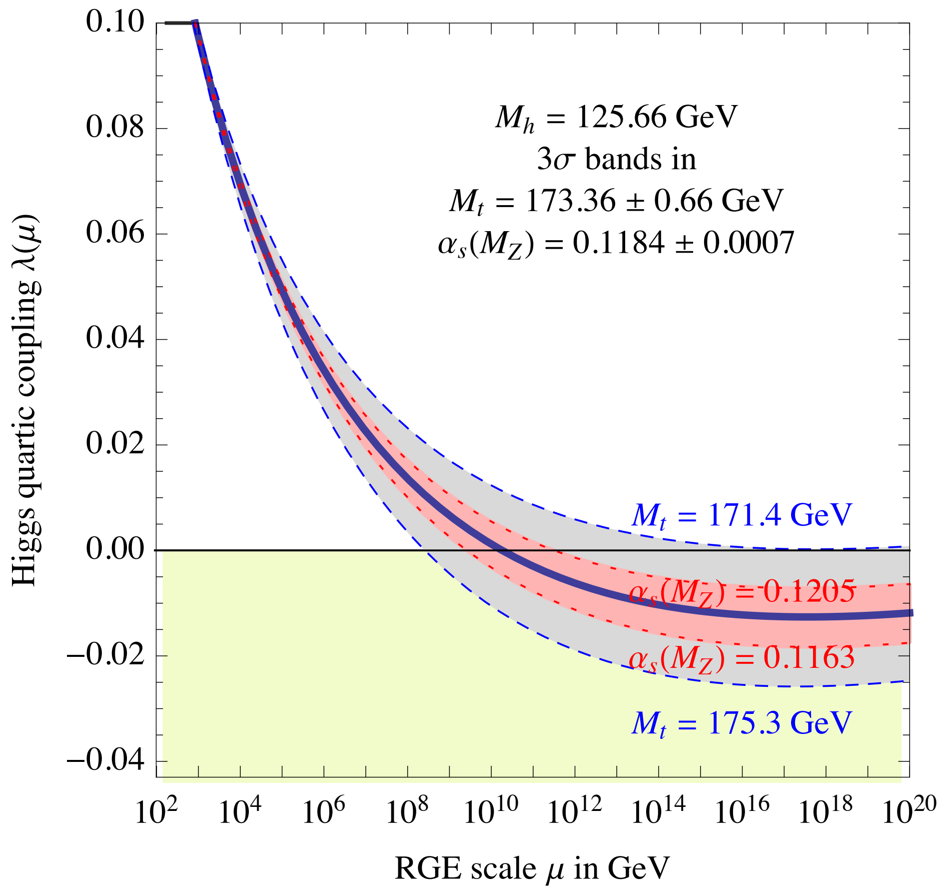
What if there is only the SM ?

$$\lambda_4(v) = m_h^2/v^2 = 0.26$$

$\lambda_4(Q)$ vanishes at $Q \sim 10^{8-14}\,\mathrm{GeV}$

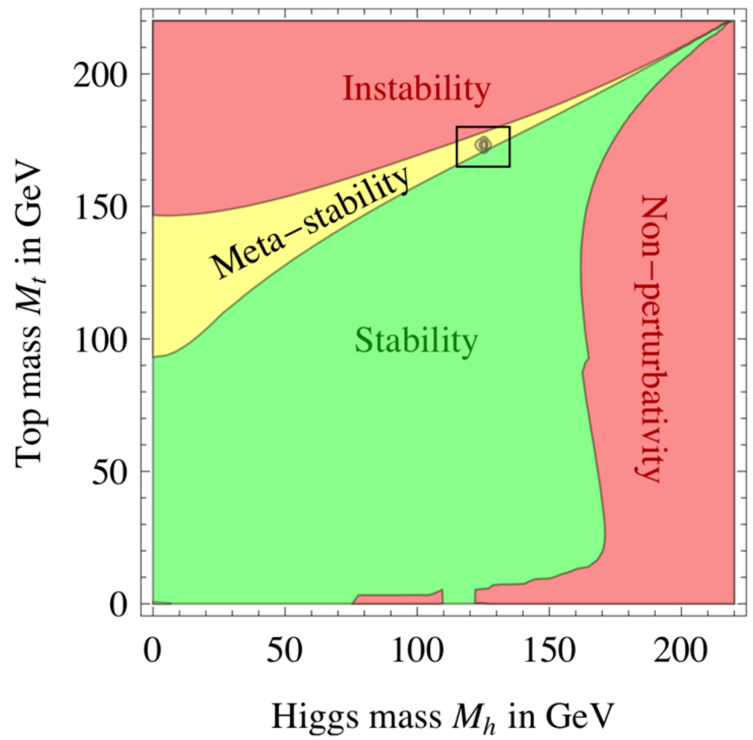
Huge energy domain in which the theory is viable and perturbative

from: G. Degrassi et al. JHEP 1208 (2012) 098

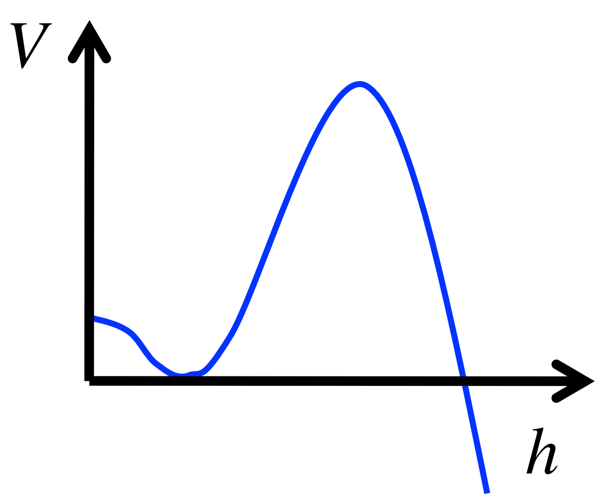


The phase diagram of the SM

[G. Degrassi et al. JHEP 1208 (2012) 098]



$$V_{eff}(h) = -m_H^2\, h^2 + \frac{\lambda_4(h)}{4} h^4$$



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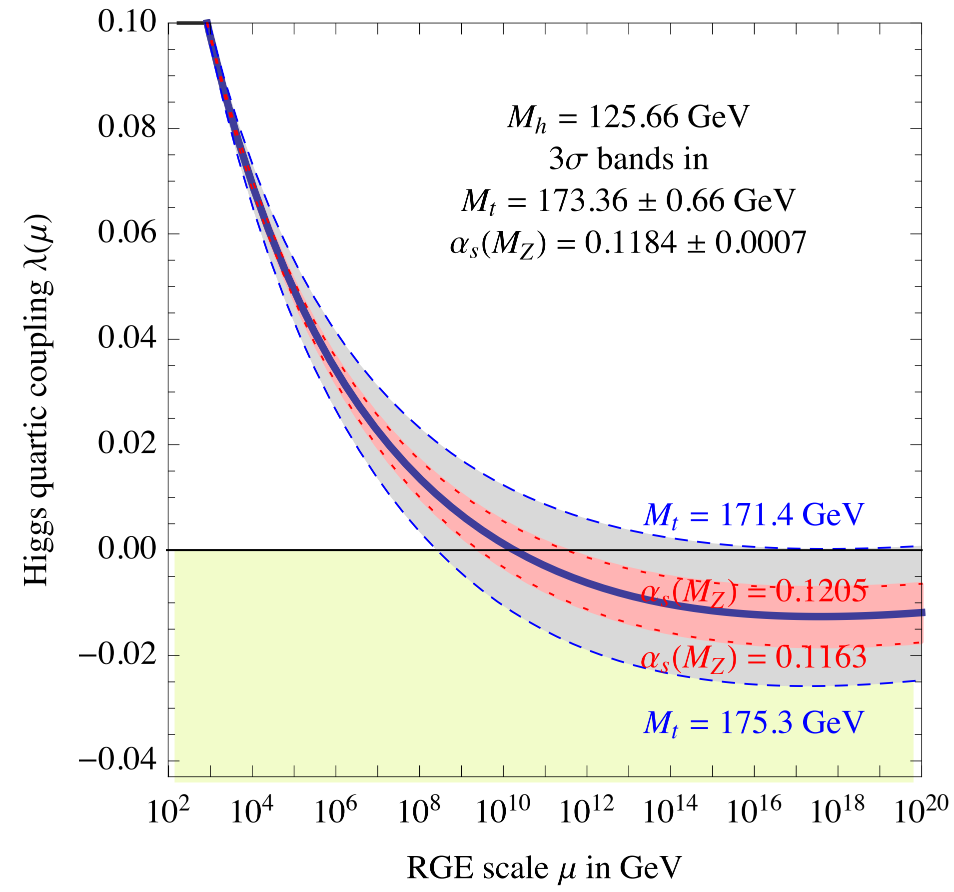

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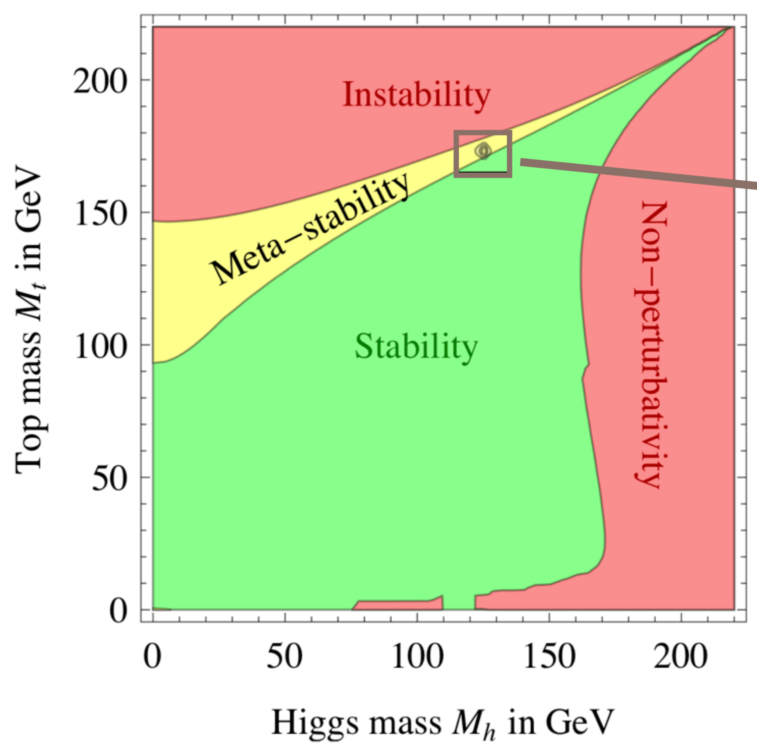

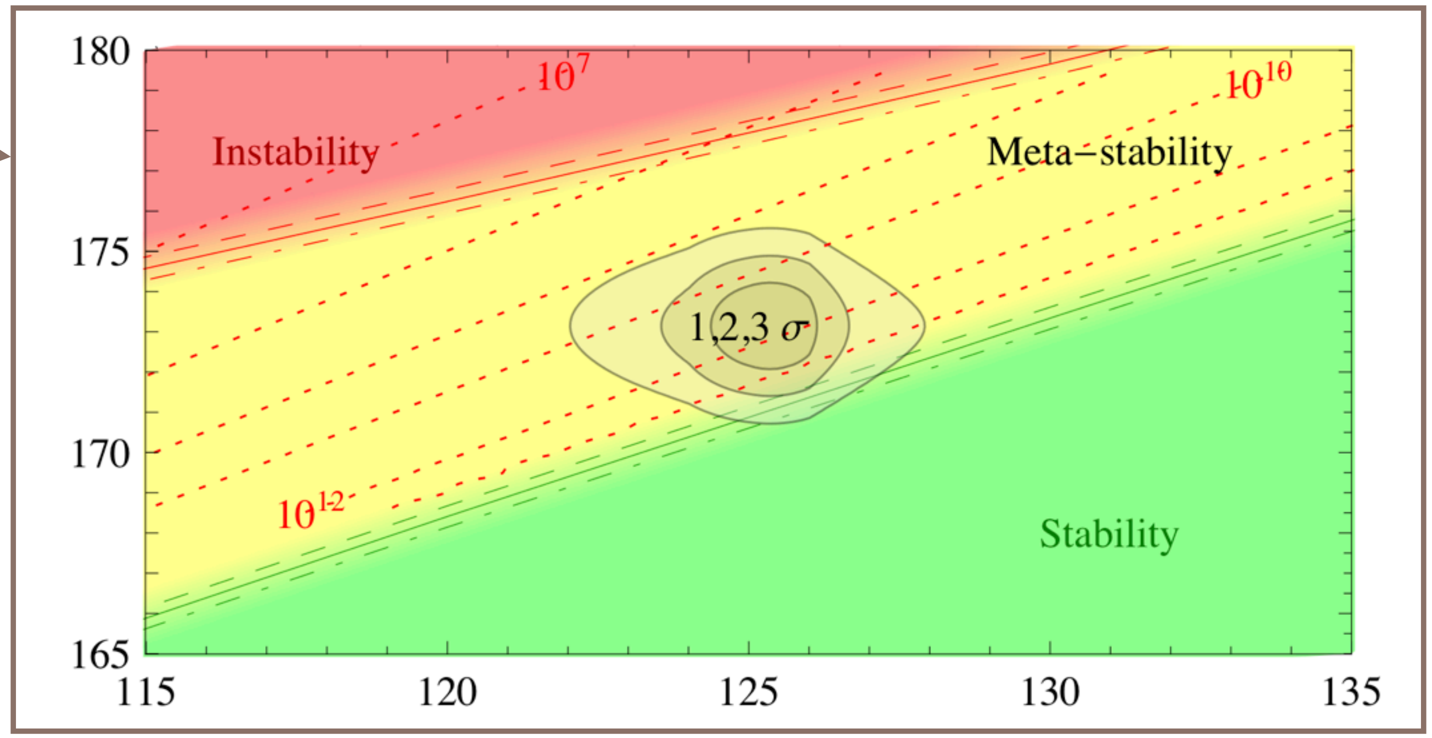

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We seem to live near
a *critical* condition

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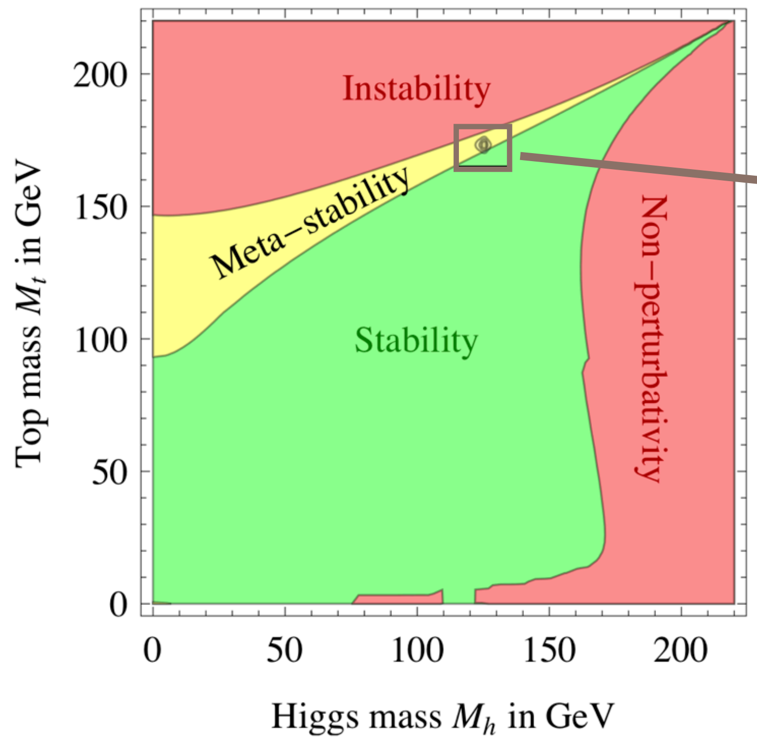
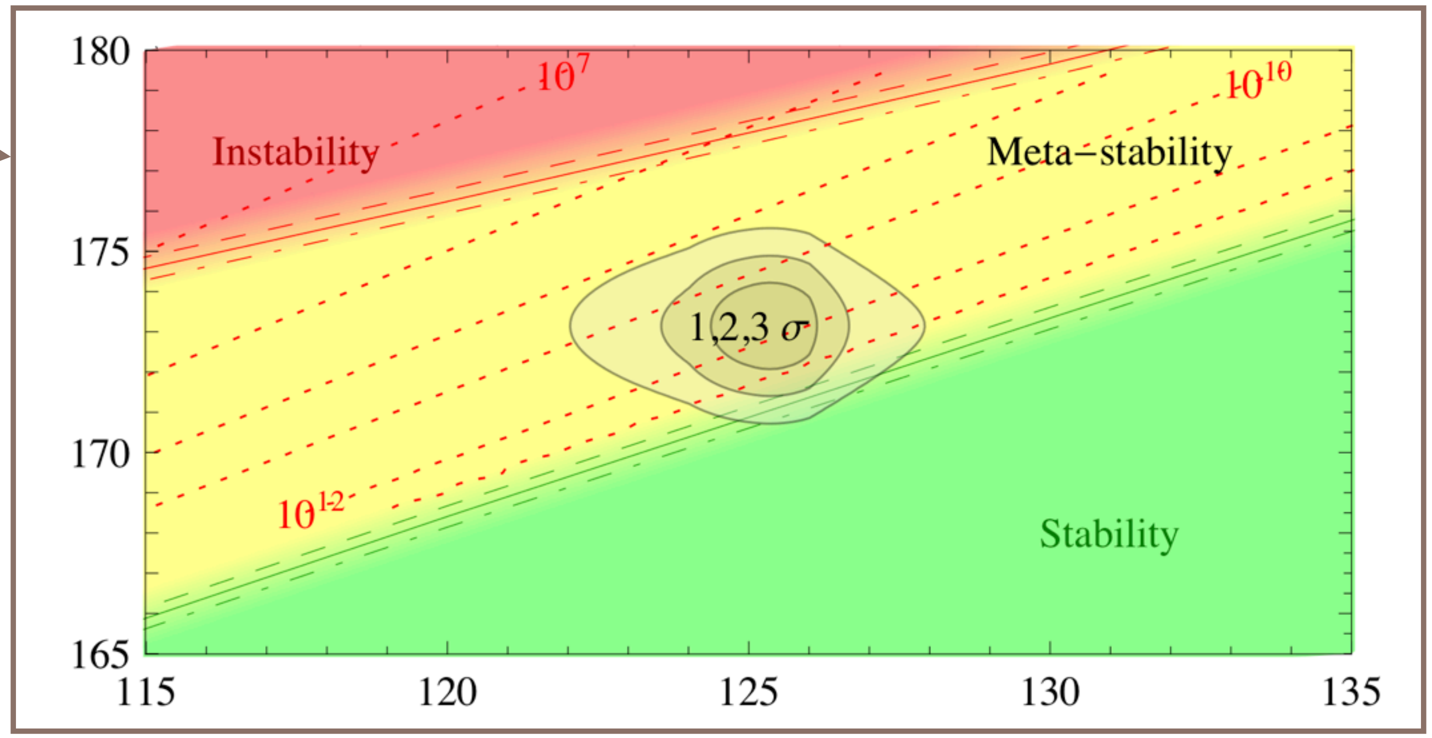
G. Giudice and A. Strumia





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G. Degrassi et al. JHEP 1208 (2012) 098
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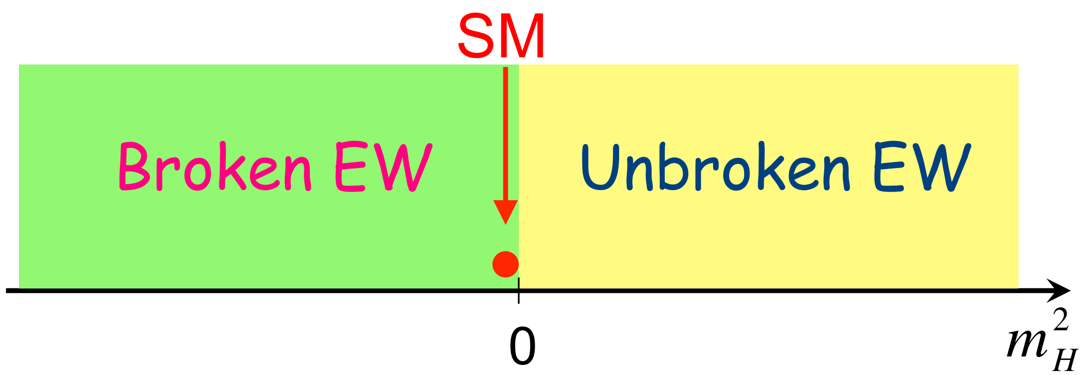
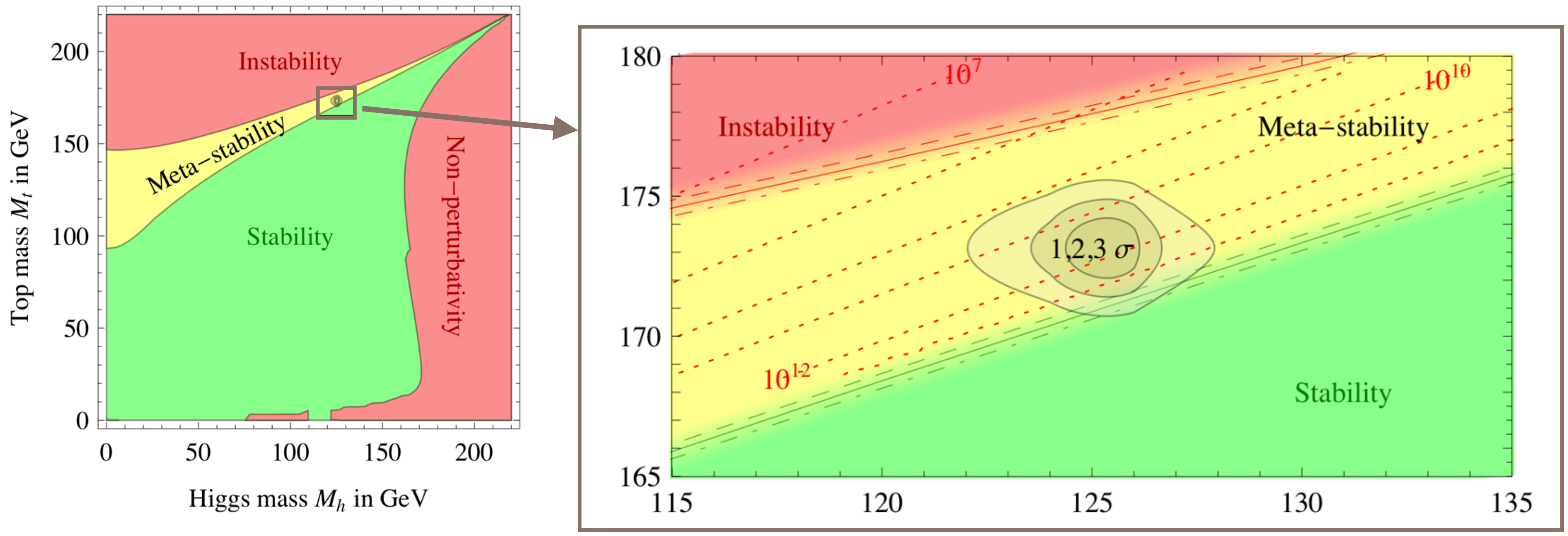
The Planck-EW hierarchy itself
is a problem of criticality

G. Giudice, R. Rattazzi, NPB 757 (2006) 19





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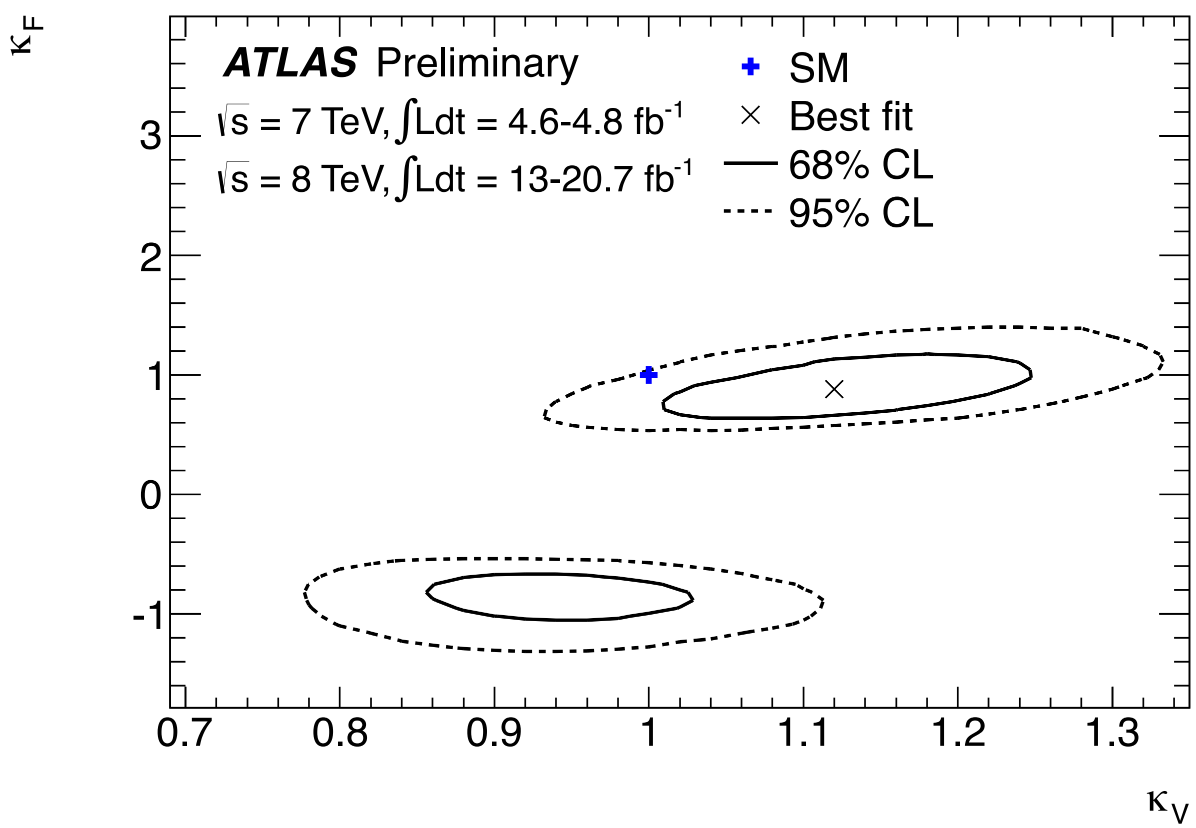
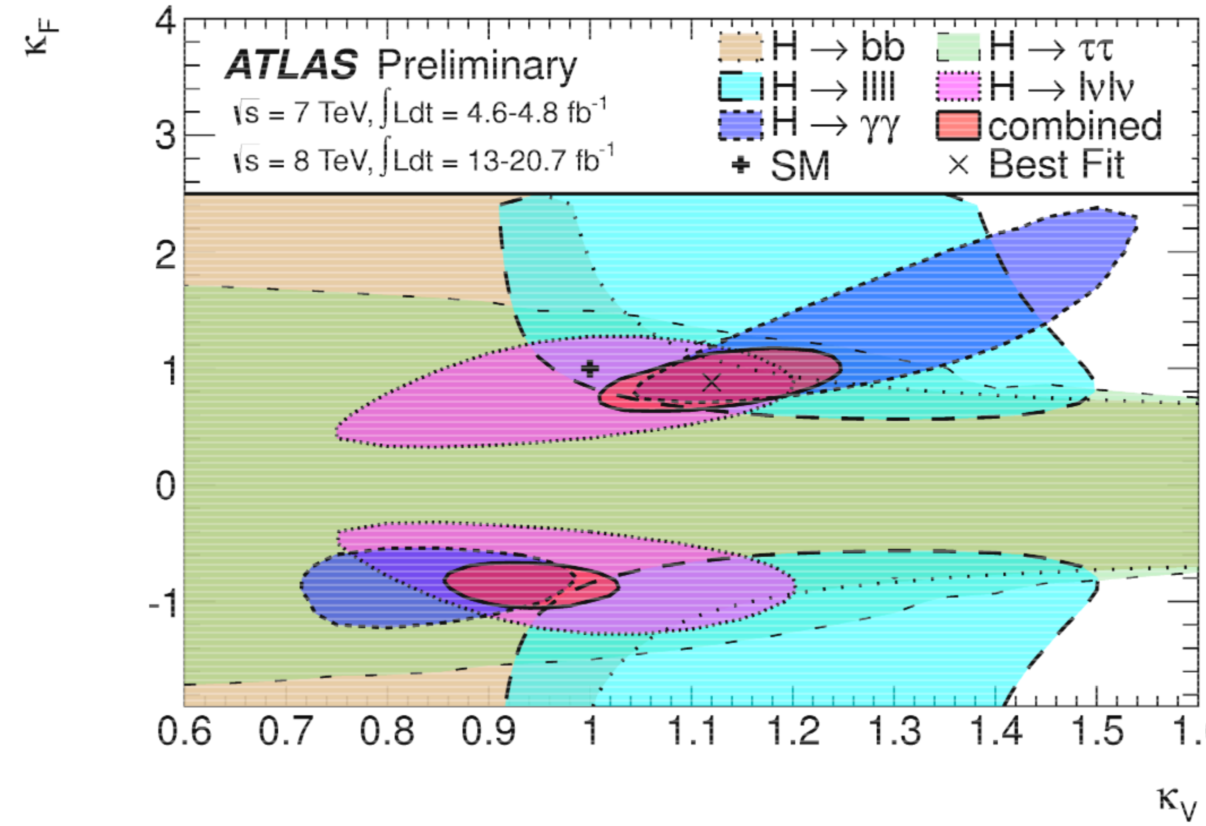
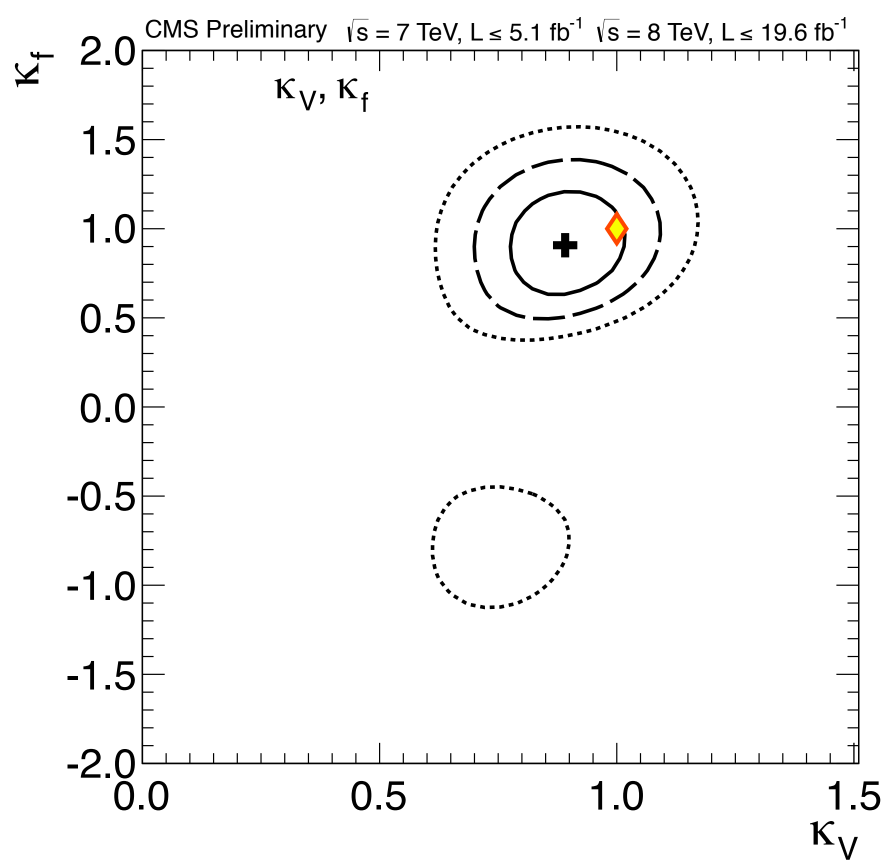
Self-organized criticality due to statistical pressure ?

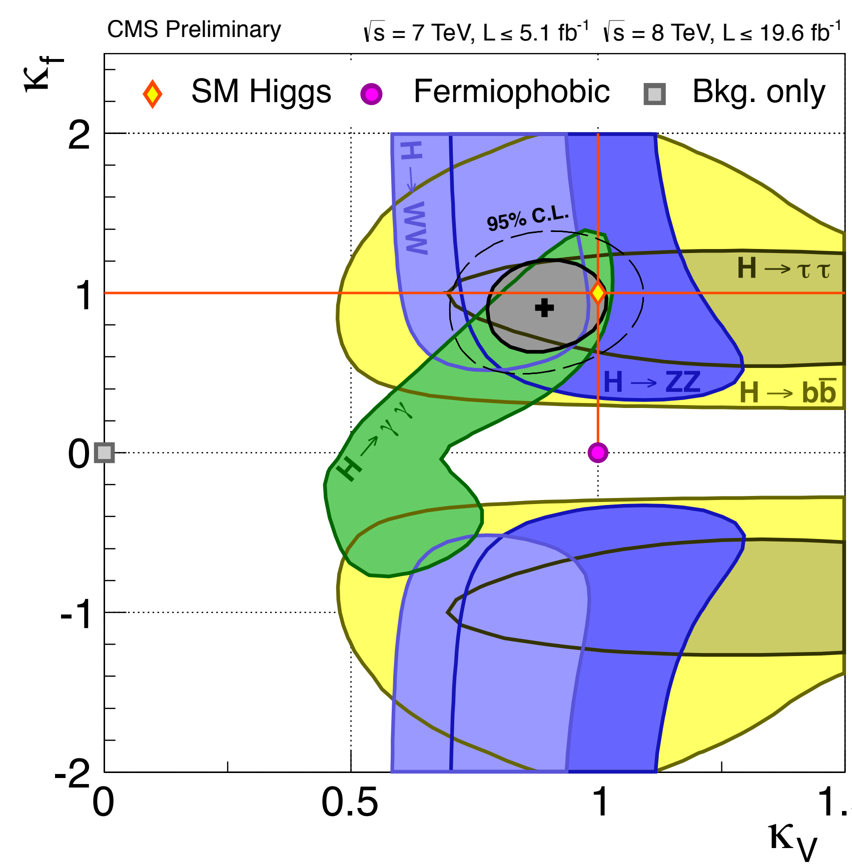
EXTRA SLIDES

Fit in the plane (kV,kF) by ATLAS and CMS









Theorist's fit in the plane (c_b,c_t) for ATLAS and CMS

Made by Jamison Galloway