Open Questions in the Higgs Sector

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ATLAS-D, 9/2012

Immediate questions

4th of July fireworks

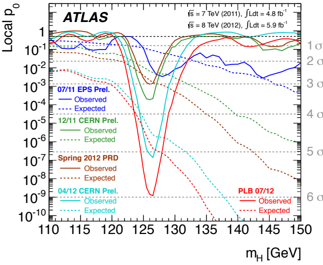
– ‘silver channel’ $H \to \gamma\gamma$
  4.5σ (ATLAS), 4.1σ (CMS)

– ‘golden channel’ $H \to ZZ \to 4\ell$
  3.4σ (ATLAS), 3.2σ (CMS)

– ‘pain-in-the-ass channels’ $H \to WW, \tau\tau, bb$
  adding little still

– combined 5.0σ (ATLAS), 4.9σ (CMS) [LEE 4.3

$\Rightarrow$ resonance at $m_H = 125 - 126$ GeV discovered



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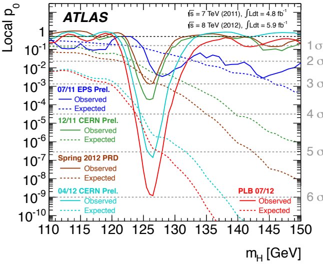

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One

1– Are all analyses air tight? [Would you tell me if not?]

- alternatively: can we help?

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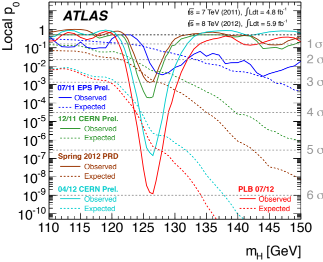

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Two

2– What are the quantum numbers?

- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected
- spin-1 vector unlikely
- spin-2 graviton unexpected
- strictly speaking: operators in Lagrangian

Immediate questions

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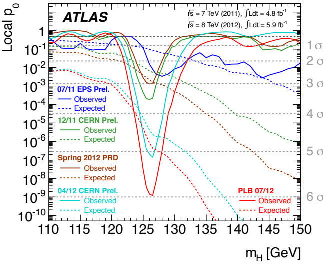

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Three

3– What are the coupling values?

- after fixing operator basis
- Standard Model Higgs?
- anomalous/effective couplings?

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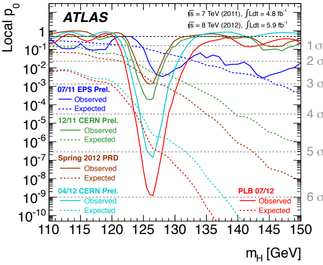

Four

4– What can we expect in the future?

- WBF analyses essentially missing
- VH and $t\bar{t}H$ missing
- self coupling not accessible?

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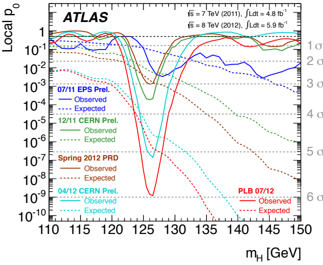

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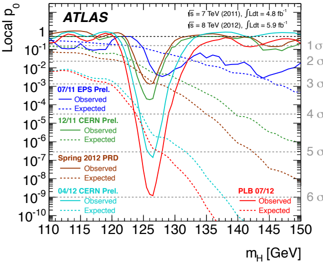

Immediate questions

1– Are all analyses air tight?

2– What are the quantum numbers?

3– What are the coupling values?

4– What can we expect in the future?

5– Where is supersymmetry?

Operators

First question [not first answer]

– what are the Higgs quantum numbers?

– what is the structure of the Higgs Lagrangian?

– can the Higgs give mass to heavy states?

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Heavy flavor inspiration

– for any observed Higgs coupling there exists a renormalizable operator

– except Higgs production in gluon fusion

– except Higgs decay to photons

– except g_{WWH} might accompany $HW^{\mu} W_{\mu}$(D4) or $HW^{\mu\nu} W_{\mu\nu}$(D6)

– Higgs Lagrangian all but trivial

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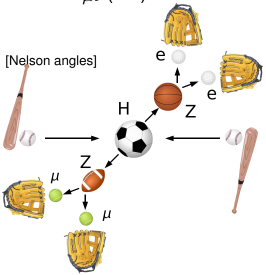
- except g_{WWH} might accompany $HW^\mu W_\mu$(D4) or $HW^{\mu\nu} W_{\mu\nu}$(D6)
- Higgs Lagrangian all but trivial
- operator structure visible in angular correlations [Nelson angles]

$\Rightarrow$ analyze Higgs decay kinematics



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Short cuts

– employ dimensional analysis
– re-write in terms of coupling strengths

$$g_{HZZ}^{\text{D4}} \leftrightarrow g_{HZZ}^{\text{D6}} \leftrightarrow g_{H\gamma\gamma}^{\text{D6}} \leftrightarrow g_{HZ\gamma}^{\text{D6}}$$

$\Rightarrow$ valuable first constraints...

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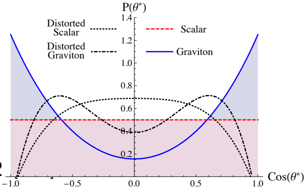

More solid [in my opinion]

– first step: Higgs polar angle for spin-0 vs spin-2

$$\frac{d\Gamma_0}{d\cos\theta^*} \sim P_0(\theta^*) = 1 \qquad\qquad P_2(\theta^*) \sim 1+6\cos^2\theta^*+\cos^4\theta^*$$

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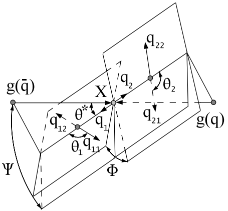

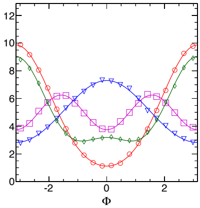

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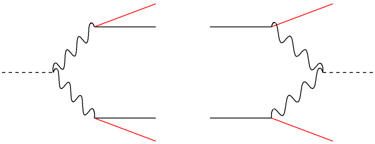

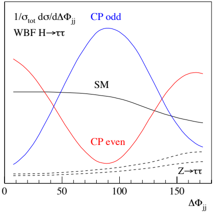

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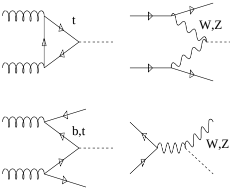
$\Rightarrow$ curious which channel works first

Couplings



Current model [cf question One]

– assume: narrow CP-even scalar
SM-like D4 structures
SM-induced D6 structures

– couplings from production & decay combinations?

$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \; (1+\Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}}$$

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Why 126 GeV is perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012; Contino et al]

– measurements: $GF : H \to ZZ, WW, \gamma\gamma$ [2011]
  $WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$ [2012]
  $VH : H \to b\bar{b}$ [2015: BDRS?]
  $t\bar{t}H : H \to b\bar{b}...$ [2015: boosted?]

– parameters: g_{HXX} with $X = W, Z, t, b, \tau, g, \gamma$ [plus Higgs mass]

– correlations: $N_{\text{ev}} \propto \dfrac{g_p^2 g_d^2}{\Gamma_{\text{tot}}(g_X^2)}$

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SFitter ansatz [(Dührssen), Klute, Lafaye, TP, Rauch, Zerwas]

- experimental/theory errors on signal and backgrounds [RFit]
  ATLAS and CMS both included
  total width from observed partial widths
- starting point: exclusive likelihood map
  individual coupling: profile likelihood
  best fit: Minuit
  errors: toy measurements

$\Rightarrow$ global and local analysis possible

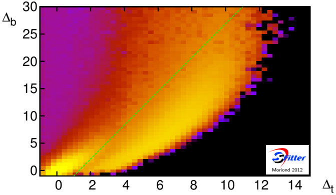
Global/local 7 TeV analysis

Global view on 7 TeV data [Klute, Lafaye, TP, Rauch, Zerwas]

– is there a SM-like solution?
  are there alternative solutions?

(1) expected 2011: SM central values, measured error bars

– large-coupling solution separable



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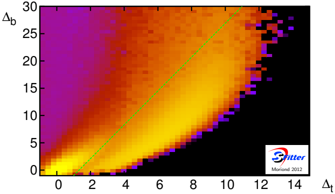
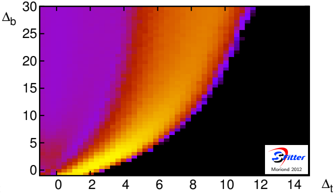
  error bars inflated





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Local view on 7 TeV data

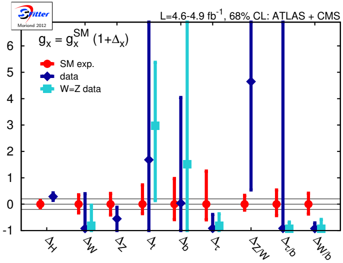
– focus on SM solution where possible

– five couplings from data

$g_W \sim 0$ while g_Z okay
g_b and g_t hurt by secondary solution
g_τ inconclusive in data

– poor man's analysis great: $\Delta_j \equiv \Delta_H$

$\Rightarrow$ pointing towards Standard Model?



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– g_W now improved

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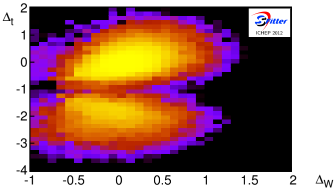
– two symmetric solutions



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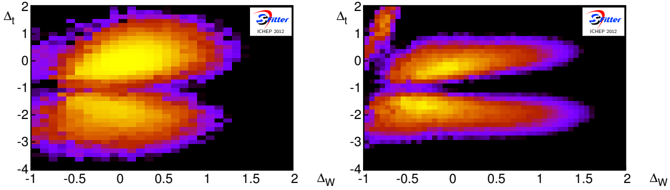
– alternative solution separated and weakened
improved $\Delta_{W,b,t}$ error bars



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Local view on 8 TeV data

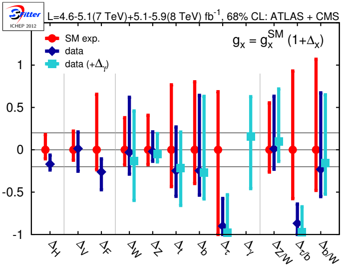
– focus on SM solution

– six couplings from data

$g_{W,Z}$ okay
$g_{t,b}$ indirectly
g_τ poor
g_γ possible

– poor man's analyses great: $\Delta_H, \Delta_V, \Delta_f$

$\Rightarrow$ moving towards Standard Model?



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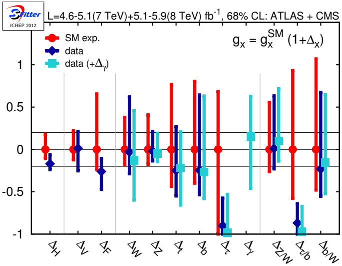
Testing the Higgs

– six couplings determined [g_{ggH} still missing]

– error bars $20 - 50\%$

– central value $\Delta_\gamma = 0.16$

– all good fits



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hypothesis	$\chi^2_{2012}/\mathrm{dof}$	solutions
Standard Model	43.3/54	
form factor Δ_H	32.2/53	1
two-parameter $\Delta_{V,f}$	29.0/52	2
independent Δ_x	27.7/49	3
including Δ_γ	27.3/48	2

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$\Rightarrow$ what's next?

More on couplings

Anomalous Higgs couplings [Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

– anomalous couplings from D6 operators f_j [index '2' for $W_{\mu\nu} W^{\mu\nu}$]

$$g_{Hgg} = -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \qquad g_{H\gamma\gamma} = -\frac{g M_W}{\Lambda^2} \frac{s^2 (f_{BB} + f_{WW} - f_{BW})}{2}$$

$$g^{(1)}_{HZ\gamma} = \frac{g M_W}{\Lambda^2} \frac{s(f_W - f_B)}{2c} \qquad g^{(2)}_{HZ\gamma} = \frac{g M_W}{\Lambda^2} \frac{s[2s^2 f_{BB} - 2c^2 f_{WW} + (c^2 - s^2) f_{BW}]}{2c}$$

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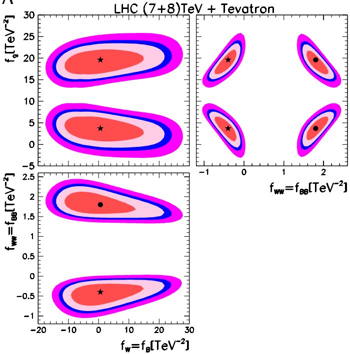
– asume $f_W = f_B$ [otherwise no convergence]
fit f_{gg}, f_{WW}, f_{BB}
observe usual sign-flip degeneracy
compare to $\Delta\kappa$ and Λ in g_{WWV}



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A word on benchmarks

– known to ‘say more about authors than about physics’

– bottom-up approach crucial

– theory benchmarks really only interesting for authors [I like the Higgs portal]

Bottom Yukawa

Direct vs indirect measurements

– no $b\bar{b}H$ production observed
  no $H \to b\bar{b}$ decay observed [which I trust]

– information from BR$(H \to b\bar{b}) \sim 58\%$ [HDecay]

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Bottom Yukawa

Direct vs indirect measurements

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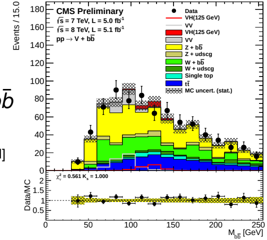
Best channel $q\bar{q} \to VH$, $H \to b\bar{b}$

– let me comment on CMS analysis

– focus on boosted regime $p_{T,V} \gtrsim 120$ GeV
  fudge factor Data/MC=1.91 $\pm$ 0.14 $\pm$ 0.31 for $Wb\bar{b}$
  data-estimated background $\Delta\sigma/\sigma \sim 10\%$
  12 observables in BDT [most of them work and are understood]
  no side bands with any S/B



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– ATLAS (more) honest

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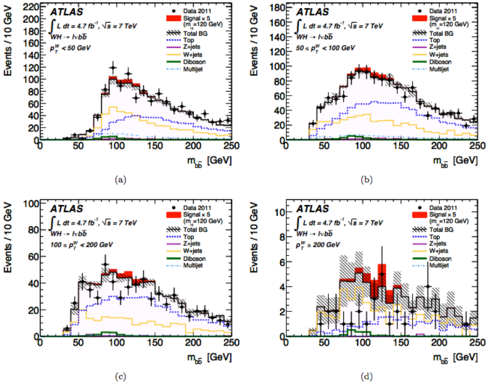
[my hopes rest on BDRS and Giacinto]



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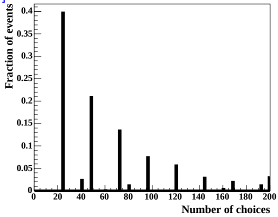

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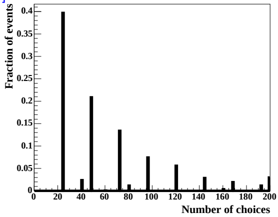

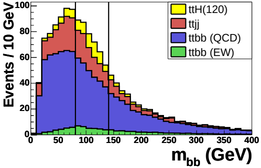

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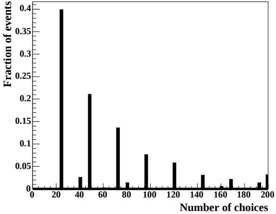

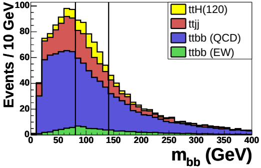

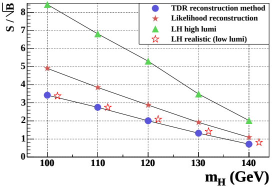

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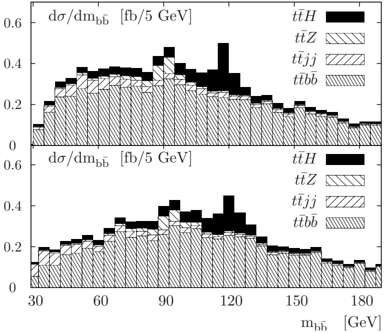
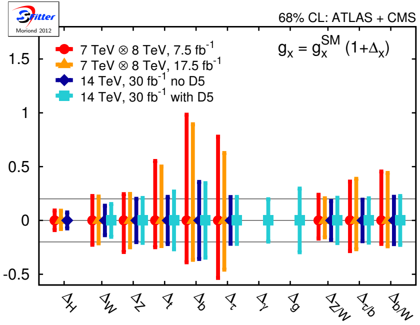
$\Rightarrow$ solving three problems [plus sidebands]



Full set of couplings

2012, 2015, etc

- 2012: meaningful WBF measurements
  g_W and g_τ accessible
- 2015: $t\bar{t}H$ and $H \to b\bar{b}$ measurements
  g_g and g_γ fully accessible
- eventually case for a linear collider [$ZH \to t\bar{t} \to t\bar{t}H$]



Self coupling

Cutting off Higgs potential?

– potential and mass to dimension-6

$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4 + \frac{f_2}{3\Lambda} |\phi|^6 + \cdots$$

$$m_H^2 = 2\lambda v^2 \left(1 + \frac{f_2 v^2}{2\Lambda^2 \lambda} + \cdots \right)$$

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– generic offset of Higgs mass vs (self) coupling

– more general: not all scalars form potential

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– extract λ_{HHH} from s-channel diagram

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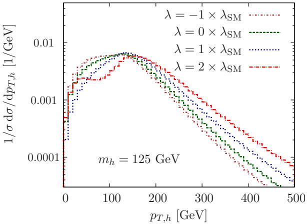

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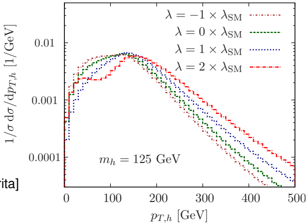

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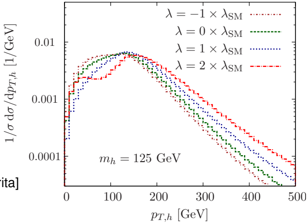

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Weak scale

From D6 operators to new physics

– SM: non-decoupling chiral fermions $g_{Hgg} \sim \alpha_s/(12\pi v)$

– new physics always present

– new particle with charge Q and SU(3) Casimir $C(R)$ [Reece]

$$R_\gamma = \frac{g_{H\gamma\gamma}}{g^{\text{SM}}_{H\gamma\gamma}} = \left[1 + 0.28\xi \left(1 \mp \sqrt{R_g}\right)\right]^2 , \qquad \xi = \frac{3Q^2}{C_2(R)}$$

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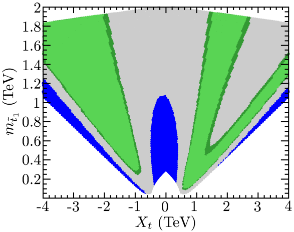

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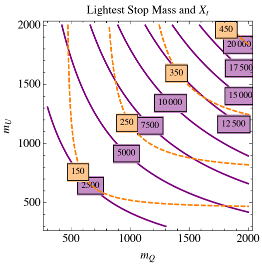

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⇒ no final word on the MSSM

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High-scale effects

– Higgs mass related to self coupling: $m_H = v\sqrt{2\lambda}$
top mass related to Yukawa: $\lambda_t = \sqrt{2}m_t/v$

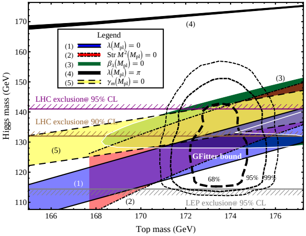
$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

– IR fixed point for λ/λ_t^2 fixing m_H^2/m_t^2 [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1}\times 4.1 - \frac{\alpha_s - 0.1176}{0.002}\times 1.5$$

– Planck-scale conditions [Holthausen, Lim, Lindner]

$\Rightarrow$ Higgs and top strongly linked



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