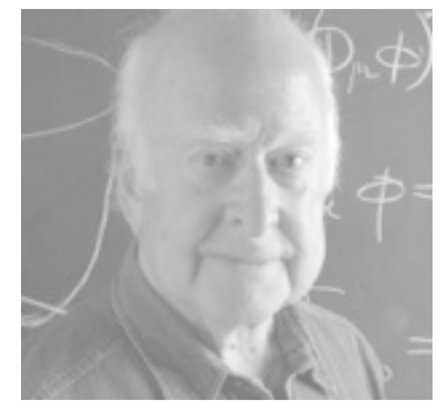
Goldstone meets Higgs
@
the LHC



Javi Serra

UC Davis Joint Theory Seminar, March 18, 2013

What does the recently discovered
125 GeV Higgs
imply for models of strong dynamics?

... besides

$$\mathcal{L}_{eff}(\mu < \Lambda)$$

d<4	d=4	d>4
$\epsilon\Lambda^2\|H\|^2$	$\bar{\psi}\not{D}_\mu\psi$	$\frac{c_{ij}}{\Lambda}\ell_i H H \ell_j$
	$F_{\mu\nu}^2/g^2$	$\frac{c_{ijkl}}{\Lambda^2}\bar{\psi}_i\psi_j\bar{\psi}_k\psi_l$
	$Y_{ij}\bar{\psi}_i H\psi_j$	$\frac{1}{\Lambda^2}H^\dagger W_{\mu\nu} H B^{\mu\nu}$
	$\lambda\|H\|^4$	$\vdots$

$$\mathcal{L}_{eff}(\mu < \Lambda)$$

d<4	d=4	d>4
$\epsilon\Lambda^2\|H\|^2$	$\bar{\psi}\not{D}_\mu\psi$	$\frac{c_{ij}}{\Lambda}\ell_i H H \ell_j$
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	$\lambda\|H\|^4$	$\vdots$

Nature seems to suggest the point-like limit of the SM:

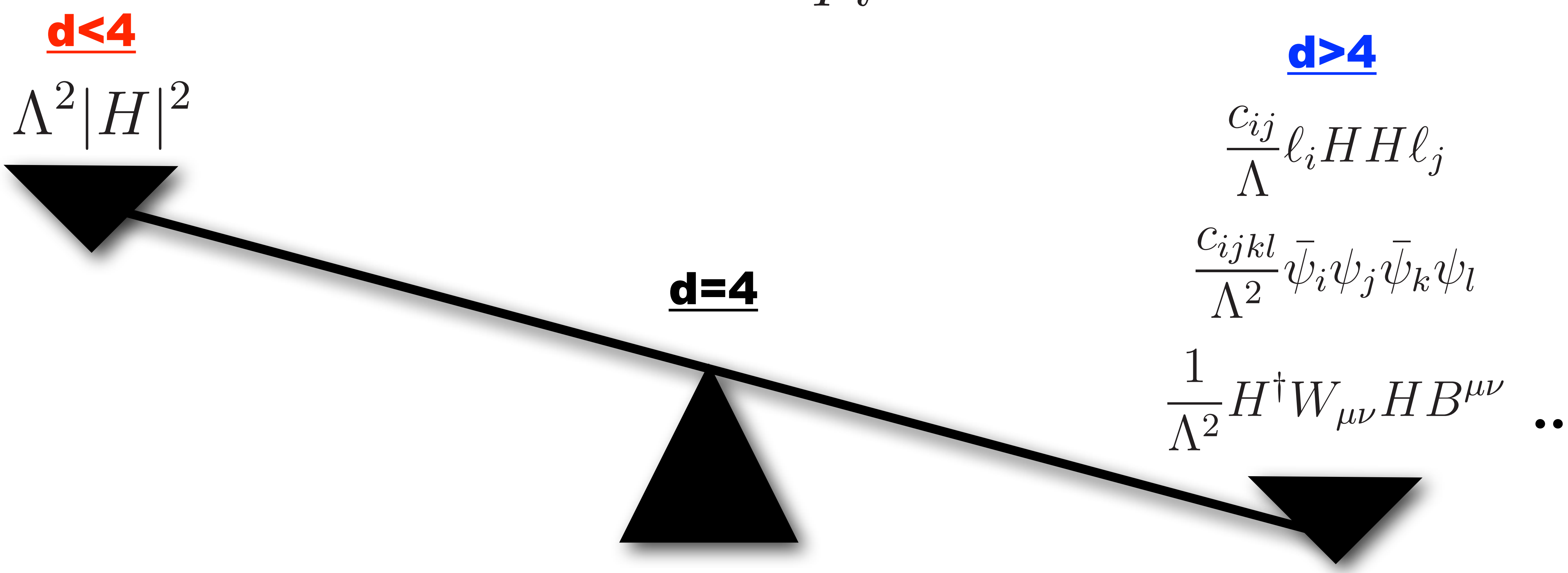
$$\Lambda \to M_{Pl}$$
$$\epsilon \to 10^{-34}$$

it would be unprecedent!

Natural EFT

With an elementary scalar & Quantum EFT:

$$\Lambda \to M_{Pl}$$



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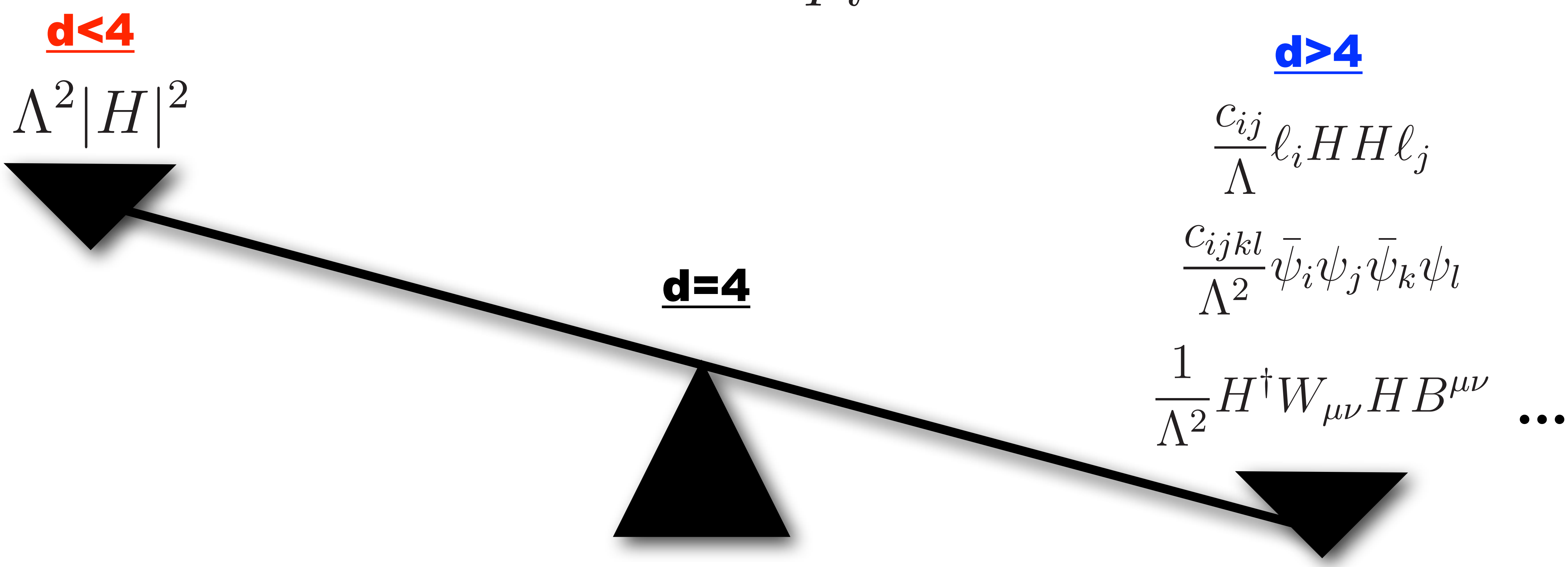
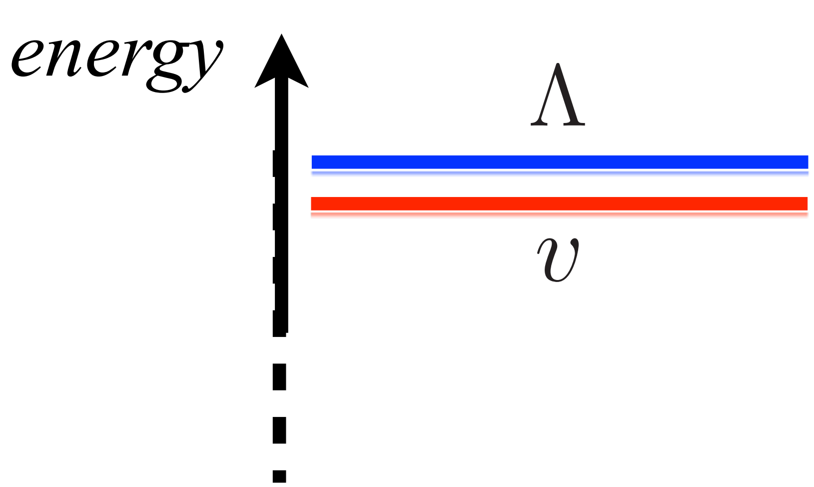




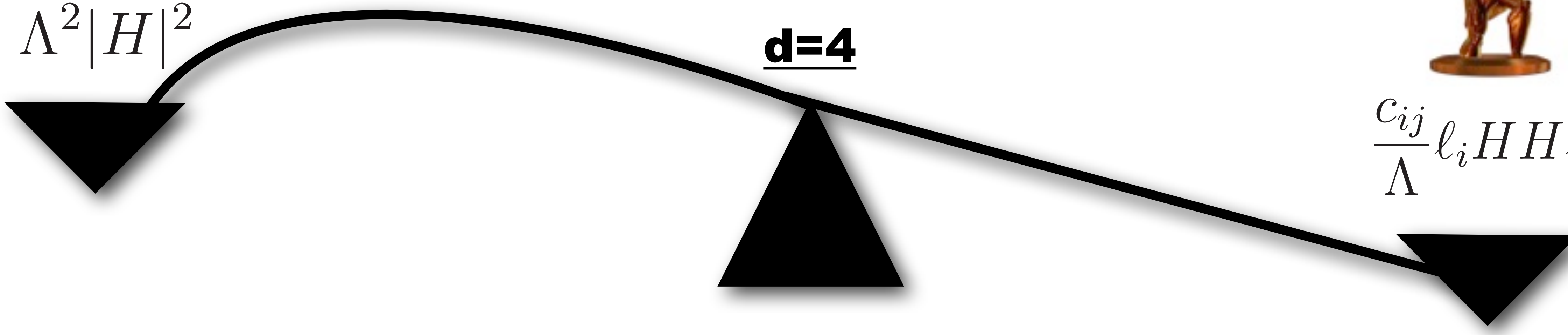
No hierarchy is generated

Unnatural EFT

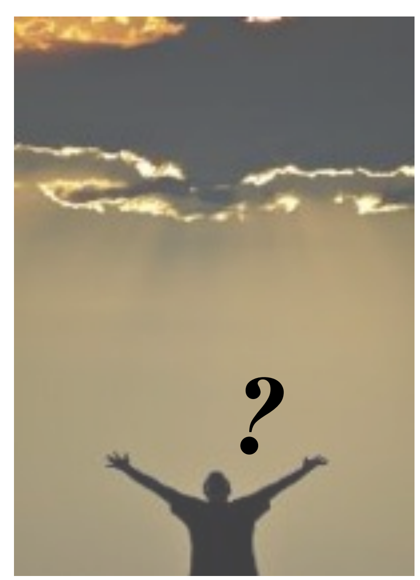
$$\Lambda \to M_{Pl}$$

I am tuning!

$\Lambda^2|H|^2$



$\frac{c_{ij}}{\Lambda}\ell_i H H \ell_j$ ...



- anthropic reasoning
- beyond EFT
- ???

$$\Lambda \sim \text{TeV}$$

a) Most dangerous operators can be protected by symmetries.

b) Dynamical mechanisms allow to split Higgs sector.

$\mathrm{U}(1)_B \times \mathrm{U}(1)_L$

$\mathrm{SU}(3)^5_F$

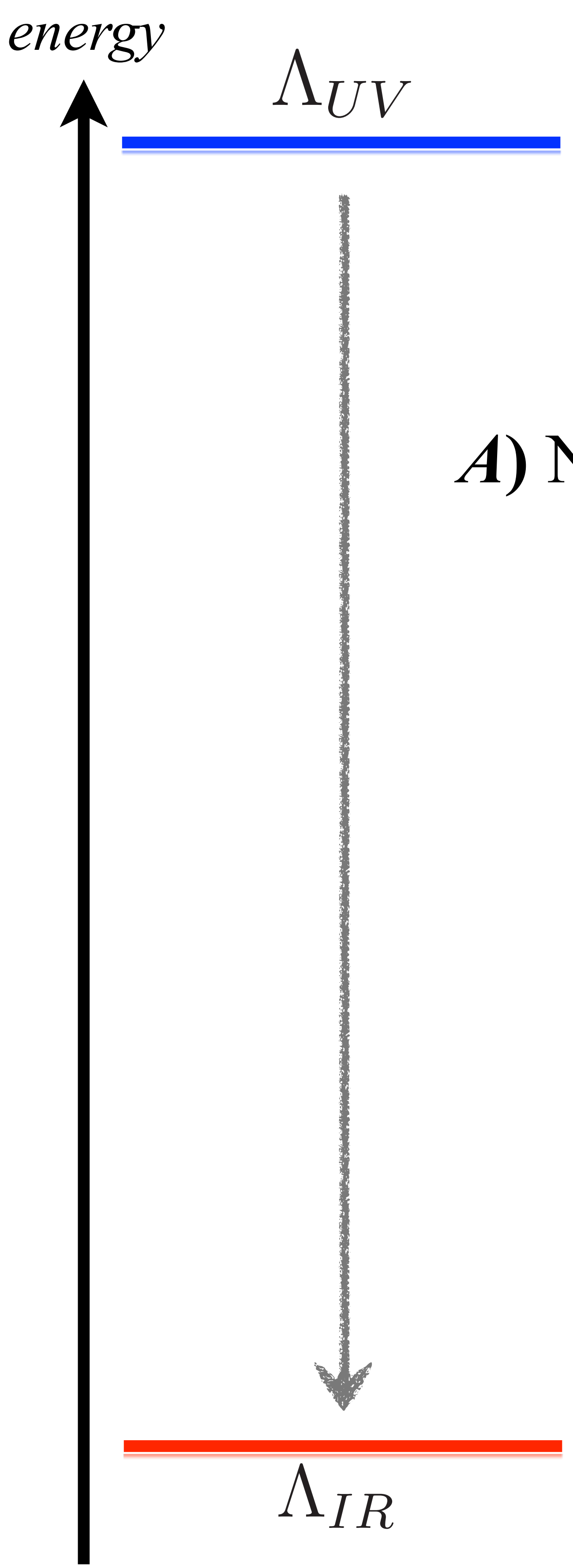
$\mathrm{SO}(4)_C$

$\Lambda^2 |H|^2$ **d=4** $\frac{1}{\Lambda^2} H^\dagger W_{\mu\nu} H B^{\mu\nu}$

***H* is different!**

It is for **Experiment** to decide if there is **New Physics** at the TeV

The ElectroWeak Hierarchy



$$\Lambda_{UV} \gg \Lambda_{IR}$$

Natural Hierarchy from Scale Invariance:

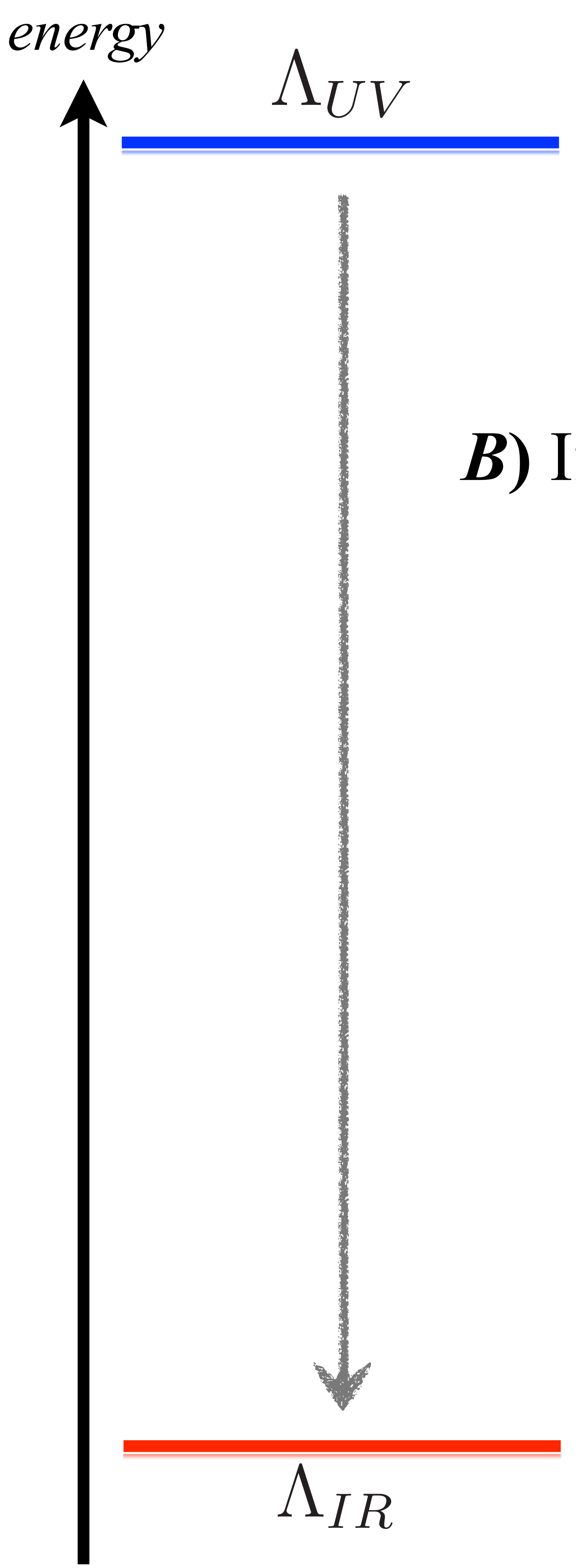
***A*) No strongly relevant operators:** $\mathcal{L} \supset \lambda \mathcal{O}\,, \quad [\mathcal{O}] = 4 - \epsilon$

$$\lambda(\mu) = \lambda_0 \left(\frac{\Lambda_{UV}}{\mu} \right)^{\epsilon}$$

$$\lambda(\Lambda_{IR}) \sim 1\,,\ \Lambda_{IR} \sim \Lambda_{UV} \lambda_0^{1/\epsilon}$$

Dimensional Transmutation

The ElectroWeak Hierarchy



$$\Lambda_{UV} \gg \Lambda_{IR}$$

Natural Hierarchy from Scale Invariance:

***B*)** If relevant operators, protected by symmetry:

- ***Compositeness:*** $H \sim \langle \psi \bar{\psi} \rangle$ *the Higgs is composite*

  fermion masses protected by Chiral sym.

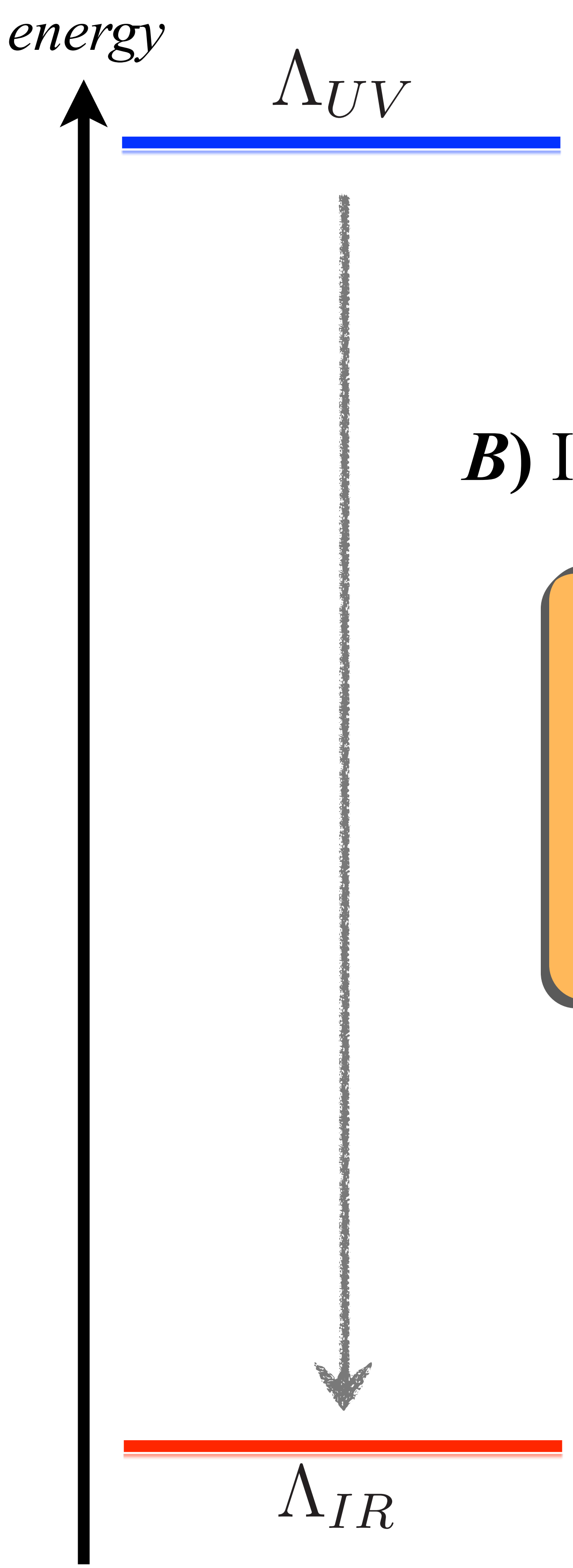
  new states at $4\pi v \sim 2\,\mathrm{TeV}$

- ***Supersymmetry:*** $H \sim \psi$ *the Higgs is chiral*

  scalar masses protected by Chiral sym.

  new states at $gv \sim 100\,\mathrm{GeV}$

The ElectroWeak Hierarchy



$$\Lambda_{UV} \gg \Lambda_{IR}$$

Natural Hierarchy from Scale Invariance:

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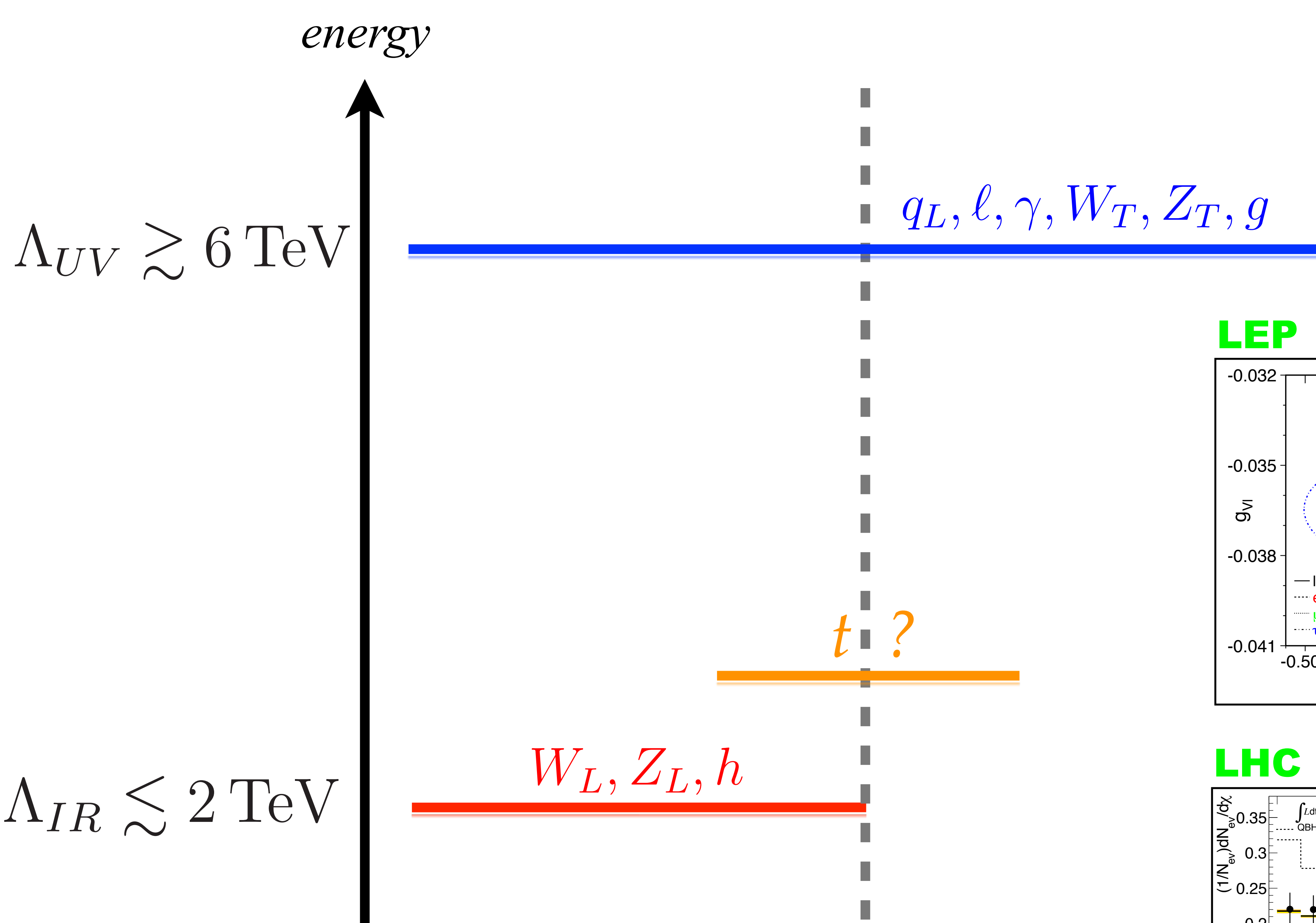
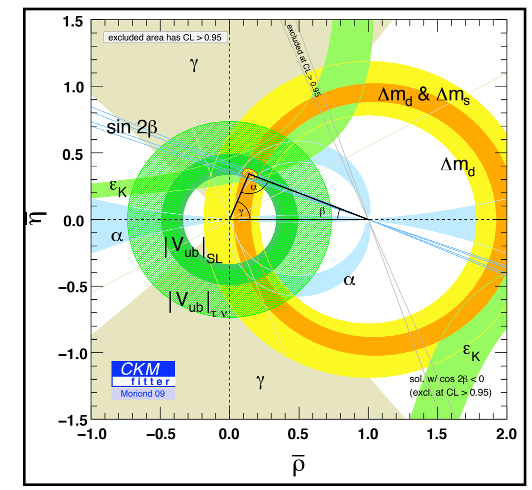
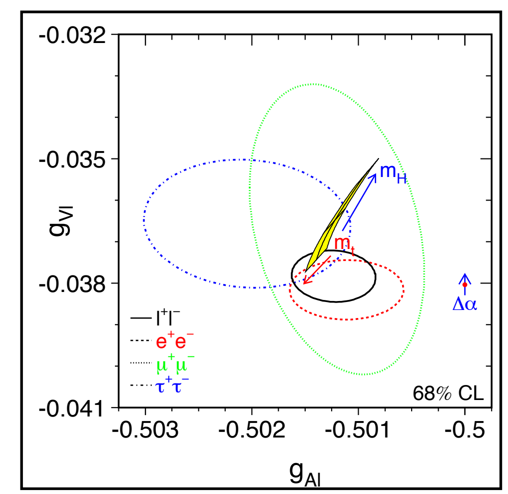
The emergent picture of the *Composite world*:



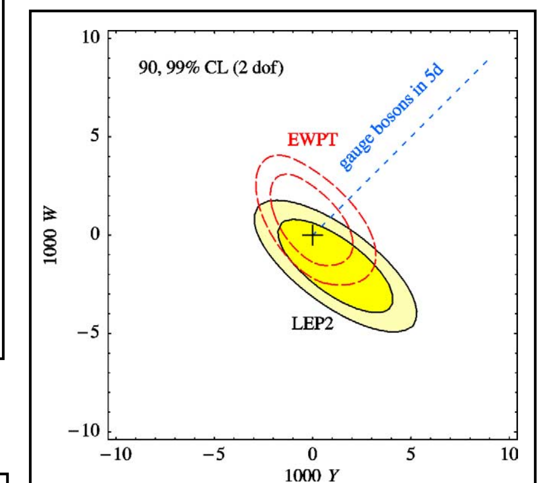
CKM fitter



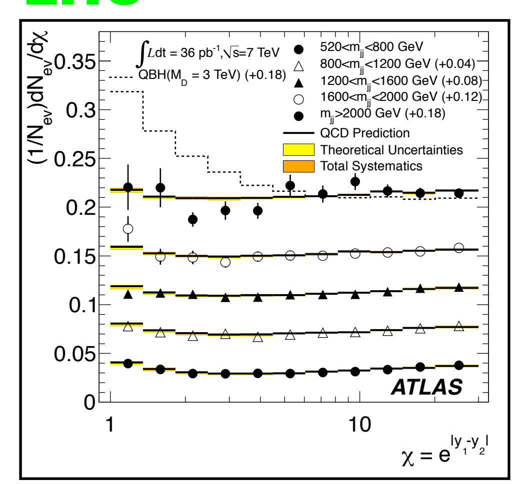
LEP



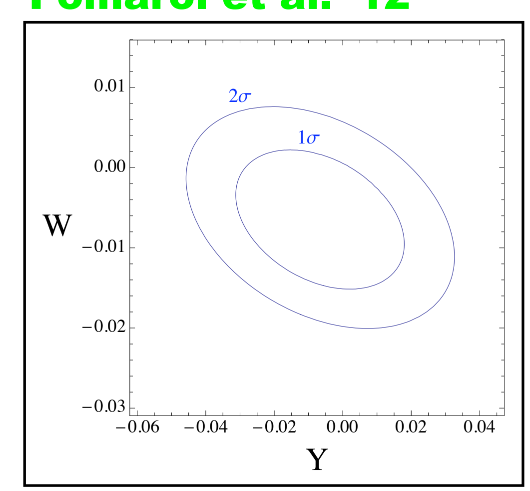
Barbieri et al. '04



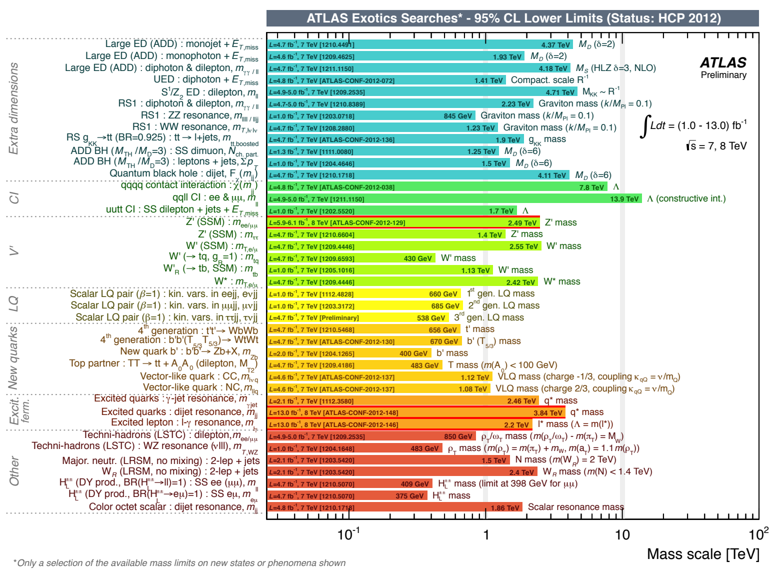
LHC



Pomarol et al. '12

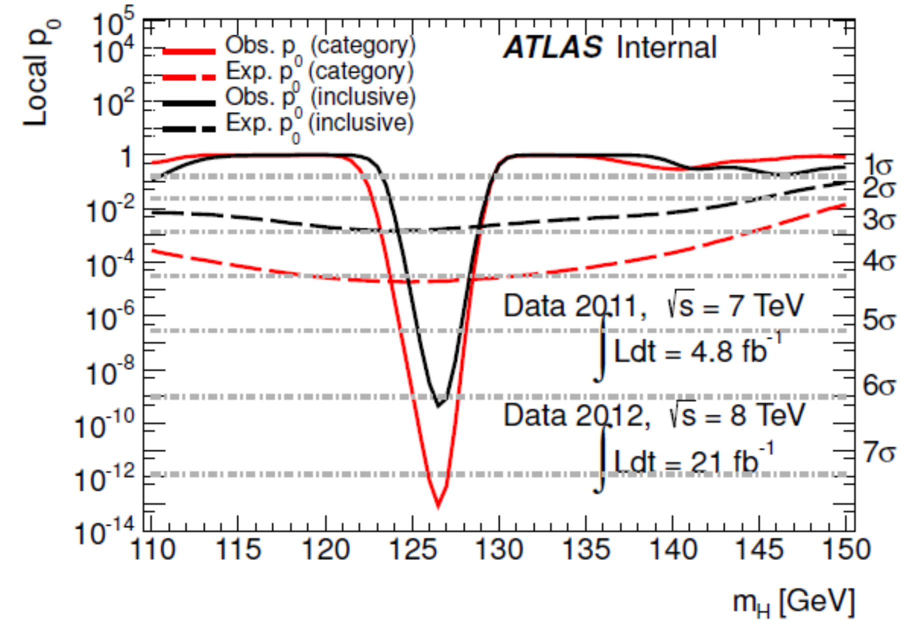


Absence of physics beyond the SM:



&

Discovery of a 125 GeV Higgs:



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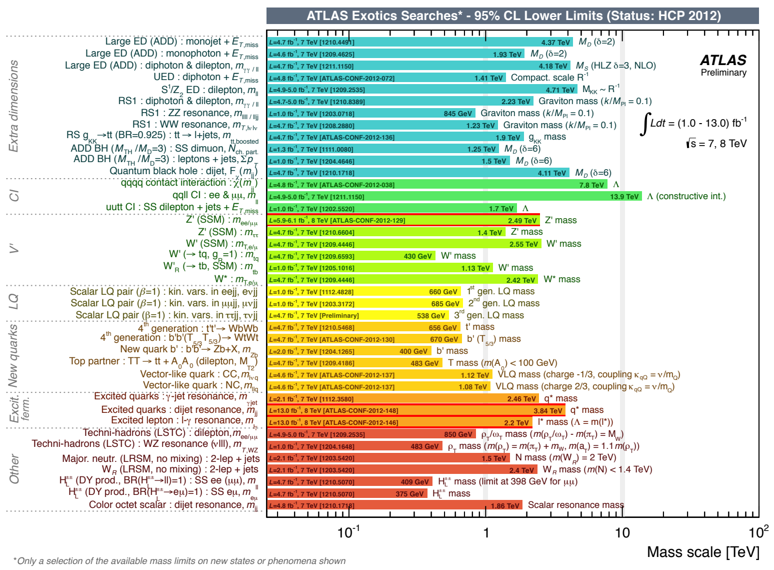
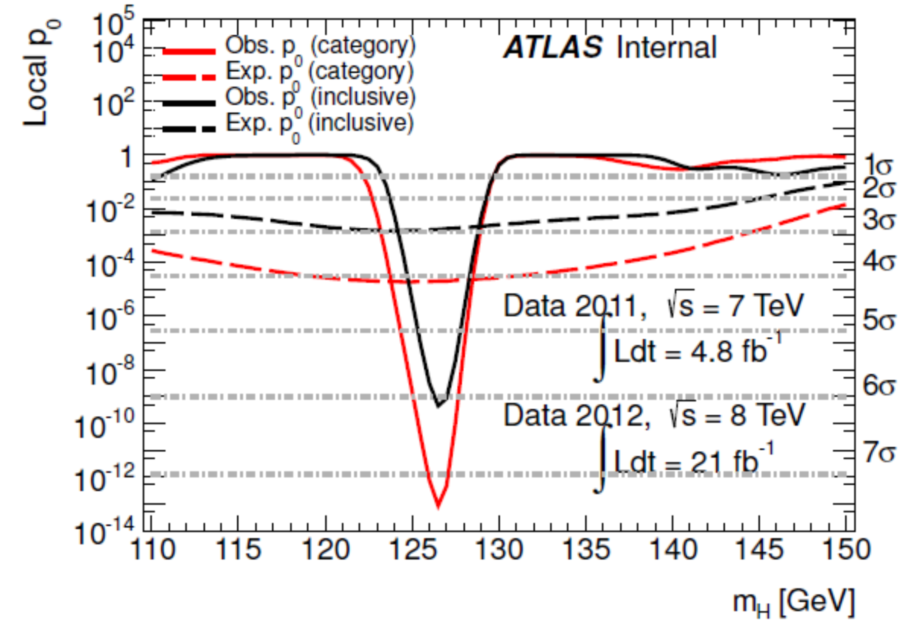


Discovery of a 125 GeV Higgs:



&

$$m_h \ll \Lambda_{IR}$$

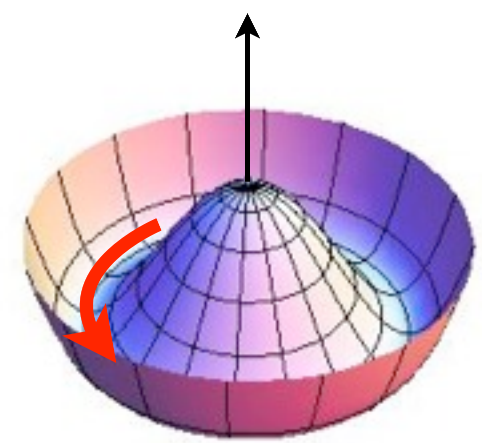
The Higgs doublet must be a (pseudo-)Goldstone boson of the new strong dynamics

Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

Spontaneous Global Symmetry Breaking

E.g.: $V(\phi) \simeq -m_\rho^2\phi^2 + g_\rho^2\phi^4\,, \qquad \phi = 5 \in \mathrm{SO}(5)$

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ f \end{pmatrix}, \qquad f \sim \frac{m_\rho}{g_\rho} \longrightarrow \mathrm{SO}(5)/\mathrm{SO}(4)$$



4 **GB**'s: $H = \begin{pmatrix} h_1 + ih_2 \\ h + ih_3 \end{pmatrix}$

$$H \to H + \alpha \longrightarrow V_{tree}(H) = 0$$

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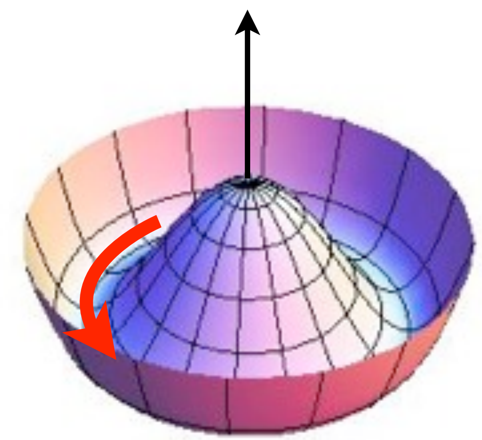


4 **GB**'s: $H = \begin{pmatrix} h_1 + i h_2 \\ h + i h_3 \end{pmatrix}$

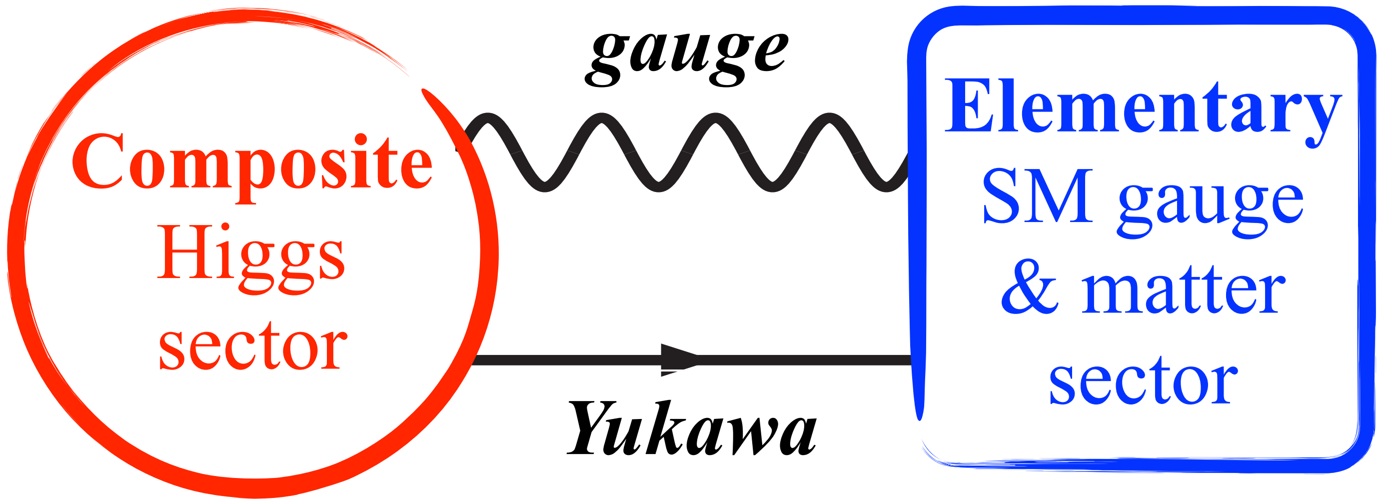
$$H \to H + \alpha \longrightarrow V_{tree}(H) = 0$$

Phenomenological requirements on $\mathcal{G}/\mathcal{H}$:

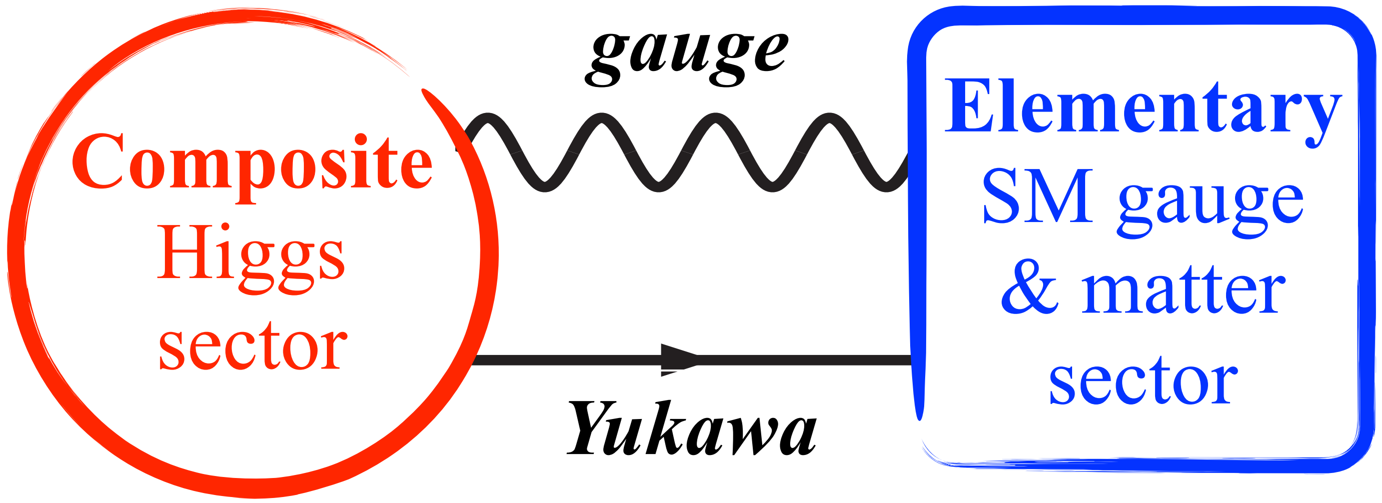
i) $\mathcal{G} \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ *weakly gauged*

ii) $\mathcal{H} \supset \mathrm{SO}(4) \cong \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ *custodial symmetry*

iii) $\mathcal{G}/\mathcal{H} \supset \mathbf{4} = (\mathbf{2}, \mathbf{2})$ *Higgs doublet*



$$\mathcal{L}_{mixing} = g A_\mu \mathcal{J}^\mu + y \bar{\psi} \mathcal{O}_\psi$$

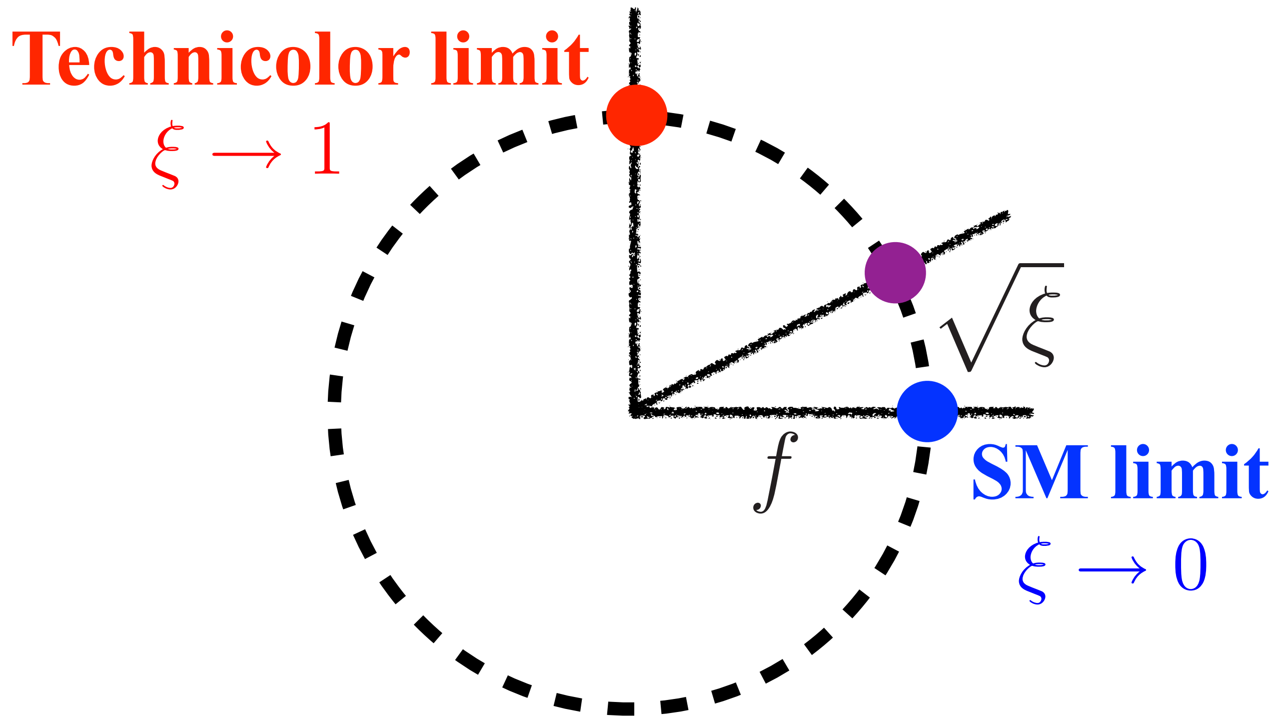


$$\mathcal{L}_{mixing} = g A_\mu \mathcal{J}^\mu + y \bar{\psi} \mathcal{O}_\psi$$

Loops:

$$V(H) \simeq 0 + \xi \frac{g_{SM}^2}{16\pi^2} m_\rho^2 |H|^2 + \frac{g_{SM}^2}{16\pi^2} g_\rho^2 |H|^4 + O(H^6)$$

$$\langle h \rangle \sim \sqrt{\xi}\frac{m_\rho}{g_\rho} = \sqrt{\xi} f \lesssim v = 246\,\mathrm{GeV} \qquad \xi = \frac{v^2}{f^2} = O(1)$$



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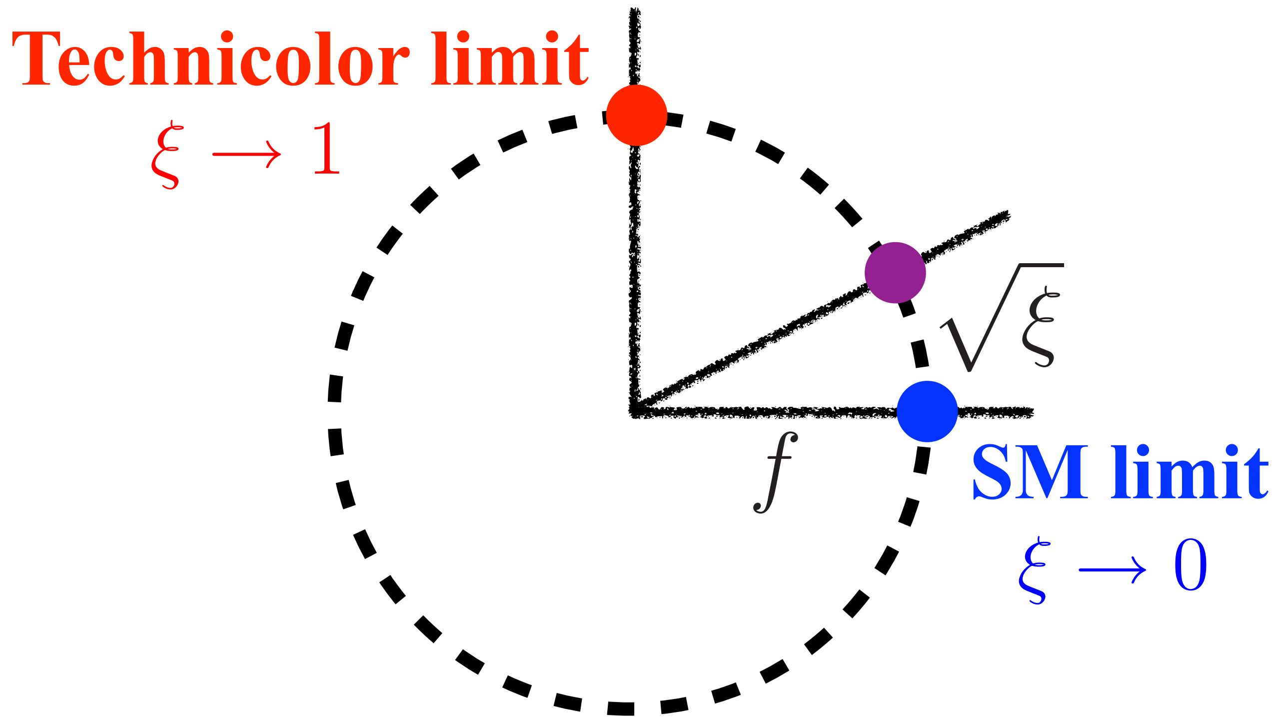
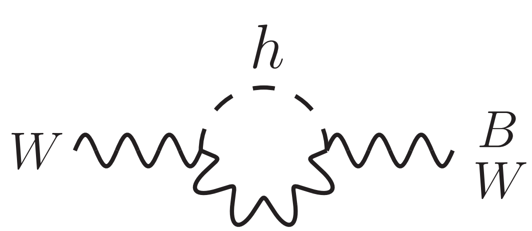
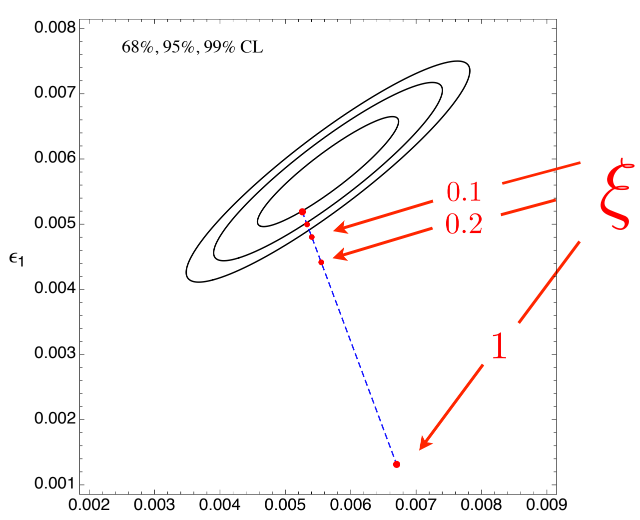


Electroweak (Higgs) precision observables:



$\propto \xi \log(\Lambda^2/m_W^2)$

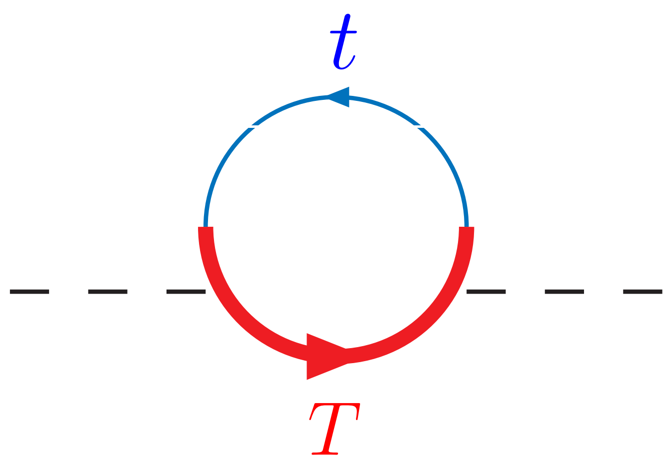


→ $\xi \lesssim 0.1$

naive tuning

clever structure

As in SUSY, the top is expected to give the largest contribution:



$$m_h^2 \sim \frac{N_C m_t^2 m_T^2}{\pi^2 f^2} \sim (125\,\mathrm{GeV})^2 \left(\frac{m_T}{700\,\mathrm{GeV}}\right)^2 \left(\frac{500\,\mathrm{GeV}}{f}\right)^2 \sim (125\,\mathrm{GeV})^2 \left(\frac{g_T}{1.5}\right)^2$$

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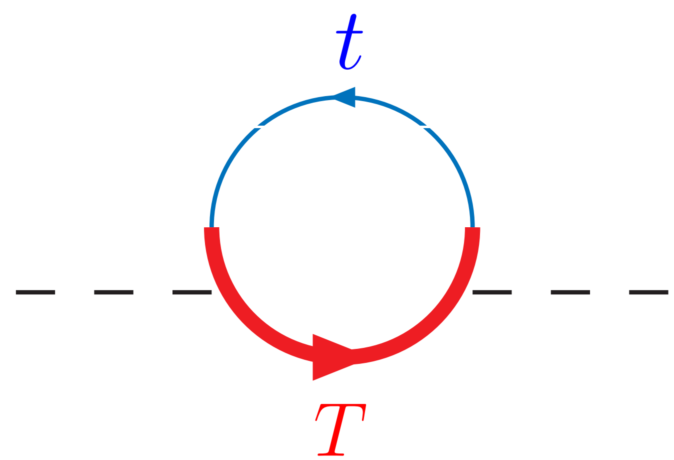

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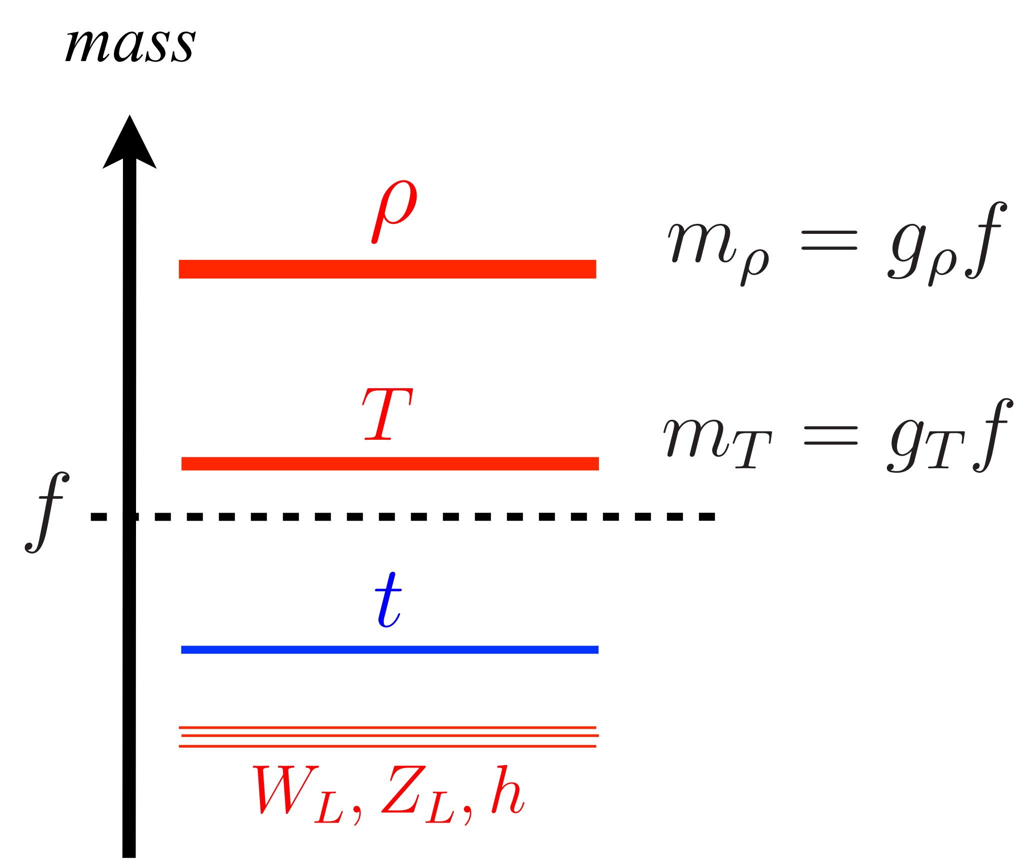
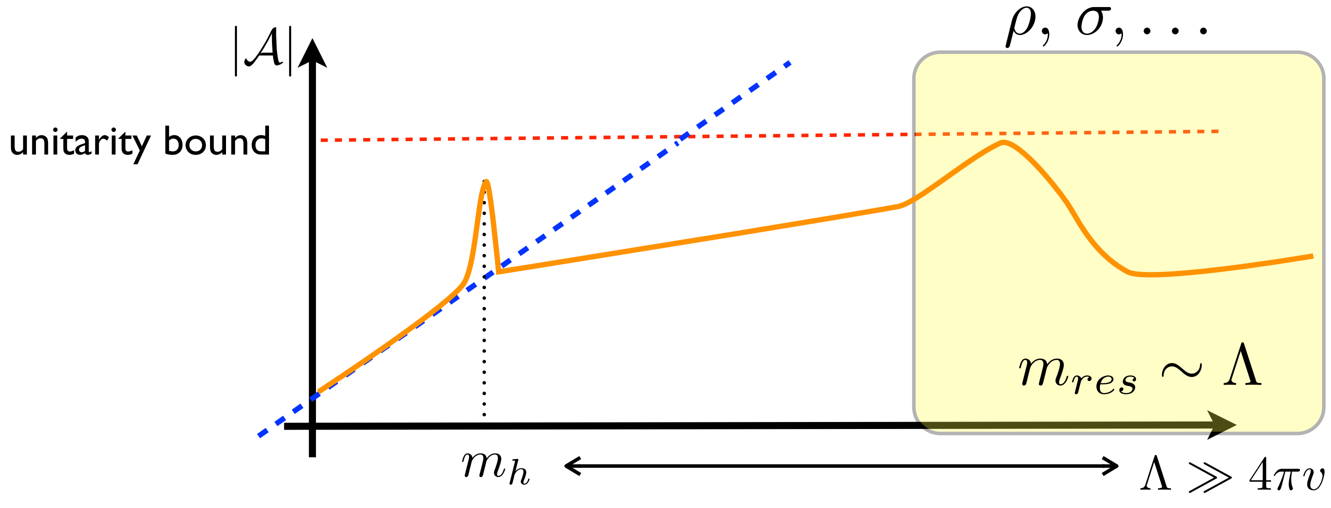
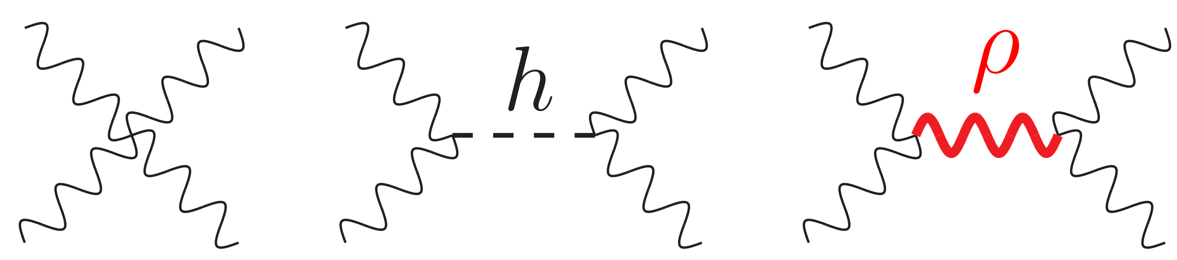
***Top-partners* must be**
parametrically lighter
(approximate Chiral sym.)



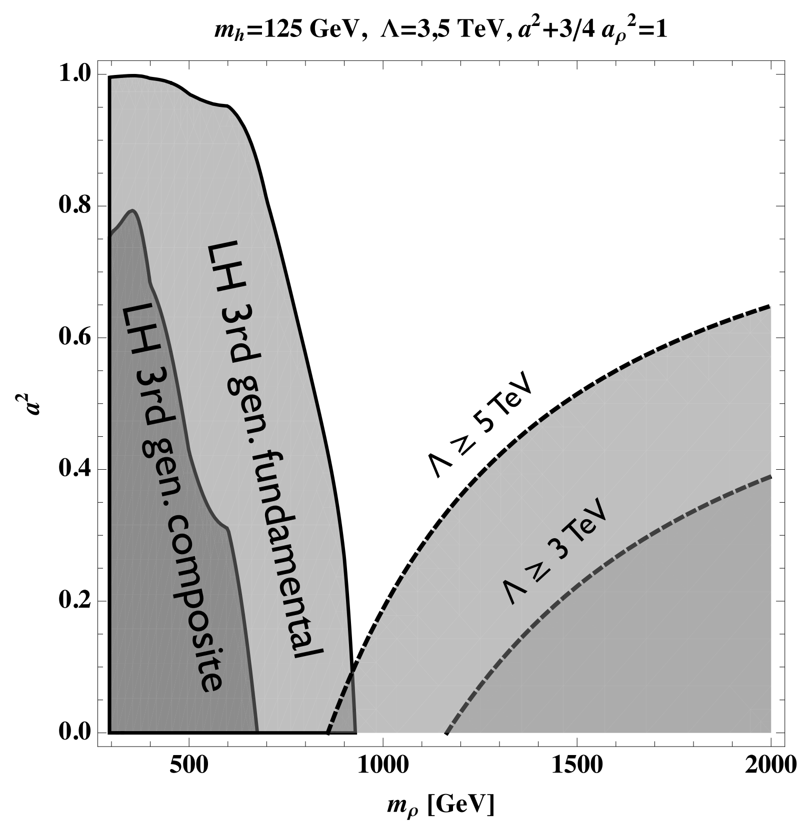
Expected *subleading* contribution to the potential, but enter ***WW* scattering**:



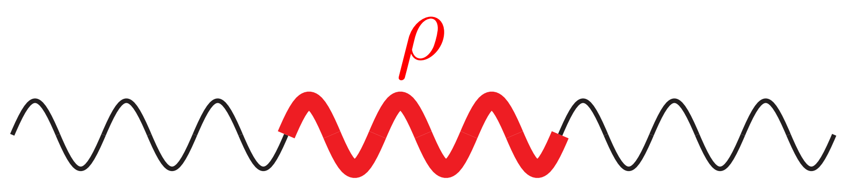


$$\delta\mathcal{A} \propto \frac{v^2}{f^2}$$

Bellazzini et al. '12



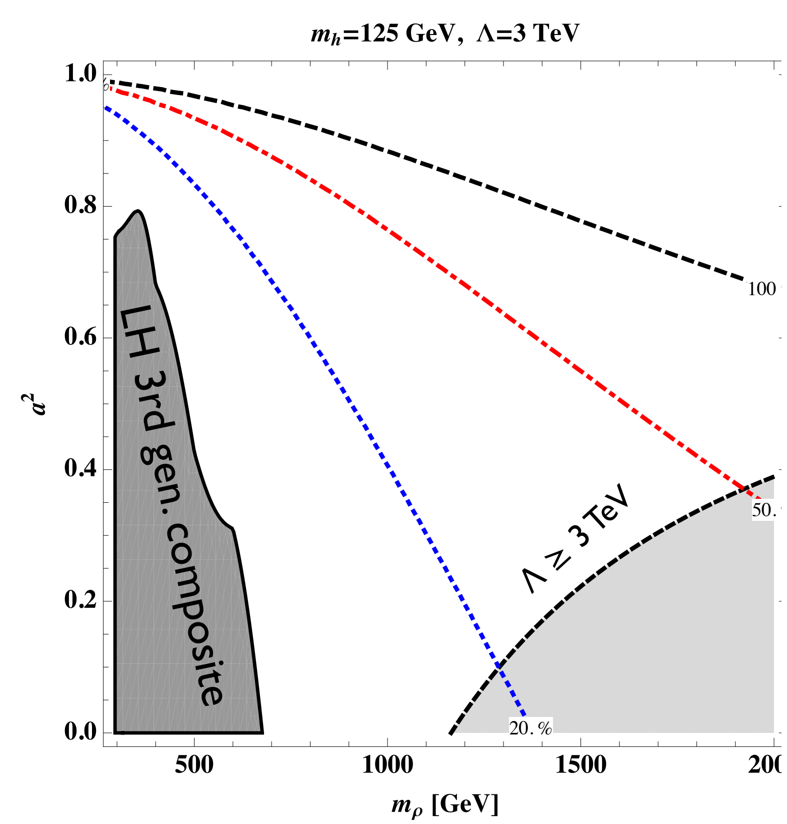
However also contribute to ***S*-parameter**:



$$\hat{S} \sim \frac{m_W^2}{m_\rho^2}$$

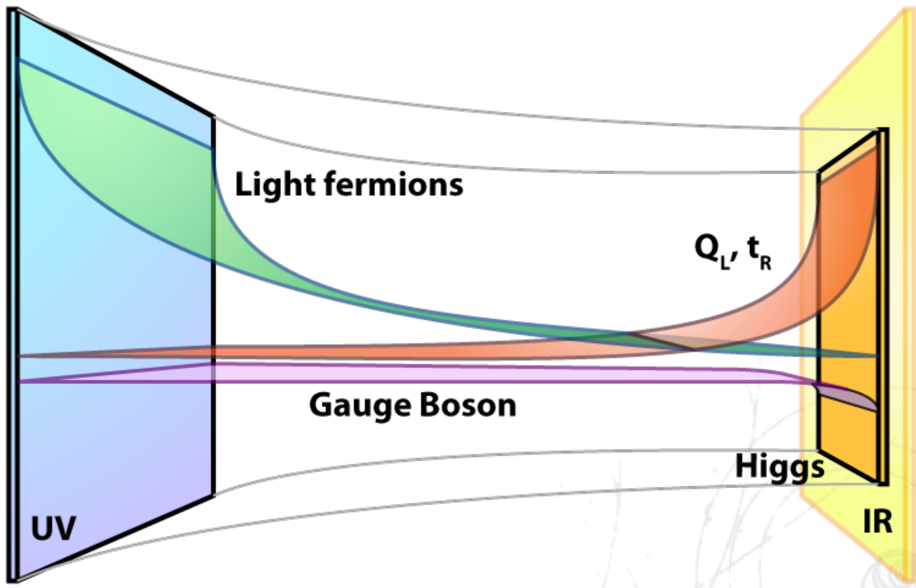
$$\hat{S} \lesssim 10^{-3} \rightarrow m_\rho \gtrsim 2.5\,\mathrm{TeV}$$

Bellazzini et al. ’12



Top-partners from AdS/CFT

$$\mathcal{L}_{mixing} = y\,\bar{\psi}\mathcal{O}_{\psi}$$

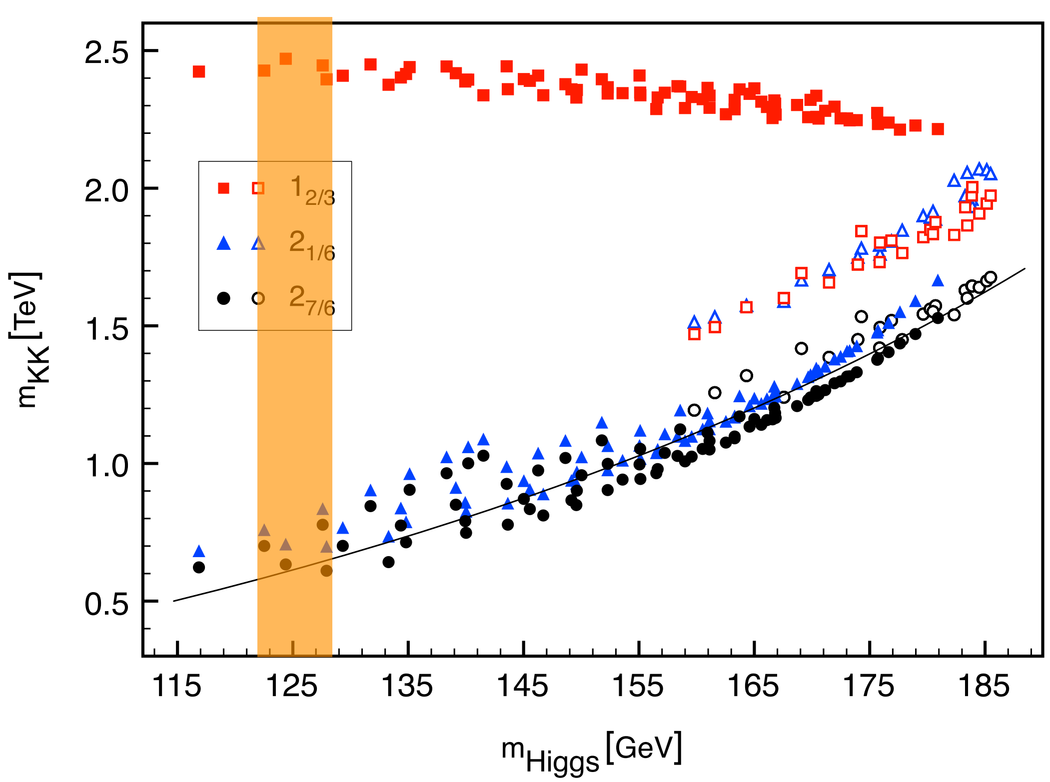


$$d[\mathcal{O}_\psi] \simeq 2 + M_\psi \longrightarrow y(\mu < f) \simeq y(\mu_0)\left(\frac{f}{\mu_0}\right)^{M_\psi - \frac{1}{2}}$$

5D mass:

- $M_\psi > 1/2$ *irrelevant*
- $|M_\psi| < 1/2$ *relevant*

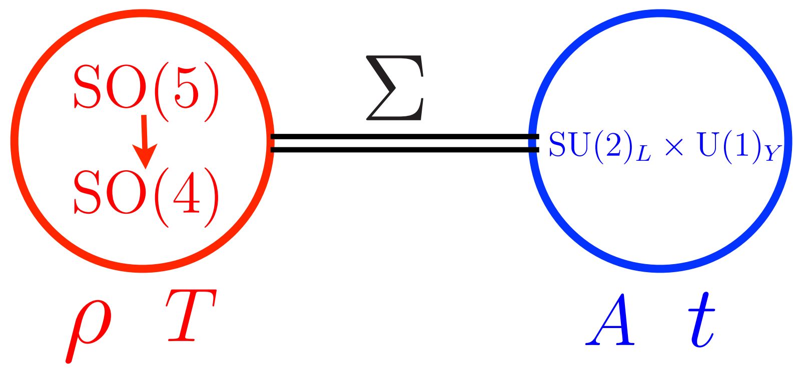
Contino, DaRold, Pomarol '07



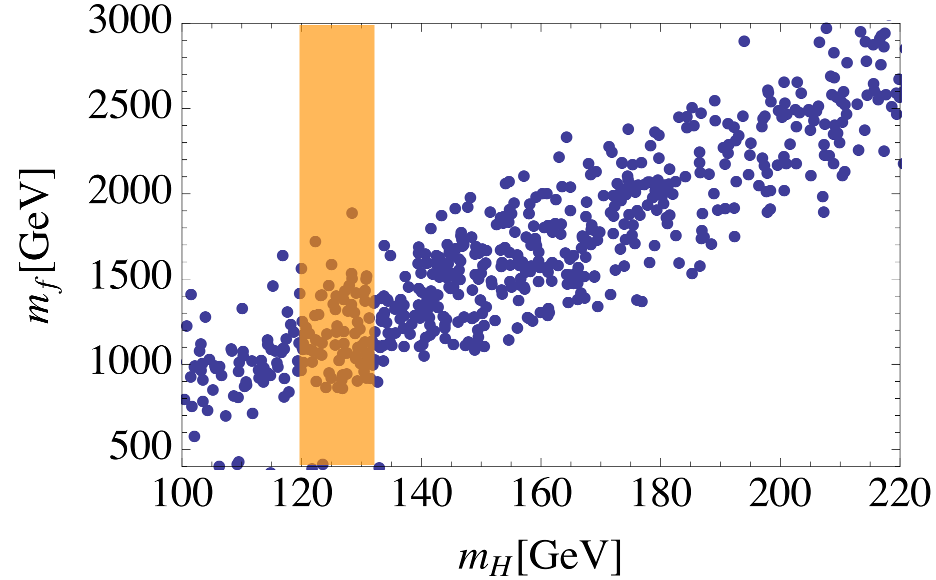
$M_\psi \rightarrow -1/2$ strongly coupled limit $\longrightarrow$ $d[\mathcal{O}_\psi] = 3/2$ free field

Light top-partners byproduct of composite top (IR localized)

Deconstruction:

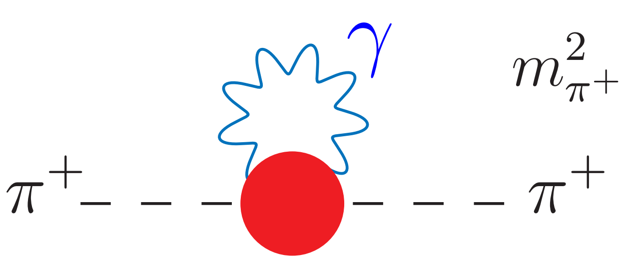


Redi, Tesi '12



"Weinberg Sum Rules":

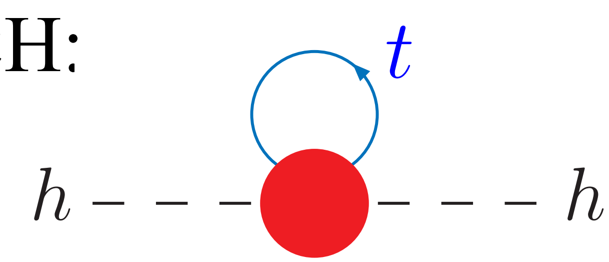
as in QCD:



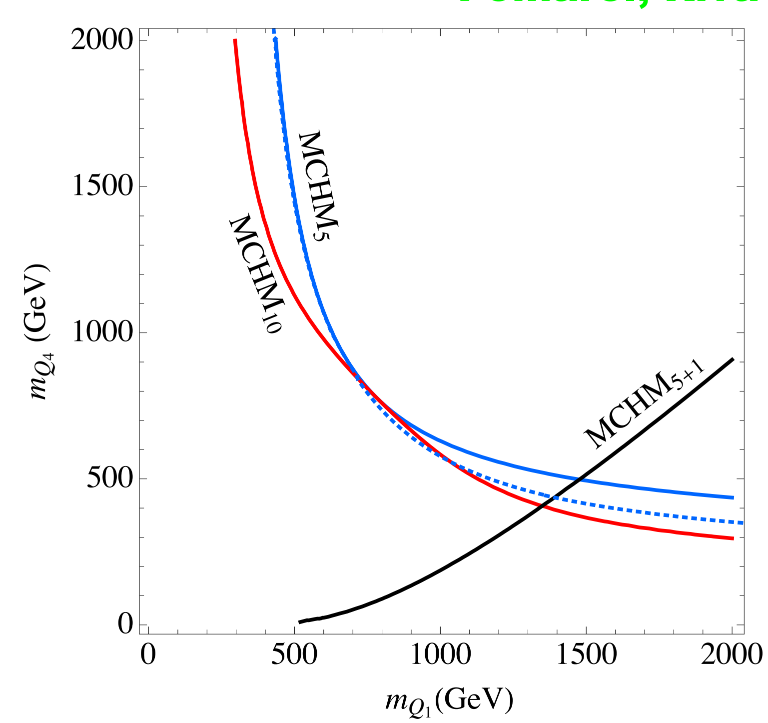
$$m^2_{\pi^+} - m^2_{\pi^0} \simeq \frac{3\alpha}{2\pi} m^2_\rho \log 2 \simeq (37\,\mathrm{MeV})^2$$

Exp.: (35 MeV)^2

in CH:



Pomarol, Riva '12



Higds mass & Tuning: Survey of Models

$$V(h) = \frac{3y_t^2 m_T^2}{16\pi^2}\left(ah^2 + bh^4/f^2 + ...\right)$$

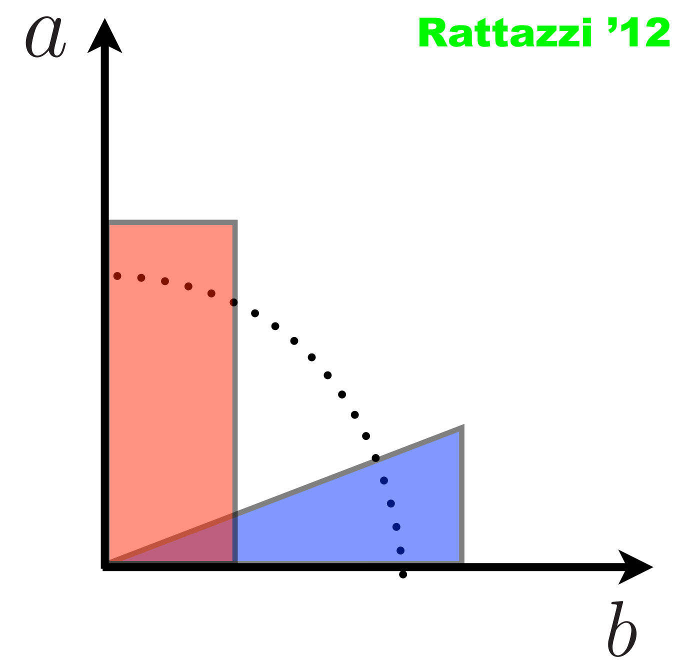
Instead of $a, b \sim O(1)$:

v/f tuning

$$a \lesssim \left(\frac{500\,\mathrm{GeV}}{m_T}\right)^2$$

m_h tuning

$$b \lesssim \left(\frac{2}{g_T}\right)^2$$



$$V(h) = \frac{3y_t^2 m_T^2}{16\pi^2}\left(ah^2 + bh^4/f^2 + \ldots\right)$$

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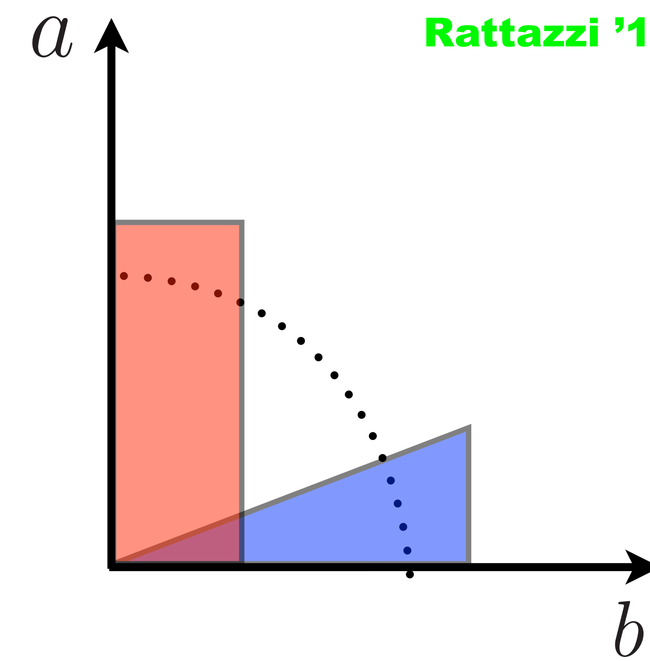
Rattazzi '12



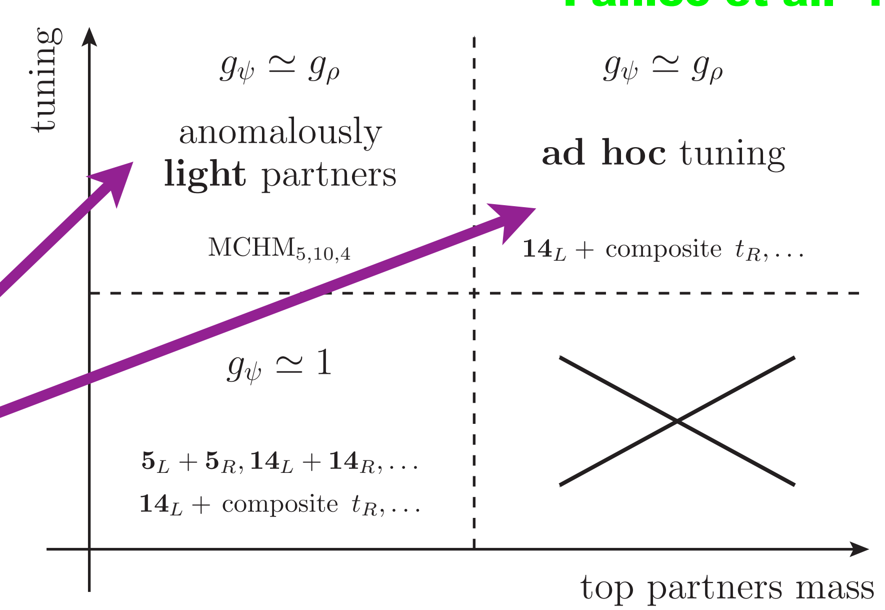
but there are unknown factors and *model dependence*:

$$\mathcal{L}_{mixing} = y\,\bar{\psi}\mathcal{O}_\psi$$

$$\mathbf{r}(\mathcal{O}_\psi) = \mathbf{5}_L + \mathbf{5}_R \quad a \sim O(y_t^2/g_T^2)\,,\ b \sim O(y_t^4/g_T^4)$$

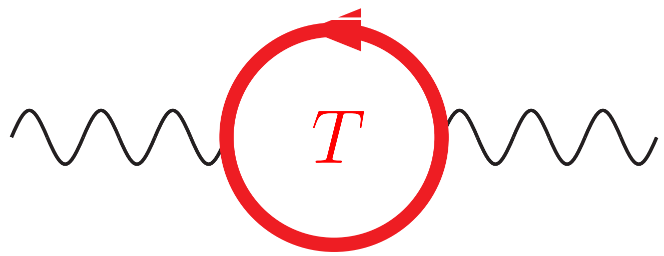
$$\mathbf{r}(\mathcal{O}_\psi) = \mathbf{14}_L + \mathbf{1}_R \quad a, b \sim O(y_t^2/g_T^2)$$

Panico et al. '12

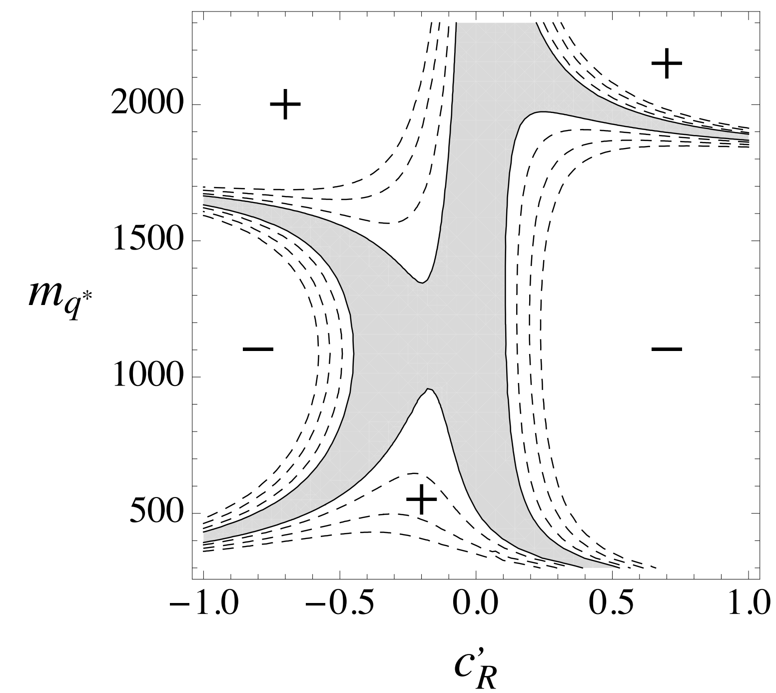


Electroweak Precision Tests:

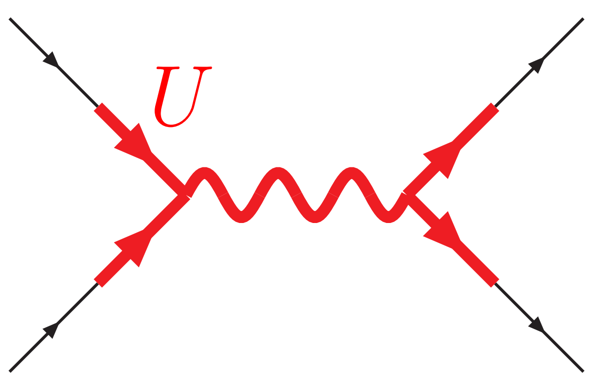
Pomarol, JS '08



$$\Delta\hat{T} \gtrsim 10^{-3} \longrightarrow m_T \lesssim 2\,\text{TeV}$$



Flavor: $\epsilon_K\,,\, B_{d,s}-\bar{B}_{d,s}, \ldots$



$$m_T \sim m_C \sim m_U$$

Barbieri et al. '12

	doublet	triplet	bidoublet
Ⓐ	4.9	1.7	1.2∗
$U(3)^3_{\rm LC}$	4.6	5.3	4.3
$U(3)^3_{\rm RC}$	-	-	3.3
$U(2)^3_{\rm LC}$	4.9	0.6	0.6
$U(2)^3_{\rm RC}$	-	-	1.1∗

$$q = +\frac{5}{3}, +\frac{2}{3}$$

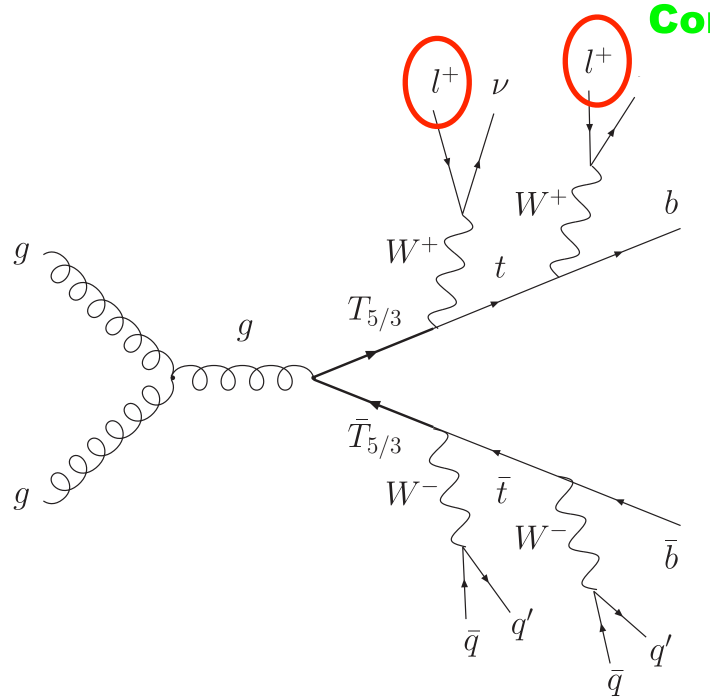
$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

	Q	T
Case (a)	$(\mathbf{2},\mathbf{2})_{\mathbf{2/3}}$	$(\mathbf{1},\mathbf{1})_{\mathbf{2/3}}$
Case (b)	$(\mathbf{2},\mathbf{2})_{\mathbf{2/3}}$	$(\mathbf{1},\mathbf{3})_{\mathbf{2/3}} + (\mathbf{3},\mathbf{1})_{\mathbf{2/3}}$

$$q = +\frac{5}{3}, +\frac{2}{3}, -\frac{1}{3}$$

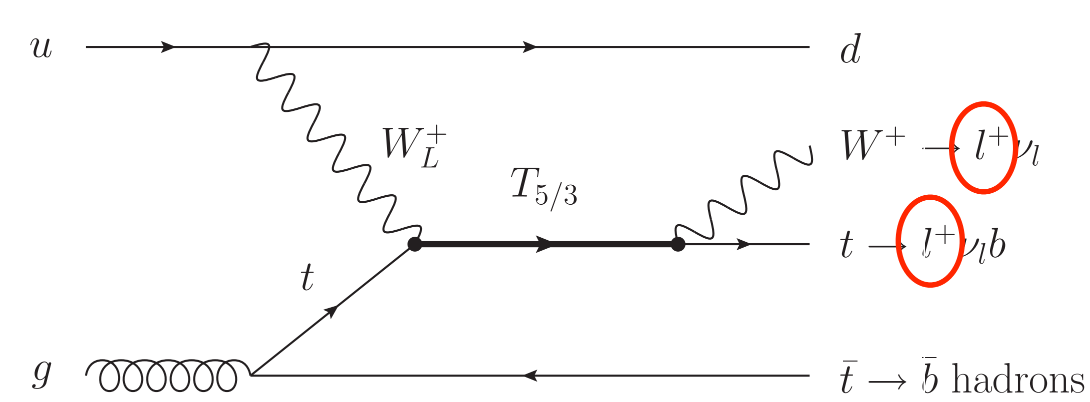
Double production

Contino, Servant ’08



Single production

Mrazek, Wulzer ’1



same sign dileptons!

$$q = +\frac{5}{3}, +\frac{2}{3}$$

$SU(2)_L \times SU(2)_R$

	Q	T
Case (a)	$(\mathbf{2},\mathbf{2})_{\mathbf{2/3}}$	$(\mathbf{1},\mathbf{1})_{\mathbf{2/3}}$
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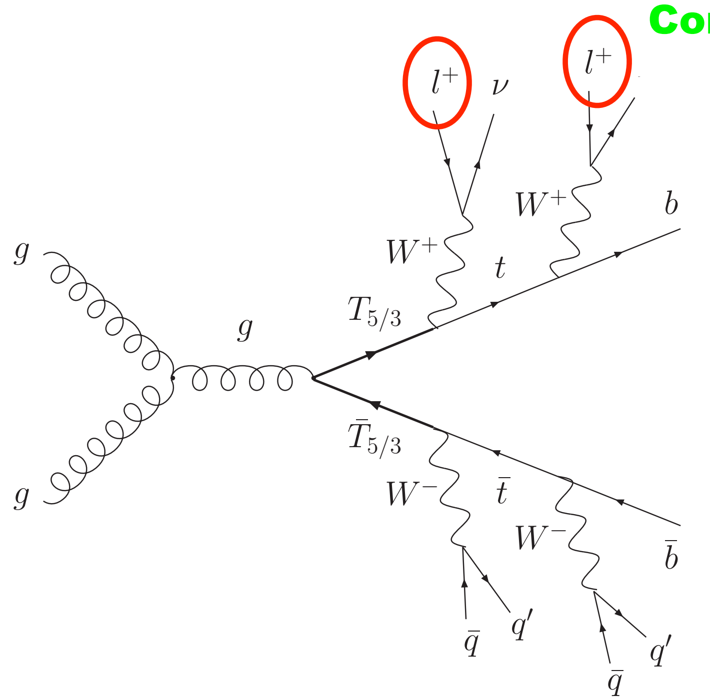
$$q = +\frac{5}{3}, +\frac{2}{3}, -\frac{1}{3}$$

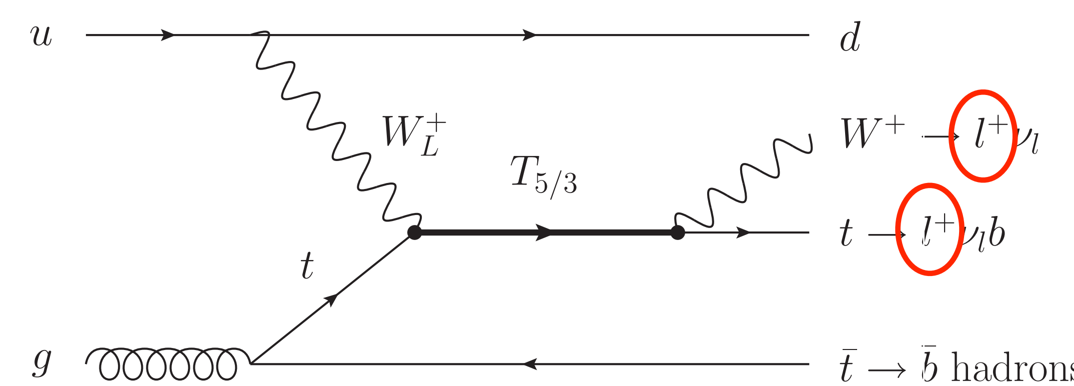
Double production

Contino, Servant '08

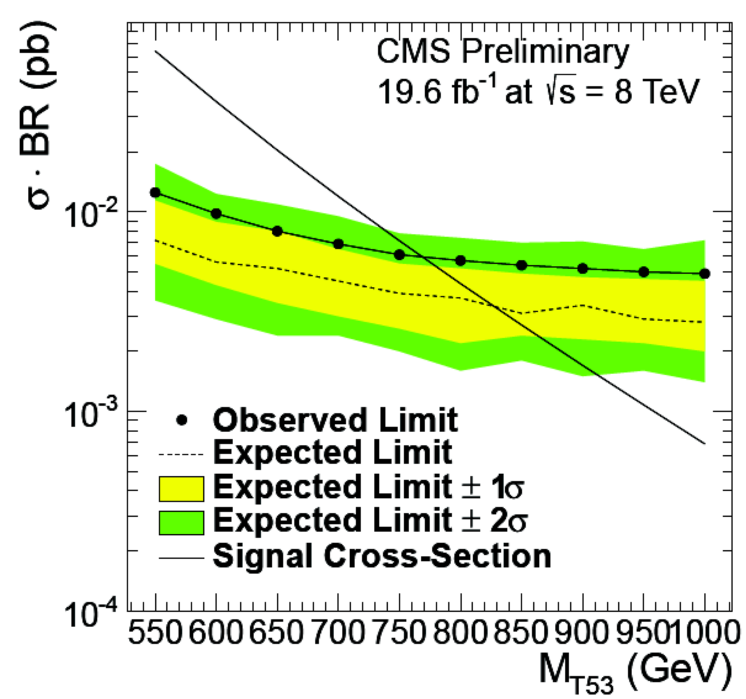


Single production

Mrazek, Wulzer '10



same sign dileptons!



Non-minimal Cosets

Mrazek et al. '12

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_\mathbf{0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

Non-minimal Cosets

Mrazek et al. '12

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \bar{\mathbf{4}}_{\mathbf{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{\mathbf{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

Beyond the Minimal Composite Higgs Model

Gripaios et al. '09
Galloway et al. '10

Interesting fact: Minimal coset from constituent fermions

$$\langle \mathbf{\Psi_a \Psi_b} \rangle \quad \cong SU(4)/Sp(4) \longrightarrow \mathbf{5} = \mathbf{4} + \mathbf{1} = (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$$

extra singlet!

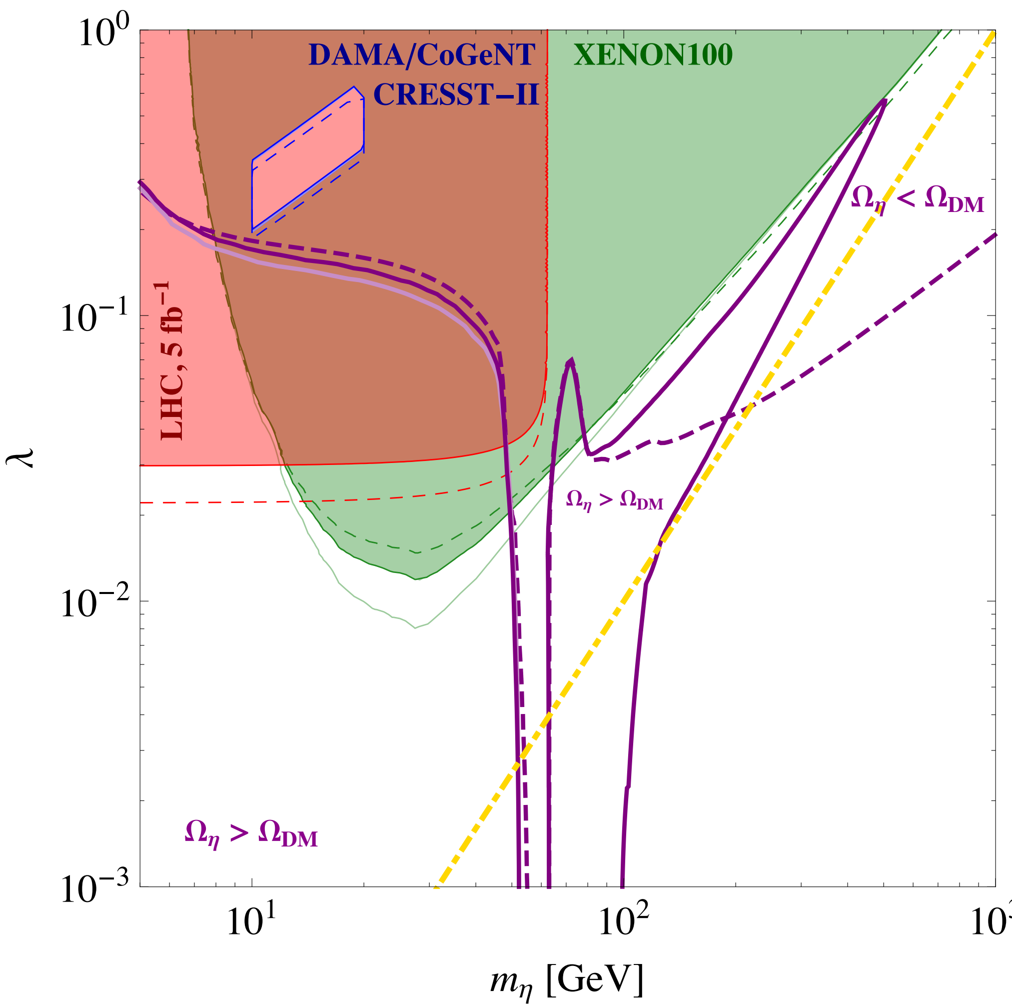
$$\mathrm{SO}(6)/\mathrm{SO}(5) \longrightarrow H + \eta$$

a) Mass of singlet very model dependent: SO(2) explicit breaking?

b) Discrete symmetry $\eta \to -\eta$ might be an exact symmetry.

Singlet could be DM!

Frigerio et al. '12

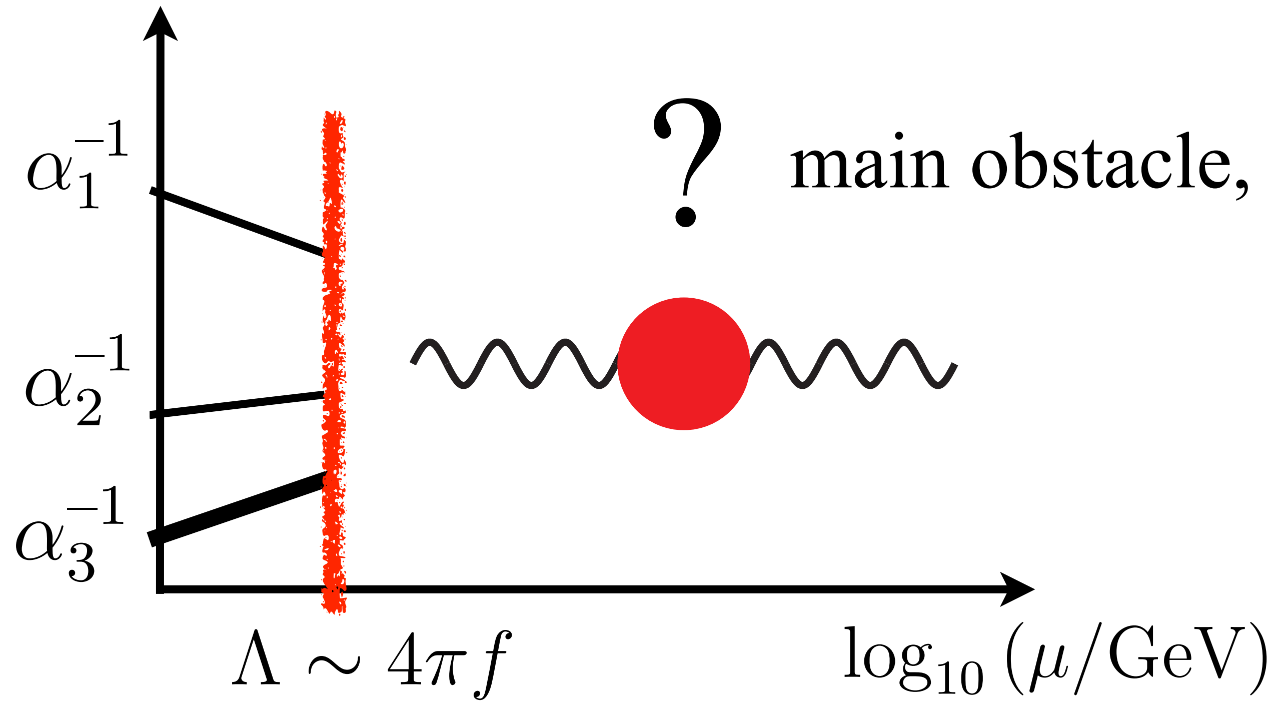


Non-minimal Cosets

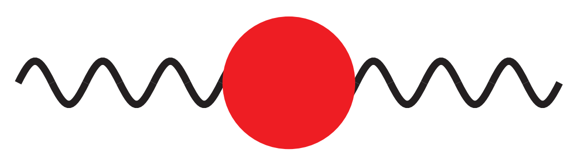
Mrazek et al. '12

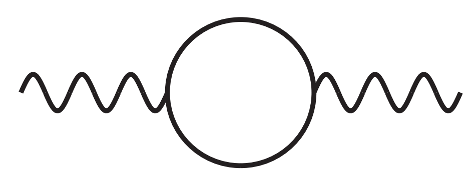
G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}}+\bar{\mathbf{4}}_{-\mathbf{2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_{\mathbf{0}}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+\mathbf{5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

many more...



Simplest Solution: Agashe, Contino, Sundrum '05; Frigerio, JS, Varagnolo '12

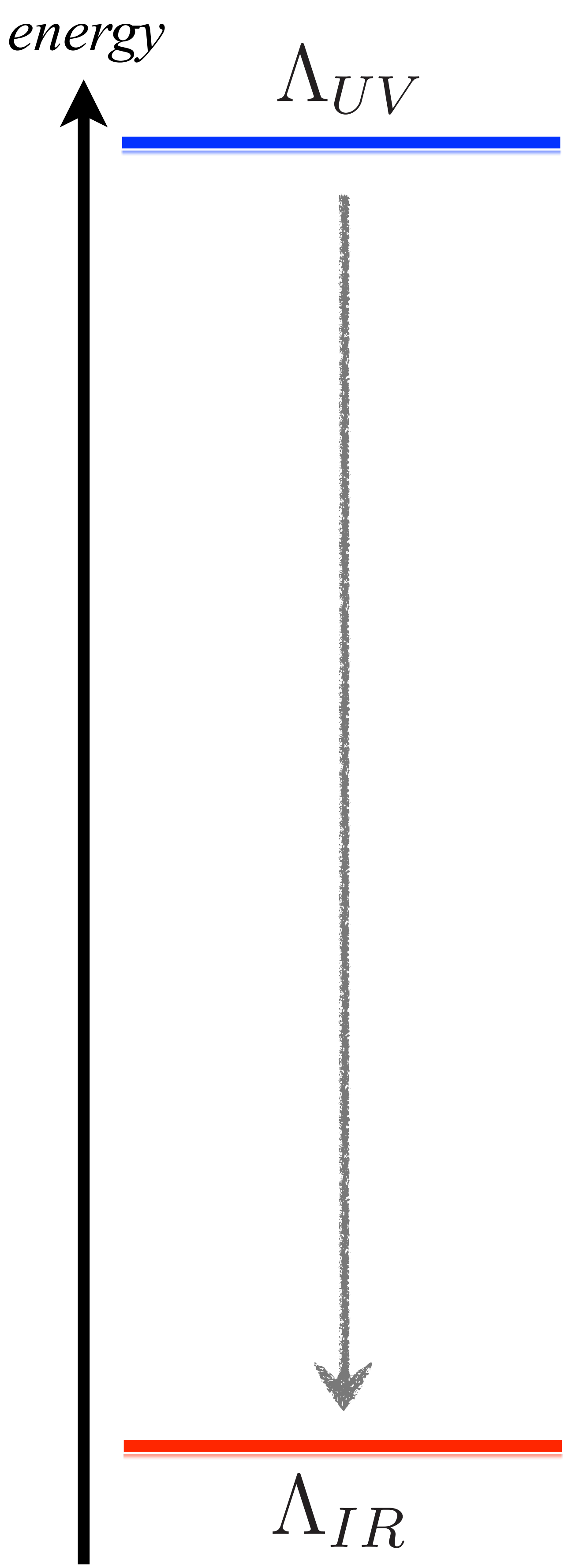
a) SO(11)/SO(10) →  $\frac{d\,\alpha_i^{-1}}{d\ln\mu} = -\frac{b^{strong}}{2\pi}$

b) Composite R-handed top →  $\{\mathrm{SM}\} - h - t_R + T'\mathrm{s}$

$$R \equiv (b_1 - b_2)/(b_2 - b_3) \simeq \mathbf{1.45}$$

Exp.: 1.395

Spontaneous Scaling Symmetry Breaking



Scale Invariant Sector (CFT)

$$\Lambda_{UV} \gg \Lambda_{IR}$$

$$x \to e^{\alpha} x\,,\ \Phi(x) \to e^{d_\Phi \alpha}\Phi(e^{\alpha}x)$$

$$\mathcal{S}_{CFT} = \sum_{\mathcal{O}} \int d^4x \mathcal{O}\,,\ d_{\mathcal{O}} = 4$$

Spontaneous Breaking of Scale Invariance

$$\langle \Phi \rangle = f^{d_\Phi}\,,\ \Lambda_{IR} \sim 4\pi f$$

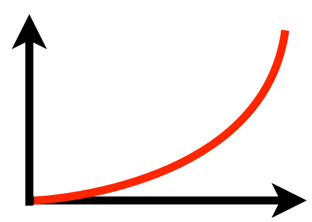
1 GB (enough) , $\mathrm{SO}(4,2)/\mathrm{SO}(3,1)$

$$\chi \equiv f e^{\sigma/f} \to e^{\alpha}\chi$$

Explicit Breaking of Scaling Symmetry & Dilaton Potential

$$V(\chi) = F_0 \chi^4$$

$F_0 > 0$

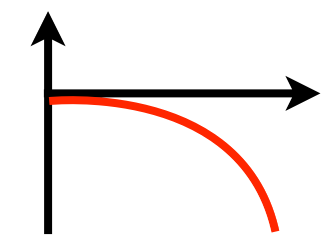


$\langle \chi \rangle \to 0$

$F_0 = 0$

$\langle \chi \rangle = f = \, ?$

$F_0 < 0$



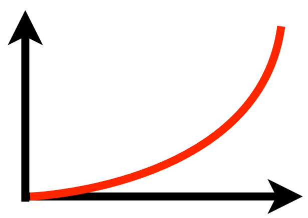
$\langle \chi \rangle \to \infty$

Need "vacuum alignment"

Explicit Breaking of Scaling Symmetry & Dilaton Potential

$$V(\chi) = F_0 \chi^4$$

$F_0 > 0$

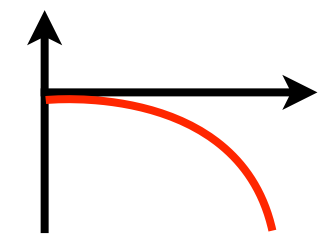


$\langle \chi \rangle \to 0$

$F_0 = 0$

$\langle \chi \rangle = f = \,?$

$F_0 < 0$



$\langle \chi \rangle \to \infty$

Need "vacuum alignment"

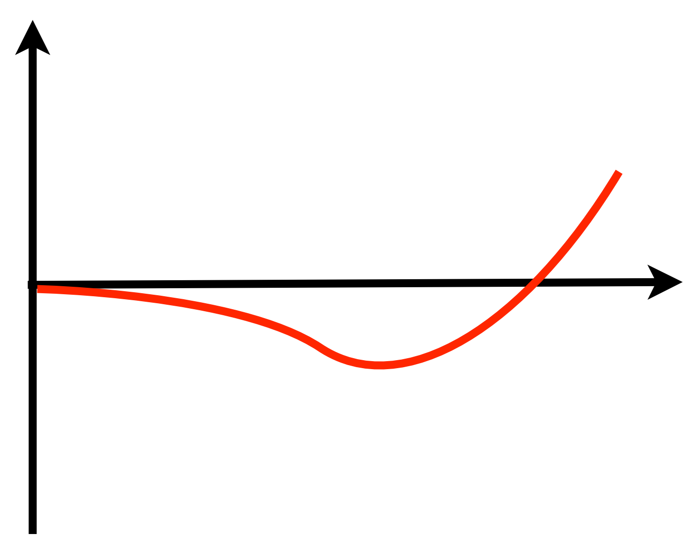
Add ***explicit breaking***

$$\mathcal{L} \supset \lambda \mathcal{O}\,, \quad [\mathcal{O}] = 4 - \epsilon$$

$$\frac{d\lambda}{d\log\mu} = \beta(\lambda) \neq 0$$

$\rightarrow$

$$V(\chi) = \chi^4 F(\lambda(\chi))$$



Dilaton mass & Tuning

*F_0 still matters for the **dilaton mass***

F at the minimum: $$F(\lambda) = F_0 + \sum_n a_n \lambda(f)^n$$

Minimization condition: $$V' = f^3[4F(\lambda(f)) + \beta F'(\lambda(f))] = 0$$

Dilaton mass: $$m_d^2 \simeq 4f^2 \beta F'(\lambda(f))$$

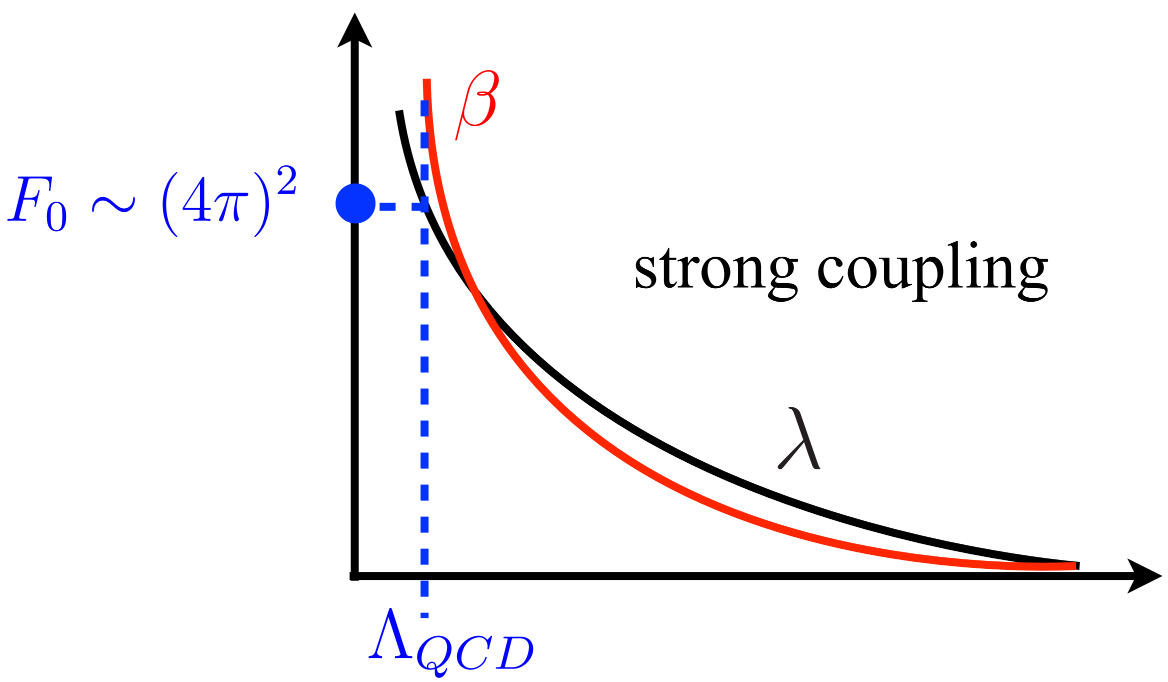
*F_0 still matters for the **dilaton mass***

F at the minimum: $$F(\lambda) = F_0 + \sum_n a_n \lambda(f)^n$$

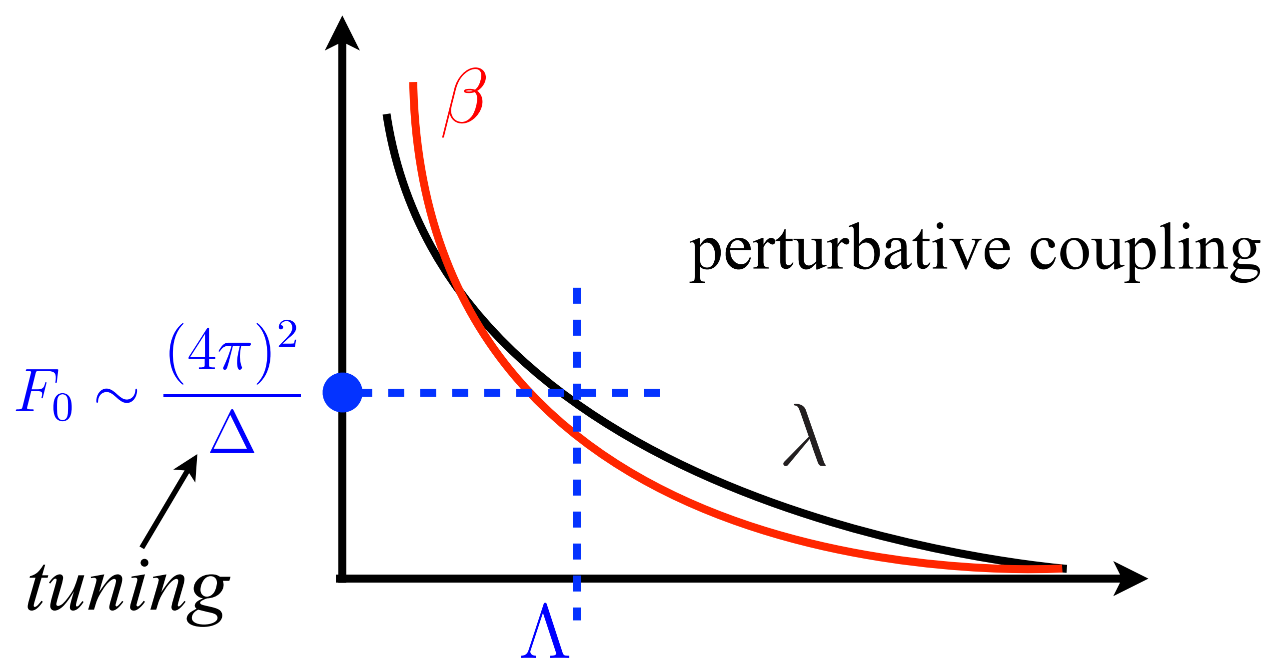
Minimization condition: $$V' = f^3[4F(\lambda(f)) + \beta F'(\lambda(f))] = 0$$

Dilaton mass: $$m_d^2 \simeq 4f^2 \beta F'(\lambda(f))$$

QCD



"tuned" QCD



$$\Delta \gtrsim 2\Lambda/m_{dil} \simeq 50 \left(\frac{f}{246\text{GeV}}\right)$$

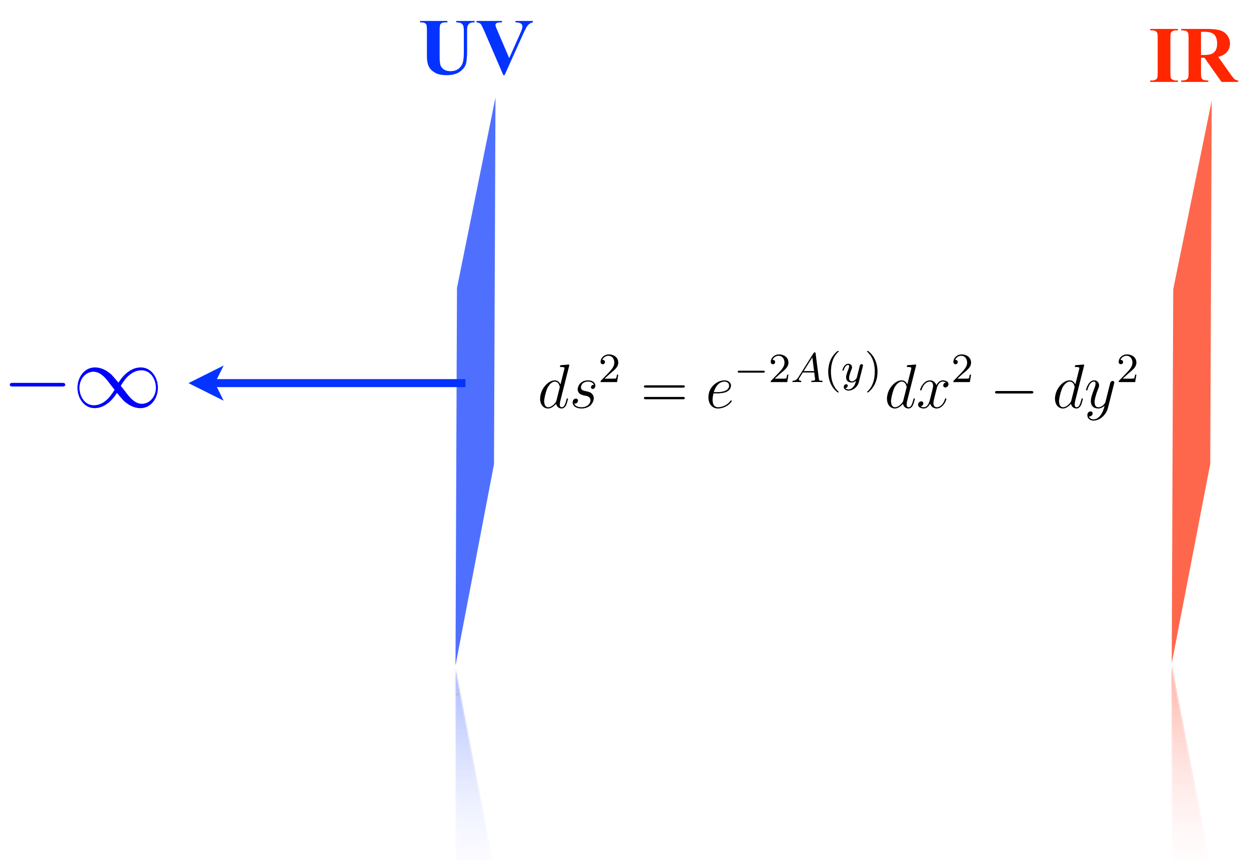
loophole

$$\beta = \epsilon(\lambda + b\lambda^2 + \ldots) \ll 1$$

$$\lambda^* : \; F(\lambda^*) \sim O(\beta)\,, V'(\lambda^*) = 0\,, \; m_d^2 \sim O(\beta)$$

Realizable in a warped extra-d: *not like Goldberger-Wise*

Goldberger, Wise '99



Sundrum '04

Contino, Pomarol , Rattazzi, '10

Still one needs to accomplish: $v/f \simeq 1$

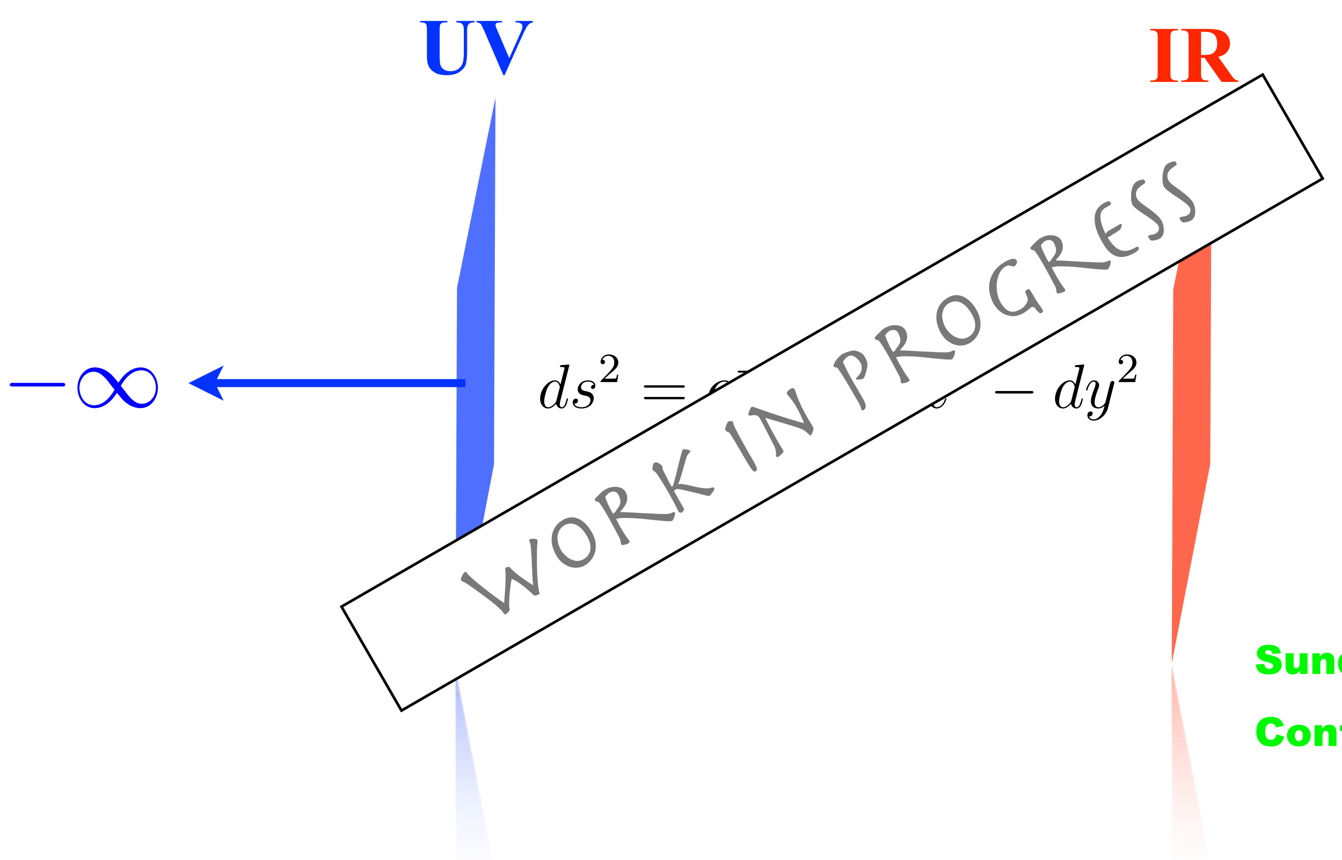
loophole

$$\beta = \epsilon(\lambda + b\lambda^2 + \ldots) \ll 1$$

$$\lambda^* : \; F(\lambda^*) \sim O(\beta) \, , V'(\lambda^*) = 0 \, , \; m_d^2 \sim O(\beta)$$

Realizable in a warped extra-d: *not like Goldberger-Wise*

Goldberger, Wise '99



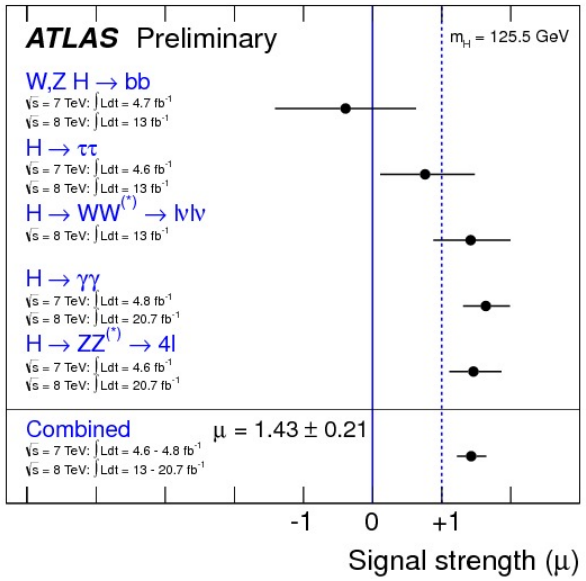
Sundrum '04

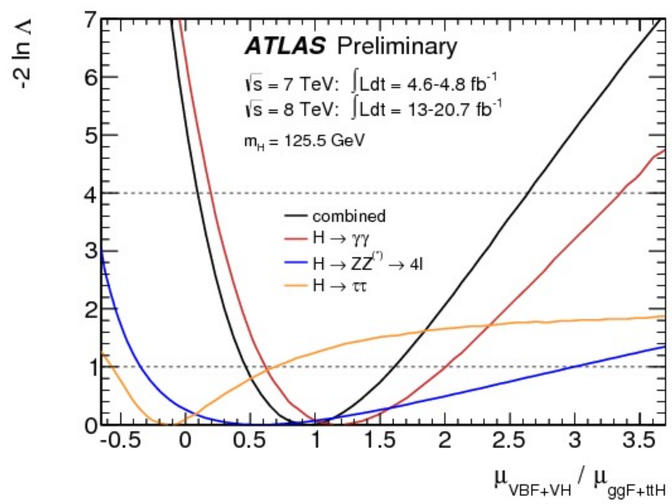
Contino, Pomarol , Rattazzi, '10

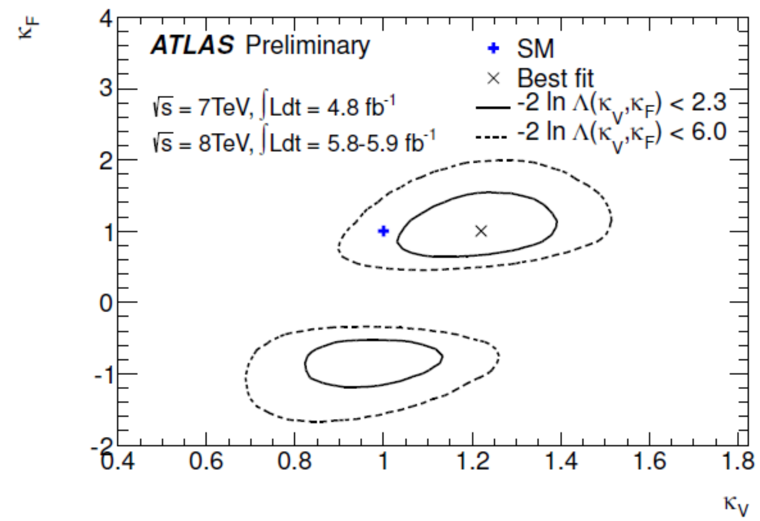
Still one needs to accomplish: $v/f \simeq 1$

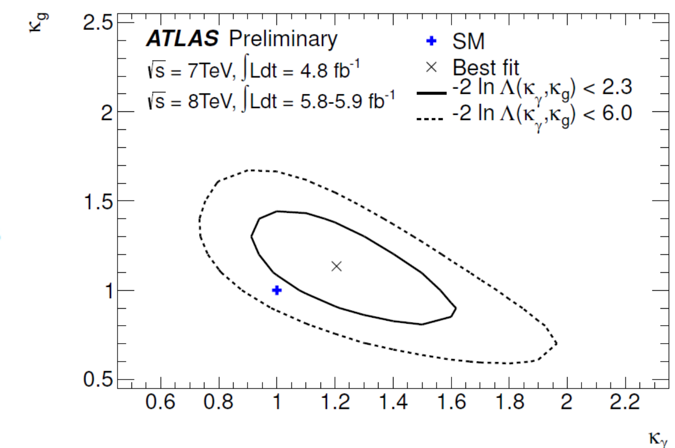
Goldstone-Higgs couplings
@
the LHC

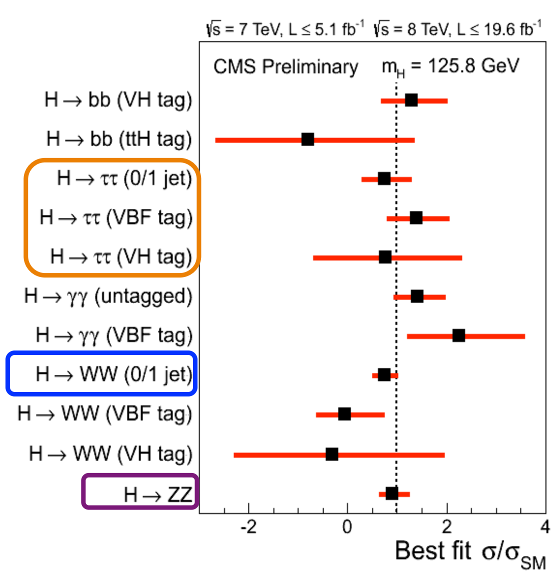
More data on EWSB than ever!

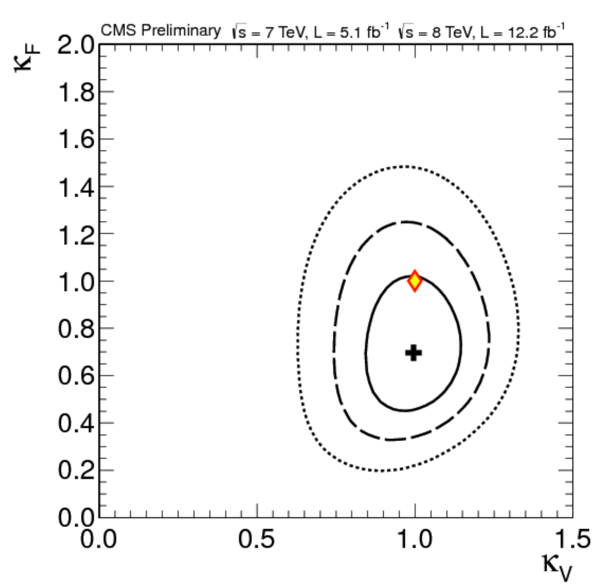


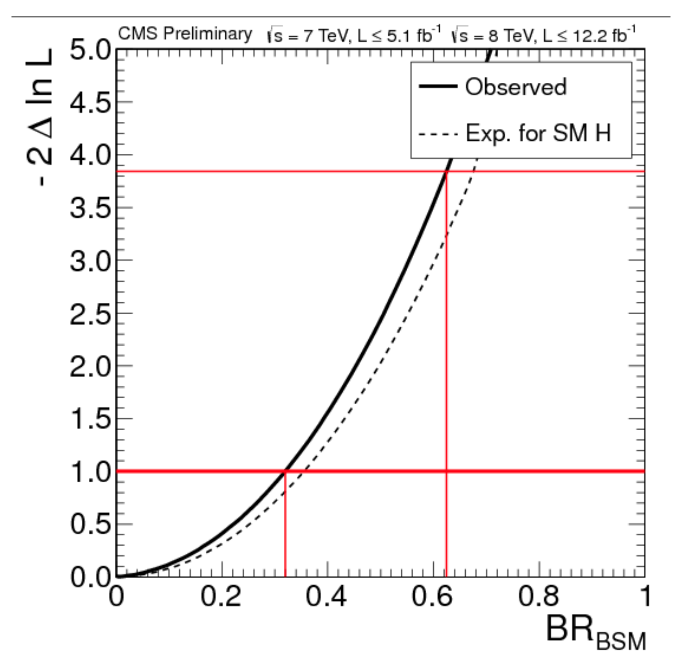


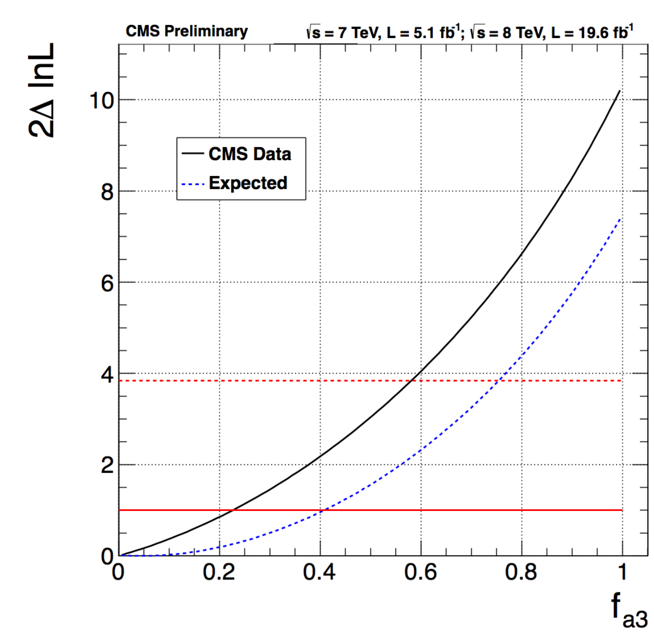












Higgs couplings Parametrization

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right) - c_t \sum_{f=u,c,t} m_f \bar{f} f - c_b \sum_{f=d,s,b} m_f \bar{f} f - c_\tau \sum_{f=e,\mu,\tau} m_f \bar{f} f\right]$$

$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} + c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + 2c_{Z\gamma} A_{\mu\nu} Z^{\mu\nu} + c_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} - c_{gg} G_{\mu\nu}^a G_{\mu\nu}^a\right]$$

$$c_{WW} = c_{\gamma\gamma} + \frac{g_L}{g_Y} c_{Z\gamma}\,, \qquad c_{ZZ} = c_{\gamma\gamma} + \frac{g_L^2 - g_Y^2}{g_L g_Y} c_{Z\gamma}$$

Standard Model

$$c_V = c_t = c_b = c_\tau = 1$$

$$c_{\gamma\gamma} = c_{Z\gamma} = c_{gg} = 0$$

SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

$$c_{\gamma\gamma,gg} \sim \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v^2}{f^2}\frac{y_t^2}{g_\rho^2}$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v^2}{f^2}$$

dilaton

$$c_V = \frac{v}{f}$$

$$c_f = \frac{v}{f}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

SO(5)/SO(4)

dilaton

< **1** (model independent)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_V = \frac{v}{f}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

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$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v^2}{f^2}$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

Higgs couplings Predictions

SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

< **1** (m.i.)

$$c_{\gamma\gamma,gg} \sim \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v^2}{f^2}\frac{y_t^2}{g_\rho^2}$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v^2}{f^2}$$

dilaton

$$c_V = \frac{v}{f}$$

< **1** / > **1** (m.d.)

$$c_f = \frac{v}{f}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

$$c_{\gamma\gamma,gg} \sim \boxed{\frac{(g'^2, g_S^2)}{16\pi^2}} \frac{v^2}{f^2}\frac{y_t^2}{g_\rho^2}$$

$$c_{Z\gamma} \sim \boxed{\frac{g^2}{16\pi^2}} \frac{v^2}{f^2}$$

dilaton

$$c_V = \frac{v}{f}$$

$$c_f = \frac{v}{f}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \boxed{\frac{(g'^2, g_S^2)}{16\pi^2}} \frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \boxed{\frac{g^2}{16\pi^2}} \frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

SM-like

SO(5)/SO(4)

$$c_V = \sqrt{1 - v^2/f^2}$$

$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

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suppression (m.i.)

SO(5)/SO(4)

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$$c_f = \frac{1-(1+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

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Goldstone suppression

dilaton

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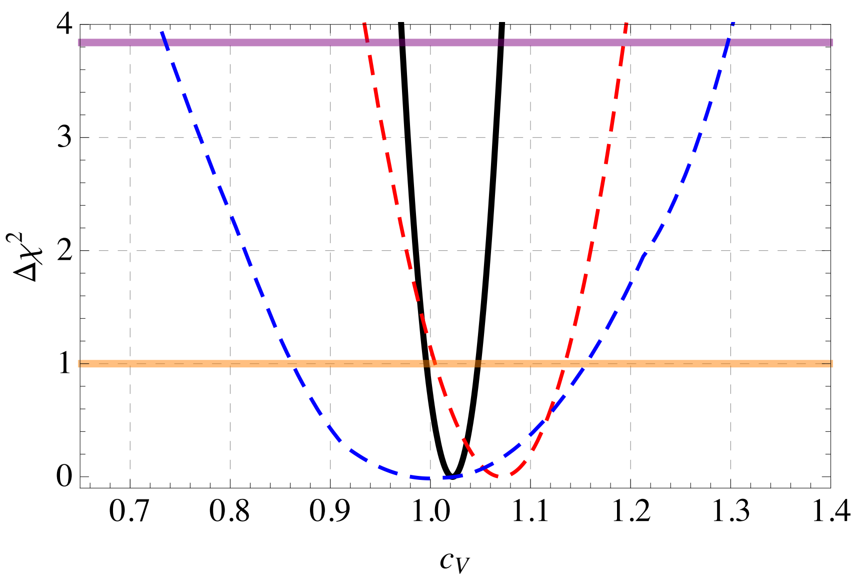
$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

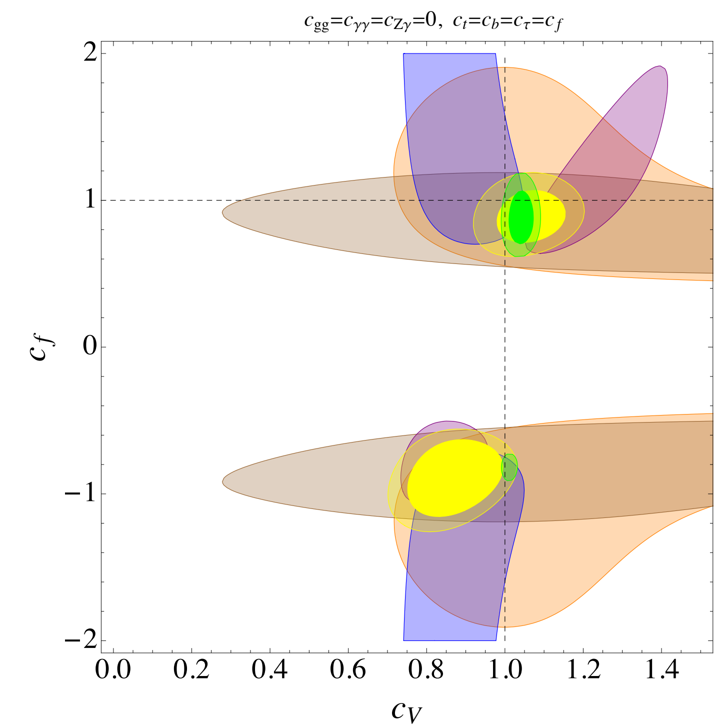
Scale anomaly

Contrasting results with Data

Falkowsky, Riva, Urbano '13

EW precision tests & Higgs couplings:





Falkowsky, Riva, Urbano '13

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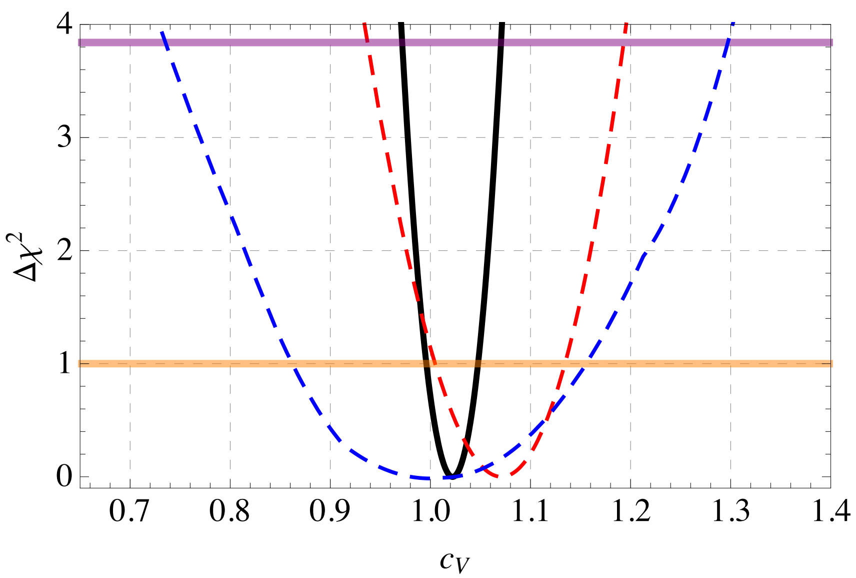
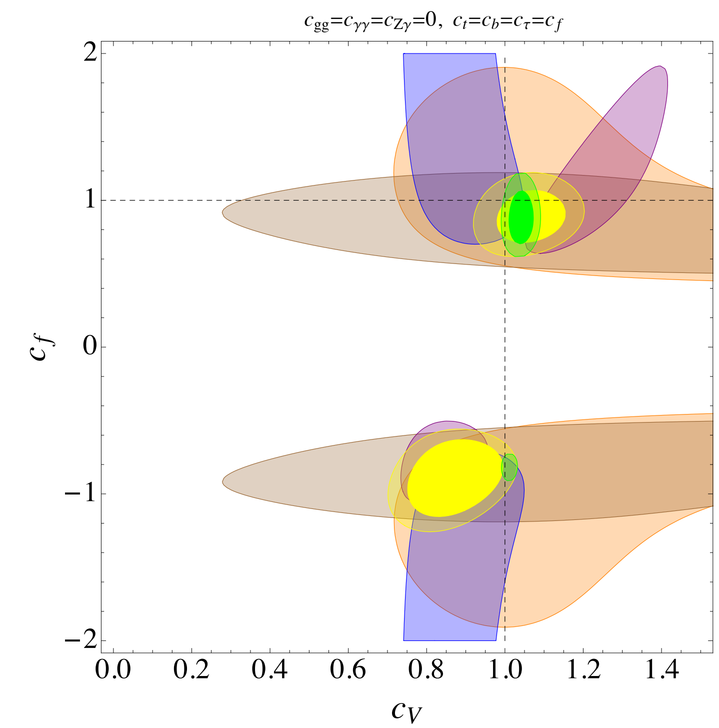
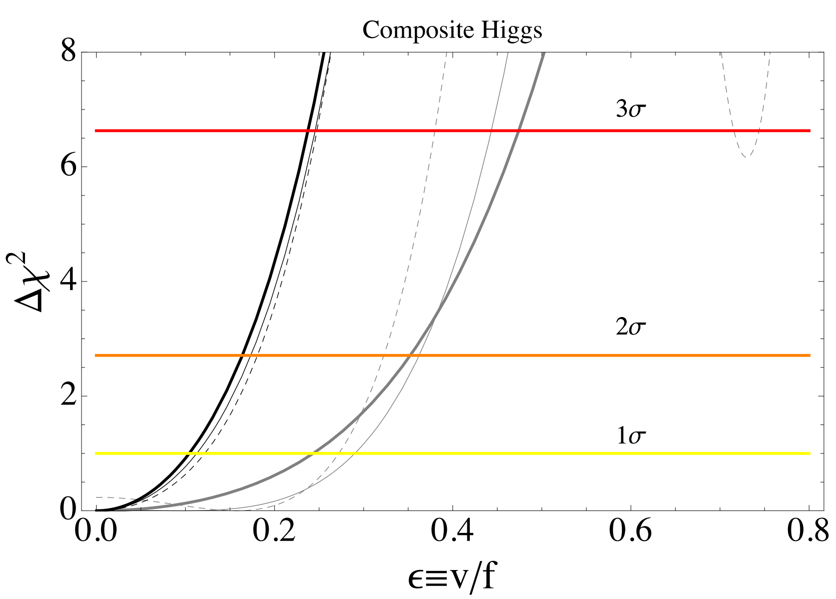




SO(5)/SO(4)



Falkowsky, Riva, Urbano '13

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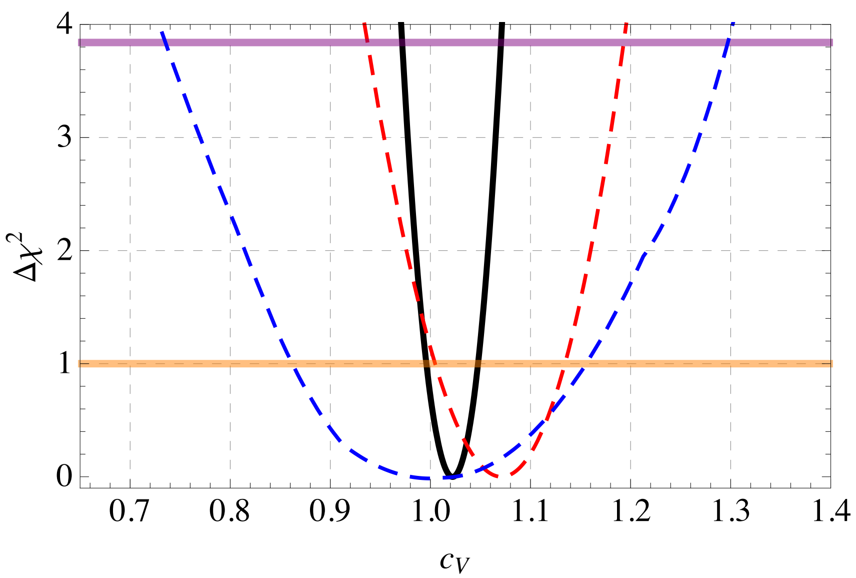
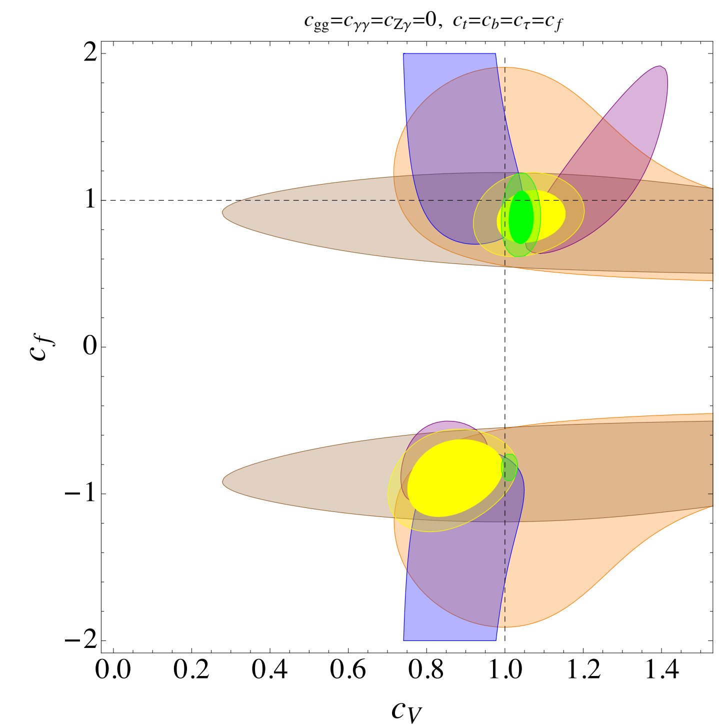
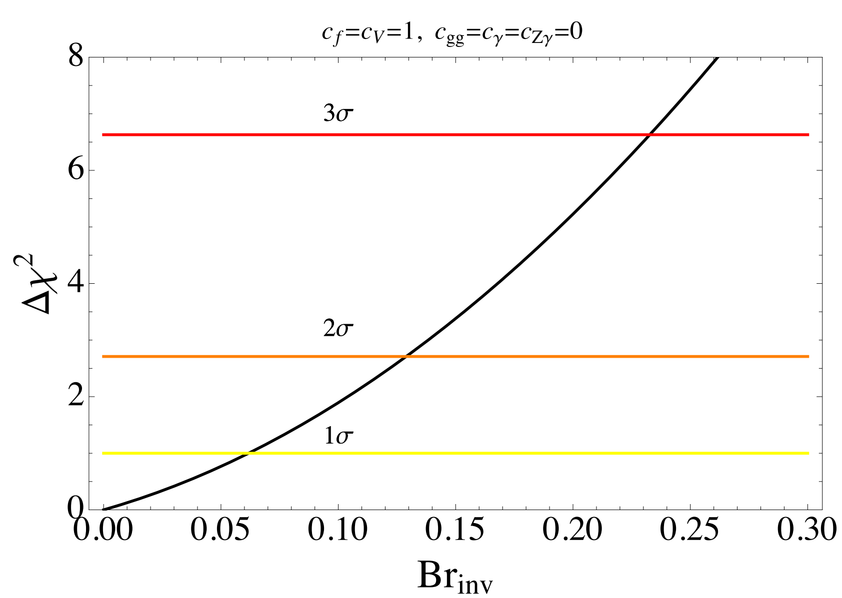




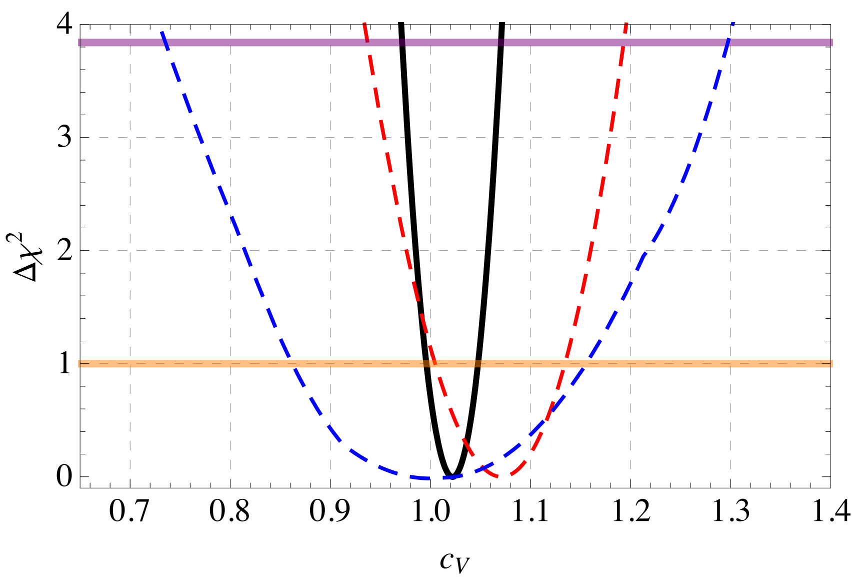
SO(6)/SO(5) $h \to \eta\eta = \not{E}_T$

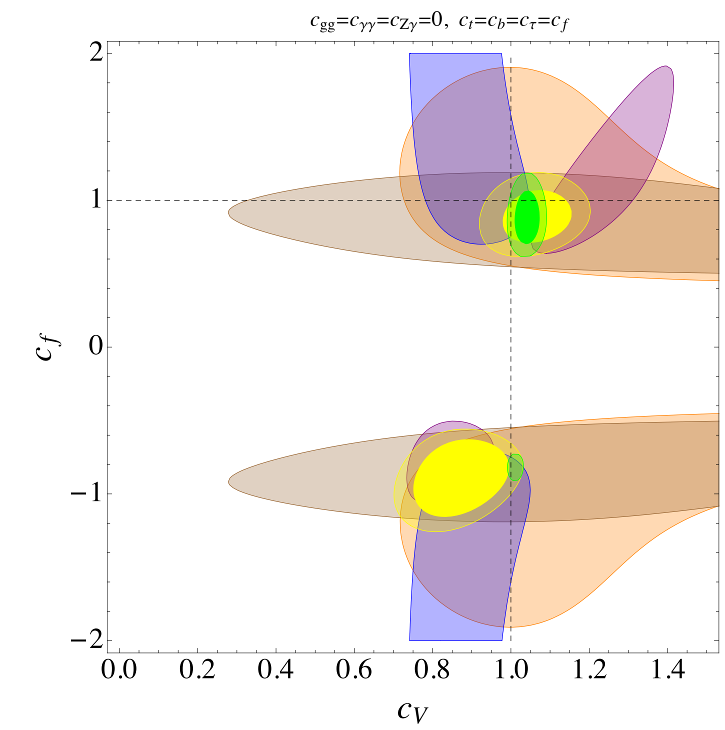


Contrasting results with data

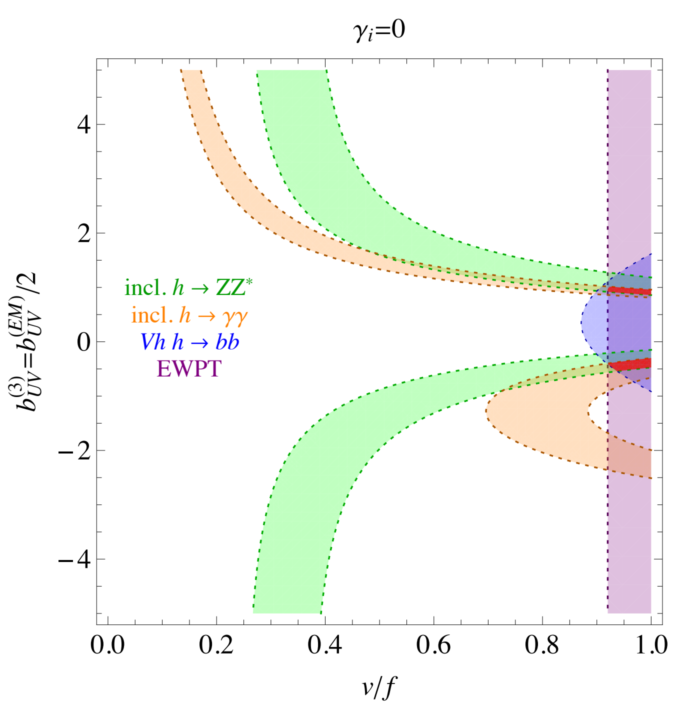
Falkowsky, Riva, Urbano '13

EW precision tests & Higgs couplings:

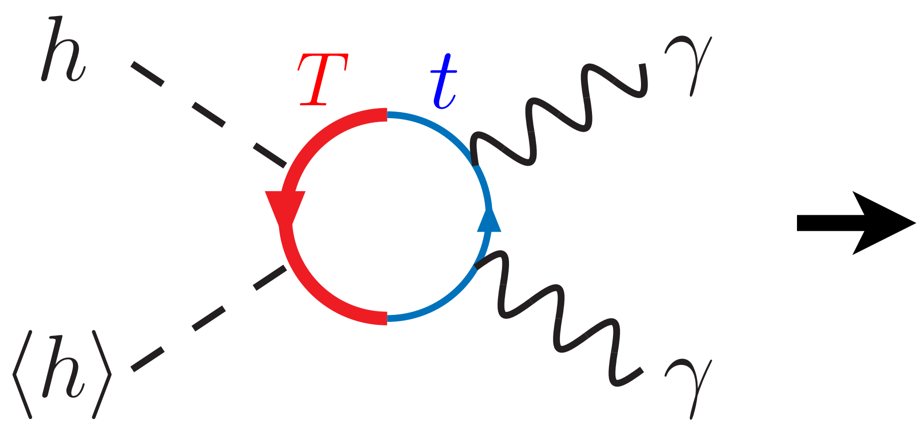




dilaton



h to photons from composite resonance:



$$c_\gamma \frac{g'^2}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{g_{SM}^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

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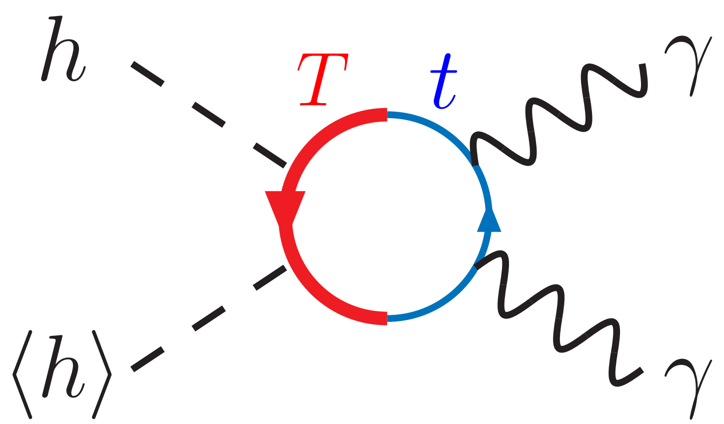
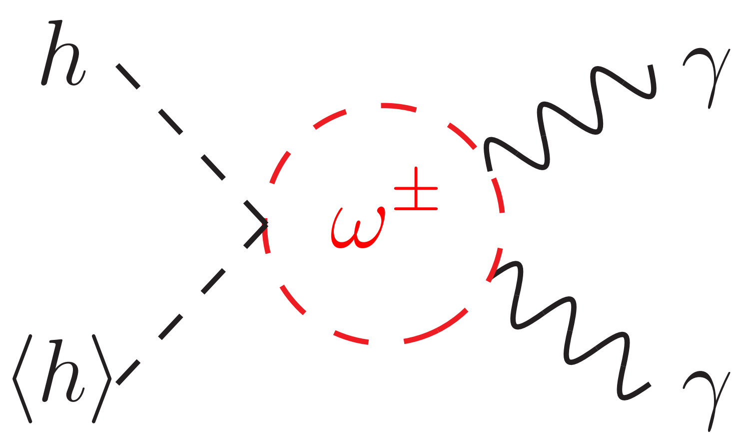


$$\rightarrow \quad c_\gamma \frac{g'^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g_{SM}^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu}$$

h to photons from **extra Goldstone's**:



$$\rightarrow \quad \tilde{c}_\gamma \frac{g'^2}{m_\Pi^2}\frac{g_\Pi^2}{16\pi^2} H^\dagger H B_{\mu\nu}B^{\mu\nu}$$

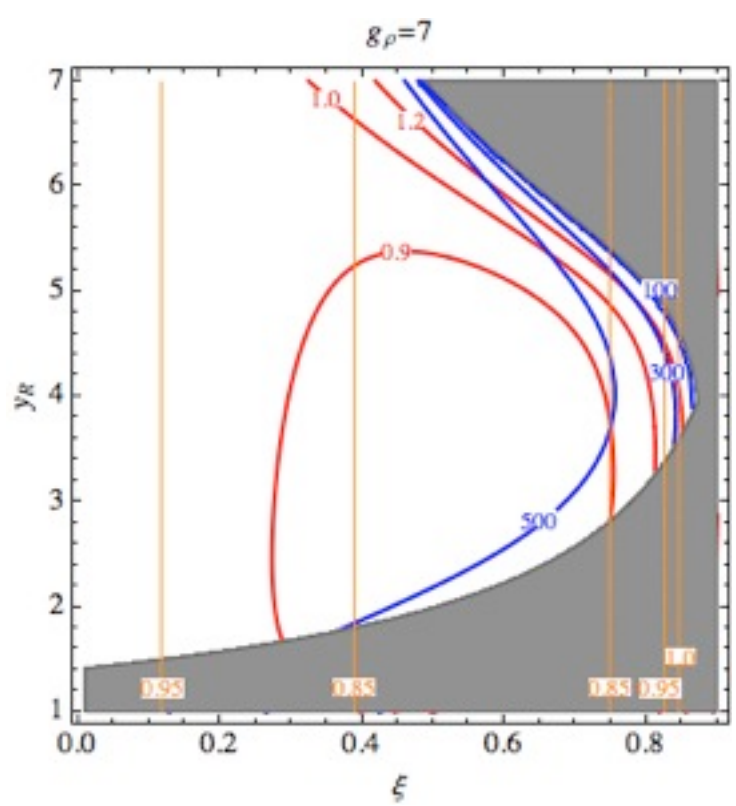
$$m_\Pi^2 \sim \frac{g_\rho^2}{16\pi^2} g_{SM}^2 f^2 \quad \& \quad g_\Pi^2 \sim \frac{g_\rho^2}{16\pi^2} g_{SM}^2 \quad \rightarrow \quad \boxed{c_\gamma \sim \tilde{c}_\gamma \frac{g_\rho^2}{g_{SM}^2}}$$

E.g.: SO(8)/SO(7) & Higgs to photons

$$\mathrm{SO}(8)/\mathrm{SO}(7) \cong \mathrm{SO}(7)/\mathrm{G}_2 \quad \longrightarrow \quad \mathbf{7} = (\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) = H + \omega$$

Sigma-model: $$\frac{f^2}{2}\partial_\mu \Sigma^T \partial^\mu \Sigma = \frac{f^2}{2}\left\{(\partial h)^2 + (\partial\omega)^2 + \frac{(h\partial h + \omega\partial\omega)^2}{1-h^2-\omega^2}\right\}$$

Potential: $$V = m_1^2 h^2 + m_2^2 \omega^2 + \lambda_1 h^4 + \lambda_2 \omega^4 + \lambda_3 h^2 \omega^2$$



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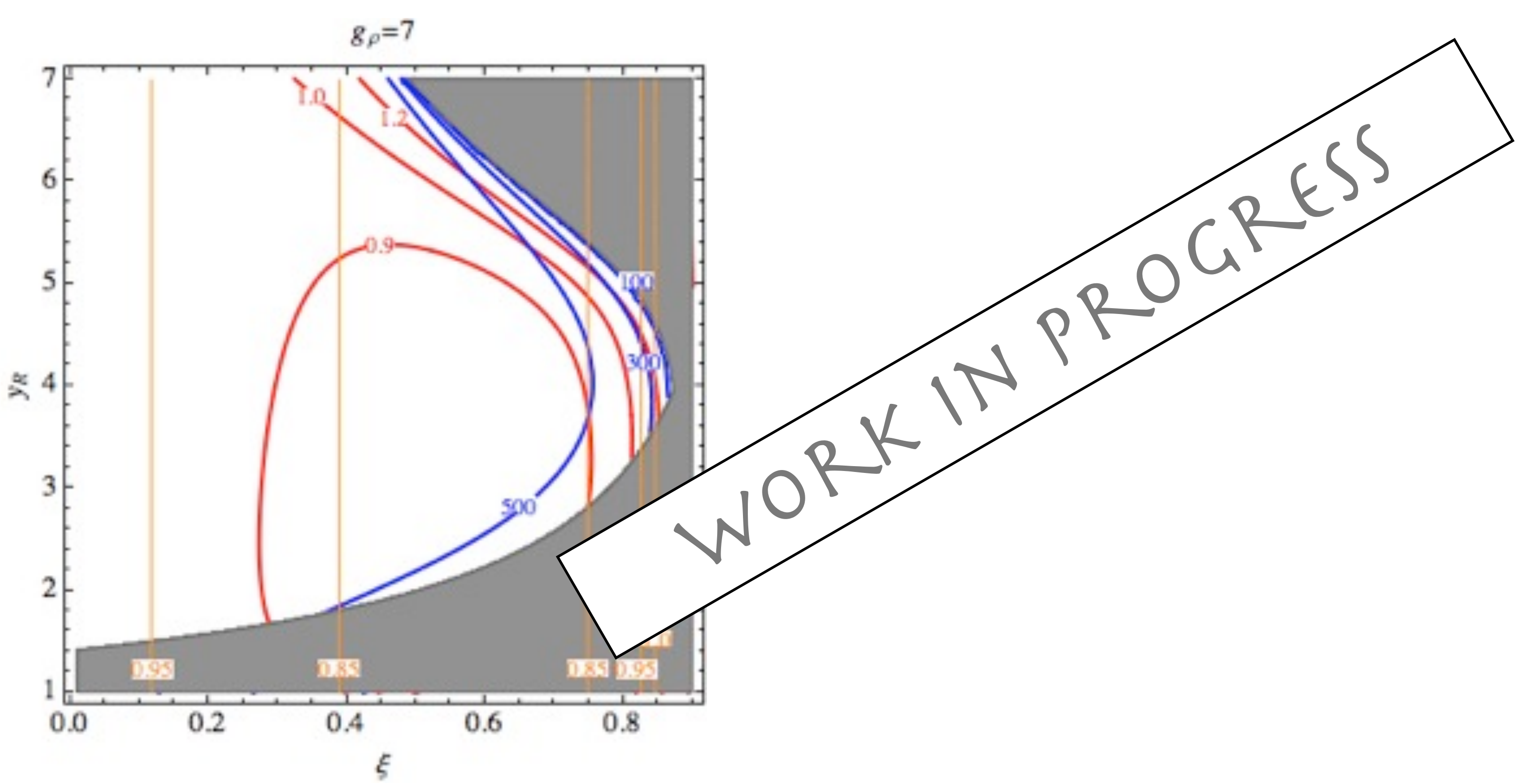

Nature has given us a light higgs for EWSB

✦ If a composite Higgs, the expectation is that it behaves as a Goldstone boson.

✦ A 125 GeV composite Higgs implies light and weakly coupled top resonances, with masses around the current bound 700 GeV.

✦ Light W and Z resonances are disfavored by EW precision data and Higgs couplings measurements.

✦ We have clear predictions for composite Higgs couplings (deviations), which we should look for.

✦ Extra Goldstone's might play an important role and deserve further study.

Thank you for your attention