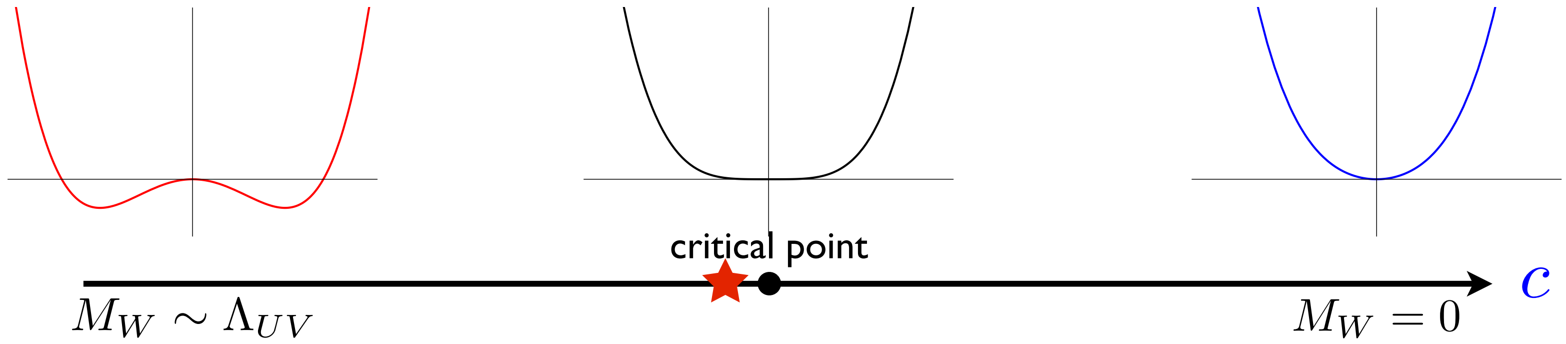
Aspects of composite Higgs phenomenology

Duccio Pappadopulo

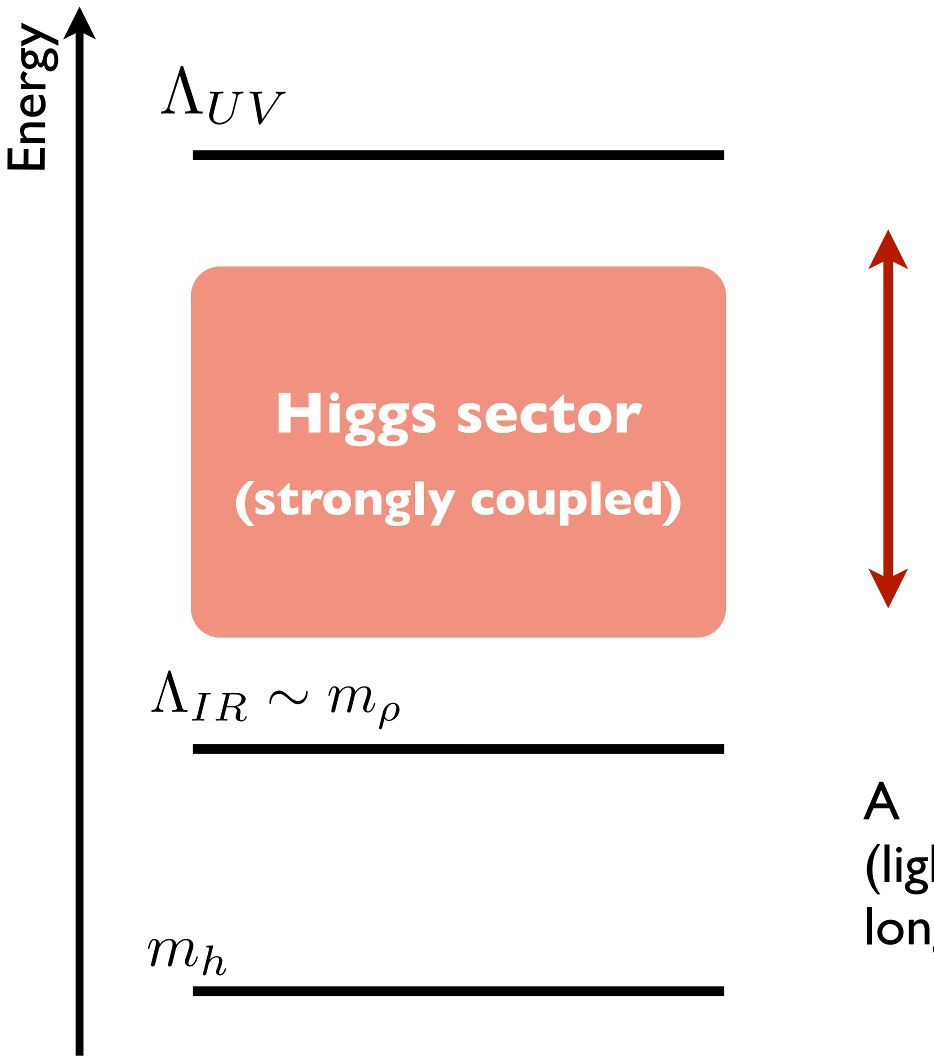
weak force ≫ gravity $\longleftrightarrow$ $M_W \ll M_P$

$$c\,\Lambda_{UV}^2 H^\dagger H$$



$$\Lambda_{UV} \sim M_P \Rightarrow c \sim 10^{-32}$$

Higgs compositeness as a solution



The UV - IR hierarchy is generated by dimensional transmutation.

A light scalar can be accidentally present (light dilaton) or related by symmetry to the longitudinal W and Z (PGB Higgs).

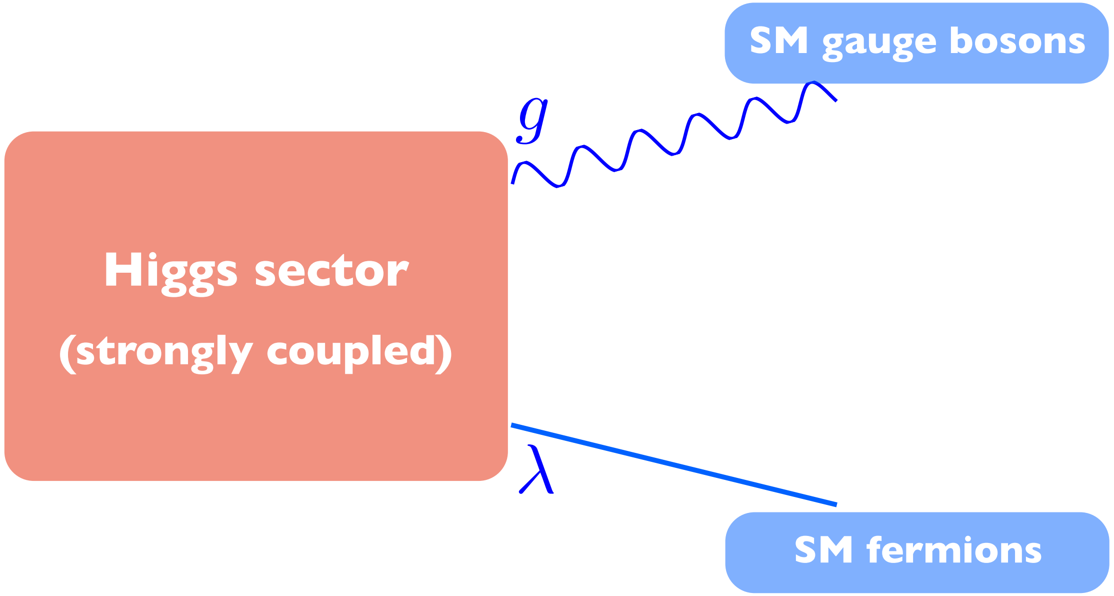
Two objections

No sign of compositeness so far

First things we expect to see in weakly coupled models are new particles. Not in this case: heavy physics but strongly coupled. Indirect signals should come first. Cure: model building + fine-tuning

No compelling single model

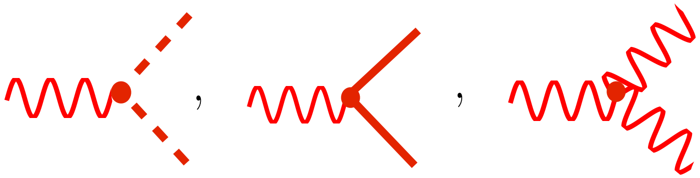
Can be a virtue as it forces to understand generic features first.



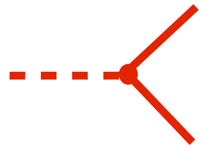
Transverse gauge fields and light fermions are external to the strongly interacting sector.

Couplings of SM fields break global symmetry G and generate a potential for H which determines the vacuum of the theory.

Jargon

 $\sim g_\rho$

coupling to vector resonances

 $\sim g_\Psi$

composite "Yukawa"
(can be naturally smaller due to chiral symmetries)

f : sigma-model scale, expansion parameter for Higgs (goldstones) self interactions $\quad F\left(\frac{\pi}{f}\right)$

 $\sim m_\rho \sim g_\rho f$

 $\sim m_\Psi \sim g_\Psi f$

$m_h \ll \Lambda_{IR}$ by Goldstone symmetry

The strong dynamics breaks some global symmetry of the UV theory delivering a set of Goldstone fields

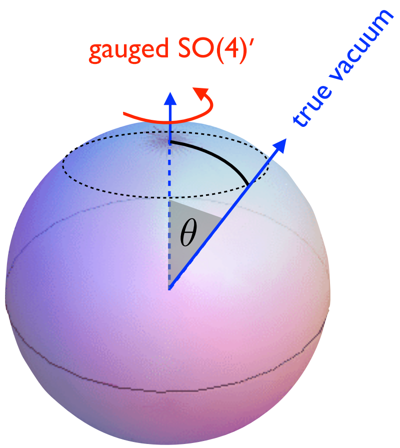
Unitarity (compact cosets)

+

Custodial symmetry

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	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2},\mathbf{2})$
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)	$[\mathrm{SO}(3)]^3$	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	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Mrazek et al '11



$$\phi = e^{i\pi^{\hat a}T^{\hat a}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat\pi^1\\\hat\pi^2\\\hat\pi^3\\\hat\pi^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta + h(x)/f)\quad e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

Gauged SO(4)

SO(4) invariant physical Higgs excitation

Eaten Goldstones

$$\phi^T\phi = 1$$

The symmetry structures fixes Higgs self interactions at low energy.

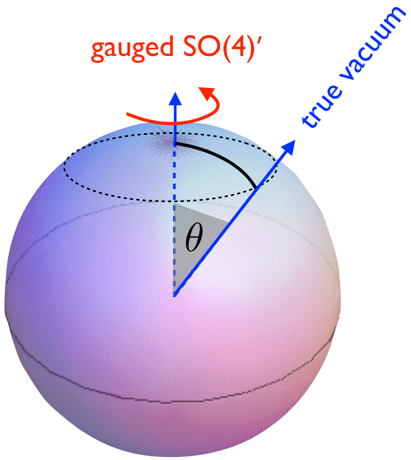
$$\mathcal{L} = \frac{f^2}{2}(D_\mu\phi)^T(D^\mu\phi) = \frac{1}{2}(\partial_\mu h)^2 + \frac{f^2}{2}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\sin^2\left(\theta + \frac{h(x)}{f}\right)$$

$$= \tfrac{1}{2}(\partial_\mu h)^2 + \left(m_W^2 W^+W^- + \tfrac{m_Z^2}{2}Z^2\right)\left(1 + \boxed{2\sqrt{1-\xi}\,\tfrac{h}{v}} + (1-2\xi)\tfrac{h^2}{v^2} + \dots\right)$$

$$\boxed{m_W^2 = \frac{g^2 f^2}{4}\sin^2\theta}$$

$$\xi = \frac{v^2}{f^2} = \sin^2\theta$$

Higgs coupling to fermions is model dependent (see later)



$\sin\theta = 0$: unbroken EW

$\sin\theta = 1$: technicolor limit

The misalignment angle is determined dynamically

$$V(h) \sim \frac{m_\rho^4}{g_\rho^2} \frac{g_{\not{G}}^2}{16\pi^2} F\left(\frac{h}{f}\right) \quad \Rightarrow \quad \frac{v}{f} \approx 1 \quad ✱$$

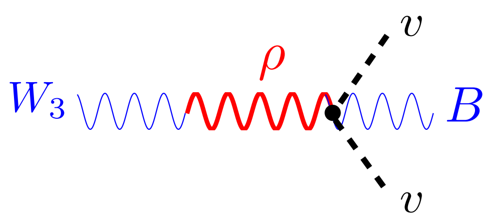
G-breaking interactions (top mass,...)

unless fine tuning

✱

unless complicated model building (see little Higgs models)

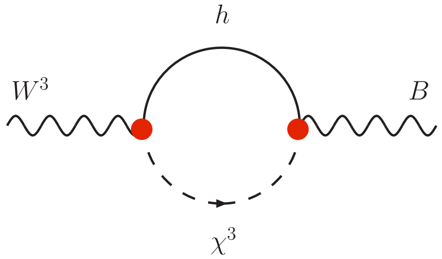
Small v/f (large f) decouples new physics and allow to live with the bounds from EW physics



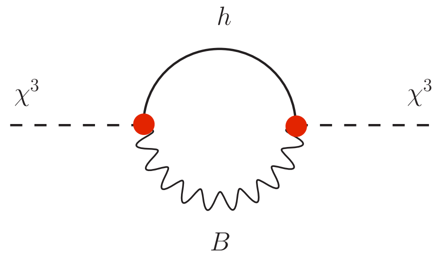
$$\Rightarrow \quad \hat{S} \sim \frac{m_W^2}{m_\rho} \sim \frac{g^2}{g_\rho^2}\,\boxed{\frac{v^2}{f^2}}$$

+ Infrared logs:

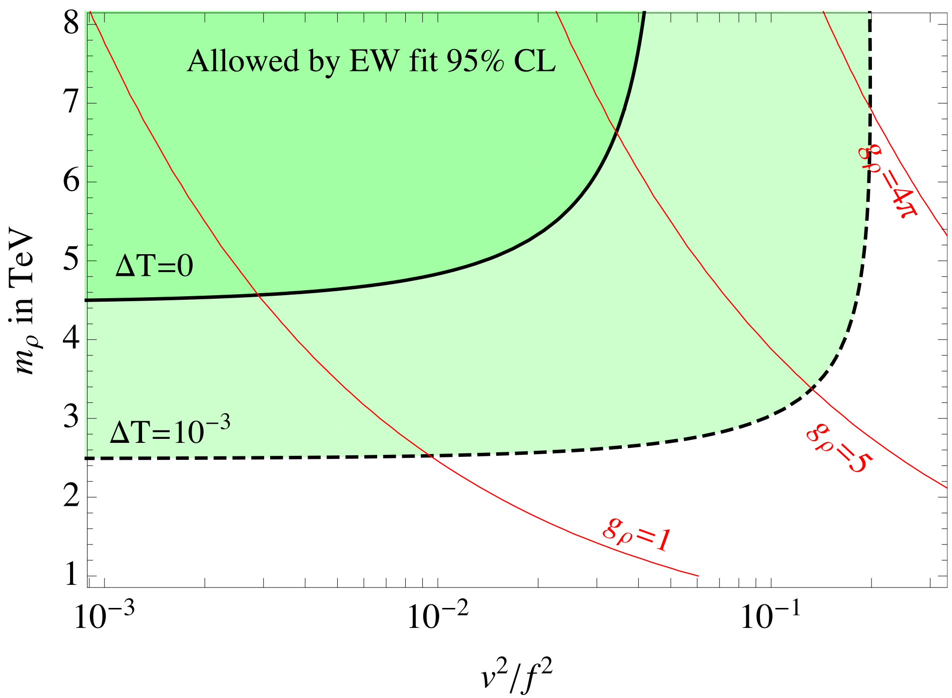
$\Delta\hat{S}$:



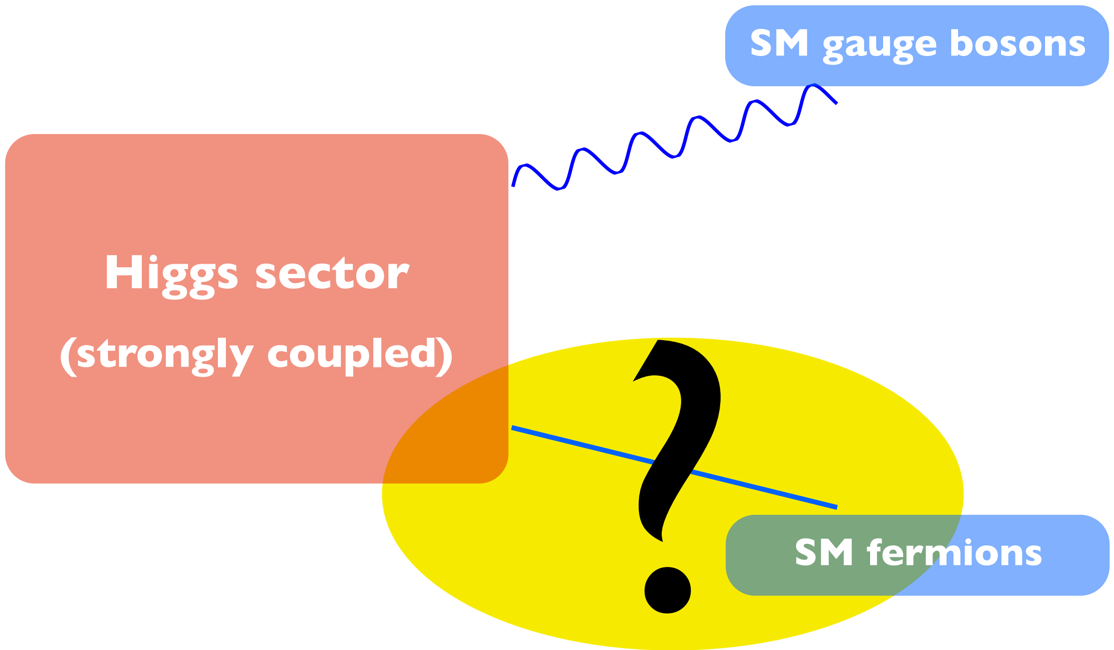
$\Delta\hat{T}$:



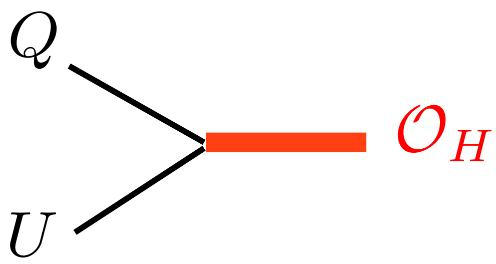
$$\boxed{\propto \frac{v^2}{f^2}}$$



The bound on xi cannot be relaxed assuming the existence of non-oblique NP contribution to the Zbb vertex (curing AFB and Rb anomalies)



SM gauge bosons
Higgs sector
(strongly coupled)
?
SM fermions



Yukawa

plain small N technicolor: $f = v,\ g_\rho \sim 4\pi,\ m_\rho \sim 4\pi v$

$$\frac{4\pi}{\Lambda_F^{d_H-1}} \boxed{QU\,\mathcal{O}_H} \to 4\pi \left(\frac{m_\rho}{\Lambda_F}\right)^{d_H-1} QU\,H$$

$$\Lambda_F \sim 4\pi v \left(\frac{4\pi v}{m_t}\right)^{\frac{1}{d_H-1}}$$

You could in principle cure the flavor problem with very large f: requires too much tuning.

$$\boxed{\begin{array}{c}\mathcal{O}_H = \Psi\Psi \\ d_H \sim 3 \Rightarrow \Lambda_F \approx 10\,\mathrm{TeV}\end{array}}$$

Flavor violation

$$\frac{\boxed{y_s y_d(\Lambda_F)}}{\Lambda_F^2}(s^c d)^2$$

$$\boxed{d_H \sim 3 \Rightarrow \Lambda_{\mathrm{eff}} \approx 10^4\,\mathrm{TeV}}$$

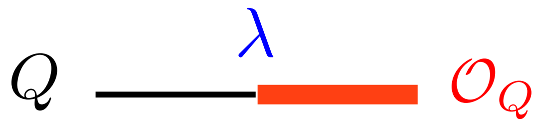
still too small

Caveat emptor...

Luty, Okui ('04) but also Rattazzi, Rychkov, Tonni, Vichi ('08) ...

One way out: **partial compositeness**

Kaplan '91



$$\lambda_Q \, Q\mathcal{O}_Q + \lambda_U \, U\mathcal{O}_U \quad \Rightarrow y_t \sim \frac{\lambda_Q \lambda_U}{g_\Psi} \equiv g_\Psi \epsilon_Q \epsilon_U$$

$\epsilon \equiv \lambda / g_\Psi$: measures the mixing between elementary and composite states.*

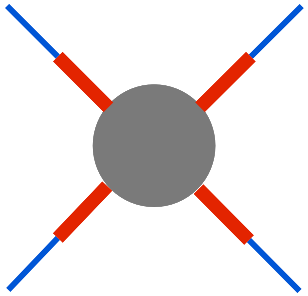
$$\lambda = \lambda_{UV} \left(\frac{\Lambda_{IR}}{\Lambda_{UV}} \right)^{5/2 - d_{\mathcal{O}}}$$

Maybe ad hoc d = 5/2 decouples the UV flavor problem completely without reintroducing a hierarchy problem. d > 5/2 explains Yukawa hierarchies.

*(weak gauging of a global symmetry of the strong sector automatically implement PC in the gauge sector)

Flavor violation at the IR scale is controlled by the mixing selection rules (differs from FN, to be thought as a non compact U(1))

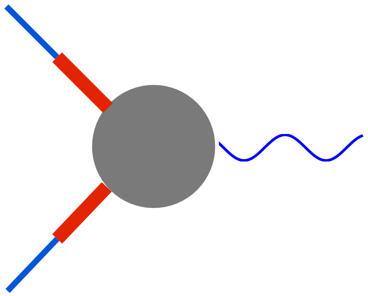
$\Delta F = 2$



$$\epsilon_i \epsilon_j \epsilon_k \epsilon_h \frac{g_\rho^2}{m_\rho^2} \bar{f}_i f_j \bar{f}_h f_k$$

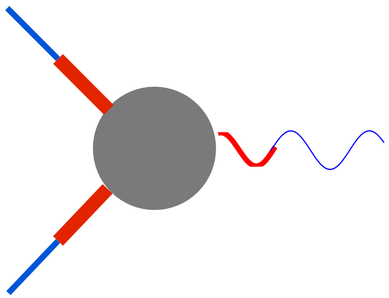
$$\Delta S = 2 : \boxed{\begin{matrix} m_\rho \gtrsim 10\,\mathrm{TeV}\, \frac{g_\rho}{g_\Psi} \\ m_\Psi \gtrsim 2\,\mathrm{TeV}\, \frac{1}{\epsilon_R^2} \frac{3}{g_\Psi} \end{matrix}} \Rightarrow \frac{v^2}{f^2} \lesssim 0.02 \left(\frac{g_\Psi}{5}\right)^2$$

$\Delta F = 1$



$$\epsilon_i \epsilon_j g_\Psi \frac{v}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \bar{f}_i \sigma(eF) f_j$$

$$b \to s,\ \frac{\epsilon'}{\epsilon} : m_\rho \gtrsim 10 \div 15\,\mathrm{TeV}\, \frac{g_\rho}{4\pi} \Rightarrow \frac{v^2}{f^2} \lesssim 0.04$$



$$\epsilon_i \epsilon_j \frac{g_\rho^2}{m_\rho^2} \bar{f}_i \gamma^\mu f_j\, i H^\dagger D_\mu H$$

$$B_s \to \mu^+ \mu^- : \frac{v^2}{f^2} \lesssim 0.4 \left(\frac{g_\Psi}{5}\right)^2$$

$\Delta F = 0$

$$d_n : m_\rho \gtrsim 30 \div 50\,\mathrm{TeV}\, \frac{g_\rho}{4\pi} \Rightarrow \frac{v^2}{f^2} \lesssim 0.008$$

Huber '03
...
Davidson, Isidori, Uhlig '07
...
Keren-Zur, Lodone, DP, Rattazzi, Vecchi '12

The constraints are much worse in the lepton sector

$$BR(\mu \to e\gamma) < 2.4 \times 10^{-12} \Rightarrow m_\rho \gtrsim 150\,\mathrm{TeV}\,\frac{g_\rho}{4\pi}$$

(with a choice of the mixings which minimizes the constraints)

In general one may want to give up complete explanation of the flavor structure and assume the existence of appropriate flavor symmetries.

$$MFV,\ U(2)^3\ \ldots$$

MFV and PC

Barbieri, Isidori, DP '09
Redi, Weiler '11
Barbieri, Buttazzo, Sala, Straub, Tesi '13

$$\boxed{\lambda^Q} Q^i \mathcal{O}^i_Q + \lambda^U_{ij} U^i \mathcal{O}^j_U + \lambda^D_{ij} D^i \mathcal{O}^j_D$$

U(3) symmetry in the strong sector broken by right-handed mixing. Realizes MFV.

No FCNC (but assume CP)

quark compositeness:	$m_\Psi > 1\,\text{TeV}\,\frac{1}{\epsilon_R^2}\,\frac{3}{g_\Psi}$
quark-lepton universality:	$m_\Psi > 5\,\text{TeV}\,\frac{1}{\epsilon_R}$

$$\lambda^{Q_u}_{ij} Q^i \mathcal{O}^j_{Q_u} + \lambda^{Q_d}_{ij} Q^i \mathcal{O}^j_{Q_d} + \boxed{\lambda^U} U^i \mathcal{O}^i_U + \boxed{\lambda^D} D^i \mathcal{O}^i_D$$

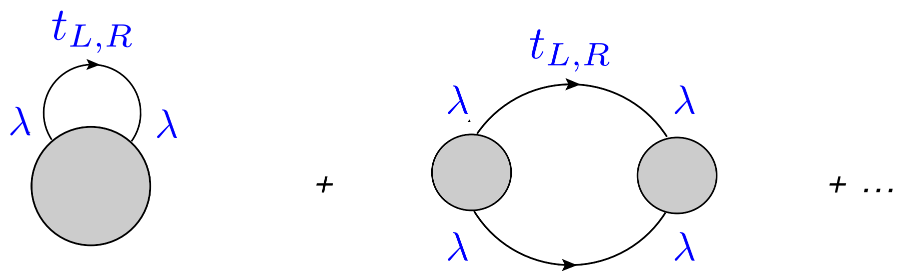
U(3)xU(3) symmetry in the strong sector broken by left-handed mixing. Realizes MFV.

epsK:	$m_\Psi > 1\,\text{TeV}\,\frac{1}{\epsilon_R^2}\,\frac{3}{g_\Psi}$
quark compositeness:	$m_\Psi > 11\,\text{TeV}\,\epsilon_R^2\,\frac{g_\Psi}{3}$

Bounds can be relaxed below the TeV with LHComp and more elaborated flavor structures: U(2)xU(2)xU(2).

The Higgs potential and tuning

The potential is dominated by the top quark sector.



2 loops

$$V(h) = \frac{N_C m_\Psi^4}{16\pi^2} \times \left[\frac{\lambda^2}{g_\Psi^2} f_1\left(\frac{h}{f}\right) + \frac{\lambda^4}{g_\Psi^4} f_2\left(\frac{h}{f}\right) + \frac{g_\Psi^2}{16\pi^2} \times \dots \right]$$

$$f_1\left(\frac{h}{f}\right) = a_1 I_1\left(\frac{h}{f}\right) + a_2 I_2\left(\frac{h}{f}\right) + \dots$$

sum of simple trigonometric functions

The explicit form of the trigonometric invariants is fixed by symmetry (for the normalization you need a complete model)

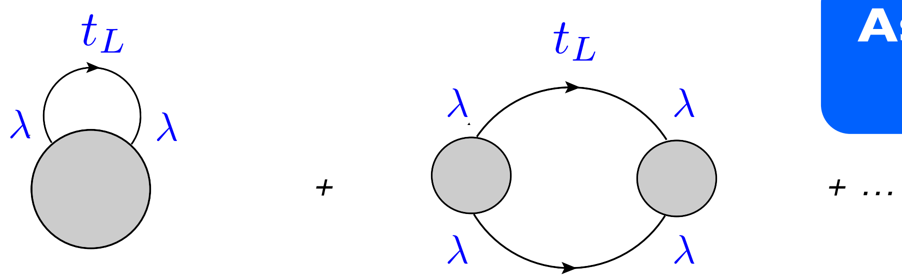
$$\bar{q}_L^\alpha \, (\lambda_L)_{\alpha I} \, \mathcal{O}_L^I + \bar{t}_R \, (\lambda_R)_I \, \mathcal{O}_R^I$$

All that matter are the SO(5) representations of O_L and O_R

(This choice also determines Higgs-fermion couplings)

The potential is dominated by the top quark sector.

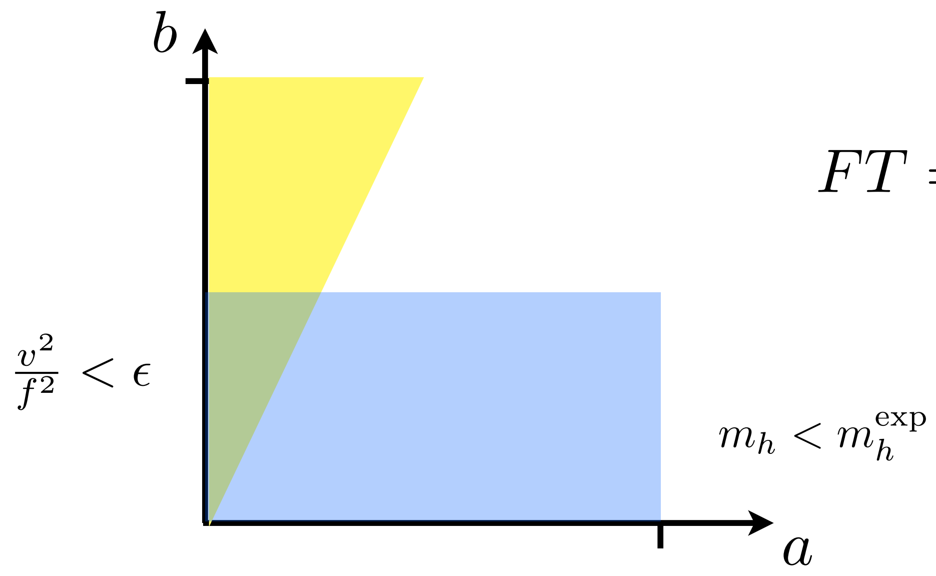
Assume singlet top-right



2 loops

$$y_t = \lambda_L \epsilon_R$$

$$V(h) = \frac{N_C y_t^2}{16\pi^2}\frac{m_\Psi^2}{\epsilon_R^2}\left(a h^2 + b\frac{h^4}{f^2} + \dots\right)$$



$$FT = \left(\frac{450\mathrm{GeV}}{m_\Psi}\right)^2 \left(\frac{3}{g_\Psi}\right)^2 \epsilon_R^2$$

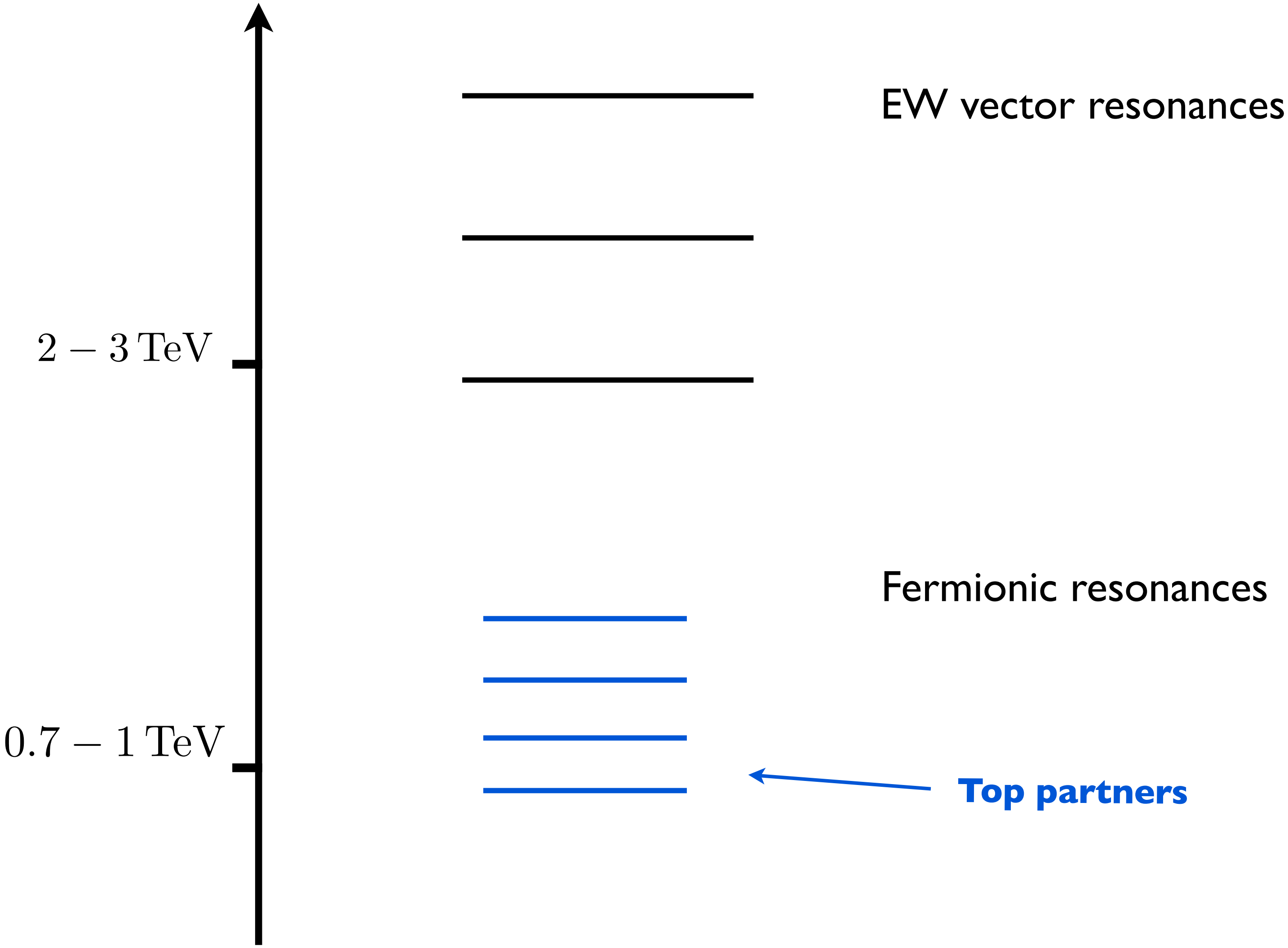
stolen without permission from R.Rattazzi

Natural EWSB requires light top partners.

Light Higgs requires them to be not too strongly coupled.

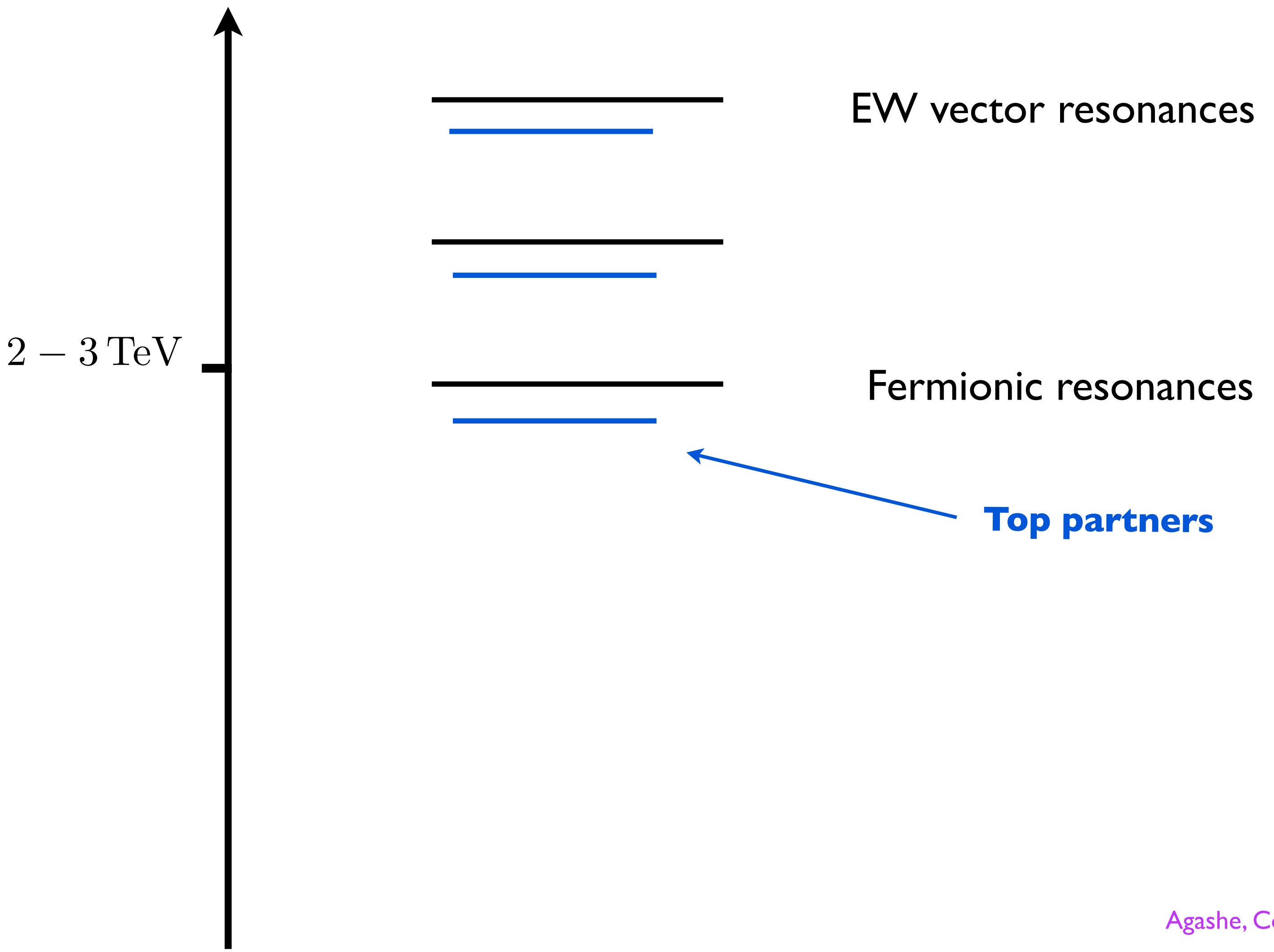
A non generic spectrum (~ SUSY)

$g_\Psi < g_\rho$



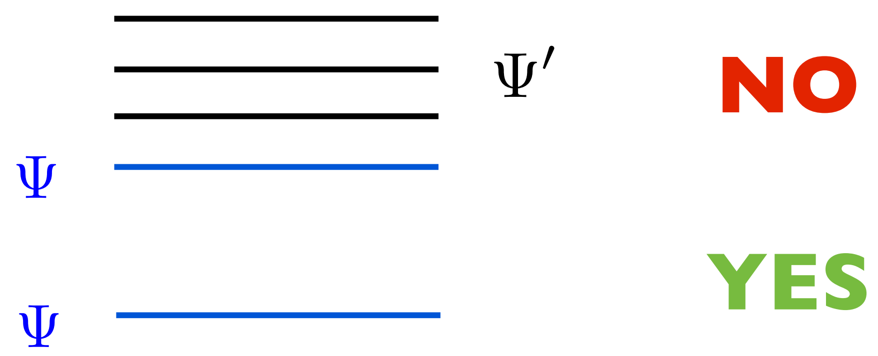
Extra dimensional realizations

$g_\Psi \sim g_\rho$



Agashe, Contino, Pomarol
...
DP, Torre, Thamm '13

Is it possible to study the resonances which are typical of composite Higgs models (EW resonances, heavy gluons, top partners) avoiding to pick a specific model?



$$\Delta m \gg m_{\Psi}$$

Allows to develop a quantitatively valid EFT description of the lowest lying resonance (quantum numbers, few couplings).

The light state is lighter because more weakly coupled $g_{\Psi} < g_{\Psi'}$

Makes it possible to have a lighter resonance without lowering the cutoff.

("Partial UV completion")

Contino, Marzocca, DP, Rattazzi '11 (Effect of vector resonances on WW scattering)

In the limit $\Delta m \sim m_{\Psi}$ still have a valid qualitative description.

Application to the study of top partners

De Simone, Matsedonskyi, Rattazzi, Wulzer '13

Assumptions: PGB higgs + partial compositeness + fully composite R-handed top

Inputs: SO(5) quantum numbers of the operator mixing with L-handed top
SO(4) quantum numbers of the light state

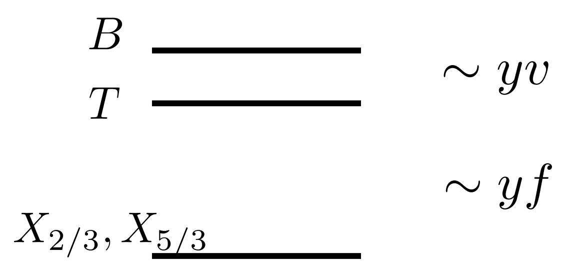
$t_L :$ $\quad \mathbf{4} = (\mathbf{2},\mathbf{1}) \oplus (\mathbf{1},\mathbf{2})$ disfavored by T and Zbb $\quad \mathbf{5} = \mathbf{4} \oplus \mathbf{1} \quad 10 = \mathbf{4} \oplus \mathbf{6} \quad 14 = \mathbf{9} \oplus \mathbf{4} \oplus 1$

$$\mathcal{L} \sim \bar{\Psi}(i\not{D} - M)\Psi + ic_1 \bar{\Psi}\not{\partial}\pi t_R + y_1 f q_L f_1(\pi)\Psi_R + y_2 f q_L f_2(\pi) t_R$$

Affects single production

Affect the spectrum

$$\Psi = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$$



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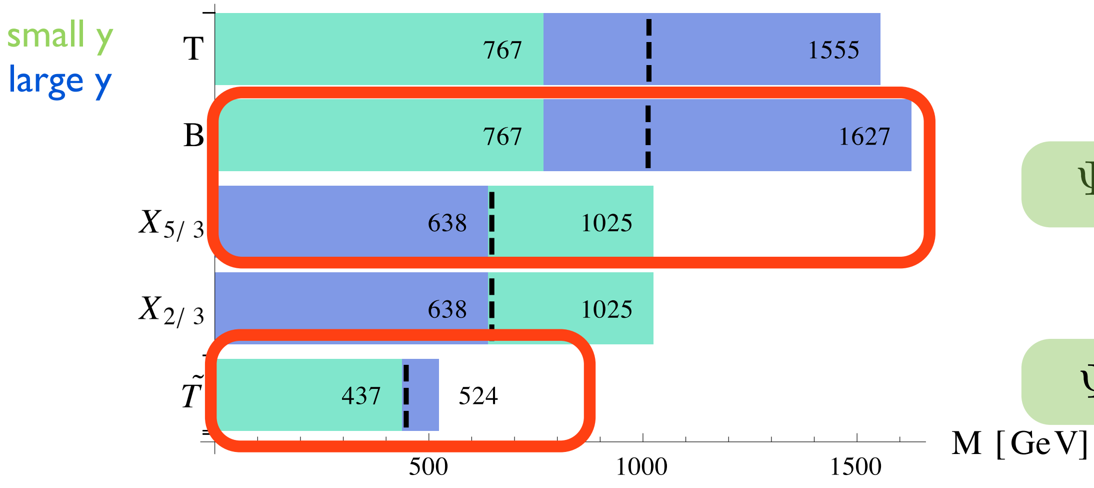
$$\mathcal{L} \sim \bar{\Psi}(i\not{D} - M)\Psi + \cancel{ic_1 \bar{\Psi}\not{\partial}\pi t_R} + y_1 f q_L f_1(\pi)\Psi_R + y_2 f q_L f_2(\pi) t_R$$

Affects single production

Affect the spectrum



$$\Psi = \mathbf{4}_{X=2/3} \in SO(4)$$

$$\Psi = \mathbf{1}_{X=2/3} \in SO(4)$$

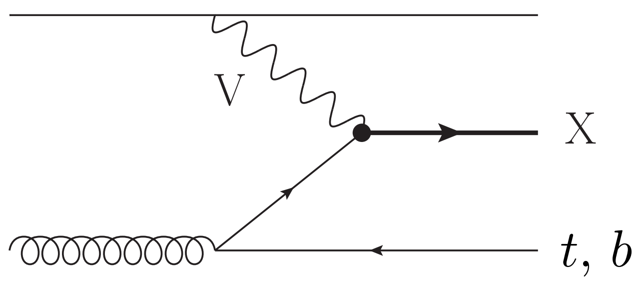
(At small y, B is lighter and contributes to the signal together with the 5/3 quark. That's why the bound is stronger.)

Bounds from:

$$[\mathrm{CMS}]\, b' \to Wb: \;\; b + \ell\ell(SS)/\ell\ell\ell \;\; (5\,\mathrm{fb}^{-1}[7\,\mathrm{TeV}]) \qquad X_{5/3},\, B$$

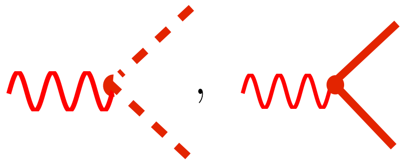
$$[\mathrm{CMS}]\, t' \to Wb: \;\; bb + \ell\ell(OS) + M_{\ell b} > 170\,\mathrm{GeV} \;\; (5\,\mathrm{fb}^{-1}[7\,\mathrm{TeV}]) \qquad \widetilde{T}$$

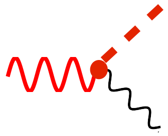
Experimental searches are optimized for pair production.
Single production dominates for heavy top partners.

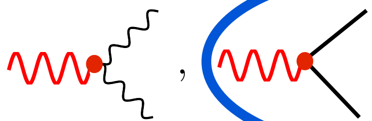


Bosonic resonances

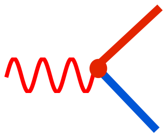
coupling to elementary fields

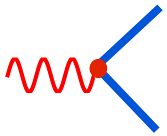
 $\sim g_\rho$

 $\sim g_w$

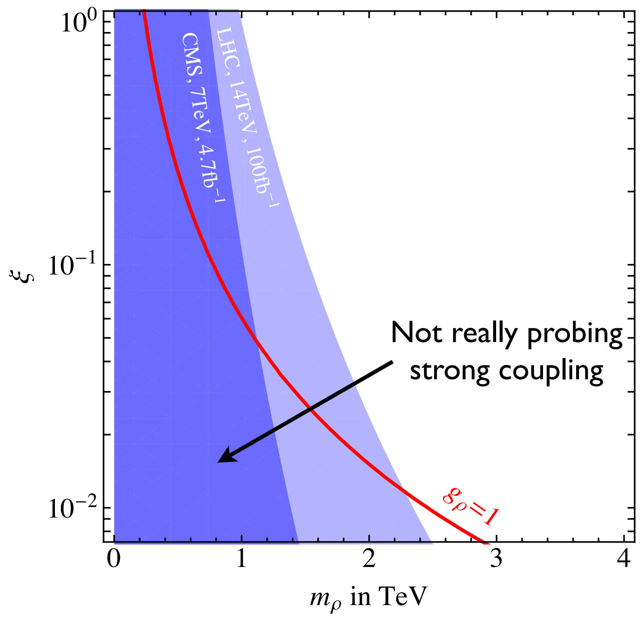
 $\sim \frac{g_w^2}{g_\rho}$

Relevant for DY production

 $\sim g_\rho \epsilon$

 $\sim g_\rho \epsilon^2$

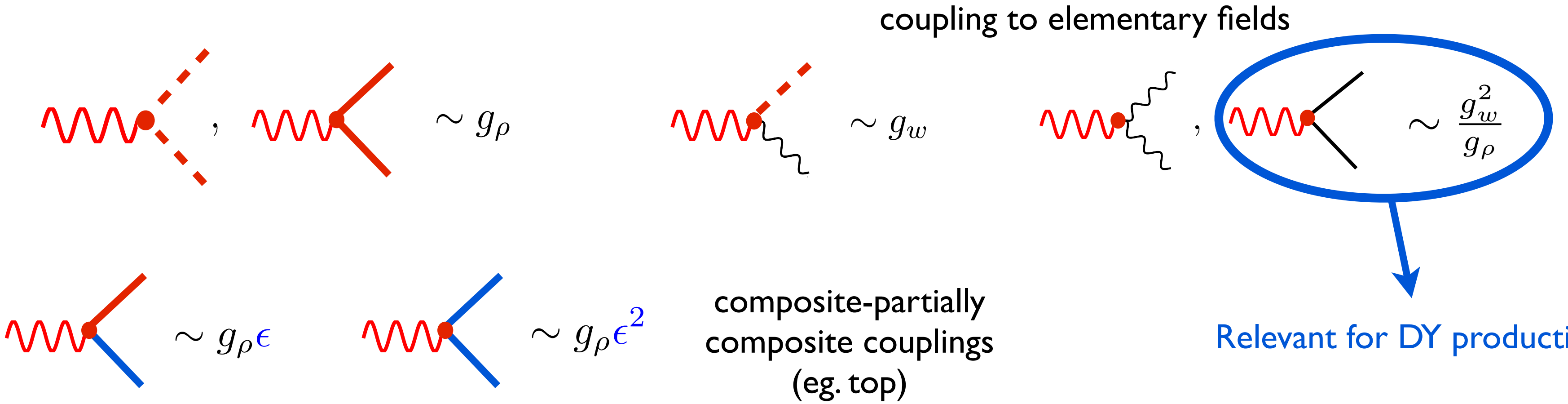
composite-partially composite couplings (eg. top)

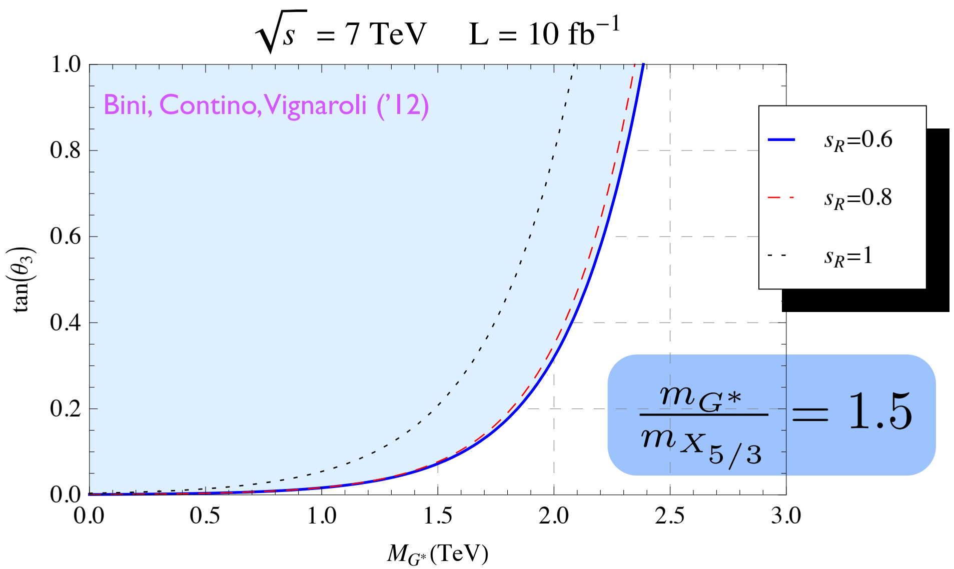


EW resonances

Grojean et al. ('12)

Bosonic resonances

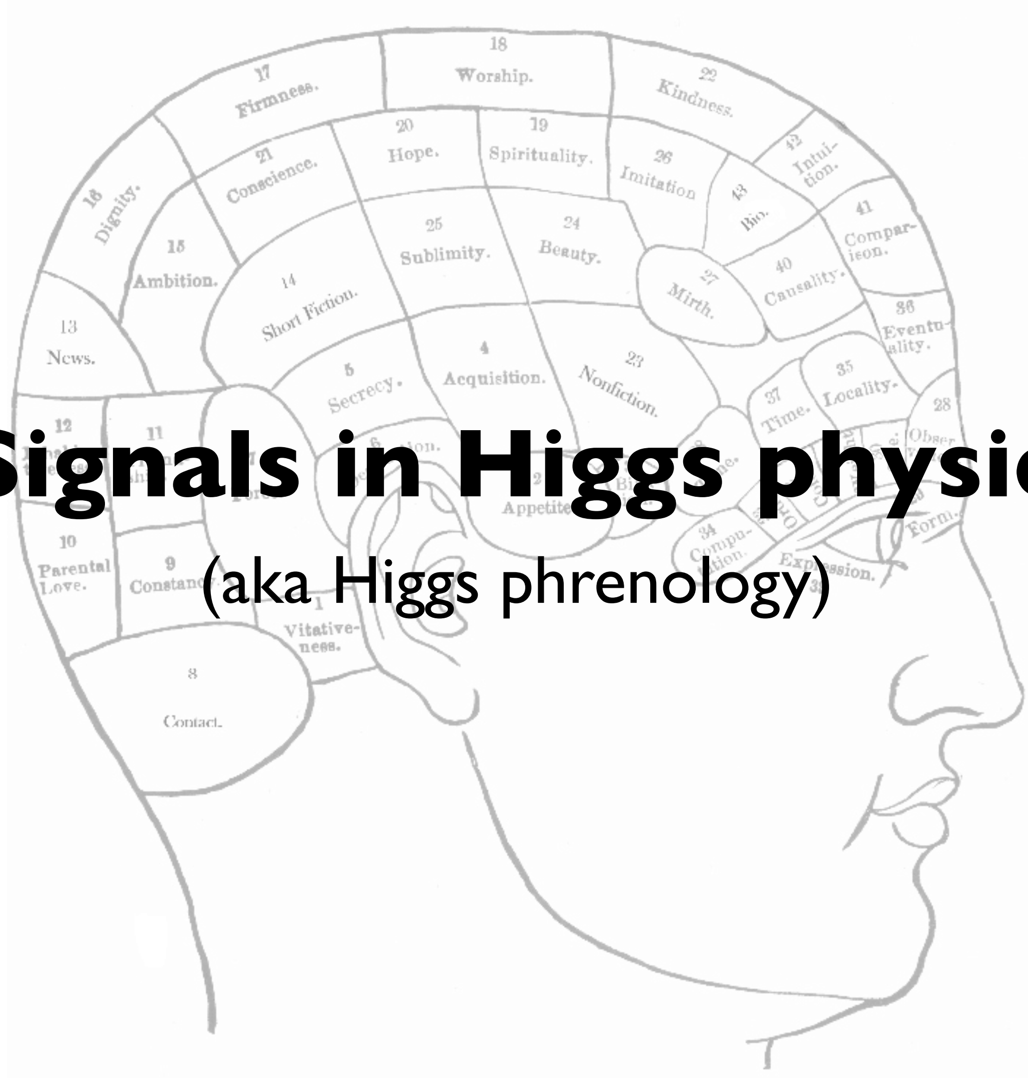




$$pp \to G^* \to \bar{T}t + \bar{B}b \to Wtb \to \ell bbjj \not{E}_T$$

Heavy gluon

A cut on the large Wb invariant mass allows to reduce the background. The channel is more sensitive than the tt final state.



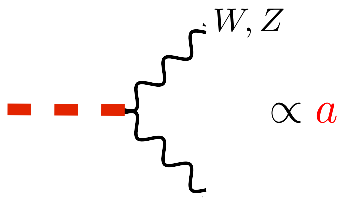
Signals in Higgs physics

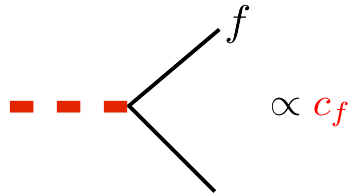
(aka Higgs phrenology)

The PGB Higgs and PC hypothesis imprint very specific signatures on Higgs couplings

Giudice et al ’07

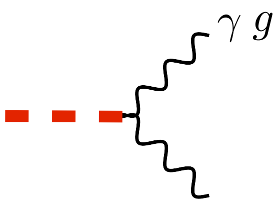
$$\frac{c_H}{f^2}\partial_\mu |H|^2 \partial^\mu |H|^2 + \frac{c'_H}{f^4}|H|^2\partial_\mu |H|^2\partial^\mu |H|^2 + \dots \qquad \frac{c_y}{f^2} y_f \bar{f} H f |H|^2$$





$$\frac{c_\gamma e^2}{16\pi^2 f^2}\frac{y_t^2}{g_\Psi^2}|H|^2 F^2 + \frac{c_g g_s^2}{16\pi^2 f^2}\frac{y_t^2}{g_\Psi^2}|H|^2 G^2$$

Sub-leading at strong coupling



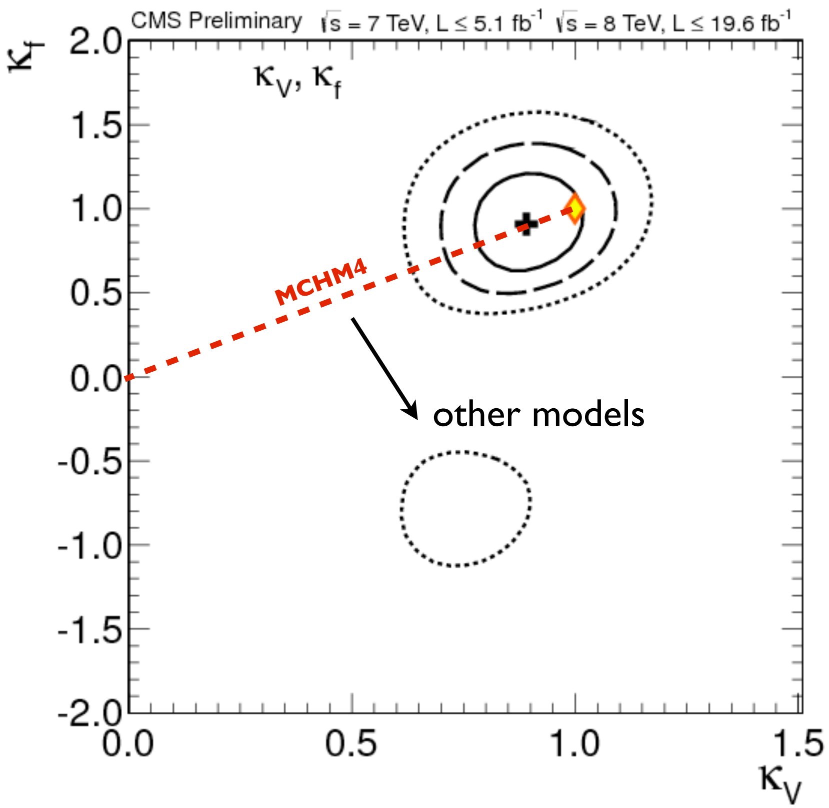
$$\frac{ig}{16\pi^2 f^2}(D_\mu H)^\dagger W^{\mu\nu} D_\nu H + \dots \qquad \frac{g}{m_\rho^2}(H^\dagger \sigma^a D_\mu H) D_\nu W^{a\mu\nu} + \dots$$

Less relevant (angular distributions?)

$$a = \sqrt{1 - \frac{v^2}{f^2}}$$

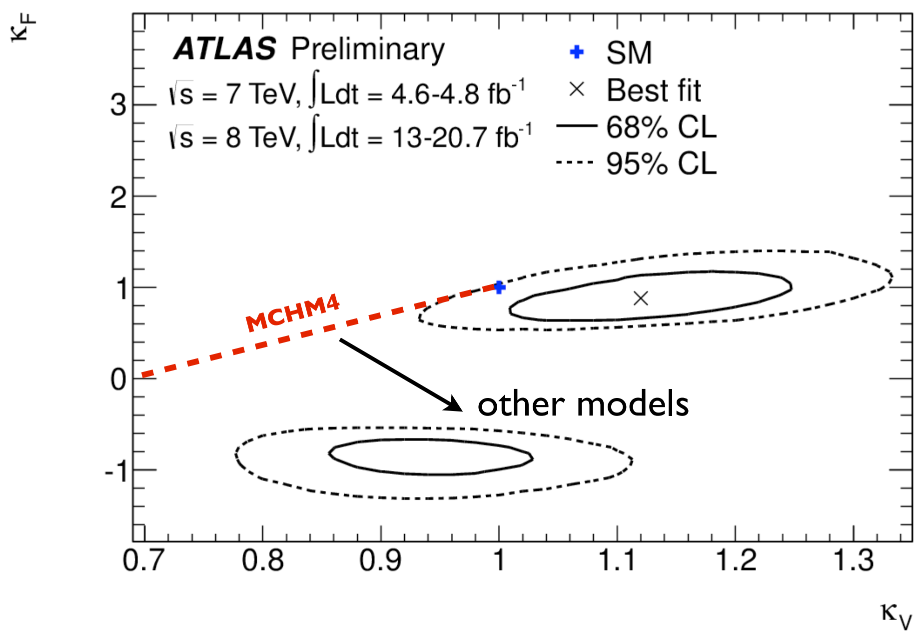
fixed by the coset

c depends on the fermion representations



$(\gamma\gamma)$ **m_X = 125.4 ± 0.8 GeV**
μ = 0.78 ± 0.27

(ZZ) **m_X = 125.8 ± 0.5 GeV**



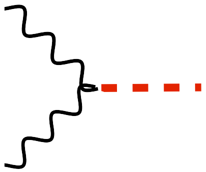
$(\gamma\gamma)$ m_H =126.8 ± 0.2(stat) ± 0.7(syst) GeV
μ = 1.65 ± 0.24(stat) ± 0.22(syst)

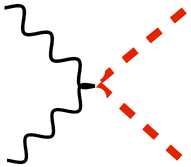
(ZZ) **m_H = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV**

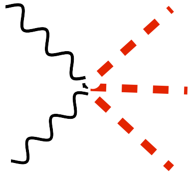
large deviations still allowed

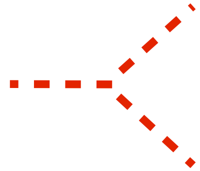
The role of the SM Higgs boson:

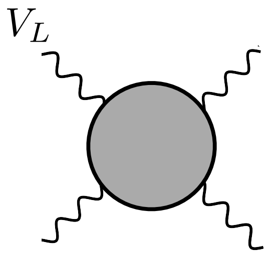
The SM is singled out as the unique theory which can be extrapolated at weak coupling at arbitrarily high energies. For other parameter choices new states at high energy (weakly or strongly coupled).

 $\propto a$

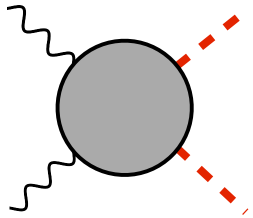
 $\propto b$

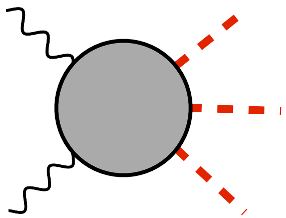
 $\propto b_3$

 $\propto d_3$

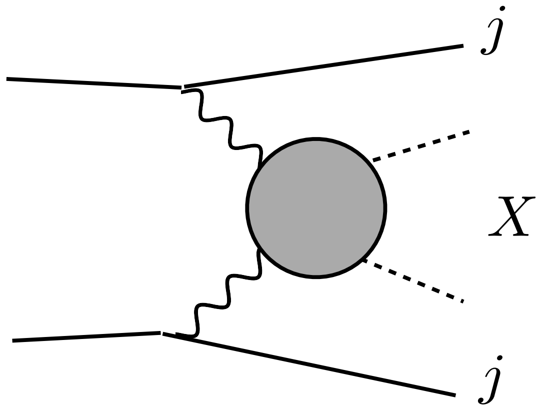


$\propto (a^2 - 1)\frac{E^2}{v^2}$

 $\propto (a^2 - b)\frac{E^2}{v^2}$

 $\propto (4ab^2 - 4a^3 - 3b_3)\frac{E^2}{v^3}$

Similar effects for the fermions but delayed to higher energies.

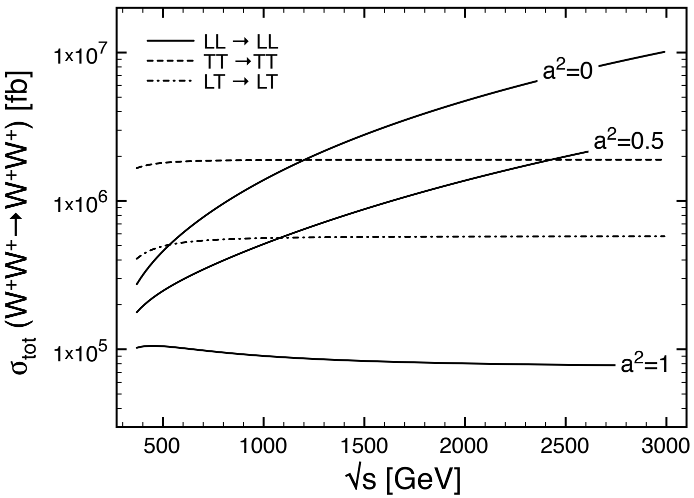


Naive ratio between signal (s-wave amplitude) and 'irreducible' background (dominated by a Coulomb pole in the SM)

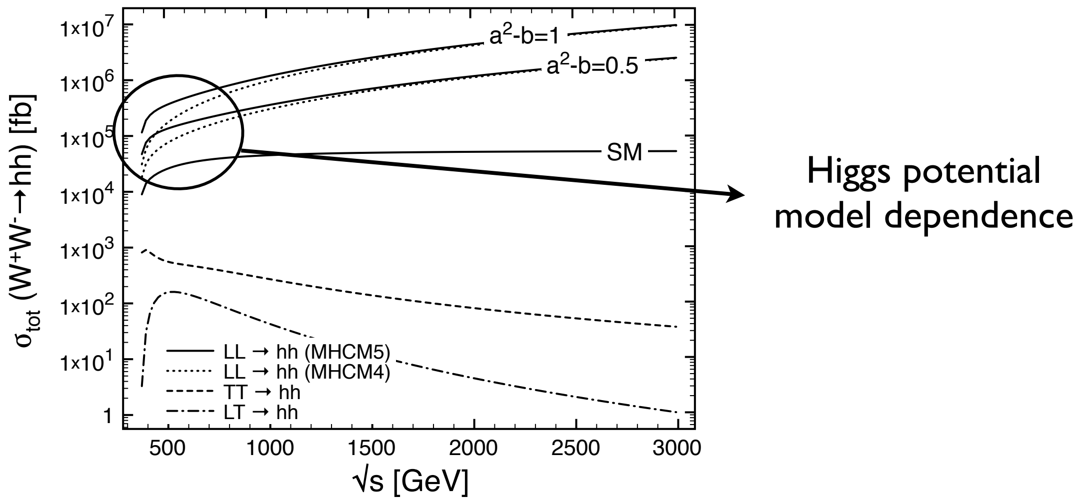
$$\frac{\sigma_{\rm sig}}{\sigma_{\rm bkg}} \sim \frac{\hat{s}\, t_{\rm min}}{m_W^4}$$

Enough to have $t_{\rm min} \gtrsim m_W^2$?

NO



YES!



Reduction of the rate to isolate the signal

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

WW final state

Ballestrero et al '09-'11

$\xi = 1$ $100\,\text{fb}^{-1}$	S	B
$pp \to jjW(\ell\nu)V(jj)$	130	1100
$pp \to jjW^{\pm}(\ell^{\pm}\nu)W^{\pm}(\ell^{\pm}\nu)$	13	6
$pp \to jjZ(\ell^+\ell^-)Z(\nu\nu)$	6	1

Identification cuts +

$$|\Delta\eta| > 4.5, \quad |\eta_{\max}| > 2.5, \quad |m^2_{\ell\ell}| > 400\,\text{GeV}$$

Parton level analysis including $\alpha^6_{EM},\ \alpha^4_{EM}\alpha^2_S,\ \alpha^2_{EM}\alpha^4_S$ backgrounds.

Combining all channels $\sigma(pp \to jjX) = \xi^2 \sigma(pp \to jjX)_{\xi=1}$

$$200\text{fb}^{-1}:\ \Delta\xi \sim 0.5$$
$$1000\text{fb}^{-1}:\ \Delta\xi \sim 0.3$$
$$3\sigma \text{ discovery}$$

Double Higgs production

Contino et al '10

Detection of double Higgs production is hampered by the more difficult final state.
Heavy Higgs (~180 GeV) was required to have sizable BR in VV.
The trileptonic channel is the cleanest

$$\mathcal{S}_3 = pp \to hhjj \to l^+l^-l^\pm\ \not{E}_T + 4j$$

$$\Delta\eta^{ref}_{JJ} \geq 4.5 \qquad m^{ref}_{JJ} \geq 700\,\text{GeV} \qquad m^h_{JJl} \leq 160\,\text{GeV}$$

# Events with $300\,\text{fb}^{-1}$		3 leptons signal	3 leptons bckg.	2 leptons signal	2 leptons bckg.
MCHM4	$\xi = 1$	4.9	1.1	15.0	16.6
	$\xi = 0.8$	3.3	1.2	10.1	18.3
	$\xi = 0.5$	1.5	1.4	4.9	21.0
MCHM5	$\xi = 0.8$	4.5	1.8	14.3	26.0
	$\xi = 0.5$	2.3	1.2	7.6	18.4
SM	$\xi = 0$	0.2	1.7	0.8	25.4

LHC can only test the TC limit (before lumi. upgrade). No chance to measure the Higgs potential.

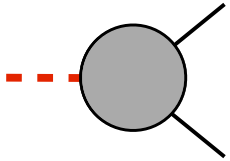
Long term questions

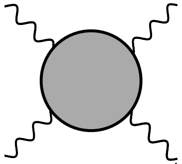
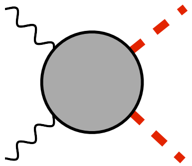
$$(t \to \infty?)$$

Contino, Grojean, DP,
Rattazzi, Thamm (to appear)

LHC is over and at most δ_{LHC}=O(10-20%) deviation in Higgs couplings is observed. Maybe new particles discovered but with no clear role. Many relevant questions remain open.

Weak or strong coupling? Large effects due to heavy (invisible) physics suggest strong coupling.

$\delta =$  $\sim \left(\frac{g_{NP} v}{m_{NP}}\right)^2 \rightarrow g_{NP} \gtrsim \sqrt{\delta_{LHC}} \frac{m_{NP}}{v}$

$g_{NP}(E) \equiv$  ,  $\sim \xi \frac{E^2}{v^2} \rightarrow g_{NP}(E) \gtrsim \sqrt{\xi_{\rm obs}} \frac{E}{v}$

Bounding the effect from 4 derivative interactions allows to improve the bound

$$\mathcal{A}(2 \to 2) = \tfrac{s}{v^2} \left(1 + c \tfrac{s}{m_*^2}\right)$$

$$c < \epsilon \Rightarrow g_{NP}(E) \gtrsim \sqrt{\tfrac{\xi_{\rm obs}}{\epsilon}} \tfrac{E}{v}$$

Does h belong to a doublet? If so then WW→WW and WW→hh are equal up to higher order terms. No way to answer the question testing only single Higgs couplings. Need to measure b.

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

$\Delta a^2 \sim 0.2$ requires % precision on b

If there are indications for a composite Higgs, **is this particle light due to Goldstone symmetry?** Check relation between a and b. Look for triple Higgs production.

$$\Delta b = 2\Delta a^2$$

$\Delta b = \Delta a^2$: dilaton

Triple Higgs production is suppressed for a PGB Higgs

$\pi \to -\pi$

grading belongs to SO(4)

Polarisation	Amplitude for PNGB	Amplitude for SILH
$V_L V_L \to hhh$	$g^2 v/f^2$	$\hat{s} v/f^4$
$V_L V_T \to hhh$	$\sqrt{\hat{s}} g/f^2$	
$V_T V_T \to hhh$	$g^2 v/f^2$	

σ [ab] \ ξ	0	0.05	0.1	0.2	0.3	0.5	0.99
PNGB	0.32	0.46	0.71	1.47	2.41	4.13	0.30
SILH	0.32	0.71	0.87	7.56	42.89	407.9	7808

$e^+ e^- \to \nu \bar{\nu} hhh$ @ 3 TeV

The final answer to these questions requires a high energy linear collider

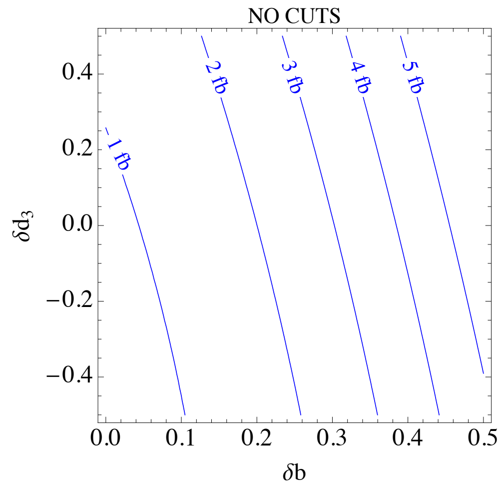
see also
Barger, Cheung, Han, Phillips '95
Boos, He, Kilian, Pukhov, Yuan, Zerwas '97
Barger, Han, Langacker, McElrath, Zerwas '03

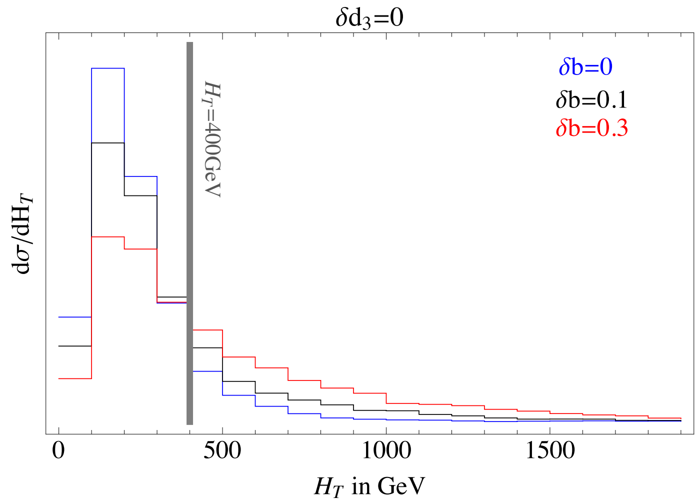
ILC (500GeV): $(1\,\mathrm{ab}^{-1})$ $\Delta a^2 \gtrsim 0.5 \times 10^{-2}$

CLIC (3TeV): $(1\,\mathrm{ab}^{-1})$

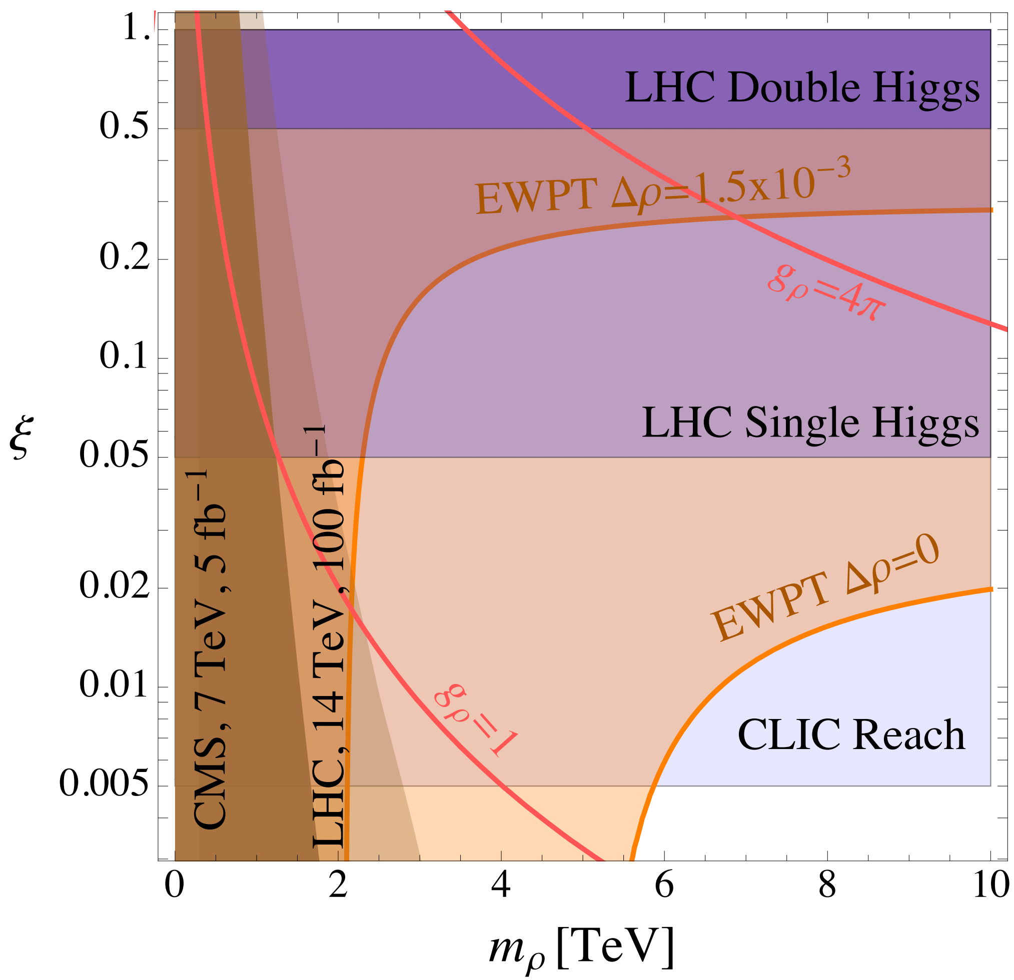
$$\Delta b \gtrsim 1 \div 2 \times 10^{-2}$$

$$\Delta d_3 \gtrsim 5 \times 10^{-2}$$

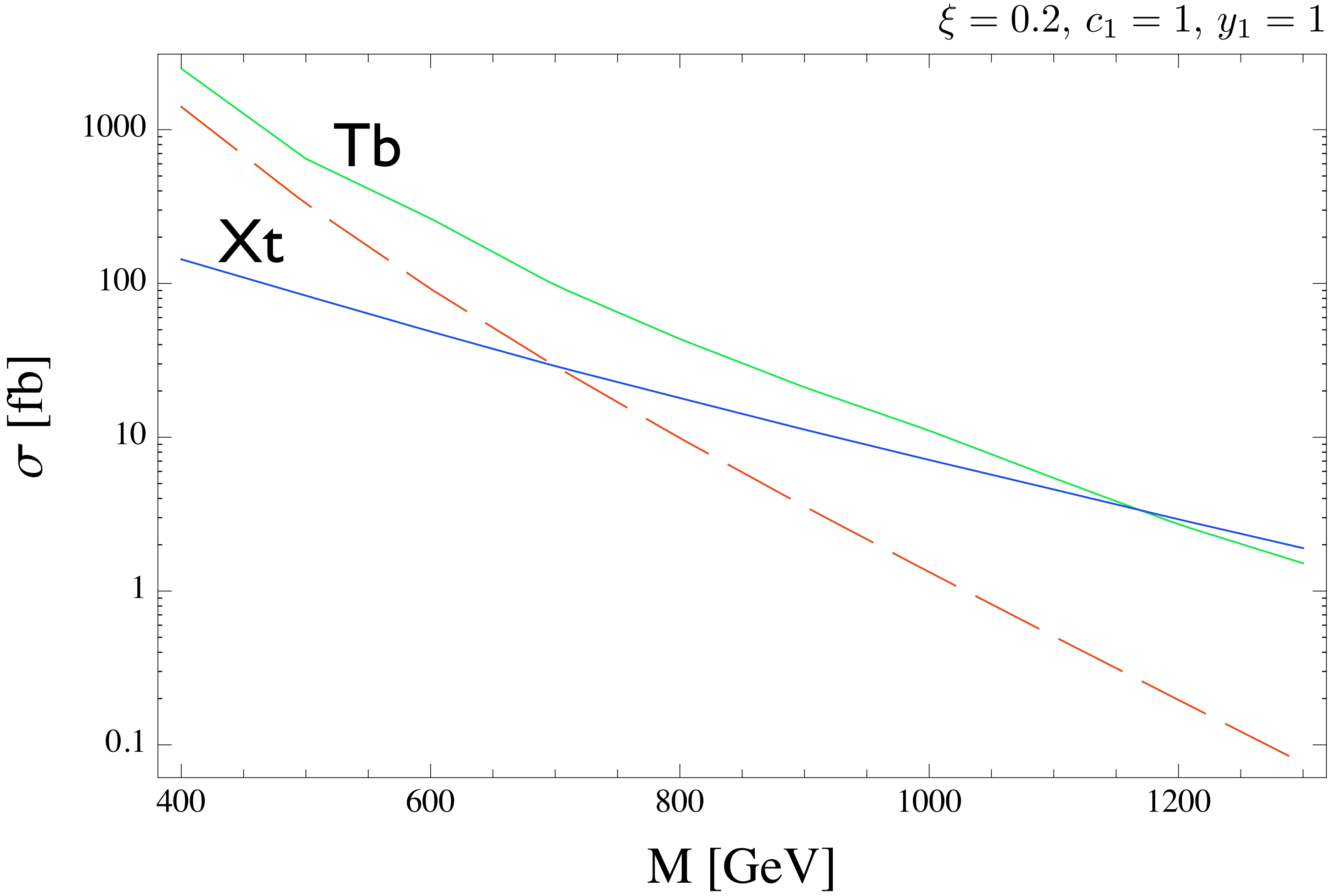




Conclusions



Backup



$\xi = 0.2,\ c_1 = 1,\ y_1 = 1$
Tb
Xt
1000
100
10
1
0.1
σ [fb]
400
600
800
1000
1200
M [GeV]

Partial Compositness vs MFV

A full comparison between the two approaches requires the specification of a **coupling** and a **mass scale** to completely define the structure of flavor-violating higher dimensional operators.

Eg: in SUSY with gauge mediation universal soft masses are generated at Mmess, non-universality generated through running respect MFV. Four-fermions operator at superpartner scale have the form

$$\frac{g_s^2}{16\pi^2}\frac{g_s^2}{\tilde{m}^2}\left(\bar{q}_L\frac{Y_U Y_U^\dagger}{16\pi^2}q_L\right)^2$$

$$\tilde{m}^2 = m_0^2$$

M_{mess}

$$\tilde{m}^2 = m_0^2\left(1 + c\frac{Y_U Y_U^\dagger}{(4\pi)^2} + \ldots\right)$$

$\tilde{m}$

d-d structures

Structure	MFV	PC
$\bar{d}_{iL}d_{jL}$	$V_{3i}^* V_{3j}$	$V_{3i}^* V_{3j}$
$\bar{d}_{iR}d_{jR}$	$y_i^d y_j^d V_{3i}^* V_{3j}$	$\frac{y_i^d y_j^d}{V_{3i}^* V_{3j}}$
$\bar{d}_{iL}d_{jR}$	$y_j^d V_{3i}^* V_{3j}$	$y_j^d \frac{V_{3i}}{V_{3j}}$

Shows only the structure in flavor space other coupling constants have been suppressed