Composite Higgs Models in the LHC Era

INFN

Michele Redi

OUTLINE

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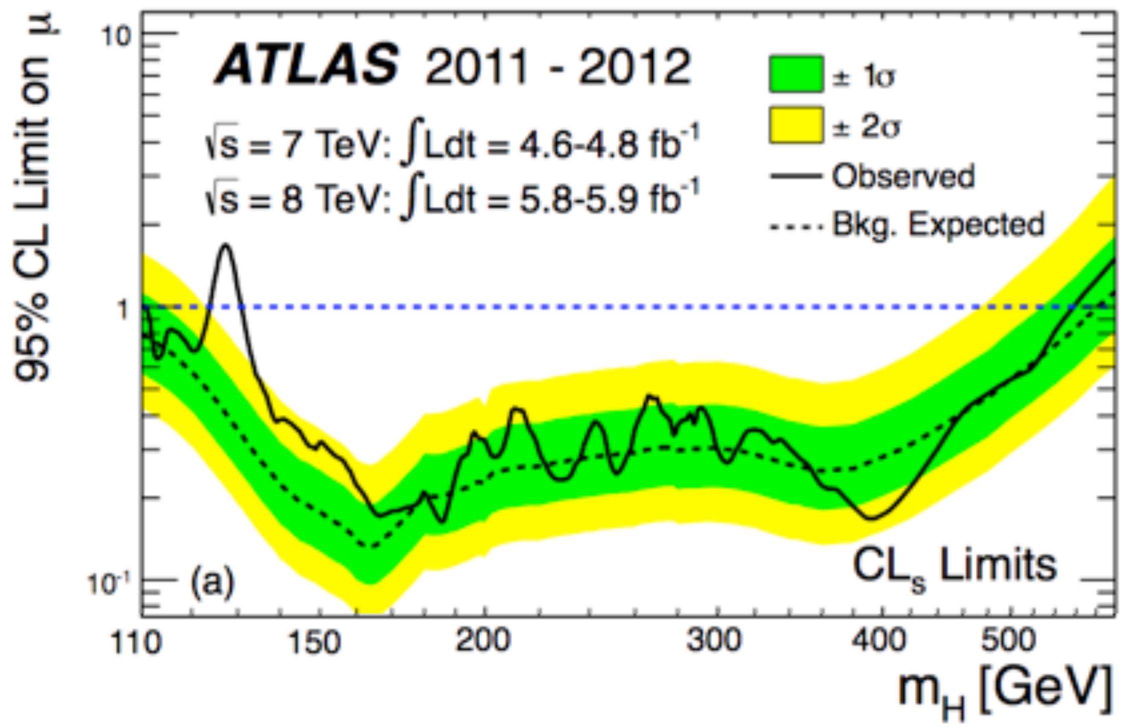
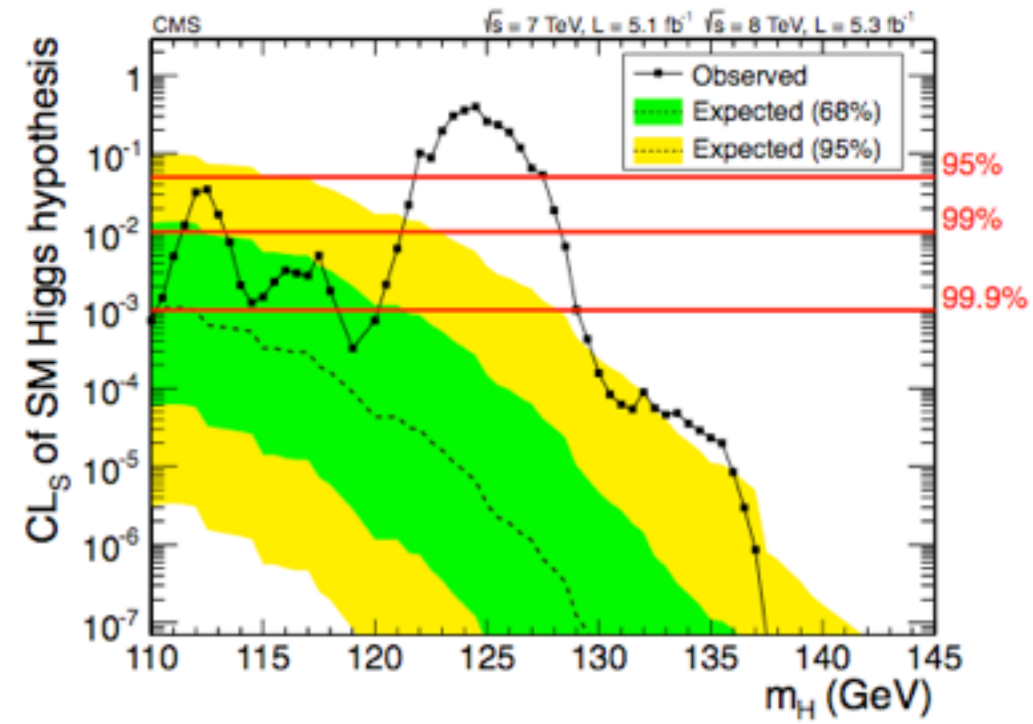
- Standard Model Higgs
- Higgs as Nambu-Goldstone boson
- Realizations in 4d and 5d
- EWPT, flavor and LHC searches
- Higgs potential

July 31, 2012   Phys. Lett. B716





$$m_h \approx 125\,\mathrm{GeV}$$

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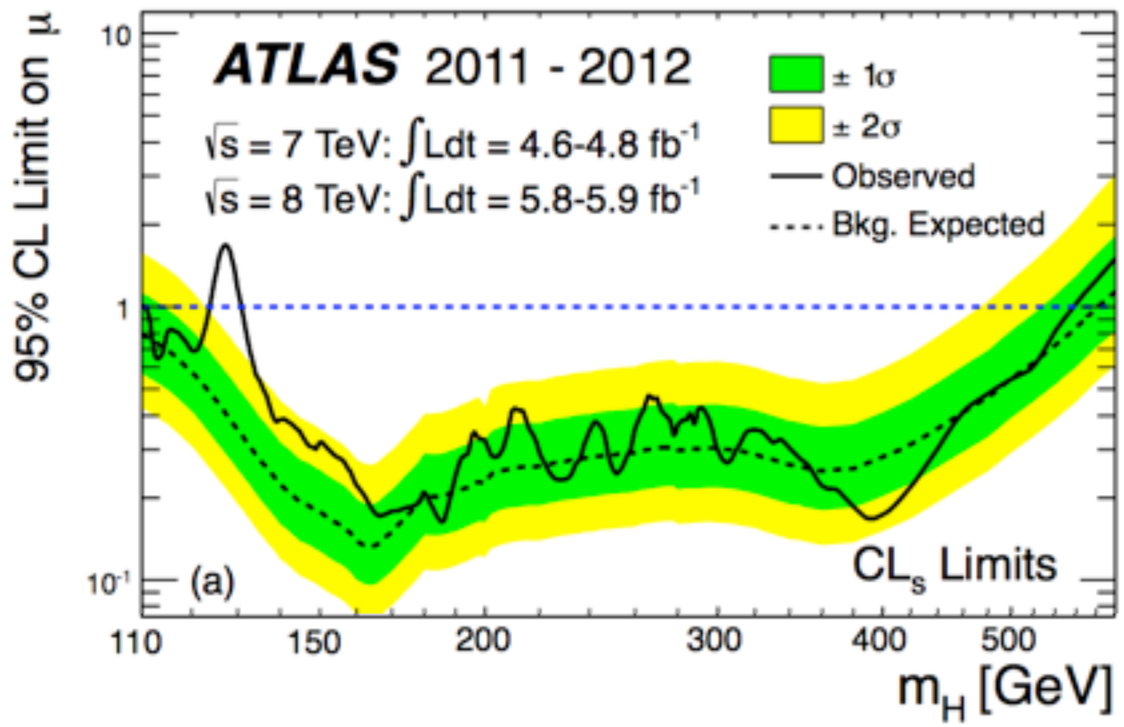

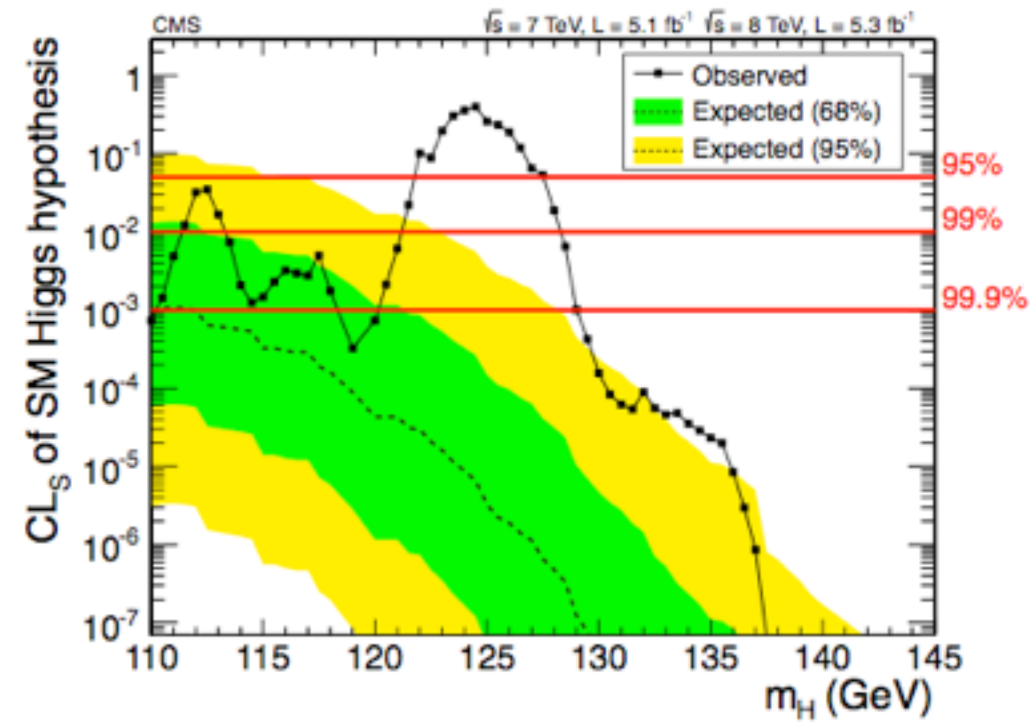

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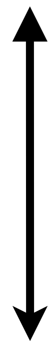
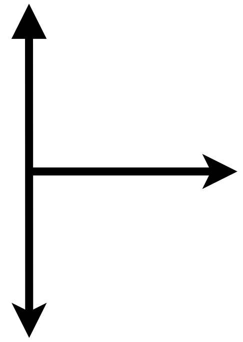
What is the nature of the Higgs particle?

Mass for gauge bosons means new degrees of freedom

$m_1 = 0$



$m_1 \neq 0$



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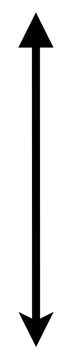

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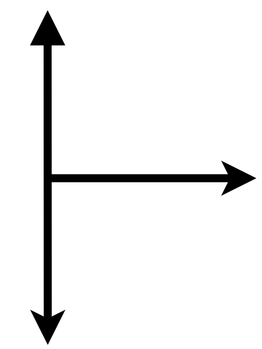


Nambu-Goldstone Bosons

$$SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

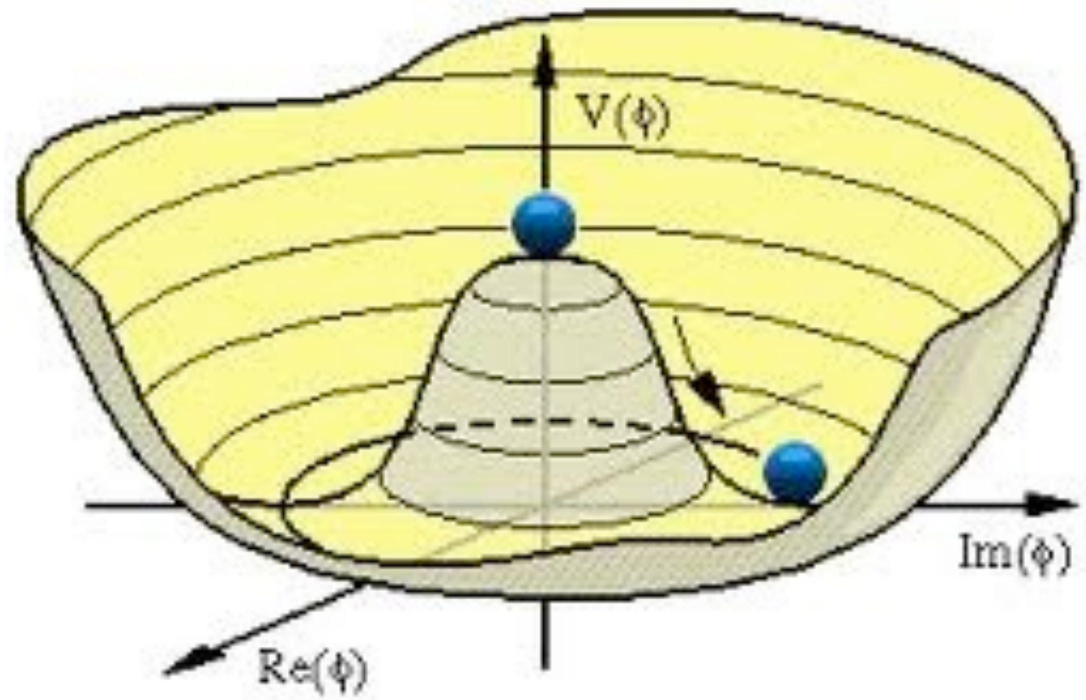
become longitudinal polarizations of W & Z

Custodial symmetry

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1 \qquad \longrightarrow \qquad SU(2)_c$$

In SM electro-weak symmetry broken by scalar doublet

$$V(H) = \lambda\left(|H|^2 - v^2\right)^2$$

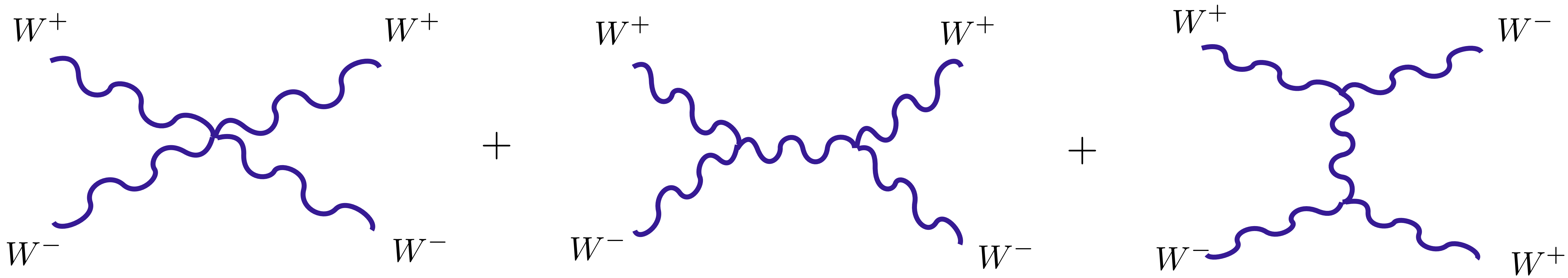


$$H(x) = U(x)\begin{pmatrix} 0 \\ \frac{v+h(x)}{\sqrt{2}} \end{pmatrix} \qquad v = 246\,\mathrm{GeV}$$

$$\frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \longrightarrow \rho \approx 1$$

Physical scalar is the Higgs boson $m_h = \sqrt{\lambda}\,v$

In principle Higgs scalar not even needed



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{v^2}(s+t)$$

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] = \frac{1}{2}\left(1 - \frac{\pi^i\pi^i}{v^2} + \dots\right)\partial_\mu \pi^i \partial^\mu \pi^i$$

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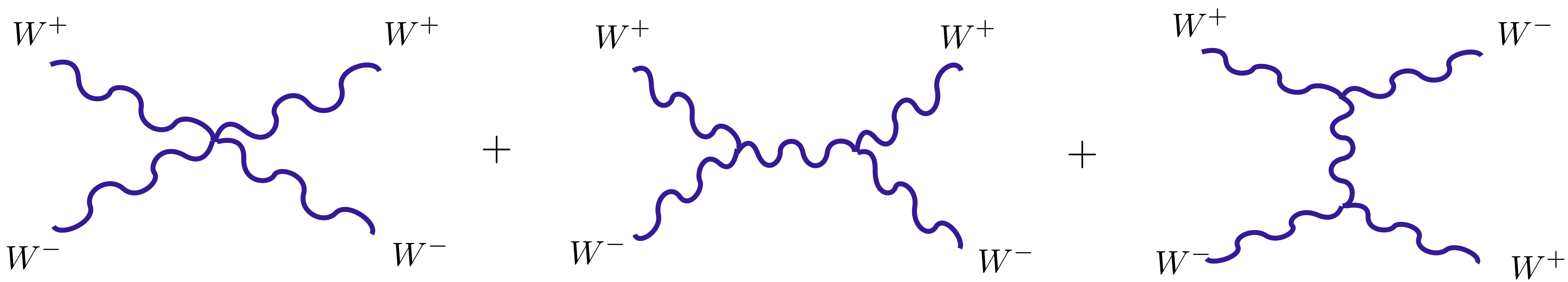

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New physics must appear below

$$\Lambda = 4\pi v \sim 3\mathrm{TeV}$$

QCD breaks electro-weak symmetry

$$< \bar{\Psi}^i_L \Psi^j_R >= \Lambda^3_{QCD}\, \delta_{ij} \quad \longrightarrow \quad \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \quad \longrightarrow \quad \mathcal{L} = f_\pi^2\, Tr\left[\partial_\mu U \partial^\mu U^\dagger\right]$$

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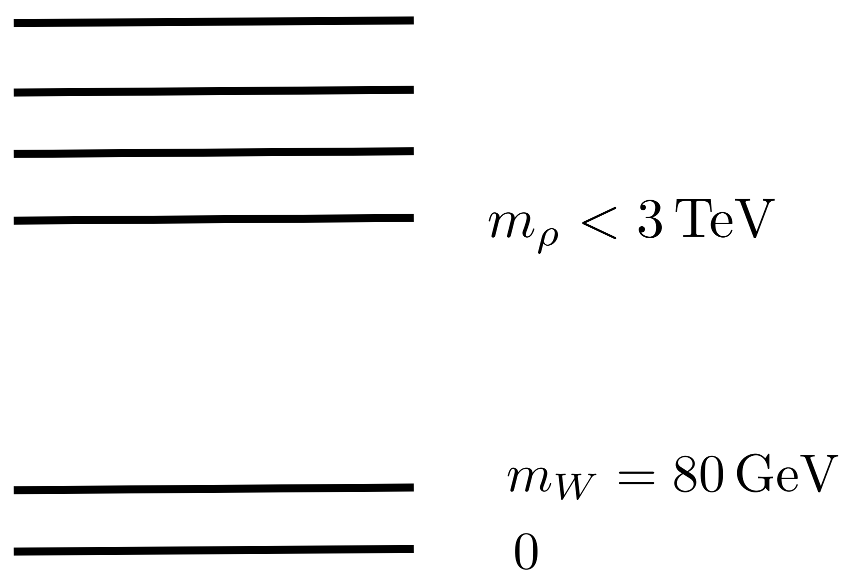
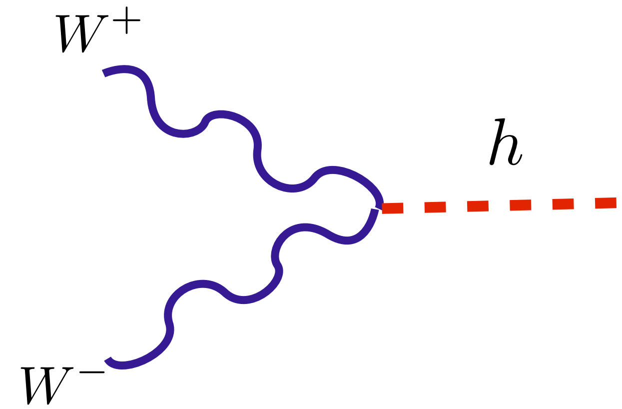
Technicolor is a rescaled version of QCD f=v.
No Higgs scalar but techni-resonances (spin 0, 1/2, 1, ... etc.).

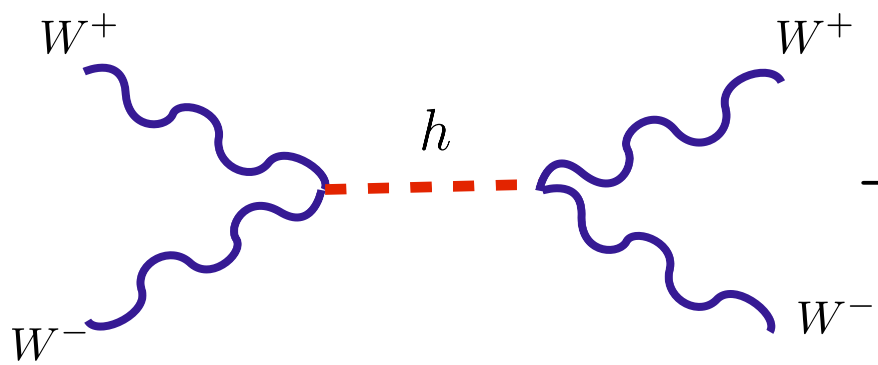


Ruled out.

In the SM:



$$= 2i\frac{m_W^2}{v}a$$

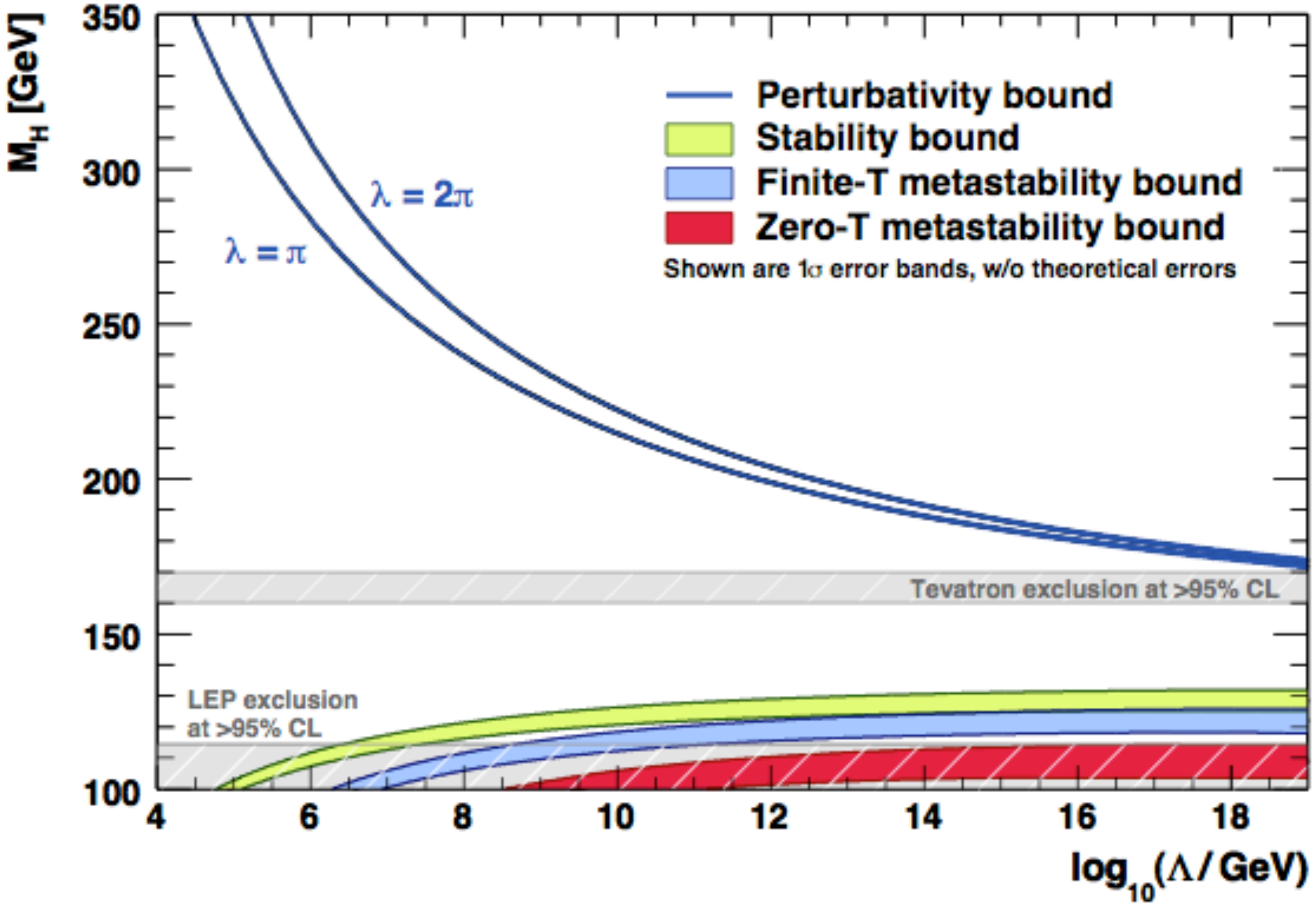


$$+ \ldots$$

$$A(W_L^+W_L^- \to W_L^+W_L^-) \simeq \left[s - a^2\frac{s^2}{s-m_h^2} + (s\to t\right]$$

Amplitude goes to constant if a=1

$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

$$115\,\mathrm{GeV} < m_h < 160\,\mathrm{GeV}$$

With 125 GeV Higgs SM can be valid up Mp.

HIERARCHY PROBLEM

SM is an effective theory valid up to Λ

$$\mathcal{L} = \mathcal{L}_{kin} + g\, A_\mu \bar{\psi} \gamma^\mu \psi + y\, \bar{\psi} H \psi - \lambda\, |H|^4 \qquad D = 4$$

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Irrelevant interactions:

$$\frac{1}{\Lambda}(lH^c)^2 \qquad \frac{1}{\Lambda^2}(\bar{\psi}\psi)^2 \qquad \frac{1}{\Lambda}\bar{\psi}\,\sigma^{\mu\nu}\psi F_{\mu\nu} \qquad D > 4$$

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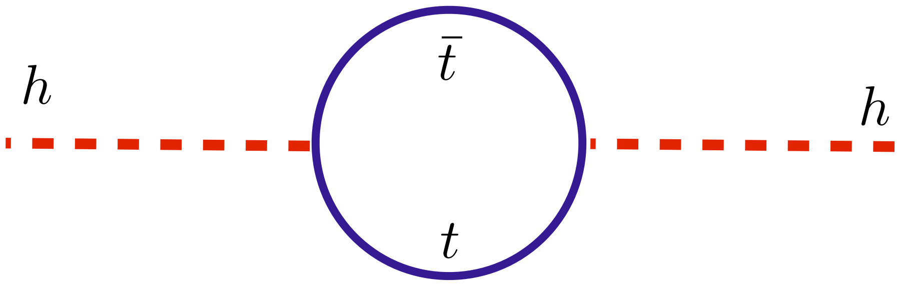
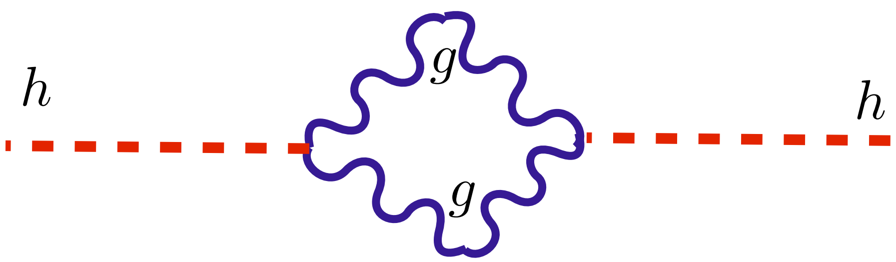
One relevant operator

$$[H^2] \approx 2 \qquad m_h \sim \Lambda$$

Perturbatively:

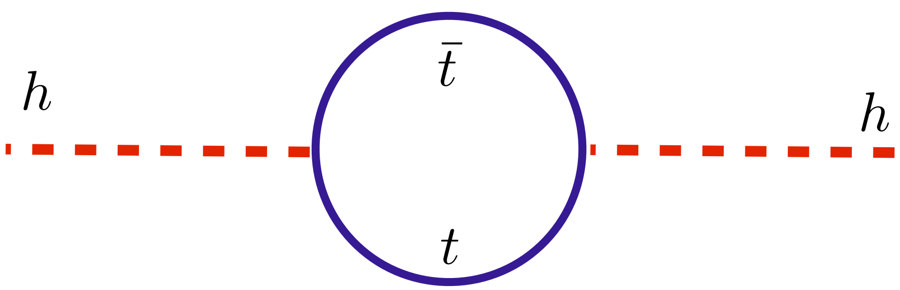


$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2 \longrightarrow \Lambda_t \sim 3\, m_h$$



$$\delta m_h^2 = \frac{9g^2 + 3g'^2}{32\pi^2}\Lambda_g^2 \longrightarrow \Lambda_g \sim 9\, m_h$$

Perturbatively:



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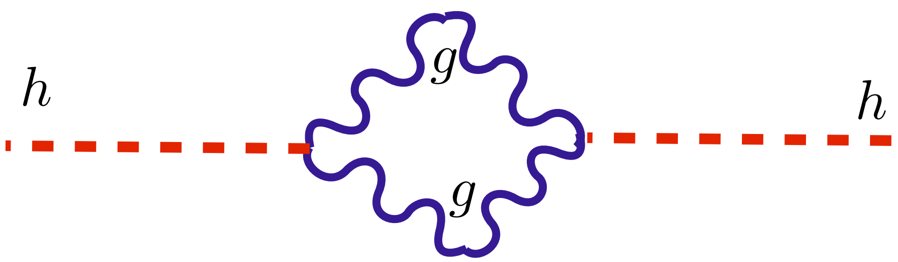

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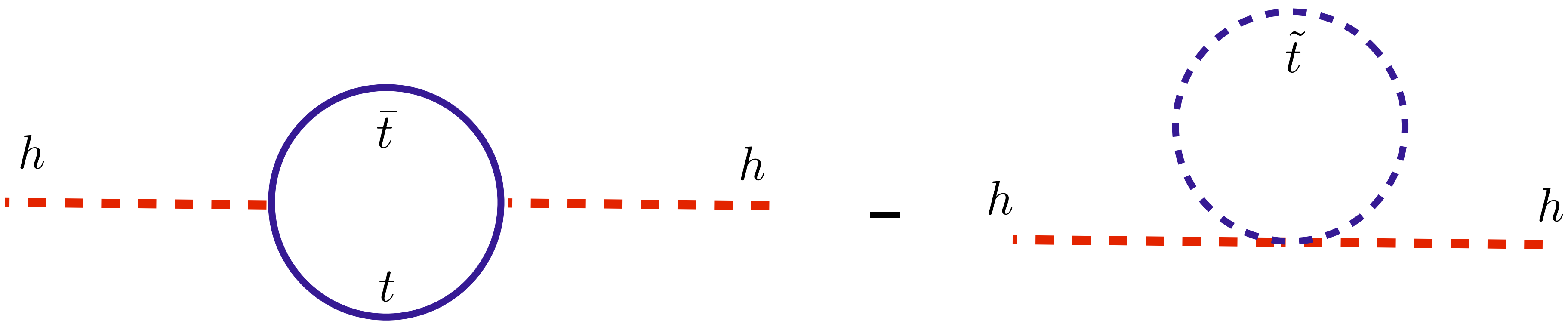
If the theory is natural new physics beyond SM must exist at the TEV scale.

Two paradigms:

- Weak Coupling:
  Supersymmetry



$\sim\ 100\,\mathrm{GeV}$

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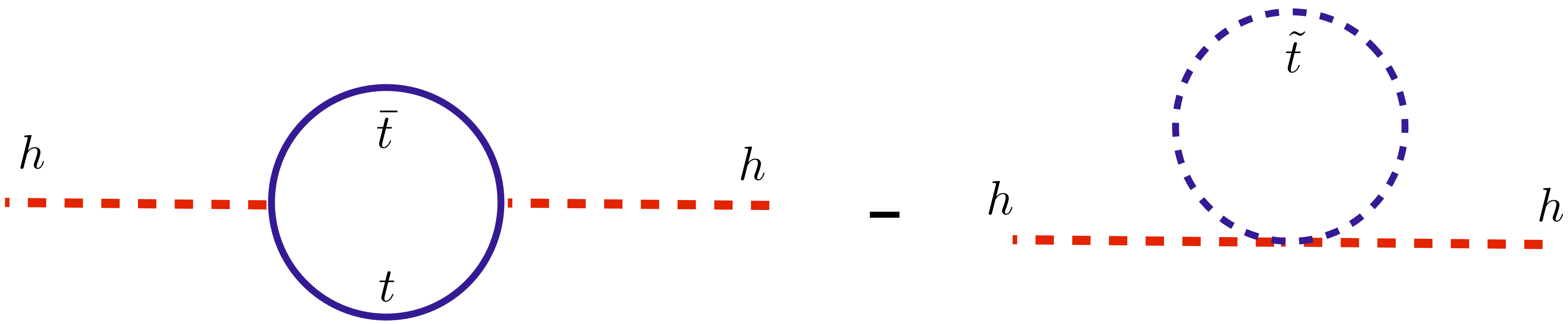
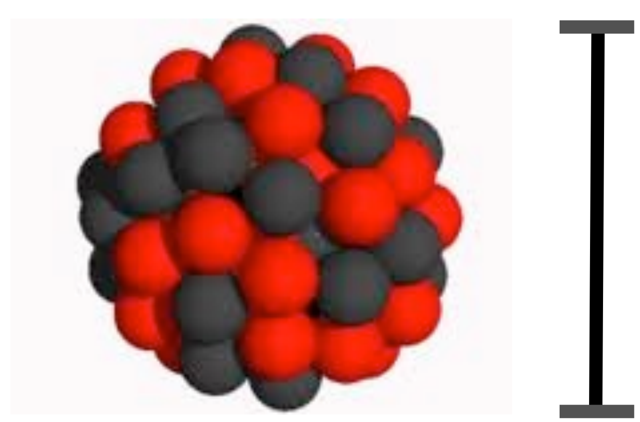


$\sim\ 100\,\mathrm{GeV}$

- Strong Coupling:
  Technicolor, Composite Higgs, Higgsless, Extra-dimensions ...



$$\sim \frac{1}{\mathrm{TeV}}$$

HIGGS NGB

Higgs doublet could be a light remnant of strong dynamics.

Strong sector:
resonances +
Higgs bound state

spin1

spin 1/2

spin 0.... $2_{\frac{1}{2}}$

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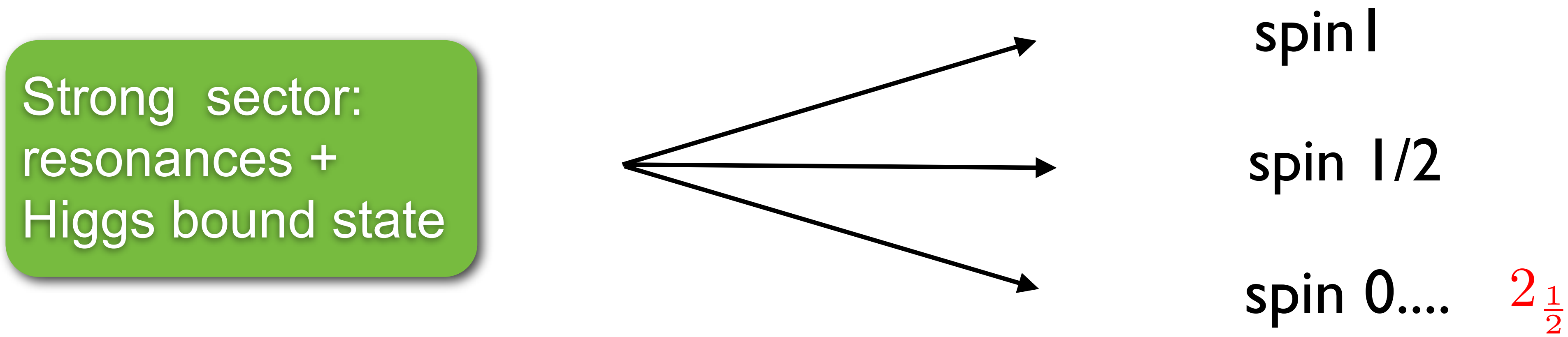


Two parameters:

$$m_\rho \qquad g_\rho \qquad (1 < g_\rho < 4\pi)$$

$$\text{Large N}: \quad g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

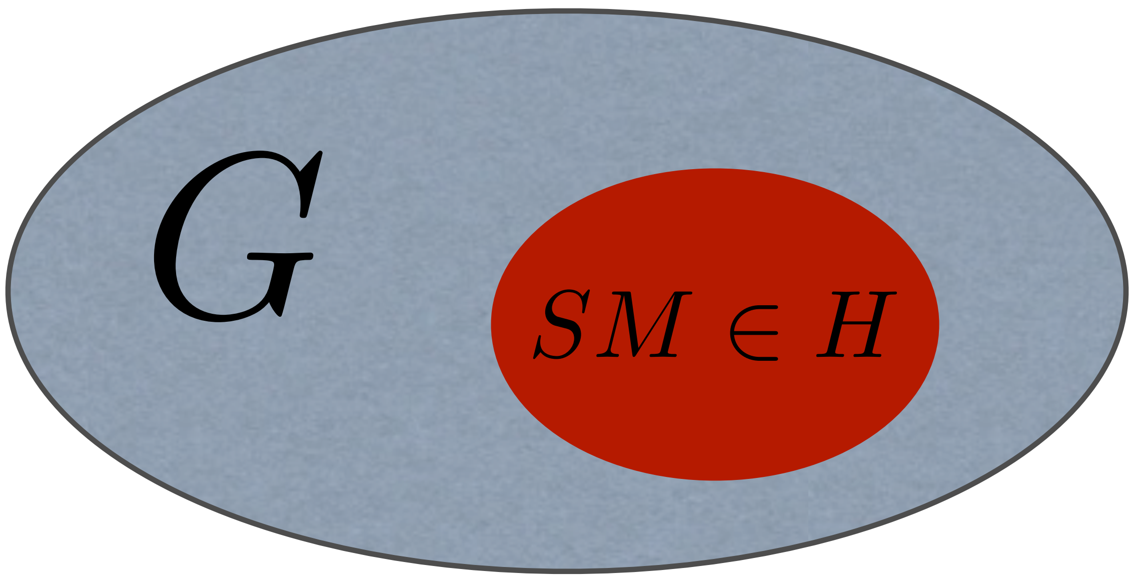
Relieves hierarchy problem

$$\delta m_h^2 \sim \frac{3\lambda_t^2}{8\pi^2} m_\rho^2$$

The Higgs scalar itself could be a NGB.

If the symmetry is exact it is massless.

Georgi, Kaplan '80s



$$\mathrm{NGB} = \frac{G}{H}$$

$$U = e^{i\frac{\pi^{\hat{a}} T^{\hat{a}}}{f}}$$

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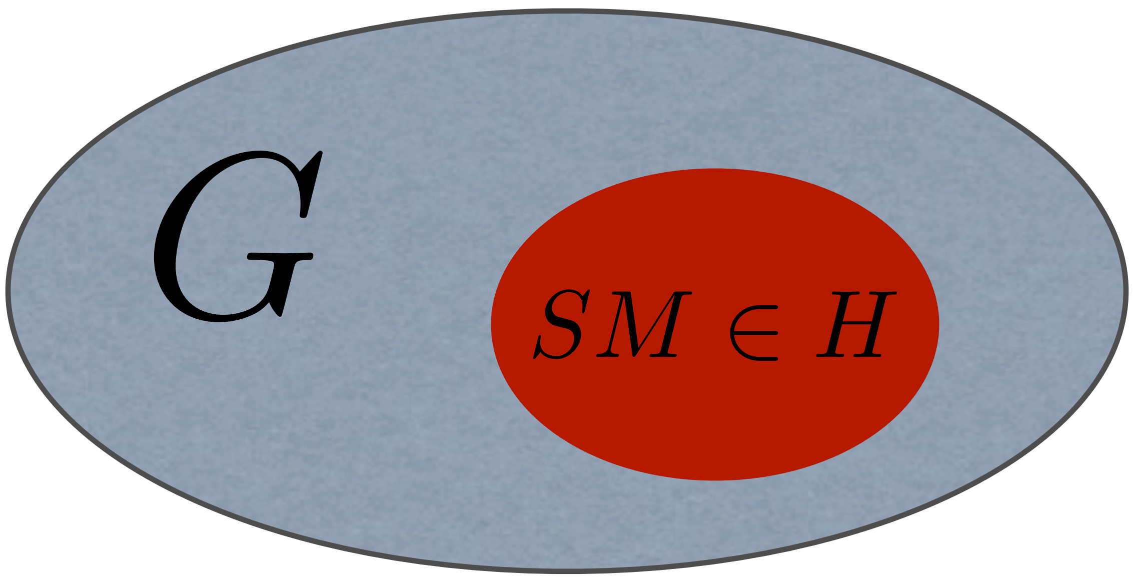

$$\mathrm{NGB} = \frac{G}{H}$$

$$U = e^{i\frac{\pi^{\hat{a}} T^{\hat{a}}}{f}}$$

Low energy lagrangian

$$\mathcal{L} = f^2 D^{\hat{a}}_{\mu} D^{\hat{a}\mu} + \dots$$

$$m_\rho = g_\rho f$$

$$\delta\pi = c + \dots$$

Ex:

$$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$$

Agashe , Contino, Pomarol, '04

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Agashe , Contino, Pomarol, '04

Many possibilities:

G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × 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)	$[\mathrm{SO}(3)]^3$	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	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

Mrazek et al., '11

Deviations from SM:

$$\mathcal{O}\left(\frac{v^2}{f^2}\right)$$

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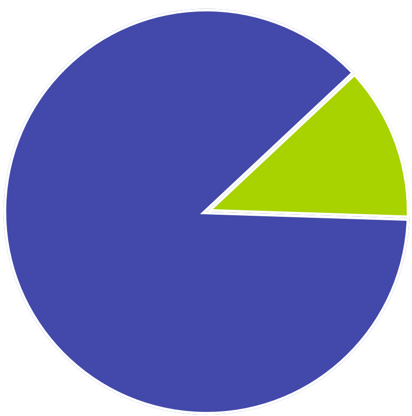
Higgs is an angle,



$0 < h < 2\pi f$

$\text{TUNING} \propto \frac{f^2}{v^2}$

Small Tuning $\quad f < TeV$

Spectrum:

$m_\rho = g_\rho f$

$m_h = 125\,\text{GeV}$

$m_W = 80\,\text{GeV}$

0

Higgs cannot be exact NGB

$$h \to h + c$$

G

G symmetry broken explicitly in SM

$$\lambda^u_{ij} \bar{q}^i_L H^c u^j_R + \lambda^d_{ij} \bar{q}^i_L H d^j_R + h.c.$$

$$|\partial_\mu H + i A_\mu H|^2$$

$SU(2) \times U(1)$

Higgs cannot be exact NGB

$$h \to h + c \qquad G$$

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$$|\partial_\mu H + i A_\mu H|^2 \qquad SU(2) \times U(1)$$

Similar to QCD:

$$U(2)_L \times U(2)_R \longrightarrow U(1)_{em} \times U(1)$$

- Bilinear couplings

$$\frac{1}{\Lambda^{d-1}}\,\bar{q}_L\langle\mathcal{O}\rangle q_R$$

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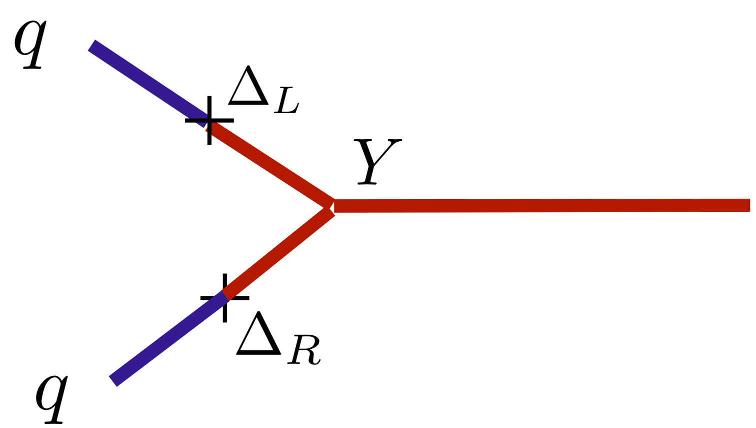
$$\frac{1}{\Lambda^{d-1}}\bar{q}_L\langle\mathcal{O}\rangle q_R$$

- Linear couplings (partial compositeness)



$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

$$\epsilon = \frac{\Delta}{m_Q}$$

$$\Delta_R \bar{q}_R \mathcal{O}_L \; + \; \Delta_L \bar{q}_L \mathcal{O}_R \; + \; Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

- **Anarchic scenario**

Strong sector couplings have no hierarchies

$$Y^{U,D} \sim g_\rho \qquad\qquad y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

SM hierarchies are generated by the mixings:

- Light quarks elementary
- Top strongly composite

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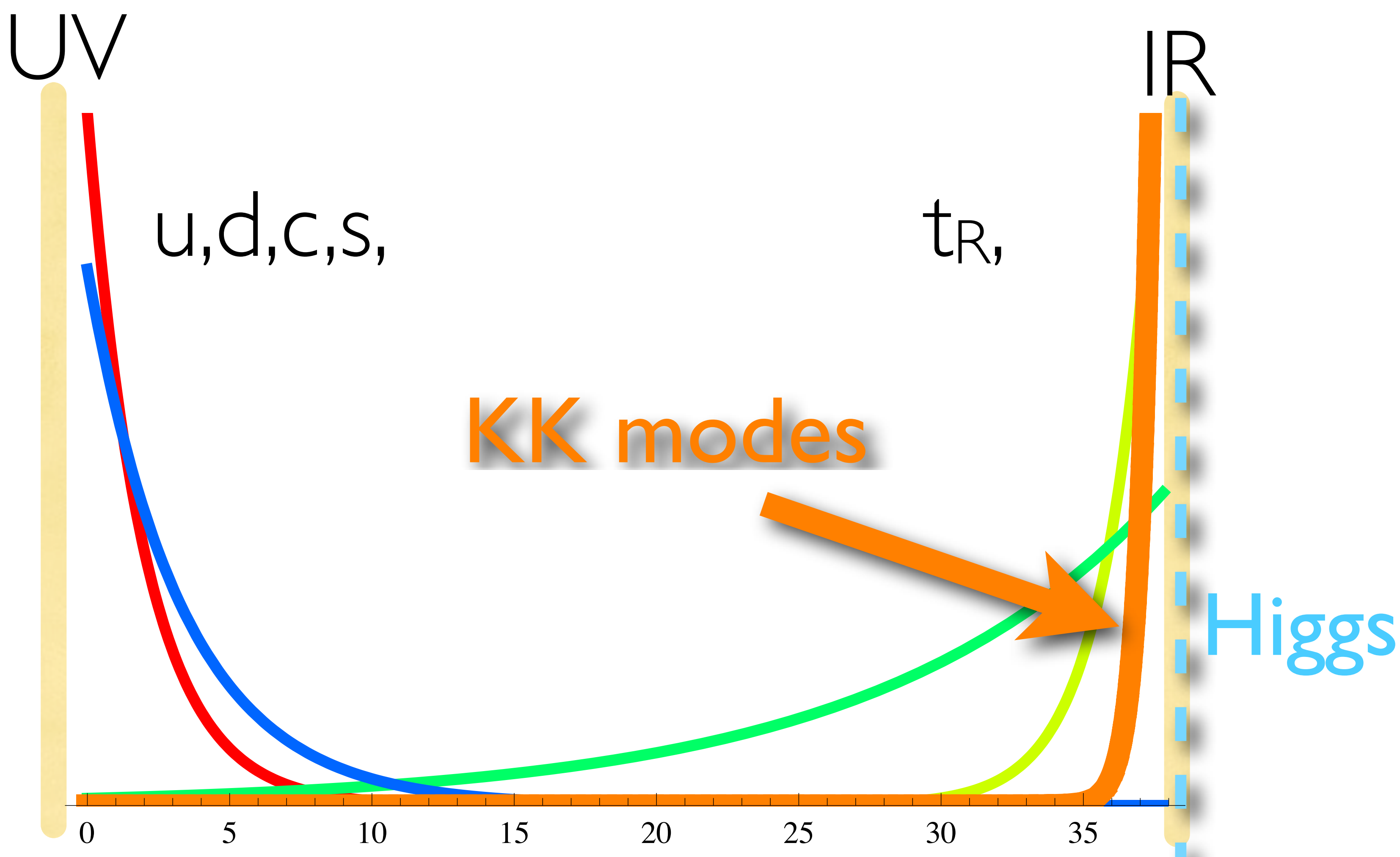
- **MFV scenario**

$$\epsilon_R \propto Id \qquad\qquad \epsilon_L \propto y_{SM}$$

Redi Weiler, '11

MODELS

- **5D Models**



(Randall-Sundrum '99)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

Through AdS/CFT correspondence dual to 4D CFTs.
Relevant physics dominated by the lowest modes.

SM gauge fields are obtained from zero modes of bulk fields

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$$

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NGB of G/H obtained from a G gauge theory

$SU(2)_L \otimes U(1)_Y$

Neumann

$SO(5)$

$A_\mu^{\hat{a}} = 0$ $\qquad \dfrac{SO(5)}{SO(4)}$

$\partial_z A_\mu^a = 0$ $\qquad SO(4)$

Higgs is a Wilson line

$$H = \int_{z_{UV}}^{z_{IR}} A_z dz$$

Each SM chirality is associated to a 5D field of mass c k.
SM chiral fermions are obtained by boundary conditions

$$\begin{pmatrix} + \\ + \\ . \\ . \\ + \end{pmatrix} \qquad \Psi_D \in G \qquad \begin{pmatrix} - \\ - \\ . \\ . \\ + \end{pmatrix}$$

$$\psi_0 \propto \left(\frac{z}{z_{IR}}\right)^{2-c}$$

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Yukawas hierarchies are generated

$$y_{ij}^{SM} = \epsilon_{Li}\, Y_{ij}^{5}\, \epsilon_{Rj} \qquad \epsilon \sim \left(\frac{\text{TeV}}{M_p}\right)^{c-\frac{1}{2}}$$

CHM5:

Agashe , Contino, Da Rold, Pomarol, '06

$$\mathbf{5} = (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$$

$$SU(3)_c \times SO(5) \times U(1)_X$$

$SU(2)_L \otimes U(1)_Y$

Neumann

$A^{\hat{a}}_\mu = 0$ $\qquad \dfrac{SO(5)}{SO(4)}$

$\mathbf{5}^{\mathbf{t_L}}_{\frac{\mathbf{2}}{\mathbf{3}}}$ $\qquad \mathbf{5}^{\mathbf{t_R}}_{\frac{\mathbf{2}}{\mathbf{3}}}$

$\partial_z A^a_\mu = 0$ $\qquad SO(4)$

$\mathbf{5}^{\mathbf{b_L}}_{-\frac{\mathbf{1}}{\mathbf{3}}}$ $\qquad \mathbf{5}^{\mathbf{b_R}}_{-\frac{\mathbf{1}}{\mathbf{3}}}$

$$\widetilde{m}_u\, \overline{(\mathbf{2},\mathbf{2})}^{\mathbf{q_1}}_{\mathbf{L}} (\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{R}} + \widetilde{M}_u\, \overline{(\mathbf{1},\mathbf{1})}^{\mathbf{q_1}}_{\mathbf{R}} (\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{L}} + \widetilde{m}_d\, \overline{(\mathbf{2},\mathbf{2})}^{\mathbf{q_2}}_{\mathbf{L}} (\mathbf{2},\mathbf{2})^{\mathbf{d}}_{\mathbf{R}} + \widetilde{M}_d\, \overline{(\mathbf{1},\mathbf{1})}^{\mathbf{q_2}}_{\mathbf{R}} (\mathbf{1},\mathbf{1})^{\mathbf{d}}_{\mathbf{L}} + h.c.$$

5D models are dual to 4D strongly coupled theories

Arkani-Hamed, Porrati, Randall '00

5D gauge symmetry $\longrightarrow$ 4D global symmetry

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Arkani-Hamed, Porrati, Randall '00

5D gauge symmetry $\longrightarrow$ 4D global symmetry

$$\mathcal{L} = \lambda \bar{q}_L O_R^d$$

$$\mu \frac{d\lambda}{d\mu} = (d - \frac{5}{2})\lambda$$

Contino, Pomarol '04

- d>5/2 irrelevant, small in IR (light generations)

- d<5/2 relevant, large in IR (top)

Hierarchies from dimensional transmutation

- **4D Models**

Low energy lagrangian determined by the symmetries.
CCWZ procedure

$$U(\Pi) = e^{\frac{i\Pi^{\widehat{a}} T^{\widehat{a}}}{f}} \qquad\qquad U(\Pi') = gU(\Pi)h^\dagger(\Pi, g) \quad g \in G, \quad h \in H(x)$$

$$U^\dagger \partial_\mu U = iE^a_\mu T^a + iD^{\widehat{a}}_\mu T^{\widehat{a}}$$

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$$U^{\dagger}\partial_{\mu}U = iE^{a}_{\mu}T^{a} + iD^{\widehat{a}}_{\mu}T^{\widehat{a}}$$

An effective lagrangian can be built similar to QCD

$$\mathcal{L} = \frac{m_{\rho}^{4}}{g_{\rho}^{2}}\left[\mathcal{L}^{(0)}(U,\Phi,\partial/m_{\rho}) + \frac{g_{\rho}^{2}}{(4\pi)^{2}}\mathcal{L}^{(1)}(U,\Phi,\partial/m_{\rho}) + \frac{g_{\rho}^{4}}{(4\pi)^{4}}\mathcal{L}^{(2)}(U,\Phi,\partial/m_{\rho}) + \ldots\right]$$

Giudice, Grojean, Pomarol, Rattazzi'07

SM fields are assigned to SO(5)

$$\Delta^{ij}\bar{q}^{i}\mathcal{O}^{j} \qquad\qquad \mathcal{O} \in G$$

To introduce resonances start from G/H

$$\frac{G}{H}$$

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$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \Omega \to g_L \Omega g_R^\dagger \qquad + \qquad \frac{G}{H}$$

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and gauge $G_R + G$

$$\mathcal{L}_{2-site} = \frac{f_1^2}{4} \mathrm{Tr}\, |D_\mu \Omega|^2 + \frac{f_2^2}{2} \mathcal{D}_\mu^{\widehat{a}} \mathcal{D}^{\mu \widehat{a}} - \frac{1}{4 g_\rho^2} \rho_{\mu\nu}^A \rho^{A\mu\nu}$$

$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu \Omega + i \Omega \rho_\mu$$

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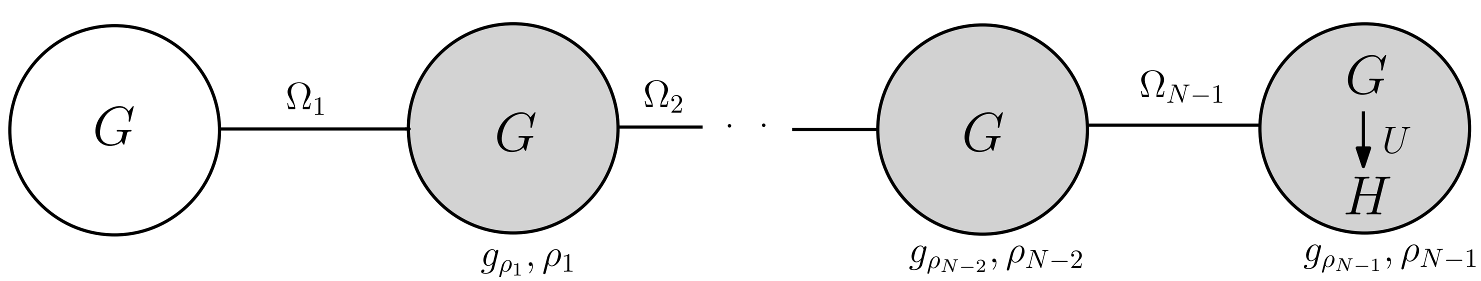
$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu \Omega + i \Omega \rho_\mu$$

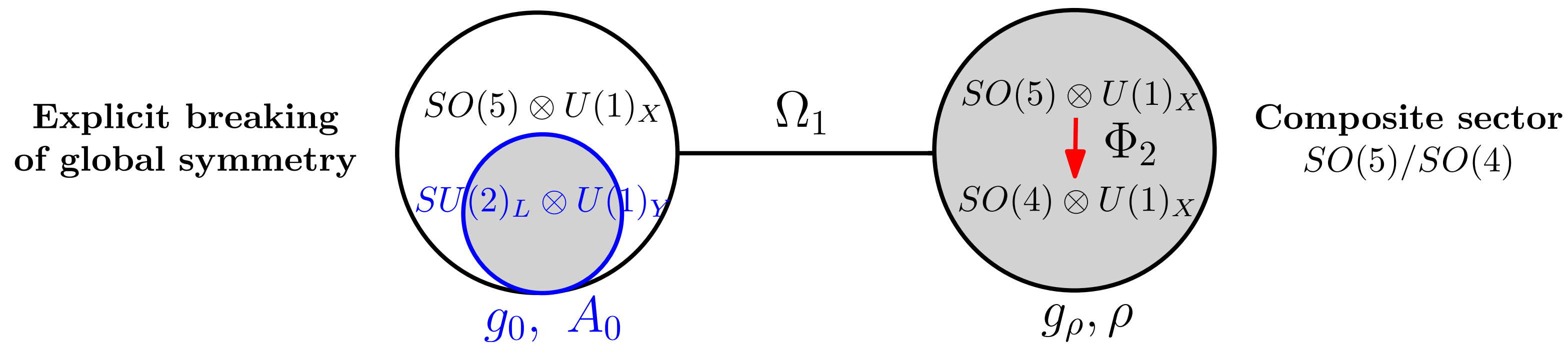
More resonances can be added.

Nearest neighbor interaction reproduce extra-dim:



Minimal SO(5)/SO(4) model

De Curtis, Redi, Tesi, '11



Composite spin-1 lagrangian:

$$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad\qquad \Phi = \frac{SO(5)}{SO(4)}$$

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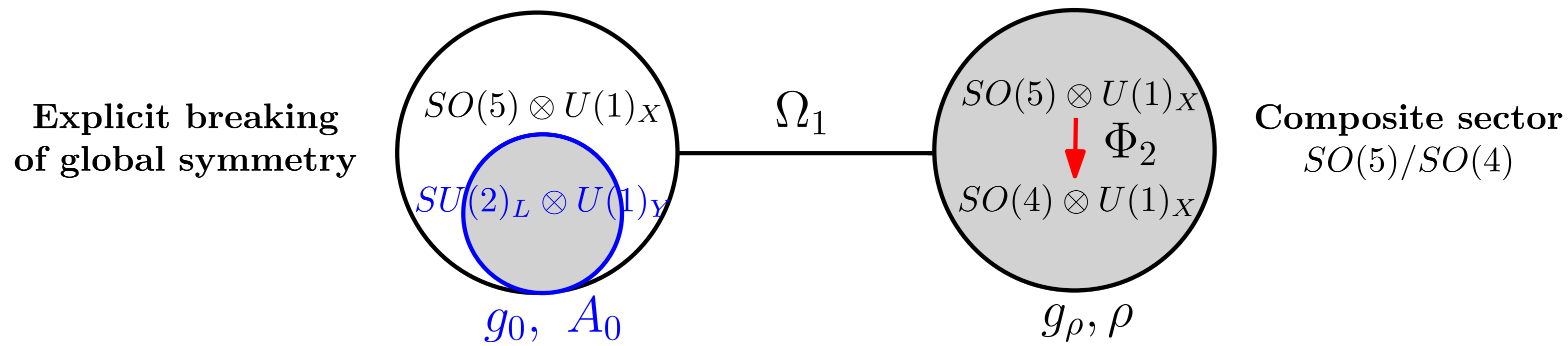

Composite spin-1 lagrangian:

$$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad \Phi = \frac{SO(5)}{SO(4)}$$

$$\frac{f_1^2}{4} \mathrm{Tr} \left| D_\mu \Omega \right|^2 + \frac{f_2^2}{2} \left(D_\mu \Phi \right)^T \left(D^\mu \Phi \right) - \frac{1}{4 g_\rho^2} \rho^a_{\mu\nu} \rho^{a\mu\nu}$$

$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu \Omega + i \Omega \rho_\mu \qquad D_\mu \Phi = \partial_\mu \Phi - i \rho_\mu \Phi$$

SO(4) and SO(5)/SO(4) spin-1 resonances.

Spectrum:

$$
\begin{aligned}
m_\rho^2 &= \frac{g_\rho^2 f_1^2}{2} \\
m_{a_1}^2 &= \frac{g_\rho^2 (f_1^2 + f_2^2)}{2} \\
m_{\rho_X}^2 &= \frac{g_{\rho_X}^2 f_X^2}{2}
\end{aligned}
$$

SM fields are introduced adding kinetic terms for the sources

$$
\mathcal{L}_{gauge}^{el} = -\frac{1}{4g_0^2} F_{\mu\nu}^a F_{\mu\nu}^a - \frac{1}{4g_{0Y}^2} Y_{\mu\nu} Y^{\mu\nu}
$$

Physical parameters:

$$
\begin{aligned}
\frac{1}{g^2} &= \frac{1}{g_0^2} + \frac{1}{g_\rho^2} \\
\frac{1}{g'^2} &= \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho_X}^2}
\end{aligned}
$$

$$
m_{\rho_{aL}} = \frac{m_\rho}{\cos\theta_L}, \quad \tan\theta_L = \frac{g_0}{g_\rho}
$$

Each SM fermion couples to Dirac fermion in a rep of SO(5).

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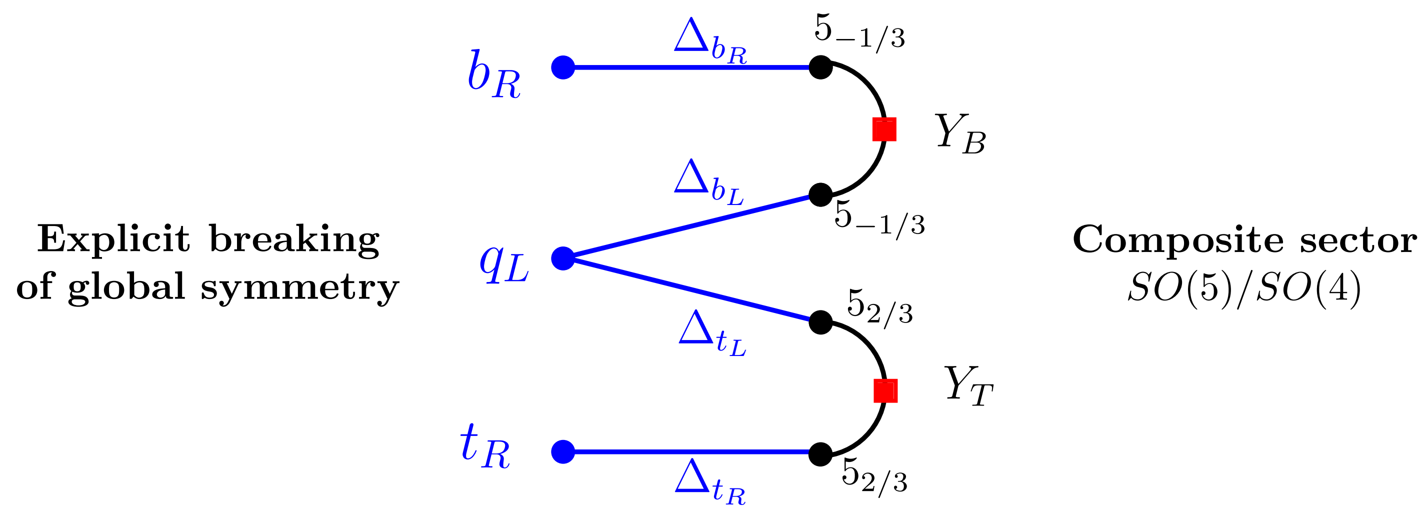
CHM5:



Third generation:

$$
\begin{aligned}
\mathcal{L}^{\mathrm{CHM}_5} &= \mathcal{L}^{el}_{fermions} \\
&+ \Delta_{t_L}\, \bar{q}^{el}_L \Omega_1 \Psi_T + \Delta_{t_R}\, \bar{t}^{el}_R \Omega_1 \Psi_{\widetilde{T}} + h.c. \\
&+ \bar{\Psi}_T (i \not{D}^\rho - m_T)\Psi_T + \bar{\Psi}_{\widetilde{T}}(i \not{D}^\rho - m_{\widetilde{T}})\Psi_{\widetilde{T}} \\
&- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\widetilde{T},R} - m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\widetilde{T},R} + h.c. \\
&+ (T \to B)
\end{aligned}
$$

→ Explicit SO(5) breaking

→ Composite physics
SO(5)/SO(4)

Useful a simple 4D description:

- theoretical:
  - only very few resonances (1?) weakly coupled
  - relevant physics largely independent of 5D or AdS
  - what are the most general models?

- practical:
  - LHC will at best produce the lightest resonances
  - Simplified model useful for LHC

SIGNATURES

Higgs NGB:

$$\text{Higgs} \subset \frac{G}{H}$$

Higgs NGB:

$$\text{Higgs} \subset \frac{G}{H}$$

Strong sector:
Higgs + (top)
m_ρ g_ρ

λ_L λ_R g

Gauging SU(3)xSU(2)xU(1)
mixing to fermionic operators

Elementary:
SM Fermions
+ Gauge Fields

Elementary-composite states talk through linear couplings:

$$\mathcal{L}_{gauge} = g\, A_\mu J^\mu$$

$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \xrightarrow{\epsilon \sim \frac{\lambda}{Y}} y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

Light generations are elementary, top composite.

- Precision Tests

$$
\begin{aligned}
\mathcal{L}_{eff} = \quad & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y}{f^2} H^\dagger H\,\bar{\psi}_L H\psi_R + \text{h.c.}\right) \\
+ \quad & \frac{c_\gamma g^2}{16\pi^2 m_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g y_t^2}{16\pi^2 m_\rho^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
+ \quad & \frac{ic_W}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
+ \quad & \frac{ic_{HW}}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB}}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}
\end{aligned}
$$

$$f = \frac{m_\rho}{g_\rho} \ll m_\rho$$

Giudice, Grojean, Pomarol, Rattazzi 07

Typical modifications

$$\delta g_{SM} = \kappa \frac{v^2}{m_\rho^2}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1$$

$$\delta\rho_{naive} = \frac{v^2}{f^2}$$

$$\delta\rho_{max} \sim 10^{-3} \longrightarrow f > 5\,\mathrm{TeV}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1 \qquad\qquad \delta\rho_{naive} = \frac{v^2}{f^2}$$

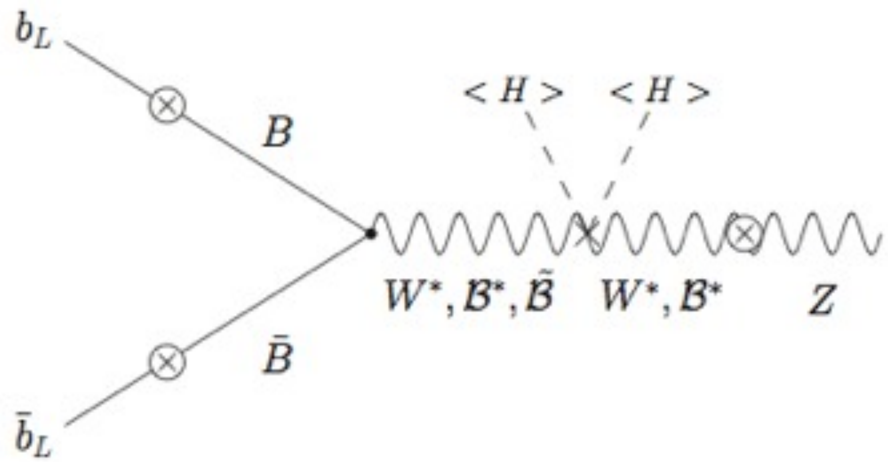
$$\delta\rho_{max} \sim 10^{-3} \longrightarrow f > 5\,\mathrm{TeV}$$

Custodial Symmetry $SU(2)_c$ $\longrightarrow$ $SU(2)_L \times SU(2)_R \in H$

Composite sector has $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ symmetry $(Y = T_{3R} + U(1)_X)$

Extended Higgs sectors require extra symmetry

Third generation Z-couplings



$$\frac{\delta g_L}{g_L} \sim \frac{g_\rho^2 v^2}{m_\rho^2} \epsilon_L^2$$

$$\left.\frac{\delta g_{Lb}}{g_{Lb}}\right|_{max} \sim 10^{-3} \qquad \epsilon_{Lb} > \frac{\lambda_t}{g_\rho \epsilon_{Rt}} \longrightarrow \frac{\delta g_{Lb}}{g_{L_b}} > \frac{\lambda_t^2 \, v^2}{m_\rho^2}$$

Possible problems with ρ at 1-loop

Extend $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ symmetry

Agashe , Contino,
Da Rold, Pomarol, '06

$$P_{LR}: \qquad SU(2)_L \times SU(2)_R \to O(4)$$

Couplings protected if symmetry respected.

$$T_{3L} = T_{3R}$$

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Couplings protected if symmetry respected.

$$T_{3L} = T_{3R}$$

Ex:

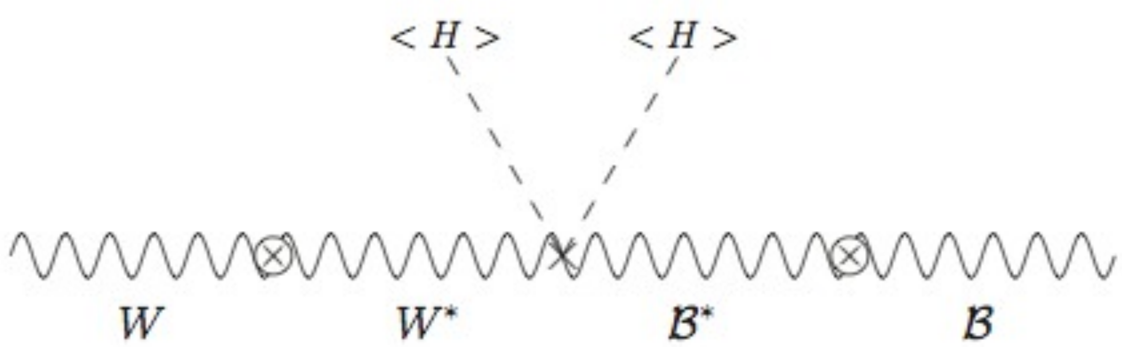
$$q_L \longrightarrow (2,2)_{\frac{2}{3}} \qquad L_U = \begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix}$$

$$u_R \longrightarrow (1,1)_{\frac{2}{3}} \qquad U$$

S-parameter:

$$\frac{S}{16\pi v^2}\left(H^\dagger \tau^a H\right) W^a_{\mu\nu} B^{\mu\nu}$$

Tree-level:

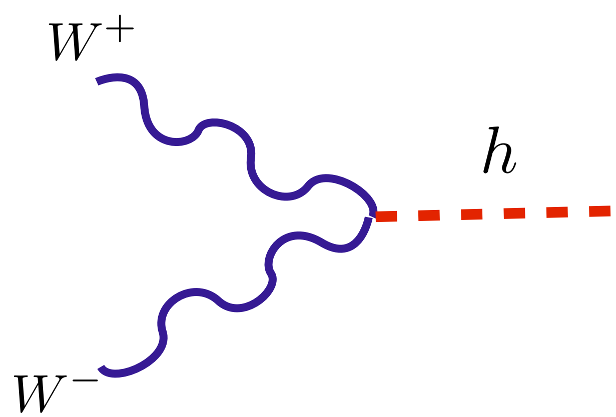


$$S \sim 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2}\right)$$

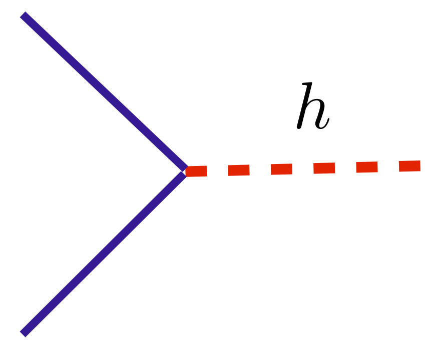
$$S < 0.3 \longrightarrow m_\rho > 2 - 3\,\mathrm{TeV}$$

General Higgs lagrangian:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2\kappa_V \frac{h}{v} + \kappa_{hh}\frac{h^2}{v^2}\ldots\right]$$
$$- m_i \bar{\psi}_{Li}\Sigma\left(1 + \kappa_F \frac{h}{v} + \ldots\right)\psi_{Ri} + h.c. + \ldots$$



$$= 2i\frac{m_W^2}{v}k_V$$



$$-i\frac{m_f}{v}k_V$$

$$\mathrm{SM}: \qquad \kappa_F = \kappa_V = 1$$

Corrections determined by group theory:

$$m_W^2 = \frac{g^2 f^2}{4}\sin^2\frac{h}{f} \longrightarrow \qquad \kappa_V = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

CHM5:

$$m_t \propto \sin\frac{h}{f}\cos\frac{h}{f} \longrightarrow \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

CHM4:

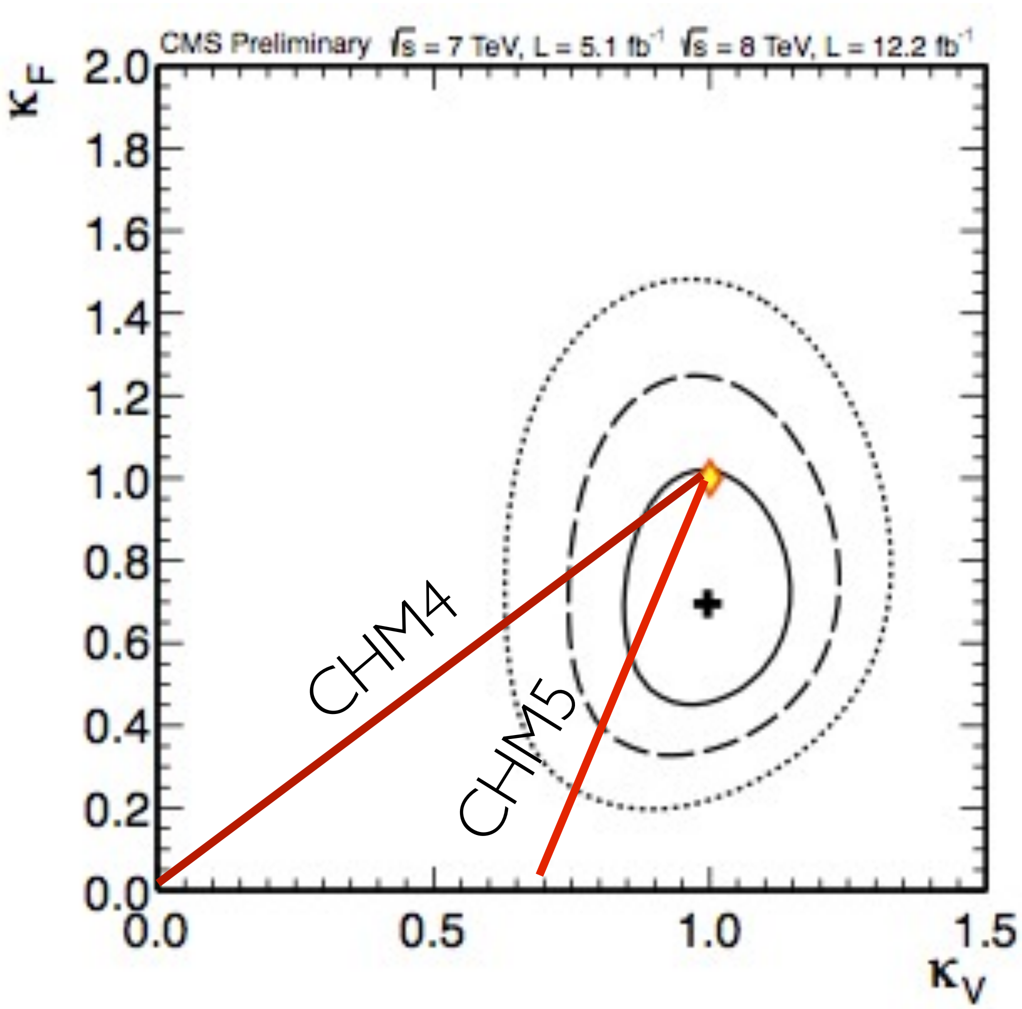
$$m_t \propto \sin\frac{h}{f} \longrightarrow \kappa_F = \sqrt{1-\xi}$$

CHM5:

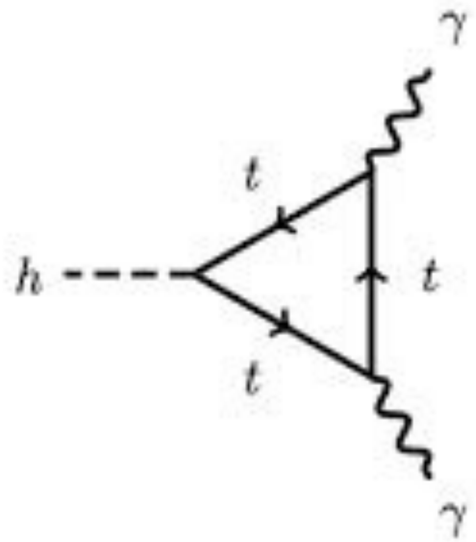
$$m_t \propto \sin\frac{h}{f}\cos\frac{h}{f} \longrightarrow \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

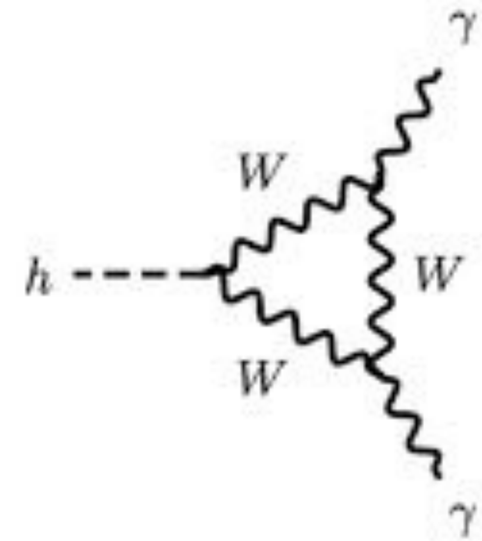
CHM4:

$$m_t \propto \sin\frac{h}{f} \longrightarrow \kappa_F = \sqrt{1-\xi}$$

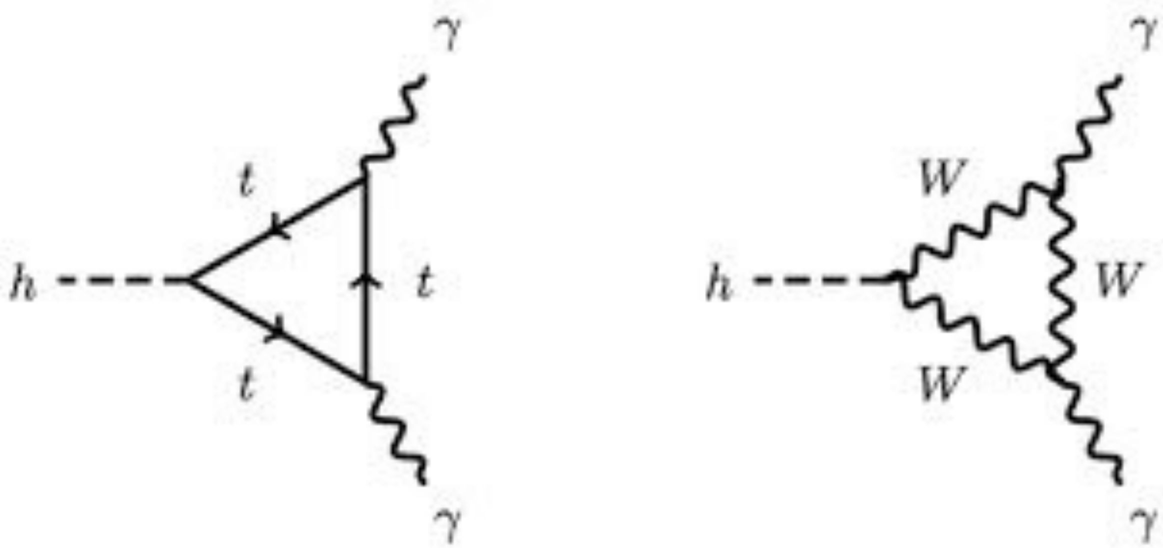


$$\xi < \frac{1}{2}$$



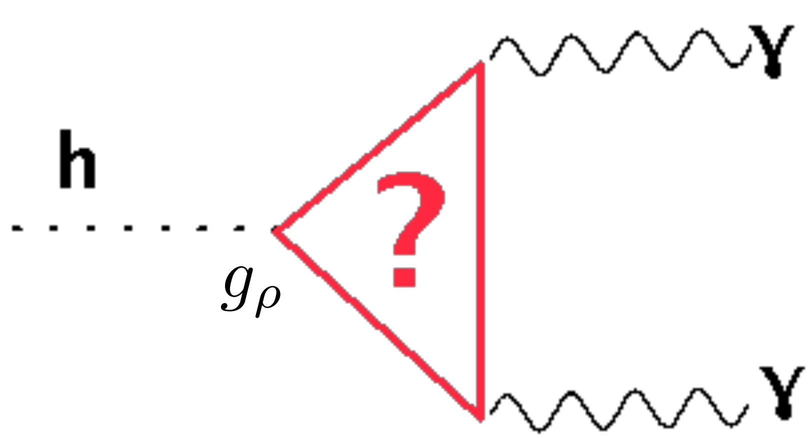


$$\approx \frac{\alpha}{\pi v} F_{\mu\nu}^2 h$$



$$\approx \frac{\alpha}{\pi v} F_{\mu\nu}^2 h$$

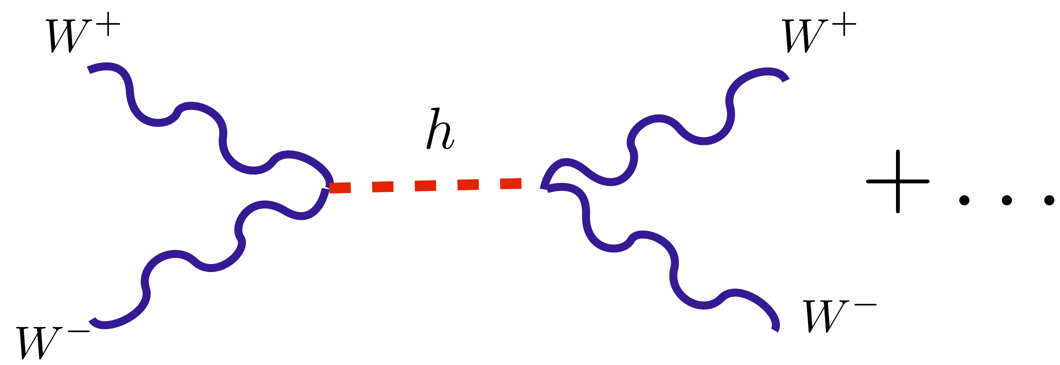
NGB symmetry protects the couplings



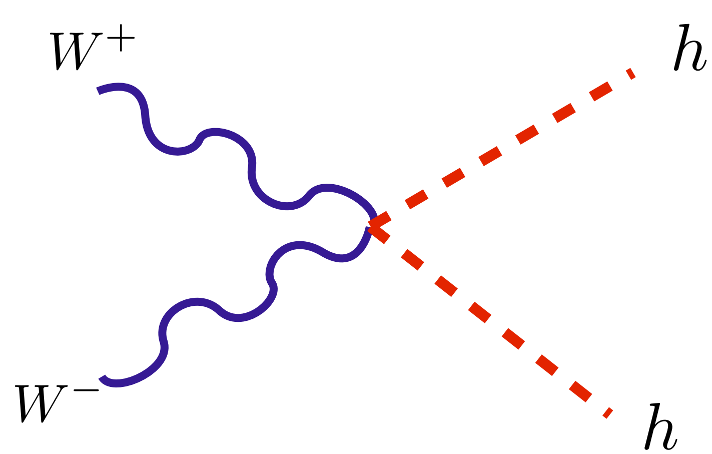
$$\frac{\delta A}{A_{SM}} \sim \frac{v^2}{f^2}$$

No large deviations expected.

WW scattering non perfectly unitarized



$$A(W^+W^- \to W^+W^-) \simeq \frac{s}{v^2}(1-\kappa_V^2)$$



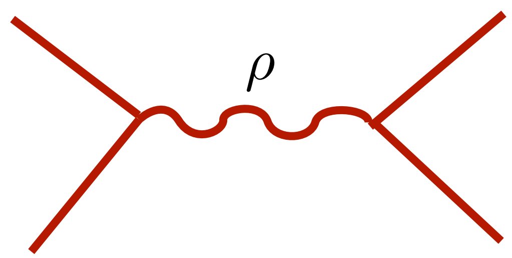
$$A(W^+W^- \to hh) \simeq \frac{s}{v^2}(\kappa_{hh}-\kappa_V^2)$$

Most likely not visible at LHC

Contino et al. '09

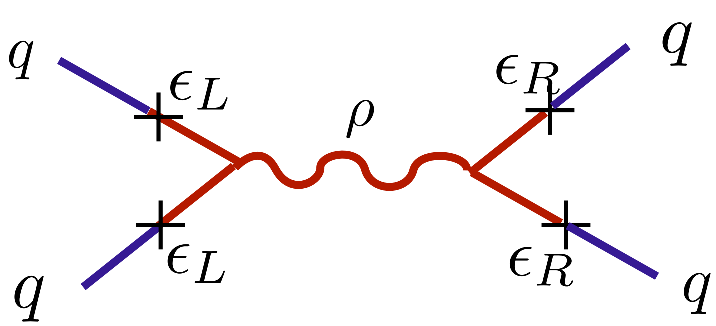
- **Flavor**

Resonance exchange generates 4-Fermi operators



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

$\Delta F = 2$ transitions generated by mixing



$$\epsilon_L^i \epsilon_L^j \epsilon_R^k \epsilon_R^l \times \frac{g_\rho^2}{m_\rho^2} \times (\bar{q}_L^i \gamma^\mu q_L^j)((\bar{d}_R^k \gamma_\mu d_R^l)$$

FCNC of the light generation are suppressed by the mixings.

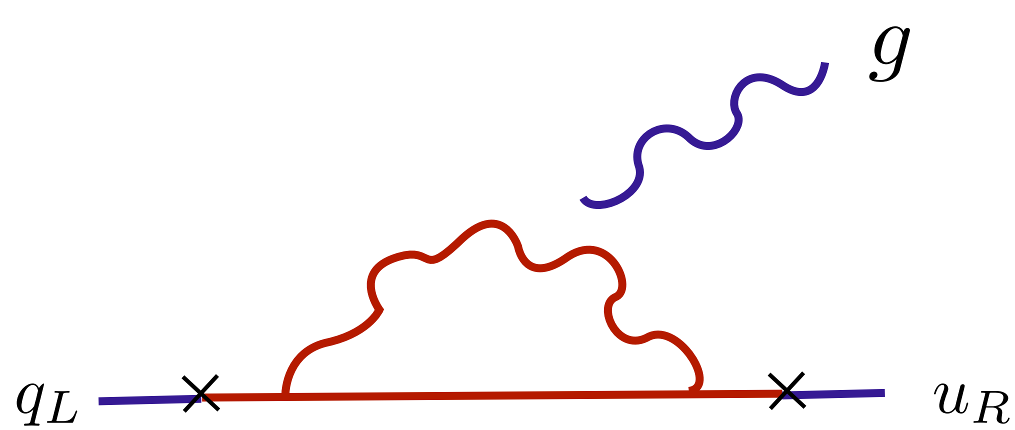
Flavor superior to TC theories though not perfect.

$$C_4^K \, \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta \qquad C_4^K \sim \frac{g_\rho^2}{m_\rho^2} \frac{m_d \, m_s}{v^2}$$

Csaki, Falkowski, Weiler, '08

$$m_\rho > 20 \text{ TeV}$$

Dipoles:



$$\epsilon_L^i \epsilon_R^j \times \frac{g_\rho v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \times \bar{q}_L^i \sigma^{\mu\nu} q_R^j G_{\mu\nu}$$

$$\left.\begin{array}{l} b \to s\gamma \\ \\ \mathrm{Neutron\,EDM} \end{array}\right\} \qquad m_\rho > 2\, g_\rho \,\mathrm{TeV}$$

$$\mu \to e\gamma \qquad\qquad m_\rho > 30\, g_\rho \,\mathrm{TeV}$$

$$\left.\begin{array}{l} b \to s\gamma \\ \\ \text{Neutron EDM} \end{array}\right\} \qquad m_\rho > 2\, g_\rho \,\text{TeV}$$

$$\mu \to e\gamma \qquad m_\rho > 30\, g_\rho \,\text{TeV}$$

CP violation in D-system:

$$a_{D^0 \to K^+ K^-} - a_{D^0 \to \pi^+ \pi^-} = (-0.67 \pm 0.16)\%$$

LHCb '12

Reasonable in composite Higgs

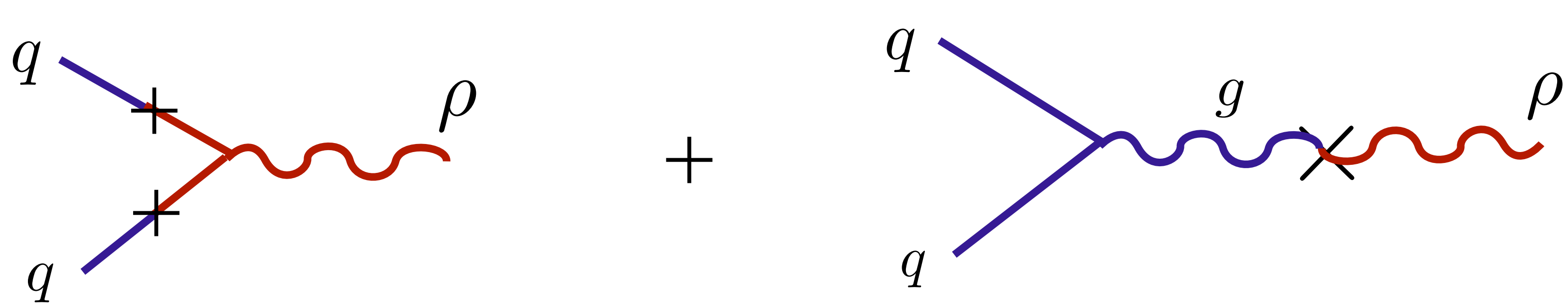
$$m_\rho \simeq \frac{g_\rho}{4\pi} \times 10\,\text{TeV}$$

Keren-Zur et al., '12

- **Direct Searches**

Heavy resonances mostly coupled to 3rd generation + Higgs

Spin-1: gluon, electro-weak



$$g_{\rho\bar{q}q} = g(\sin^2\varphi\cot\theta - \cos^2\varphi\tan\theta) \qquad \sin^2\varphi \sim \epsilon$$

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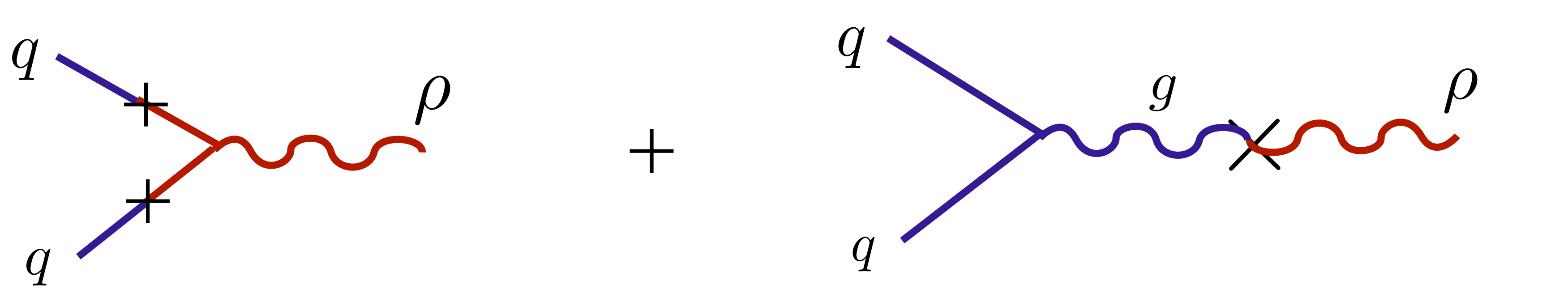
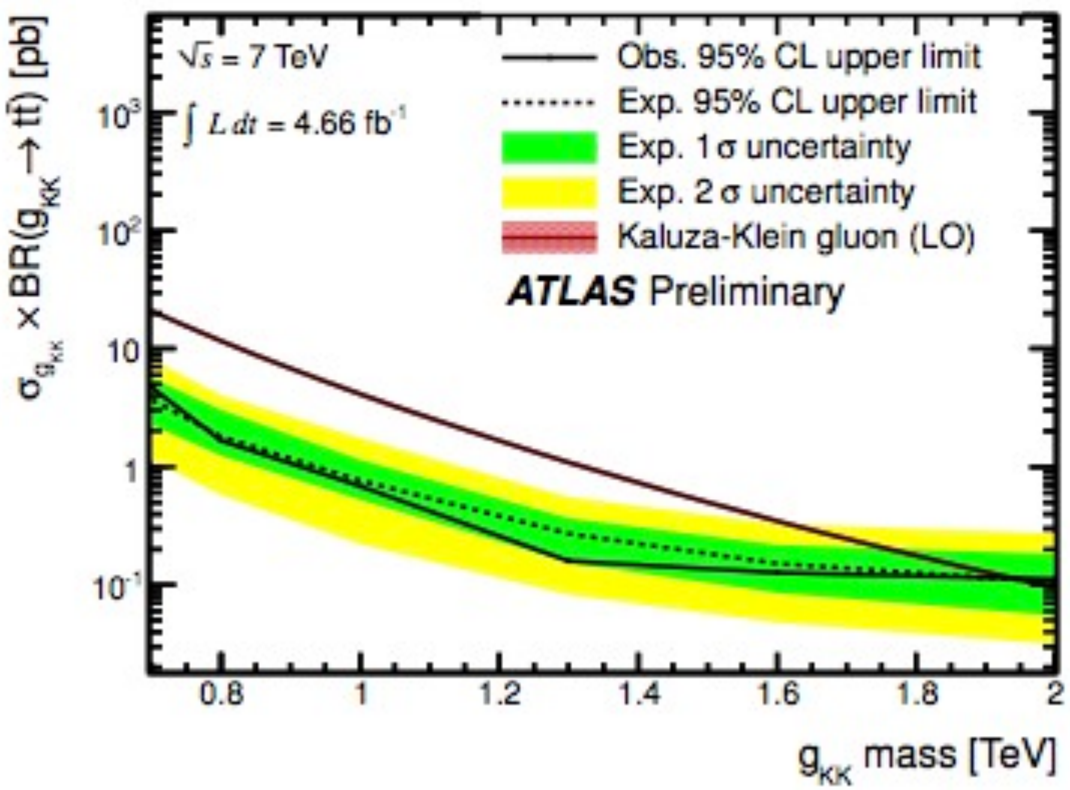
Heavy resonances mostly coupled to 3rd generation + Higgs

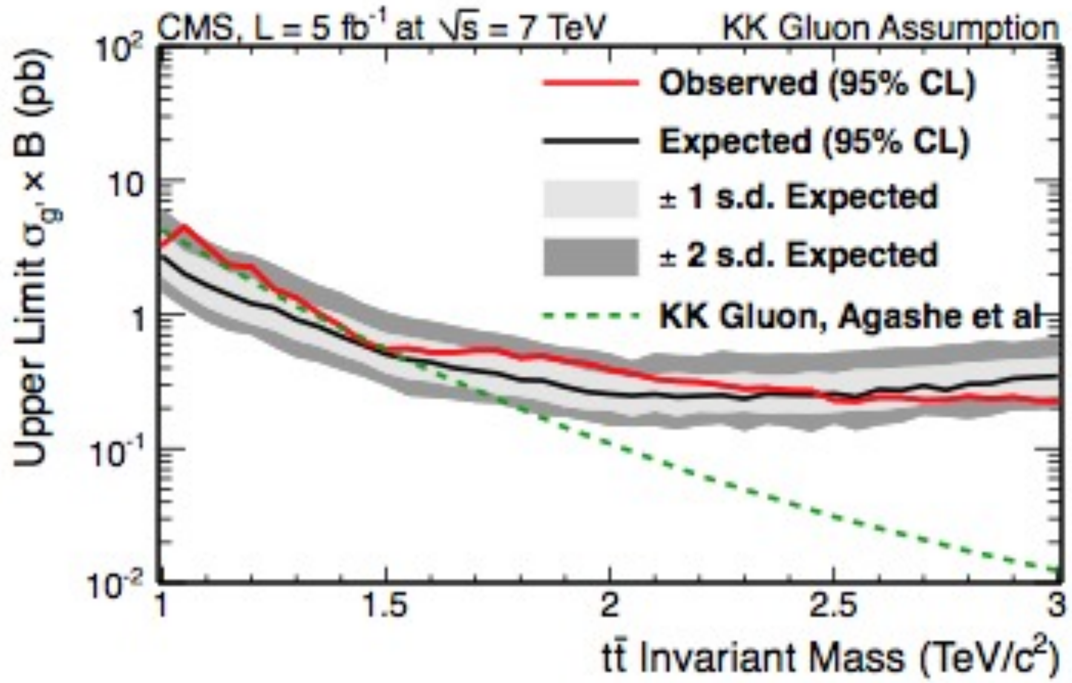
Spin-1: gluon, electro-weak



$$g_{\rho\bar{q}q} = g(\sin^2\varphi\cot\theta - \cos^2\varphi\tan\theta) \qquad\qquad \sin^2\varphi \sim \epsilon$$

Decay into 3rd generation or heavy fermions.





Gluon resonances excluded up to 2 TeV!

Spin-1/2 : Top partners could be lighter + exotic charges

$$\begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix} \qquad\qquad \tilde{T}$$

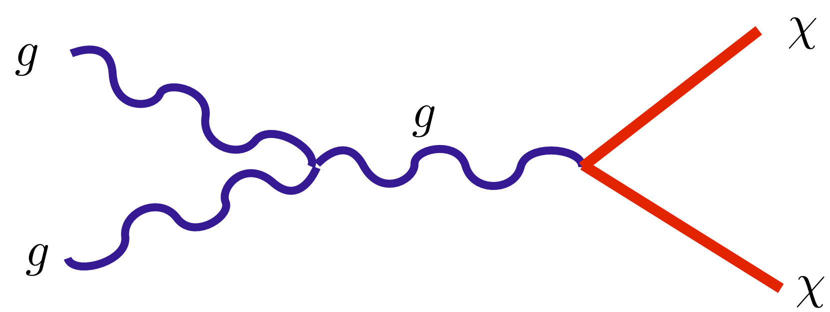
$$\begin{aligned}\mathcal{L}_{yuk} =& Y_* \sin\varphi_L \sin\varphi_R \left(\bar{t}_L \phi_0^\dagger t_R - \bar{b}_L \phi^- t_R\right) + Y_* \cos\varphi_L \sin\varphi_R \left(\bar{T}\phi_0^\dagger t_R - \bar{B}\phi^- t_R\right) \\ &+ Y_* \sin\varphi_L \cos\varphi_R \left(\bar{t}_L \phi_0^\dagger \tilde{T} - \bar{b}_L \phi^- \tilde{T}\right) + Y_* \sin\varphi_R \left(\bar{T}_{5/3}\phi^+ t_R + \bar{T}_{2/3}\phi_0 t_R\right) + \ldots\end{aligned}$$

Spin-1/2 : Top partners could be lighter + exotic charges

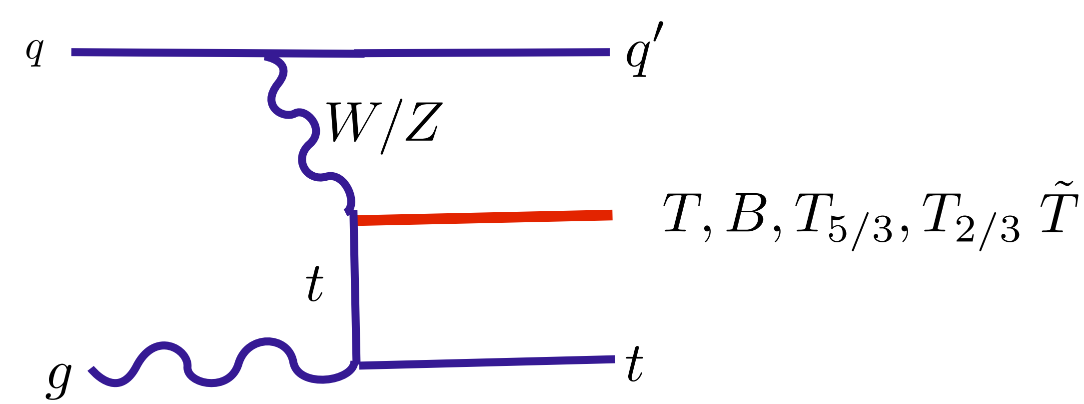
$$\begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix} \qquad \qquad \tilde{T}$$

$$\mathcal{L}_{yuk} = Y_* \sin\varphi_L \sin\varphi_R \left(\bar{t}_L \phi_0^\dagger t_R - \bar{b}_L \phi^- t_R\right) + Y_* \cos\varphi_L \sin\varphi_R \left(\bar{T}\phi_0^\dagger t_R - \bar{B}\phi^- t_R\right)$$
$$+ Y_* \sin\varphi_L \cos\varphi_R \left(\bar{t}_L \phi_0^\dagger \tilde{T} - \bar{b}_L \phi^- \tilde{T}\right) + Y_* \sin\varphi_R \left(\bar{T}_{5/3}\phi^+ t_R + \bar{T}_{2/3}\phi_0 t_R\right) + \ldots$$

Production:



Double

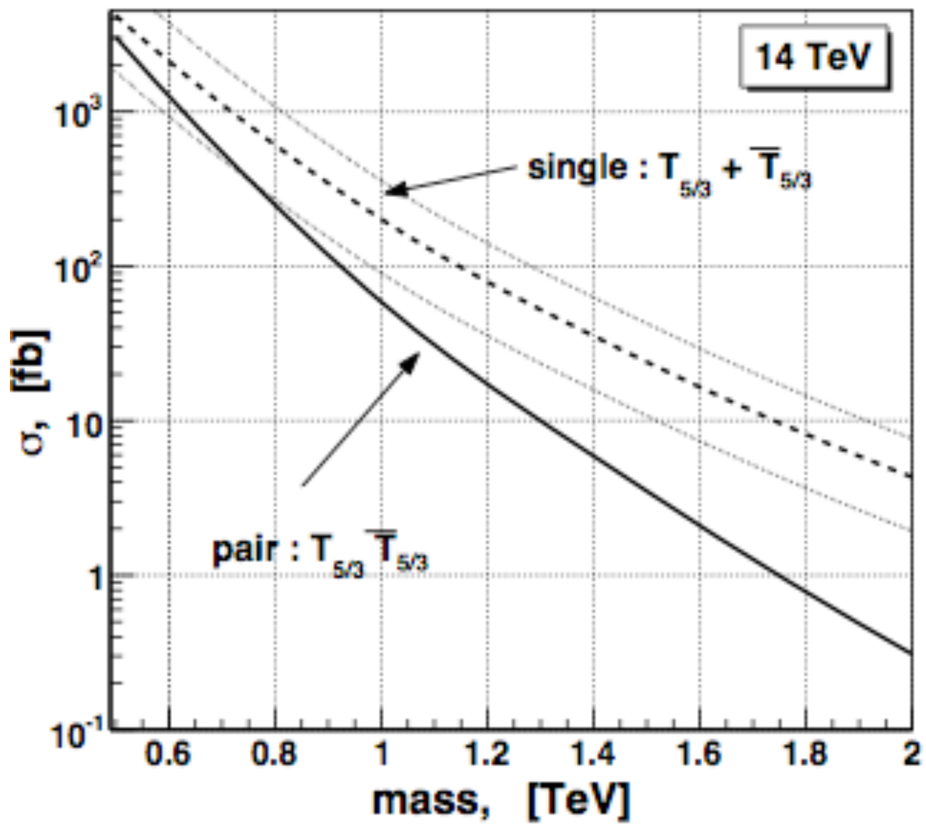


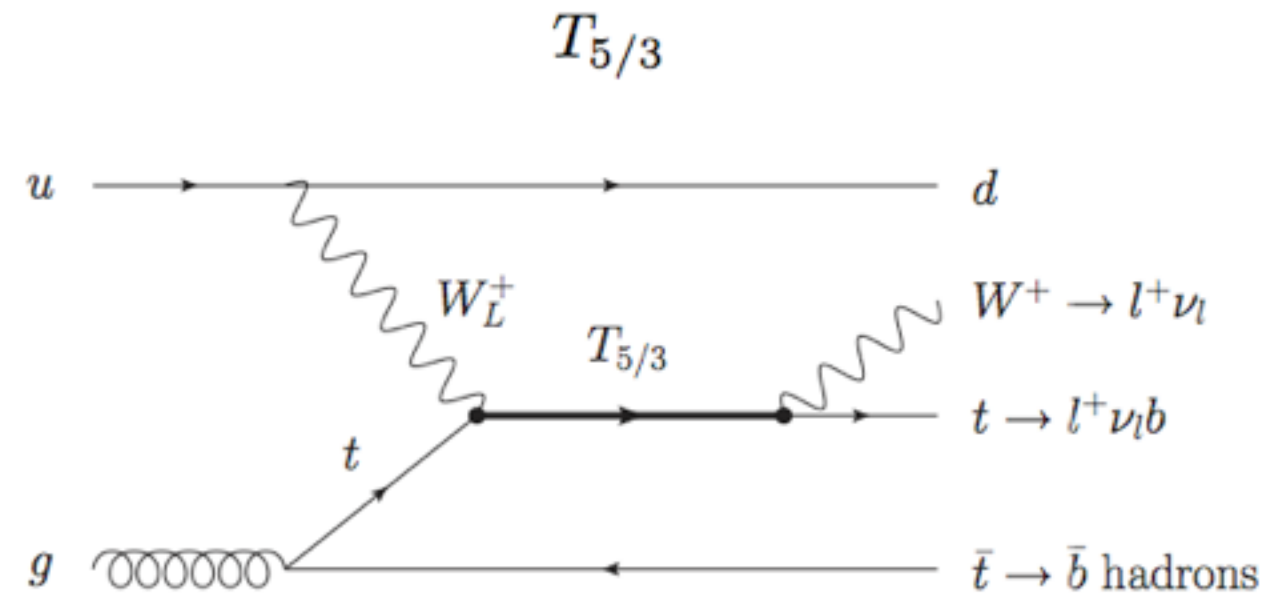
Single

Contino, Servant. '08

Mrazek, Wulzer '09

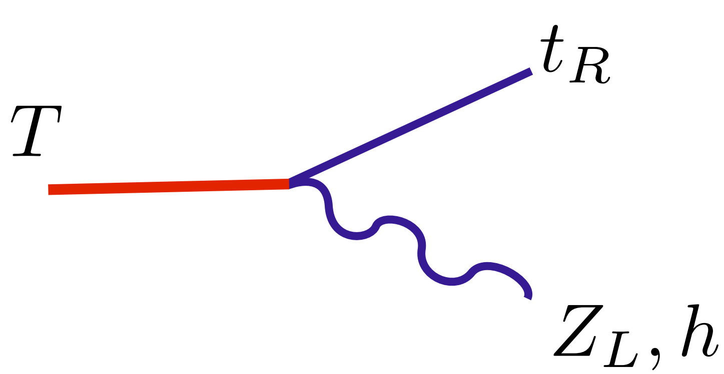
Aguilar-Saveedra '09

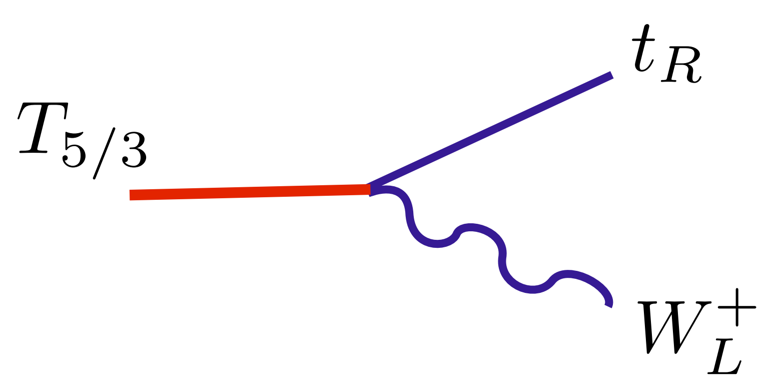


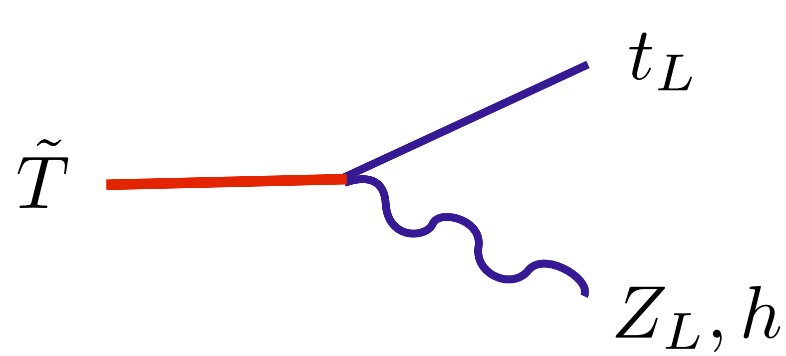


Mrazek, Wulzer '09

Decays:

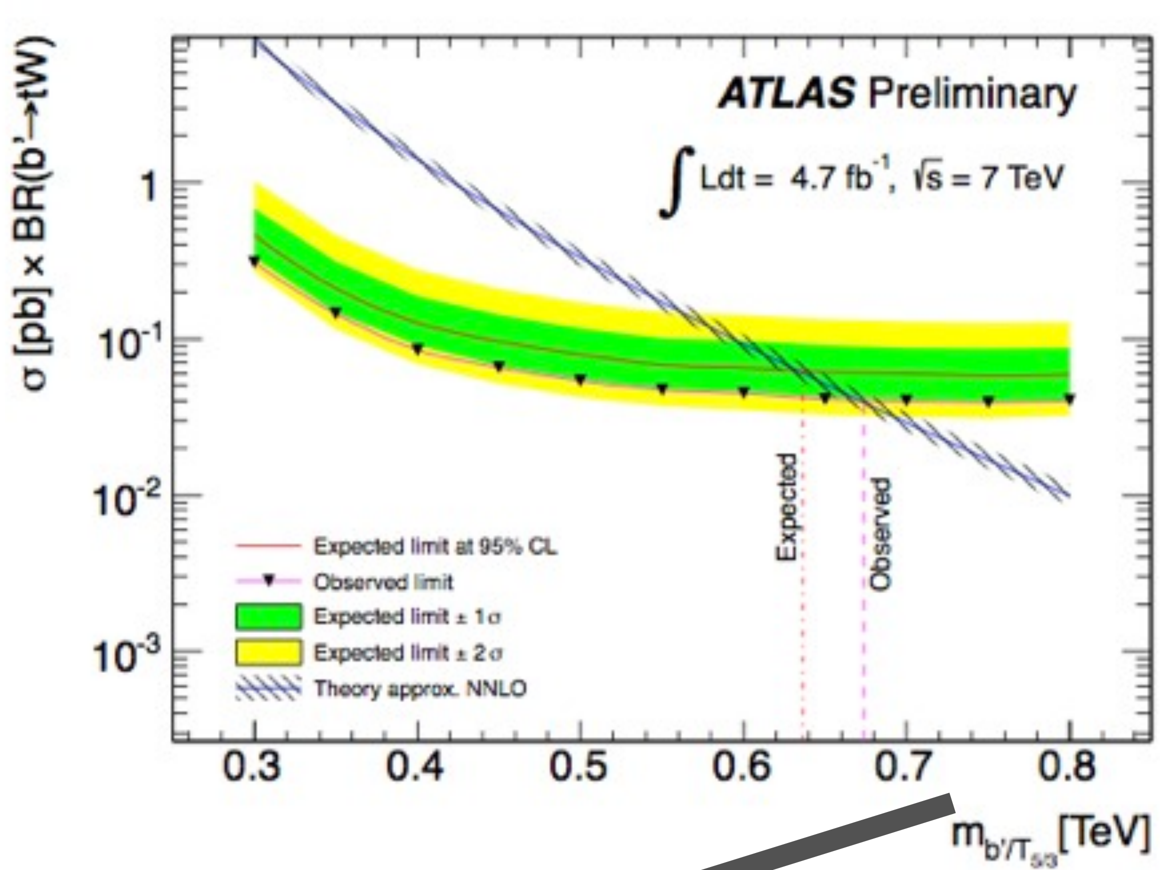


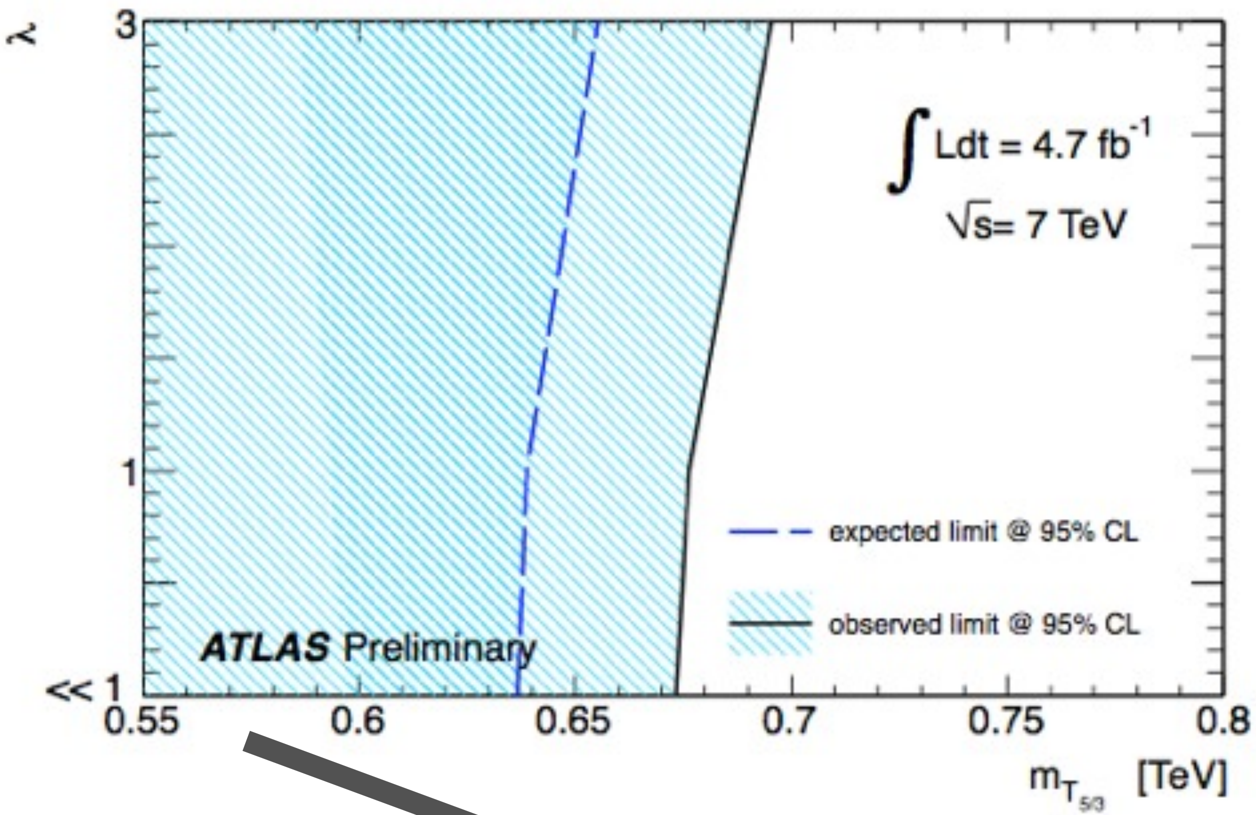




Multi-lepton signatures.

ATLAS-CONF-2012-130

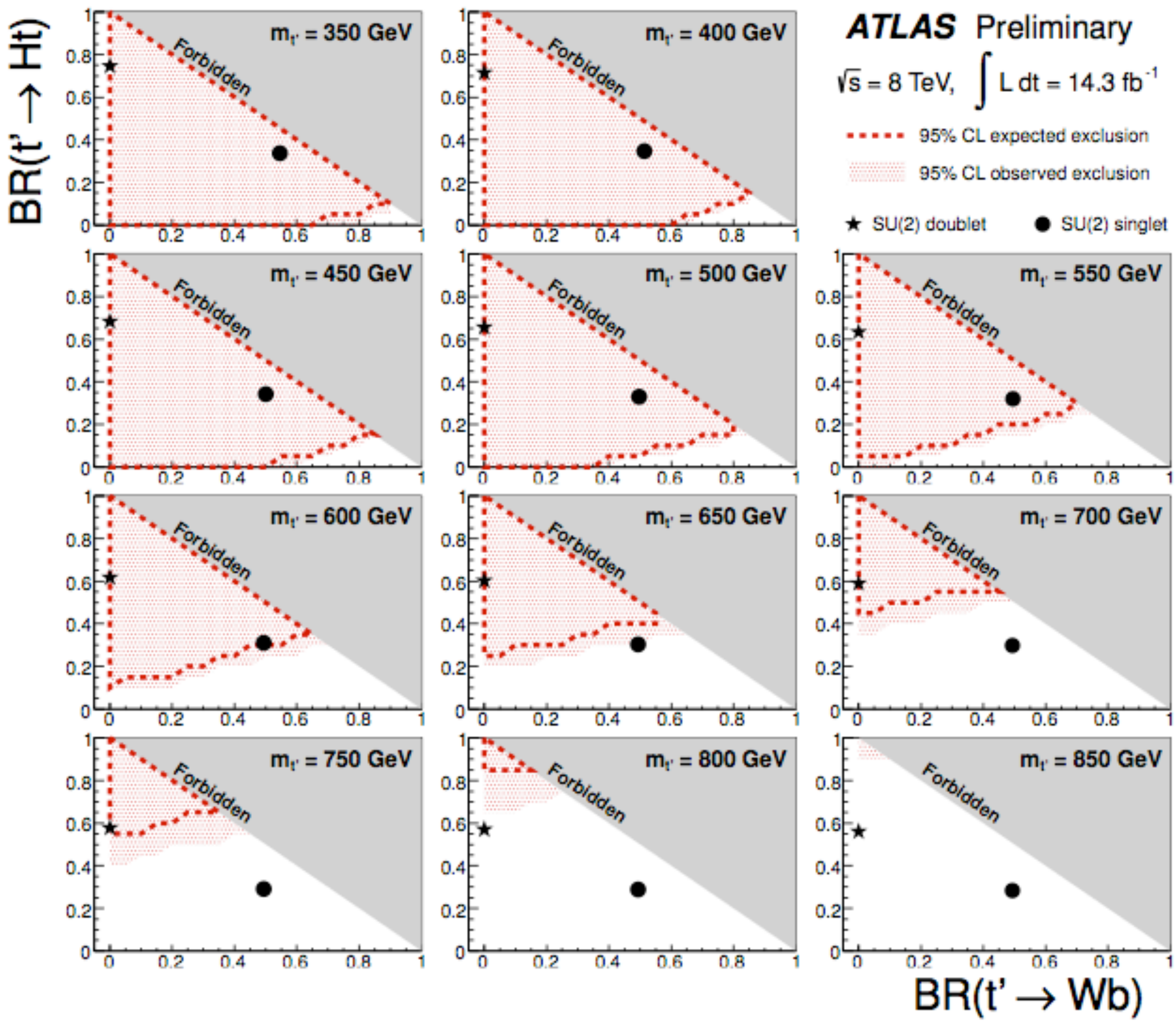




double production

double+single production

ATLAS-CONF-2012-018



HIGGS MASS

SM couplings break NGB symmetry

$$\epsilon_{t_L} \qquad \epsilon_{t_R} \qquad g$$

Higgs potential generated at 1-loop:

$$V(h) \sim \frac{N_c}{16\pi^2}\epsilon_{L,R}^2 m_\rho^4 \hat{V}\left(\frac{h}{f}\right) + \ldots$$

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Ex:

$$V(h) \approx a \sin^2\frac{h}{f} + b \sin^2\frac{h}{f}\cos^2\frac{h}{f}$$

$$v \ll f \longrightarrow a \approx -b$$

Recall pions:

$$\mathcal{L} = f_\pi^2 \left|D_\mu U\right|^2 + a\,\Lambda_{QCD}^2 \mathrm{Tr}[m \cdot (U + U^\dagger)]$$

$$D_\mu U = \partial_\mu U + ieA_\mu U$$

$$m_{\pi^+}^2 = m_{\pi^0}^2 = a'\Lambda_{QCD}(m_u + m_d)$$

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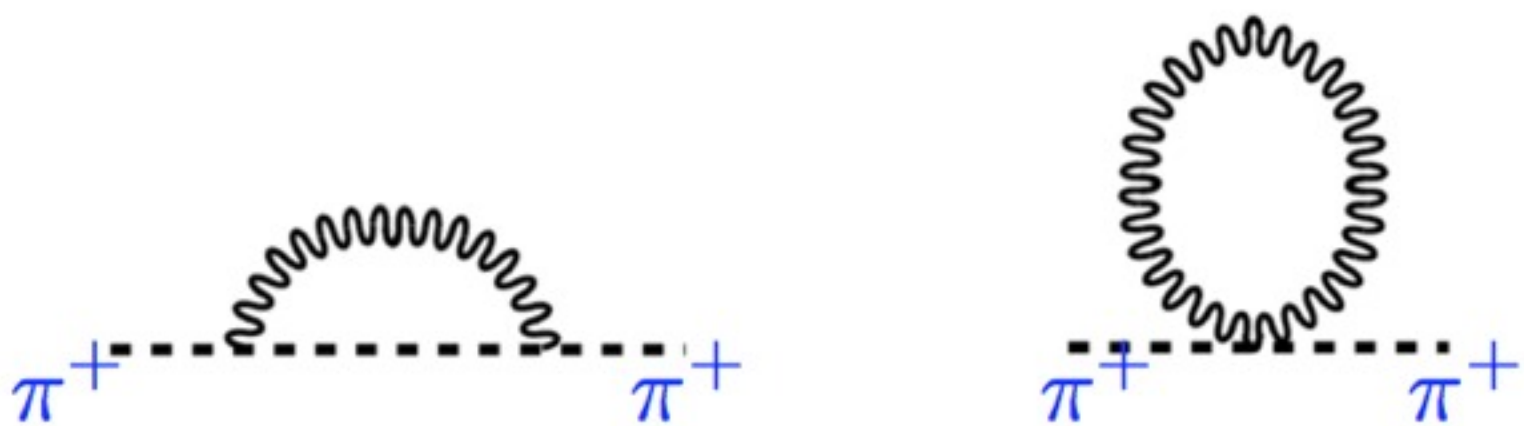
1-loop:



$$\delta m_{\pi^+}^2 = \frac{3e^2}{32\pi^2} \int dp^2 \sim \frac{3\alpha_{EM}}{8\pi} \Lambda^2$$

Vectors effective action:

$$\mathcal{L}_{\rm eff} =\frac{1}{2} P^T_{\mu\nu}\Big[\widehat{\Pi}^X_0(p^2)\, X^\mu X^\nu + \widehat{\Pi}_0(p^2)\,{\rm Tr}\big[A^\mu A^\nu\big] + \widehat{\Pi}_1(p^2)\,\Phi A^\mu A^\nu \Phi^T\Big]$$

$$\widehat{\Pi}_0(p^2) = \Pi_a(p^2), \quad \widehat{\Pi}^X_0(p^2) = \Pi_X(p^2), \quad \widehat{\Pi}_1(p^2) = 2\left[\Pi_{\widehat{a}}(p^2) - \Pi_a(p^2)\right]$$

$$\begin{aligned}\mathcal{L}^{gauge}_{\rm eff} \quad &= \quad \frac{1}{2}P^T_{\mu\nu}\Big[\left(\Pi_0(p^2) + \frac{s_h^2}{4}\Pi_1(p^2)\right) A^\mu_{aL} A^\nu_{aL} \\ &+ \quad \left(\Pi_Y(p^2) + \frac{s_h^2}{4}\Pi_1(p^2)\right) Y^\mu Y^\nu + 2 s_h^2\,\Pi_1(p^2)\,\widehat{H}^\dagger T^a_L Y \widehat{H}\, A^{aL}_\mu Y_\nu\Big]\end{aligned}$$

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Coleman-Weinberg effective potential

$$V(h)_{gauge} = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \ln\left[1 + \frac{1}{4} \frac{\Pi_1(p^2)}{\Pi_0(p^2)} \sin^2 \frac{h}{f}\right] \approx \int \frac{d^4p}{(2\pi)^4} \frac{9\Pi_1}{8\Pi_0} \sin^2 \frac{h}{f}$$

Fermions:

Contino, Da Rold ,Pomarol '06

$$V(h)_{fermions} = -2N_c \int \frac{d^4p}{(2\pi)^4} \left[\ln \Pi_{b_L} + \ln\left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi_{t_L t_R}^2\right)\right]$$

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CHM5:

$$\begin{aligned}\mathcal{L}_{\rm eff} =& \bar{q}_L \not{p} \left[\Pi_0^q(p^2) + \frac{s_h^2}{2}\left(\Pi_1^{q1}(p^2)\, \widehat{H}^c \widehat{H}^{c\dagger} + \Pi_1^{q2}(p^2)\, \widehat{H}\widehat{H}^\dagger\right)\right] q_L \\ &+ \bar{u}_R \not{p} \left(\Pi_0^u(p^2) + \frac{s_h^2}{2}\,\Pi_1^u(p^2)\right) u_R + \bar{d}_R \not{p} \left(\Pi_0^d(p^2) + \frac{s_h^2}{2}\,\Pi_1^d(p^2)\right) d_R \\ &+ \frac{s_h c_h}{\sqrt{2}} M_1^u(p^2)\, \bar{q}_L \widehat{H}^c u_R + \frac{s_h c_h}{\sqrt{2}} M_1^d(p^2)\, \bar{q}_L \widehat{H} d_R + h.c.\,.\end{aligned}$$

$$V(h)_{fermions} \approx -N_c \int \frac{d^4p}{(2\pi)^4}\left[\frac{\Pi_1^{q_1}}{\Pi_0^q} + \frac{\Pi_1^u}{\Pi_0^u}\right] \sin^2\frac{h}{f} + N_c \int \frac{d^4p}{(2\pi)^4}\left[\frac{(M_1^u)^2}{p^2\Pi_0^q\Pi_0^u}\right]\sin^2\frac{h}{f}\cos^2\frac{h}{f}$$

Simplified models:

$$\Pi_{gauge}[m_V] = \frac{p^2}{p^2 - m_V^2}$$

$$\widehat{\Pi}[m_1, m_2, m_3] = \frac{\left(m_2^2 + m_3^2 - p^2\right)}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

$$\widehat{M}[m_1, m_2, m_3] = -\frac{m_1 m_2 m_3}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

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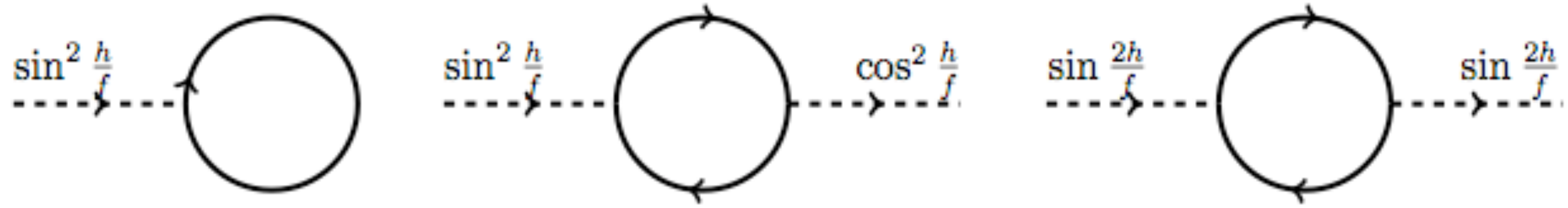
Gauge potential:

$$\begin{aligned} V(h)_{gauge} &\approx \int \frac{d^4p}{(2\pi)^4} \frac{9}{8} \frac{\Pi_1}{\Pi_0} \sin^2 \frac{h}{f} \\ &= \frac{9}{4} \frac{1}{16\pi^2} \frac{g_0^2}{g_\rho^2} \frac{m_\rho^4 \left(m_{a_1}^2 - m_\rho^2\right)}{m_{a_1}^2 - m_\rho^2(1 + g_0^2/g_\rho^2)} \ln\left[\frac{m_{a_1}^2}{m_\rho^2(1 + g_0^2/g_\rho^2)}\right] \sin^2 \frac{h}{f} \end{aligned}$$

Potential is finite with a single G multiplet!

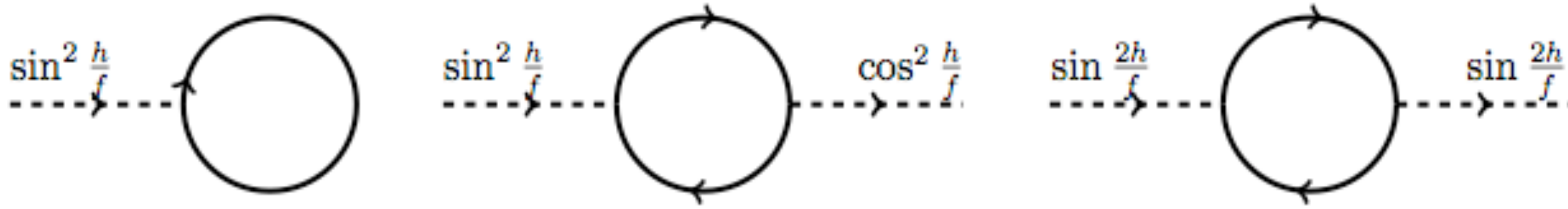
ESTIMATES



$$\mathcal{L}_{Yuk} = y_t f \, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \longrightarrow V(h)_{Yuk} \sim N_c \frac{y_t^2}{16\pi^2} m_f^2 f^2 s_h^2 c_h^2$$

$$\mathcal{L}_{kin} = \epsilon_L^2 \, s_h^2 \, \bar{t}_L \, \not{D} t_L + 2\,\epsilon_R^2 \, s_h^2 \, \bar{t}_R \, \not{D} t_R \longrightarrow V(h)_{kin} \sim N_c \frac{2\epsilon_R^2 - \epsilon_L^2}{32\pi^2} \, m_f^4 \, s_h^2$$

ESTIMATES



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Potential:

$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2 \qquad s_h \equiv \sin\frac{h}{f} = \frac{v}{f}$$

Quartic is determined by top Yukawa,

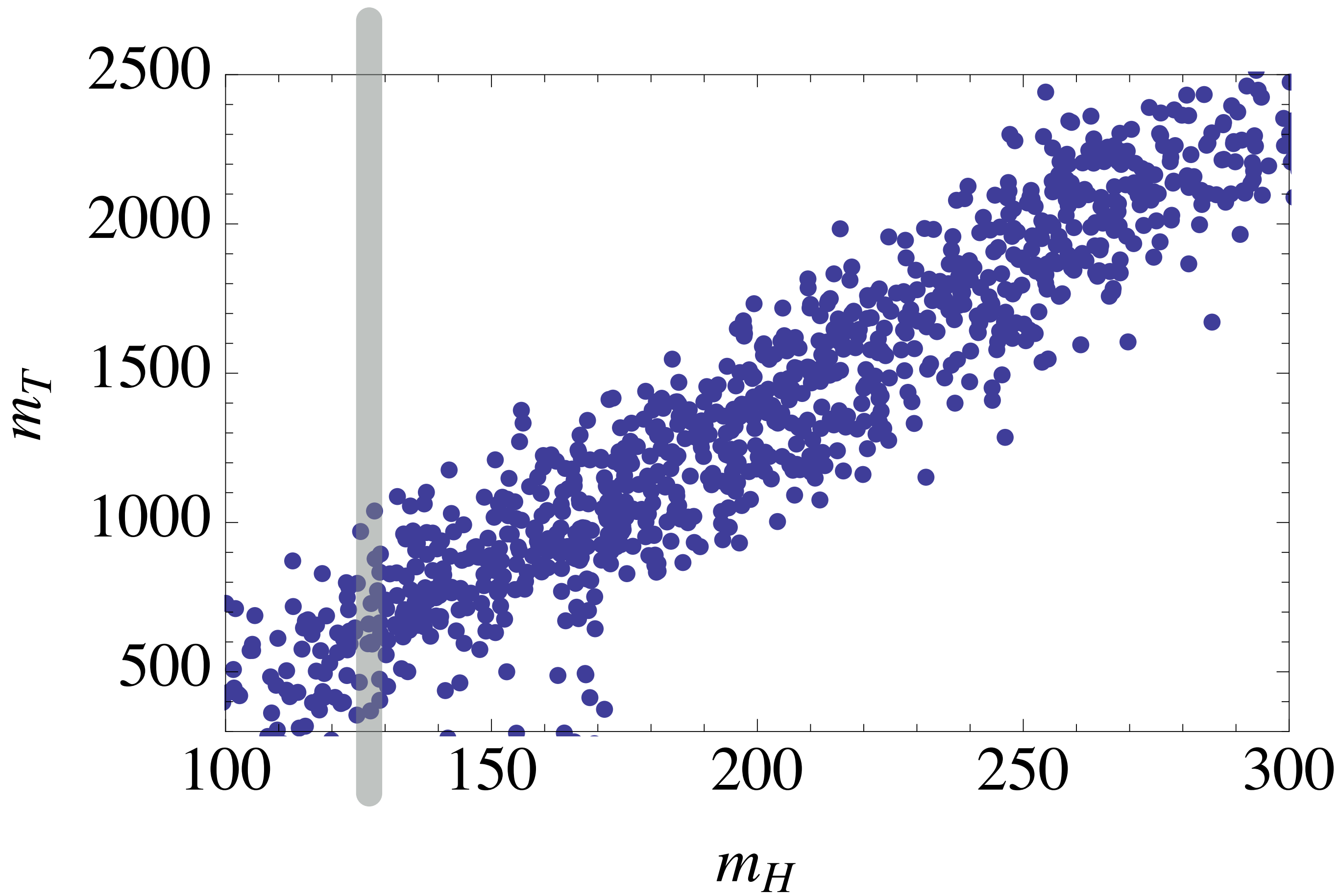
$$m_h \sim \sqrt{\frac{N_c}{2}}\, \frac{y_t}{\pi}\, \frac{m_f}{f} v$$

- CHM5

MR, Tesi '12

General scan:

$$f = 500\,\mathrm{GeV}$$



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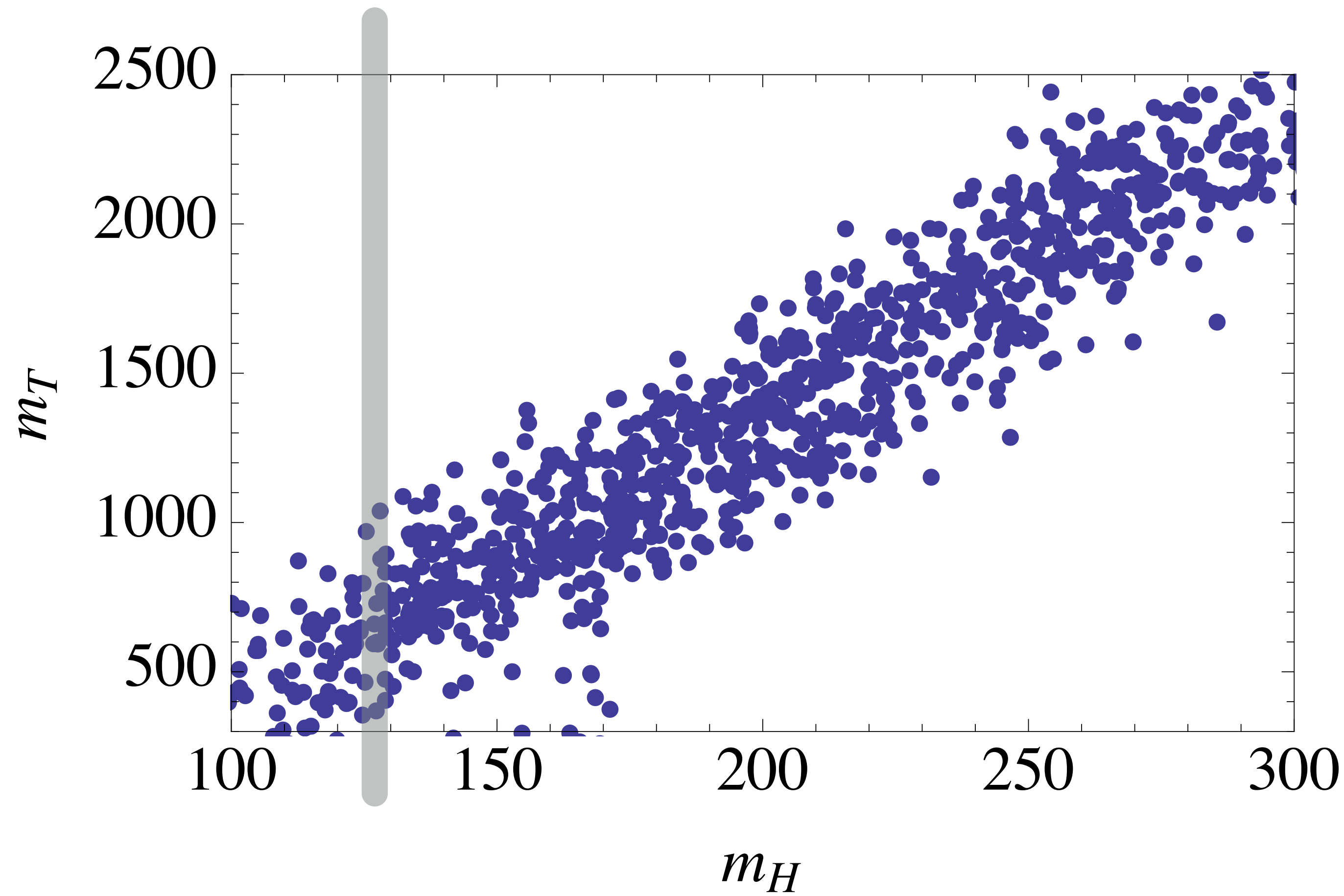
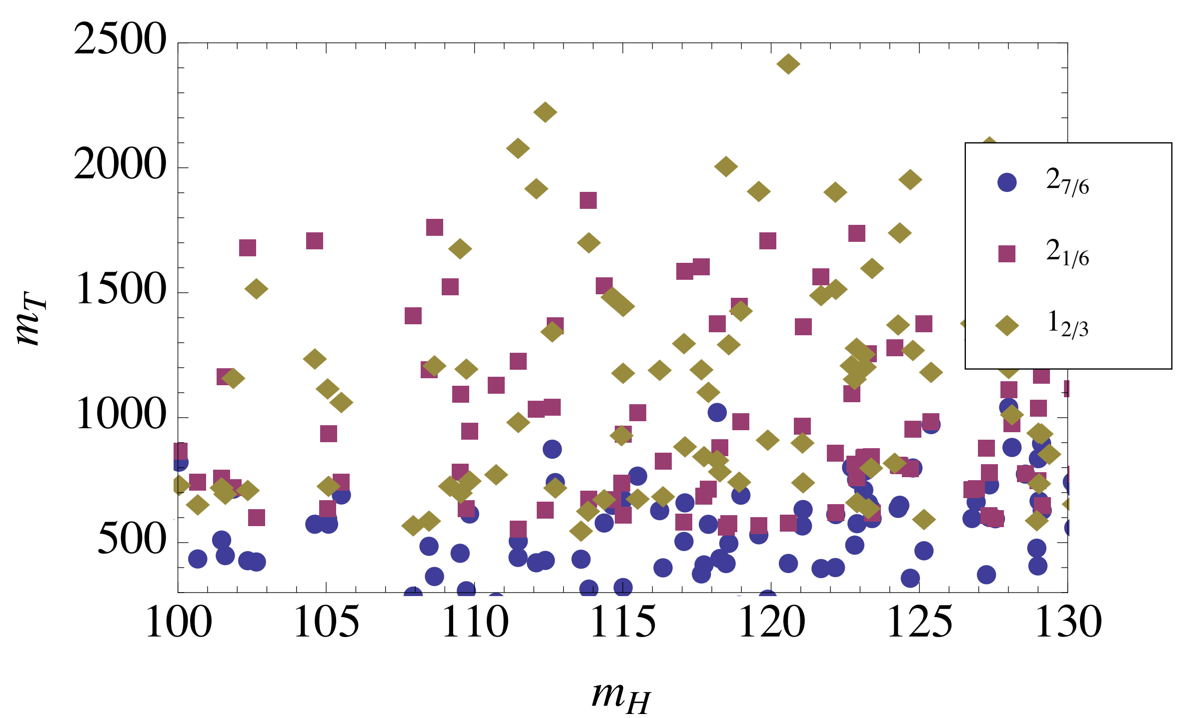
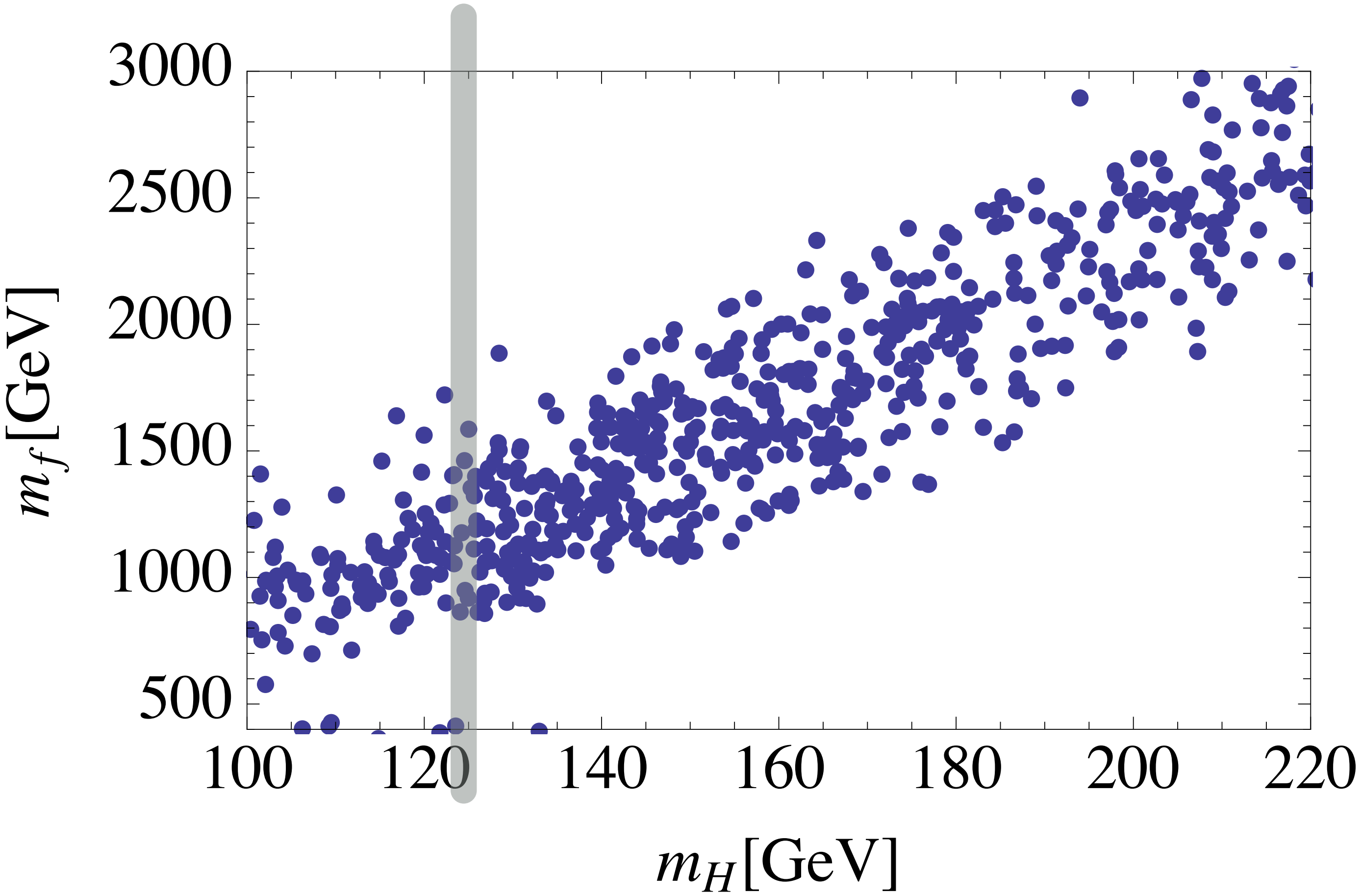


Low mass:

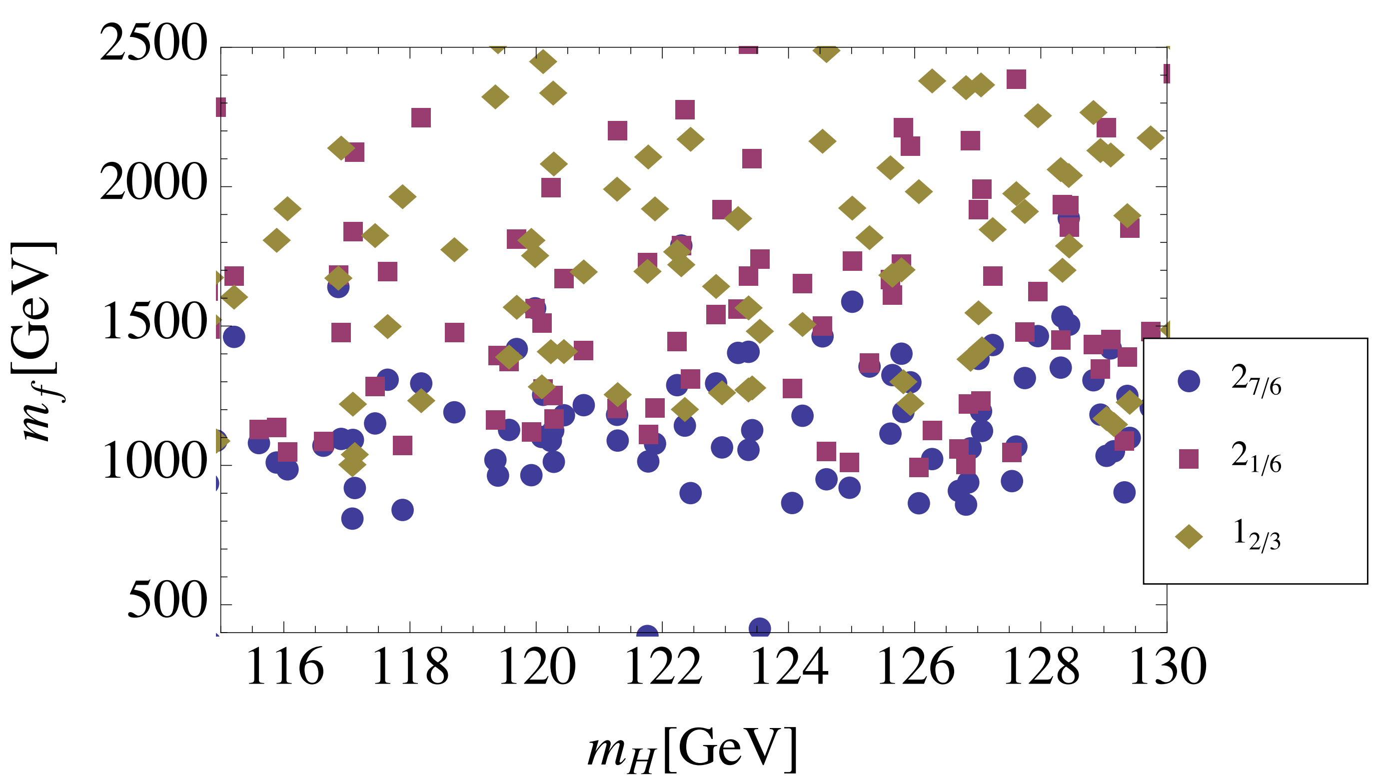


For mH=125 GeV, fermionic partners often rule out!



$f = 800\,\mathrm{GeV}$

Low mass:

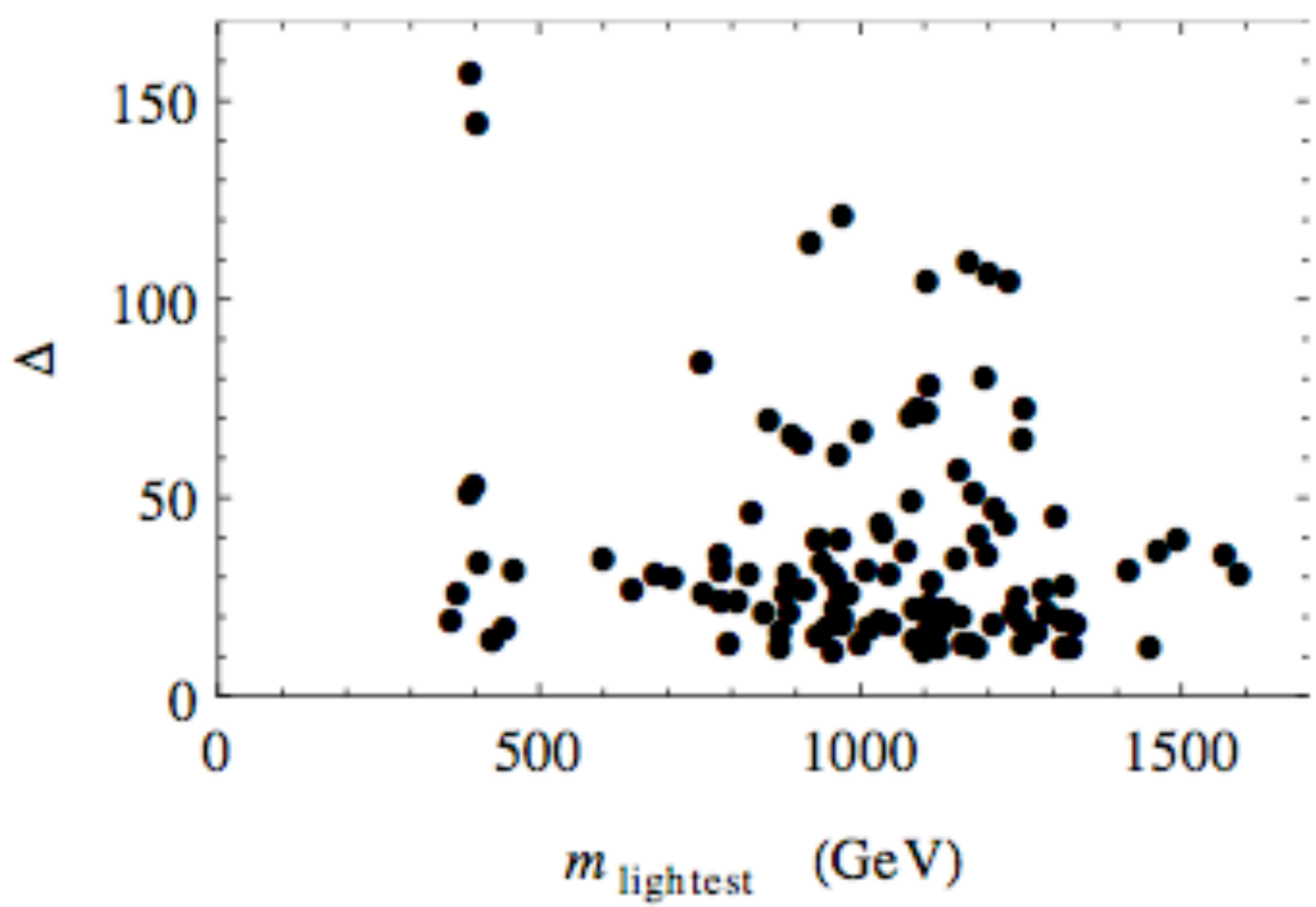


New fermions should be seen in the near future!

Tuning:

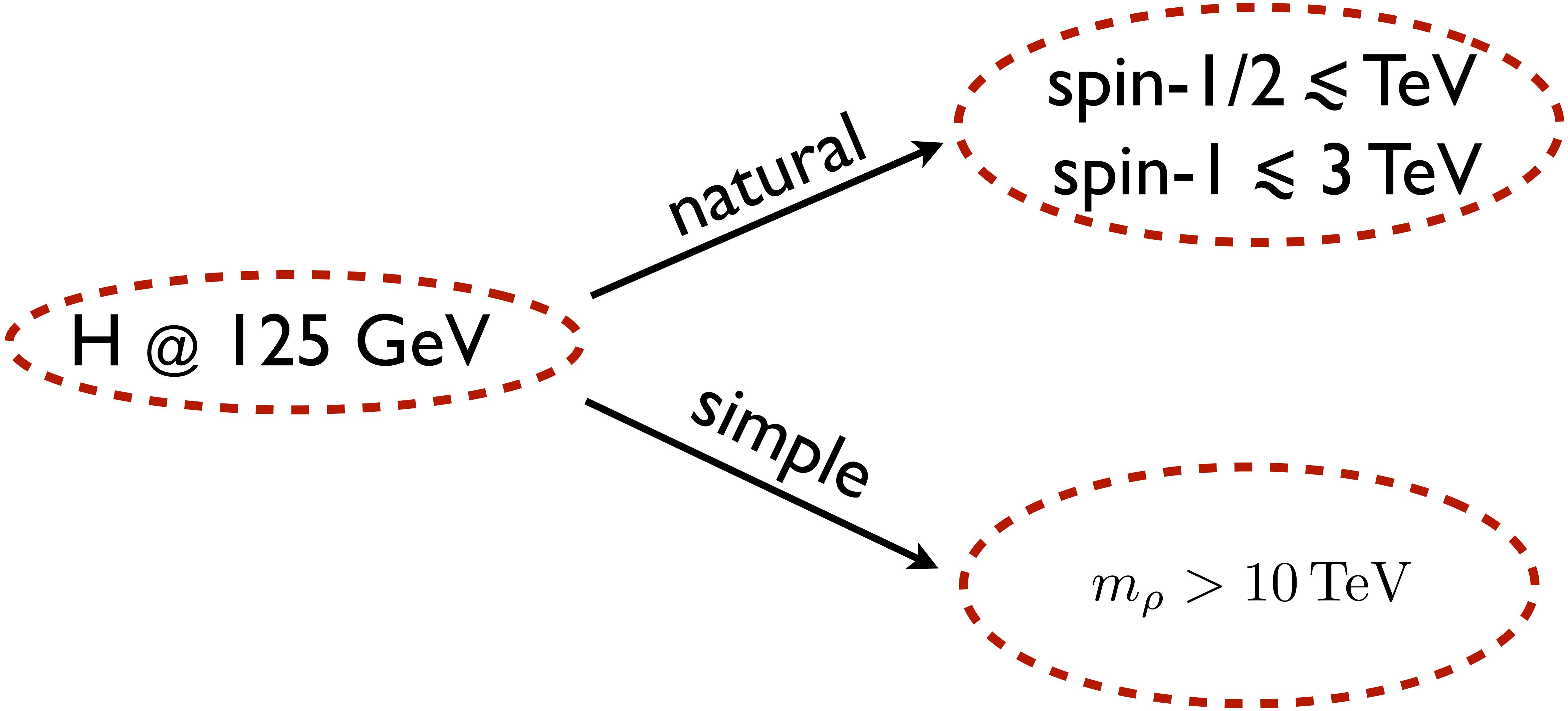
Panico, MR, Tesi, Wulzer '12

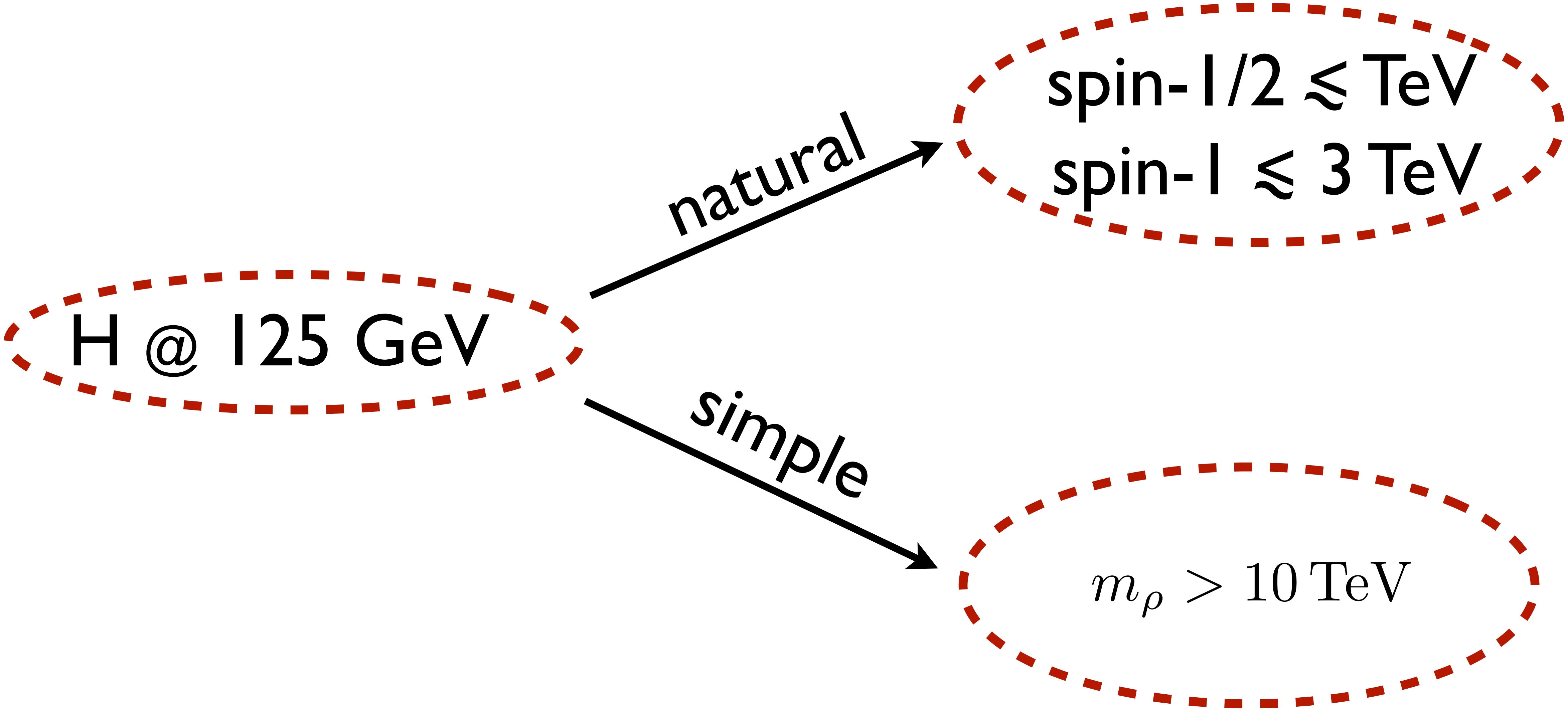
$$\Delta = \mathrm{Max_i} \left| \frac{\partial \log m_Z}{\partial \log x_i} \right|$$



$$f = 800\,\mathrm{GeV}$$

$$\Delta_{avg} \sim 30$$


H @ 125 GeV
natural
spin-1/2 $\lesssim$ TeV
spin-1 $\lesssim$ 3 TeV
simple
$m_\rho > 10\,\mathrm{TeV}$



Natural region of the theory will be tested at LHC!

SUMMARY

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± Many smart mechanisms have been proposed

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++ LHC will tell if the electro-weak scale is natural.
Very exciting experimentally.

SO(6)/SO(5):

Gripaios, Pomarol, Riva, Serra '09
Redi, Tesi '12

5 GBs:

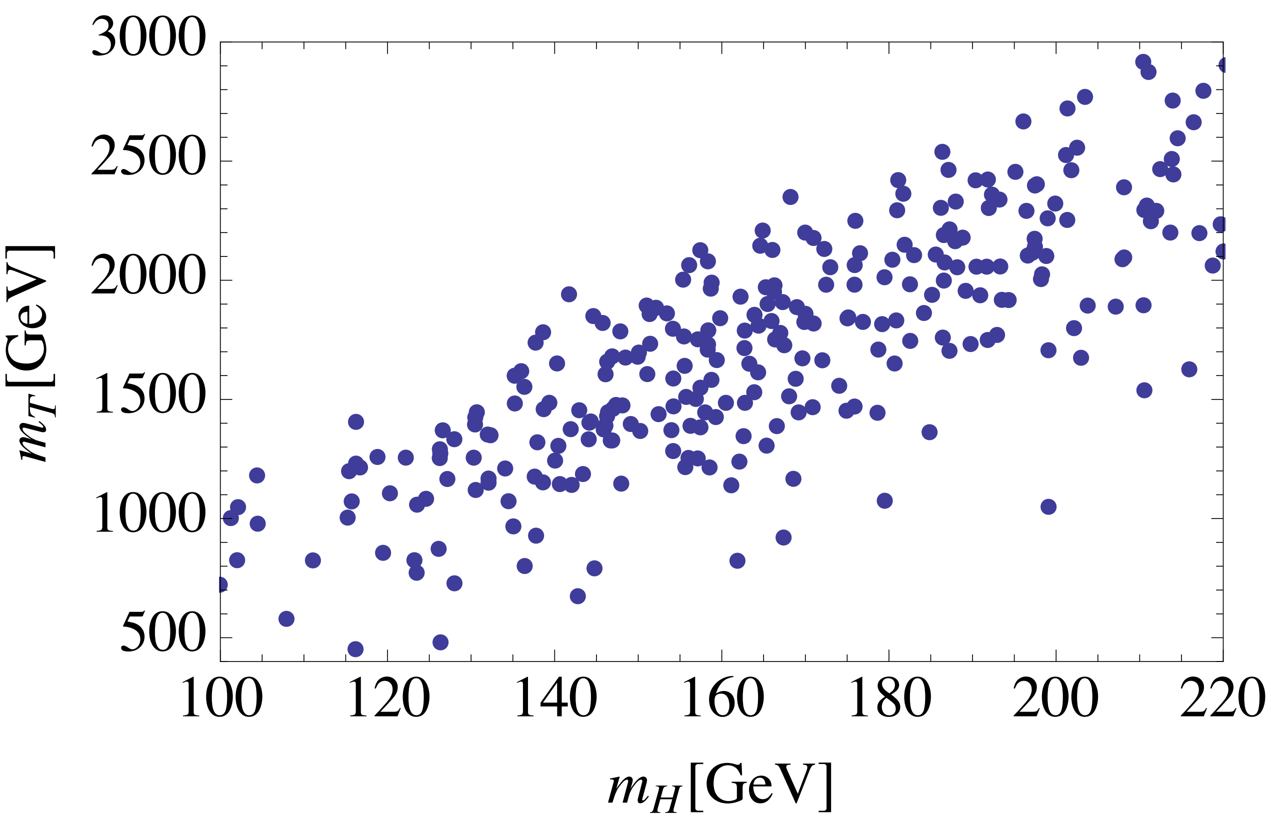
$$5 = (2,2) + 1$$

Fermions can be coupled to the 6=(2,2)+2 × 1

$$q_L \to \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} \qquad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\cos\theta\, t_R \\ \sin\theta\, t_R \end{pmatrix}$$

For $\theta = \frac{\pi}{4}$ singlet becomes exact GB.

$$f = 800\,\mathrm{GeV}$$



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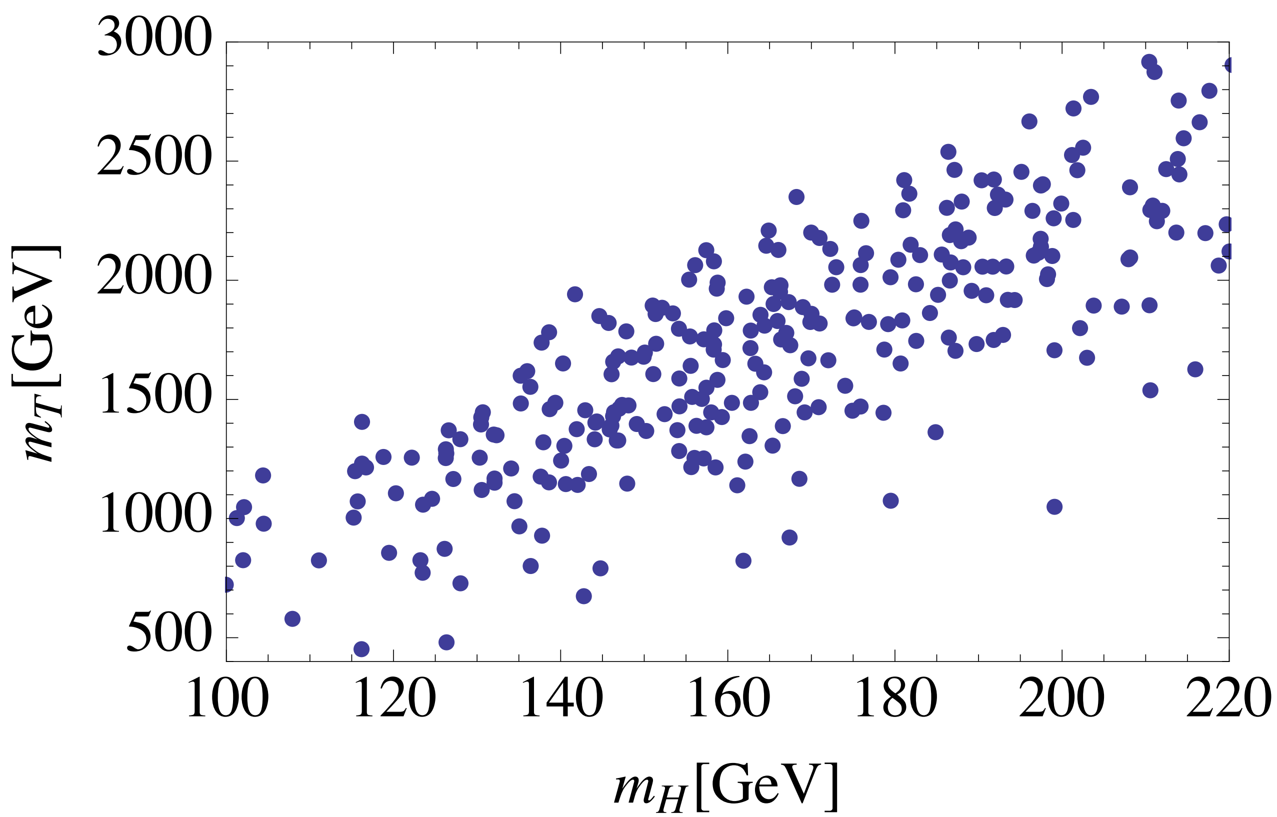

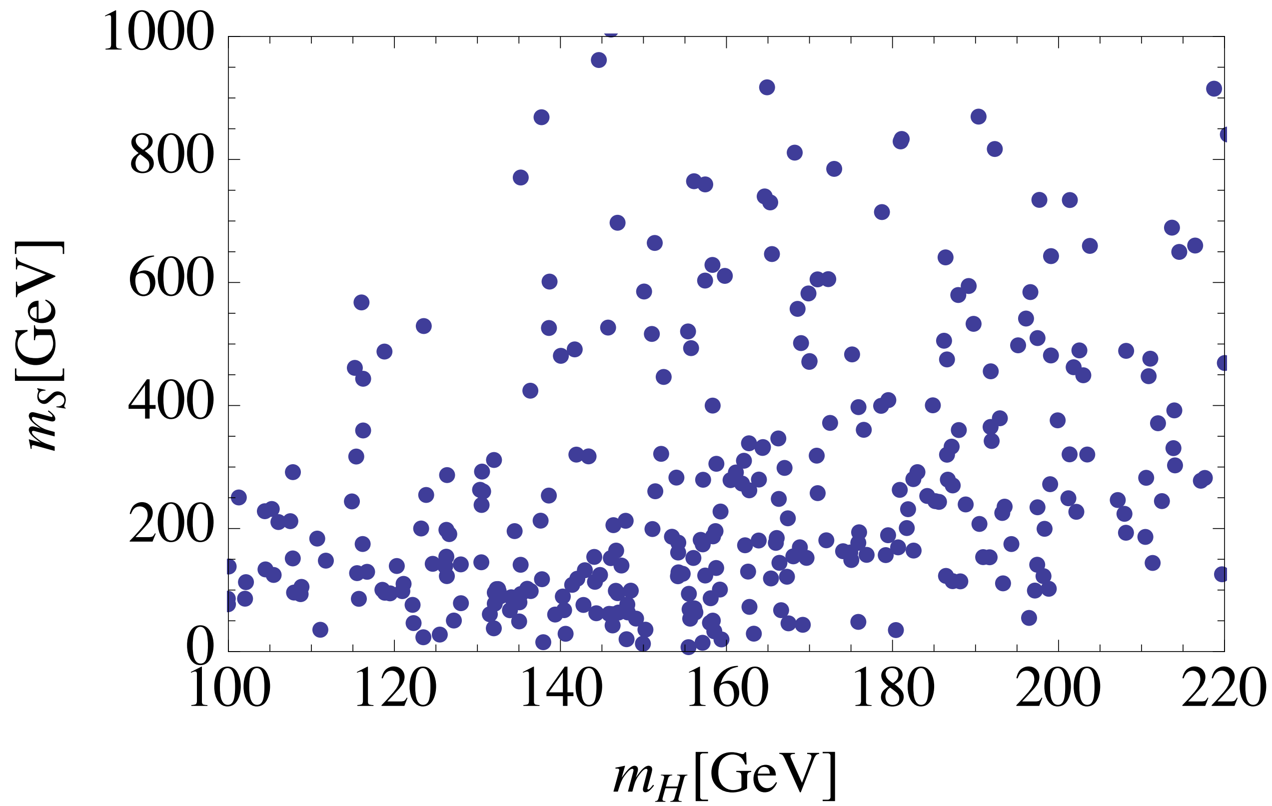

Same correlation Higgs-fermions.

Singlet typically heavier than Higgs unless $\theta \approx \frac{\pi}{4}$

ESTIMATES

$$\mathcal{L} = \left(1 + \epsilon_L^2 \sum_i I_L^{(i)}(s_h)\right) \bar{q}_L \partial q_L + \left(1 + \epsilon_R^2 \sum_i I_R^{(i)}(s_h)\right) \bar{t}_R \partial t_R$$
$$+ y_t f\, M(s_h) \bar{t}_L t_R + h.c.\,,$$

Loops of SM fields generate:

$$V_{\text{leading}} \sim \frac{N_c}{16\pi^2} m_\psi^4 \sum_i \left[\epsilon_L^2\, I_L^{(i)}(s_h) + \epsilon_R^2\, I_R^{(i)}(s_h)\right]$$

$$V_{\text{sub-leading}} \sim \frac{N_c}{16\pi^2} m_\psi^2 f^2 \;\left[y_t^2\, M^2(s_h) + \dots\right] \qquad \left(y_t \sim \epsilon_L \epsilon_R \frac{m_\psi}{f}\right)$$

$$s_h \equiv \sin\frac{h}{f} = \frac{v}{f}$$

Two different trigonometric structures needed to tune.

- Tuning at leading order

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t \frac{m_\psi^3}{f^3} v^2 \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$

- Tuning with sub-leading terms (CHM5, CHM10...)

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t^2 \frac{m_\psi^2}{f^2} v^2 \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{m_\psi}{y_t f} \times \frac{f^2}{v^2}$$

- Composite tR (CHM14)

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t^2 \frac{m_\psi^2}{f^2} v^2 \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$