4D Composite Higgs

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with Stefania de Curtis
and Andrea Tesi
arxiv:1110.1613[hep-ph]

DESY, 28 November

Randall-Sundrum Models Demystified

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DESY, 27 November

OUTLINE

- Higgs in extra-dimensions
  - Construction
  - Basic predictions

- 4D Composite Higgs
  - Effective Lagrangian
  - Higgs Potential
  - Non Minimal Terms

Soon we will know if the Higgs is fact or fiction.

Two paradigms:

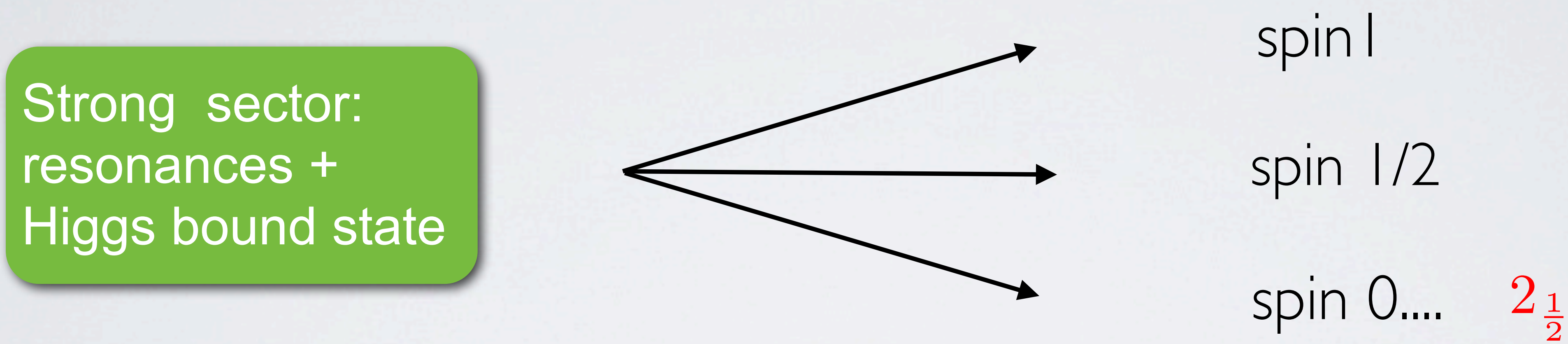
- Weak Coupling:
  SM, Supersymmetry

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

COMPOSITE HIGGS

Georgi, Kaplan '80s

A logical possibility is that Higgs doublet is a light remnant of strong dynamics.



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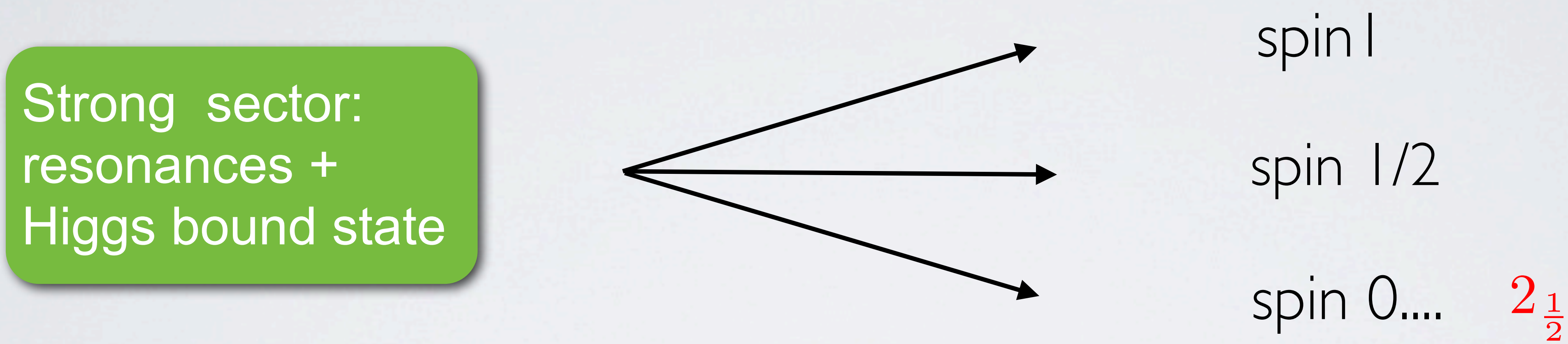

Two parameters:

m_ρ g_ρ $(1 < g_\rho < 4\pi)$

Relieves hierarchy problem:

$$\delta m_h^2 \sim \frac{3\,\lambda_t^2}{4\pi^2} m_\rho^2$$

Particularly compelling if the Higgs is a Goldstone Boson:

Massless at leading order:

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

Agashe , Contino, Pomarol, '04

Low energy lagrangian:

$$\mathcal{L} = f^2\, D_\mu \Sigma^i D^\mu \Sigma^i + \ldots \xrightarrow{SU(2)_L \otimes SU(2)_R} \rho = \frac{m_W^2}{m_Z^2 \cos\theta_W} \approx 1$$

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Extended Higgs sectors:

Ex: $\dfrac{SO(6)}{SO(5)} \qquad \dfrac{SO(6)}{SO(4)\otimes U(1)} \qquad \dfrac{SU(5)}{SU(4)\otimes U(1)} \qquad + \dots$

Gripaios, Pomarol, Serra '09

Mrazek, Pomarol, Rattazzi, MR, Serra, Wulzer '11

Main difference from techni-color is that f is not linked to v.
Increasing f CH approximates SM.

$$\mathrm{TUNING} \sim \frac{\mathrm{v}^2}{\mathrm{f}^2}$$

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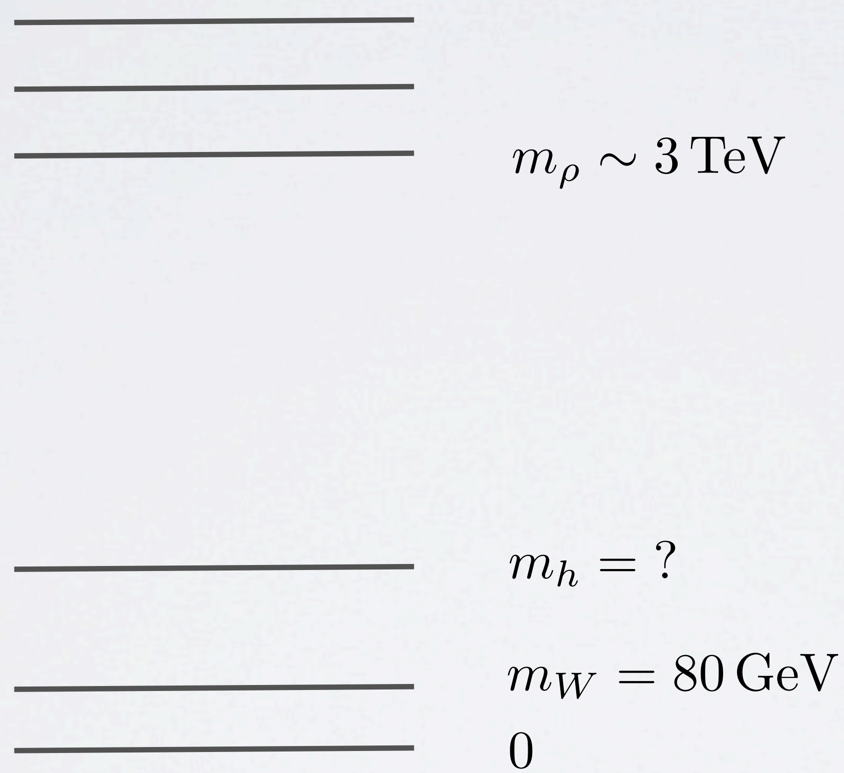
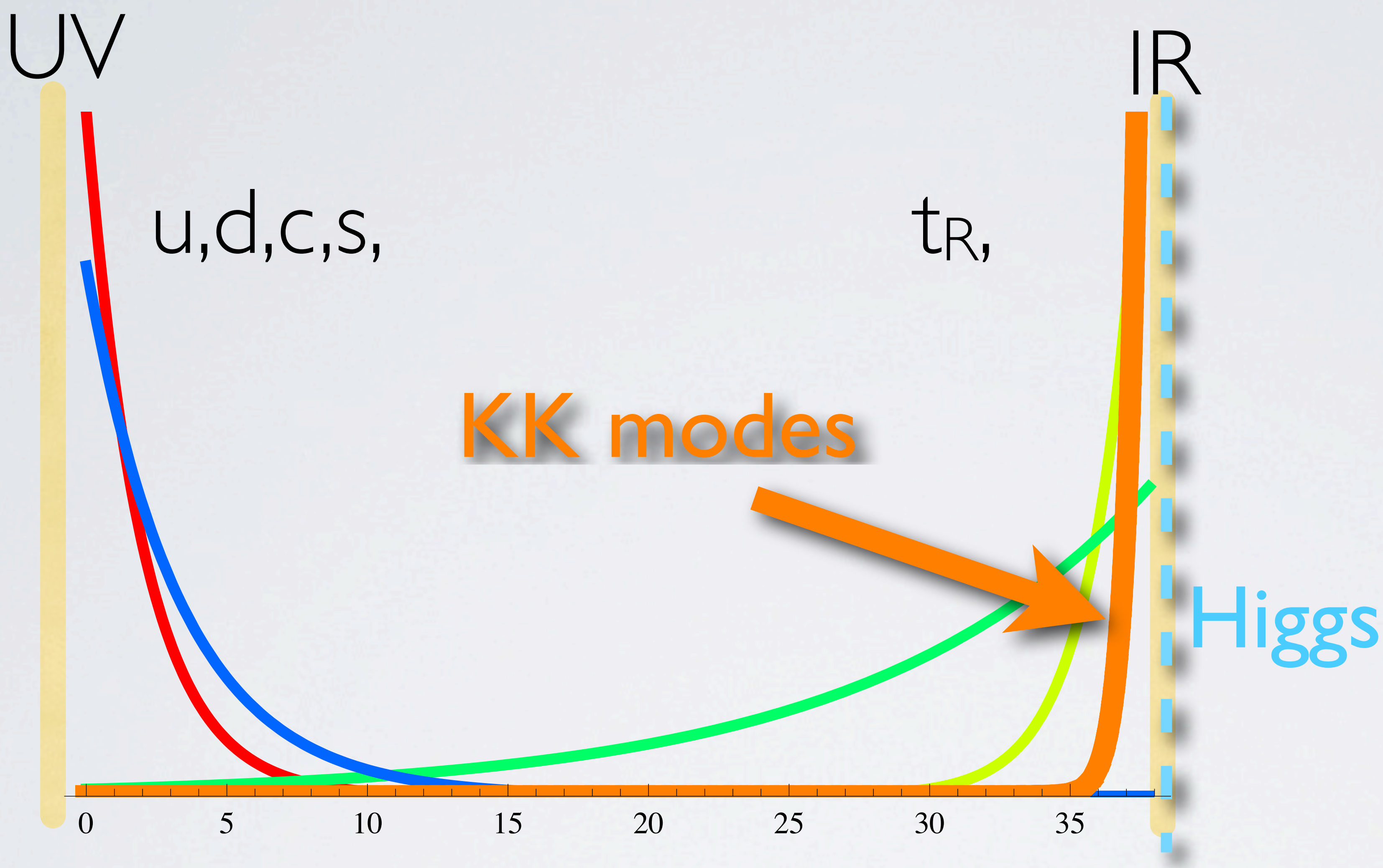
Spectrum:



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

Reasonable phenomenology can be obtained for $m_\rho \sim 3\,\text{TeV}$

Recent progress started with Randall-Sundrum constructions.



(Randall-Sundrum '99)

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

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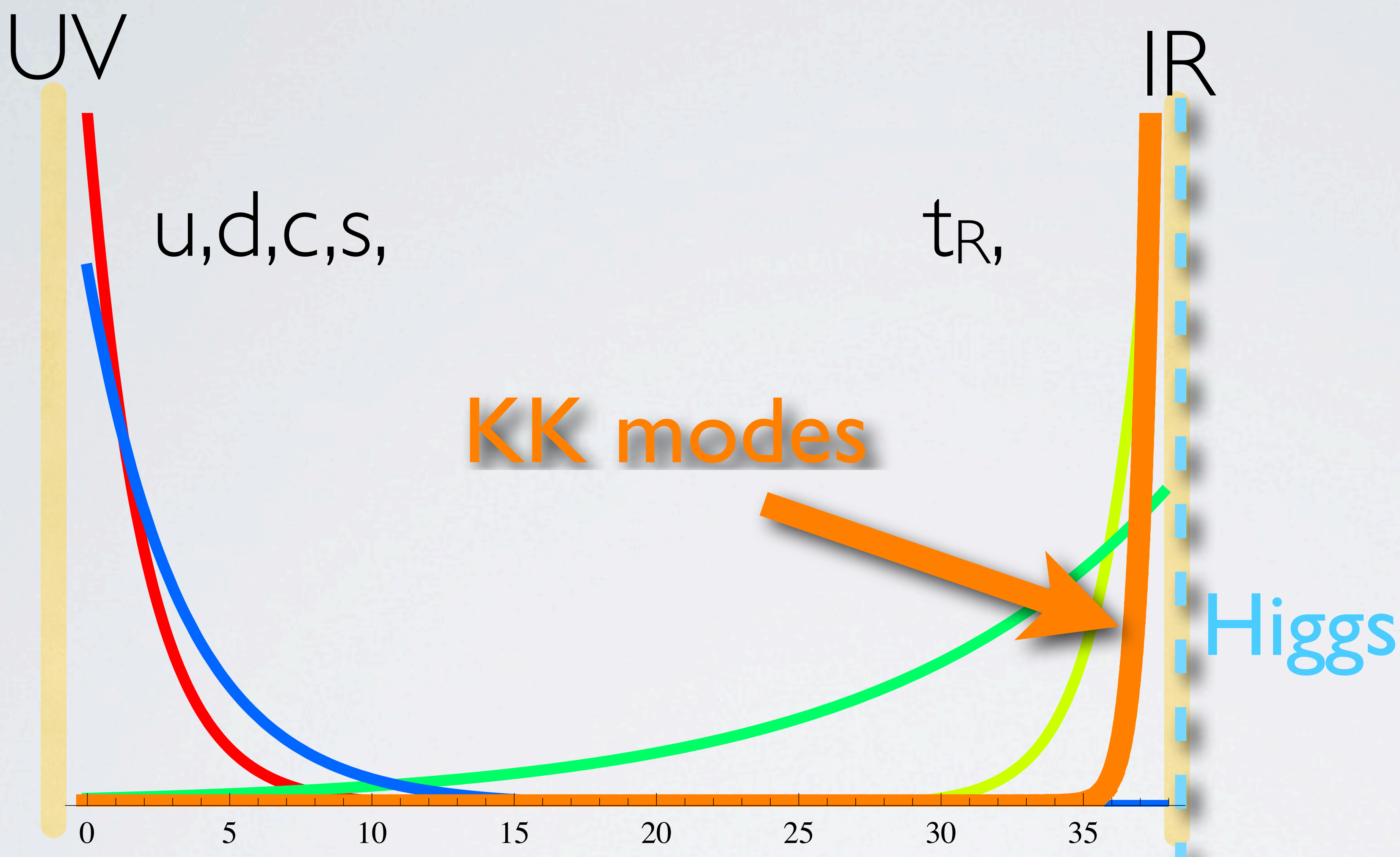

(Randall-Sundrum '99)

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

Originally the SM was localized on the IR brane and the hierarchy was "explained" by the warping.

$$\Lambda_{IR} = M_5 e^{-k\pi r_c}$$

More interesting physics is obtained with SM in the bulk.

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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Goldstone bosons 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

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

Yukawas hierarchies are generated

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

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In the standard scenario $Y^{U,D}$ are anarchic.
Small couplings are obtained from small mixings:

- Light generations mostly elementary

- Top strongly composite

We can use the AdS/CFT correspondence

Arkani-Hamed, Porrati, Randall ’00

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

We can use the AdS/CFT correspondence

Arkani-Hamed, Porrati, Randall ’00

5D gauge symmetry ⟶ 4D global symmetry

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

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

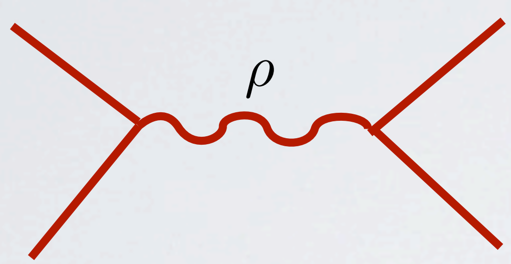
Contino, Pomarol ’04

- d>5/2 irrelevant, small in IR (light generations)
- d<5/2 relevant, large in IR (top)

Hierarchies are generated by the dimensional transmutation

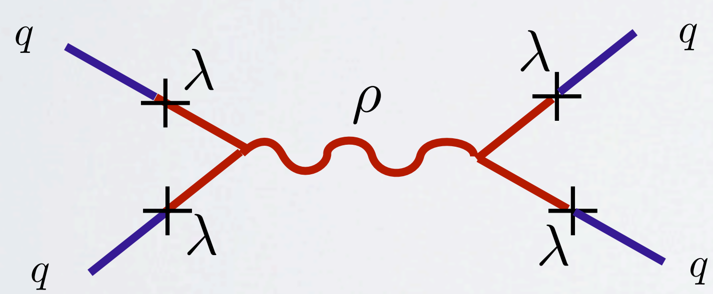
“RS-GIM”

Resonance exchange generates flavor violating 4-Fermi operators



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

FCNC of the light generation are suppressed by the mixings,

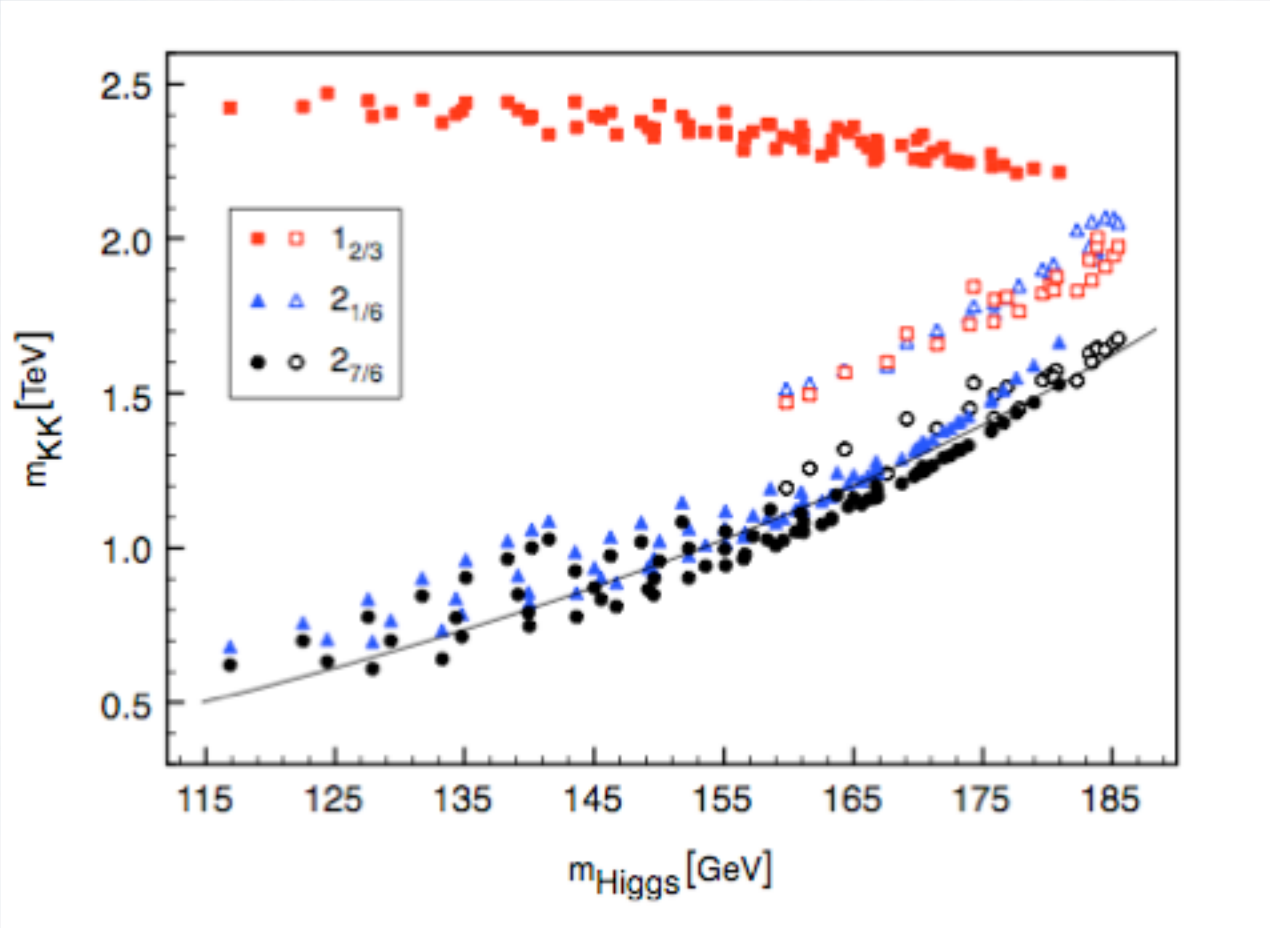


$$C_4^K \, \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta \qquad C_4^K \sim \frac{g_\rho^2}{m_\rho^2} \frac{m_d \, m_s}{v^2}$$

Csaki, Falkowski, Weiler, ’08

Flavor superior to TC theories though not perfect.

One virtue is that the 5D theory is weakly coupled and one can compute. CHM5:



(Contino, da Rold, Pomarol '06)

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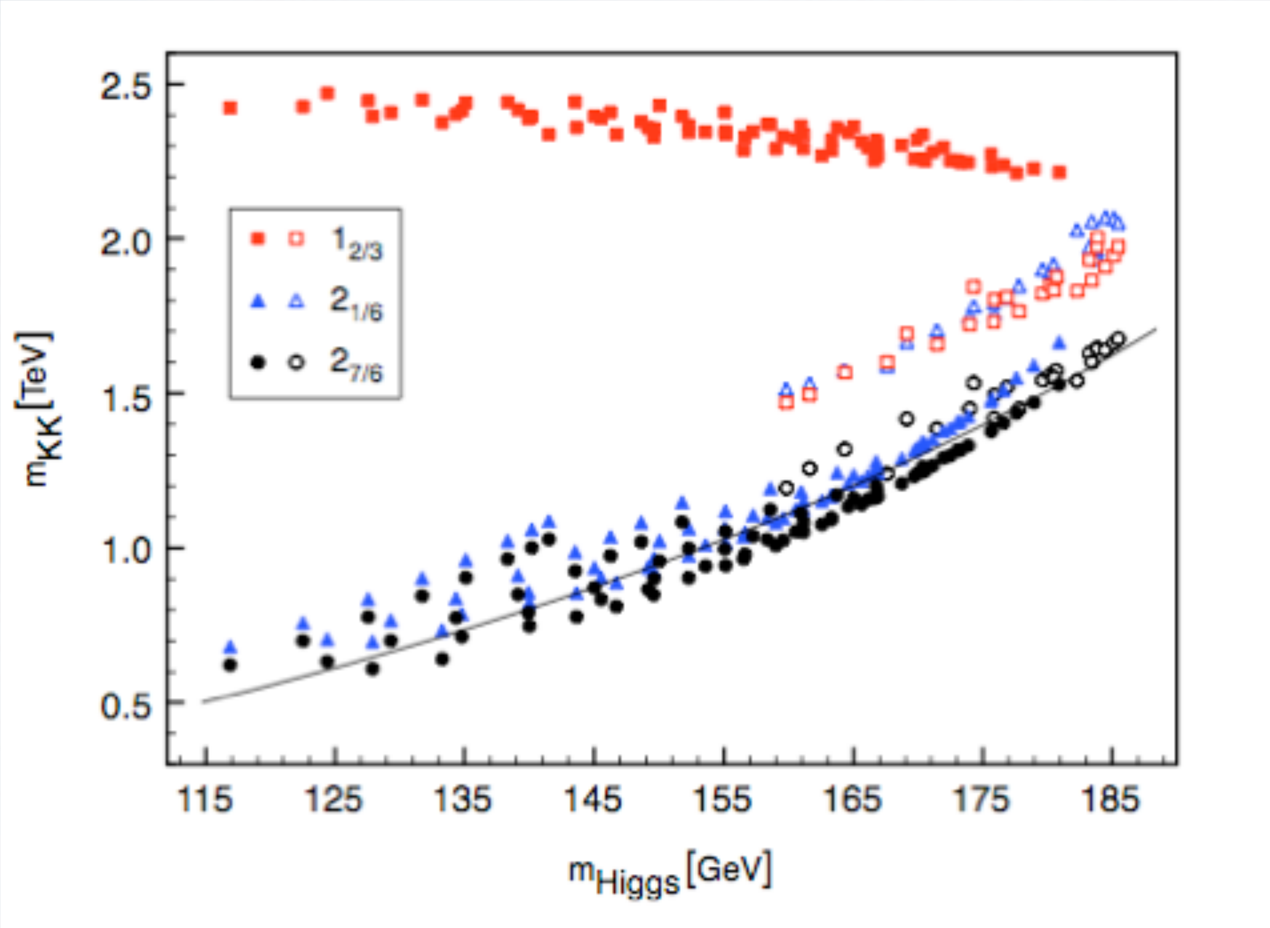

(Contino, da Rold, Pomarol '06)

In practice the 5D theory cannot be very weakly coupled

$$\Lambda = \frac{1}{g_5^2} \qquad N_{eff} \sim \frac{1}{g_5^2\, m_\rho} \qquad \hat{S} \sim \frac{N_{eff}}{16\pi^2}\frac{v^2}{f^2}$$

Composite sector more hidden if strongly coupled.

Many reason to abandon 5D:

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

- practical:
  - LHC will at best be able to produce the first resonance
  - Simplified model useful for LHC

Two sectors:

Contino, Kramer, Son, Sundrum '06
Giudice, Grojean, Pomarol, Rattazzi'07
Panico, Wulzer '11
de Curtis, MR, Tesi '11

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

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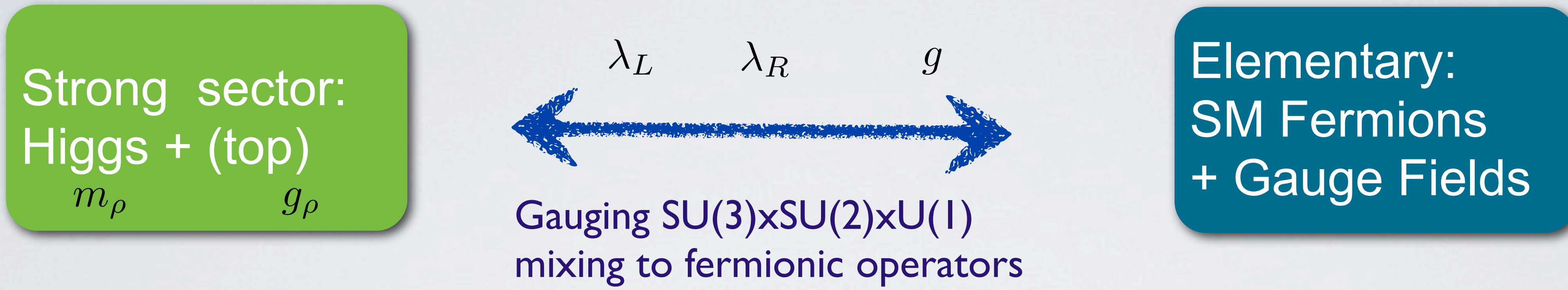

They talk through linear couplings:

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

$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \quad \xrightarrow{\tan\varphi \sim \frac{\lambda}{g_\rho}} \quad y \sim \frac{\lambda_L \lambda_R}{g_\rho}$$

Potential generated at 1-loop:

$$V(H) \propto \frac{m_\rho^4}{g_\rho^2} \frac{\lambda_{L,R}^2}{16\pi^2} \hat{V}\left(\frac{H}{f}\right)$$

Contino, Kramer, Son, Sundrum '06

Simplified 2 site picture:

Each SM chirality has a Dirac fermionic partner

$$\mathcal{L}_{composite} = \bar{Q}(i \not{D} - m_Q)Q + \bar{T}(i \not{D} - m_T)T + Y_T \bar{Q}\tilde{H}T$$

$$\mathcal{L}_{mixing} = \frac{m_\rho}{g_\rho}\left[\lambda_L \bar{q}_L Q_R + \lambda_R t_R \bar{T}_L + \text{h.c.}\right]$$

Mass basis:

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} = \begin{pmatrix} \cos\varphi_{q_L} & -\sin\varphi_{q_L} \\ \sin\varphi_{q_L} & \cos\varphi_{q_L} \end{pmatrix} \begin{pmatrix} q_L^{el} \\ Q_L^{co} \end{pmatrix}$$

$$m_H = \frac{m_Q}{\cos\varphi_{q_L}}$$

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$$m_H = \frac{m_Q}{\cos\varphi_{q_L}}$$

Gauge fields:

$$\begin{pmatrix} A_\mu \\ \rho_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu^{el} \\ \rho_\mu^{co} \end{pmatrix}$$

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

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

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

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To generate Yukawa for the down sector

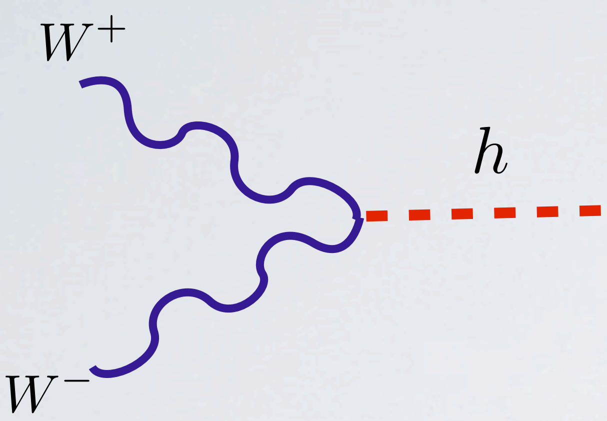
q_L	$\longrightarrow$	$(2,2)_{-\frac{1}{3}}$	$L_D = \begin{pmatrix} B_{-\frac{1}{3}} & T' \\ B_{-\frac{4}{3}} & B' \end{pmatrix}$
d_R	$\longrightarrow$	$(1,1)_{-\frac{1}{3}}$	D

Corrections to SM couplings of down quarks are small and zero for right quarks.

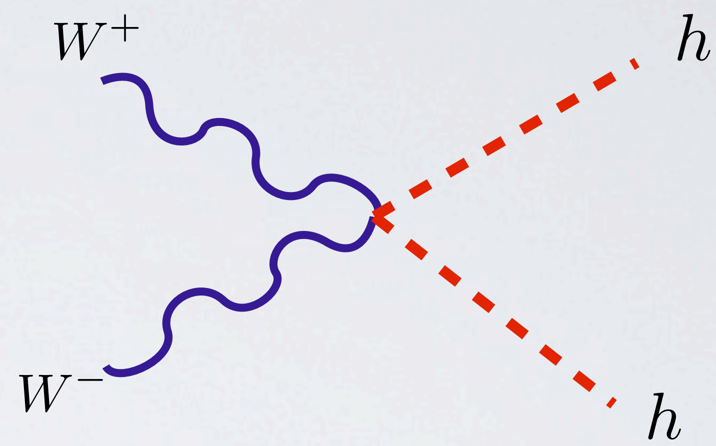
Agashe , Contino,
da Rold, Pomarol, '04

This description misses the GB structure.

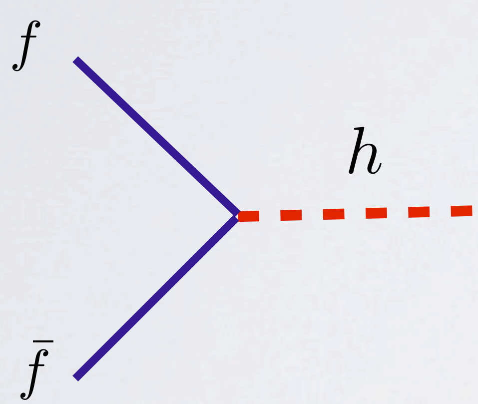
Modified couplings:



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



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



$$= -\frac{m_f}{\sqrt{2} v} b$$

$$\mathrm{SM:} \quad \mathrm{a = b = c = 1}$$

a, b, c receive corrections of order (v/f)^2.

Modified Higgs cross-sections.

WW scattering not exactly unitarized.

Take G broken to H. Low energy lagrangian determined by CCWZ constructions

$$U(\Pi) = e^{\frac{i\Pi^{\hat{a}} T^{\hat{a}}}{f}}$$

$$U(\Pi') = gU(\Pi)h^\dagger(\Pi, g) \quad g \in G, \quad h \in H(x)$$

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

GB lagrangian

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

Matter couplings,

$$\bar{\psi}\gamma^\mu(\partial_\mu + iE_\mu)\psi$$

Many ways to introduce resonances. We add

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

and gauge $G_R + G$

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

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

Natural to have H and G/H resonances.
In QCD these are vector and axial resonances.

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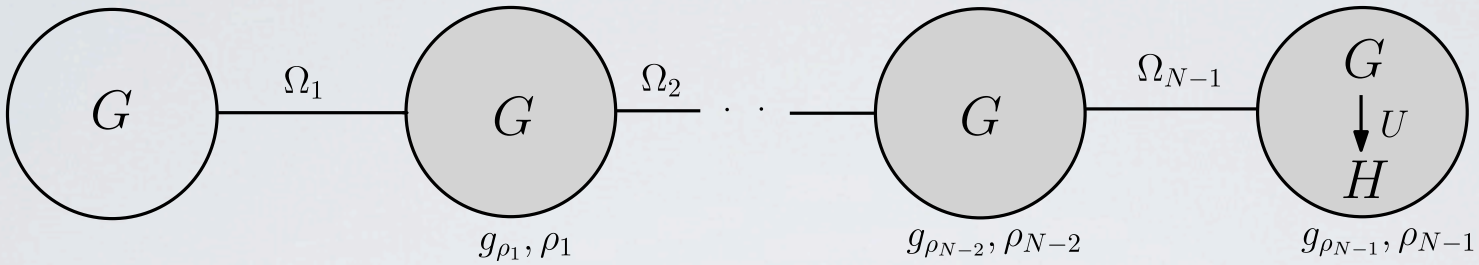
In QCD these are vector and axial resonances.

We recover CCWZ for $f_2 \to \infty$

$$\mathcal{L} = \frac{f^2}{2} D_\mu^{\widehat{a}} D^{\mu \widehat{a}} - \frac{1}{4 g_\rho^2} \rho_{\mu\nu}^a \rho^{\mu\nu a} + \frac{f'^2}{2} (\rho_\mu^a - E_\mu^a)^2$$

In general:



$$\mathcal{L}_{N-sites} = \sum_{n=1}^{N-1} \frac{f_n^2}{4} \mathrm{Tr}\,|D_\mu \Omega_n|^2 + \frac{f_N^2}{2} \mathcal{D}_\mu^{\widehat{a}} \mathcal{D}^{\mu \widehat{a}} - \sum_{n=1}^{N-1} \frac{1}{4\, g_{\rho_n}^2} \rho_{n,\mu\nu}^A \rho_n^{A\mu\nu}$$

$$D^\mu \Omega_n = \partial^\mu \Omega_n - i\rho_{n-1}^\mu \Omega_n + i\Omega_n \rho_n^\mu, \qquad n = 1, .., N-1$$

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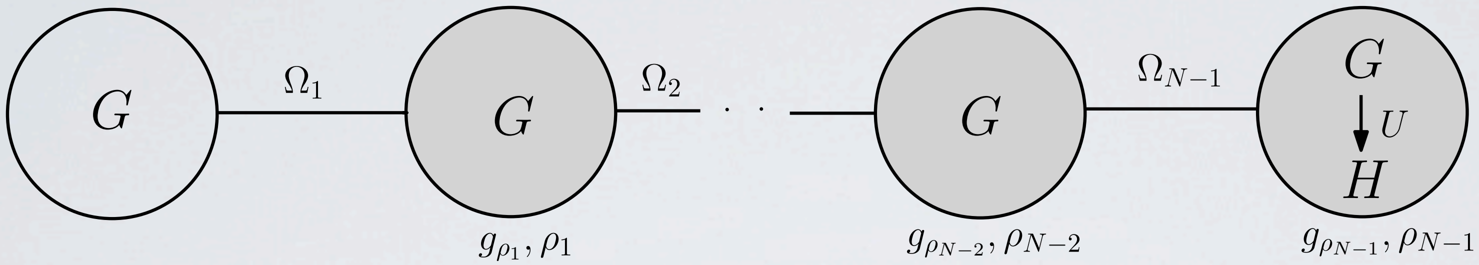

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$$D^\mu \Omega_n = \partial^\mu \Omega_n - i\rho_{n-1}^\mu \Omega_n + i\Omega_n \rho_n^\mu, \qquad n = 1, .., N-1$$

GBs are

$$\Omega_n = \exp i \frac{f}{f_n^2} \Pi, \quad n = 1, ..., N \qquad\qquad \sum_{n=1}^{N} \frac{1}{f_n^2} = \frac{1}{f^2}$$

$$\boldsymbol{U'} \equiv \left(\Pi_{n=1}^{N-1} \Omega_n\right) U$$

For N large we recover the 5D theory.
The boundary conditions are not rigid for f_N finite.

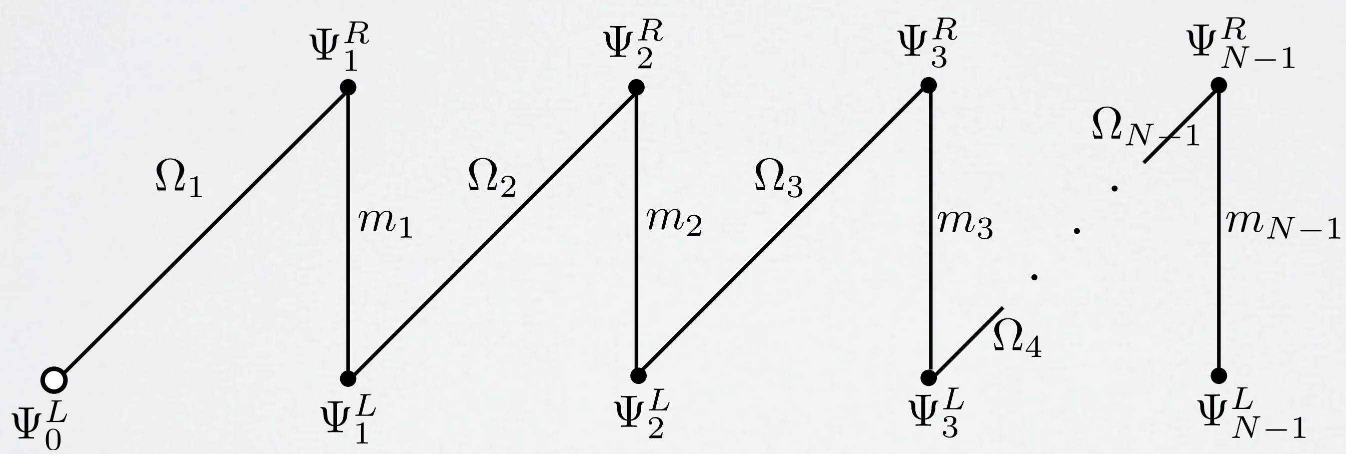
Fermions:

$$\mathcal{L}_{fermions} = \sum_{n=1}^{N-1} \bar{\Psi}_n^{(r)} \left[i \not{D}^{\rho_n} - m_n^{(r)} \right] \Psi_n^{(r)} + \sum_{n=1}^{N-1} \Delta_n^{(r)} \left(\bar{\Psi}_{r,L}^{n-1} \Omega_n \Psi_{r,R}^{n} + h.c. \right)$$

$$D^\mu \Psi_n^{(r)} = \partial^\mu \Psi_n^{(r)} - i \rho_n^\mu \Psi_n^{(r)}$$

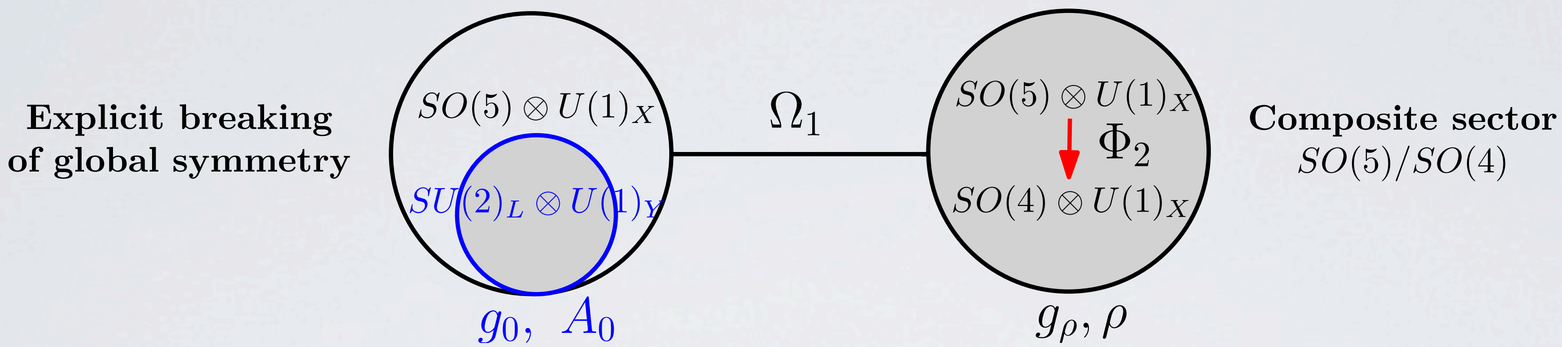
$$\mathcal{L}_{\frac{G}{H}} = m_\Psi \sum \bar{\Psi}_L^{(r),N-1} U(\Pi) P_A^{rs} U(\Pi)^\dagger \Psi_R^{(s),N-1} + h.c$$

LR structure



Inspired by 5D.

MINIMAL 4D CH



Realistic models can realized with the pattern

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

Extra $U(1)_X$

$$Y=T_{3R}+X$$

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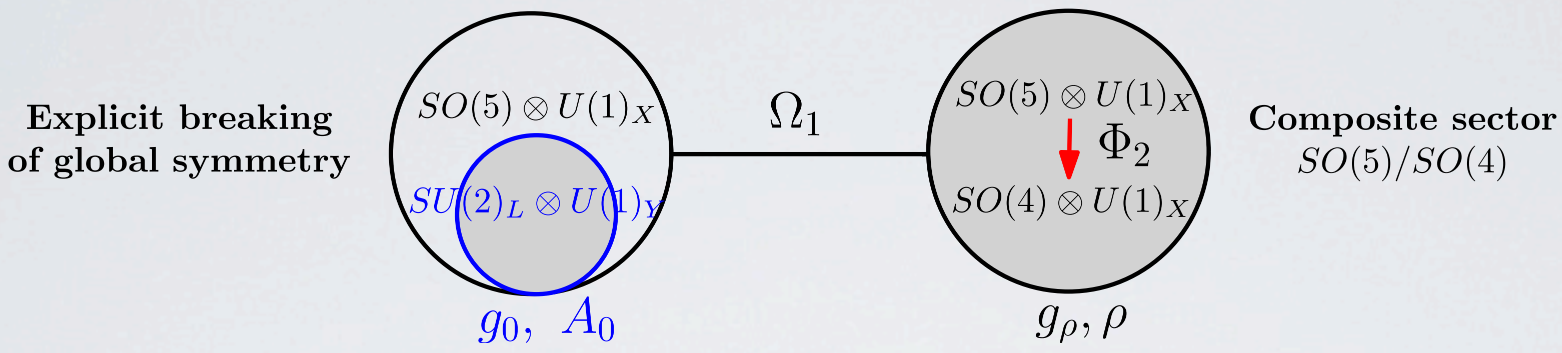

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Composite spin-1 lagrangian

$$\mathcal{L}_{gauge} = \frac{f_1^2}{4}\mathrm{Tr}\left|D_\mu\Omega_1\right|^2 + \frac{f_2^2}{2}\left(D_\mu\Phi_2\right)\left(D^\mu\Phi_2\right)^T - \frac{1}{4g_\rho^2}\rho^A_{\mu\nu}\rho^{A\mu\nu}$$

$$\Omega_1 = \mathbf{1} + i\frac{s_1}{h}\Pi + \frac{c_1-1}{h^2}\Pi^2 \qquad \Phi_2 = \phi_0 e^{-i\frac{\Pi}{f_2}} = \frac{1}{h}\sin\frac{h}{f_2}\left(h_1,\, h_2,\, h_3,\, h_4,\, h\cot\frac{h}{f_2}\right)$$

Spectrum:

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

SM fields are introduced adding kinetic terms for the sources

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

Physical parameters

$$\frac{1}{g^2} = \frac{1}{g_0^2} + \frac{1}{g_\rho^2}$$
$$\frac{1}{g'^2} = \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho X}^2}$$

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

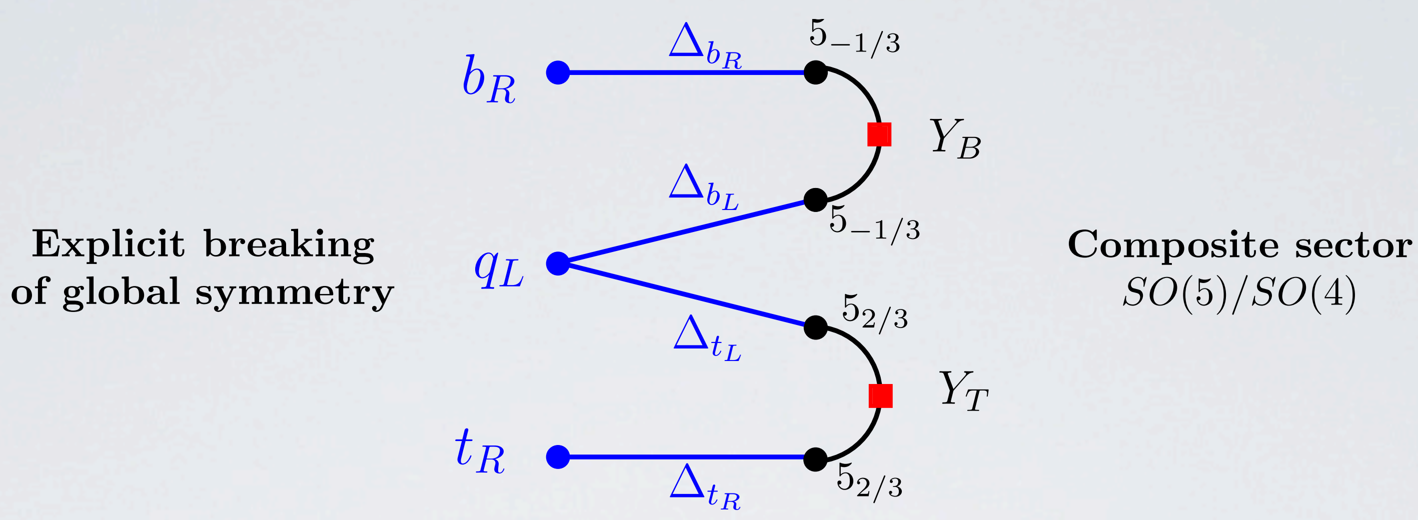
Composite fermions are associated to a reps of SO(5).
In CHM5 up quarks couple to

$$\mathbf{5}_{2/3} = (\mathbf{2},\mathbf{2})_{2/3} \oplus (\mathbf{1},\mathbf{1})_{2/3}, \quad (\mathbf{2},\mathbf{2})_{2/3} = \begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix}$$

Left and right components correspond to different 5.

Down quarks

$$\mathbf{5}_{-1/3} = (\mathbf{2},\mathbf{2})_{-1/3} \oplus (\mathbf{1},\mathbf{1})_{-1/3}, \quad (\mathbf{2},\mathbf{2})_{-1/3} = \begin{pmatrix} B_{-\frac{1}{3}} & T' \\ B_{-\frac{4}{3}} & B' \end{pmatrix}.$$



Third generation

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

$$\mathcal{L}^{el}_{fermions} = \frac{1}{y^2_{q_L}} \bar{q}^{el}_L i \not{D}^{el} q^{el}_L + \frac{1}{y^2_{t_R}} \bar{t}^{el}_R i \not{D}^{el} t^{el}_R + \frac{1}{y^2_{b_R}} \bar{b}^{el}_R i \not{D}^{el} b^{el}_R$$

Masses

$$m_t \sim \frac{v}{\sqrt{2}} \frac{y_{t_L}\Delta}{m_T} \frac{y_{t_R}\Delta}{m_{\widetilde{T}}} \frac{Y_T}{f}$$

Higgs potential generated from the Coleman-Weinberg effective potential

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

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

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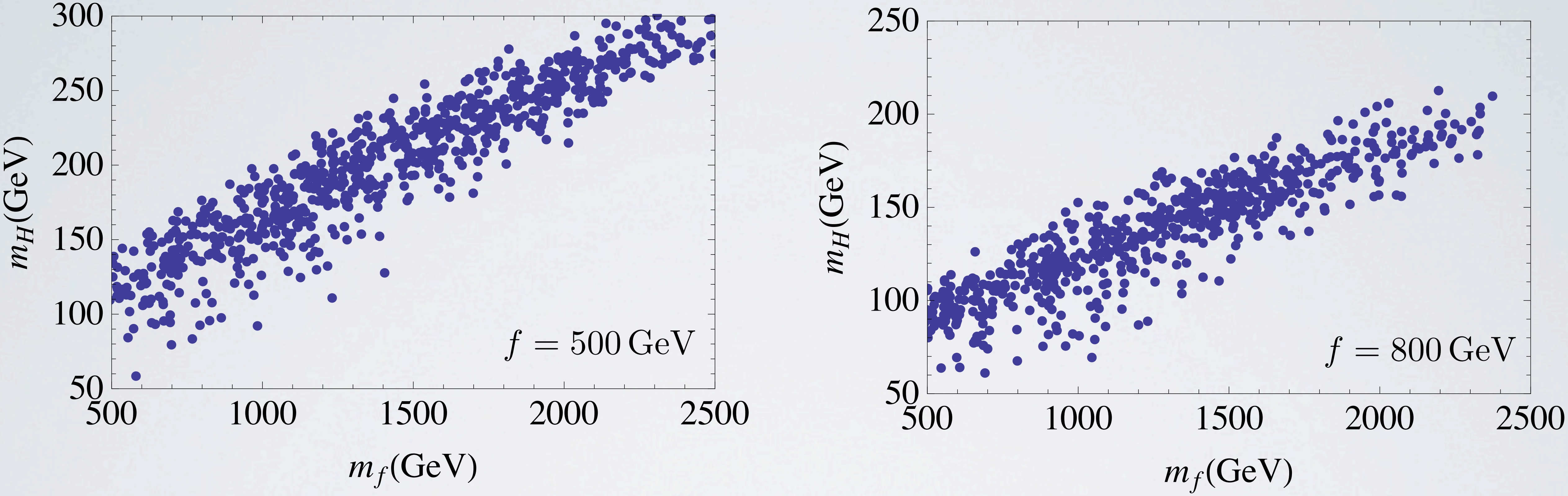
Form factors are simple functions build out of

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

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

Potential is calculable with a single SO(5) resonance!

General scan:



de Curtis, MR, Tesi '11

If light Higgs is found, nearby fermionic partners expected.
If lucky visible at LHC7.

Most sensitive experimental searches (1-slide snapshot)

- Looking for pair production

[CMS L=1.14 fb-1] PAS-EXO-11-050 — $T\bar{T} \to WbW\bar{b} \to b\bar{b}\, l^+ l^- \not{E}_T$ — $m_T > 422\,\mathrm{GeV}$

[CMS L=0.80 fb-1] PAS-EXO-11-051 — $T\bar{T} \to WbW\bar{b} \to b\,3j\, l^\pm \not{E}_T$ — $m_T > 450\,\mathrm{GeV}$

[CMS L=191 pb-1] PAS-EXO-11-005 — $T\bar{T} \to tZ\,\bar{t}Z \to (l^+ l^-) l^\pm\, jj$ — $m_T > 417\,\mathrm{GeV}$

[CMS L=1.14 fb-1] PAS-EXO-11-036 — $B\bar{B} \to Wt\,W\bar{t} \to l^\pm l^\pm\, b\,3j\, \not{E}_T$, $\to lll\, b\, 1j\, \not{E}_T$ — $m_B > 495\,\mathrm{GeV}$

- Looking for single production

[D0 L=5.4 fb-1] arXiv:1010.1466 — $Q\bar{q} \to Wq\bar{q} \to l^\pm jj \not{E}_T$, $\to Zq\bar{q} \to (l^+ l^-) jj$

Notice: All analyses assume 100% BR to the considered channel

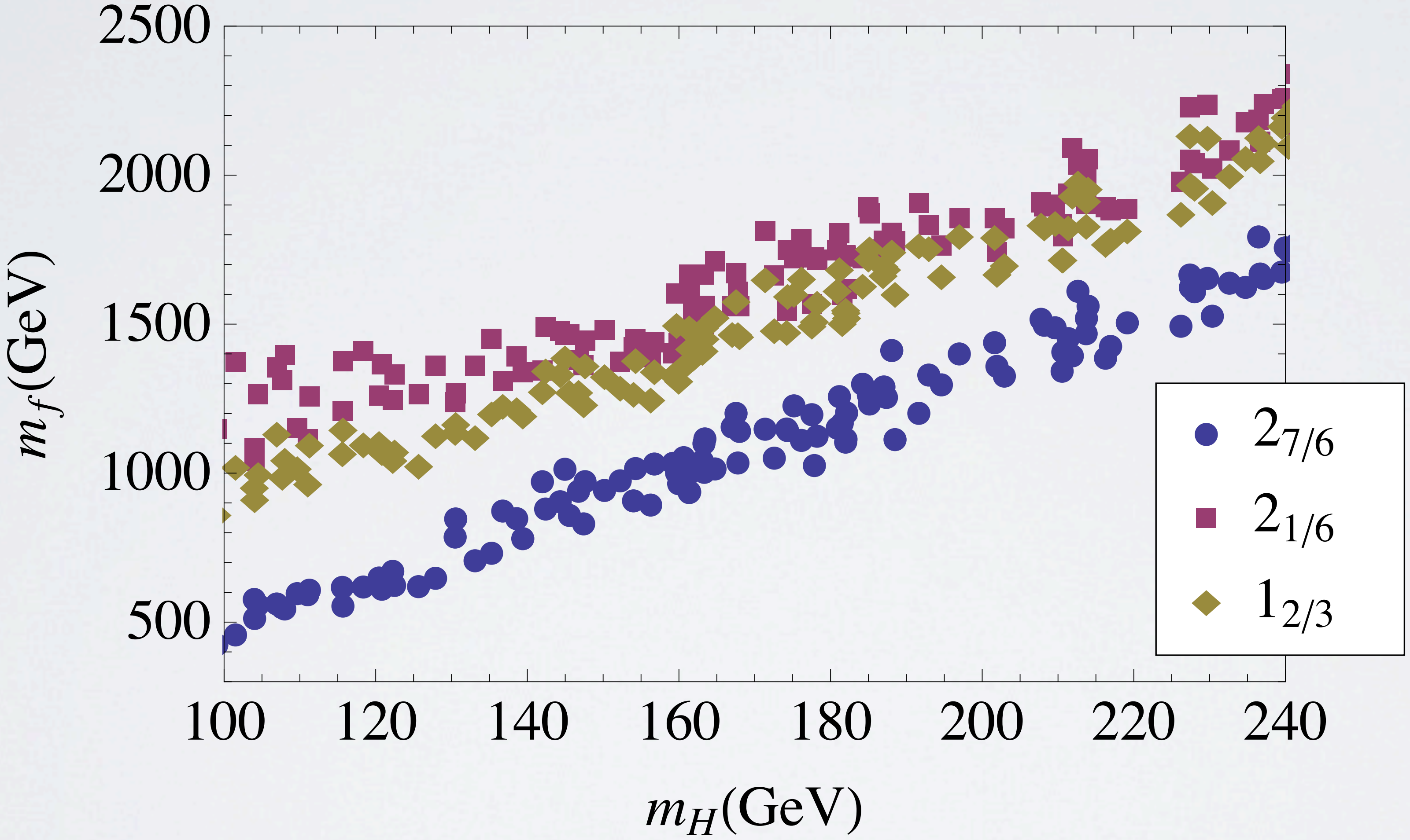
by R. Contino

Large mixing:

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

$1.2 \leq \Delta_{t_L}/m_T \leq 1.8$ $\qquad$ $0.7 \leq \Delta_{t_R}/m_{\widetilde{T}} \leq 1.3$

$0.5 \leq Y_T \leq 3$ $\qquad$ $-1.2 Y_T \leq m_{Y_T} \leq -0.8 Y_T$

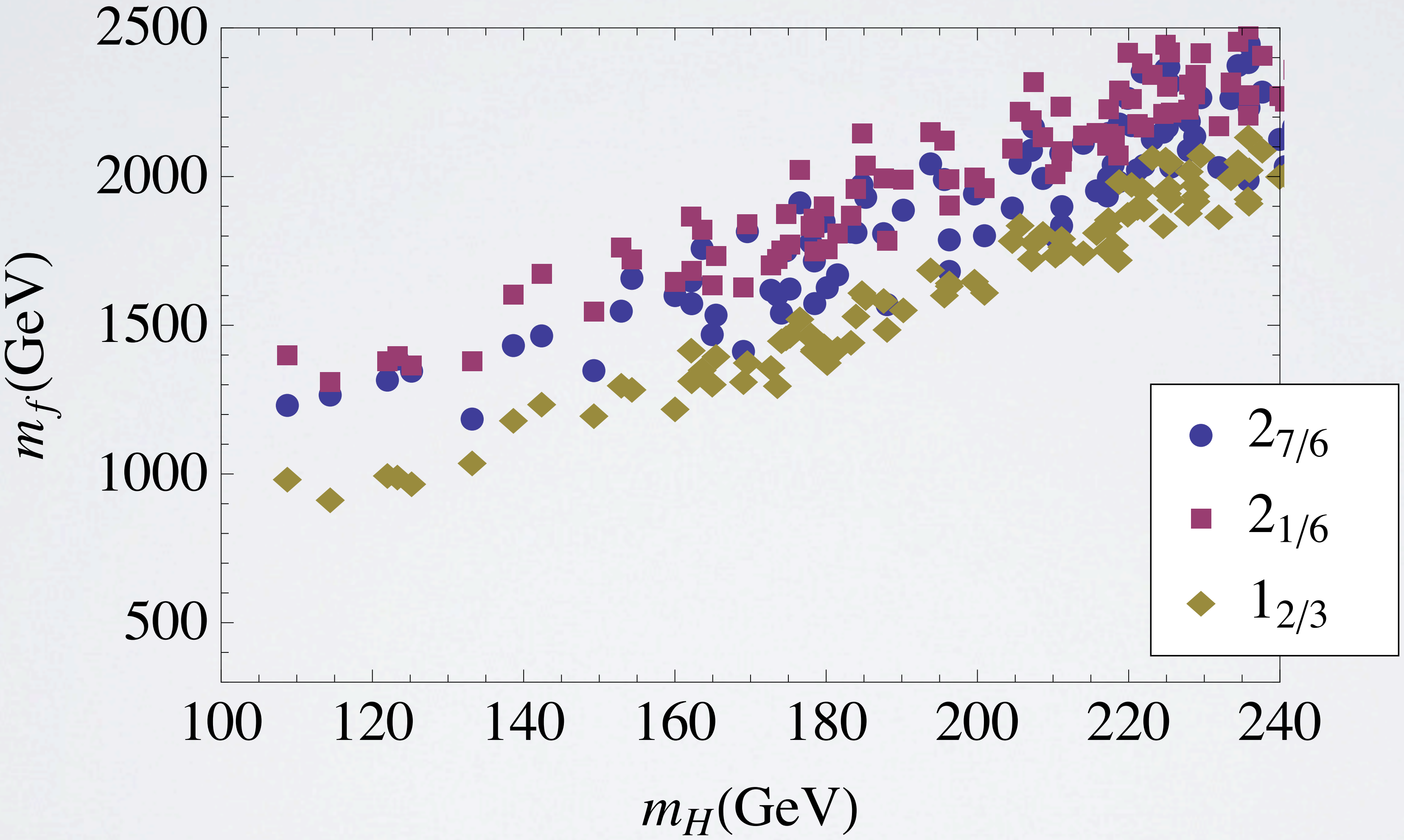


Doublet lightest fermion

Moderate mixing

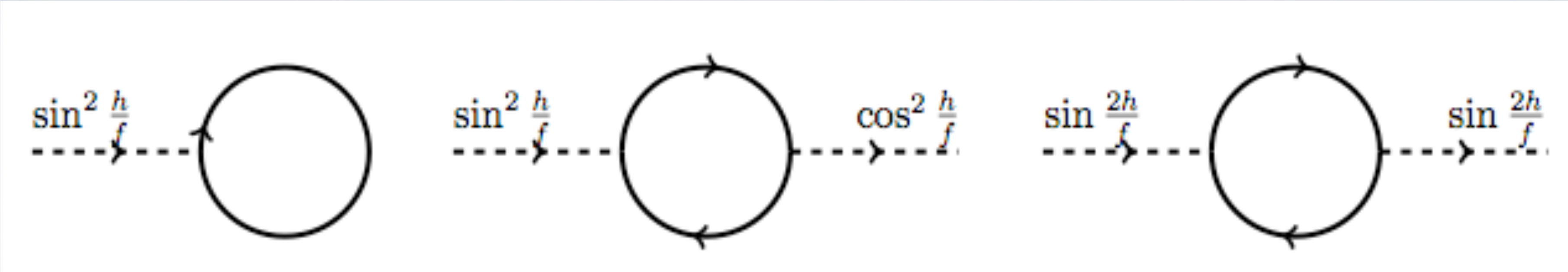
$0.6 \leq \Delta_{t_L}/m_T \leq 0.9$ $\quad$ $0.35 \leq \Delta_{t_R}/m_{\widetilde{T}} \leq 0.7$

$0.5 \leq Y_T \leq 3$ $\quad$ $-0.5 \leq m_{Y_T} \leq 0.5$



Singlet lightest fermion

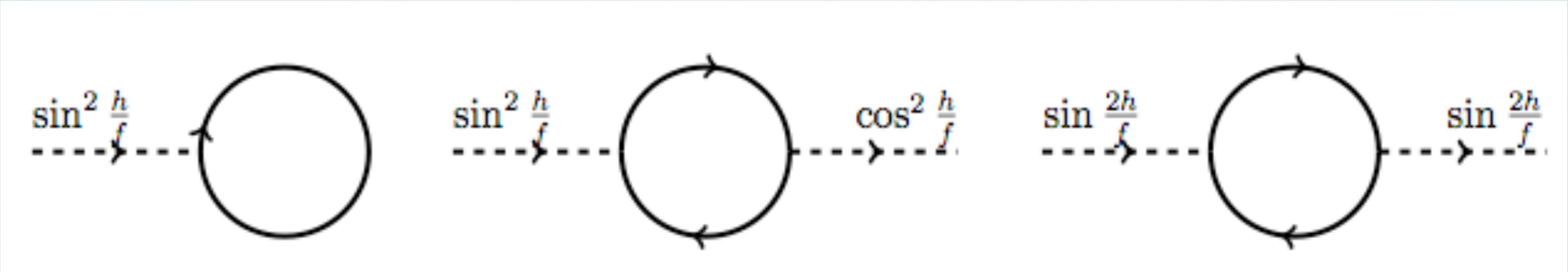
NATURALNESS



Potential CHM5:

$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$

NATURALNESS

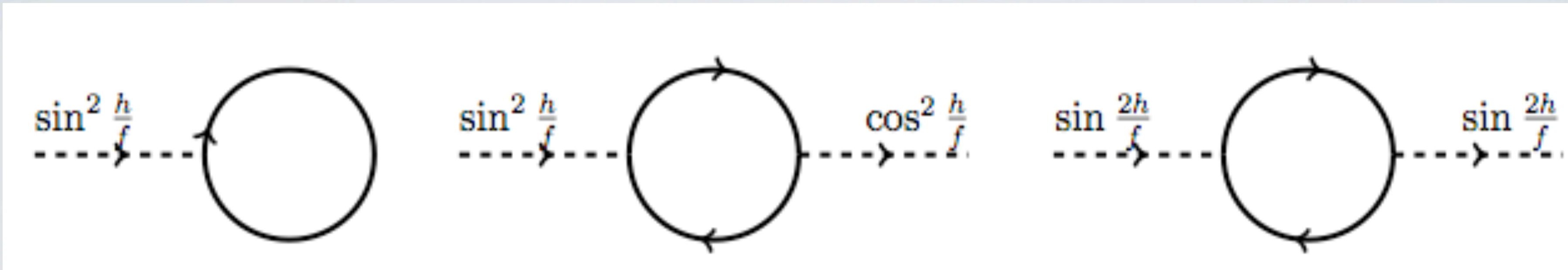


Potential CHM5:

$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$

$$\mathcal{L}_{Yuk} = y_t f\, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \longrightarrow V(h)_{Yuk} \sim N_c \frac{y_t^2}{4\pi^2} m_T^2 f^2\, s_h^2 c_h^2$$

NATURALNESS



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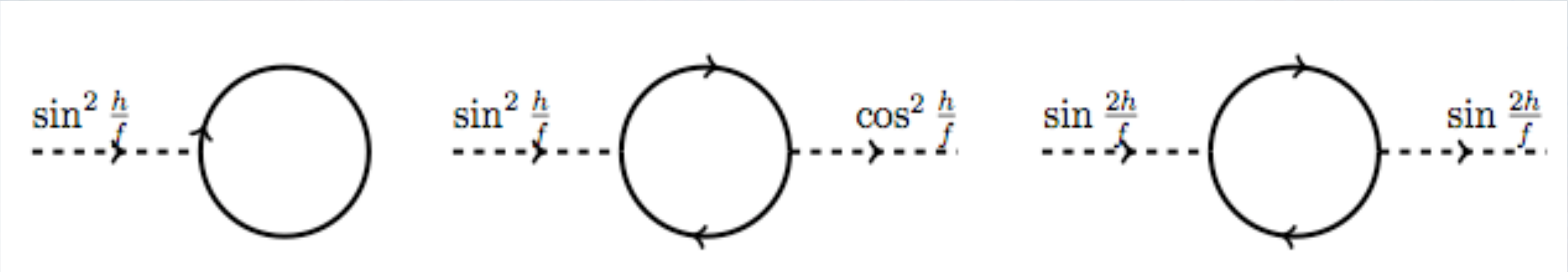
$$\mathcal{L}_{kin} = \frac{y_{t_L}^2}{2 y_T^2} s_h^2\, \bar{t}_L\, \not{D} t_L + \frac{y_{t_R}^2}{y_{\tilde{T}}^2} c_h^2\, \bar{t}_R\, \not{D} t_R$$

$$V(h)_{kin}^{(1)} \sim N_c \frac{2 y_{t_R}^2 - y_{t_L}^2}{32\pi^2} \frac{m_T^4}{y_T^2}\, s_h^2$$

$$V(h)_{kin}^{(2)} \sim N_c \frac{y_{t_{L,R}}^4}{16\pi^2} \frac{m_T^4}{y_T^4}\, s_h^2 c_h^2$$

NATURALNESS



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$$V(h)_{kin}^{(2)} \sim N_c \frac{y_{t_{L,R}}^4}{16\pi^2} \frac{m_T^4}{y_T^4}\, s_h^2 c_h^2$$

Demanding electro-weak VEV

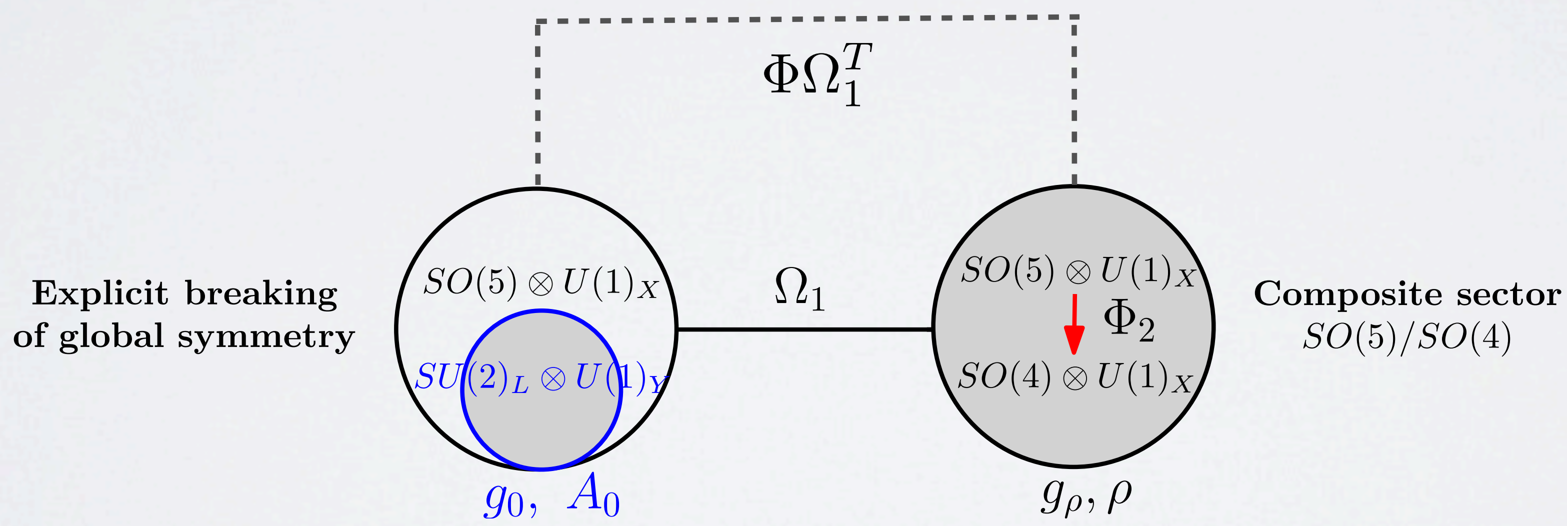
$$m_H \sim 0.3\, y_t \frac{m_T}{f} v$$

NON MINIMAL TERMS

Most general 2-site lagrangian contains

$$\frac{f_0^2}{2}(D_\mu\Phi)(D^\mu\Phi)^T \qquad\qquad \Phi = \Phi_2\Omega_1^T$$

$$f^2 = f_0^2 + \frac{f_1^2 f_2^2}{f_1^2 + f_2^2}$$



Similar terms are considered in QCD and TC.

Falkowski et al. '11

New term modifies interactions

$$g_{\rho\pi\pi} = \frac{f^2 - f_0^2}{2f^2}\, g_\rho$$

$$(m_{a_1} \to \infty)$$

$$m_\rho^2 = 2\frac{f^2}{f^2 - f_0^2}\, g_{\rho\pi\pi}^2\, f^2$$

Coset resonance could give further modifications.

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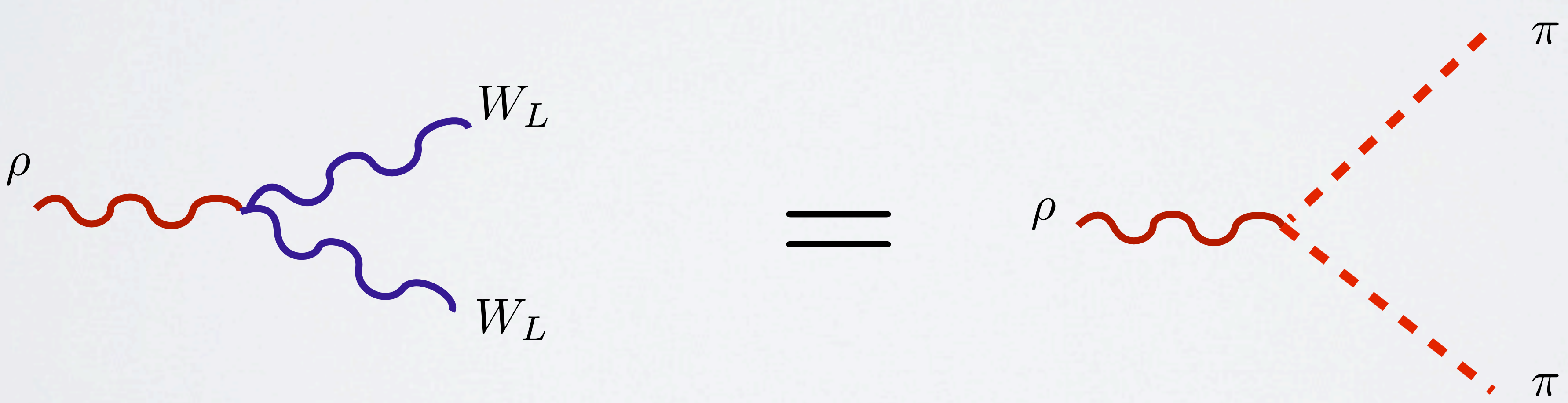
Coset resonance could give further modifications.

Important for decay and production



$$\Gamma(\rho^3 \to Zh) = \Gamma(\rho^3 \to W^+W^-) = \frac{g_{\rho\pi\pi}^2}{192\pi} m_\rho$$

New term contributes to S-parameter:

$$S = 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2} \right) \frac{f^2 - f_0^2}{f^2}$$

S can vanish

$$f_0 = f$$

H and G/H resonances degenerate and decoupled.
Same in TC theories.

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H and G/H resonances degenerate and decoupled.
Same in TC theories.

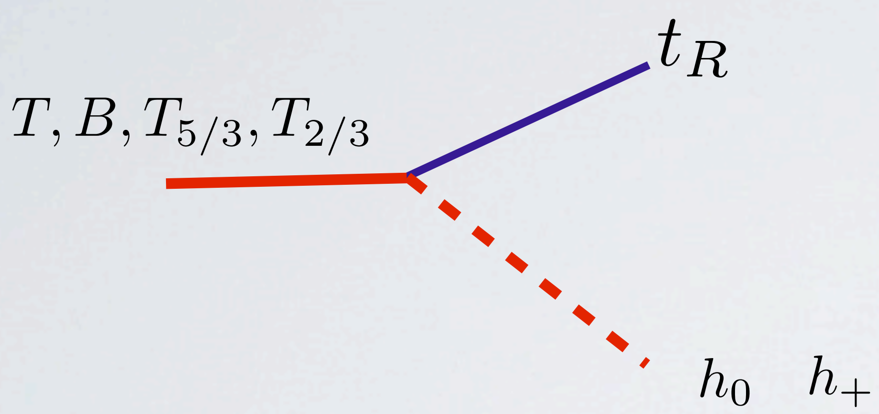
In QCD:

$$f_0^2 \sim -f^2$$

General?

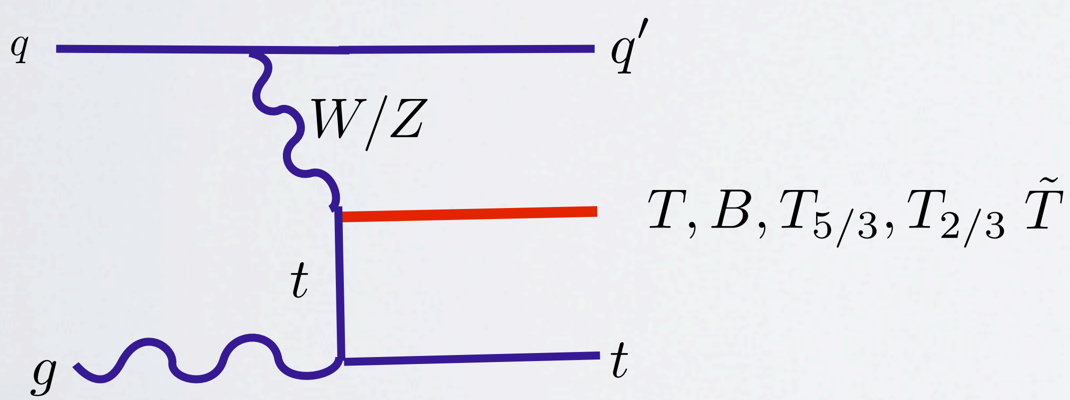
Coupling to fermions also modified.

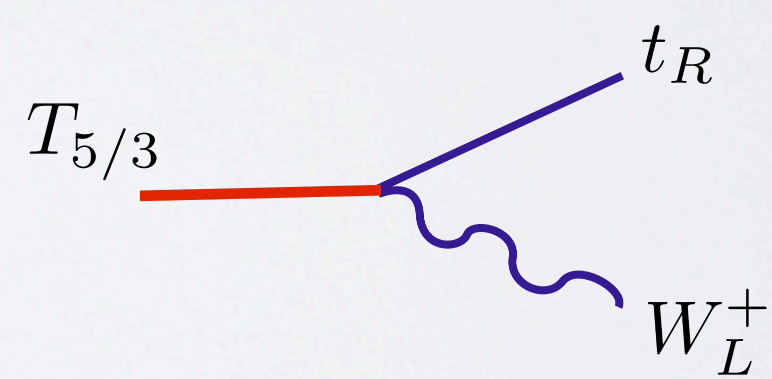
$$Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} \longrightarrow \frac{Y_T}{2h} \sin \frac{2hf}{f_2^2} Tr \left[\begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix}_L \cdot \begin{pmatrix} h_0^\dagger & h_+ \\ h_+^\dagger & h_0 \end{pmatrix} \right] \tilde{T}_R$$



$$\sim \frac{Y_T f}{f_2^2} c_L s_R \qquad \left(2 - \mathrm{site} : \frac{\mathrm{Y_T}}{\mathrm{f}} \mathrm{c_L s_R} \right)$$

Production and decay can be very different from 2 site





Relevant phenomenologically!

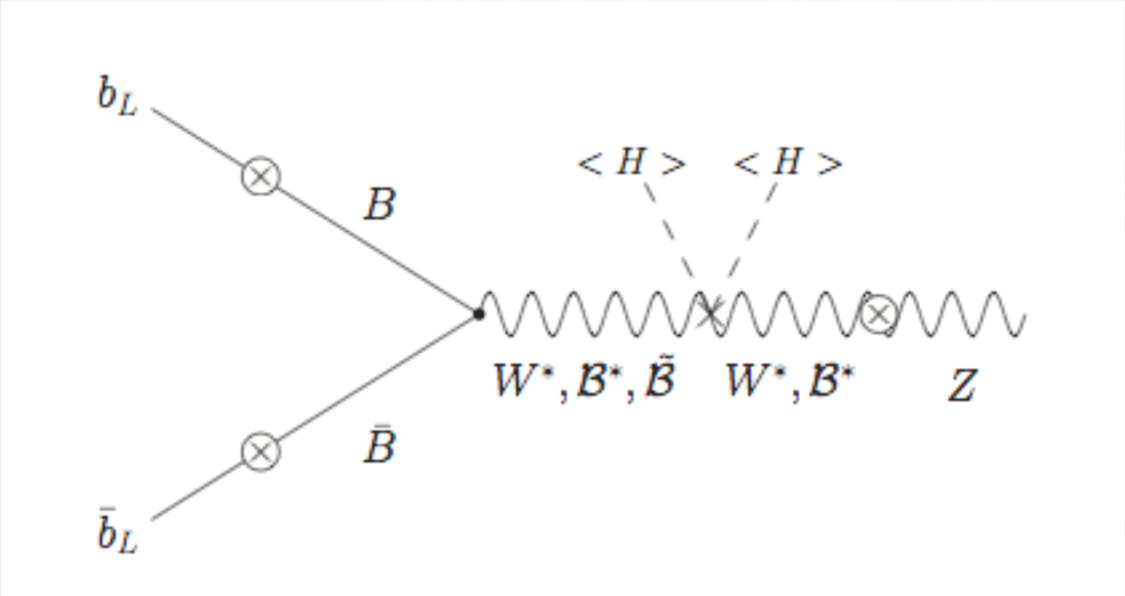
CONCLUSIONS

- All relevant features of CHM can be reproduced from a 4D point view. First resonance sufficient for LHC.
- In general a light Higgs requires light fermionic partners for naturalness.
- More general models can be considered in 4D than 5D. Contributions to S and modified couplings.

SM fermions couple to multiplets of $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

In general modified couplings problematic

$$\delta g \approx \frac{Y_{U,D}^2 v^2}{2\, m_\rho^2} \sin^2 \varphi_\psi \, (T'_{3L}(Q) - T_{3L}) + g_{*2}^2 \frac{v^2}{4m_\rho^2} \sin^2 \varphi_\psi (T_{3R} - T_{3L})$$



Possible to have L-R symmetry.
Corrections vanish if

$$T_L^3 = T_R^3$$

Agashe , Contino,
da Rold, Pomarol, '04