Status and Prospects of Composite Higgs Models

Michele Redi

CERN

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OUTLINE

- Review of Composite Higgs Models
  - Successes & Challenges
  - Phenomenology at LHC

- Beyond Minimal Models
  - Solving the Flavor Problem
  - Composite right-handed quarks

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 ...

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- Weak Coupling:
  SM, Supersymmetry

  3+8 talks

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

  2 talks

WHAT WE KNOW

SM is a gauge theory based on $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$\mathcal{L}_{Kinetic} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}W^b_{\mu\nu}W^{b\mu\nu} + i\sum_{j=1}^{3}\left(\bar{\Psi}^j_L \not{D}\Psi^j_L + \bar{\Psi}^j_R \not{D}\Psi^j_R\right)$$

$$\Psi_{L,R} = (3,2)_{\frac{1}{6}} \oplus (3,1)_{\frac{2}{3}} \oplus (3,1)_{-\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}} \oplus (1,1)_{-1}$$

(3 couplings)

Unbroken gauge symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q$$

Mass terms can be written,

$$\mathcal{L}_{mass} = \sum_{i,j=1}^{3}\left[\bar{u}^i_L M^u_{i,j} u_R + \bar{d}^i_L M^d_{i,j} d_R + \bar{e}^i_L M^e_{i,j} e_R\right] + h.c.$$

$$+m^2_W W^2 + \frac{1}{2}m^2_Z Z^2$$

O(20) parameters

Mass for gauge bosons implies new degrees of freedom

$m_1 = 0$

$m_1 \neq 0$

The extra degrees of freedom are Goldstone Bosons

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

which become longitudinal polarizations of W & Z

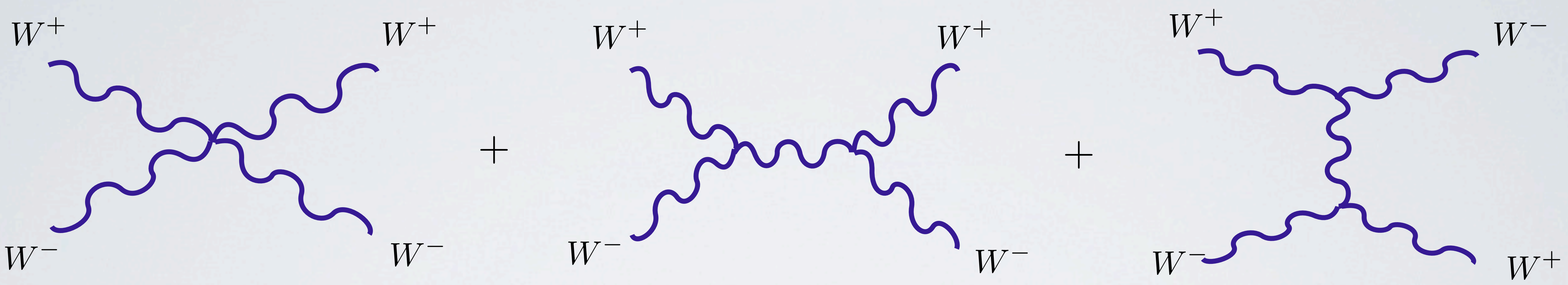
Important hint:

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

Custodial Symmetry

$SU(2)_c$

In principle the Higgs scalar is not necessary for EWSB



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

Interactions become strongly coupled around TeV.
Perturbativity is violated at

$$\Lambda \sim 3\,\mathrm{TeV}$$

In technicolor new strong interaction break EWS,

$$\langle \bar{\Psi}^i_L \Psi^j_R \rangle \sim v^3 \delta^{ij} \quad \longrightarrow \quad \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}$$

Longitudinal polarizations of W & Z are composite states.

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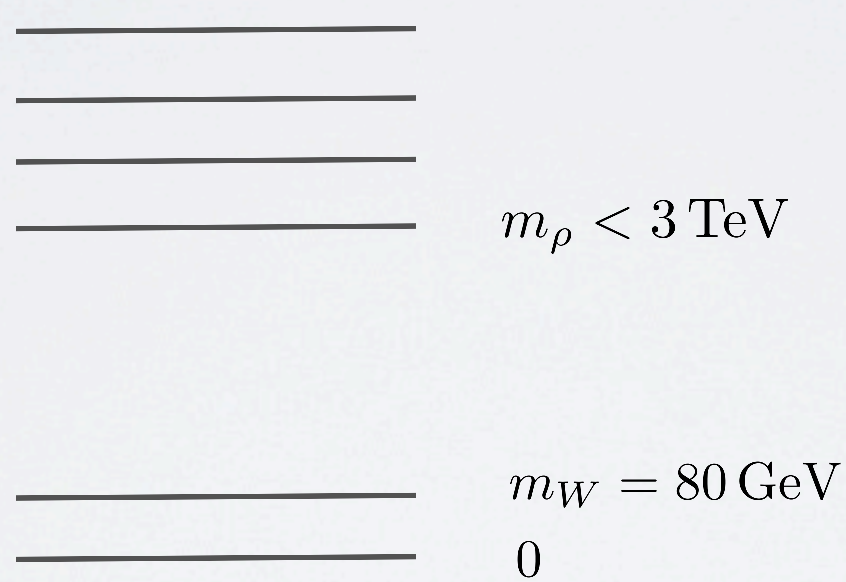
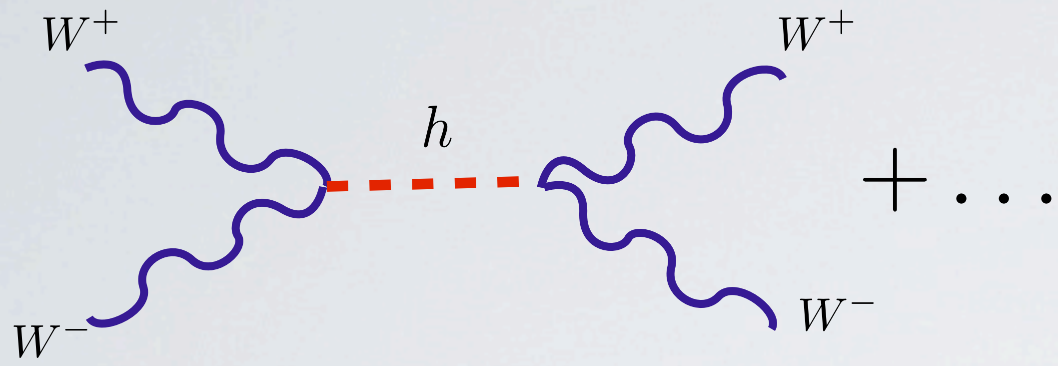
Longitudinal polarizations of W & Z are composite states.

No Higgs scalar but techni-resonances (spin 0, 1/2, 1 etc.).



Sadly phenomenologically highly problematic:
precision electro-weak measurements and flavor

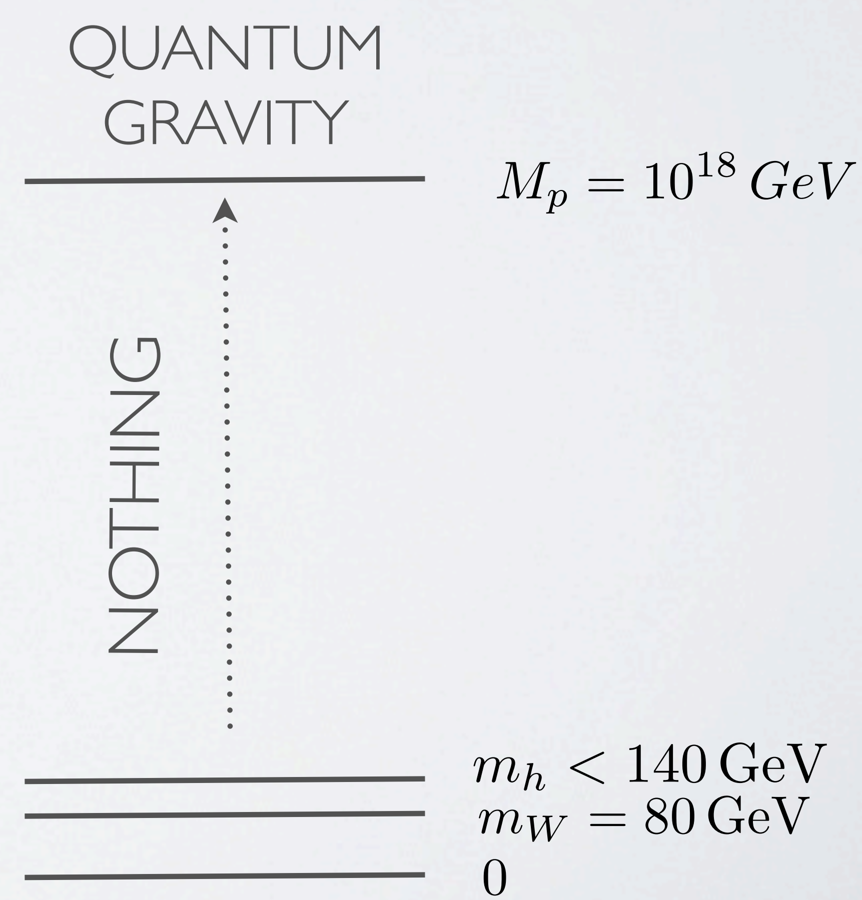
In the SM:



$$A(W_L^+W_L^- \to W_L^+W_L^-) \simeq \frac{1}{v^2}\left[s - \frac{s^2}{s-m_h^2} + (s \to t)\right]$$

Amplitude does not grow so SM can be valid up to the Planck scale.

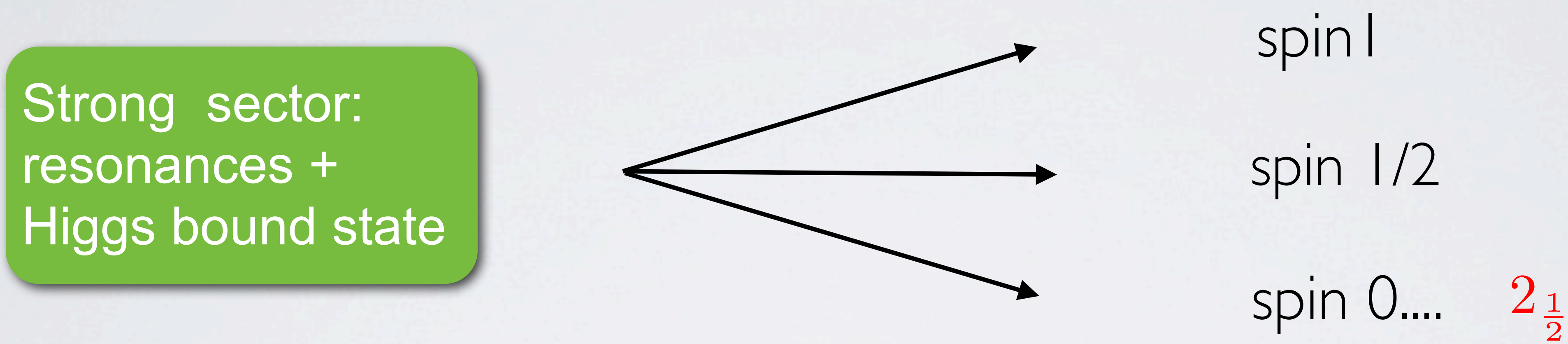
- Hierarchy problem
- Dark Matter
- Origin of Yukawas, CP
- Explains nothing



COMPOSITE HIGGS

Georgi, Kaplan '80s

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



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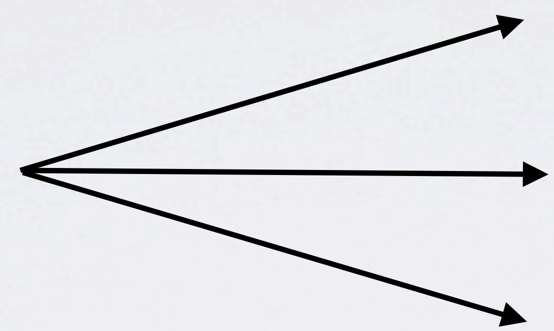
Strong sector:
resonances +
Higgs bound state



spin 1

spin 1/2

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

Two parameters:

m_ρ $\quad g_\rho \quad (1 < g_\rho < 4\pi)$

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:

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

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Extended Higgs sectors:

Ex: $\frac{SO(6)}{SO(5)}$ $\frac{SO(6)}{SO(4) \otimes U(1)}$ $\frac{SU(5)}{SU(4) \otimes U(1)}$ $+ \ldots$

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.

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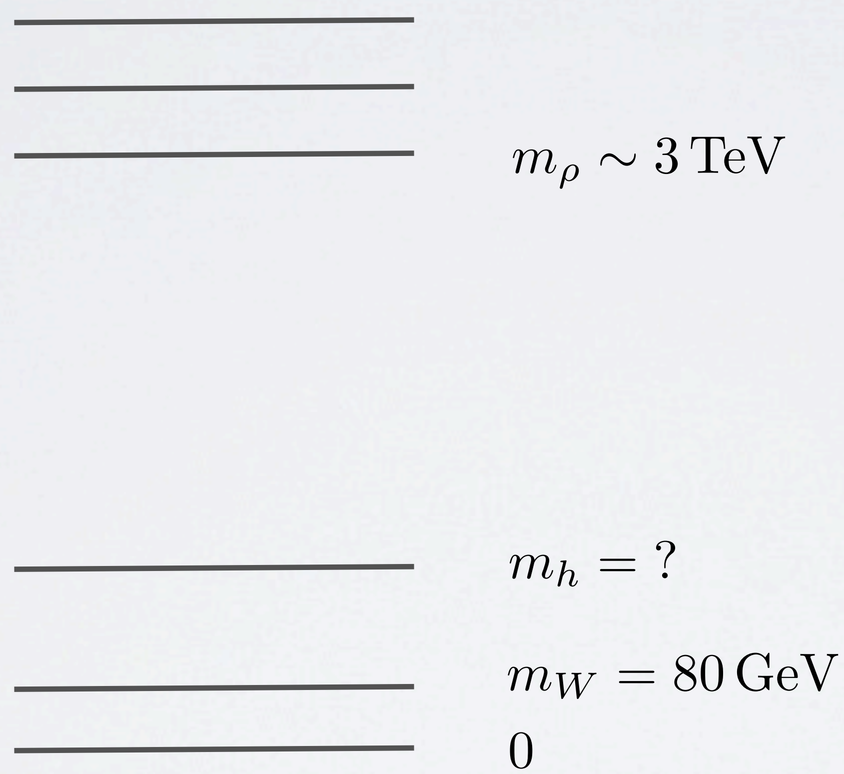
Spectrum:



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

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

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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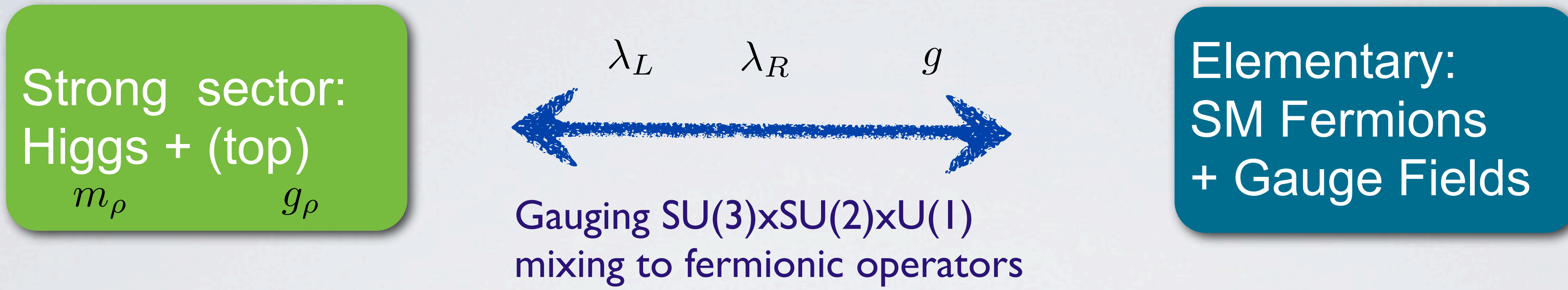

They talk through linear couplings:

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

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

Potential generated at 1-loop:

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

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

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

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

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To generate Yukawa for the down sector

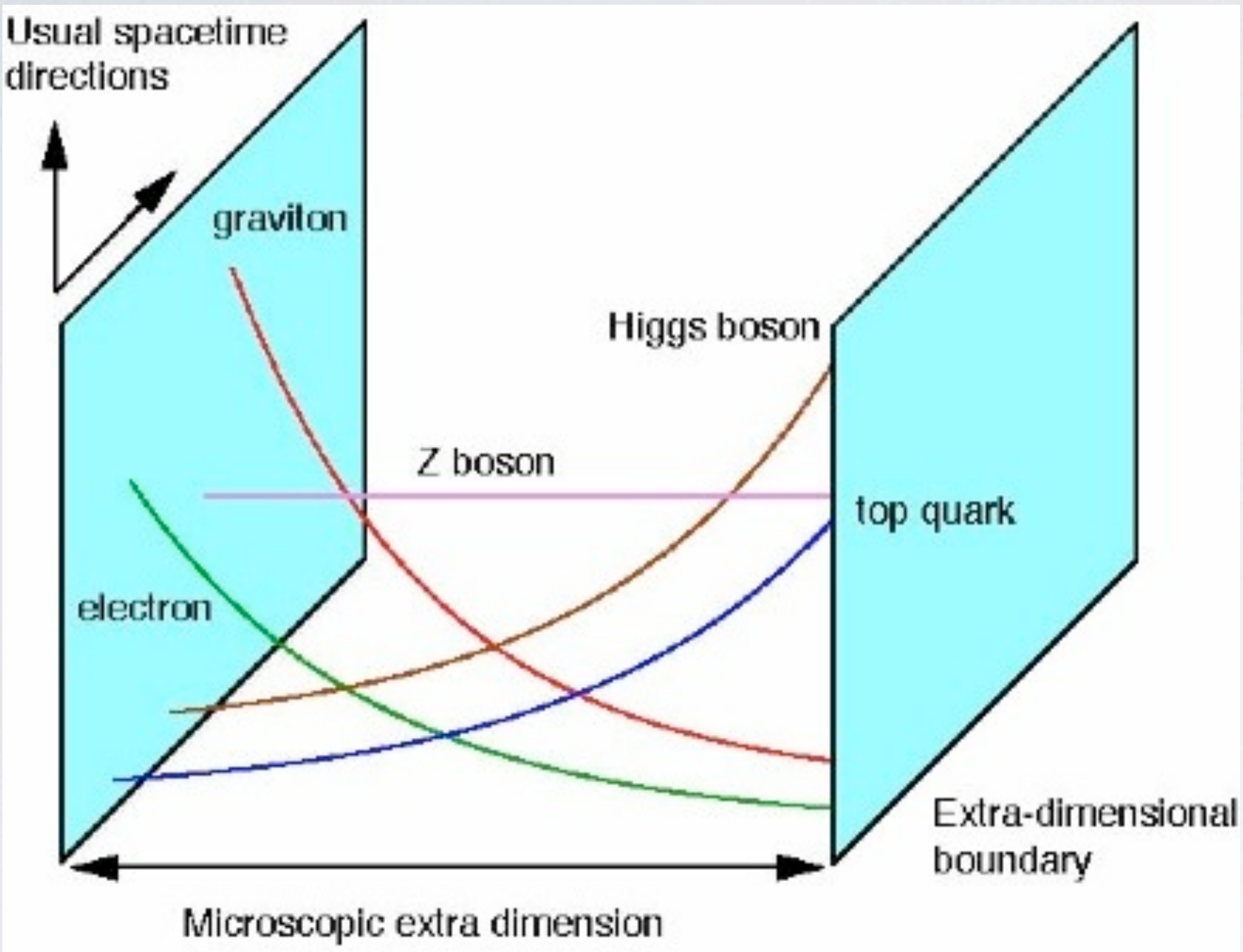
$q_L \longrightarrow (2,2)_{-\frac{1}{3}}$ $\quad L_D = \begin{pmatrix} B_{-\frac{1}{3}} & T' \\ B_{-\frac{4}{3}} & B' \end{pmatrix}$

$d_R \longrightarrow (1,1)_{-\frac{1}{3}}$ $\quad D$

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

Agashe , Contino,
da Rold, Pomarol, '04

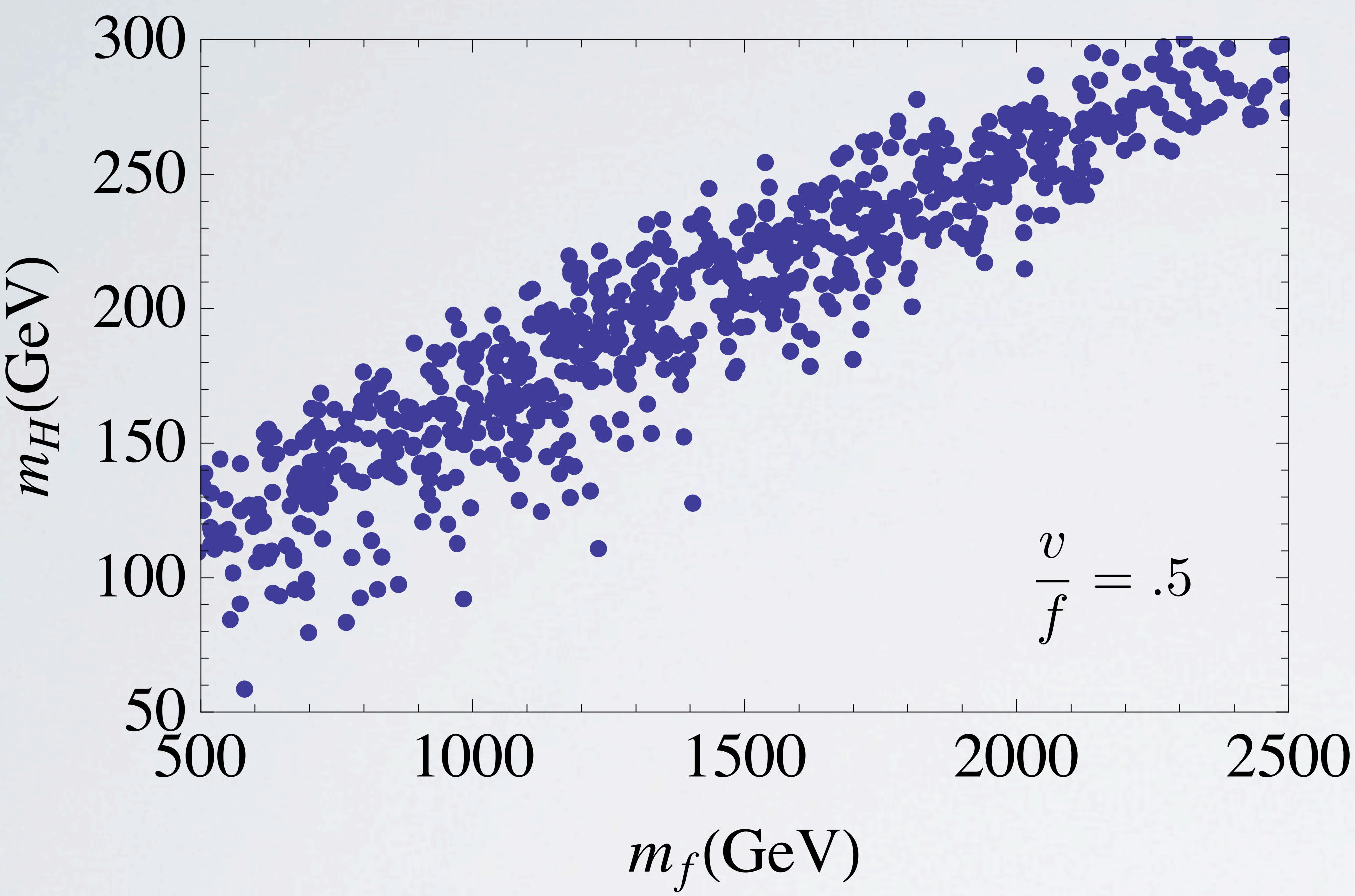
Recent progress started with Randall-Sundrum constructions.



(Randall-Sundrum '99)

Relevant physics largely independent from 5D constructions.
Only first resonance accessible to LHC.

Potential can be computed with one resonance.



de Curtis, MR, Tesi '11

If light Higgs is found, nearby fermionic partners expected.

If lucky visible at LHC7.

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:

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

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

Contino, Kramer, Son, Sundrum '06

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

Gauge fields:

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

Yukawas:

$$y^u = \frac{\lambda_{Lu}}{g_\rho} \cdot Y^U \cdot \frac{\lambda_{Ru}^\dagger}{g_\rho} \qquad y^d = \frac{\lambda_{Ld}}{g_\rho} \cdot Y^D \cdot \frac{\lambda_{Rd}^\dagger}{g_\rho}$$

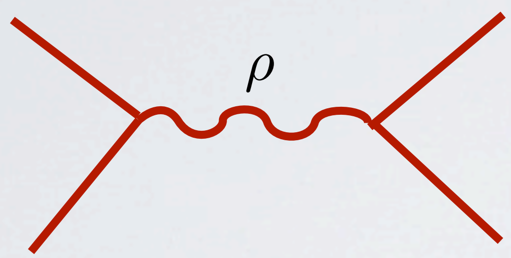
In the standard scenario $Y^{U,D}$ are anarchic.
Small couplings are obtained from small mixings:

- Light generations mostly elementary
- Top strongly composite

Flavor hierarchies can be dynamically generated if the composite sector is conformal.

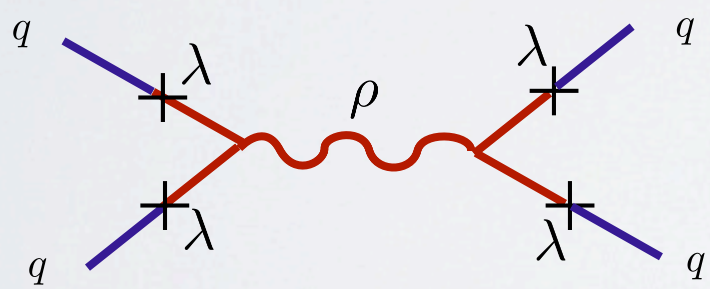
FLAVOR

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,



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

Flavor superior to TC theories.

SIGNATURES

Heavy resonances mostly coupled to 3rd generation + Higgs

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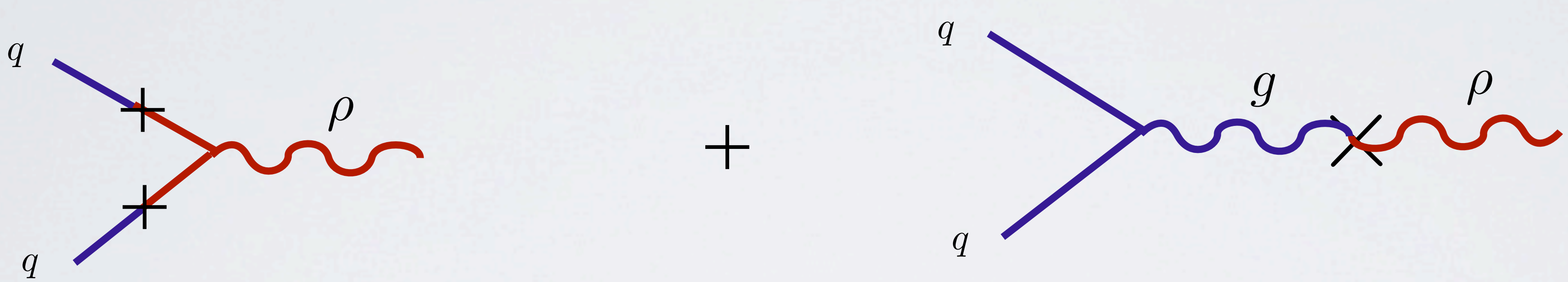
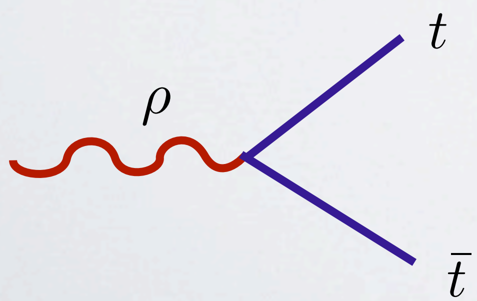
Spin-1: gluon, electro-weak

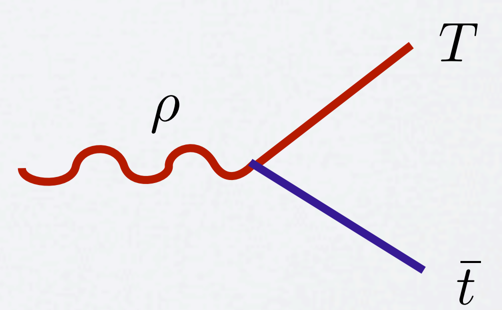


$$g_{\rho\bar{q}q} = g(\sin^2\varphi \cot\theta - \cos^2\varphi \tan\theta)$$

First term negligible.

Decay into 3rd generation or heavy fermions.





Bini, Contino, Vignaroli '11

Barcelo', Carmona, Chala, Masip, Santiago '11

Bound:

$m_\rho > 1000\,\mathrm{GeV}$

CMS-pas-exo-11-006
866/pb

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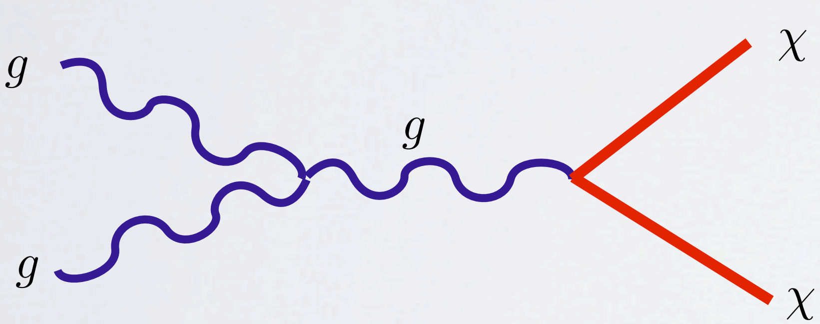
$m_\rho > 1000\,\mathrm{GeV}$

CMS-pas-exo-11-006
866/pb

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

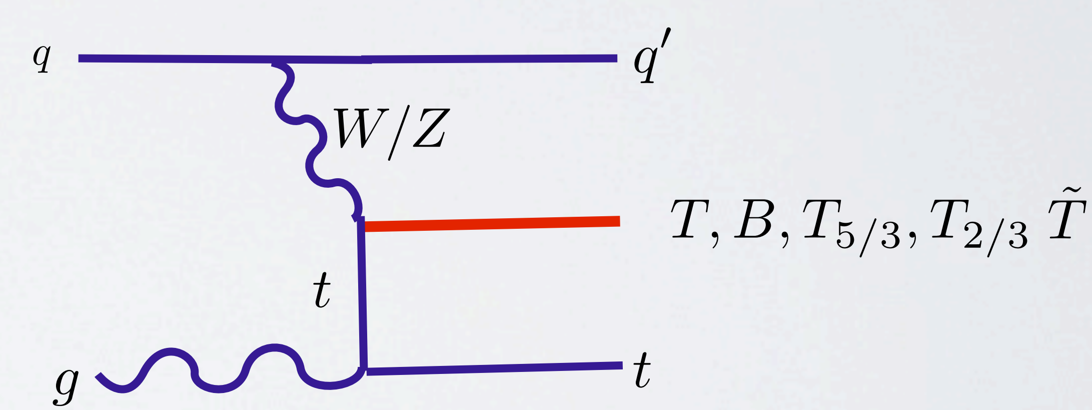
$$\begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix} \qquad \tilde{T}$$

Production:



Double

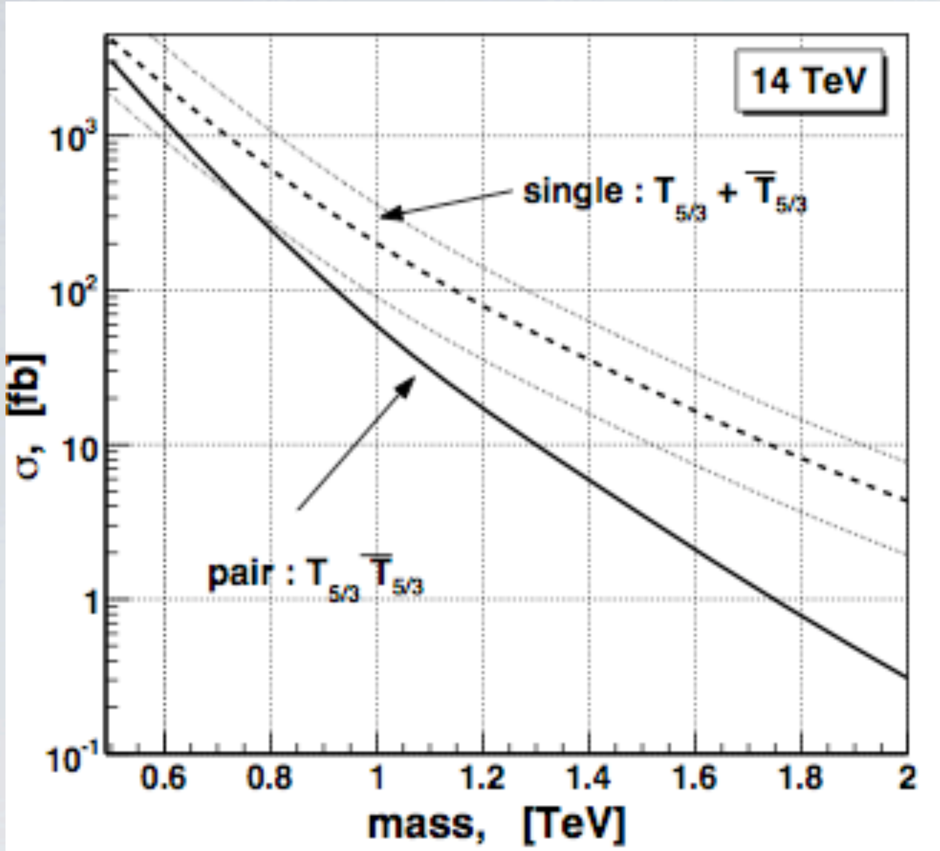
Contino, Servant. '08

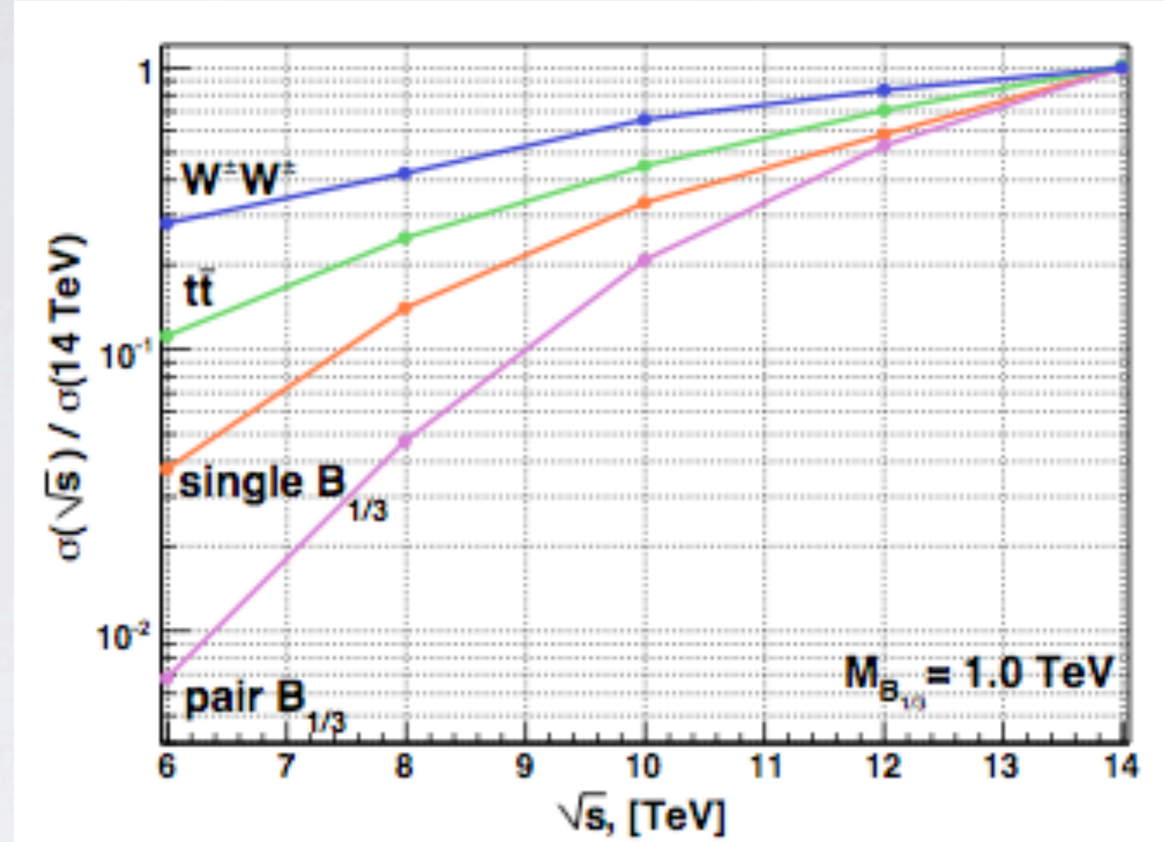


Single

Mrazek, Wulzer '09

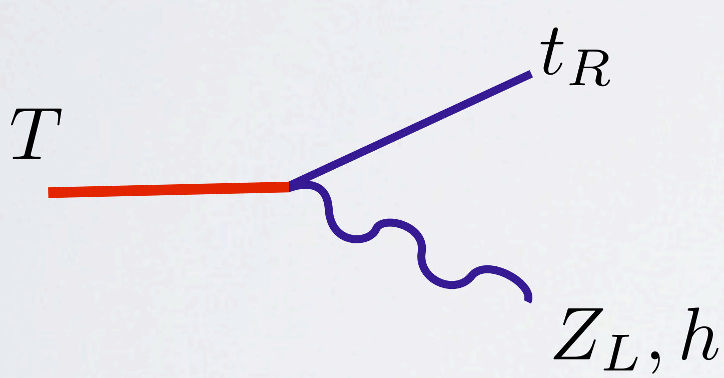
Aguilar-Saveedra '09

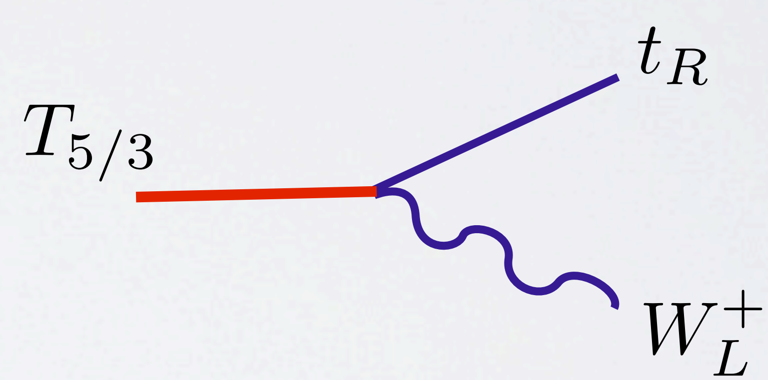


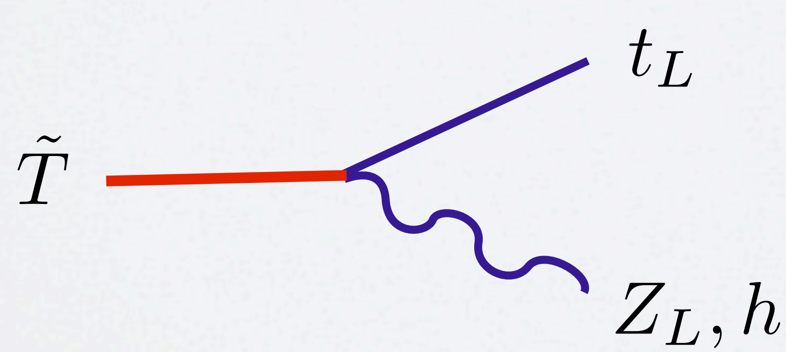


Mrazek, Wulzer '09

Decays:







Multi-lepton signatures.

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	$B\bar{B} \to Wt\,W\bar{t} \to l^\pm l^\pm\, b\, 3j\, \not{E}_T$ $\to lll\, b\, 1j\, \not{E}_T$	$m_B > 495\,\mathrm{GeV}$

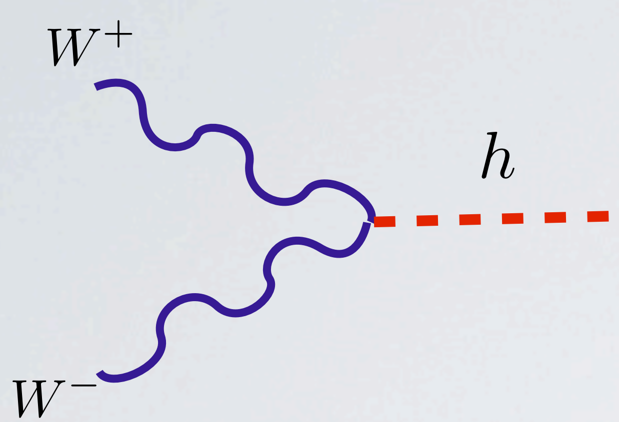
- Looking for single production

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

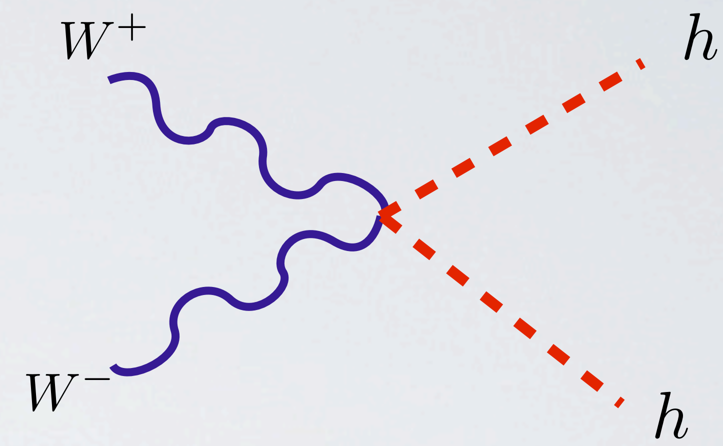
Notice: All analyses assume 100% BR to the considered channel

by R. Contino

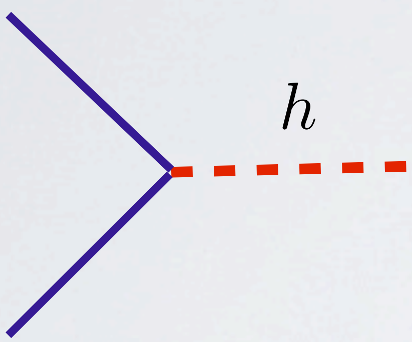
Modified couplings:



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



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



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

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

a, b, c receive corrections of order (v/f)^2.
Modified Higgs cross-sections hard to see at LHC7.

WW scattering is not exactly unitarized.
Unfortunately beyond LHC reach unless v/f~1.

Contino et al. '10

Within "anarchic" hypothesis only third generation and Higgs affected by compositeness: hard to distinguish from SM at LHC7.

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Models are however imperfect.
Some tension exists particularly with flavor

- **Kaon:** $m_\rho > 10\,\frac{g_\rho}{Y^D}\,\mathrm{TeV}$
- **EDMs:** $m_\rho > 2\,Y^D\,\mathrm{TeV}$

Also $b \to s\gamma$ and ϵ'/ϵ, leptons...

Abandon the anarchic hypothesis?

FLAVOR SYMMETRIES

with Andreas Weiler
arxiv:1106.6357[hep-ph]
+ work in progress

See also:
Weiler et al. '07
Barbieri, Isidori, Pappadopulo '08
Delaunay, Gedalia, Lee, Perez, Ponton '11

Adding a flavor symmetry:

All flavor violation comes from the mixings.

$$y_u \propto \lambda_{Lu}\lambda_{Ru}$$

$$y_d \propto \lambda_{Ld}\lambda_{Rd}$$

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Simple realizations of Minimal Flavor Violation:

mixings ~ SM Yukawas

- Left-handed compositeness:

$$\lambda_{Lu} \propto Id\,, \qquad \lambda_{Ld} \propto Id$$
$$\lambda_{Ru} \propto y_u\,, \qquad \lambda_{Rd} \propto y_d$$

$$+ \qquad \begin{array}{c} SU(3)_F \\ L_U\,, L_D\,, U\,, D \in 3_F \end{array}$$

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$$\lambda_{Ru} \propto Id\,, \qquad \lambda_{Rd} \propto Id$$

$$+ \qquad \begin{array}{c} SU(3)_U \otimes SU(3)_D \\ L_U\,, U \in (3,1) \quad L_D\,, D \in (1,3) \end{array}$$

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$+$

$$SU(3)_F$$
$$L_U\,, L_D\,, U\,, D \in 3_F$$

- Right-handed compositeness:

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$+$

$$SU(3)_U \otimes SU(3)_D$$
$$L_U\,, U \in (3,1) \qquad L_D\,, D \in (1,3)$$

MFV ⟶ Mixing of one chirality of light quarks is large.

Flavor bounds are automatically satisfied.
No EDMs are generated to leading order.

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LEP bounds,

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

Modified couplings strongly constrained

$$\frac{\delta R_h}{R_h} \approx .57\frac{\delta g_{Lu}}{g_{Lu}} + .11\frac{\delta g_{Ru}}{g_{Ru}} + 1.28\frac{\delta g_{Ld}}{g_{Ld}} + .04\frac{\delta g_{Rd}}{g_{Rd}}$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \qquad \frac{\delta g_{Ru}}{g_{Ru}} < .01 \qquad \frac{\delta g_{Ld}}{g_{Ld}} < .001 \qquad \frac{\delta g_{Rd}}{g_{Rd}} < .02$$

Flavor bounds are automatically satisfied.
No EDMs are generated to leading order.

LEP bounds,

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

Modified couplings strongly constrained

$$\frac{\delta R_h}{R_h} \approx .57\frac{\delta g_{Lu}}{g_{Lu}} + .11\frac{\delta g_{Ru}}{g_{Ru}} + 1.28\frac{\delta g_{Ld}}{g_{Ld}} + .04\frac{\delta g_{Rd}}{g_{Rd}}$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \qquad \frac{\delta g_{Ru}}{g_{Ru}} < .01 \qquad \frac{\delta g_{Ld}}{g_{Ld}} < .001 \qquad \frac{\delta g_{Rd}}{g_{Rd}} < .02$$

protected reps

Similar bound is found from unitarity of CKM

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \approx 1 - .7\,\frac{\delta g_{Lu}}{g_{Lu}}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = .9999 \pm .0012$$

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LH COMPOSITENESS:

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \quad \xrightarrow{\;m_t\;} \quad \sin\varphi_{t_R} \geq 35\frac{m_t}{m_\rho}$$

Strongly constrained and only possible if tR is composite.

RH COMPOSITENESS:

No bounds from LEP!!

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No bounds from LEP!!

Main constraint from recent di-jet searches,

$$\frac{g_\rho^2}{4\,m_\rho^2}\sin^4\varphi_{q_R}\left(\bar{q}^i_{R\alpha}\gamma^\mu q^i_{R\beta}\bar{q}^j_{R\beta}\gamma_\mu q^j_{R\alpha}\right) \xrightarrow{\text{COMPOSITENESS}} \sin^2\varphi_{q_R} \leq \frac{2}{g_\rho}\left(\frac{m_\rho}{3\,\text{TeV}}\right)$$

Large or full compositeness is still allowed with $m_\rho = 3$ TeV

If RH quarks are fully composite MFV follows from the flavor symmetry.

LHC PHENO

Exciting phenomenology with RH compositeness: proton could be half composite!

LHC PHENO

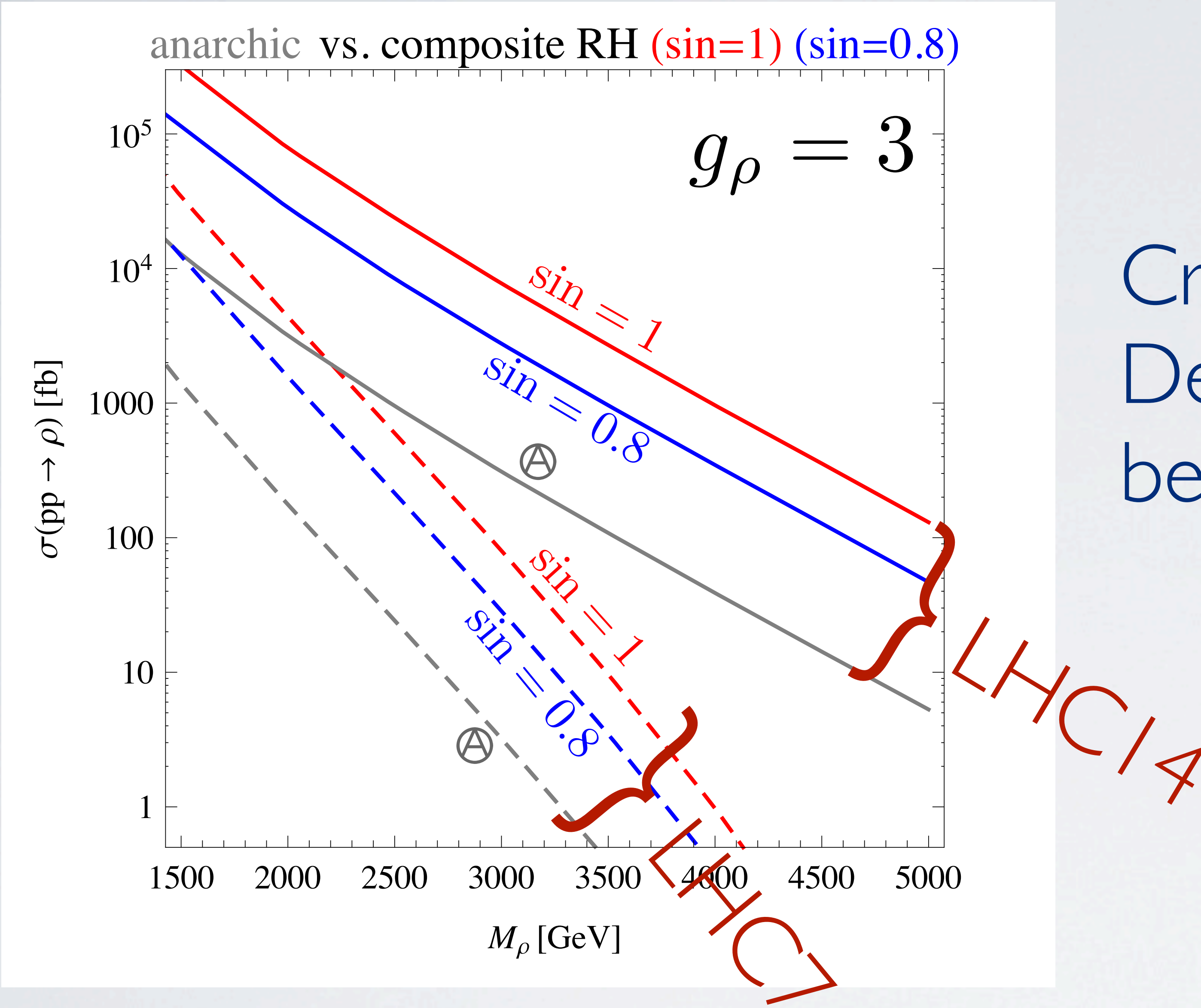
Exciting phenomenology with RH compositeness:
proton could be half composite!

Spin-1: gluon, electro-weak, flavor resonances

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

First term easily dominates for RH compositeness.

Gluon resonances:

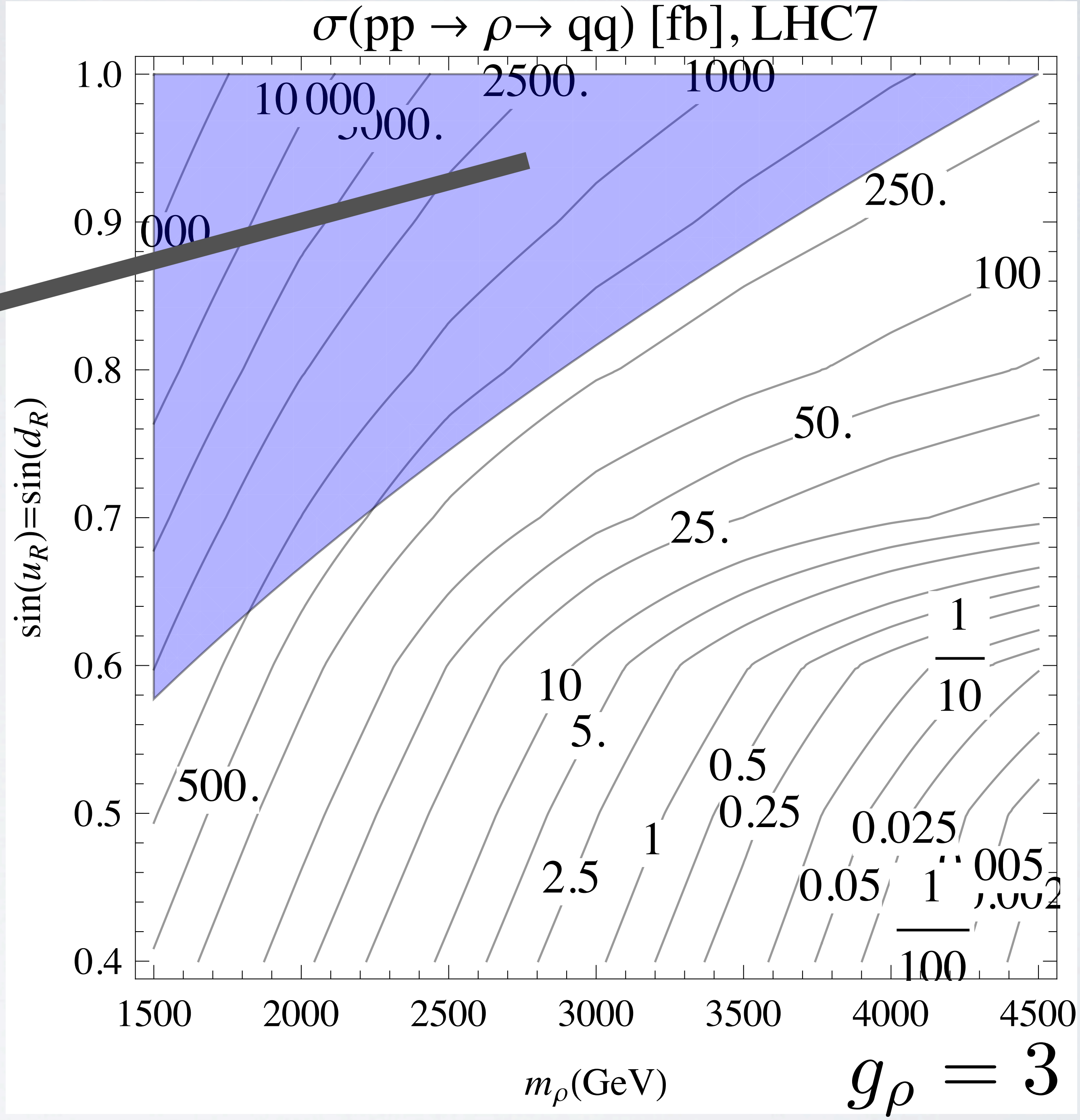


Cross-sections O(10) larger.
Decay into light generation can be important.

g_ρ	$\sin\varphi_{u_R}$	$\sin\varphi_{d_R}$	σ(pb)	Γ(GeV)	$Br(u\bar{u})$	$Br(t_L\bar{t}_L)$	$Br(t_R\bar{t}_R)$
3	AN	AN	0.31	190	0.03	0.004	0.84
5	AN	AN	0.1	480	0.004	0.0005	0.98
3	0.4	0.4	0.17	50	0.07	0.35	0.005
5	0.4	0.4	0.38	60	0.14	0.1	0.12
3	0.8	0.8	2.8	340	0.17	0.0003	0.16
5	0.5	0.5	1.1	140	0.17	0.01	0.16
3	1	0.25	5.2	490	0.33	0.001	0.32
5	1	0.25	15	1400	0.33	0.0002	0.33

LHC14

LHC7 bounds already relevant:



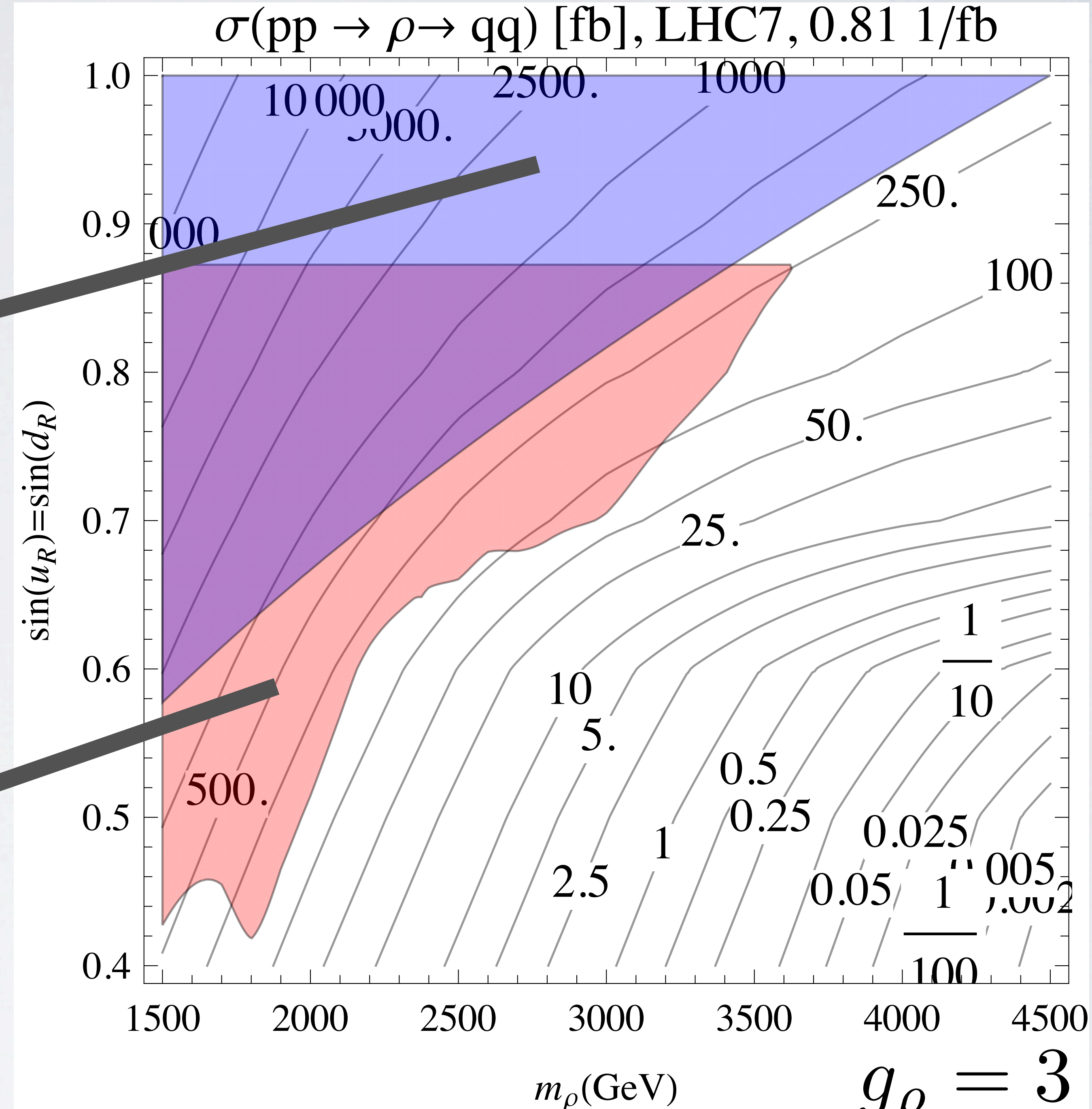
Di-jet bounds 35/pb

Expected signals in di-jet!

LHC7 bounds already relevant:

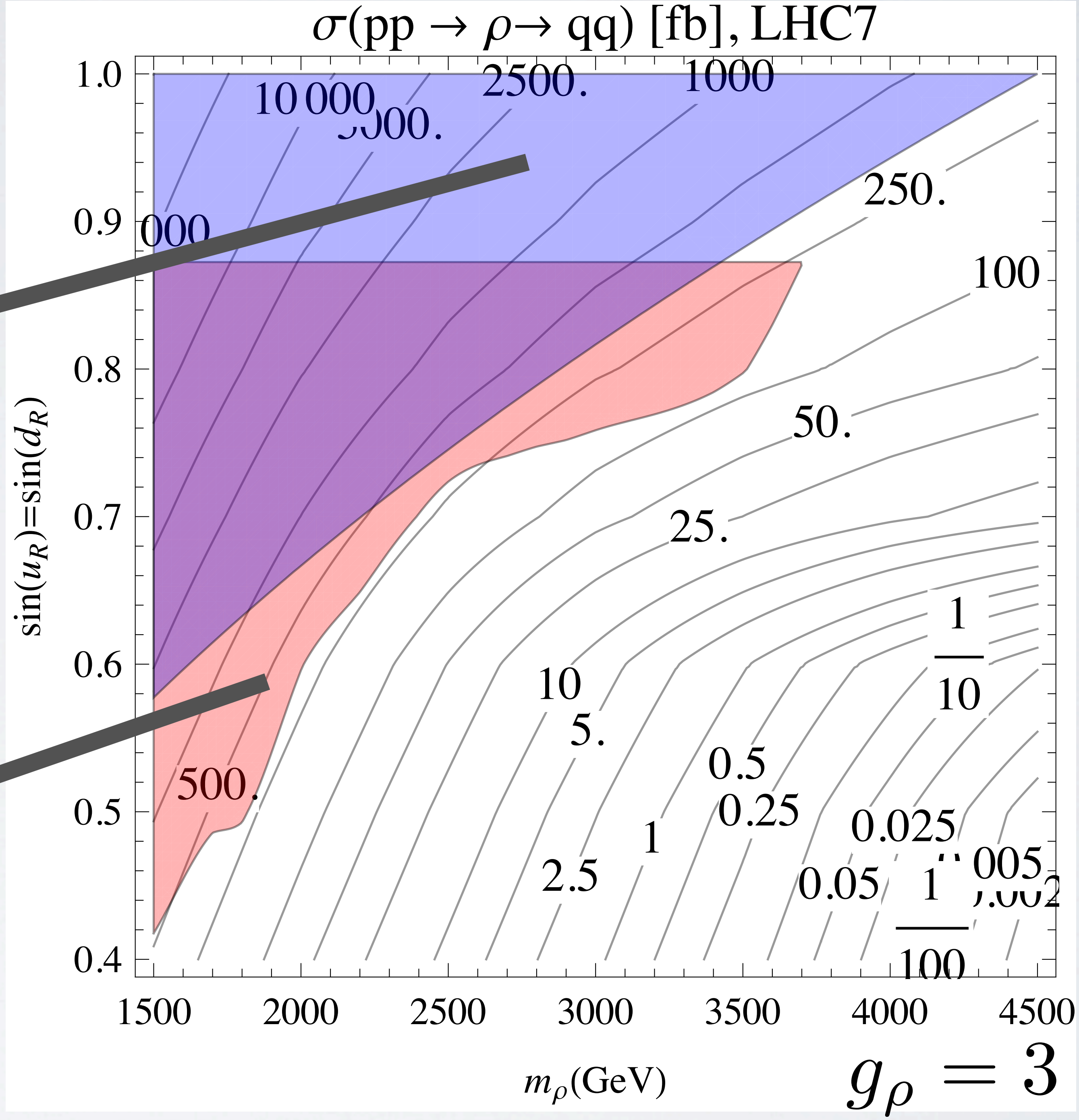
Di-jet bounds 35/pb

Atlas-Conf-2011-081
Bump search 810/pb



Expected signals in di-jet.

LHC7 bounds already relevant:



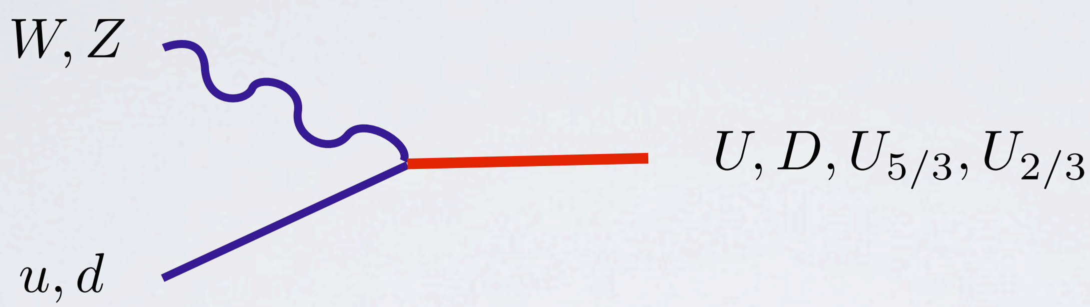
Di-jet bounds 35/pb

CMS-EXO-11-015
1/fb

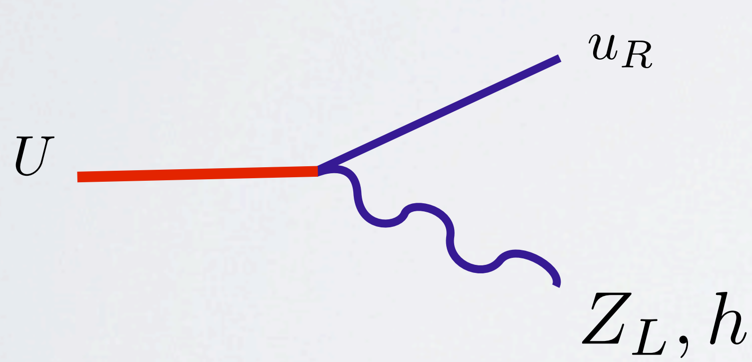
Expected signals in di-jet.

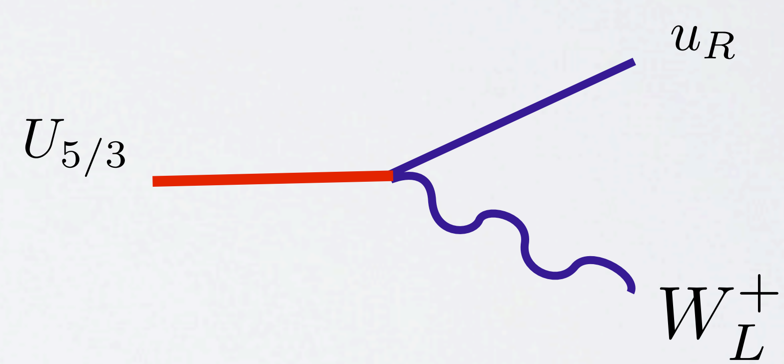
Spin-1/2 :

Partners of first generation mostly produced.

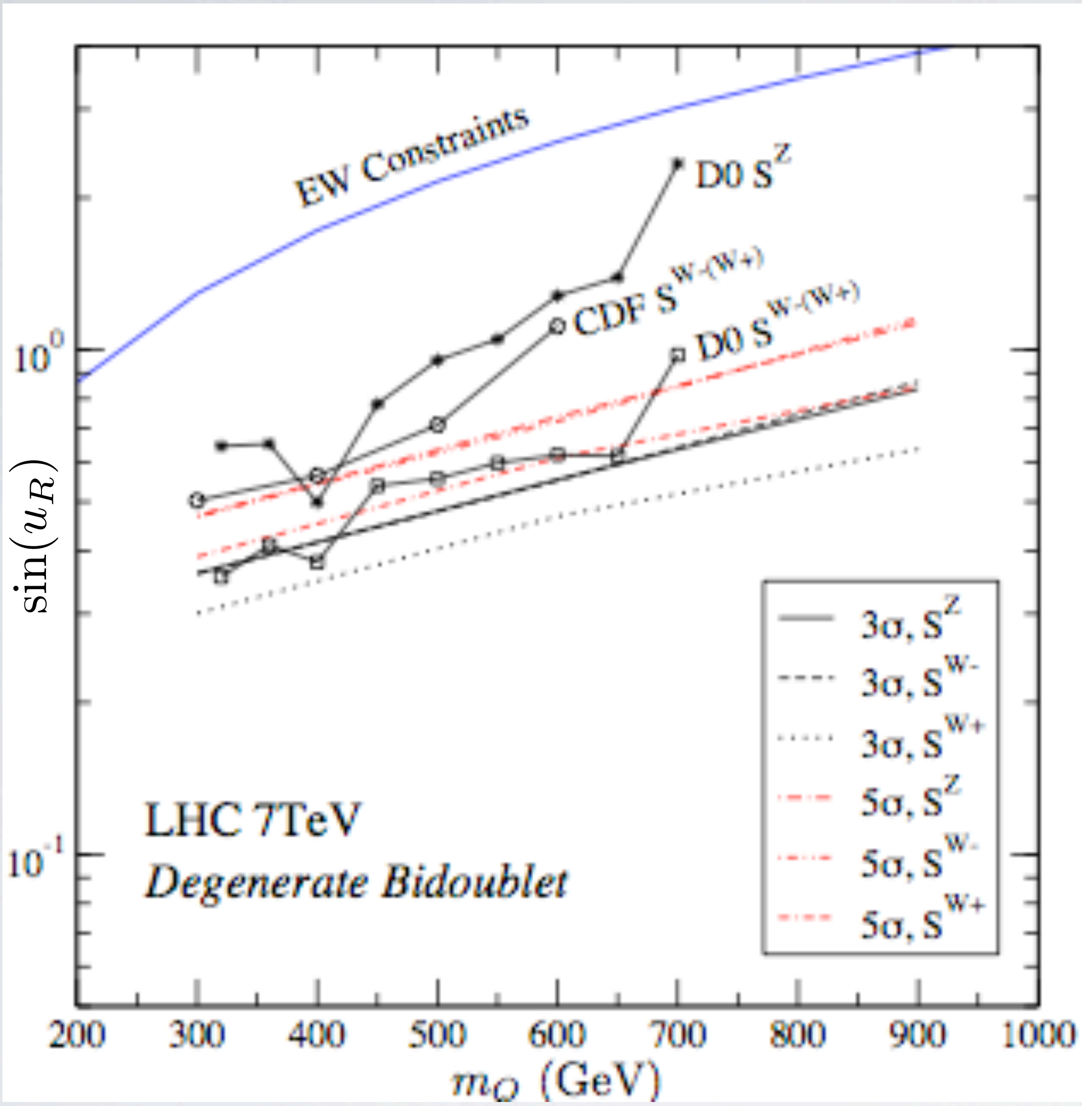


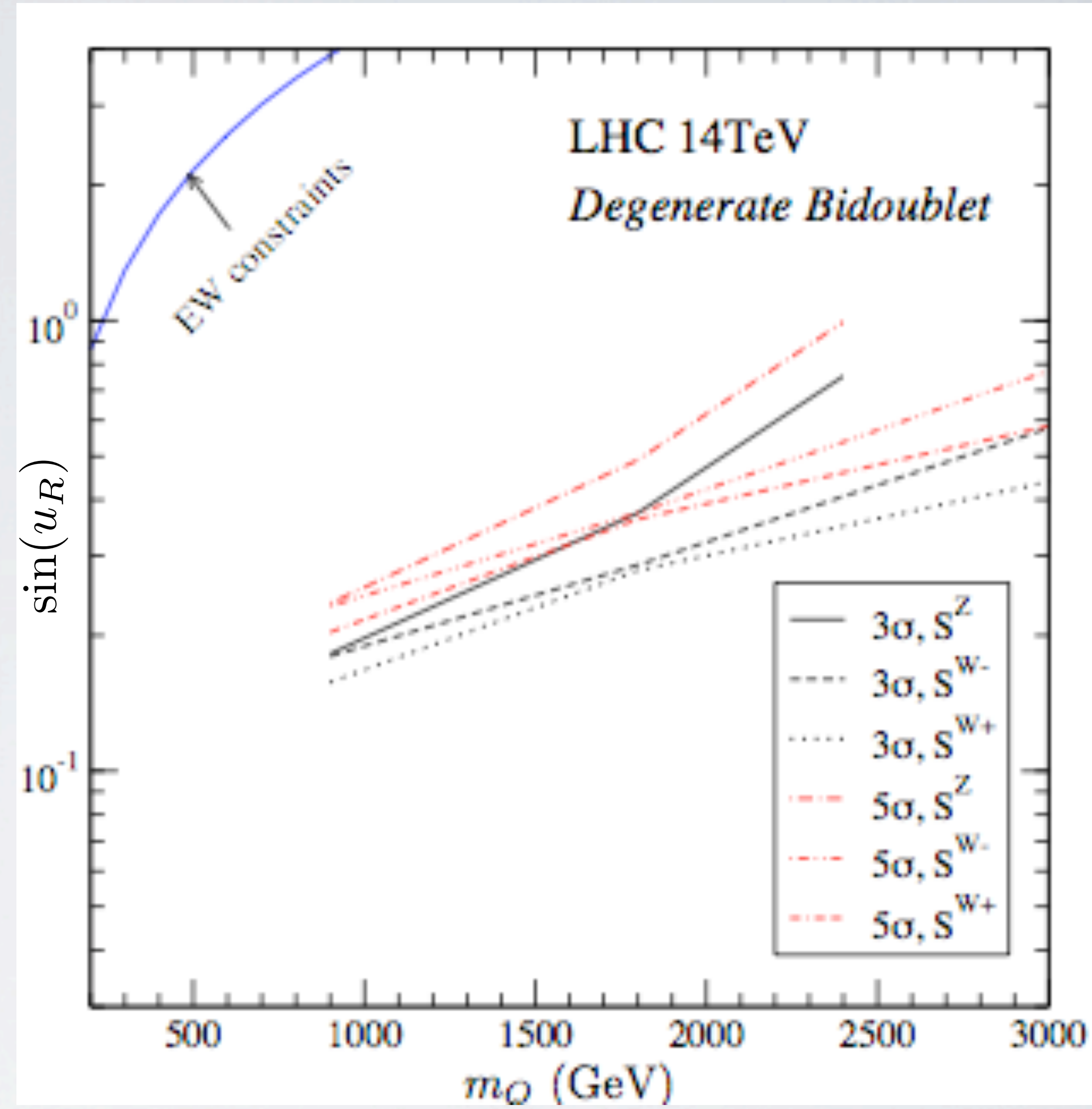
Large enhancement from access to valence quarks.





W, Z+ jets final states.

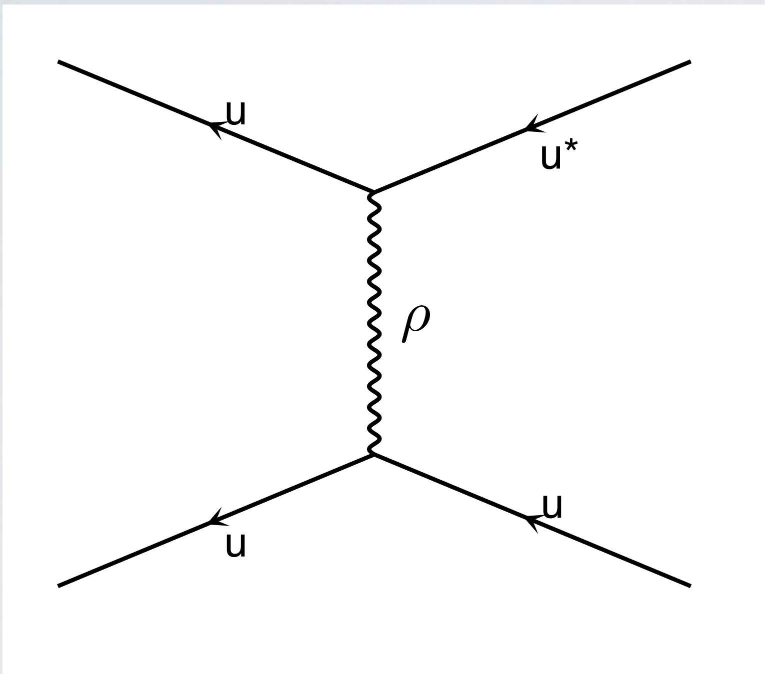


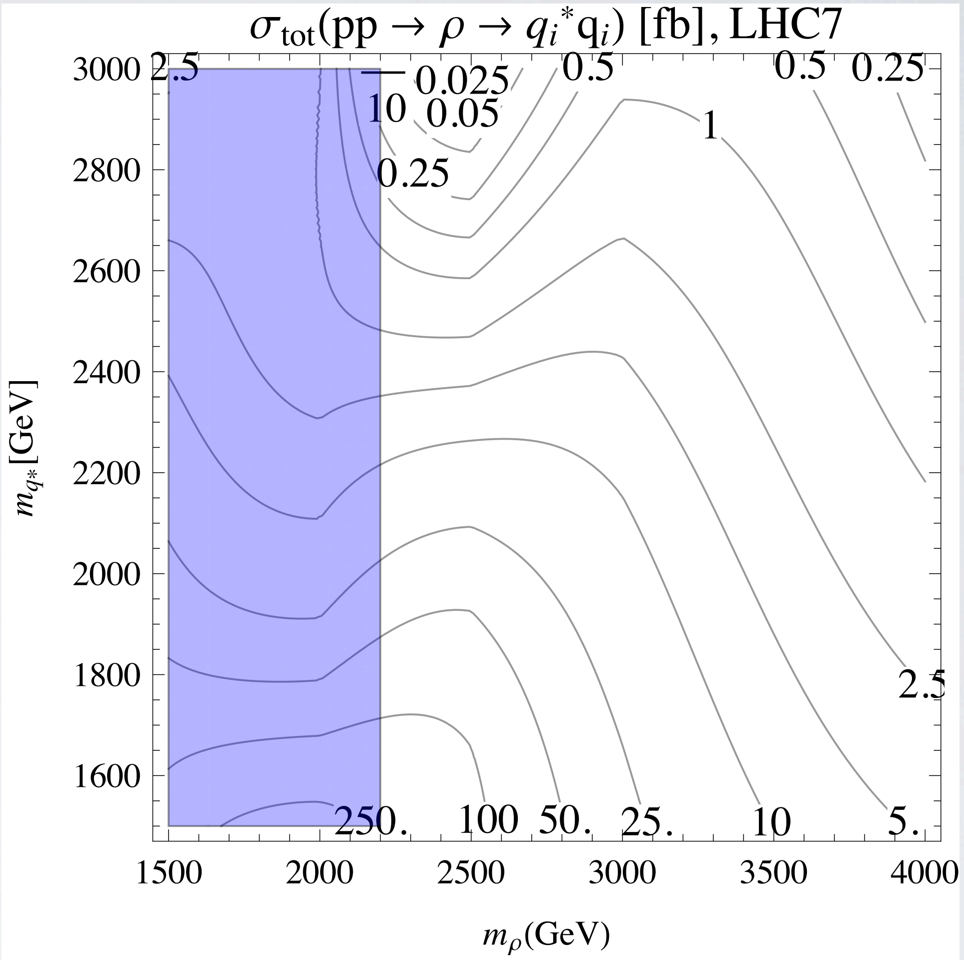


Atre, Azuelos, Carena, Han,
Ozcan, Santiago, Unel ’11

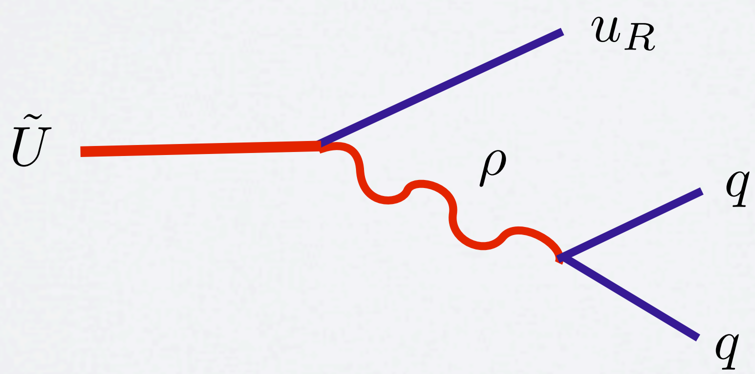
LHC searches could already probe fermions up to 1 TeV.
LHC14 will either discover or exclude the model.

Right quark partners produced by resonance exchange.





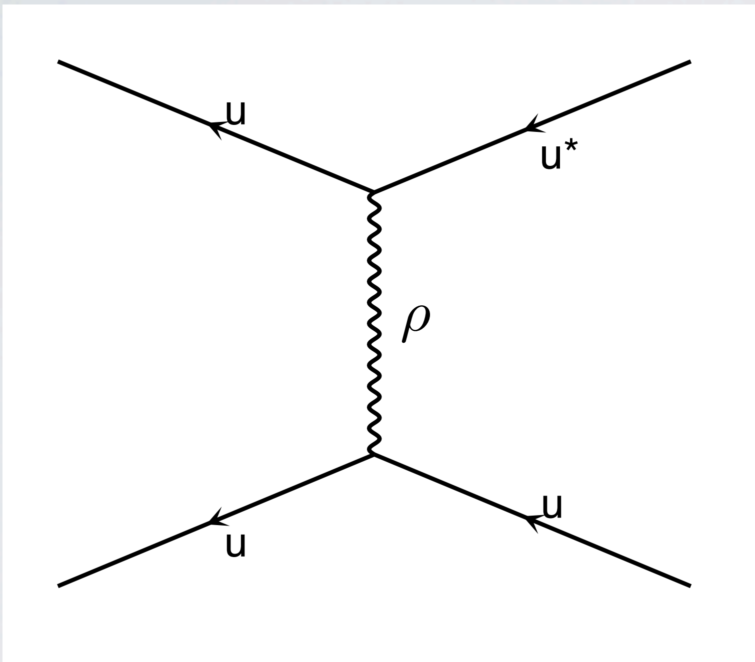
$g_\rho = 3\,, \sin\varphi_{u_R} = .7\,, \sin\varphi_{d_R} = 1/6$

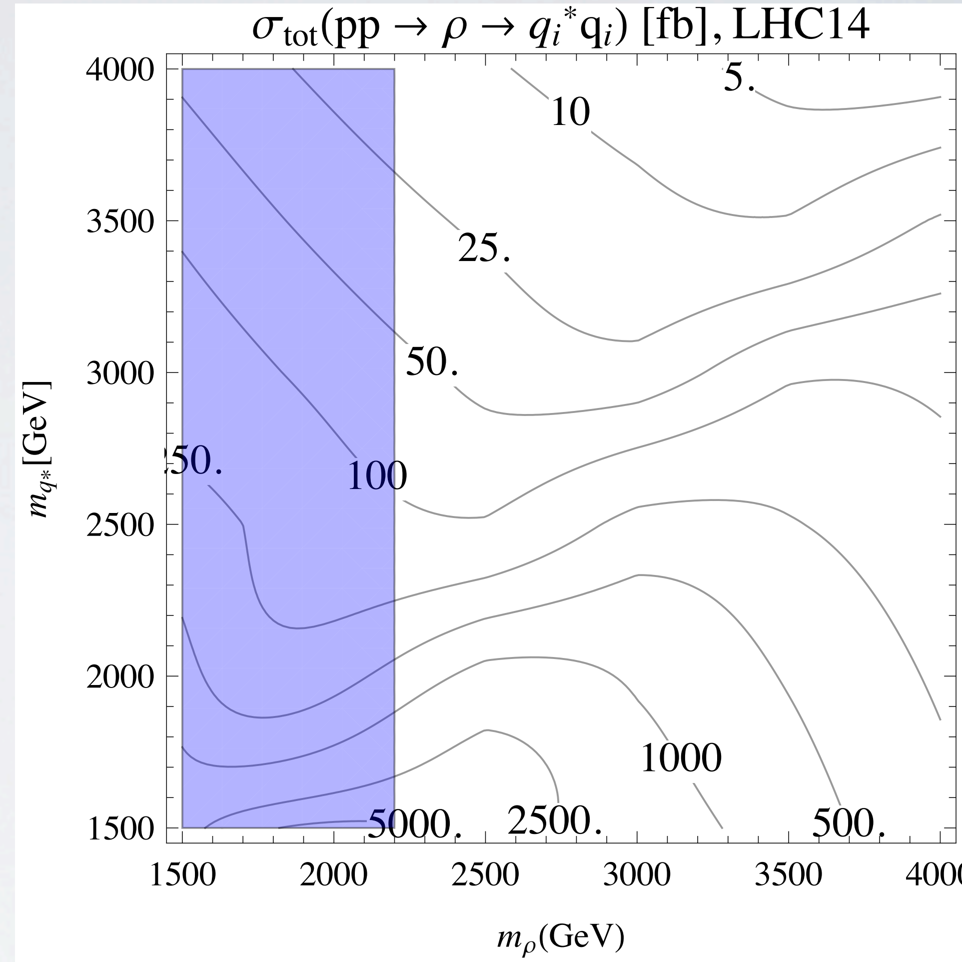


MR, Sanz, Weiler, in progress

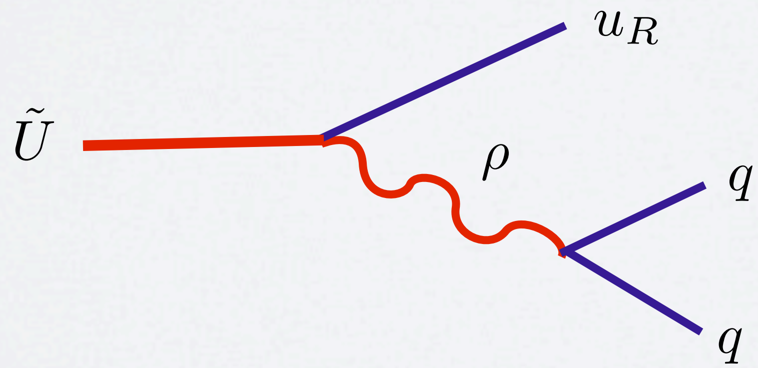
3-4 jets final states.

Right quark partners produced by resonance exchange.





$$g_\rho = 3\,, \sin\varphi_{u_R} = .7\,, \sin\varphi_{d_R} = 1/6$$



MR, Sanz, Weiler, in progress

3-4 jets final states.

CONCLUSIONS

- As in the SM in CH the Higgs will be found at LHC7.
- Within standard assumptions it will be hard to distinguish SM and CH at LHC7.
- If flavor symmetries are at work light quarks are partially composite and exciting signals could be seen at LHC7.

Flavor vs. Composite Higgs at LHC

Contino, Kramer, Son, Sundrum '06

Simplified 2 site picture:
Each SM chirality has a Dirac fermionic partner

$$\mathcal{L}_{composite} = \bar{Q}^i(i\not{D} - m_Q^i)Q^i + \bar{U}^i(i\not{D} - m_U^i)U^i + \bar{D}^i(i\not{D} - m_D^i)D^i$$
$$+Y_{ij}^U \bar{Q}^i \tilde{H} U^j + Y_{ij}^D \bar{Q}^i H D^j$$

$$\mathcal{L}_{mixing} = \frac{m_\rho}{g_\rho}\left[\lambda_q^{ij}\bar{q}_{Li}Q_{Rj} + \lambda_u^{ij}u_{Ri}\bar{U}_{Lj} + \lambda_d^{ij}d_{Ri}\bar{D}_{Lj} + \text{h.c.}\right]$$

Mass basis:

$$\begin{pmatrix} q_{Li} \\ Q_{Li} \end{pmatrix} = \begin{pmatrix} \cos\varphi_{q_{Li}} & -\sin\varphi_{q_{Li}} \\ \sin\varphi_{q_{Li}} & \cos\varphi_{q_{Li}} \end{pmatrix} \begin{pmatrix} q_{Li}^{el} \\ R_{ij}^L Q_{Lj}^{co} \end{pmatrix}$$

Contino, Kramer, Son, Sundrum '06

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Gauge fields:

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