Lepton Flavor Violation in Composite Higgs

Michele Redi

1106.6357 (with A. Weiler)
+ 1203.4220
+ to appear

Lecce, 6 May

OUTLINE

- Composite Higgs Models

- LFV in anarchic scenarios

- MFV theories and composite leptons

- SU(2) theories

$$\Lambda \sim M_p$$

$$\downarrow$$

$$m_h^2 = 1000000000000000000000000000000.01\,\mathrm{TeV}^2$$
$$- 1000000000000000000000000000000.00\,\mathrm{TeV}^2$$

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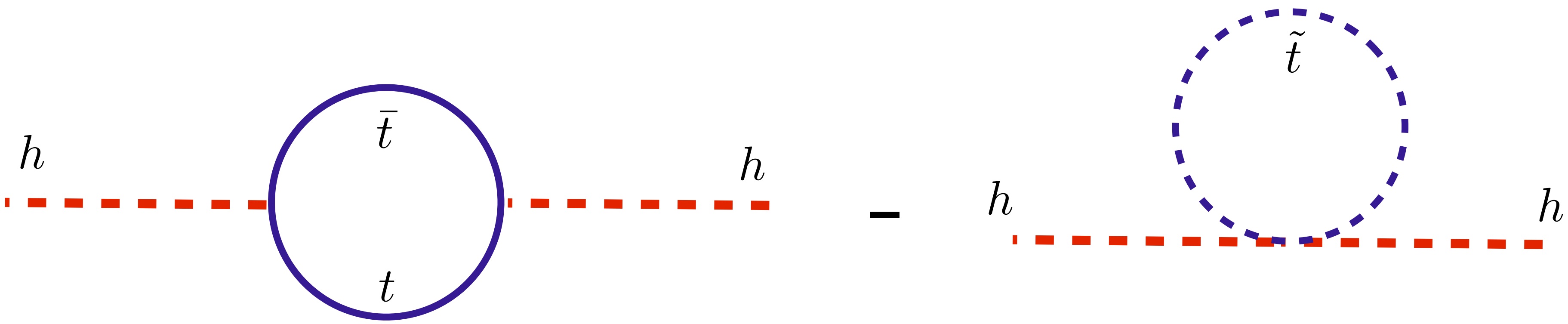
Natural theory:

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

Naturalness hints to new dynamics at TeV scale:

- Weak Coupling:
  Supersymmetry



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

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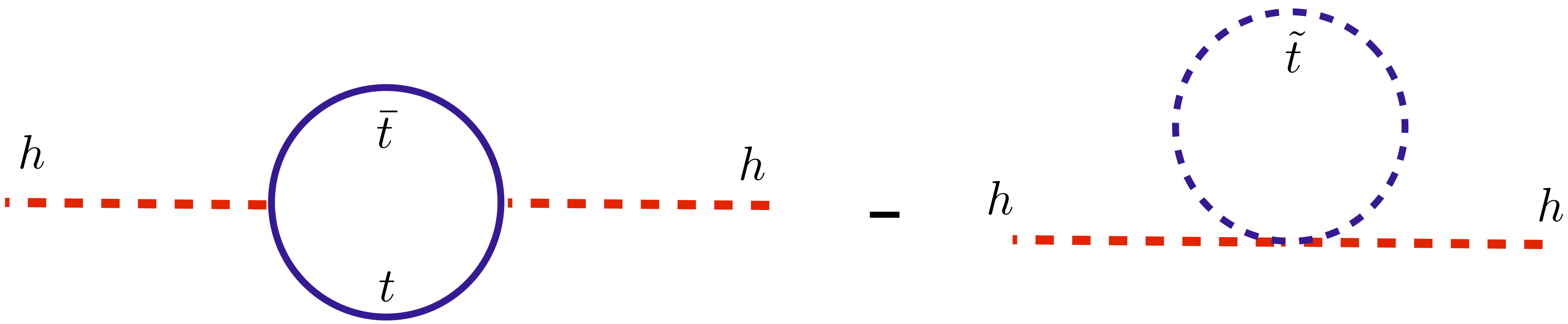
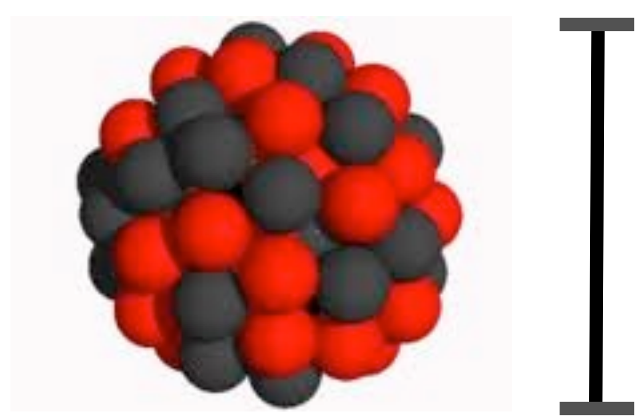


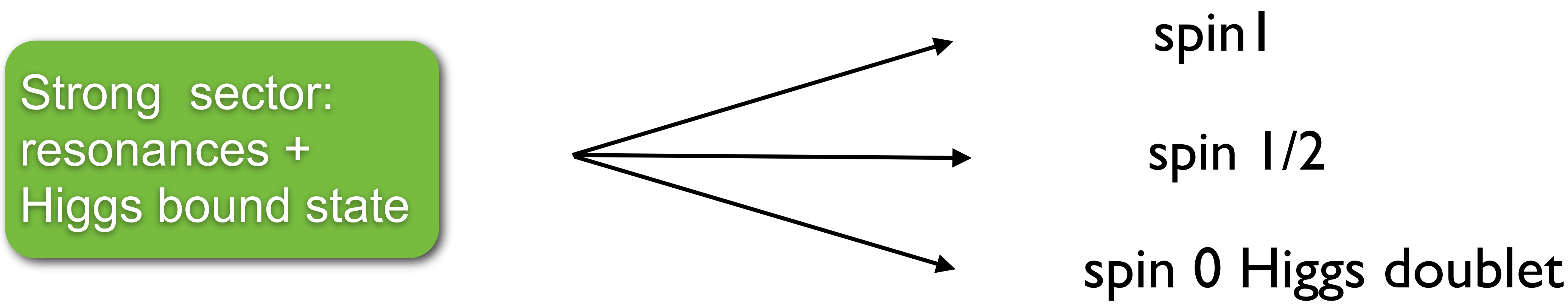
$\sim 100\,\mathrm{GeV}$

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



$\sim \frac{1}{\Lambda}$

Higgs doublet could be a bound state



Higgs doublet could be a bound state

Strong sector:
resonances +
Higgs bound state

→ spin 1

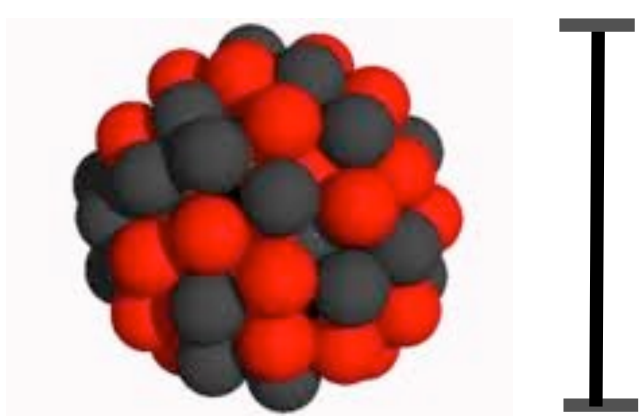
→ spin 1/2

→ spin 0 Higgs doublet

Compositeness scale acts as cut-off

$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} m_\rho^2$$

Natural theory



$$\frac{1}{m_\rho} \sim \frac{1}{\text{TeV}} = 10^{-18}\text{m}$$

Scalars automatically massless if they are Goldstone bosons

$$\frac{G}{H} \xrightarrow{f > v} \text{\# GB} = \text{Dim}[G] - \text{Dim}[H]$$

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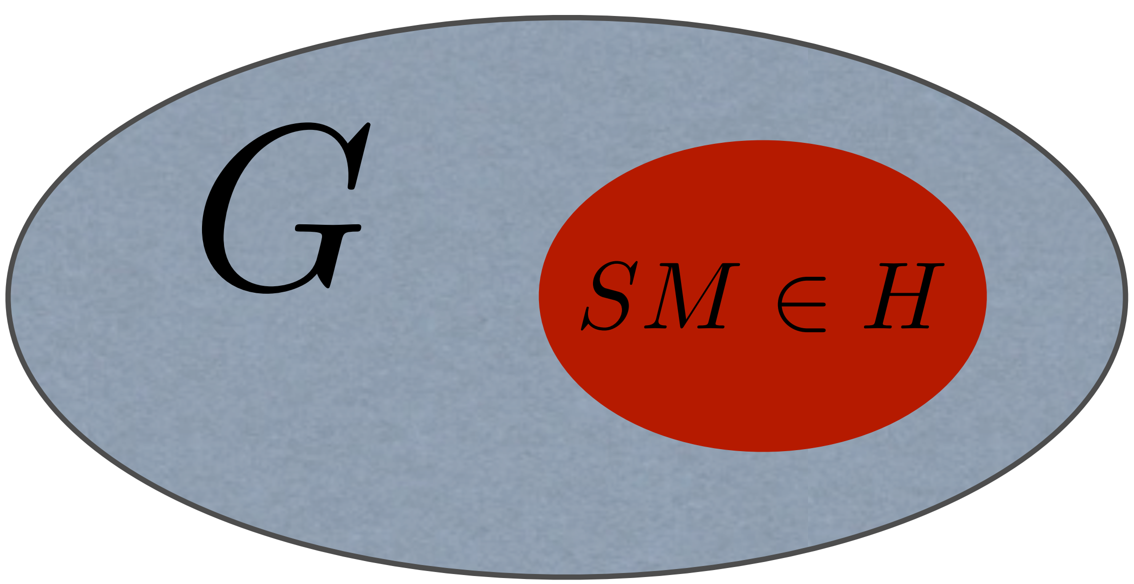
Higgs could be an approximate GB



Georgi, Kaplan '80s

Ex:

Agashe , Contino, Pomarol, '04

$$\frac{SO(5)}{SO(4)} \longrightarrow \mathrm{GB} = 4$$

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

Mrazek et al., '11

Deviations from SM:

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

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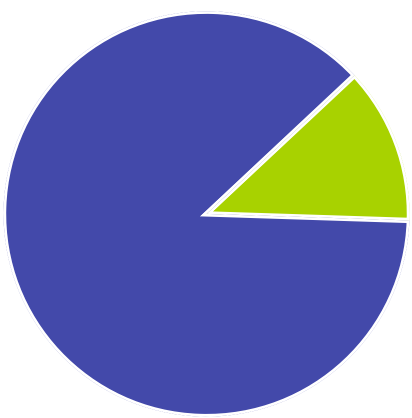
Higgs is an angle,



$$0 < h < 2\pi f \longrightarrow \text{TUNING} \propto \frac{f^2}{v^2}$$

Small Tuning $\quad f < TeV$

Spectrum:

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

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

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

$$0$$

Flavor:

- Bilinear couplings (a la technicolor)

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

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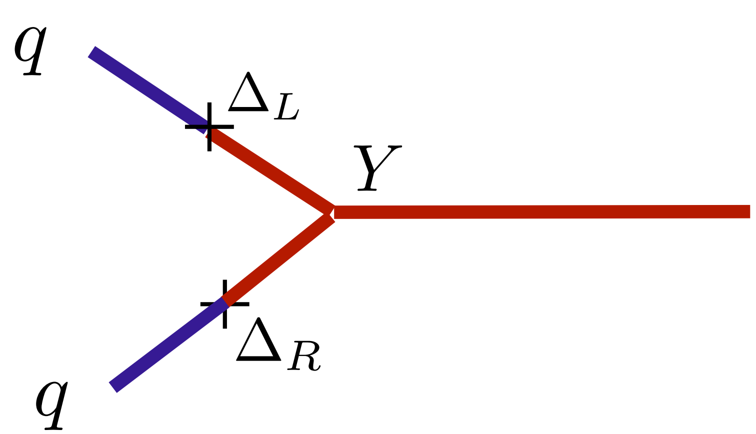
- Linear couplings (partial compositeness)



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

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

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

Partial Compositeness

D. B. Kaplan '92
Grossman, Neubert '99
Huber '01
...

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

Partial Compositeness

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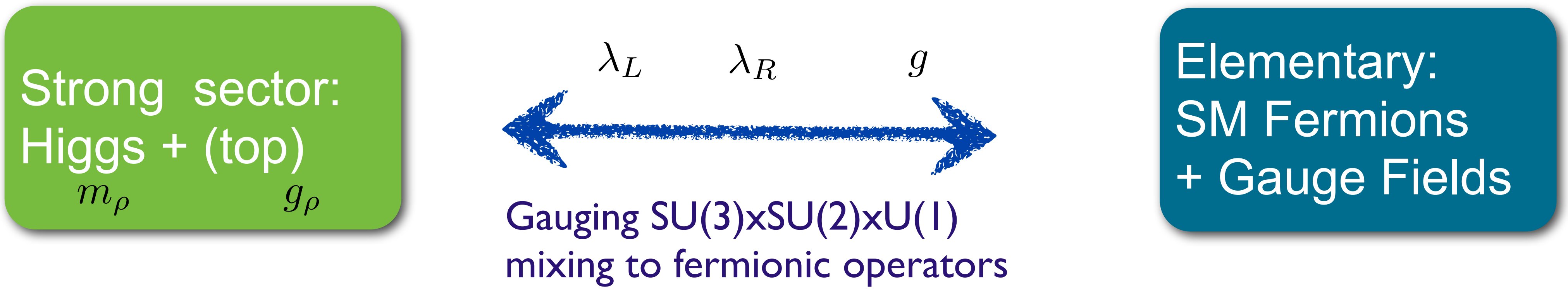

Elementary-composite states talk through linear couplings:

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

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

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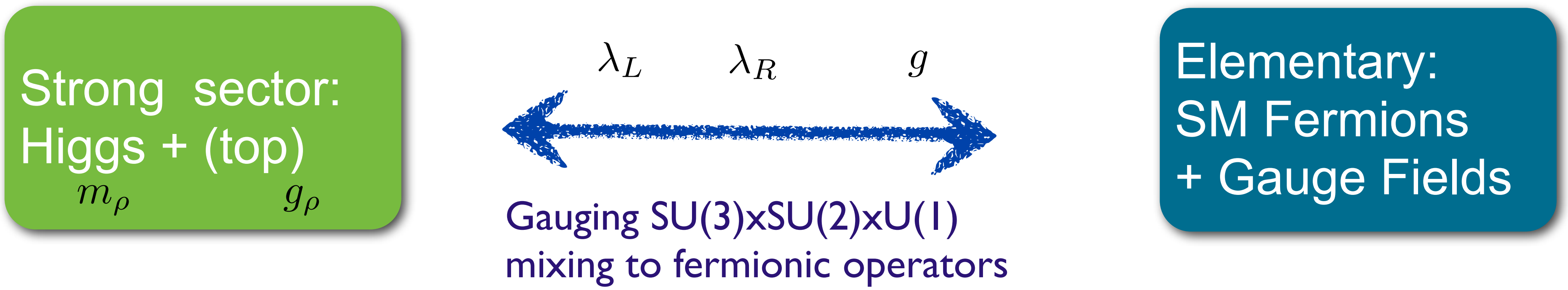

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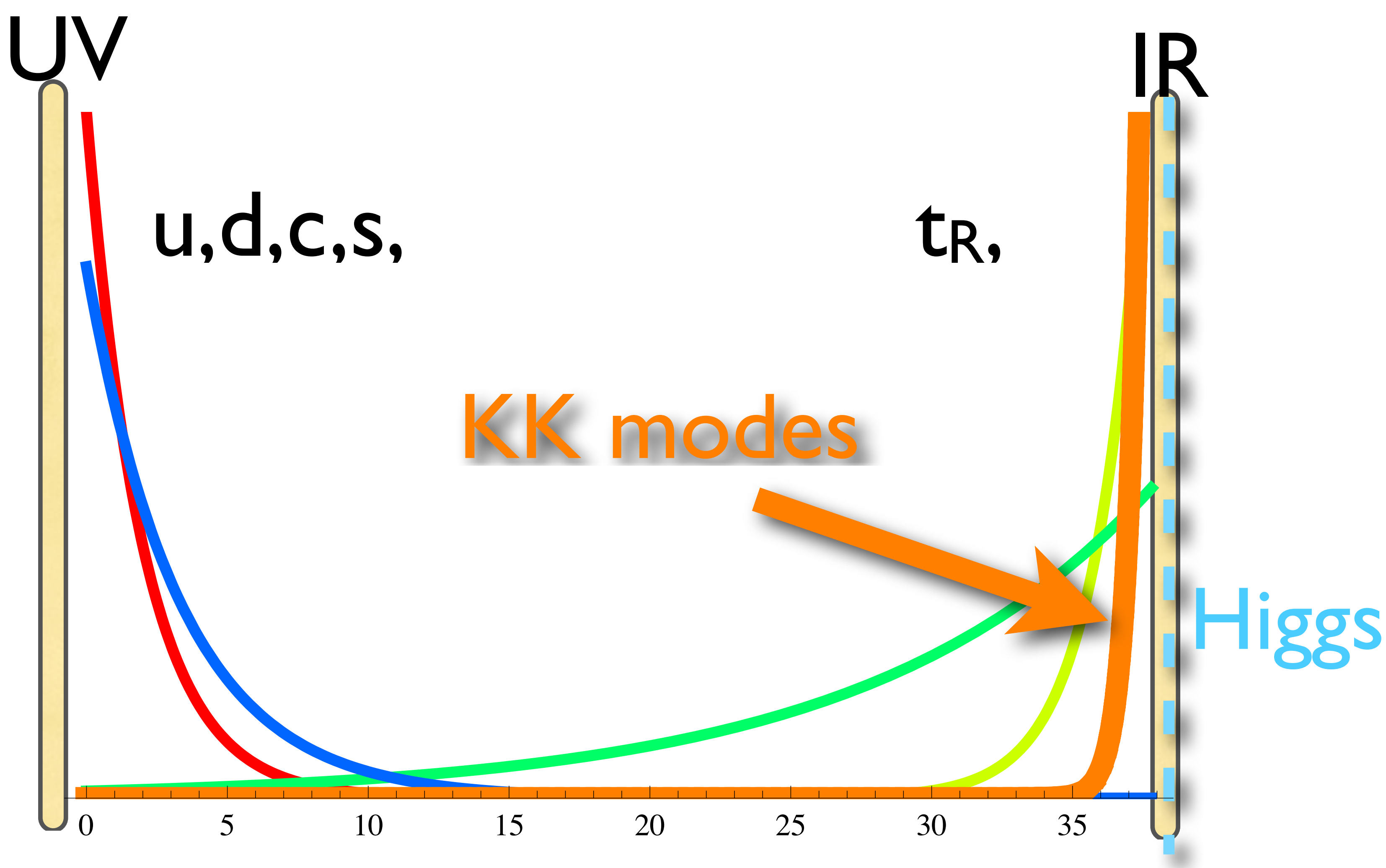
Two scenarios:

- Anarchic
- Minimal Flavor Violation

Progress started with Randall-Sundrum constructions.



(Randall-Sundrum '99)

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

Different profiles generate hierarchies.
Dual to 4D CFTs through AdS-CFT.

Relevant physics largely independent from 5D.

First resonance sufficient for practical purposes.

Panico, Wulzer '11

de Curtis, MR, Tesi '11

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Bosons:

$$A^{\mu}_{SM} \longrightarrow \rho^{\mu} \in \text{Adj}[G]$$

g_{ρ}

m_{ρ}

Fermions:

$$f_{SM} \longrightarrow F \in G$$

y_{*}

m_{ψ}

ANARCHIC SCENARIO

For leptons see:
Agashe, Blechman, Petriello'06
Csaki et al. '10
Keren-Zur et al. '12

Strong sector has no hierarchies

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

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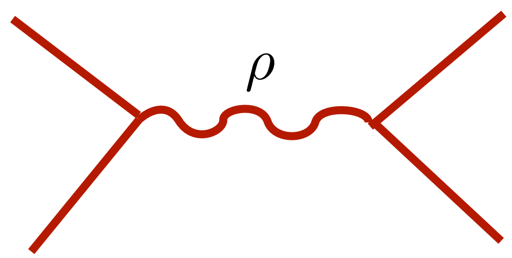
SM hierarchies are generated by the mixings:

- Light quarks elementary
- Top strongly composite

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

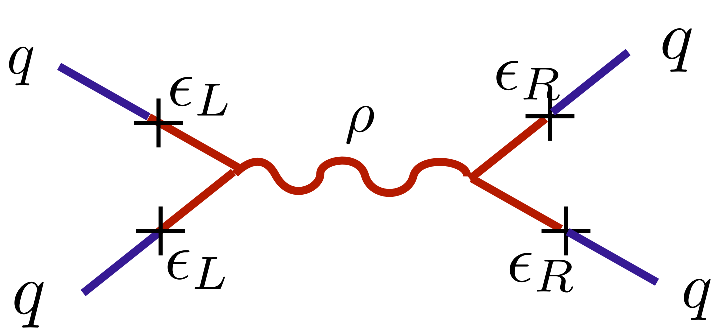
- **Flavor Protection**

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 but 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

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

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

Also:

- EDMs:

$$m_\psi > 2 y_* \, \text{TeV}$$

- b-> s gamma, ...

Marginally consistent in the quark sector

Extension to leptons in principle trivial.

Simplest option vectorial copy of SM.

$$L = \begin{pmatrix} N \\ E \end{pmatrix} \qquad \tilde{L} = \begin{pmatrix} \tilde{N} \\ \tilde{E} \end{pmatrix}$$

$$\mathcal{L}_{comp} = m_L \bar{L} L + m_{\tilde{L}} \bar{\tilde{L}} \tilde{L} + y_* \bar{L} H \tilde{L}$$

$$\mathcal{L}_{mixing} = \Delta_L \bar{l}_L L_R + \Delta_e \bar{\tilde{E}}_L e_R + \Delta_\nu \bar{\tilde{N}}_L \nu_R$$

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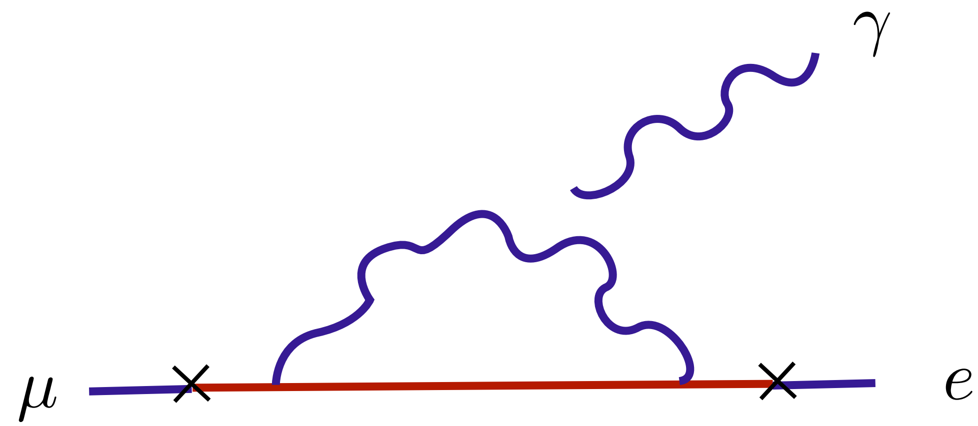
See-saw

$$M_{ij} \nu_R^i \nu_R^j$$

$$m_\nu = v^2 \epsilon_L \cdot Y_e \cdot \epsilon_{R\nu} \cdot M^{-1} \cdot \epsilon_{R\nu}^T \cdot Y_\nu^T \cdot \epsilon_L^T$$

Dipoles:



$$\left(\frac{y_*}{4\pi}\right)^2 \frac{e}{m_\psi^2} \left(\frac{\epsilon_L^\mu}{\epsilon_L^e} m_e \bar{\mu}_L \sigma^{\mu\nu} e_R + \frac{\epsilon_L^e}{\epsilon_L^\mu} m_\mu \bar{e}_L \sigma^{\mu\nu} \mu_R\right) F_{\mu\nu}$$

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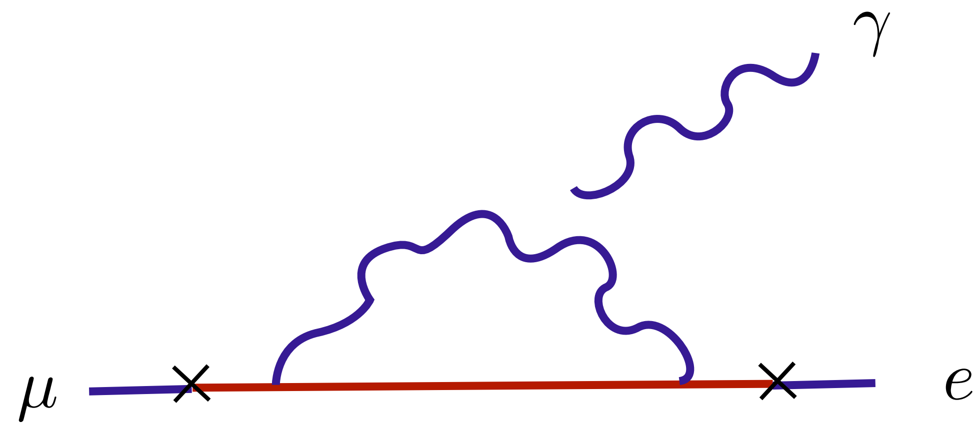

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Most favorable choice:

$$\frac{\epsilon_L^i}{\epsilon_L^j} \sim \frac{\epsilon_R^i}{\epsilon_R^j} \sim \sqrt{\frac{m_i}{m_j}} \longrightarrow e\left(\frac{y_*}{4\pi}\right)^2 \frac{\sqrt{m_e\, m_\mu}}{m_\psi^2} \bar{\mu}\sigma^{\mu\nu} e\, F_{\mu\nu}$$

Estimate:

(see also Csaki, Grossman, Tanedo, Tsai '10)

$$\mathrm{Br}(\mu \to e\gamma) \sim 5 \times \left(\frac{y^*}{3}\right)^4 \times \left(\frac{3\,\mathrm{TeV}}{m_\psi}\right)^4 \times 10^{-8}$$

MEG, '13

$\mathrm{Br}(\mu \to e\gamma) < 5 \times 10^{-13}$ ⟶ $y_* \sim .1!!!$

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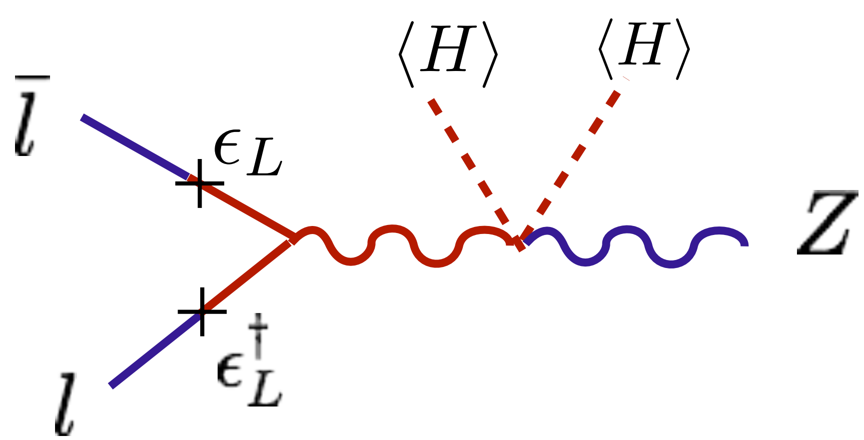
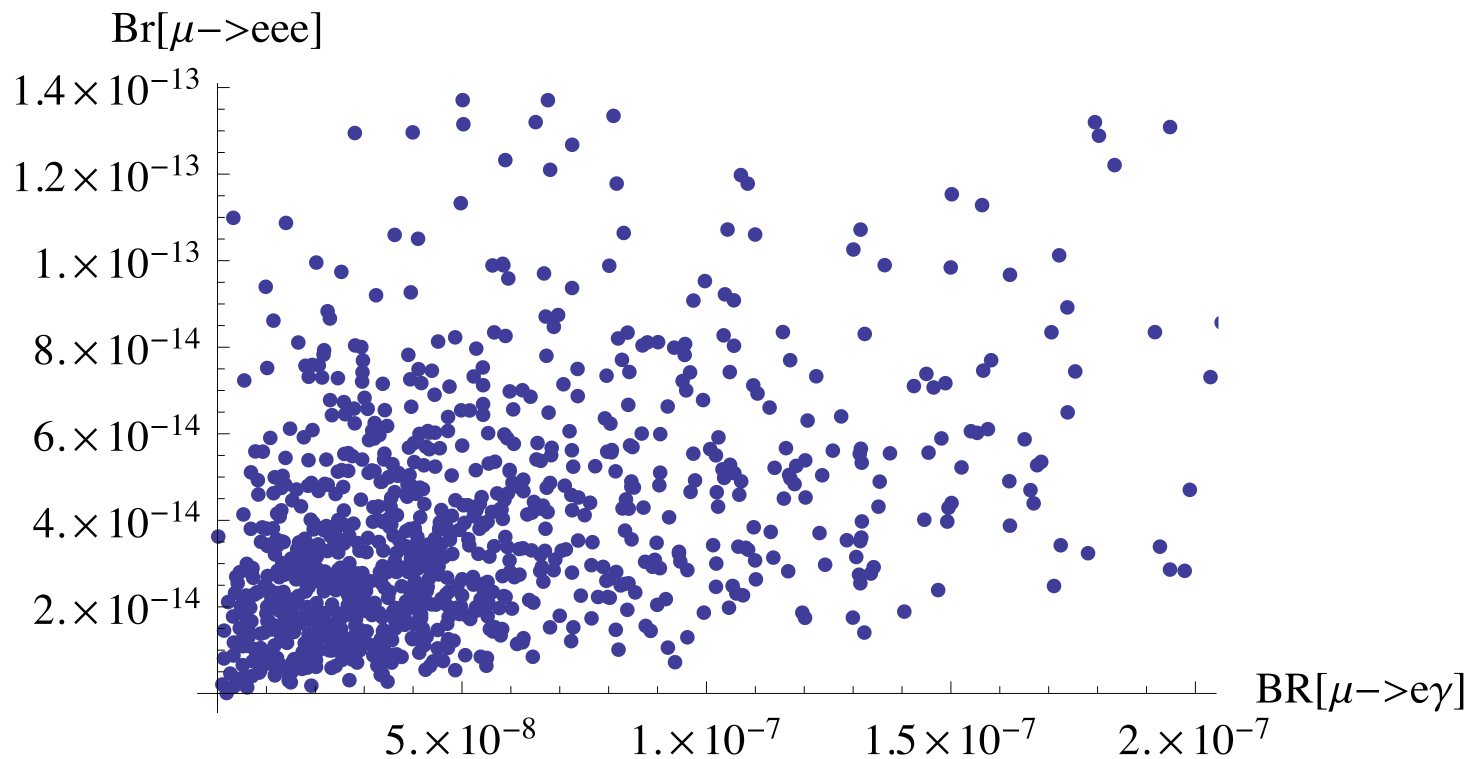
Flavor violating Z-couplings



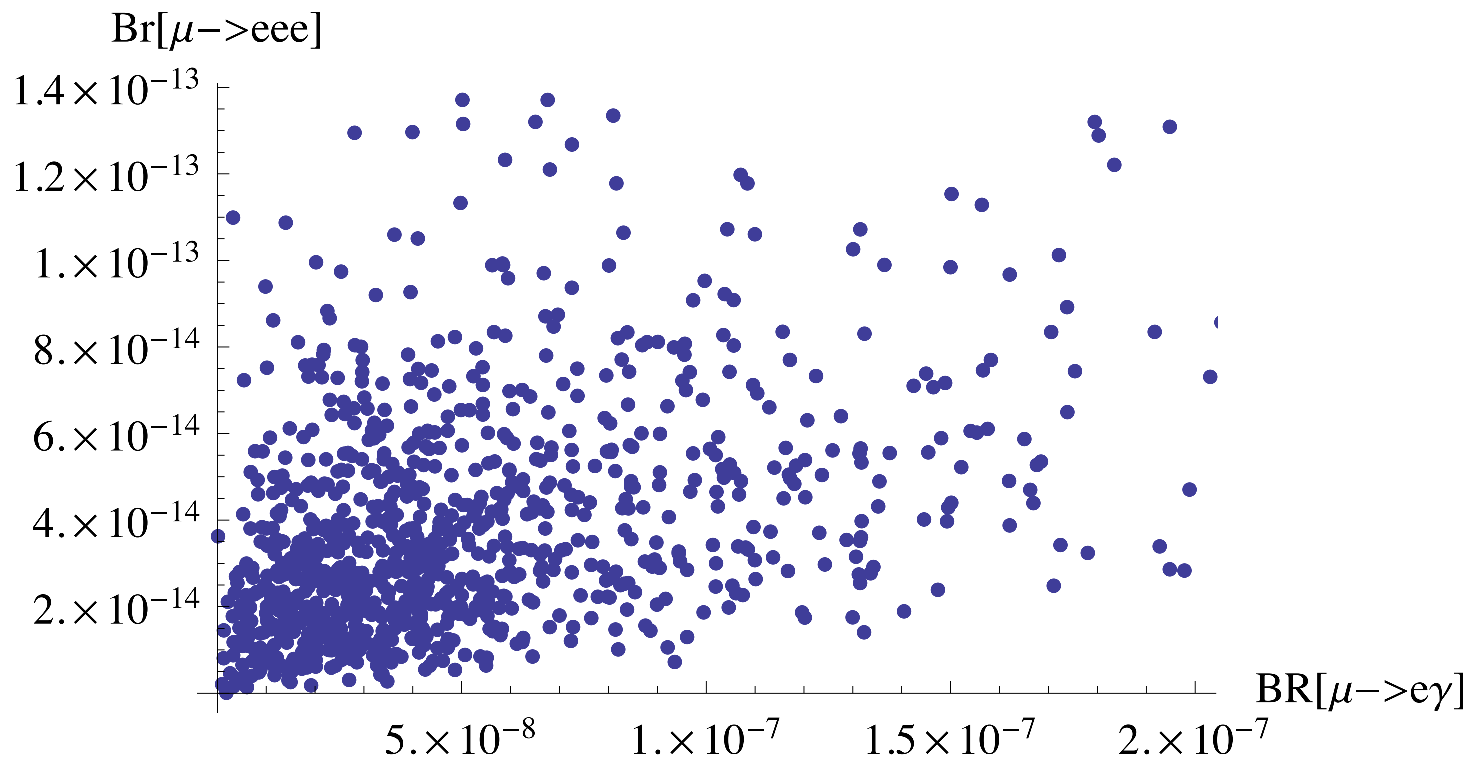
$$\frac{\delta g_L}{g_L} \sim \frac{g_\rho^2 v^2}{m_\rho^2} \epsilon_L \epsilon_L^\dagger$$

$$\mathrm{Br}(\mu \to eee) \sim \left(\frac{g_\rho^2}{3\,y_*}\right)^2 \times \left(\frac{3\,\mathrm{TeV}}{m_\rho}\right)^4 \times 10^{-13}$$



$$y_* = 3$$

$$m_\chi = 3\,\mathrm{TeV}$$



$y_* = 3$

$m_\chi = 3\,\text{TeV}$

	L_1	L_2	EXP
$\text{Br}(\mu \to e\gamma)$	$5 \cdot 10^{-8}$	10^{-6}	$5 \cdot 10^{-13}$
$\text{Br}(\tau \to e\gamma)$	10^{-9}	10^{-7}	$3 \cdot 10^{-8}$
$\text{Br}(\tau \to \mu\gamma)$	10^{-7}	10^{-6}	$4 \cdot 10^{-8}$
$\text{Br}(\mu \to 3e)$	10^{-13}	10^{-12}	10^{-12}
$\text{Br}(\tau \to 3e)$	10^{-13}	10^{-12}	$3 \cdot 10^{-8}$
$\text{Br}(\tau \to 3\mu)$	$5 \cdot 10^{-11}$	10^{-12}	$2 \cdot 10^{-8}$

L_1 : "Optimal"

$L_2 : \epsilon_L = (.01, .02, .025)$

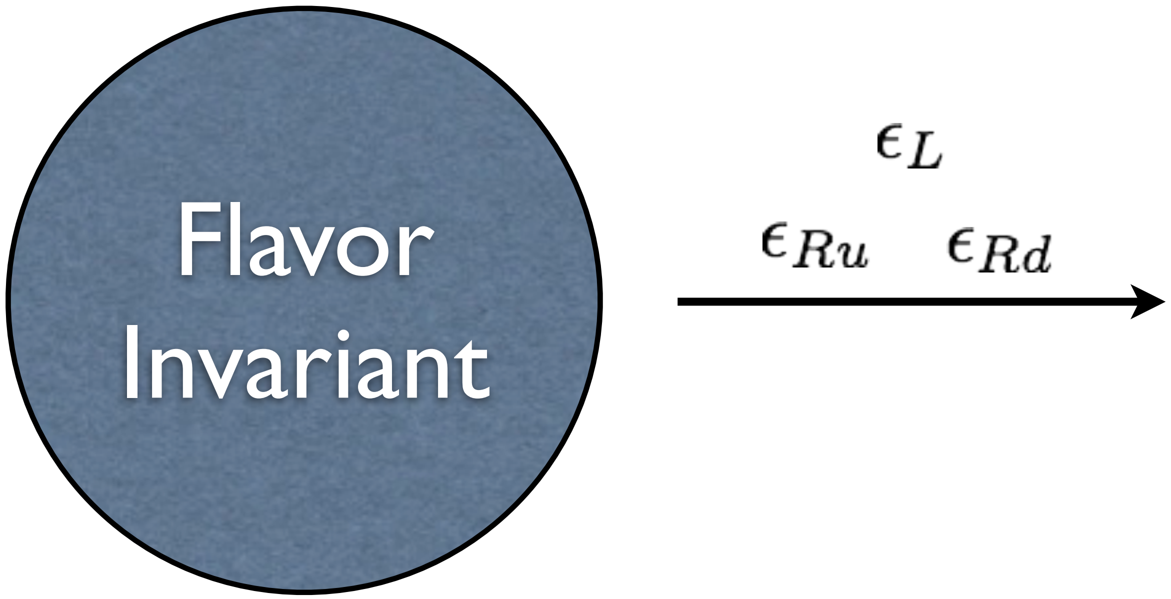
Anarchic scenarios don't fit well leptons!

MFV SCENARIO

MR and A. Weiler, 1106.6357
+ work in progress

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

Adding a flavor symmetry:



All flavor violation comes from the mixings.

$$y_u \propto \epsilon_L \epsilon_{Ru}$$

$$y_d \propto \epsilon_L \epsilon_{Rd}$$

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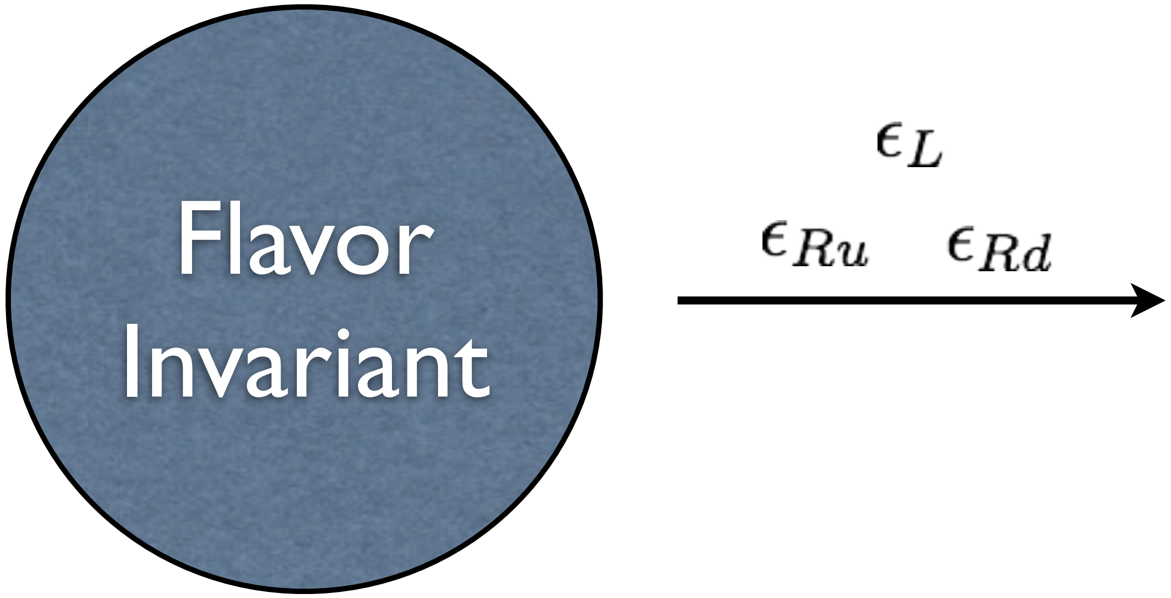

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Simple realizations of Minimal Flavor Violation:

mixings ~ SM Yukawas

- Left-handed compositeness

$$\epsilon_L \propto \mathrm{Id}$$

$$\epsilon_{Ru} \propto y_u \qquad \epsilon_{Rd} \propto y_d \qquad + \qquad SU(3)_F$$

- Right-handed compositeness

$$\epsilon_{Lu} \propto y_u \qquad \epsilon_{Ld} \propto y_d$$

$$+ \qquad SU(3)_U \otimes SU(3)_D$$

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MFV $\longrightarrow$ Mixing of one chirality of light quarks is large.

L-compositeness constrained by precision tests

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

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002$$

$$\frac{y_*^2 v^2}{m_\chi^2} \epsilon_L^2 < 0.002$$

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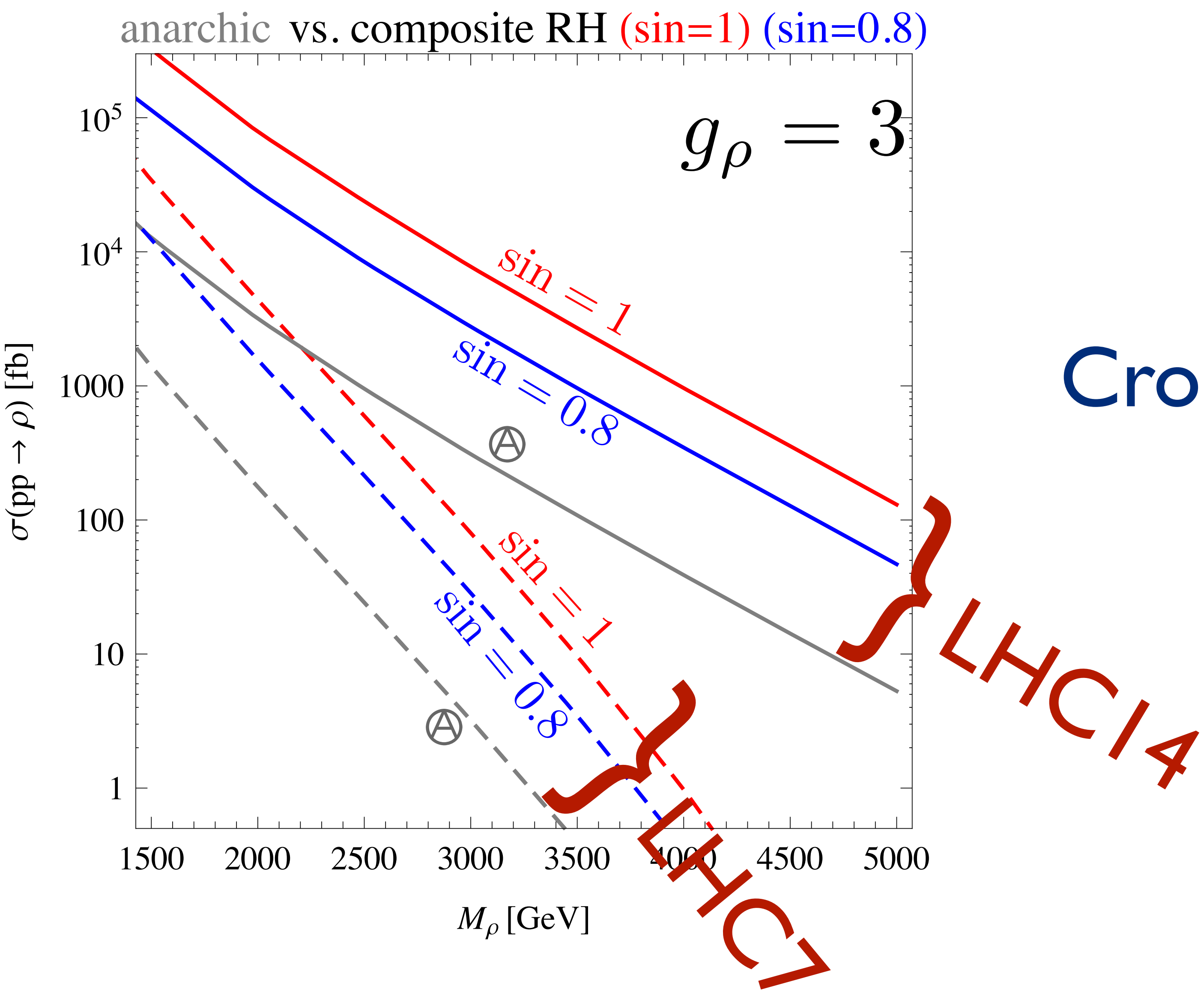
R-compositeness constrained by LHC flavor

$$\mathcal{L}_{4-Fermi} = \frac{2\pi}{\Lambda^2}\left(\bar{q}_L \gamma^\mu q_L\right)^2 \qquad\qquad \Lambda > 6\,\mathrm{TeV}$$

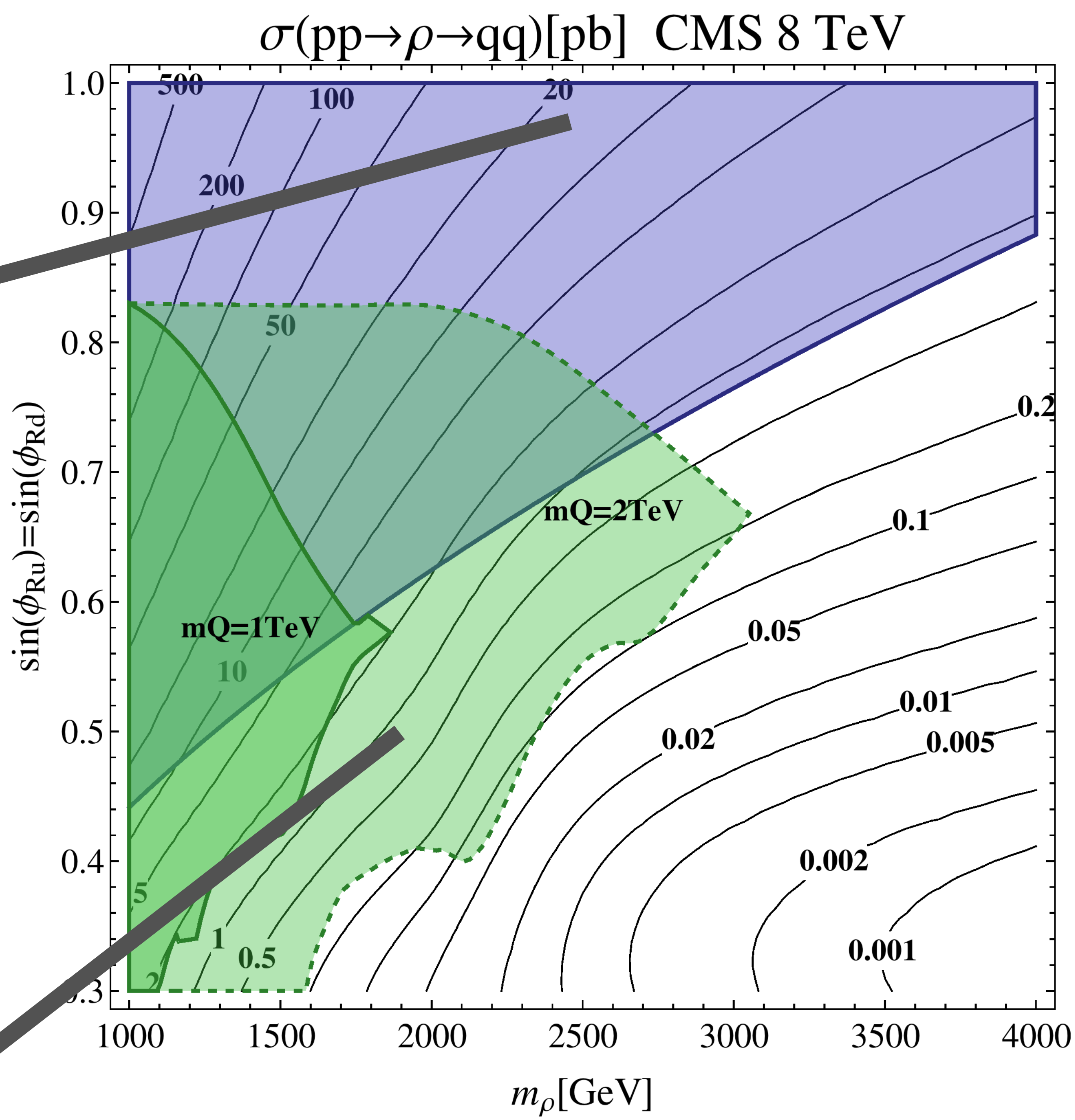
$$\frac{g_\rho^2}{4\,m_\rho^2}\,\epsilon_R^4\,\left(\bar{q}^i_{R\alpha}\gamma^\mu q^i_{R\beta}\bar{q}^j_{R\beta}\gamma_\mu q^j_{R\alpha}\right) \xrightarrow{\text{COMPOSITENESS}} \epsilon_R^2 \leq \frac{2}{g_\rho}\left(\frac{m_\rho}{3\,\mathrm{TeV}}\right)$$

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

Gluon resonances:



Cross-sections O(10)x anarchic



Di-jet bounds

Bump-hunter search

MR, Sanz, de Vries, Weiler, 1305.xxxx

Leptons: we focus on L-compositeness

$$\epsilon_L \propto \mathrm{Id}$$

Compositeness can be small

$$\epsilon_L = \frac{m_\tau}{y_* v \epsilon_{R\tau}} \longrightarrow \epsilon_L > \frac{1}{100\, y_*}$$

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Compositeness can be small

$$\epsilon_L = \frac{m_\tau}{y_* v \epsilon_{R\tau}} \longrightarrow \epsilon_L > \frac{1}{100\, y_*}$$

Consistent with

$$y_* > 1$$

CLFV as in the SM. No deviations expected.

Muon g-2

$$\delta^{\mu}_{g-2} \sim \left(\frac{y_*}{4\pi}\right)^2 \frac{m_\mu^2}{m_\psi^2}$$

Anomaly (2 x 10^-9),

$$m_\psi \sim y_* \times 150\,\mathrm{GeV}$$

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Suggests light leptons.
Other anomalies predicted

$$\delta^{e}_{g-2} = \delta^{\mu}_{g-2} \frac{m_e^2}{m_\mu^2}$$

No EDM if strong sector respects CP

Indirect bounds:

- "compositeness"

$$\frac{2\pi}{\Lambda^2}(\bar{l}\gamma_\mu l)^2 \qquad \Lambda > 10\,\mathrm{TeV}$$

$$\frac{g_\rho^2}{m_\rho^2}\epsilon_L^4 \longrightarrow \epsilon_L^2 < \frac{1}{4g_\rho} \times \frac{m_\rho}{3\,\mathrm{TeV}}$$

- Excited leptons

$$\frac{1}{\Lambda}\bar{l}_R\sigma^{\mu\nu}\left[g\frac{\tau^a}{2}W^a_{\mu\nu} + g'\frac{Y}{2}B_{\mu\nu}l_L\right]F_{\mu\nu}$$

Atlas 1201.3293

$$\Lambda > 2\,\mathrm{TeV}$$

Weak bound if loop generated.

- Z-couplings

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu^+\mu^-)} = 20.0767 \pm 0.25 \longrightarrow \frac{\delta g_{Z\mu\bar{\mu}}}{g_{Z\mu\bar{\mu}}} < 0.002$$

$$\frac{\delta g_{Z\mu\bar{\mu}}}{g_{Z\mu\bar{\mu}}} \sim \frac{y_*^2 v^2}{m_\psi^2}\epsilon_L^2 \longrightarrow \epsilon_L < \frac{1}{10 y_*}\left(\frac{m_\psi}{500\,\mathrm{GeV}}\right)$$

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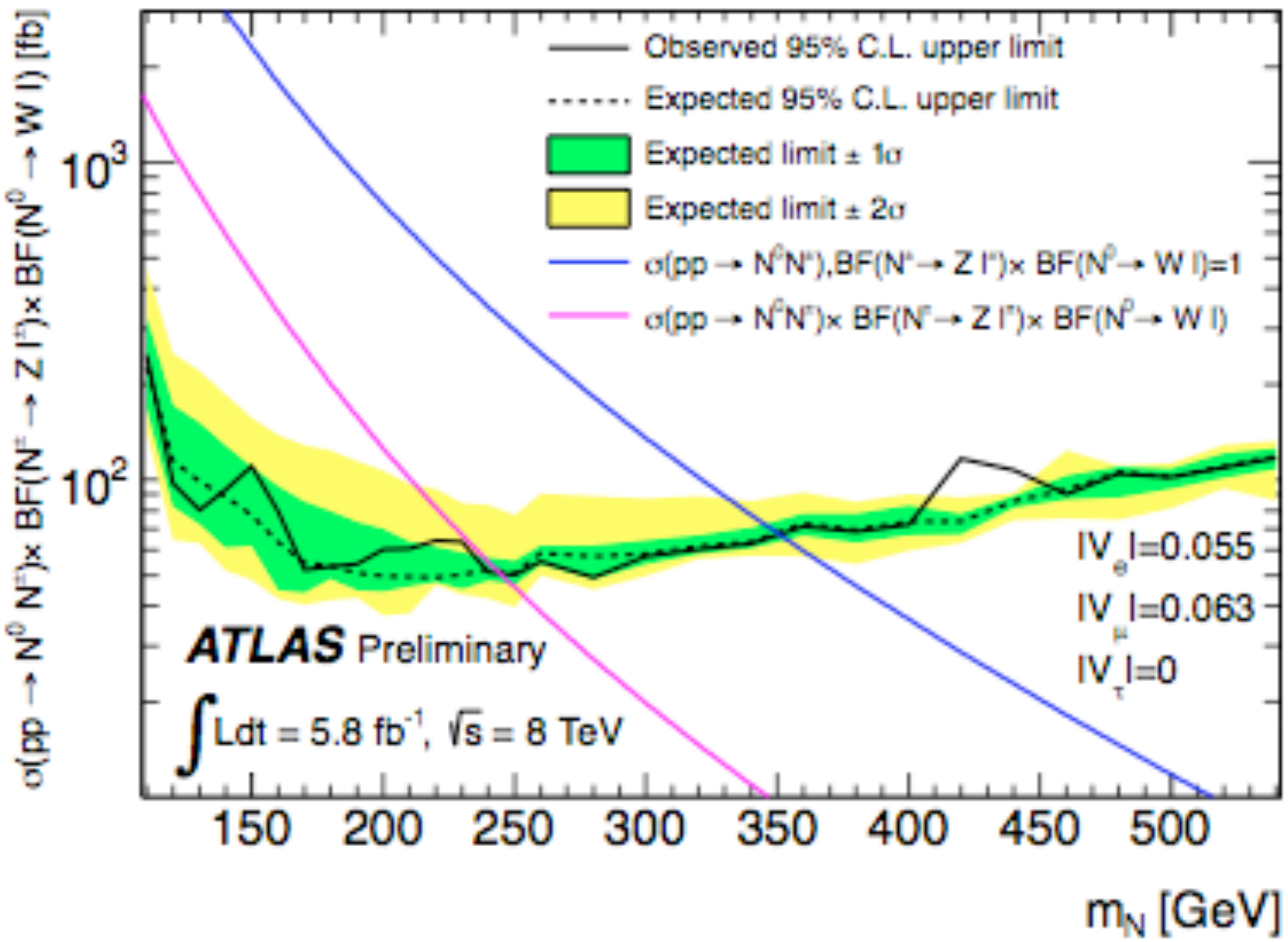
Lepton flavor universality automatic.

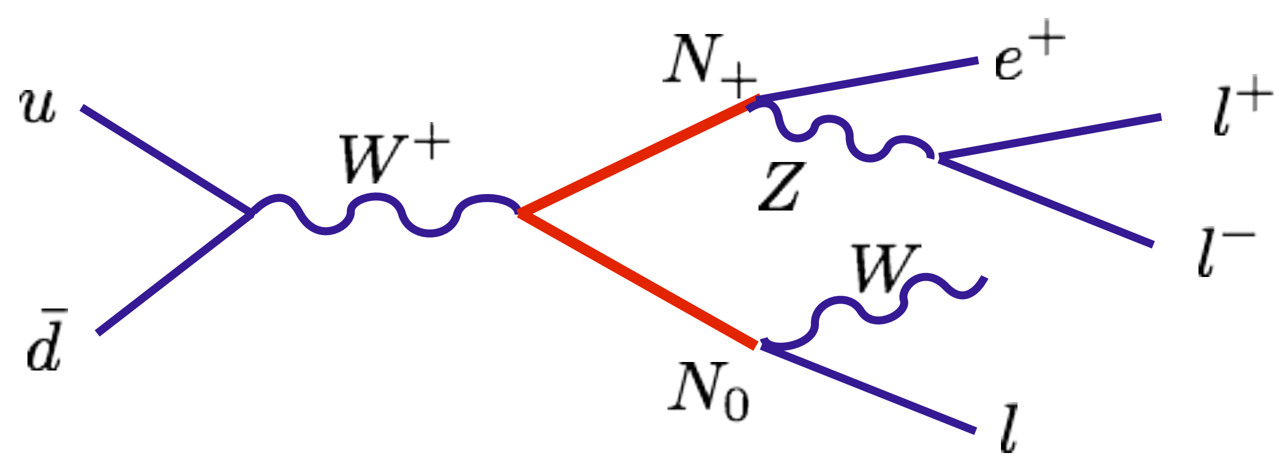
$$\hat{T} \sim \frac{y_*^4 \epsilon_R^4}{16\pi^2}\frac{v^2}{m_\psi^2}$$

Only relevant for τ



Type III see-saw
(ATLAS-CONF-2013-019)

Massive SU(2) triplet, N_+ , N_- , N_0



Sensitive to:

$$\sigma(pp \to N_\pm N_0) \times Br(N_\pm \to Zl) \times Br(N_0 \to l\nu)$$

With composite leptons

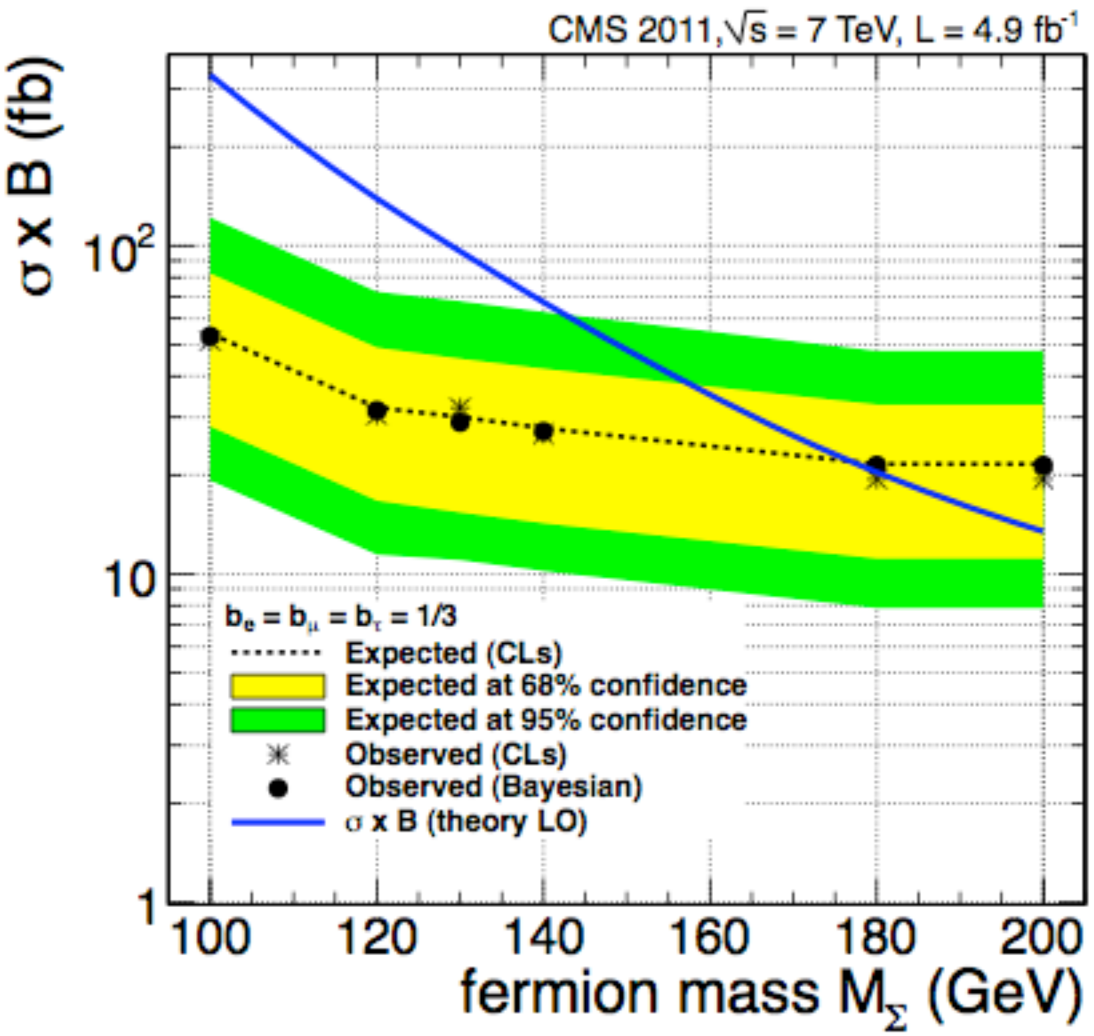
$$\Gamma[E \to Zl] = \Gamma[E \to hl] = \frac{1}{2}\Gamma[N \to Wl] = \frac{y_*^2 \epsilon_R^2}{32\pi} m_\psi$$

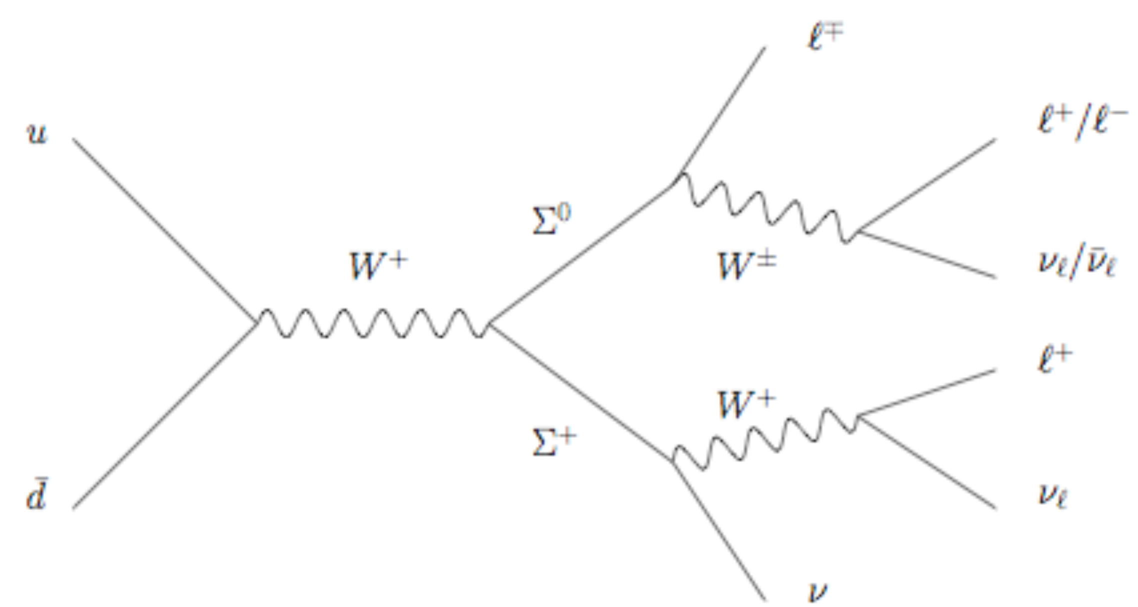
$$\sigma(pp \to E\bar{E})^{P.C} \approx \frac{1}{2}\sigma(pp \to N_\pm N_0)^{III}$$

Exclusion:

$$\frac{[\sigma \times \mathrm{Br}]^{P.C.}}{[\sigma \times \mathrm{Br}]^{III}} \sim 2 \longrightarrow m_\psi > 300\,\mathrm{GeV}$$

CMS-1210.1797





More work to be done at LHC!

Beyond MFV

MR 1203.4220

Barbieri et al. 1203.4218

Top mass suggest splitting third family

SU(2) $\longrightarrow$ $$Y = \begin{pmatrix} y_*^1 & 0 & 0 \\ 0 & y_*^1 & 0 \\ 0 & 0 & y_*^2 \end{pmatrix}$$

$$\epsilon_L = (a\,,a\,,b) \longrightarrow U(2)_L \otimes U(3)_{Rd} \otimes U(3)_{Ru}$$

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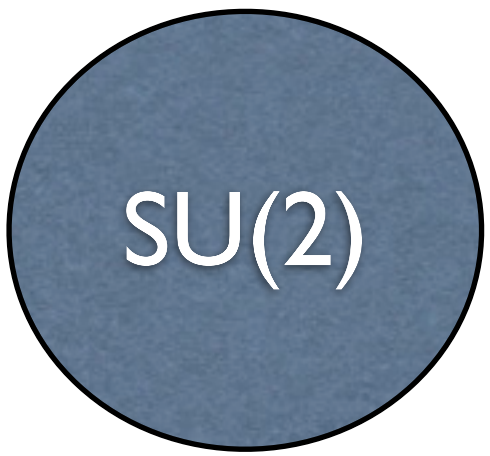

$$\longrightarrow \quad Y = \begin{pmatrix} y_*^1 & 0 & 0 \\ 0 & y_*^1 & 0 \\ 0 & 0 & y_*^2 \end{pmatrix}$$

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Light generations can be more elementary. For quarks equally good as MFV but much weaker bounds from precision tests.

Same structure inherited by leptons.

Lepton flavor universality:

Channel	$\Delta r^{\mu/\tau}$
$\Gamma(\pi \to \mu\,\bar{\nu}_\mu)/\Gamma(\tau \to \pi\,\nu_\tau)$	0.016 ± 0.008 [14]
$\Gamma(K \to \mu\,\bar{\nu}_\mu)/\Gamma(\tau \to K\,\nu_\tau)$	0.037 ± 0.016 [14]
$\Gamma(Z \to \mu^+\mu^-)/\Gamma(Z \to \tau^+\tau^-)$	-0.0011 ± 0.0034 [15–18]
$\Gamma(W \to \mu\,\bar{\nu}_\mu)/\Gamma(W \to \tau\,\bar{\nu}_\tau)$	-0.060 ± 0.021 [15–18]
$\Gamma(\mu \to \nu_\mu\,e\,\bar{\nu}_e)/\Gamma(\tau \to \nu_\tau\,e\,\bar{\nu}_e)$	-0.0014 ± 0.0044 [14]
Channel	$\Delta r^{e/\tau}$
$\Gamma(Z \to e^+e^-)/\Gamma(Z \to \tau^+\tau^-)$	-0.0020 ± 0.0030 [15–18]
$\Gamma(W \to e\,\bar{\nu}_e)/\Gamma(W \to \tau\,\bar{\nu}_\tau)$	-0.044 ± 0.021 [15–18]
$\Gamma(\mu \to \nu_\mu\,e\,\bar{\nu}_e)/\Gamma(\tau \to \nu_\tau\,\mu\,\bar{\nu}_\mu)$	-0.0032 ± 0.0042 [14]

Table 1: Experimental constraints on $\Delta r^{e/\tau}$ and $\Delta r^{\mu/\tau}$.

from Isidori,
Giudice, Paradisi ’12

$$y_*^2 v^2 \Delta\left[\frac{\epsilon_L^2}{m_\psi^2}\right] < \text{few} \times 10^{-3} \longrightarrow \epsilon_L^\tau < \frac{1}{10 y_*}\left(\frac{m_\psi}{500\,\text{GeV}}\right)$$

Ex:

$$L_1 : \qquad \epsilon_L = (0.05\,, 0.05\,, 0.1)$$

$$L_2 : \qquad \epsilon_L = (0.01\,, 0.01\,, 0.1)$$

	L_1	L_2	EXP
$\mathrm{Br}(\mu \to e\gamma)$	10^{-9}	10^{-12}	$5 \cdot 10^{-13}$
$\mathrm{Br}(\tau \to e\gamma)$	10^{-8}	10^{-9}	$3 \cdot 10^{-8}$
$\mathrm{Br}(\tau \to \mu\gamma)$	10^{-8}	10^{-10}	$4 \cdot 10^{-8}$
$\mathrm{Br}(\mu \to 3e)$	10^{-12}	10^{-15}	10^{-12}
$\mathrm{Br}(\tau \to 3e)$	10^{-10}	10^{-12}	$3 \cdot 10^{-8}$
$\mathrm{Br}(\tau \to 3\mu)$	10^{-10}	10^{-12}	$2 \cdot 10^{-8}$

LFV can be observable!

CONCLUSIONS

- Absence of CLFV is at odds with anarchic flavor structure in composite Higgs models.

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  In SU(2) extensions possible flavor effects.

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- Absence of CLFV is at odds with anarchic flavor structure in composite Higgs models.
- No CLFV in MFV scenario, fermions can be light.
  In SU(2) extensions possible flavor effects.
- Interesting interplay of g-2, collider and CLFV.

In SM only one flavor and CP structure:

$$SU(3)_L \otimes SU(3)_U \otimes SU(3)_D \qquad \begin{matrix} y_u = (3, \bar{3}, 1) \\ y_d = (3, 1, \bar{3}) \end{matrix} \longrightarrow V_{CKM}$$

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In Composite Higgs:

$$SU(3)^3_{el} \otimes SU(3)^4_{comp}$$

$$\lambda_{Lu} = (3, 1, 1, \bar{3}, 1, 1, 1) \qquad \lambda_{Ru} = (1, \bar{3}, 1, 1, 1, 3, 1)$$

$$\lambda_{Ld} = (3, 1, 1, 1, \bar{3}, 1, 1) \qquad \lambda_{Rd} = (1, 1, \bar{3}, 1, 1, 1, 3)$$

$$Y_u = (1, 1, 1, 1, 3, \bar{3}, 1) \qquad Y_d = (1, 1, 1, 1, 3, 1, \bar{3})$$

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$$Y_u = (1,1,1,1,3,\bar{3},1) \qquad Y_d = (1,1,1,1,3,1,\bar{3})$$

Anarchic scenario:

$$12 - 7 = 5 \qquad \text{Flavor Structures}$$

Too much flavor violation!

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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Left-Handed Compositeness:

$$\delta g \sim \frac{Y^2 v^2}{2\,m_\rho^2} \sin\varphi_q^2$$

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

Strongly constrained and only possible if tR is composite.

Higgs cannot be exact NGB

$$h \to h + c$$

G

G symmetry broken explicitly in SM

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

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

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

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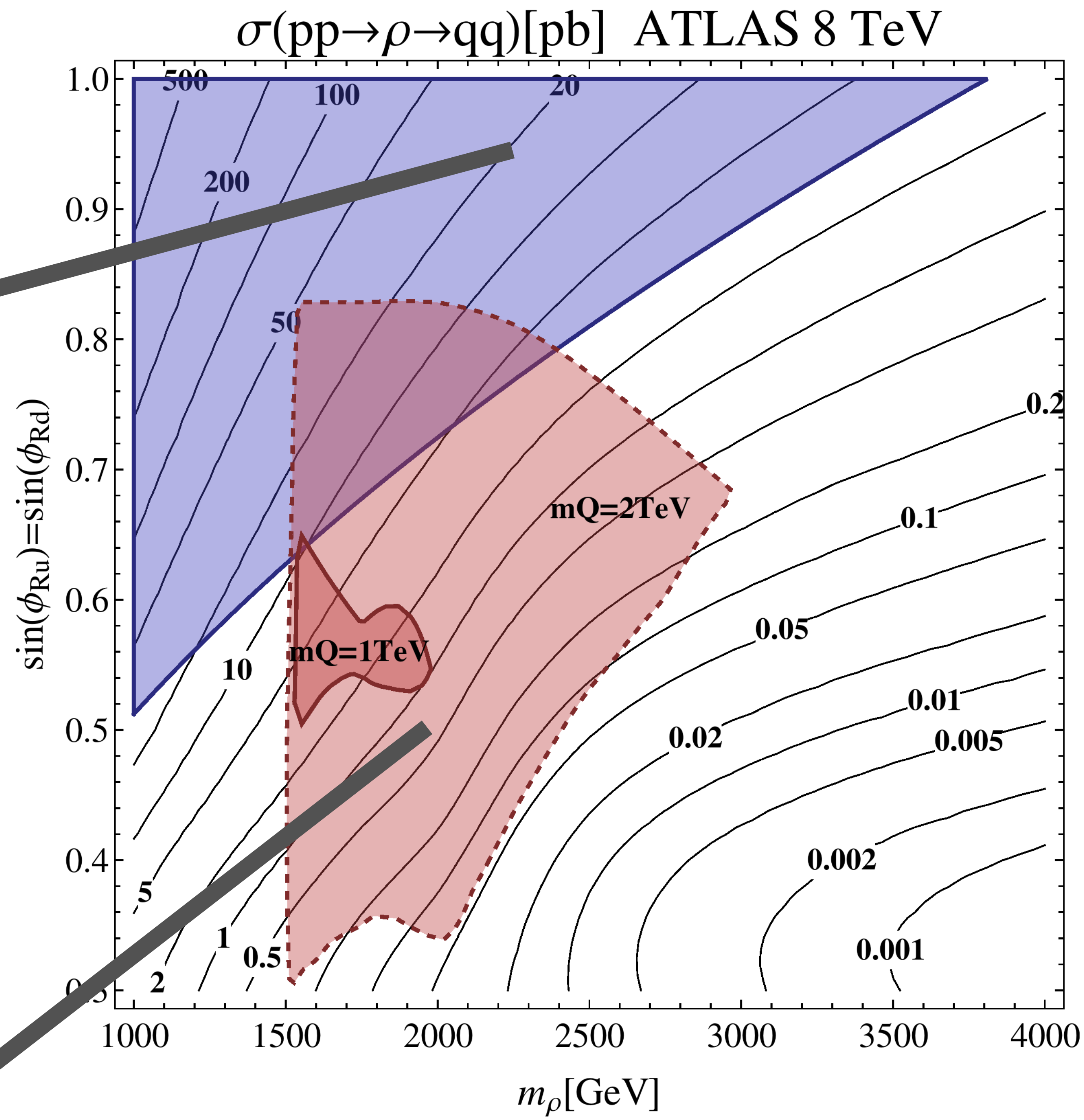
$SU(2) \times U(1)$

Similar to QCD:

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

Di-jet bounds



Bump-hunter search

MR, Sanz, de Vries, Weiler, 1305.xxxx