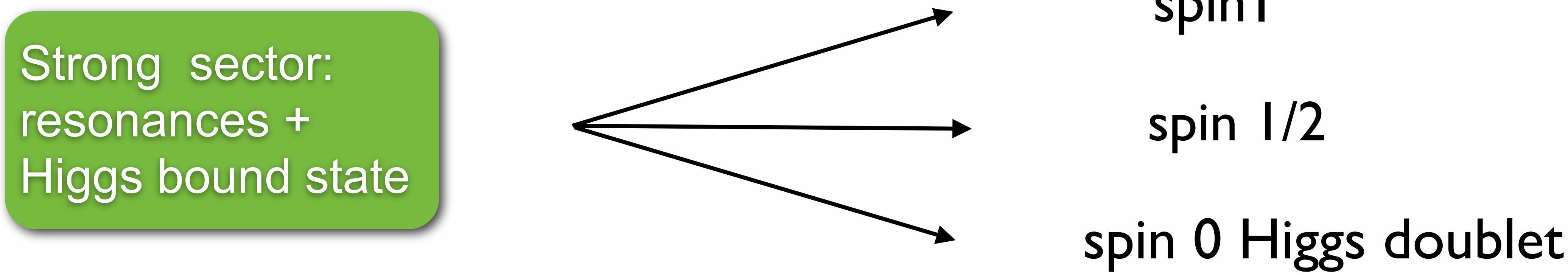
Muon g-2 and the Goldstone Boson Higgs

Michele Redi

Antipin, De Curtis, MR, Sacco, to appear
+ 1306.1525

Brighton, June 20

Higgs doublet could be a bound state



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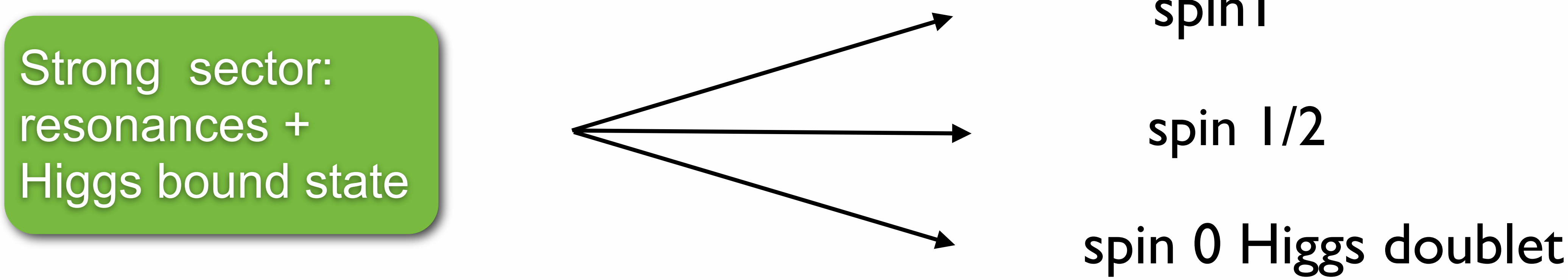
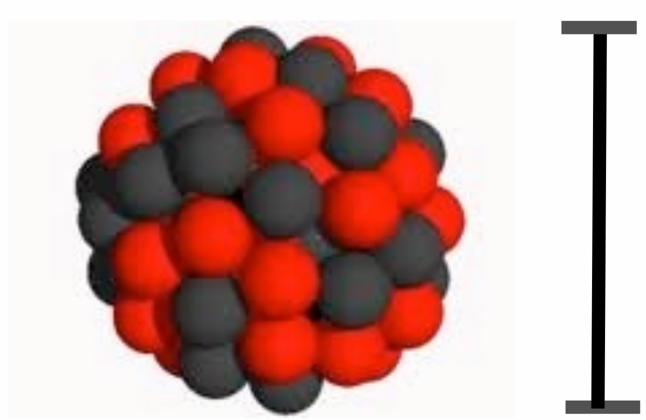


Compositeness scale acts as cut-off

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

Natural theory



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

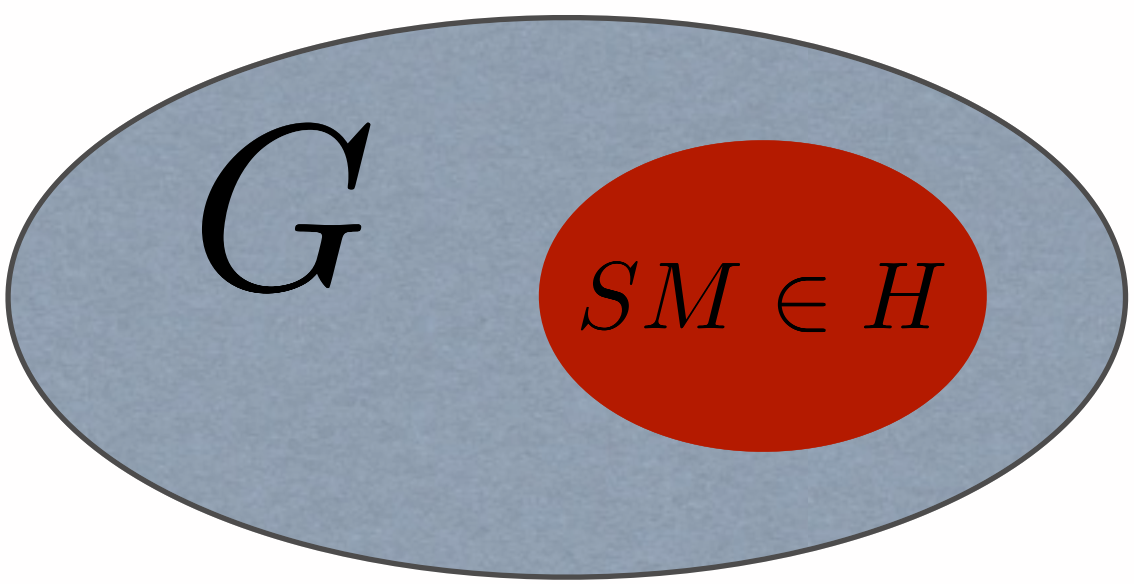
Scalars automatically massless if they are Goldstone bosons

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

Scalars automatically massless if they are Goldstone bosons

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

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.$[\mathrm{SU}(2) \times \mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \bar{\mathbf{4}}_{\mathbf{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
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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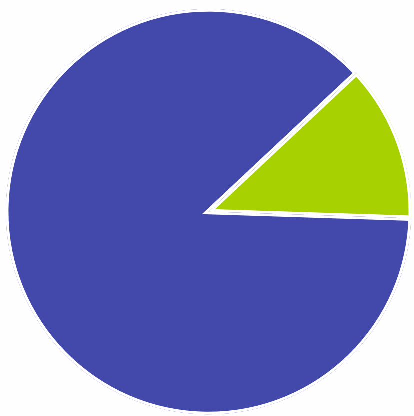
Higgs is an angle,



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

Small Tuning $\quad f < TeV$

Spectrum:

$m_\rho = g_\rho f$

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

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

0

Partial Compositeness

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

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

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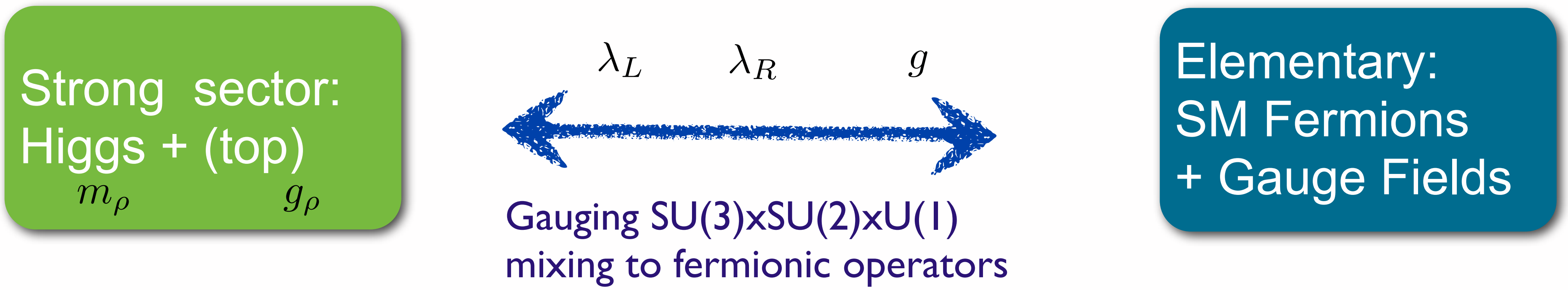

Elementary-composite states talk through linear couplings:

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

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

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m_ρ g_ρ

λ_L λ_R g

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

Elementary:
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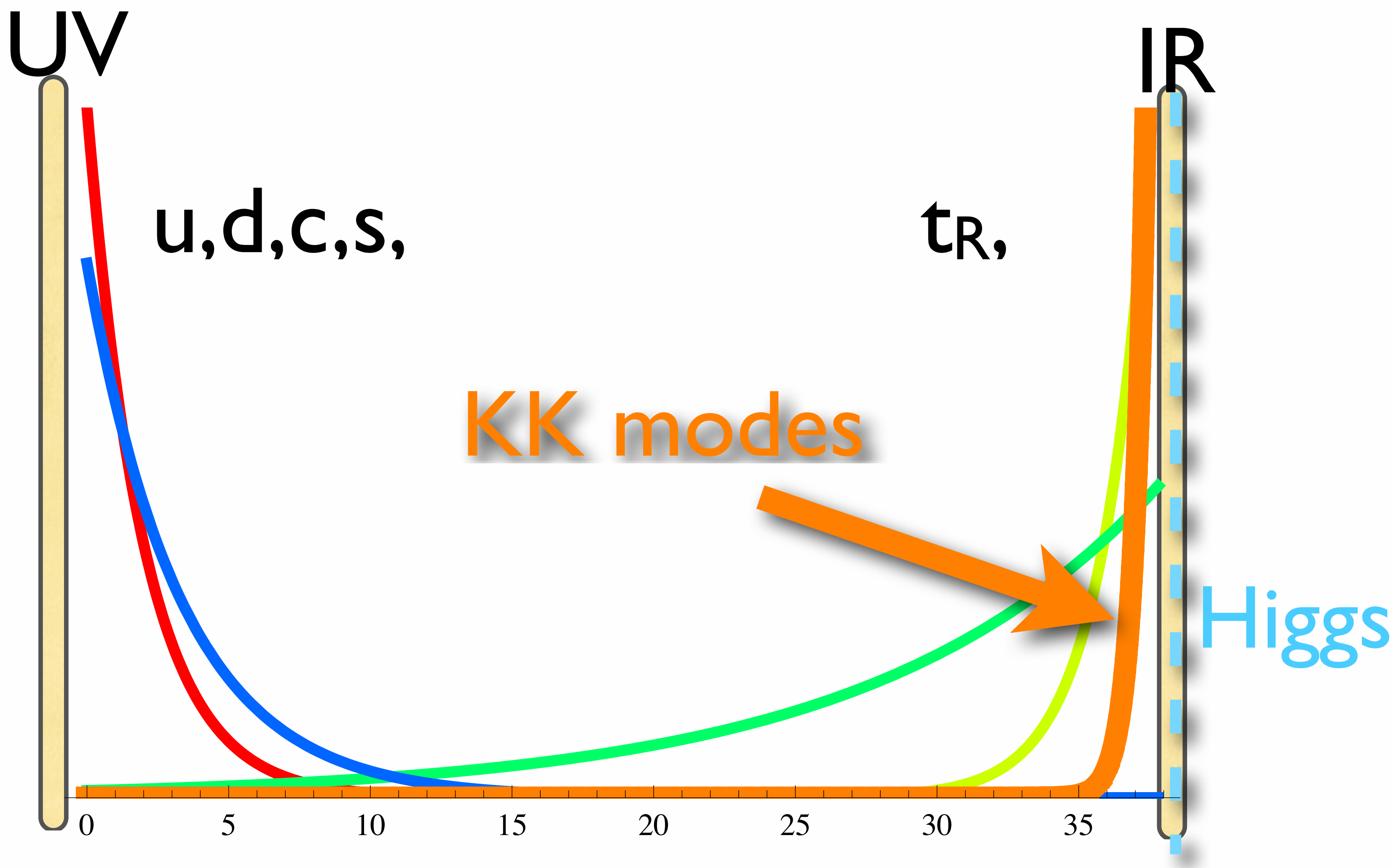
Two scenarios:

- Anarchic
- Minimal Flavor Violation

Progress started with Randall-Sundrum constructions.



(Randall-Sundrum '99)

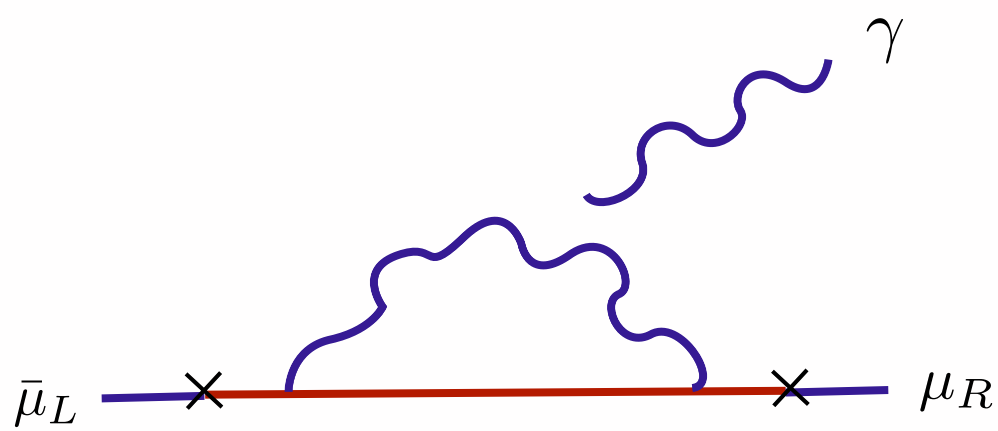
Relevant physics largely independent from 5D.

First resonance captures main features.

→ Rohrwild's talk

$$(g-2)_\mu$$

Composite resonances contribute to dipoles



$$\Delta a_\mu \equiv \frac{(g-2)_\mu}{2} \sim \frac{g_\psi^2}{(4\pi)^2}\frac{m_\mu}{m_\psi^2}\epsilon_L g_\psi H \epsilon_R \sim \frac{g_\psi^2}{(4\pi)^2}\frac{m_\mu^2}{m_\psi^2}$$

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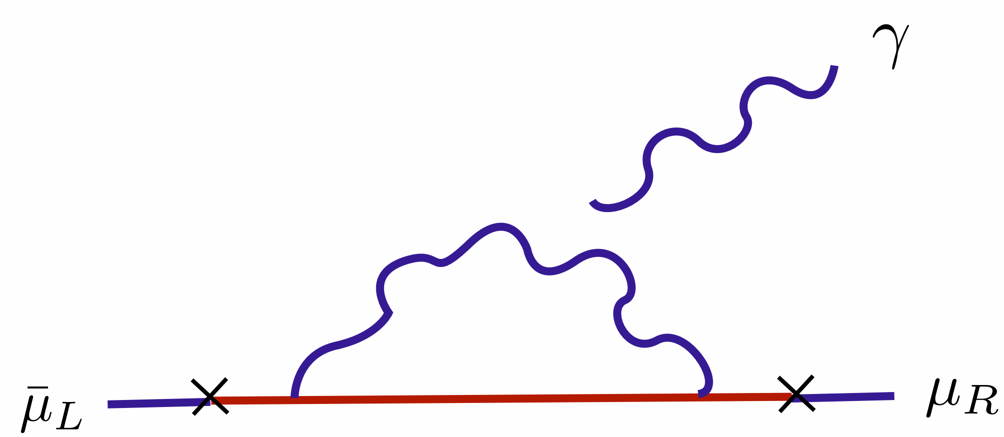

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Experimental anomaly

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} \approx (2.8 \pm 0.8) \times 10^{-9}$$

Not unreasonable to reproduce discrepancy.
GB Higgs enters in interesting way.

Simplified model SO(5)/SO(4)

$$\psi_4 = \frac{1}{\sqrt{2}} \begin{pmatrix} i(E_{-2} - N) \\ E_{-2} + N \\ i(E_{-1} + E) \\ E - E_{-1} \end{pmatrix} \qquad \psi_1 = \tilde{E}$$

EFT:

$$\mathcal{L}_{comp} = \overline{\psi}_4 (i \not{D} - m_4)\, \psi_4 + \overline{\psi}_1 (i \not{D} - m_1)\, \psi_1 \\ + i \left(c_L\, \overline{\psi}^{\hat{a}}_{4L}\, \gamma^\mu\, \psi_{1L} + c_R\, \overline{\psi}^{\hat{a}}_{4R}\, \gamma^\mu\, \psi_{1L} + h.c. \right) d^{\hat{a}}_\mu$$

$$d^{\hat{a}}_\mu = \frac{D_\mu h^a}{f} + \dots$$

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$$d^{\hat{a}}_\mu = \frac{D_\mu h^a}{f} + \dots$$

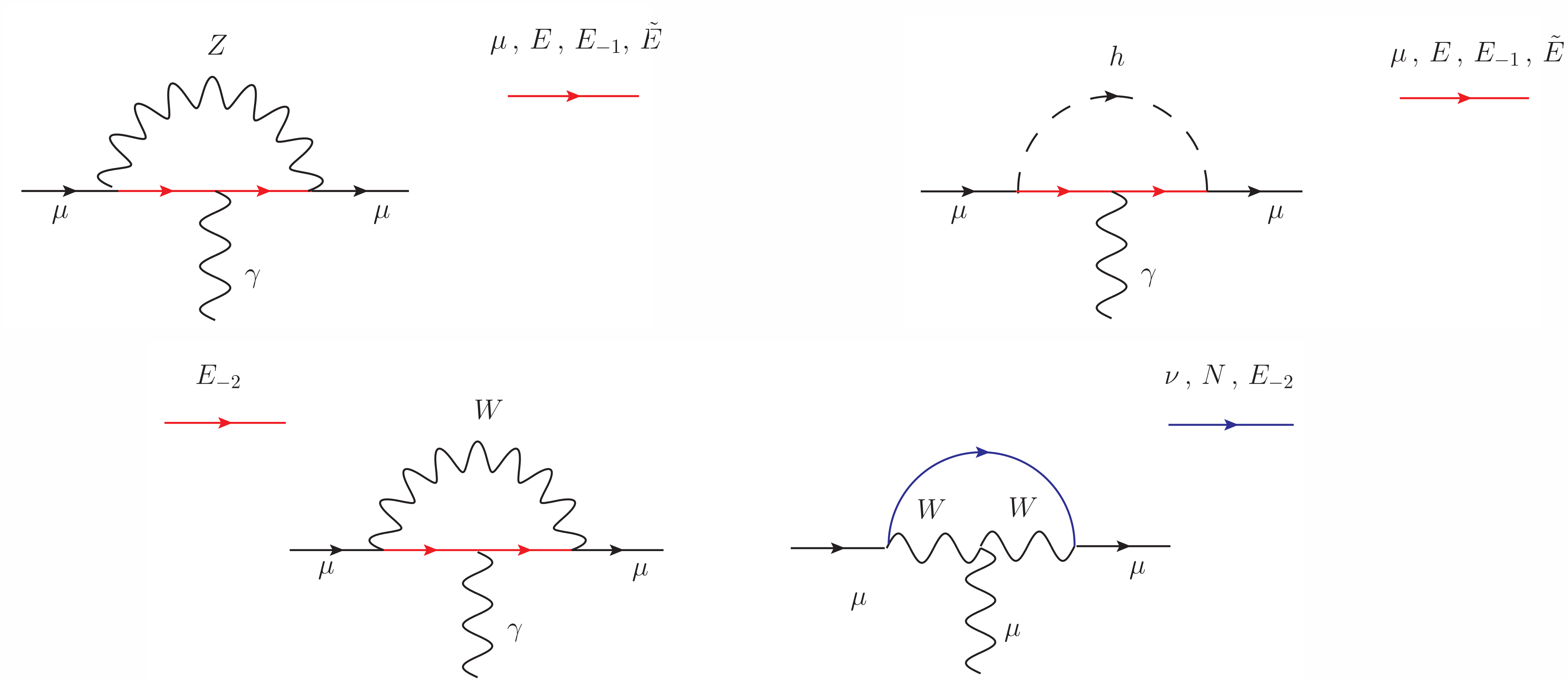
Mixings:

$$\mathcal{L}_{mixing} = y_{L_4}\, f\, (\bar{q}^{\mathbf{5}}_L)^I U_{Ij}\, \psi^j_4 + y_{L_1}\, f\, (\bar{q}^{\mathbf{5}}_L)^I U_{I5}\, \psi_1 + + y^*_{R_4}\, f\, (\bar{\mu}^{\mathbf{5}}_R)^I U_{Ij}\, \psi^j_4 + y^*_{R_1}\, f\, (\bar{\mu}^{\mathbf{5}}_R)^I U_{I5}\, \psi_1 + h.c.$$

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

$$m_\mu \approx \frac{f^2}{\sqrt{2}} \left(\frac{y_{L_4} y_{R_4}}{m_4} - \frac{y_{L_1} y_{R_1}}{m_1} \right) s_h c_h$$

- Non-derivative interactions

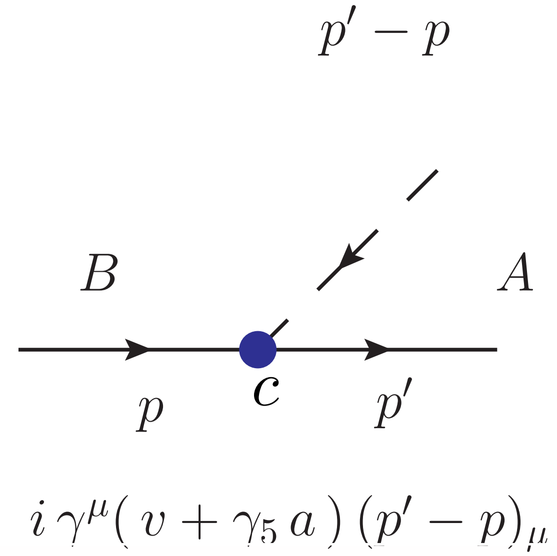


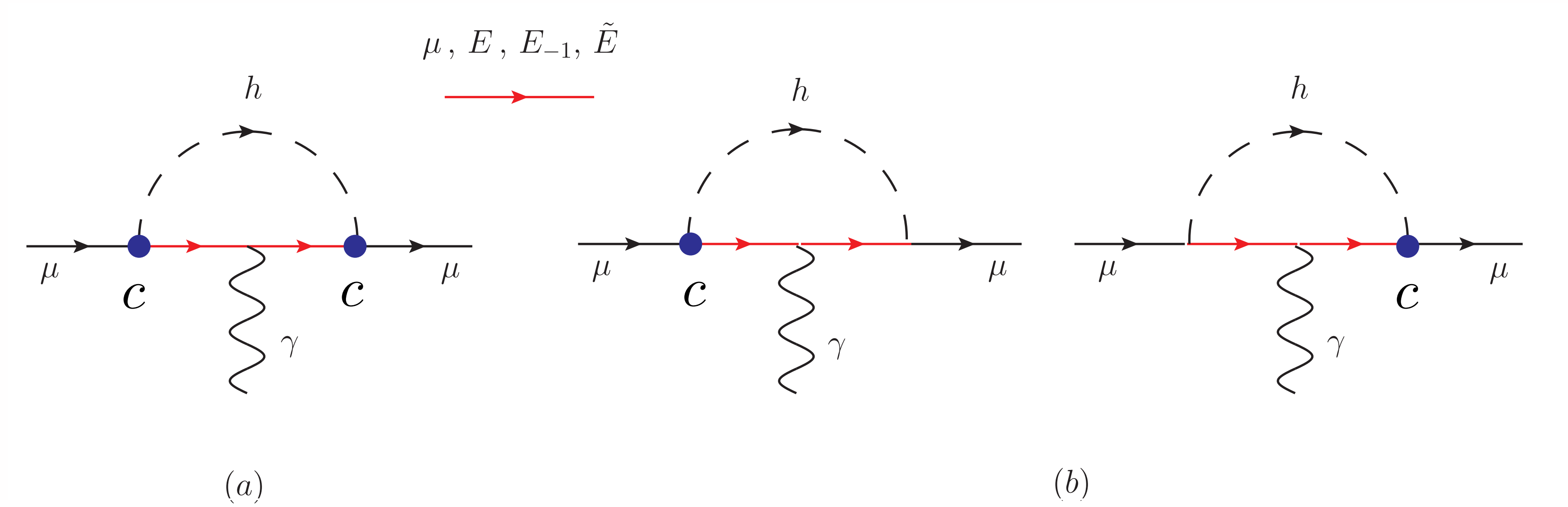
$$y_{L1} = y_{L4} \quad \& \quad y_{R1} = y_{R4} \quad \& \quad c_L = c_R = c$$

$$\Delta a_\mu = \frac{m_\mu^2}{16\pi^2 f^2}\left[1 + \frac{(m_1 - c\sqrt{2}m_4)^2}{m_1\,(m_1 - m_4)}\right]$$

In general mixings dependence.

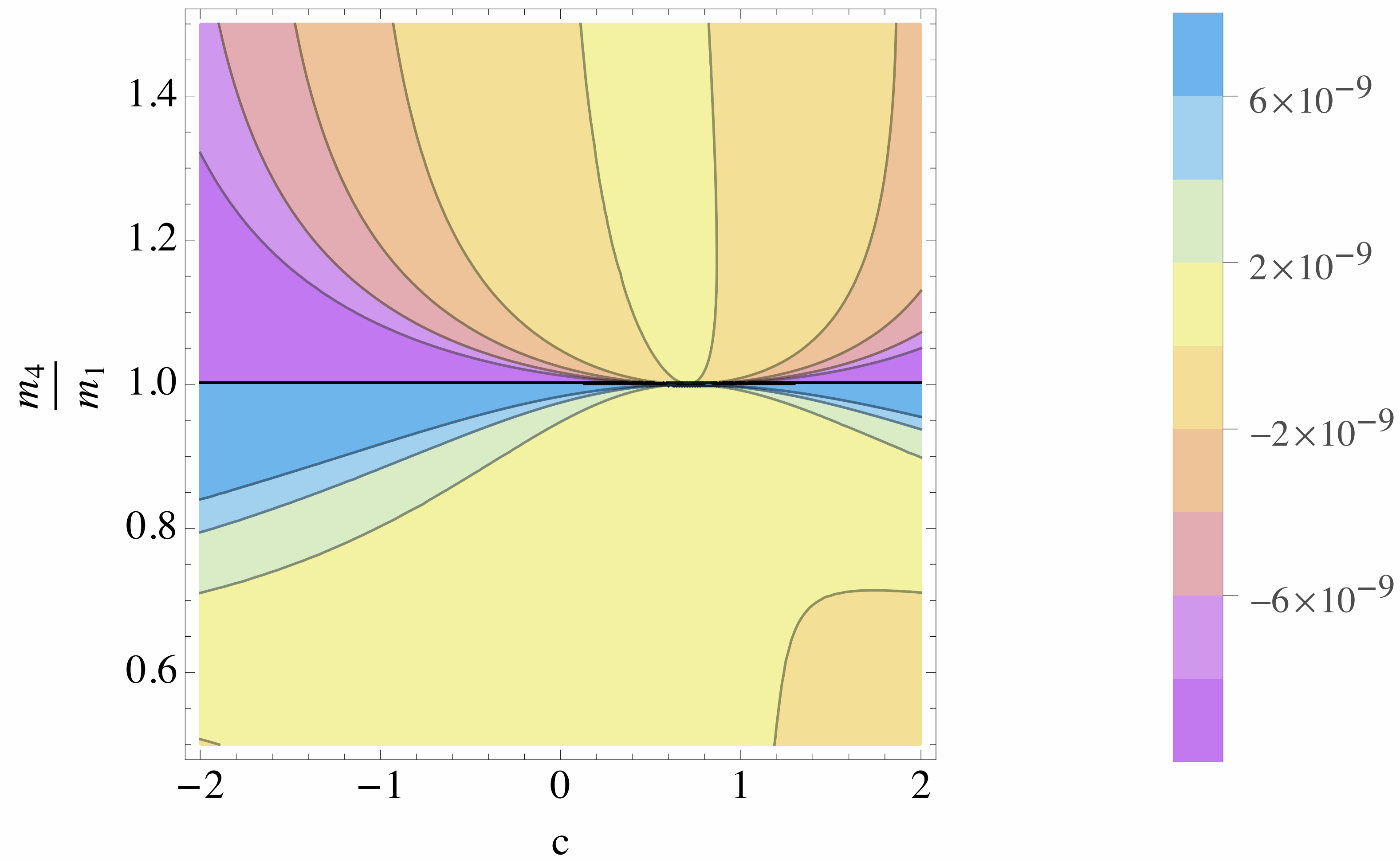
- Derivative Interactions



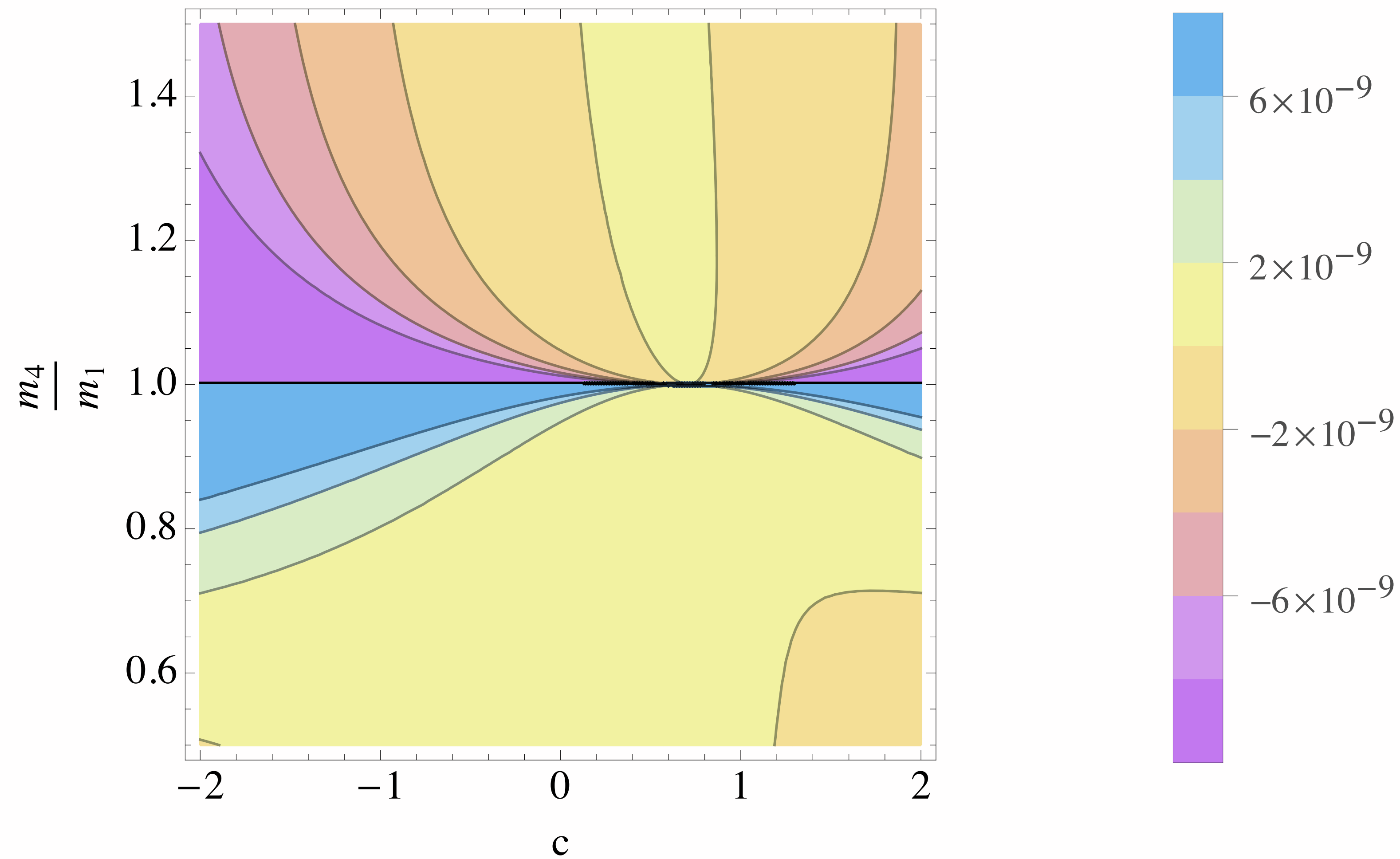


$$\Delta a_\mu = \frac{m_\mu^2}{16\pi^2 f^2}\left[\frac{4\sqrt{2}}{3}c - \frac{2}{3}\frac{m_1^2 + m_1 m_4 + m_4^2}{m_1 m_4}c^2\right]$$

If c complex similar contributions for EDMs.



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



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

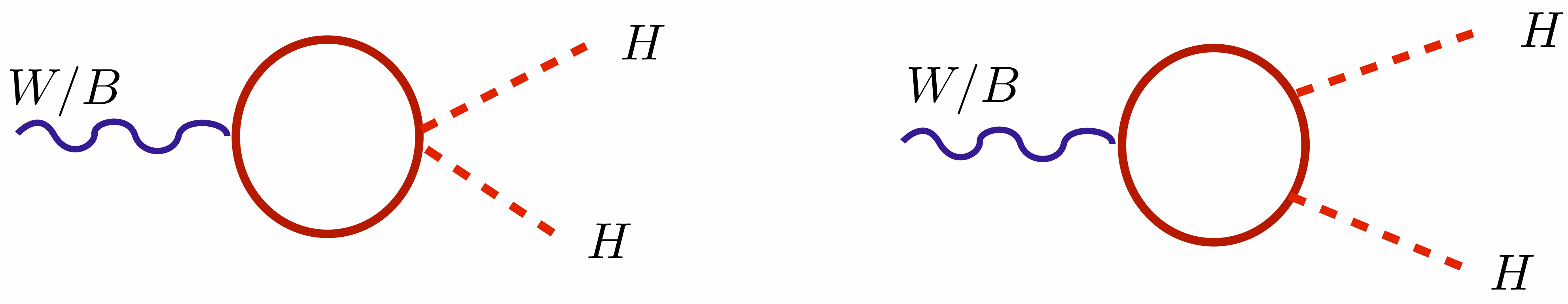
UV contributions also exist

$$\mathcal{O} = \frac{\kappa}{\Lambda}\,\overline{\Psi}^i_{4L}\sigma^{\mu\nu}\Psi^j_{4R}(T^a)_{ij}(f^+_{\mu\nu})^a \qquad \Delta a_\mu^{UV} \sim \frac{1}{16\pi^2}\frac{m_\mu^2}{f^2}$$

Modified Higgs couplings:

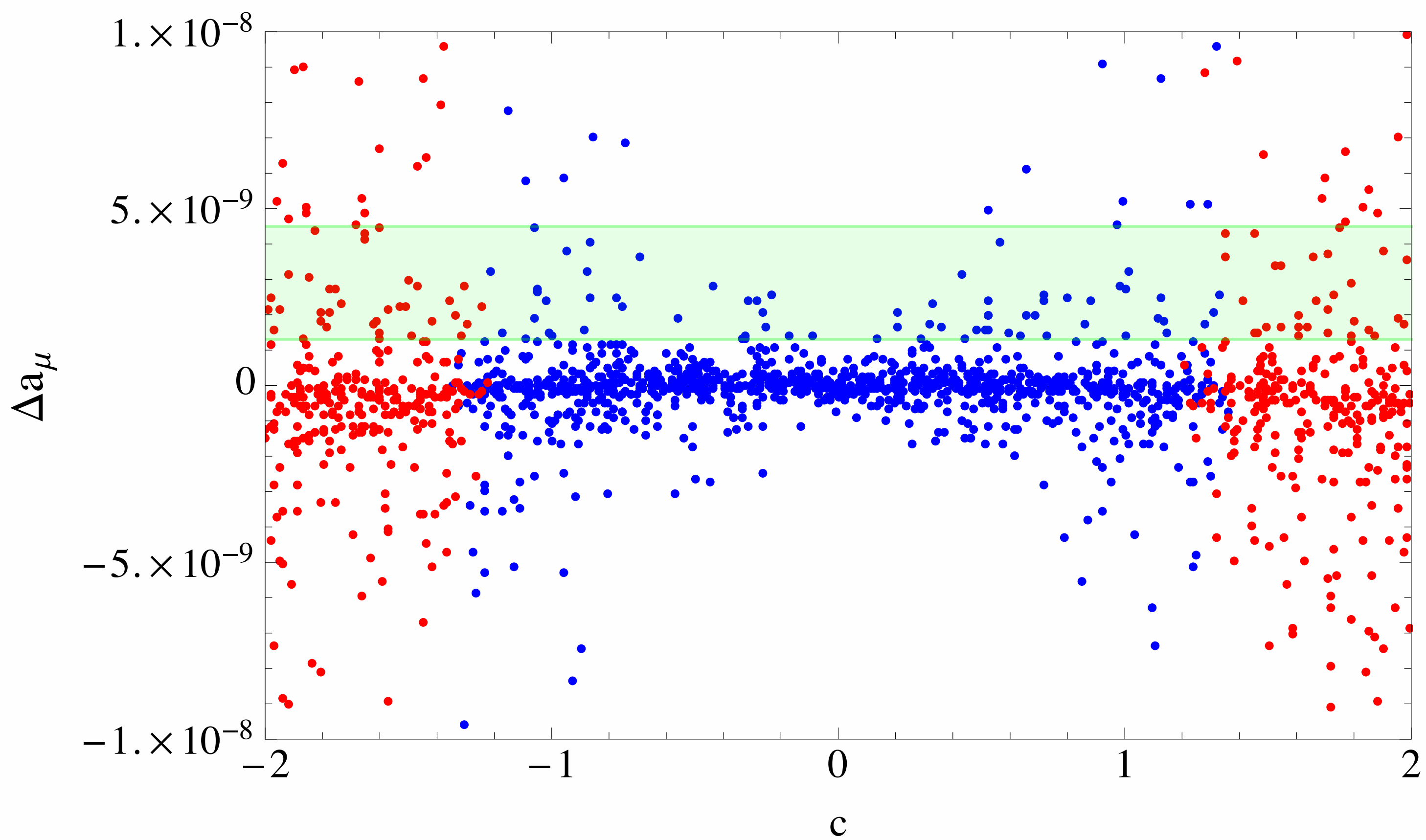
$$\frac{h_{\mu\mu}}{h^{SM}_{\mu\mu}} \approx 1 - \frac{3}{2}\frac{v^2}{f^2}$$

c also control contributions to S-parameter



Panico et al., '13
Contino et al. '13

$$\Delta S \approx \frac{2}{\pi}\frac{v^2}{f^2}(1-2c^2)\log\frac{\Lambda^2}{m_4^2}$$



FLAVOR PICTURE

MR and A. Weiler, 1106.6357
MR 1203.4220, MR 1305.3818

See also:
Weiler et al. '07
Barbieri, Isidori, Pappadopulo '08
Delaunay et al. '11 + '13

- Anarchic scenario

Strong sector has no hierarchies

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

FCNC suppressed by hierarchies of mixings.

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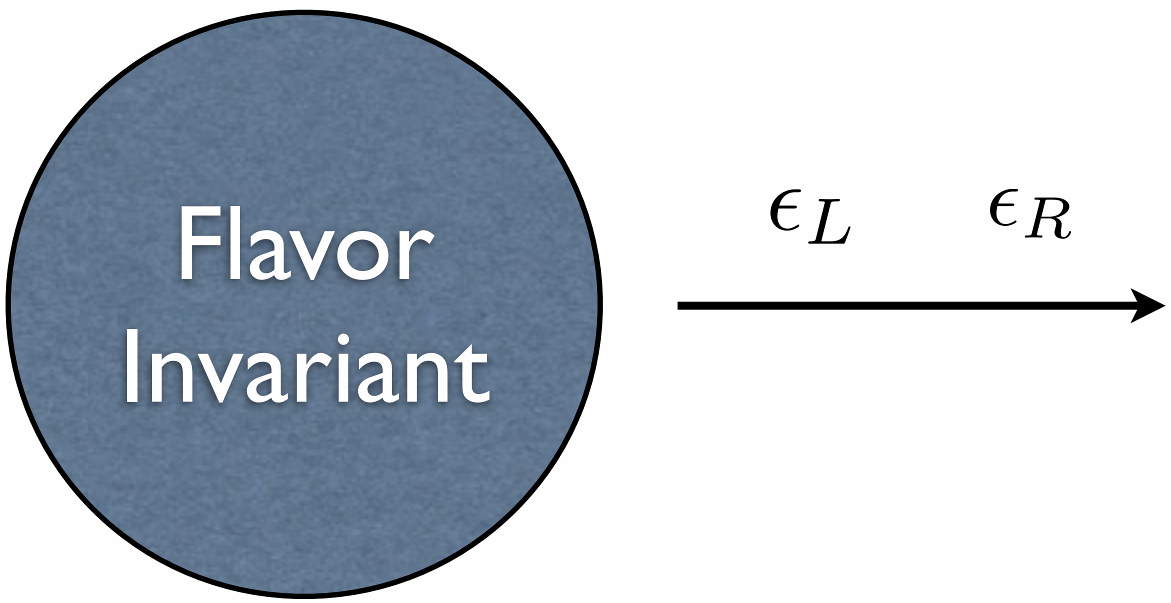
Severe tension with leptons:

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

MEG, '13

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

- MFV scenario



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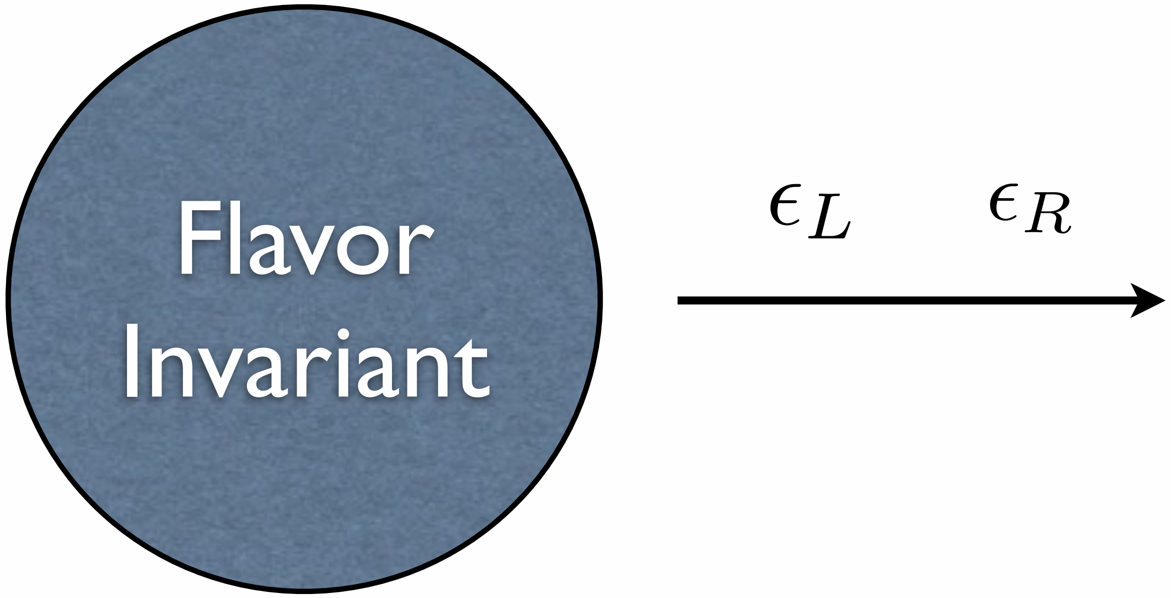

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Simple realizations of Minimal Flavor Violation:

mixings ~ SM Yukawas

- Left-handed compositeness

$$\epsilon_L \propto \mathrm{Id} \qquad \epsilon_R \propto y^e$$

- Right-handed compositeness

$$\epsilon_R \propto \mathrm{Id} \qquad \epsilon_L \propto y^e$$

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Mixing of left or right chirality universal.

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

For leptons mixings can be small: weak bounds from compositeness and precision tests

(Giudice-Paradisi-Passera '12)

MFV implies:

$$\Delta a_e = \Delta a_\mu \frac{m_e^2}{m_\mu^2}$$

$$\Delta a_e \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 7 \times 10^{-14}$$

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EDMs:

$$d_e \approx \left(\frac{\Delta a_e}{7\times 10^{-14}}\right) 10^{-24} \tan\phi_e \, e \ \ \text{cm}$$

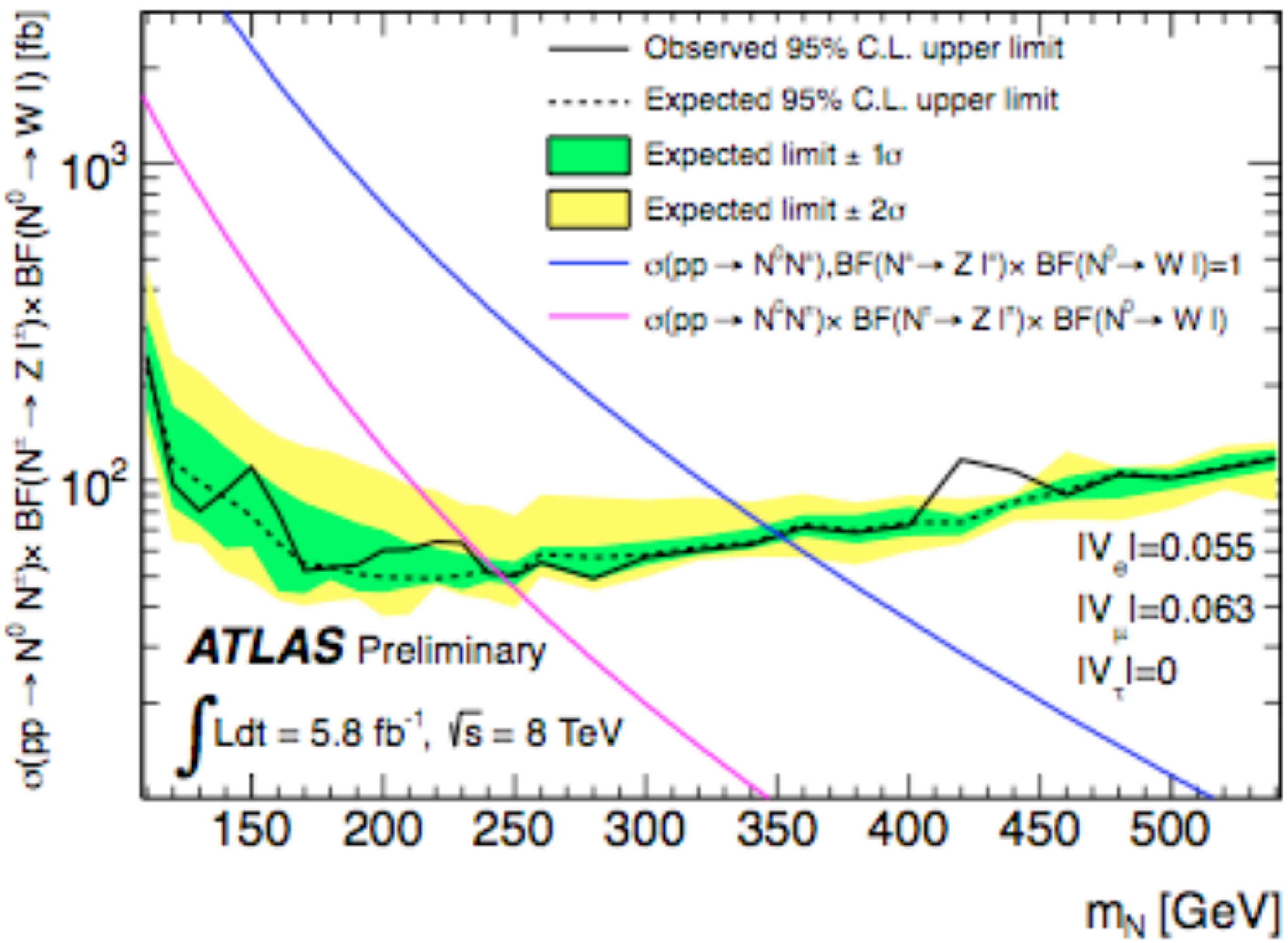
$$d_e^{\text{exp}} < 10^{-28} \text{ e cm}$$

$$d_\mu \approx \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 2\times 10^{-22} \tan\phi_\mu \, e \ \ \text{cm}$$

$$d_\mu^{\text{exp}} < 10^{-18} \text{ e cm}$$

Electron phase must be suppressed.

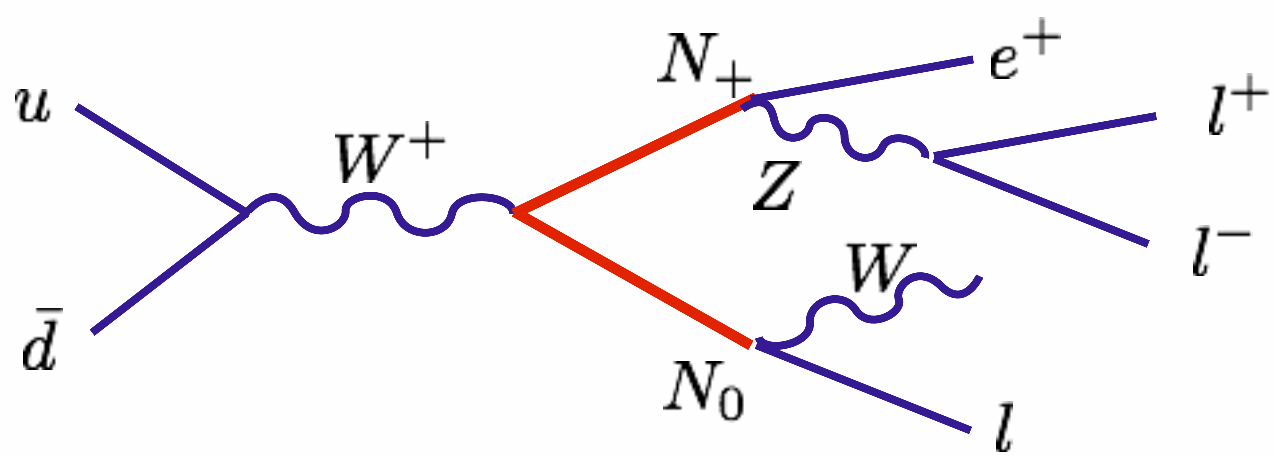
EDMs not generated if composite sector CP invariant.



Type III see-saw

(ATLAS-CONF-2013-019)

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



CONCLUSIONS

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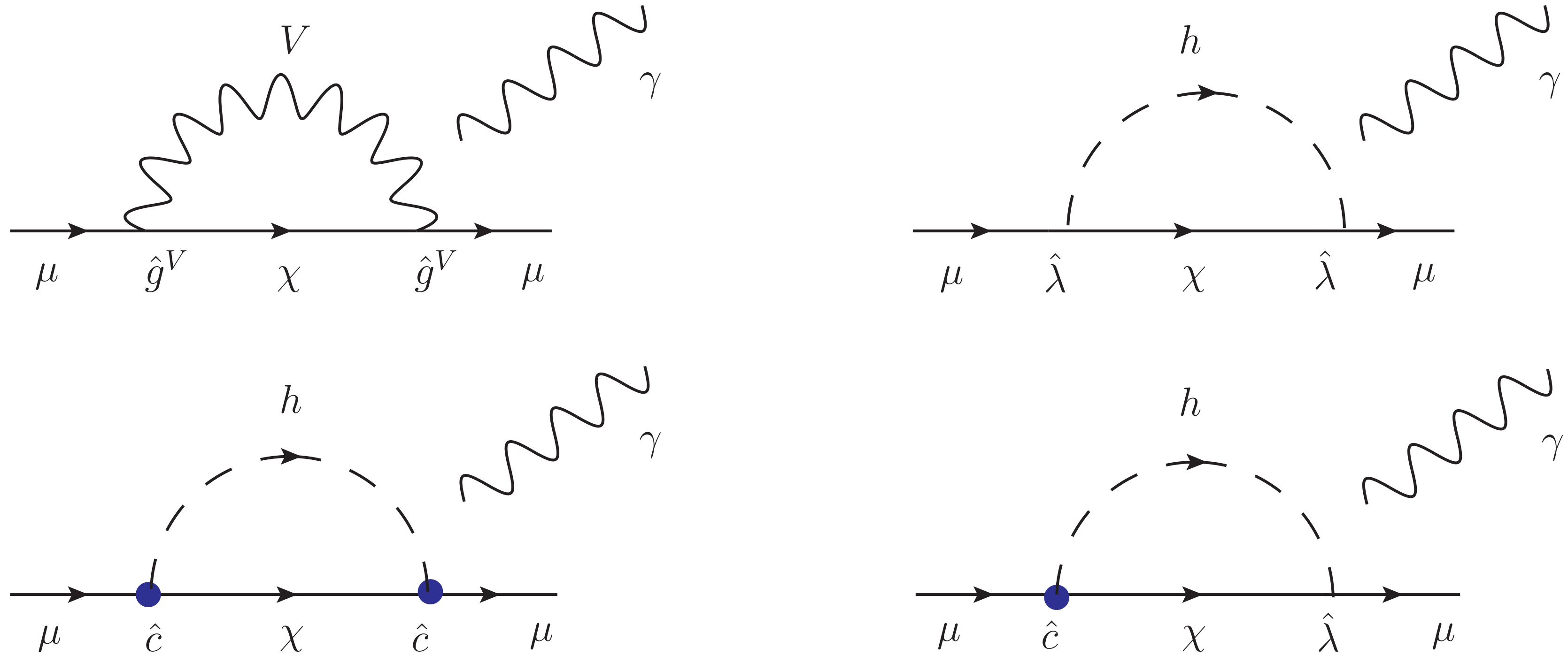
- Dipoles have novel features in theories with Goldstone Boson Higgs. Possibility to fit muon (g-2)anomaly.

- MFV must be realized to avoid flavor bounds especially in the lepton sector. If the composite sector preserves CP no significant bounds from EDMs.

- Interesting correlation of observables. Composite partners can be searched at LHC.



$$\Delta X_\mu^Z = \frac{g^2}{16\pi^2}\frac{m_\mu m_\chi}{m_Z^2}\,(\hat{g}_Z^L)\,(\hat{g}_Z^R)^*$$

$$\Delta X_\mu^{W^+} = -\frac{g^2}{32\pi^2}\frac{m_\mu m_\chi}{m_W^2}\,(\hat{g}_{W+}^L)\,(\hat{g}_{W+}^R)^*$$

$$\Delta X_\mu^{W^-} = \frac{g^2}{32\pi^2}\frac{m_\mu m_\chi}{m_W^2}\,(\hat{g}_{W-}^L)\,(\hat{g}_{W-}^R)^*$$

$$\Delta X_\mu^h = \frac{1}{16\pi^2}\frac{m_\mu}{m_\chi}\,(\hat{\lambda}_L)\,(\hat{\lambda}_R)^*$$

$$\Delta X_\mu^{(\partial h)^2} = -\frac{1}{48\pi^2}\frac{m_\mu m_\chi}{f^2}\,C_L\,C_R^*$$

$$\Delta X_\mu^{\partial h h} = \frac{1}{24\pi^2}\frac{m_\mu}{f}\,(C_L\,\lambda_R^* - \lambda_L\,C_R^*)\ ,$$

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

Estimate:

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

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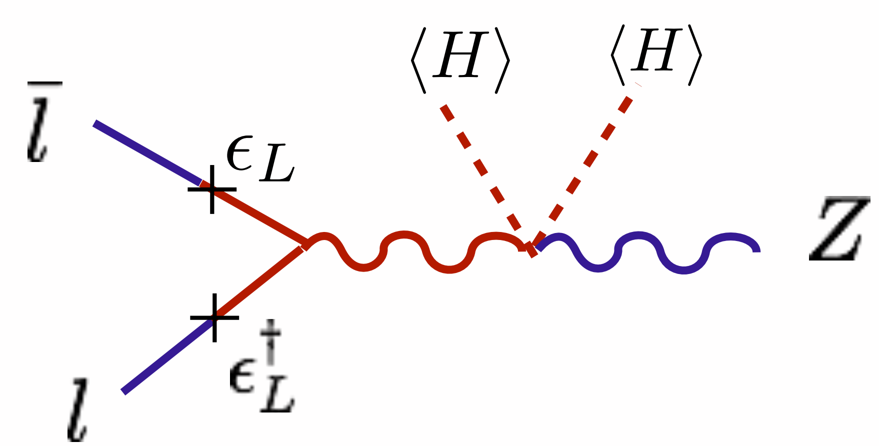
Flavor violating Z-couplings



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

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