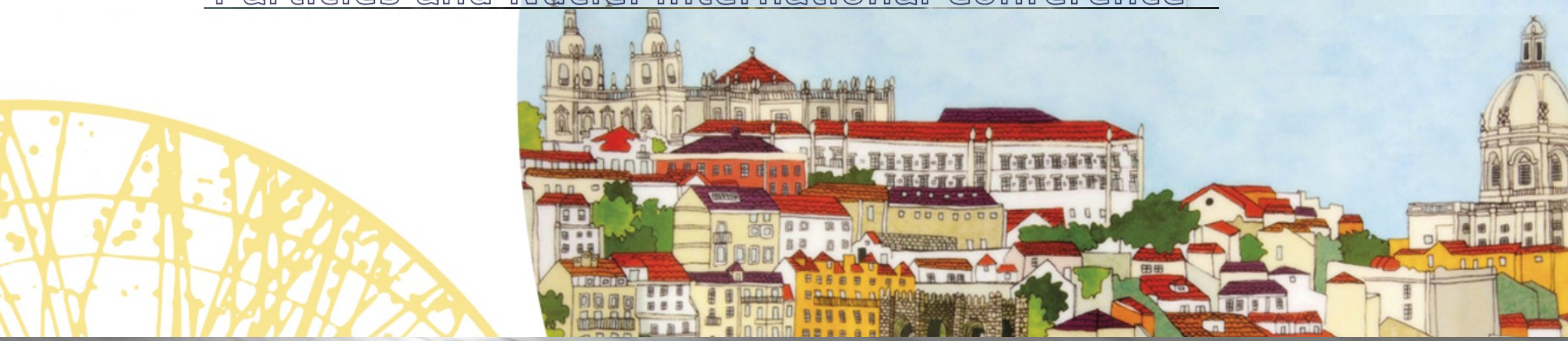
Lepton Flavor in Composite Higgs Models

22nd edition
PANIC Lisbon Portugal
Particles and Nuclei International Conference



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05.09.2021

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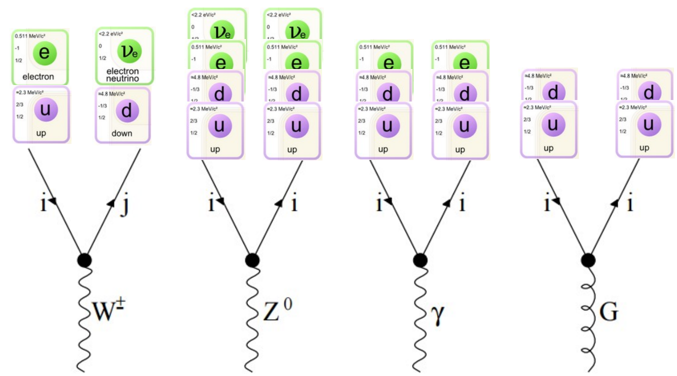
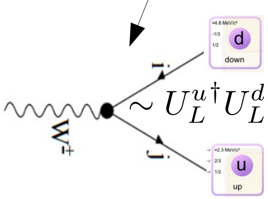
SM and Flavor

Basic interactions in the SM

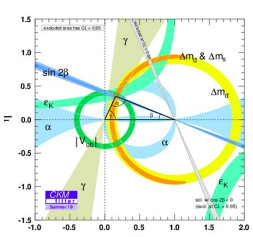


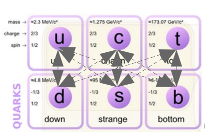
+ similar for other generations

$$\underbrace{}_{\times U^\dagger U = \mathbf{1}}$$



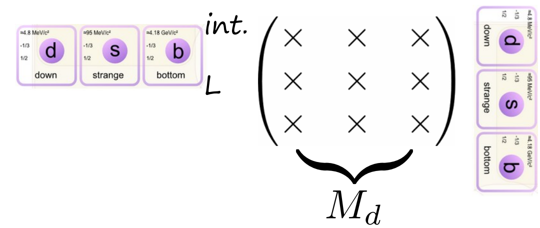
$$\sim U_L^{u\dagger} U_L^d \equiv \boxed{V_{\mathrm{CKM}}}$$



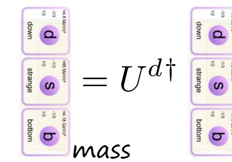


Leptons: V_{PMNS}

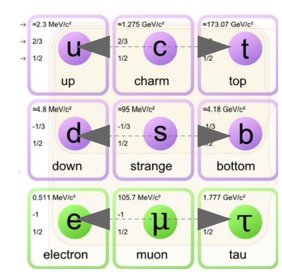
Interaction Basis → Mass Basis



$$\rightarrow U_L^{d\dagger} M_d U_R^d = \boxed{\mathrm{diag}(m_d, m_s, m_b)}$$



$$U^{q\dagger} \mathbb{1} U^q = \mathbb{1} \rightarrow$$ No FCNCs @tree level

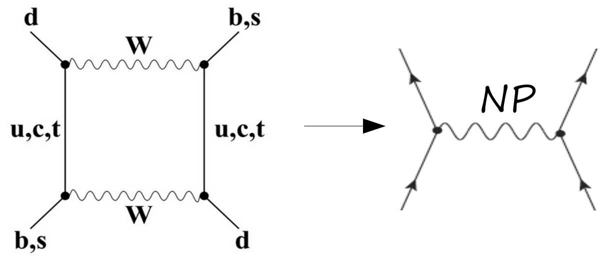


Universality of gauge interactions

→ different in BSM: severe constraints!

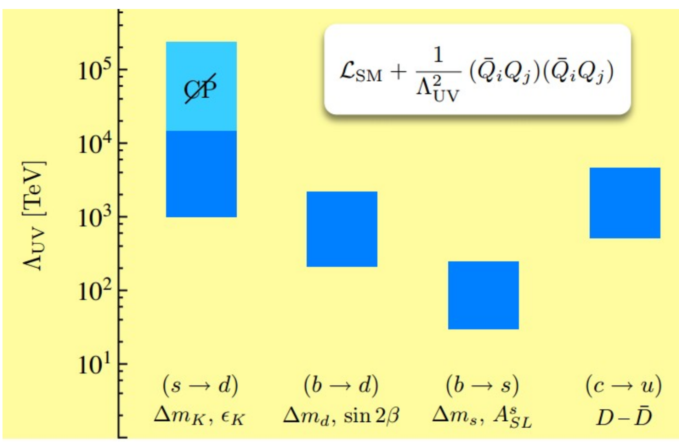
Flavor and NP

Flavor Physics allows to test enormous mass scales (FCNCs) ...



$\sim \frac{g_*^2}{M_{\rm NP}^2}$

suppressed (GIM) → large NP sensitivity $g_* \sim 1$; $\boxed{M_{\rm NP} \gg v}$



Neubert, EPS 2011

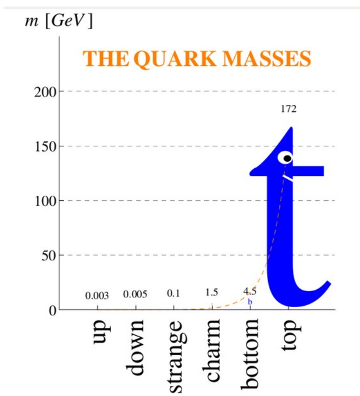
	Λ (TeV) ($\lvert C \rvert = 1$)	LFV Process
$C^{\mu e}_{e\gamma}$	6.3×10^4	$\mu \to e\gamma$
$C^{\mu e}_{e\gamma}$	1.6×10^4	$\mu \to 3e$
$C^{\mu e}_{e\gamma}$	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C^{\tau e}_{e\gamma}$	6.5×10^2	$\tau \to e\gamma$
$C^{\tau\mu}_{e\gamma}$	6.1×10^2	$\tau \to \mu\gamma$
$C^{\mu e}_{eZ}$	2.7×10^3	$\mu \to e\gamma$ [1-loop]
$C^{\tau e}_{eZ}$	28	$\tau \to e\gamma$ [1-loop]
$C^{\tau\mu}_{eZ}$	26	$\tau \to \mu\gamma$ [1-loop]

Feruglio, Paradisi, Pattori, 1509.03241

Protection mechanism for NP?
Partial Compositeness, flavor symmetries, ...

Flavor Puzzle as Motivation for NP

- Large hierarchies in quark + lepton masses
  and in CKM matrix



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \quad \lambda \sim 0.23$$

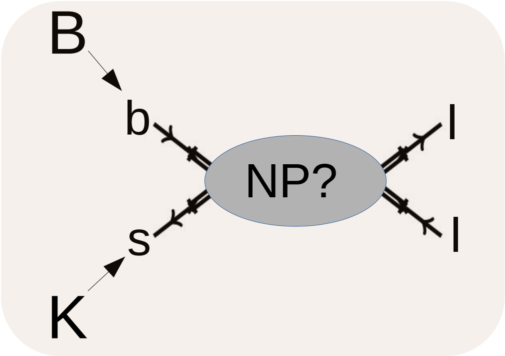
NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Hints for NP in Flavor Physics

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*e^+e^-)}$$

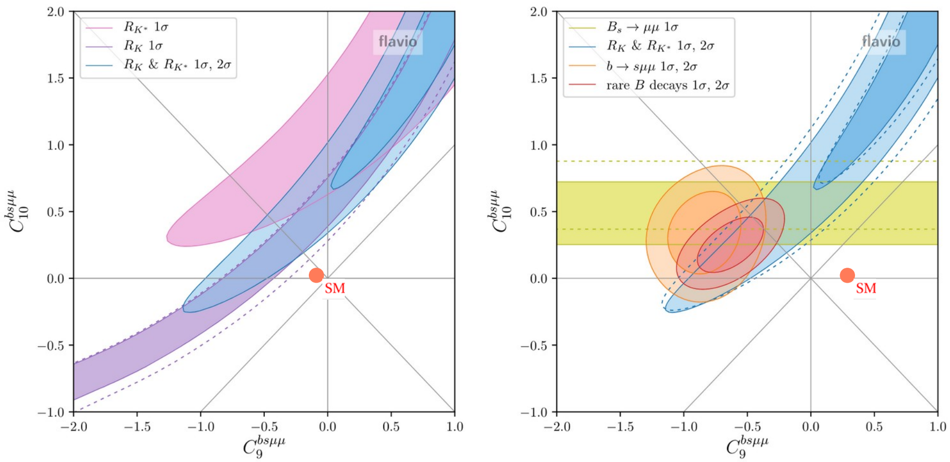


$$R_K^{[1,6]\,\mathrm{exp}} = 0.846\ {}^{+0.042}_{-0.039}\ {}^{+0.013}_{-0.012}$$

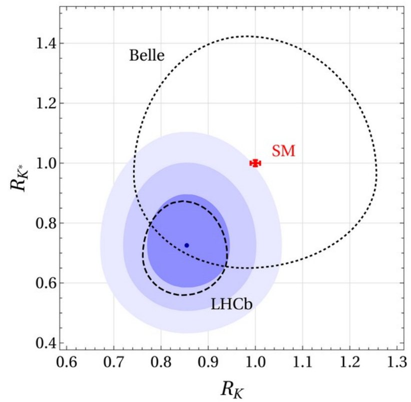
$$R_{K^*}^{[1.1,6]\mathrm{exp}} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

LHCb 2103.11769, 1705.05802

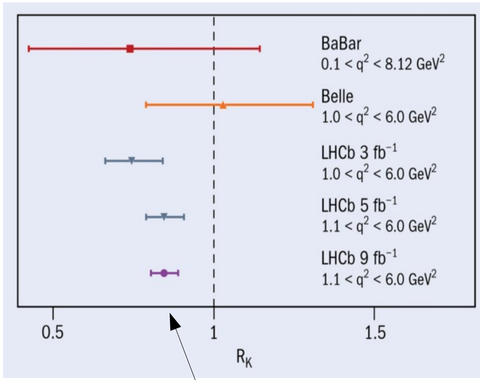
$\boxed{\mathrm{SM:}\ R_K \approx R_{K^*} \approx 1}$: lepton-flavor universality (LFU)



Altmannshofer, Stangl, 2103.13370



Altmannshofer, Dev, Soni, Sui, 2002.12910 .....



$\boxed{3.1\,\sigma}$

LHCb '21

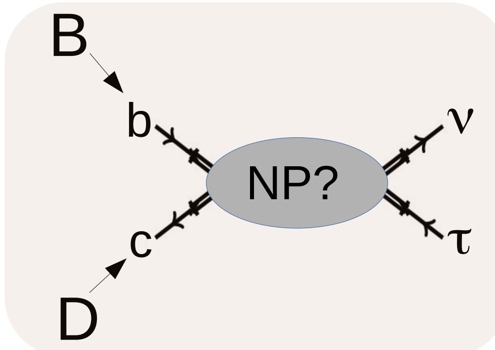
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

	$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	$\boxed{5.7\sigma}$
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	$\boxed{5.9\sigma}$

Hints for NP in Flavor Physics

$$R_D \equiv \frac{\mathcal{B}(\bar{B} \to D\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D\ell\bar{\nu})}$$

$$R_D^* \equiv \frac{\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})} \quad \ell = e, \mu$$



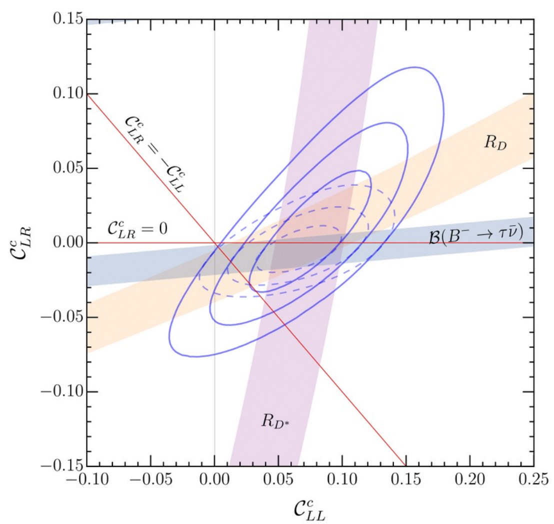
$$R_D^{\text{exp}} = 0.340 \pm 0.030$$

$$R_{D^*}^{\text{exp}} = 0.295 \pm 0.014$$

1909.12524 and hflav.web.cern.ch

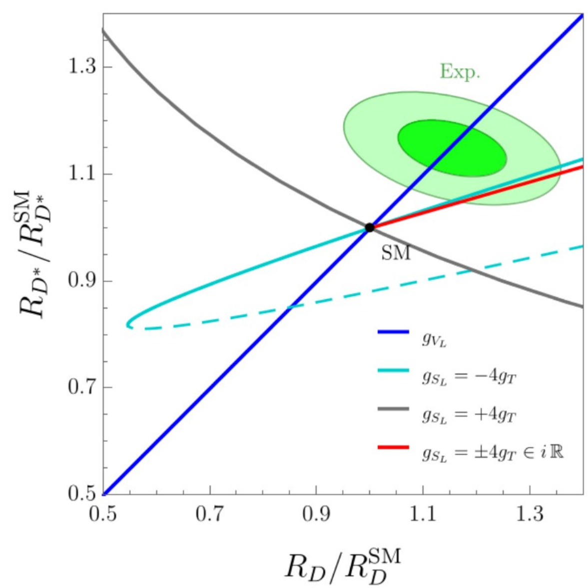
$$R_D^{\text{SM}} = 0.293 \pm 0.008$$

$$R_{D^*}^{\text{SM}} = 0.257 \pm 0.003$$



$$\mathcal{L}_{b\to u_i\tau\nu} = -\frac{4G_F}{\sqrt{2}} \sum_{i=1,2} V_{ib} \left[\left(1 + \mathcal{C}^{u_i}_{LL}\right) (\bar{u}^i_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2\,\mathcal{C}^{u_i}_{LR}\,(\bar{u}^i_L b_R)(\bar{\tau}_R \nu_L) \right]$$

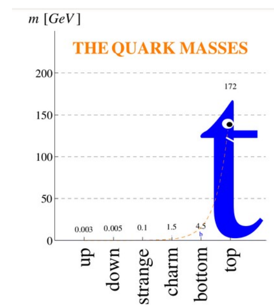
Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert, 2103.16558



Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

Flavor Puzzle as Motivation for NP

- Large hierarchies in fermion masses and in CKM matrix



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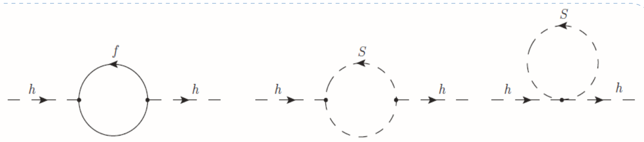
Hierarchy Problem & Flavor Puzzle as Motivation for NP

- Instability of Higgs mass

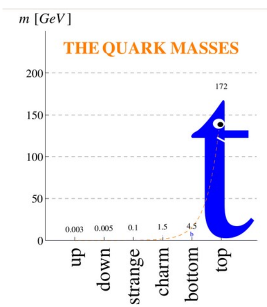
$\Delta m_h^2 \sim \Lambda^2$ 

$$\mathcal{L} \supset m_H^2 |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2} \qquad \Lambda^2 \gg m_H^2 \quad (??)$$

Expect coefficient of unprotected D=2 operator H² to reside at cutoff: $m_H^2 \sim \Lambda^2 \gg (100\,\mathrm{GeV})^2$

$$\Lambda \sim M_{\mathrm{PL}}, M_{\mathrm{GUT}}, \ldots$$

- Large hierarchies in fermion masses and in CKM matrix



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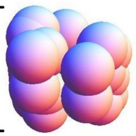
Composite Higgs Models

Kaplan, Georgi, Dimopoulos, ...

- Higgs is composite at small distances l_H (new strong force)



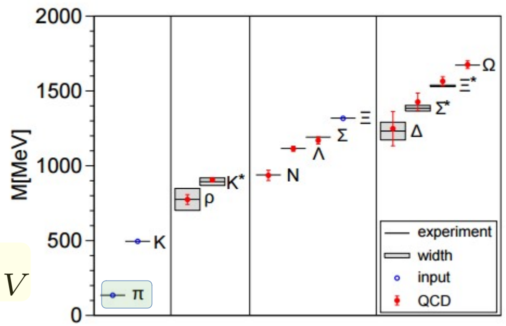
➡ Hierarchy Problem solved

- Higgs = (pseudo) Nambu-Goldstone Boson
  of spon. broken global symmetry

➡ $m_H << m_\rho$

like pions

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q}q \rangle \neq 0} SU(2)_V$$



0906.3599

- MCHM: $\boxed{SO(5) \rightarrow SO(4)}$

Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

minimal: 4 Higgs dof (SO(5)/SO(4)), custodial sym.

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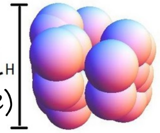

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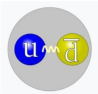
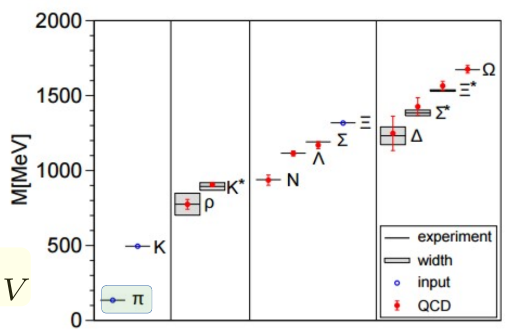


like pions

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q} q \rangle \neq 0} SU(2)_V$$



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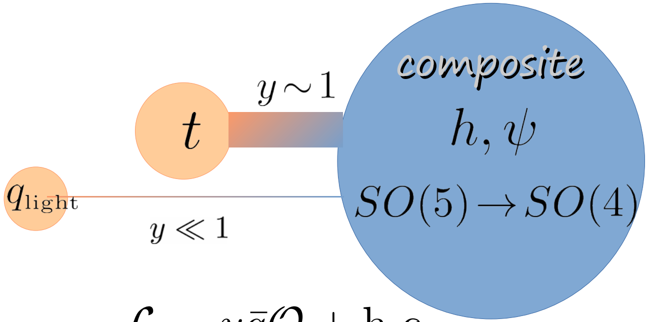
+ Addresses the flavor puzzle:

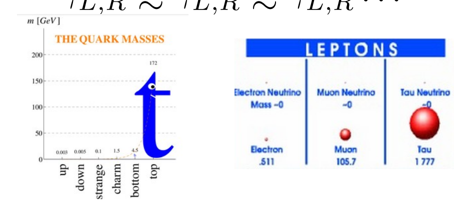


$$\mathcal{L} = y \bar{q} \mathcal{O} + \text{h.c.}$$

$$y^q_{L,R} \sim (\Lambda/\Lambda_{UV})^{\gamma_{L,R}}$$
$$\gamma_{L,R} = [\mathcal{O}_{L,R}] - 5/2$$

→ Hierarchies naturally from small differences in anomalous dimensions

$$\gamma^u_{L,R} \gtrsim \gamma^c_{L,R} \gtrsim \gamma^t_{L,R} \cdots$$



- MCHM: $\boxed{SO(5) \to SO(4)}$ Contino, Nomura, Pomarol, ph/0306259
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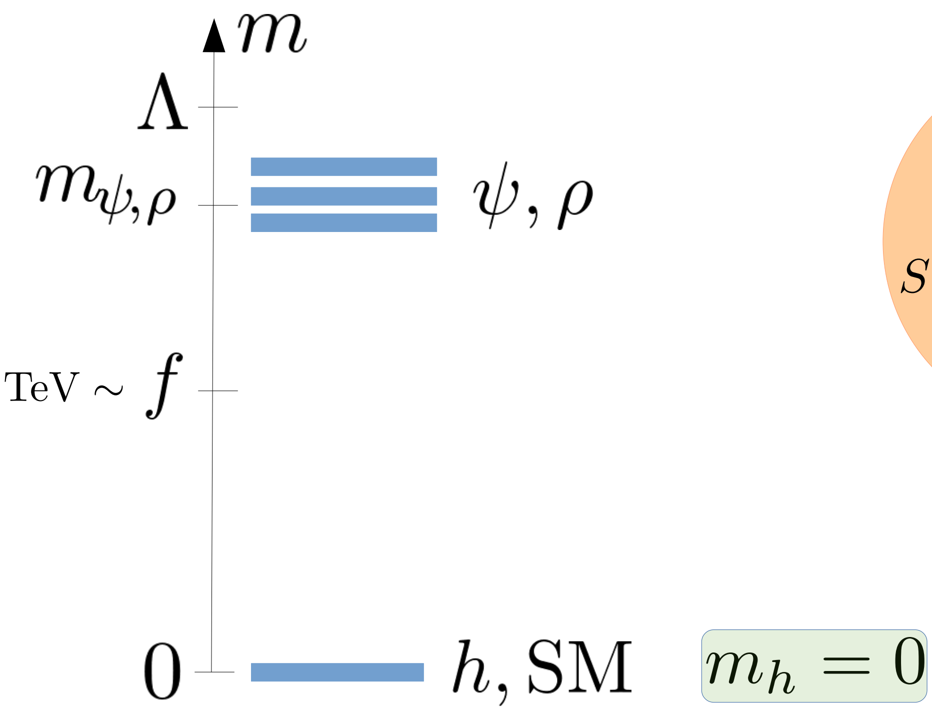
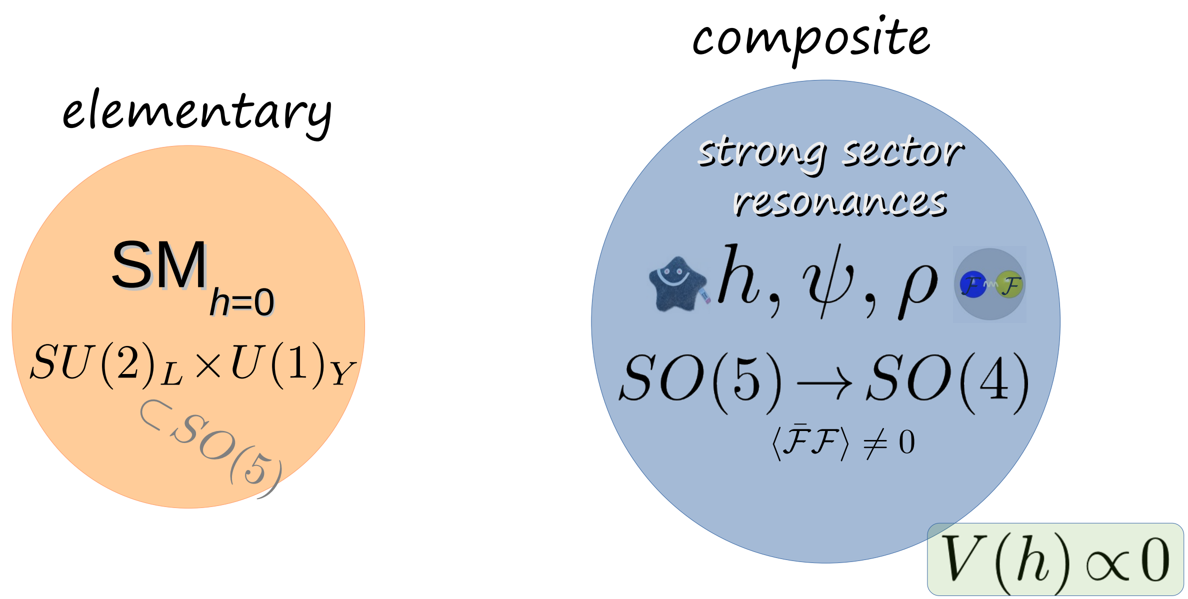
minimal: 4 Higgs dof (SO(5)/SO(4)), custodial sym.

SO(5)→SO(4) Composite Higgs





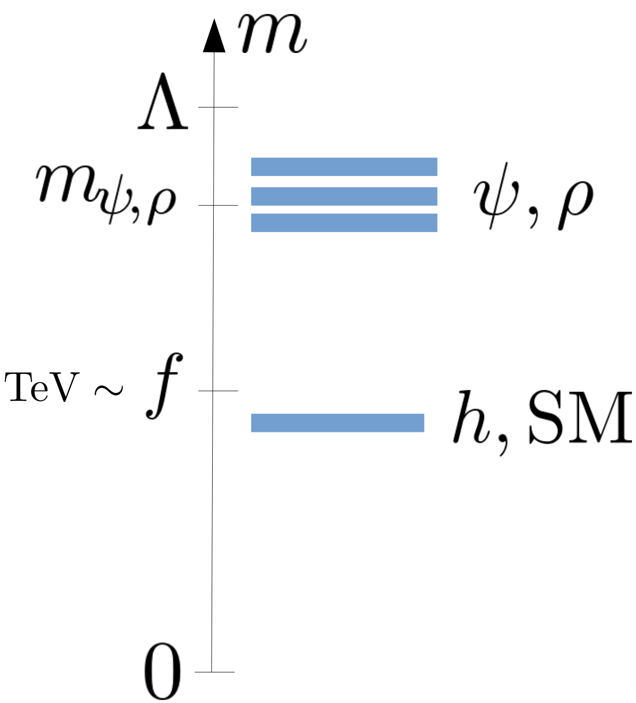
- $G \to H$ via condensation of fermions $\langle \bar{\mathcal{F}}\mathcal{F} \rangle \neq 0$ at scale Λ_c (new confining force)
- Higgs as composite Goldstone
- Confining group $G_{\mathrm{TC}} = SU(N_{\mathrm{TC}}), SO(N_{\mathrm{TC}}), Sp(N_{\mathrm{TC}})$

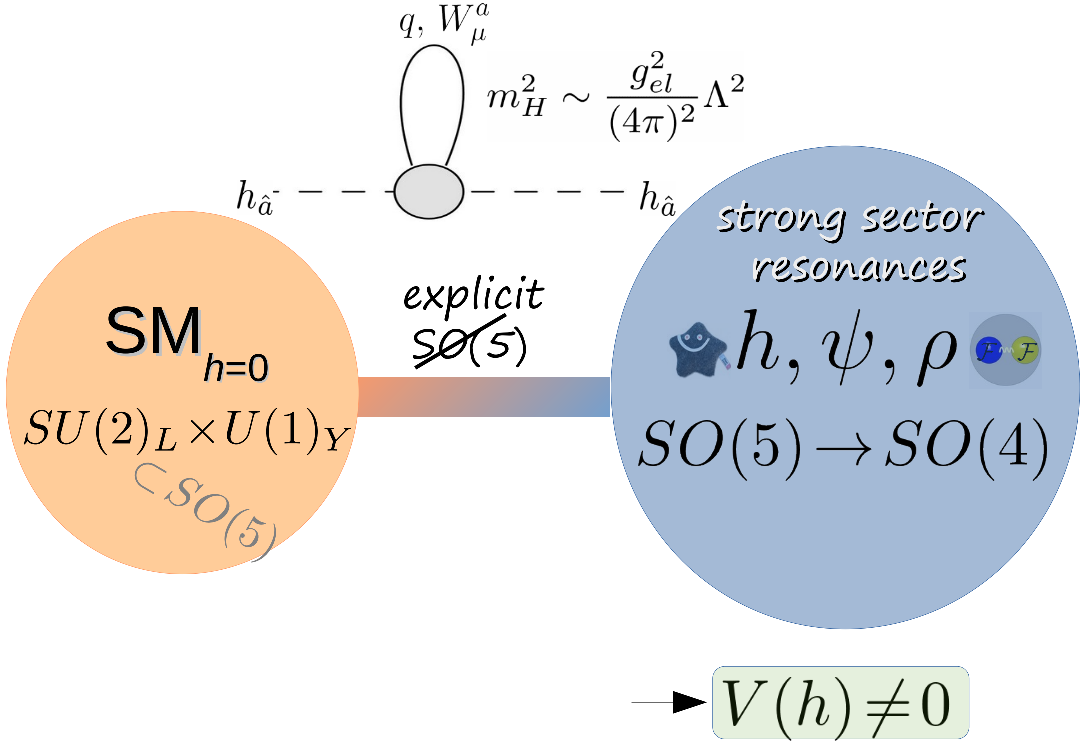
$E \ll \Lambda_c$: non-linear sigma model (EFT)

$\sim 4\pi f$

$$\Sigma = \Sigma_0\, e^{-i\frac{\sqrt{2}}{f} h_{\hat{a}} T^{\hat{a}}}$$

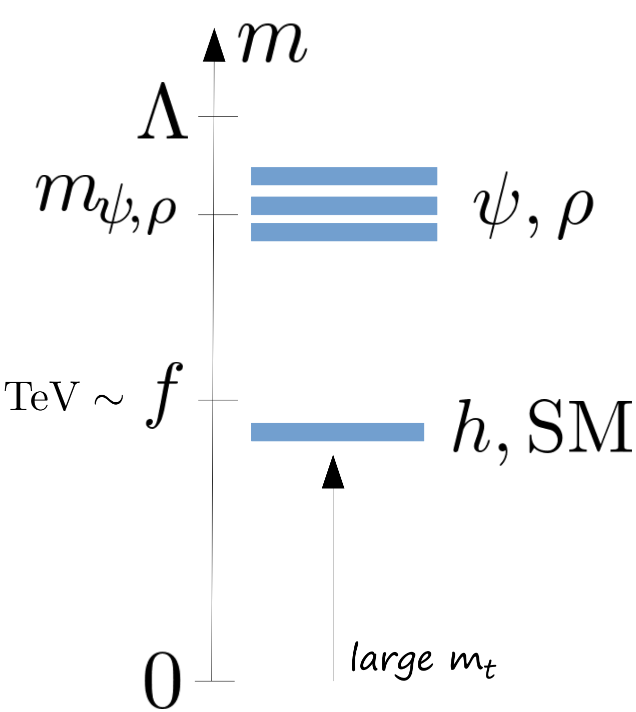
Coupling to SM breaks SO(5)

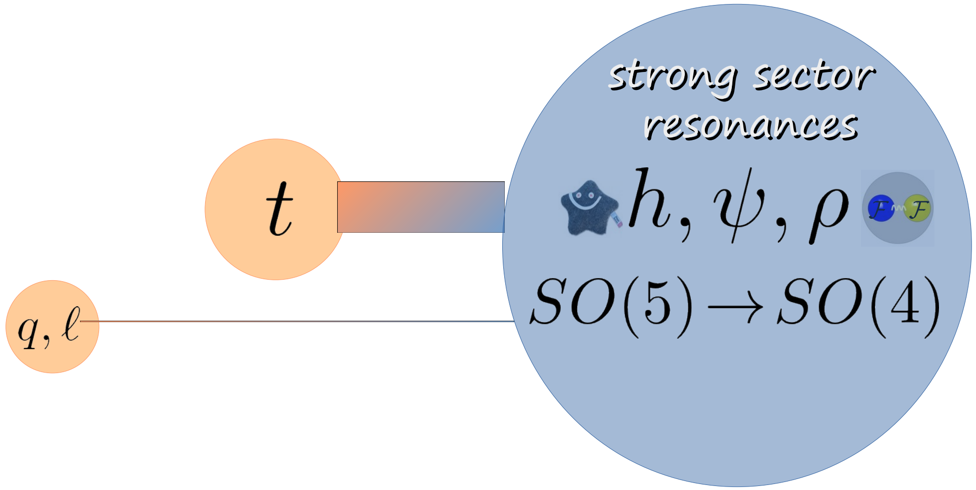




See Contino, 1005.4269, Azatov, 1212.1380, Bellazzini, Csáki, Serra 1401.2457,
Panico, Wulzer, 1506.01961 & Goertz, 1812.07362 for comprehensive & condensed reviews

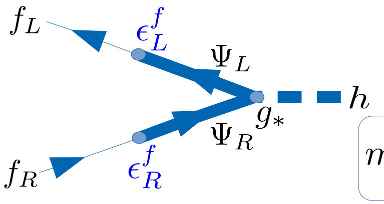
Partially Composite Fermions





$$\mathcal{L}_{\rm mix} \supset \boxed{\frac{\lambda_L^f}{\Lambda_{\rm UV}^{\gamma_L^f}}} \bar{f}_L \mathcal{O}_L^{\psi_f} + \boxed{\frac{\lambda_R^f}{\Lambda_{\rm UV}^{\gamma_R^f}}} \bar{f}_R \mathcal{O}_R^{\psi_f}$$

5 of $SO(5)$
10 of $SO(5)$
...



$$m_f \sim \frac{g_* v}{\sqrt{2}} \epsilon_L^f \epsilon_R^f$$

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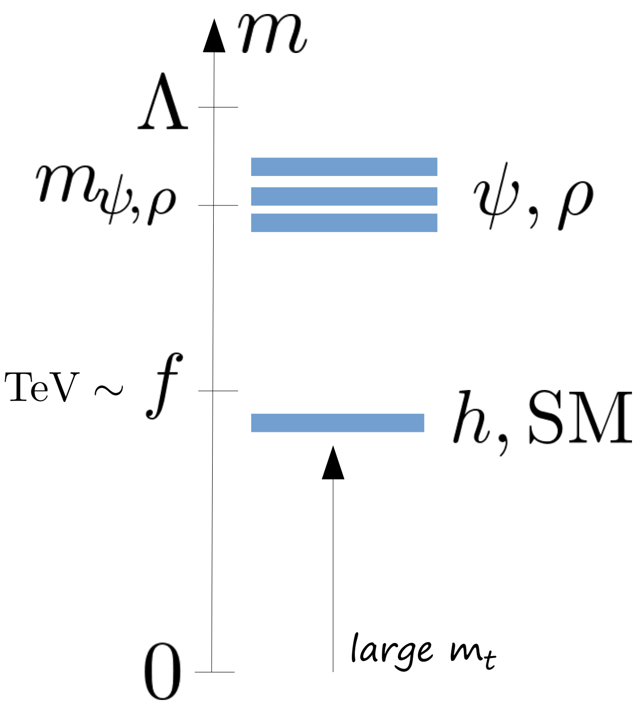

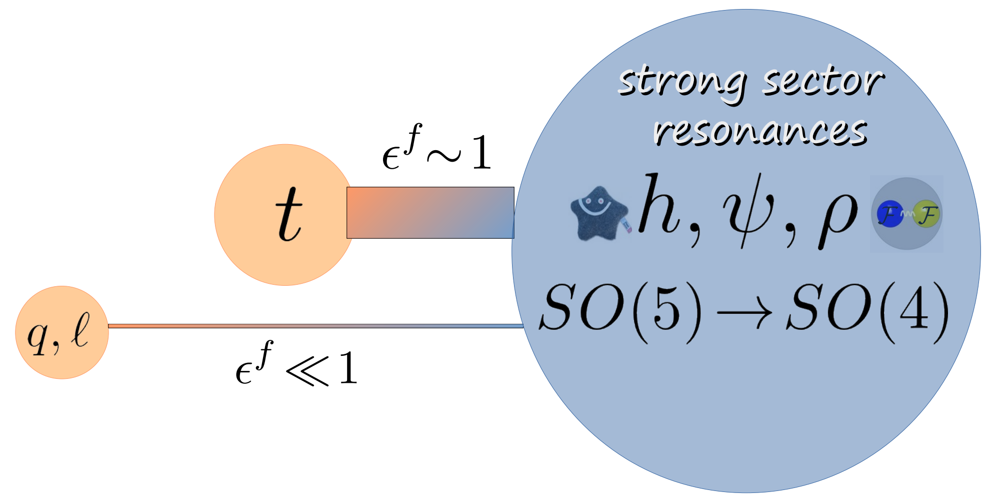

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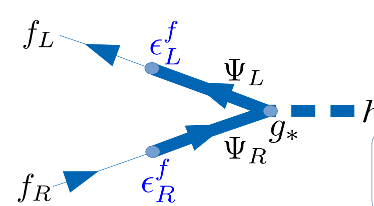
5 of $SO(5)$
10 of $SO(5)$
$\dots$

'compositeness' $\boxed{\epsilon_{L,R}^f \sim \frac{\lambda_{L,R}^f}{g_*} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\gamma_{L,R}^f}}$



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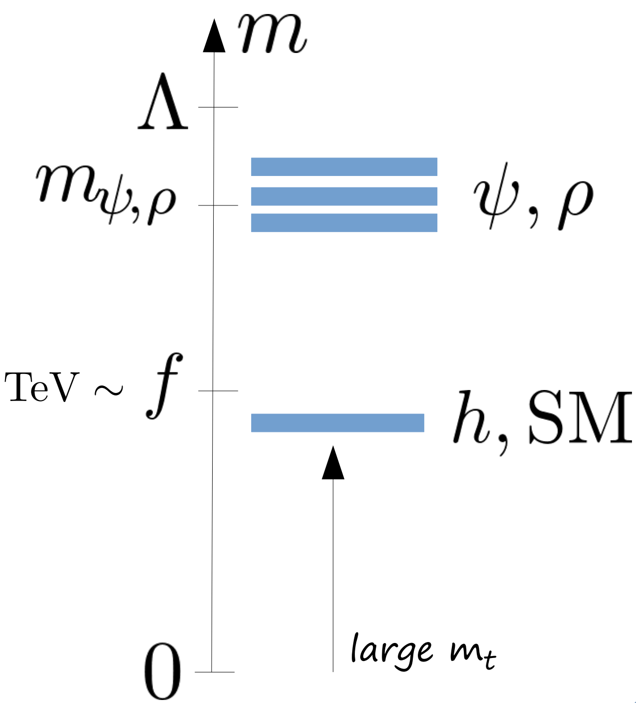
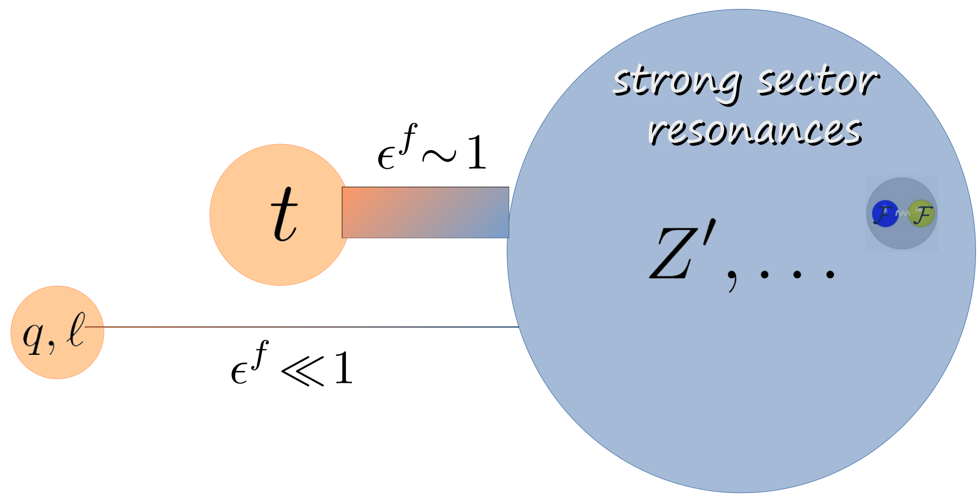
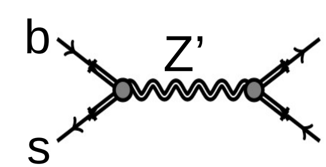




non-universal Z' couplings $\sim \epsilon^f_{L,R}$

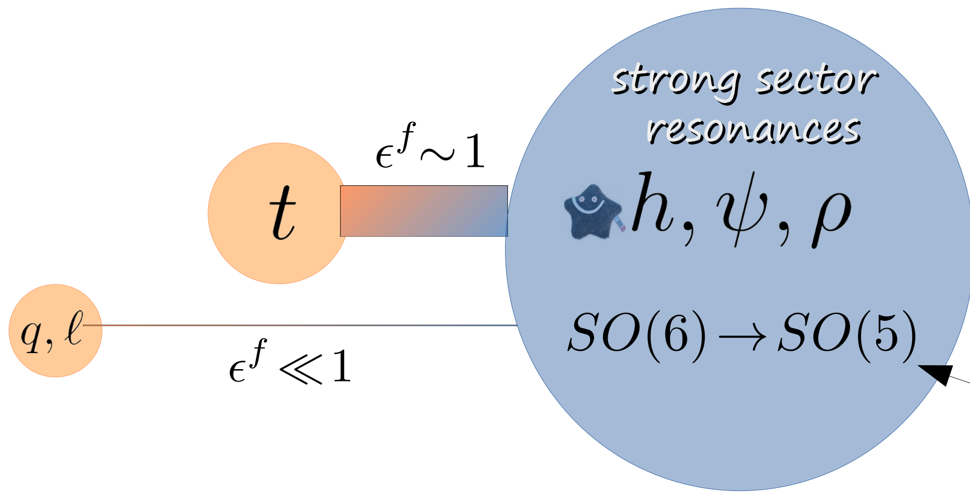


FCNC protection via GIM-like mechanism

(light f: flavor universal)

See Contino, 1005.4269, Azatov, 1212.1380, Bellazzini, Csáki, Serra 1401.2457,
Panico, Wulzer, 1506.01961 & Goertz, 1812.07362 for comprehensive & condensed reviews

UV Completion?!



$G_{\rm TC} = Sp(N_{\rm TC})$ tensor

vacuum orientation

$$\langle \mathcal{F}^a \epsilon_{\rm TC} \mathcal{F}^b \rangle = \Lambda_c f^2 \Sigma_\theta^{ab}$$

$$\Rightarrow \boxed{SU(4) \to Sp(4)}$$

$$\cong$$

$$SO(6) \to SO(5)$$

$$\mathcal{L}_{\rm mix} \supset \frac{\lambda_L^f}{\Lambda_{\rm UV}^{\gamma_L^f}} \bar{f}_L \mathcal{O}_L^{\psi_f} + \frac{\lambda_R^f}{\Lambda_{\rm UV}^{\gamma_R^f}} \bar{f}_R \mathcal{O}_R^{\psi_f}$$

"(minimal) fundamental partial compositeness"

Cacciapaglia, Gertov, Sannino, Thomsen, 1704.07845

Sannino, Strumia, Tesi, Vigiani, 1607.01659

$$-\mathcal{L} \sim (f)^i_{\ a} \epsilon_{ij} \mathcal{S}^j \epsilon_{\rm TC} \mathcal{F}^a$$

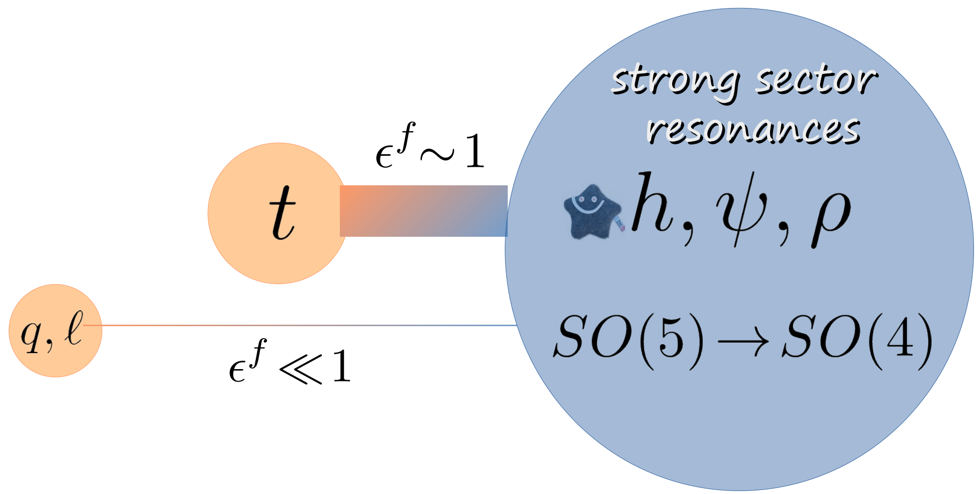
scalars

fermions

$a = 1, .., 4 : SU(4)_{\mathcal{F}}$

See Barnard, Gherghetta, Ray 1311.6562,
Ferretti, Karateev, 1312.5330
Cacciapaglia, Sannino 1402.0233,
Vecchi, 1506.00623, Ma, Cacciapaglia, 1508.07014
Cacciapaglia, Pica, Sannino, 2002.04914

Models of Lepton Flavor

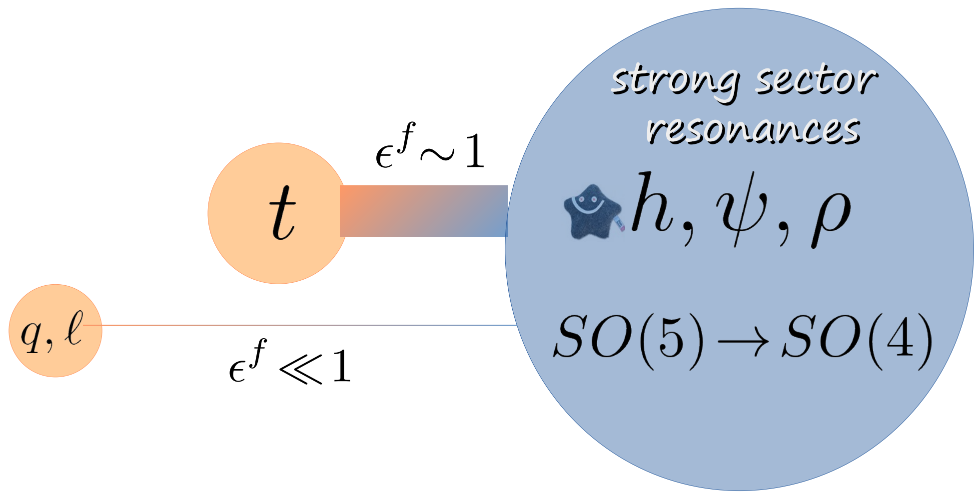


canonical model:
$\mathcal{O}^i_{L,R}$ fundamental
of $SO(5)$

m_ν

$$\mathcal{L}_{\rm mix} \supset \frac{\boxed{\lambda_L^\ell}}{\Lambda_{\rm UV}^{\gamma_L^\ell}} \bar{l}_L^\ell \mathcal{O}_L^\ell + \frac{\boxed{\lambda_R^\ell}}{\Lambda_{\rm UV}^{\gamma_R^\ell}} \bar{l}_R^\ell \mathcal{O}_R^\ell + \frac{\lambda_L'^\ell}{\Lambda_{\rm UV}^{\gamma_L'^\ell}} \bar{l}_L^\ell \mathcal{O}_L^{\ell'} + \frac{\lambda_R^{\nu_\ell}}{\Lambda_{\rm UV}^{\gamma_R^{\nu_\ell}}} \bar{\nu}_R^\ell \mathcal{O}_R^{\nu_\ell}$$

Models of Lepton Flavor



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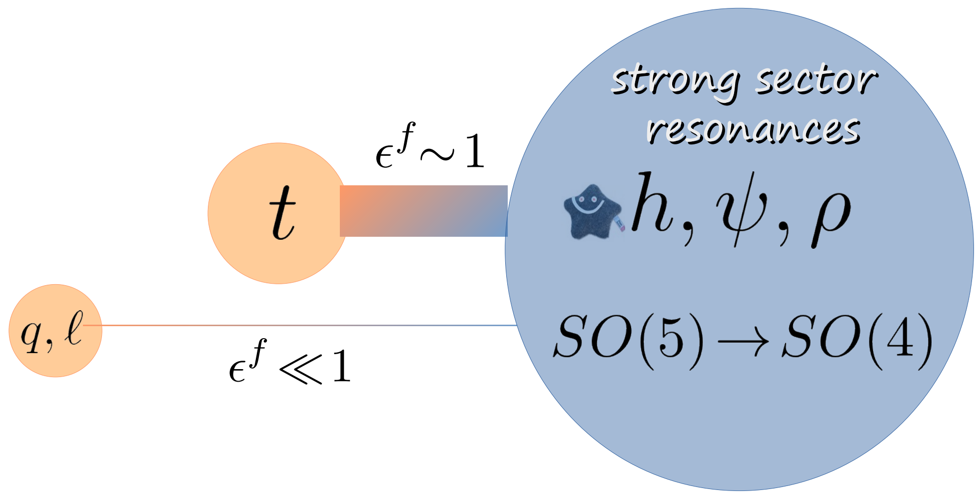
1: 'Anarchic' Model



$$\mathcal{L}_{\rm mix} \supset \frac{\boxed{\lambda_L^\ell}}{\Lambda_{\rm UV}^{\gamma_L^\ell}} \bar{l}_L^\ell \mathcal{O}_L^\ell + \frac{\boxed{\lambda_R^\ell}}{\Lambda_{\rm UV}^{\gamma_R^\ell}} \bar{l}_R^\ell \mathcal{O}_R^\ell$$

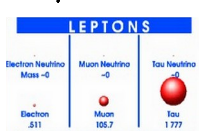
$\mathcal{O}(1) \sim \gamma_{L,R}^e \gtrsim \gamma_{L,R}^\mu \gtrsim \gamma_{L,R}^\tau \cdots$

RGE $\lambda_{L,R}^\ell(\mu) \simeq \boxed{\lambda_{L,R}^\ell} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\gamma_{L,R}^\ell} \boxed{\ll 1}$

$\gamma_{L,R} = [\mathcal{O}_{L,R}] - 5/2$

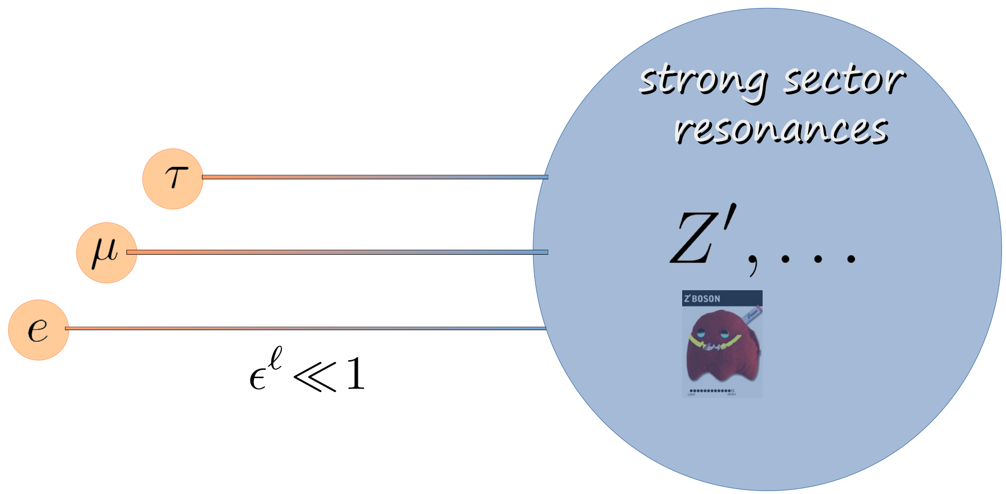
$\mathcal{O}(1)$'anarchic'

'compositeness' $\boxed{\epsilon_{L,R}^\ell} \sim \lambda_{L,R}^\ell(\mu)/g_*$



$m_\ell \sim \frac{g_* v}{\sqrt{2}} \boxed{\epsilon_L^\ell \epsilon_R^\ell}$

1: 'Anarchic' Model



$\epsilon^e \ll \epsilon^\mu \ll \epsilon^\tau \ll 1$

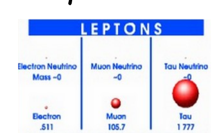
FCNC protection via GIM-like mechanism

RGE $\lambda^\ell_{L,R}(\mu) \simeq \boxed{\lambda^\ell_{L,R}} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\gamma^\ell_{L,R}} \ll 1$

$\mathcal{O}(1)$

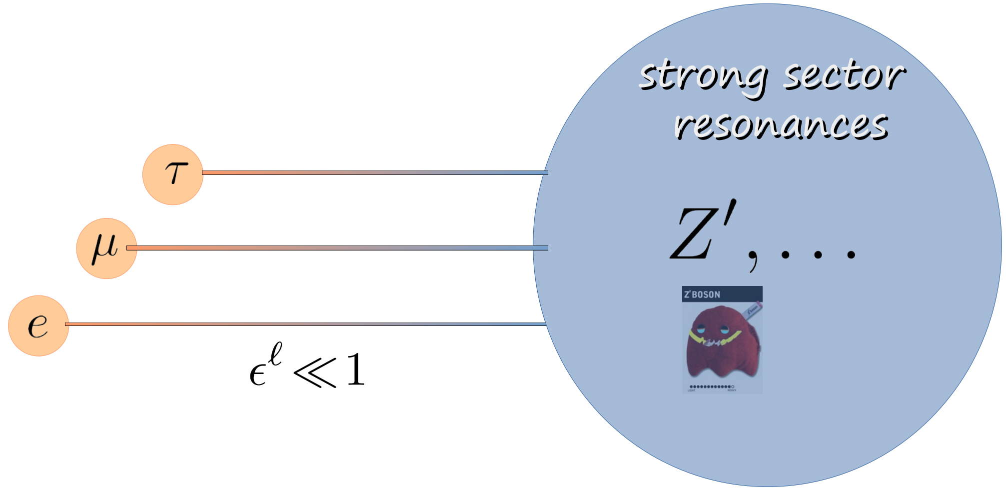
$\mathcal{O}(1)$'anarchic'

'compositeness' $\epsilon^\ell_{L,R} \sim \lambda^\ell_{L,R}(\mu)/g_*$



$m_\ell \sim \frac{g_* v}{\sqrt{2}} \epsilon^\ell_L \epsilon^\ell_R$

1: 'Anarchic' Model



$\epsilon^e \ll \epsilon^\mu \ll \epsilon^\tau \ll 1$

FCNC protection via GIM-like mechanism

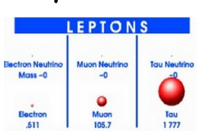
Not quite sufficient
→ see below

RGE $\lambda^\ell_{L,R}(\mu) \simeq \boxed{\lambda^\ell_{L,R}} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\gamma^\ell_{L,R}} \boxed{\ll 1}$

$\mathcal{O}(1)$

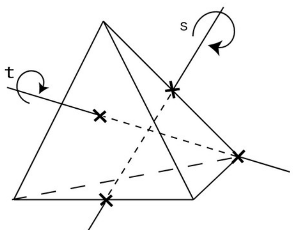
$\mathcal{O}(1)$'anarchic'

'compositeness' $\boxed{\epsilon^\ell_{L,R}} \sim \lambda^\ell_{L,R}(\mu)/g_*$

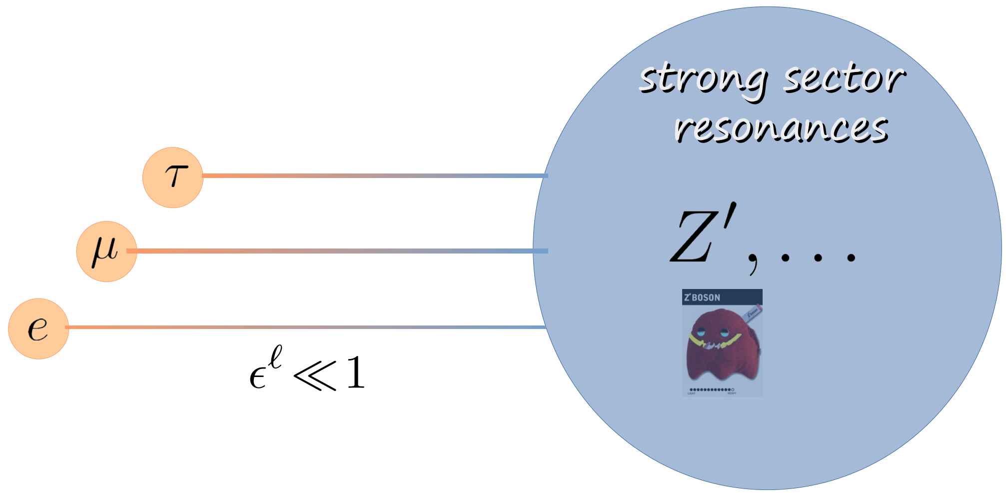


$m_\ell \sim \frac{g_* v}{\sqrt{2}} \boxed{\epsilon^\ell_L \epsilon^\ell_R}$

2: Flavor Symmetries



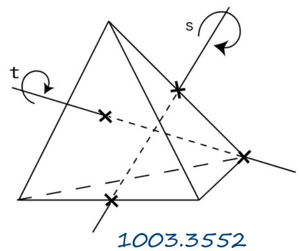
1003.3552

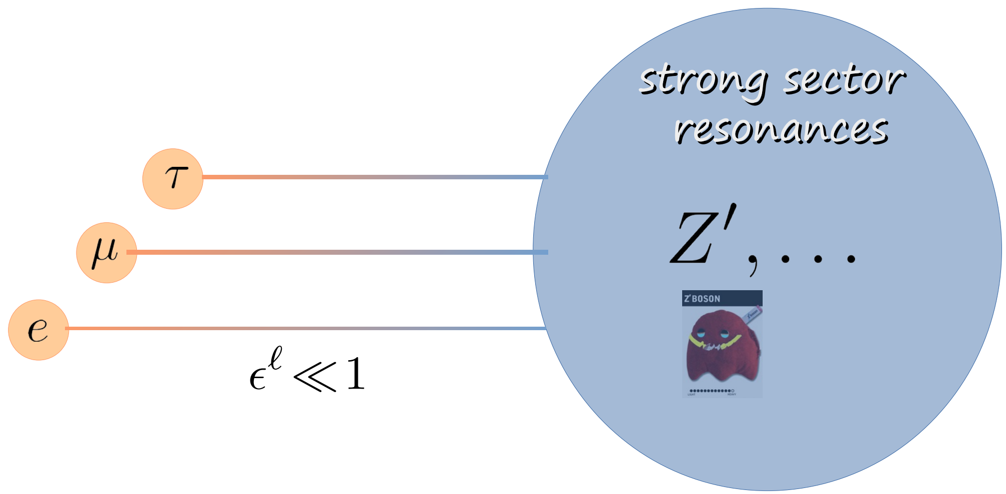


G_f	$A_4 \times Z_N$	$S_4 \times Z_N^n$	$X \times Z_N$	$\Delta(27) \times Z_4 \times Z_4'$	S_3	T'	$U(N)$
Ref.	Csaki, Delaunay, Grojean, Grossman, 0806.0356 del Aguila, Carmona, Santiago, 1001.5151 Kadosh, Pallante, 1004.0321 Kadosh, 1303.2645	Hagedorn, Serone, 1106.4021 Hagedorn, Serone, 1110.4612 Ding, Zhou, 1304.2645	Hagedorn, Serone, 1110.4612	Chen, Ding, Alma, Rojas, Valle, 1509.06683	Frank, Hamzaoui, Pourtolami, Toharia, 1406.2331	Chen, Mahanthappa, Yu, 0907.3963	von Gersdorff, Quiros, Wiechers, 1208.4300 Frigerio, Nardecchia, Serra, Vecchi, 1807.04279

$X \in \{A_5, \Delta(96), \Delta(384)\}$

2: Flavor Symmetries





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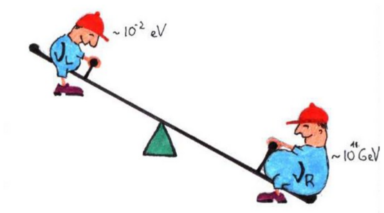
A_4 (spont. broken): $\mathbf{3}$ $\mathbf{1, 1', 1''}$ $\mathbf{3}$ $\mathbf{3}$

→ allows to rotate to an approximately flavor-diagonal basis

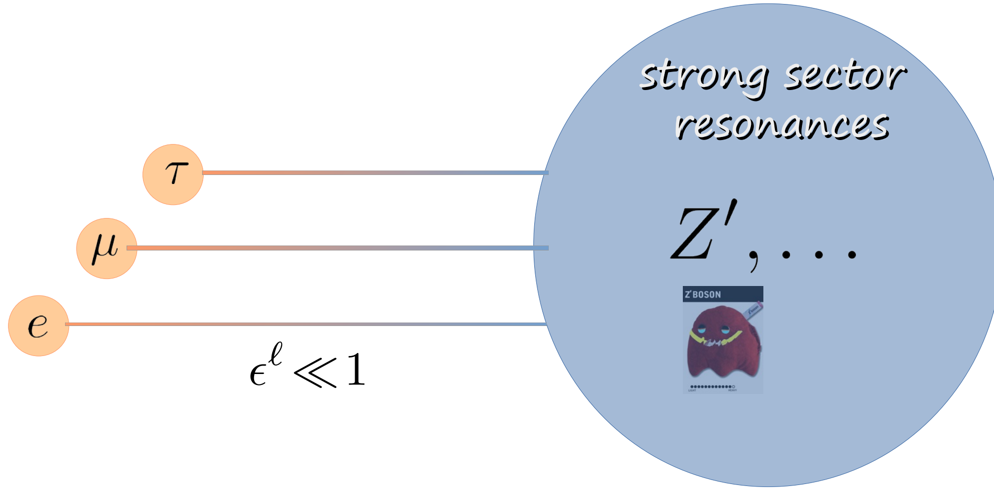
→ generates ~ TBM mixing

3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)



Grossman, TASI 2002



canonical model:
$\mathcal{O}^i_{L,R}$ fundamental of SO(5)

m_ν

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3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
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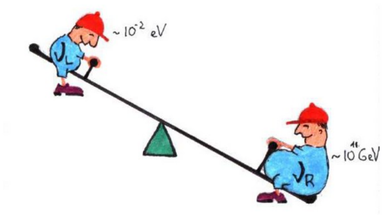

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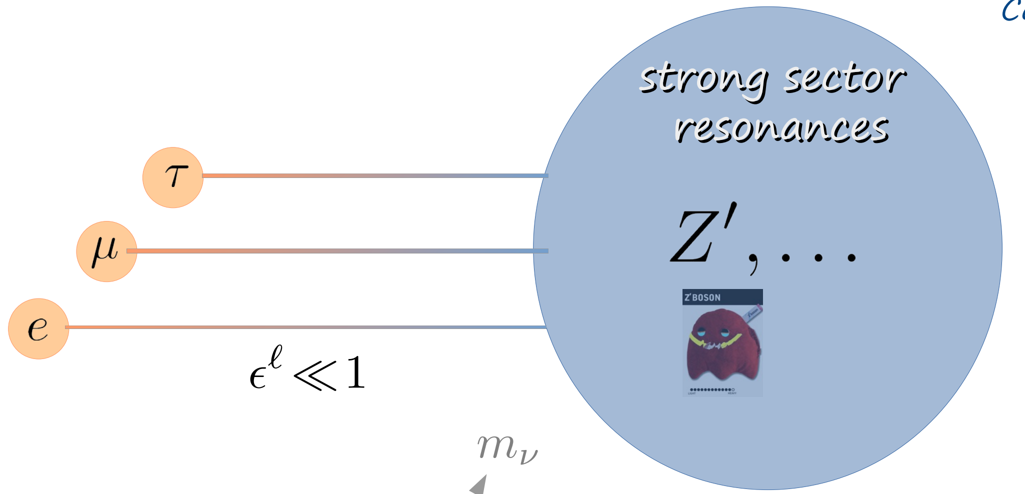

$\mathcal{O}_L^{\ell}$ fundamental
$\mathcal{O}_R^{\ell}$ symmetric

m_ν

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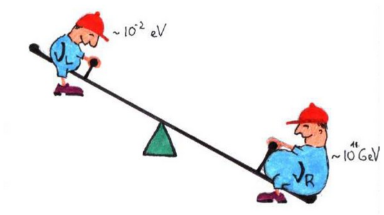
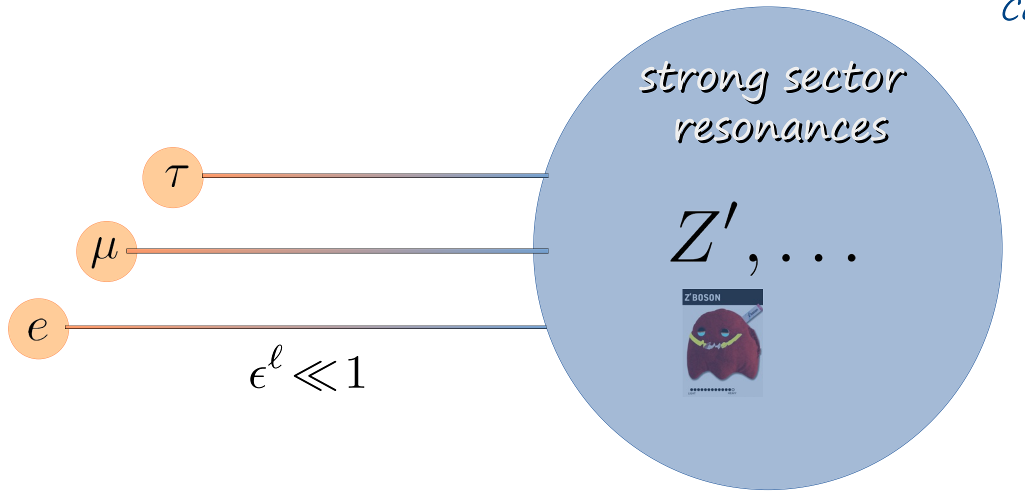
ℓ_R Σ_R seesaw triplet
→ small m_ν

3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)



Grossman, TASI 2002



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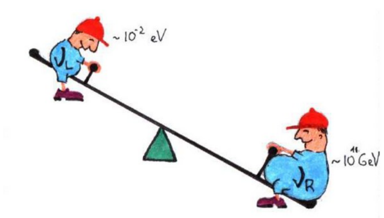
$\ell_L \quad \nu_L$

$\ell_R \quad \Sigma_R$ seesaw triplet
→ small m_ν

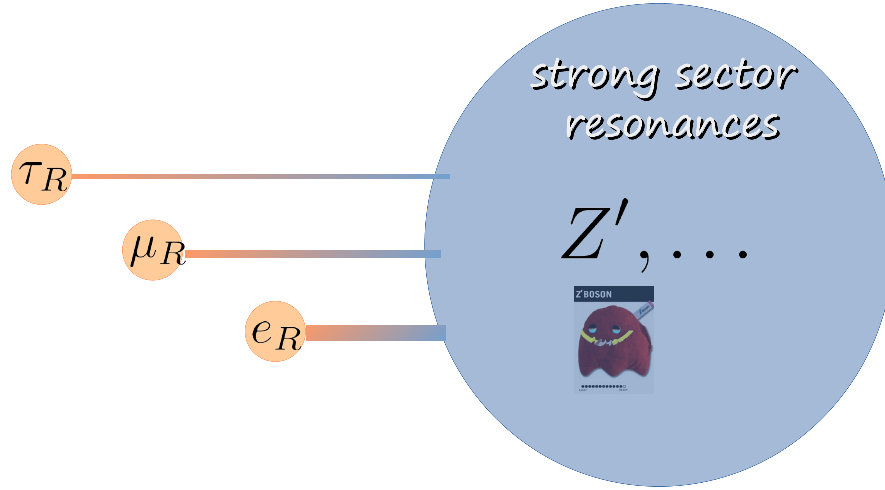
Unification of LH and RH fields!!
very minimal realization of lepton sector...

3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)



Grossman, TASI 2002



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$\ell_L \quad \nu_L$

$\ell_R \quad \Sigma_R$ seesaw triplet

Unification of LH and RH fields!!

very minimal realization of lepton sector...

rather composite $\Rightarrow$ $\epsilon_R^\ell \gg 0$

$m_\ell \rightarrow \epsilon_L^e \ll \epsilon_L^\mu \ll \epsilon_L^\tau \ll 1$

$M_\nu \rightarrow \epsilon_L^\ell \epsilon_R^\ell \sim \text{const.} \rightarrow 0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$

3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
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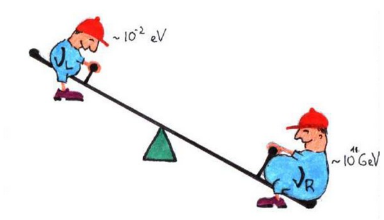
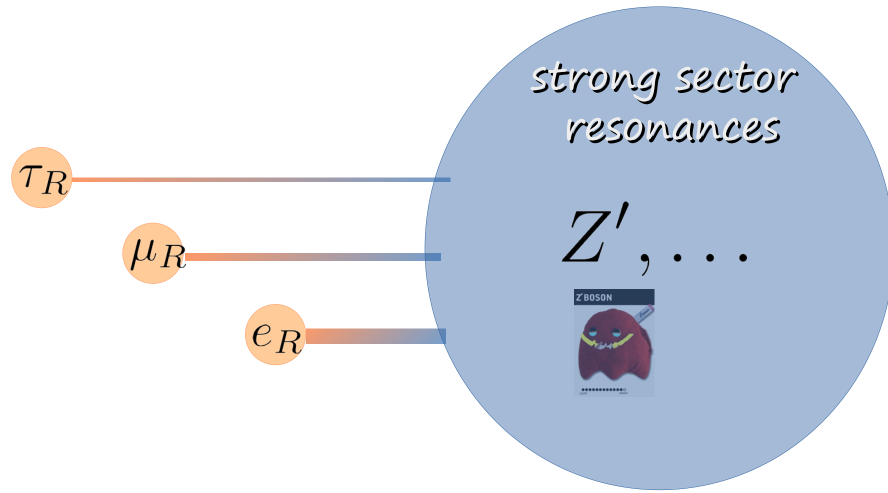


Grossman, TASI 2002



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$\ell_L \quad \nu_L \qquad\qquad \ell_R \quad \Sigma_R$

Unification of LH and RH fields!!
very minimal realization of lepton sector...

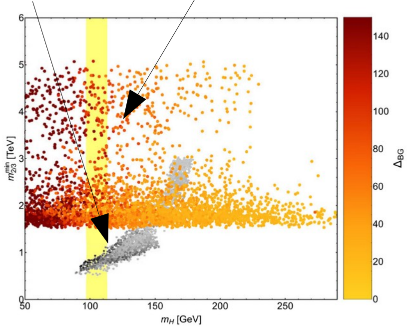
$0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$:

only 2 $\mathcal{O}_{L,R}^\ell$ → strong flavor protection:
flavor symmetry broken by single spurion → diagonalize
& custodial protection for $Z\bar{\ell}_R\ell_R$

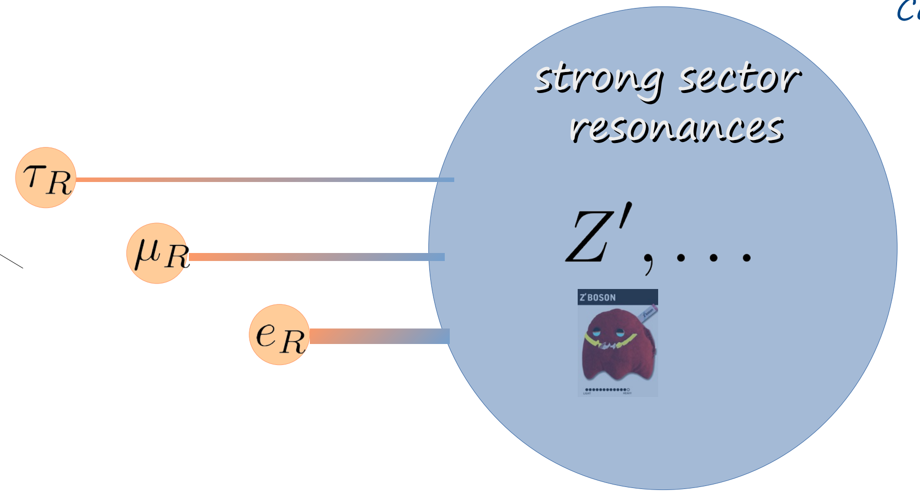
3: Minimal Seesaw Model

Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)

+ Lepton compositeness solves issue with light top partners:



Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)



$\mathcal{O}_L^\ell$ fundamental
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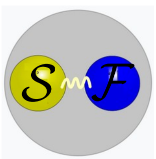
$\ell_L \quad \nu_L \qquad \ell_R \quad \Sigma_R$

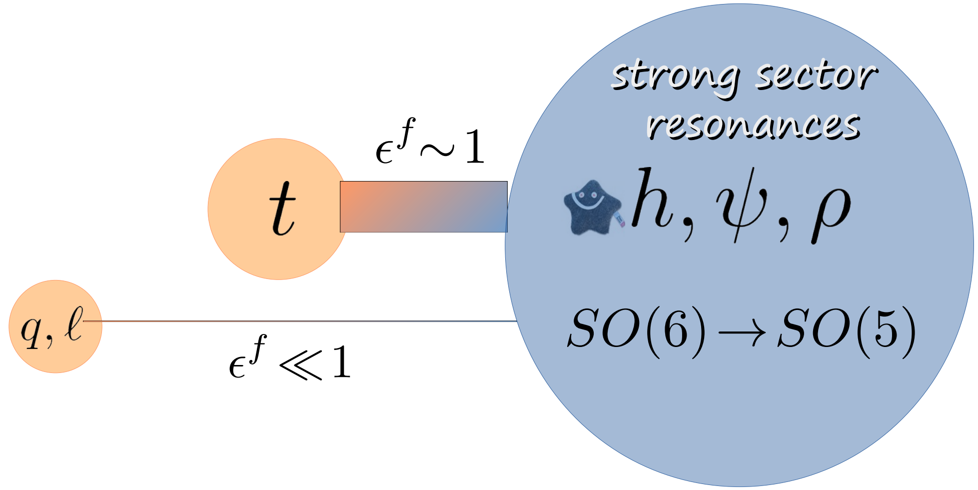
Unification of LH and RH fields!!

very minimal realization of lepton sector...

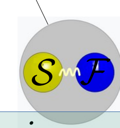
4: "Minimal" Fundamental PC

Sannino, Strumia, Tesi, Vigiani, 1607.01659





$$\mathcal{L}_{\rm mix} \supset \frac{\lambda_L^f}{\Lambda_{\rm UV}^{\gamma_L^f}}\, \bar{f}_L \boxed{\mathcal{O}_L^{\psi_f}} + \frac{\lambda_R^f}{\Lambda_{\rm UV}^{\gamma_R^f}}\, \bar{f}_R \boxed{\mathcal{O}_R^{\psi_f}}$$

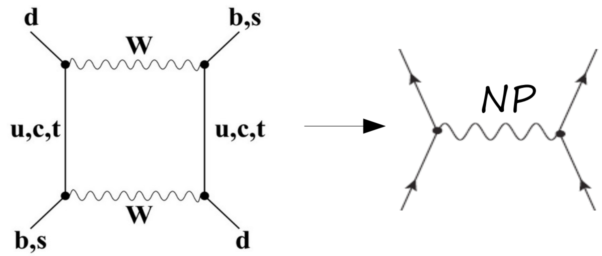


$$\mathcal{L} \sim -(f)^i{}_a \epsilon_{ij} \boxed{\mathcal{S}^j \epsilon_{\rm TC} \mathcal{F}^a}$$

scalar fermion

Flavor Observables

Flavor Physics allows to test enormous mass scales (FCNCs) …



$$\sim \frac{g_*^2}{M_{\rm NP}^2}$$

suppressed (GIM) → large NP sensitivity $g_* \sim 1$; $M_{\rm NP} \gg v$

	Λ (TeV) ($\lvert C\rvert = 1$)	LFV Process
$C_{e\gamma}^{\mu e}$	6.3×10^4	$\mu \to e\gamma$
$C_{e\gamma}^{\mu e}$	1.6×10^4	$\mu \to 3e$
$C_{e\gamma}^{\mu e}$	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{e\gamma}^{\tau e}$	6.5×10^2	$\tau \to e\gamma$
$C_{e\gamma}^{\tau\mu}$	6.1×10^2	$\tau \to \mu\gamma$
$C_{eZ}^{\mu e}$	2.7×10^3	$\mu \to e\gamma$ [1-loop]
$C_{eZ}^{\tau e}$	28	$\tau \to e\gamma$ [1-loop]
$C_{eZ}^{\tau\mu}$	26	$\tau \to \mu\gamma$ [1-loop]

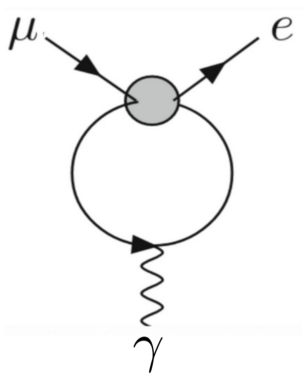
Protection mechanism for NP?
Partial Compositeness, flavor symmetries, …

Lepton Flavor Violation and Dipole Moments

$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu}\bar{\ell}_L \sigma^{\mu\nu}\ell'_R$$

Dipole operator

$\mu \to e\gamma$



$\boxed{\ell = \mu, \ell' = e}$

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ @ 90% CL

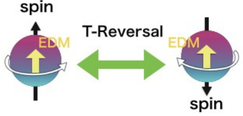
Baldini et al., 1605.05081

$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$

RPP 2020

Electron EDM



$\boxed{\ell = \ell' = e}$

$d_e < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$

ACME 2018

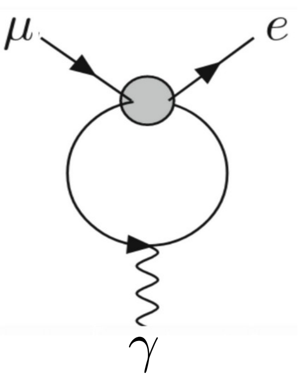
LFV and Dipole Moments

1: 'Anarchic' Model

$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu} \bar{\ell}_L \sigma^{\mu\nu} \ell'_R$$

Dipole operator

$\mu \to e\gamma$

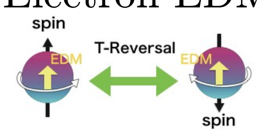


$\boxed{\ell = \mu, \ell' = e}$

$$\mathrm{BR}(\mu \to e\gamma) = 96\pi^2 e^2 \frac{v^6}{m_\mu^2} \left(\left| C^{\gamma}_{\mu e} \right|^2 + \left| C^{\gamma}_{e\mu} \right|^2 \right)$$

$$C^{\gamma}_{\mu e} \sim \frac{1}{16\pi^2} \frac{g_*^3}{\sqrt{2} m_*^2} \epsilon_L^{\mu} \epsilon_R^{e}, \quad C^{\gamma}_{e\mu} \sim \frac{\sqrt{1}}{16\pi^2} \frac{g_*^3}{\sqrt{2} m_*^2} \epsilon_L^{e} \epsilon_R^{\mu}$$

Electron EDM



$\boxed{\ell = \ell' = e}$

$$d_e \sim \mathrm{Im}(c_e) \frac{e}{16\pi^2} \frac{g_*^3}{m_*^2} \epsilon_L^{e} \epsilon_R^{e} \frac{v}{\sqrt{2}}$$

$\mathcal{O}(1) \in \mathbb{C}$

$m_* \sim g_* f$

Exchange of heavy resonances

See also Agashe, Blechman, Petriello, hep-ph/0606021
Csaki, Grossman, Tanedo, Tsai, 1004.2037
Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi, 1205.5803
Agashe, Bauer, FG, Lee, Vecchi, Wang, Yu, arXiv:1310.1070
Frigerio, Nardecchia, Serra, Vecchi, 1807.04279

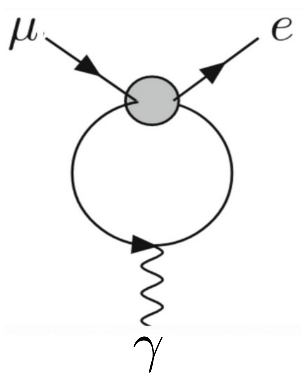
LFV and Dipole Moments

1: 'Anarchic' Model

$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu}\bar{\ell}_L \sigma^{\mu\nu}\ell'_R$$

Dipole operator

$\mu \to e\gamma$



$\boxed{\ell = \mu, \ell' = e}$

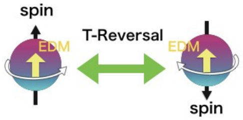
$$\mathrm{BR}(\mu \to e\gamma) = 96\pi^2 e^2 \frac{v^6}{m_\mu^2}\left(\left|C^{\gamma}_{\mu e}\right|^2 + \left|C^{\gamma}_{e\mu}\right|^2\right)$$

$$C^{\gamma}_{\mu e} \sim \frac{1}{16\pi^2}\frac{g_*^3}{\sqrt{2}m_*^2}\epsilon_L^{\mu}\epsilon_R^{e}, \quad C^{\gamma}_{e\mu} \sim \frac{\sqrt{1}}{16\pi^2}\frac{g_*^3}{\sqrt{2}m_*^2}\epsilon_L^{e}\epsilon_R^{\mu}$$

$$\Rightarrow \boxed{\frac{g_*^3}{m_*^2}\sqrt{|\epsilon_L^{\mu}\epsilon_R^{e}|^2 + |\epsilon_L^{e}\epsilon_R^{\mu}|^2} \lesssim \frac{10^{-7}}{\mathrm{TeV}^2}} \xrightarrow[\epsilon_L^{\ell} \sim \epsilon_R^{\ell}]{m_\ell \sim g_* v/\sqrt{2}\,\epsilon_L^{\ell}\epsilon_R^{\ell}} \frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$$

$$g_* \sim 4 \longrightarrow m_* \gtrsim 80\,\mathrm{TeV}$$

Electron EDM



$\boxed{\ell = \ell' = e}$

$$d_e \sim \mathrm{Im}(c_e)\frac{e}{16\pi^2}\frac{g_*^3}{m_*^2}\epsilon_L^{e}\epsilon_R^{e}\frac{v}{\sqrt{2}}$$

$\mathcal{O}(1) \in \mathbb{C}$

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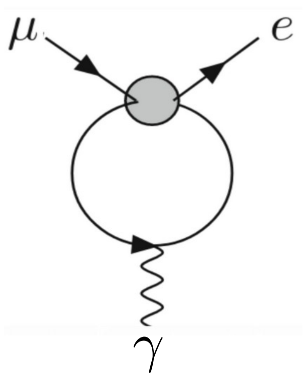

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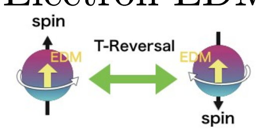
Electron EDM



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Exchange of heavy resonances

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Lepton Flavor Violation and Dipole Moments

$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu}\bar{\ell}_L\sigma^{\mu\nu}\ell'_R$$

Dipole operator

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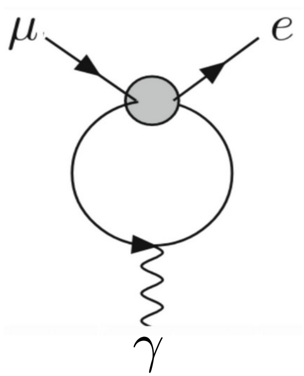

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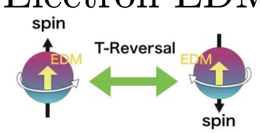
Electron EDM



$\boxed{\ell = \ell' = e}$

1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC
$\frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$		
$\mathrm{Im}(c_e)\sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\mathrm{TeV}$		

Lepton Flavor Violation and Dipole Moments

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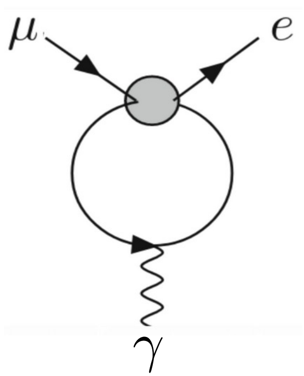
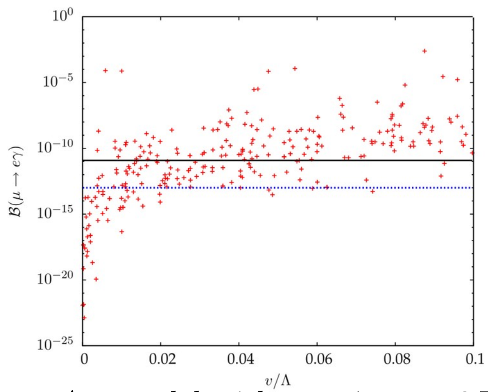


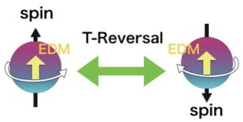
$\ell = \mu, \ell' = e$



A_4-model with $g_* = 4,\ m_* = 3\,\mathrm{TeV}$

del Aguila, Carmona, Santiago, 1001.5151

Electron EDM



$\ell = \ell' = e$

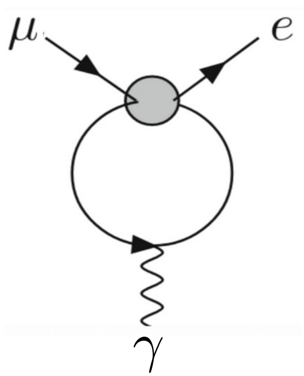
1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC
$\frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$	$\frac{m_*}{g_*} \gtrsim (0.1-1)\,\mathrm{TeV}$	
$\mathrm{Im}(c_e) \sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\mathrm{TeV}$		

Lepton Flavor Violation and Dipole Moments

$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu}\bar{\ell}_L \sigma^{\mu\nu}\ell'_R$$

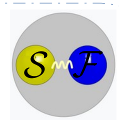
Dipole operator

$\mu \to e\gamma$



$\ell = \mu, \ell' = e$

$\mathcal{L} \sim -(f)^{i}{}_{a}\epsilon_{ij}\, \boxed{\mathcal{S}^j \epsilon_{\mathrm{TC}} \mathcal{F}^a}$

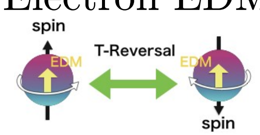


MFPC: Flavor structure induced by fundamental constituents

If $m_{\mathcal{S}}^2 \sim \mathbf{1}$ ($\leftarrow$ mass only via TC ints.)

$\rightarrow \boxed{C^{\gamma}_{\ell\ell'} \sim y^{\mathrm{SM}}_{\ell\ell'}}$ $\rightarrow$ diagonal, real

Electron EDM



$\ell = \ell' = e$

More stringent limits from $Z \to f\bar{f}$ ...

	1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC ($m_{\mathcal{S}}^2 \sim \mathbf{1}$)
$\mu \to e\gamma$	$\frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$	$\frac{m_*}{g_*} \gtrsim (0.1-1)\,\mathrm{TeV}$	$\frac{m_*}{g_*} \gtrsim 0.1\,\mathrm{TeV}$
Electron EDM	$\mathrm{Im}(c_e) \sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\mathrm{TeV}$		$\frac{m_*}{g_*} \gtrsim 0.1\,\mathrm{TeV}$

Lepton Flavor Violation and Dipole Moments

In general less stringent bounds from

$\boxed{\mu - e \text{ conversion } \& \ \mu \to eee}$

$$\frac{\Gamma(\mu Au \to e Au)}{\Gamma_{\text{capture}}(\mu Au)} < 7 \times 10^{-13} \Rightarrow \frac{m_*}{\sqrt{g_*}} \gtrsim 3\,\text{TeV} \ll$$

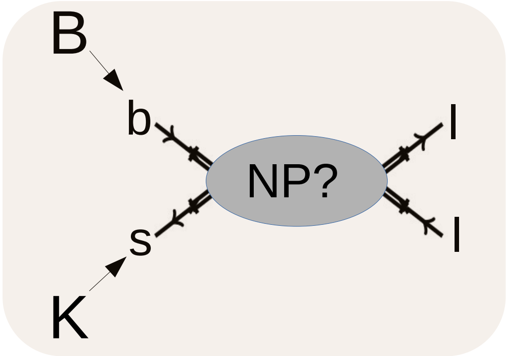
SINDRUMII

1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC ($m_S^2 \sim 1$)
$\frac{m_*}{g_*} \gtrsim 20\,\text{TeV}$	$\frac{m_*}{g_*} \gtrsim (0.1-1)\text{TeV}$	$\frac{m_*}{g_*} \gtrsim 0.1\,\text{TeV}$
$\text{Im}(c_e) \sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\text{TeV}$		$\frac{m_*}{g_*} \gtrsim 0.1\,\text{TeV}$

LFU Tests

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*e^+e^-)}$$



$$R_K^{[1,6]\,\mathrm{exp}} = 0.846\ {}^{+0.042}_{-0.039}\ {}^{+0.013}_{-0.012}$$

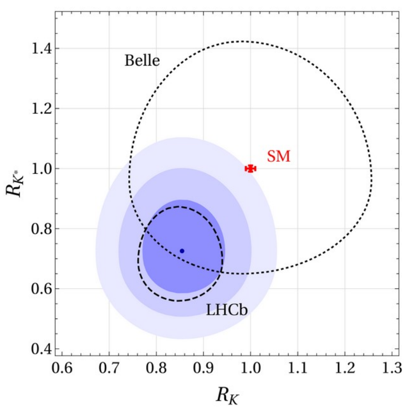
$$R_{K^*}^{[1.1,6]\mathrm{exp}} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

LHCb 2103.11769, 1705.05802

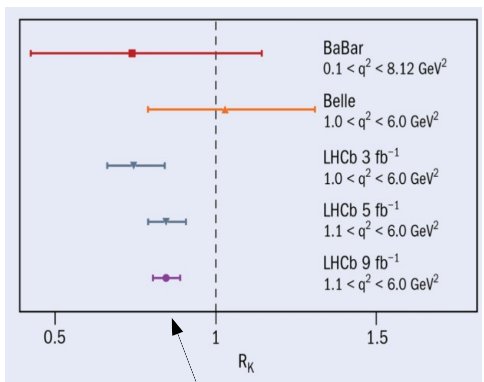
$\mathrm{SM:}\ R_K \approx R_{K^*} \approx 1$

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Altmannshofer, Stangl, 2103.13370



Altmannshofer, Dev, Soni, Sui, 2002.12910 .....



$3.1\,\sigma$

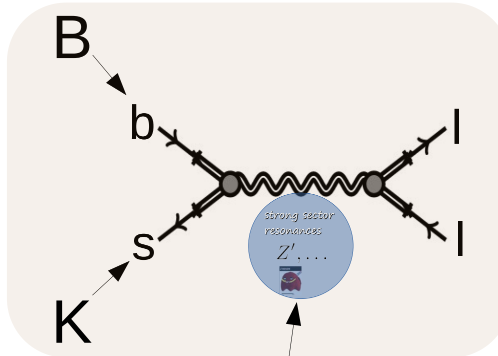
LHCb '21

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

LFU Violation

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*e^+e^-)}$$



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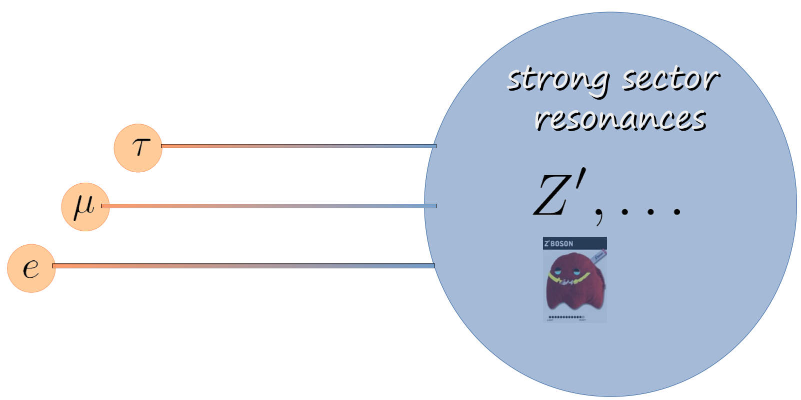
LHCb 2103.11769, 1705.05802

$R_K, R_{K^*} \neq 1$ generic prediction in CHM



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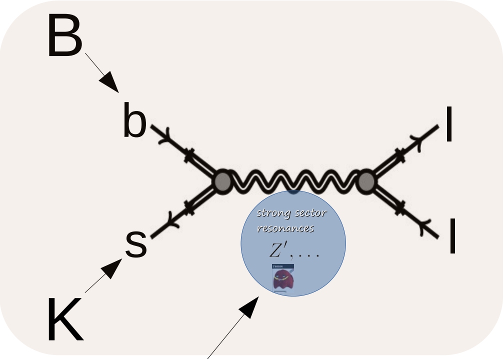

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LHCb 2103.11769, 1705.05802

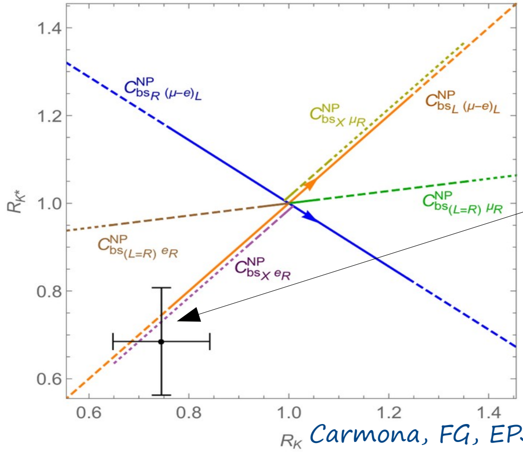
$$\mathcal{O}_{XY}^{q^1q^2\ell^1\ell^1} = (\bar{q}_X^1\gamma_\mu q_X^2)(\bar{\ell}_Y^1\gamma^\mu \ell_Y^2)$$

$$\boxed{C_{XY}^{q^1q^2\ell^1\ell^2} \sim \frac{g_*^2}{m_*^2}\epsilon_X^{q^1}\epsilon_X^{q^2}\epsilon_Y^{\ell^1}\epsilon_Y^{\ell^2}}$$

LH muons: $\frac{g_*^2}{m_*^2}\epsilon_L^s\epsilon_L^b\epsilon_L^\mu\epsilon_L^\mu \sim \frac{10^{-3}}{\mathrm{TeV}^2}$

RH electrons: $\frac{g_*^2}{m_*^2}\epsilon_X^s\epsilon_X^b\epsilon_R^e\epsilon_R^e \sim 4\cdot\frac{10^{-3}}{\mathrm{TeV}^2}$

$X = L, R$



Carmona, FG, EPJC (1712.02536)

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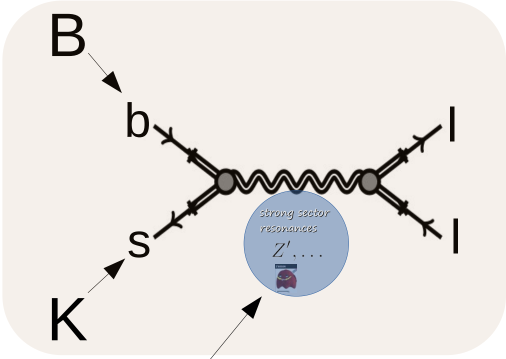

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LH muons: $\dfrac{g_*^2}{m_*^2}\epsilon_L^s\epsilon_L^b\epsilon_L^\mu\epsilon_L^\mu \sim \dfrac{10^{-3}}{\mathrm{TeV}^2}$

RH electrons: $\dfrac{g_*^2}{m_*^2}\epsilon_X^s\epsilon_X^b\epsilon_R^e\epsilon_R^e \sim 4\cdot\dfrac{10^{-3}}{\mathrm{TeV}^2}$

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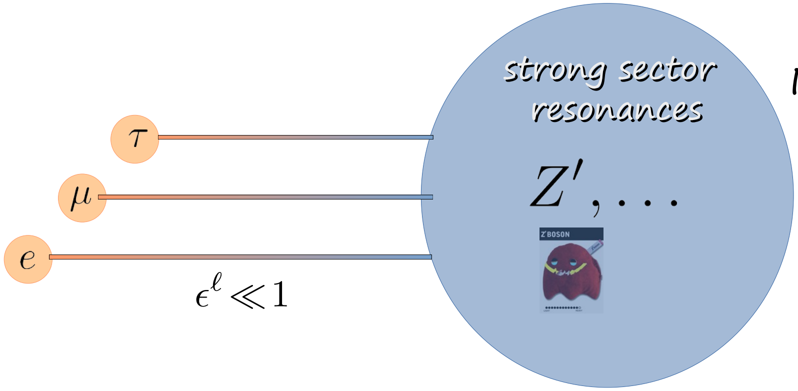

Rather small effects natural in anarchic setup

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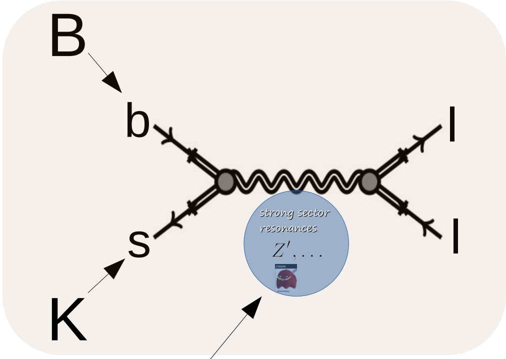

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LH muons: $\displaystyle \frac{g_*^2}{m_*^2}\epsilon_L^s\epsilon_L^b\epsilon_L^\mu\epsilon_L^\mu \sim \frac{10^{-3}}{\mathrm{TeV}^2}$

Fit anomalies

(and use other chirality to reproduce mass...)

Niehoff, Stangl, Straub, 1503.03865

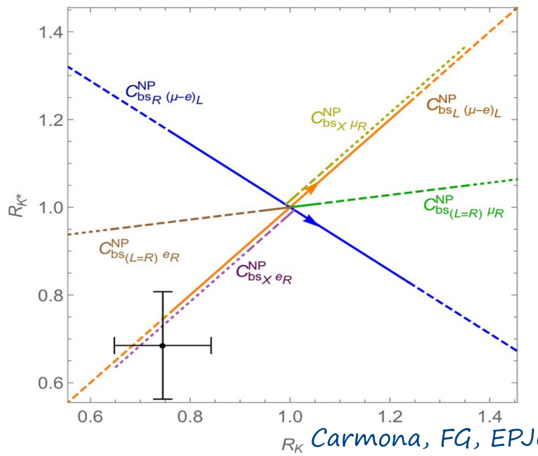
Megias, Panico, Pujolas, Quiros, 1608.02362

Megias, Quiros, Salas, 1703.06019

Megias, Quiros, Salas, 1707.08014

Sannino, Stangl, Straub, Thomsen (MFPC), 1712.07646

Frigerio, Nardecchia, Serra, Vecchi, 1807.04279



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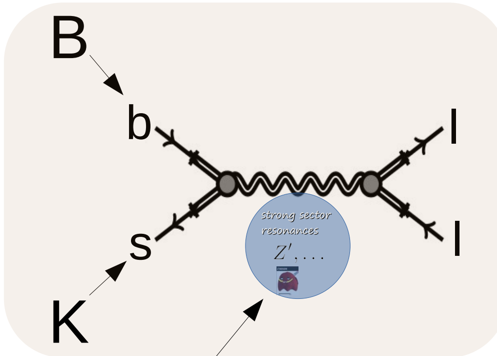

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LH muons: $\boxed{\frac{g_*^2}{m_*^2}\epsilon_L^s\epsilon_L^b\epsilon_L^\mu\epsilon_L^\mu \sim \frac{10^{-3}}{\mathrm{TeV}^2}}$

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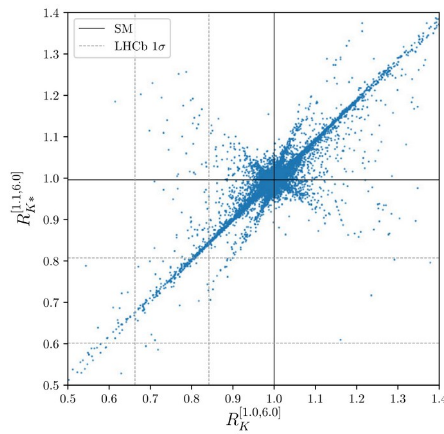
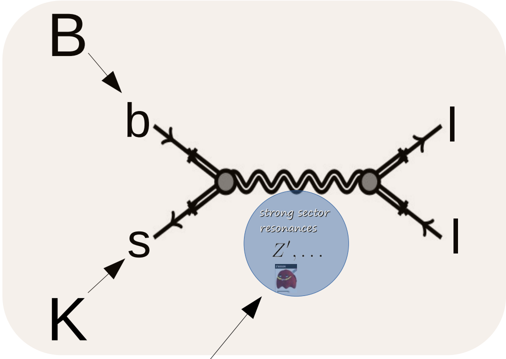
Niehoff, Stangl, Straub, 1503.03865
Megias, Panico, Pujolas, Quiros, 1608.02362
Megias, Quiros, Salas, 1703.06019
Megias, Quiros, Salas, 1707.08014
Sannino, Stangl, Straub, Thomsen (**MFPC**), 1712.07646
Frigerio, Nardecchia, Serra, Vecchi, 1807.04279



LFU Violation

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^*e^+e^-)}$$



$$R_K^{[1,6]\,\mathrm{exp}} = 0.846 \;{}^{+0.042}_{-0.039}\;{}^{+0.013}_{-0.012}$$

$$R_{K^*}^{[1.1,6]\mathrm{exp}} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

LHCb 2103.11769, 1705.05802

$$\mathcal{O}_{XY}^{q^1q^2\ell^1\ell^1} = (\bar{q}_X^1\gamma_\mu q_X^2)(\bar{\ell}_Y^1\gamma^\mu\ell_Y^2)$$

$$\boxed{C_{XY}^{q^1q^2\ell^1\ell^2} \sim \frac{g_*^2}{m_*^2}\epsilon_X^{q^1}\epsilon_X^{q^2}\epsilon_Y^{\ell^1}\epsilon_Y^{\ell^2}}$$

LH muons: $\frac{g_*^2}{m_*^2}\epsilon_L^s\epsilon_L^b\epsilon_L^\mu\epsilon_L^\mu \sim \frac{10^{-3}}{\mathrm{TeV}^2}$

Fit anomalies
(and use other chirality to reproduce mass...)

Niehoff, Stangl, Straub, 1503.03865
Megias, Panico, Pujolas, Quiros, 1608.02362
Megias, Quiros, Salas, 1703.06019
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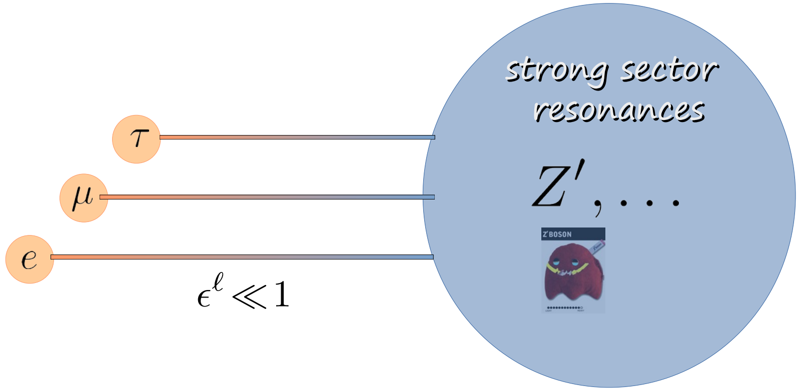

Rather small effects natural in anarchic setup

Origin of lepton compositeness?

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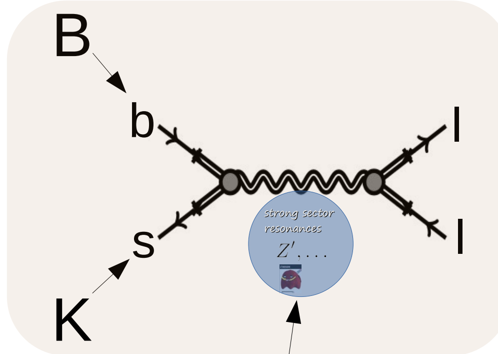

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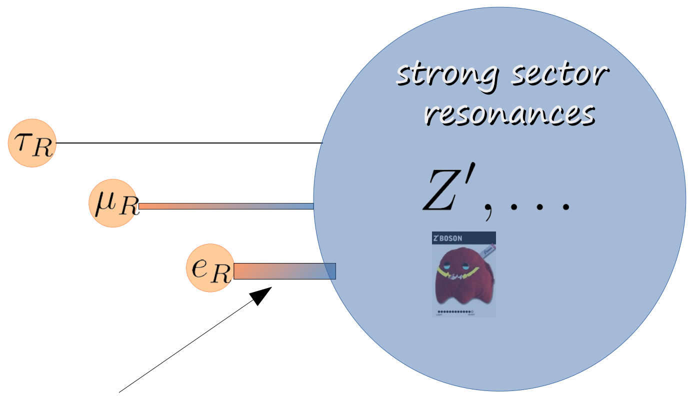
LHCb 2103.11769, 1705.05802

$R_K, R_{K^*} \neq 1$ generic prediction in CHM



RH electr.: $\frac{g_*^2}{m_*^2} \epsilon_X^s \epsilon_X^b \epsilon_R^e \epsilon_R^e \sim 4 \cdot \frac{10^{-3}}{\mathrm{TeV}^2}$

$X = L, R$

Large effects predicted in min. seesaw model!

Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)

LFU Violation

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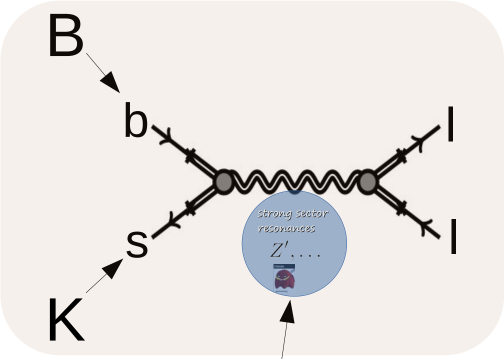

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LHCb 2103.11769, 1705.05802

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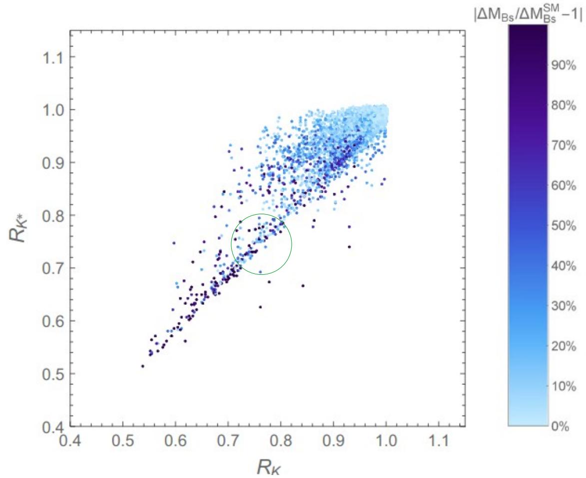

correct direction

$R_K, R_{K^*} > 1$ would have excluded model

Carmona, FG, EPJC (1712.02536)
Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)

LFU Violation II

$$R_D \equiv \frac{\mathcal{B}(\bar{B} \to D\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D\ell\bar{\nu})}$$

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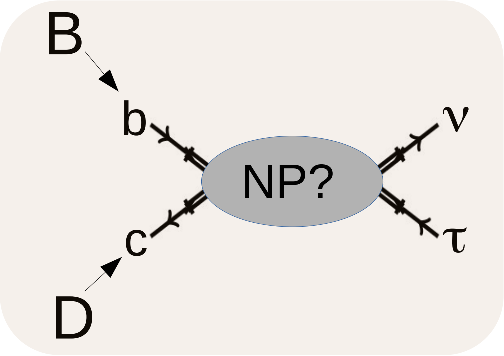


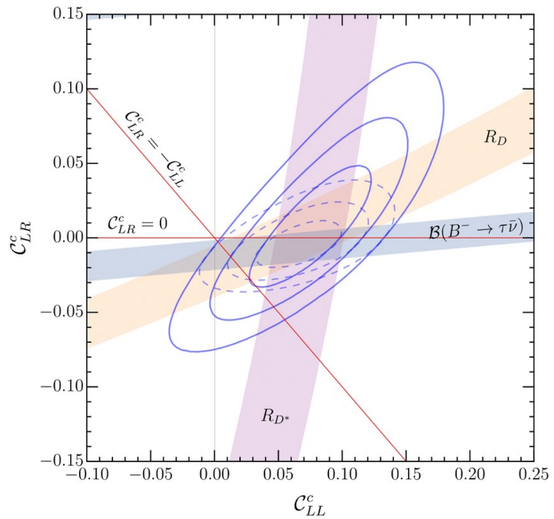
$$R_D^{\rm exp} = 0.340 \pm 0.030$$

$$R_{D^*}^{\rm exp} = 0.295 \pm 0.014$$

1909.12524 and hflav.web.cern.ch

$$R_D^{\rm SM} = 0.293 \pm 0.008$$

$$R_{D^*}^{\rm SM} = 0.257 \pm 0.003$$



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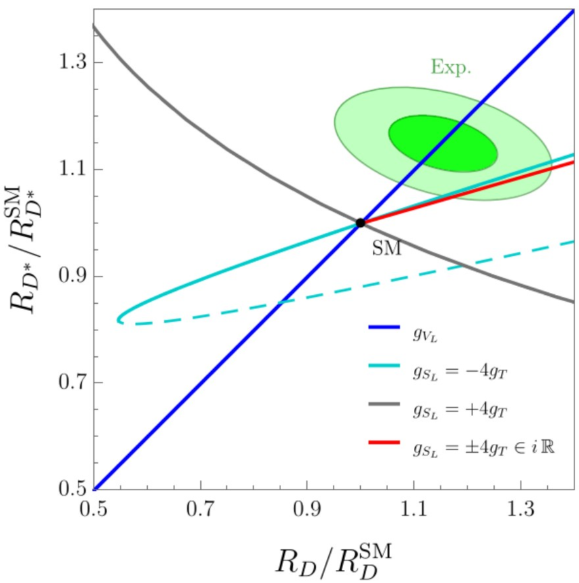
Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert, 2103.16558

Natural CH explanation very challenging

- Megias, Quiros, Salas, 1703.06019
- Megias, Quiros, Salas, 1707.08014
- Sannino, Stangl, Straub, Thomsen, 1712.07646
- Carena, Megias, Quiros, Wagner, 1809.01107



Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

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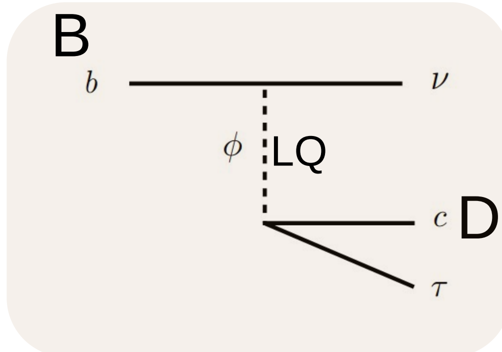

Bauer, Neubert, 1511.01900

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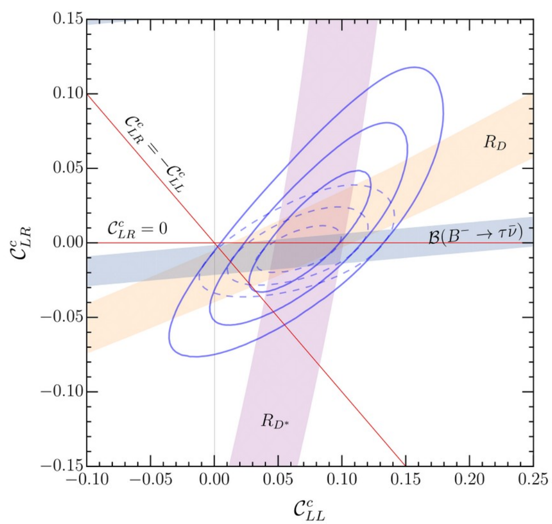
Sannino, Stangl, Straub, Thomsen, 1712.07646

Carena, Megias, Quiros, Wagner, 1809.01107

Attractive Candidates: Leptoquarks

...



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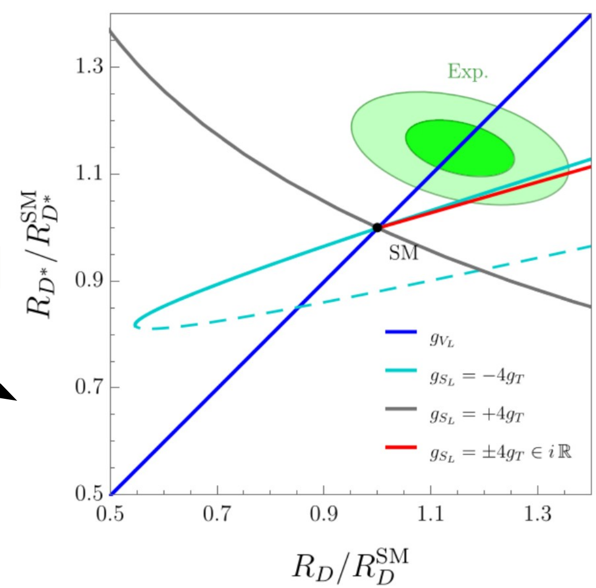
Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert, 2103.16558



Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

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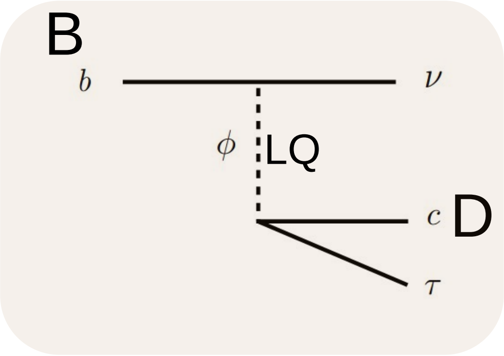

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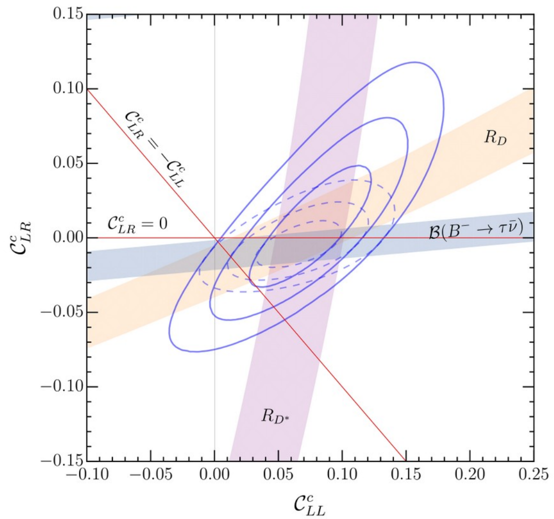

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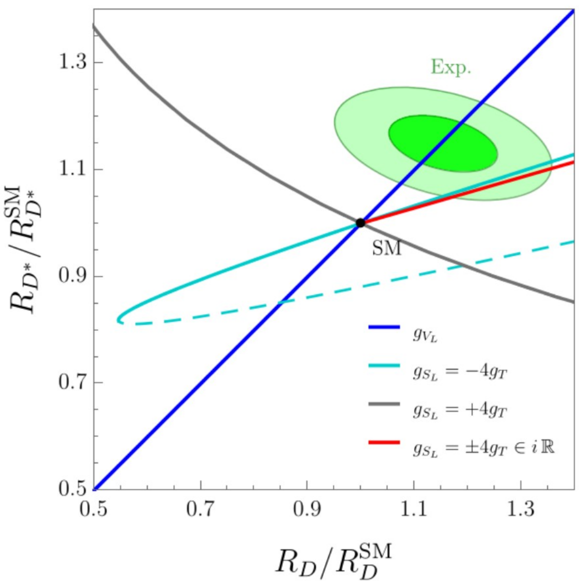
Sannino, Stangl, Straub, Thomsen, 1712.07646
Carena, Megıas, Quiros, Wagner, 1809.01107

Composite Leptoquarks

Barbieri, Murphy, Senia, 1611.04930
Blanke, Crivellin, 1801.07256
Fuentes-Martin, Stangl, 2004.11376
(see also Gripaios, Nardecchia, Renner, 1412.1791)



Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

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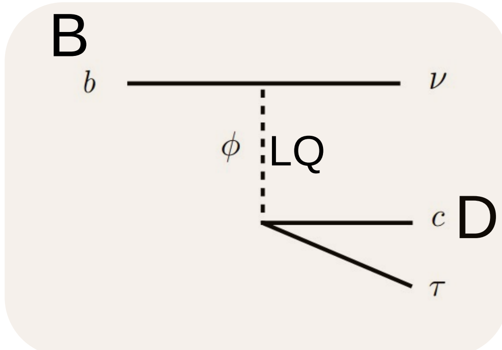

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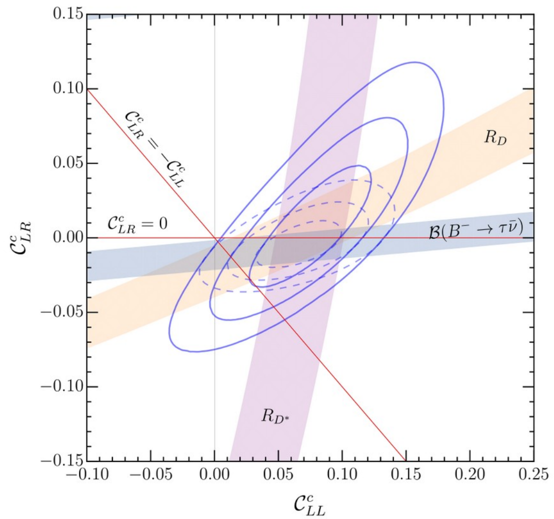

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Megias, Quiros, Salas, 1707.08014

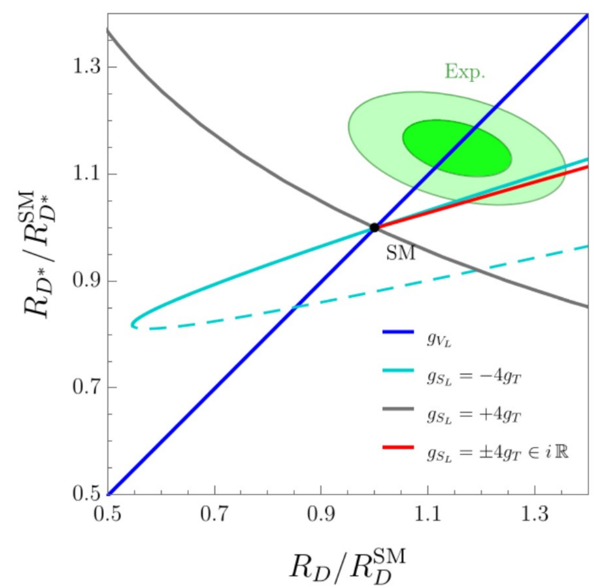
Sannino, Stangl, Straub, Thomsen, 1712.07646

Carena, Megias, Quiros, Wagner, 1809.01107

Composite Leptoquarks

Potential Origin in Composite Higgs GUT
('Gauge-Higgs-Grand-Unification')

Angelescu, Bally, Blasi, FG, 2104.07366



Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

Composite $SU(6)/SU(5)$ GUT

Angelescu, Bally, Blasi, FG, 2104.07366

$SU(5)$

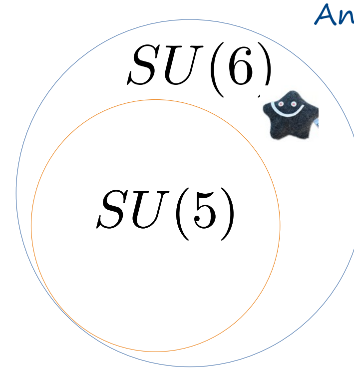
gauged symmetry

strong sector

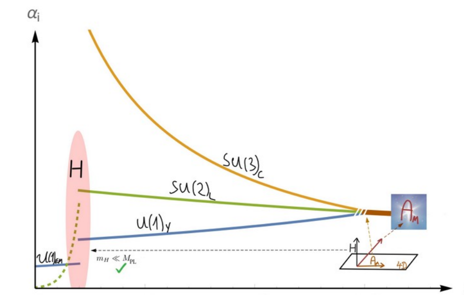
$SU(6) \to G_{\rm SM}$

$\langle \bar{\mathcal{F}}\mathcal{F} \rangle \neq 0$

SSB by condensation



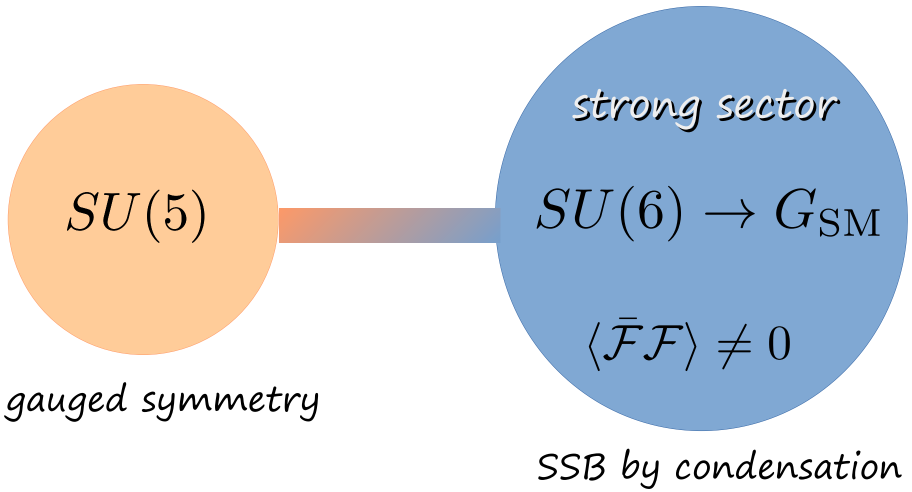
Unifies Higgs & Gauge Ints.!!

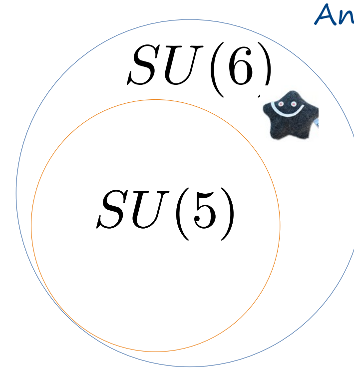


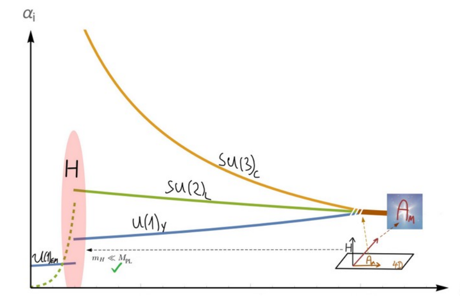
$$(23 - 12) = 11 \text{ GBs} \to \text{Higgs} \boxed{+ \text{ singlet } + (\mathbf{3},\mathbf{1})_{-1/3}\,\text{LQ}}$$

Composite $SU(6)/SU(5)$ GUT

Angelescu, Bally, Blasi, FG, 2104.07366







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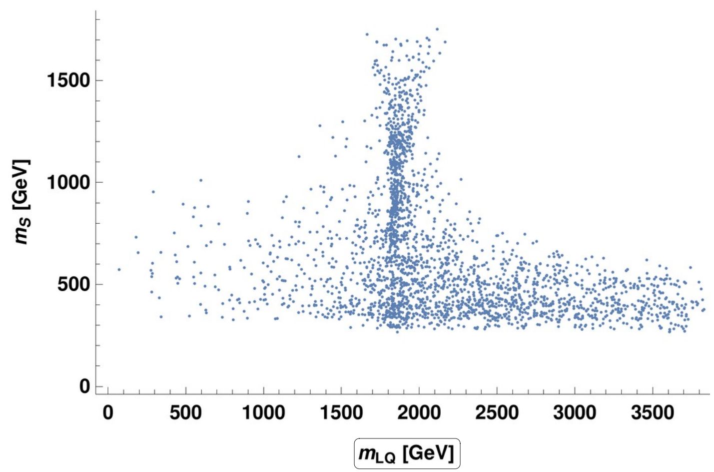
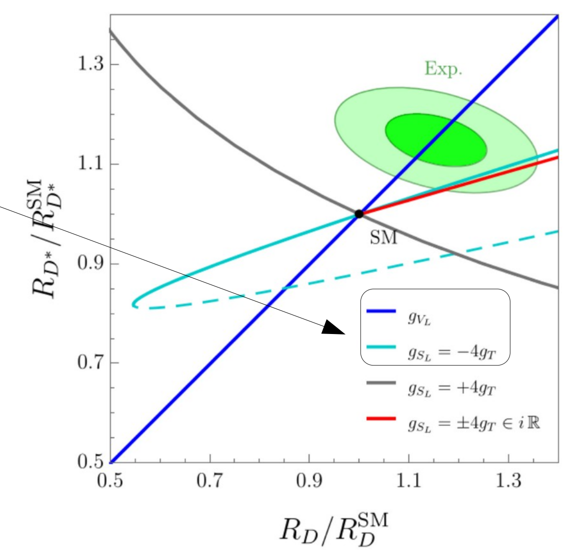
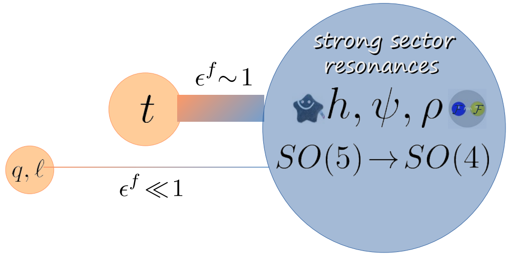


$(\mathbf{3},\mathbf{1})_{-1/3}\,\mathrm{LQ}$

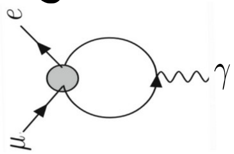


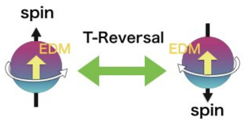
Conclusions

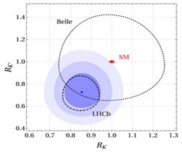
- Lepton Flavor Physics provides powerful probe of Composite Higgs and Partial Compositeness paradigm

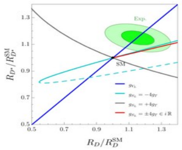


- Constraints/Signatures can be used to test different variants

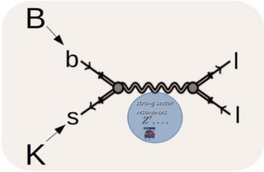








- Minimal model of leptons naturally addresses R_K and R_{K^*} anomalies



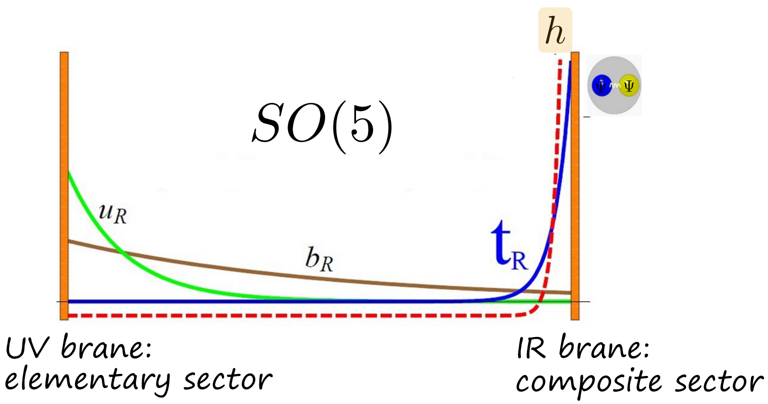
- Flavor as a first window on the Composite Higgs

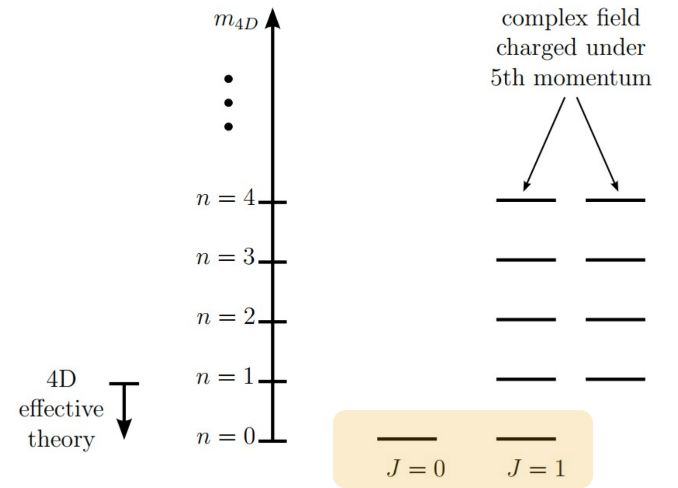
Backup

Holographic pNGB Higgs

Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

- Higgs = 5^{th} comp. of gauge field → pNGB
  → Gauge-Higgs Unification Manton, Hosotani, Fairlie, Hatanaka, Inami, Lim...

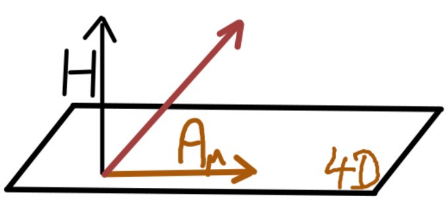




5D vector field $A_M^A = (A_\mu^A, \boxed{A_5^A})$

SO(5)

4D vector 4D scalar → Higgs



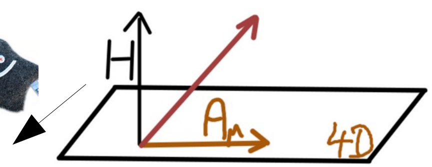
Massless pNGB: 4D shift sym. ↔ 5D gauge sym.

One Step Further:

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!

Gauge-Higgs Unification

$$SO(5): \; A_M^A = (A_\mu^A, \boxed{A_5^A})$$



$$U(1)_X: \; X_M = (X_\mu, X_5)$$

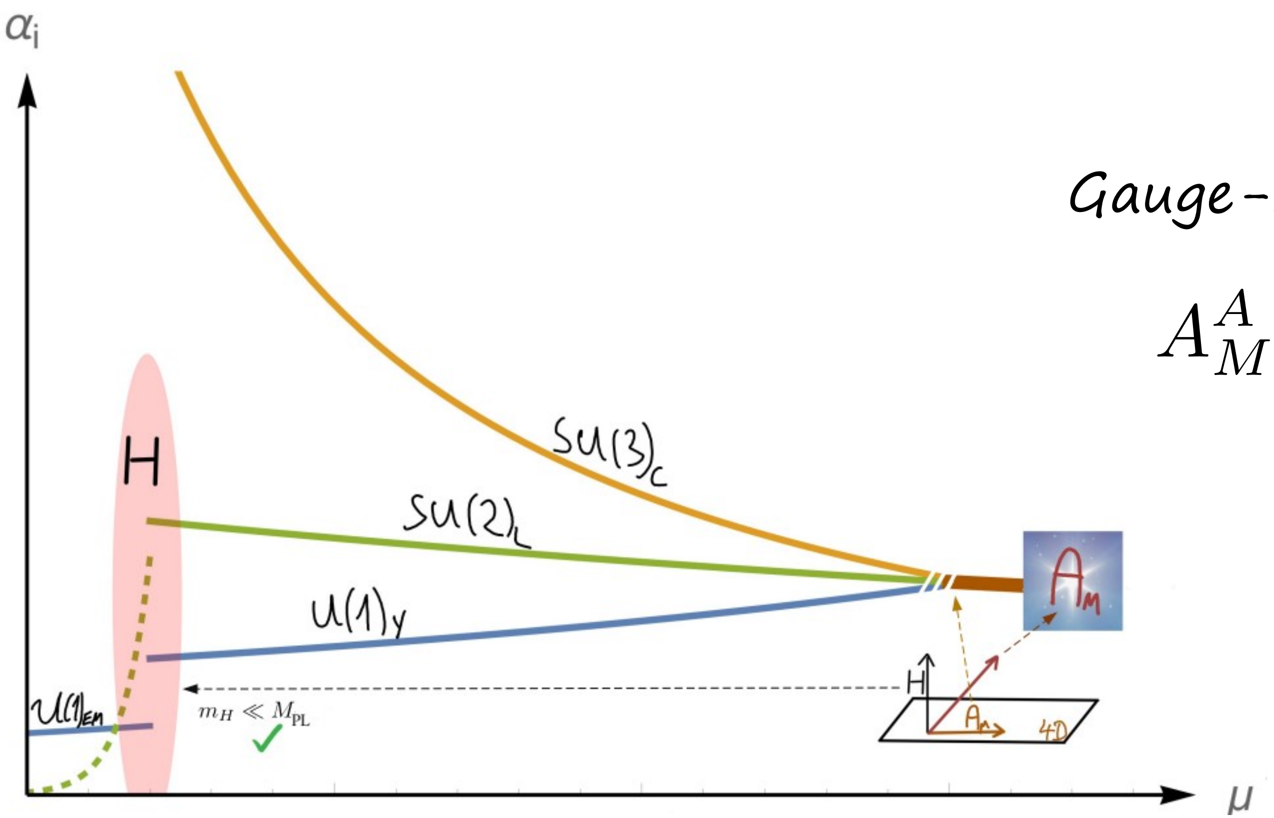
$$SU(3)_c: \; G_M^A = (G_\mu^A, G_5^A)$$

Gauge-Higgs Grand Unification

$$A_M^A = (A_\mu^A, \boxed{A_5^A}) \quad G_{\mathrm{GUT}}$$

Gauge-Higgs Grand Unification

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!



Gauge-Higgs ~~Grand~~ Unification

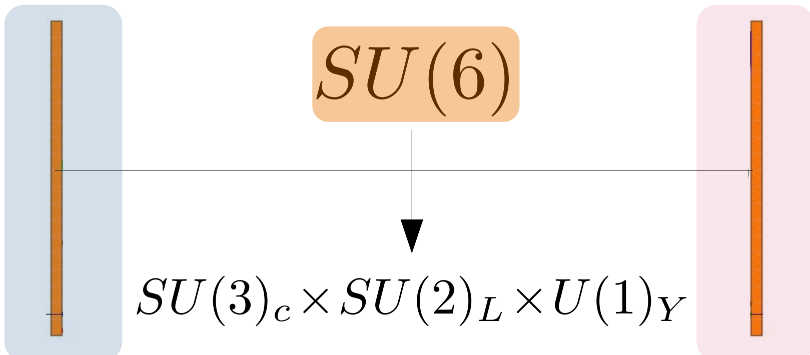
$$A_M^A = (\boxed{A_\mu^A}, \boxed{A_5^A}) \quad G_{\mathrm{GUT}}$$

Novel Breaking Pattern

Angelescu, Bally, Blasi, FG, 2104.07366

and warped...

$SU(5)$ $\qquad$ $SU(2)_L \times SU(3)_c \times U(1)_Y = G_{\rm SM}$



UV brane:
elementary sector

IR brane:
composite sector

$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (+-) & (+-) & (+-) & (--) \\ (++) & (++) & (+-) & (+-) & (+-) & (--) \\ \hline (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ \hline (--) & (--) & (--) & (--) & (--) & (--) \end{array}\right)$$

$A_5 : + \leftrightarrow -$

$$(23 - 12) = 11 \text{ GBs} \to \text{Higgs} \boxed{+ \text{ singlet } + (\mathbf{3},\mathbf{1})_{-1/3} \text{ LQ}}$$

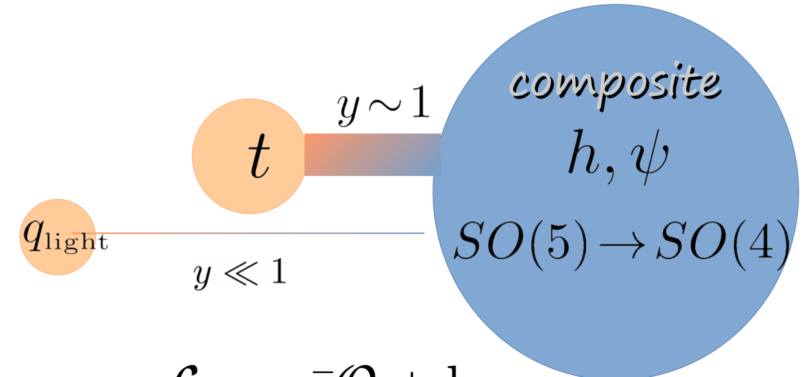
- Scalars want to be heavy ... :)
- Could use them ...

RS - Partial Compositeness

- Addresses the flavor puzzle:

$$y^q_{L,R} \sim (\Lambda/\Lambda_{UV})^{\gamma_{L,R}}\,, \qquad \gamma_{L,R} = [\mathcal{O}_{L,R}] - 5/2$$

→ Hierarchies generated naturally



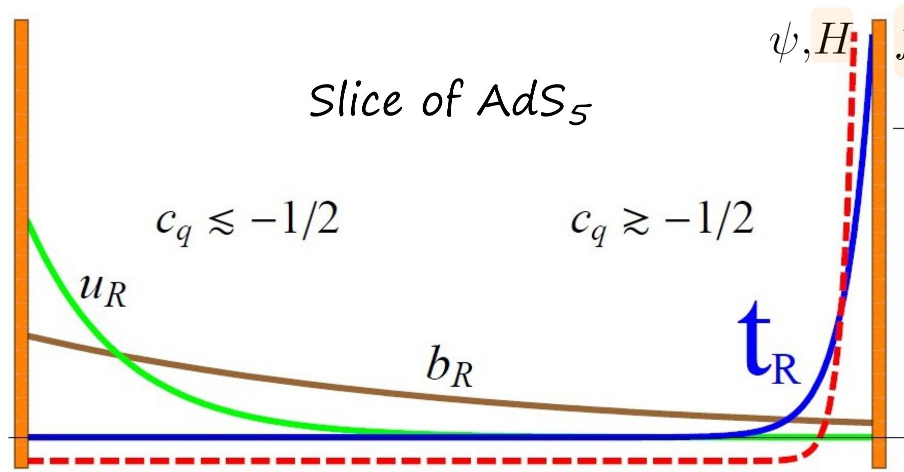
$$\mathcal{L} = y\bar{q}\mathcal{O} + \text{h.c.}$$

$$\gamma_R = |c_R - 1/2| - 1$$

Overlap with Higgs → mass

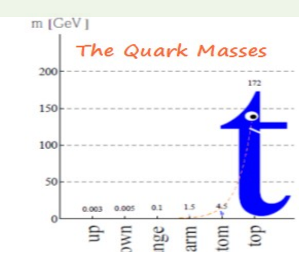
$$f_0^R(\pi) \sim (1 - \epsilon^{1+2c})^{-1/2}$$

Dual picture:
Extra Dimension



UV brane:
elementary
sector

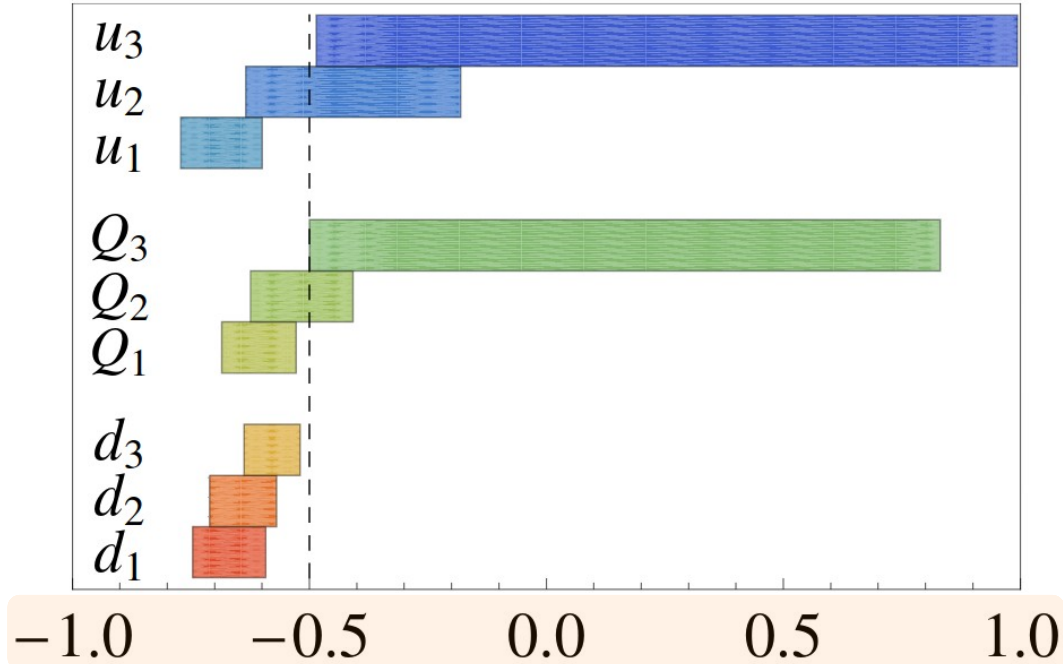
→ Froggatt-Nielsen-like mass matrices



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

Anomalous Dimensions γ ↔ XD Localization c ↔ FN U(1) charge

Solution to Flavor Puzzle



Goertz, 1112.6387

$c_{u_i,Q_i,d_i} \sim \mathcal{O}(1)$

- Profiles $f_0^R(\phi) \propto e^{ckr|\phi|}$
  (RH)

$c \equiv -m/k$

$$f_0^R(\pi) \propto \sqrt{\frac{1+2c}{1-\epsilon^{1+2c}}}$$

$$\epsilon \equiv e^{-kr\pi} \approx 10^{-16}$$