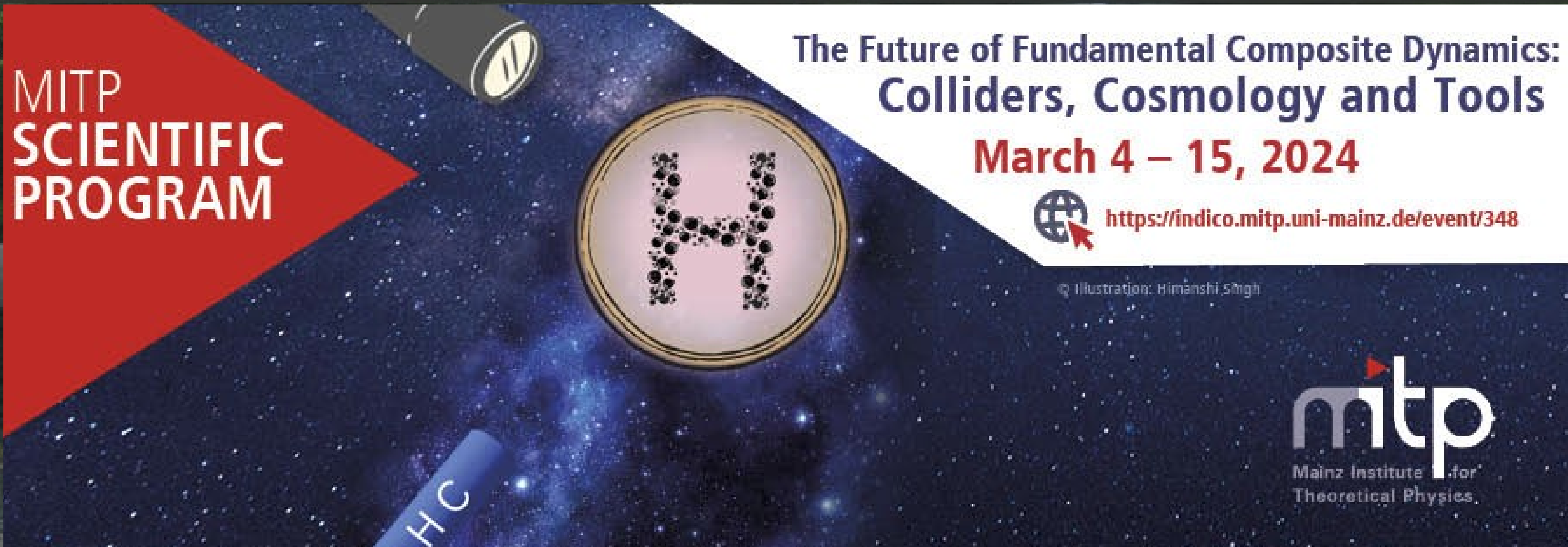


Flavor hierarchies in models with partial compositeness

Florian Goertz

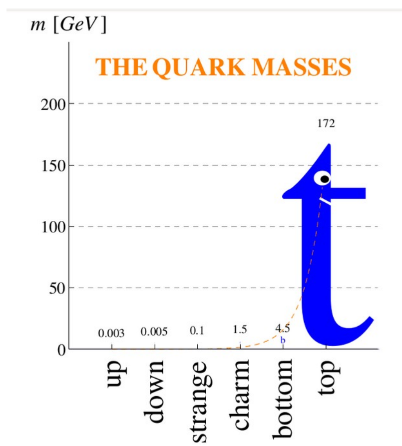
08.03.2024

NEWFO

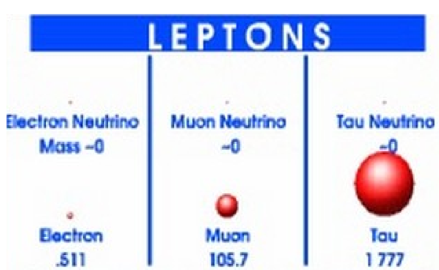
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Flavor Puzzle as Motivation for NP

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



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

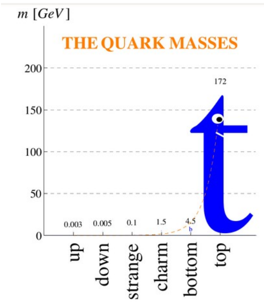


NuFIT 3.0 (2016)

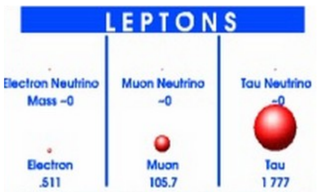
$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Flavor Puzzle as Motivation for NP

- Large hierarchies in fermion masses and in CKM matrix



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



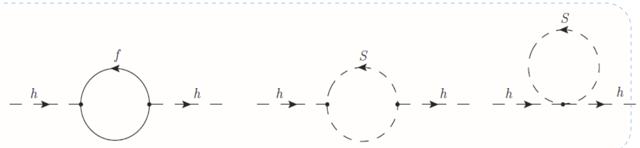
NuFIT 3.0 (2016)

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

Hierarchy Problem & Flavor Puzzle as Motivation for NP

- Instability of Higgs mass

$$\Delta m_H^2 \sim \Lambda^2$$



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

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

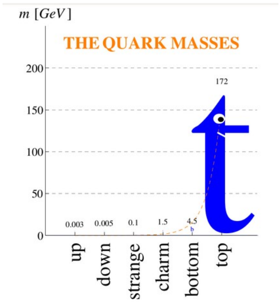
?

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

$\Leftrightarrow g_{\mathrm{grav}} \ll g_{\mathrm{weak}}$

www.sport.de

- Large hierarchies in fermion masses and in CKM matrix



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

NuFIT 3.0 (2016)

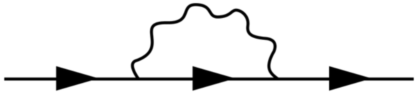
$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Care about Naturalness? Historic Examples

- Puzzleing hierarchies/naturalness often understood via new physics
  → progress (calculability) & discoveries

rest energy $\boxed{m_e} = (m_e)_0 \quad + \quad \Delta E_{\text{Coulomb}}$ $\qquad \Delta E_{\text{Coulomb}} = \frac{1}{4\pi}\frac{e^2}{r_e}\,, \quad r_e \lesssim 10^{-17}\,\text{cm}$

$\boxed{0.511\,\text{MeV}} = -9999.498\,\text{MeV} + 10000.000\,\text{MeV}$



Murayama, hep-ph/0002232

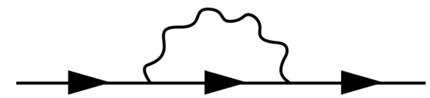
Care about Naturalness? Historic Examples

- Puzzleing hierarchies/naturalness often understood via new physics
  → progress (calculability) & discoveries

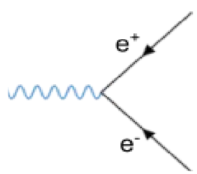
rest energy $\boxed{m_e} = (m_e)_0 \quad + \quad \Delta E_{\text{Coulomb}}$ $\qquad \Delta E_{\text{Coulomb}} = \frac{1}{4\pi}\frac{e^2}{r_e}\,, \qquad r_e \lesssim 10^{-17}\,\text{cm}$

$\boxed{0.511\,\text{MeV}} = -9999.498\,\text{MeV} + 10000.000\,\text{MeV}$

Murayama, hep-ph/0002232



cutoff: positron



$r_\Lambda \gtrsim \frac{1}{2m_e} \sim 10^{-11}\,\text{cm}$

chiral sym.

$\boxed{m_e} = (m_e)_0 + \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = (m_e)_0 \left[1 + \frac{3\alpha}{4\pi}\log\frac{1}{(m_e)_0\, r}\right]$ ✓

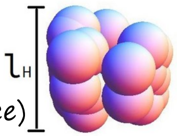
Weisskopf, Phys. Rev. 56, 72 (1939)

- More examples: pion mass splitting, K_L-K_S mass difference, ...

Composite Higgs Models

Kaplan, Georgi, Dimopoulos, ...

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

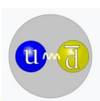


➡ Hierarchy Problem solved

- Higgs = (pseudo) Nambu-Goldstone Boson

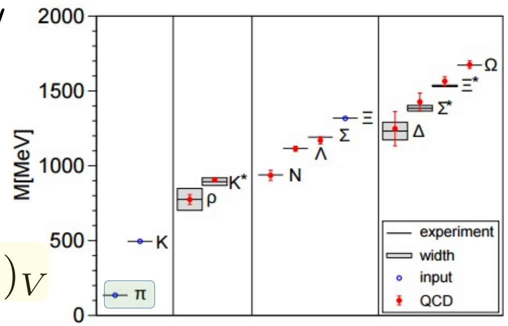
of spon. broken global symmetry

➡ $m_H \ll m_\rho$



like pions

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



0906.3599

- MCHM: $SO(5) \to SO(4)$ $\supset SU(2)_L \times U(1)_Y$

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

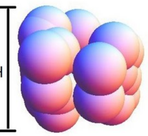
minimal: 4 Higgs dof (SO(5)/SO(4)), custodial sym.

Composite Higgs Models

Kaplan, Georgi, Dimopoulos, ...

- Higgs is composite at small distances l_H

(new strong force)

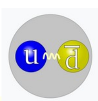


➡ Hierarchy Problem solved

- Higgs = (pseudo) Nambu–Goldstone Boson

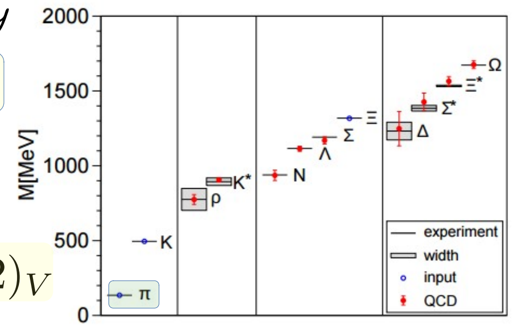
of spon. broken global symmetry

➡ $m_H \ll m_\rho$



like pions

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



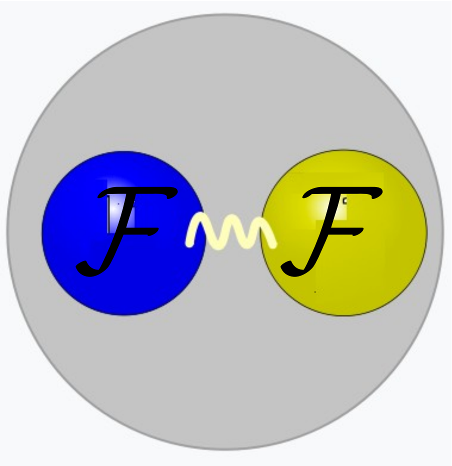
0906.3599

- MCHM: $\boxed{SO(5) \to SO(4)}$ $\supset SU(2)_L \times U(1)_Y$

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

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

→ holographic construction / EFT



...

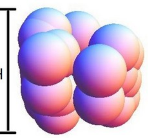
Minimal UV completions??

$$\rightarrow \boxed{SU(4)/Sp(4) \cong SO(6)/SO(5)}$$

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
Cacciapaglia, Deandrea, Sridhar, et al, EPJ ST 231, 1221
...

Composite Higgs Models

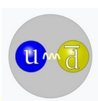
- Higgs is composite at small distances l_H (new strong force)



➡ Hierarchy Problem solved

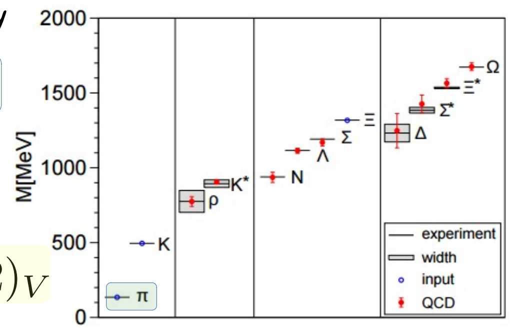
- Higgs = (pseudo) Nambu-Goldstone Boson
  of spon. broken global symmetry

➡ $m_H \ll m_\rho$



like pions

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

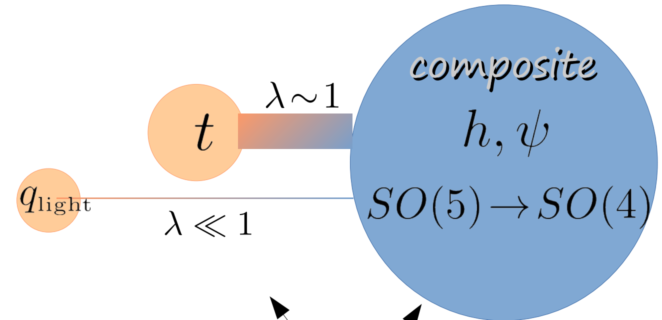


0906.3599

- 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.

\+ Addresses the flavor puzzle:



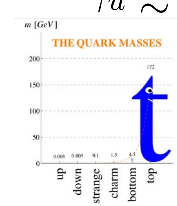
$$\mathcal{L} = \lambda \, \bar{q} \, \mathcal{O} + \text{h.c.}$$

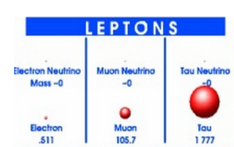
$$\lambda_f \sim (\Lambda/\Lambda_{UV})^{\gamma_f}$$

$$\gamma_f = [\mathcal{O}_f] - 5/2$$

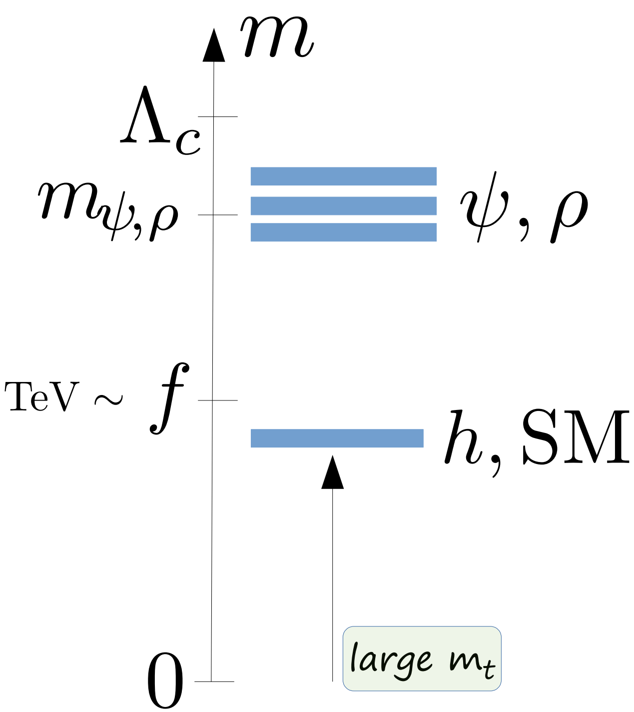
→ Hierarchies naturally from small differences in anomalous dimensions

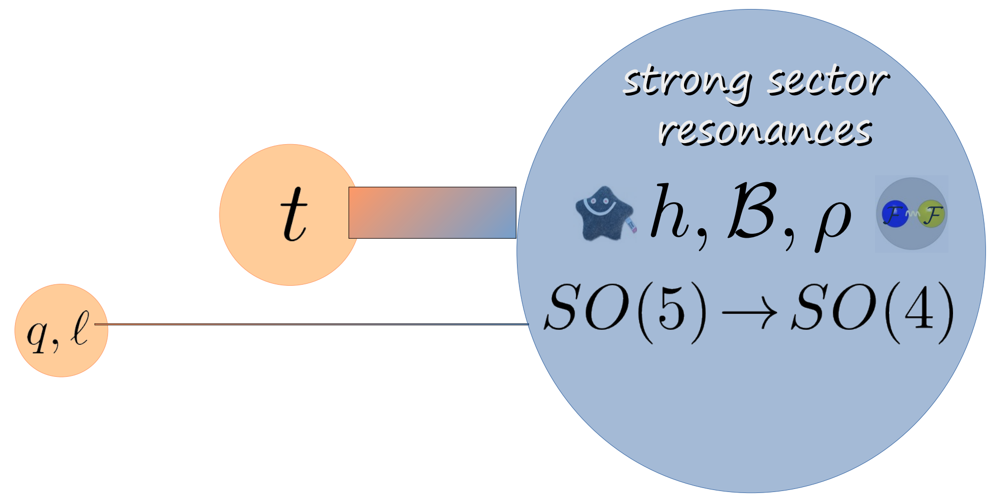
$$\gamma_u \gtrsim \gamma_c \gtrsim \gamma_t \ldots$$





Partially Composite Fermions





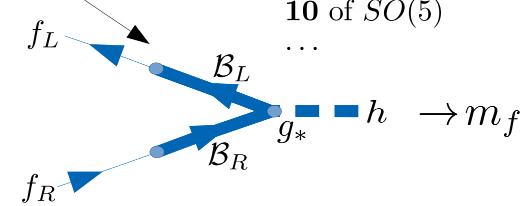
$$\mathcal{L}_{\rm mix} \supset \boxed{\lambda_q[\Lambda_c]}\, \overline{q}_L \mathcal{O}^q_{\mathcal{B}} + \boxed{\lambda_t[\Lambda_c]}\, \overline{t}_R \mathcal{O}^t_{\mathcal{B}}$$

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

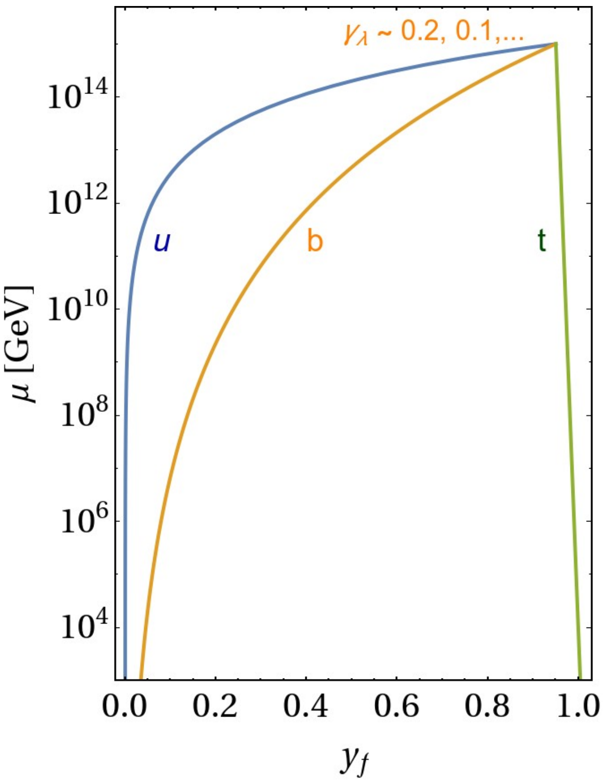
$\mathcal{O}(1)$ (UV)

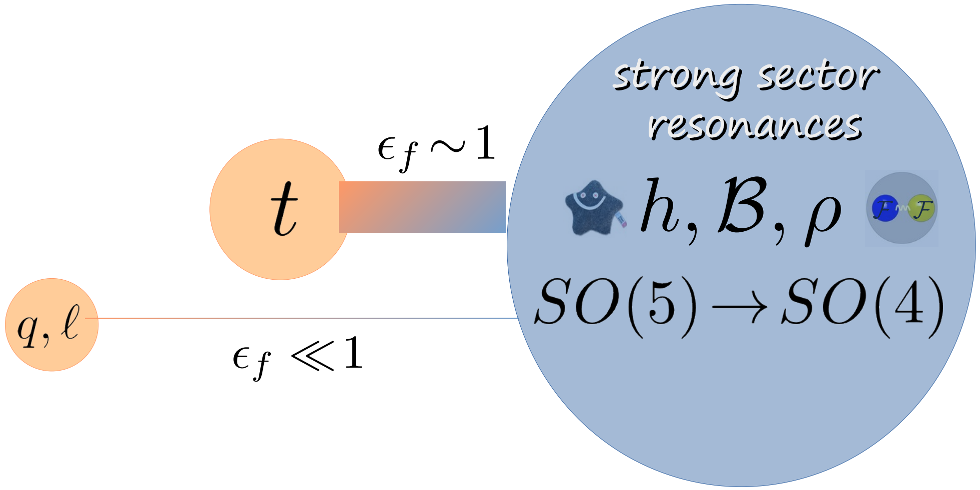
$$\lambda_q[\Lambda_c] \approx \lambda_q \left(\frac{\Lambda_c}{\Lambda_{\rm UV}}\right)^{\gamma_{\lambda_q}}$$

$\ll 1$



Partially Composite Fermions





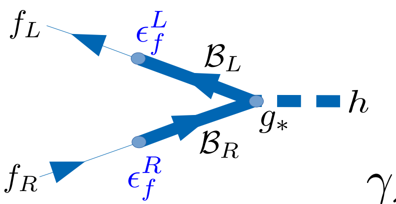
$$\mathcal{L}_{\text{mix}} \supset \lambda_q[\Lambda_c]\,\bar{q}_L \mathcal{O}^q_{\mathcal{B}} + \lambda_t[\Lambda_c]\,\bar{t}_R \mathcal{O}^t_{\mathcal{B}}$$

$\mathcal{O}(1)$ $\quad\to \Lambda_c \sim \text{TeV}$

$$\boxed{y_f \sim g_* \epsilon^L_f \epsilon^R_f}$$

'compositeness' $\boxed{\epsilon^L_q \equiv \frac{\lambda_q[\mu]}{g_*} = \frac{\lambda_q}{g_*}\left(\frac{\mu}{\Lambda_{\text{UV}}}\right)^{\gamma_{\lambda_q}}}$

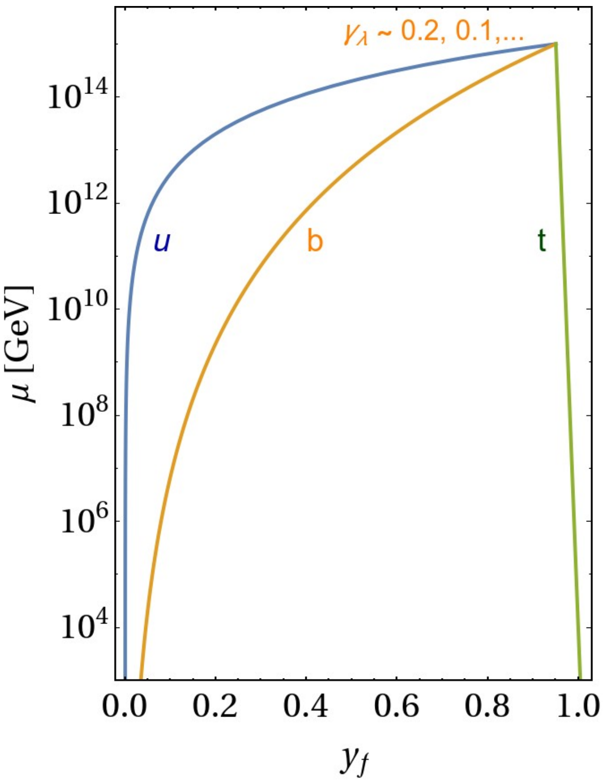
coupling of resonances

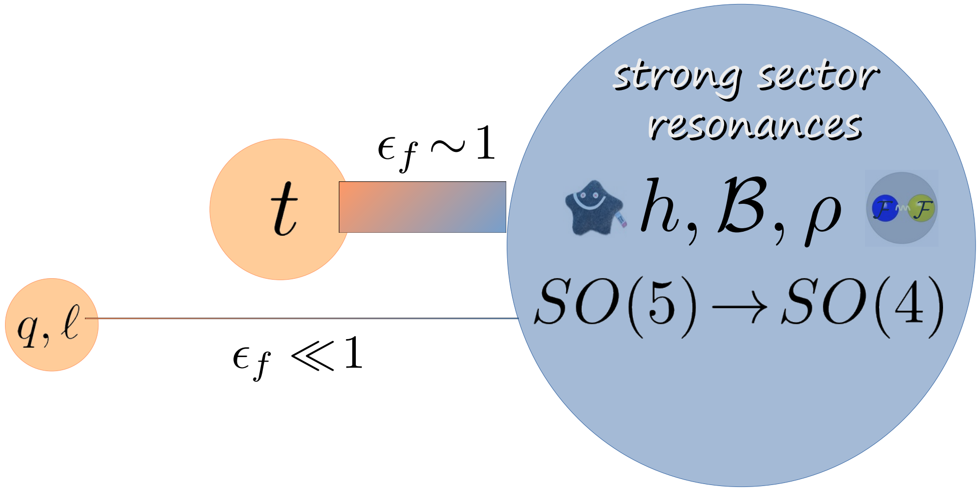


$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

$$m_f = \frac{v}{\sqrt{2}} y_f$$

Partially Composite Fermions





$$\mathcal{L}_{\rm mix} \supset \lambda_q[\Lambda_c]\, \bar{q}_L \mathcal{O}^q_{\mathcal{B}} + \lambda_t[\Lambda_c]\, \bar{t}_R \mathcal{O}^t_{\mathcal{B}}$$

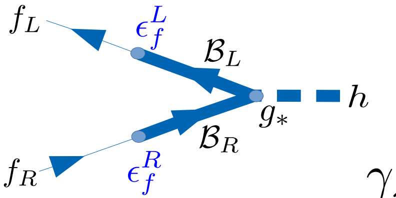
$$\boxed{y_f \sim g_* \epsilon^L_f \epsilon^R_f}$$

'compos

'anarchic approach'

$\mathcal{O}(1)$ $\quad \to \Lambda_c$

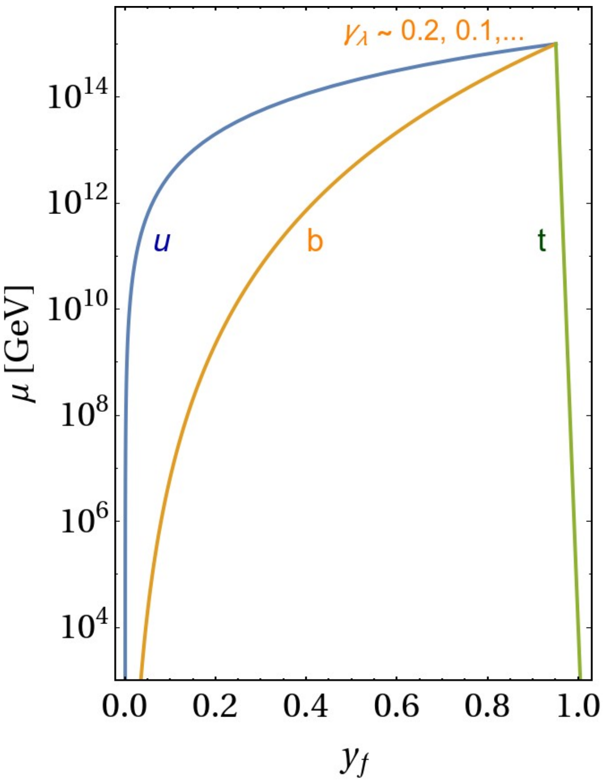
$$\frac{{}_q[\mu]}{g_*} = \frac{\lambda_q}{g_*}\left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\gamma_{\lambda_q}}$$

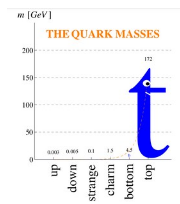


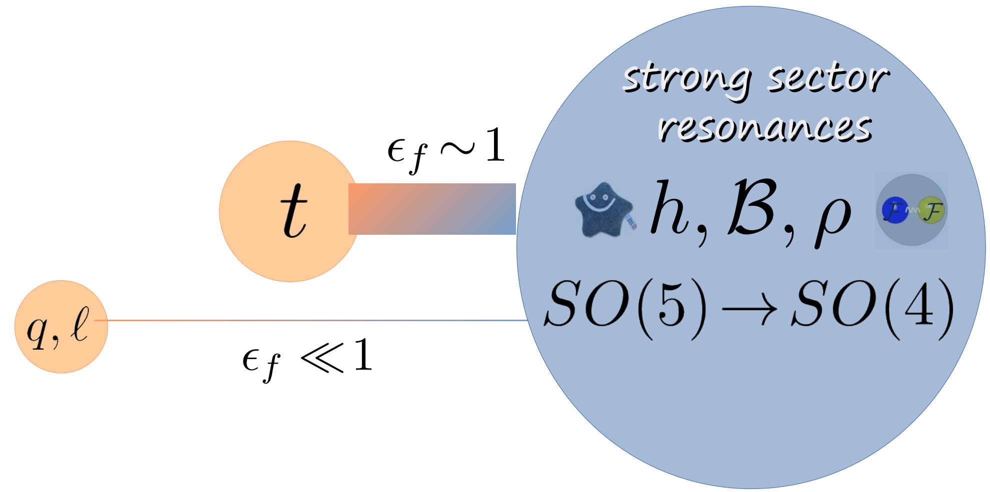
$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

$$m_f = \frac{v}{\sqrt{2}} y_f$$

Partially Composite Fermions



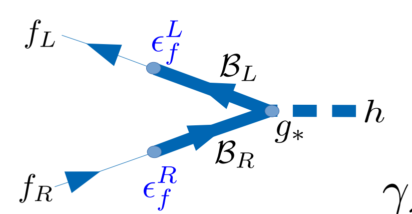




$$\mathcal{L}_{\text{mix}} \supset \lambda_q[\Lambda_c]\,\bar{q}_L \mathcal{O}_{\mathcal{B}}^q + \lambda_t[\Lambda_c]\,\bar{t}_R \mathcal{O}_{\mathcal{B}}^t$$

$$\boxed{y_f \sim g_* \epsilon_f^L \epsilon_f^R}$$

'compositeness' $\boxed{\epsilon_q^L \equiv \frac{\lambda_q[\mu]}{g_*} = \frac{\overbrace{\lambda_q}^{\mathcal{O}(1)}}{g_*}\left(\frac{\mu}{\Lambda_{\text{UV}}}\right)^{\gamma_{\lambda_q}}}$, $\mu \to \Lambda_c$

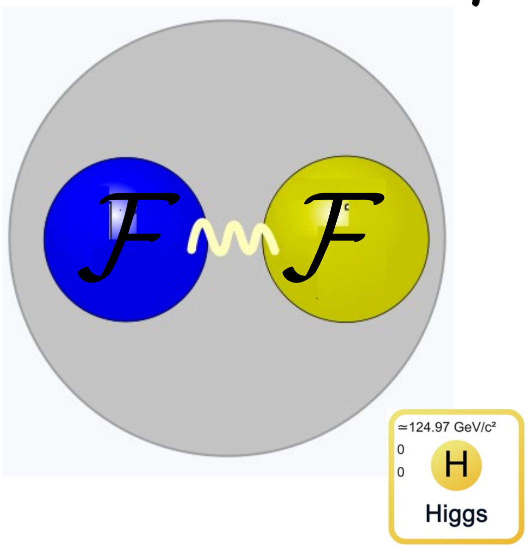


$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

$$m_f = \frac{v}{\sqrt{2}} y_f$$

Composite Higgs: What's Inside?

- 4D UV Completion



$\langle \mathcal{F}^a \epsilon_{\mathrm{TC}} \mathcal{F}^b \rangle = \Lambda_c f^2 \Sigma_\theta^{ab} \xrightarrow{\text{minimal}} SO(6) \to SO(5)$

→ 5 Goldstones: Higgs + EW Singlet

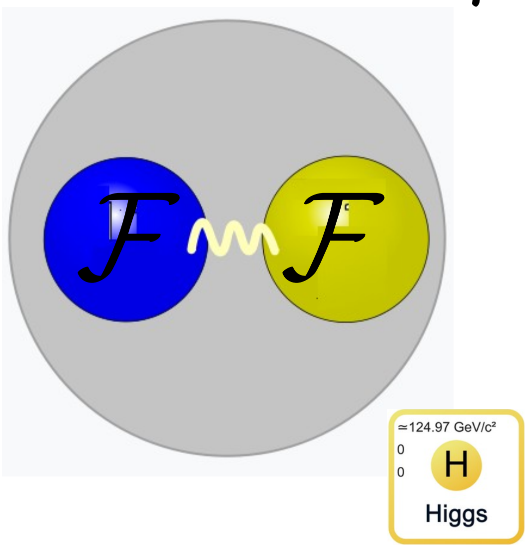
$G_{\mathrm{TC}} = Sp(N)_{\mathrm{TC}}$, with $N_F = 4$ Weyl fermions

see Cacciapaglia, Pica, Sannino, 2002.04914
& Cacciapaglia, Deandrea, Sridhar, et al, EPJ ST 231, 1221 for Review

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

Composite Higgs: What's Inside?

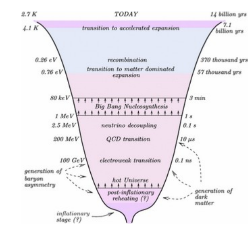
- 4D UV Completion



$\langle \mathcal{F}^a \epsilon_{\mathrm{TC}} \mathcal{F}^b \rangle = \Lambda_c f^2 \Sigma_\theta^{ab}$ $\xrightarrow{\text{minimal}}$ $SO(6) \to SO(5)$

$\longrightarrow$ 5 Goldstones: Higgs + EW Singlet

- Baryogenesis ?



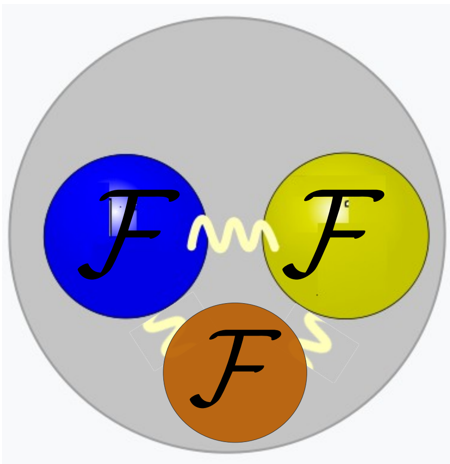
Espinosa, Gripaios, Konstandin, Riva, 1110.2876
De Curtis, Delle Rose, Panico, 1909.07894.
Bian, Wu, Xie, 1909.02014, 2005.13552.
Angelescu, FG, Tada, 2112.12087

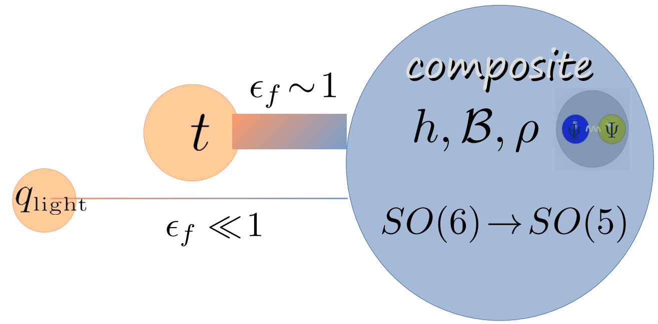
$G_{\mathrm{TC}} = Sp(N)_{\mathrm{TC}}$, with $N_F = 4$ Weyl fermions

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

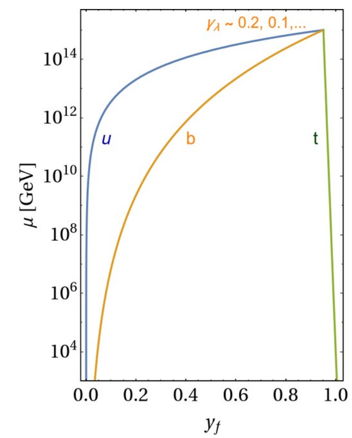
What's Inside?

- 4D UV Completion





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



Fermionic resonances $\mathcal{B}$?

$$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{F}\mathcal{F}$$

$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

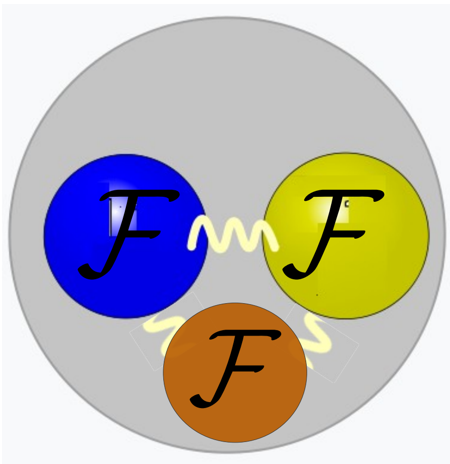
Lattice suggests: $0 \ll \gamma_\lambda \lesssim 2$

$$\lambda \sim (\Lambda/\Lambda_{UV})^{\gamma_\lambda} \ll 1$$

DeGrand, Shamir, 1508.02581
Pica, Sannino, 1604.02572
Ayyar, DeGrand, Hackett, Jay, Neil, Shamir, Svetitsky, 1812.02727...

What's Inside?

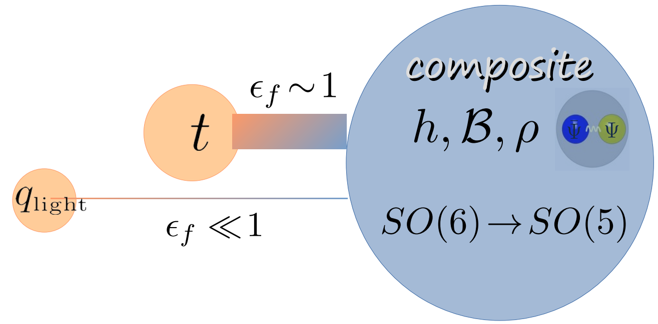
- 4D UV Completion



Fermionic resonances $\mathcal{B}$?

$$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{F}\mathcal{F}$$

$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

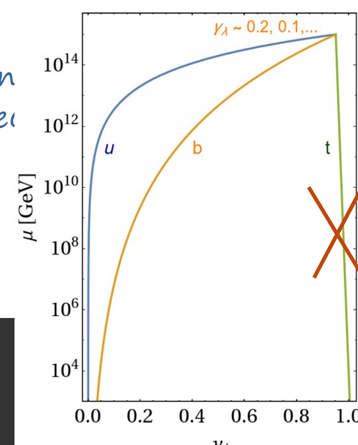


$$\mathcal{L} = \lambda\, \bar{q}\, \mathcal{O} + \text{h.c.}$$

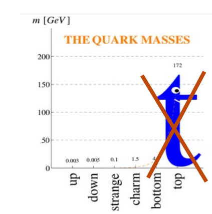
Lattice suggests: $0 \ll \gamma_\lambda \lesssim 2$

$$\lambda \sim (\Lambda/\Lambda_{UV})^{\gamma_\lambda} \ll 1$$

DeGrand, Pica, Sann Ayyar, De eil, Shamir, Svetitsky, 1812.02727

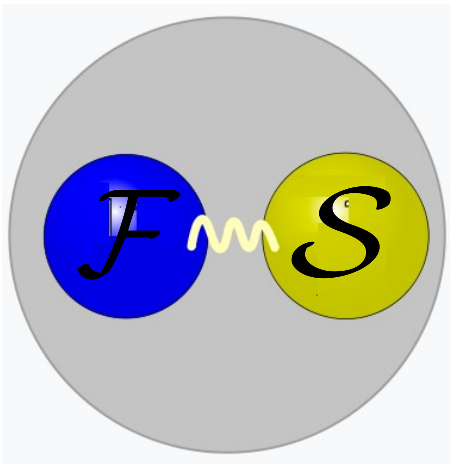


challenging



What's Inside?

- 4D UV Completion



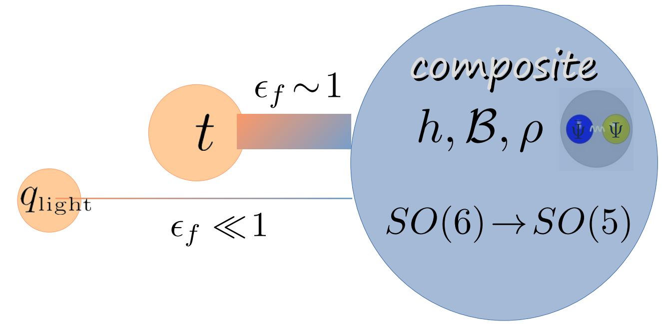
Fermionic resonances $\mathcal{B}$?

$$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$$

fermion scalar

$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

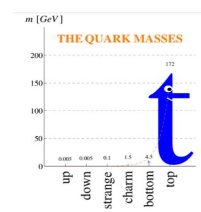
"(minimal) fundamental partial compositeness"



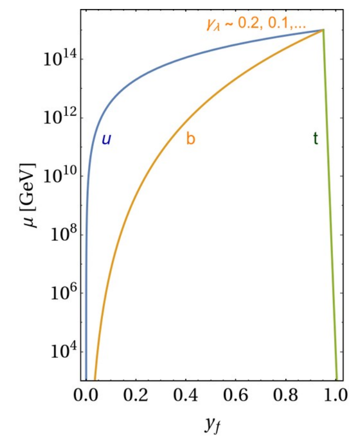
$$\mathcal{L} = \lambda\, \bar{q}\, \mathcal{O} + \text{h.c.}$$

$\gamma_\lambda \sim 0 \ll 2$??

$\lambda \sim (\Lambda/\Lambda_{UV})^{\gamma_\lambda} \ll 1$



✓ ??

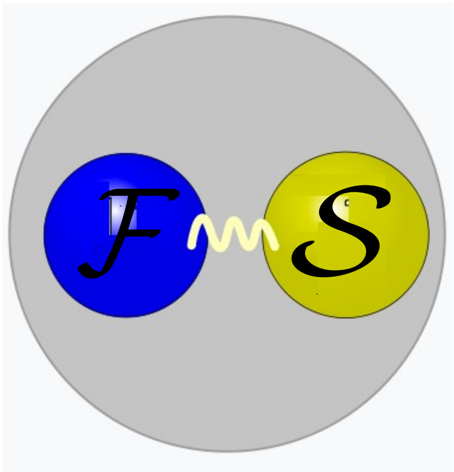


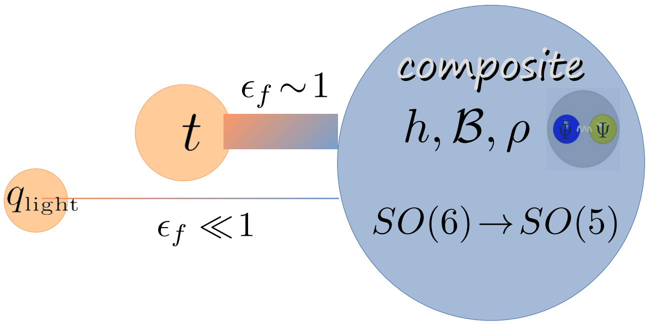
Cacciapaglia, Gertov, Sannino, Thomsen, 1704.07845
Sannino, Strumia, Tesi, Vigiani, 1607.01659 ...

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

What's Inside?

- 4D UV Completion





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

Fermionic resonances $\mathcal{B}$?

$$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$$

$$\lambda \sim (\Lambda/\Lambda_{UV})^{\gamma_\lambda} \ll 1$$

$$\gamma_\lambda \approx [\mathcal{O}_{\mathcal{B}}] - 5/2$$

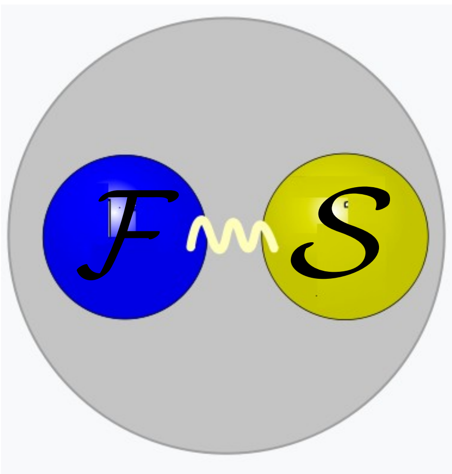
Derive with non-perturbative functional Renormalization Group (fRG)

U. Ellwanger, hep-ph/9308260, T. R. Morris, hep-ph/9308265, C. Wetterich, Z.Phys. C57, 451 (1993)

FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

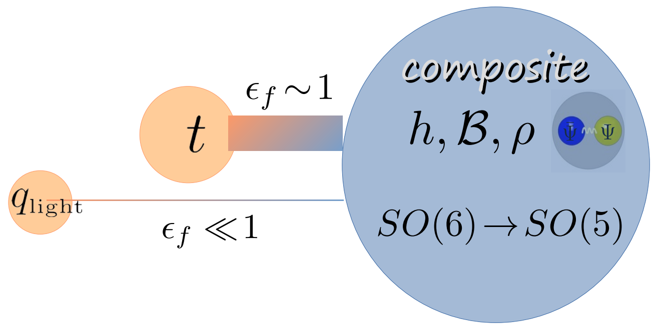
- Effective Action



$$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$$

weak doublet
+ 2 singlets

3 gen. of color triplets
+ singlets (→ leptons)



$$\Gamma_{\rm mix} = \int_x \lambda_q\, k\, Z_q^{1/2} Z_{\mathcal{B}}^{1/2}\ \bar{q}_L \mathcal{B}_R^q + \cdots$$

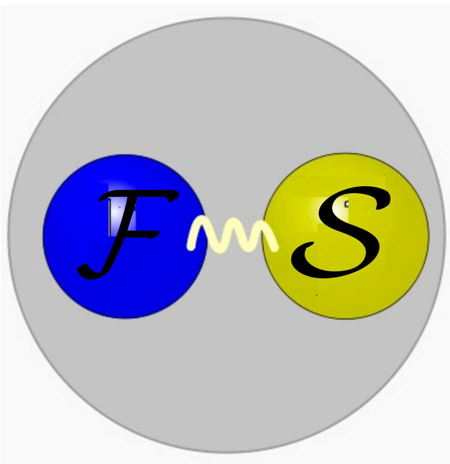
RG-scale

Cacciapaglia, Gertov, Sannino, Thomsen, 1704.07845
Sannino, Strumia, Tesi, Vigiani, 1607.01659 ...

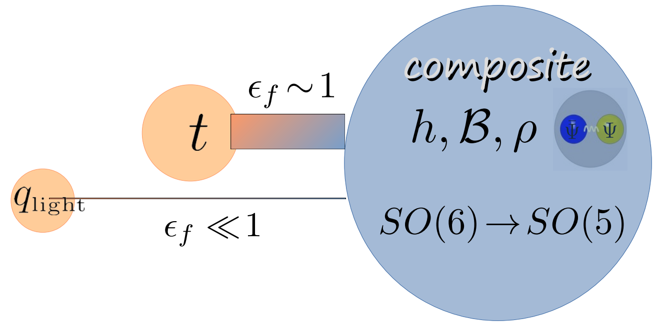
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

- Effective Action



$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$

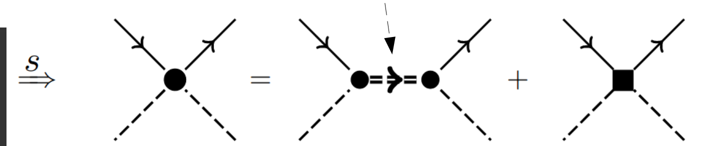


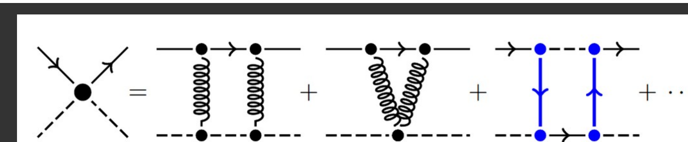
$$\Gamma_{\mathrm{mix}} = \int_x \lambda_q \, k \, Z_q^{1/2} Z_{\mathcal{B}}^{1/2} \;\; \bar{q}_L \mathcal{B}_R^q + \cdots$$

$$\Gamma_{\mathrm{CH}} = \int_x \Big\{ \frac{Z_A}{4} G_{\mu\nu} G_{\mu\nu}$$
$$+ \frac{Z_{\mathcal{S}}}{2} \left[\left(D_\mu \mathcal{S}^i \right)^\dagger \left(D_\mu \mathcal{S}^i \right) + \mathcal{S}^{i\dagger} m_{\mathcal{S}}^2 \, \mathcal{S}^i \right]$$
$$+ Z_{\mathcal{F}} \, \bar{\mathcal{F}}^a \left(\sigma_\mu D_\mu + m_{\mathcal{F}} \right) \mathcal{F}^a$$
$$+ \sqrt{Z_\psi \, Z_{\mathcal{F}} \, Z_{\mathcal{S}}} \, y_{\mathrm{TC}}^{i,a} \, \underset{q}{\psi^{i,a}} \, \epsilon_{ij} \, \underset{\mathcal{S}}{\Phi^j} \, \epsilon_{\mathrm{TC}} \, \mathcal{F}^a + \mathrm{h.c.} + \cdots \Big\}$$

emergent composites extension of 'dynamical hadronization' (Gies, Wetterich, Pawlowski, Flörchinger,...)

$$\Gamma_{\mathcal{B}} = \int_x \Big\{ Z_{\mathcal{B}} \bar{\mathcal{B}} \left(\sigma_\mu \partial_\mu + m_{\mathcal{B}} \right) \mathcal{B}$$
$$+ h_{\mathcal{B}} \sqrt{Z_{\mathcal{B}} Z_{\mathcal{S}} Z_{\mathcal{F}}} \left[\mathcal{S} \left(\bar{\mathcal{B}} \mathcal{F} \right) + \mathcal{S}^\dagger \left(\bar{\mathcal{F}} \mathcal{B} \right) \right] + \cdots \Big\}$$

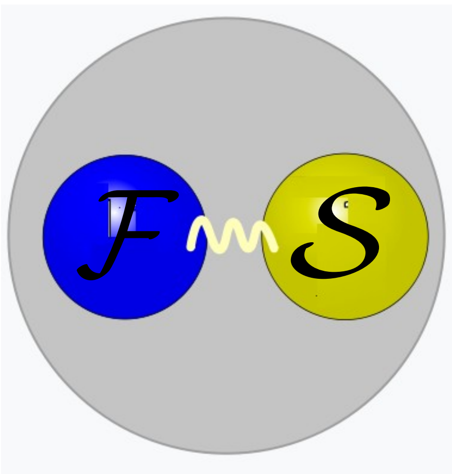




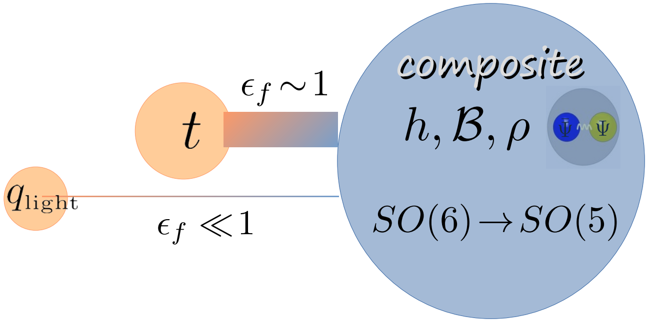
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

- Effective Action



$\mathcal{O}_\mathcal{B} \sim \mathcal{F}\mathcal{S}$



$$\boxed{\Gamma_{\text{mix}} = \int_x \lambda_q \, k \, Z_q^{1/2} Z_\mathcal{B}^{1/2} \;\; \bar{q}_L \mathcal{B}_R^q} + \cdots$$

$$\boxed{\gamma_{\lambda_q} = \frac{\partial_t \lambda_q}{\lambda_q} \approx -1 - \gamma_\mathcal{B}/2} \qquad \partial_t \equiv k\partial_k$$

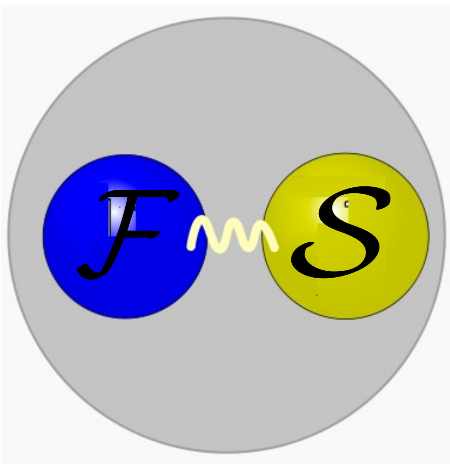
$$\Gamma_\mathcal{B} = \int_x \Big\{ Z_\mathcal{B} \bar{\mathcal{B}} \left(\sigma_\mu \partial_\mu + m_\mathcal{B}\right) \mathcal{B} + h_\mathcal{B} \sqrt{Z_\mathcal{B} Z_\mathcal{S} Z_\mathcal{F}} \left[\mathcal{S}\left(\bar{\mathcal{B}}\mathcal{F}\right) + \mathcal{S}^\dagger \left(\bar{\mathcal{F}}\mathcal{B}\right)\right] + \cdots \Big\}$$

$$\gamma_\mathcal{B} = \frac{\partial_t Z_\mathcal{B}}{Z_\mathcal{B}} = \left. \frac{-\,\partial_{p^2}\left(\sigma_\mu \, p_\mu \; \partial_t \Gamma^{(2)}_{\mathcal{B}\bar{\mathcal{B}},k}\right)}{Z_\mathcal{B}\, \text{tr}\left[\sigma_\mu \sigma_\nu\right]} \right|_{p=0}$$

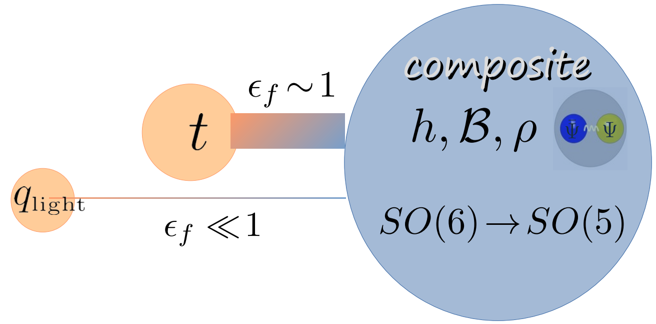
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

- Effective Action



$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$

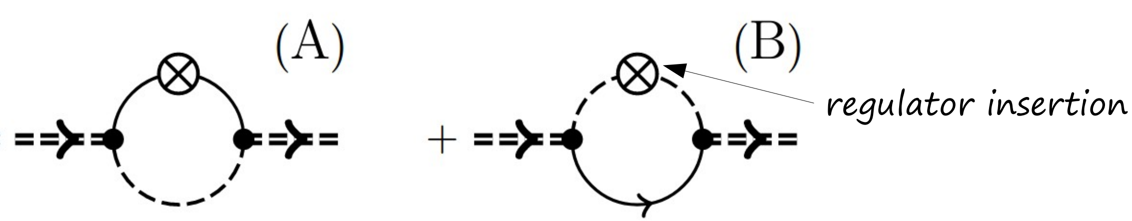


$$\Gamma_{\text{mix}} = \int_x \lambda_q \, k \, Z_q^{1/2} Z_{\mathcal{B}}^{1/2} \;\; \bar{q}_L \mathcal{B}_R^q + \cdots$$

$$\gamma_{\lambda_q} \approx -1 - \gamma_{\mathcal{B}}/2$$

$$\gamma_{\mathcal{B}} = \frac{\partial_t Z_{\mathcal{B}}}{Z_{\mathcal{B}}} = \frac{-\,\partial_{p^2}\left(\sigma_\mu \, p_\mu \; \partial_t \Gamma^{(2)}_{\mathcal{B}\bar{\mathcal{B}},k}\right)}{Z_{\mathcal{B}} \, \mathrm{tr}\left[\sigma_\mu \sigma_\nu\right]}\Bigg|_{p=0}$$

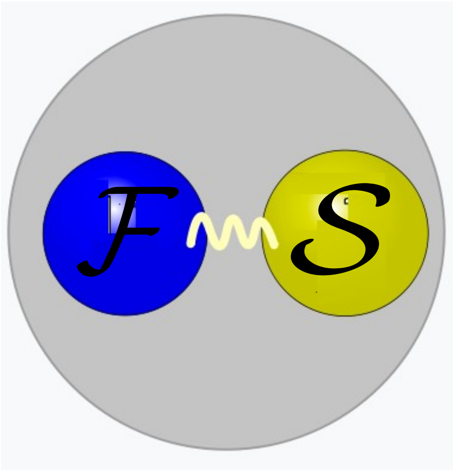
Wetterich Eq. → RG flow
(one-loop exact)

$\partial_t \Gamma^{(2)}_{\mathcal{B}\bar{\mathcal{B}},k} =$ 

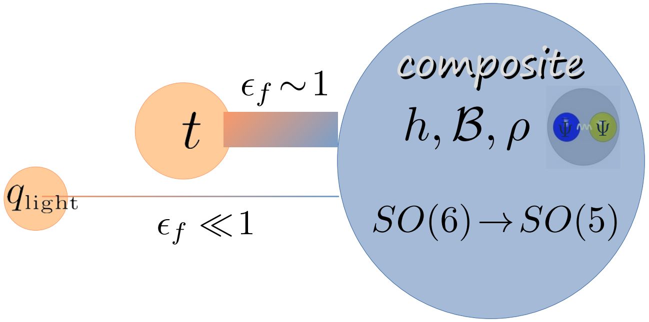
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

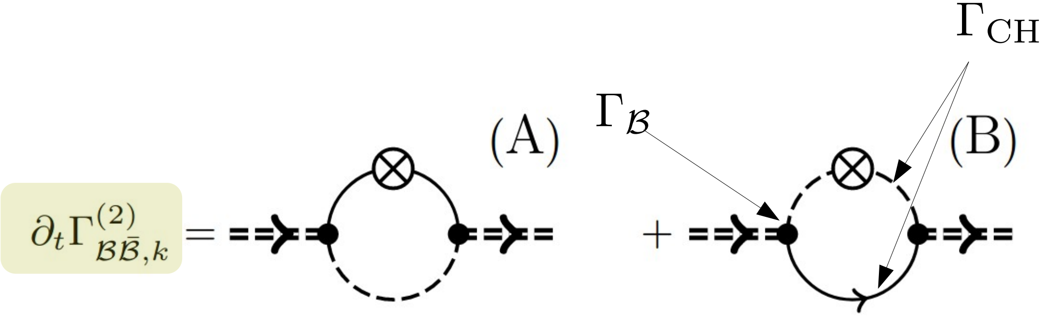
- Effective Action



$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$



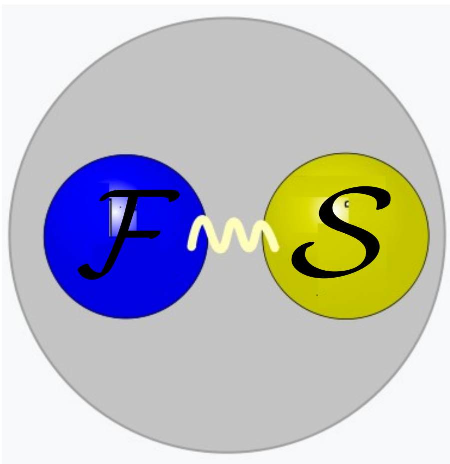
Wetterich Eq. → RG flow
(one-loop exact)



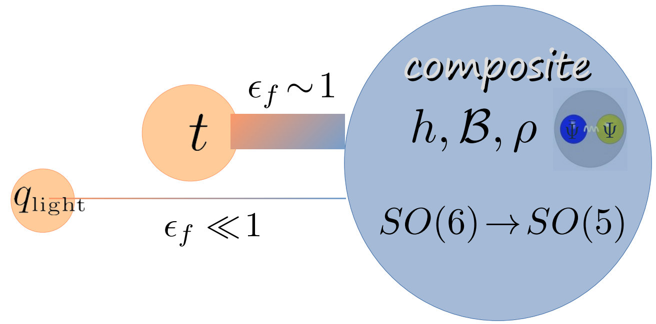
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?

- Effective Action



$\mathcal{O}_{\mathcal{B}} \sim \mathcal{F}\mathcal{S}$



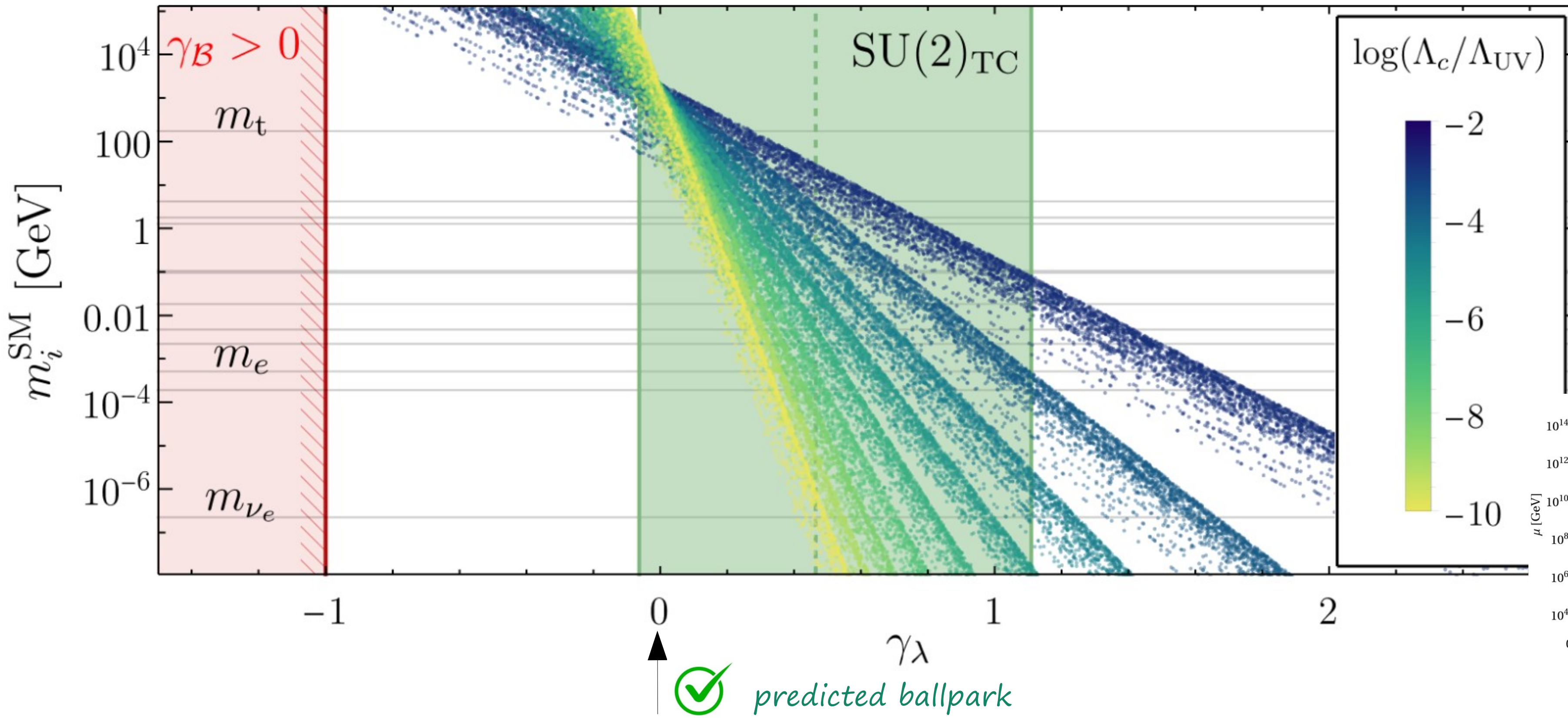
$$\gamma_{\mathcal{B}} \approx -\frac{h_{\mathcal{B}}^2}{16\pi^2}\frac{N_{\rm TC}}{2}\left(1+\frac{\gamma_{\mathcal{S}}}{5}\right) < 0$$

$$\boxed{\gamma_{\lambda_q} \approx -1 - \gamma_{\mathcal{B}}/2 \gtrsim -1}$$

$$m_t \sim \frac{v}{\sqrt{2}}\left(\frac{\Lambda_c}{\Lambda_{\rm UV}}\right)^{\gamma_{\lambda_q}+\gamma_{\lambda_t}}$$

FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

What's Inside?



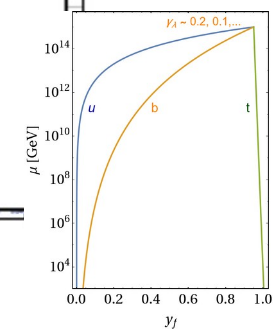
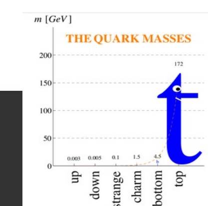


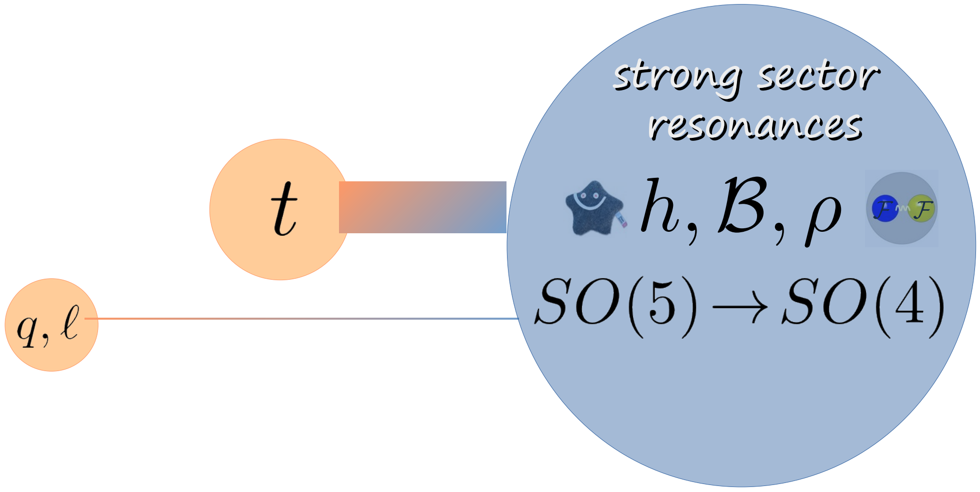
FIG. 4. SM fermion masses as a function of the anomalous scaling γ_λ defined in (48). The colourful clouds of points show a parameter investigation in which $\mathcal{Y}_f \in [0.1, 4\pi]$ and $\gamma_\lambda \in [-1, 3]$. From blue to yellow, the size of the walking regimes is discretely increased by varying $\Delta\Lambda = \log(\Lambda_c/\Lambda_{UV})$ from $\Delta\Lambda = -2$ to $\Delta\Lambda = -10$. The red-shaded region depicts the prohibited area inaccessible due to the found negativity of the composite's anomalous dimension and coincidentally to the unitarity bound of the coupling λ_f. The green dashed line indicates the estimated ballpark of γ_λ in the MFPC scenario with two additional Dirac fermions in (59). The green-shaded region shows a 20% variation in the estimate of $h_{\mathcal{B}}$ in (43) and serves only as an indicative measure of the dependence of γ_λ on $h_{\mathcal{B}}$.

$$m_t \sim \frac{v}{\sqrt{2}} \left(\frac{\Lambda_c}{\Lambda_{UV}}\right)^{\overbrace{\gamma_{\lambda_q} + \gamma_{\lambda_t}}^{2\gamma_\lambda}}$$



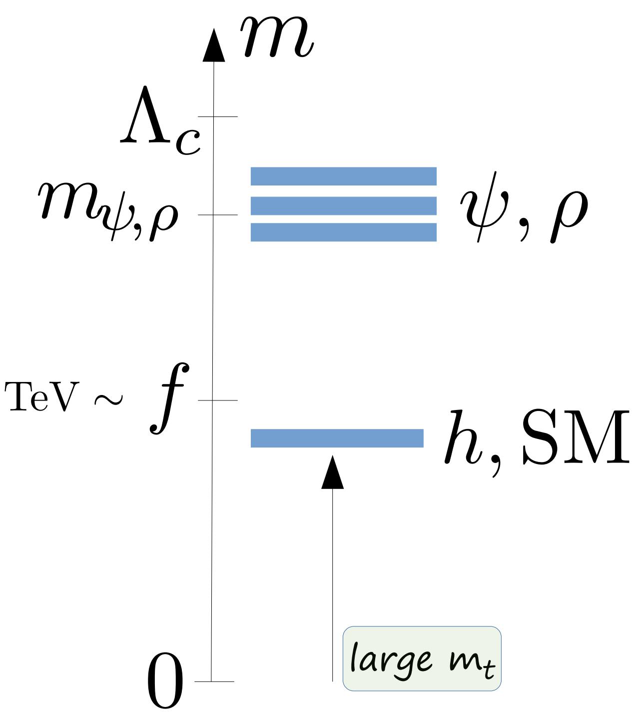
FG, Pastor-Gutiérrez, Pawlowski [PRD] 2307.11148

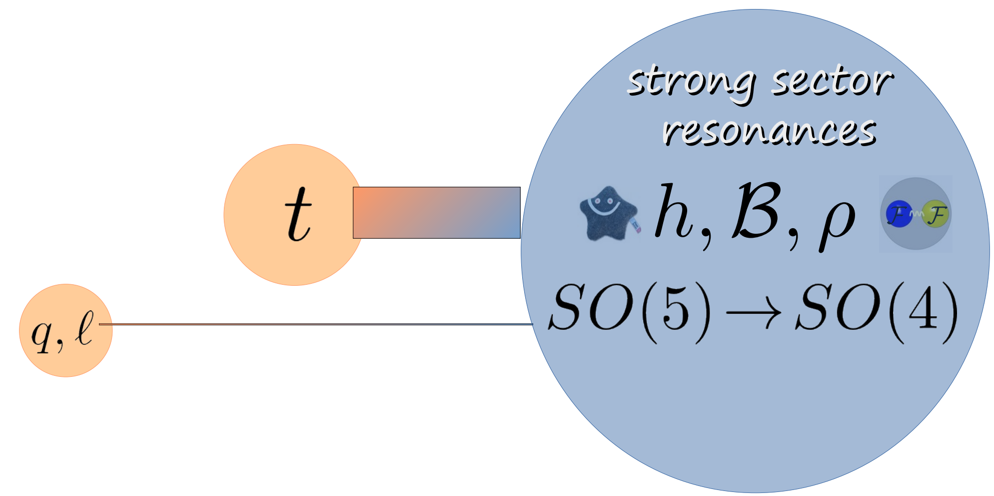
Back to Low Energy EFT



Partial Compositeness:
Top Partners & Tuning

Partially Composite Fermions





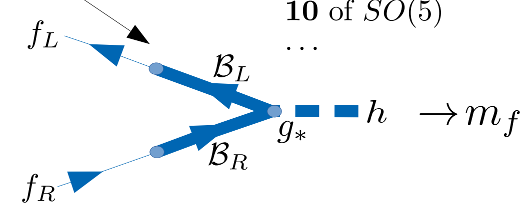
$$\mathcal{L}_{\text{mix}} \supset \boxed{\lambda_q[\Lambda_c]}\, \overline{q}_L \mathcal{O}^q_{\mathcal{B}} + \boxed{\lambda_t[\Lambda_c]}\, \overline{t}_R \mathcal{O}^t_{\mathcal{B}}$$

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

$\mathcal{O}(1)$ (UV)

$$\lambda_q[\Lambda_c] \approx \lambda_q \left(\frac{\Lambda_c}{\Lambda_{\text{UV}}}\right)^{\gamma_{\lambda_q}}$$

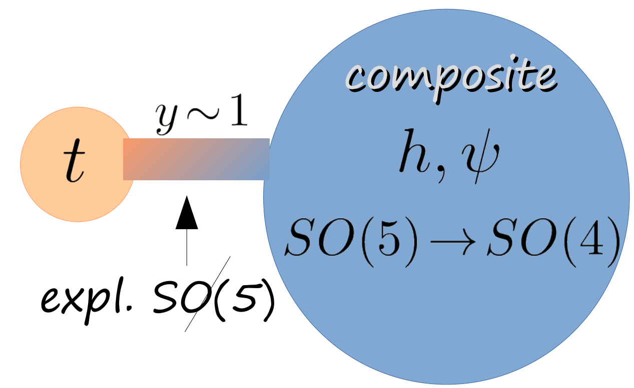
$\ll 1$



The Higgs Potential and the Tuning

General Parametrization of Potential

$$V(h) \approx \boxed{\alpha} \sin^2(h/f) + \boxed{\beta} \sin^4(h/f)$$



$$\text{Minimum}: \boxed{\sin(v/f)^2 \approx -\frac{\alpha}{2\beta}}$$

$\to$ minimal tuning: $\Delta^{-1} \sim \sin(v/f)^2$ → $O(10\%)$

- *However, minimal models (like $MCHM_5$, $MCHM_{10}$):*

$\boxed{\alpha} \sim y_t^2/g_\Psi^2\,, \quad \boxed{\beta} \sim (y_t^2/g_\Psi^2)^{\boxed{2}} \ll \alpha \quad \to$ double tuning: $\Delta^{-1} \sim \boxed{\frac{y_t^2}{g_\Psi^2}} \sin(v/f)^2 \ll 1$

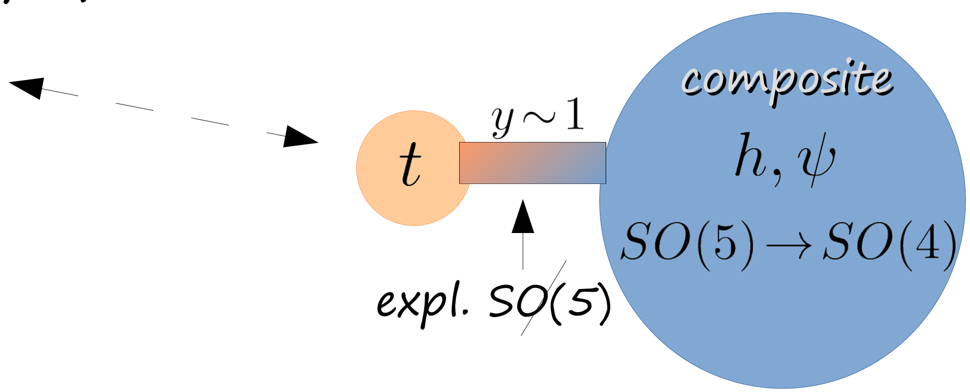
→ $O(1\%)$

$y_t \equiv \lambda_q \sim \lambda_t \;, \quad g_\Psi \sim 3$

Light Top Partners

- *Most important SO(5) breaking: top quark*
- *Large top yukawa → large m_h*

$$m_h^2 = 2\beta/f^2 \sin^2(2v/f)$$
$$\sim y_t^4 v^2$$



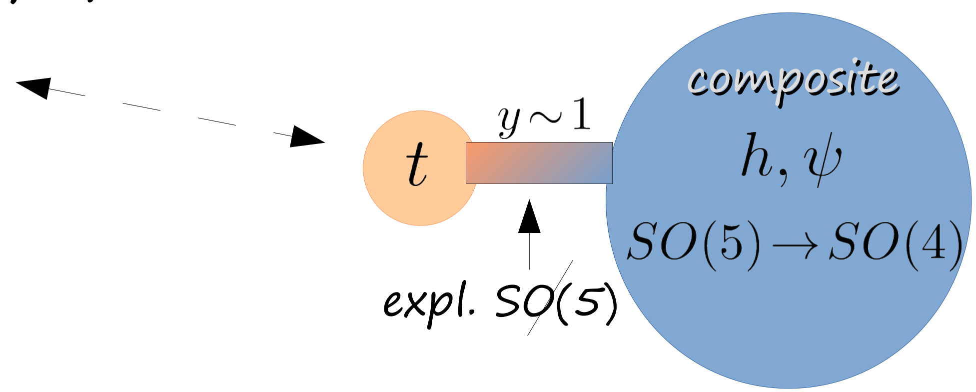
$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

Light Top Partners

- *Most important SO(5) breaking: top quark*
- *Large top yukawa → large m_h*

$$m_h^2 = 2\beta/f^2 \sin^2(2v/f)$$
$$\sim y_t^4 v^2$$
$$\sim (m_T^{\text{min}})^2/f^2 \; m_t^2$$

$$m_t \sim \frac{\lambda_q \lambda_t f}{\sqrt{2} m_T^{\text{min}}} v$$

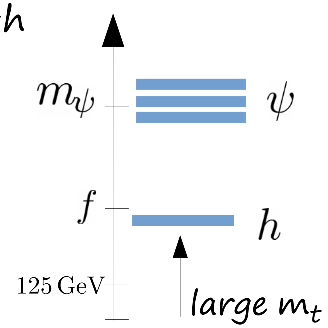


$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

Light Top Partners

- Large top yukawa → large m_h

$$m_h \sim y_t^2\, v \sim m_t\, m_T/f$$

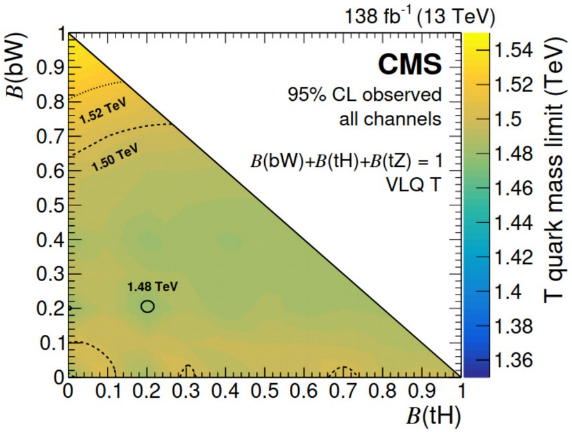


=> light top partners:

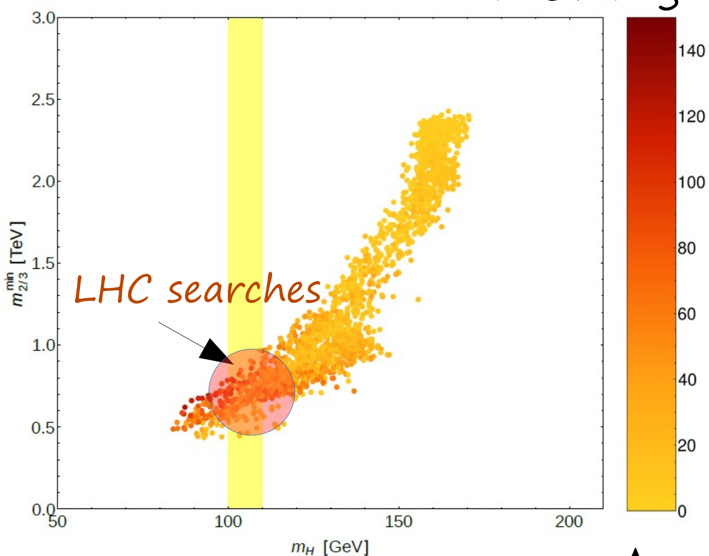
$$m_T \sim f \sim 800\,\mathrm{GeV}$$

→ $m_T \gtrsim 1500\,\mathrm{GeV}$

latest limit



MCHM$_5$



Carmona, FG [JHEP] (1410.8555) Δ_{BG}

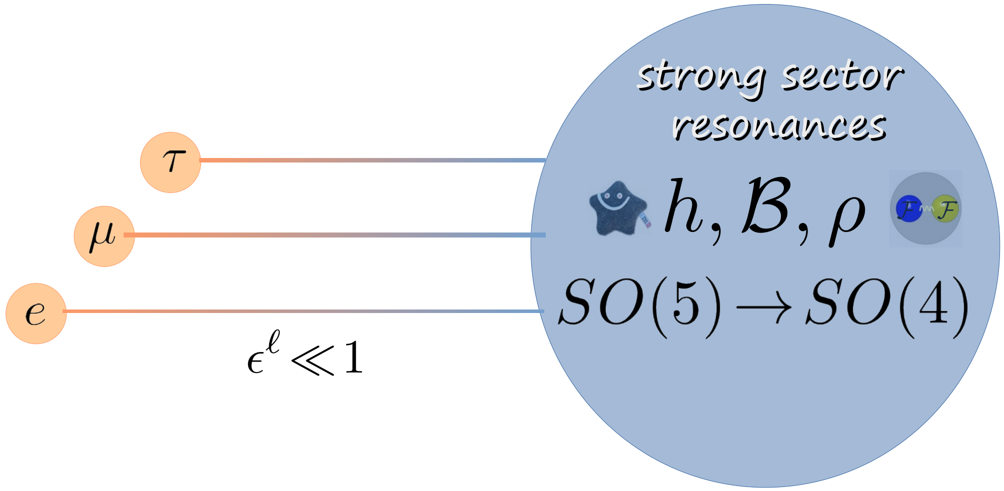
$f = 800\,\mathrm{GeV}$

currently strongest constraints

➡ avoidable?

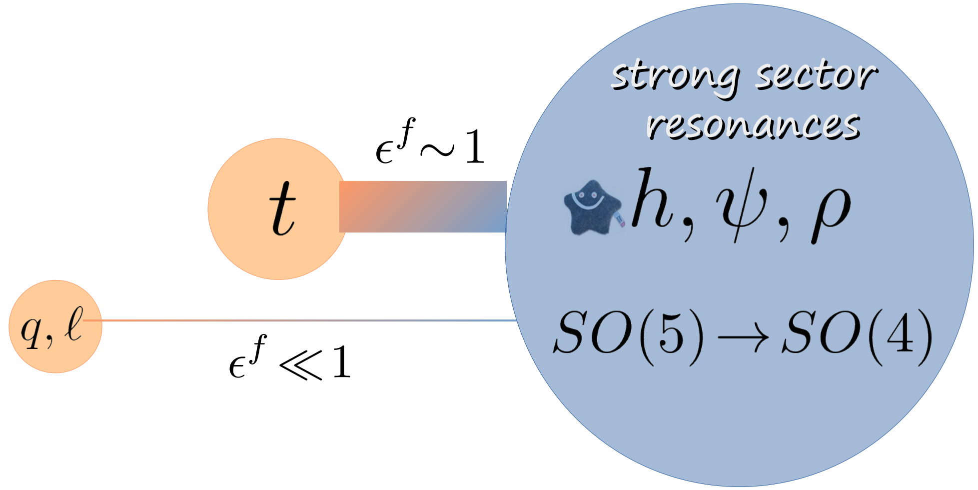
Matsedonskyi, Panico, Wulzer, 1204.6333;
Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954;
De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434; Carmona, FG, 1410.8555

Interlude



Partial Compositeness in the Lepton Sector

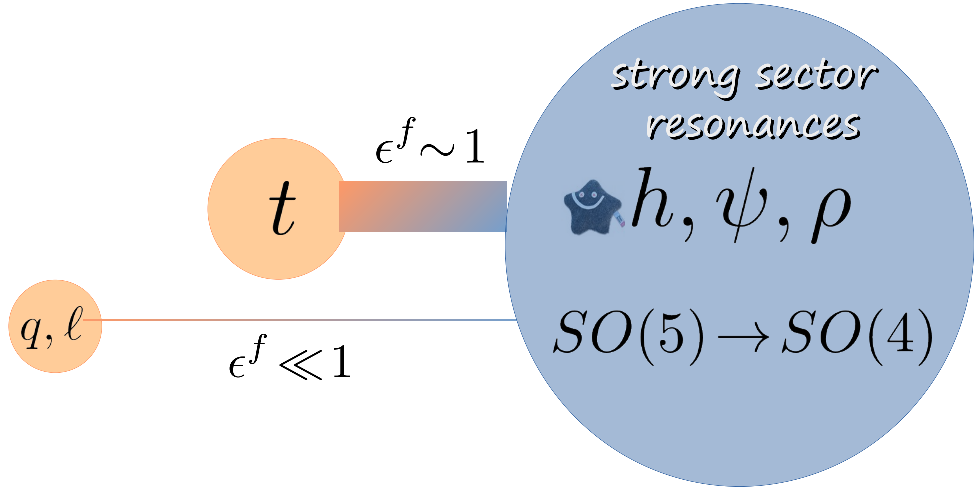
Models of Lepton Flavor



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

$$\mathcal{L}_{\rm mix} \supset \boxed{\lambda_L^\ell}\, \bar{l}_L^\ell \mathcal{O}_L^\ell + \boxed{\lambda_R^\ell}\, \bar{l}_R^\ell \mathcal{O}_R^\ell + \lambda_L^{\prime\ell}\, \bar{l}_L^\ell \mathcal{O}_L^{\ell'} + \lambda_R^{\nu_\ell}\, \bar{\nu}_R^\ell \mathcal{O}_R^{\nu_\ell}$$

1: 'Anarchic' Model



$$\mathcal{L}_{\rm mix} \supset \boxed{\lambda_L^\ell}\, \bar{l}_L^\ell \mathcal{O}_L^\ell + \boxed{\lambda_R^\ell}\, \bar{l}_R^\ell \mathcal{O}_R^\ell$$

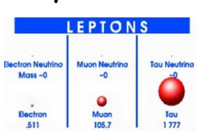
$\mathcal{O}(1) \sim \gamma^e_{L,R} \gtrsim \gamma^\mu_{L,R} \gtrsim \gamma^\tau_{L,R} \cdots$

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

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

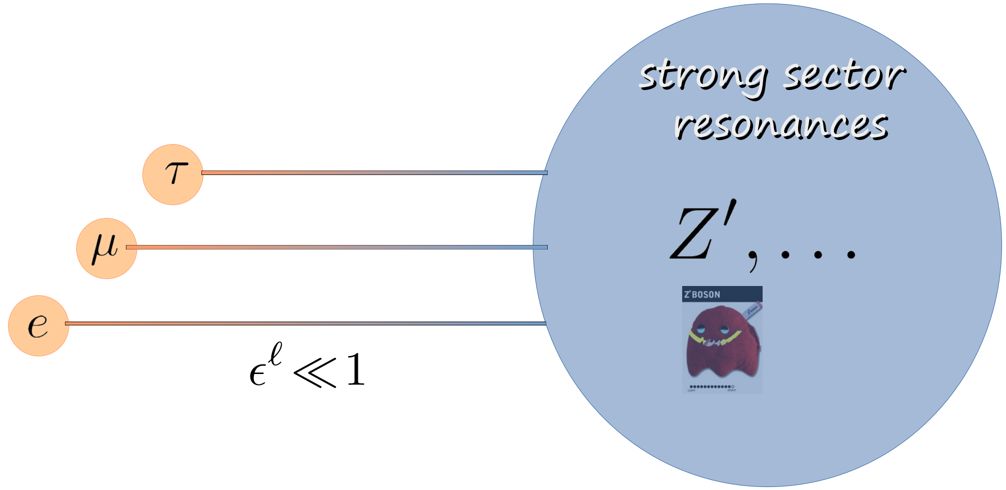
$\mathcal{O}(1)$'anarchic'

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



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

1: 'Anarchic' Model



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

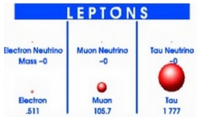
FCNC protection via GIM-like mechanism

$\mathcal{O}(1)$

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

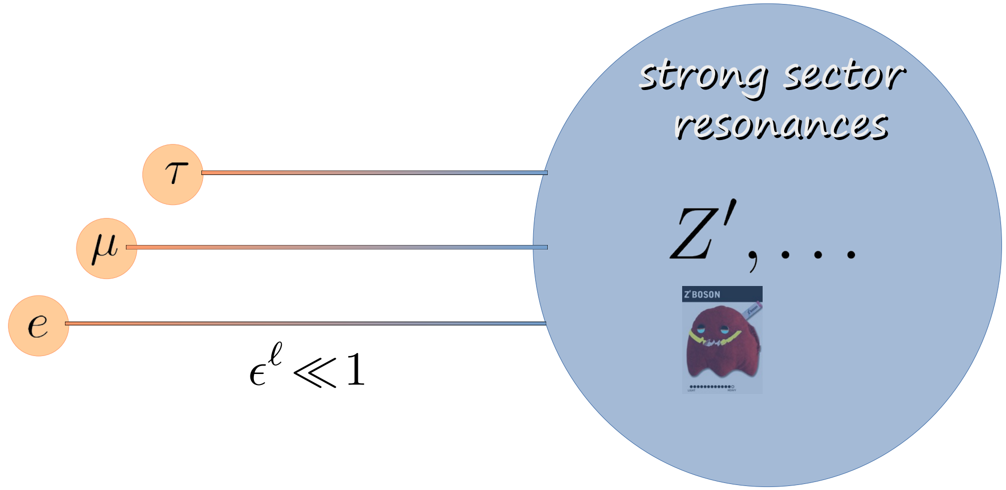
$\mathcal{O}(1)$'anarchic'

'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

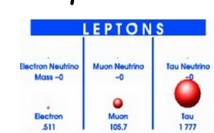


$\epsilon^e \ll \epsilon^\mu \ll \epsilon^\tau \ll 1$

FCNC protection via GIM-like mechanism → Not quite sufficient

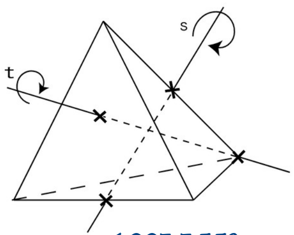
$$\text{RGE } \lambda^\ell_{L,R}(\mu) \simeq \underbrace{\boxed{\lambda^\ell_{L,R}}}_{\mathcal{O}(1)\text{'anarchic'}} \left(\frac{\mu}{\Lambda_{\mathrm{UV}}}\right)^{\overbrace{\gamma^\ell_{L,R}}^{\mathcal{O}(1)}} \ll 1$$

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

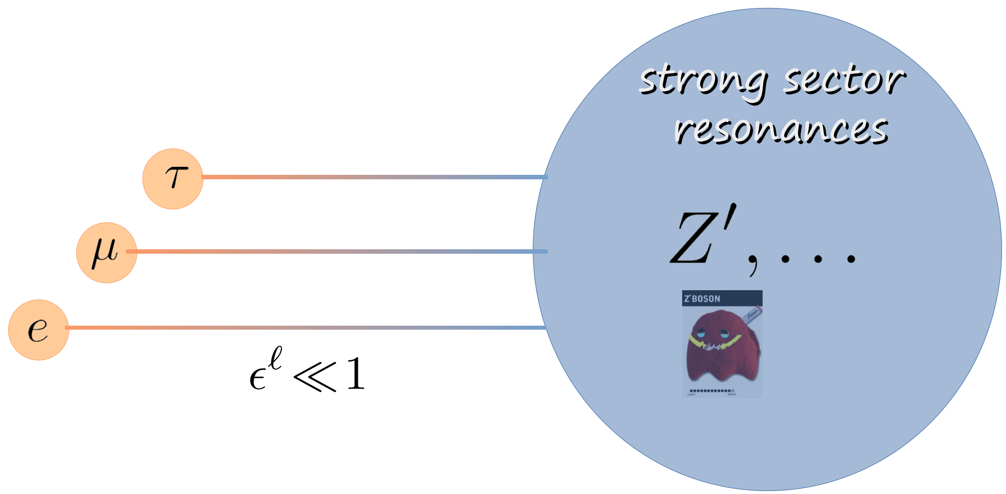


$$m_\ell \sim \frac{g_* v}{\sqrt{2}}\, \epsilon^\ell_L \epsilon^\ell_R$$

2: Flavor Symmetries



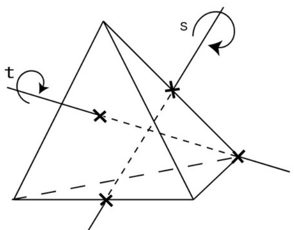
1003.3552



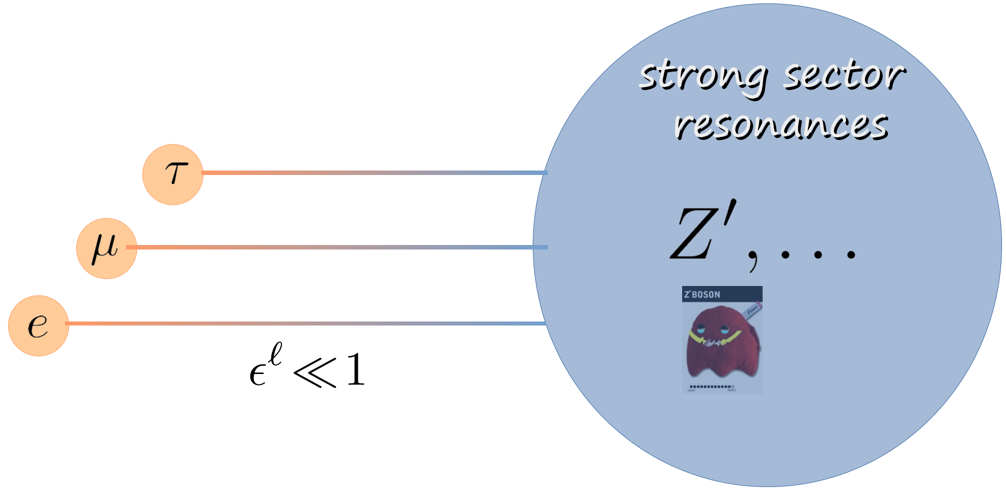
G_f	$A_4 \times Z_N$	$S_4 \times Z_N^n$	$X \times Z_N$	$\Delta(27) \times Z_4 \times Z_4'$	S_3	T'	$U(N)$
Ref.	Csaki, Delaunay, Grojean, Grossman, 0806.0356 del Aguila, Carmona, Santiago, 1001.5151 Kadosh, Pallante, 1004.0321 Kadosh, 1303.2645	Hagedorn, Serone, 1106.4021 Hagedorn, Serone, 1110.4612 Ding, 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



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	Hagedorn, Serone, 1106.4021	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

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

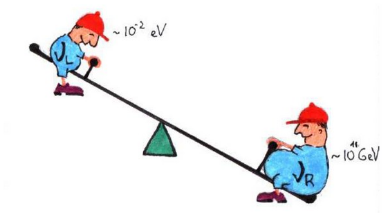
A_4 (spont. broken)	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{3}$	$\mathbf{3}$

→ allows to rotate to an approximately flavor-diagonal basis

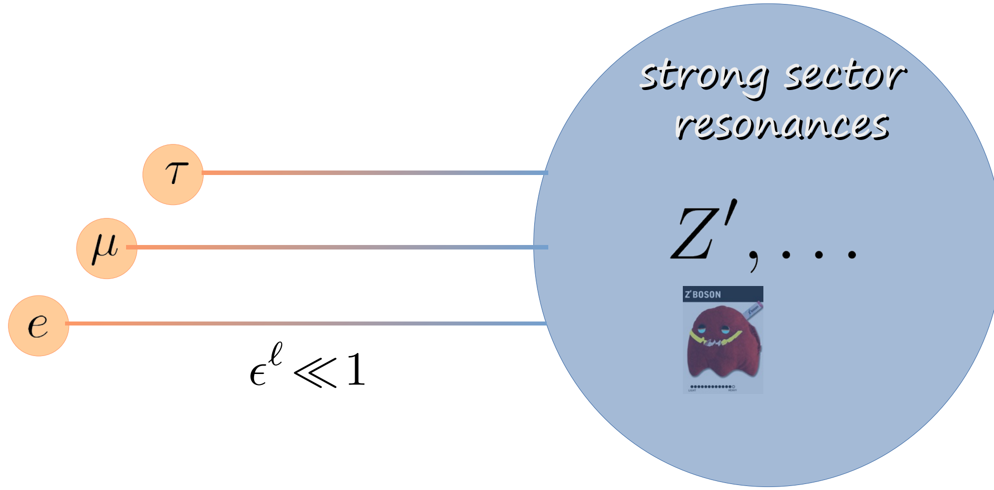
→ generates ~ TBM mixing

3: Minimal Seesaw Model

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



Grossman, TASI 2002



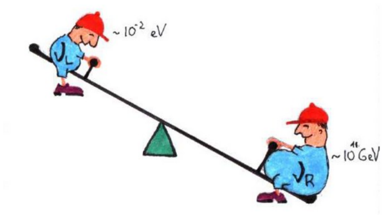
canonical model:
$\mathcal{O}^i_{L,R}$ fundamental of SO(5)

m_ν

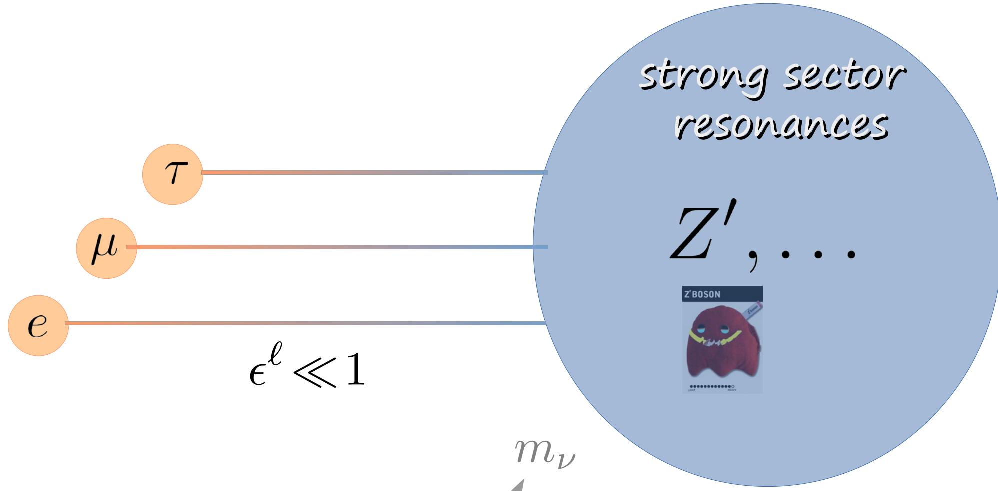
$$\mathcal{L}_{\rm mix} \supset \lambda^\ell_L\, \bar{l}^\ell_L \mathcal{O}^\ell_L + \lambda^\ell_R\, \bar{l}^\ell_R \mathcal{O}^\ell_R + \lambda'^\ell_L\, \bar{l}^\ell_L \mathcal{O}^{\ell'}_L + \lambda^{\nu_\ell}_R\, \bar{\nu}^\ell_R \mathcal{O}^{\nu_\ell}_R$$

3: Minimal Seesaw Model

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



Grossman, TASI 2002



m_ν

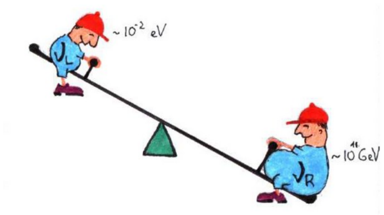
$$\mathcal{L}_{\rm mix} \ni \lambda_L^\ell \bar{l}_L^\ell \mathcal{O}_L^\ell + \lambda_R^\ell \bar{l}_R^\ell \mathcal{O}_R^\ell$$

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

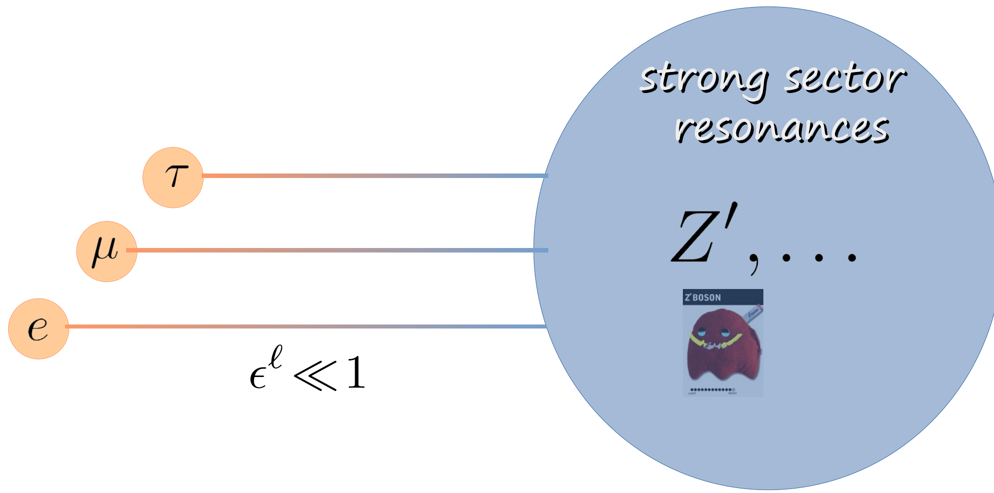
ℓ_R Σ_R seesaw triplet
→ small m_ν

3: Minimal Seesaw Model

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



Grossman, TASI 2002



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

$$\mathcal{L}_{\rm mix} \supset \lambda_L^\ell \, \bar{L}_L^\ell \mathcal{O}_L^\ell + \lambda_R^\ell \, \bar{L}_R^\ell \mathcal{O}_R^\ell$$

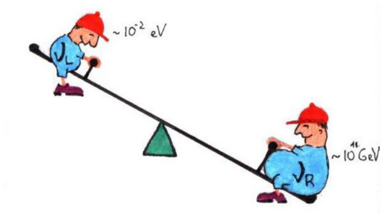
$\ell_L \quad \nu_L$

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

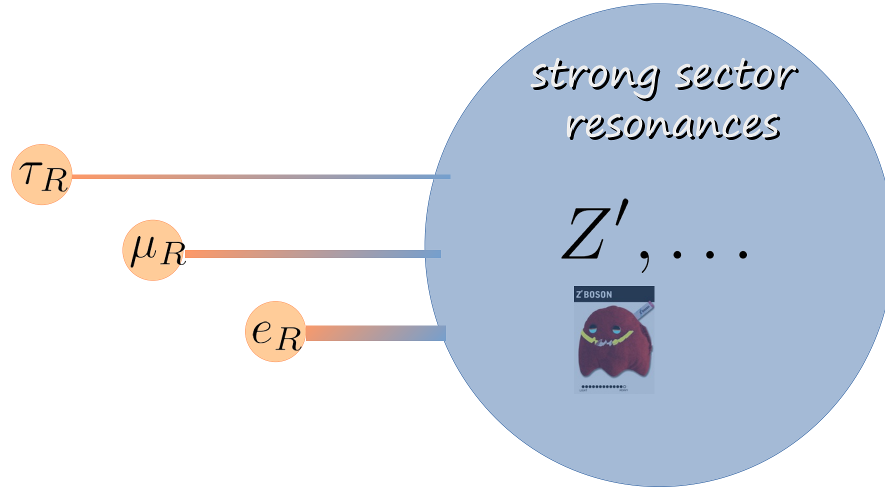
Unification of LH and RH fields!!
very minimal realization of lepton sector...

3: Minimal Seesaw Model

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



Grossman, TASI 2002



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

$$\mathcal{L}_{\rm mix} \supset \lambda_L^\ell \, \bar{L}_L^\ell \mathcal{O}_L^\ell + \lambda_R^\ell \, \bar{L}_R^\ell \mathcal{O}_R^\ell$$

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

Unification of LH and RH fields!!

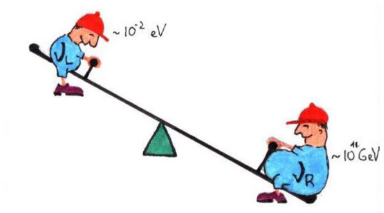
very minimal realization of lepton sector...

rather composite ⇒ $\epsilon_R^\ell \gg 0 \quad (M_{\rm GUT} \ll M_{\rm Pl})$

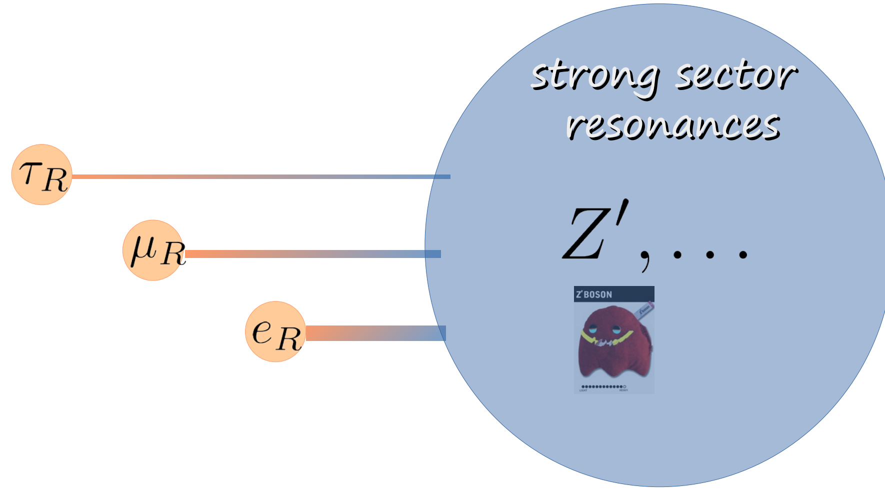
$$m_\ell \to \epsilon_L^e \ll \epsilon_L^\mu \ll \epsilon_L^\tau \ll 1$$
$$M_\nu \to \epsilon_L^\ell \epsilon_R^\ell \sim \text{const.} \to 0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$$

3: Minimal Seesaw Model

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



Grossman, TASI 2002



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

$$\mathcal{L}_{\rm mix} \supset \lambda_L^\ell \, \bar{L}_L^\ell \mathcal{O}_L^\ell + \lambda_R^\ell \, \bar{L}_R^\ell \mathcal{O}_R^\ell$$

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

Unification of LH and RH fields!!

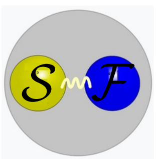
very minimal realization of lepton sector...

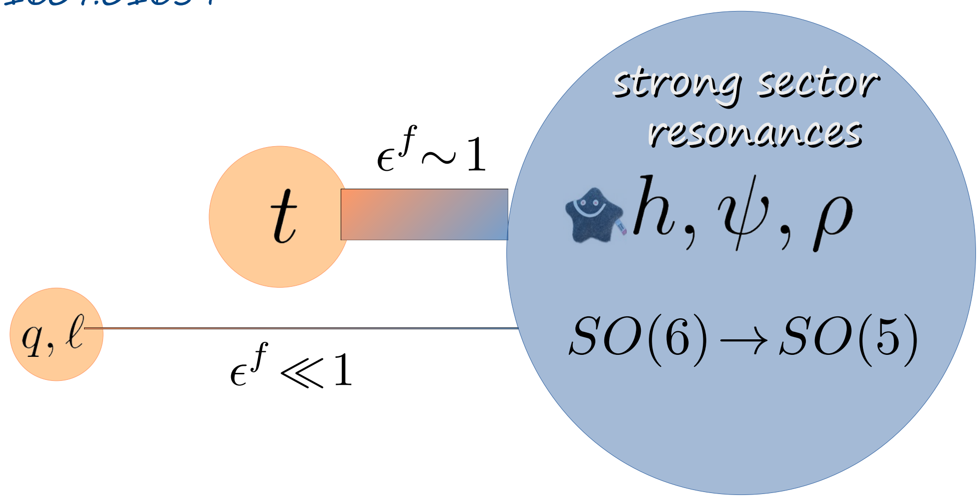
$0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$:

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

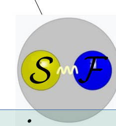
4: "Minimal" Fundamental PC

Sannino, Strumia, Tesi, Vigiani, 1607.01659





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



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

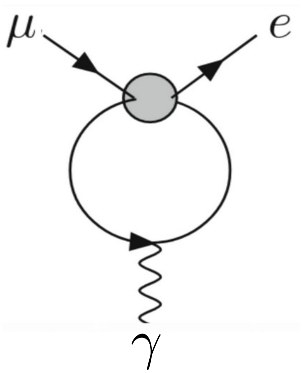
scalar fermion

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

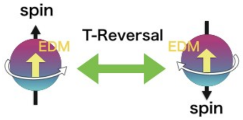
Baldini et al., 1605.05081

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

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

RPP 2020

Electron EDM



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

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

ACME 2018

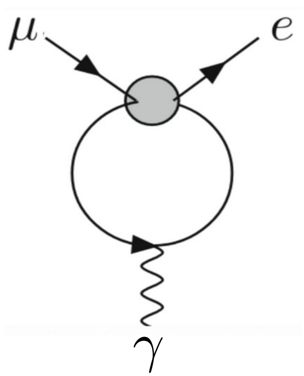
LFV and Dipole Moments

1: ‘Anarchic’ Model

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

Dipole operator

$\mu \to e\gamma$

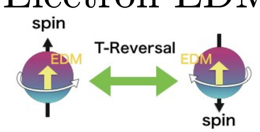


$\ell = \mu, \ell' = e$

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

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

Electron EDM



$\ell = \ell' = e$

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

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

$m_* \sim g_* f$

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

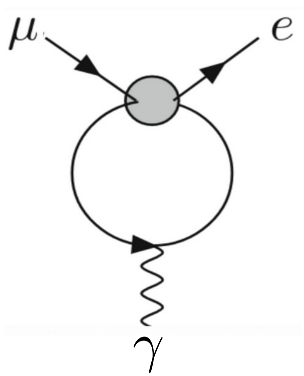
LFV and Dipole Moments

1: 'Anarchic' Model

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

Dipole operator

$\mu \to e\gamma$



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

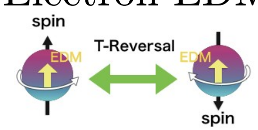
$$\mathrm{BR}(\mu \to e\gamma) = 96\pi^2 e^2 \frac{v^6}{m_\mu^2}\left(\left|C^{\gamma}_{\mu e}\right|^2 + \left|C^{\gamma}_{e\mu}\right|^2\right)$$

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

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

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

Electron EDM



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

$$d_e \sim \mathrm{Im}(c_e)\frac{e}{16\pi^2}\frac{g_*^3}{m_*^2}\epsilon^{e}_{L}\epsilon^{e}_{R}\frac{v}{\sqrt{2}}$$

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

$m_* \sim g_* f$

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

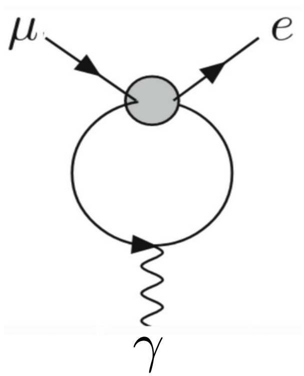
LFV and Dipole Moments

1: 'Anarchic' Model

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

Dipole operator

$\mu \to e\gamma$



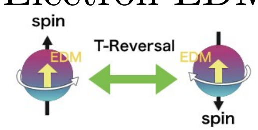
$\boxed{\ell = \mu, \ell' = e}$

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

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

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

Electron EDM



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

$$d_e \sim \mathrm{Im}(c_e)\frac{e}{16\pi^2}\frac{g_*^3}{m_*^2}\epsilon_L^{e}\epsilon_R^{e}\frac{v}{\sqrt{2}} \xrightarrow[\epsilon_L^{\ell} \sim \epsilon_R^{\ell}]{m_\ell \sim g_* v/\sqrt{2}\,\epsilon_L^{\ell}\epsilon_R^{\ell}} \frac{m_*}{g_*} \gtrsim 75\ \mathrm{TeV}$$

Exchange of heavy resonances 

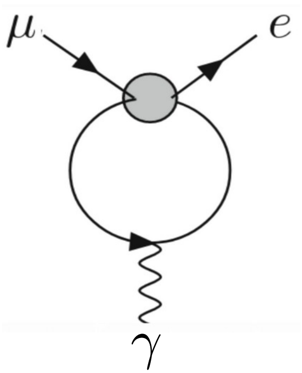
See also Agashe, Blechman, Petriello, hep-ph/0606021
Csaki, Grossman, Tanedo, Tsai, 1004.2037
Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi, 1205.5803
Agashe, Bauer, FG, Lee, Vecchi, Wang, Yu, arXiv:1310.1070
Frigerio, Nardecchia, Serra, Vecchi, 1807.04279

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

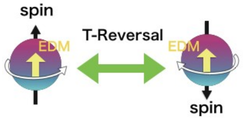
$\mu \to e\gamma$



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

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

Electron EDM



$\ell = \ell' = e$

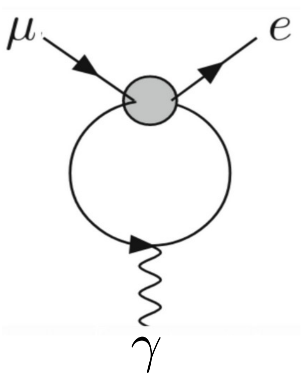
1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC
$\frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$		
$\mathrm{Im}(c_e) \sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\mathrm{TeV}$		

Lepton Flavor Violation and Dipole Moments

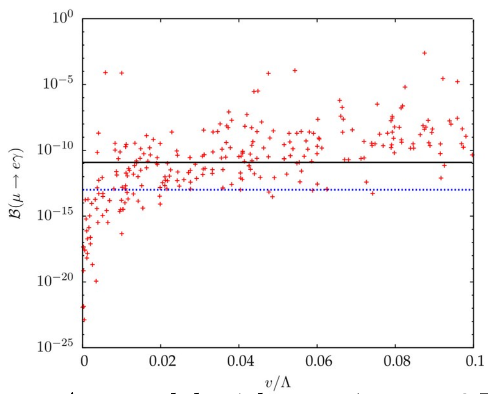
$$\mathcal{O}^{\gamma}_{\ell\ell'} \equiv ev\, F_{\mu\nu}\bar{\ell}_L\sigma^{\mu\nu}\ell'_R$$

Dipole operator

$\mu \to e\gamma$



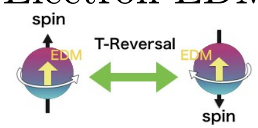
$\boxed{\ell=\mu, \ell'=e}$



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

del Aguila, Carmona, Santiago, 1001.5151

Electron EDM



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

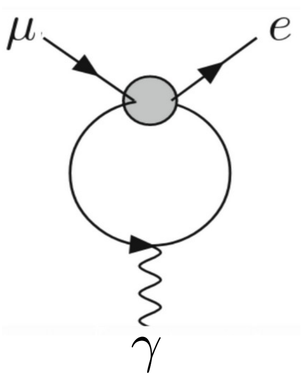
1. Anarchic Model	2./3. A_4/Min. Seesaw	4. MFPC
$\frac{m_*}{g_*} \gtrsim 20\,\mathrm{TeV}$	$\frac{m_*}{g_*} \gtrsim (0.1-1)\,\mathrm{TeV}$	
$\mathrm{Im}(c_e)\sim 1$ $\frac{m_*}{g_*} \gtrsim 75\,\mathrm{TeV}$		

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

$\mu \to e\gamma$



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

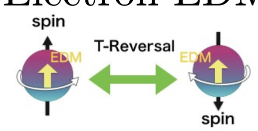
$\mathcal{L} \sim -(f)^i{}_a \epsilon_{ij} \boxed{\mathcal{S}^j \epsilon_{\rm TC} \mathcal{F}^a}$

MFPC: Flavor structure induced by fundamental constituents

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

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

Electron EDM



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

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

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

Lepton Flavor Violation and Dipole Moments

In general less stringent bounds from

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

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

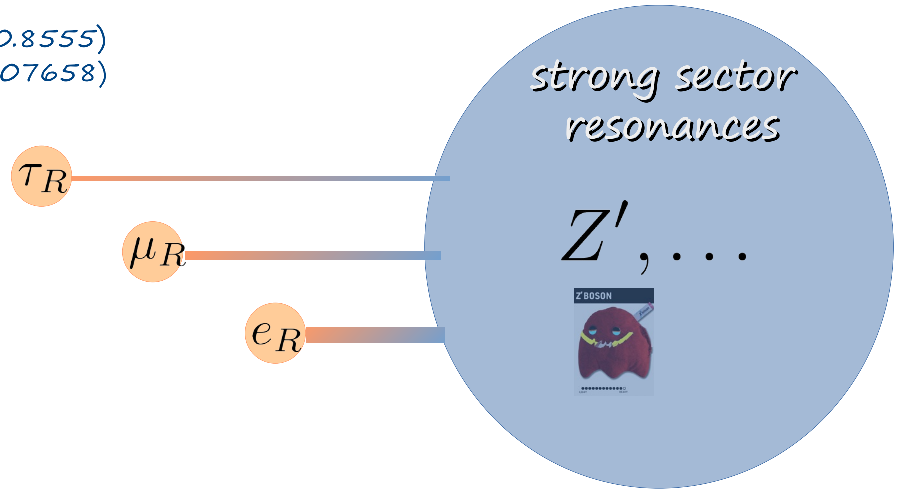
SINDRUMII

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

Avoiding Light Top Partners I

Minimal Seesaw Model
→ lepton compositeness

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



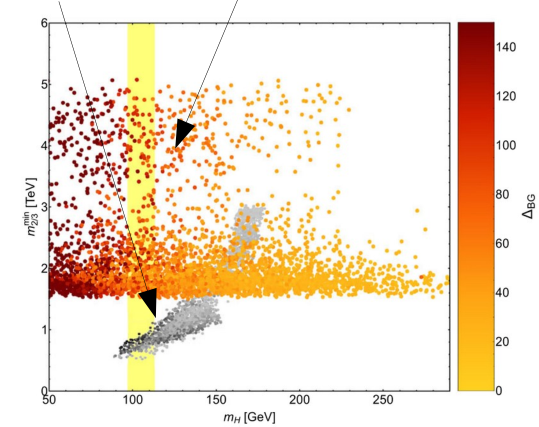
$\mathcal{O}_L^\ell$ fundamental
$\mathcal{O}_R^\ell$ symmetric

$$\mathcal{L}_{\rm mix} \supset \lambda_L^\ell\, \bar{L}_L^\ell \mathcal{O}_L^\ell + \lambda_R^\ell\, \bar{L}_R^\ell \mathcal{O}_R^\ell$$

ℓ_L ν_L ℓ_R Σ_R

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

Lepton compositeness solves issue with light top partners:

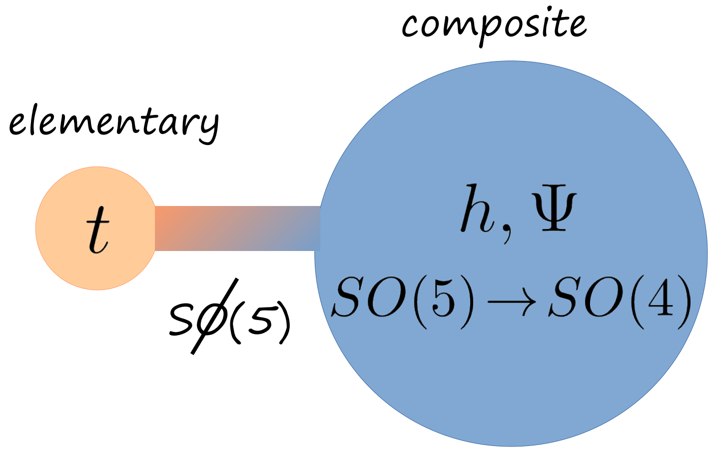


Carmona, FG, JHEP (1410.8555)
Carmona, FG, PRL (1510.07658)

Avoiding Light Top Partners II

Change the nature of explicit Goldstone-symmetry breaking

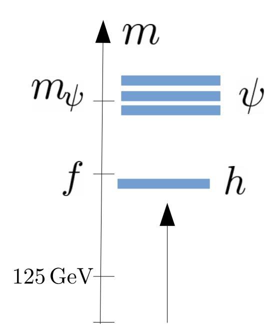
Blasi, FG, PRL (1903.06146)



Make partial compositeness respect global symmetry

$$\boxed{\bar{q}_L} \cdot \boxed{\Psi_R^T}$$

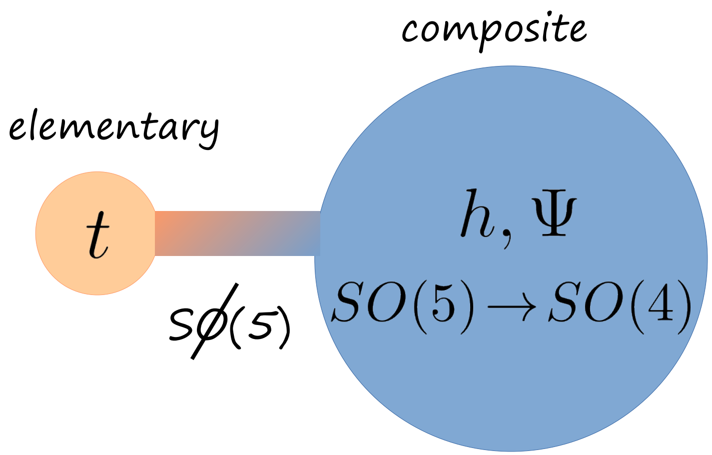
$\mathbf{5}$ of $SO(5)$

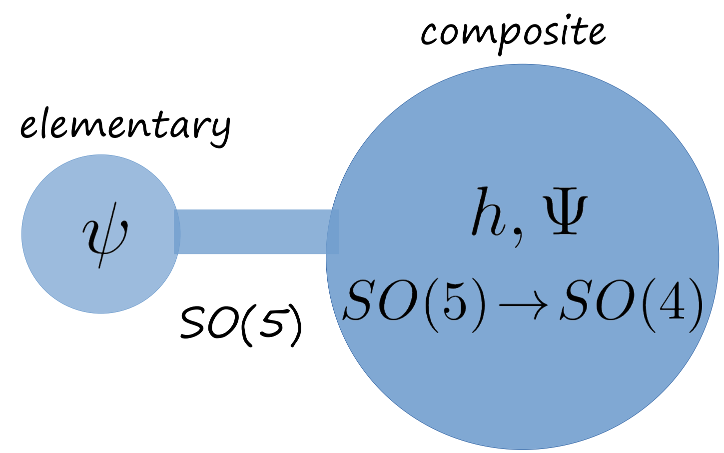


Avoiding Light Top Partners II

Change the nature of explicit Goldstone-symmetry breaking

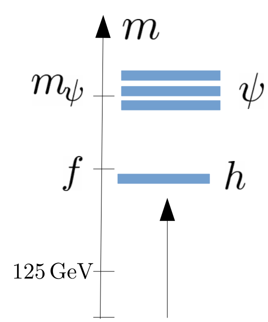
Blasi, FG, PRL (1903.06146)





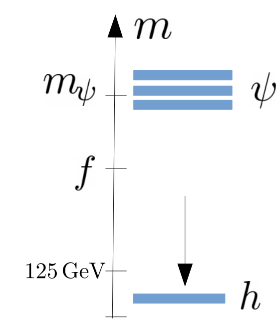
$\boxed{\bar{q}_L} \cdot \boxed{\Psi_R^T}$

5 of $SO(5)$



$\boxed{\bar{\psi}_L \cdot \Psi_R^T}$

$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ \boxed{t_L} + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$

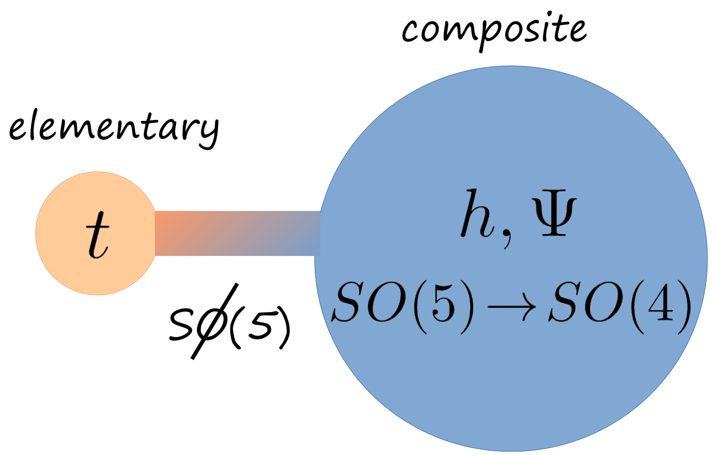


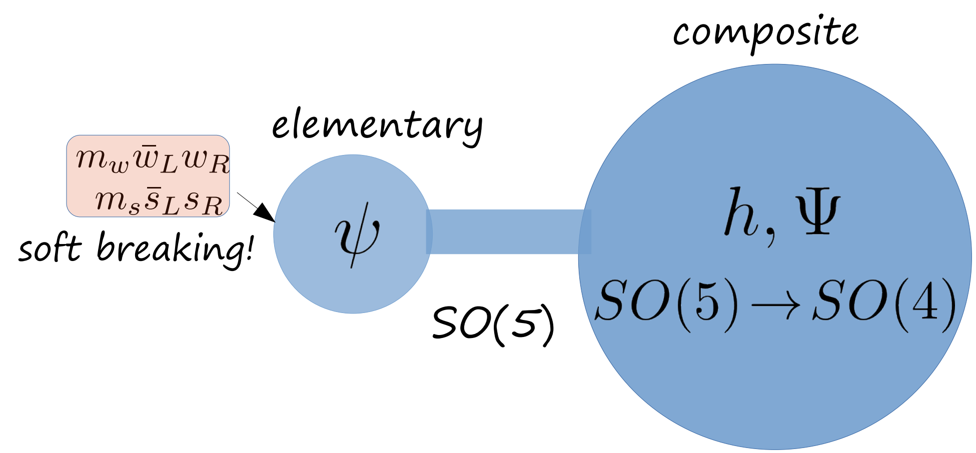
+ similar for RH

Avoiding Light Top Partners II

Change the nature of explicit Goldstone-symmetry breaking

Blasi, FG, PRL (1903.06146)

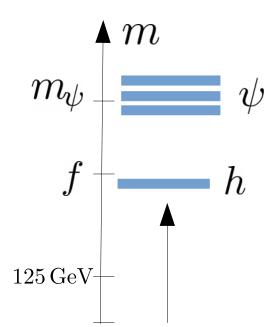




$\bar{q}_L \cdot \Psi_R^T$

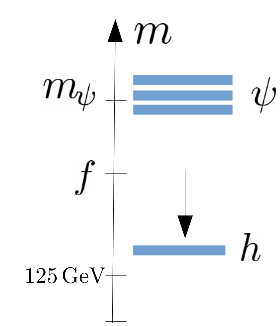
$\uparrow$

$\mathbf{5}$ of $SO(5)$



$\bar{\psi}_L \cdot \Psi_R^T$

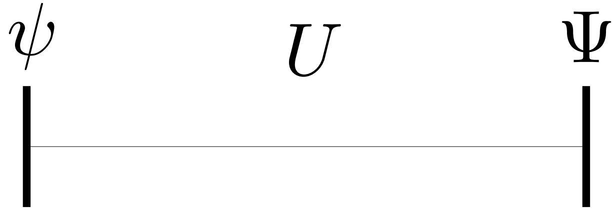
$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$



+ similar for RH

$m_w, m_s \gtrsim \mathrm{TeV}$

Two-Site Model Lagrangian



$\mathbf{4}$ $\mathbf{1}$ of $SO(4)$

Resonances $\Psi = U(Q,\, \tilde{T})^T$

$$U = e^{-i\frac{\sqrt{2}}{f}h_a(x)T^a}$$

Partial Compositeness:

$$\begin{aligned}\mathcal{L}_{\text{mass}} = & - m_Q \bar{Q}_L Q_R - \tilde{m}_T \bar{\tilde{T}}_L \tilde{T}_R \\ & - y_L f\, \bar{\psi}_{LI} \left(U_{Ii} Q^i_R + U_{I5} \tilde{T}_R \right) \\ & - y_R f\, \bar{\psi}_{RI} \left(U_{Ii} Q^i_L + U_{I5} \tilde{T}_L \right) + \text{h.c.}\end{aligned}$$

Vector-like elementary masses:

$$-\mathcal{L}_{\text{el}} = m_s \bar{s}_L s_R + m_v \bar{v}_L v_R + m_w \bar{w}_L w_R + \text{h.c.}$$

SO(5) Breaking Spurions

Standard MCHM$_5$

$$\psi_L = \Delta_L^\dagger q_L \qquad \Delta_L = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 & -i & 0 \\ 1 & i & 0 & 0 & 0 \end{pmatrix}$$

$$\psi_R = \Delta_R^\dagger t_R \qquad \Delta_R = -i\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{L}_{\text{mass}} \supset -\, y_L f\ \bar{q}_L \boxed{\Delta_L} U \Psi_R^T \\ -\, y_R f\ \bar{t}_R \boxed{\Delta_R} U \Psi_L^t$$

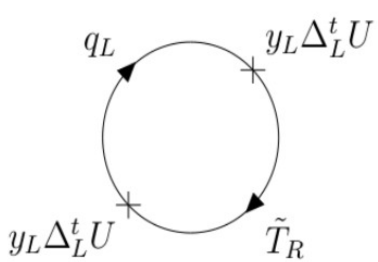
sMCHM$_5$

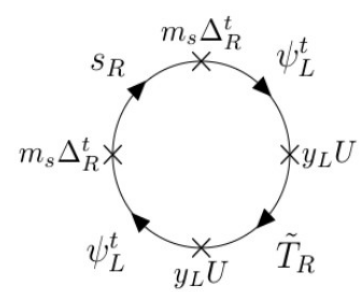
$$\psi_L \sim \mathbf{5}$$

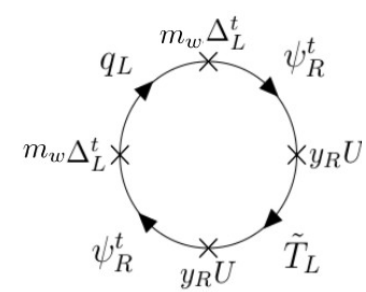
$$\psi_R \sim \mathbf{5}$$

$$-\mathcal{L}_{\text{el}} = m_w \bar{\psi}_L \psi_R + m_v \bar{v}_L \boxed{\Delta_L} \psi_R \\ + m_s \bar{s}_R \boxed{\Delta_R} \psi_L \\ - m_w \bar{q}_L \boxed{\Delta_L} \psi_R \\ - m_w \bar{\psi}_L \boxed{\Delta_R}^* t_R + \text{h.c.}$$

$V(h) \sim$







SO(5) Breaking Spurions

Standard MCHM$_5$

$$\psi_L = \Delta_L^\dagger q_L \qquad \Delta_L = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 & -i & 0 \\ 1 & i & 0 & 0 & 0 \end{pmatrix}$$

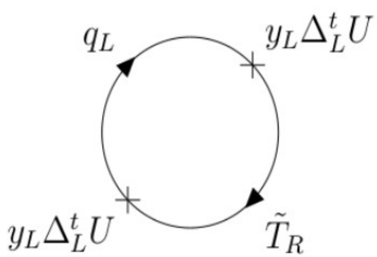
$$\psi_R = \Delta_R^\dagger t_R \qquad \Delta_R = -i\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

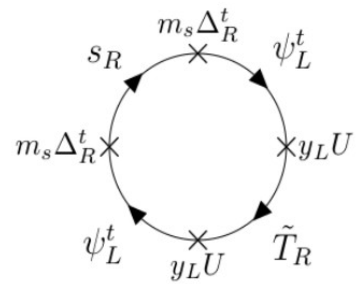
sMCHM$_5$

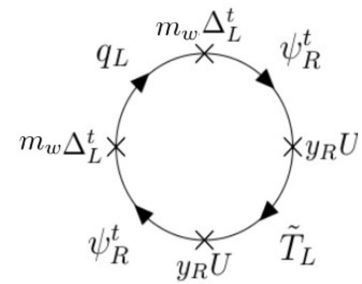
$$\psi_L \sim \mathbf{5}$$

$$\psi_R \sim \mathbf{5}$$

$$V(h) \sim$$







$$m_h \simeq \frac{m_T}{f} m_t \boxed{\frac{\sqrt{\epsilon}}{2(1-\epsilon/4)}}$$

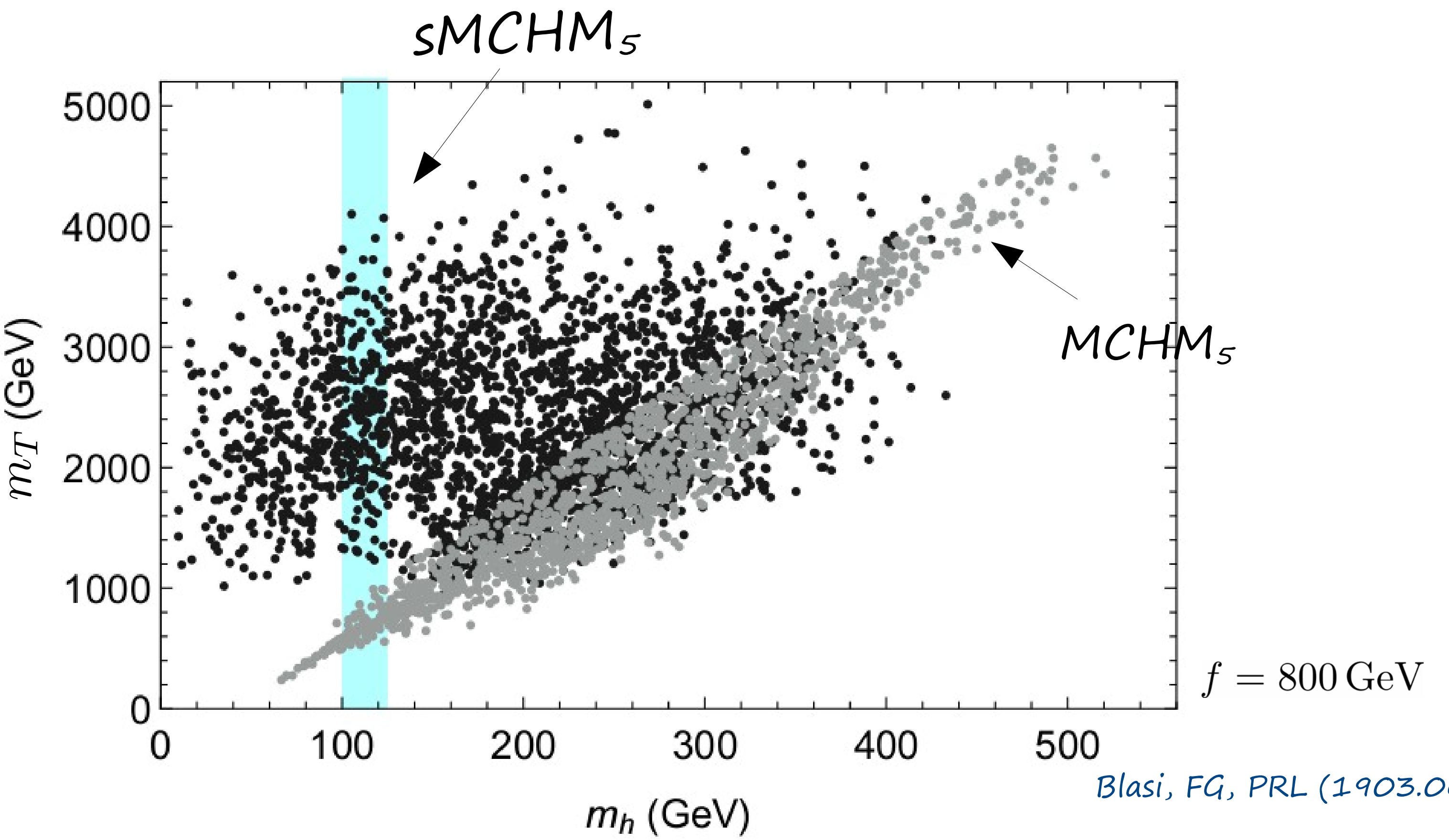
$$< 1$$

$$\boxed{\epsilon \equiv 1 - M/m_s}$$

$$m_Q = -\, m_{\tilde{T}} \equiv M$$

$$m_s \ll m_w, m_v$$

Full Results



Blasi, FG, PRL (1903.06146)

$$1 \le |y_{L,R}| \le 2\,,\ 5 \le |\tilde{m}_T/\mathrm{TeV}| \le 10\,,\ -2 \le m_Q/\tilde{m}_T \le -0.3\,,\ 1.5 \le |\tilde{m}_T/m_s| \le 5\,,\ 2 \le |m_{w,v}/m_s| \le 4$$

Tuning in $MCHM_5$

$$\boxed{V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)}$$

$$\Delta \simeq \frac{f^2}{v^2} \times \boxed{\left(\frac{\alpha}{2\beta}\right)} \xrightarrow{MCHM_5:\ f \sim m_T} \Delta_5 \simeq \boxed{100} \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

double-tuning → further increase symmetry

‘Maximal Symmetry’

Enhanced global symmetry eliminates double-tuning

Csaki, Ma, Shu, PRL (1702.00405), 1810.07704 (+Yu)

$$SO(5)_L \times SO(5)_R \xrightarrow{m_Q,\,\tilde{m}_T} SO(5)_{V'} \supset SO(4)$$

chiral symmetry in composite sector

$$\mathcal{L}_{\text{mass}} = \underbrace{-m_Q \bar{Q}_L Q_R - \tilde{m}_T \bar{\tilde{T}}_L \tilde{T}_R}_{\displaystyle -\bar{\Psi}_L \left((m_Q + \tilde{m}_T) + (m_Q - \tilde{m}_T)V\right)\Psi_R} + \cdots$$

$$\Psi = (Q,\, \tilde{T})^T$$

$\mathbf{4}$ $\mathbf{1}$ of $SO(4)$

I: $\boxed{m_Q = \tilde{m}_T} \to SO(5)_V \to \boxed{V(h) = 0}$ $\quad SO(5)_V : \ L = R$

II: $\boxed{m_Q = -\tilde{m}_T} \to SO(5)_{V'} \to V(h) \neq 0$ $\quad \boxed{SO(5)_{V'} : \ L^\dagger V R = V}$ ‘Maximal Symmetry’

$$V = \begin{pmatrix} \mathbf{1}_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

Higgs-Parity Operator

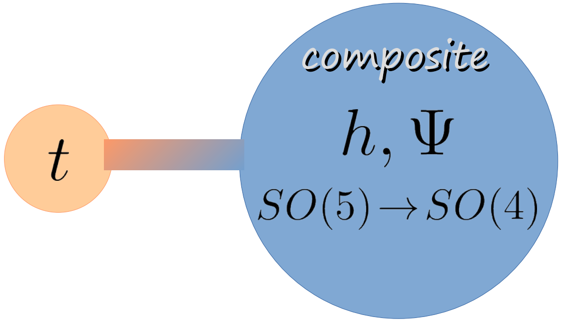
$V T^a V^\dagger = T^a\,,\ V T^{\hat{a}} V^\dagger = -T^{\hat{a}}$

Maximal Symmetry

$$\boxed{SO(5)_L \times SO(5)_R \longrightarrow SO(5)_{V'}}$$

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$\text{Minimum}: \boxed{\sin^2(v/f) = -\frac{\alpha}{2\beta}}$$



$SO(5)_{V'}$: $\boxed{\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta \;\; \to \text{No double tuning :)}}$

$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right) \xrightarrow[\alpha \sim \beta]{f \sim m_T} \boxed{10}\left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

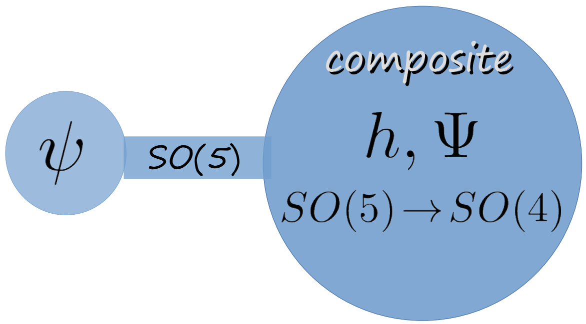
$\alpha + \beta = 0 \to \boxed{\sin^2(v/f) = 1/2}$ ↯ $\to$ cancel with gauge contr.

Maximal Symmetry + Soft Breaking

$$\boxed{SO(5)_L \times SO(5)_R \longrightarrow SO(5)_{V'}}$$

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$\text{Minimum}: \boxed{\sin^2(v/f) = -\frac{\alpha}{2\beta}}$$



$SO(5)_{V'}$: $\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta$ → No double tuning :)

$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L - w_{1L}^1 \\ -ib_L - iw_{1L}^1 \\ t_L + w_{1L}^2 \\ it_L - iw_{1L}^2 \\ -i\sqrt{2}\, s_L \end{pmatrix}$$

soft breaking

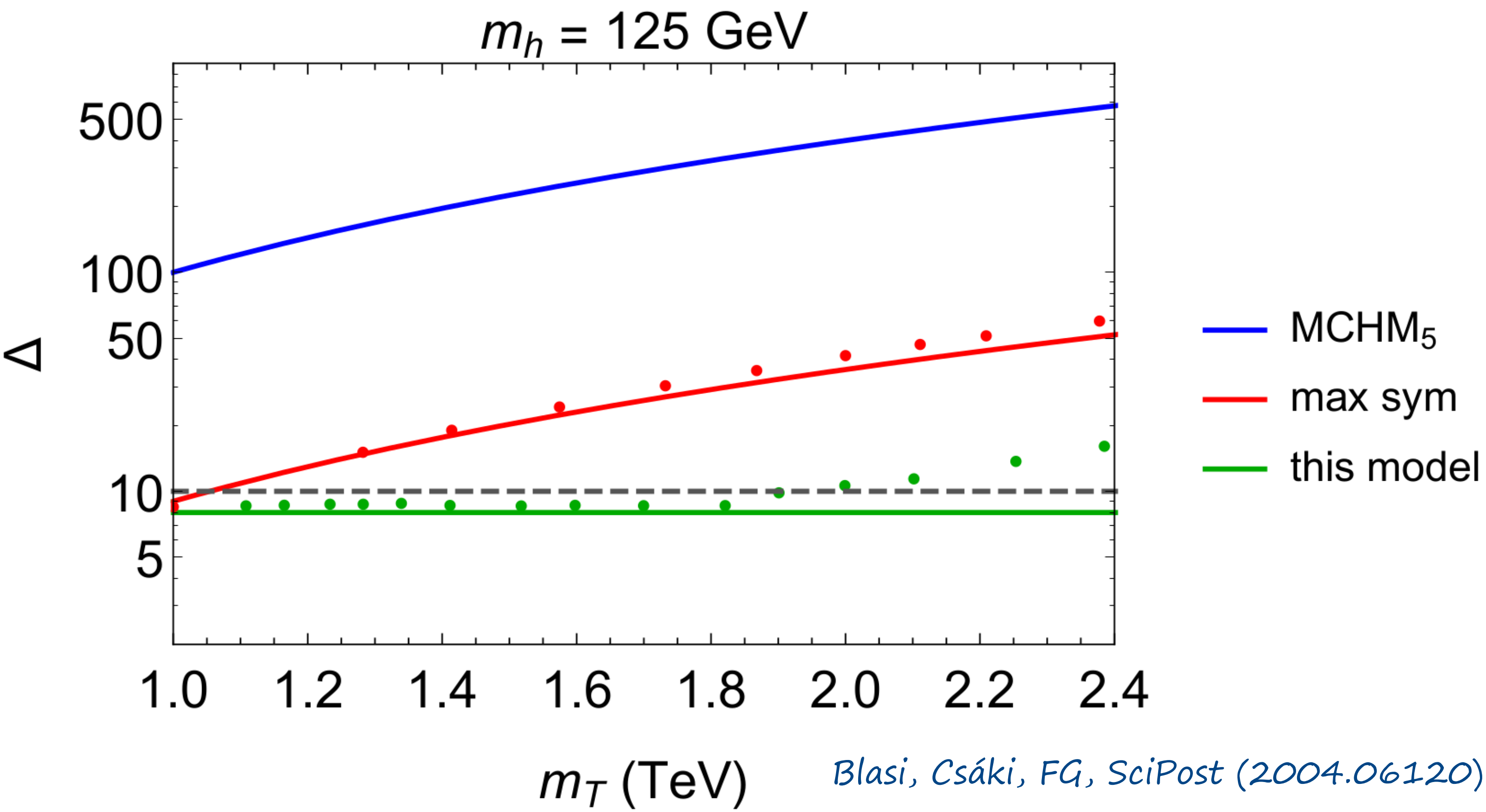
$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right) \xrightarrow[\alpha \sim \beta]{f \approx 800\,\mathrm{GeV} \not\sim m_T} 10 \left(\cancel{\frac{m_T}{1\,\mathrm{TeV}}}\right)^2 > 1$$

$$\psi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} v_R^2 - w_{2R}^1 \\ -iv_R^2 - iw_{2R}^1 \\ v_R^1 + w_{2R}^2 \\ iv_R^1 - iw_{2R}^2 \\ -i\sqrt{2}\, t_R \end{pmatrix}$$

$$\alpha + \beta \sim y_L^2 y_R^2 m_{w_1}^2 (m_v^2 - m_{w_2}^2) \neq 0 \rightarrow \sin^2(v/f) \neq 1/2$$

Blasi, Csáki, FG, SciPost (2004.06120)

Tuning: Max Symmetry + Soft Breaking



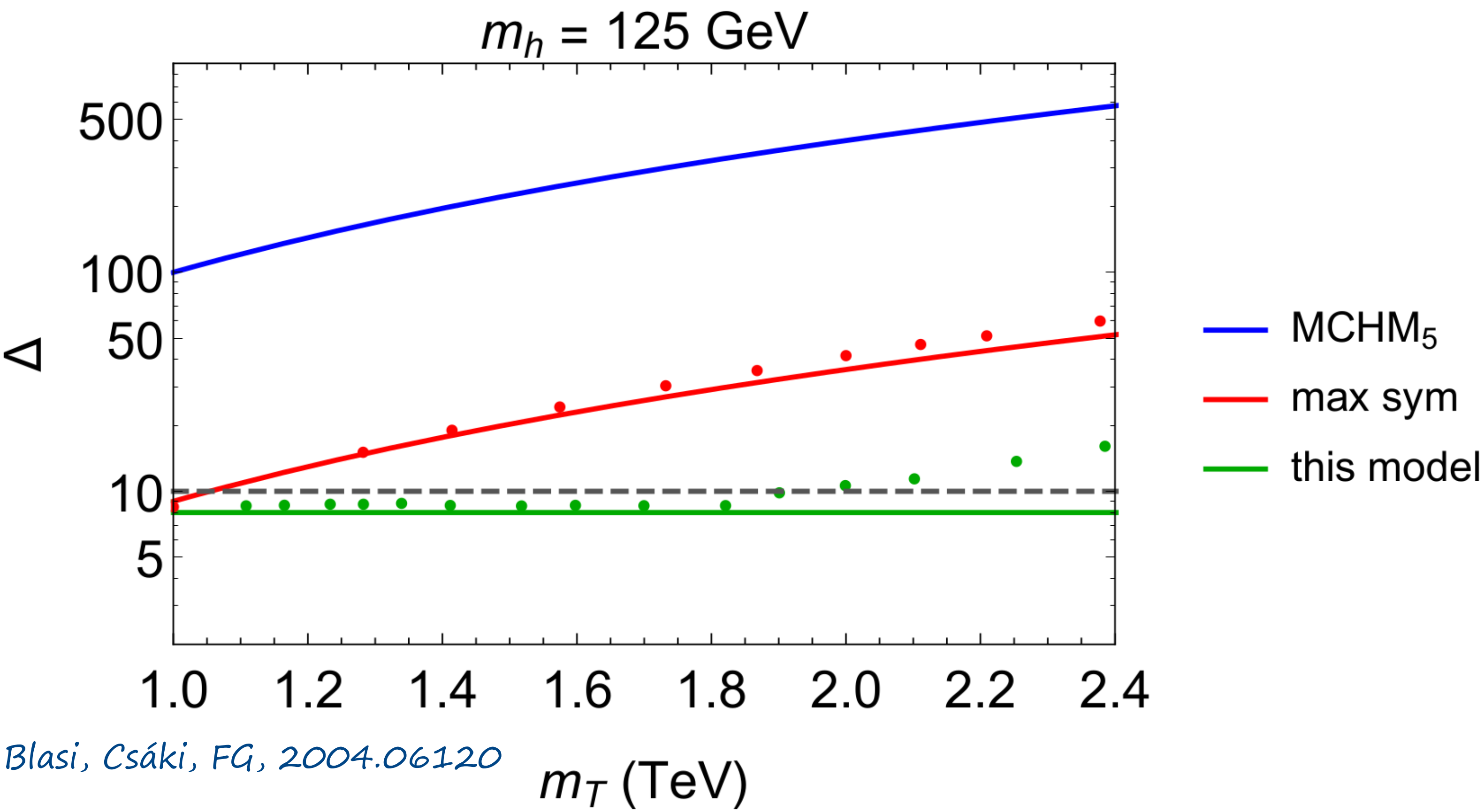
$$\Delta \simeq 100 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

$$\Delta \simeq 10 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

$$\Delta \simeq 10$$

Blasi, Csáki, FG, SciPost (2004.06120)

Tuning: Max Symmetry + Soft Breaking



$$\Delta \simeq 100 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

$$\Delta \simeq 10 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

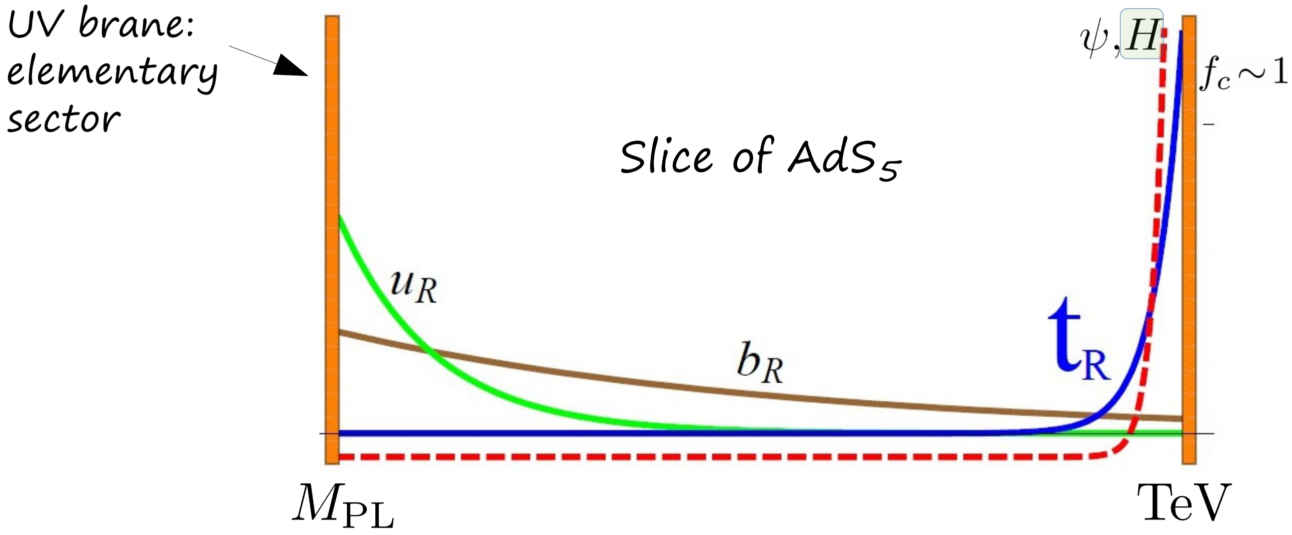
$$\Delta \simeq 10$$

Blasi, Csáki, FG, 2004.06120

- $m_T > 2\,\text{TeV}$ possible without notable tuning
- beyond that, no longer flat $\leftrightarrow$ tuning in ϵ

$$m_h \simeq \frac{m_T}{f} m_t \, \frac{\sqrt{\epsilon}}{2(1-\epsilon/4)} \qquad \epsilon \equiv \; 1 - M/m_s$$

Natural 5D Picture



MCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[-,+] & t[+,+] \\ w_1^2[-,+] & b[+,+] \end{pmatrix} \oplus s[-,+]$$

SO(5) broken hardly by Dirichlet
UV-boundary conditions

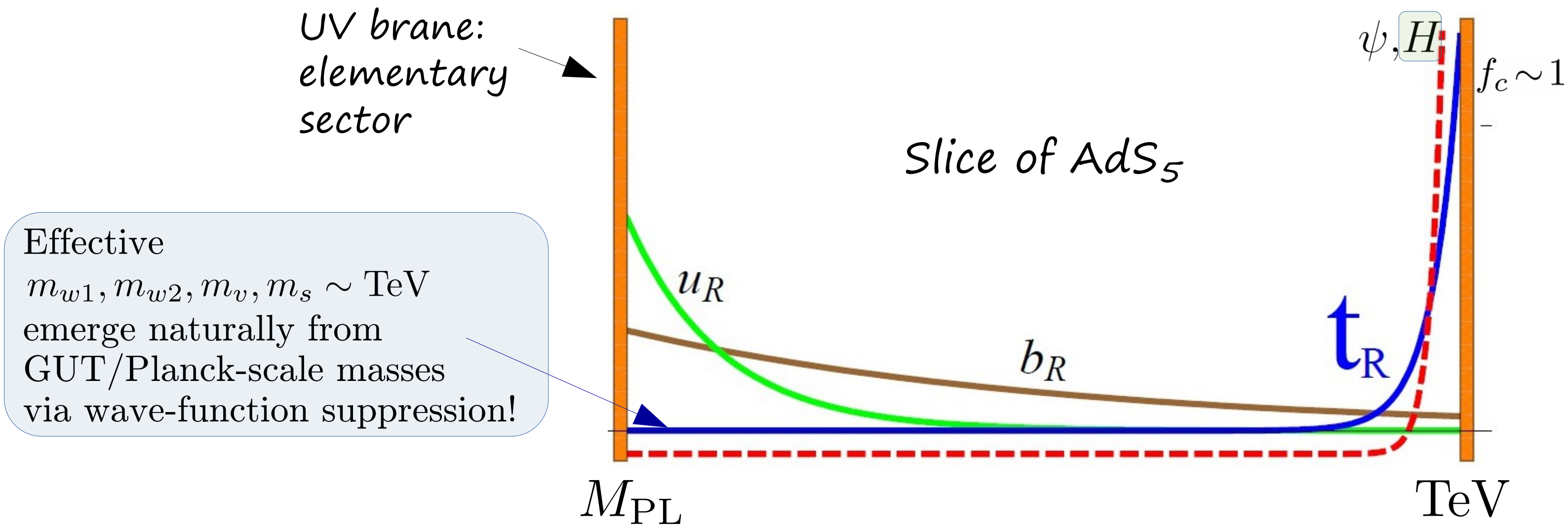
sMCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[+,+] & t[+,+] \\ w_1^2[+,+] & b[+,+] \end{pmatrix} \oplus s[+,+]$$

SO(5) preserving universal BCs,
breaking by finite UV-brane masses

$\mathbf{5} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1})$

Natural 5D Picture



MCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[-,+] & t[+,+] \\ w_1^2[-,+] & b[+,+] \end{pmatrix} \oplus s[-,+]$$

SO(5) broken hardly by Dirichlet UV-boundary conditions

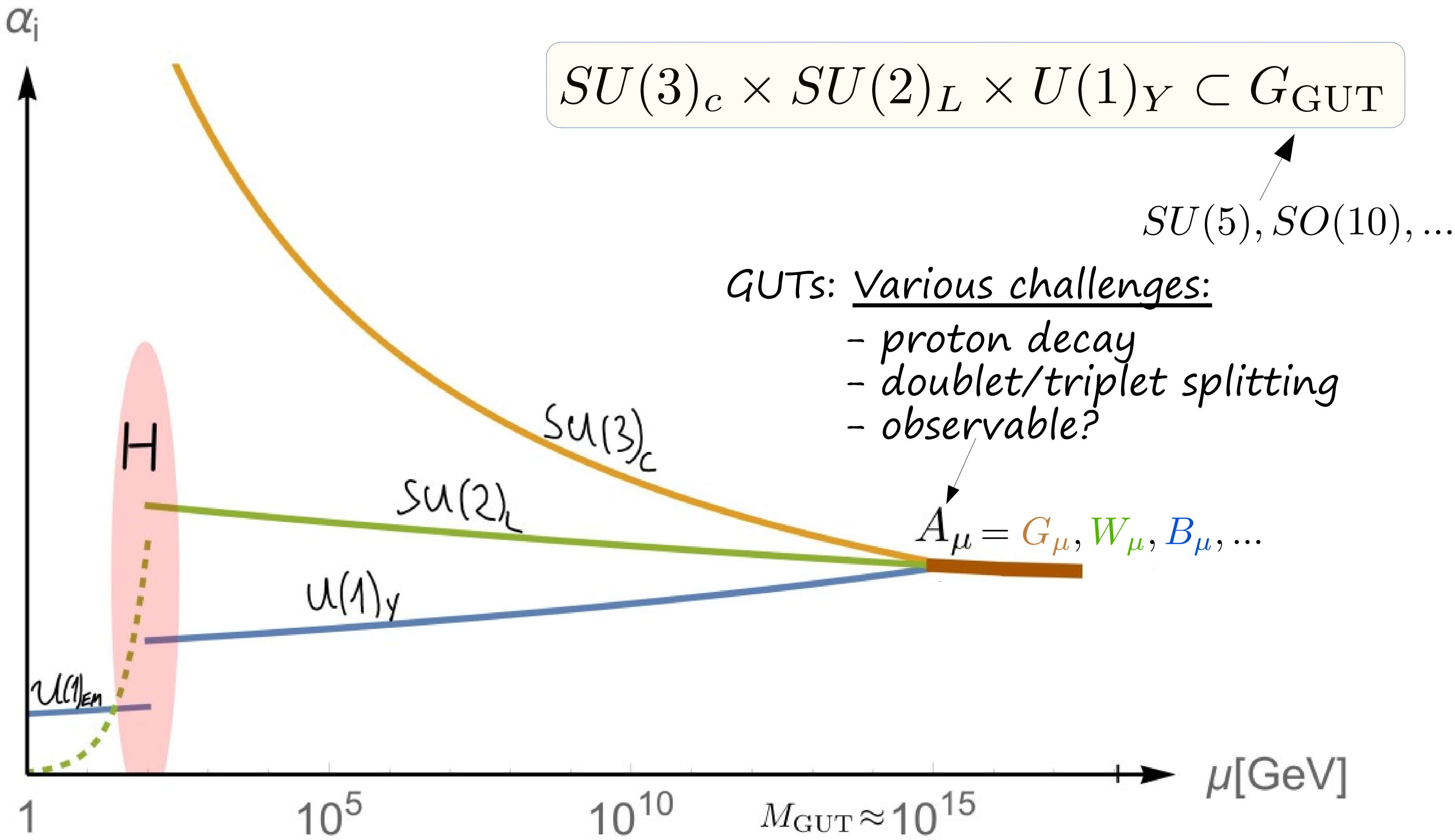
sMCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[+,+] & t[+,+] \\ w_1^2[+,+] & b[+,+] \end{pmatrix} \oplus s[+,+]$$

SO(5) preserving universal BCs, breaking by finite UV-brane masses

$$\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$$

Avoiding Light Top Partners III: Restoring Naturalness in GUT-embedding



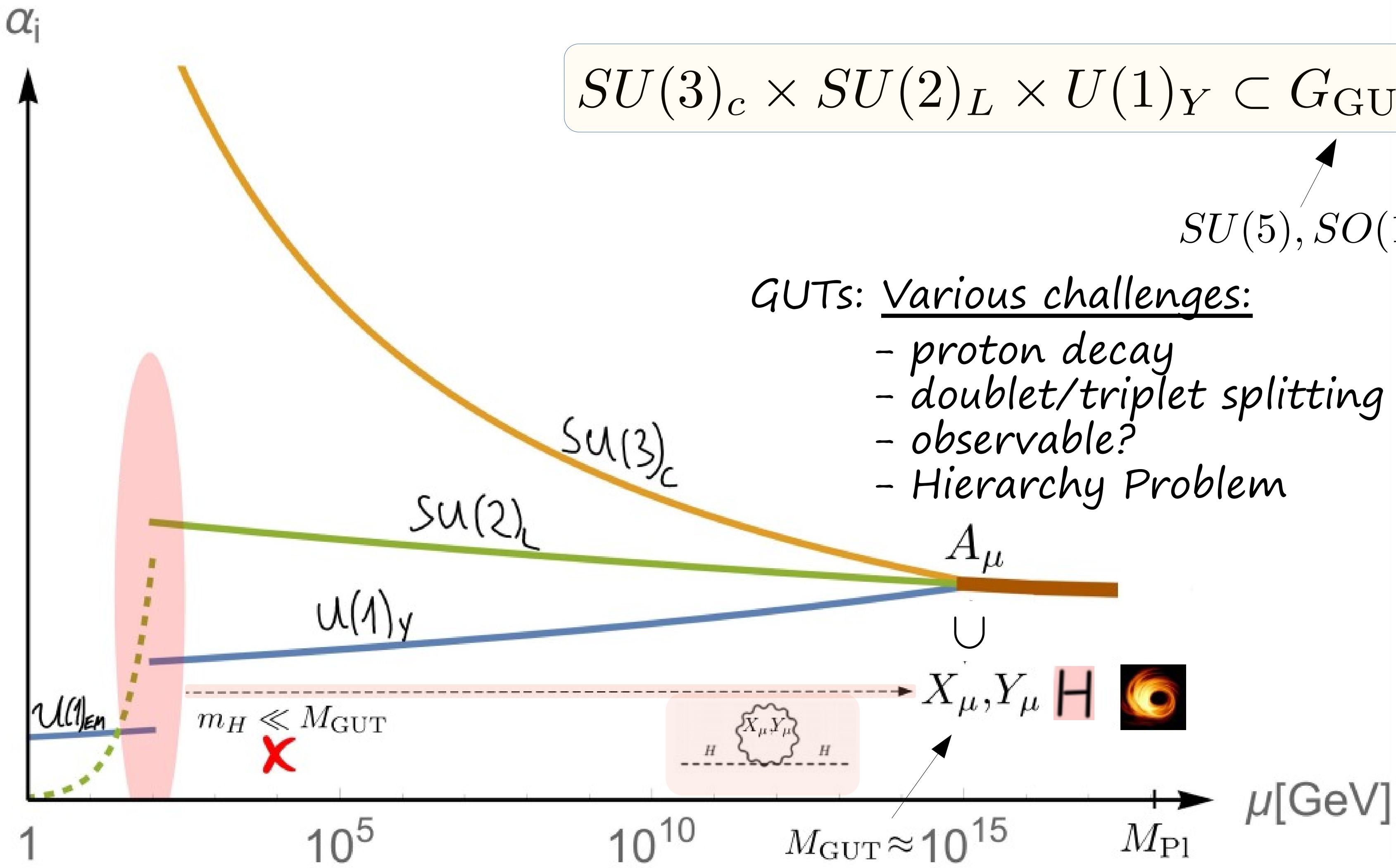
+ GUT Hierarchy Problem

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{\mathrm{GUT}}$$

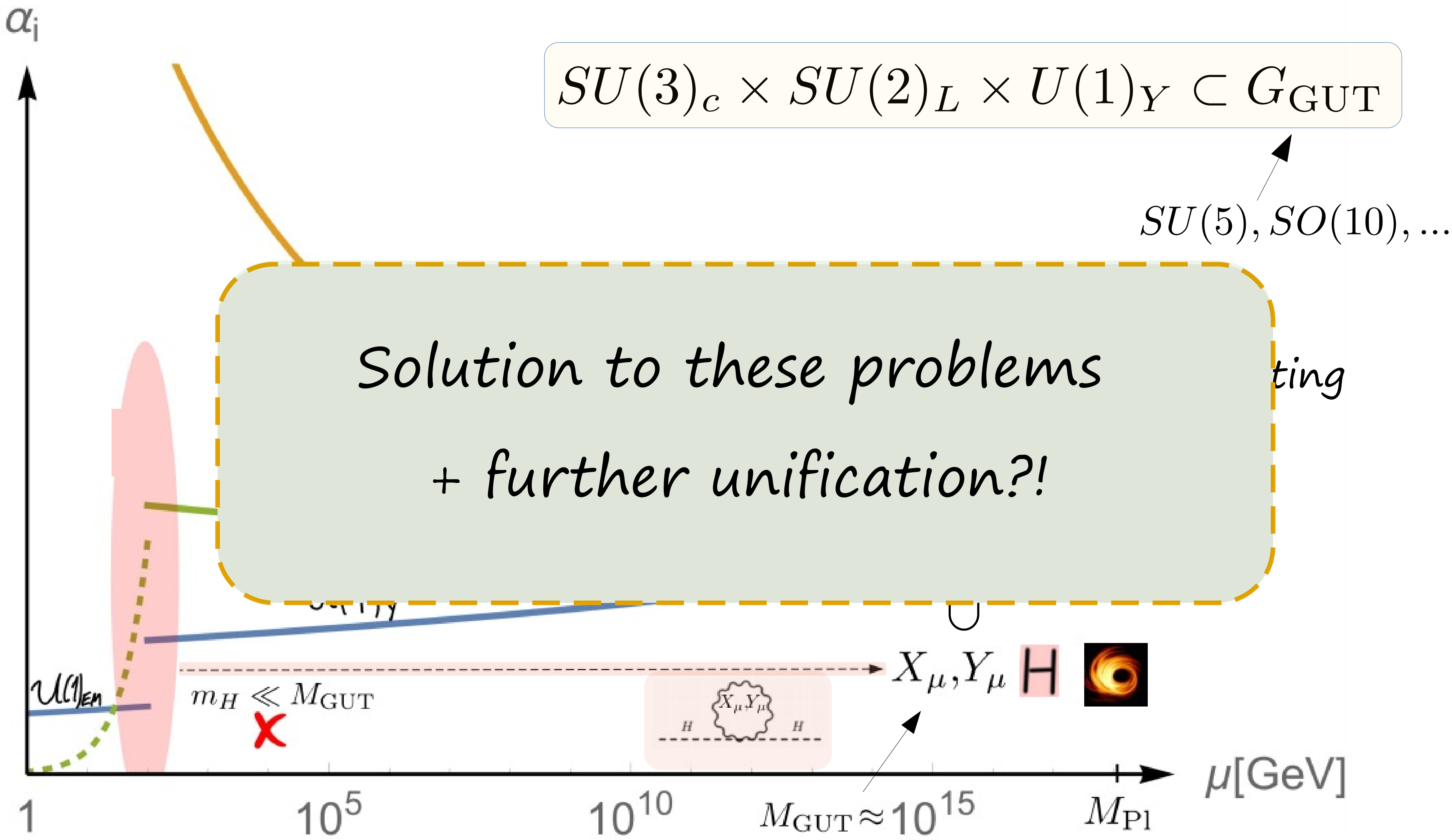
$SU(5), SO(10), \ldots$

GUTs: Various challenges:

- proton decay
- doublet/triplet splitting
- observable?
- Hierarchy Problem

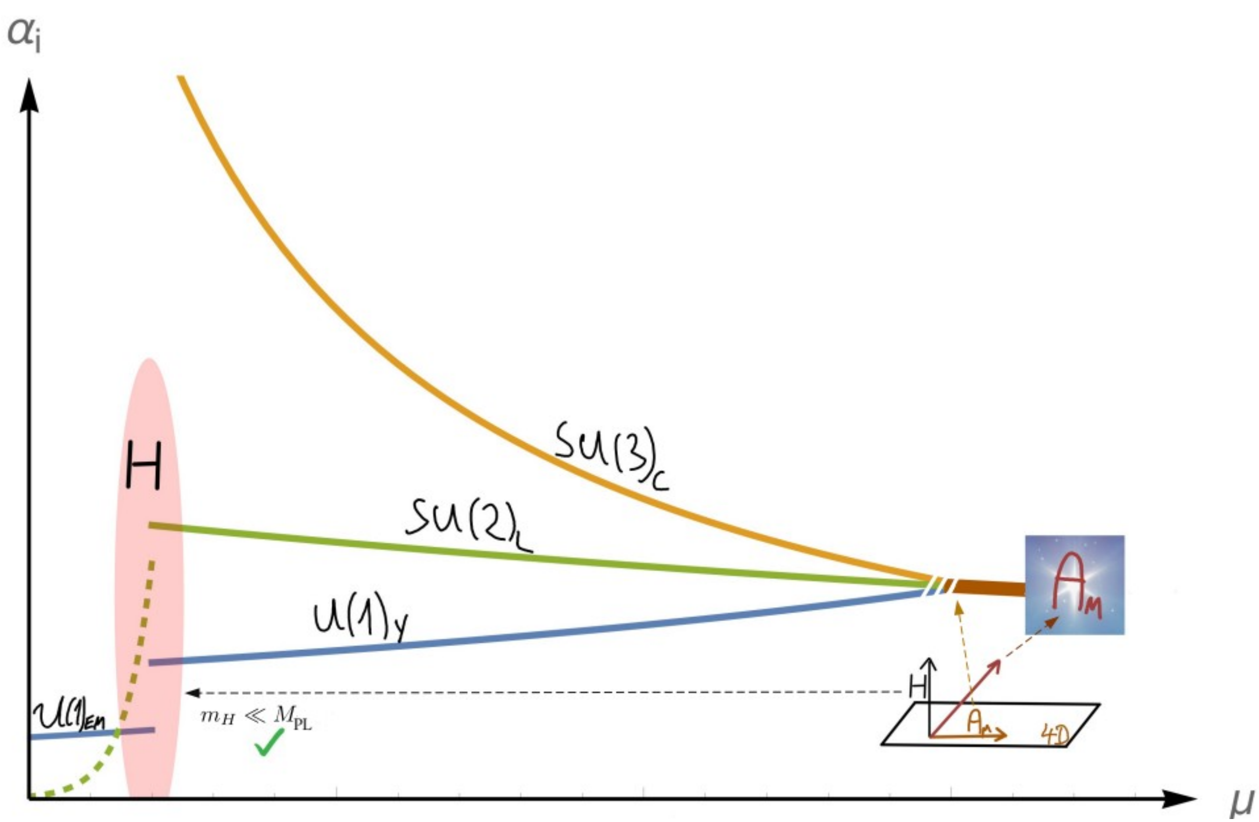


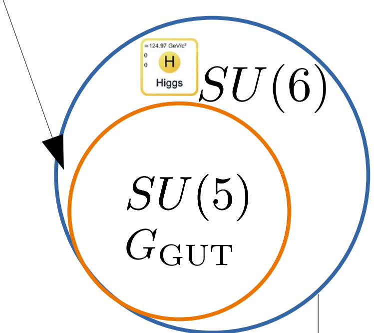
Grand Unification



Gauge-Higgs Grand Unification

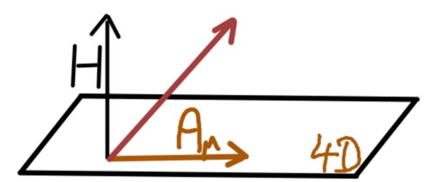
- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!



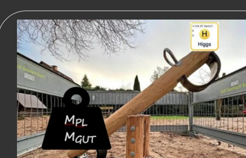


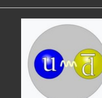
$$A_M^A = (\boxed{A_\mu^A}, \boxed{A_5^A})$$

4D vector   4D scalar → Higgs



Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...
Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

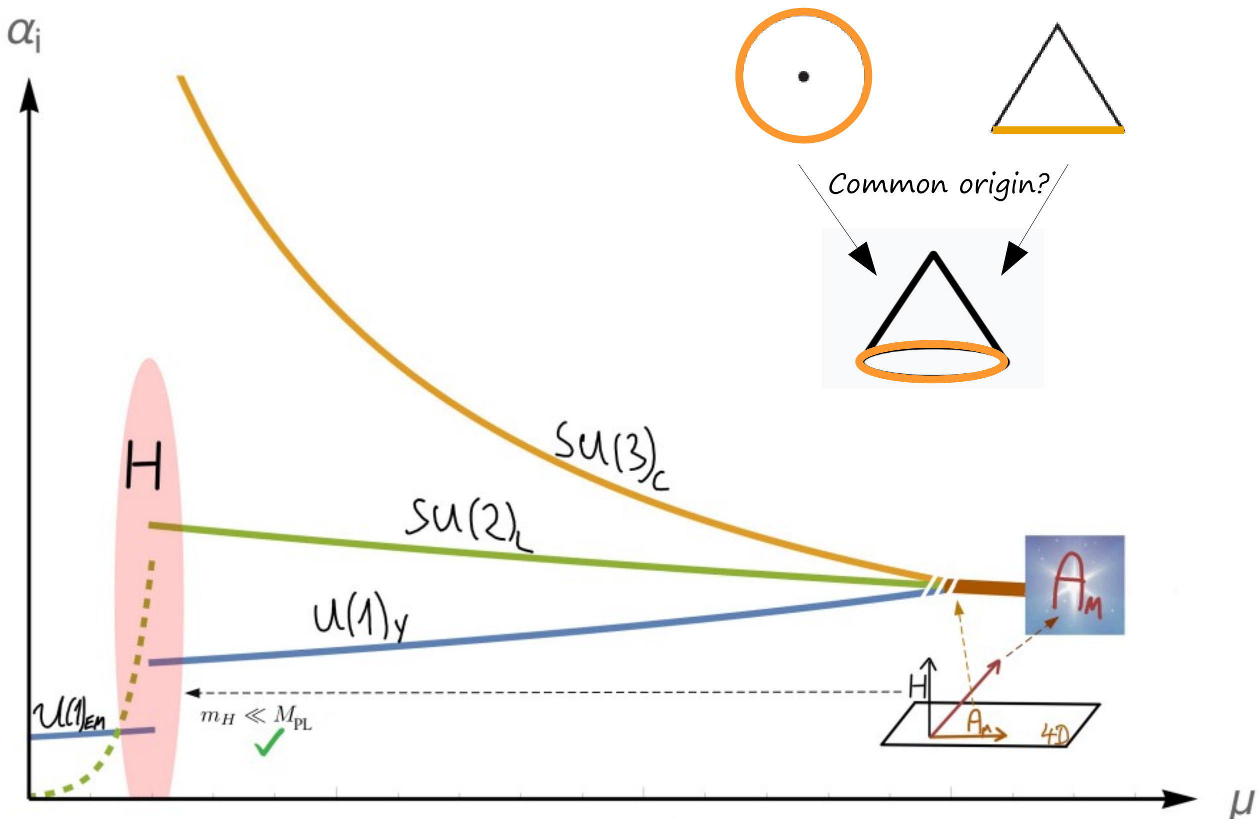


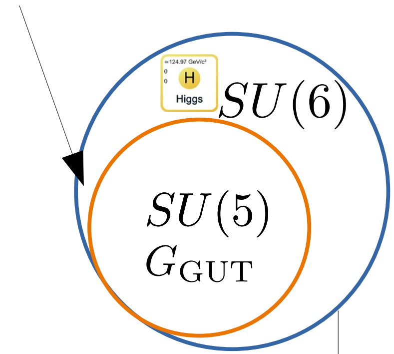


light pNGB: ✓
4D shift sym. ↔ 5D gauge sym.

Gauge-Higgs Grand Unification

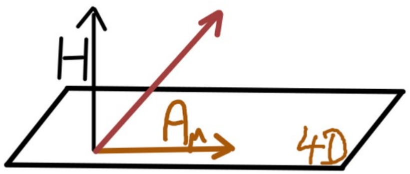
- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!





$$A_M^A = (\boxed{A_\mu^A}, \boxed{A_5^A})$$

4D vector   4D scalar → Higgs



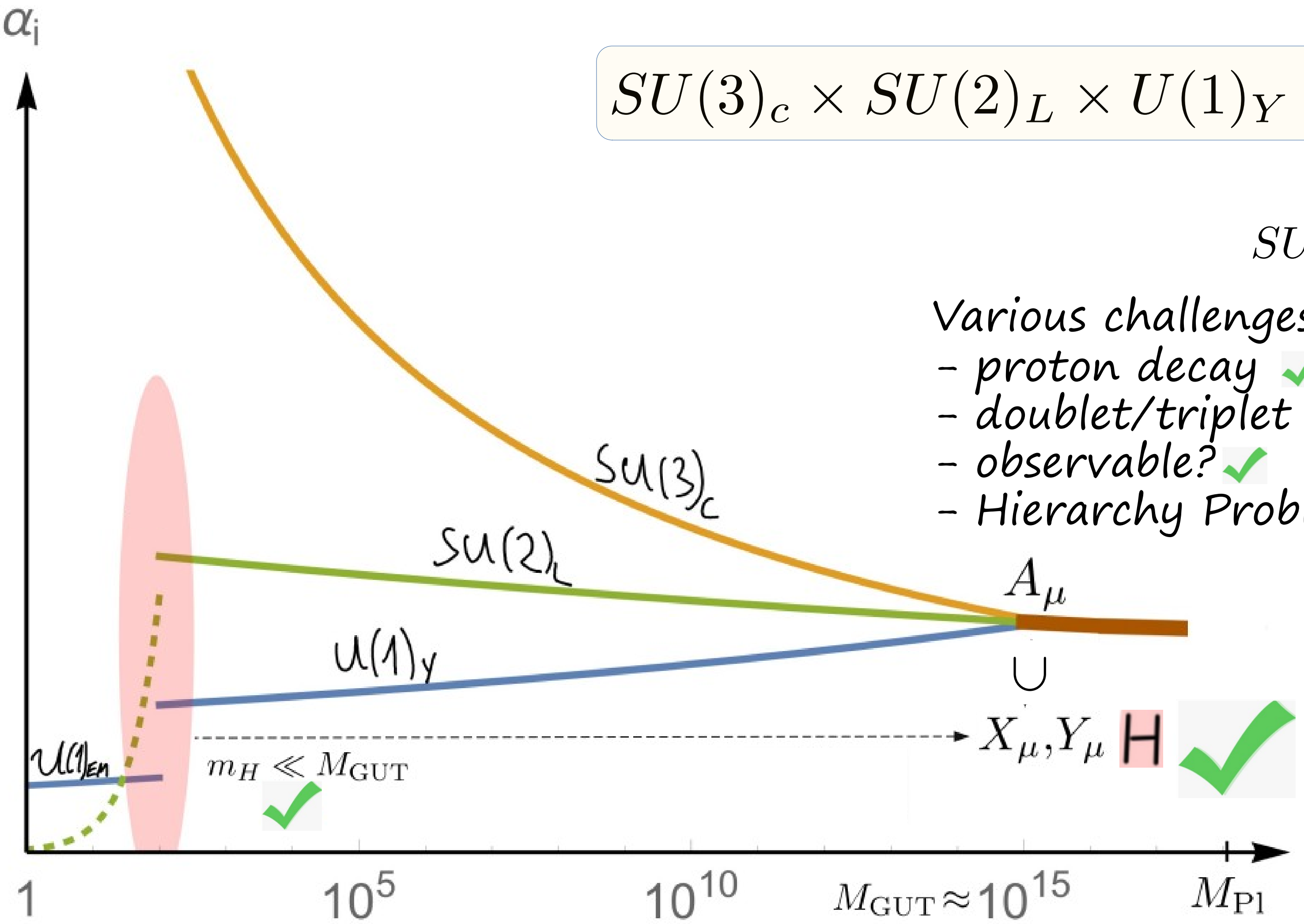
Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...
Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

Gauge-Higgs Grand Unification

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{\mathrm{GUT}}$$

$SU(5), SO(10), \ldots$

Various challenges:
- proton decay ✓
- doublet/triplet splitting ✓
- observable? ✓
- Hierarchy Problem ✓



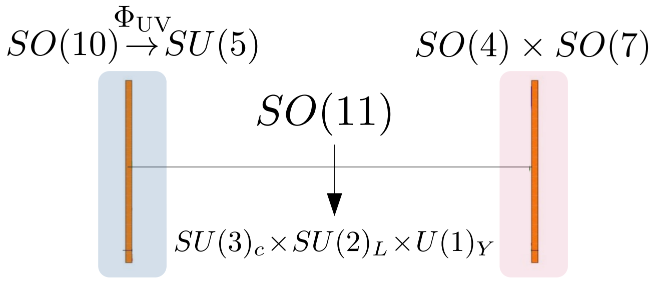
Gauge-Higgs Grand Unification

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

- Two considered setups:

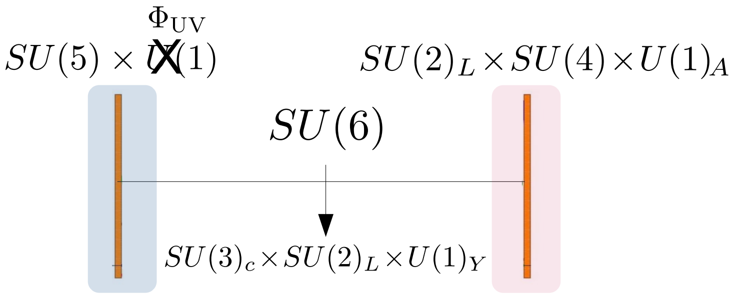
$SO(11)$

Hosotani, Yamatsu, 1504.03817
Furui, Hosotani, Yamatsu, 1606.07222
Hosotani, 1606.08108
(see also Agashe, Contino, Sundrum, hep-ph/0502222,
Frigerio, Serra, Varagnolo, 1103.2997,...)



$SU(6)$

Burdman, Nomura, hep-ph/0210257
Lim, Maru, 0706.1397
...
see also Cacciapaglia 2309.10098



Too Good To be True?

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

Severe phenomenological challenges:

$SO(11)$

$SU(6)$

- (too) light exotic states due to large irreps of bigger symmetry
- Difficult to obtain correct EWSB/m_H
- Degenerate/massless quarks&leptons

...

Too Good To be True?

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

Severe phenomenological challenges:

$SO(11)$

$SU(6)$

- go to 6D Hosotani, Yamatsu, 1706.03503, 1710.04811
- abandon bulk SM & introduce new BSM 5D multiplets + addtl. mirror fermions
  Maru, Yatagai, 1903.08359, 1911.03465 ...

Too Good To be True?

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

$$\left.\begin{array}{l} SO(11) \\ \\ SU(6) \end{array}\right\}$$

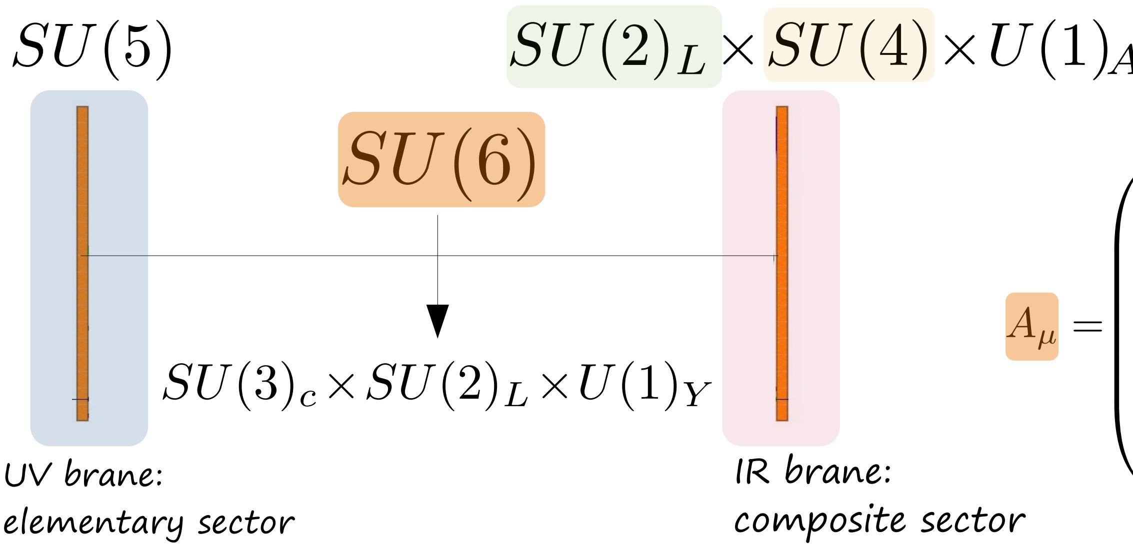
Minimal Alternative

⇩

SU(6) In warped space with different breaking pattern and brane masses

Original SU(6) Breaking

but warped...



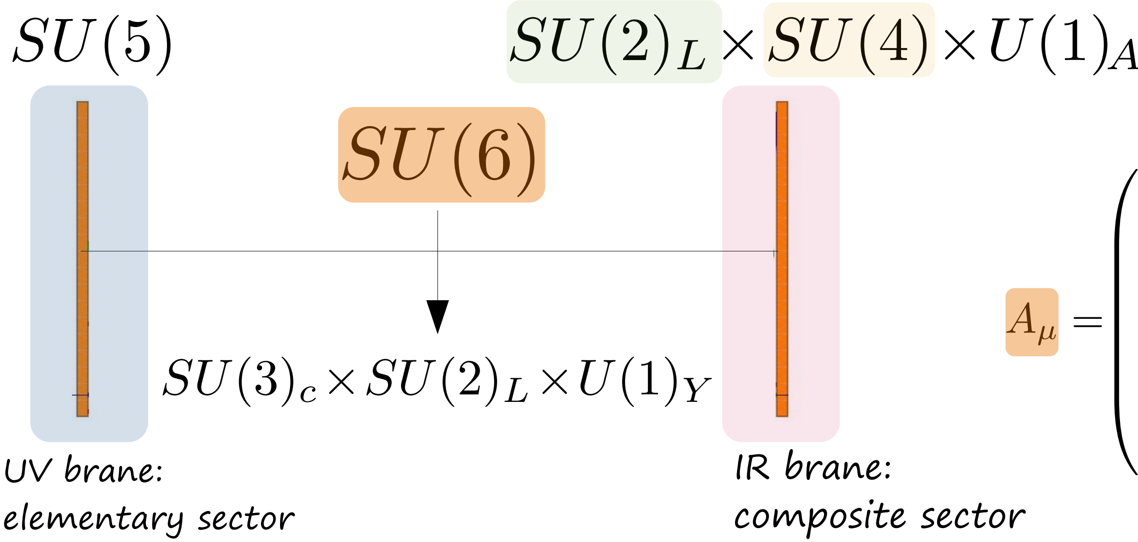
$$A_\mu = \left(\begin{array}{cc|ccc|c}
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
\hline
(+-) & (+-) & (++) & (++) & (++) & (-+) \\
(+-) & (+-) & (++) & (++) & (++) & (-+) \\
(+-) & (+-) & (++) & (++) & (++) & (-+) \\
\hline
(--) & (--) & (-+) & (-+) & (-+)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

$A_5 : + \leftrightarrow -$

$$(16 - 12) = 4 \text{ GBs} \rightarrow \text{Higgs}$$

Original SU(6) Breaking

but warped...



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

$A_5 : + \leftrightarrow -$

Fermion irreps (min. attempt):

RH 0-mode

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus \tilde{e}_R(\mathbf{1},\mathbf{1})^{-,-}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}$$
$$\oplus\, d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

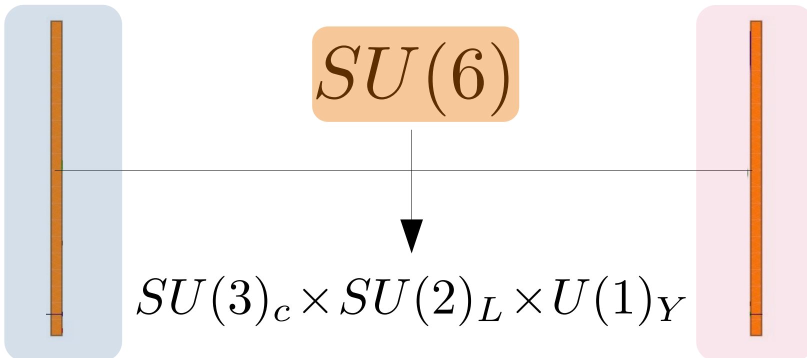
$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0}$$

$m_e (= m_u) = 0$

Novel Breaking Pattern

but warped...

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



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

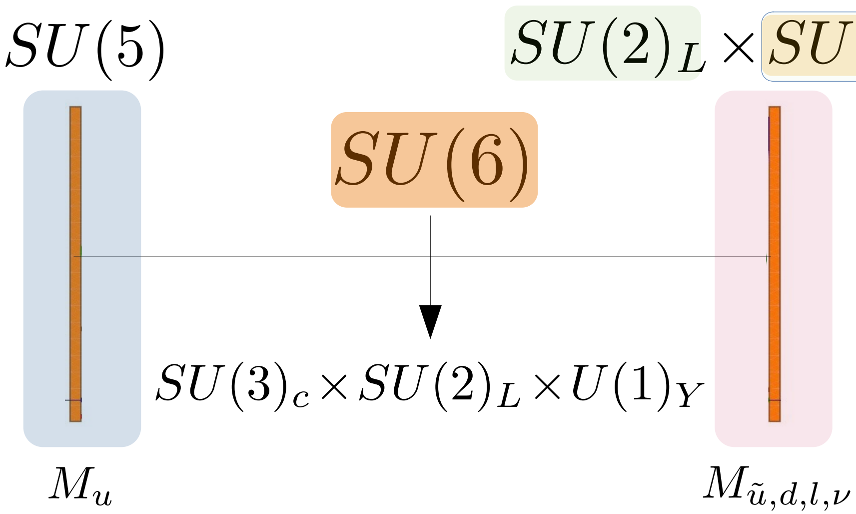
$A_5 : + \leftrightarrow -$

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

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

Novel Breaking Pattern

but warped...



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

$A_5 : + \leftrightarrow -$

Fermion irreps:

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}$$
$$\oplus (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0}$$

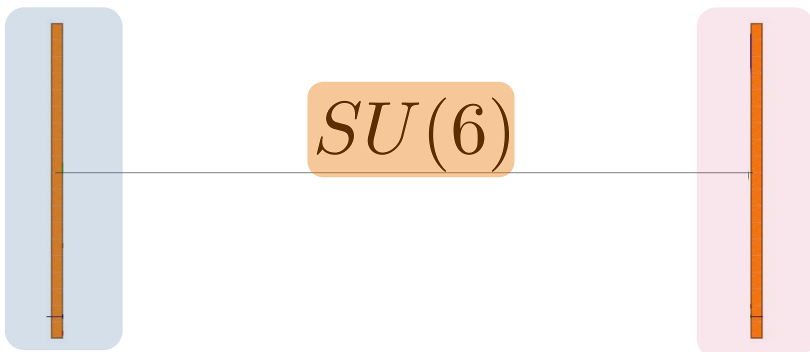
$M_u \to m_u$
$M_{\tilde{u}} \to V(H)$
$M_{d,l} \to m_e \neq m_d$
$M_\nu \to$ light ν

viable spectrum ✓
+EWSB!

Novel Breaking Pattern

Original Model

$SU(5)$ $\quad SU(2)_L \times SU(4) \times U(1)_A$



SM at low energies? ✗

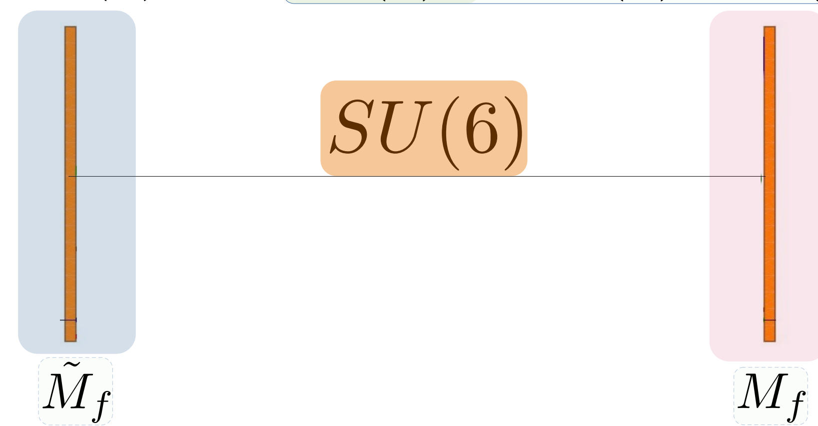
$m_e (= m_u) = 0$ $\quad \tilde{e}_R(\mathbf{1},\mathbf{1})_1$

$m_h \not\approx 125\,\mathrm{GeV}$

New Pattern

$G_{\rm SM}$

$SU(5)$ $\quad SU(2)_L \times SU(3)_c \times U(1)_Y$



Reproduces SM at low energies! ✓
(incl. EWSB, m_H, ...)

Angelescu, Bally, Blasi, FG [PRD] (2104.07366)
Angelescu, Bally, FG, Weber [JHEP] (2208.13782)

Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ

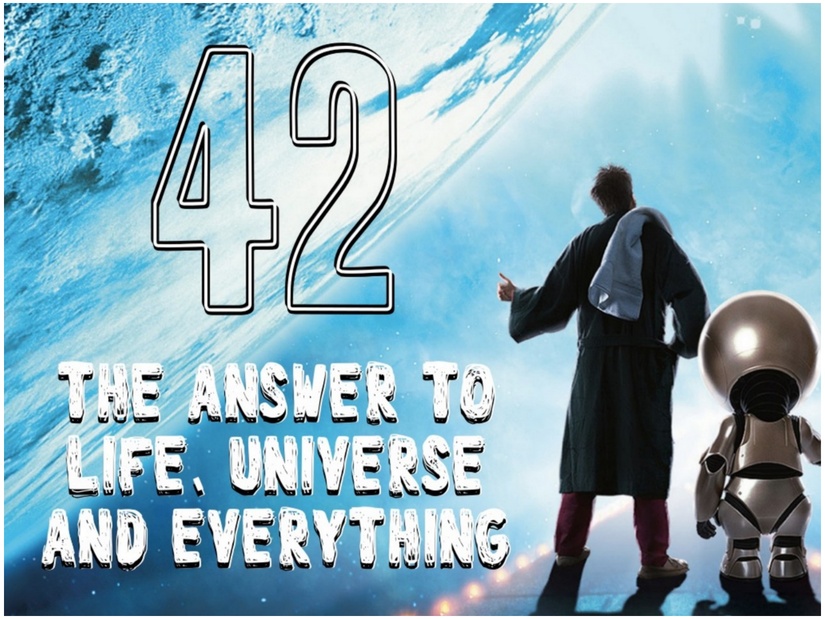
The Model is True!

$\boxed{\text{Higgs} + \text{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\ \text{LQ}}$

- The mode is true....

  ... well, because 20+15+6+1 = 

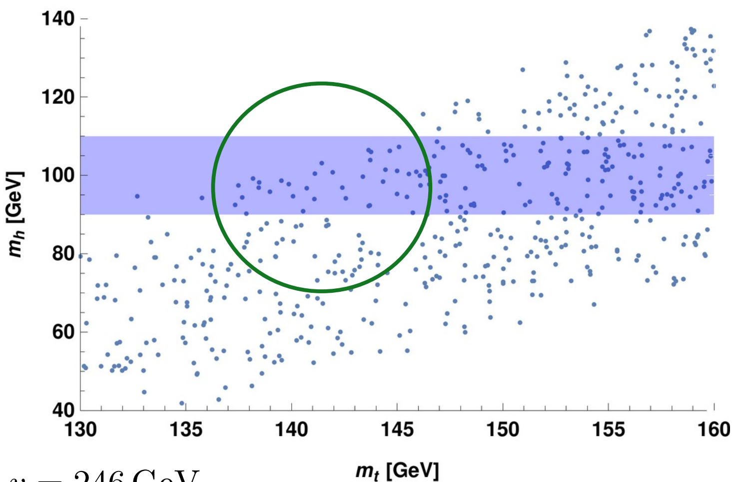
 :)



Phenomenology

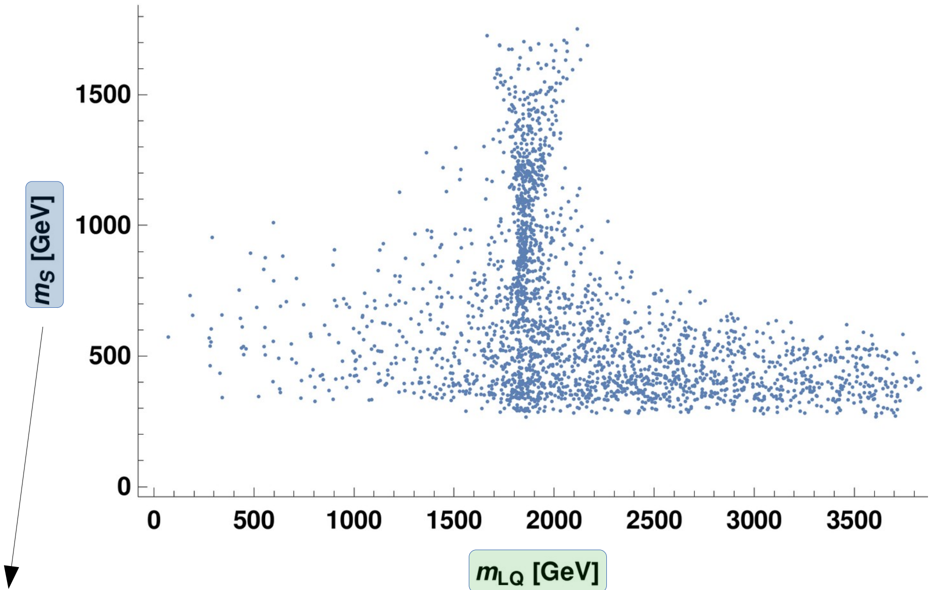
Angelescu, Bally, Blasi, FG [PRD] (2104.07366)

$\text{Higgs} + \text{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\,\text{LQ}$

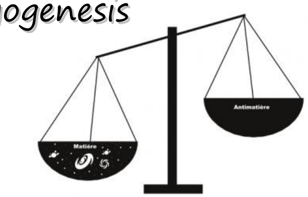


$v = 246\,\text{GeV}$

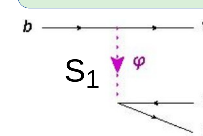
Correct quartic/m_H predicted!



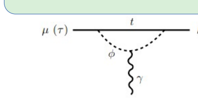
Potentially induce strong 1^{st} order Phase transition (PhT) → Baryogenesis

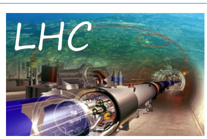


Address (CC) B anomalies?



Muon (g-2)?





$\cup$

X_μ, Y_μ Excitations at TeV!

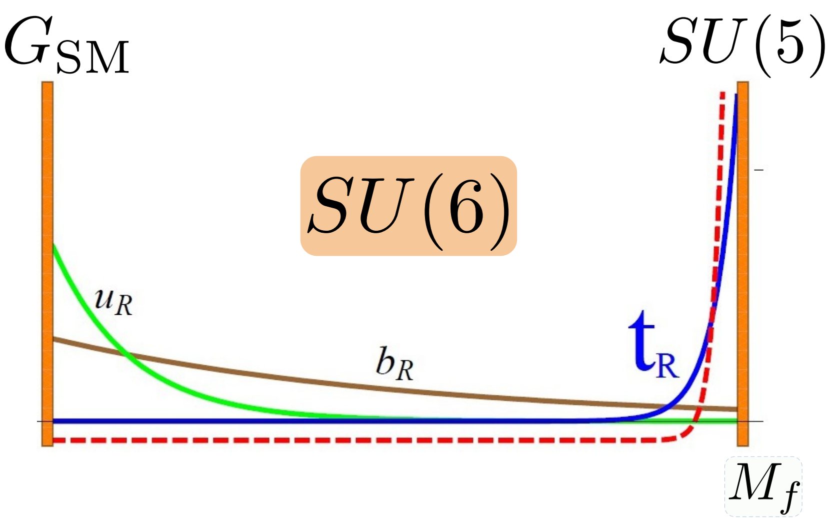
Bauer, Neubert, 1511.01900

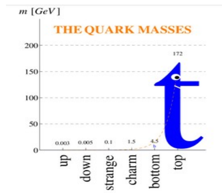
Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

Phenomenology

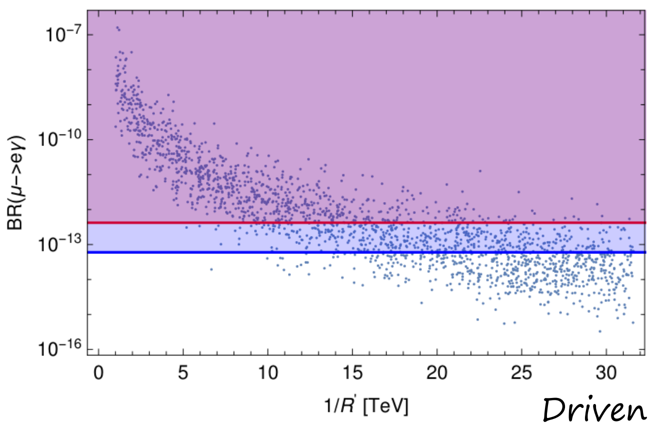
Angelescu, Bally, FG, Weber [JHEP] (2208.13782)

- Flavor Hierarchies

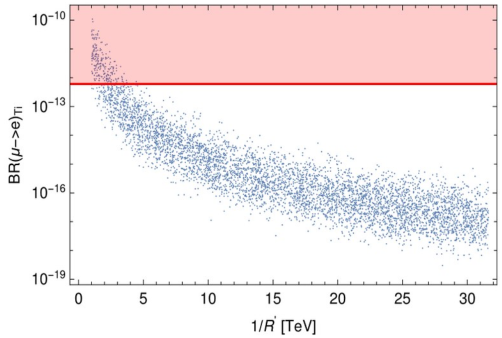


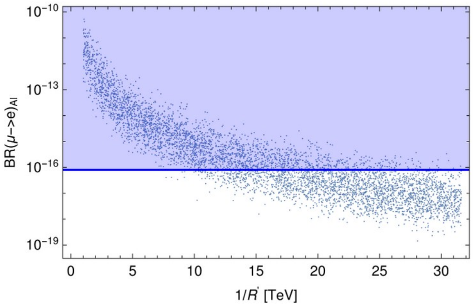


- Tests



Driven by LQ!





5D generation of masses + GUT nature

→ down-type hierarchies *predicted* correctly from PMNS anarchy and CKM hierarchies!

$m_b/m_s/m_d \sim 1/\lambda_{\rm CKM}^2/\lambda_{\rm CKM}^3$ ✓

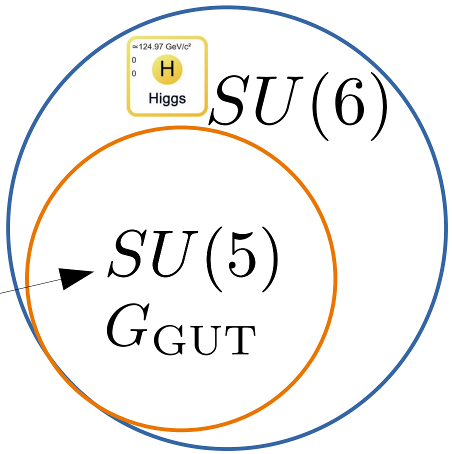
$\lambda_{\rm CKM} \approx 0.23$

Restoring Naturalness ...

... via conjugate fermions

$$\mathbf{20} \to \mathbf{10} \oplus \overline{\mathbf{10}}$$

$SU(6) \supset SU(5)$

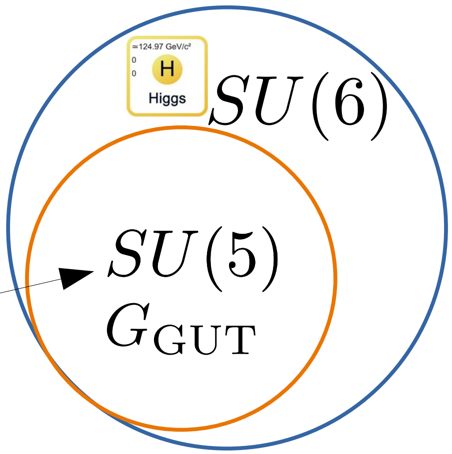


Restoring Naturalness ...

... via conjugate fermions

$$\mathbf{20} \rightarrow \mathbf{10} \oplus \mathbf{\overline{10}}$$

$SU(6) \supset$ $SU(5)$



Fermion irreps:

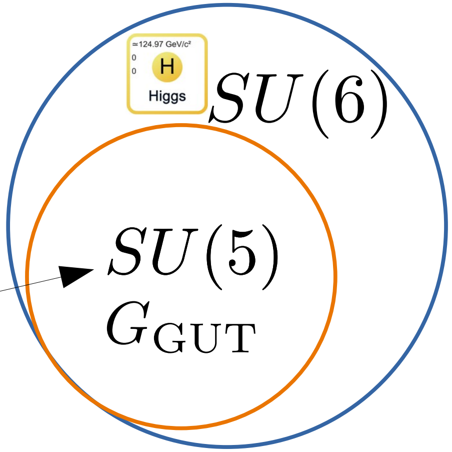
$$\mathbf{20_L} \rightarrow (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

Restoring Naturalness …

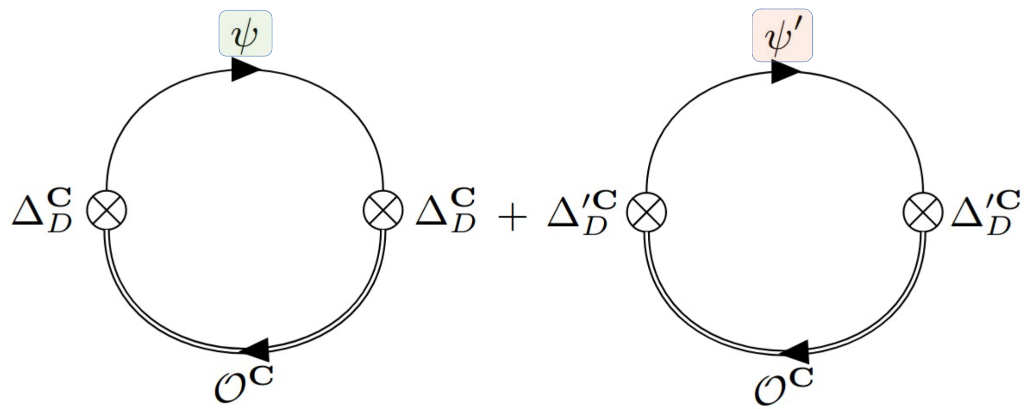
… via conjugate fermions

$$\mathbf{20} \to \boxed{\mathbf{10}} \oplus \boxed{\overline{\mathbf{10}}}$$

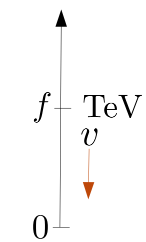
$SU(6) \supset \qquad SU(5)$



$V(h) \simeq$

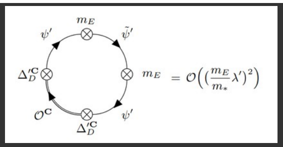


$\simeq 0$



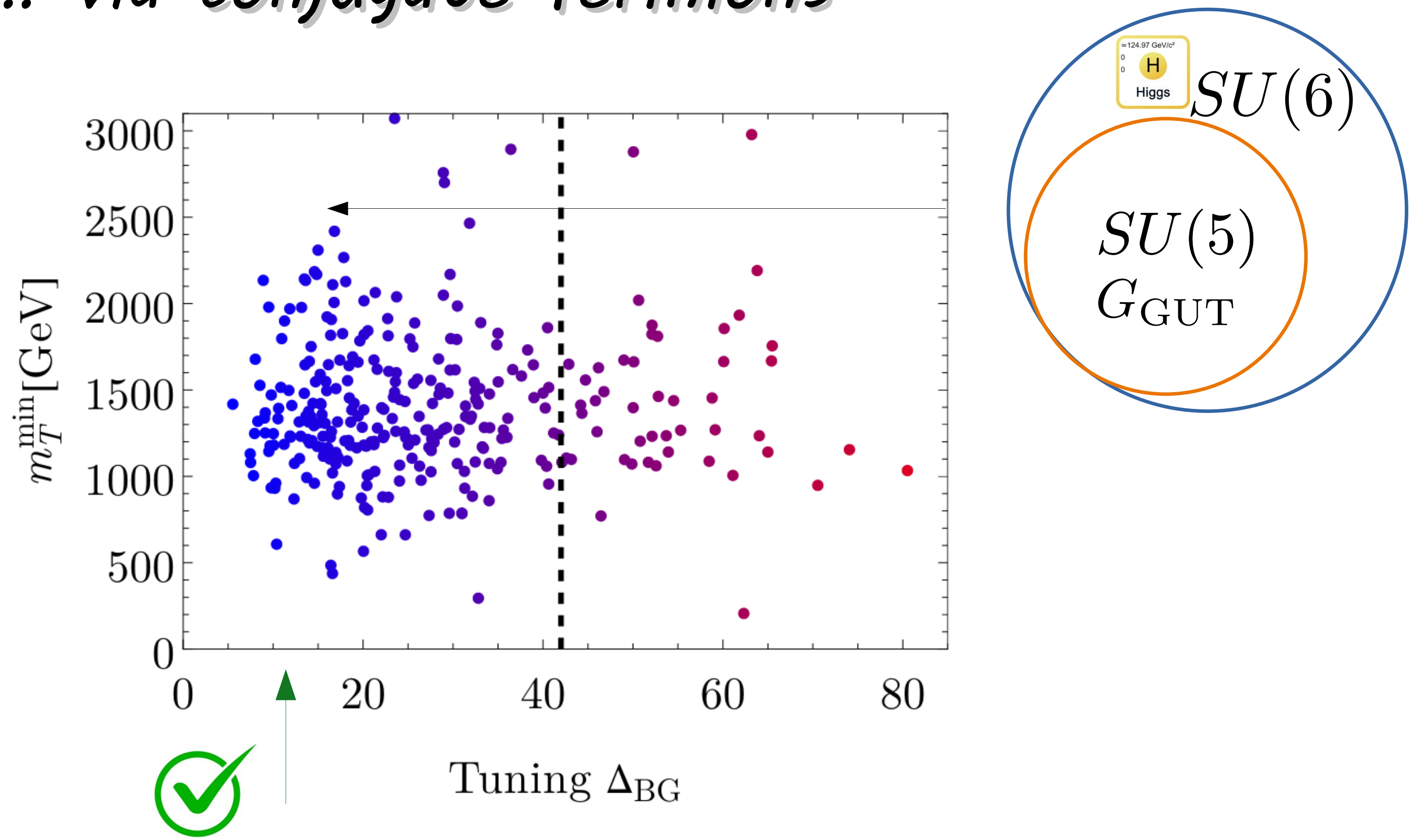
Angelescu, Bally, FG, Hager, 2309.05698

$$\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta$$



Restoring Naturalness ...

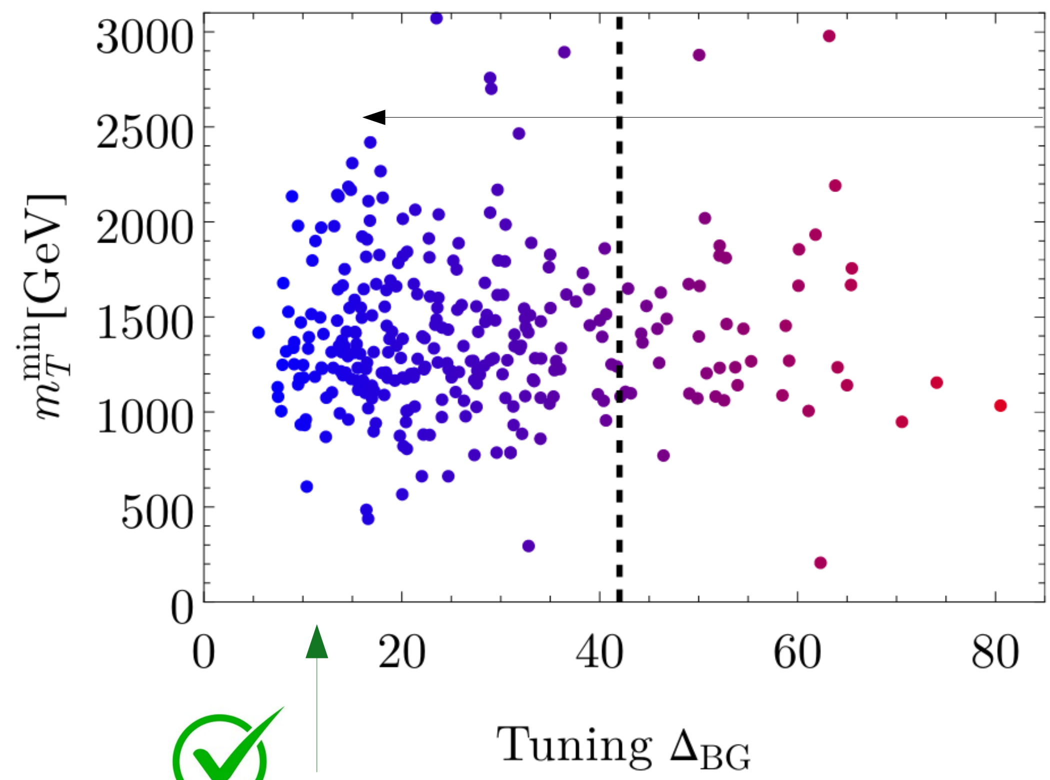
... via conjugate fermions

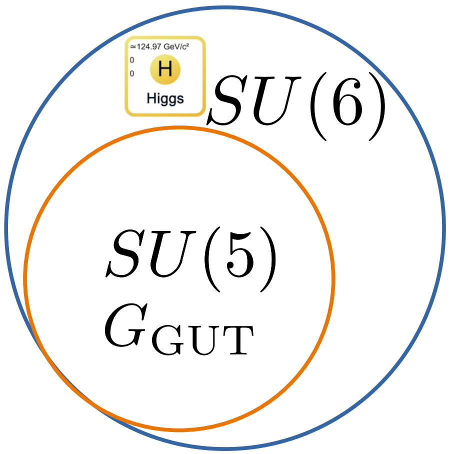


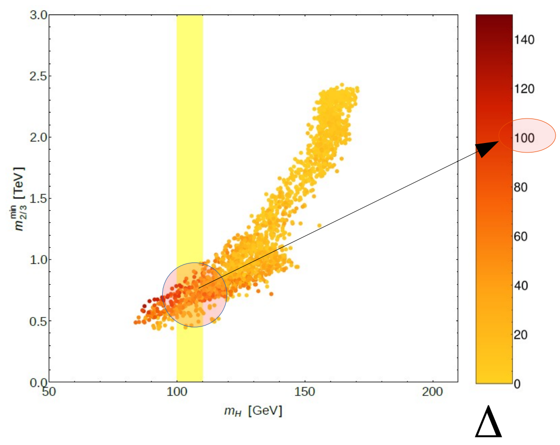
Angelescu, Bally, FG, Hager, 2309.05698

Restoring Naturalness ...

... via conjugate fermions







Angelescu, Bally, FG, Hager, 2309.05698

Phenomenology

$$\mathbf{20} \to \boxed{\mathbf{10}} \oplus \boxed{\overline{\mathbf{10}}}$$

- Exotic quarks with baryon number B=2/3

$$\mathrm{BR}(\omega \to tb\tau^-) \approx 1$$

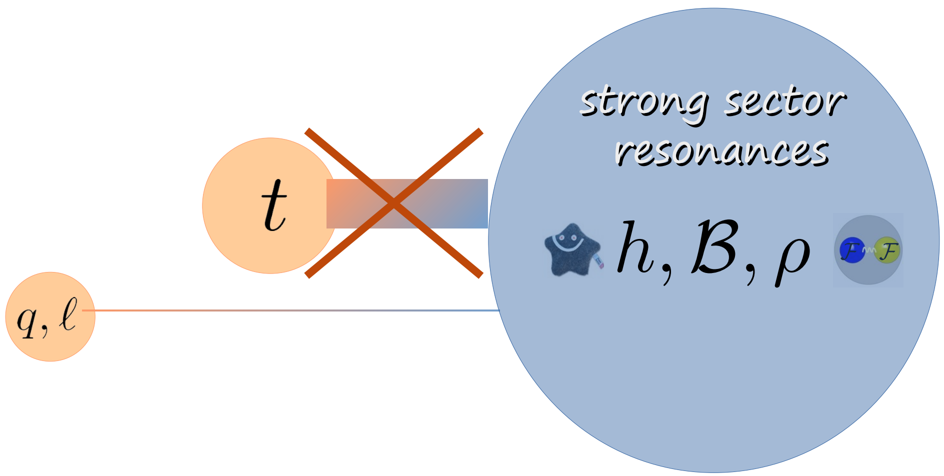
via off-shell leptoquark

- $pp \to \omega\bar{\omega} \to \boxed{t\bar{t}b\bar{b}\tau^+\tau^-}$ signature

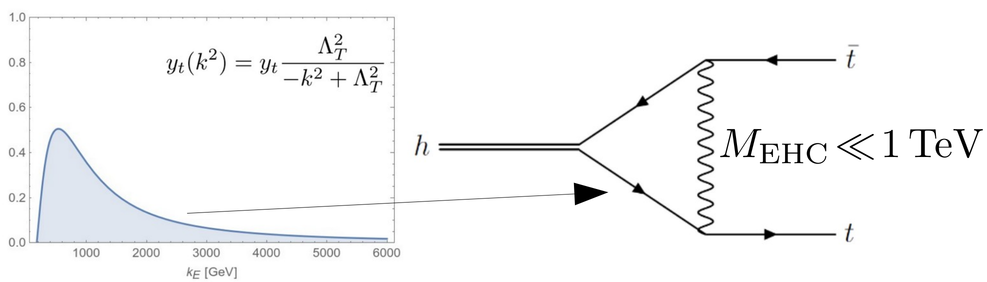
Angelescu, Bally, FG, Hager, 2309.05698

Avoiding Light Top Partners IV

Low scale Extended Hypercolor



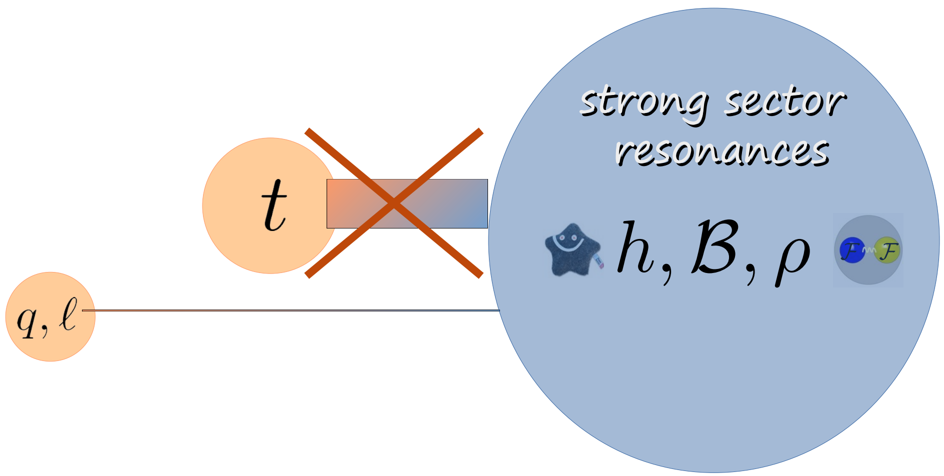
- Decouple the top...



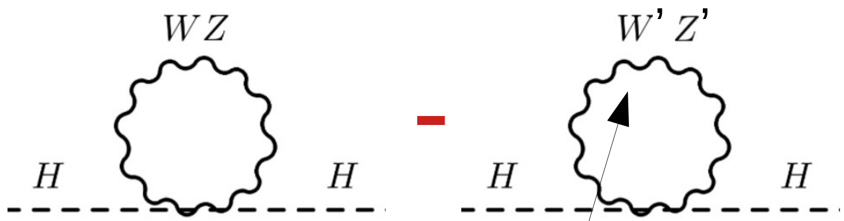
Bally, Chung, FG [PRD] (2211.17254); Chung, 2309.00072; Chung, FG, 2311.17169

Avoiding Light Top Partners IV

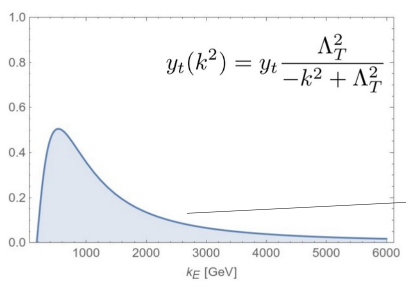
Low scale Extended Hypercolor + collective symmetry breaking (little Higgs)

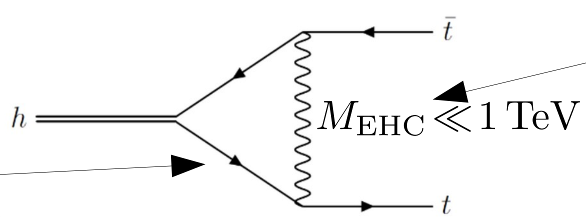


&



3rd-generation-philic

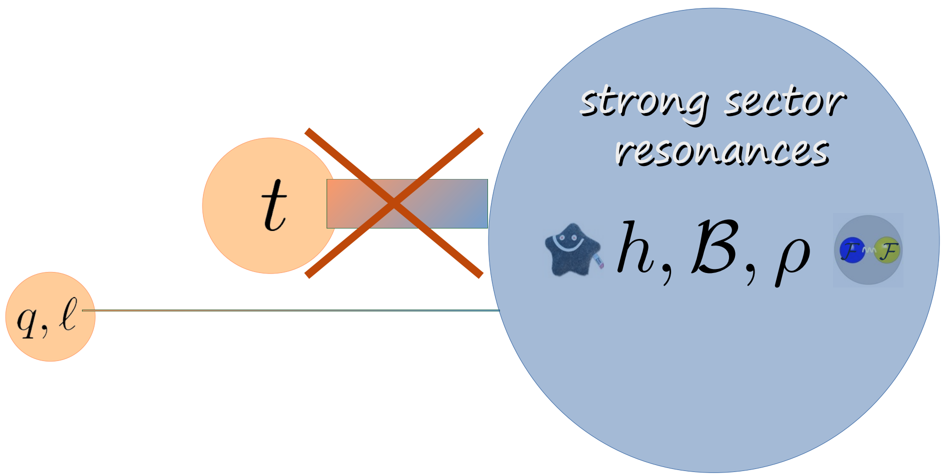




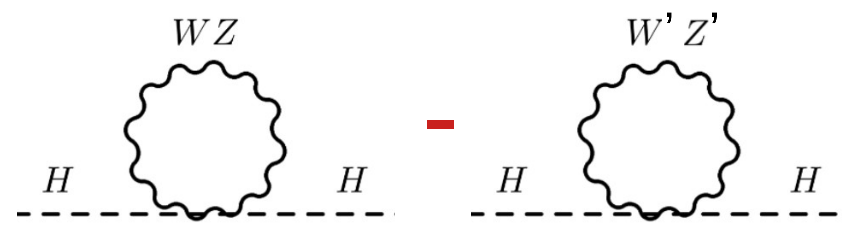
Chung, FG, 2311.17169 → Yi's Talk

Third-generation-philic Hidden Naturalness

Low scale Extended Hypercolor + collective symmetry breaking (little Higgs)



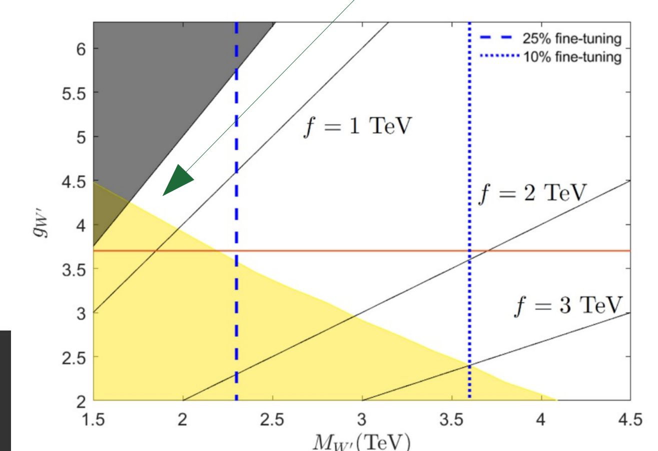
&



3rd-generation-philic

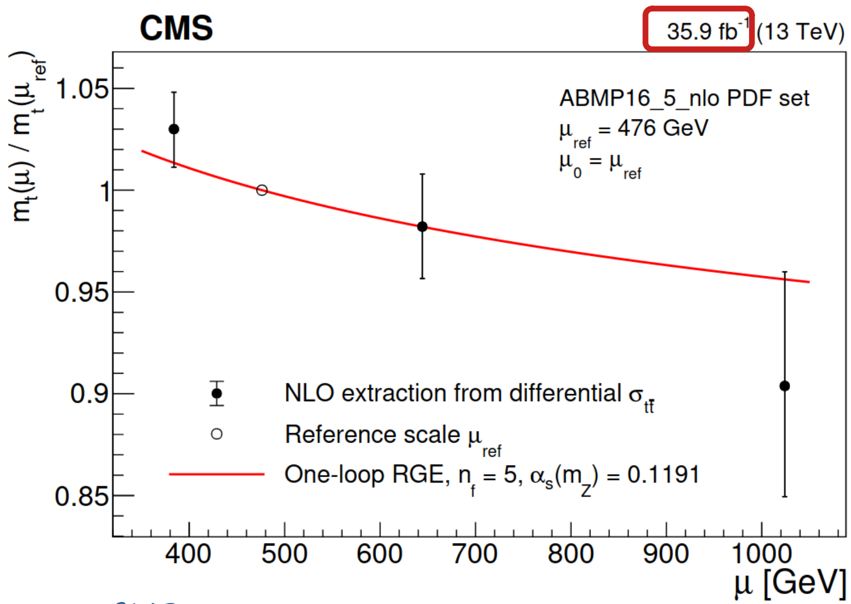
emerges *naturally* in $SU(6)/Sp(6)$ FCHM

No tuning!

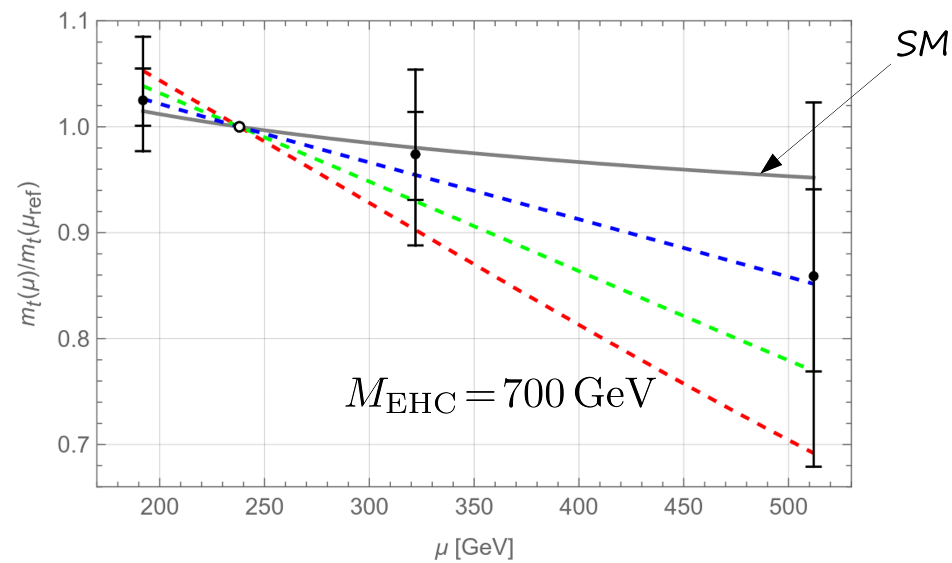


Chung, FG, 2311.17169 → Yi's Talk

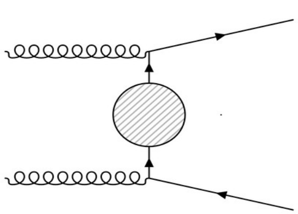
Running Top Mass



CMS, 1909.09193



Bally, Chung, FG [PRD] (2211.17254), Chung, 2309.00072



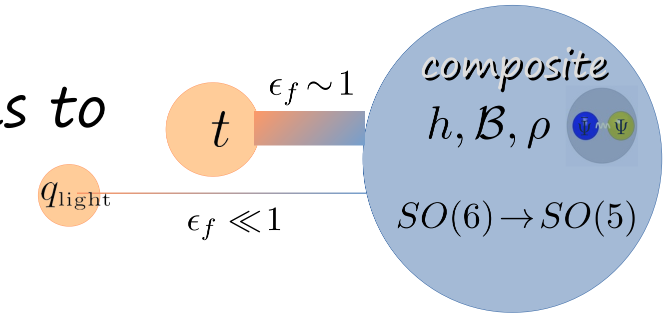
differential tt cross section

New direct test of Naturalness...

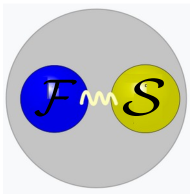
→ diagnose Hierarchy Problem

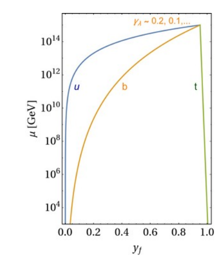
Conclusions

- Partial Compositeness offers attractive means to understand flavor hierarchies



- Models with $\mathcal{O}_\mathcal{B} \sim \mathcal{F}\mathcal{S}$ to solve issues in reproducing heavy top quark: first fRG results suggest that spectrum can indeed emerge naturally





- New ingredients in Fermion-mass generation (+ unifcation) remove tensions with LHC data