A Flavorful Composite Higgs Model

Connect the B anomalies with the Hierarchy Problem

based on arXiv:2108.08511, 2110.03125

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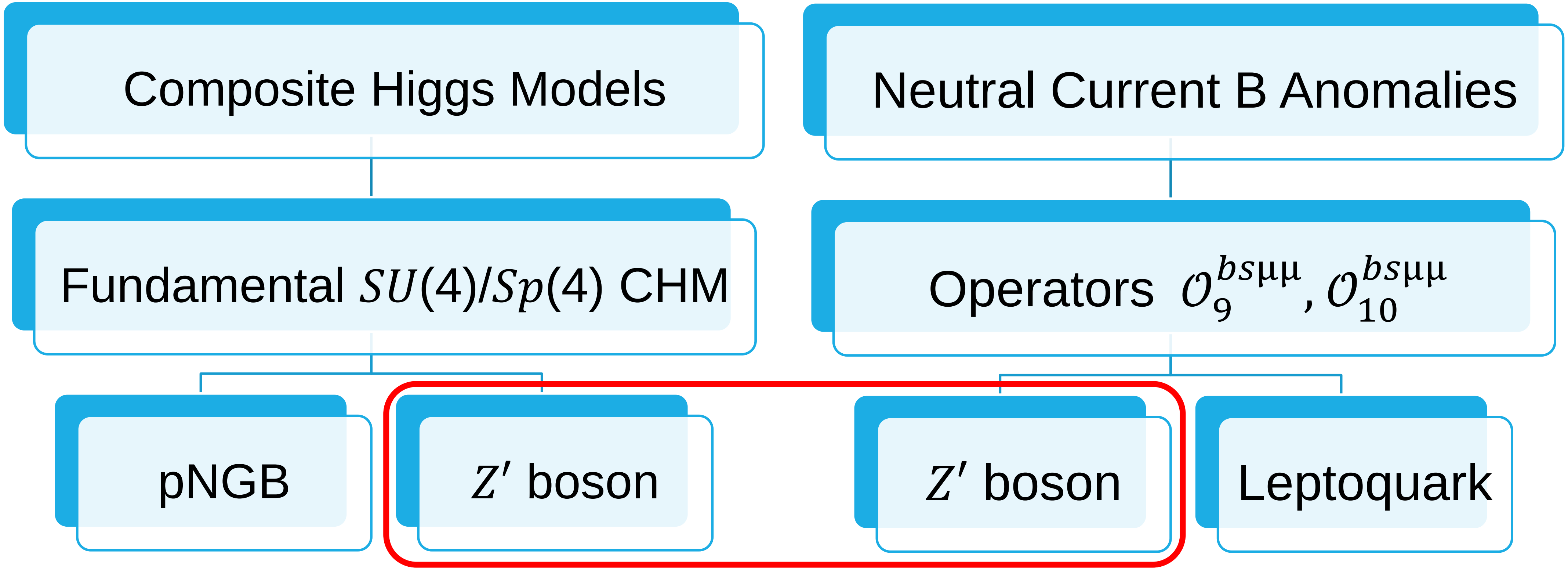
A brief overview: the connection

- Composite Higgs Models
  - Fundamental $SU(4)/Sp(4)$ CHM
    - pNGB
    - Z' boson
- Neutral Current B Anomalies
  - Operators $\mathcal{O}_9^{bs\mu\mu}, \mathcal{O}_{10}^{bs\mu\mu}$
    - Z' boson
    - Leptoquark

A brief overview: the connection



Scale of CHM f **Might be related!!** **Scale of anomalies f'**

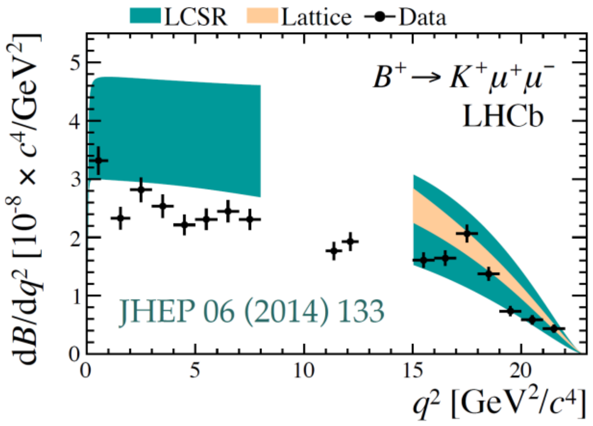
Outline

- **Neutral Current B anomalies**
  - Hints of new physics from B-meson semileptonic decays
  - EFT approach and simplified model
- **Composite Higgs Models**
  - $SU(4)/Sp(4)$ Fundamental CHM
  - $U(1)'$ symmetry and $\boldsymbol{Z'}$ boson
- **$\boldsymbol{Z'}$ phenomenology**
  - Solution to the Neutral Current B anomalies
  - Constraints from FCNCs & Direct $\boldsymbol{Z'}$ Searches
- **Connect the B anomalies with the Hierarchy Problem**

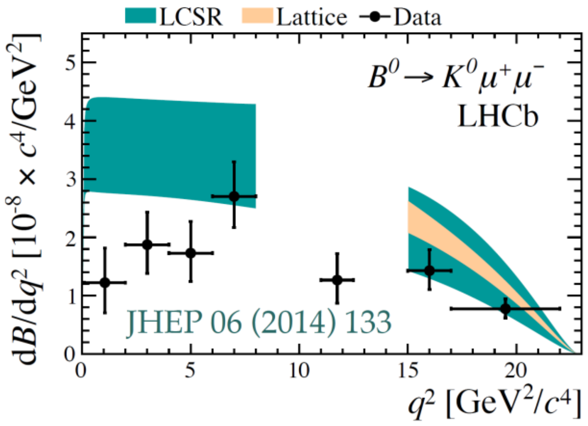
Neutral Current B anomalies

Semileptonic $b \to s\mu\mu$ decays

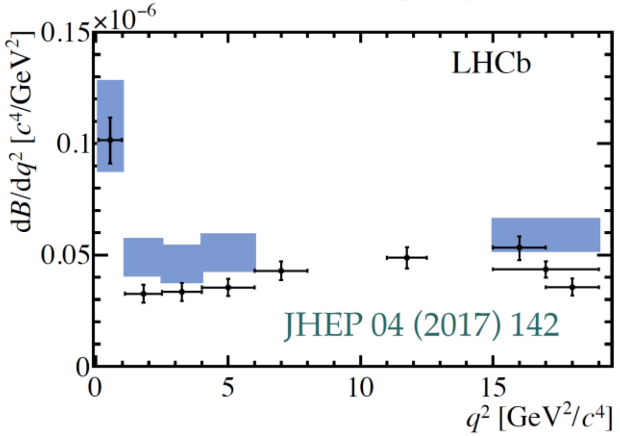
$B^+ \to K^+\mu^+\mu^-$



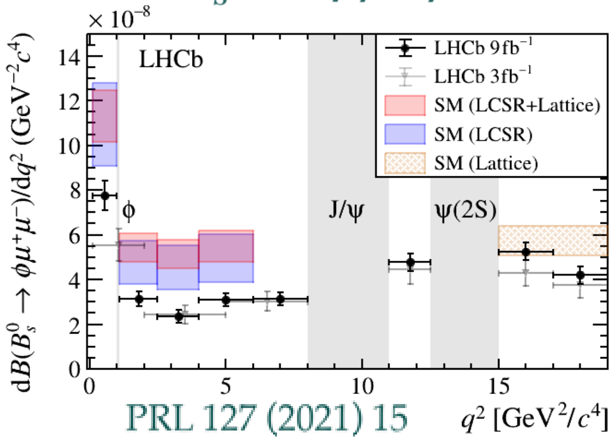
$B^0 \to K^0\mu^+\mu^-$



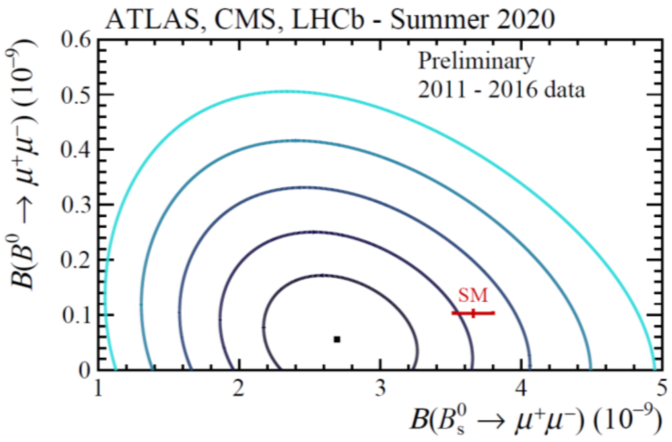
$B^0 \to K^{*0}\mu^+\mu^-$



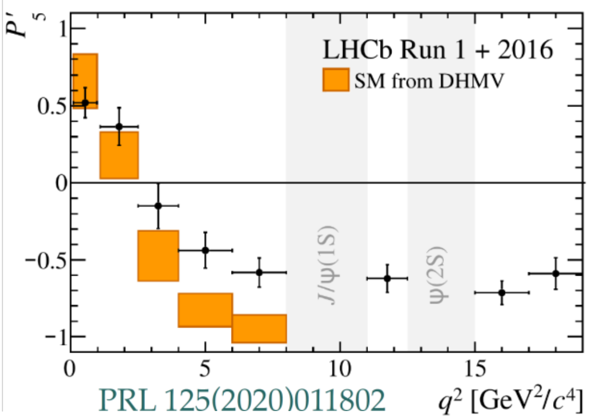
$B_s \to \phi\mu^+\mu^-$



$B_s^0 \to \mu^+\mu^-$



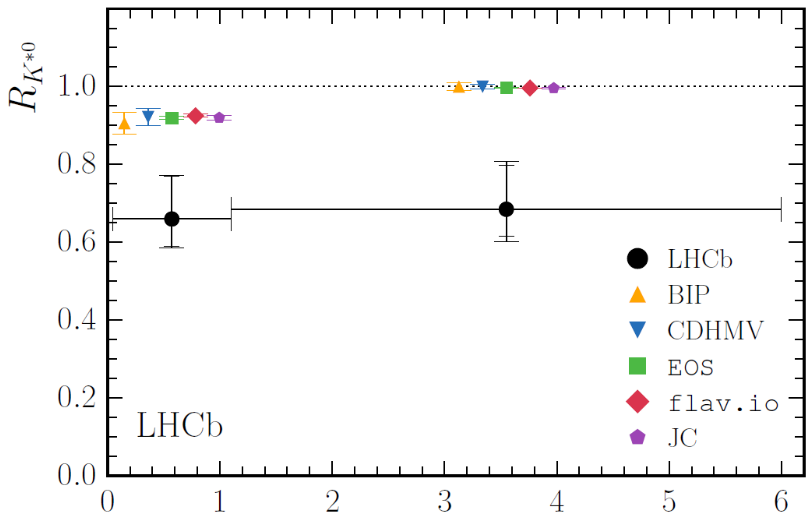
angular observables P_5'



Tests of Lepton Flavor Universality

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

$B^0 \to K^{*0}\ell^+\ell^-$

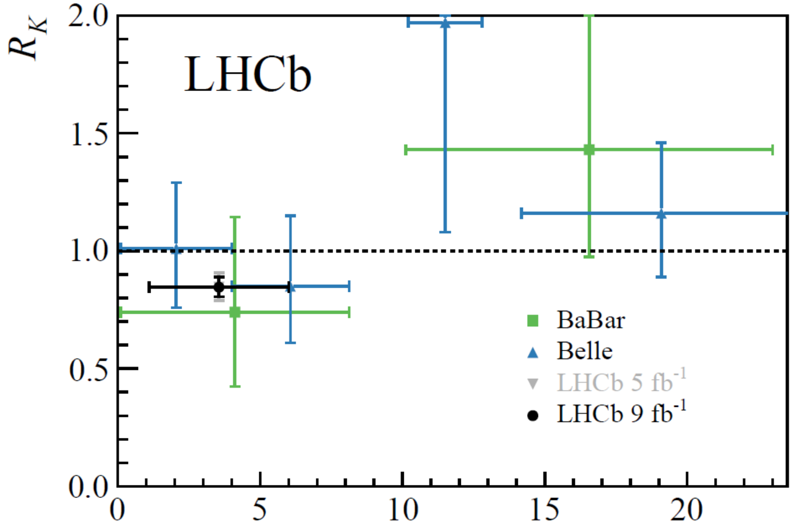


LHCb, JHEP 08 (2017) 055 q^2 [GeV$^2/c^4$]

$$R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad (\sim 2.5\sigma)$$

$$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad (\sim 2.5\sigma)$$

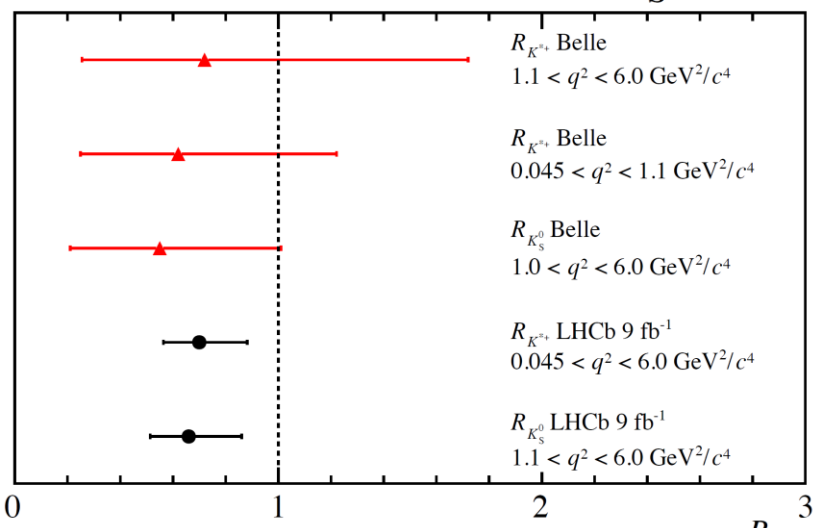
$B^+ \to K^+\ell^+\ell^-$



LHCb arXiv:2103.11769 q^2 [GeV$^2/c^4$]

$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012} \quad (\sim 3.1\sigma)$$

$B^+ \to K^{*+}\ell^+\ell^-$ and $B^0 \to K^0_S\ell^+\ell^-$



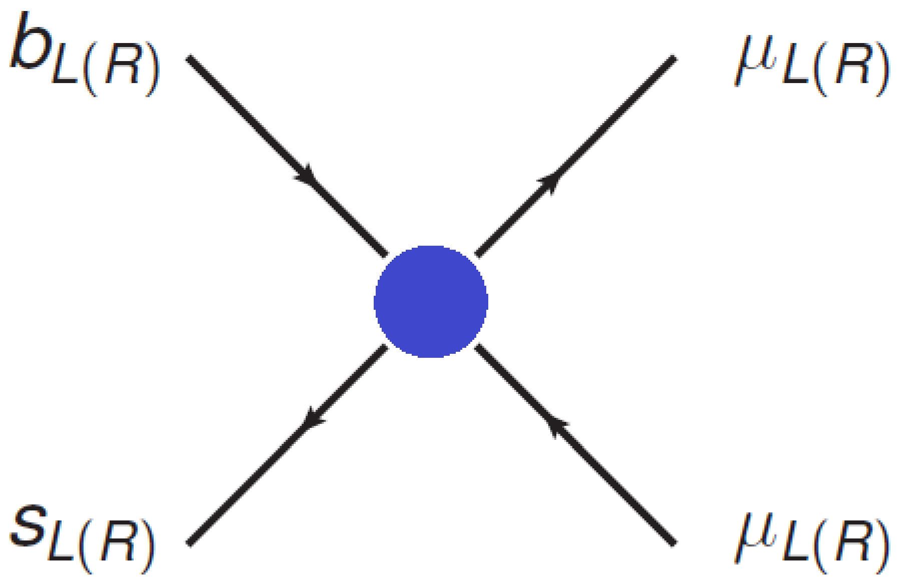
LHCb arXiv:2110.09501

$$R_{K^{*+}} = 0.70^{+0.18+0.03}_{-0.13-0.04} \quad (\sim 1.4\sigma)$$

$$R_{K^0_S} = 0.66^{+0.20+0.02}_{-0.15-0.04} \quad (\sim 1.5\sigma)$$

SMEFT coefficients

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) + \text{h.c.}\,.$$

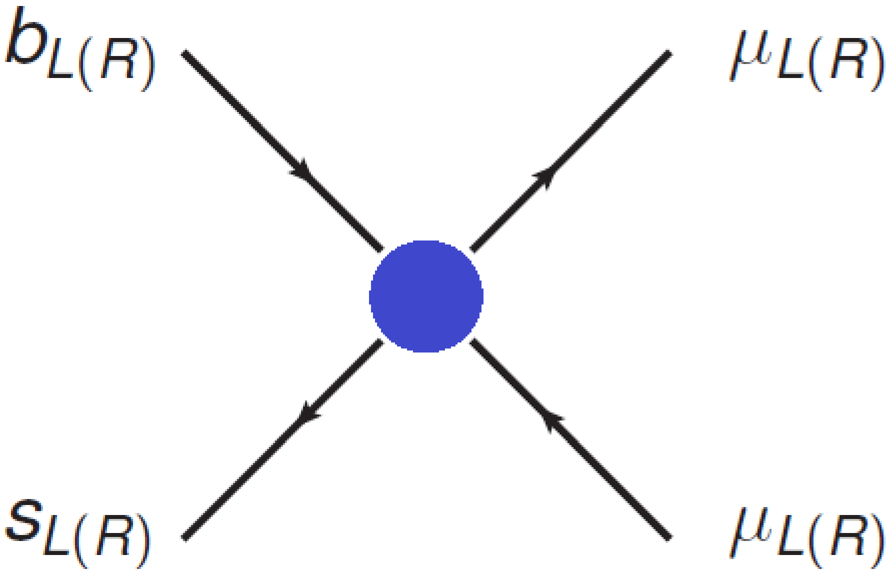


$\Rightarrow$

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \,, \\
\mathcal{O}_{9\ell}^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \,, \\
\mathcal{O}_{10\ell}^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \,, \\
\mathcal{O}_{S\ell}^{(\prime)} &= (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \,, \\
\mathcal{O}_{P\ell}^{(\prime)} &= (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell) \,, \\
\mathcal{O}_{T\ell} &= (\bar{s}\sigma_{\mu\nu} b)(\bar{\ell}\sigma^{\mu\nu} \ell) \,, \\
\mathcal{O}_{T5\ell} &= (\bar{s}\sigma_{\mu\nu} b)(\bar{\ell}\sigma^{\mu\nu} \gamma_5 \ell) \,.
\end{aligned}$$

SMEFT coefficients

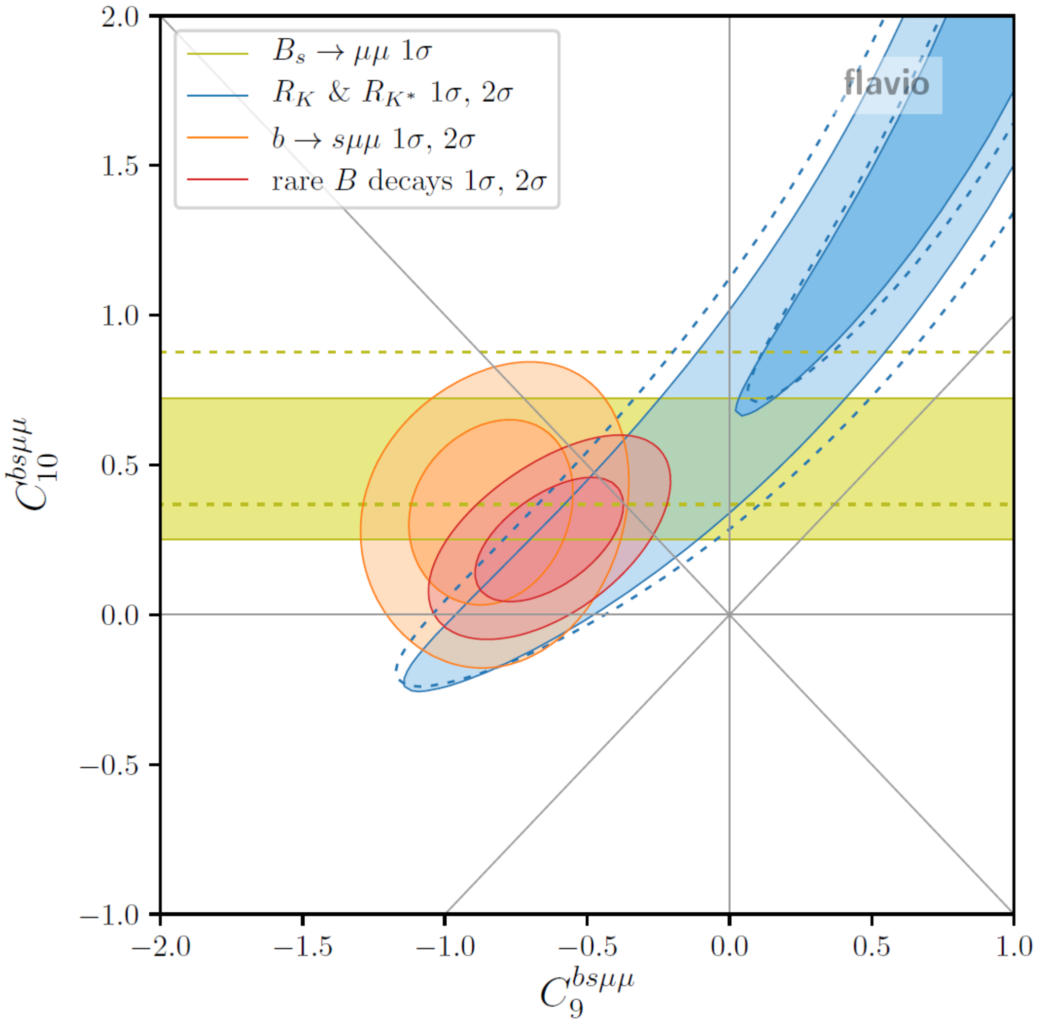
$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) + \text{h.c.}\,.$$



$\Rightarrow$

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

Global fit to SMEFT coefficients

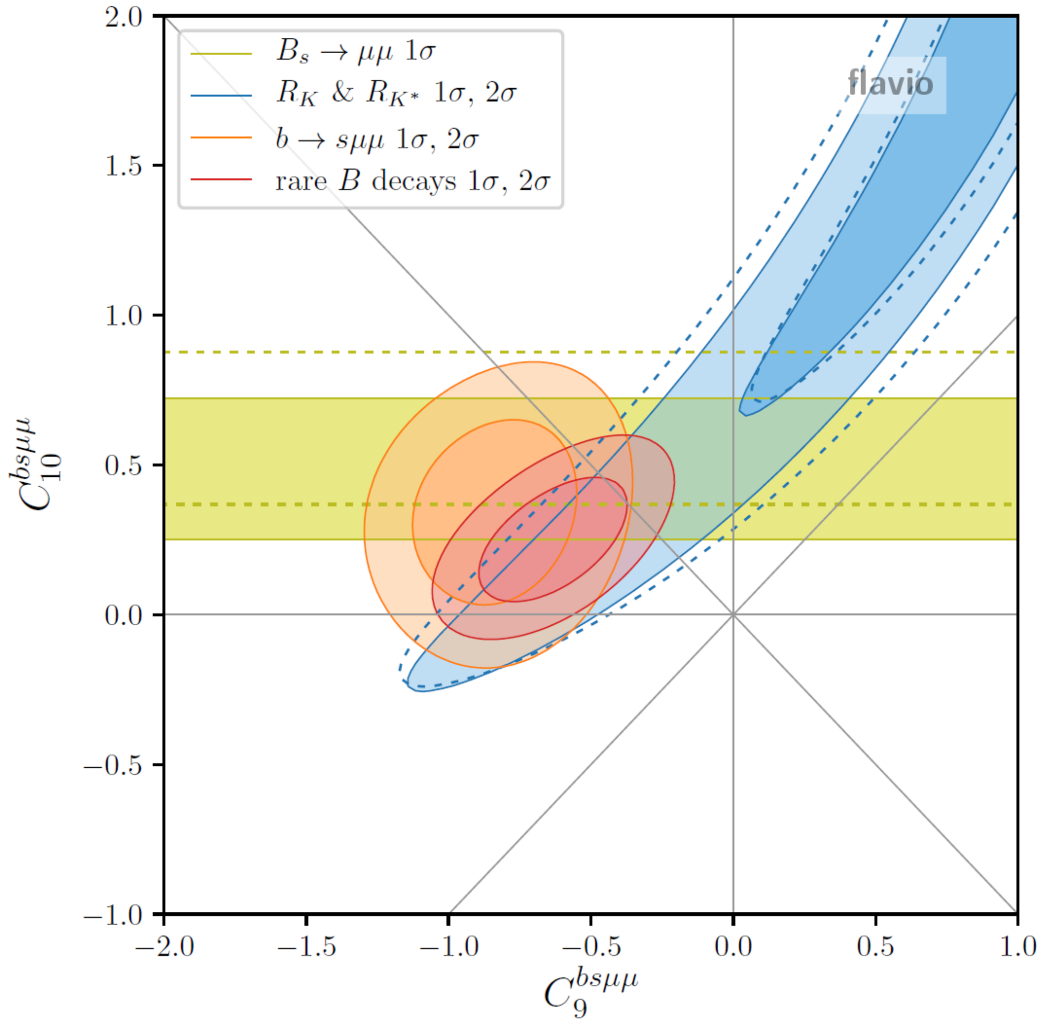


Altmannshofer, Stangl 2103.13370

Wilson coefficient	$b \to s\mu\mu$ best fit	pull	LFU, $B_s \to \mu\mu$ best fit	pull	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	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
$C_9'^{bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}'^{bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

For comparison, $C_9^{SM} = 4.1$, $C_{10}^{SM} = -4.3$

Global fit to SMEFT coefficients



Altmannshofer, Stangl 2103.13370

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
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$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
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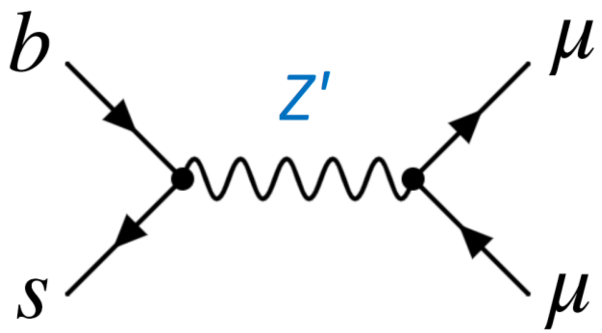
$\Rightarrow C_{LL} = -0.82$

For comparison, $C_9^{\rm SM} = 4.1$, $C_{10}^{\rm SM} = -4.3$

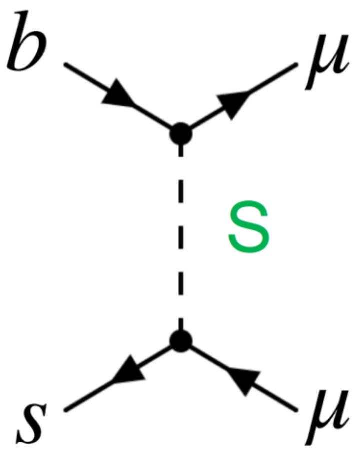
Simplified Model: Tree-level Mediators

Z′ boson

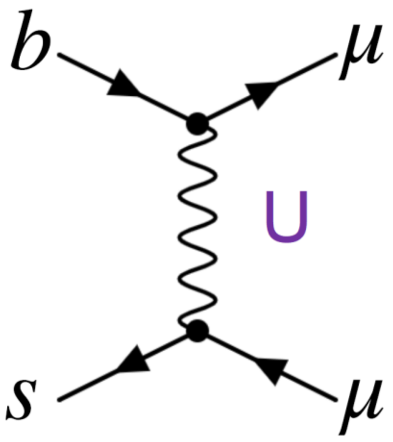


New $U(1)'$ local symmetry

Scalar leptoquark



Vector leptoquark



Quark-Lepton global/local symmetry

The scale of the New Physics

- Generic Tree: $\frac{1}{f_{\rm NP}^2}(\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu \mu)$ $\Rightarrow$ $f_{\rm NP} \sim \sqrt{C_{\rm NP}} \times 36\ {\rm TeV}$
- MFV Tree : $\frac{1}{f_{\rm NP}^2} V_{tb}V_{ts}^*(\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu \mu)$ $\Rightarrow$ $f_{\rm NP} \sim \sqrt{C_{\rm NP}} \times 7\ {\rm TeV}$
- The exact scale is also related to the ratio of charges. If it is $1/4$, it becomes

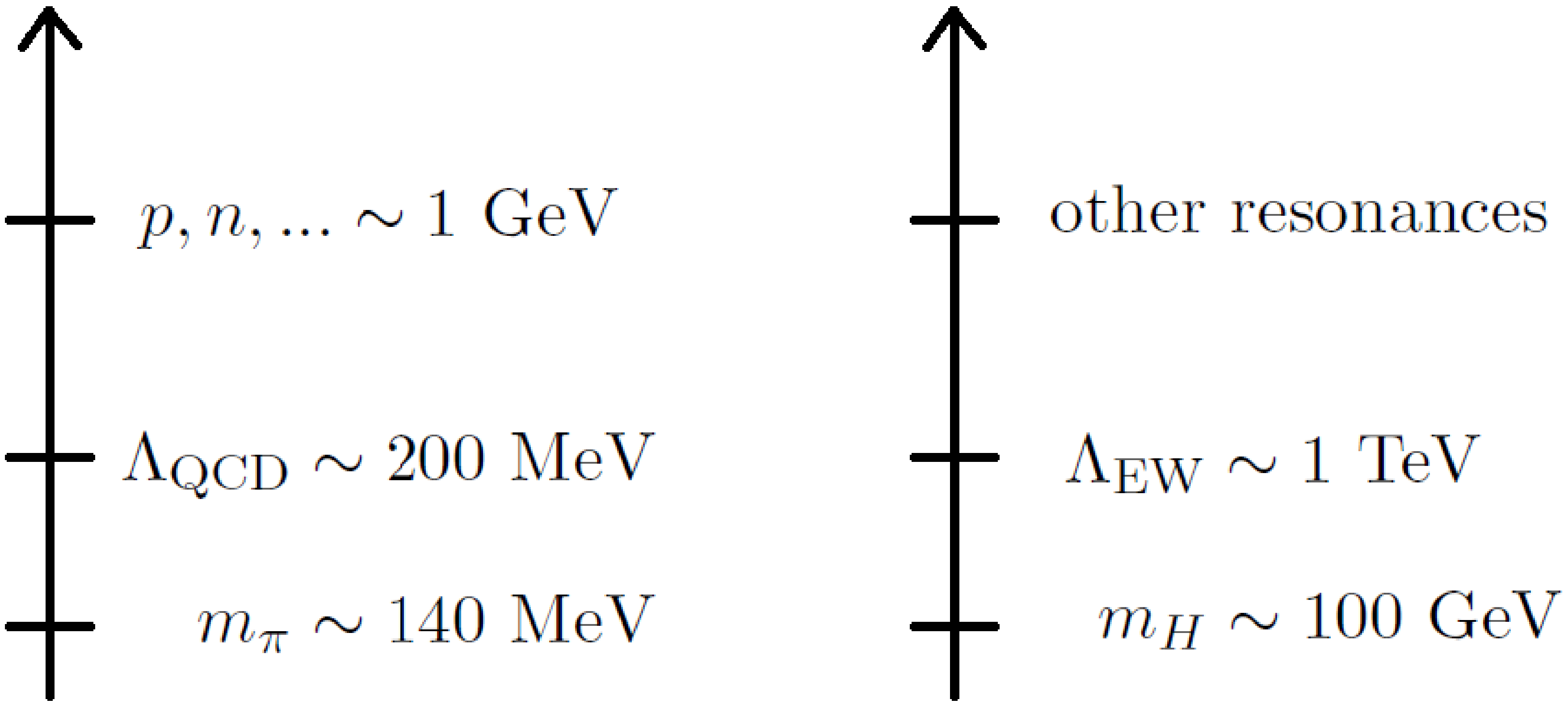
$$f = (Q_{\rm SM}/Q_{\rm vacuum})\, f_{\rm NP} \sim 1-2\ {\rm TeV}$$

which is precisely the scale we expect for a solution to the Hierarchy Problem !!

Composite Higgs Models

Higgs as pseudo-Nambu-Goldstone bosons

Light pions in QCD ↔ Light Higgs in EW



Composite Higgs Models

- Chiral symmetry breaking in Λ_{QCD}

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

which gives three massless NG bosons, i.e. pions!!

However, the symmetry is broken by EM interactions and quark masses, and we get massive pions.

- (Some global) symmetry breaking in $\Lambda_{\mathrm{EW}} = f \sim 1\ \mathrm{TeV}$

$$\mathcal{G} \to \mathcal{H} \ni SU(2)_L \times U(1)_Y$$

which gives (at least) four NG bosons as **Higgs doublet!!** **(ex: $SO(5)/SO(4)$ MCHM)**

The symmetry can be broken by different interactions (usually by electroweak interaction and Yukawa interaction) and give us the nontrivial Higgs potential.

Vacuum misalignment and the scale f

- If the vacuum $\langle\Sigma\rangle = \vec{F}$, the EW symmetry is preserved, and the Higgs is a massless Goldstone boson.
- Once Higgs gets a nontrivial potential and VEV, the electroweak symmetry is broken by

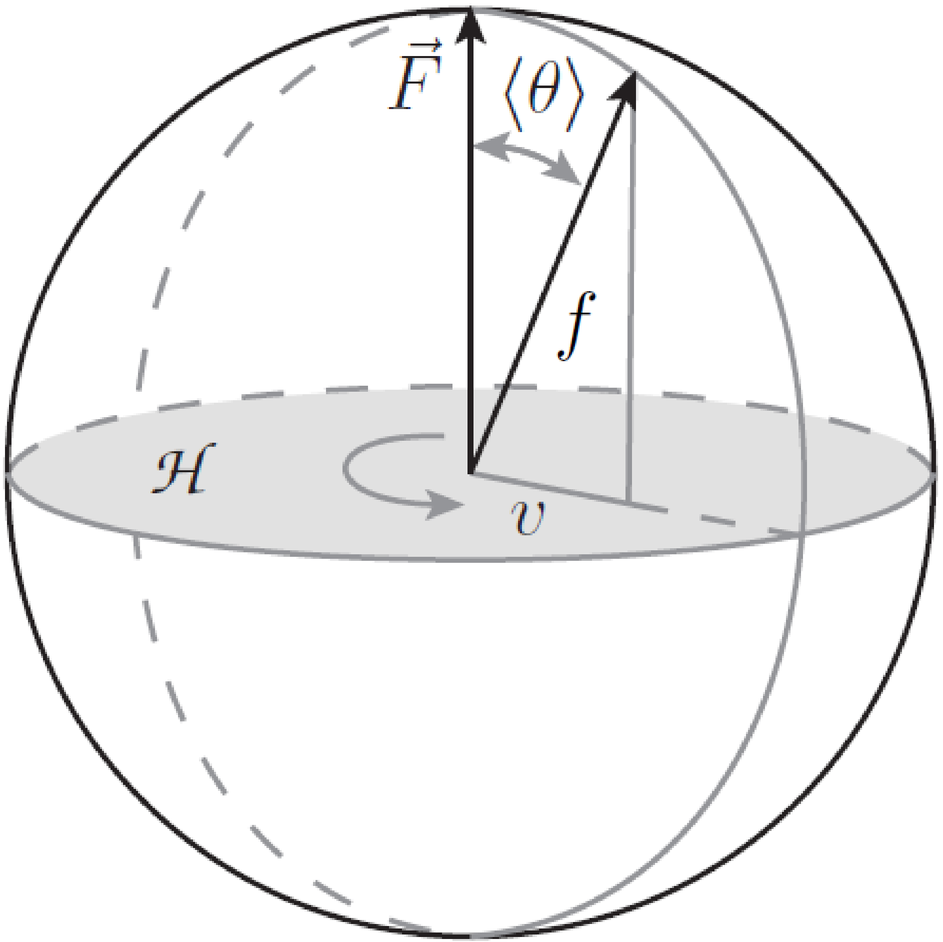
$$v = f\sin\langle\theta\rangle = f\sin\frac{\langle h\rangle}{f}$$

- The nonlinearity is described by the parameter

$$\xi \equiv \frac{v^2}{f^2} = \sin^2\langle\theta\rangle = \sin^2\frac{\langle h\rangle}{f}$$

For example, Higgs coupling

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{SM}} = \cos\langle\theta\rangle = \sqrt{1-\xi} \approx 1 - \frac{\xi}{2}$$



Panico, Wulzer

Choose a coset $\mathcal{G}/\mathcal{H}$

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_\mathcal{H} = \mathbf{r}_{\mathrm{SU(2)\times SU(2)}}\ (\mathbf{r}_{\mathrm{SU(2)\times U(1)}})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[\mathrm{SU(2)}]^2 \times \mathrm{U(1)}$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[\mathrm{SU(2)}]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$	[34]
$[\mathrm{SU(3)}]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[\mathrm{SO(5)}]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$	[30, 47]
$[\mathrm{SO(6)}]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$	[36]

Fundamental Composite Higgs Models

- Fundamental gauge dynamics with fermionic matter fields Cacciapaglia, Sannino 2002.04914
- The global flavor symmetry is bound to be (for species of N_f Dirac fermion)

  $SU(2N_f)$ for (pseudo-)real rep. Or $SU(N_f) \times SU(N_f)$ for complex rep.

  which leads to following breaking pattern

1. Real representation : $\boldsymbol{SU(2N_f)/SO(2N_f)}$, e.g. $\boldsymbol{SU(4)/SO(4)}$ ….
2. Pseudo-real representation : $\boldsymbol{SU(2N_f)/Sp(2N_f)}$, e.g. $\boldsymbol{SU(4)/Sp(4)}$ ….
3. Complex representation : $\boldsymbol{SU(N_f) \times SU(N_f)/SU(N_f)}$, e.g. $\boldsymbol{SU(3) \times SU(3)/SU(3)}$ ….

- MCHM $\boldsymbol{SO(5)/SO(4)}$ does not satisfied ⇒ Next-to-MCHM $\boldsymbol{SU(4)/Sp(4)}$ with 5 pNGBs

The $SU(4)/Sp(4)$ FCHM

- The minimal coset include the Higgs doublet - **$SU(4)/Sp(4)$ FCHM**

- 4 Weyl hyperfermions in the fundamental representation of the *Sp(N$_{HC}$)* hypercolor group

$$\psi_L = (U_L, D_L) = (1,2,0), \quad \begin{matrix} U_R = (1,1,1/2) \\ D_R = (1,1,-1/2) \end{matrix} \quad \Longrightarrow \quad \psi = (U_L, D_L, U_R^c, D_R^c)^T$$

- Once the hypercolor becomes strongly coupled, hyperfermions form a condensate and breaks $SU(4) \to Sp(4)$, which can be described by a nonlinear Sigma model.

$$\langle \Sigma \rangle = \frac{1}{2\sqrt{2}} \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix} \cdot \boxed{f} \quad \Longrightarrow \quad i\pi_a X_a = \begin{pmatrix} ia\,\mathbb{I} & \sqrt{2}\left(\tilde{H} H\right) \\ -\sqrt{2}\left(\tilde{H} H\right)^\dagger & -ia\,\mathbb{I} \end{pmatrix}$$

Sym. Breaking scale

Goldstone matrix

- The coset SU(4)/Sp(4) contains 5 pNGBs, including Higgs doublet H and a real singlet a

$U(1)'$ symmetry and Z' boson

- The real singlet a is the NGB of broken $U(1)'$ symmetry

$$i\pi_a X_a = \begin{pmatrix} ia\,\mathbb{I} & \sqrt{2}\left(\tilde{H}H\right) \\ -\sqrt{2}\left(\tilde{H}H\right)^\dagger & -ia\,\mathbb{I} \end{pmatrix} \qquad U(1)' : \begin{pmatrix} \mathbb{I} & 0 \\ 0 & -\mathbb{I} \end{pmatrix} \subset SU(4)$$

If the $U(1)'$ symmetry is gauged $\Longrightarrow$ **a TeV-scale Z' boson**

- What is this $U(1)'$ symmetry?

$$\psi = (U_L, D_L, U_R^c, D_R^c)^T \quad \Longrightarrow \quad U(1)_{HB} \text{ symmetry}$$

- Gauging the symmetry?

$$\mathcal{L}_{\text{int}} = g_{Z'} Z'_\mu \left(Q_{HB} \bar{\psi} \gamma^\mu \psi \right) \quad \Longrightarrow \quad SU(2)^2\, U(1)_{HB} \text{ anomaly!?}$$

$= 1/N_{HC}$

$U(1)_{\text{SM3-HB}}$ symmetry and Z' boson

- Interaction of the Z' boson (the minimal anomaly free setup)

$$\mathcal{L}_{\text{int}} = g_{Z'} Z'_\mu \left(Q_{SM} \bar{F}_3 \gamma^\mu F_3 - Q_{HB} \bar{\psi} \gamma^\mu \psi \right)$$

$= 1/4$ $\quad\quad$ $= 1/N_{HC}$

(SM_3 number – HB number)

- The Z' mass

$$M_{Z'} = 2\, Q_{HB}\, g_{Z'} f \cos\left(\frac{V}{f}\right) = \frac{2}{N_{HC}} g_{Z'} f \cos\left(\frac{V}{f}\right)$$

- The Z' scale (B anomalies scale)

$$f' \equiv \frac{M_{Z'}}{g_{Z'}} = \frac{2}{N_{HC}} f \cos\left(\frac{V}{f}\right) \approx \frac{2}{N_{HC}} f$$

$U(1)_{\text{SM3-HB}}$ symmetry and Z' boson

- Interaction of the Z' boson (the minimal anomaly free setup)

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$= 1/4$ $= 1/N_{HC}$

(SM_3 number – HB number)

- The Z' mass

$$M_{Z'} = 2\, Q_{HB}\, g_{Z'} f \cos\left(\frac{V}{f}\right) = \frac{2}{N_{HC}} g_{Z'} f \cos\left(\frac{V}{f}\right)$$

- The Z' scale (B anomalies scale)

$$f' \approx \frac{2}{N_{HC}} f$$

$\Rightarrow$ **Relation between the two scales!!**

Z' phenomenology

Specified Mixing Matrices

- For the SM fermion sector, we have

$$\mathcal{L}_{\rm int} = g_{Z'} Z'_\mu \left(\bar{F}^m_L \gamma^\mu Q^m_{F_L} F^m_L + \bar{F}^m_R \gamma^\mu Q^m_{F_R} F^m_R \right)$$

with the transformation and charge matrices (**for left-handed $f = d, e$ only**)

$$U_{f_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_f & \sin\theta_f \\ 0 & -\sin\theta_f & \cos\theta_f \end{pmatrix} \Longrightarrow Q^m_{f_L} = \frac{1}{4} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_f & -\frac{1}{2}\sin 2\theta_f \\ 0 & -\frac{1}{2}\sin 2\theta_f & \cos^2\theta_f \end{pmatrix}$$

- Two terms of our interest are

$$g_{sb} \equiv \frac{1}{4} g_{Z'} \epsilon_{sb} \quad \text{with} \quad \epsilon_{sb} = -\frac{1}{2}\sin 2\theta_d \ ,$$

$$g_{\mu\mu} \equiv \frac{1}{4} g_{Z'} \epsilon_{\mu\mu} \quad \text{with} \quad \epsilon_{\mu\mu} = \sin^2\theta_e \ .$$

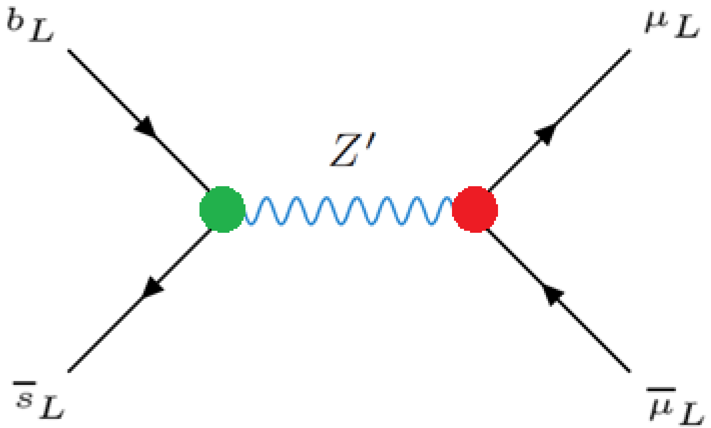
- The 3 key parameters are the scale f', the mixing ϵ_{sb} and $\epsilon_{\mu\mu}$

Z' solution for Neutral Current B Anomalies

- Under the specified mixing metrices

$$\Delta\mathcal{L} = C_{LL}(\bar{s}_L\gamma^\rho b_L)(\bar{\mu}_L\gamma_\rho\mu_L)$$ from

with $$C_{LL} = -\frac{g_{sb}g_{\mu\mu}}{M_{Z'}^2}(36\ \text{TeV})^2$$



- The global fit result considering all rare B decay gives

$$C_{LL} = -\frac{g_{sb}g_{\mu\mu}}{M_{Z'}^2}(36\ \text{TeV})^2 = -\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2}(9\ \text{TeV})^2 = -0.82 \pm 0.14$$

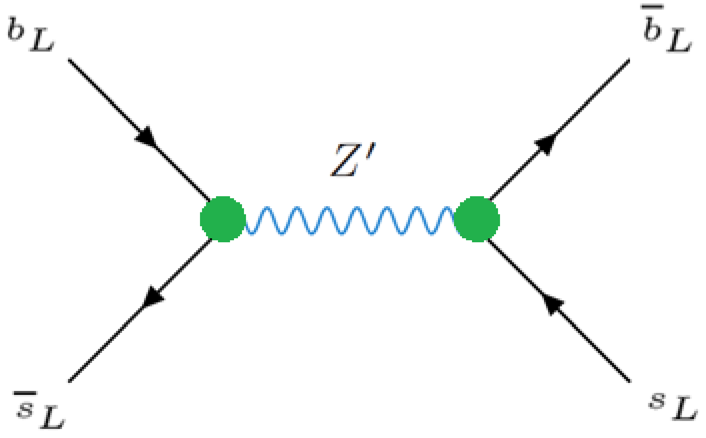
which requires

$$\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2} = \frac{1}{(10\ \text{TeV})^2}\left(\frac{C_{LL}}{-0.82}\right) \Longrightarrow f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}\left(\frac{-0.82}{C_{LL}}\right)}\,(10\ \text{TeV})$$

FCNC Constraints - quark vertex

- $\boldsymbol{B_s - \bar{B}_s}$ Meson Mixing

$$C_{B_s} \equiv \frac{\Delta M_s}{\Delta M_s^{SM}} \approx 1 + 5576 \left(\frac{g_{sb}}{M_{Z'}}\right)^2$$



- The current bound :

$$\text{Exp: } 17.757 \pm 0.021 \text{ ps}^{-1} \quad \text{(CDF+LHCb)}$$
$$\text{SM: } 18.5^{+1.2}_{-1.5} \text{ ps}^{-1} \quad \text{(Sum Rules)}$$

- The constraint :

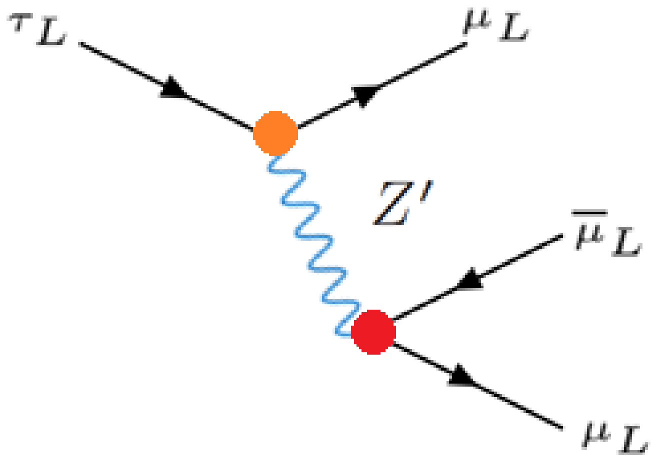
$$\frac{g_{sb}}{M_{Z'}} \leq \frac{1}{194 \text{ TeV}} \implies f' \geq \epsilon_{sb} \cdot 48.5 \text{ (TeV)} \overset{\text{NCBA}}{\implies} f' \leq \epsilon_{\mu\mu} \cdot 2 \text{ (TeV)} \text{ (combined)}$$

$$\epsilon_{sb} \leq 0.04$$

$$f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}} \text{ (10 TeV)}$$

FCNC Constraints - lepton vertex

- Lepton Flavor Violation τ → μμμ



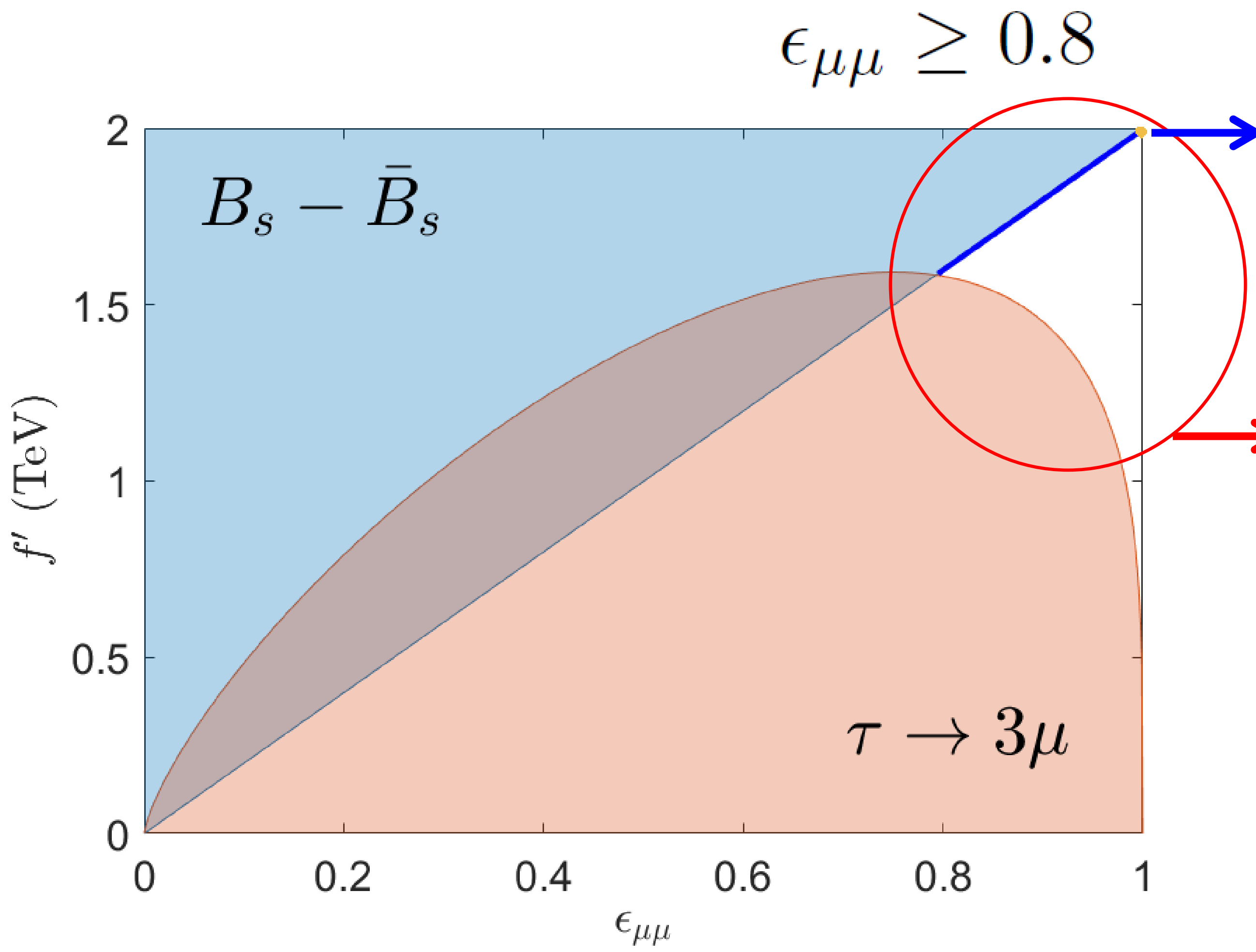
$$BR(\tau \to 3\mu) = \frac{2m_\tau^5}{1536\pi^3\Gamma_\tau}\left(\frac{g_{Z'}^2}{16M_{Z'}^2}\sin^3\theta_e\cos\theta_e\right)^2$$

$$= 1.28 \times 10^{-6}\left(\frac{1\ \mathrm{TeV}}{f'}\right)^4 \epsilon_{\mu\mu}^3(1-\epsilon_{\mu\mu})$$

- The current bound : $< 2.1 \times 10^{-8}$ at 90% CL
- The constraint :

$$\left(\frac{1\ \mathrm{TeV}}{f'}\right)^4 \epsilon_{\mu\mu}^3(1-\epsilon_{\mu\mu}) < 1.6 \times 10^{-2} \sim \frac{1}{60}$$

Combined Analysis : f' v. s. $\epsilon_{\mu\mu}$



$$f' = \epsilon_{\mu\mu} \cdot 2 \text{ (TeV)}$$

$$f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}} \text{ (10 TeV)}$$

Direct Z' Searches

- Decay width

$$\frac{\Gamma_{Z'}}{M_{Z'}} = \frac{1}{24\pi} g_{Z'}^2 \sim 1.3\,\% \cdot g_{Z'}^2$$

- Branching ratio

$$Br(t\bar{t}) \sim Br(b\bar{b}) \sim 37.5\%$$

$$Br(\mu\mu) \sim 6.25\ \epsilon_{\mu\mu}^2\ \%$$

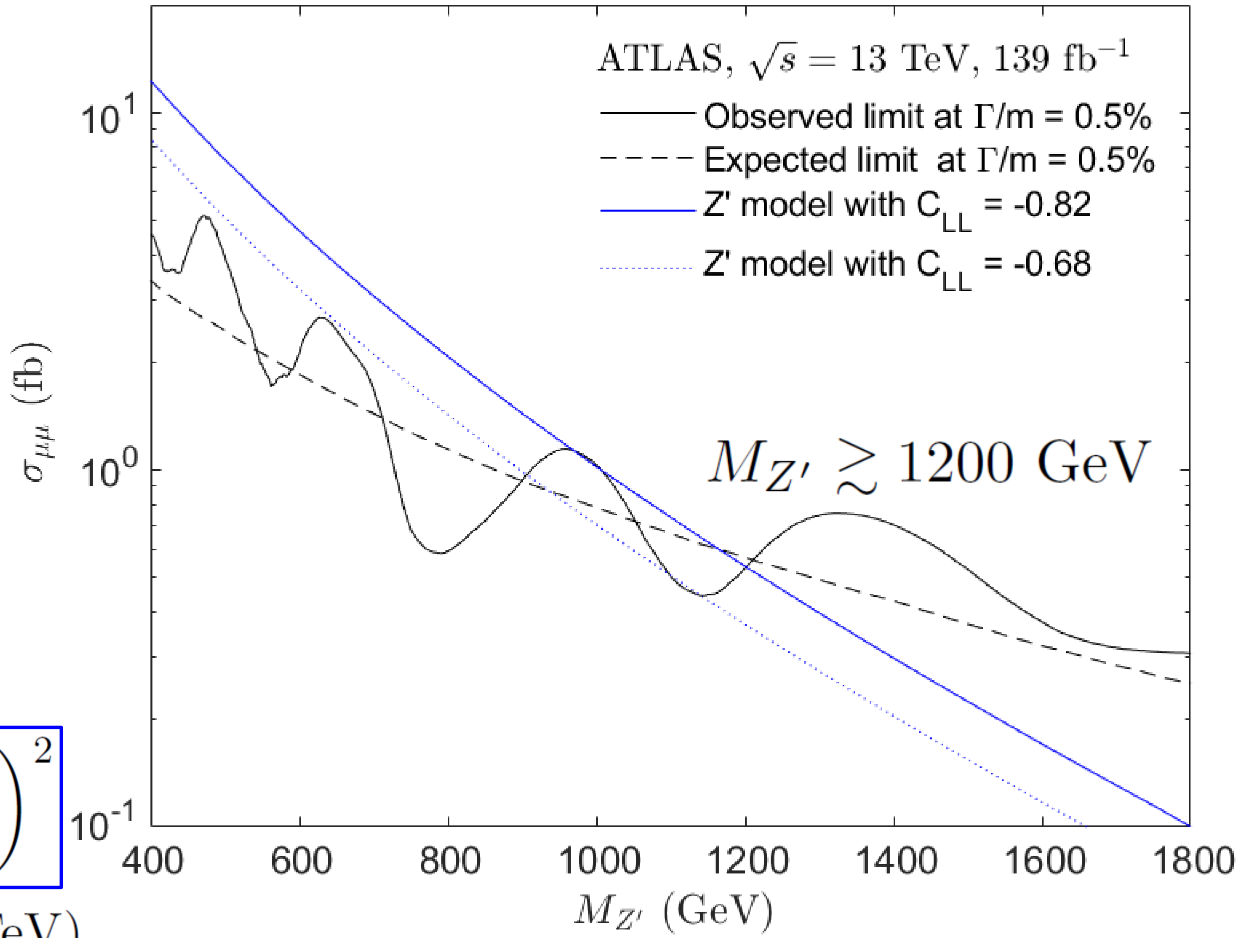
- Cross section

$$\sigma(b\bar{b} \to Z') \equiv \frac{g_{Z'}^2}{16} \cdot \sigma_{bb}(M_{Z'})$$

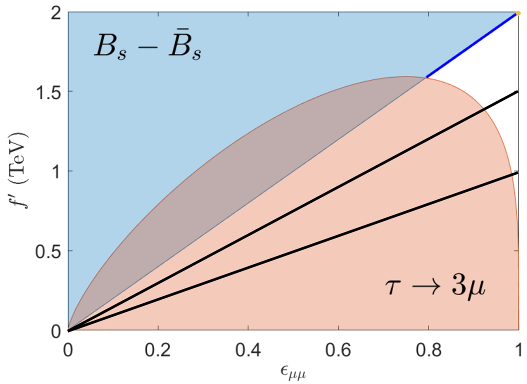
$$\sigma_{\mu\mu} \equiv \sigma \times Br(\mu\mu) = \frac{1}{256} \sigma_{bb} \cdot g_{Z'}^2\ \epsilon_{\mu\mu}^2$$

$$\geq \frac{1}{256} \sigma_{bb} \cdot g_{Z'}^2 \left(\frac{f'}{2\ \mathrm{TeV}}\right)^2 = \boxed{\sigma_{bb} \left(\frac{M_{Z'}}{32\ \mathrm{TeV}}\right)^2}$$

$$f' = \epsilon_{\mu\mu} \cdot 2\ (\mathrm{TeV})$$



Combined Analysis : f' v. s. $M_{Z'}$

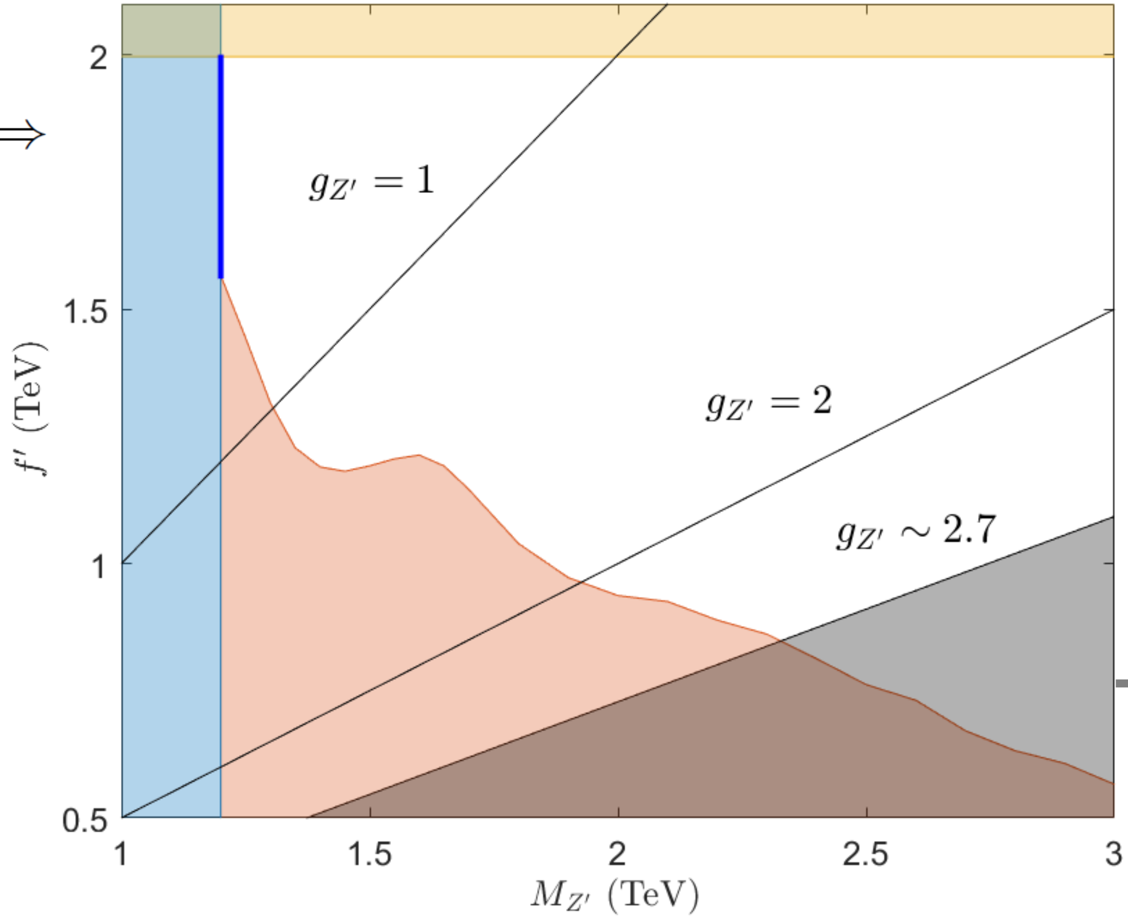


$$f' = \epsilon_{\mu\mu} \cdot f'_0 \text{ (TeV)}$$

$$\sigma_{\mu\mu} = \sigma_{bb} \left(\frac{M_{Z'}}{4 f'_0 \text{ TeV}} \right)^2$$

Use exp. constraint to determine f'_0 and f'_{min}

$\Longrightarrow$



Parameter space around boundary will be probed in the next Run!!

$$\frac{\Gamma_{Z'}}{M_{Z'}} > 10\%$$

Connecting with FCHM

Put back the FCHM assumption

- The interaction of the Z' boson

$$\mathcal{L}_{\rm int} = g_{Z'} Z'_\mu \left(Q_{SM} \bar{F}_3 \gamma^\mu F_3 - Q_{HB} \bar{\psi} \gamma^\mu \psi \right)$$

$= \mathbf{1/4}$ $= \mathbf{1/N_{HC}}$

⇒ The strength and running of gauge coupling $\boldsymbol{g_{z'}}$

- The relation between the Z' scale (B anomalies scale)

$$f' \approx \frac{2}{N_{HC}} f$$

⇒ include the constraints on the CHM scale f

Constraints on the gauge coupling $g_{Z'}$

- The running of $g_{Z'}$ is calculated and expressed using $\alpha_{Z'}$

$$\alpha_{Z'}^{-1}(\mu) = \alpha_{Z'}^{-1}(\text{TeV}) + 0.37\, b' \log_{10}\left(\frac{\mu}{\text{TeV}}\right) \qquad \text{where} \qquad b' = -\frac{2}{3}\left[1 + \frac{4}{N_{HC}}\right]$$

- The coupling becomes non-perturbative when $\Lambda = 10^n$ TeV, where

$$n = -\frac{\alpha_{Z'}^{-1}(\text{TeV})}{0.37\, b'} \approx \left(\frac{51\, N_{HC}}{4 + N_{HC}}\right)\frac{1}{g_{Z'}^2(\text{TeV})}$$

- To avoid reaching the Landau pole too fast, there are bounds for $g_{Z'}$ at the TeV

$$N_{HC} = 2\, (b' = -2\,) \;:\quad \Lambda > 10^{16}\ \text{TeV}, \quad g_{Z'} < 1.0 \qquad \Lambda > 10^{3}\ \text{TeV}, \quad g_{Z'} < 2.4$$

$$N_{HC} = 4\, (b' = -\frac{4}{3}\,) \;:\quad \Lambda > 10^{16}\ \text{TeV}, \quad g_{Z'} < 1.3 \qquad \Lambda > 10^{3}\ \text{TeV}, \quad g_{Z'} < 2.9$$

Constraints on the CHM scale *f*

- Lower bound : Higgs coupling measurement

CHM : $\kappa = \kappa_V = \kappa_F = \cos\left(\frac{\langle h \rangle}{f}\right) = \sqrt{1-\xi}$

EXP : $\kappa_V = 1.03 \pm 0.03\ , \qquad \kappa_F = 0.97 \pm 0.07$

$\Rightarrow \quad \xi \leq 0.1, \qquad f \geq 780\ \mathrm{GeV}$

- Upper bound : required fine-tuning

$$V(h) = \alpha f^2 \sin^2\left(\frac{h}{f}\right) + \beta f^4 \sin^4\left(\frac{h}{f}\right)$$

$\alpha \simeq -(63\ \mathrm{GeV})^2\ , \qquad \beta \simeq 0.033$

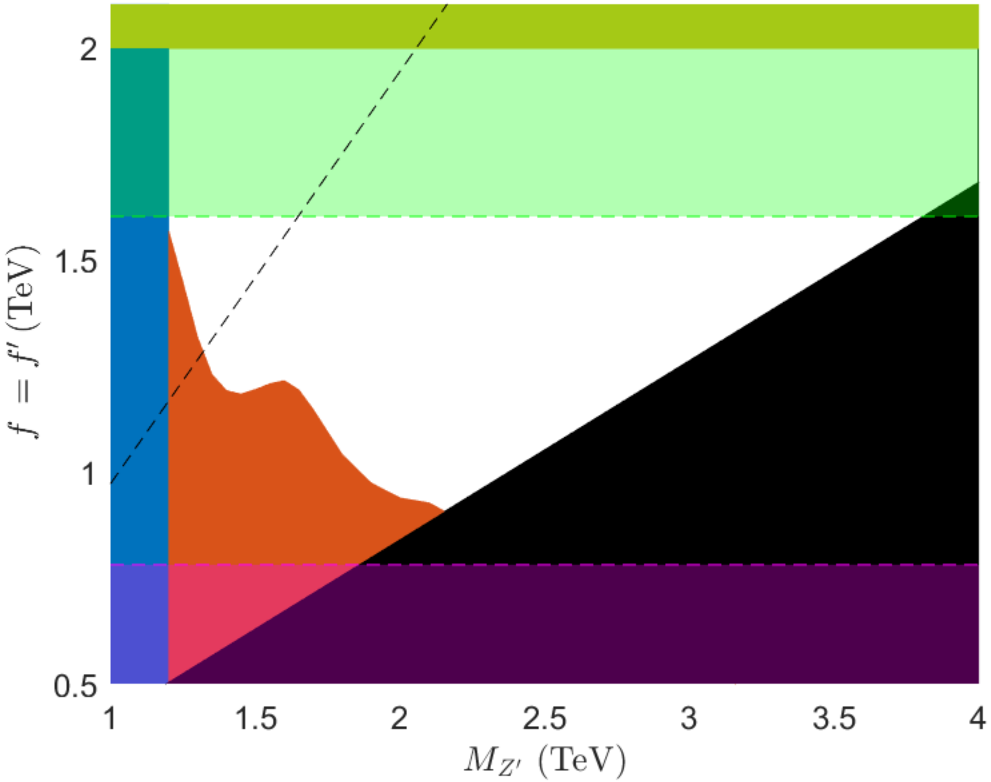
$\Rightarrow$ (personal) $f \lesssim 1600\ \mathrm{GeV}$

$4\pi\sqrt{-\alpha} \sim 800\ \mathrm{GeV}$

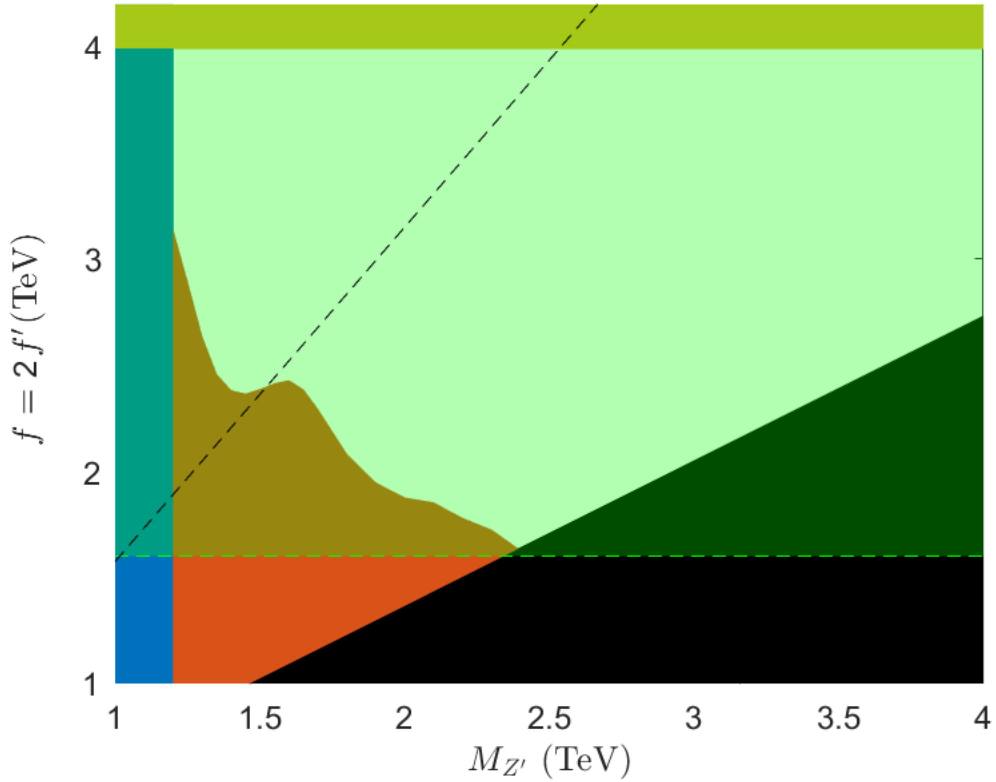
Combined Analysis : $f(f')$ v. s. $M_{Z'}$

$f' \approx \frac{2}{N_{HC}} f$

$(1)\ N_{HC} = 2 : \quad f \approx f'$



$(2)\ N_{HC} = 4 : \quad f \approx 2f'$



Conclusions

- **The Z' boson from $SU(4)/Sp(4)$ FCHM can explain the B anomalies**
- $U(1)'$ symmetry is the 3rd generation number minus Hyperbaryon number
- A TeV-scale Z' boson with universal couplings to the 3rd generation fermions
- The Z' scale and the CHM scale and are related by $f' \approx (2/N_{HC})\, f$
- Interesting parameter space is still viable and will be probed in near future

What is the next !?

- Relieve the assumptions (parameter space with smaller θ_e ?)
- Connect with the flavor puzzle (why the third generation is much heavier ?)

Backup

More about Z' direct searches

- The cross sections for each decay channel based on $M_{Z'}$ = 1.4 TeV with different f'.

f'(TeV)	$g_{Z'}$	σ_{tt}(fb)	σ_{bb}(fb)	$\sigma_{\tau\tau}$(fb)	$\sigma_{\mu\mu}$(fb)
1.2	1.17	4.7	4.7	0.78	0.78
1.5	0.93	3.0	3.0	0.50	0.50
1.8	0.78	2.1	2.1	0.35	0.35
Current bounds		∼40	6	1.5	0.7
Future prospects		∼10	∼2	∼0.6	∼0.2

- There could also be flavor violating decays like $Z' \to \mu\tau$
- Important difference from other Z' models – the partial width ratio

$$\Gamma_{tt} : \Gamma_{bb} : \Gamma_{\ell\ell} : \Gamma_{\nu\nu} \sim 3 : 3 : 1 : 1.$$

Extended Hypercolor Group

- The 4 Weyl fermions required under $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\psi_L = (U_L, D_L) = (1, 2, 0),$$
$$U_R = (1, 1, 1/2), \quad D_R = (1, 1, -1/2).$$

- The SM fermion and hyperfermions under $SU(4)_{PS_3} \times SP(N_{HC}) \times SU(2)_L \times SU(2)_R$

$$F_L = (4, 1, 2, 1), \quad \psi_L = (1, N_{HC}, 2, 1),$$
$$F_R = (\bar{4}, 1, 1, 2), \quad \psi_R = (1, N_{HC}, 1, 2).$$

- The minimal unified group $G_{EHC_3} = SU(4 + N_{HC})_{EHC_3} \times SU(2)_L \times SU(2)_R$

$$f_{L/R} = \begin{pmatrix} t^r & t^g & t^b & \nu_\tau & U^1 & \cdots & U^{N_{HC}} \\ b^r & b^g & b^b & \tau & D^1 & \cdots & D^{N_{HC}} \end{pmatrix}_{L/R} \Rightarrow Y' = c_{Y'} \, \mathrm{Diag}(1, 1, 1, 1, -\frac{4}{N_{HC}}, \cdots - \frac{4}{N_{HC}})$$

Generation-dependence from Horizontal group

- The generation-dependence can can arise naturally if the U(1)’ symmetry is the linear combination of $U(1)_{SM\text{-}HB}$ and $U(1)_H$,

	$SM_{1,2}$	SM_3	HF
Q_{SM-HB}	$1/12$	$1/12$	$-1/N_{HC}$
Q_H	$-1/12$	$1/6$	0
$Q' = Q_{SM-HB} + Q_H$	0	$1/4$	$-1/N_{HC}$

- Or from the linear combination of $U(1)_{EHC}$ and $U(1)_H$,

	$SM_{1,2}$	SM_3	$HF_{1,2}$	HF_3
Q_{EHC}	$1/12$	$1/12$	$-1/(3\,N_{HC})$	$-1/(3\,N_{HC})$
Q_H	$-1/12$	$1/6$	$-1/12$	$1/6$
$Q' = Q_{EHC} + Q_H$	0	$1/4$	$-1/12 - 1/(3\,N_{HC})$	$1/6 - 1/(3\,N_{HC})$