A Flavorful Composite Higgs Model

connect the B anomalies with the Hierarchy Problem

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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

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

Scale of CHM f

Might be related!!

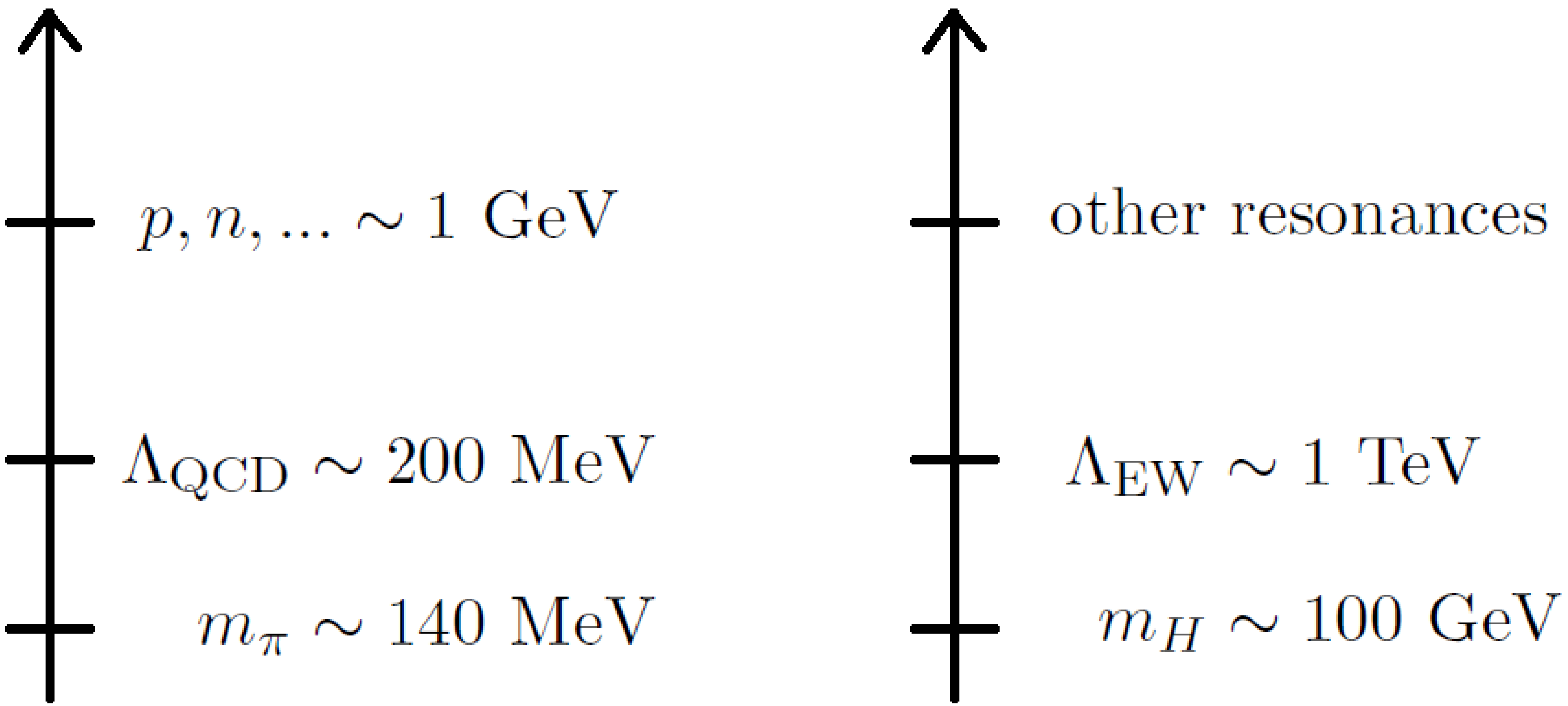
Scale of anomalies f'

Outline

- **Composite Higgs Models**
  - $SU(4)/Sp(4)$ Fundamental CHM
  - $U(1)'$ symmetry and $\boldsymbol{Z'}$ boson
- **Z' solution for Neutral Current B anomalies**
  - Constraints from FCNCs
  - Direct $\boldsymbol{Z'}$ Searches
- Conclusions

Higgs as pseudo-Nambu-Goldstone bosons

Light pions in QCD $\leftrightarrow$ Light Higgs in EW



Composite Higgs Models

- Chiral symmetry breaking in Λ_{QCD}

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

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 Λ_{EW}

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

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

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

Fundamental Composite Higgs Models

- Fundamental gauge dynamics with fermionic matter fields   Cacciapaglia, Sannino 2002.04914

$SU(N_f) \times SU(N_f)/SU(N_f)$ $\qquad SU(2N_f)/SO(2N_f)$ $\qquad SU(2N_f)/Sp(2N_f)$

- The minimal coset include the Higgs doublet - $\boldsymbol{SU(4)/Sp(4)}$ **FCHM**
  - 4 Weyl hyperfermions in the fundamental representation of the SU(2) = Sp(2) hypercolor group

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

  - Nonlinear Sigma model Σ as an anti-symmetric tensor representation

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

Sym. Breaking scale

Goldstone matrix

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

The symmetry breaking scale f

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

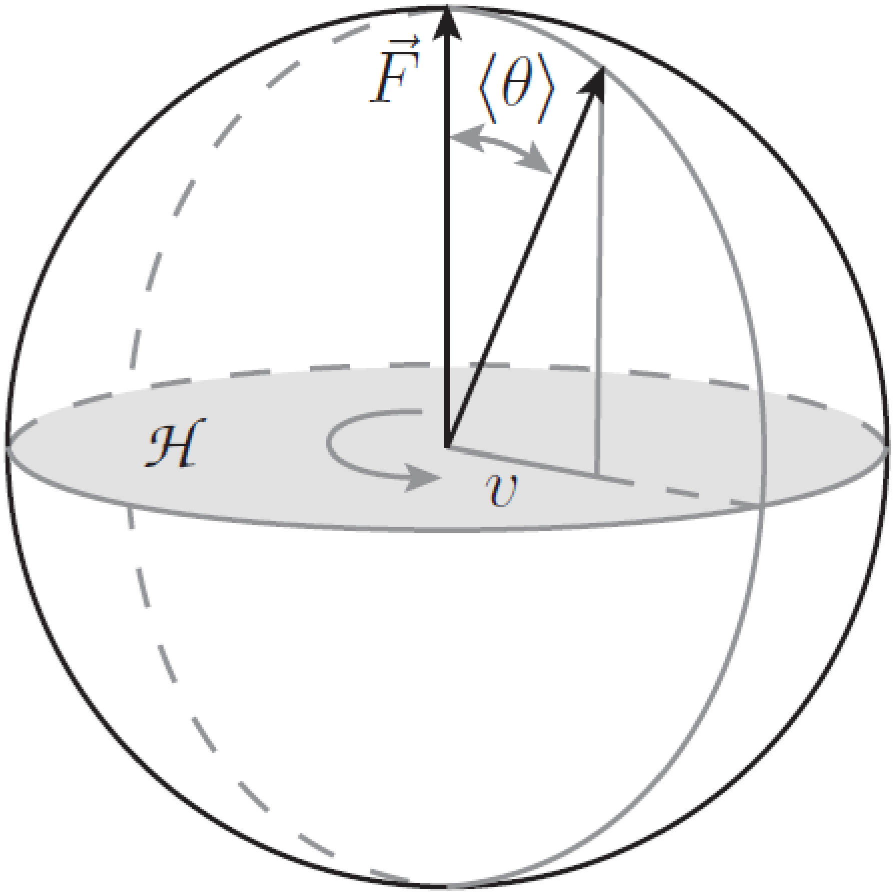
$$v = f\sin\langle\theta\rangle = f\sin\frac{\langle h\rangle}{f}$$

- 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

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



$f \gtrsim 1$ TeV

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

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

$\psi = (U_L, D_L, U_R^c, D_R^c)^T$

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

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

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- Interaction of the Z' boson

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

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

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

= 1 **= -2**

(SM_3 number – HF number)

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

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- The Z' mass

$$M_{Z'} = g_{Z'} \left(2\,|Q_{HC}|\,f\right) \equiv g_{Z'} f' \quad \text{with} \quad \boxed{f' = 2\,|Q_{HC}|\,f = 4f}$$

Relation between the two scales!!

Specified Mixing Matrices

For the SM fermion sector, we have

$$\mathcal{L}_{\text{int}} = g_{Z'} Z'_\mu \left(\bar{F}_L^m \gamma^\mu Q^m_{F_L} F_L^m + \bar{F}_R^m \gamma^\mu Q^m_{F_R} F_R^m \right)$$

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

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

Two terms of our interest are

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

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

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

Neutral Current B Anomalies

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

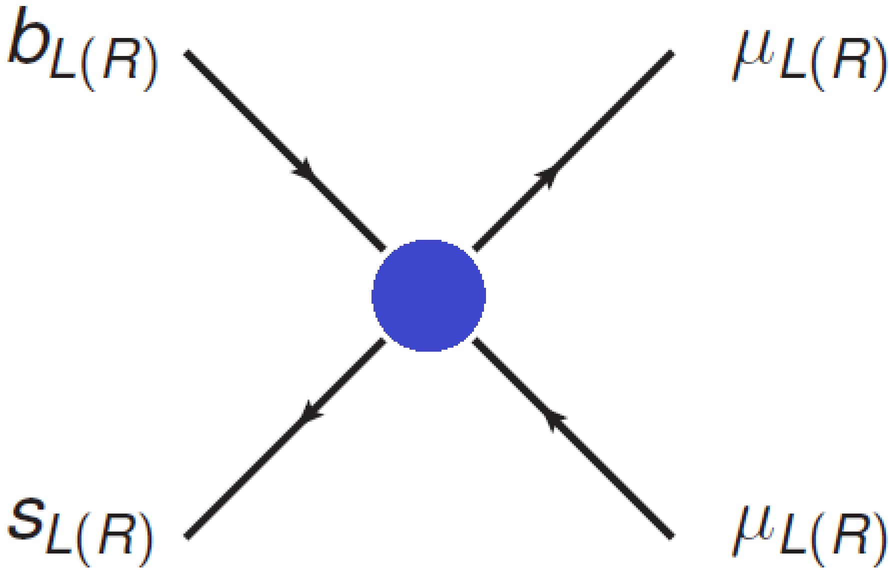
$$R_K^{[1,6]\mathrm{GeV}^2} = 0.846^{+0.042+0.013}_{-0.039-0.012} \quad (\sim 3.1\sigma)$$

$$R_{K^*}^{[1.1,6]\mathrm{GeV}^2} = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad (\sim 2.5\sigma)$$

$$R_{K^*}^{[0.045,1.1]\mathrm{GeV}^2} = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad (\sim 2.5\sigma)$$

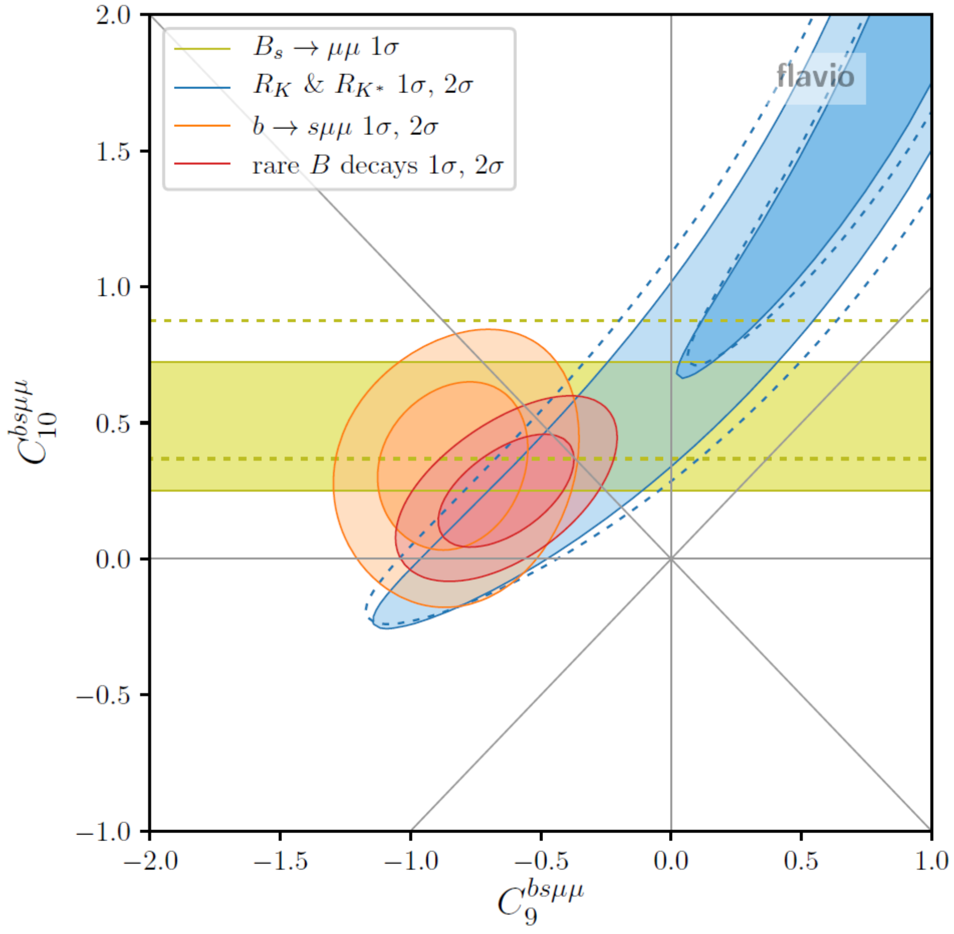
$$\vdots$$

$$\Longrightarrow$$



$$C_9(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$
$$C_{10}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma^5 \mu)$$

Global fit to SMEFT coefficients



Altmannshofer, Stangl 2103.13370

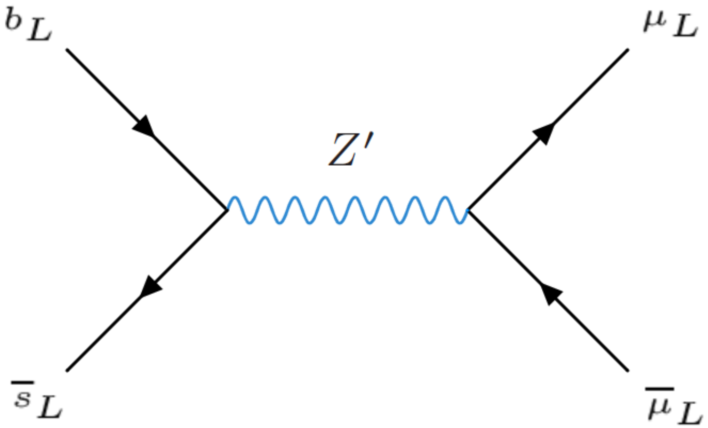
Wilson coefficient	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.74^{+0.20}_{-0.21}$	4.1	$-0.80^{+0.14}_{-0.14}$	5.7
$C_{10}^{bs\mu\mu}$	$+0.60^{+0.14}_{-0.14}$	4.7	$+0.55^{+0.12}_{-0.12}$	4.8
$C_9'^{bs\mu\mu}$	$-0.32^{+0.16}_{-0.17}$	2.0	$-0.14^{+0.13}_{-0.13}$	1.0
$C_{10}'^{bs\mu\mu}$	$+0.06^{+0.12}_{-0.12}$	0.5	$+0.04^{+0.10}_{-0.10}$	0.4
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.43^{+0.18}_{-0.18}$	2.4	$-0.01^{+0.12}_{-0.12}$	0.1
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.35^{+0.08}_{-0.08}$	4.6	$-0.41^{+0.07}_{-0.07}$	5.9

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 $$C_{LL} = \frac{g_{sb}g_{\mu\mu}}{M_{Z'}^2}\,(35\ \mathrm{TeV})^2$$



- The global fit result considering all rare B decay gives

$$C_{LL} = \frac{g_{sb}g_{\mu\mu}}{M_{Z'}^2}\,(35\ \mathrm{TeV})^2 = -\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2}\,(35\ \mathrm{TeV})^2 = -0.82 \pm 0.14$$

which requires

$$\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2} = \frac{1}{(39\ \mathrm{TeV})^2} \implies f' \sim \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}}\,(39\ \mathrm{TeV}).$$

FCNC Constraints

$B_s - \overline{B}_s$ Meson Mixing

- Constraint on the sb vertex

$$\frac{g_{Z'}}{M_{Z'}}\epsilon_{sb} \leq \frac{1}{194\ \text{TeV}}$$

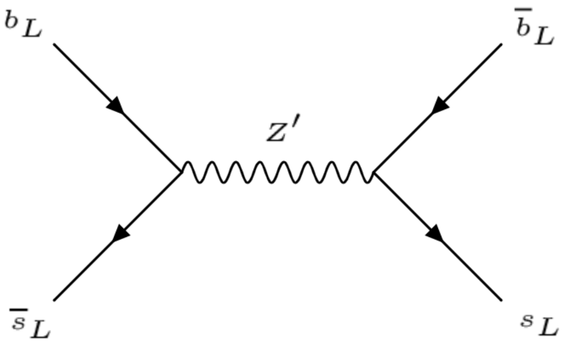
$$\implies f' \geq \epsilon_{sb} \cdot 194\ (\text{TeV})$$

$f' \sim \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}}\ (39\ \text{TeV})$

$$\implies f' \leq \epsilon_{\mu\mu} \cdot 7.7\ (\text{TeV})\ (\text{combined})$$

$$\Downarrow$$

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



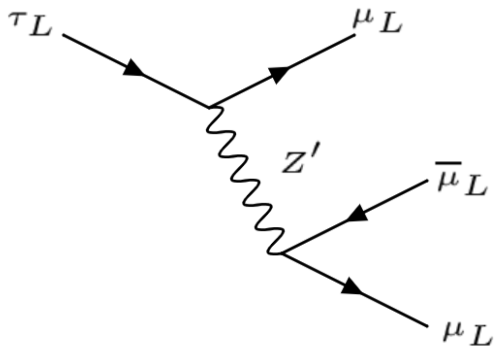
Lepton Flavor Violation $\tau \to \mu\mu\mu$

- Constraint on the $\tau\mu$ vertex (and thus $\mu\mu$)

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

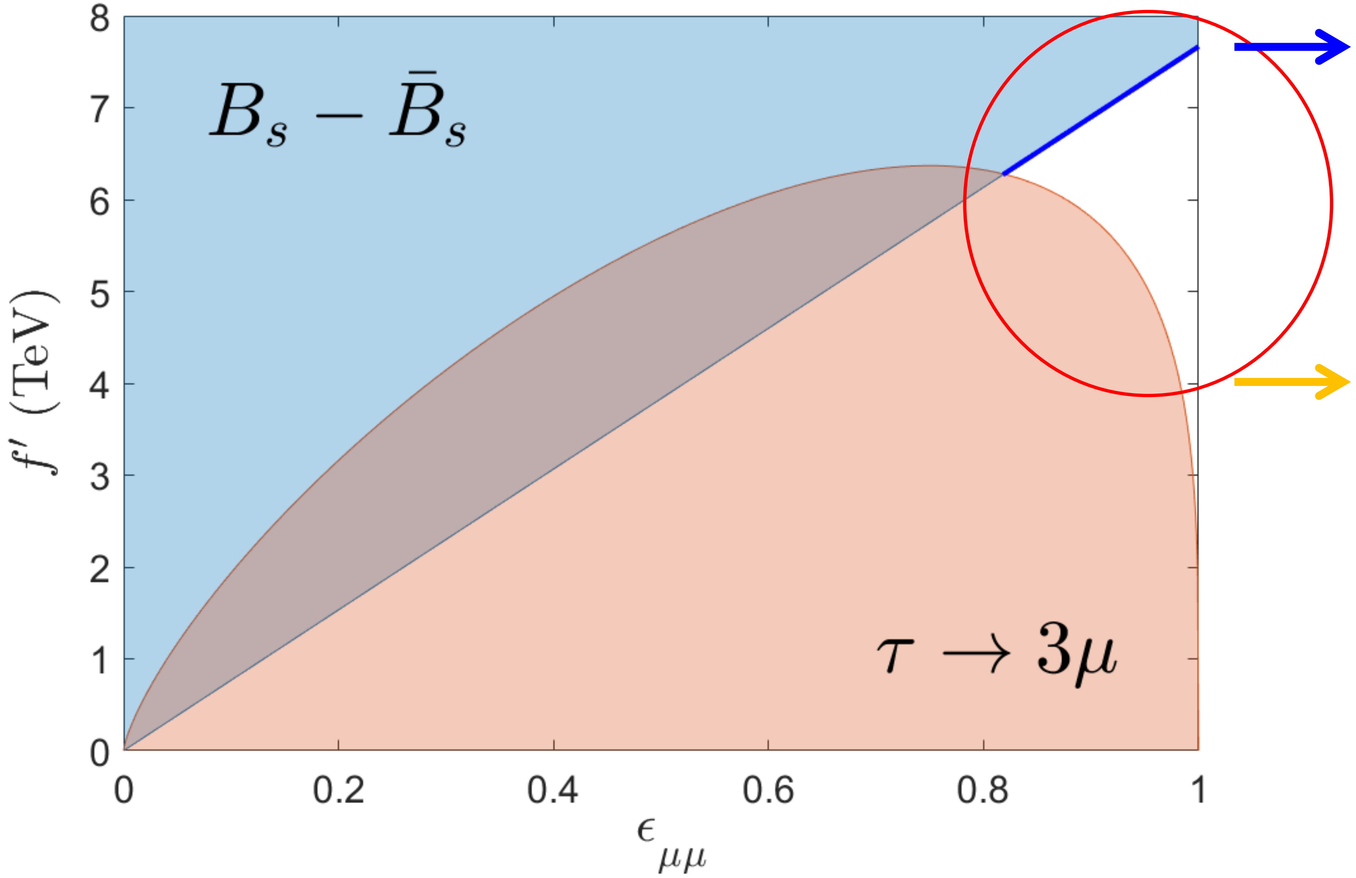
$$= 3.28 \times 10^{-4}\left(\frac{1\ \text{TeV}}{f'}\right)^4 \epsilon_{\mu\mu}^3(1-\epsilon_{\mu\mu})$$

$$< 2.1 \times 10^{-8}\ \text{at}\ 90\%\ \text{CL}$$



Combined Analysis

$$\epsilon_{\mu\mu} \geq 0.82$$



$$f' = \epsilon_{\mu\mu} \cdot 7.7 \text{ (TeV)}$$

which corresponds to minimal $M_{Z'}$

$$f' = 4f \gtrsim 4 \text{ (TeV)}$$

$$f' \sim \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}} \text{ (39 TeV)}$$

Direct Z' Searches

- Decay width

$$\frac{\Gamma_{Z'}}{M_{Z'}} = \frac{16}{24\pi} g_{Z'}^2 \sim 0.2\ g_{Z'}^2$$

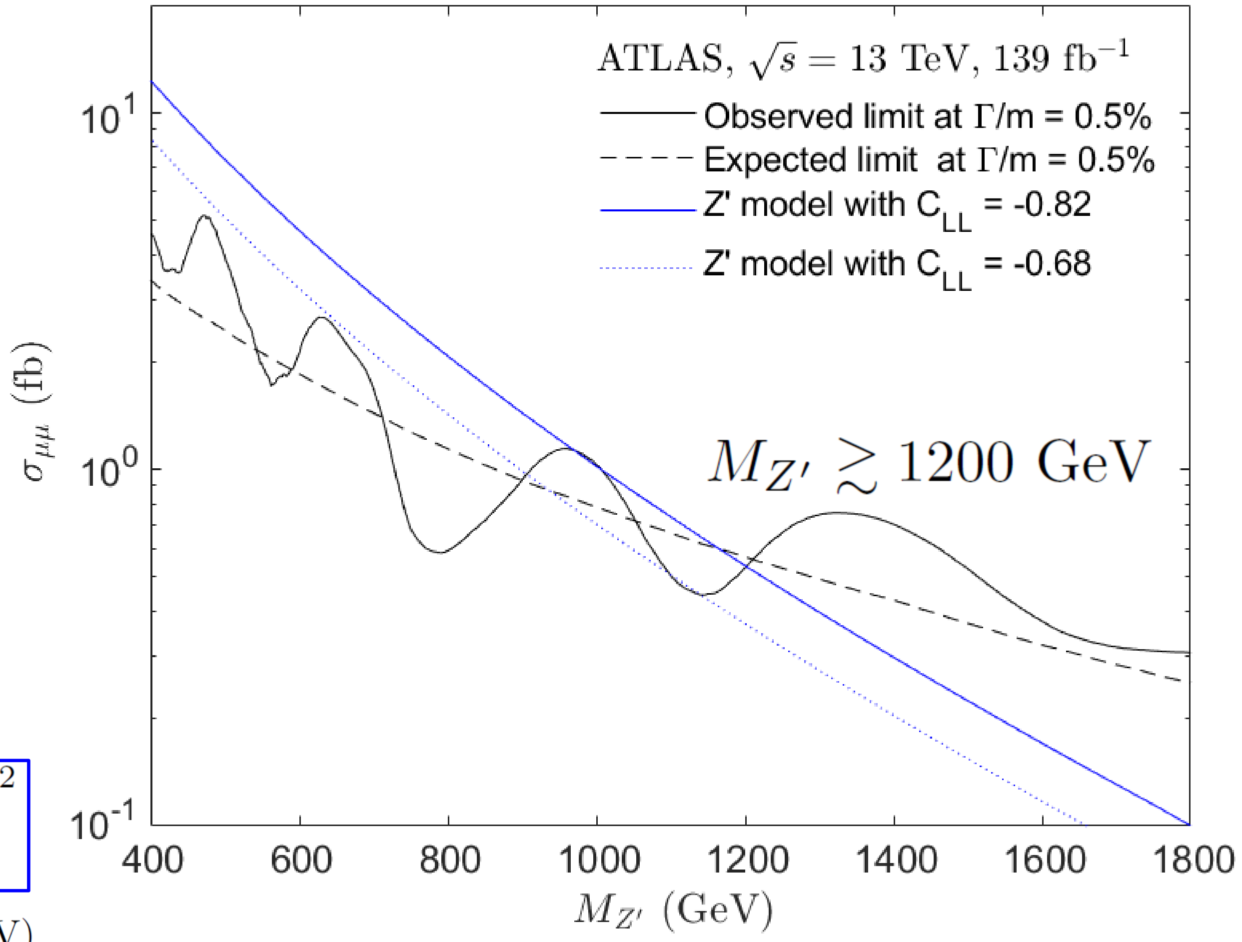
- Branching ratio

$$Br(t\bar{t}) \sim Br(b\bar{b}) \sim 37.5\%$$
$$Br(\mu\mu) \sim 6.25\ \epsilon_{\mu\mu}^2\ \%$$

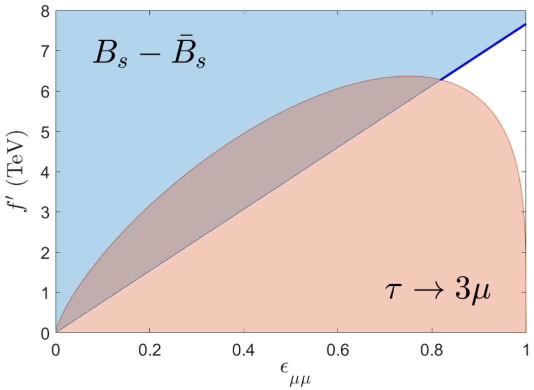
- Cross section

$$\sigma(b\bar{b} \to Z') \equiv g_{Z'}^2 \cdot \sigma_{bb}(M_{Z'})$$
$$\sigma_{\mu\mu} \equiv \sigma \times Br(\mu\mu) = \frac{1}{16} \sigma_{bb} \cdot g_{Z'}^2\ \epsilon_{\mu\mu}^2$$
$$\geq \frac{1}{16} \sigma_{bb} \cdot g_{Z'}^2 \left(\frac{f'}{7.7\ \text{TeV}}\right)^2 = \boxed{\sigma_{bb}\left(\frac{M_{Z'}}{31\ \text{TeV}}\right)^2}$$

$$f' = \epsilon_{\mu\mu} \cdot 7.7\ (\text{TeV})$$



Combined Analysis

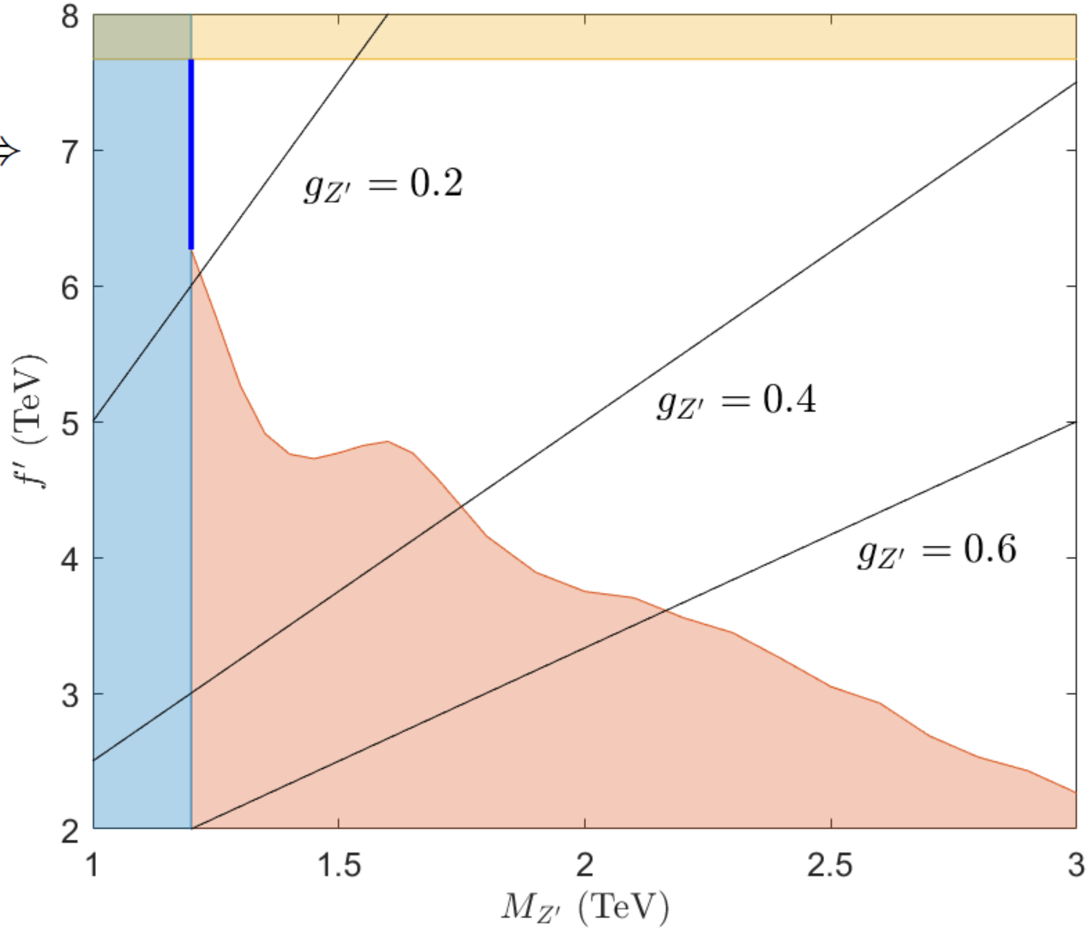


$$f' = \epsilon_{\mu\mu} \cdot f'_0 \ (\mathrm{TeV})$$

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

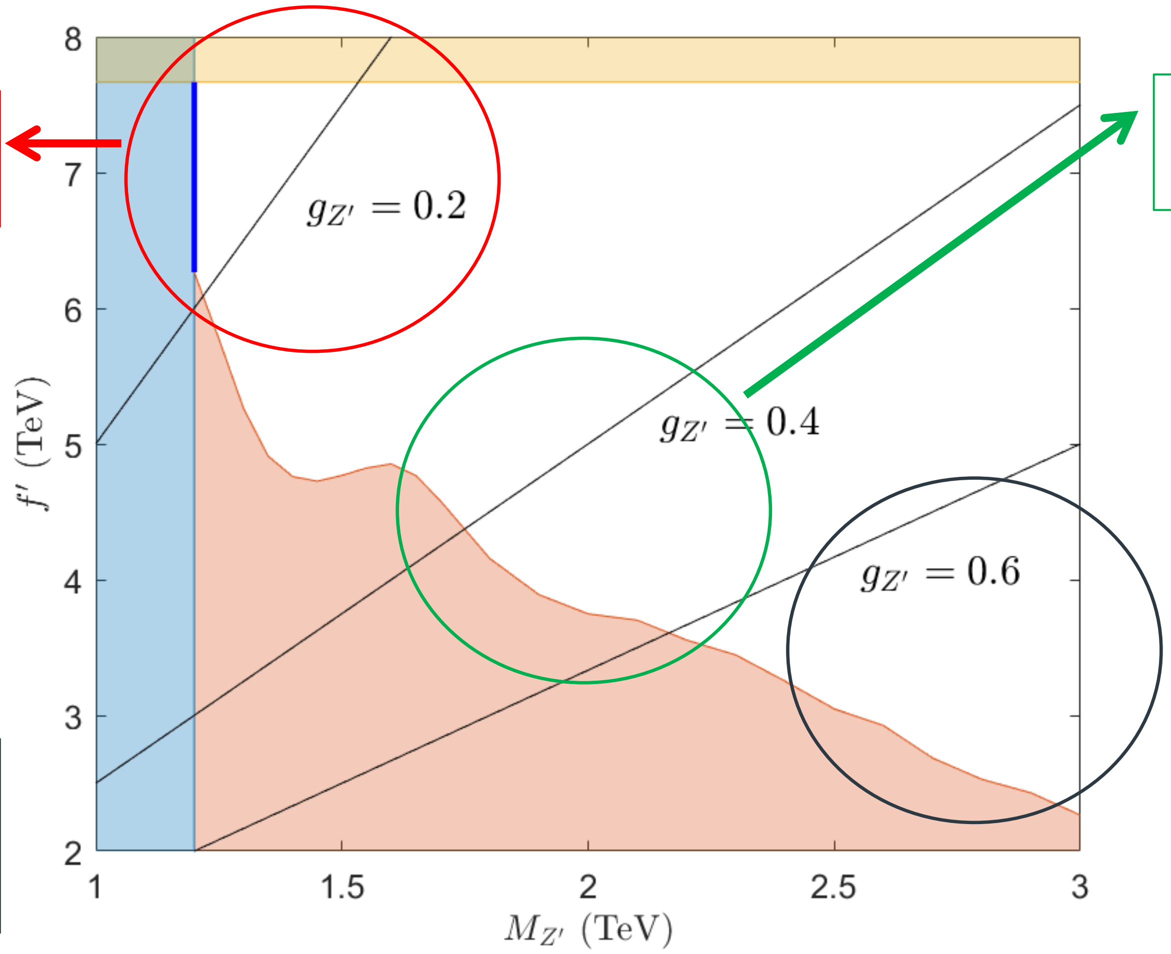
Use exp. constraint to determine f'_0 and f'_{min}

$\Longrightarrow$



Combined Analysis

light Z' boson 1.2 – 1.5 TeV
small $g_{Z'}$ & $f' = 4f > 4\ \mathrm{TeV}$



heavier Z' boson $\sim$2 TeV
moderate $g_{Z'}$ & $f' = 4f \sim 4\ \mathrm{TeV}$

heavier Z' boson > 2 TeV
large $g_{Z'}$ & $f' = 4f < 4\ \mathrm{TeV}$

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

Conclusions

- Z' solution of B anomalies can come from $SU(4)/Sp(4)$ **FCHM**
- A TeV-scale Z' boson with universal couplings to the 3rd generation fermions
- The two scales are related by $f' = 2\,|Q_{HC}|\,f = 4f$
- Interesting regions are still viable and will be probed in near future

To go further!?

- Origin of the $U(1)'$ gauge symmetry
- SM Yukawa couplings and the flavor puzzle

  $\Rightarrow$ Extended Hypercolor ?? Horizontal Symmetry ??

Thank you

Backup

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 $SU(4)_{PS3} \times SU(2)_{HC} \times SU(2)_L \times SU(2)_R$

$$F_L = (4, 1, 2, 1), \quad F_R = (4, 1, 1, 2),$$
$$\psi_L = (1, 2, 2, 1), \quad \psi_R = (1, 2, 1, 2).$$

- The minimal unified group $G_{EHC} = SU(6)_{EHC} \times SU(2)_L \times SU(2)_R$

$$f_{L/R} = \begin{pmatrix} t^r & t^g & t^b & \nu_\tau & U^\uparrow & U^\downarrow \\ b^r & b^g & b^b & \tau & D^\uparrow & D^\downarrow \end{pmatrix}_{L/R} \Longrightarrow \quad Y' = \mathrm{Diag}(1, 1, 1, 1, -2, -2).$$

Strength of gauge coupling $g_{Z'}$

- As a subgroup of SU(N) gauge group, we need to renormalize

$$g_{EHC} = \sqrt{24}\, g_{Z'} \sim 5\, g_{Z'}$$

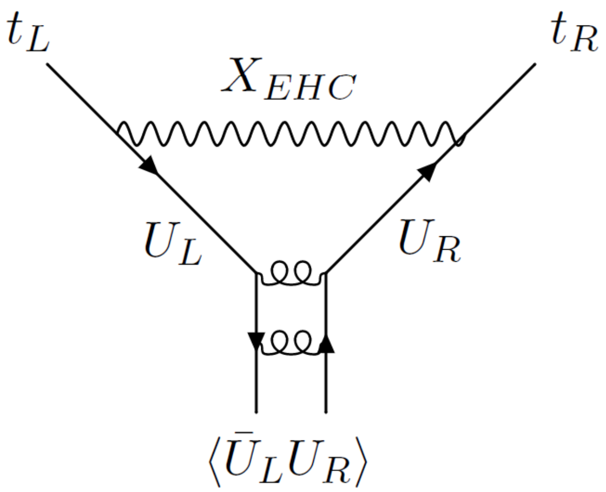
so the coupling is much stronger than we thought.

- However, the beta function is small (only include SM_3 and HF)

$$\alpha^{-1}(\mu) \sim \alpha^{-1}(\mathrm{TeV}) - 0.5 \times \log\left(\frac{\mu}{\mathrm{TeV}}\right)$$

Yukawa couplings and flavor puzzle

- Like the original idea of EHC, we can have Yukawa coupling from



with $$m_t \sim \frac{g_{EHC}^2}{M_{EHC}^2} \langle \bar{U}_L U_R \rangle_{EHC}$$

- We can further extend $$\left(\begin{array}{c|c|c|c} SM_1 & SM_2 & SM_3 & HF \end{array} \right)$$
$$\Lambda_1 \qquad \Lambda_2 \qquad \Lambda_3$$

which can partially solve the flavor puzzle… but still far from completion