Connect B anomalies with Hierarchy Problem

Z' boson in Composite Higgs Models

based on arXiv:2108.08511, 2110.03125, 2207.?????

Yi Chung

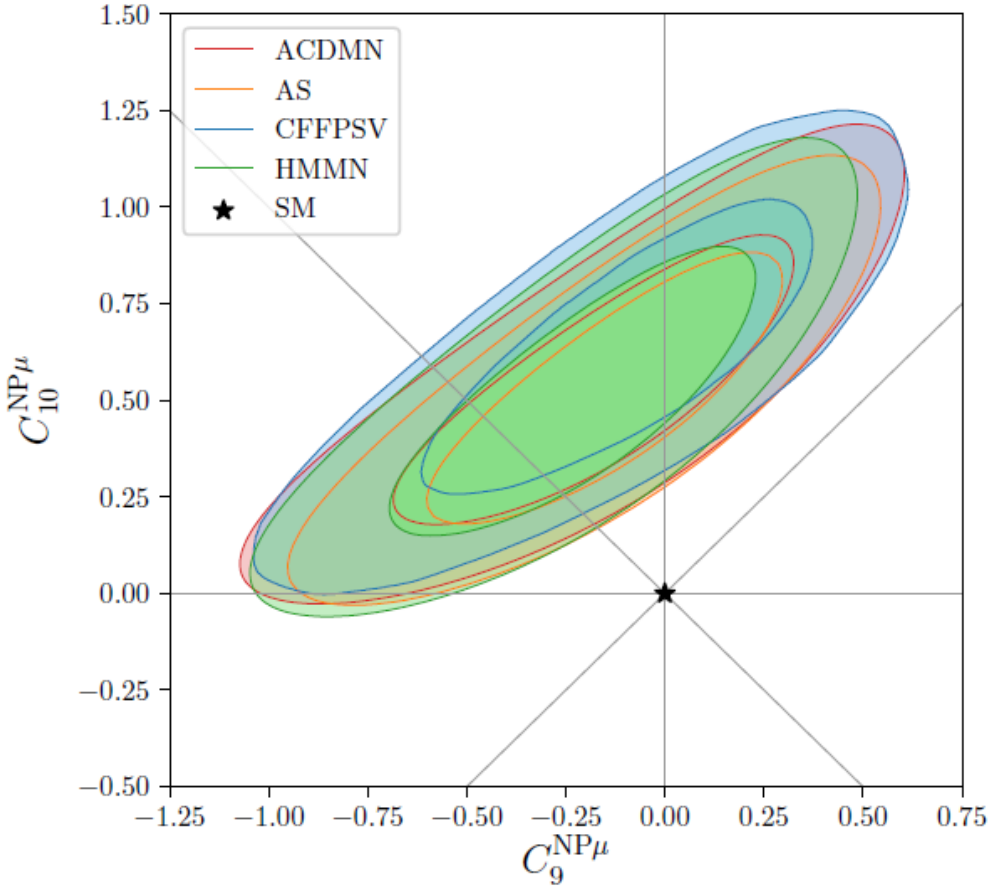
Max-Planck-Institut für Kernphysik, Heidelberg

July 4th, 2022

LF(U)V Workshop, Universität Zürich

Implications of NC B anomalies

Global fit to SMEFT coefficients



fit to LFU observables + $B_s \to \mu\mu$

ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
arXiv:2104.08921

AS (W. Altmannshofer, P. Stangl)
arXiv:2103.13370

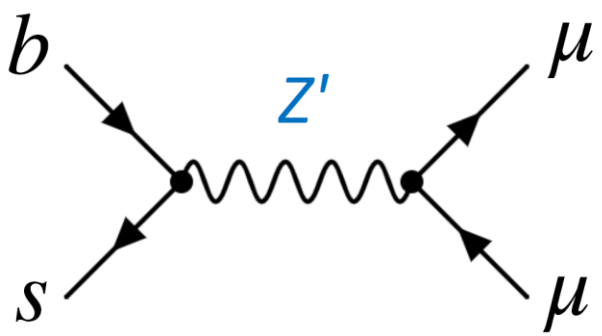
CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
arXiv:2011.01212

HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
arXiv:2104.10058

By B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl in Flavour Anomaly Workshop 2021

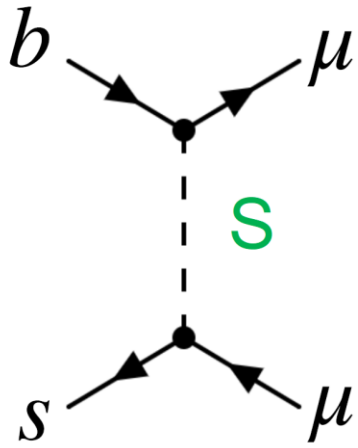
The three tree-level candidates

Z' boson

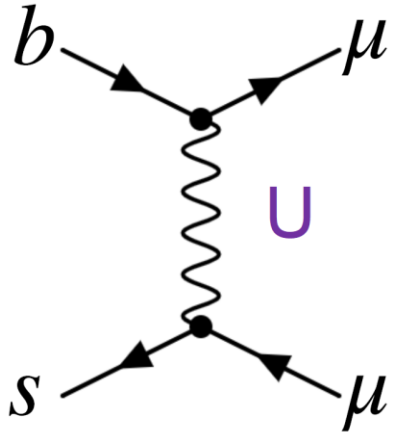


New $U(1)'$ local symmetry

Scalar leptoquark



Vector leptoquark



Quark-Lepton global/local symmetry

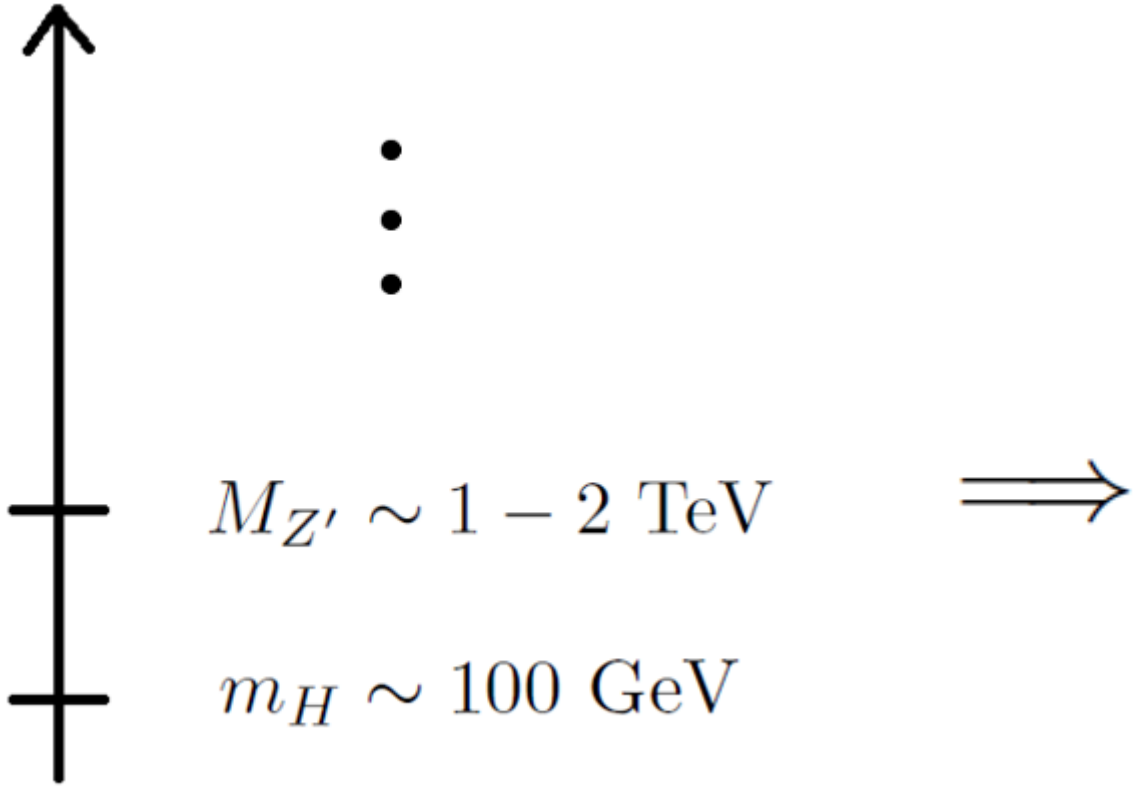
The scale of the New Physics

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

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

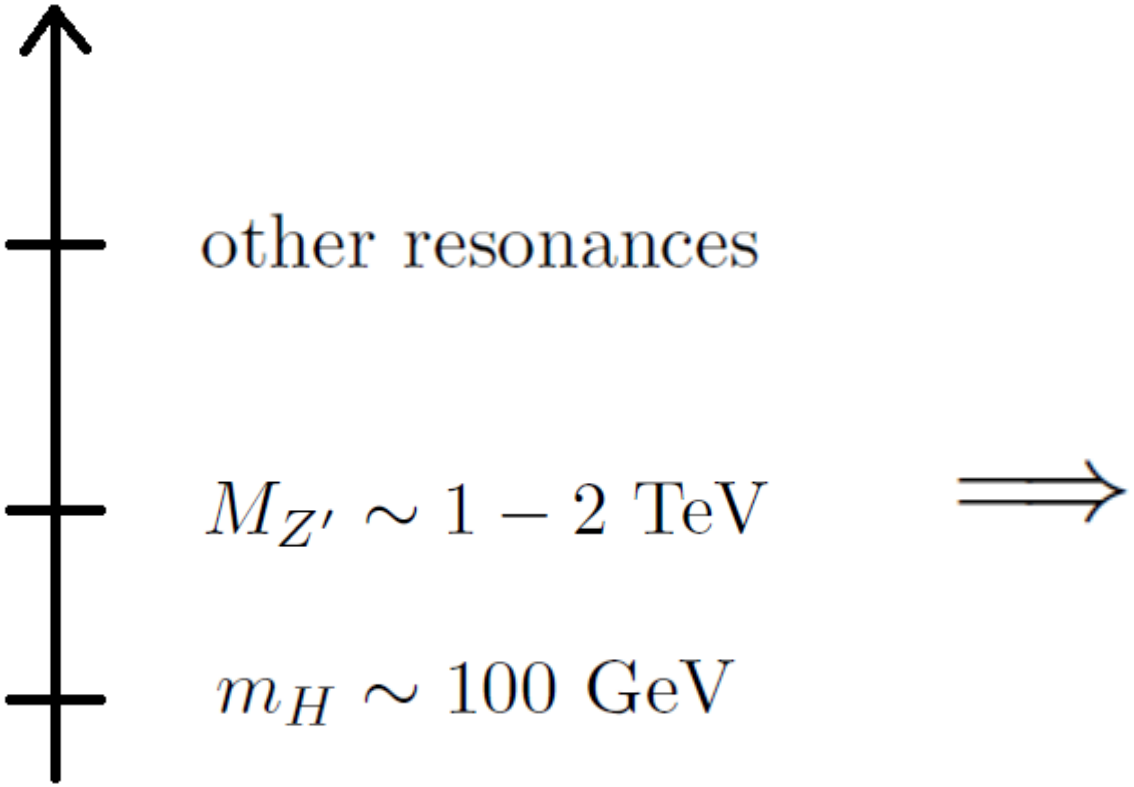
which is precisely the scale we expect for a solution to the Hierarchy Problem !!

The spectrum of unknown bosons



$\Longrightarrow$ Model ?

The spectrum of unknown bosons



$\Longrightarrow$

Composite Higgs Models with 5 pNGBs :

4 → SM Higgs doublet

1 → (global) Scalar singlet

(local) **TeV Z' boson!!**

Composite Higgs Models

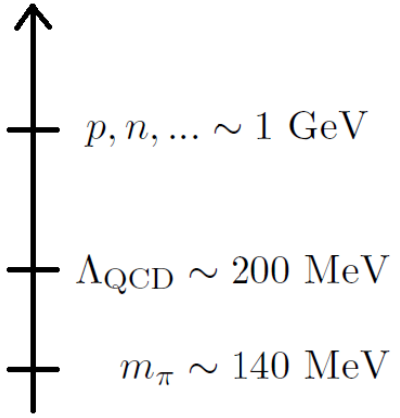
Composite Higgs Models

- 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.

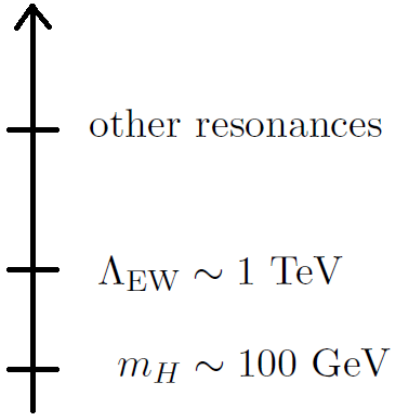


- (Some global) symmetry breaking in $\Lambda_{\mathrm{EW}} = f \sim 1$ TeV

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

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

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

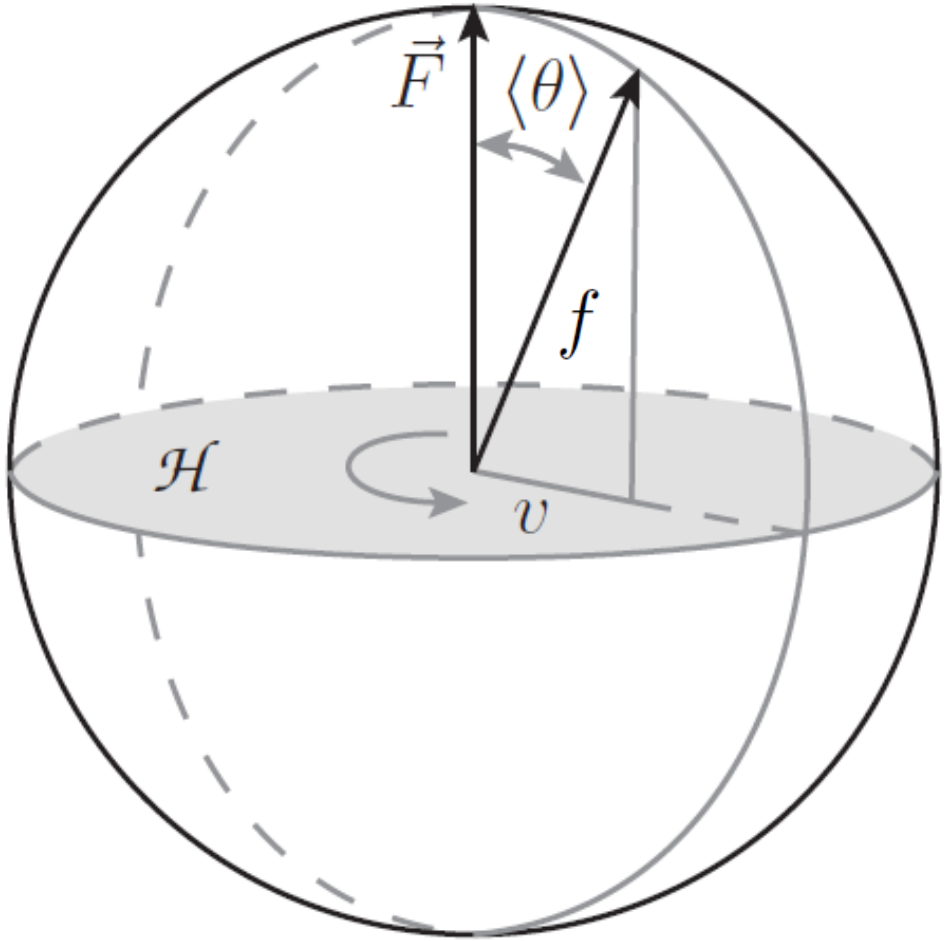
$$v = f \sin\langle\theta\rangle = f \sin\frac{\langle h \rangle}{f}$$

- 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)	$\mathrm{G_2}$	✓*	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]

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)	$\mathrm{G_2}$	✓*	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]

Two candidates

$SU(4)/SP(4)$

- Fundamental Composite Higgs Model
- New fermions with SU(4) global sym.

$$(U_L, D_L) = (1,2)_0 \ , \quad \begin{matrix} U_R = (1,1)_{1/2} \\ D_R = (1,1)_{-1/2} \end{matrix}$$

- Strong Sp(N) gauge group
- Higgs as a bound state of U and D
- Broken U(1): HB (Hyperbaryon number)
- Modified U(1): $SM_3 - HB$
- Ref: 2108.08511, 2110.03125

$SU(3)/SU(2)$

- Composite Higgs Model with Top-seesaw
- New fermions with $U(3)_L$ x $U(2)_R$ global sym.

$$(t_L, b_L) \rightarrow (T_L, t_L, b_L)$$
$$(t_R) \rightarrow (T_R, t_R)$$

- Strong broken gauge interaction (NJL)
- Higgs as a bound state of q_L and T_R
- Broken U(1): L_8 (T_8 of $SU(3)_L$)
- Modified U(1): 3rd gen's $L_8 - R_8$
- Ref: 2207.?????

The $SU(4)/Sp(4)$ Fundamental CHM

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

$$\psi = (U_L, D_L, U_R^c, D_R^c)^T \quad \Longrightarrow \quad \boldsymbol{U(1)_{HB}}$$ **symmetry (each with $\boldsymbol{1/N_{HC}}$)**

(like Majorana mass break the U(1) Lepton number)

- Is it valid to gauge the symmetry?

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

$= 1/N_{HC}$

$U(1)_{SM_3\text{-}HB}$ symmetry and Z' boson

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

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

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

(SM_3 number – HB number) like hyperversion of *B-L*

Flavor Physics
LHC Direct Search

SM fermion | Hyperfermion

Higgs Physics

$U(1)_{SM_3\text{-}HB}$ symmetry and Z' boson

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

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

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

(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) and The CHM scale

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

$(f' = 1/4\, f_{\text{NP}})$

$U(1)_{SM_3\text{-}HB}$ symmetry and Z' boson

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

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

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

(SM_3 number – HB number)

- The Z' mass

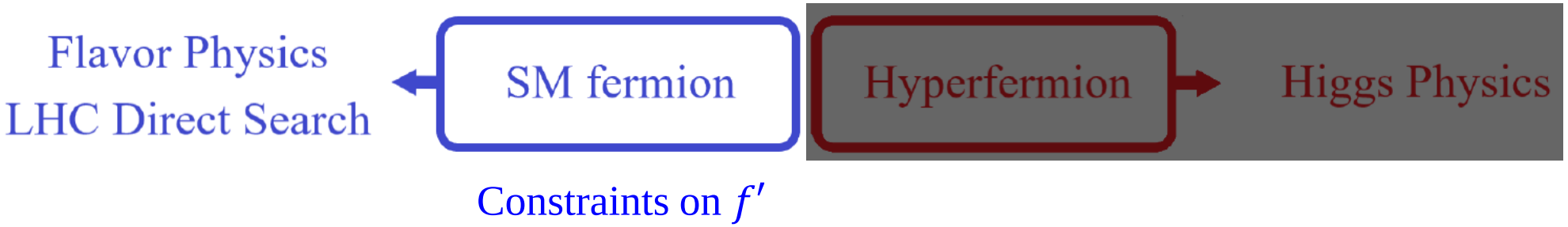
$$M_{Z'} = 2\, Q_{HB}\, g_{Z'} f \cos\left(\frac{V}{f}\right) = \frac{2}{N_{HC}} g_{Z'} f \cos\left(\frac{V}{f}\right)$$

- The Z' scale (B anomalies scale) and The CHM scale

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

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

Z' phenomenology



Constraints on f'

Specified Mixing Matrices

- For the SM fermion sector, we have

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

$$\frac{1}{4}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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

- Two terms of our interest are

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

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

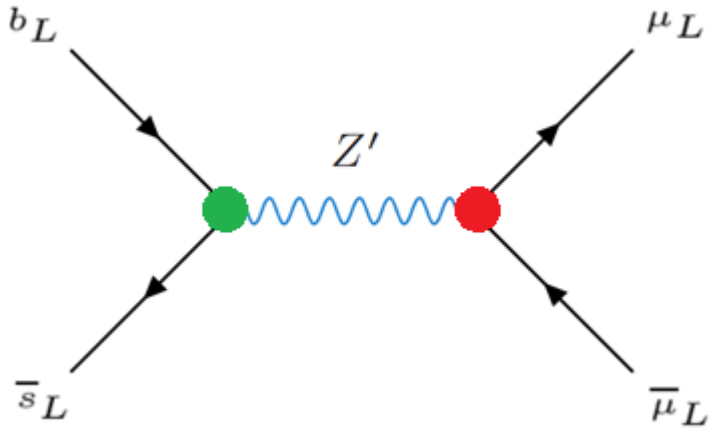
- The 3 key parameters are the scale f' , the mixing ϵ_{sb} and $\epsilon_{\mu\mu}$

Z' solution for Neutral Current B Anomalies

- Under the specified mixing metrices

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

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



- The global fit result considering all rare B decay gives

$$C_{LL} = -\frac{g_{sb}g_{\mu\mu}}{M_{Z'}^2}\ (36\ \text{TeV})^2 = -\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2}\ (9\ \text{TeV})^2 = -0.70 \pm 0.16$$

$$(-0.38 \text{ for } 2\sigma \text{ higher})$$

which requires

$$\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2} = \frac{1}{(11\ \text{TeV})^2}\left(\frac{C_{LL}}{-0.70}\right)$$

(NCBA condition)

FCNC Constraints

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

- Constraint on the sb vertex

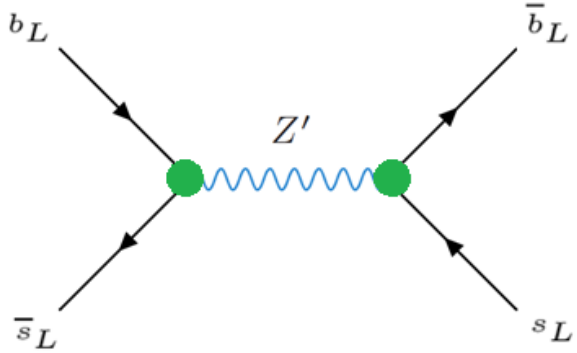
$$\frac{g_{sb}}{M_{Z'}} \leq \frac{1}{194\ \text{TeV}}$$

$$\implies \epsilon_{sb} \leq f' \ / \ 48.5\ \text{TeV}$$

$$\implies \epsilon_{\mu\mu} \geq f' \ / \ 2.3\ \text{TeV (combined)}$$

NCBA

$$\frac{\epsilon_{sb}\epsilon_{\mu\mu}}{f'^2} = \frac{1}{(11\ \text{TeV})^2}$$



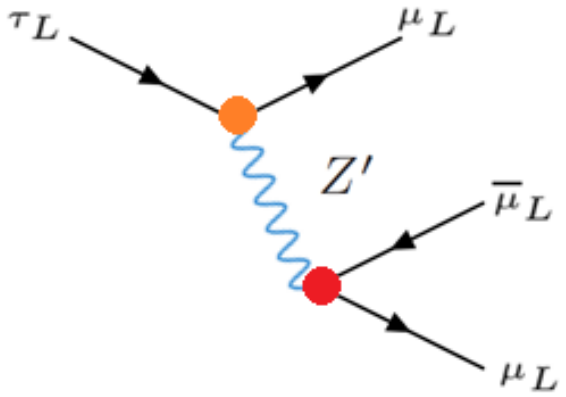
Lepton Flavor Violation $\tau \to \mu\mu\mu$

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

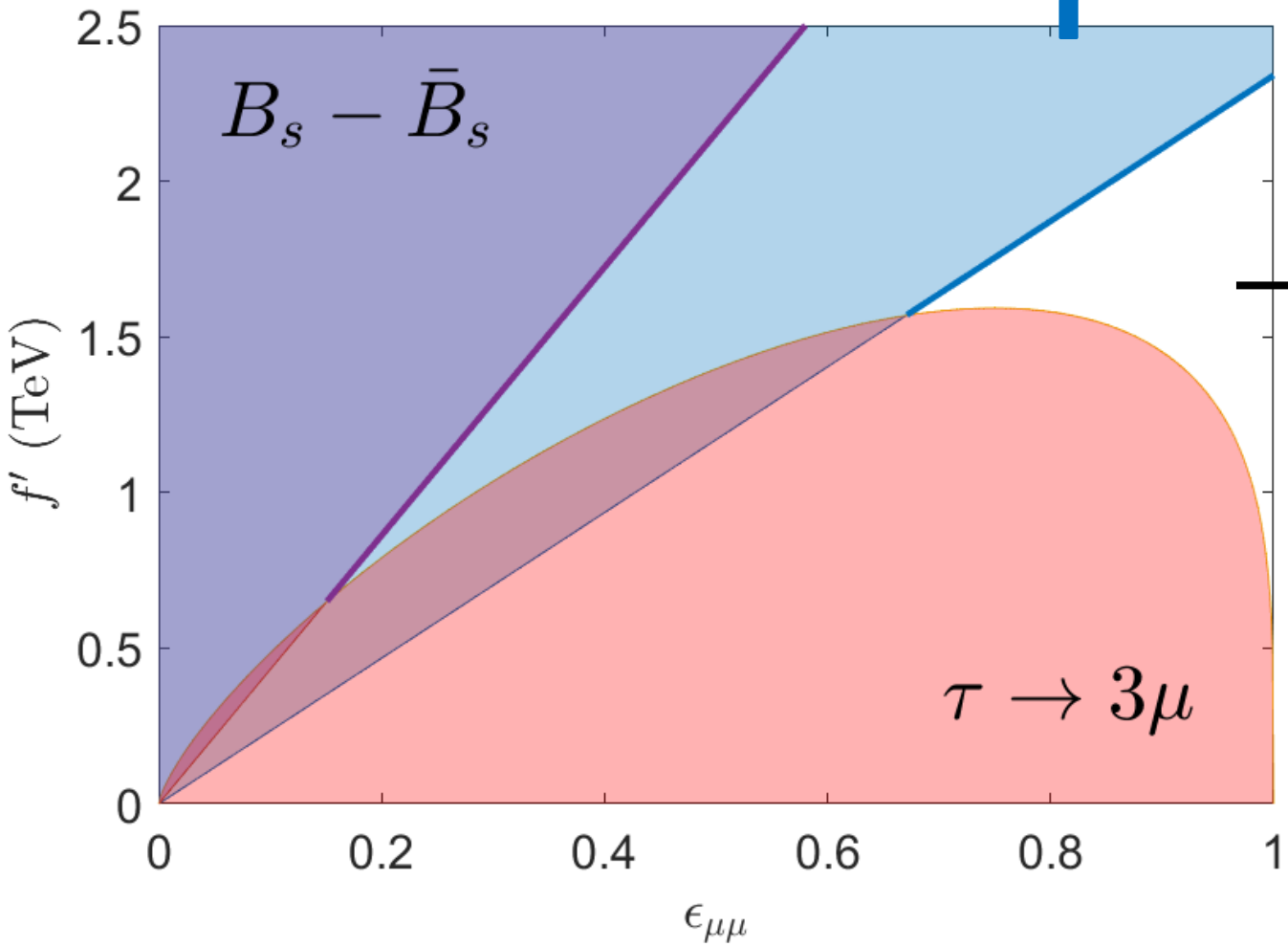
$$BR(\tau \to 3\mu) = \frac{2m_\tau^5}{1536\pi^3\Gamma_\tau}\left(\frac{g_{Z'}^2}{16M_{Z'}^2}\sin^3\theta_e\cos\theta_e\right)^2$$

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

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



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



$C_{LL} = -0.70$

$f' \leq \epsilon_{\mu\mu} \cdot 2.3$ (TeV)

(fit to all LFU)

Large angle region:

$\epsilon_{\mu\mu} \geq 0.67$

$f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}}$ (11 TeV)

only $\mu\mu$ matters

$C_{LL} = -0.38$

$f' \leq \epsilon_{\mu\mu} \cdot 4.3$ (TeV)

($+2\sigma$ value)

Small angle region:

$\epsilon_{\mu\mu} \geq 0.15$

$f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}}$ (14 TeV)

$\mu\tau, \tau\tau$ also matter

Direct Z' Searches – μμ channel

- Decay width

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

- Branching ratio

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

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

- Production and Cross section

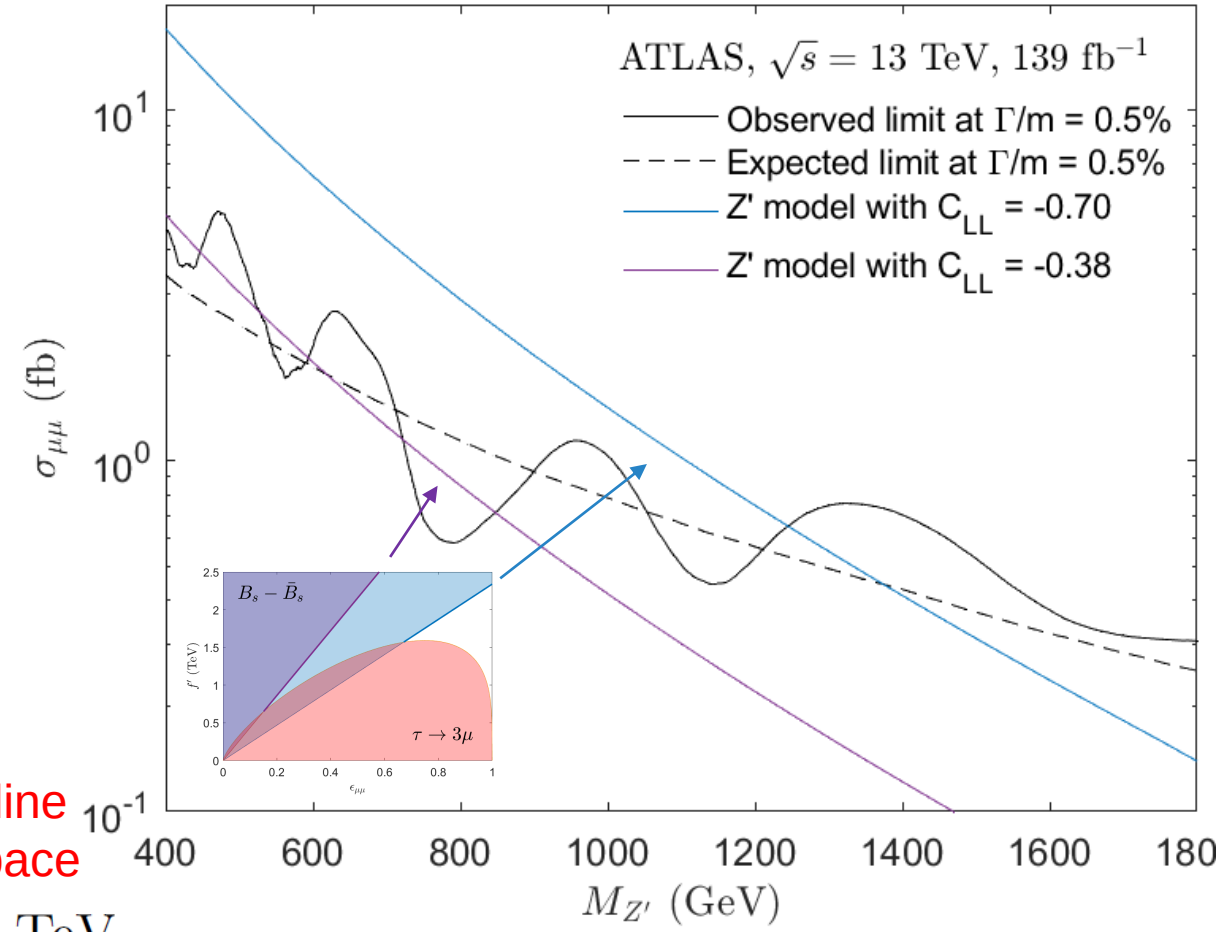
$$\sigma(b\bar{b} \to Z') \equiv \frac{g_{Z'}^2}{16} \cdot \sigma_{bb}(M_{Z'})$$

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

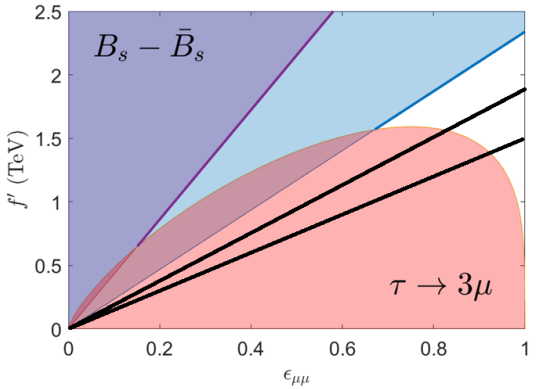
$$= \boxed{\frac{1}{256}\,\sigma_{bb} \cdot g_{Z'}^2 f'^2} \boxed{\left(\frac{\epsilon_{\mu\mu}}{f'}\right)^2}$$

A straight line in para. space

Function of $M_{Z'}$ $\geq 1/\,2.3\ (4.3)$ TeV



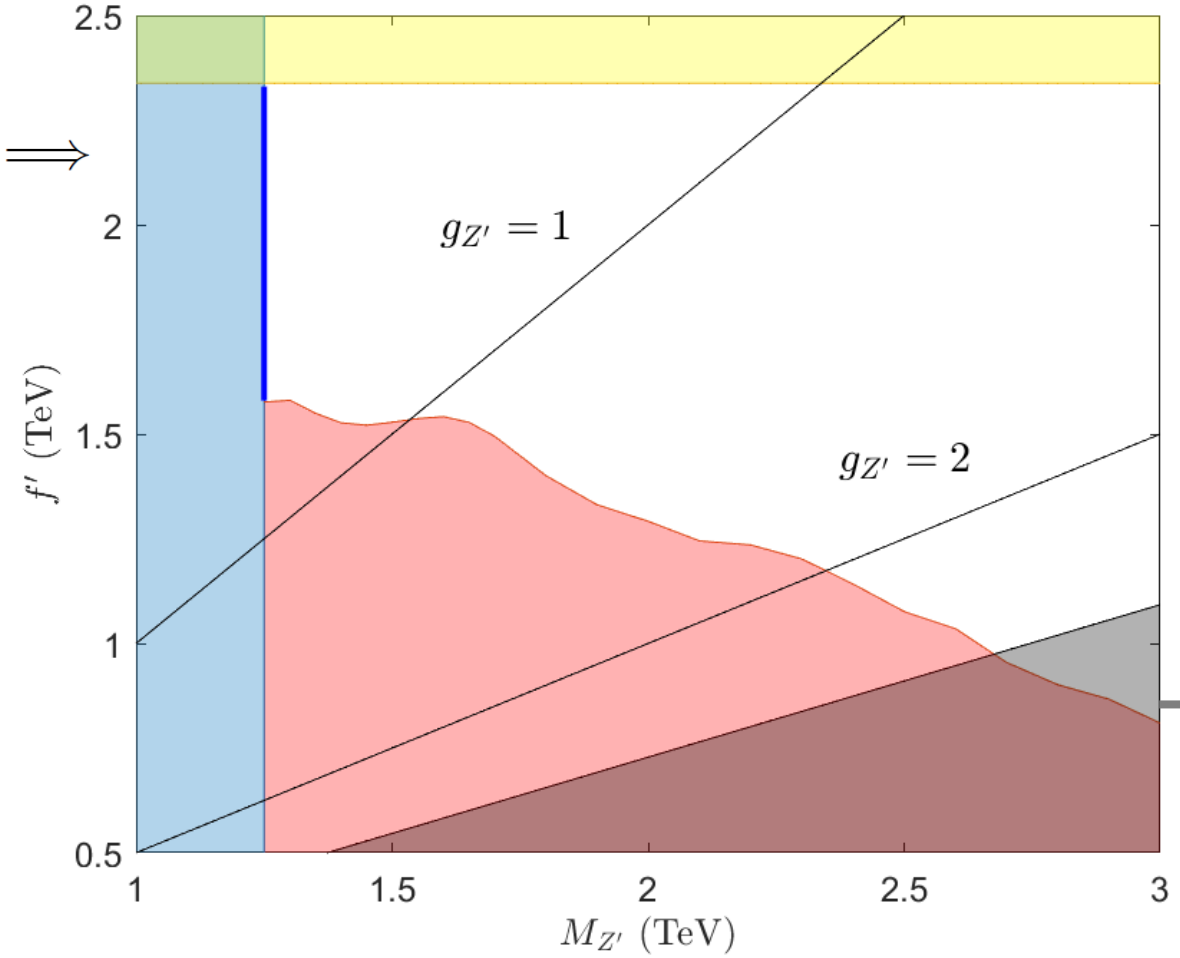
Combined Analysis : f' v. s. $M_{Z'}$ (large angle)



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

$$\sigma_{\mu\mu} = \sigma_{bb} \left(\frac{M_{Z'}}{16\, f'_0 \ \mathrm{TeV}} \right)^2$$

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

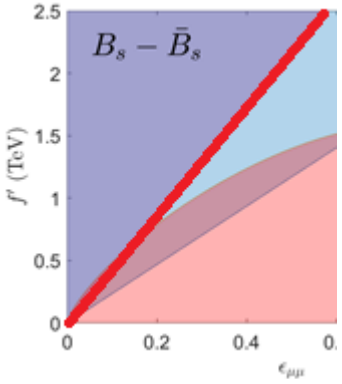


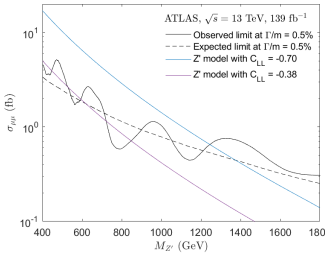
Parameter space around boundary will be probed in the next Run!!

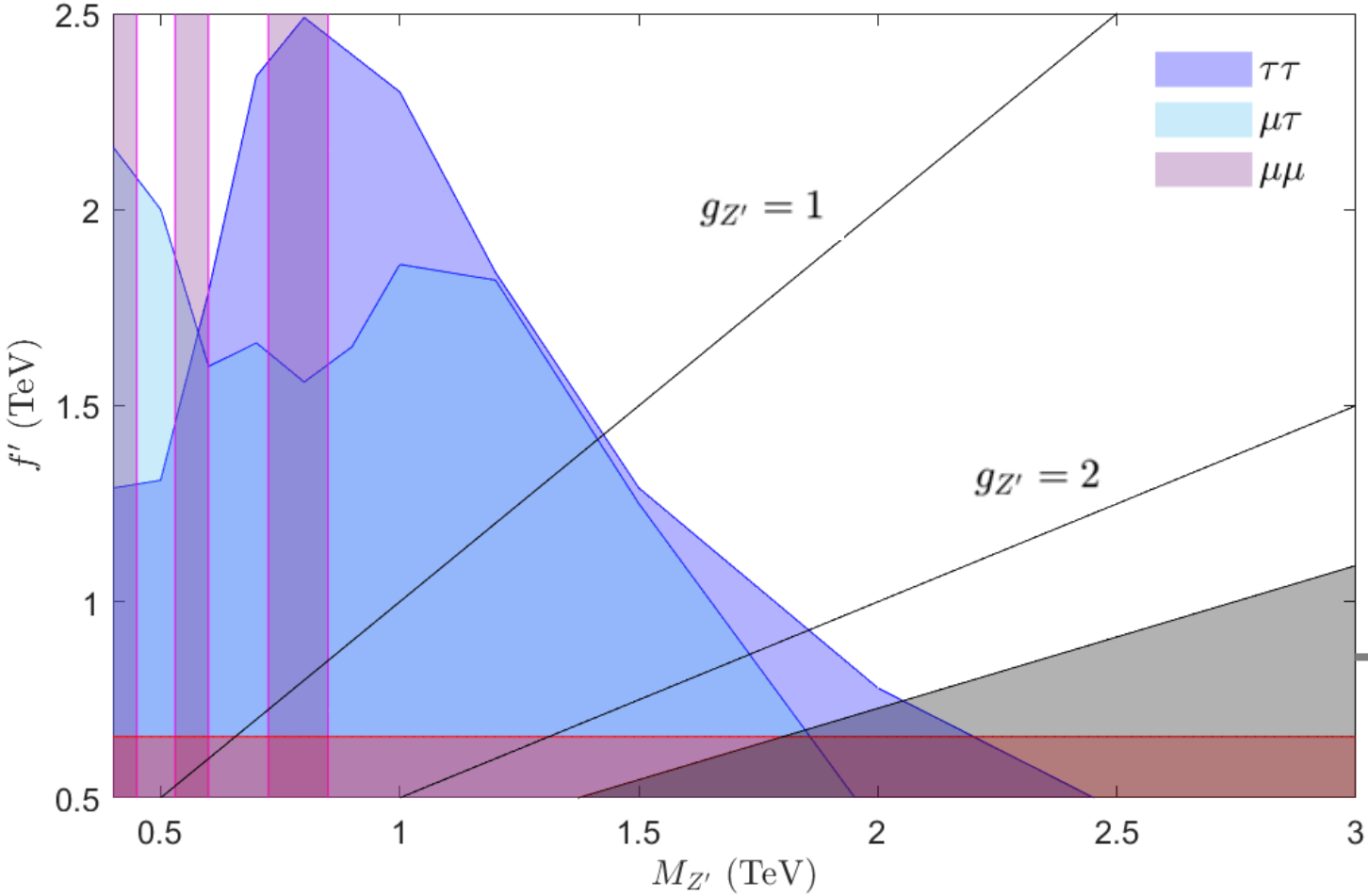
$$\frac{\Gamma_{Z'}}{M_{Z'}} > 10\%$$

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

only red line



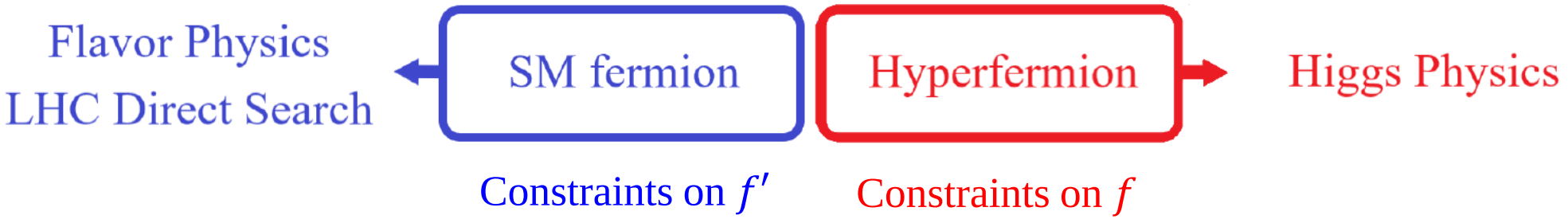




Parameter space around boundary will be probed in the next Run!!

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

Connecting with FCHM



Put back the FCHM assumption

- The interaction of the Z' boson

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

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

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

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

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

  ⇒ include the constraints on the CHM scale f

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

$\Rightarrow \quad \xi \leq 0.1, \quad \boxed{f \geq 780\ \text{GeV}}$

- Upper bound : required fine-tuning

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

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

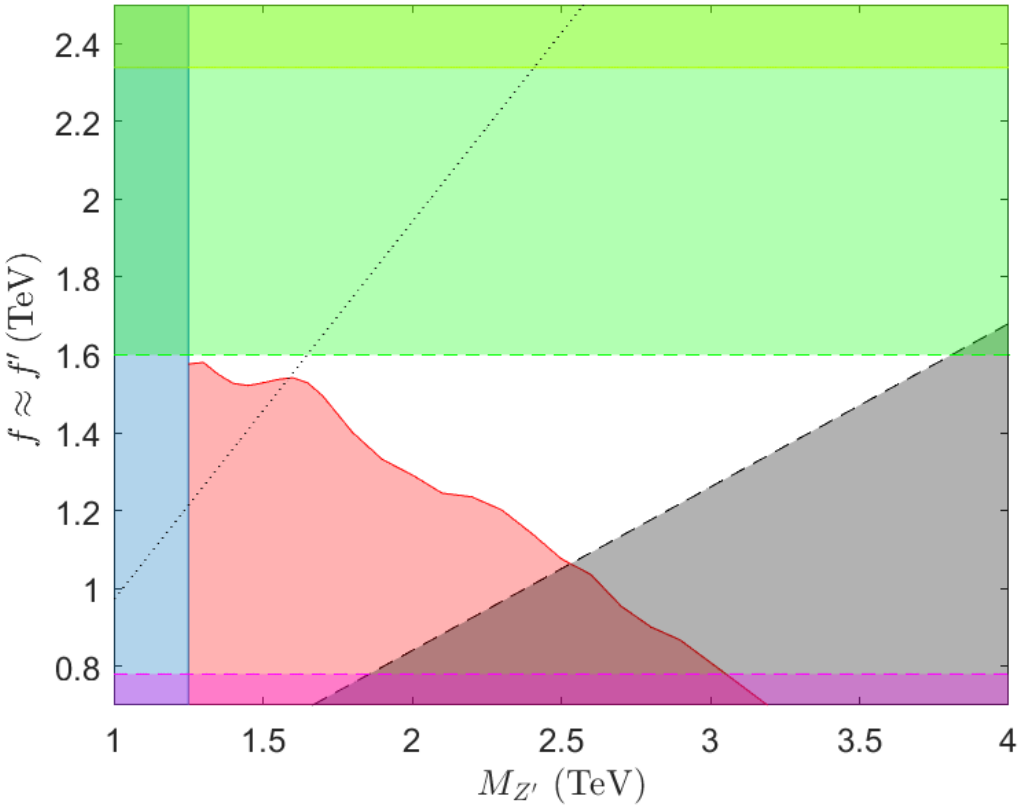
$\Rightarrow$ (personal) $\boxed{f \lesssim 1600\ \text{GeV}}$

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

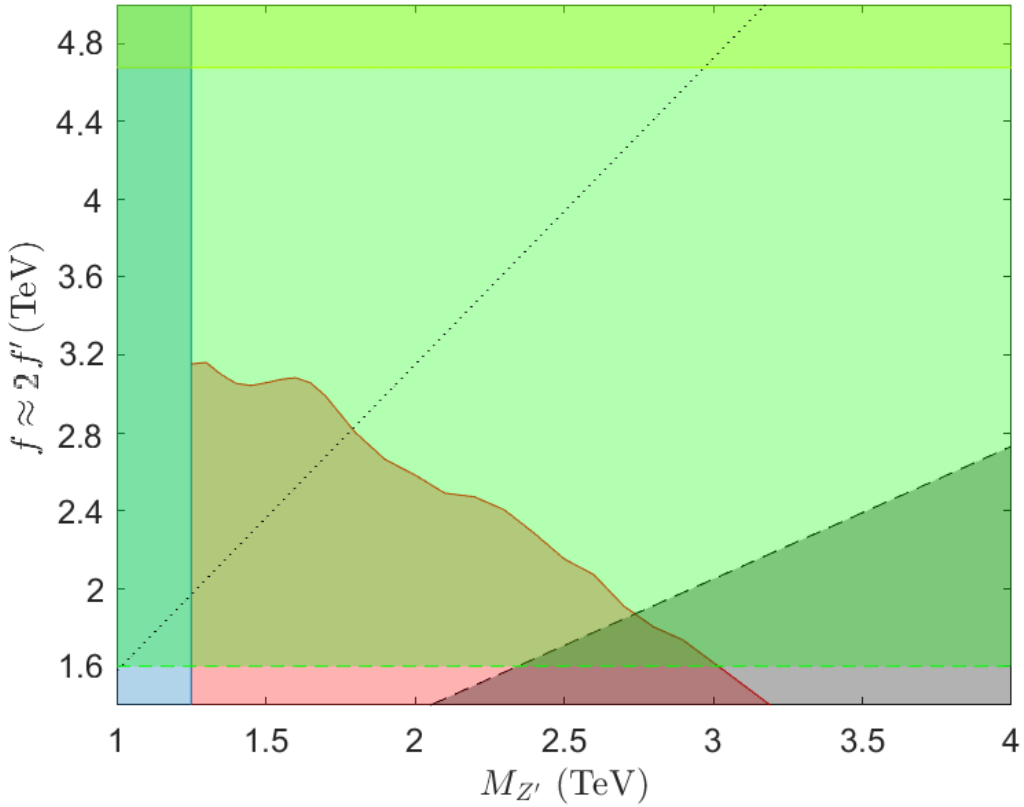
Combined Analysis : $f(f')$ v. s. $M_{Z'}$ (large angle)

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

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

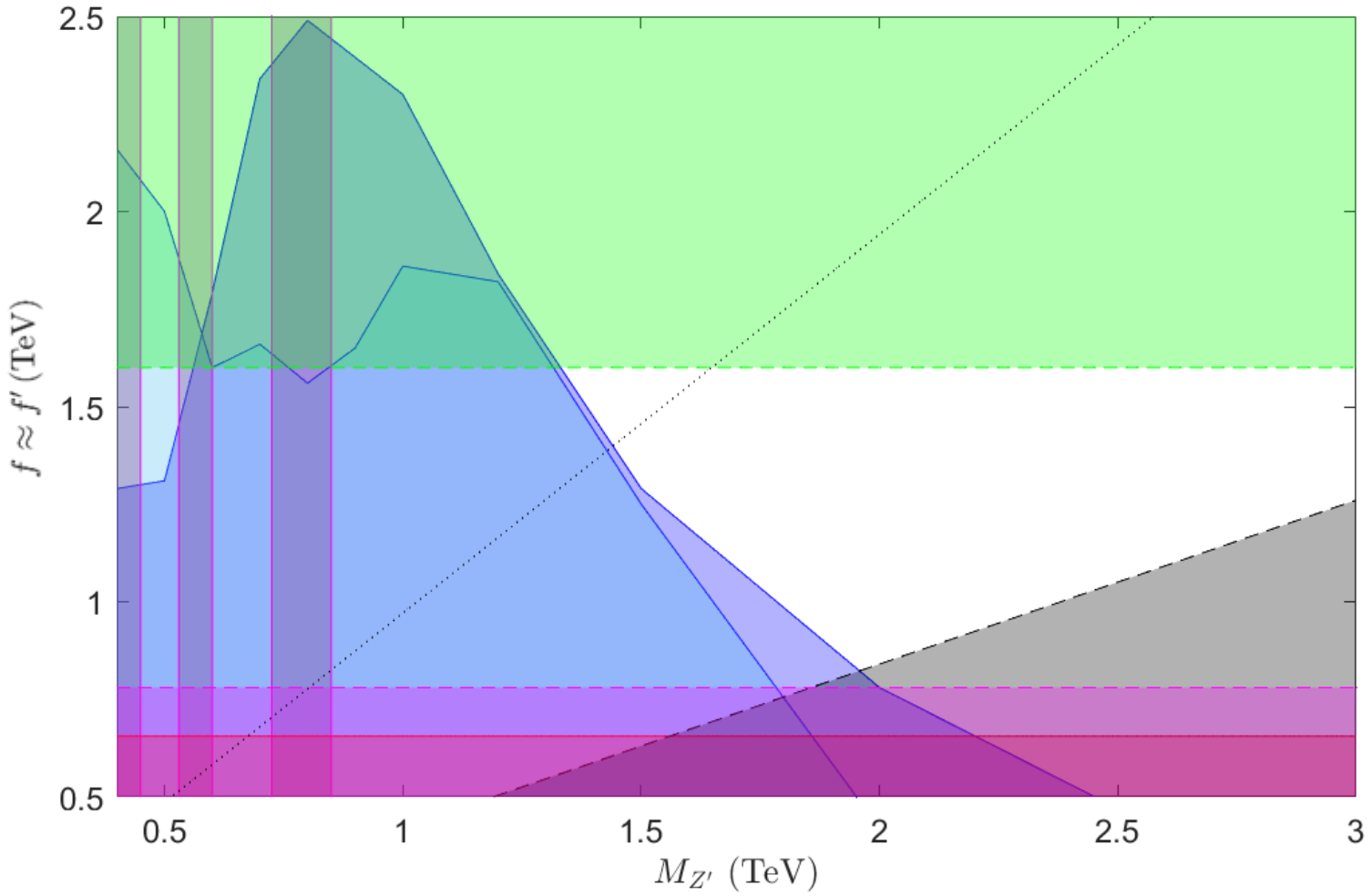


$$(2)\ N_{HC} = 4 : \quad f \approx 2f'$$



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

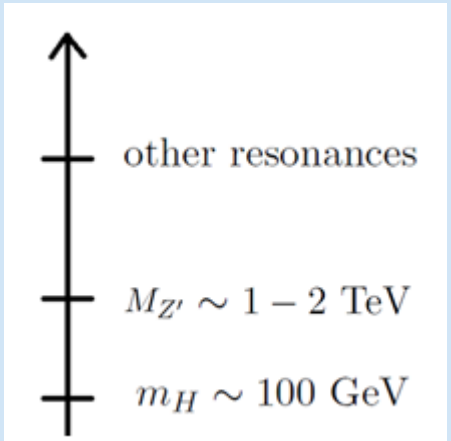
$$f' \approx \frac{2}{N_{HC}} f \qquad N_{HC} = 2 : \quad f \approx f'$$



Conclusions

- **The Z' boson in the $SU(4)/Sp(4)$ FCHM can explain the B anomalies**
- Interesting parameter space is still viable and will be probed in near future

Spectrum



$U(1)_{SM_3-HB}$

- Naturally broken in Fund. CHM
- To gauge it, SM fermions need to be included

Ratio 1/4

- $Q_{SM}/Q_{vacuum} = (1/4)/(2/N_{HC})$
- Can be achieved with $N_{HC} = 2$, i.e. $Sp(2)(= SU(2))$

3rd-gen. Z'

- Small cross section $b\bar{b}$ fusion
- Still possible to be at 1-2 TeV

Backup

Future work

Pheno —

Turn on RH rotation
bound → weaker??

Other constraints
$B \to K\nu\nu, \tau \to \mu\nu\nu$

Future prospect
$\tau \to \mu\mu\mu, Z' \to \ell\ell'$

Model —

Top Yukawa
Ongoing in MPIK!!

Higgs potential
Fine-tuning

UV completion
??? → SM_3-HB

More about Z' direct searches

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

$f'(\mathrm{TeV})$	$g_{Z'}$	$\sigma_{tt}(\mathrm{fb})$	$\sigma_{bb}(\mathrm{fb})$	$\sigma_{\tau\tau}(\mathrm{fb})$	$\sigma_{\mu\mu}(\mathrm{fb})$
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 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	$1/4$	$-1/N_{HC}$

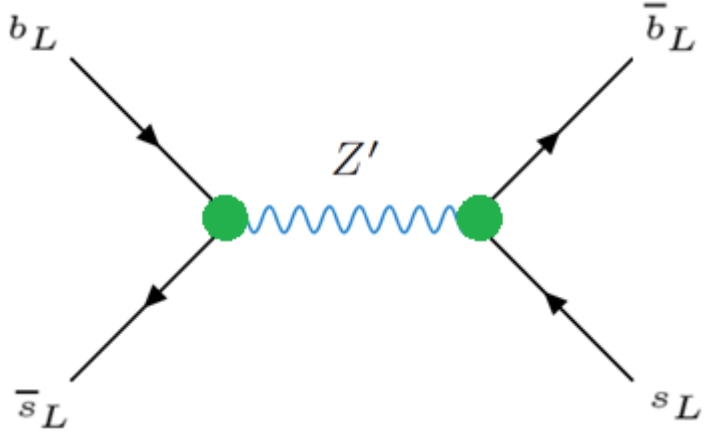
- Or from the linear combination of $U(1)_{EHC}$ and $U(1)_H$,

	$SM_{1,2}$	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	$1/4$	$-1/12 - 1/(3\,N_{HC})$	$1/6 - 1/(3\,N_{HC})$

FCNC Constraints - quark vertex

- $B_s - \bar{B}_s$ 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 :

$$\epsilon_{sb} \lesssim 0.05$$

$$\frac{g_{sb}}{M_{Z'}} \leq \frac{1}{194 \text{ TeV}} \implies f' \geq \epsilon_{sb} \cdot 48.5 \text{ (TeV)} \quad \overset{\text{NCBA}}{\implies} \quad f' \leq \epsilon_{\mu\mu} \cdot 2.3 \text{ (TeV)} \text{ (combined)}$$

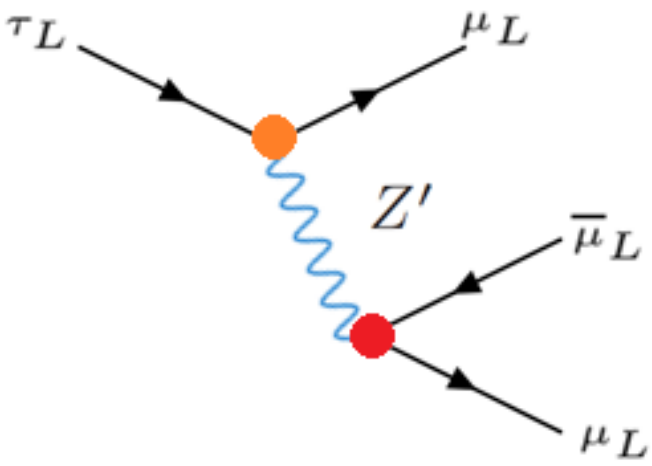
$$f' = \sqrt{\epsilon_{sb}\epsilon_{\mu\mu}} \text{ (11 TeV)}$$

FCNC Constraints - lepton vertex

➢ Lepton Flavor Violation τ → μμμ

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

$$= 1.28\times10^{-6}\left(\frac{1\ \text{TeV}}{f'}\right)^4\epsilon_{\mu\mu}^3(1-\epsilon_{\mu\mu})$$



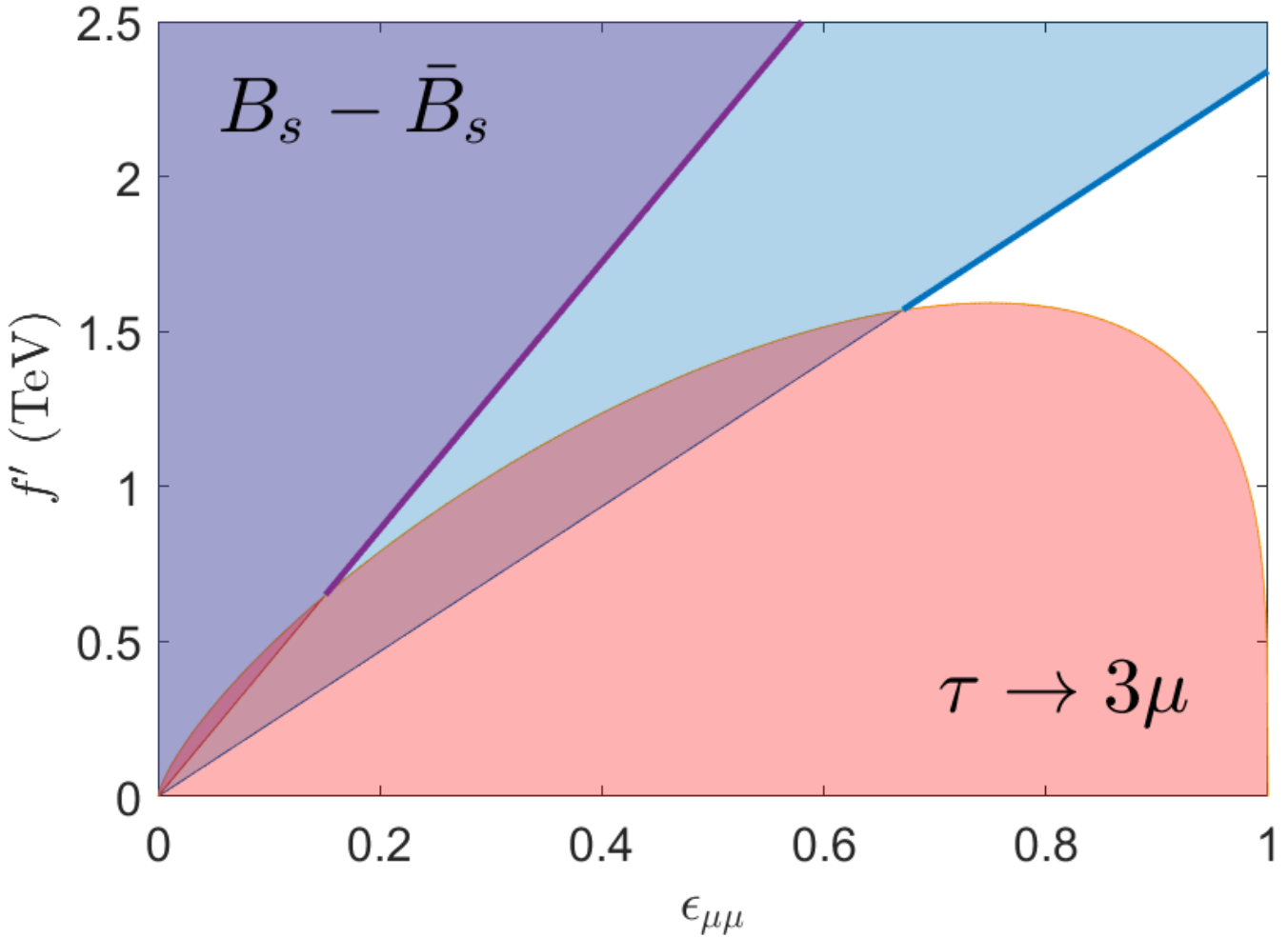
- The current bound : $< 2.1\times10^{-8}$ at 90% CL
- The constraint :

$$\left(\frac{1\ \text{TeV}}{f'}\right)^4\epsilon_{\mu\mu}^3(1-\epsilon_{\mu\mu}) < 1.6\times10^{-2}$$

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

$$C_{LL} = -0.38$$

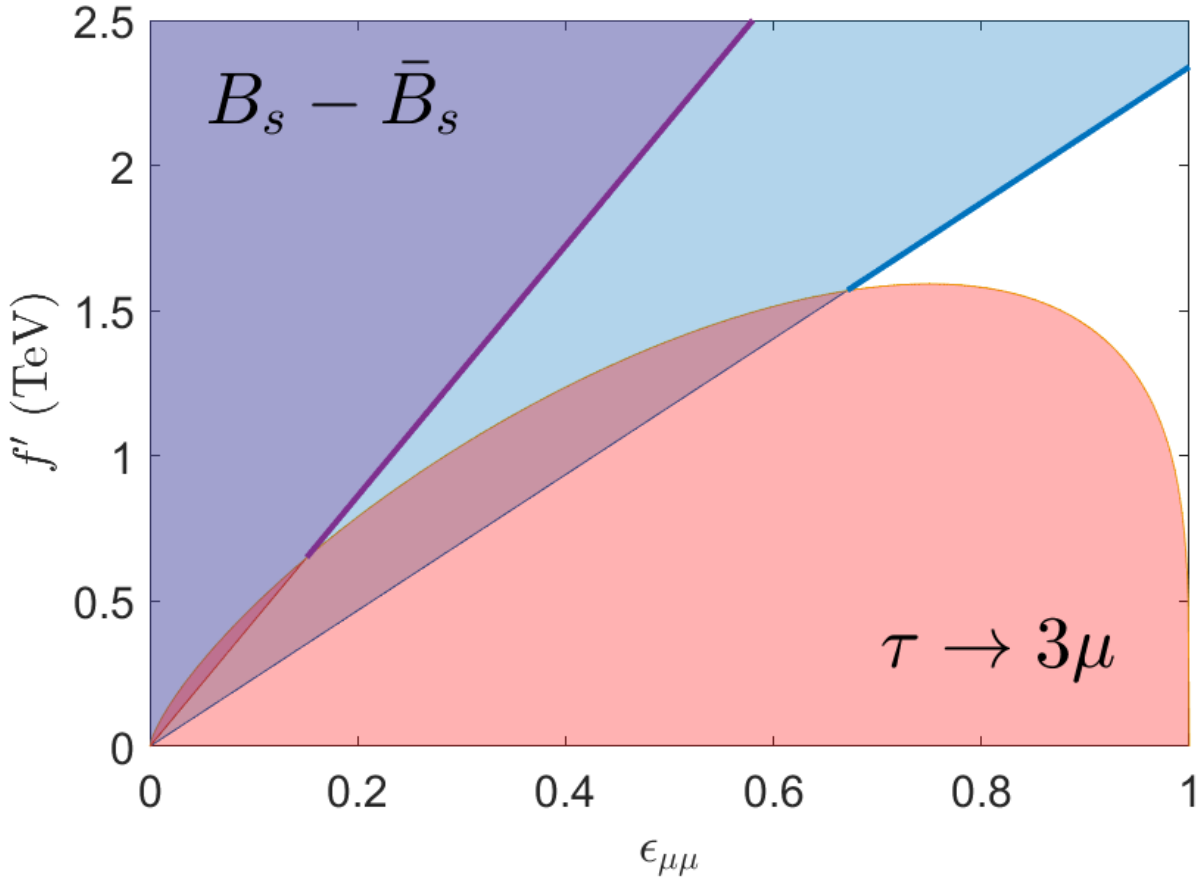
$$f' \leq \epsilon_{\mu\mu} \cdot 4.3 \text{ (TeV)}$$

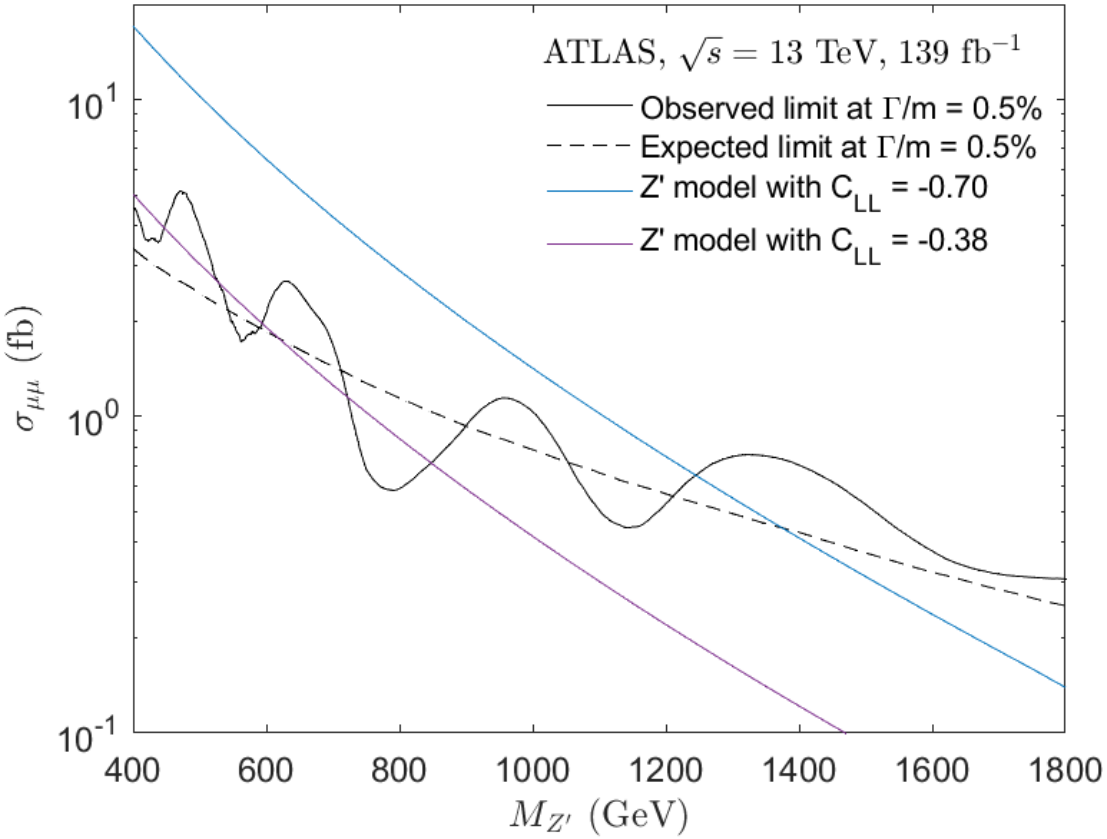


$$C_{LL} = -0.70$$

$$f' \leq \epsilon_{\mu\mu} \cdot 2.3 \text{ (TeV)}$$

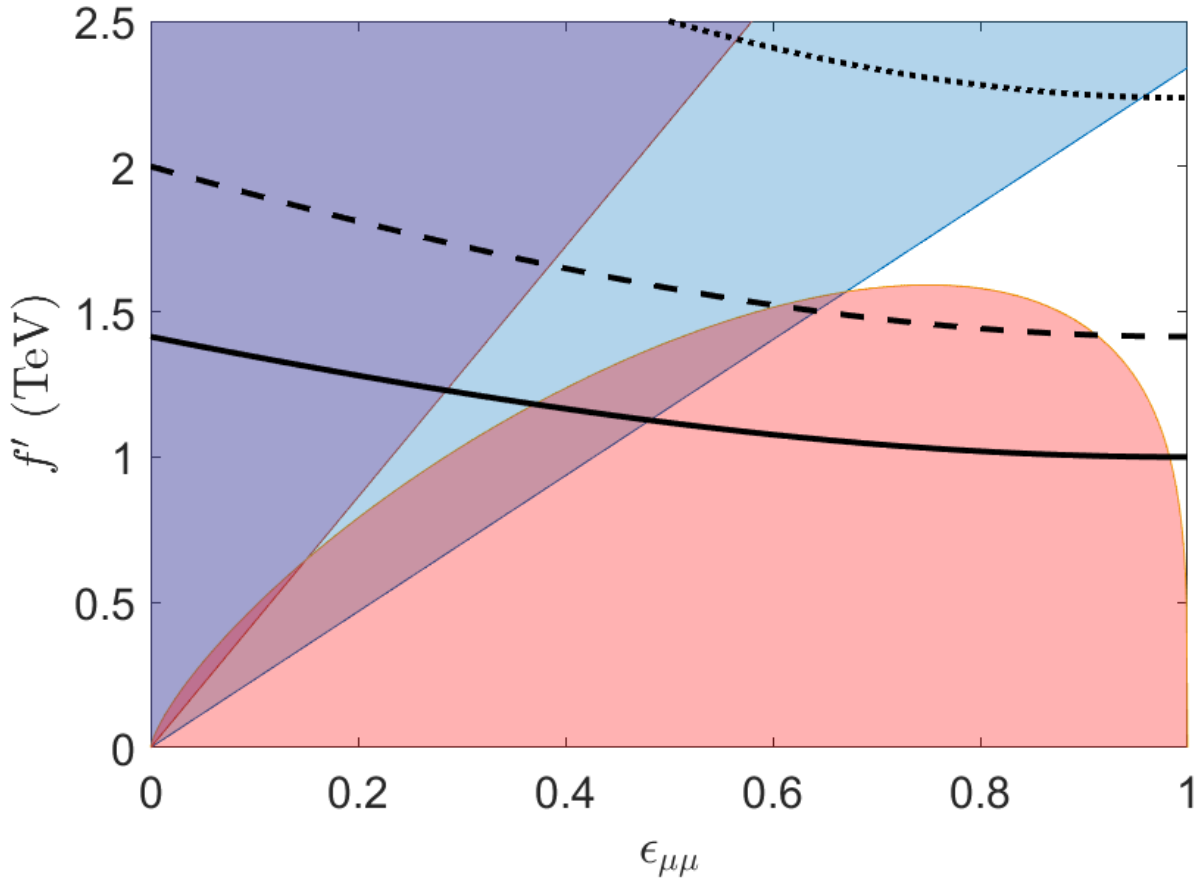
Direct Z' Searches – μμ channel

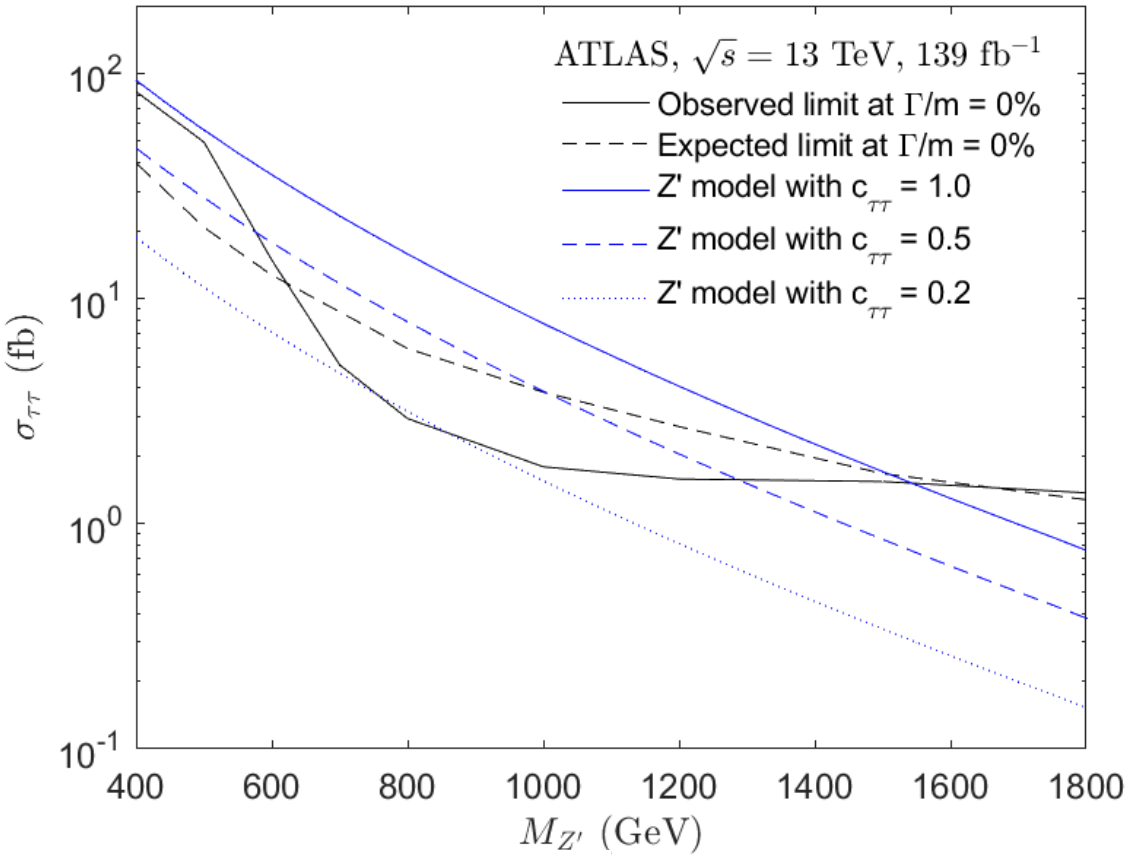




$$\sigma_{\mu\mu} \equiv \sigma \times Br(\mu\mu) = \frac{1}{256}\,\sigma_{bb} \cdot g_{Z'}^2\ \epsilon_{\mu\mu}^2$$

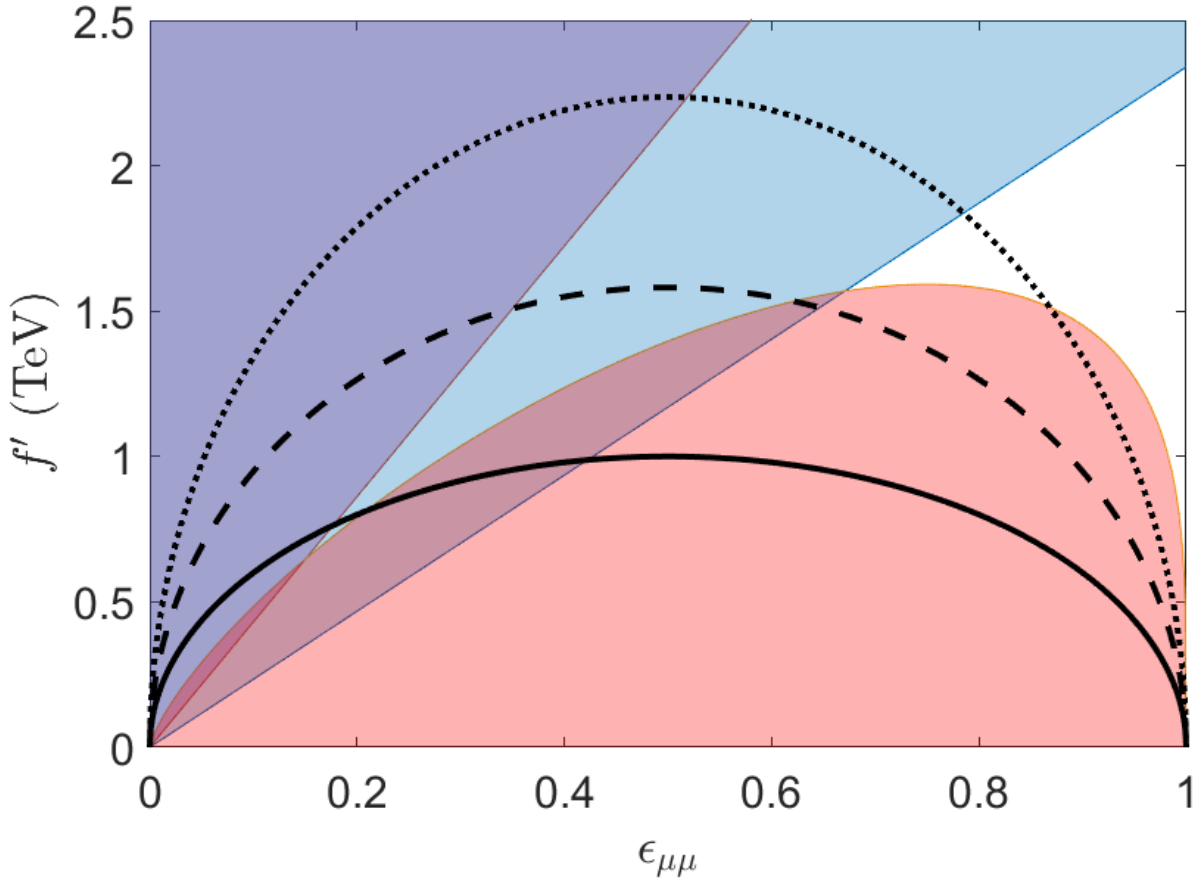
Direct Z' Searches – ττ channel

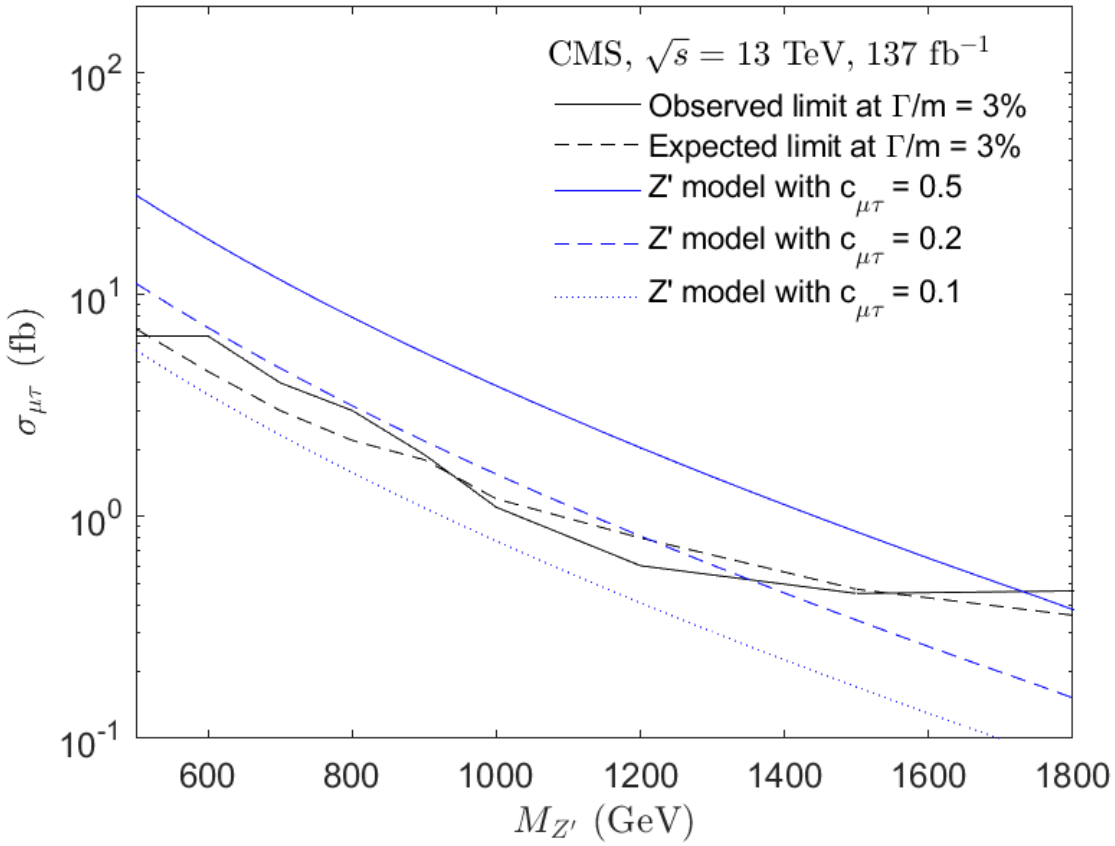




$$\sigma_{\tau\tau} \equiv \sigma \times Br(\tau\tau) = \frac{1}{256}\,\sigma_{bb} \cdot g_{Z'}^2\,\left(1 + (1-\epsilon_{\mu\mu})^2\right)$$

Direct Z' Searches – μτ channel





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

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

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

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

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

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

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

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

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