UNIVERSITY OF Southampton
School of Physics and Astronomy

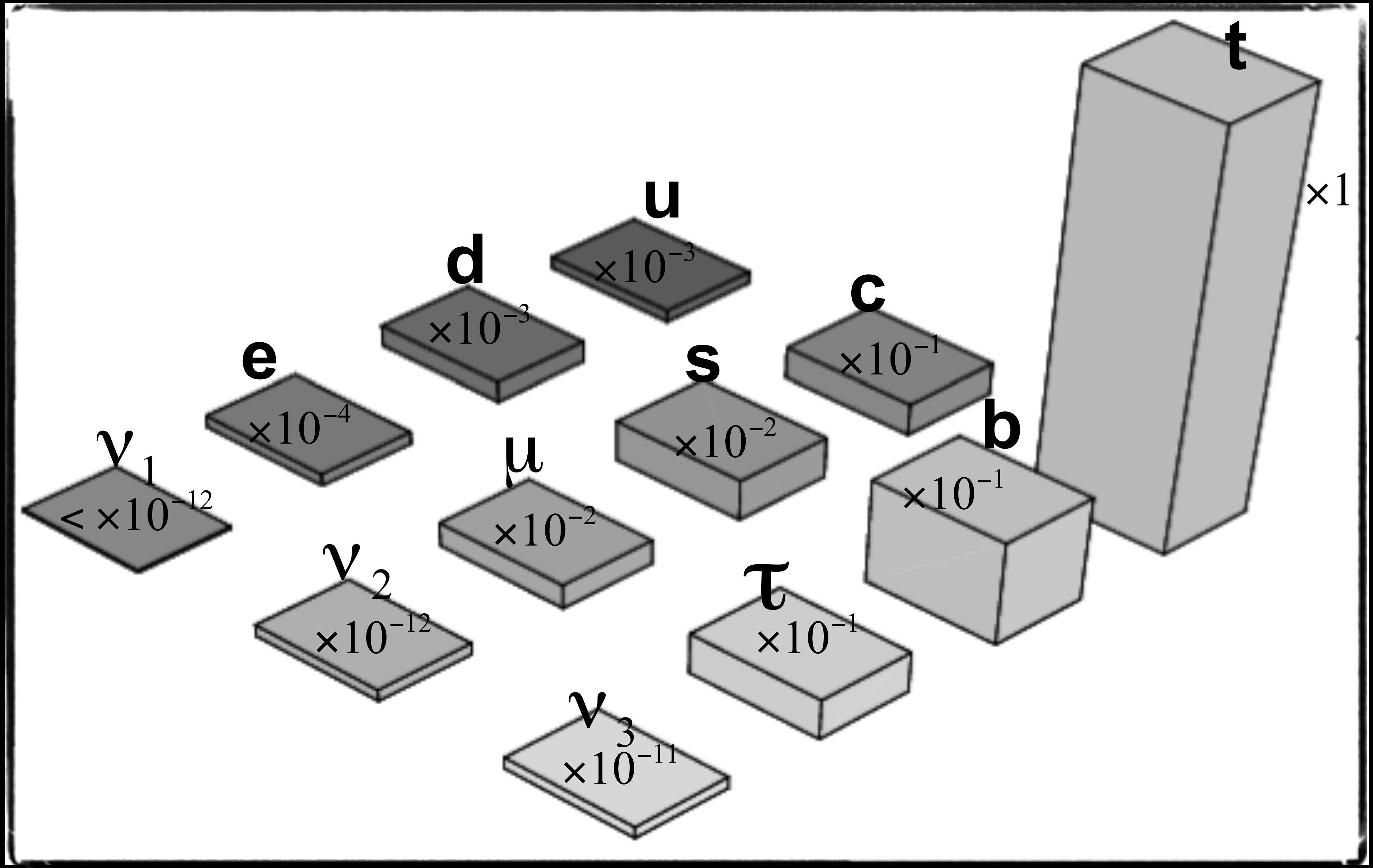
elusiVes invisiblesPlus
neutrinos, dark matter & dark energy physics

B anomalies linked to the problem of the origin of Yukawa Couplings

Steve King, 3rd September 2019, Corfu

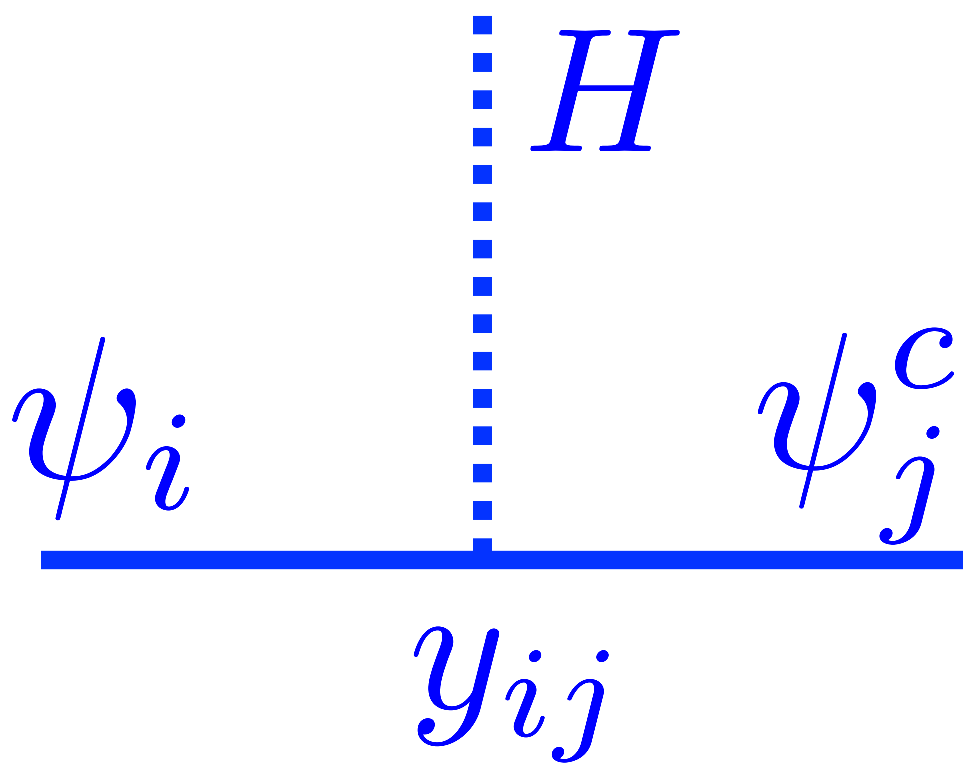
EISA
European Institute for Sciences and Their Applications

Flavour Problem



Yukawa couplings

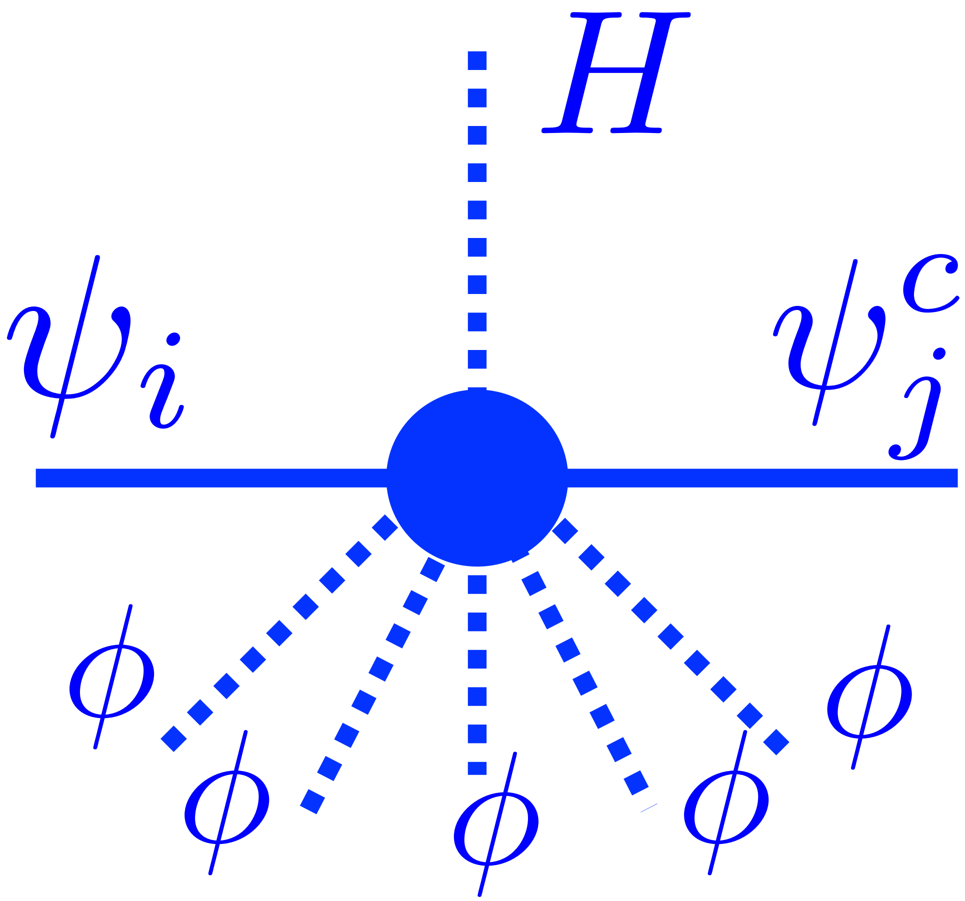
$$y_{ij} H \psi_i \psi_j^c$$



Why so small (apart from top quark)?

Effective Yukawa couplings

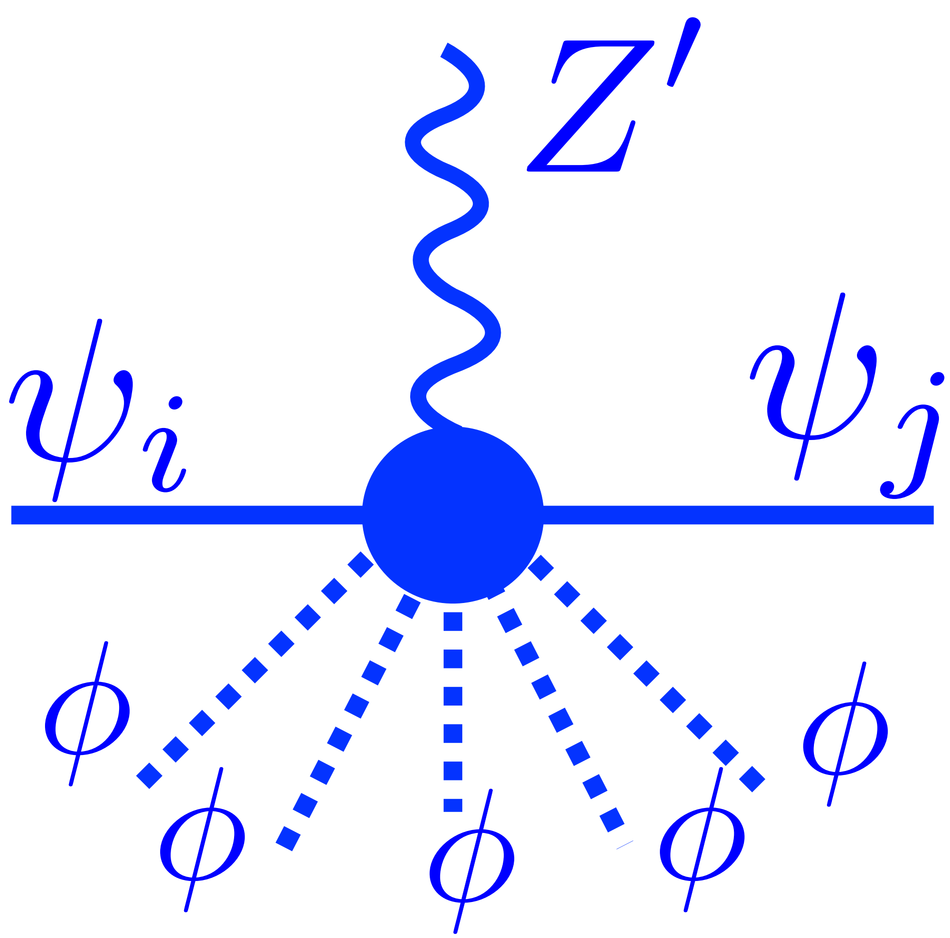
$$\left(\frac{\langle\phi_i\rangle}{\Lambda^{\psi}_{i,n}}\right)^n \left(\frac{\langle\phi_j\rangle}{\Lambda^{\psi^c}_{j,m}}\right)^m H\psi_i\psi^c_j$$



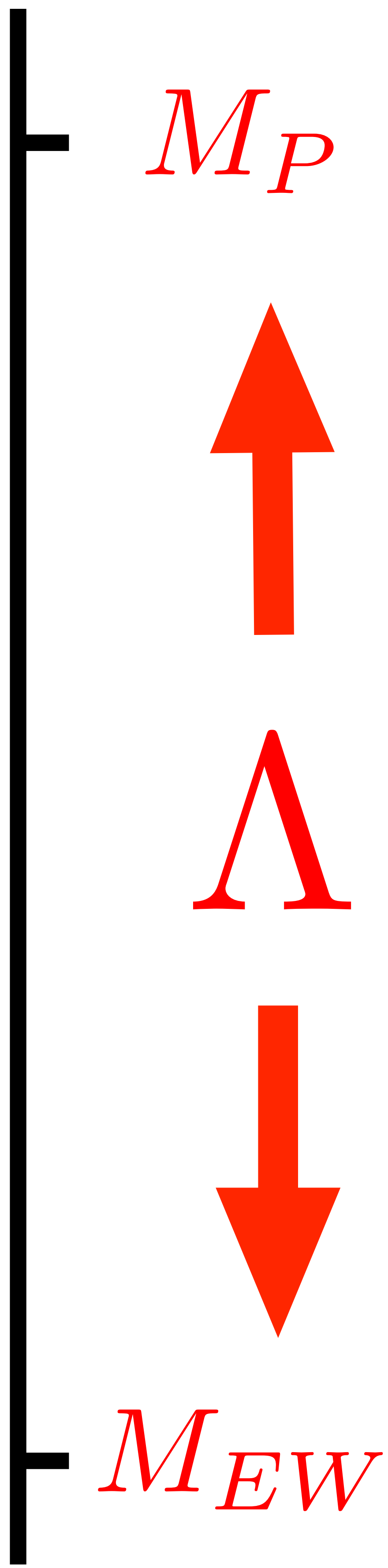
Yukawas small due to powers of ratios $\frac{\langle\phi\rangle}{\Lambda}$

Effective Z' couplings

$$\left(\frac{\langle\phi_i^\dagger\rangle}{\Lambda'^{\psi}_{i,n}}\right)^n \left(\frac{\langle\phi_j\rangle}{\Lambda'^{\psi}_{j,m}}\right)^m g' Z'_\mu \psi_i^\dagger \gamma^\mu \psi_j$$

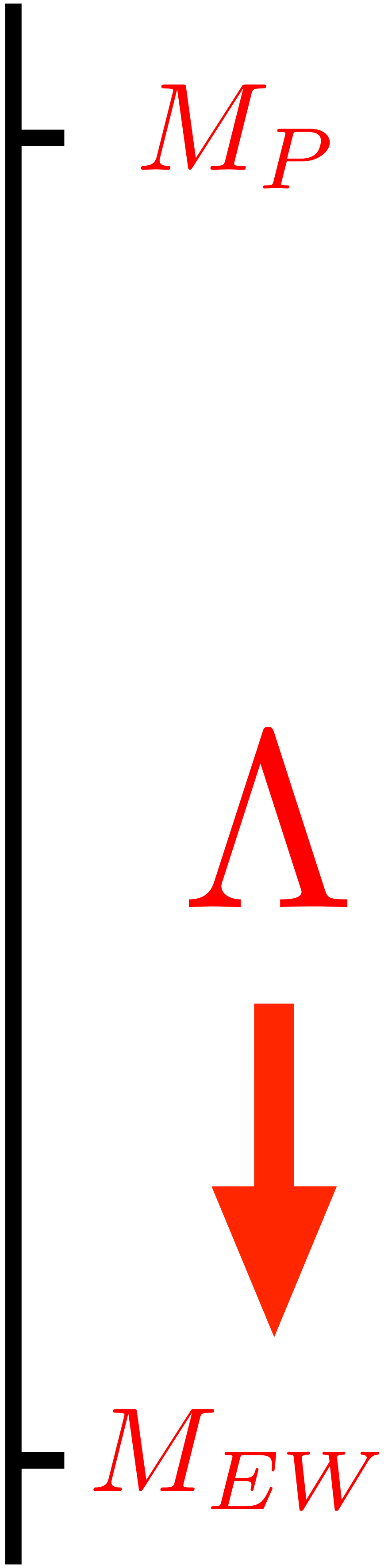


Z' couplings may be small due to powers of ratios $\frac{\langle\phi\rangle}{\Lambda}$



Flavour scales can be from the Planck scale to electroweak scale

Keeping fixed ratios $\dfrac{\langle \phi \rangle}{\Lambda}$



Main conclusion of this talk

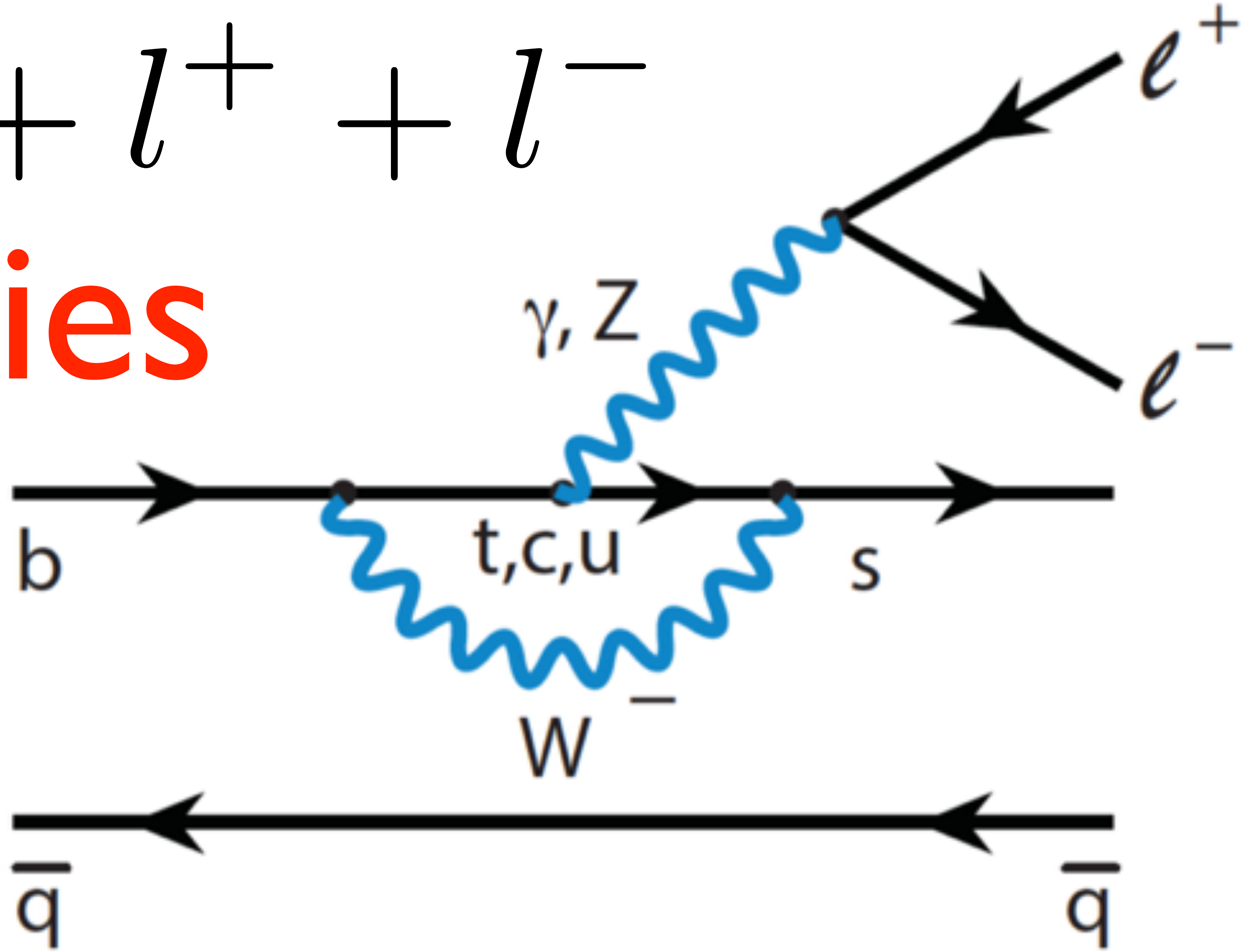
Phenomenological hints from B physics **may** suggest low scale theory of flavour

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

Anomalies

Here we focus exclusively on these decays

See Later Talks



- $b \to s l^+ l^-$ transitions are rare in the SM (no tree level contributions: GIM, CKM, in some cases helicity suppressed)
- ideally suited for indirect New Physics searches (indirectly sensitive to energy scales O(100TeV))

LFU tests with B→K(*)μμ and B→K(*)ee decays: R(K) and R(K*)

See Next Talk

- Theoretical uncertainties on the exclusive B→K(*)ll branching fractions are **reduced to a per-mille level** in ratios *(hadronic effects cancel)*:

2.5σ deviations

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} = 0.846\ {}^{+0.060}_{-0.054}\ {}^{+0.016}_{-0.014}\,, \qquad \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$$

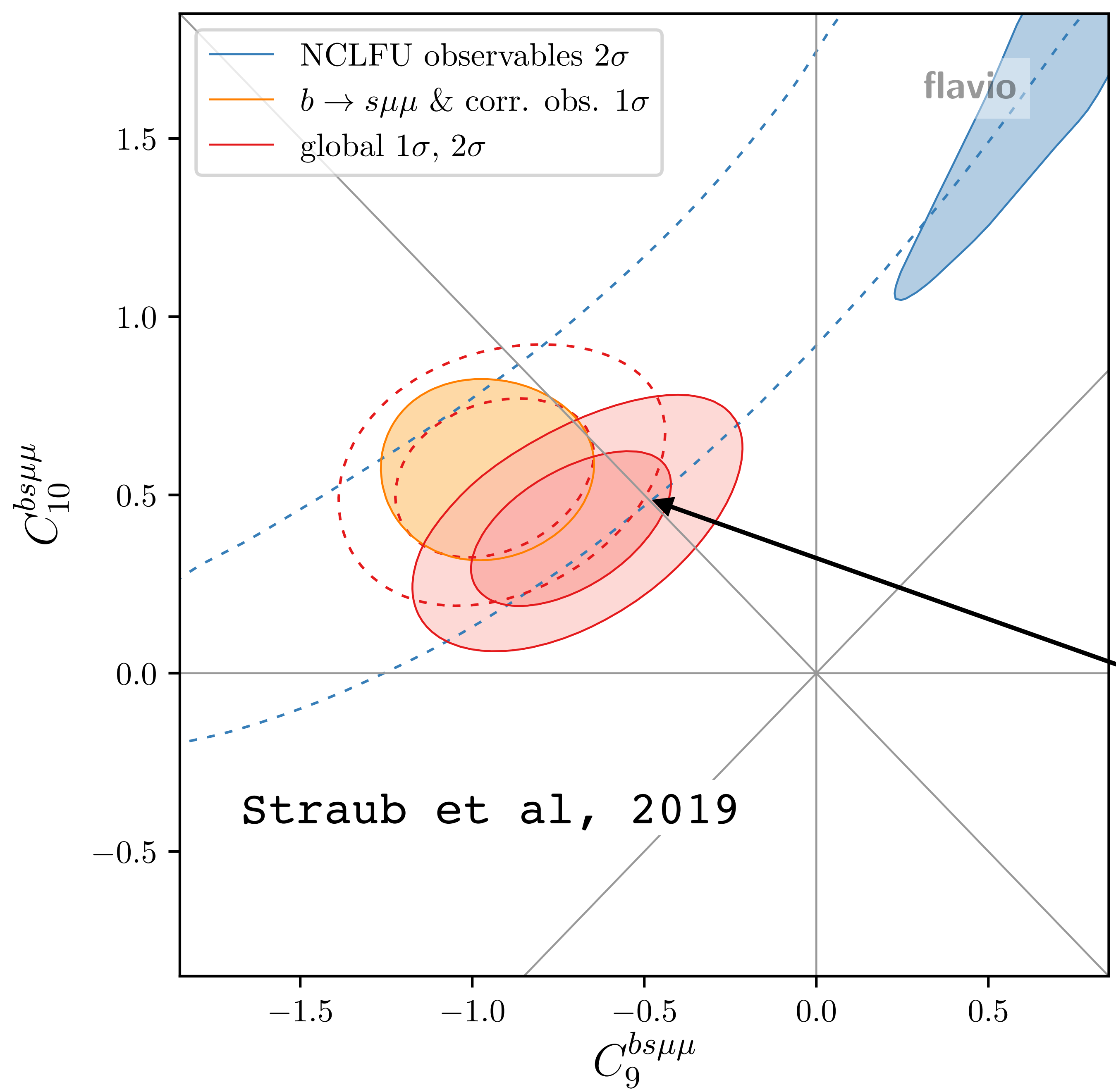
$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu\mu)}{\mathrm{BR}(B \to K^*ee)} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03\,, & \text{for } 0.045\,\mathrm{GeV}^2 < q^2 < 1.1\,\mathrm{GeV}^2\,, \\ 0.69^{+0.11}_{-0.07} \pm 0.05\,, & \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2\,, \end{cases}$$

- SM, R(K) and R(K*) expected to be close to unity.
- Sensitive to new neutral and heavy gauge bosons, lepto-quarks, Z' models.

See later LQ+Z' model

Possible operators for R_K, R_{K^*}

$$\mathcal{L}^{\rm NP}_{b\to s\mu\mu} \supset \frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\left(\delta C^\mu_9 O^\mu_9 + \delta C^\mu_{10} O^\mu_{10}\right) + \text{h.c.}$$



$$O^\mu_9 = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu)\,,$$

$$O^\mu_{10} = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma_5\mu)\,.$$

Assuming LH currents and LFU observables

$$\text{Re}\left(\delta C^\mu_9\right) = -\text{Re}\left(\delta C^\mu_{10}\right)$$

$$\frac{1.1}{(35\text{TeV})^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

SFK 1706.06100, 1806.06780 De Medeiros Varzielas, SFK 1807.06023, 1902.09266

$R_{K^{(*)}}$ and the origin of Yukawa couplings

SFK 1905.02660

Z'

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0
u_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	0
d_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
L_4	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
e_4^c	$\mathbf{1}$	$\mathbf{1}$	1	1
ν_4^c	$\mathbf{1}$	$\mathbf{1}$	0	1
$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
$\overline{d_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	-1
$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e_4^c}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\overline{\nu_4^c}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	1
S_3	$\overline{\mathbf{3}}$	$\mathbf{3}$	$1/3$	-2

4th vector-like family

VEV $\langle \phi \rangle$

LQ

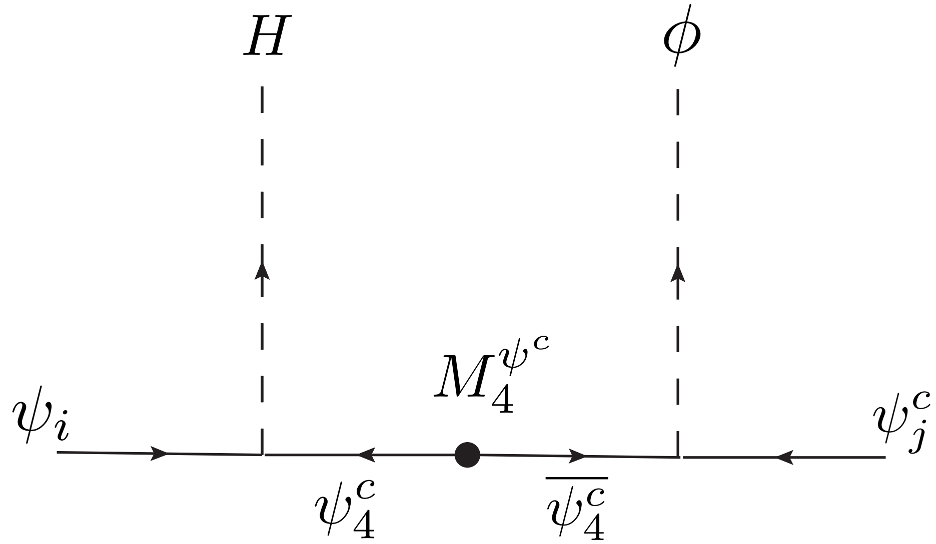
Basic idea of model:

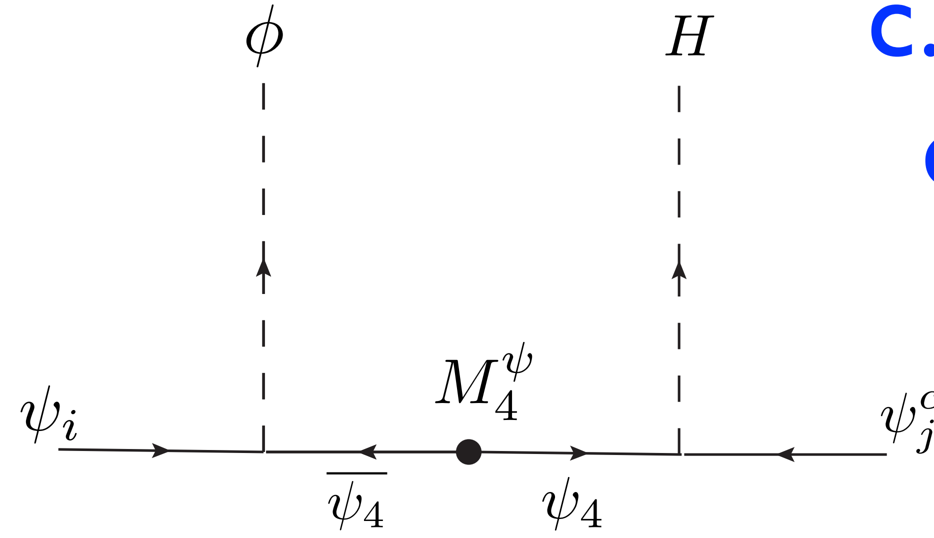
- $\langle \phi \rangle$ breaks U(1)' give **Z' mass**
- **Leptoquark S_3** carries U(1)'
- **Vector-like 4th family** charged under U(1)'
- SM families neutral under U(1)'
- Higgs charged under U(1)' so usual Yukawas **forbidden**
- Effective Yukawa, Z' and leptoquark couplings via mixing w/vector-like 4th family

Effective Yukawa couplings

Only generated via mixing with fourth family

Ferretti, SFK, Romanino hep-ph/0609047





c.f. Seesaw diagrams later

$$\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} y_{i4}^{\psi} H\psi_i\psi_j^c + \frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}} y_{4j}^{\psi} H\psi_i\psi_j^c$$

Yukawa matrices in a certain basis

$$y_{ij}^{e,u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \varepsilon_{22}^{e,u} & \varepsilon_{23}^{e,u} \\ 0 & \varepsilon_{32}^{e,u} & y_{33}^{e,u} + \varepsilon_{33}^{e,u} \end{pmatrix}, \quad y_{ij}^{d} = \begin{pmatrix} 0 & \varepsilon_{12}^{d} & \varepsilon_{13}^{d} \\ 0 & \varepsilon_{22}^{d} & \varepsilon_{23}^{d} \\ 0 & \varepsilon_{32}^{d} & y_{33}^{d} + \varepsilon_{33}^{d} \end{pmatrix}$$

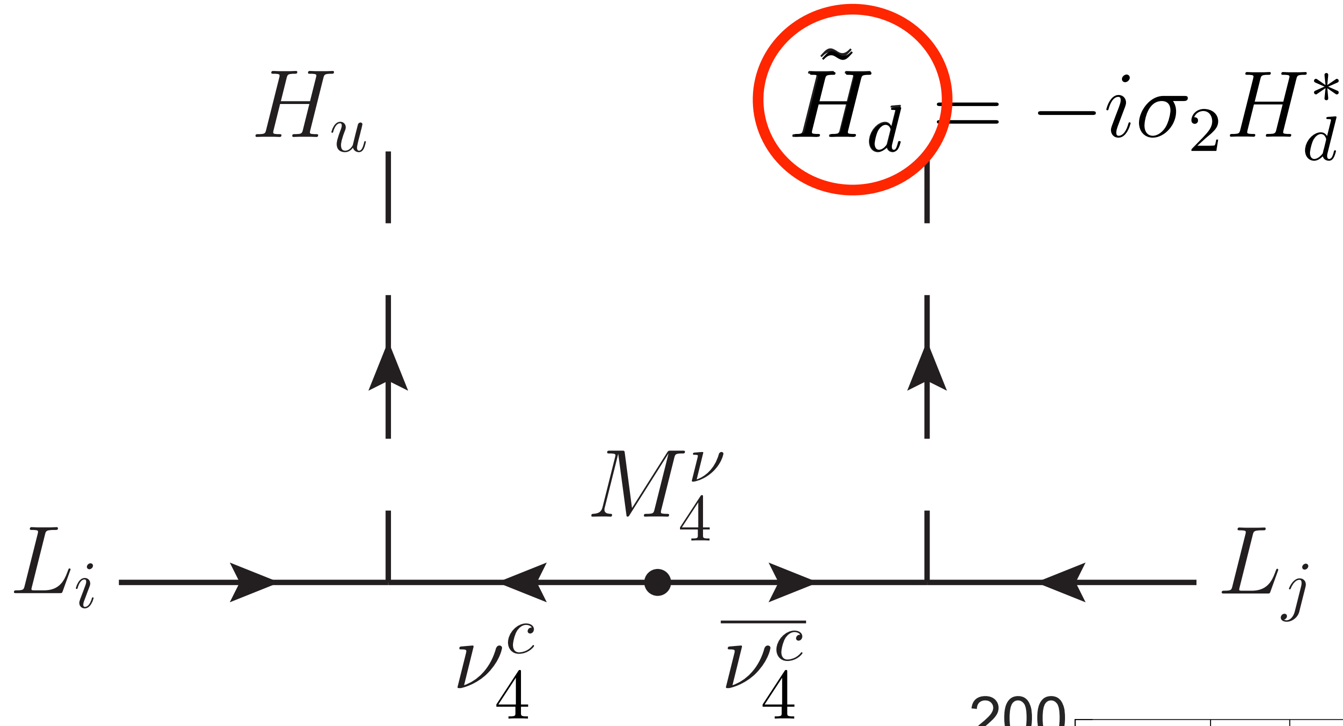
Rank 2 matrices - hence first family massless

$$\varepsilon_{ij} \ll y_{33}, \text{ assuming } M_4^{L,Q} \ll M_4^{e^c,u^c,d^c}$$

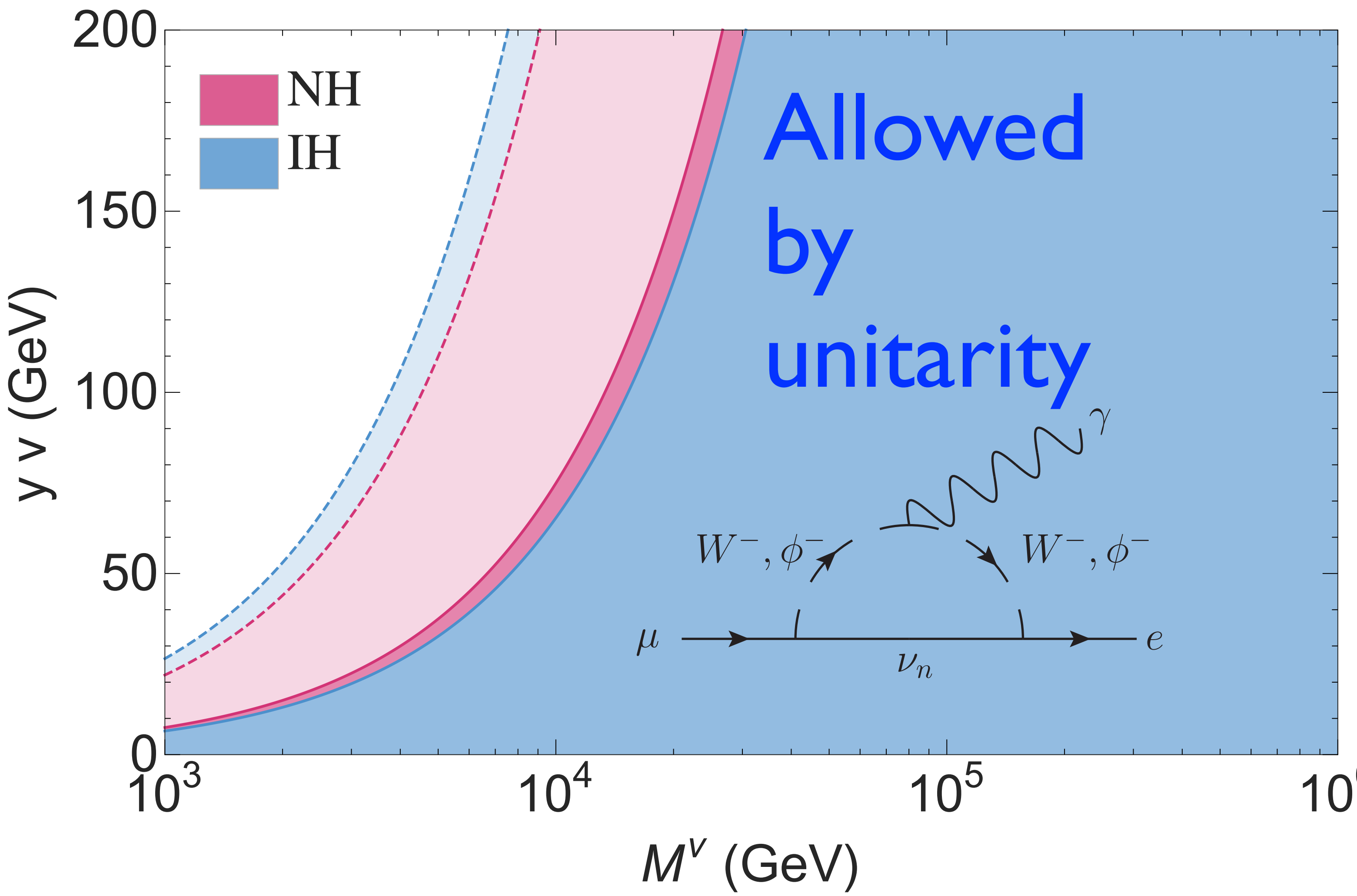
$$y_\tau \approx y_{33}^e \approx y_{43}^e \left(\frac{x_3^L\langle\phi\rangle}{M_4^L}\right), \qquad y_t \approx y_{33}^u \approx y_{43}^u \left(\frac{x_3^Q\langle\phi\rangle}{M_4^Q}\right), \qquad y_b \approx y_{33}^d \approx y_{43}^d \left(\frac{x_3^Q\langle\phi\rangle}{M_4^Q}\right)$$

New Weinberg operator for neutrino mass

Hernandez-Garcia and SFK 1903.01474



Type Ib seesaw (usual Type 1a seesaw involves Hu only)

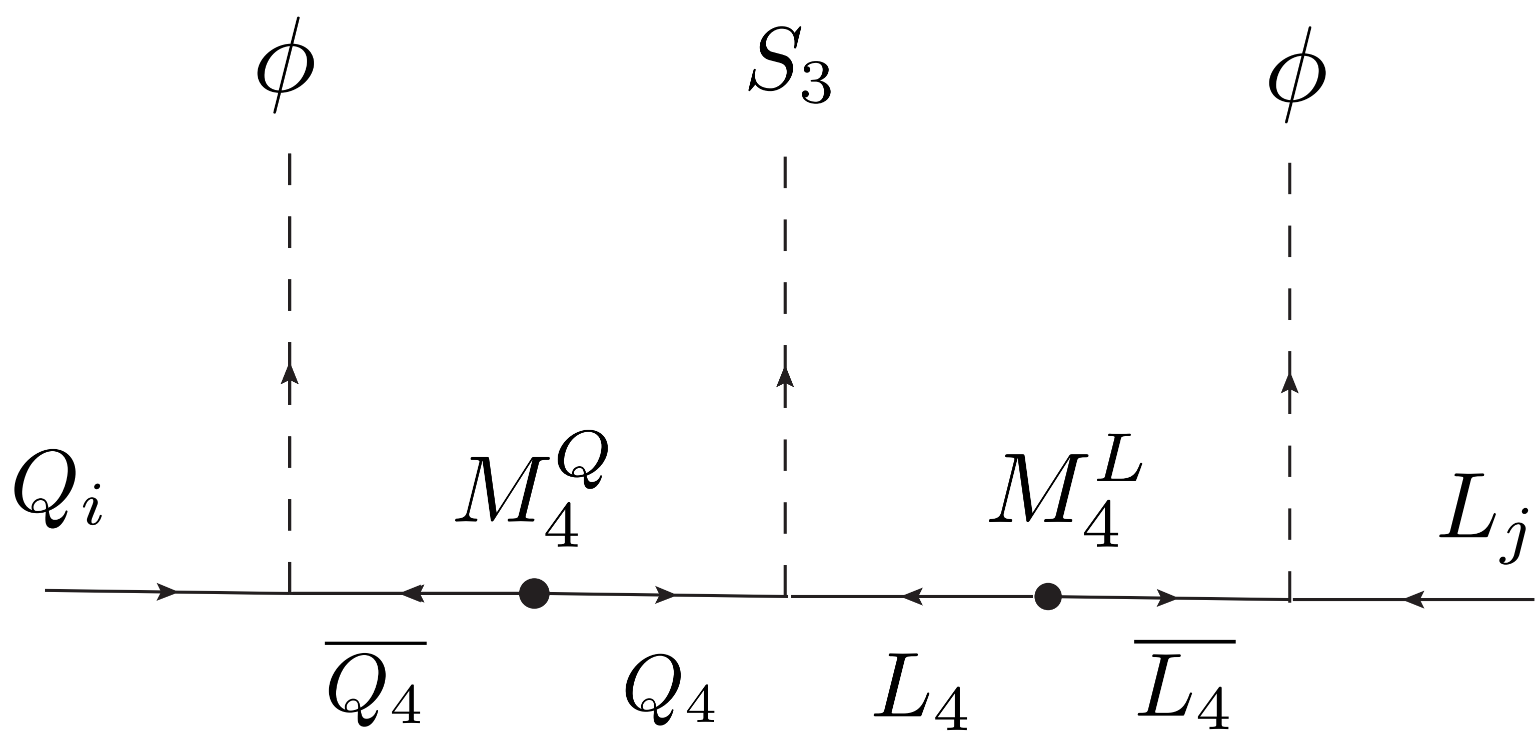


c.f. Yukawa diagrams previously

Effective Leptoquark couplings

Only generated via mixing with fourth family

De Medeiros Varzielas, SFK 1902.09266

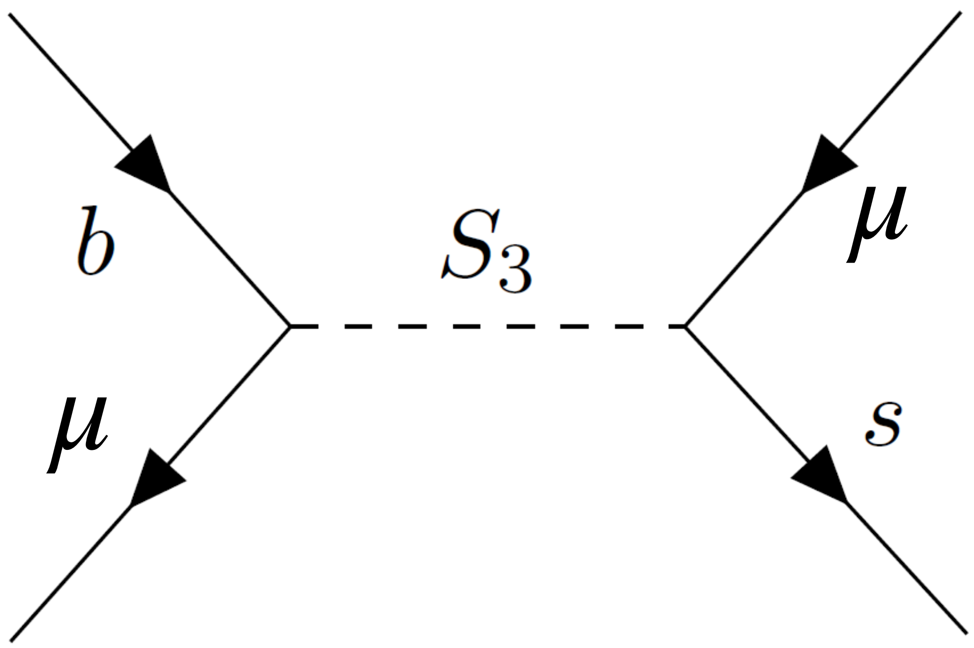


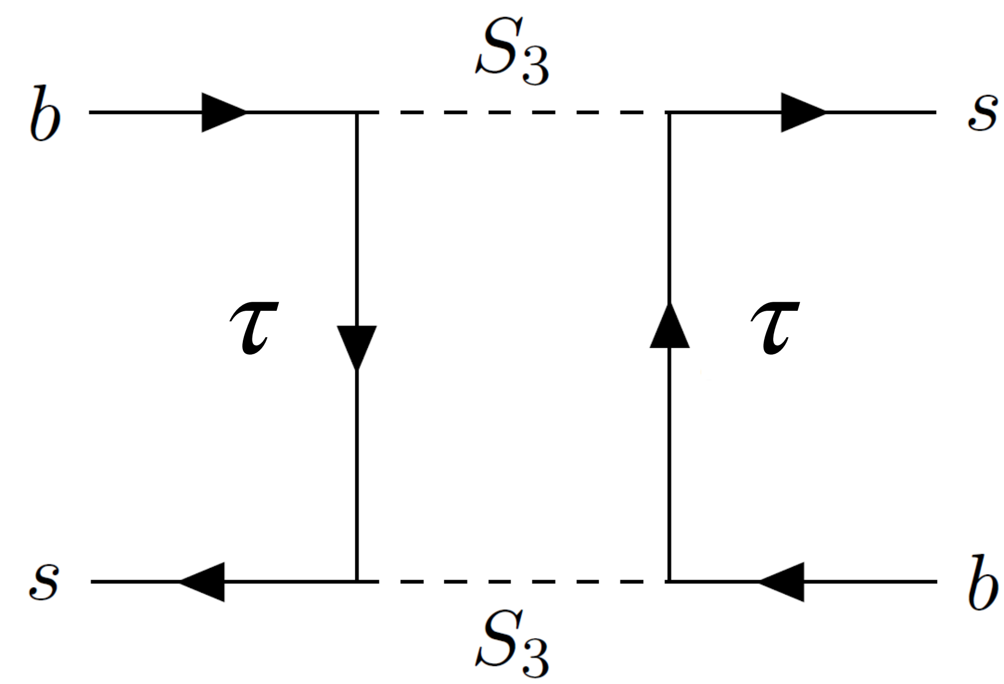
$$\lambda_4 \left(\frac{x_3^L \langle \phi \rangle}{M_4^L} \right) \left(\frac{x_3^Q \langle \phi \rangle}{M_4^Q} \right) S_3 Q_3 L_3 \approx y_\tau y_t S_3 Q_3 L_3$$

$$\longrightarrow \quad y_\tau S_3 Q_3 L_3, \quad y_\tau V_{ts} S_3 Q_2 L_3, \quad y_\tau \theta^e_{23} S_3 Q_3 L_2, \quad y_\tau \theta^e_{23} V_{ts} S_3 Q_2 L_2, \quad \ldots$$

$S_3 b\tau$ $\quad S_3 s\tau$ $\quad S_3 b\mu$ $\quad S_3 s\mu$

$R_{K^{(*)}}$ Bs mixing





$$y_\tau^2(\theta_{23}^e)^2 \approx 2.2 \times 10^{-2} \left(\frac{M_{S_3}}{1\ \mathrm{TeV}}\right)^2$$

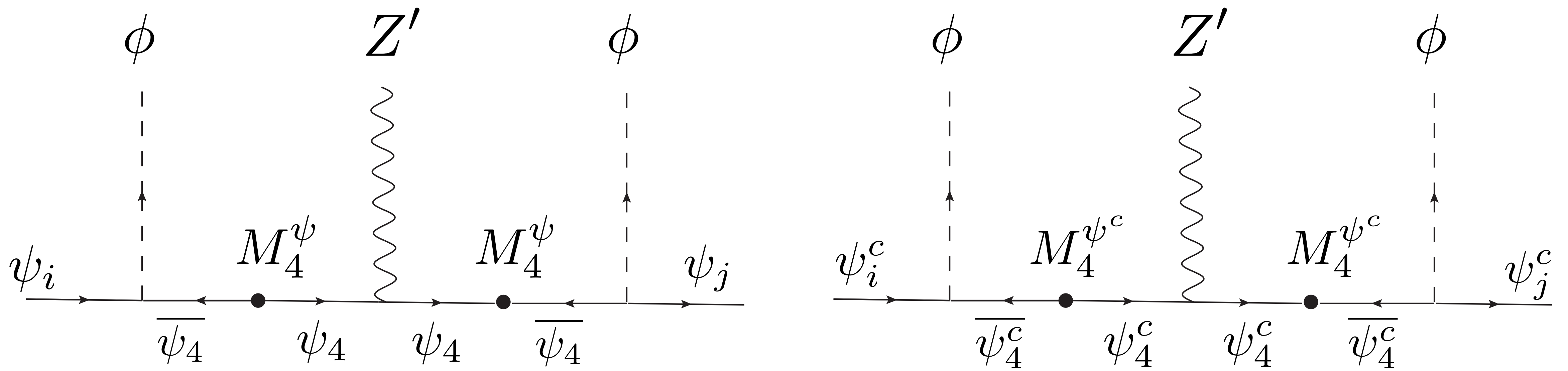
$$y_\tau^4 \leq 5.0 \left(\frac{M_{S_3}}{1\ \mathrm{TeV}}\right)^2$$

- $R_{K^{(*)}}$ suggests M_{S3} ~ TeV
- Bs mixing is OK

Effective Z' couplings

Only generated via mixing with fourth family

SFK 1706.06100, 1806.06780



In the chosen basis LH couplings are

(RH couplings suppressed)

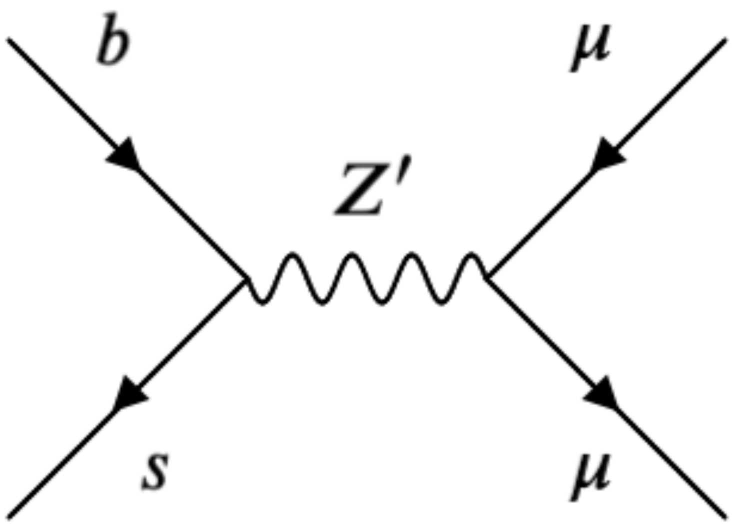
$$M_4^{L,Q} \ll M_4^{e^c,u^c,d^c}$$

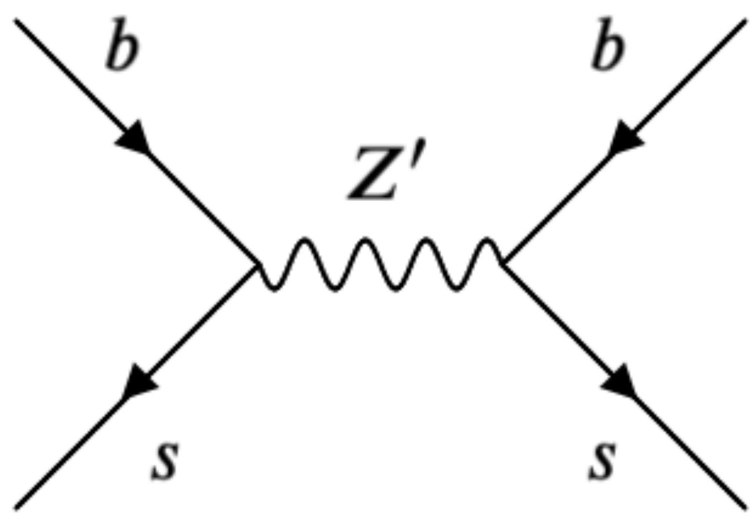
$$y_t^2 g' Z'_\mu Q_3^\dagger \gamma^\mu Q_3 + y_\tau^2 g' Z'_\mu L_3^\dagger \gamma^\mu L_3$$

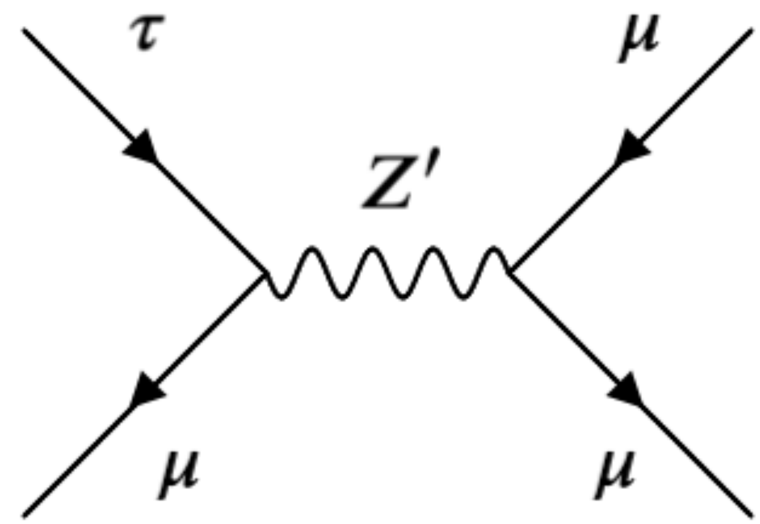
$$\rightarrow \quad V_{ts} Z'_\mu Q_3^\dagger \gamma^\mu Q_2, \quad V_{ts}^2 Z'_\mu Q_2^\dagger \gamma^\mu Q_2, \quad \theta_{23}^e y_\tau^2 Z'_\mu L_3^\dagger \gamma^\mu L_2, \quad (\theta_{23}^e)^2 y_\tau^2 Z'_\mu L_2^\dagger \gamma^\mu L_2$$

$Z'bs$ $\qquad$ $Z'ss$ $\qquad$ $Z'\mu\tau$ $\qquad$ $Z'\mu\mu$

$R_{K^{(*)}}$ | B_s mixing | $\tau \to \mu\mu\mu$







$$\frac{g_{\mu\mu} g_{bs}}{M_{Z'}^2} \approx \frac{1.1}{(35\ \text{TeV})^2}$$

$$\frac{g_{bs}}{M_{Z'}} \leq \frac{1}{(140\ \text{TeV})}$$

$$\frac{g_{\mu\mu}}{M_{Z'}} \leq \frac{(\theta_{23}^e)^{1/2}}{(16\ \text{TeV})}$$

Tension

$$\frac{g_{\mu\mu}}{M_{Z'}} \frac{g_{bs}}{M_{Z'}} \leq \frac{(\theta_{23}^e)^{1/2}}{(47\ \text{TeV})^2}$$

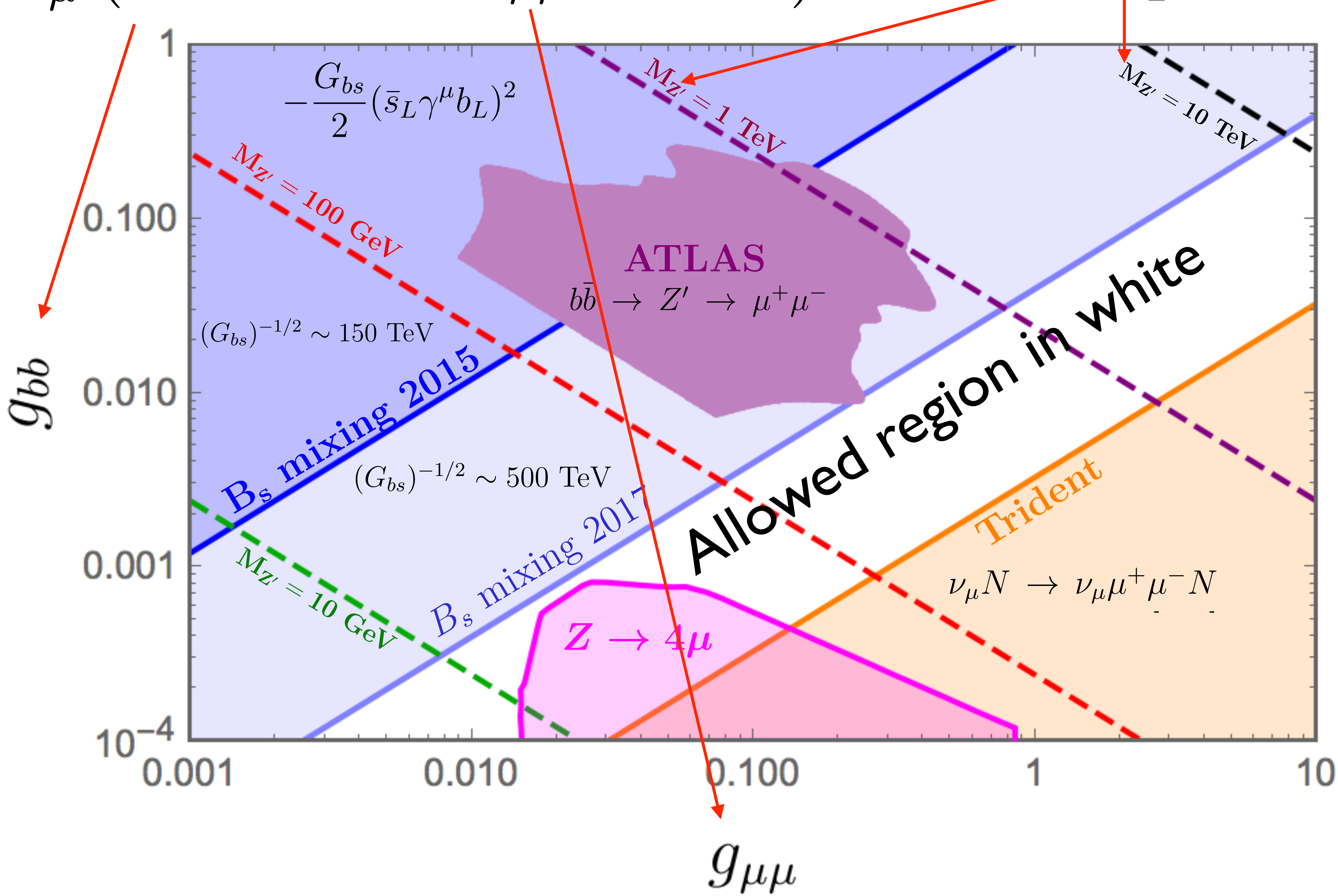
- $R_{K^{(*)}}$ requires $M_{Z'}$ ~ TeV since g_{bs}~V_{ts}

Simplified Model

Falkowski, SFK, Perdomo, Pierre
1803.04430

$$Z'_\mu \left(g_{bb} \bar{b}_L \gamma^\mu b_L + g_{\mu\mu} \bar{\mu}_L \gamma^\mu \mu_L \right)$$

R_K, R_{K^*} fixes $\frac{g_{bb} g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4 \text{ TeV})^2}$



Conclusion

- $R_{K^{(*)}}$ may be related to the origin of Yukawa couplings
- The Yukawa, Z' and leptoquark S_3 couplings may all be generated via mixing with vector-like 4th family
- Need Z' and S_3 masses ~ TeV (or so) to explain $R_{K^{(*)}}$
- Z' mass ~ $\langle \phi \rangle$ ~ TeV implies low scale origin of Yukawas
- But such Z' is in tension with Bs mixing and $\tau \to \mu\mu\mu$
- S_3 mass ~ TeV no problem for Bs mixing but does **not** imply low scale origin of Yukawas (S_3 mass is free)