University of Southampton
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elusives invisiblesPlus
neutrinos, dark matter & dark energy physics

Flavourful Z' models for $R_{K^{(*)}}$

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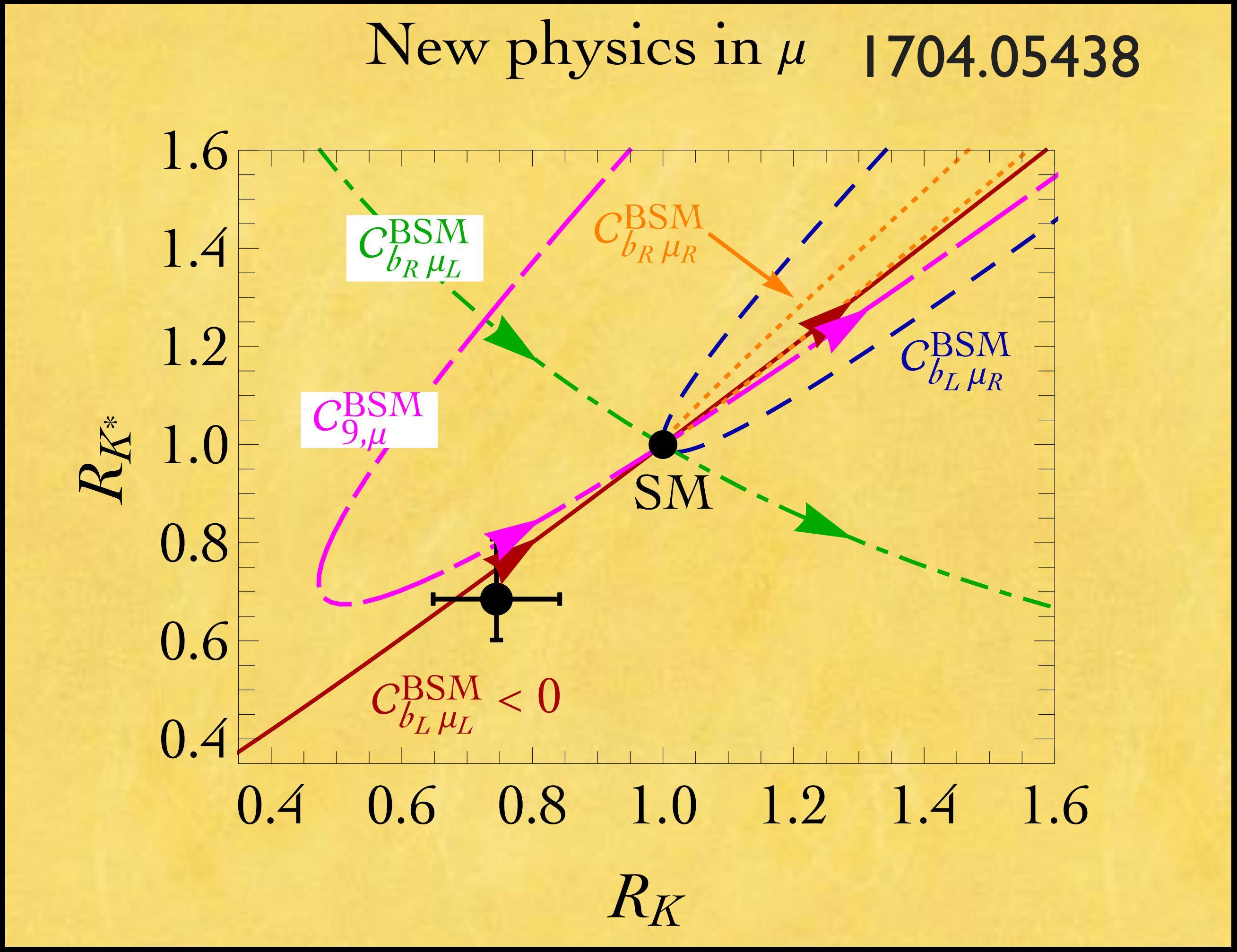
SFK 1706.06100 JHEP 1708 (2017) 019
Antusch, Hohl, SFK, Susic (in prep)
Crispim Romao, SFK, Leontaris (in prep)

B physics anomalies: R_K, R_{K^*}

$$R_K = \frac{\mathrm{BR}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{BR}\left(B^+ \to K^+e^+e^-\right)} = 0.745 \pm 0.09_{\text{stat}} \pm 0.036_{\text{syst}}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & (2m_\mu)^2 < q^2 < 1.1\,\mathrm{GeV}^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2 \end{cases}$$



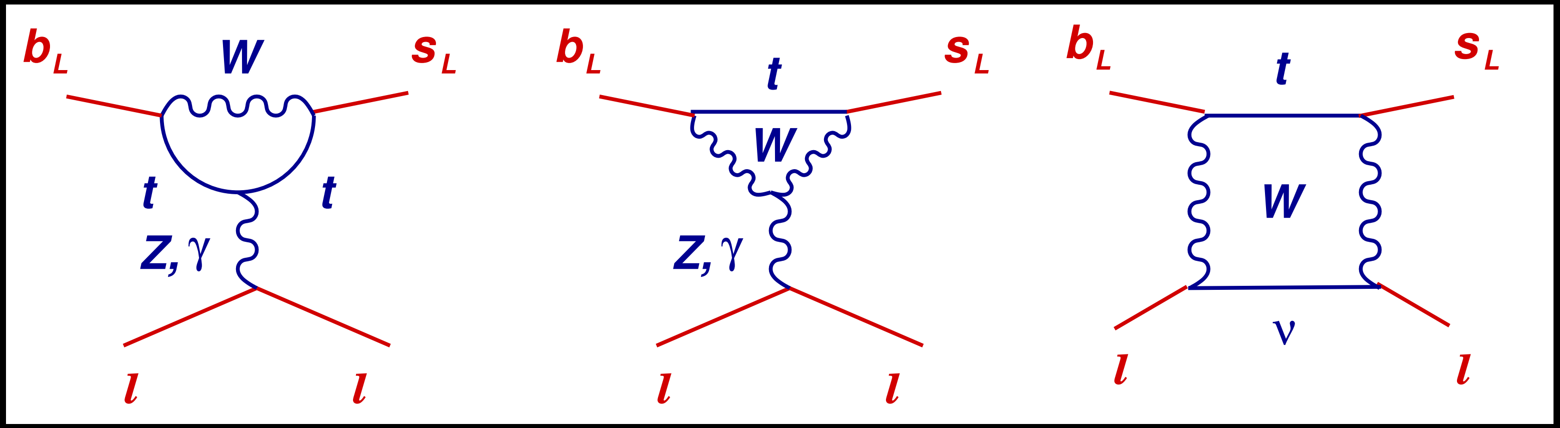
Best fit operator

$$V_{tb}V_{ts}^*\frac{\alpha_{em}}{4\pi v^2}\left(C^{\text{SM}}_{b_L\mu_L} + C^{\text{BSM}}_{b_L\mu_L}\right)\bar{b}_L\gamma^\mu s_L\,\bar{\mu}_L\gamma_\mu\mu_L$$

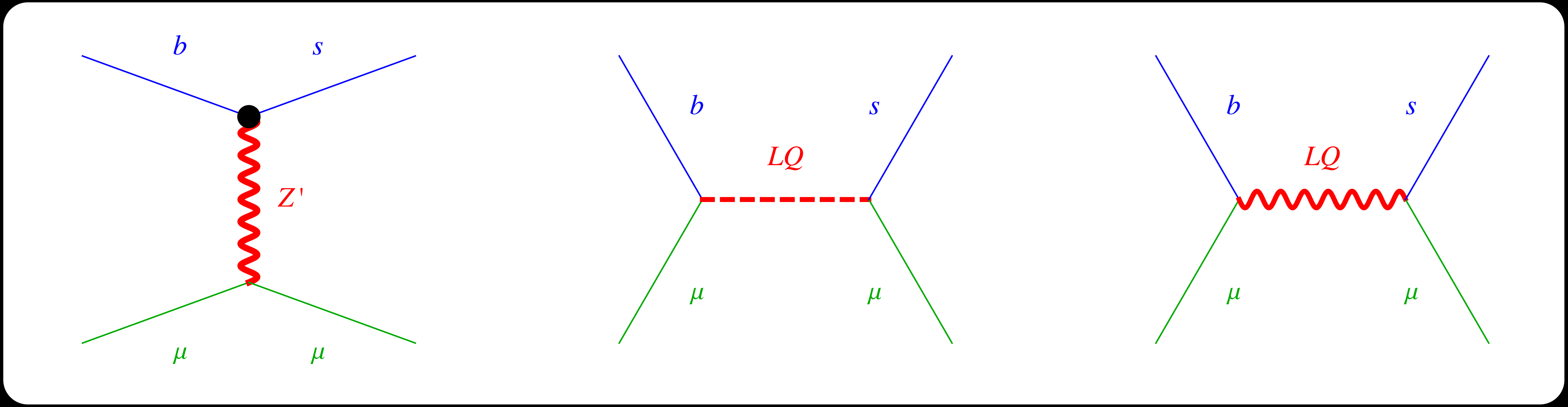
$8.64 \quad -1.3$

$$V_{tb}V_{ts}^*\frac{\alpha_{em}}{4\pi v^2} \approx \frac{1}{(36\ \mathrm{TeV})^2}$$

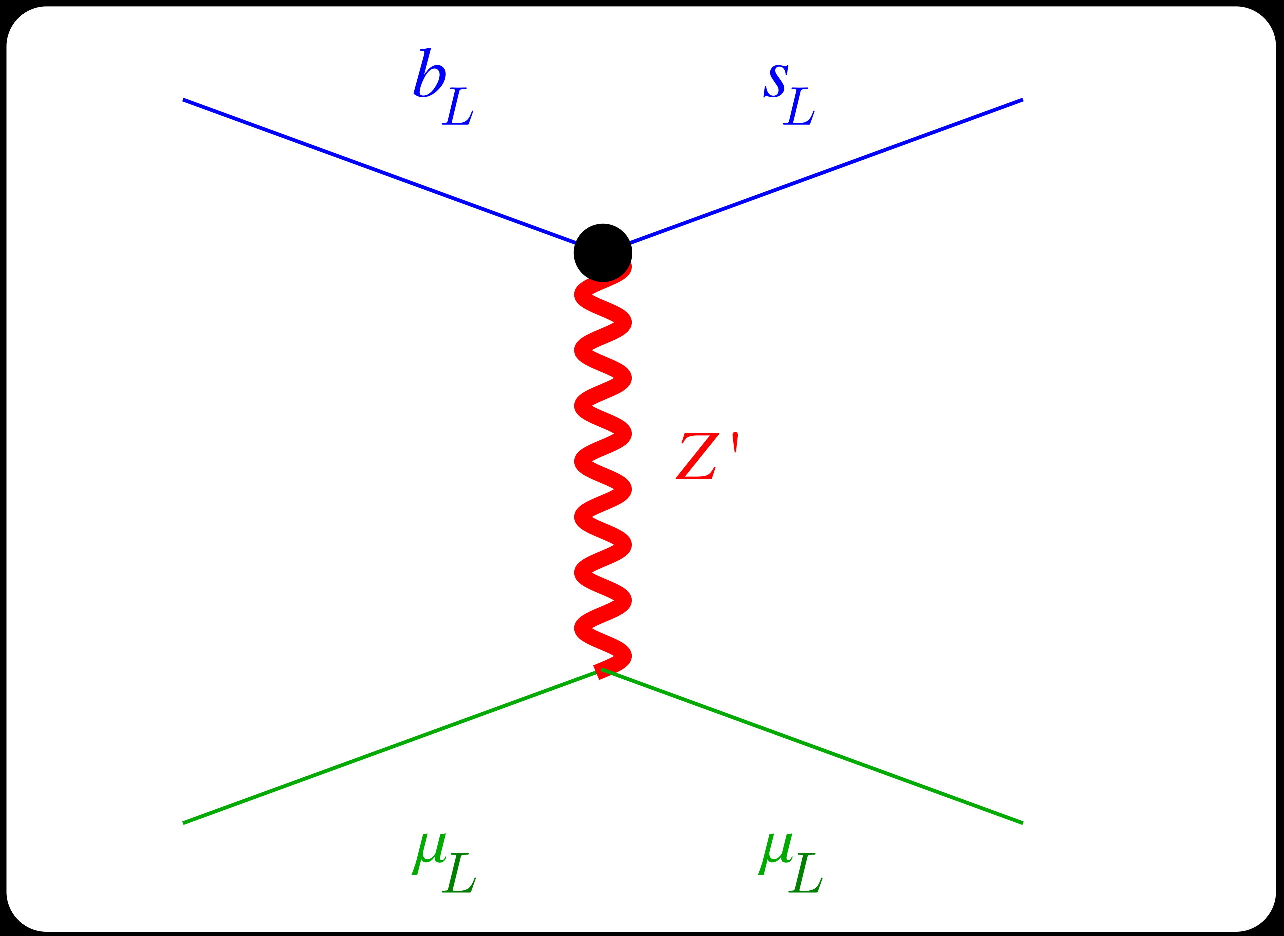
SM penguins are universal



BSM should be non-universal



Z' models



$$G^{\rm BSM}_{b_L\mu_L} = g^{Z'}_{b_L} g^{Z'}_{\mu_L} \left(\frac{g'^2}{{M_{Z'}}^2}\right) \approx -\frac{1}{(33\ \text{TeV})^2}$$

Typically small so Z' mass in LHC range

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Flavourful Z' models

Field	Representation/charge			
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_{Li}	$\mathbf{3}$	$\mathbf{2}$	$1/6$	q_{Q_i}
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$2/3$	q_{u_i}
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	q_{d_i}
L_{Li}	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	q_{L_i}
e_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1	q_{e_i}
ν_{Ri}	$\mathbf{1}$	$\mathbf{1}$	0	q_{ν_i}

Three families of quarks and leptons with universal charges

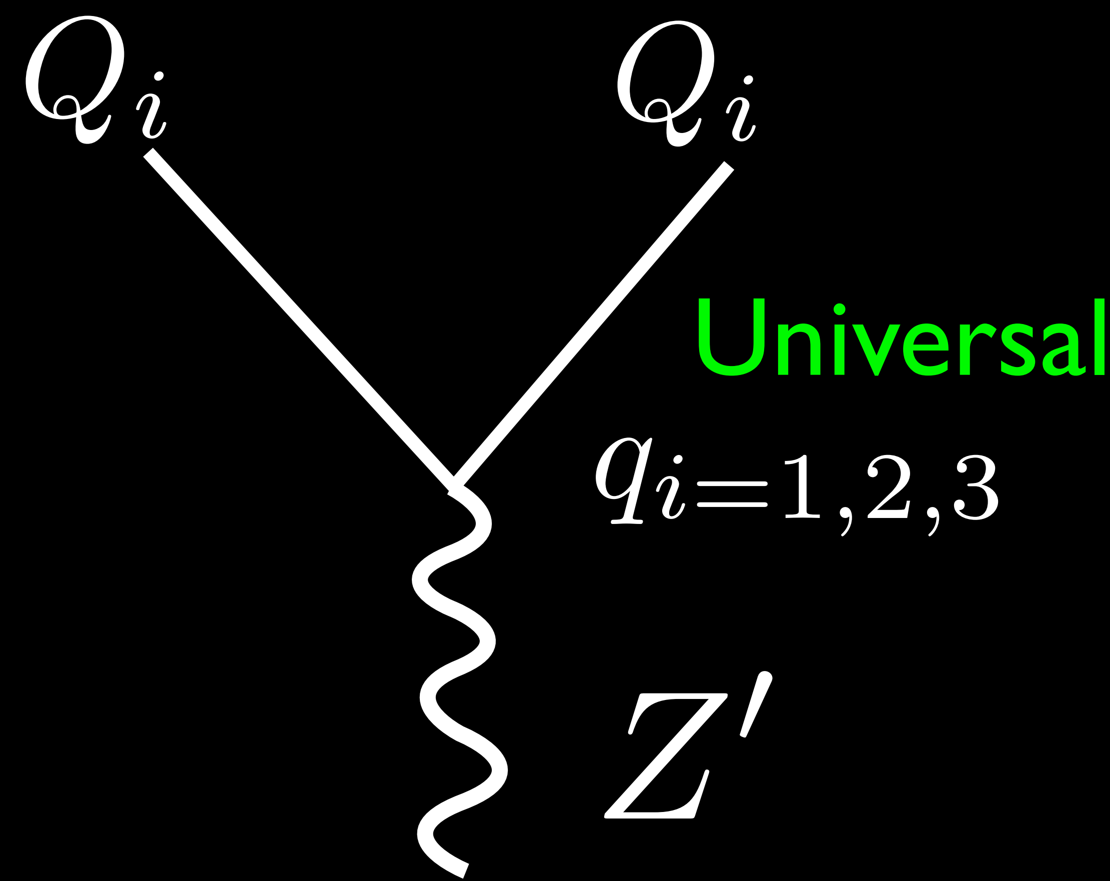
Field	Representation/charge			
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$Q_{L4},\tilde{Q}_{R4}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	q_{Q_4}
$u_{R4},\tilde{u}_{L4}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	q_{u_4}
$d_{R4},\tilde{d}_{L4}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	q_{d_4}
$L_{L4},\tilde{L}_{R4}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	q_{L_4}
$e_{R4},\tilde{e}_{L4}$	$\mathbf{1}$	$\mathbf{1}$	-1	q_{e_4}
$\nu_{R4},\tilde{\nu}_{L4}$	$\mathbf{1}$	$\mathbf{1}$	0	q_{ν_4}

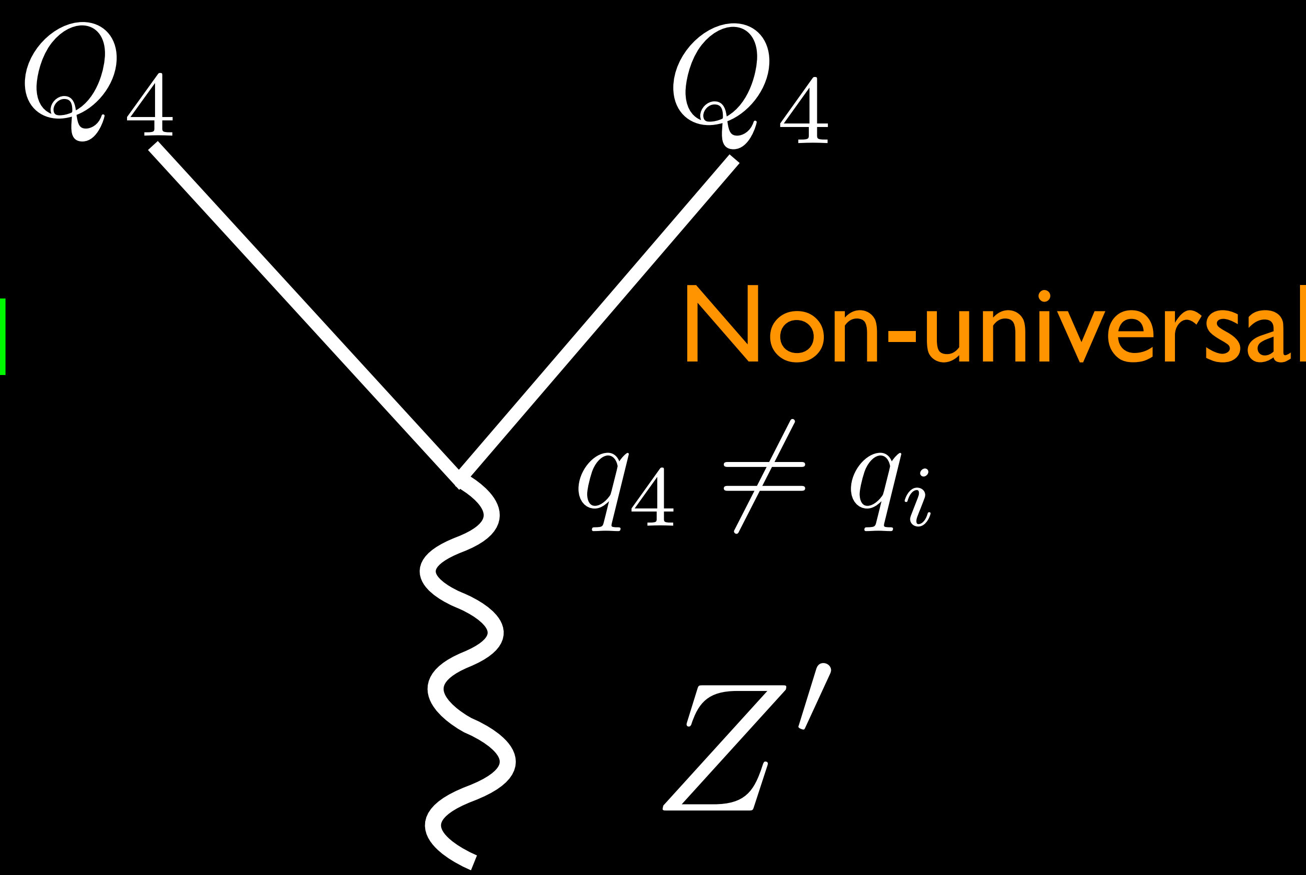
Vector-like fourth family with non-universal U(1)’ charges

$$q_1 = q_2 = q_3 \neq q_4$$

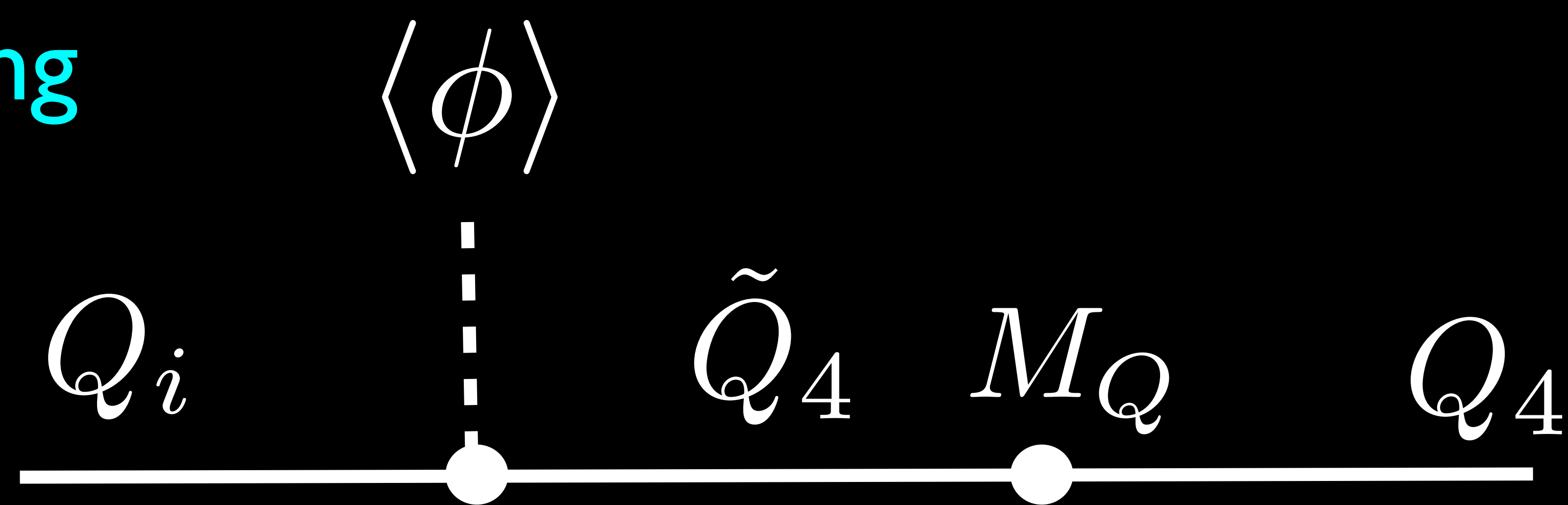
When U(1)’ is broken, mass mixing of the four families leads to Z’ flavour violation

This mechanism works for any Z’ model





Mass mixing

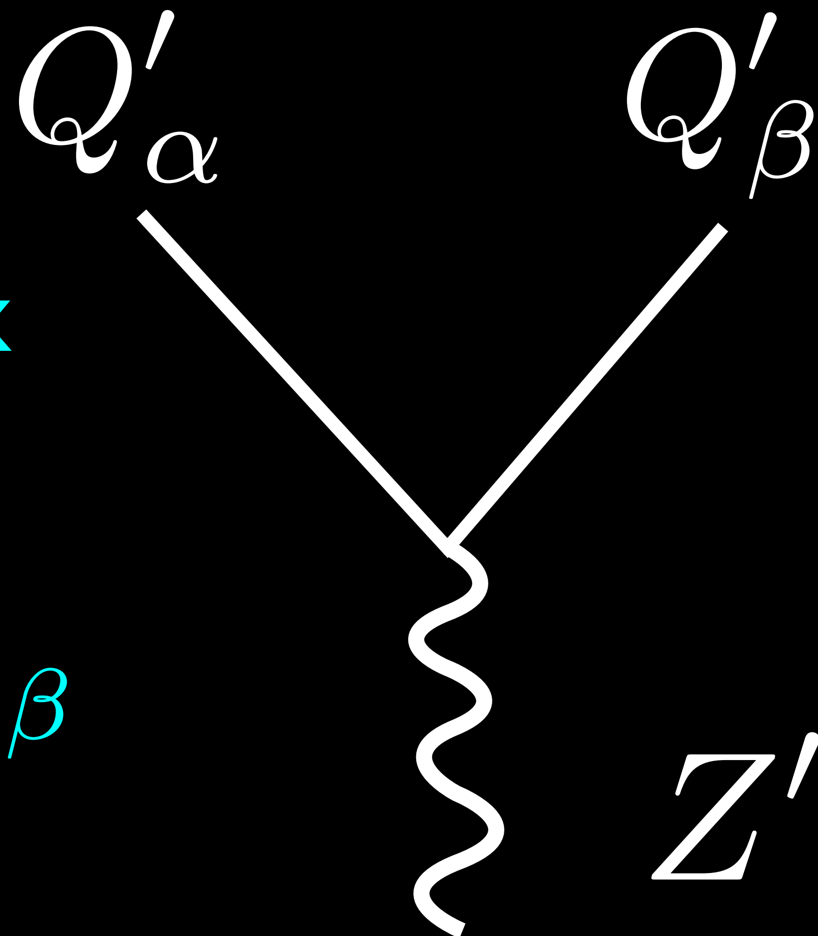


Light quarks contain admixtures of non-universal Q_4

After mass matrix is diagonalised

$$Q'_\alpha = V_Q^{\alpha\beta} Q_\beta$$

4x4



Non-universal and flavour changing couplings

$$V_Q D_Q V_Q^\dagger$$

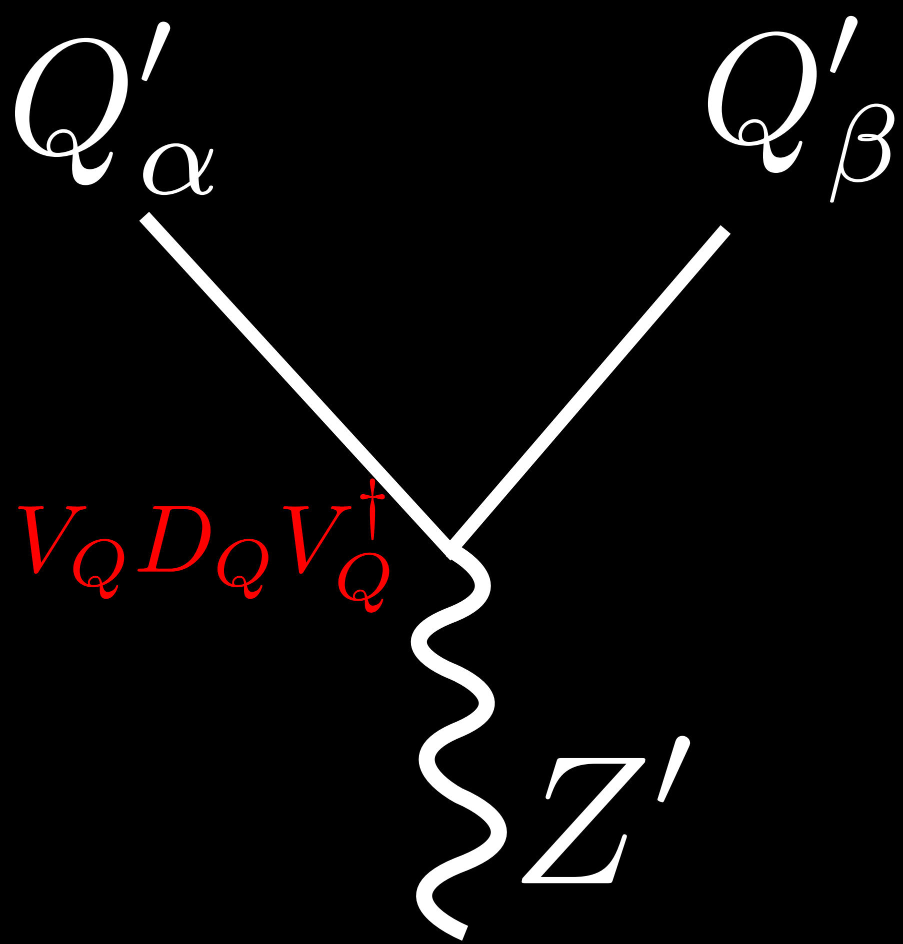
non-universal charge matrix

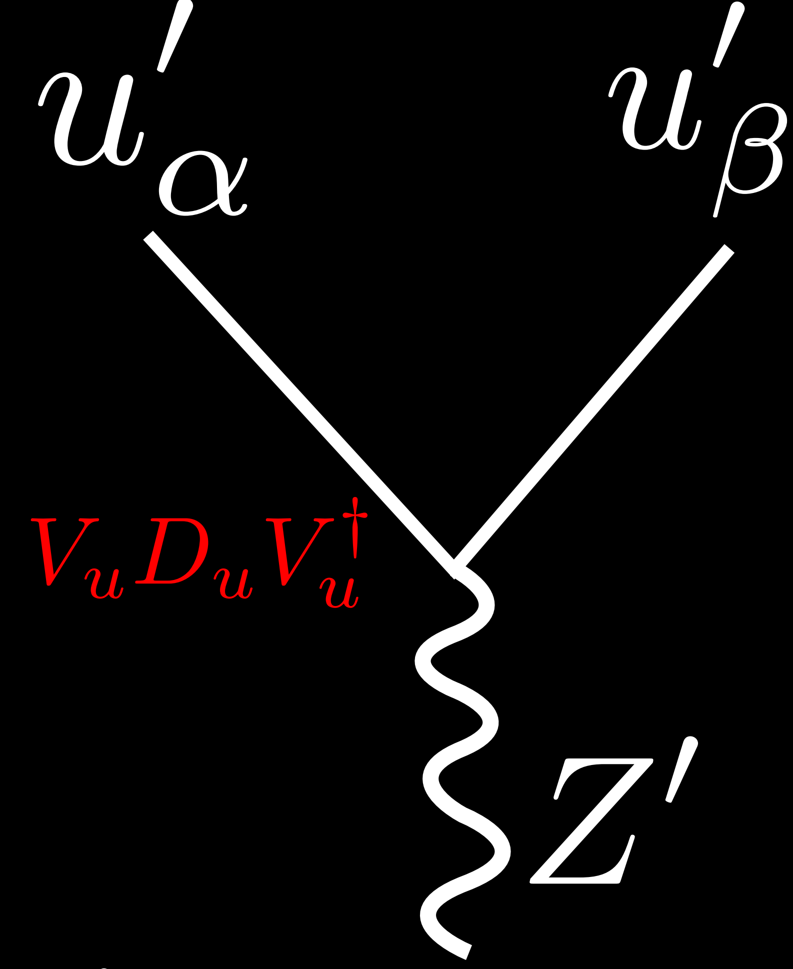
$$D_Q = \mathrm{diag}(q_1, q_2, q_3, q_4)$$

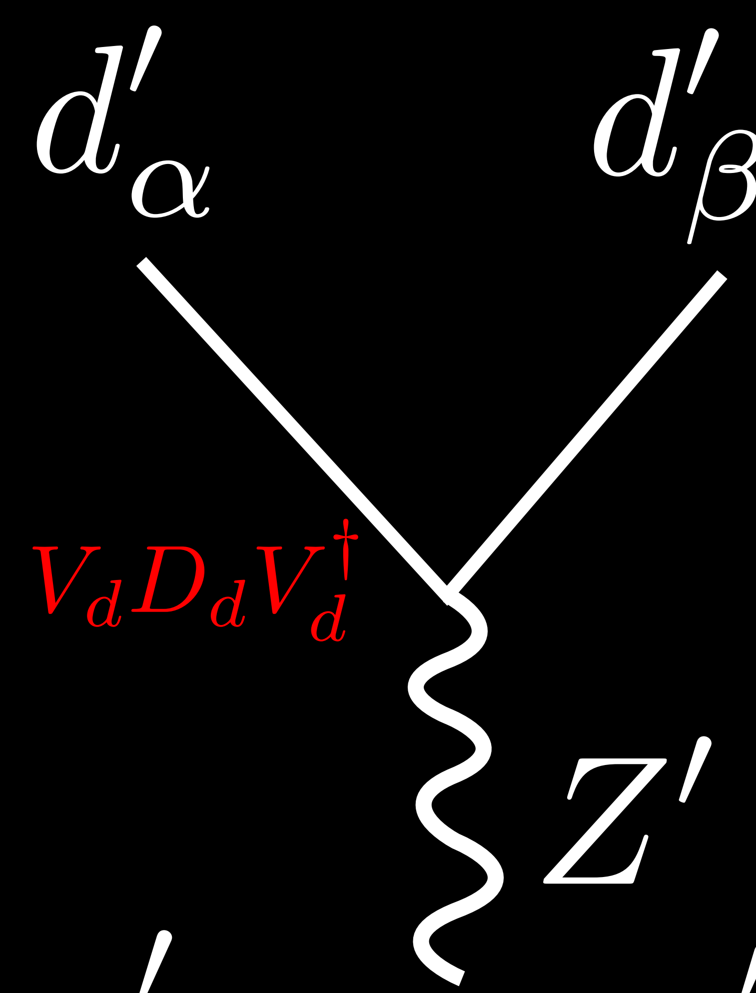
Three light quarks $Q'_{\alpha=1,2,3}$ contain some Q_4

One heavy vector-like quark $Q'_{\alpha=4}$

$$\tilde{M}_4^Q \overline{Q'}_4 \tilde{Q}_4$$

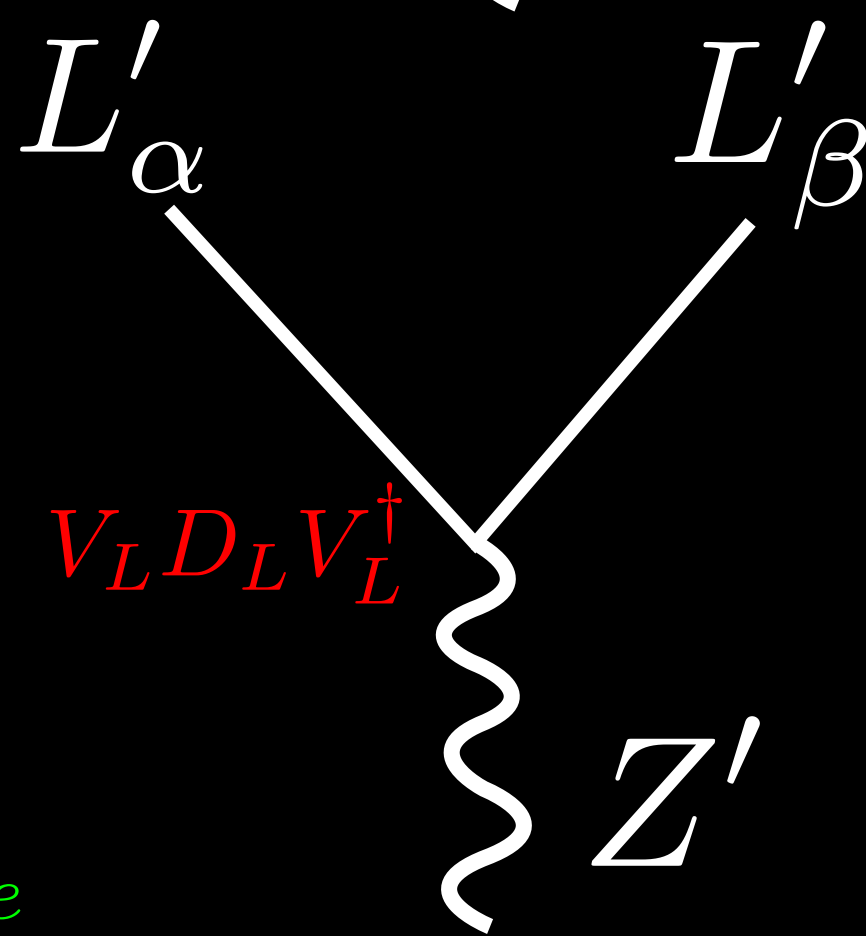


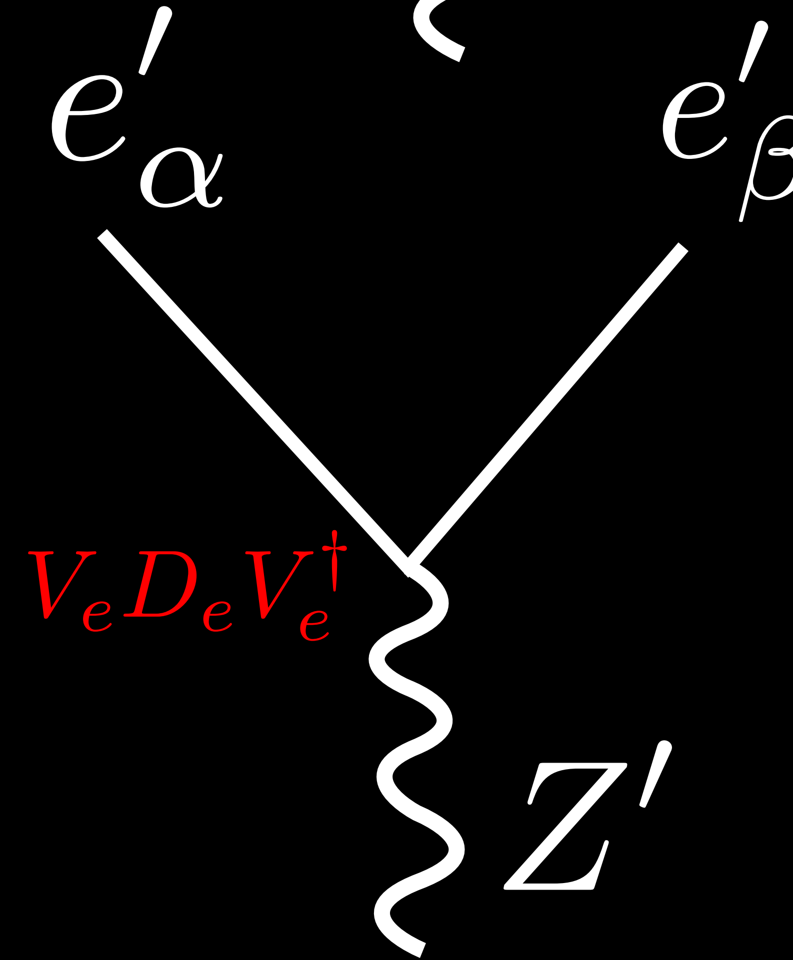




4x4 mixing matrices

V_Q, V_u, V_d, V_L, V_e





non-universal
charge matrices

D_Q, D_u, D_d, D_L, D_e

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SO(10) GUT model

$$SO(10) \to SU(5) \times U(1)_X$$

Broken at TeV scale

Broken at GUT scale

$$\mathbf{16}_{Fi} \to (\mathbf{10}, 1)_i + (\overline{\mathbf{5}}, -3)_i + (\mathbf{1}, 5)_i$$

Three families of quarks and leptons

$$\mathbf{10}_F \to (\mathbf{5}, -2) + (\overline{\mathbf{5}}, 2),$$

$$\mathbf{45}_F \to (\mathbf{10}, -4) + (\overline{\mathbf{10}}, 4) + (\mathbf{1}, 0) + (\mathbf{24}, 0)$$

TeV scale vector-like fourth family with non-universal charges

GUT scale masses splitting requires 210_H

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Flavourful Z' from SO(10)

Field	Representation			
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Q_i	3	2	$1/6$	1
u_i^c	$\overline{3}$	1	$-2/3$	1
d_i^c	$\overline{3}$	1	$1/3$	-3
L_i	1	2	$-1/2$	-3
e_i^c	1	1	1	1
ν_i^c	1	1	1	5

Three families of quarks and leptons with universal charges

$$\overline{\mathbf{5}} \to L, d^c \ , \quad \mathbf{10} \to Q, u^c, e^c$$

Field	Representation			
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Q_4	3	2	$1/6$	-4
u_4^c	$\overline{3}$	1	$-2/3$	-4
d_4^c	$\overline{3}$	1	$1/3$	2
L_4	1	2	$-1/2$	2
e_4^c	1	1	1	-4
$\tilde{Q}_4$	$\overline{3}$	$\overline{2}$	$-1/6$	4
$\tilde{u}_4^c$	3	1	$2/3$	4
$\tilde{d}_4^c$	3	1	$-1/3$	-2
$\tilde{L}_4$	1	$\overline{2}$	$1/2$	-2
$\tilde{e}_4^c$	1	1	-1	4

Vector-like fourth family with non-universal $U(1)_X$ charges

$$\mathcal{L}^q_{Z'} = g' Z'_\mu \begin{pmatrix} \overline{u}_L & \overline{c}_L & \overline{t}_L \end{pmatrix} V'_{uL} \tilde{D}'_Q V'^{\dagger}_{uL} \gamma^\mu \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}$$

$$+ \; g' Z'_\mu \begin{pmatrix} \overline{d}_L & \overline{s}_L & \overline{b}_L \end{pmatrix} V'_{dL} \tilde{D}'_Q V'^{\dagger}_{dL} \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

+ other quarks and leptons

CKM mixing

$$(\tilde{D}'_Q)_{ij} = (V_{Q_L} D_Q V^\dagger_{Q_L})_{ij}$$

$$V_{Q_L} = V^{Q_L}_{34} V^{Q_L}_{24} V^{Q_L}_{14}, \qquad V^{Q_L}_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c^{Q_L}_{34} & s^{Q_L}_{34} e^{-i\delta^{Q_L}_{34}} \\ 0 & 0 & -s^{Q_L}_{34} e^{i\delta^{Q_L}_{34}} & c^{Q_L}_{34} \end{pmatrix},$$

Vector-like mass mixing matrices

$$V^{Q_L}_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c^{Q_L}_{24} & 0 & s^{Q_L}_{24} e^{-i\delta^{Q_L}_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s^{Q_L}_{24} e^{i\delta^{Q_L}_{24}} & 0 & c^{Q_L}_{24} \end{pmatrix}, \quad V^{Q_L}_{14} = \begin{pmatrix} c^{Q_L}_{14} & 0 & 0 & s^{Q_L}_{14} e^{-i\delta^{Q_L}_{14}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s^{Q_L}_{14} e^{i\delta^{Q_L}_{14}} & 0 & 0 & c^{Q_L}_{14} \end{pmatrix}.$$

+ other quarks and leptons

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SO(10) for $R_{K^{(*)}}$

Assuming only θ^Q_{34} and θ^L_{14} non-zero

Universal Non-universal

Z' coupling matrices

$$\tilde{D}'_L = -\frac{3}{2\sqrt{10}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}+\frac{5}{2\sqrt{10}}\begin{pmatrix}(s^L_{14})^2&0&0\\0&0&0\\0&0&0\end{pmatrix}$$

$$\tilde{D}'_Q = \frac{1}{2\sqrt{10}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}-\frac{5}{2\sqrt{10}}\begin{pmatrix}0&0&0\\0&0&0\\0&0&(s^Q_{34})^2\end{pmatrix}$$

$$G^{\mathrm{BSM}}_{b_L\mu_L}\ \bar{b}_L\gamma^\lambda s_L\left[\ \bar{\mu}_L\gamma_\lambda\mu_L+\left(1-\frac{5}{3}(s^L_{14})^2\right)\bar{e}_L\gamma_\lambda e_L+\frac{1}{3}\bar{\mu}_R\gamma_\lambda\mu_R+\frac{1}{3}\bar{e}_R\gamma_\lambda e_R+\cdots\right]$$

$$G^{\mathrm{BSM}}_{b_L\mu_L}=\frac{3}{8}(s^Q_{34})^2(V'^{\dagger}_{dL})_{32}\left(\frac{g'^2}{{M'_Z}^2}\right)$$

$$M'_Z\approx(s^Q_{34})\,(V'^{\dagger}_{dL})^{1/2}_{32}\ (9\ \mathrm{TeV})$$

Close to LHC bound 3 TeV

Antusch, Hohl, SFK, Susic (in prep)

SO(10) GUT model continued...

Singlet for inverse/ linear seesaw

$$\mu \mathbf{1}_F^2 + m_{10} \mathbf{10}_F^2 + m_{45} \mathbf{45}_F^2$$ ← Vector-like fermion masses

$$+ y_1 \mathbf{16}_F^2 \cdot \mathbf{10}_H$$ ← Quark and lepton Yukawa couplings

$$+ Y_1 \mathbf{16}_F \cdot \mathbf{1}_F \cdot \overline{\mathbf{16}}_H + Y_2 \mathbf{16}_F \cdot \mathbf{10}_F \cdot \mathbf{16}_H + Y_3 \mathbf{16}_F \cdot \mathbf{45}_F \cdot \overline{\mathbf{16}}_H$$

Singlet-neutrino couplings

Quark/lepton mixing with vector-like fermions

Antusch, Hohl, SFK, Susic (in prep)

Inverse vs linear seesaw

$$m_\nu^{inv} \sim \mu \left(\frac{y_1 v_u}{Y_1 \bar{v}_R} \right)^2$$

$$m_\nu^{lin} \sim \frac{y_1 v_u \overline{v}_L}{\overline{v}_R}$$

$$(\nu_{Li}, \nu_{Ri}, s_i, \nu_{L4}, \tilde{\nu}_{R4})$$

Dirac

Linear

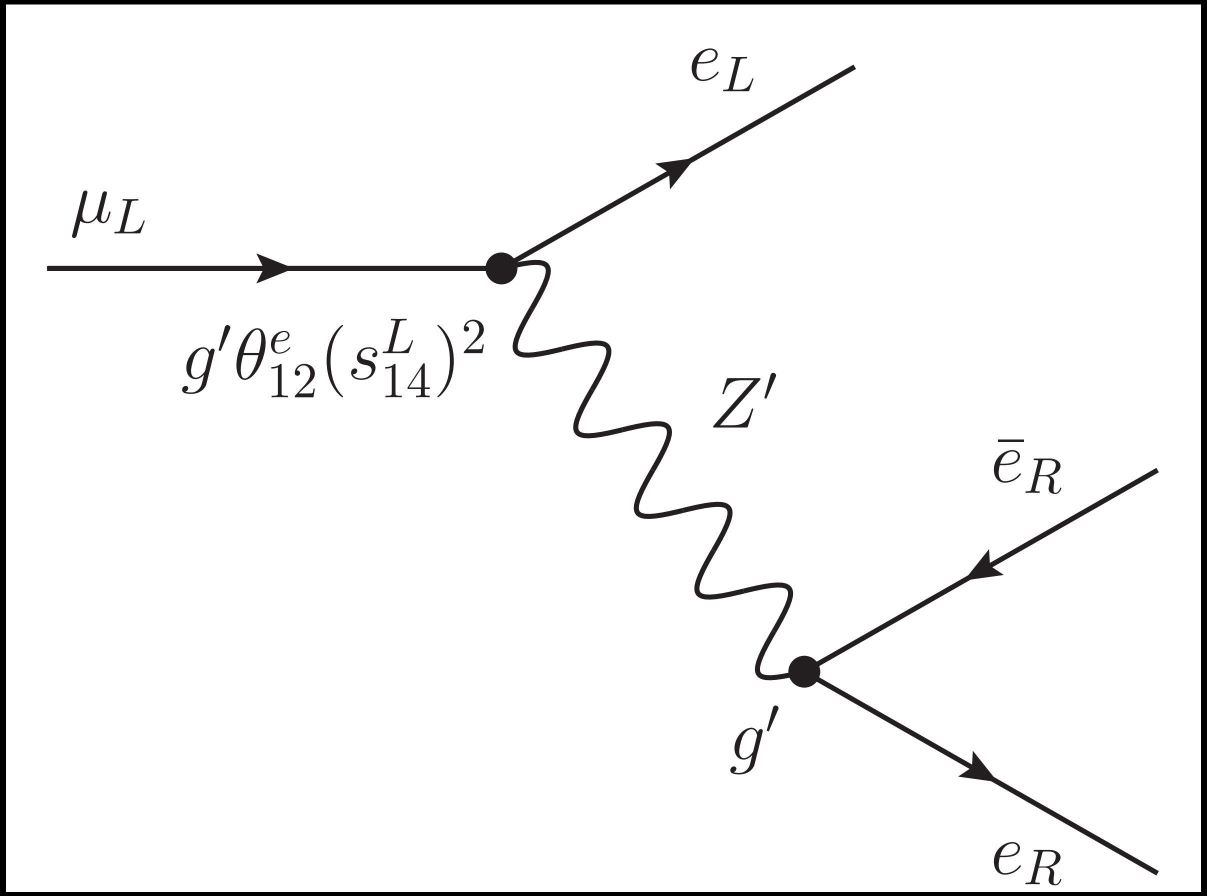
Inverse

$$M_\nu = \begin{pmatrix} 0 & y_1 v_u & Y_1 \bar{v}_L & 0 & Y_2 v_R \\ y_1 v_u & 0 & Y_1 \bar{v}_R & 0 & Y_2 v_L \\ Y_1 \bar{v}_L & Y_1 \bar{v}_R & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{10} \\ Y_2 v_R & Y_2 v_L & 0 & m_{10} & 0 \end{pmatrix}$$

$$\overline{16}_H \to (\overline{10}, -1)_H + (5,3)_H + (1,-5)_H$$

Antusch, Hohl, SFK, Susic (in prep)

Lepton flavour violation



$$\mathrm{Br}(\mu \to 3e) \approx \frac{1}{8^2} \cdot (\theta^e_{12})^2 (s^L_{14})^4 \cdot \frac{g'^4 M_W^4}{g_2^4 M_{Z'}^4}$$

Near current bound 10^{-12}

$$\approx 1.64 \cdot 10^{-12} \left(\frac{\theta^e_{12}}{3^\circ}\right)^2 \left(\frac{3.2 \cdot 10^3 \text{ GeV}}{M_{Z'}}\right)^4$$

Crispim Romao, SFK, Leontaris (in prep)

F-theory Z' models

E_8

Higgs $\downarrow$

$SU(5)_{GUT} \times SU(5)_{Perp}$

Higgs $\downarrow$

$SU(5)_{GUT} \times U(1)^4_{Perp}$

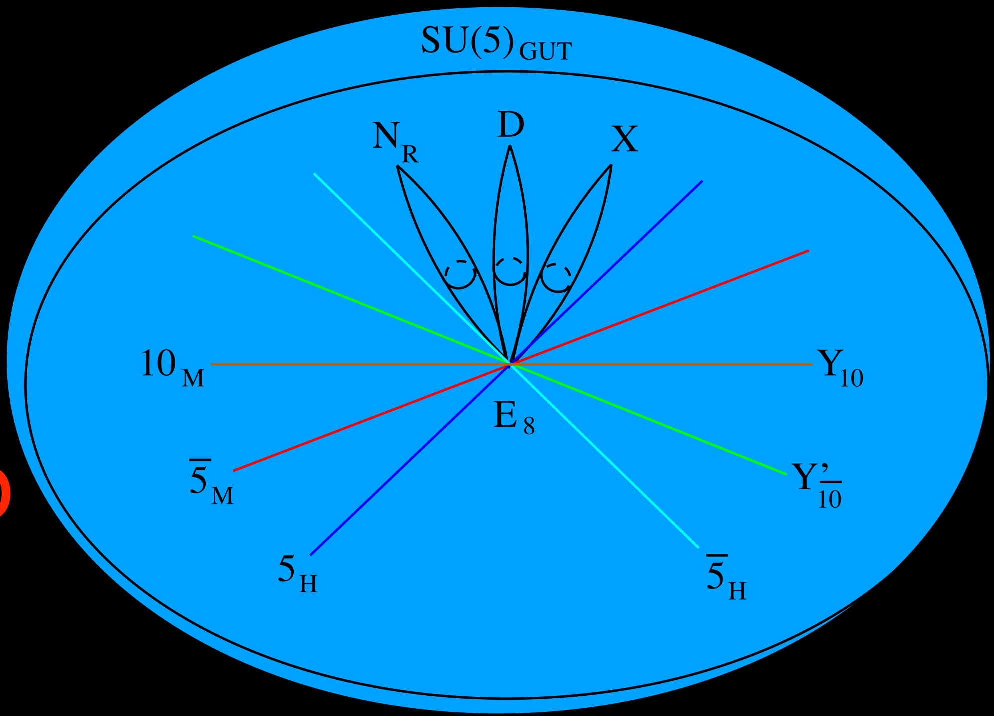
Flux $\downarrow$ Z_2 monodromy

$SU(3) \times SU(2) \times U(1)_Y \times U(1)^3_{Perp}$

Singlets $\downarrow$

$SU(3) \times SU(2) \times U(1)_Y \times U(1)_X$

Non-universal Z'



Heckman,Tavanfar,Vafa

Crispim Romao, SFK, Leontaris (in prep)

F-theory Z' models

Three chiral families with non-universal Z'

Model 1: $(H_u)_{2\frac{1}{\sqrt{15}}} + (H_d)_{-2\frac{1}{\sqrt{15}}} + 3\times\bar{5}_{\frac{1}{2}\frac{1}{\sqrt{15}}} + 2\times 10_{-\frac{1}{\sqrt{15}}} + 10_{\frac{3}{2}\frac{1}{\sqrt{15}}}$

Model 2: $(H_u)_{\frac{1}{2}\frac{1}{\sqrt{15}}} + (H_d)_{-\frac{1}{2}\frac{1}{\sqrt{15}}} + 2\times\bar{5}_{2\frac{1}{\sqrt{15}}} + \bar{5}_{-\frac{7}{4}\frac{1}{\sqrt{15}}} + 3\times 10_{-\frac{1}{4}\frac{1}{\sqrt{15}}}$

Model 3: $(H_u)_{\frac{3}{2}\frac{1}{\sqrt{10}}} + \bar{5}_{-\frac{1}{4}\frac{1}{\sqrt{10}}} + \bar{5}_{\frac{1}{\sqrt{10}}} + (2L+d^c)_{-\frac{3}{2}\frac{1}{\sqrt{10}}} + 2\times 10_{-\frac{3}{4}} + 10_{\frac{7}{4}\frac{1}{\sqrt{10}}}$

Model 4: $(H_u)_{\frac{3}{2}\frac{1}{\sqrt{10}}} + (H_d)_{-\frac{3}{2}\frac{1}{\sqrt{10}}} + \bar{5}_{-\frac{1}{4}\frac{1}{\sqrt{10}}} + \bar{5}_{\frac{1}{\sqrt{10}}} + \bar{5}_{\frac{9}{4}\frac{1}{\sqrt{10}}} + 2\times 10_{-\frac{3}{4}\frac{1}{\sqrt{10}}} + 10_{\frac{1}{2}\frac{1}{\sqrt{10}}}$

Three chiral plus one vector-like family w/ non-universal Z'

Example 1: $(H_u)_{4\frac{1}{\sqrt{85}}} + (H_d)_{-4\frac{1}{\sqrt{85}}} + 3\times\bar{5}_{\frac{7}{2}\frac{1}{\sqrt{85}}} + \bar{5}_{\frac{3}{2}\frac{1}{\sqrt{85}}} + 5_{6\frac{1}{\sqrt{85}}} + 3\times 10_{2\frac{1}{\sqrt{85}}} + 10_{-\frac{11}{2}\frac{1}{\sqrt{85}}} + \overline{10}_{\frac{1}{2}\frac{1}{\sqrt{85}}}$

Example 2: $(H_u)_{\frac{3}{2}\frac{1}{\sqrt{10}}} + (H_d)_{-\frac{3}{2}\frac{1}{\sqrt{10}}} + \bar{5}_{\frac{1}{\sqrt{10}}} + \bar{5}_{-\frac{1}{4}\frac{1}{\sqrt{10}}} + \bar{5}_{-\frac{9}{4}\frac{1}{\sqrt{10}}} + L_{\frac{1}{\sqrt{10}}} + d^c_{-\frac{1}{4}\frac{1}{\sqrt{10}}} + 5_{-\frac{1}{\sqrt{10}}} + 3\times 10_{-\frac{3}{4}\frac{1}{\sqrt{10}}}$
$+ 10_{\frac{7}{4}\frac{1}{\sqrt{10}}} + \overline{10}_{-\frac{1}{2}\frac{1}{\sqrt{10}}}$

Example 3: $(H_u)_{-\frac{1}{2}} + (H_d)_{\frac{1}{2}} + 3\times\bar{5}_{-\frac{1}{4}} + \bar{5}_{\frac{3}{4}} + 5_0 + 3\times 10_{\frac{1}{4}} + 10_{-\frac{1}{2}} + \overline{10}_{\frac{1}{4}}$

Conclusion

- $R_{K^{(*)}}$ motivates non-universal Z' models
- Any Z' model can be made non-universal by adding fourth vector-like family with non-universal charges which mixes
- We studied an SO(10) GUT example with $U(1)_X$ at TeV and a vector-like family coming from 45_F and 10_F
- SO(10) GUT for $R_{K^{(*)}}$ requires Z' near 3 TeV LHC bound with mu->eee near current bound 10^{-12}
- SO(10) with $U(1)_X$ at TeV requires inverse/linear seesaw
- F-theory for non-universal Z' with optional vector-like family

Thank YOU