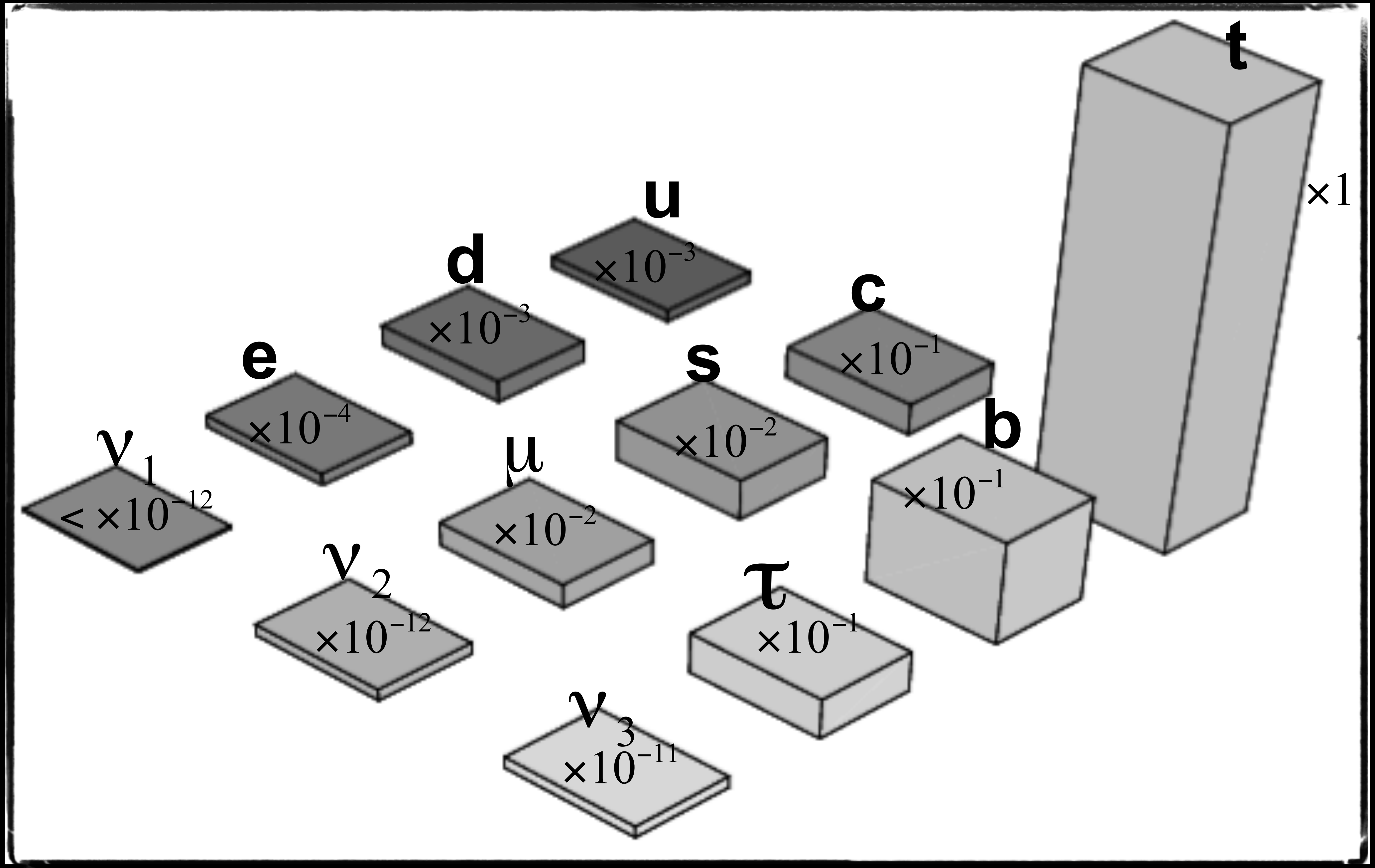
UNIVERSITY OF Southampton
School of Physics and Astronomy

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Low energy theory of Yukawa couplings, neutrino mass (and dark matter) with experimental consequences

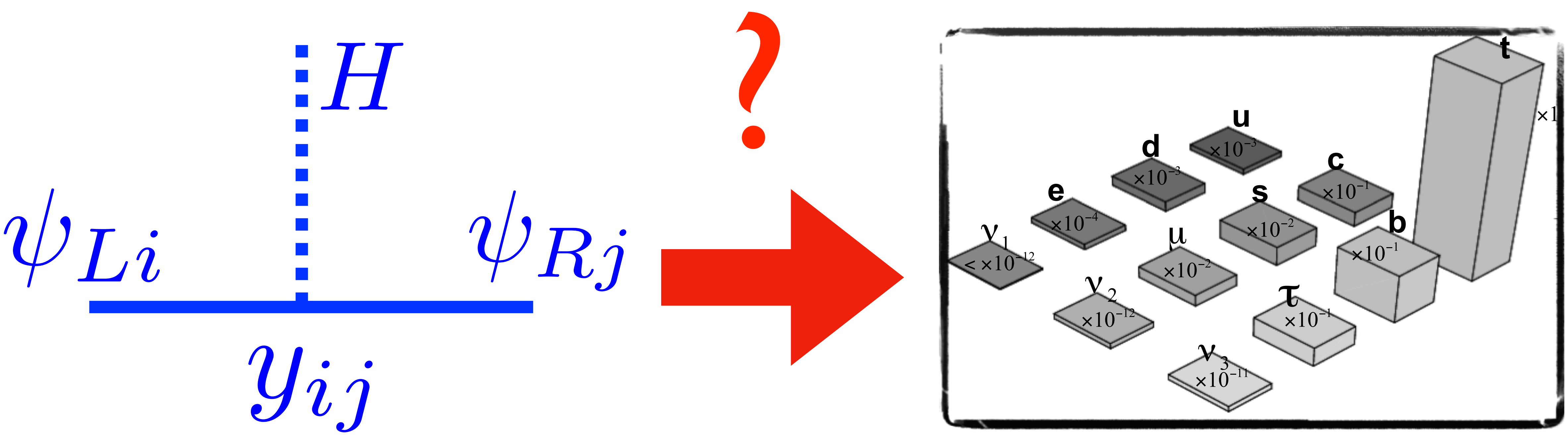
Steve King, 1st April 2021

Flavour Problem



SM Yukawa couplings

$$y_{ij} H \overline{\psi}_{Li} \psi_{Rj}$$



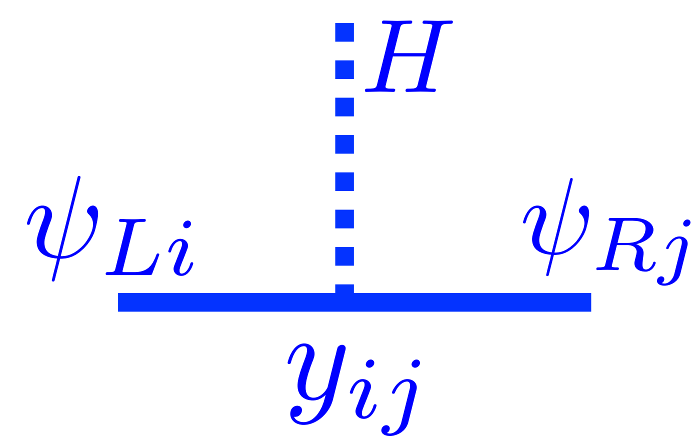
The Standard Model

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	1/6
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	2/3
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	-1/3
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
ℓ_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1

3 families of quarks and leptons (i=1,2,3)

The Standard Model with Higgs doublet

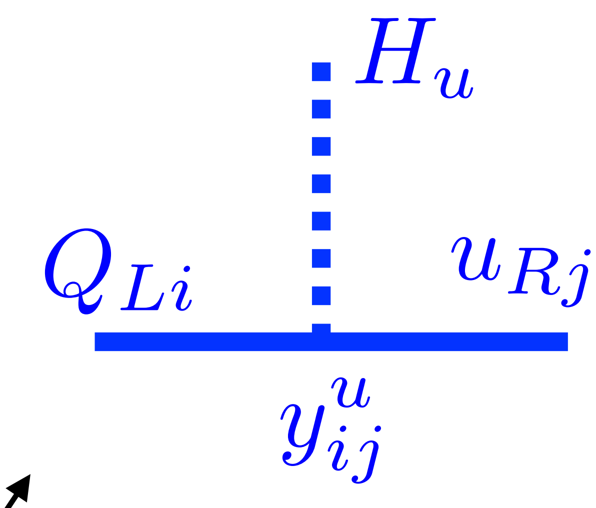
Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
ℓ_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1
$H = \begin{pmatrix} H^+ \\ (v + H^0)/\sqrt{2} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$



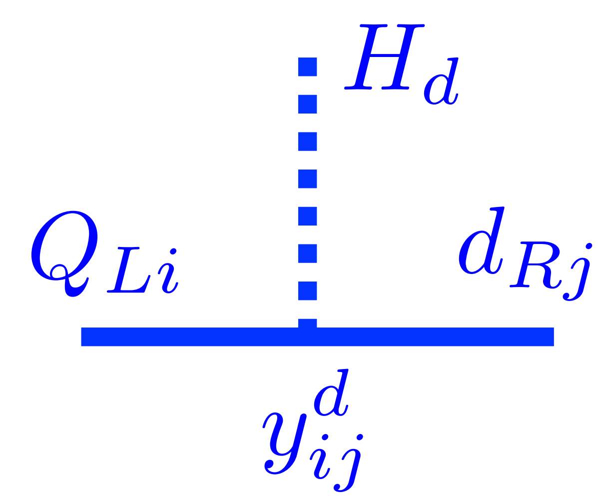
Higgs doublet

The Standard Model
with 2 Higgs doublets

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	1/6
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	2/3
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	-1/3
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
ℓ_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1/2
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2



2 Higgs doublets



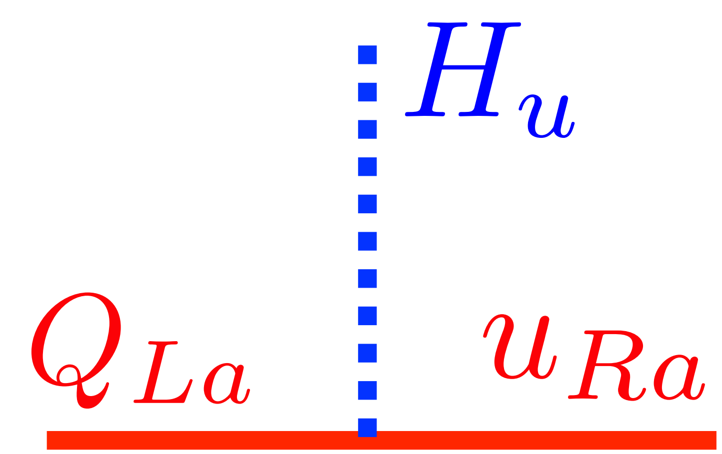
Symmetry to ensure this

The Standard Model with 2 Higgs doublets

+ 4th chiral family?

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	-$1/3$
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-$1/2$
ℓ_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-$1/2$
Q_{La}	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u_{Ra}	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_{Ra}	$\mathbf{3}$	$\mathbf{1}$	-$1/3$
L_{La}	$\mathbf{1}$	$\mathbf{2}$	-$1/2$
ℓ_{Ra}	$\mathbf{1}$	$\mathbf{1}$	-1
ν_{Ra}	$\mathbf{1}$	$\mathbf{1}$	0

Masses from Higgs?



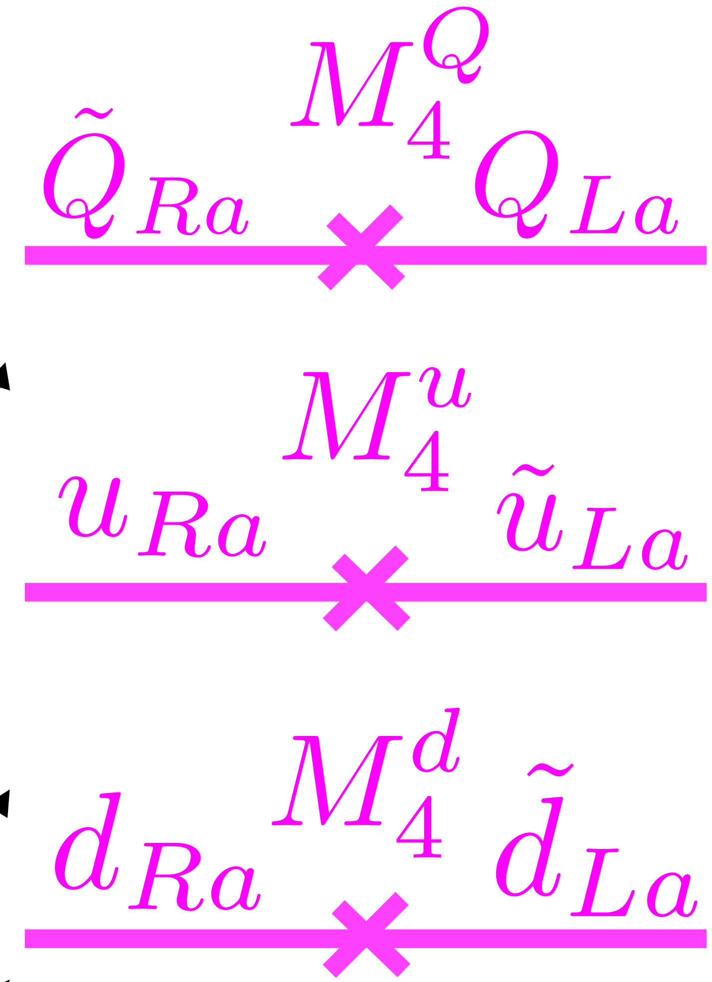
$y_{44} > 1$

EXCLUDED by Higgs physics

The Standard Model with 2 Higgs doublets + 4th Vector-like family OK

Dirac masses

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	**3**	**2**	1/6
u_{Ri}	**3**	**1**	2/3
d_{Ri}	**3**	**1**	-1/3
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	**1**	**2**	-1/2
ℓ_{Ri}	**1**	**1**	-1
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	**1**	**2**	1/2
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	**1**	**2**	-1/2
$Q_{La}, \widetilde{Q}_{Ra}$	**3**	**2**	1/6
$u_{Ra}, \widetilde{u}_{La}$	**3**	**1**	2/3
$d_{Ra}, \widetilde{d}_{La}$	**3**	**1**	-1/3
$L_{La}, \widetilde{L}_{Ra}$	**1**	**2**	-1/2
$\ell_{Ra}, \widetilde{\ell}_{La}$	**1**	**1**	-1
$\nu_{Ra}, \widetilde{\nu}_{La}$	**1**	**1**	0



Masses decouple from EWSB (not involve Higgs)

S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

The Standard Model with 2 Higgs doublets

+ 4th vector-like family

+U(1)' symmetry (gauged/global)

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	1/6	0
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	2/3	0
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	-1/3	0
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2	0
ℓ_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1	0
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1/2	-1
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2	-1
$Q_{La}, \widetilde{Q}_{Ra}$	$\mathbf{3}$	$\mathbf{2}$	1/6	1
$u_{Ra}, \widetilde{u}_{La}$	$\mathbf{3}$	$\mathbf{1}$	2/3	-1
$d_{Ra}, \widetilde{d}_{La}$	$\mathbf{3}$	$\mathbf{1}$	-1/3	-1
$L_{La}, \widetilde{L}_{Ra}$	$\mathbf{1}$	$\mathbf{2}$	-1/2	1
$\ell_{Ra}, \widetilde{\ell}_{La}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\nu_{Ra}, \widetilde{\nu}_{La}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	1

Neutral

Charged

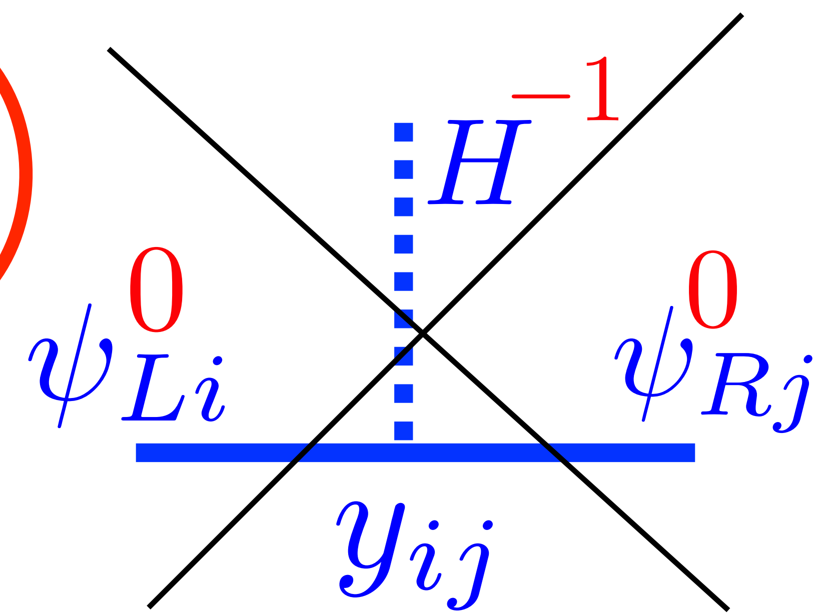
U(1)' broken by Yukon VEV

S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

The Standard Model with 2 Higgs doublets + 4th vector-like family +U(1)' and Yukon

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	**3**	**2**	1/6	0
u_{Ri}	**3**	**1**	2/3	0
d_{Ri}	**3**	**1**	-1/3	0
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	**1**	**2**	-1/2	0
ℓ_{Ri}	**1**	**1**	-1	0
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	**1**	**2**	1/2	-1
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	**1**	**2**	-1/2	-1
$Q_{La}, \widetilde{Q}_{Ra}$	**3**	**2**	1/6	1
$u_{Ra}, \widetilde{u}_{La}$	**3**	**1**	2/3	-1
$d_{Ra}, \widetilde{d}_{La}$	**3**	**1**	-1/3	-1
$L_{La}, \widetilde{L}_{Ra}$	**1**	**2**	-1/2	1
$\ell_{Ra}, \widetilde{\ell}_{La}$	**1**	**1**	-1	-1
$\nu_{Ra}, \widetilde{\nu}_{La}$	**1**	**1**	0	-1
ϕ	**1**	**1**	0	1

U(1)' forbids conventional Yukawa Couplings



Forbidden since H is charged

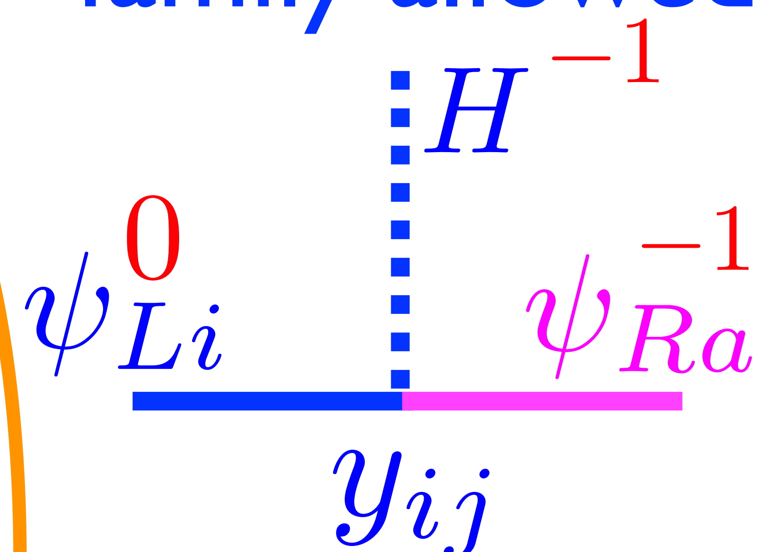
S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

The Standard Model with 2 Higgs doublets

+ 4th vector-like family +U(1)' and Yukon

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$	**3**	**2**	1/6	0
u_{Ri}	**3**	**1**	2/3	0
d_{Ri}	**3**	**1**	-1/3	0
$L_{Li} = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$	**1**	**2**	-1/2	0
ℓ_{Ri}	**1**	**1**	-1	0
$H_u = \begin{pmatrix} H_u^+ \\ (v_u + H_u^0)/\sqrt{2} \end{pmatrix}$	**1**	**2**	1/2	-1
$H_d = \begin{pmatrix} (v_d + H_d^{0*})/\sqrt{2} \\ -H_d^- \end{pmatrix}$	**1**	**2**	-1/2	-1
$Q_{La}, \widetilde{Q}_{Ra}$	**3**	**2**	1/6	1
$u_{Ra}, \widetilde{u}_{La}$	**3**	**1**	2/3	-1
$d_{Ra}, \widetilde{d}_{La}$	**3**	**1**	-1/3	-1
$L_{La}, \widetilde{L}_{Ra}$	**1**	**2**	-1/2	1
$\ell_{Ra}, \widetilde{\ell}_{La}$	**1**	**1**	-1	-1
$\nu_{Ra}, \widetilde{\nu}_{La}$	**1**	**1**	0	-1
ϕ	**1**	**1**	0	1

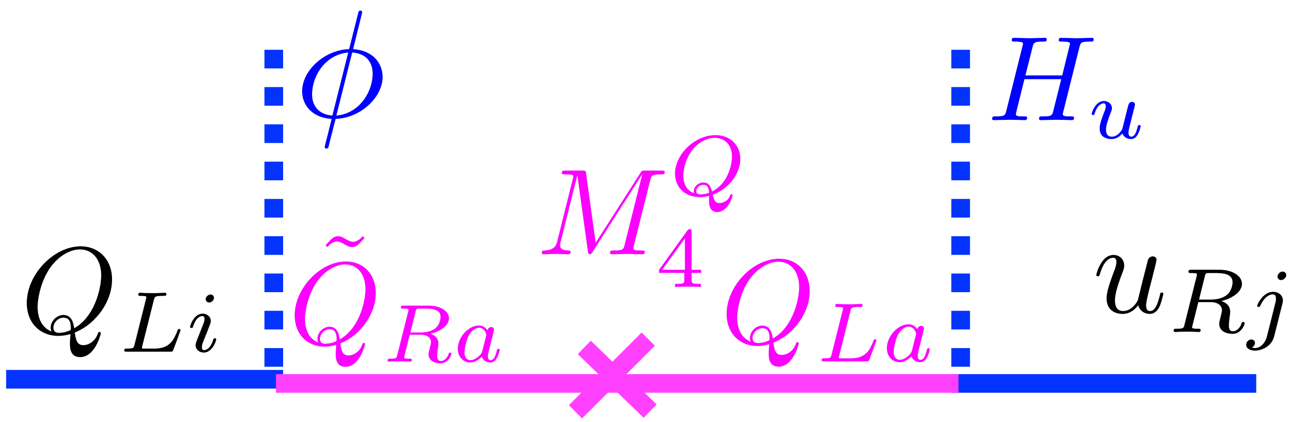
But Yukawa Couplings involving 4th family allowed



4th family is messenger of flavour

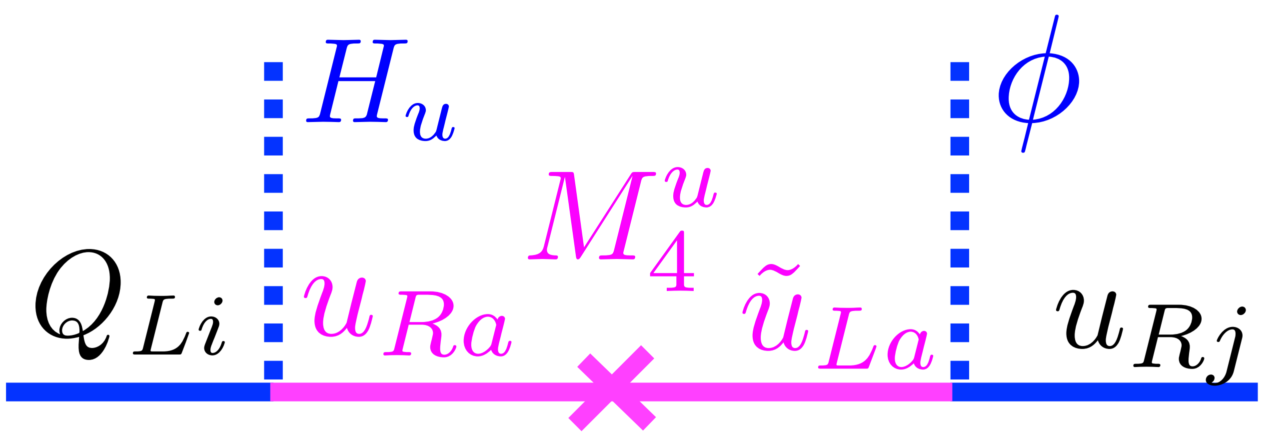
Effective Yukawa Couplings for up type quarks

Mass insertion approx in a convenient basis



$$\rightarrow \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \frac{\langle \phi \rangle}{M_4^Q}$$

Two contributions to Yukawa matrix



$$\rightarrow \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{\langle \phi \rangle}{M_4^u}$$

Rank 2 $y^{up} = 0$

Assume

$$\langle \phi \rangle \lesssim M_4^Q \ll M_4^u$$

$$y^{charm} \ll y^{top} \lesssim 1$$

S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

Effective Yukawa Couplings for quarks and leptons

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

Mass insertion approx in a convenient basis

$$y_{33}^{e} \sim \langle\phi\rangle / M_4^L \qquad y_{33}^{u,d} \sim \langle\phi\rangle / M_4^Q \qquad \varepsilon_{ij}^{e,u,d} \sim \langle\phi\rangle / M_4^{e,u,d}$$

$$\langle\phi\rangle \lesssim M_4^{L,Q} \ll M_4^{e,d} \ll M_4^{u} \Rightarrow \varepsilon_{ij}^{u} \ll \varepsilon_{ij}^{e,d} \ll y_{33}^{e,u,d} \lesssim 1$$

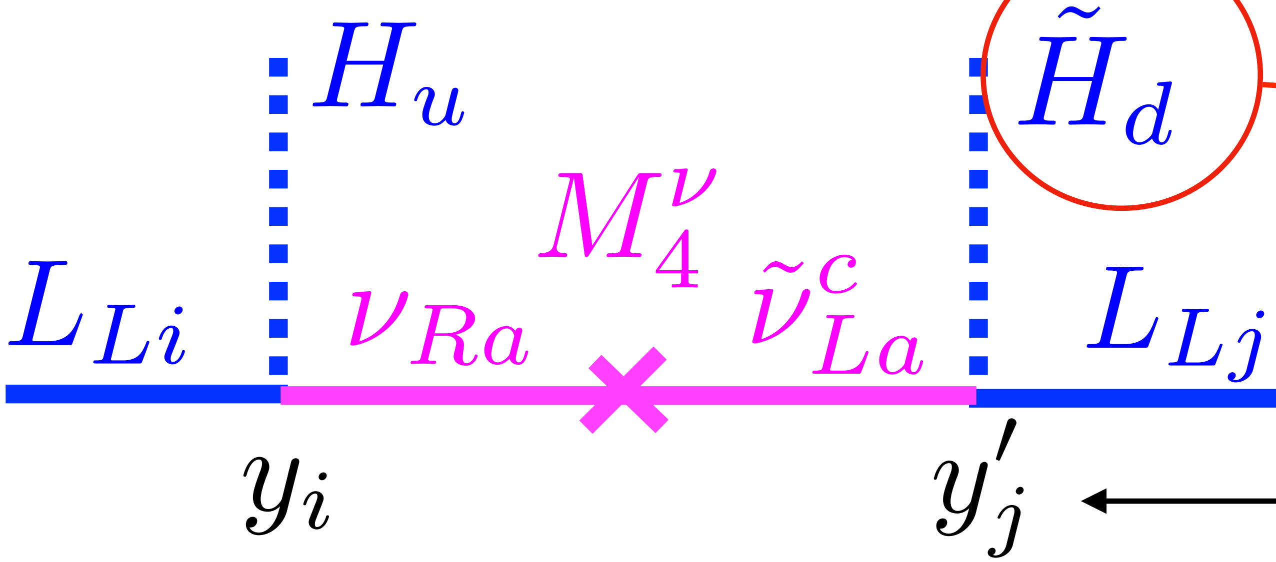
Then get large third family Yukawa couplings and small quark mixing angles from down sector

Note - massless first family so far (good approx)

Neutrino mass from type Ib seesaw (next slide)

J.Hernandez-Garcia and S.F.King, JHEP05(2019)169 [arXiv:1903.01474].

Type Ib Seesaw Mechanism

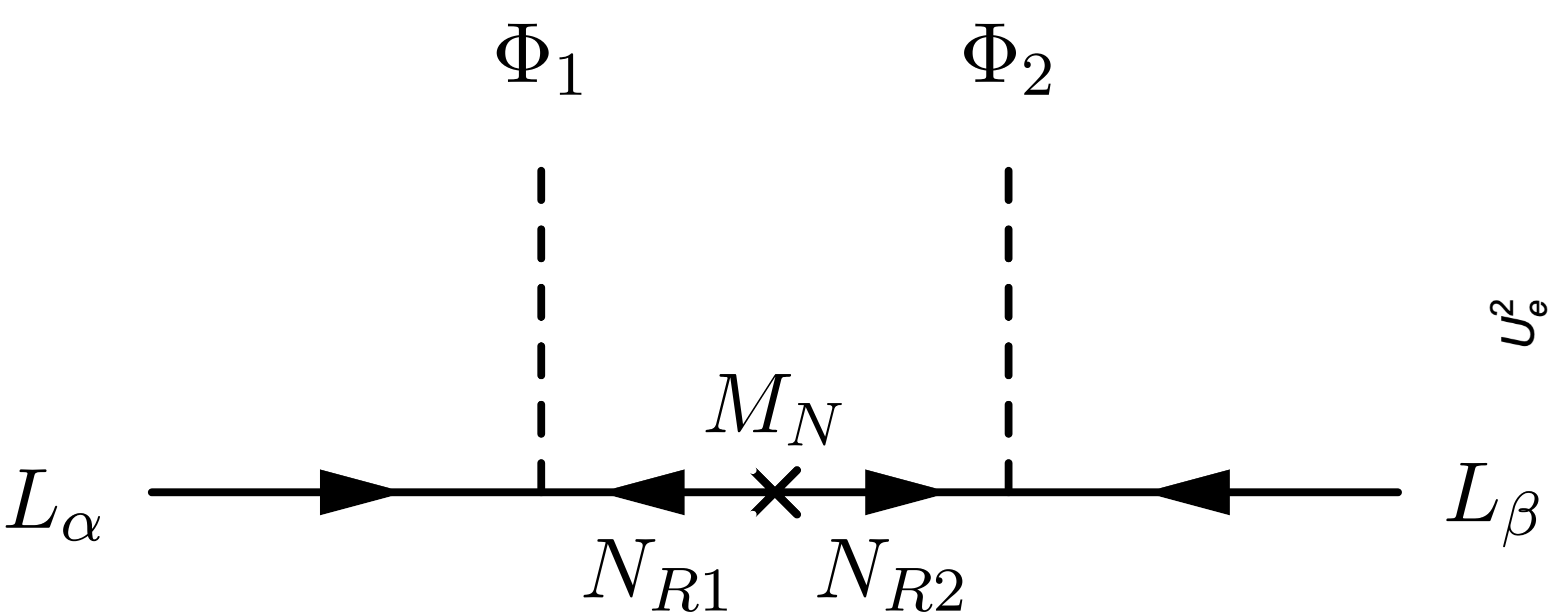


New Weinberg operator

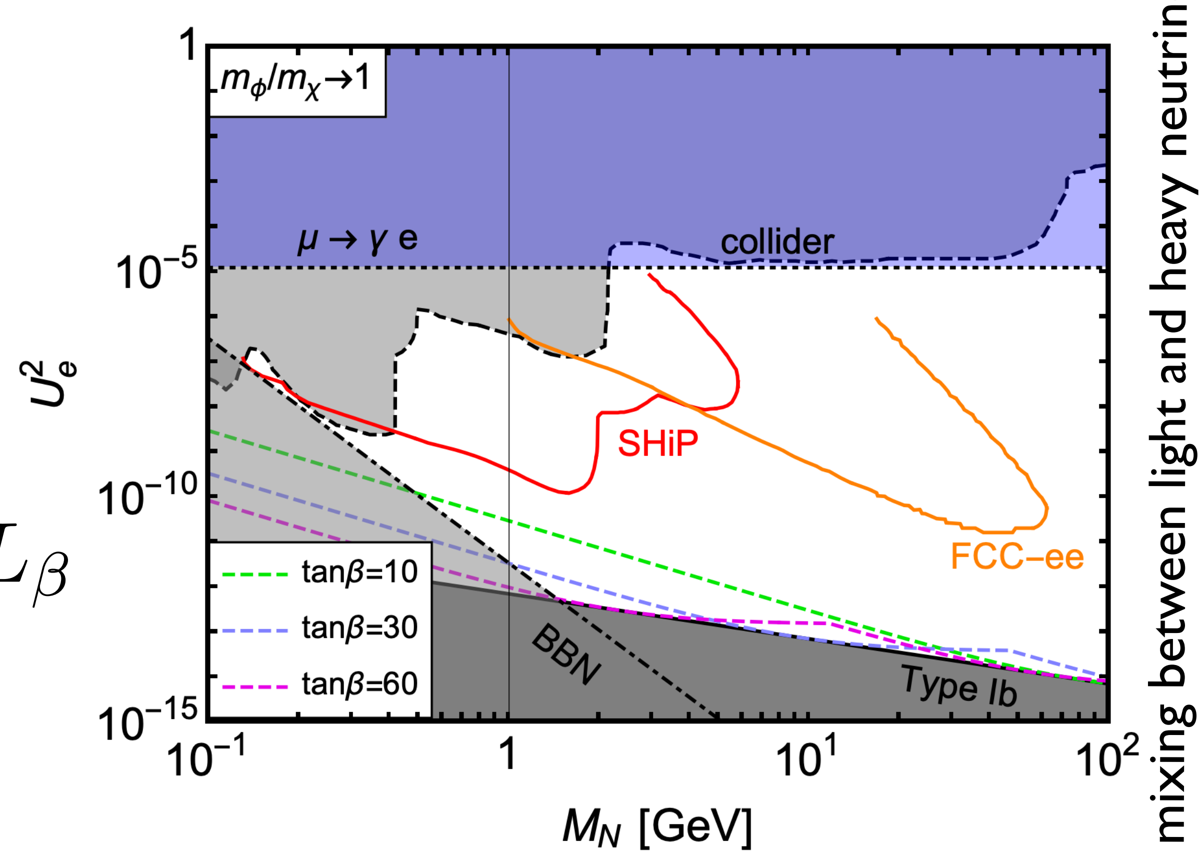
$$y_i y'_j \frac{H_u \tilde{H}_d L_{Li} L_{Lj}}{M_4^\nu}$$

y'_j small with y_i large, allows 1-100 GeV Dirac neutrino

Simpler Notation



M.Chianese, B.Fu and S.F.King, [arXiv:2102.07780].



Machine finds tantalising hints of new physics

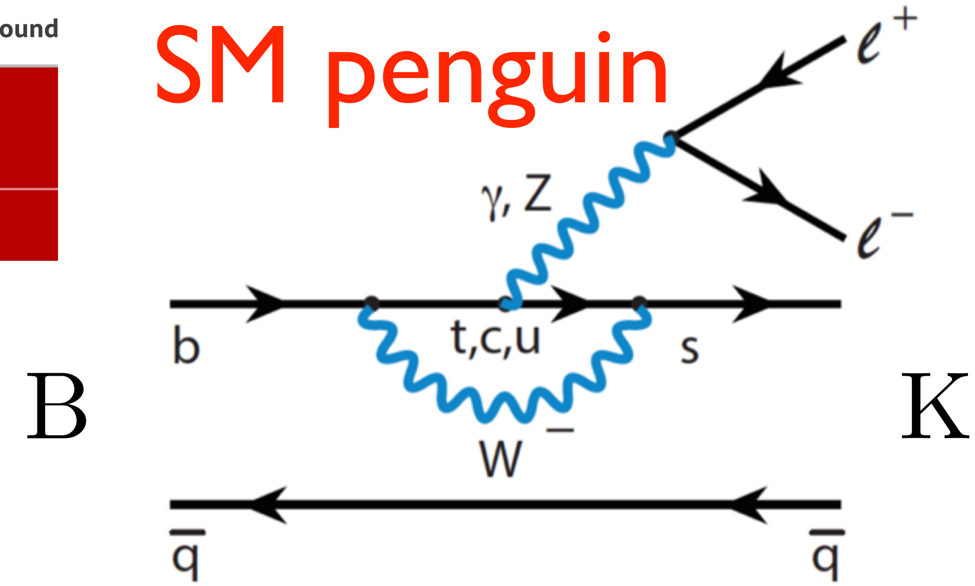
By Pallab Ghosh
Science correspondent

23 March

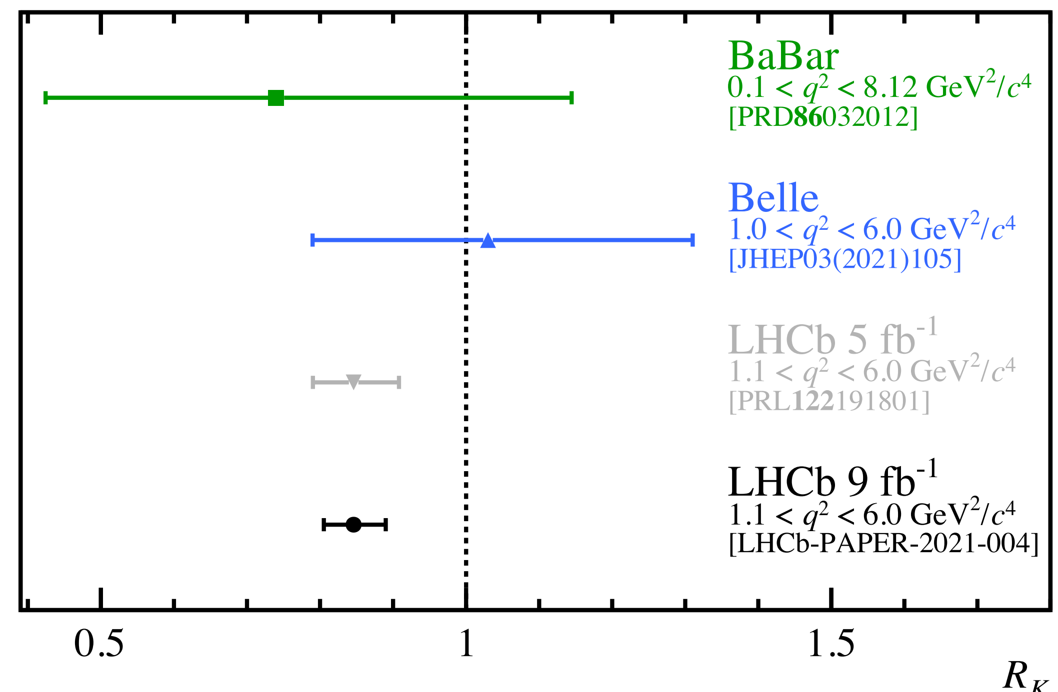
$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Physicists have uncovered a potential flaw in a theory that explains how the building blocks of the Universe behave.

SM penguin



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



$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

3.1σ departure from LFU!

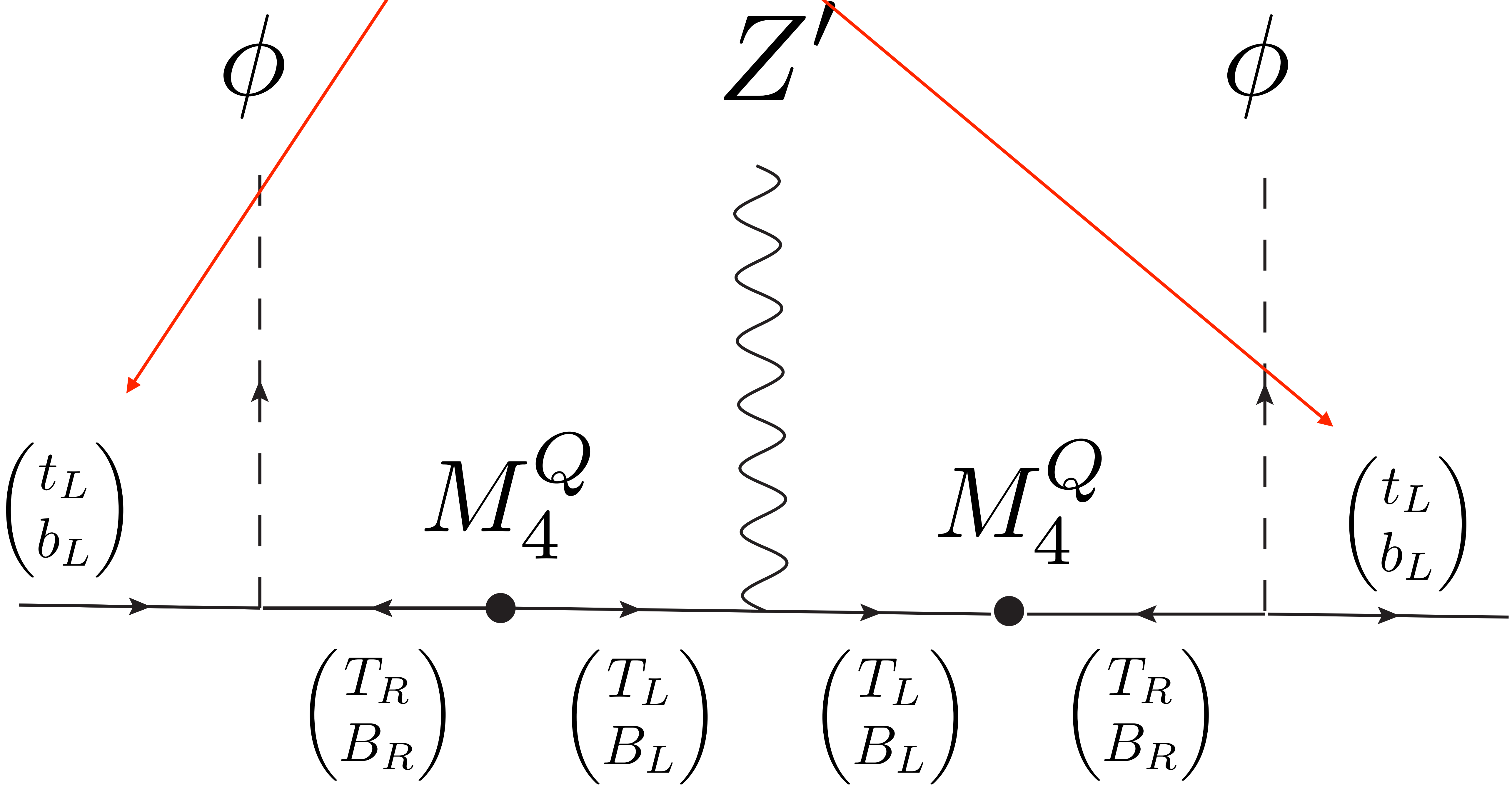
R.Aaij et al. [LHCb], [arXiv:2103.11769]

S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

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

$$\mathcal{L} = Z'_\mu (g_{bb}\overline{b}_L\gamma^\mu b_L + g_{\tau\tau}\overline{\tau}_L\gamma^\mu\tau_L)$$

Z' couples dominantly to third family



S.F.King, JHEP09(2018)069 [arXiv:1806.06780]

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

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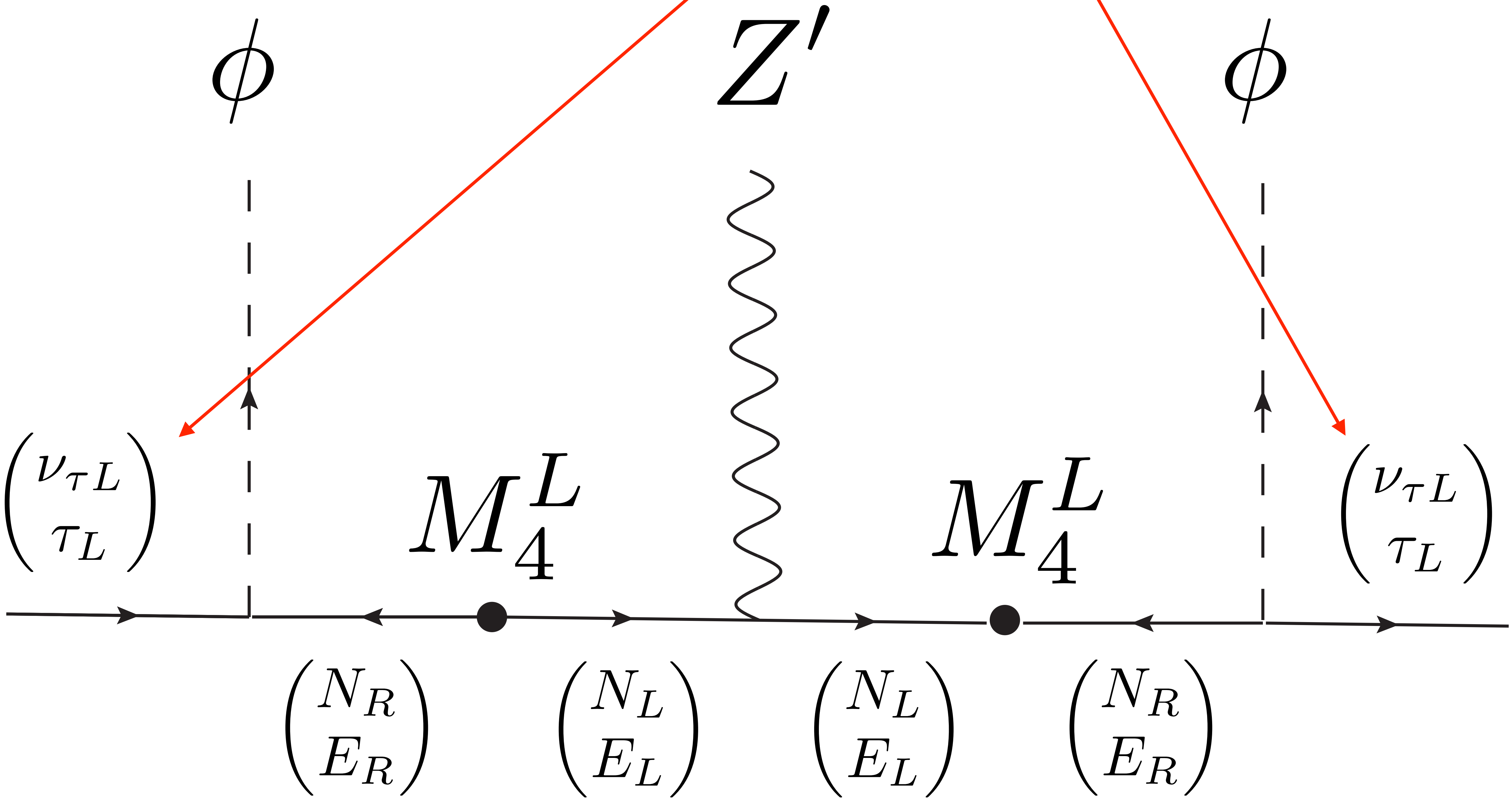
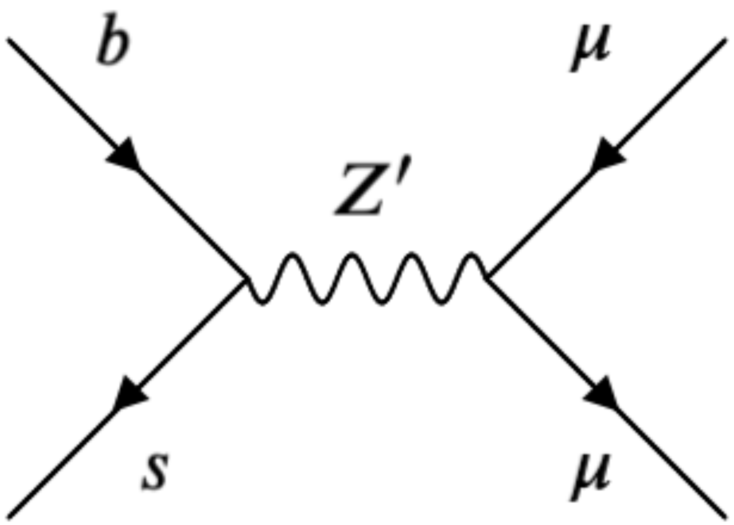
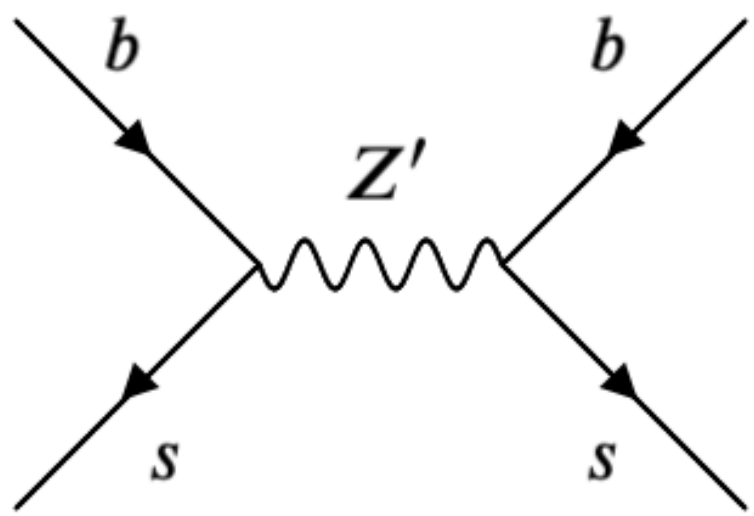
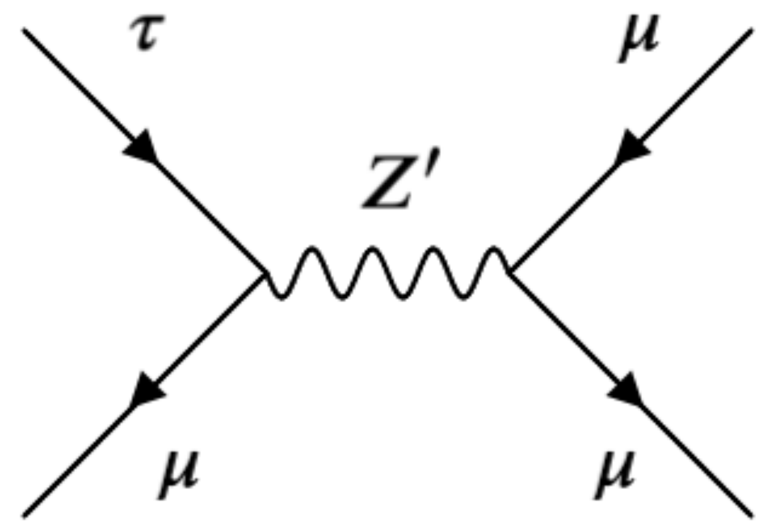


S.F.King, [arXiv:1905.02660]

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







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

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

$$\frac{g_{\mu\mu}}{M_{Z'}} \leq \frac{(\theta^e_{23})^{1/2}}{(16\ \mathrm{TeV})}$$

$$g_{bs} = V_{ts} g_{bb}$$

$$g_{\mu\tau} = \theta^e_{23} g_{\tau\tau}$$

$$g_{\mu\mu} = (\theta^e_{23})^2 g_{\tau\tau}$$

Tension

$$\frac{g_{\mu\mu}}{M_{Z'}} \frac{g_{bs}}{M_{Z'}} \leq \frac{(\theta^e_{23})^{1/2}}{(47\ \mathrm{TeV})^2}$$

- Need $M_{Z'}$ ~ few TeV since $g_{bs} \sim V_{ts} \sim 0.04$

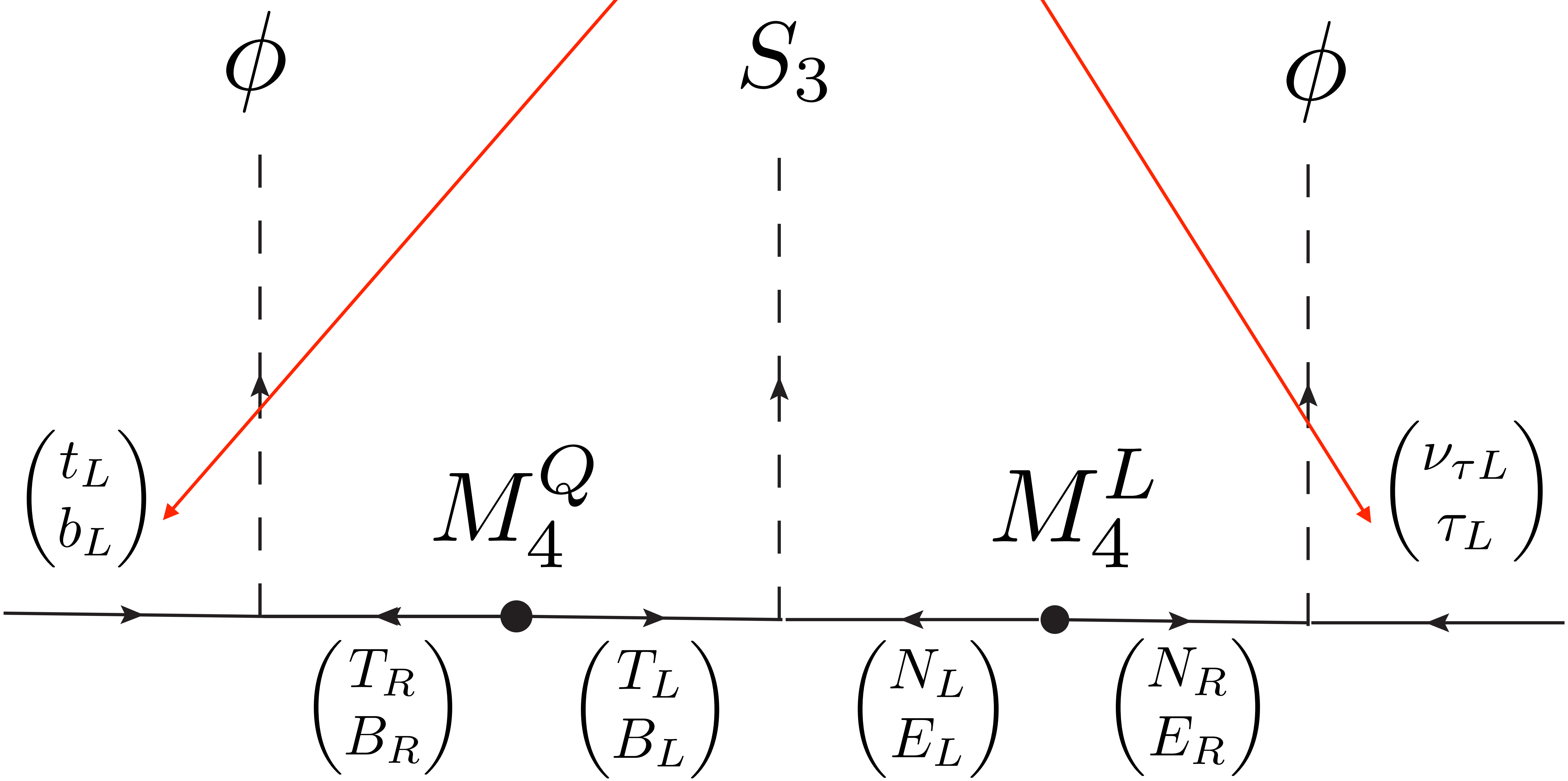
I.De Medeiros Varzielas and S.F.King, Phys RevD.99.095029 [arXiv:1902.09266] S.F.King, [arXiv:1905.02660]

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

$S_3 = (\overline{3}, 3, 1/3, -2)$

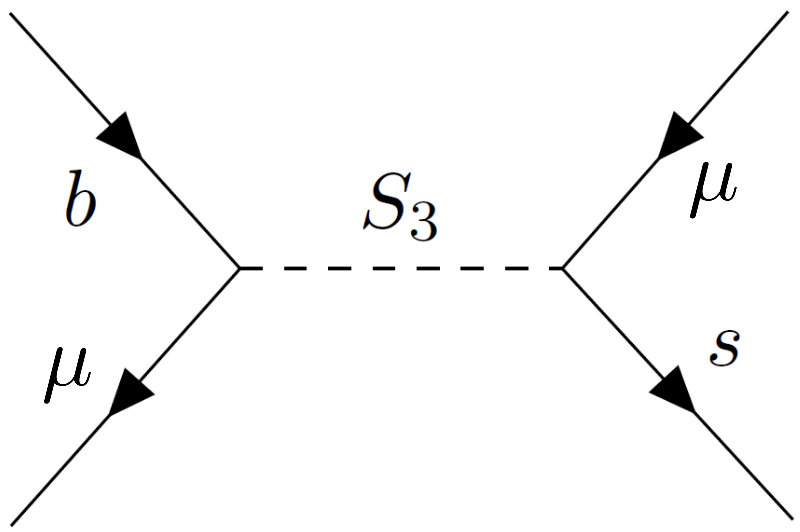
$$\mathcal{L} = \lambda_{b\tau} b_L S_3 \tau_L$$

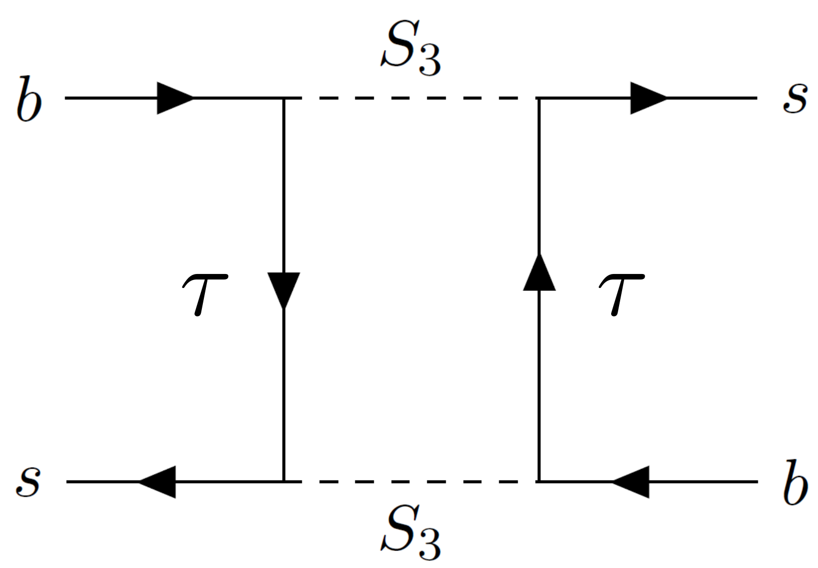
Add scalar leptoquark coupling dominantly to third family



I.De Medeiros Varzielas and S.F.King, Phys RevD.99.095029 [arXiv:1902.09266] S.F.King, [arXiv:1905.02660]

$R_{K^{(*)}}$ B_s mixing @ 1-loop





$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{M^2_{S_3}} \approx \frac{y_\tau^2(\theta^e_{23})^2 V_{ts}}{M^2_{S_3}} \approx \frac{1.1}{(35\ \mathrm{TeV})^2}$$

$$\frac{(\lambda_{s\tau}\lambda_{b\tau})^2}{16\pi^2 M^2_{S_3}} \approx \frac{y_\tau^4 V_{ts}^2}{16\pi^2 M^2_{S_3}} \leq \frac{1}{(140\ \mathrm{TeV})^2}$$

- Need M_{S3} ~ few TeV since V_{ts}~0.04
- No tension now since Bs mix and LFV occur at 1-loop

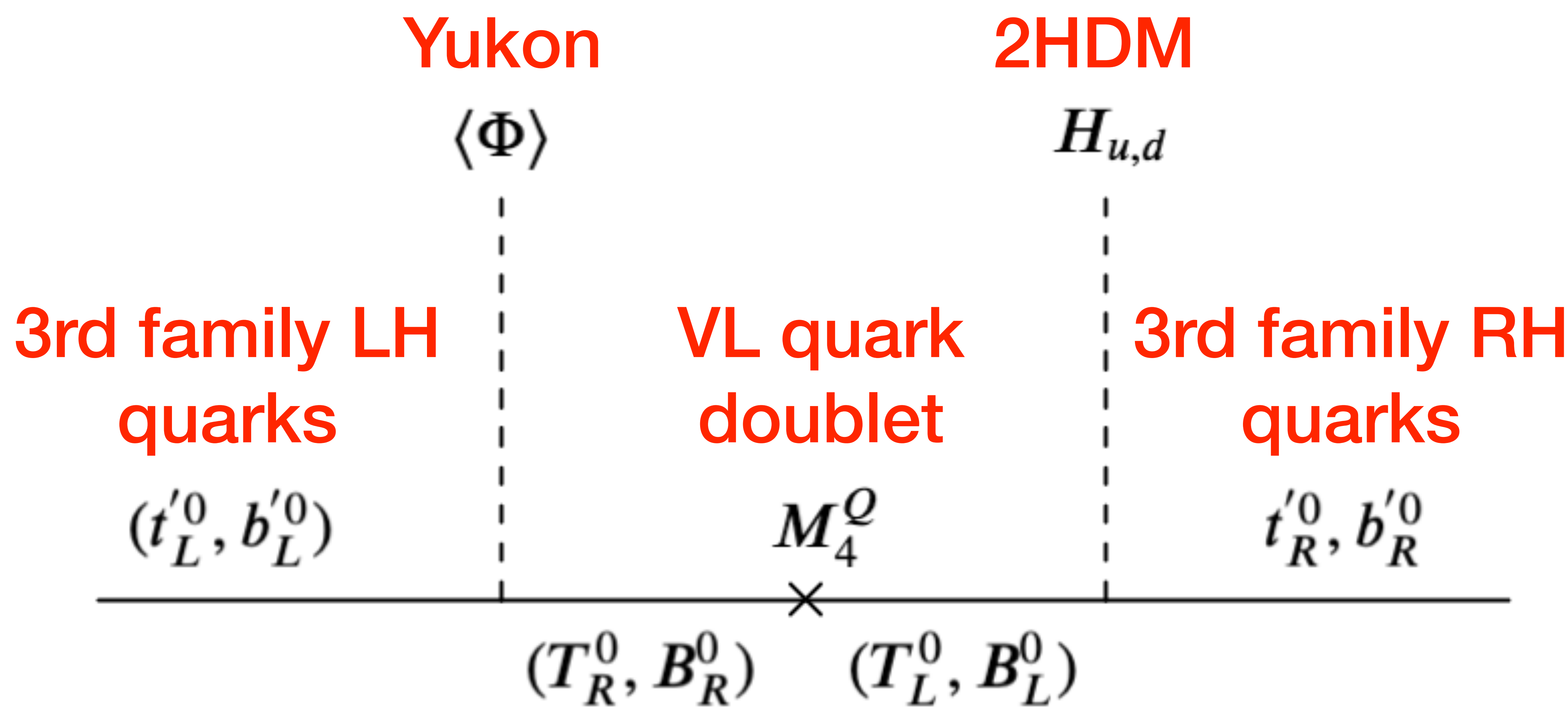
S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

LHC Phenomenology

Recall

$$\langle\phi\rangle \lesssim M_4^{L,Q} \ll M_4^{e,d} \ll M_4^{u}$$

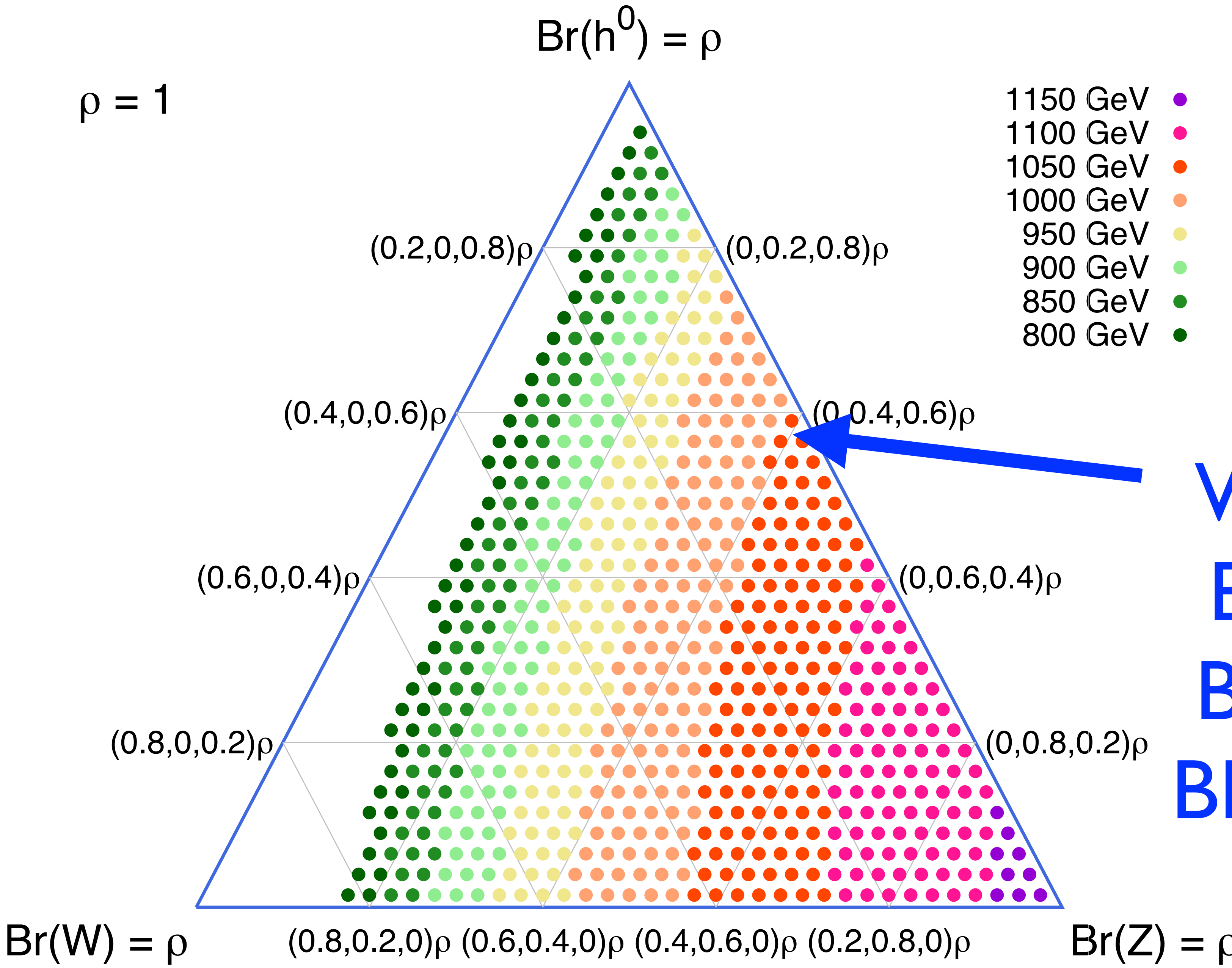
Only states relevant at LHC - consider simplified model for the origin of top and bottom Yukawa Couplings



J.A.Aguilar-Saavedra, D.E.Lopez-Fogliani and C.Munoz, JHEP06(2017)095 [arXiv:1705.02526]

Limit on T quark searches

$$\begin{pmatrix} T \\ B \end{pmatrix} \qquad M_T \approx M_B \gtrsim 1\ \text{TeV}$$



We are here

$BR(h^0 t) \sim 0.6$

$BR(Zt) \sim 0.35$

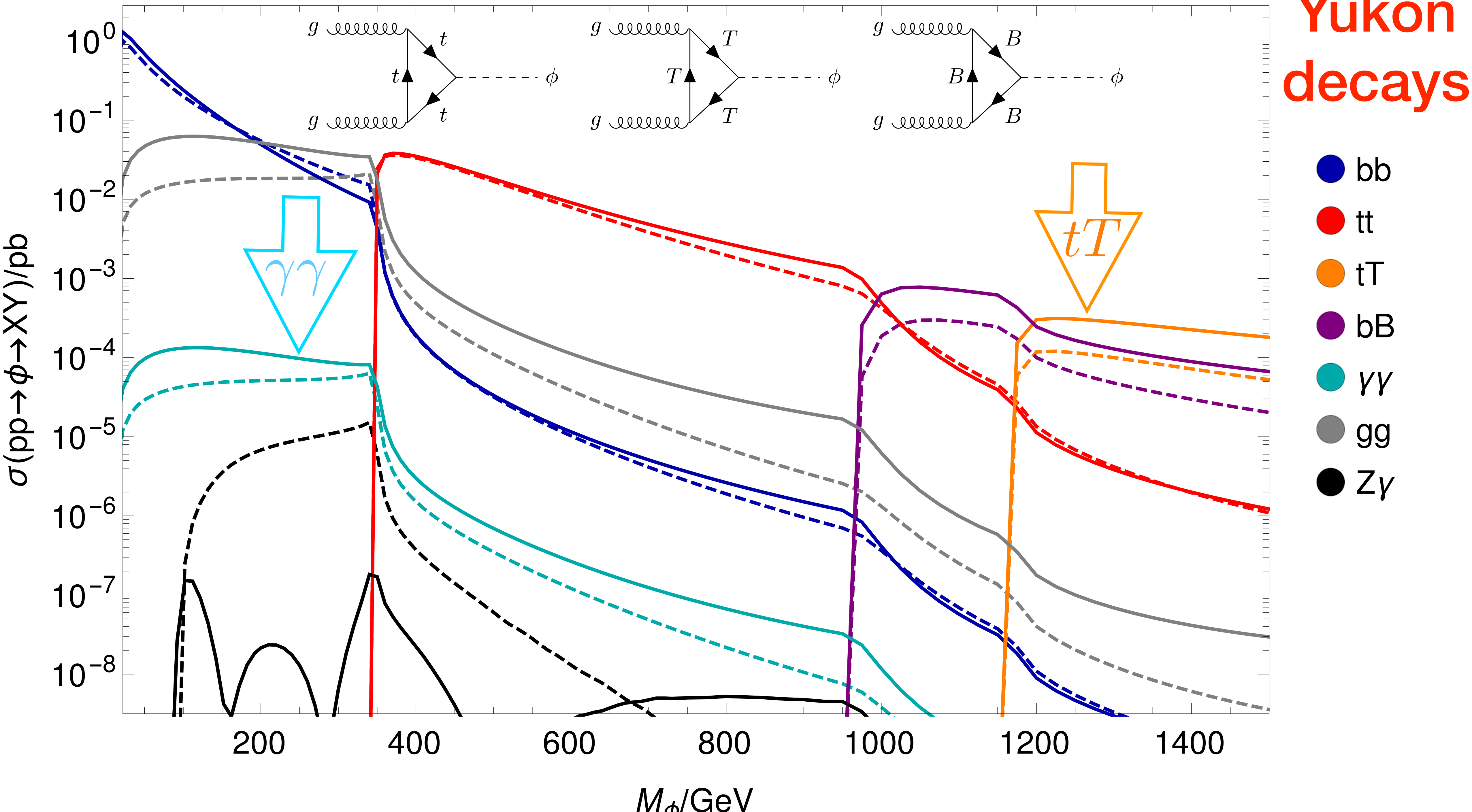
$BR(Wb) \sim 0.05$

Yukon@LHC

S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

Yukon gg production

LHC pp→ϕ→XY cross–section,
M_T=1 TeV, M_B=955.7 GeV, $M_{Z'}$=3 TeV,
g'=1, $\varphi_u=\pi$, φ_d=0, $\sqrt{s}$=14 TeV



Yukon decays

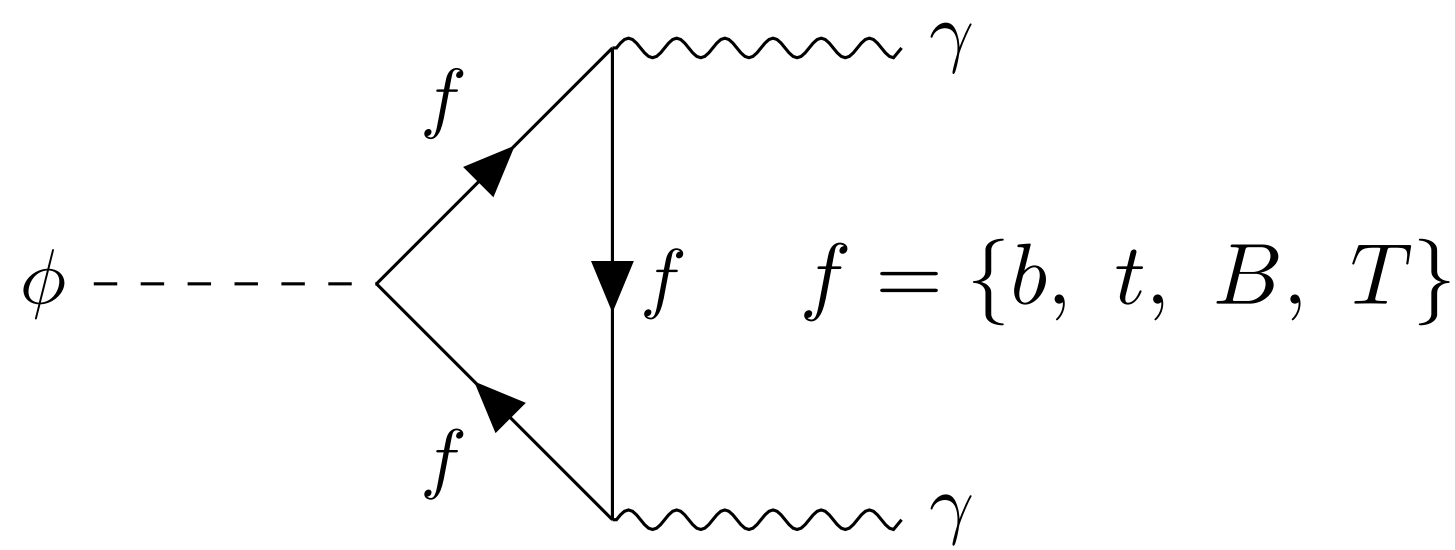
S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

Yukon@LHC

$\gamma\gamma$ channel

$M_\phi = 340$ GeV

$M_T = 1000$ GeV



$$\text{significance} \sim \frac{signal}{\sqrt{background}} \sim \frac{L \times \sigma(signal)}{\sqrt{L \times \sigma(background)}} \propto \sqrt{L}$$

Model	Experiment ($L^{\rm int} = 3000$ fb^{-1})	Significance
Gauged $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	0.66σ
$M_{Z'} = 3000$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	2.4σ
Global $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	15σ
$v_\phi = 625$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	52σ

LHC (Run 3) L_{int}= 300 fb^{-1} significance rescales to 4.7σ

Yukon 300-350 GeV could be discovered at LHC Run 3

Conclusion

- SM + 2HDM + 4th VL family + U(1)’ broken by Yukon
- Quarks/leptons U(1)’ neutral (not family symmetry)
- Effective Yukawas, quark/lepton hierarchy, small CKM mixing from heavy VL masses - dynamical, testable
- Neutrino mass in type Ib seesaw allows 1-100 GeV Dirac neutrino at SHiP/FCC-ee
- Z’ model for $R_{K^{(*)}}$ in tension - leptoquark model is OK
- VLQ doublet (T,B) at 1 TeV and 300-350 GeV Yukon in diphoton channel observable at LHC Run 3

Supplementary

M.Chianese, B.Fu and S.F.King, [arXiv:2102.07780].

• Dark Matter in Type Ib Seesaw Mechanism

A minimal type Ib seesaw model which does not involve a fourth vector-like family

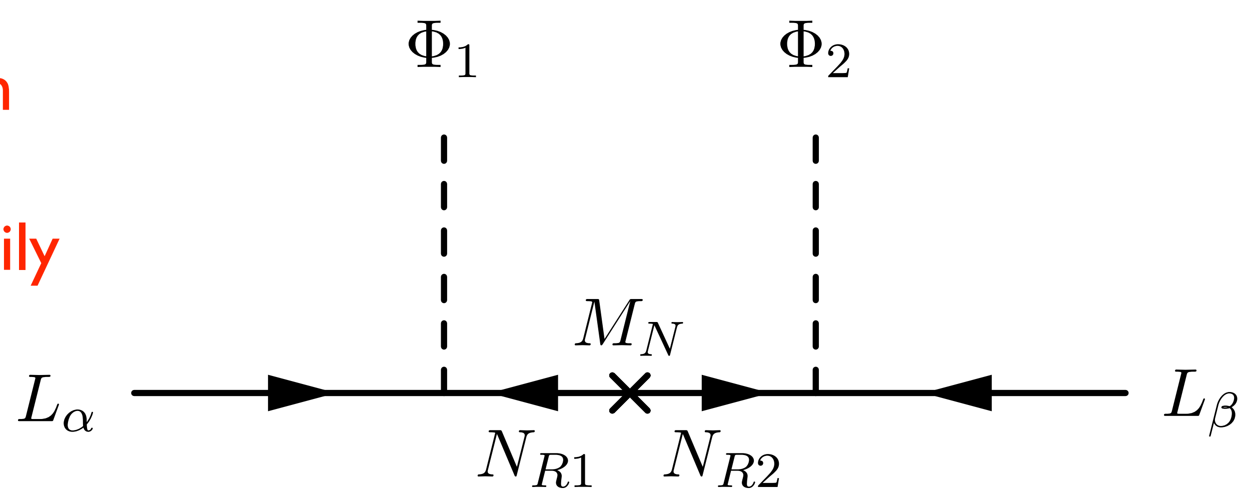


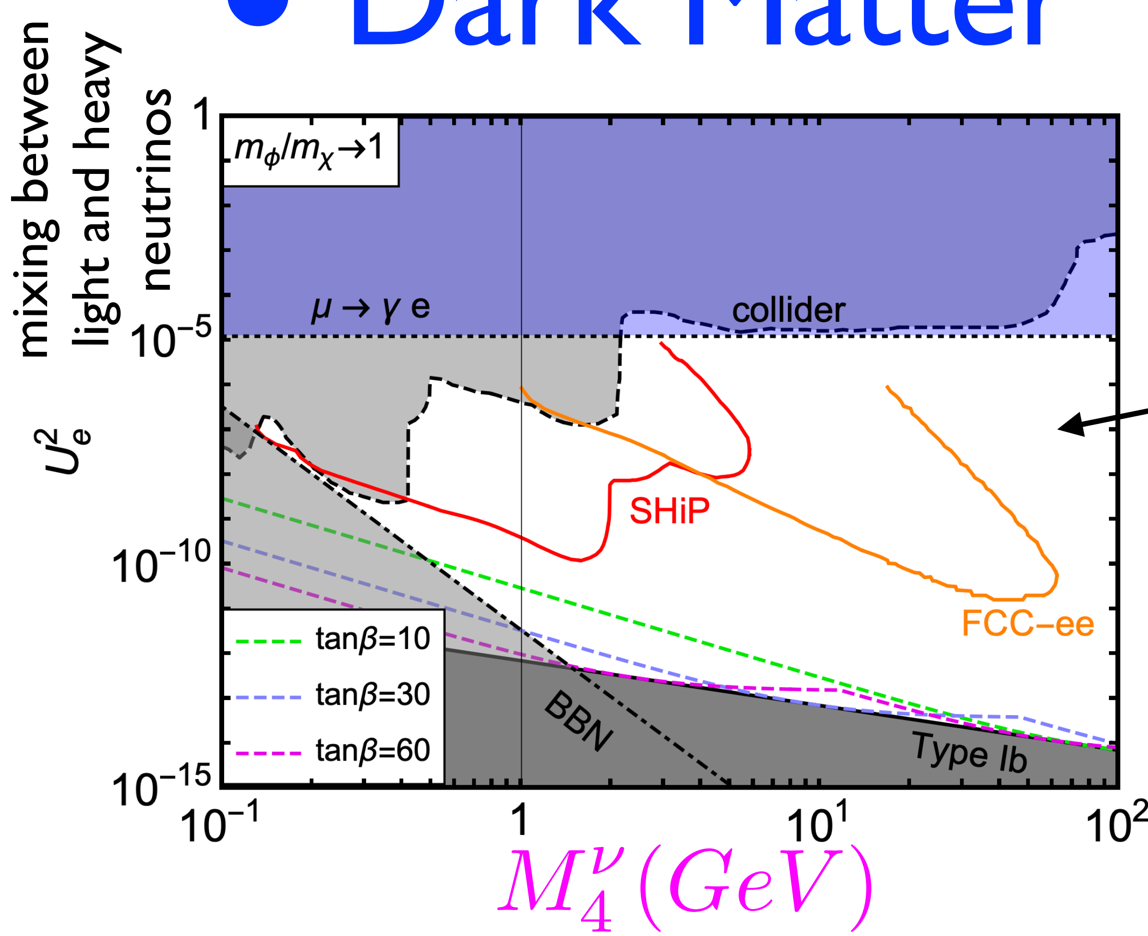
Figure 1. The type Ib seesaw mechanism involves two different Higgs doublets Φ_1 and Φ_2. The minimal model involves two right-handed neutrinos $N_{\mathrm{R}1}$ and $N_{\mathrm{R}2}$ which form a Dirac mass M_N.

Quarks and Leptons 2HDM 2RHN Dark matter

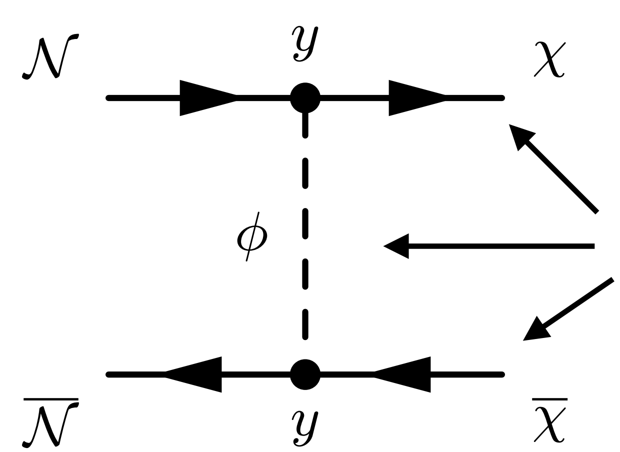
	Q_α	$u_{R\beta}$	$d_{R\beta}$	L_α	$e_{R\beta}$	Φ_1	Φ_2	$N_{\mathrm{R}1}$	$N_{\mathrm{R}2}$	ϕ	$\chi_{L,R}$
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0	0
Z_3	1	ω	ω	1	ω	ω	ω^2	ω^2	ω	ω	ω^2
Z_2	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

M.Chianese, B.Fu and S.F.King, [arXiv:2102.07780].

- Dark Matter



Freeze-in Dark Matter (white region)



Dark sector particles frozen-in

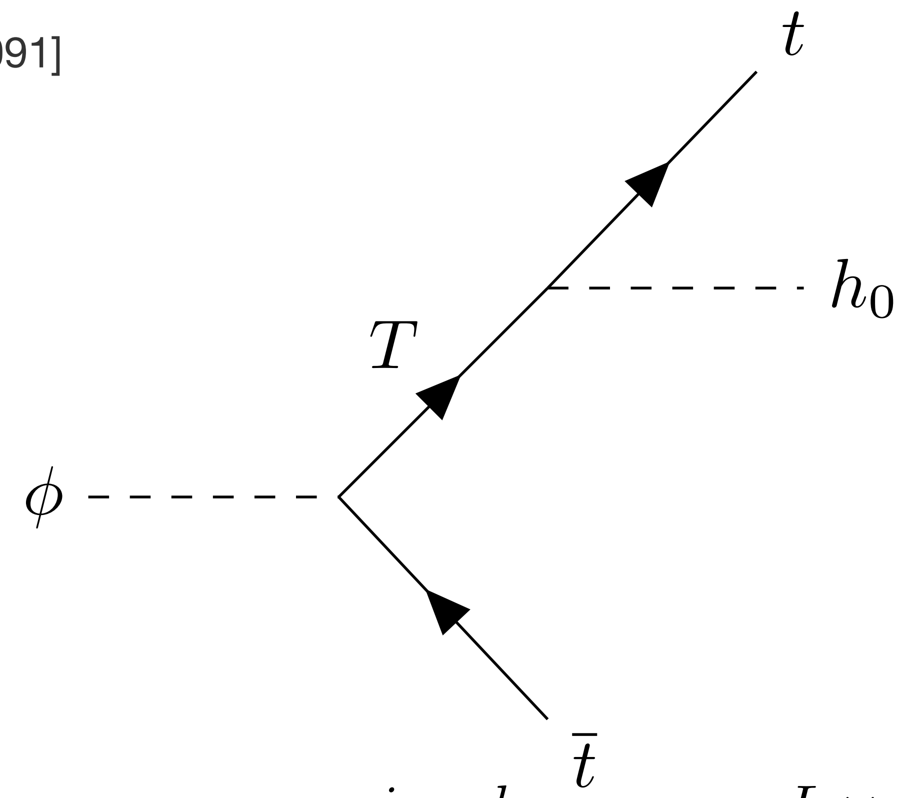
S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

Yukon@LHC

tth^0 signal

$M_\phi = 1250$ GeV

$M_T = 1000$ GeV



$$\text{significance} \sim \frac{signal}{\sqrt{background}} \sim \frac{L \times \sigma(signal)}{\sqrt{L \times \sigma(background)}} \propto \sqrt{L}$$

Model	Experiment ($L^{\text{int}} = 3000$ fb^{-1})	Significance
Gauged $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	0.080σ
$M_{Z'} = 3000$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	0.33σ
Global $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	1.6σ
$v_\phi = 625$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	8.2σ

Yukon 1250 GeV requires HE-LHC/FCC-pp

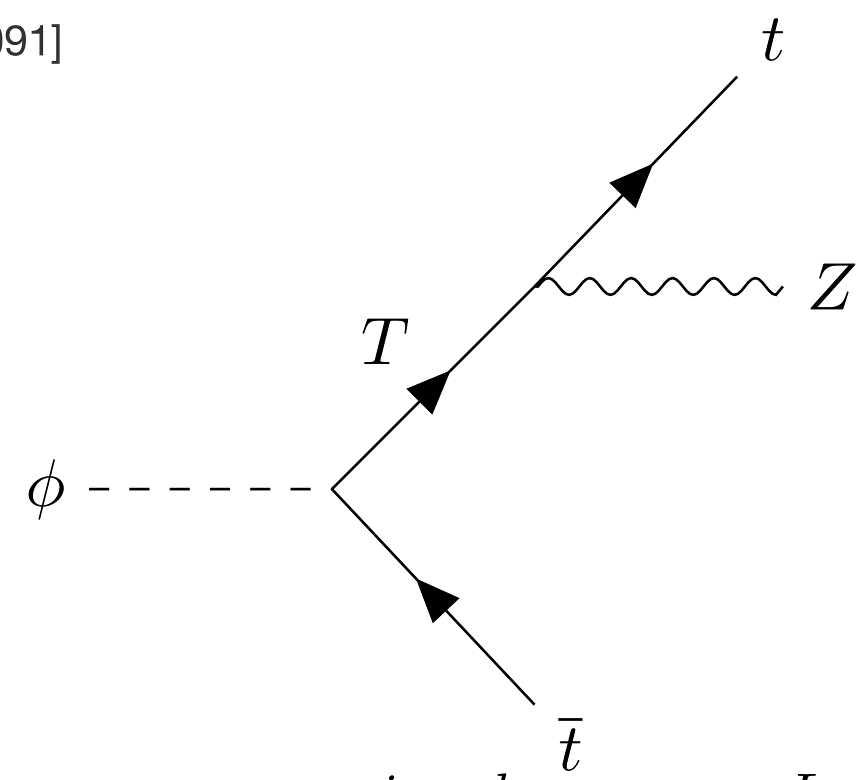
S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

Yukon@LHC

ttZ signal

$M_\phi = 1250$ GeV

$M_T = 1000$ GeV



$$\text{significance} \sim \frac{signal}{\sqrt{background}} \sim \frac{L \times \sigma(signal)}{\sqrt{L \times \sigma(background)}} \propto \sqrt{L}$$

Model	Experiment ($L^{\text{int}} = 3000\ \text{fb}^{-1}$)	Significance
Gauged $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	0.047σ
$M_{Z'} = 3000$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	0.19σ
Global $U(1)'$	HL-LHC, $\sqrt{s} = 14$ TeV	1.0σ
$v_\phi = 625$ GeV	HE-LHC/FCC, $\sqrt{s} = 33$ TeV	4.1σ

Yukon 1250 GeV requires HE-LHC/FCC-pp

S.J.D.King, S.F.King, S.Moretti and S.J.Rowley, [arXiv:2102.06091]

Signal

Channel	Energy	M_ϕ (GeV)	$\sigma_{\rm NLO}(pp \to \phi)$ (pb)		Branching Ratio	Cuts	Final Cross-Section (pb)	
			Gauge	Global			Gauge	Global
$\gamma\gamma$	$\sqrt{s} = 14$ TeV	340	0.0437	1.01	$\mathrm{BR}(\phi \to \gamma\gamma) = 0.00186$	$\epsilon = 0.81^*$	6.60×10^{-5}	0.0015
	$\sqrt{s} = 33$ TeV		0.228	5.25			0.00034	0.0078
tth^0	$\sqrt{s} = 14$ TeV	1250	0.000478	0.0110	$\mathrm{BR}(\phi \to tT \to tth^0) = 0.378$	$\epsilon(S)$	$0.00018\ \epsilon(S)$	$0.00441\ \epsilon(S)$
	$\sqrt{s} = 33$ TeV		0.00594	0.137			$0.0022\ \epsilon(S)$	$0.051\ \epsilon(S)$
ttZ	$\sqrt{s} = 14$ TeV	1250	0.000478	0.0110	$\mathrm{BR}(\phi \to tT \to ttZ) = 0.242$	$\epsilon(S)$	$0.00012\ \epsilon(S)$	$0.0028\ \epsilon(S)$
	$\sqrt{s} = 14$ TeV		0.00594	0.137			$0.0014\ \epsilon(S)$	$0.032\ \epsilon(S)$

Table 2: Table of cross-sections for Yukon ϕ production and decay in various channels, with cuts on the signal processes. Note all signals are calculated at LO, then multiplied by a k-factor of $k^{\rm NLO} = 1.7$ to get the written NLO results: $S^{\rm NLO} = S^{\rm LO} \times k^{\rm NLO}$. The parameter set used in all cases is as follows: $\{\theta^Q_{34} = \pi/4,\ \varphi_u = 0,\ \varphi_d = \pi,\ g' = 1\}$. Gauged model fixes $M_{Z'} = 3$ TeV, whereas global model fixes $v_\phi = 625$ GeV. Results for $v_\phi = 625$ are a factor $(3000/625)^2 \simeq 23$ larger than the $M_{Z'} = 3$ TeV ones in all cases, since $\sigma_{\rm NLO}(pp \to \phi) \propto v_\phi^{-2}$ and BRs are independent of v_ϕ in all channels.
*Signal cut effect on $\phi \to \gamma\gamma$ determined from fraction of SM $h^0 \to \gamma\gamma$ events observed with and without η, p_T cuts.

Background

Channel	Energy	Cuts (GeV, except η)	$\sigma_{LO}(pp \to X)$ (pb)	k-Factor	Final Cross-Section (pb)
$\gamma\gamma$	$\sqrt{s} = 14$ TeV	$\{ \lvert\eta\rvert < 2.5,\ p_T > 25$ GeV	0.0157	1.88	0.0295
	$\sqrt{s} = 33$ TeV	$336 < M_{\gamma\gamma} < 344 \}$	0.0328	1.88	0.0617
tth^0	$\sqrt{s} = 14$ TeV	$\{ 850 < M_{h^0 t} < 1150$	$0.00603^\dagger$	1.27	$0.0153 \times \epsilon(B)$
	$\sqrt{s} = 33$ TeV	$1063 < M_{tth^0} < 1438 \}$	$0.0542^\dagger$	1.27	$0.138 \times \epsilon(B)$
ttZ	$\sqrt{s} = 14$ TeV	$\{ 900 < M_{tZ} < 1100$	$0.0064^\dagger$	1.43	$0.0183 \times \epsilon(B)$
	$\sqrt{s} = 33$ TeV	$1125 < M_{ttZ} < 1375 \}$	$0.0579^\dagger$	1.43	$0.166 \times \epsilon(B)$

Table 3: Table of cross-sections and cuts on SM background processes in various channels, which will compete against the ϕ boson signal in these channels shown in the previous table, where the suggested cuts are designed to enhance the signal.
†The listed σ_{LO} results are calculated using a cut on $M_{h^0 t}$ (or M_{tZ}). To account for the alternative cut, on $M_{\bar{t}h^0}$ (or $M_{\bar{t}Z}$), one should multiply the σ_{LO} result by a factor of 2, which is included in the final cross-section.

A.E.C.Hernandez, S.F.King and H.Lee, [arXiv:2101.05819].

Muon and electron (g-2)

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10} \quad +3.5\sigma$$

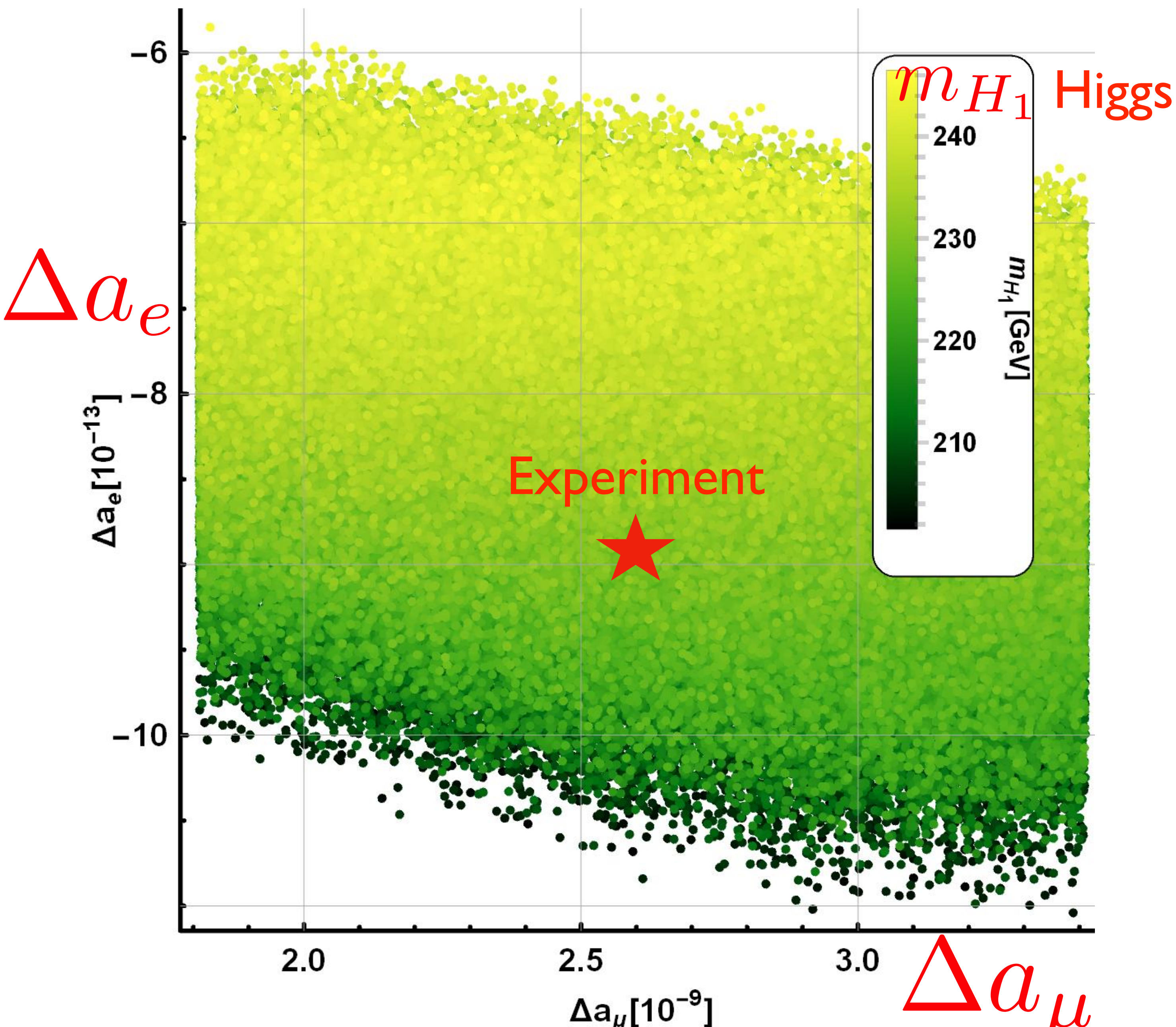
$$\Delta a_e = a_e^{\rm Exp} - a_e^{\rm SM} = (-0.88 \pm 0.36) \times 10^{-12} \quad -2.5\sigma$$

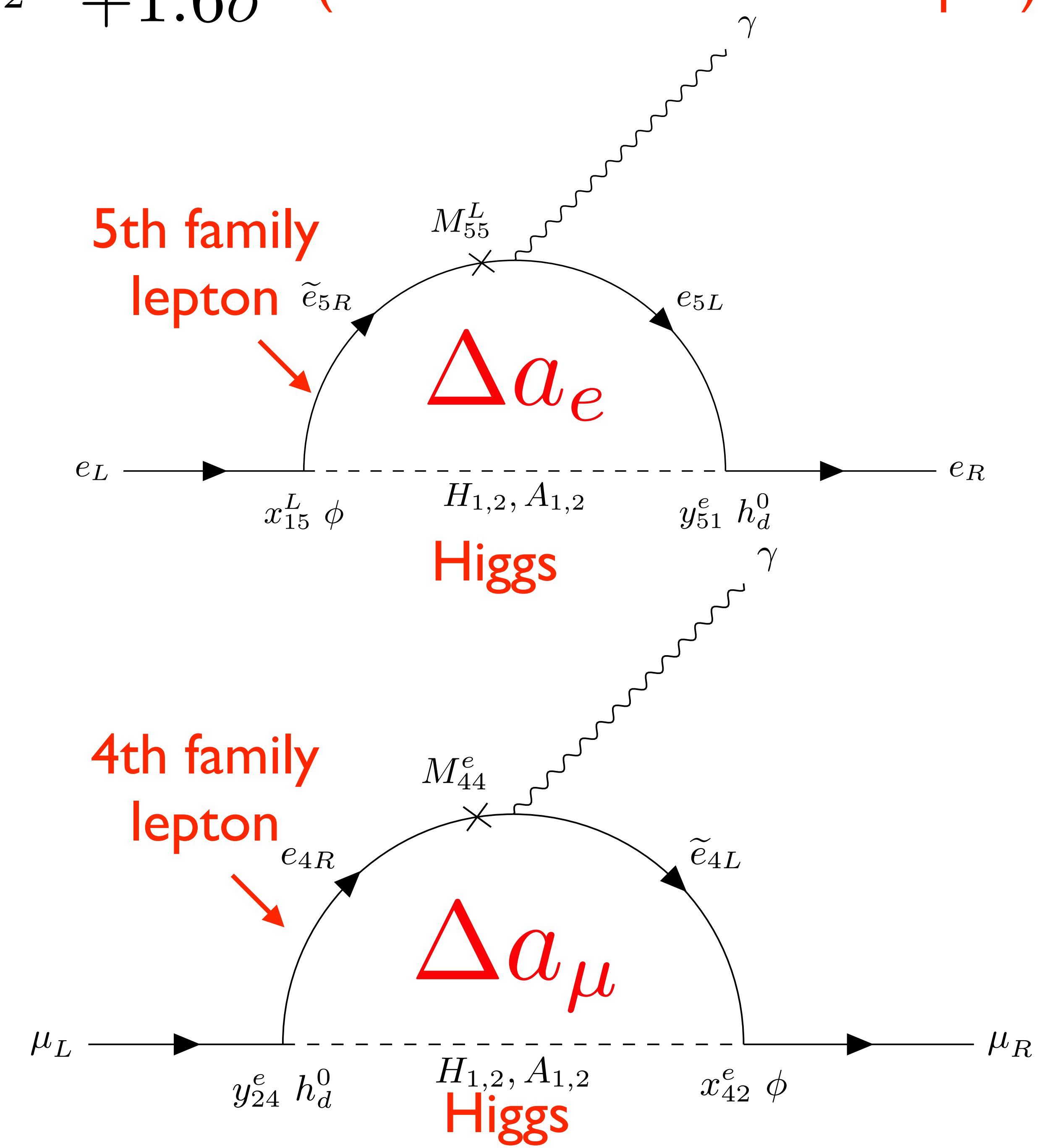
$$\Delta a_e = a_e^{\rm Exp} - a_e^{\rm SM} = (0.48 \pm 0.30) \times 10^{-12} \quad +1.6\sigma$$

Experimental discrepancy

(assumed in our paper)

(recent measurement of alpha)





A.E.C.Hernandez, S.F.King and H.Lee, [arXiv:2101.05819].

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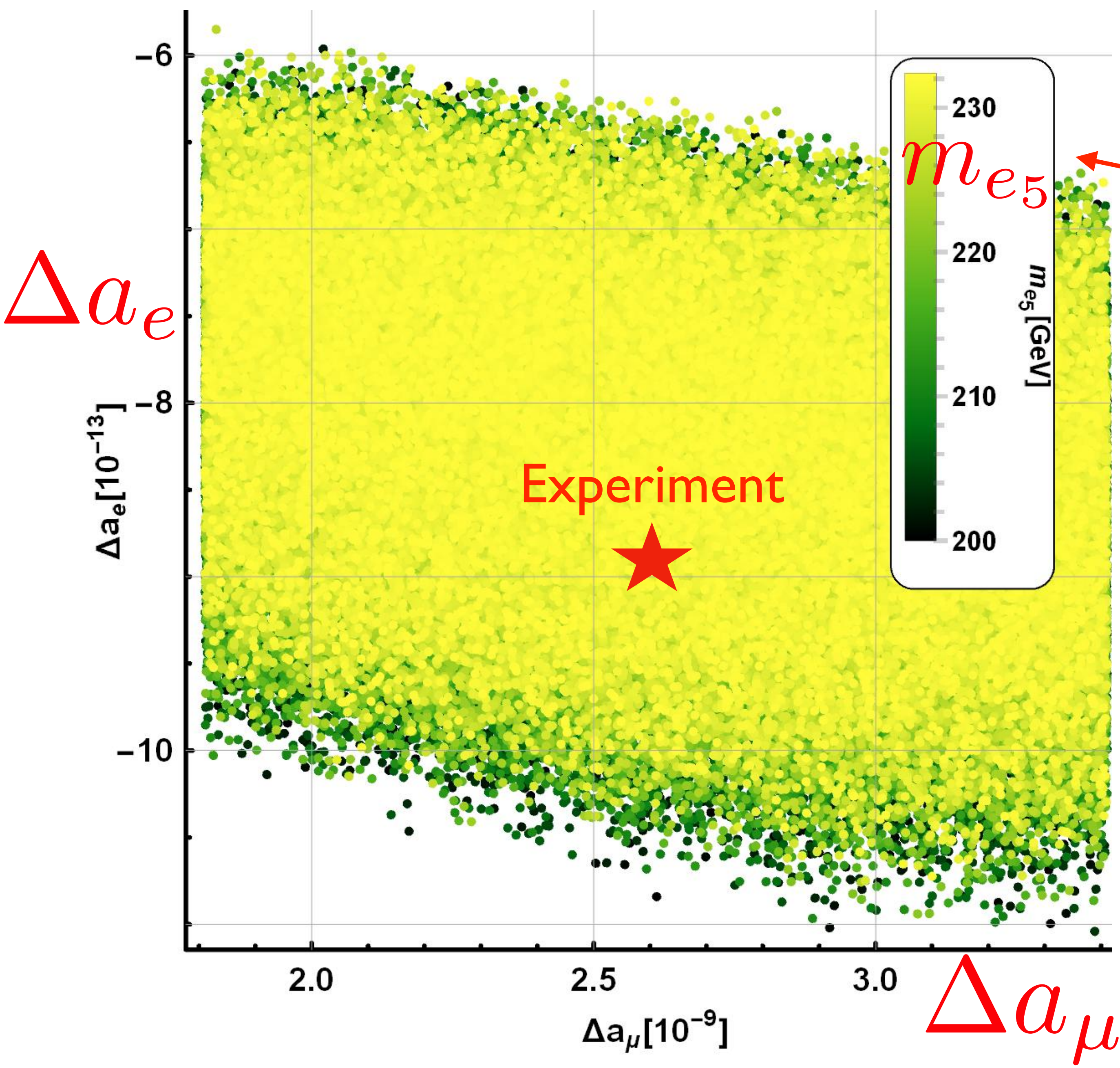
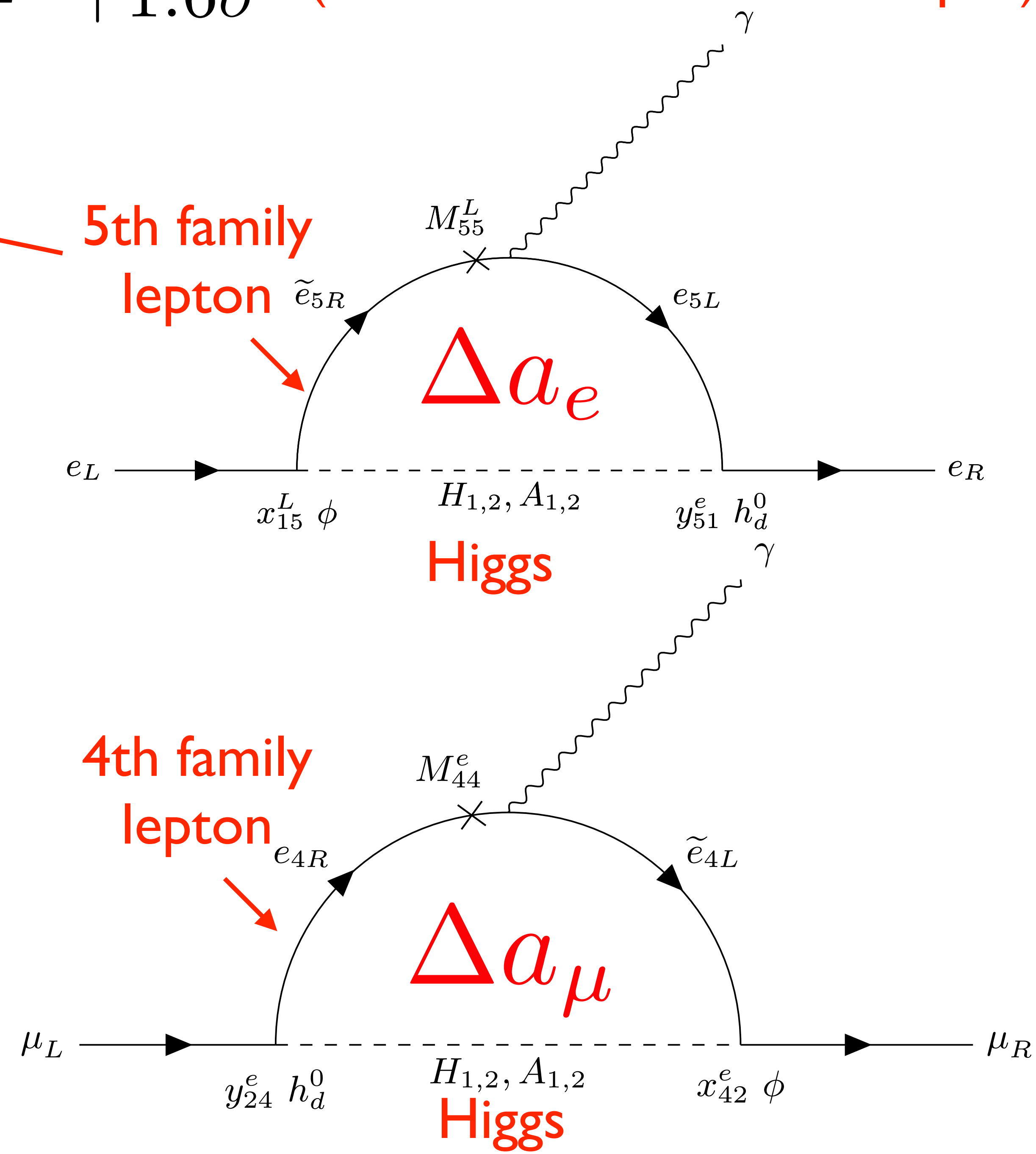
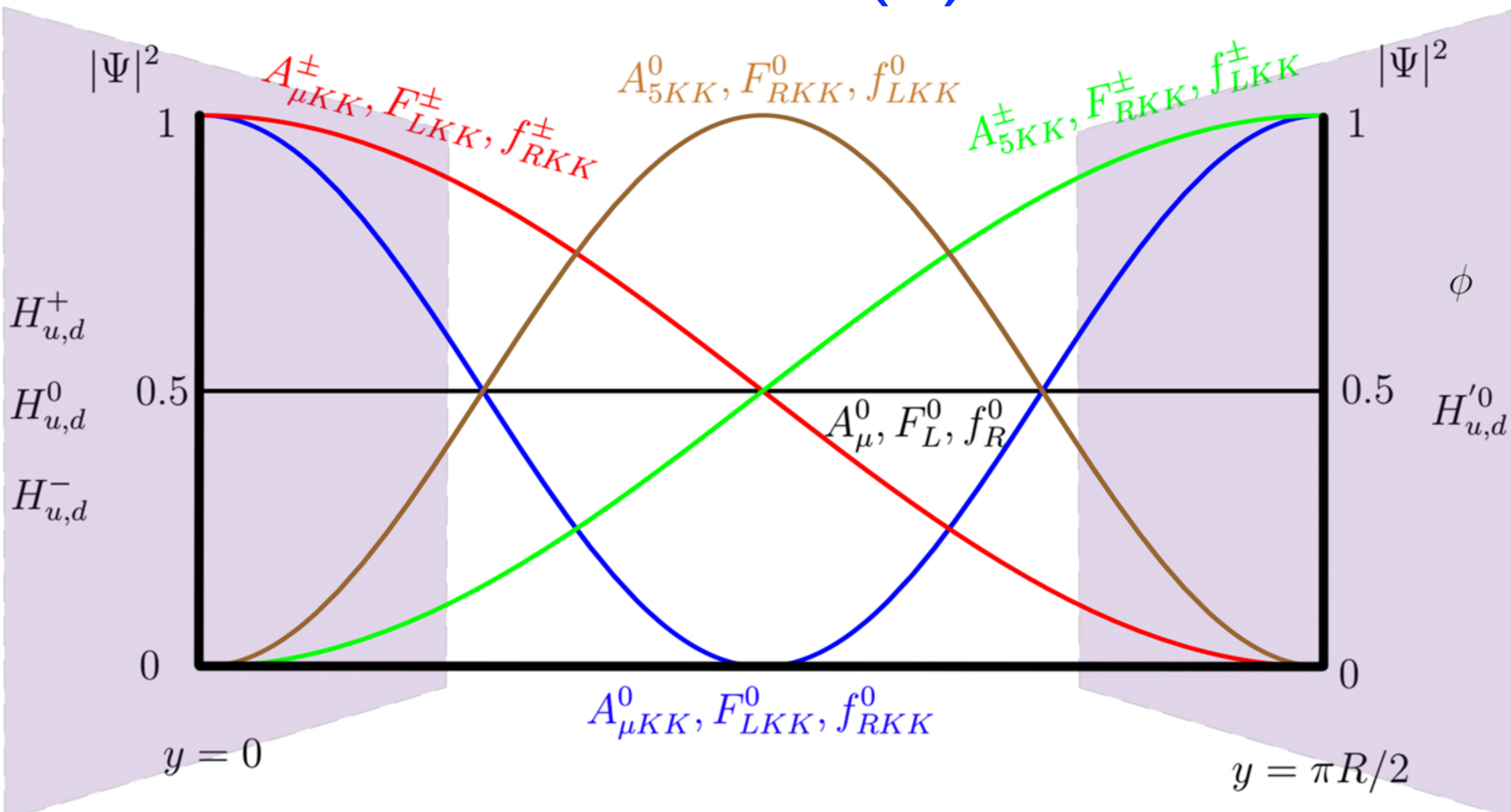




F.J.De Anda and S.F.King, JHEP03(2021)078 [arXiv:2010.00100]

VL fermions and U(1)’ from a 5d SM



- Quarks and leptons are SO(3) triplets in 5d bulk
- SO(3) broken to U(1)’ under $S^1/(Z_2 x Z_2)$
- First KK excitation gives 3 Vector-like families