

Neutrino Mass Model and Its Link to Flavor Anomalies

Anil Thapa

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UNIVERSITY of VIRGINIA

- In Standard Model $M_\nu = 0$. But, ν flavor mix. $\nu_{aL} \leftrightarrow \nu_{bL}$

$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \implies M_\nu \neq 0 \implies \text{New Physics beyond SM}$

$$U_{PNMS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

ν mass

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	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)		NuFit 5.1
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	
$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$	
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.87$	
$\sin^2 \theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \rightarrow 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \rightarrow 0.623$	
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \rightarrow 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \rightarrow 52.1$	
$\sin^2 \theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \rightarrow 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \rightarrow 0.02434$	
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \rightarrow 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.98$	
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \rightarrow 405$	287^{+27}_{-32}	$192 \rightarrow 361$	
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \rightarrow +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \rightarrow -2.413$	

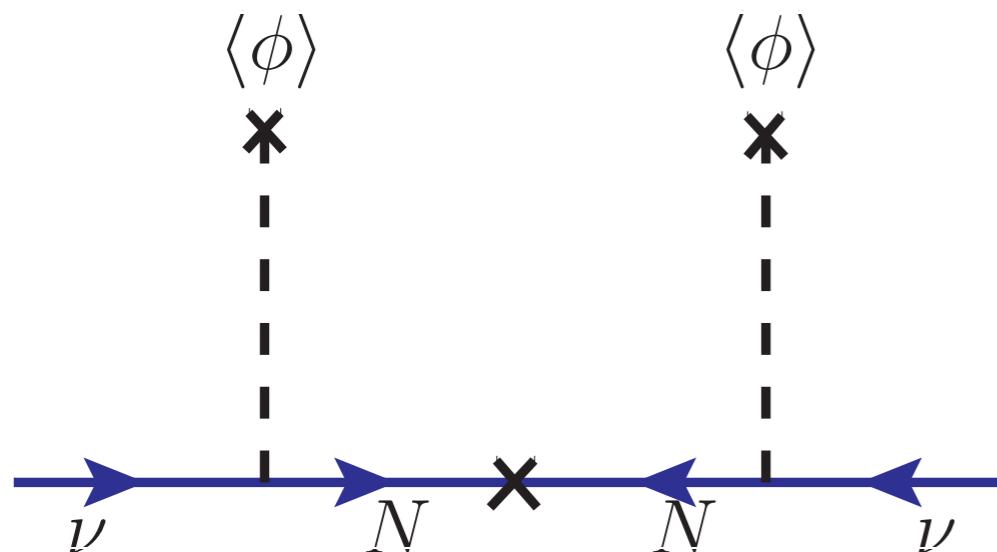


Seesaw Paradigm

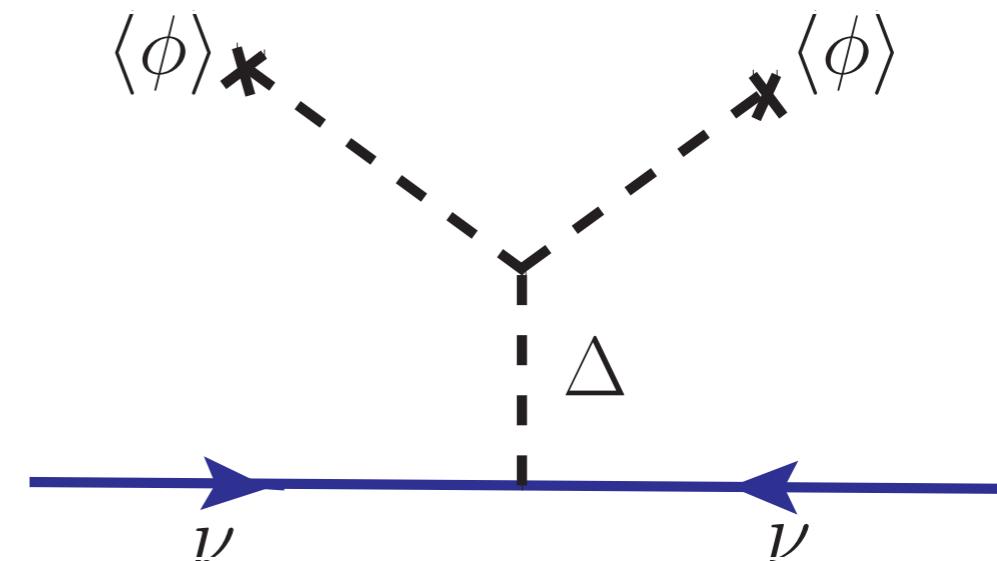
- Schemes for neutrino masses and mixings
 - Tree-level Seesaw mechanism
 - Radiative schemes

Seesaw Paradigm

- Schemes for neutrino masses and mixings
 - Tree-level Seesaw mechanism
 - Radiative schemes
- Light neutrino mass is induced via Weinberg's dim-5 operator, $LL\phi\phi$
- Large Majorana mass scale Λ to suppress the neutrino mass via $\frac{\langle\phi\rangle^2}{\Lambda}$



Type I / Type III :
 ν - mass induced from fermion exchange
 $N^1 \sim (1,1,0) \quad N^3 \sim (1,3,0)$

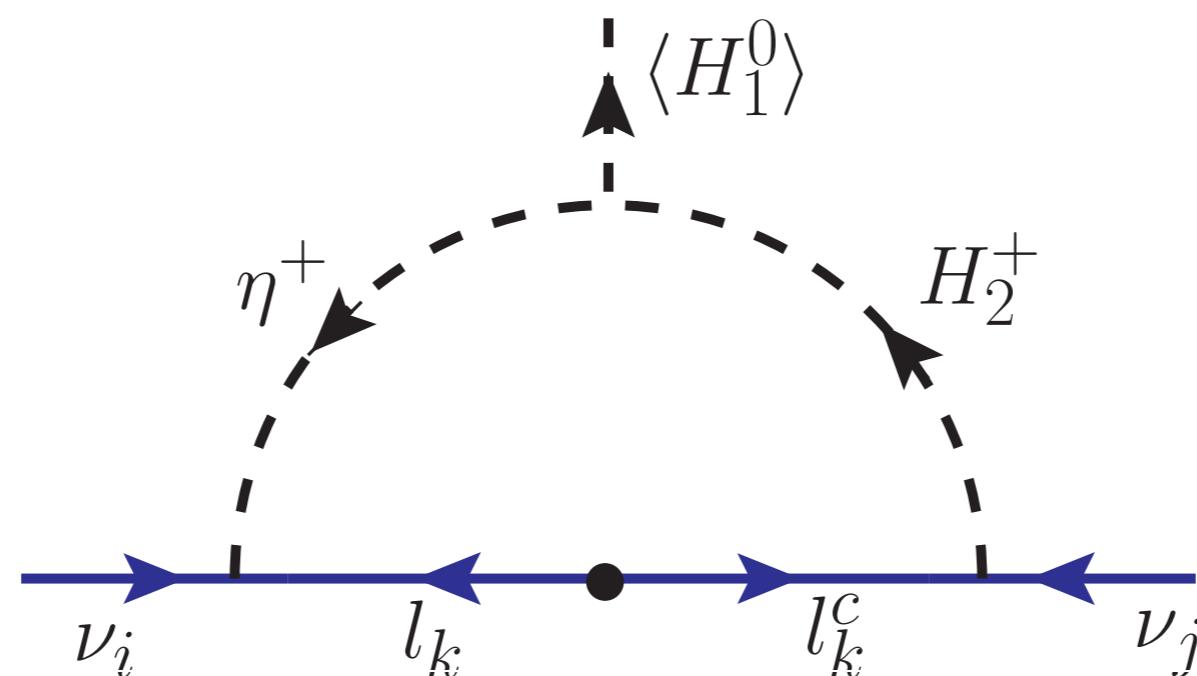


Type II :
 ν - mass induced from scalar exchange
 $\Delta \sim (1,3,1)$

- The scale of new physics can be rather high $\sim 10^{14}$ GeV

Radiative ν mass generation

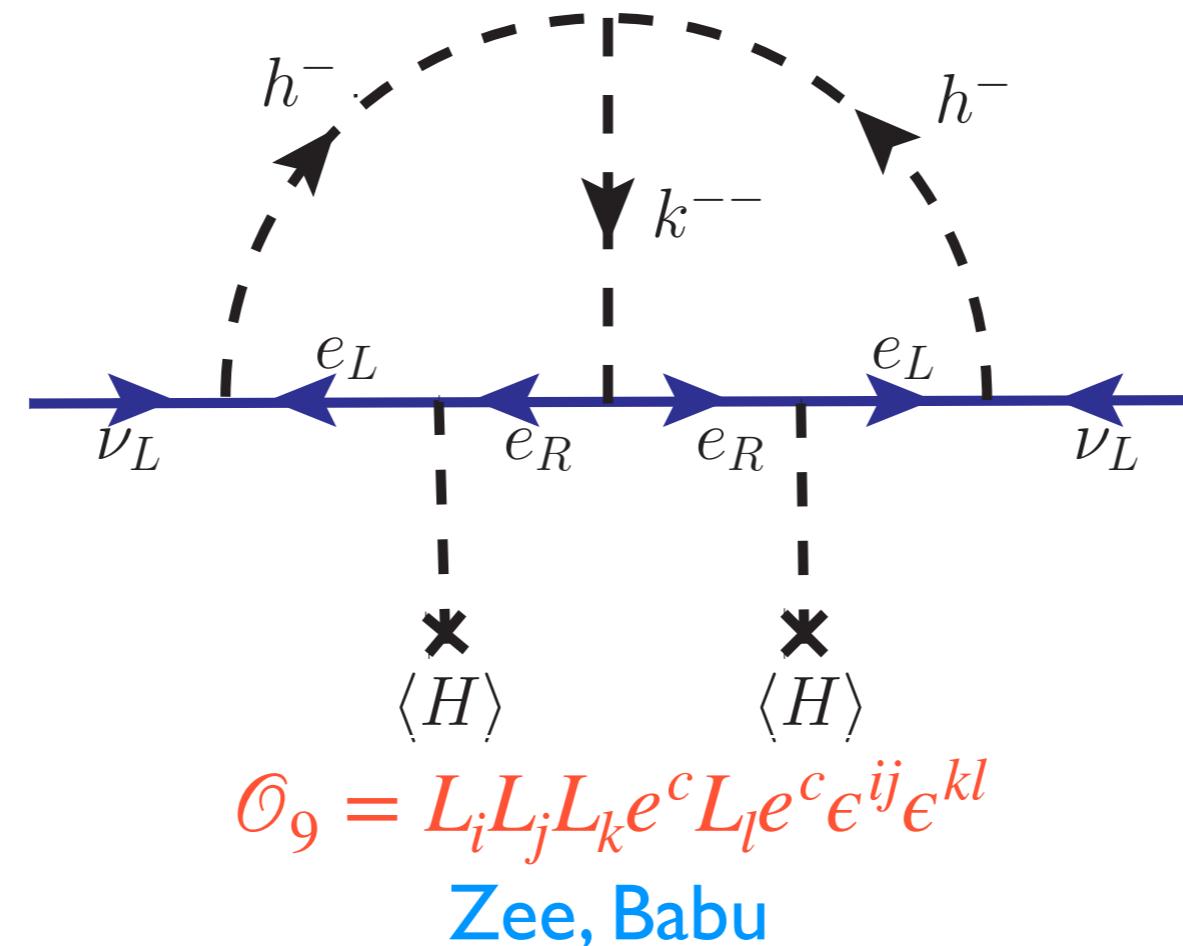
- Neutrino masses are **zero at tree level**: ν_R may be absent
- Small, finite masses are generated as **quantum corrections**
- Typically involves exchange of two scalars **leading to lepton number violation**
- Simple realization is the **Zee Model**, which has a second **Higgs doublet** and a **charged singlet**



- **Smallness of neutrino mass** is explained via **loop** and **chiral suppression**
- **New physics** in this framework may lie at the **TeV scale**

Type I radiative mechanism

- Obtained from effective $d = 7, 9, 11\dots$ operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators



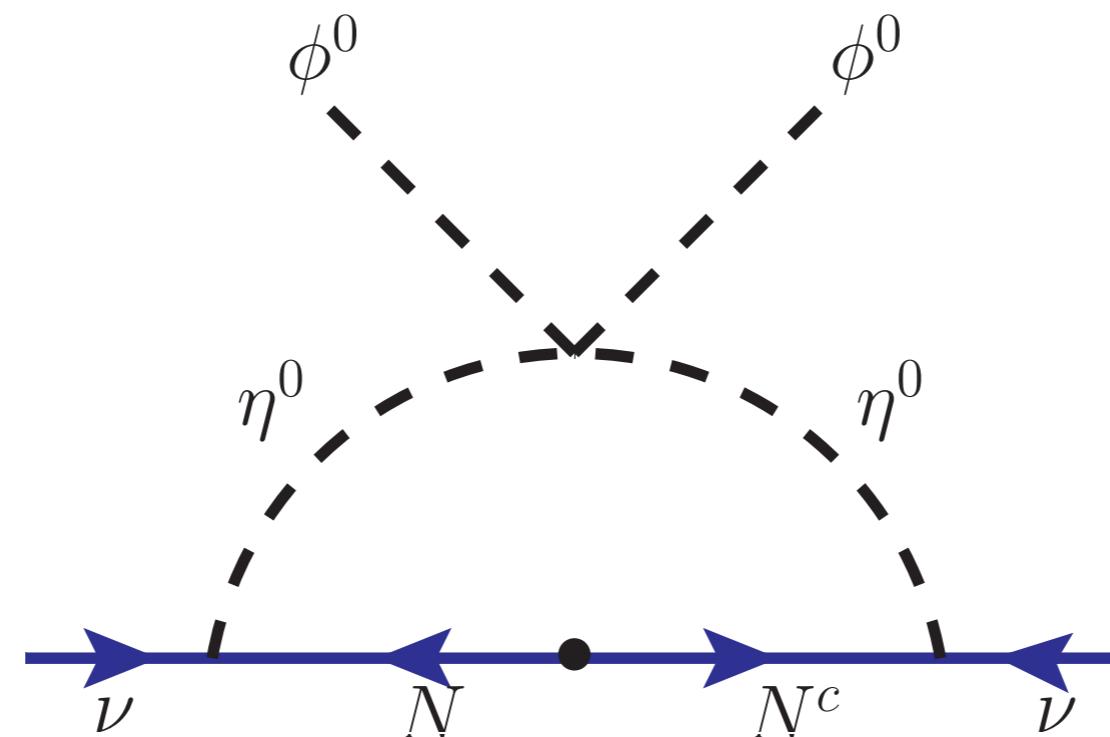
Classification : Babu, Leung (2001)

Cai, Herrero-Gracia, Schmidt, Vicente, Volkas (2017)

Babu, Dev, Jana, AT (2020)

Type II radiative mechanism

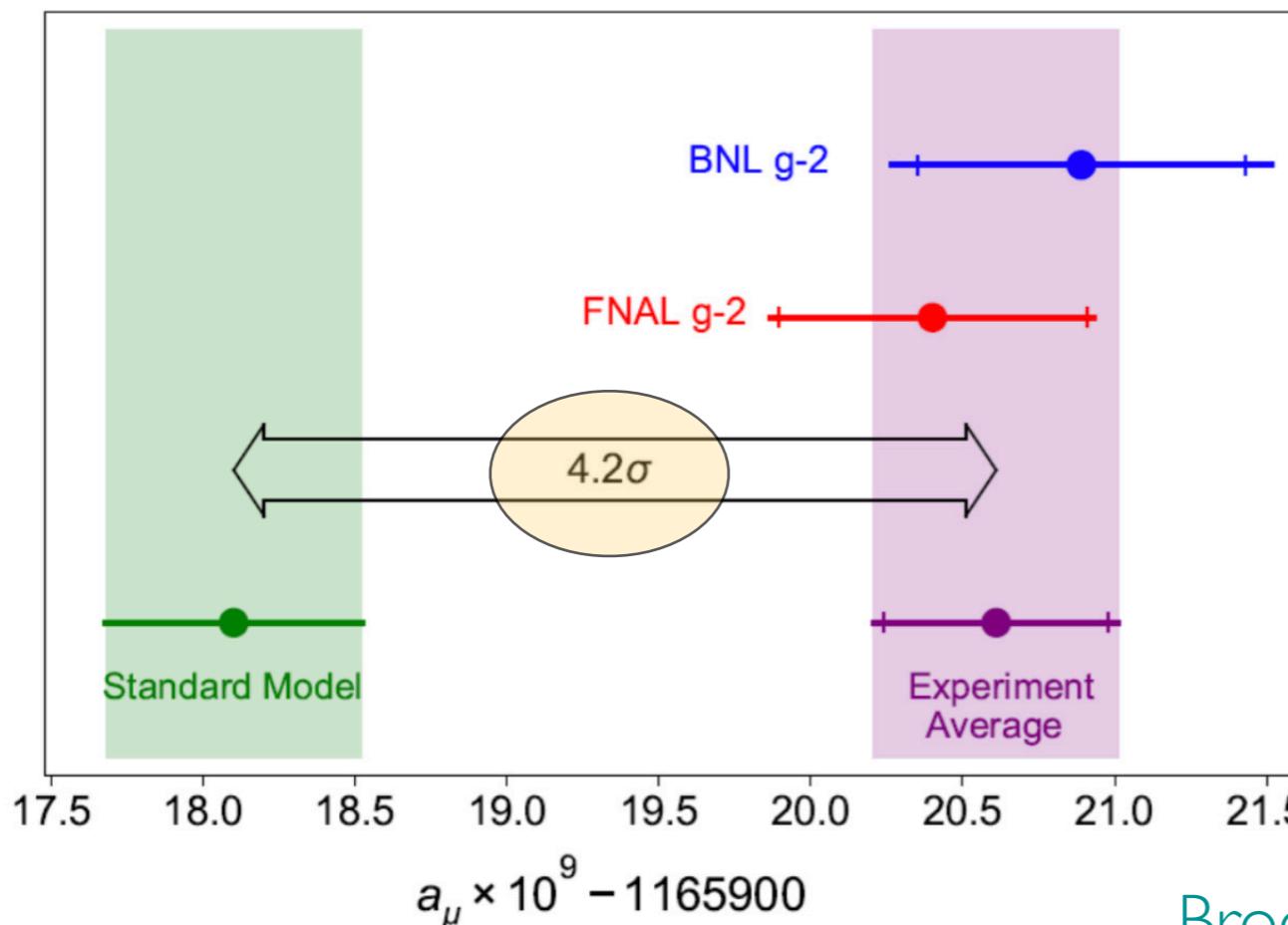
- No Standard Model particle inside the loop
- Cannot be cut to generate $d = 7, 9, \dots$ operators
- Scotogenic model is an example



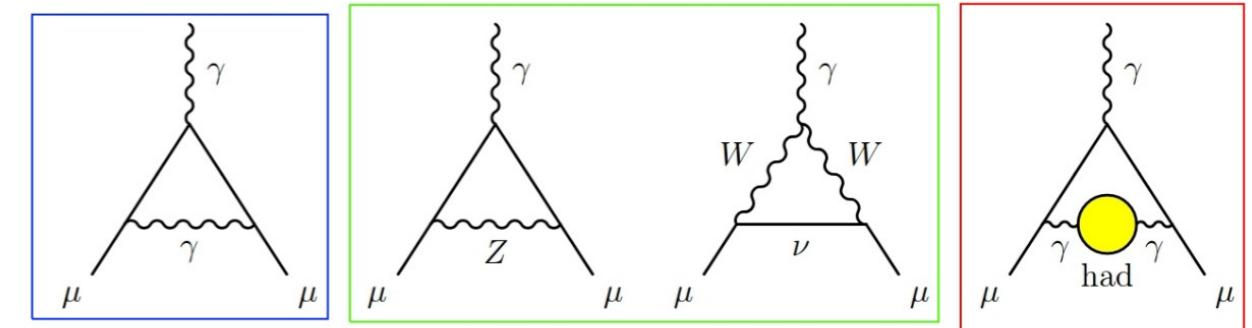
- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics

Ma (2006)

- Intrinsic magnetic property of a lepton is characterized by dimensionless number, called **g-factor** $H = -\vec{\mu} \cdot \vec{B}$, $\vec{\mu} = g \frac{e}{2m} \vec{s}$
- Anomaly, $a_\mu \equiv (g_\mu - 2)/2$, is a consequence of quantum nature of elementary particles. R. Kusch and H. M. Foley 1948, J. Schwinger 1948
- The Standard Model contribution to the lepton $g - 2$:



$$a_\ell = a_\ell(\text{QED}) + a_\ell(\text{weak}) + a_\ell(\text{hadron})$$



$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}.$$

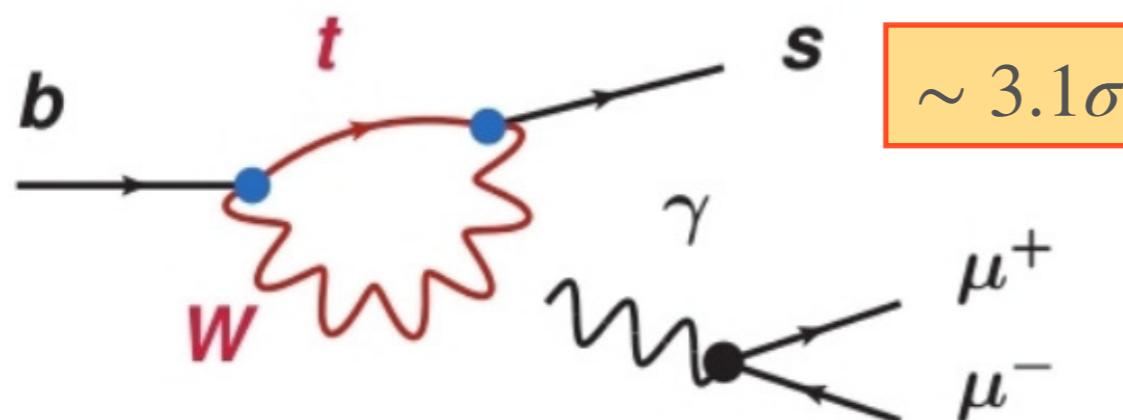
Brookhaven (2006); Fermilab (2021)

$b \rightarrow s$ anomalies

Observables: R_K and R_{K^\star}

Neutral current

1-loop in the SM



$$R_{K^{(\star)}} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^{(\star)} \mu^+ \mu^-)}{\Gamma(\bar{B} \rightarrow \bar{K}^{(\star)} e^+ e^-)}$$

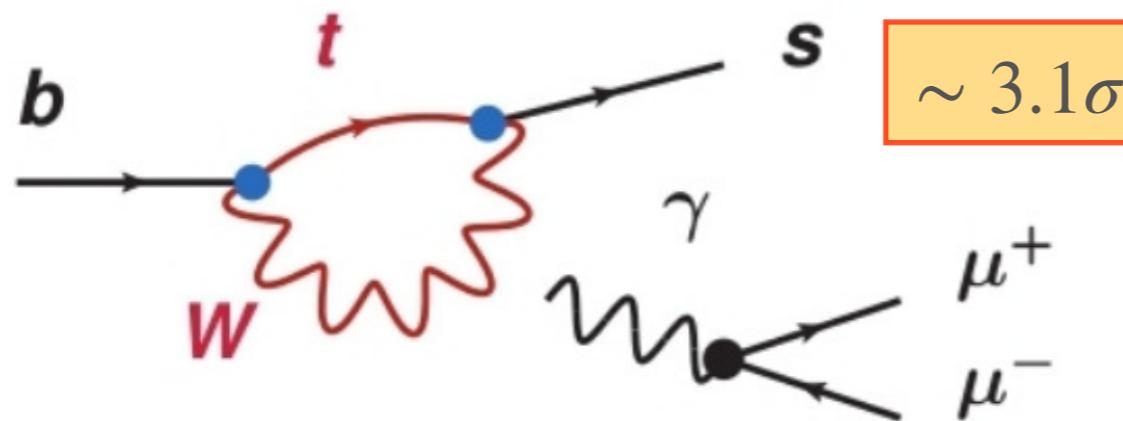
The New Physics can be heavy

$b \rightarrow s$ anomalies

Observables: R_K and R_{K^*}

Neutral current

1-loop in the SM



$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}e^+e^-)}$$

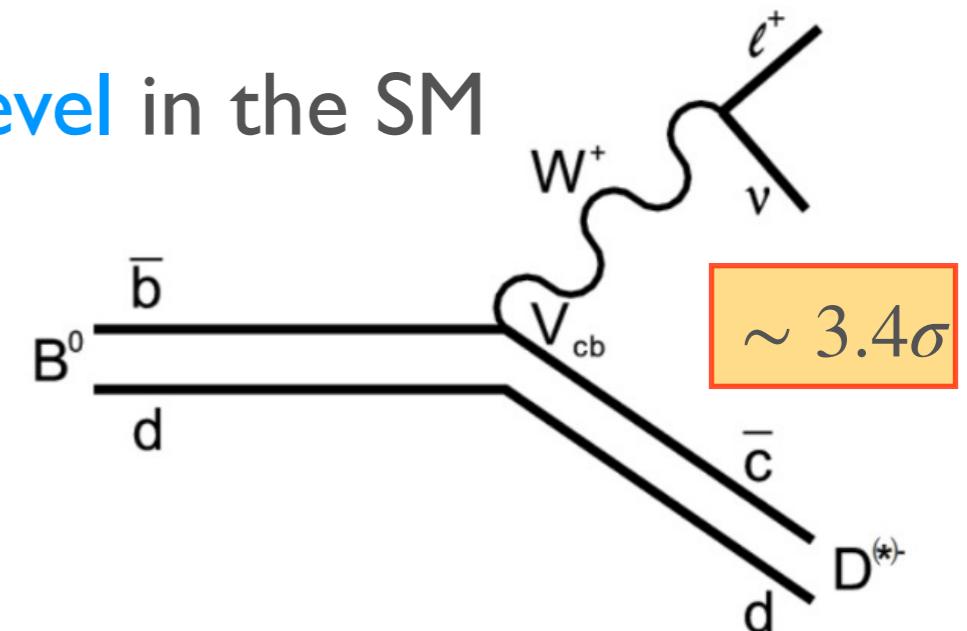
The New Physics can be **heavy**

$b \rightarrow c$ anomalies

Observables: R_D and R_{D^*}

Charged current

Tree-level in the SM



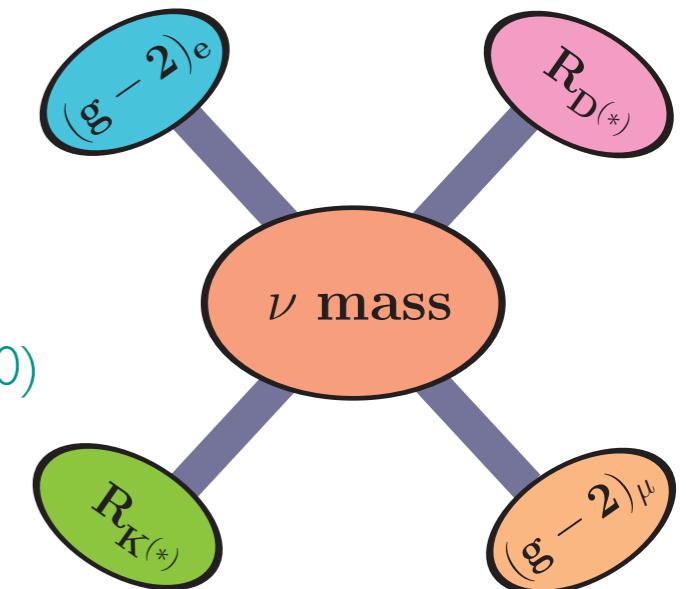
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \rightarrow D^{(*)}\tau\nu)}{\Gamma(\bar{B} \rightarrow D^{(*)}\ell\nu)}$$

The New Physics must be **light**

>> Construct a **Neutrino mass model** with **New Physics at TeV scale** that can resolve $R_{K^{(*)}}$, $R_{D^{(*)}}$ and $(g - 2)_\ell$ the following and simultaneously fit neutrino oscillation data: (Δm_{21}^2 , Δm_{31}^2 , $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{12}$, δ_{CP})

If confirmed: Implications for **New Physics**

- **Collider Phenomenology!**
- $\Delta a_\mu \iff h \rightarrow \mu\mu$ and $h \rightarrow \tau\tau$ (Crivellin, Mueller, Saturnino, 2020)

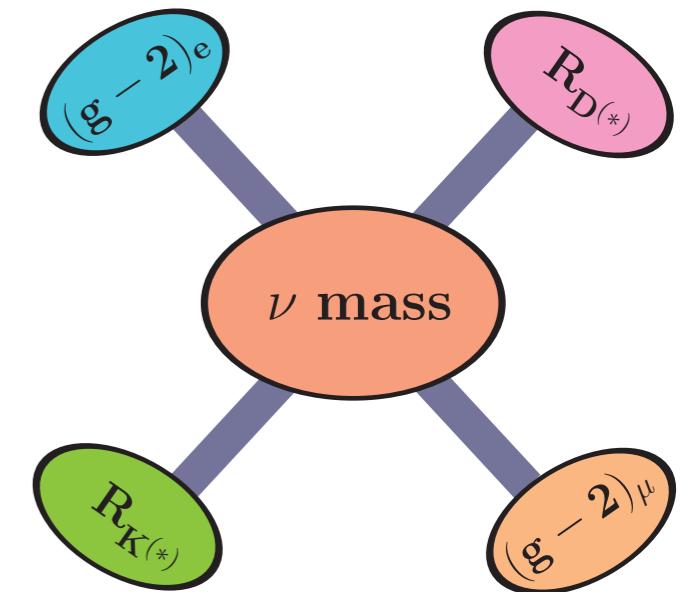


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Framework for Anomalies

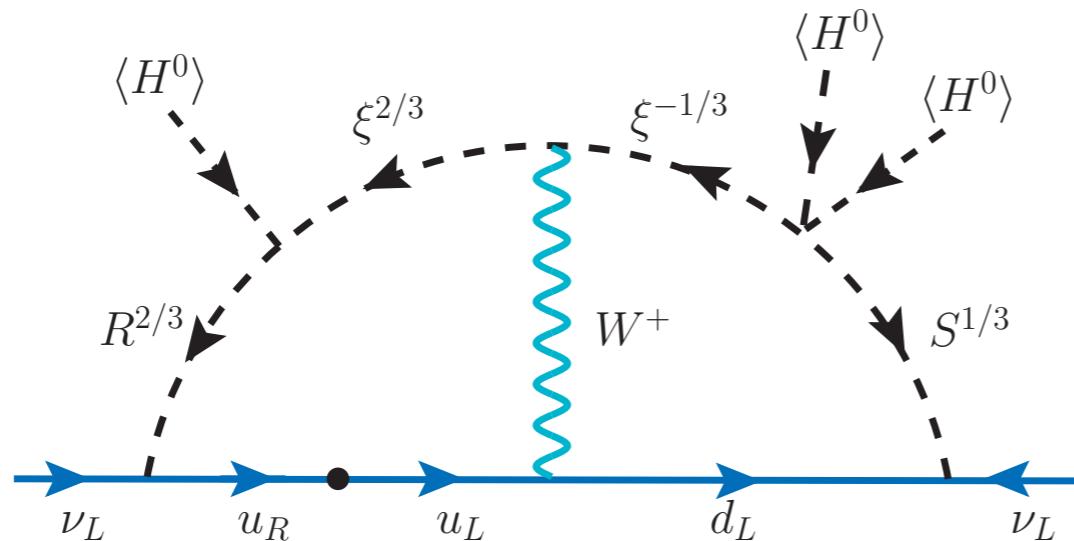
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}} \& R_{D^{(*)}}$
S_3 $(\bar{3}, 3, 1/3)$	✓	✗	✗
S_1 $(\bar{3}, 1, 1/3)$	✗	✓	✗
R_2 $(3, 2, 7/6)$	✗	✓	✗

- The **same R_2 and S_1 LQ** also induce muon $(g - 2)_\mu$
- A **pair of LQs** can generate **neutrino masses**
- Flavor structure is **very constrained**
- Framework can be **tested at LHC** as well as in processes such as $\tau \rightarrow \mu\gamma$

$SU(3)_C \times SU(2)_L \times U(1)_Y$ with an extended scalar sector

Category	Model	Fields	Loop?	Ref.
<i>Class-I</i>	Model-I	$S_1(\bar{3}, 1, 1/3)$ $\omega(\bar{6}, 1, 2/3)$	two-loop	[Babu, Leung, '01] [Kohda, Sachdeva, Waite, '19]
	Model-II	$S_3(\bar{3}, 3, 1/3)$ $\omega(\bar{6}, 1, 2/3)$	two-loop	[Babu, Leung, '01]
<i>Class-II</i>	Model-III	$S_1(\bar{3}, 1, 1/3)$ $\tilde{R}_2(3, 2, 1/6)$	one-loop two-loop	[Dorsner, Fajfer, Košnik, '17] [Catà, Mannel, '19] [Babu, Julio, '10]
	Model-IV	$S_3(\bar{3}, 3, 1/3)$ $\tilde{R}_2(3, 2, 1/6)$	one-loop	[Dorsner, Fajfer, Košnik, '17]
<i>Class-III</i>	Model-V	$R_2(3, 2, 7/6)$ $S_3(\bar{3}, 3, 1/3)$ $\chi(3, 1, 2/3)$	one-loop	[Saad, AT, '20]
	Model-VI	$R_2(3, 2, 7/6)$ $S_3(\bar{3}, 3, 1/3)$ $\Delta(1, 4, 3/2)$	one-loop	[Popov, Schmidt, White, '19] [Babu, Dev, Jana, AT, '20]
	Model-VII	$S_1(\bar{3}, 1, 1/3)$ $R_2(3, 2, 7/6)$ $\xi(3, 3, 2/3)$	two-loop	[Julio, Saad, AT, '22]

Model VII



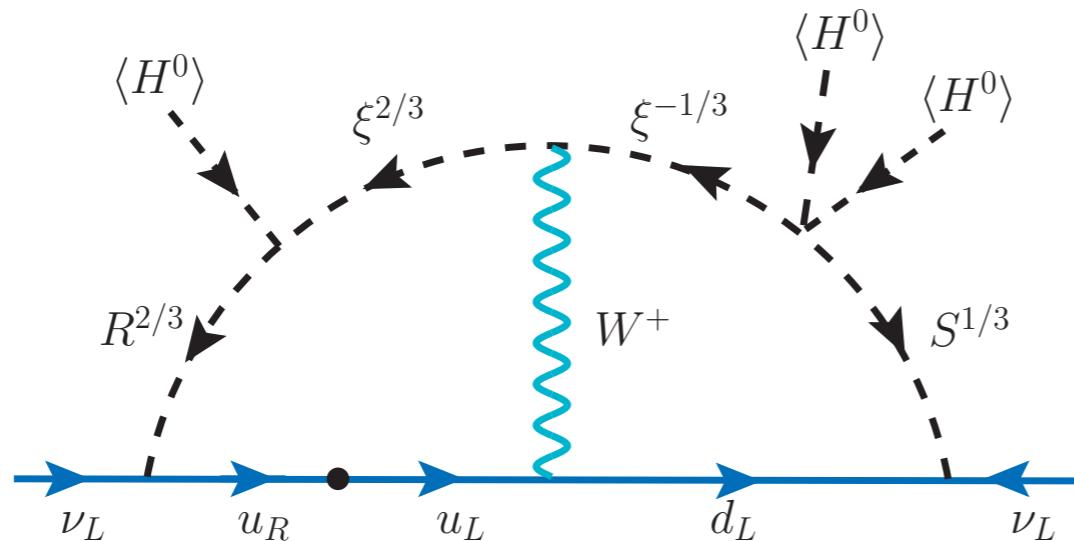
$$R_2 = \begin{pmatrix} R^{5/3} \\ R^{2/3} \end{pmatrix} \quad S_1 = S^{1/3}$$

$$\xi = \begin{pmatrix} \frac{\xi^{2/3}}{\sqrt{2}} & \xi^{5/3} \\ \xi^{-1/3} & -\frac{\xi^{2/3}}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{M}_\nu = \frac{3g^2}{\sqrt{2}(16\pi^2)^2} I_0 \left(2 (y^L)^T M_u f^L + M_\ell (y^R)^T f^L - M_\ell (f^R)^T y^L \right)$$



Model VII



$$R_2 = \begin{pmatrix} R^{5/3} \\ R^{2/3} \end{pmatrix} \quad S_1 = S^{1/3}$$

$$\xi = \begin{pmatrix} \frac{\xi^{2/3}}{\sqrt{2}} & \xi^{5/3} \\ \xi^{-1/3} & -\frac{\xi^{2/3}}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{M}_\nu = \frac{3g^2}{\sqrt{2}(16\pi^2)^2} I_0 \left(2 (y^L)^T M_u f^L + M_\ell (y^R)^T f^L - M_\ell (f^R)^T y^L \right)$$

- $f_{21}^R f_{21}^L : (g - 2)_e$
- $y_{32}^R y_{32}^L : (g - 2)_\mu$
- $f_{33}^R f_{23}^L : R_D - R_{D^\star}$

$f_{21}^R f_{31}^R : R_K - R_{K^\star}$

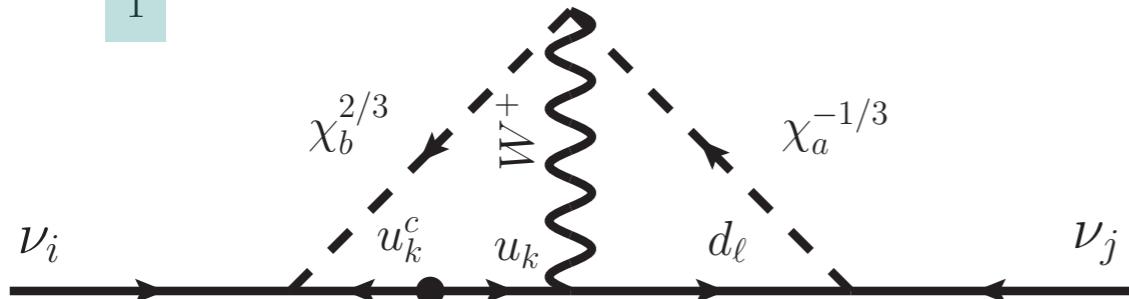
$y_{21}^L, y_{22}^L, y_{23}^R : \nu$ fit

$(\Delta m_{21}^2, \Delta m_{31}^2, \sin^2 \theta_{13}, \sin^2 \theta_{23}, \sin^2 \theta_{12})$

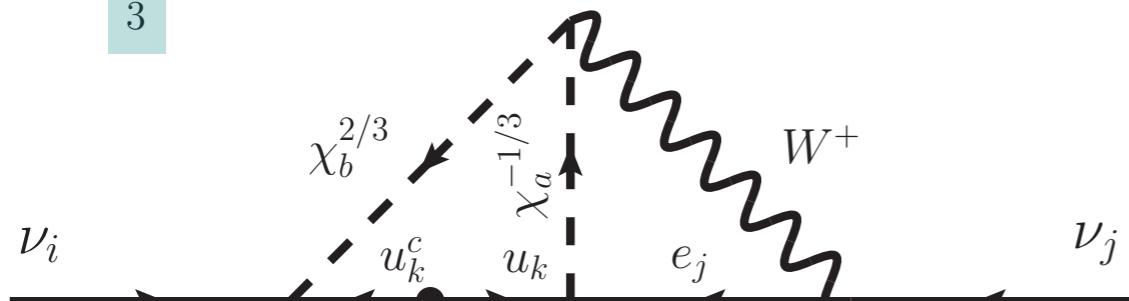
$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ f_{21}^R & 0 & 0 \\ f_{31}^R & 0 & f_{33}^R \end{pmatrix} \quad f^L = \begin{pmatrix} 0 & 0 & 0 \\ f_{21}^L & 0 & f_{23}^L \\ 0 & 0 & 0 \end{pmatrix}$$

$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_{23}^R \\ 0 & y_{32}^R & 0 \end{pmatrix} \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ y_{21}^L & y_{22}^L & 0 \\ 0 & y_{32}^L & 0 \end{pmatrix}$$

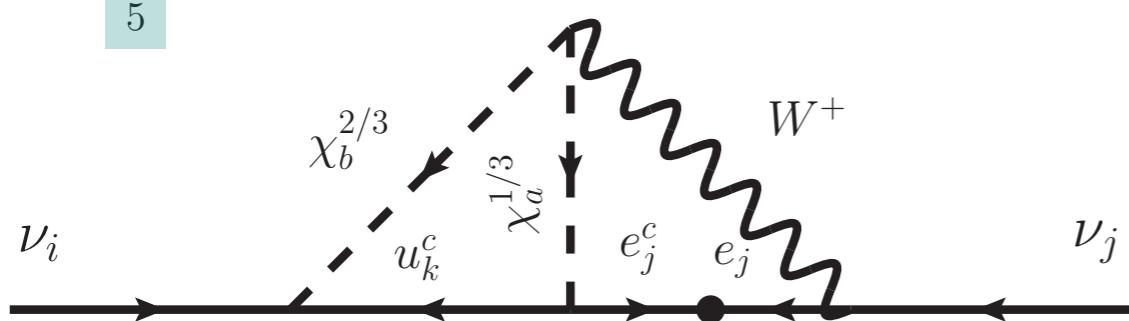
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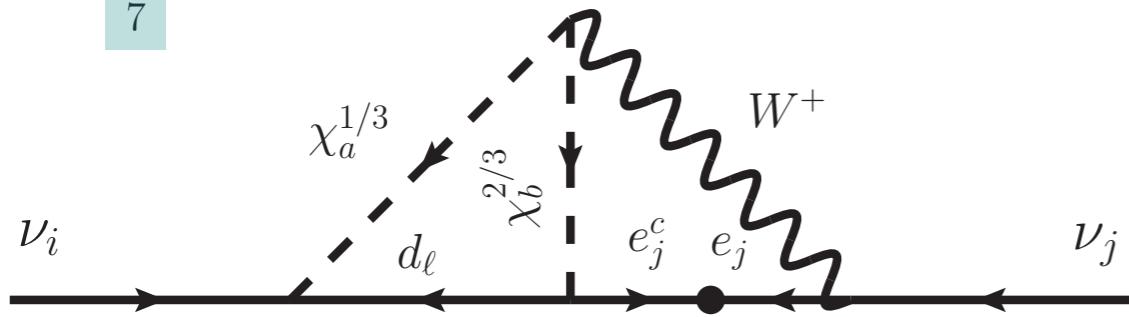
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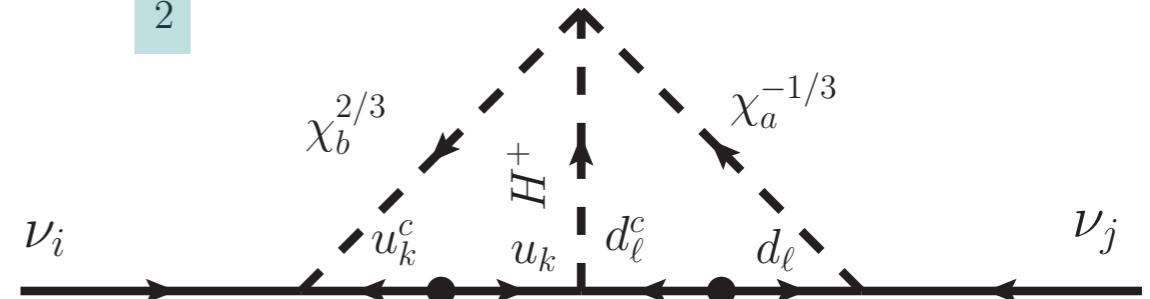
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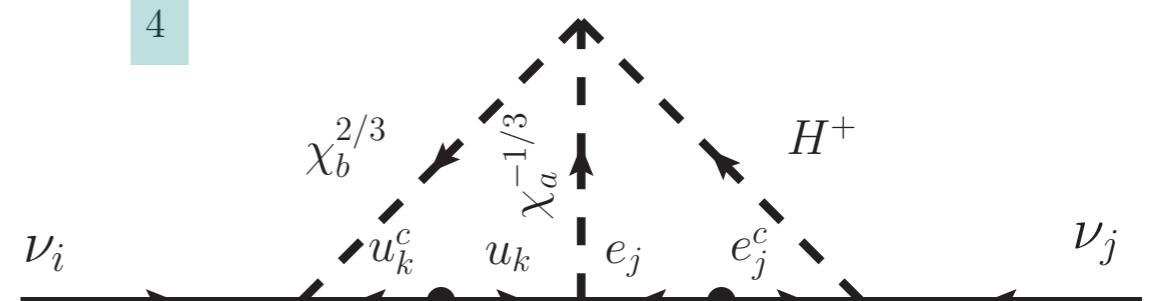
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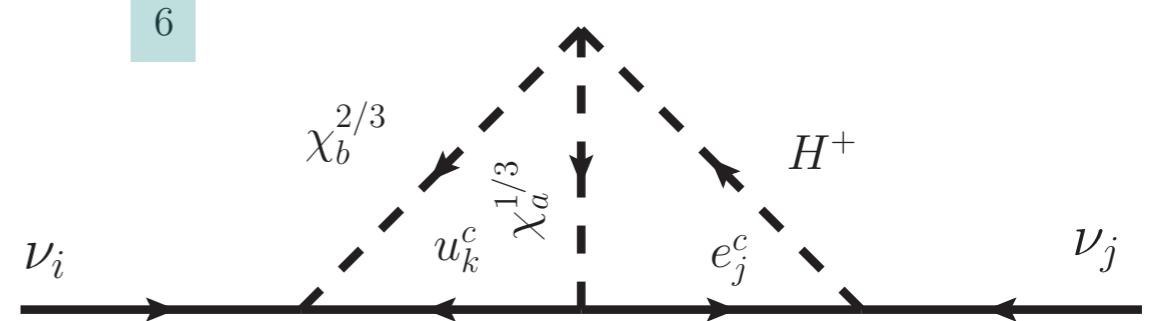
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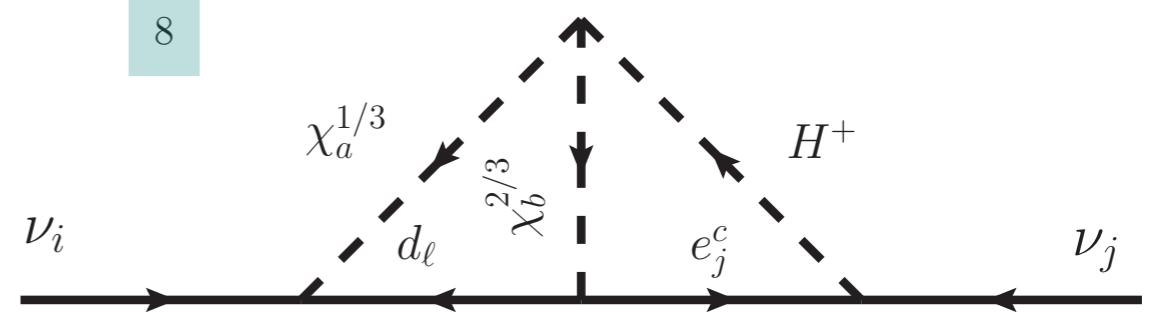
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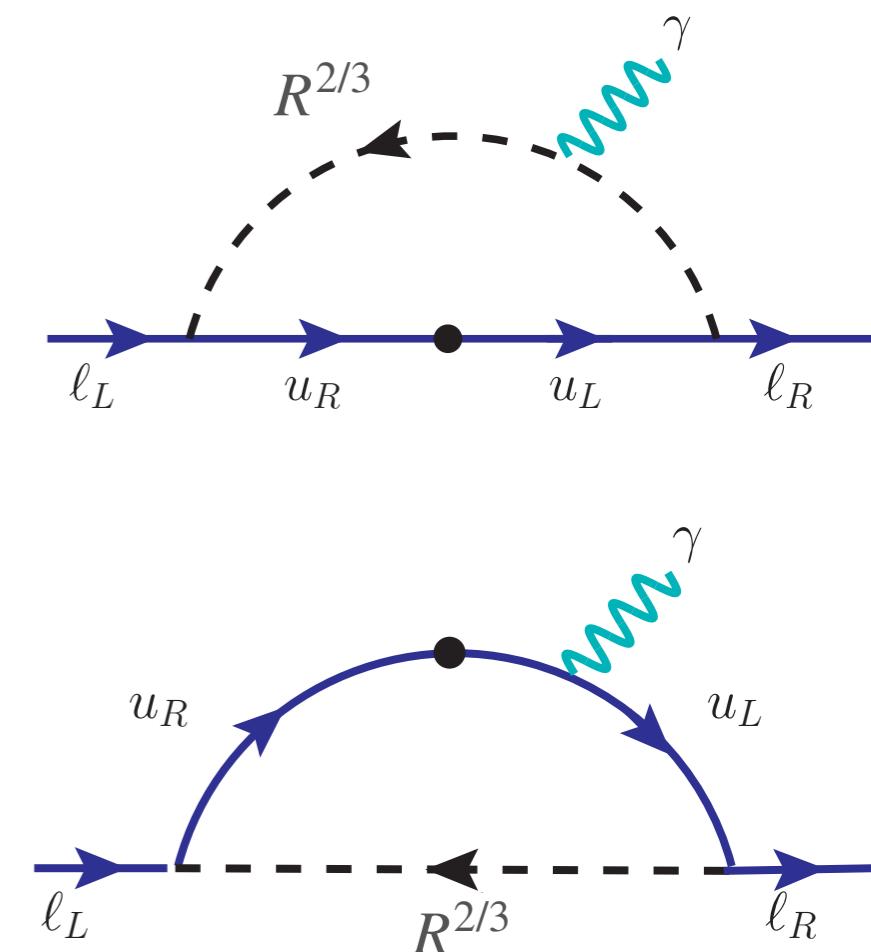
8



Experimental Constraints

- $\ell_i \rightarrow \ell_j \gamma$
- $\mu - e$ conversion
- $Z \rightarrow \tau\tau$ decay
- Rare D -meson decay
- $D^0 - \bar{D}^0$ mixing
- **Bounds from kaons**
- Collider constraints
 - Pair-production Bounds
 - Dilepton Bounds

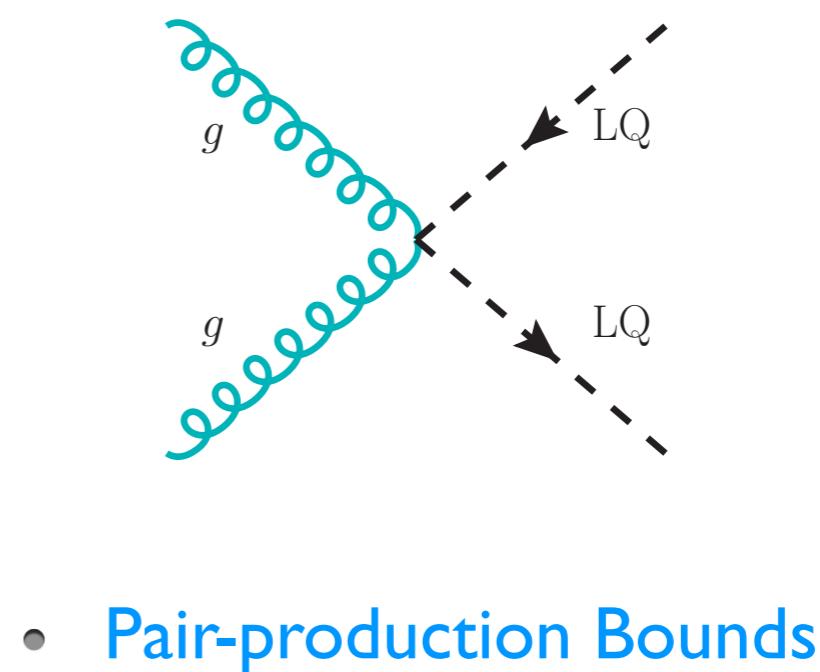
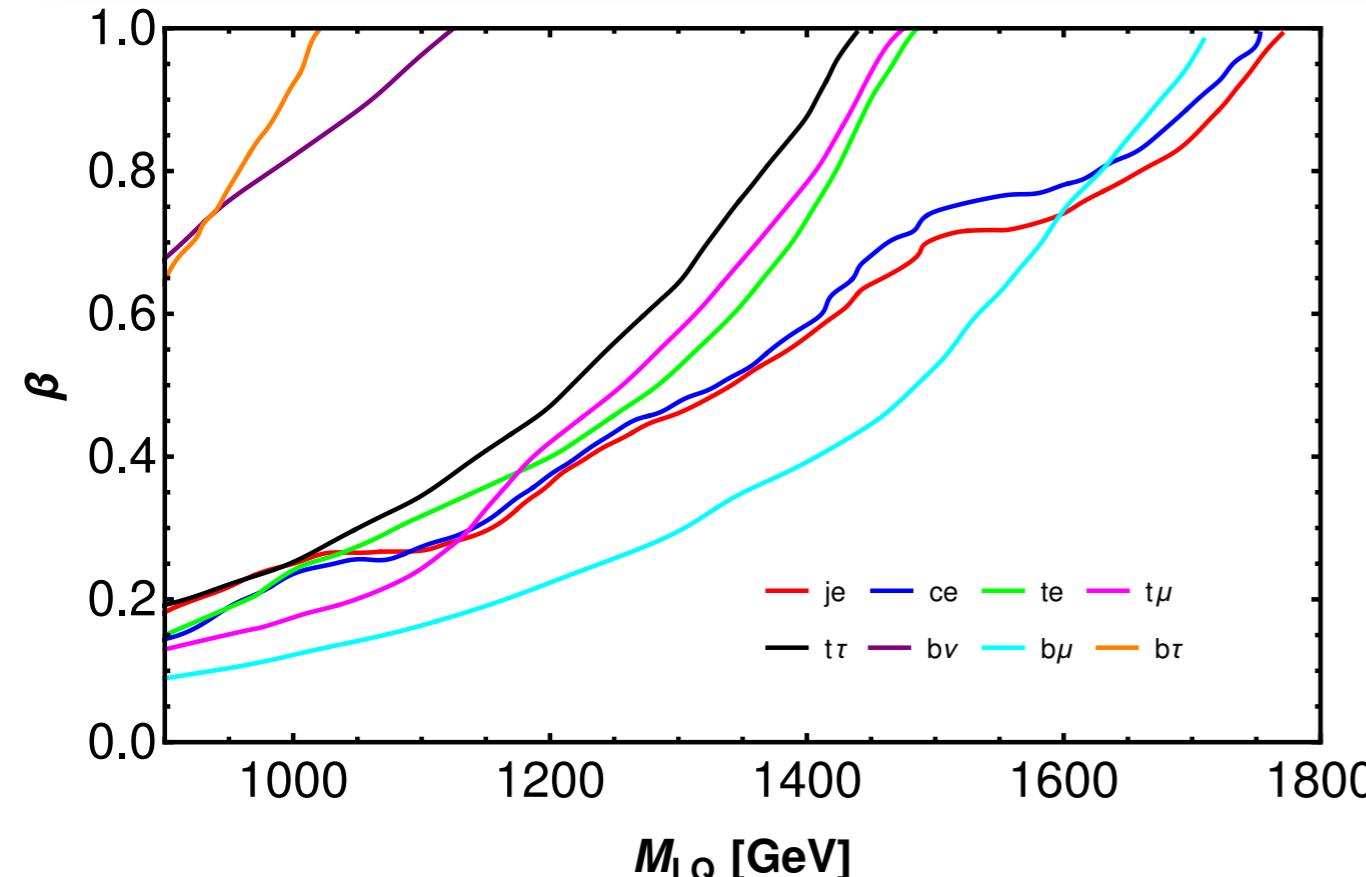
Process	Constraints
$\mu \rightarrow e\gamma$	$ f_{\alpha e}^R f_{\alpha \mu}^{R*} + f_{\alpha e}^L f_{\alpha \mu}^{L*} < 4.82 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$(f_{\alpha e}^R f_{\alpha \mu}^{L*} + f_{\alpha e}^L f_{\alpha \mu}^{R*}) \mathcal{C} < 7.63 \times 10^{-5} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1 \text{ GeV}}{m_q}\right)$
$\tau \rightarrow e\gamma$	$ f_{\alpha e}^R f_{\alpha \tau}^{R*} + f_{\alpha e}^L f_{\alpha \tau}^{L*} < 0.32 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$(f_{\alpha e}^R f_{\alpha \tau}^{L*} + f_{\alpha e}^L f_{\alpha \tau}^{R*}) \mathcal{C} < 0.85 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1 \text{ GeV}}{m_q}\right)$
$\tau \rightarrow \mu\gamma$	$ f_{\alpha \mu}^R f_{\alpha \tau}^{R*} + f_{\alpha \mu}^L f_{\alpha \tau}^{L*} < 0.37 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$(f_{\alpha \mu}^R f_{\alpha \tau}^{L*} + f_{\alpha \mu}^L f_{\alpha \tau}^{R*}) \mathcal{C} < 0.98 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1 \text{ GeV}}{m_q}\right)$
$\mu - e$	$ \hat{f}_{ue}^R \hat{f}_{u\mu}^{R*} \leq 8.58 \times 10^{-6} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$



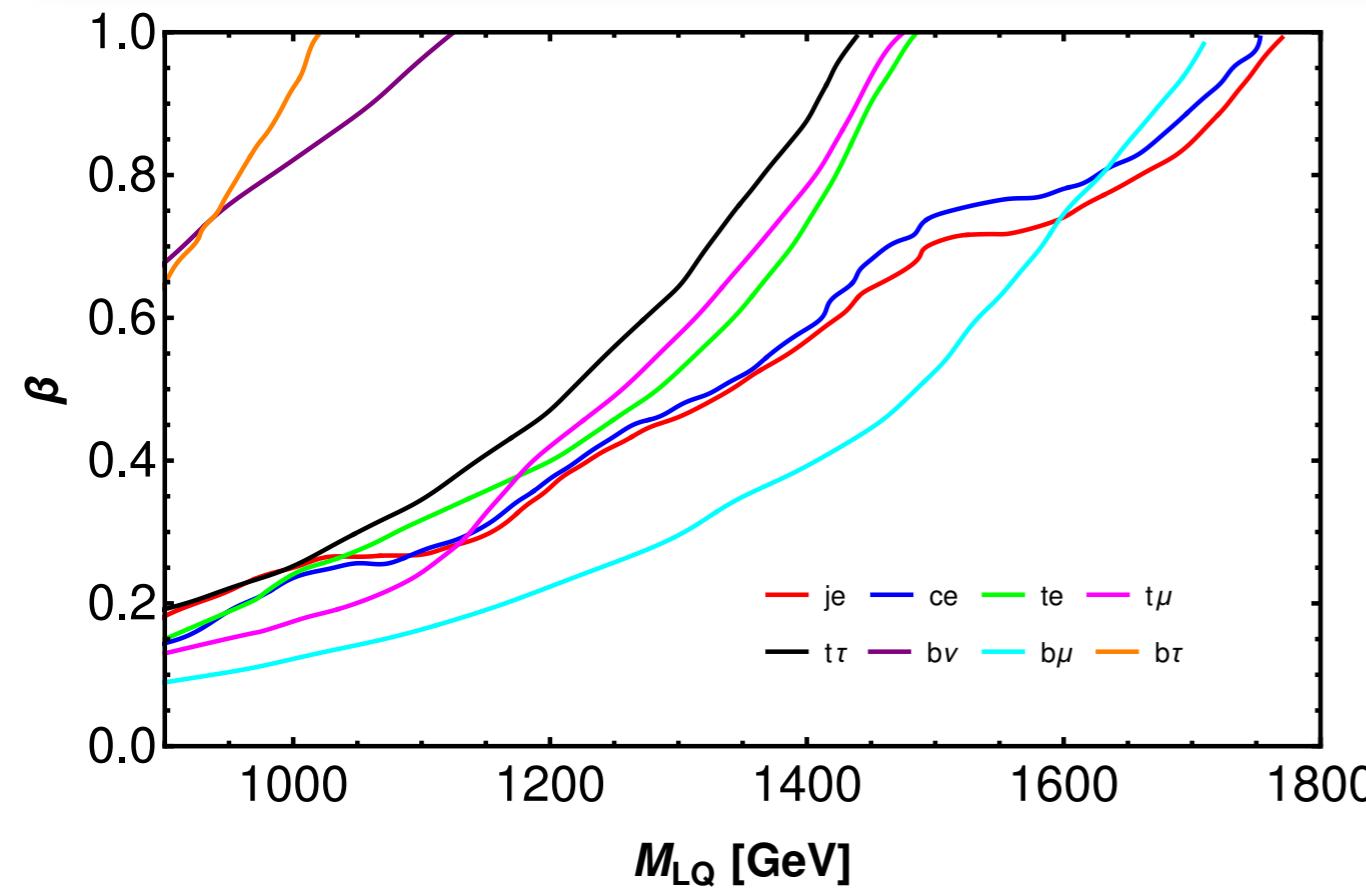
Bounds from kaons

Process	Constraints
$K_L \rightarrow e^+ e^-$	$ \hat{f}_{de}^R \hat{f}_{se}^{R*} \leq 2.0 \times 10^{-3} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K_L^0 \rightarrow e^\pm \mu^\mp$	$ \hat{f}_{d\mu}^R \hat{f}_{se}^{R*} + \hat{f}_{s\mu}^R \hat{f}_{de}^{R*} \leq 1.9 \times 10^{-5} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K_L^0 \rightarrow \pi^0 e^\pm \mu^\mp$	$ \hat{f}_{d\mu}^R \hat{f}_{se}^{R*} - f_{s\mu}^R f_{de}^{R*} \leq 2.9 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^+ \rightarrow \pi^+ e^+ e^-$	$ \hat{f}_{de}^R \hat{f}_{s\mu}^{R*} \leq 2.3 \times 10^{-2} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^+ \rightarrow \pi^+ e^- \mu^+$	$ \hat{f}_{d\mu}^R \hat{f}_{se}^{R*} , \hat{f}_{de}^R \hat{f}_{s\mu}^{R*} \leq 1.9 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K - \bar{K}$	$ \hat{f}_{d\alpha}^{R*} \hat{f}_{s\alpha}^R \leq 0.0266 \left(\frac{M_{R_2}}{\text{TeV}}\right)$
$K^+ \rightarrow \pi^+ \nu\nu$	$\text{Re}[\hat{y}_{de}^L \hat{y}_{se}^L] = [-3.7, 8.3] \times 10^{-4} \left(\frac{M_{S_1}}{\text{TeV}}\right)^2$ $[\sum_{m \neq n} \hat{y}_{dm}^L \hat{y}_{sn}^{L*} ^2]^{1/2} < 6.0 \times 10^{-4} \left(\frac{M_{S_1}}{\text{TeV}}\right)^2$
$B \rightarrow K^{(*)} \nu\nu$	$\hat{y}_{b\alpha}^L \hat{y}_{s\beta}^L = [-0.036, 0.076] \left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R_{K^*}^{\nu\bar{\nu}} < 2.7]$ $\hat{y}_{b\alpha}^L \hat{y}_{s\beta}^L = [-0.047, 0.087] \left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R_K^{\nu\bar{\nu}} < 3.9]$

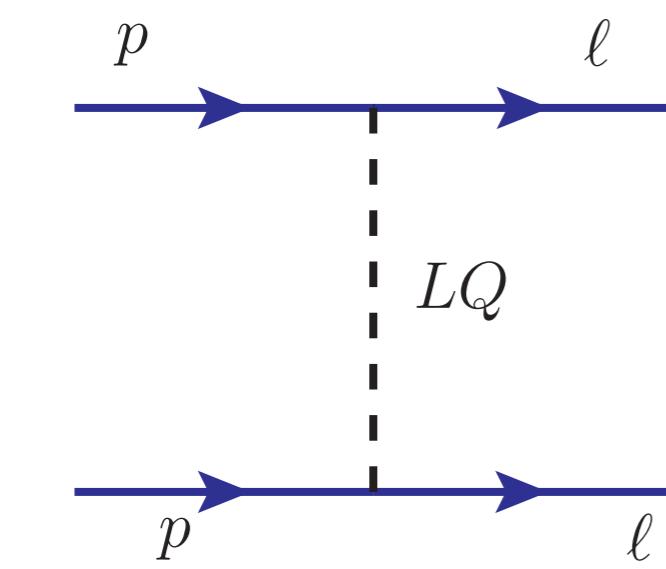
Collider Constraints



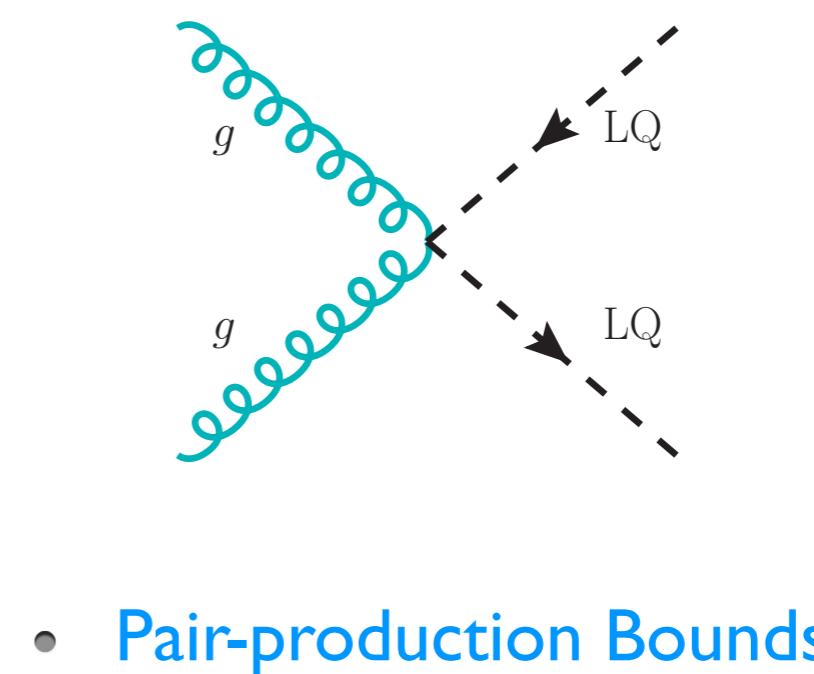
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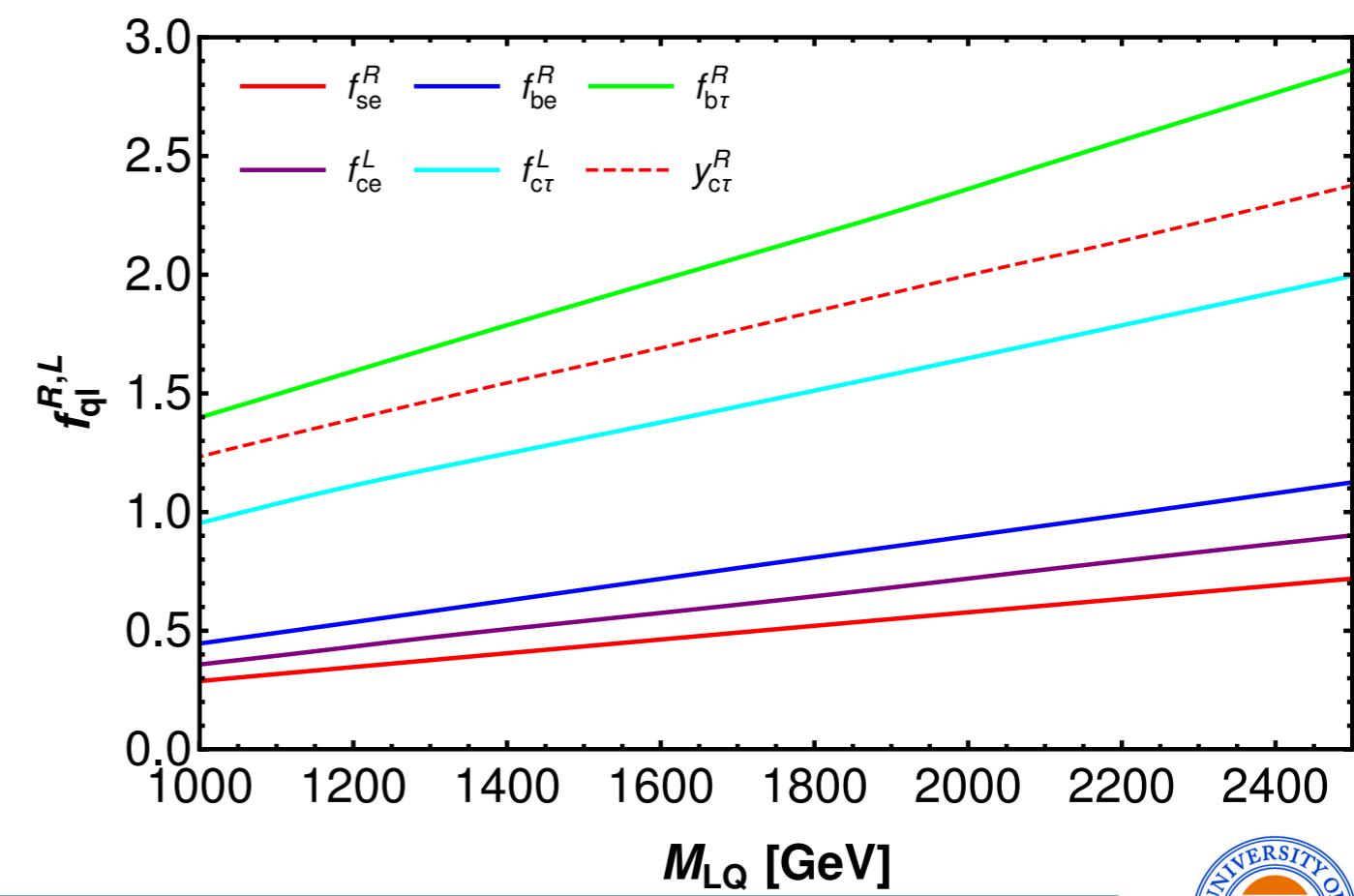
M_{LQ} [GeV]



• Dilepton Bounds



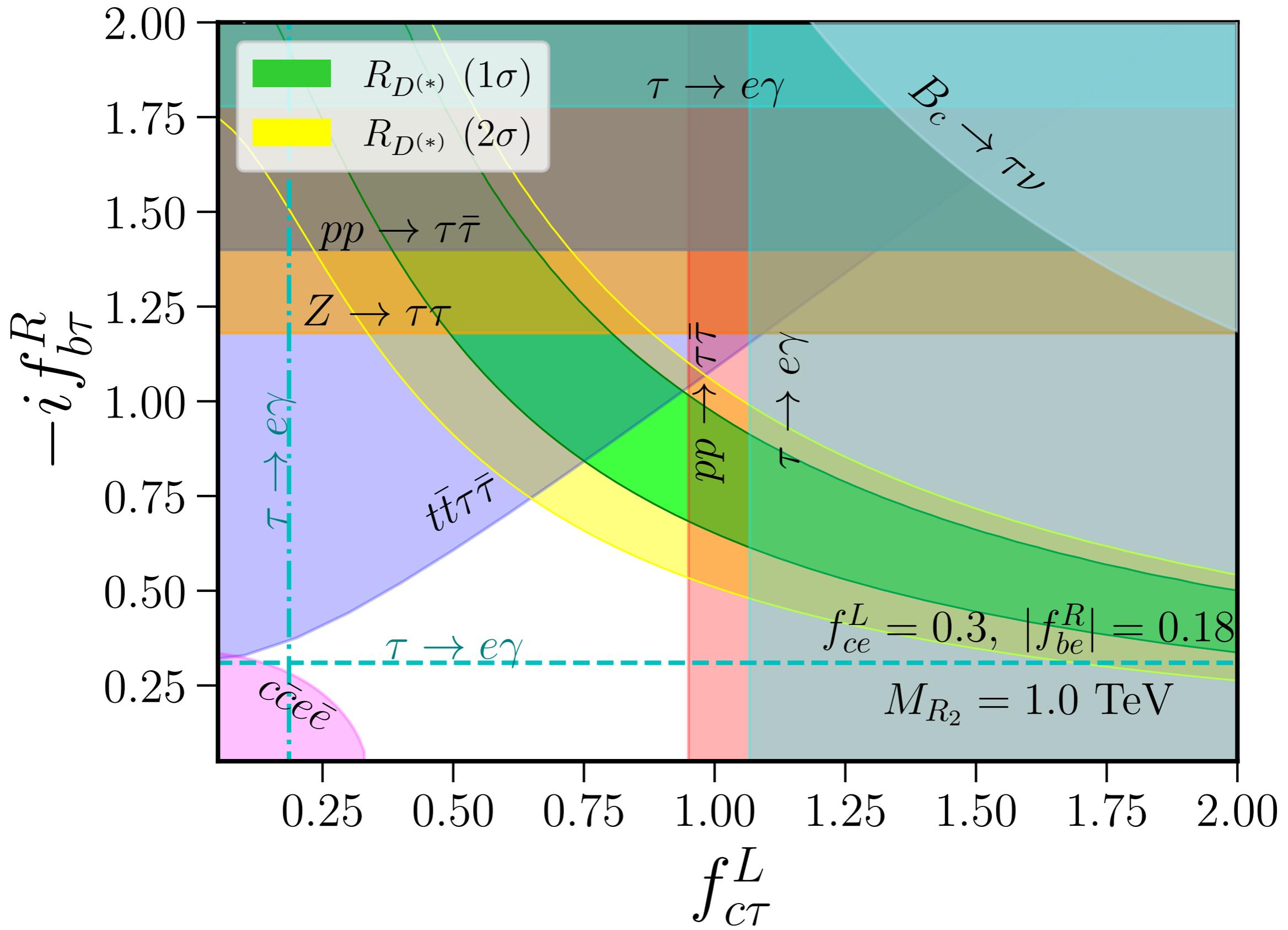
• Pair-production Bounds



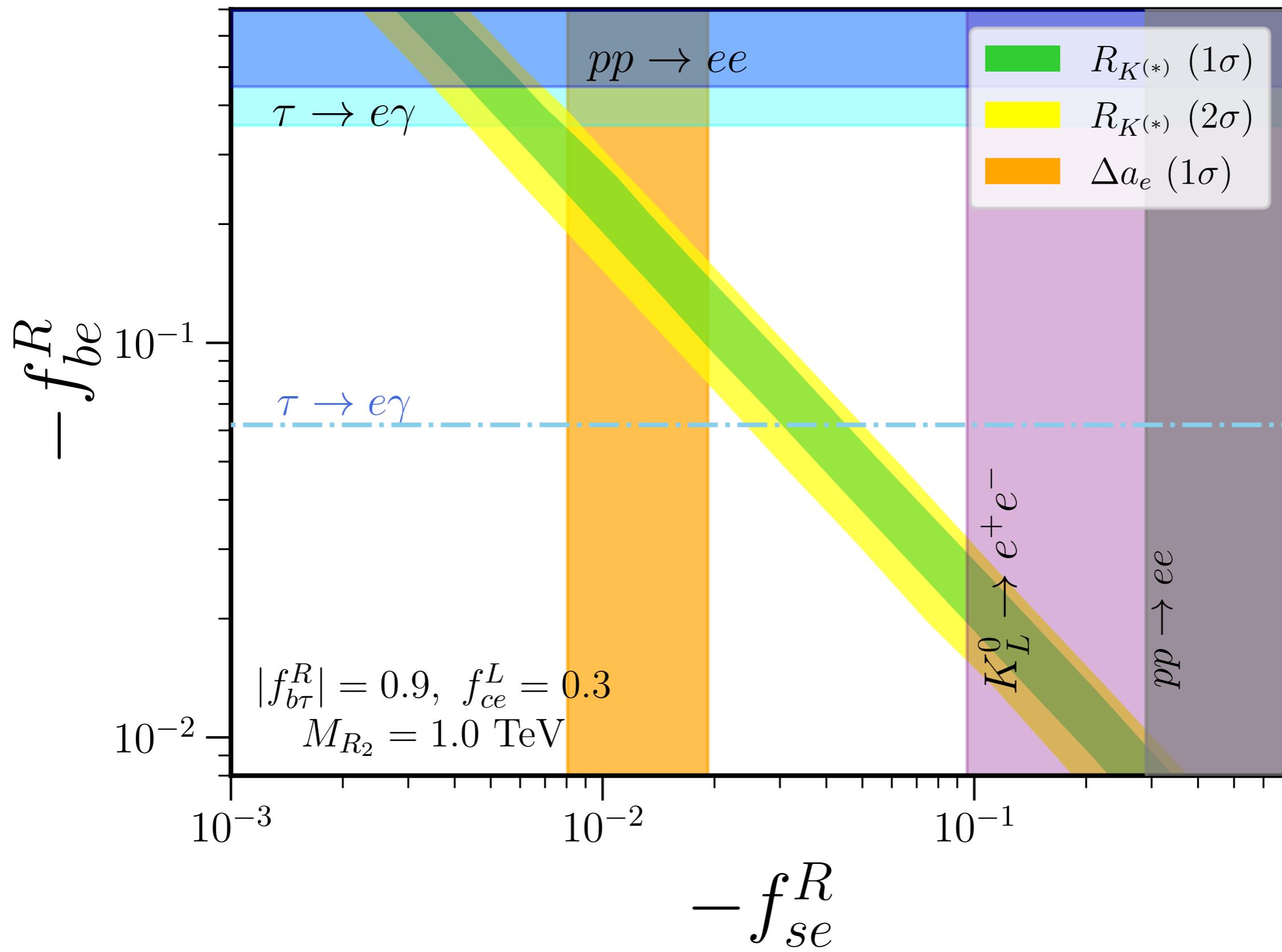
M_{LQ} [GeV]



Results: $R_D - R_{D^*}$



Results: $R_K - R_{K^\star}$



Results: Numerical Fit

$$f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0.3 & 0 & \color{red}{0.9} \\ 0 & 0 & 0 \end{pmatrix} \quad y^L = 10^{-3} \begin{pmatrix} 0 & 0 & 0 \\ -1.82 & 5.78 i & 0 \\ 0 & \color{cyan}{4.40} & 0 \end{pmatrix} \quad y^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1.85 \times 10^{-4} \\ 0 & \color{cyan}{1.0} & 0 \end{pmatrix} \quad f^R = \begin{pmatrix} 0 & 0 & 0 \\ -0.013 & 0 & 0 \\ -0.180 & 0 & \color{red}{-0.9 i} \end{pmatrix}$$

Oscillation parameters	3σ range NuFit5.1	Model prediction	
		TX I (NH)	TX II (IH)
$\Delta m_{21}^2 (10^{-5} \text{ eV}^2)$	6.82 - 8.04	7.41	7.39
$\Delta m_{23}^2 (10^{-3} \text{ eV}^2) (\text{IH})$	2.410 - 2.574	-	2.53
$\Delta m_{31}^2 (10^{-3} \text{ eV}^2) (\text{NH})$	2.43 - 2.593	2.53	-
$\sin^2 \theta_{12}$	0.269 - 0.343	0.316	0.2986
$\sin^2 \theta_{23} (\text{IH})$	0.410 - 0.613	-	0.534
$\sin^2 \theta_{23} (\text{NH})$	0.408 - 0.603	0.506	-
$\sin^2 \theta_{13} (\text{IH})$	0.02055 - 0.02457	-	0.0227
$\sin^2 \theta_{13} (\text{NH})$	0.02060 - 0.02435	0.0218	-
Observable		1σ range	
$C_9^{ee} = C_{10}^{ee}$	$[-1.65, -1.13]$	-1.39	-1.57
$(g-2)_e (10^{-14})$	-88 ± 36	-86	-84
$(g-2)_\mu (10^{-10})$	25.1 ± 6.0	22.4	24.2

Conclusion

- Simple two loop neutrino mass model utilizes TeV scale LQ and explains B - anomalies.
- Same model simultaneously explains observed muon and electron $g - 2$ anomaly.
- Same Yukawa couplings responsible for the chirally-enhanced Δa_μ give rise to SM Higgs decays to muon and tau pairs which could be tested at future hadron colliders.
- The model is consistent with observed neutrino oscillation data.



Thank you

