Neutrino Mass Model and Its Link to Flavor Anomalies

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ICHEP 2022

July 6 - 13, 2022

[2202.10479; 2009.01771]

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ν mass

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

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

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

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NuFit 5.1

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

Seesaw Paradigm

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

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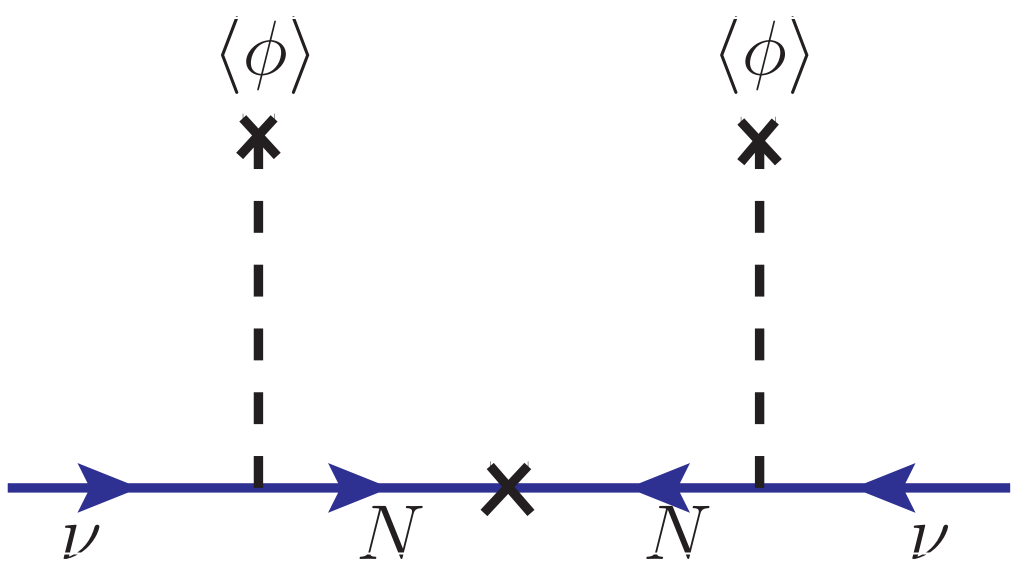
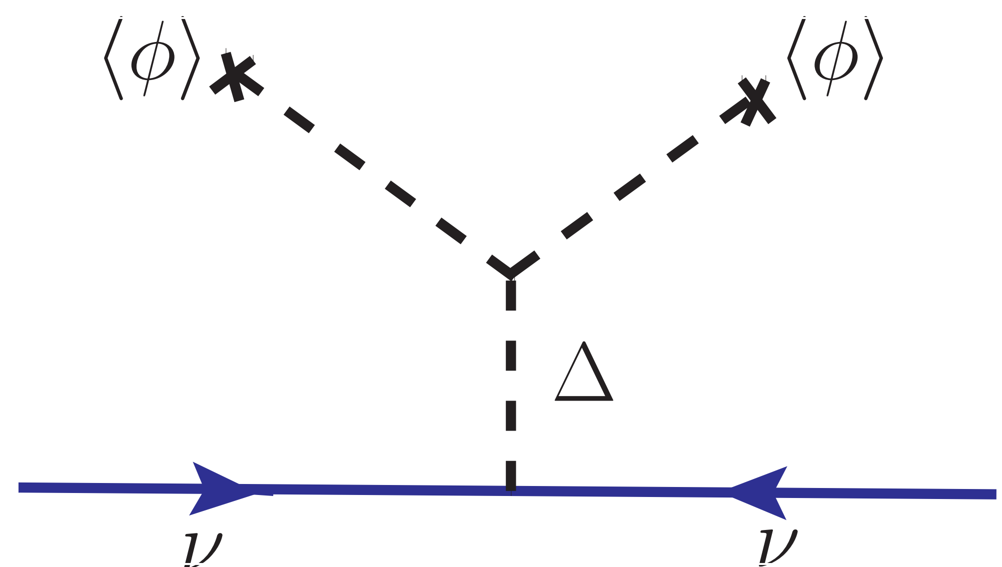
  - Tree-level Seesaw mechanism
  - Radiative schemes
- Light neutrino mass is induced via Weinberg's dim-5 operator, $LL\phi\phi$
- Large Majorana mass scale Λ to suppress the neutrino mass via $\frac{\langle\phi\rangle^2}{\Lambda}$



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 :

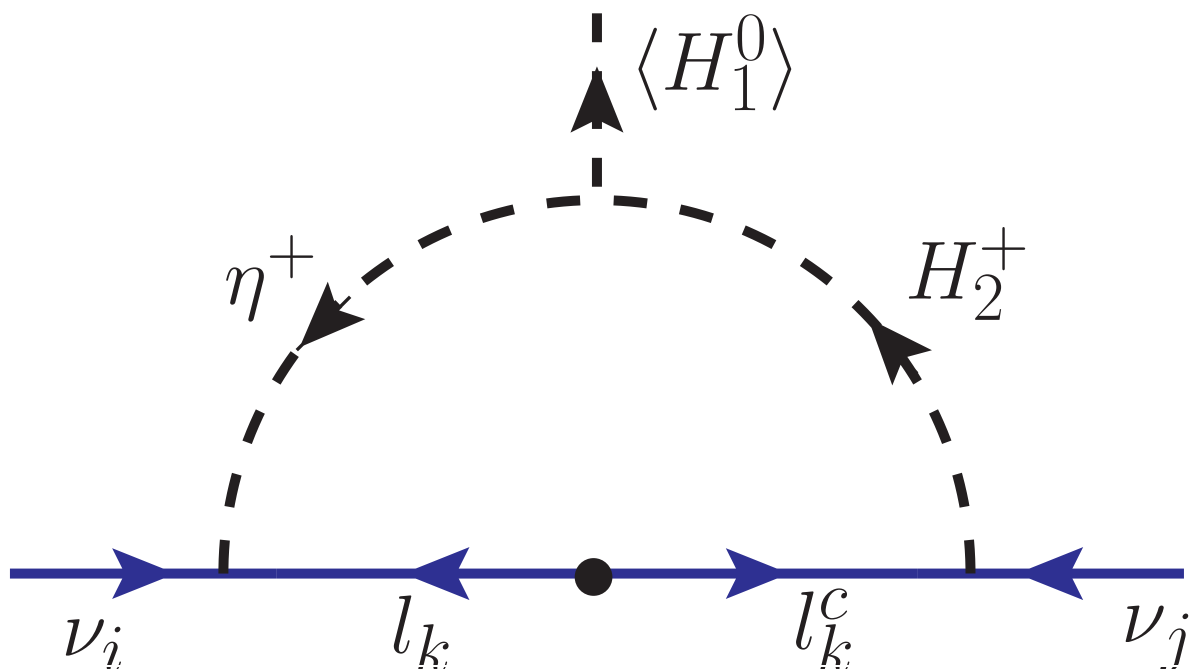
ν- mass induced from scalar exchange

$\Delta \sim (1,3,1)$

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

Radiative ν mass generation

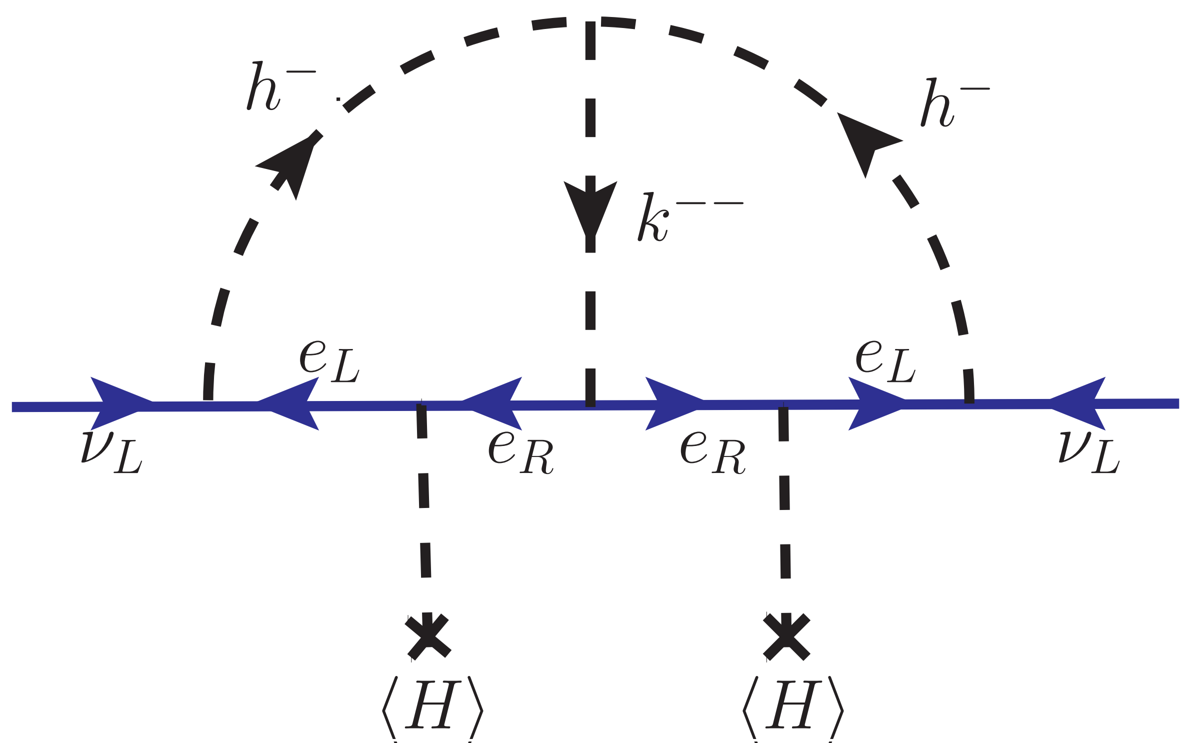
- Neutrino masses are zero at tree level: ν_R may be absent
- Small, finite masses are generated as quantum corrections
- Typically involves exchange of two scalars leading to lepton number violation
- Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet



- 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… 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



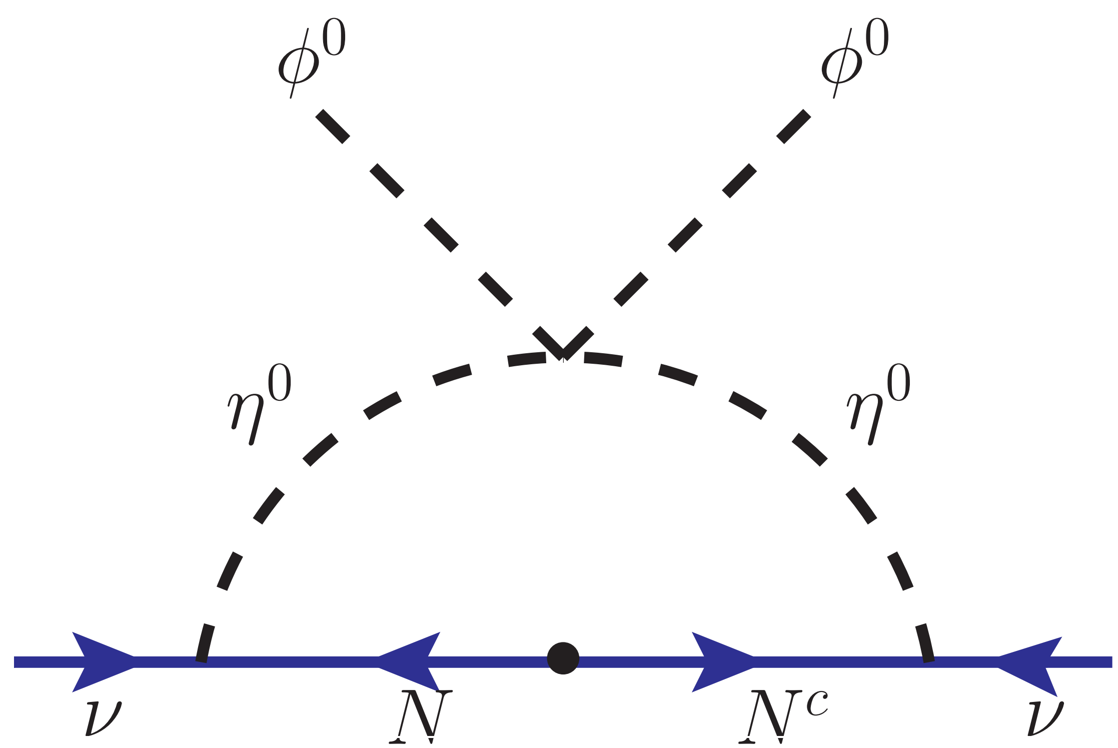
$$\mathcal{O}_9 = L_i L_j L_k e^c L_l e^c \epsilon^{ij} \epsilon^{kl}$$

Zee, Babu

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,…operators
- Scotogenic model is an example

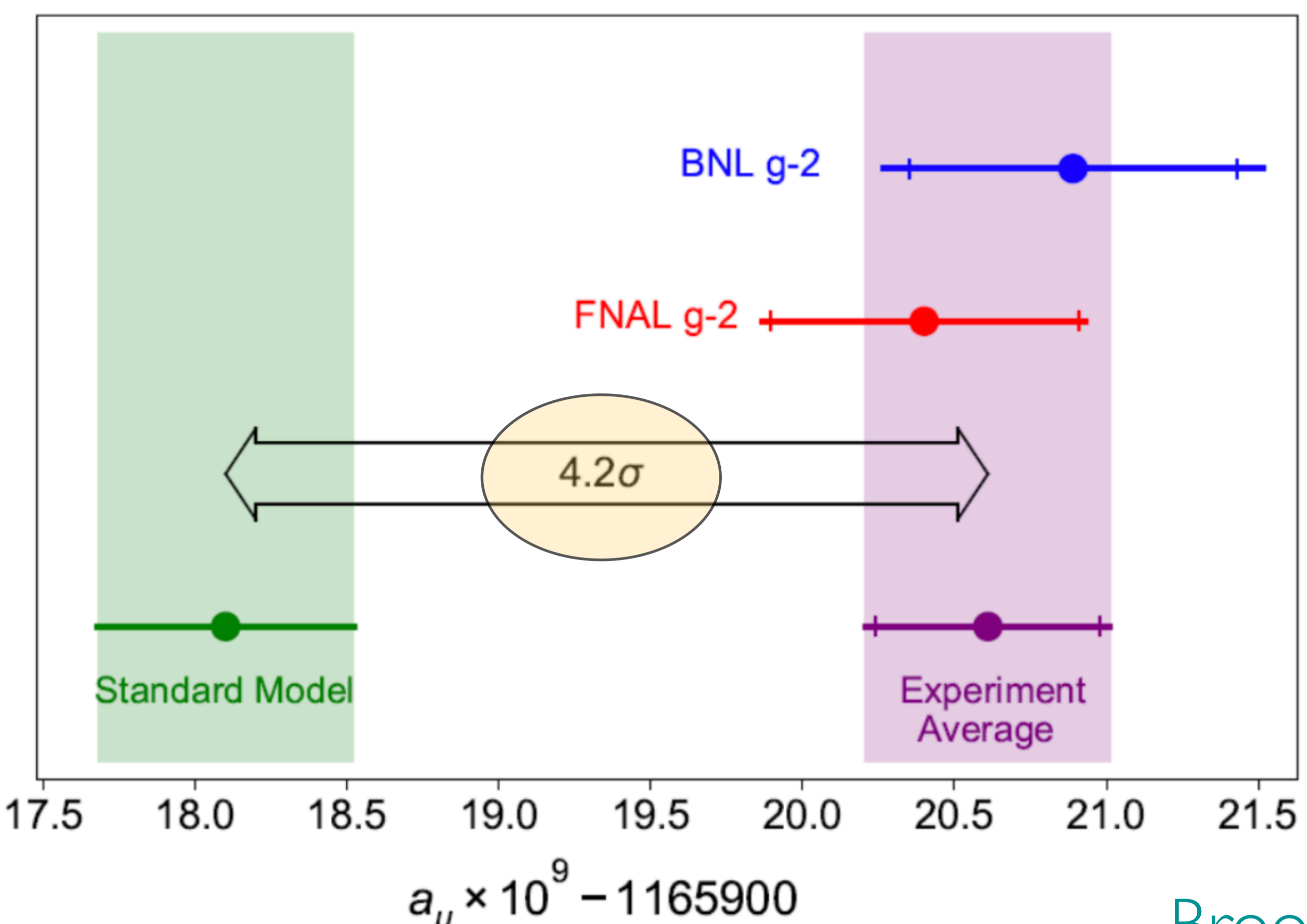


- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics

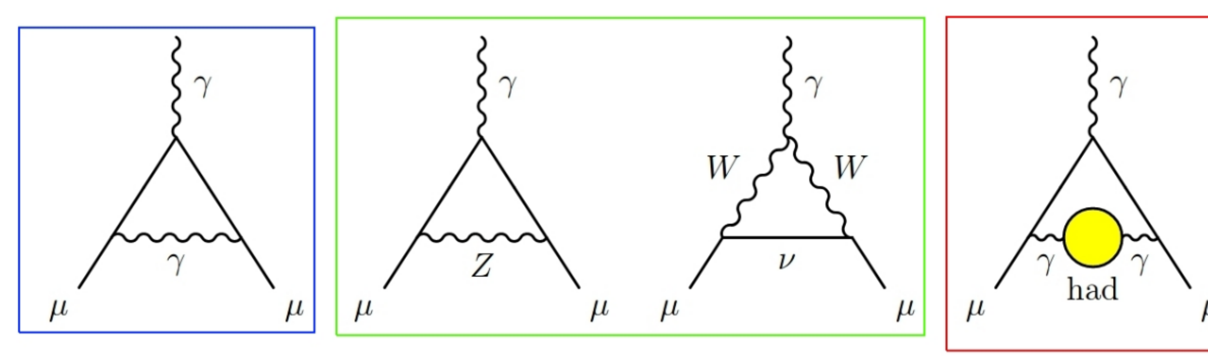
Ma (2006)

$(g-2)_\mu$

- Intrinsic magnetic property of a lepton is characterized by dimensionless number, called g-factor $H = -\vec{\mu}\cdot\vec{B}, \quad \vec{\mu} = g\frac{e}{2m}\vec{s}$
- 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 $g-2$:



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



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

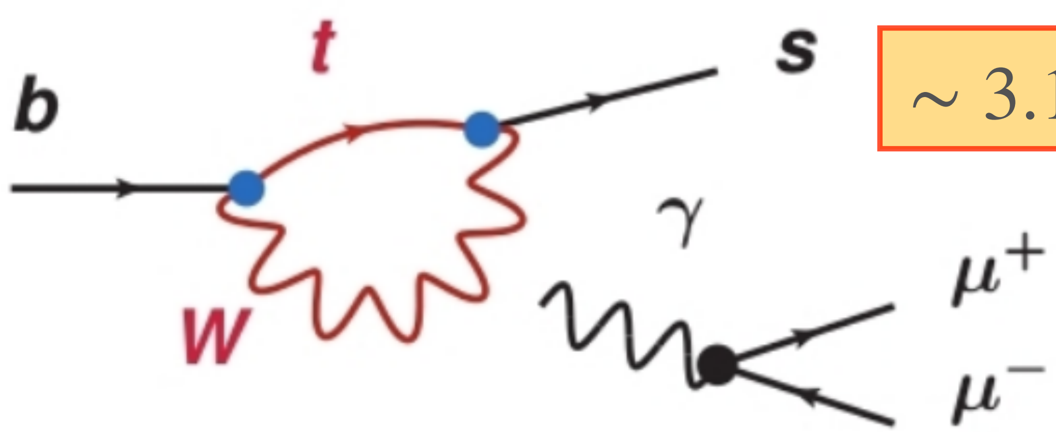
Brookhaven (2006); Fermilab (2021)

$b \to s$ anomalies

Observables: R_K and $R_{K^\star}$

Neutral current

1-loop in the SM



$\sim 3.1\sigma$

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

The New Physics can be heavy

$b \to s$ anomalies

Observables: R_K and $R_{K^\star}$

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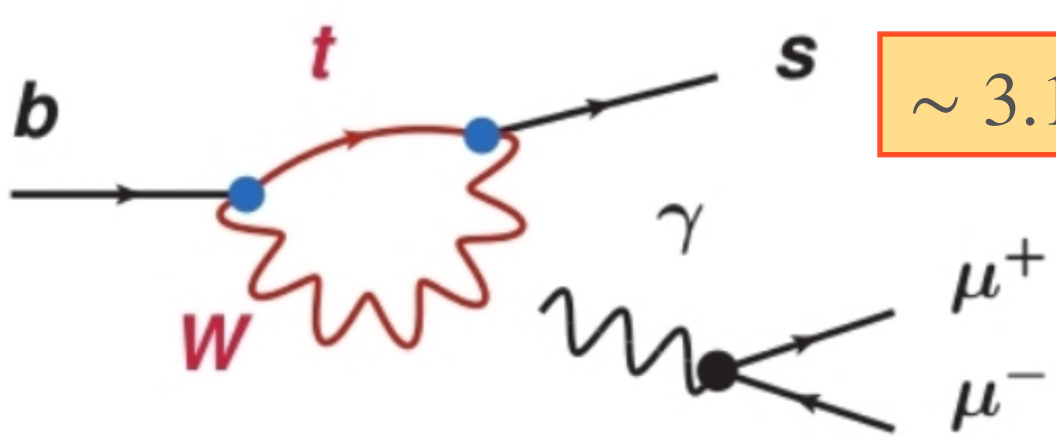


$\sim 3.1\sigma$

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

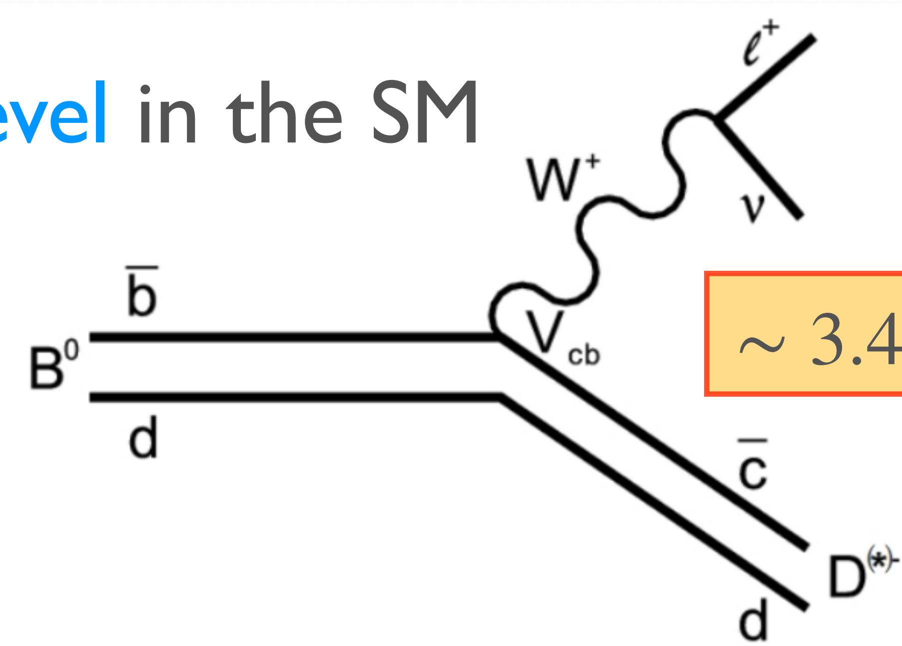
The New Physics can be heavy

$b \to c$ anomalies

Observables: R_D and $R_{D^\star}$

Charged current

Tree-level in the SM



$\sim 3.4\sigma$

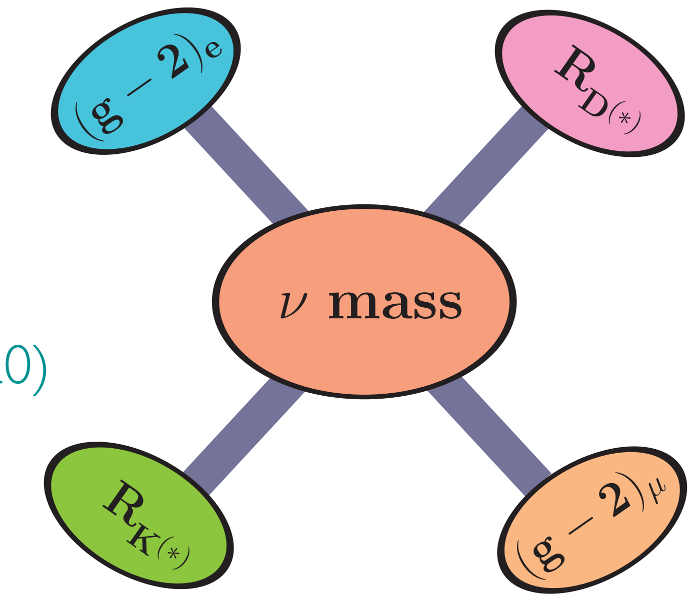
$$R_{D^{(\star)}} = \frac{\Gamma(\bar{B} \to D^{(\star)}\tau\nu)}{\Gamma(\bar{B} \to D^{(\star)}\ell\nu)}$$

The New Physics must be light

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

If confirmed: Implications for New Physics

- Collider Phenomenology!
- $\Delta a_\mu \Longleftrightarrow h \to \mu\mu$ and $h \to \tau\tau$ (Crivellin, Mueller, Saturnino, 2020)



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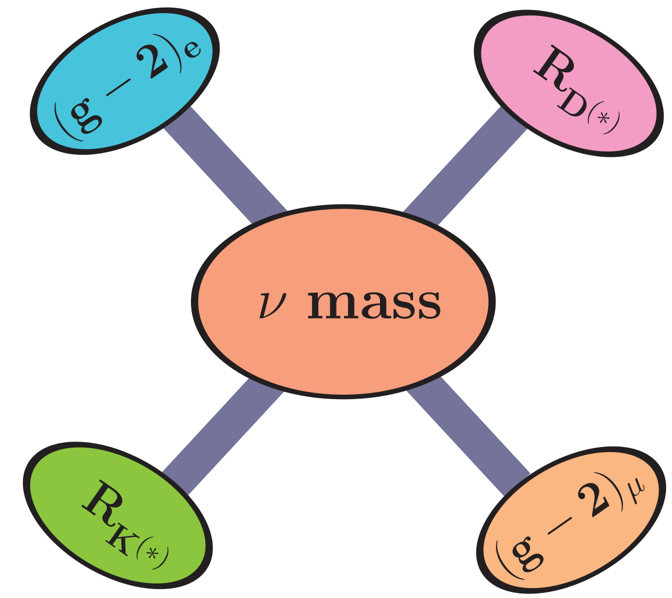


Framework for Anomalies

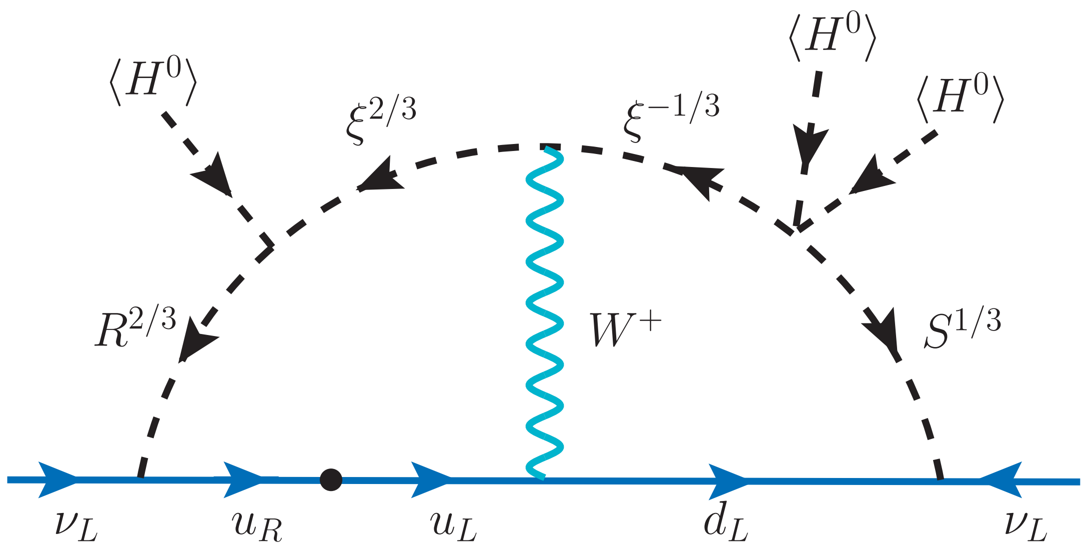
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗

- 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 $\tau \to \mu\gamma$

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

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

Model VII

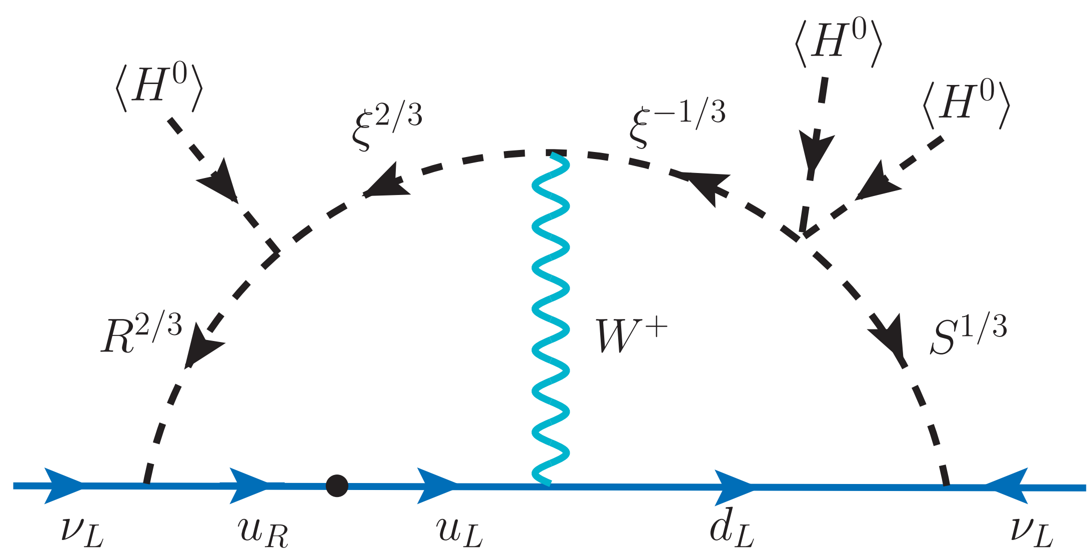


$$R_2 = \begin{pmatrix} R^{5/3} \\ R^{2/3} \end{pmatrix} \qquad S_1 = S^{1/3}$$

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

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

Model VII



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- $f^R_{21}\ f^L_{21}$: $(g-2)_e$
- $y^R_{32}\ y^L_{32}$: $(g-2)_\mu$
- $f^R_{33}\ f^L_{23}$: $R_D - R_{D^\star}$
- $f^R_{21}\ f^R_{31}$: $R_K - R_{K^\star}$
- $y^L_{21}, y^L_{22}, y^R_{23}$: ν fit

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

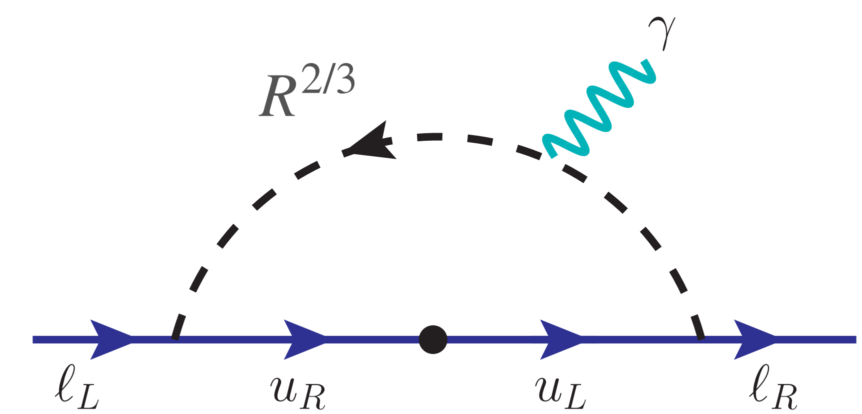
$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ f^R_{21} & 0 & 0 \\ f^R_{31} & 0 & f^R_{33} \end{pmatrix} \qquad f^L = \begin{pmatrix} 0 & 0 & 0 \\ f^L_{21} & 0 & f^L_{23} \\ 0 & 0 & 0 \end{pmatrix}$$

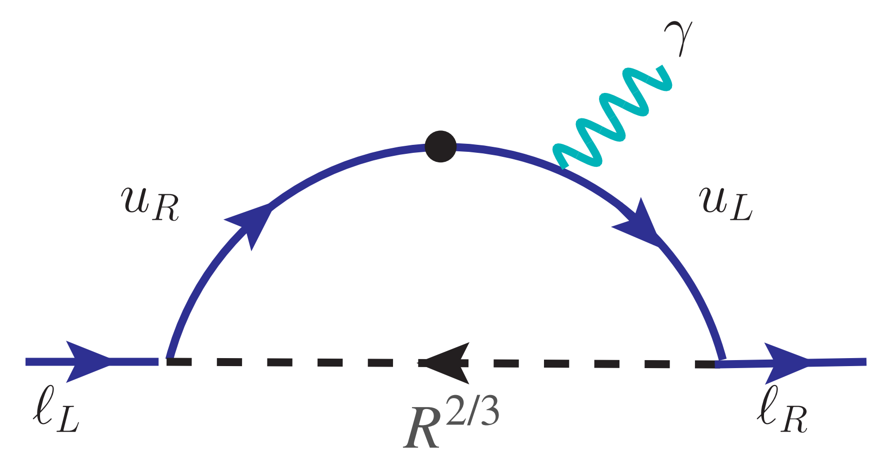
$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y^R_{23} \\ 0 & y^R_{32} & 0 \end{pmatrix} \qquad y^L = \begin{pmatrix} 0 & 0 & 0 \\ y^L_{21} & y^L_{22} & 0 \\ 0 & y^L_{32} & 0 \end{pmatrix}$$

Experimental Constraints

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

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

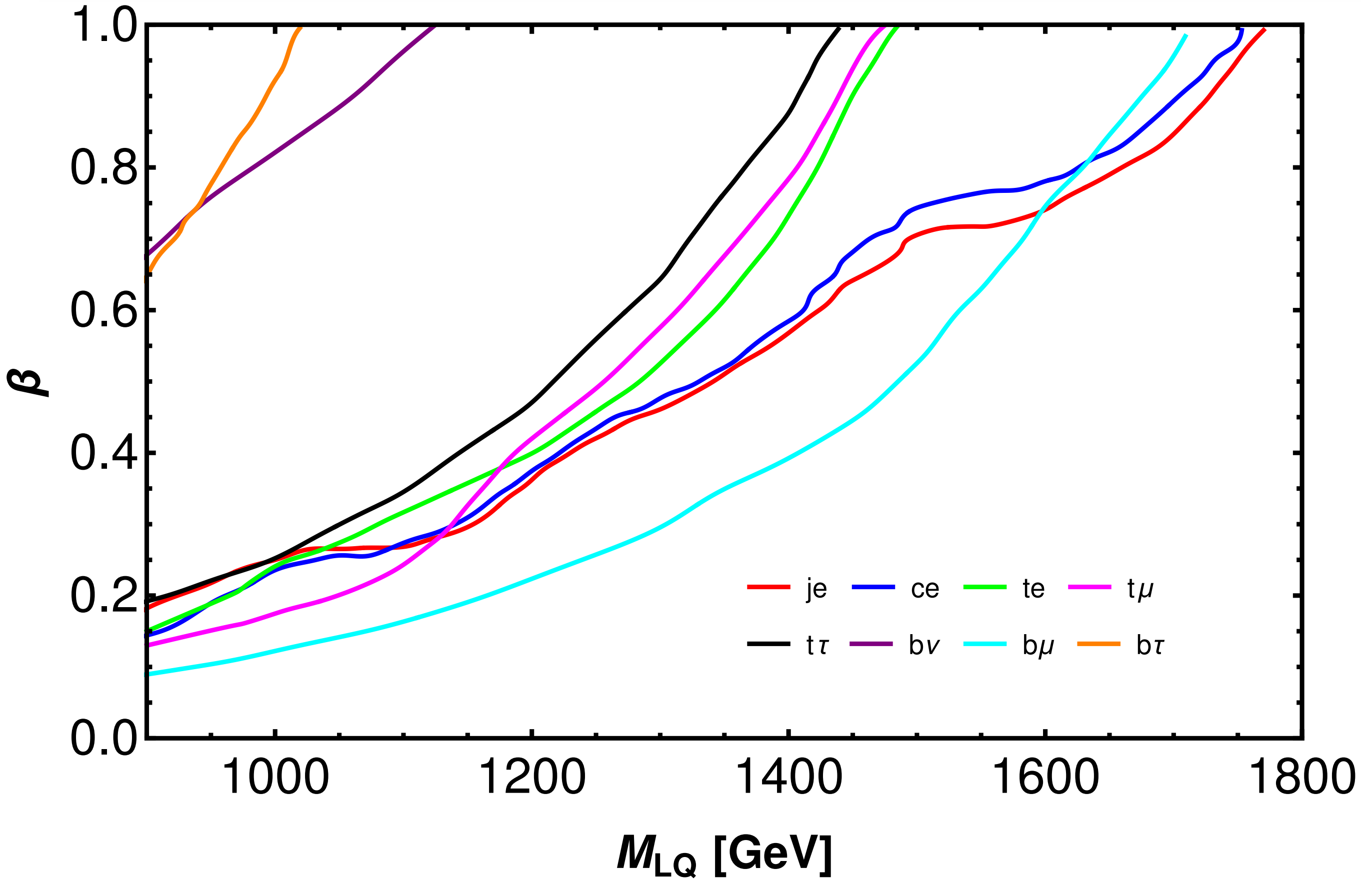


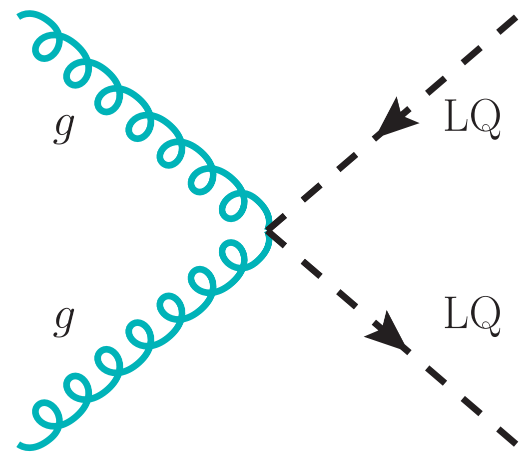


Bounds from kaons

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

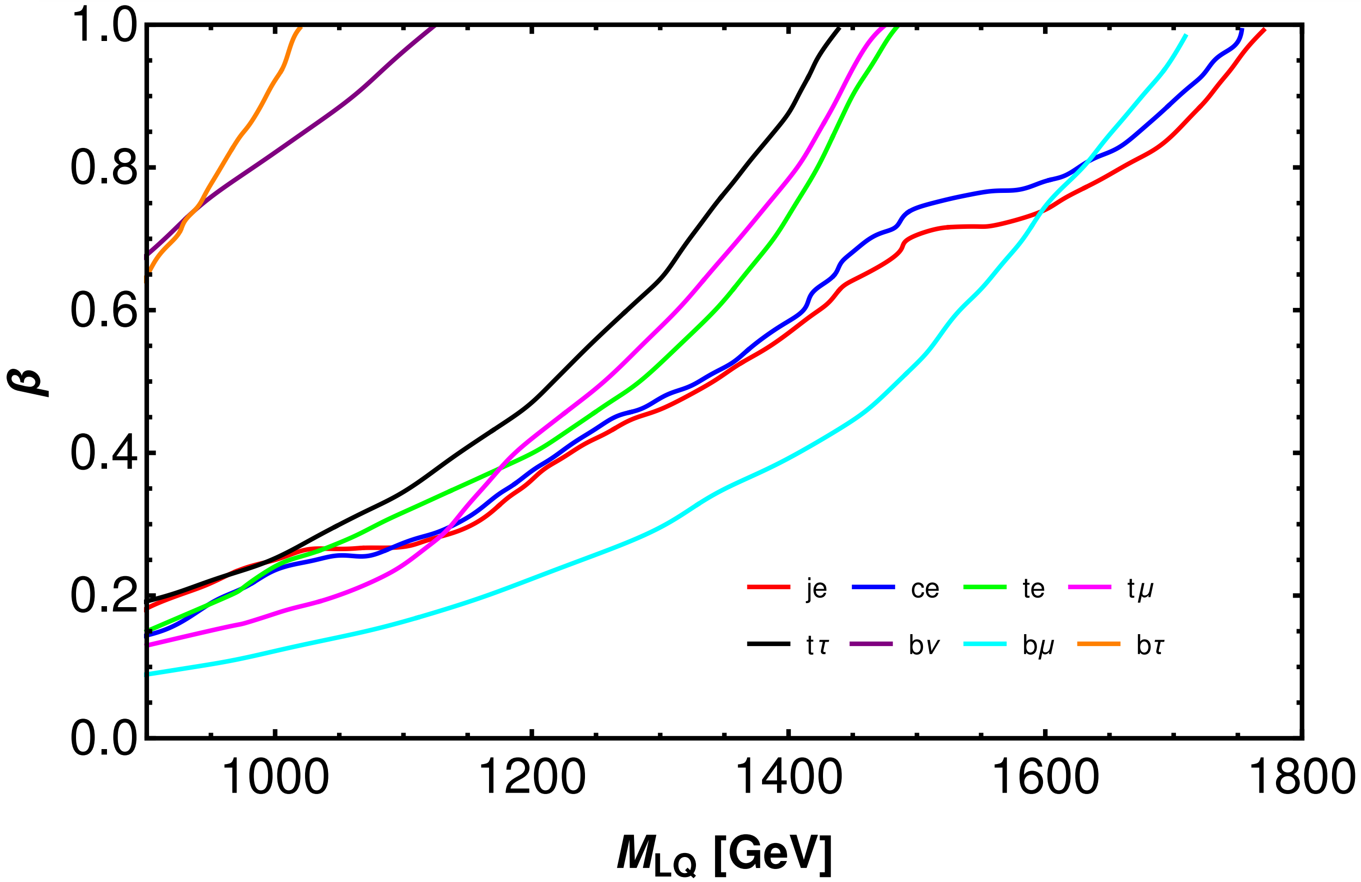
Collider Constraints

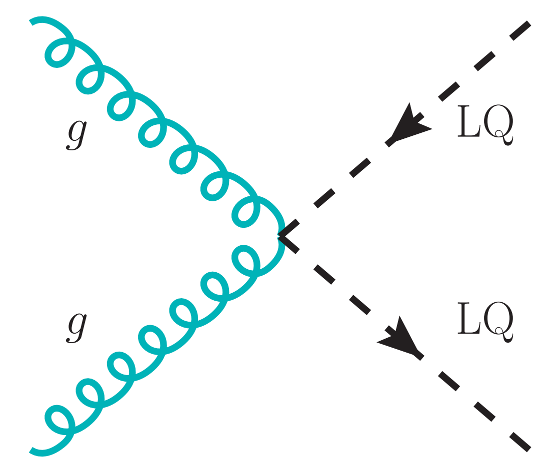




- Pair-production Bounds

Collider Constraints





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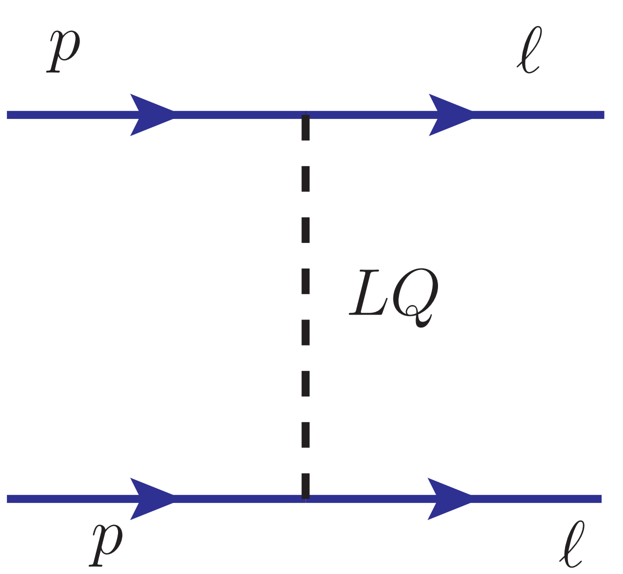
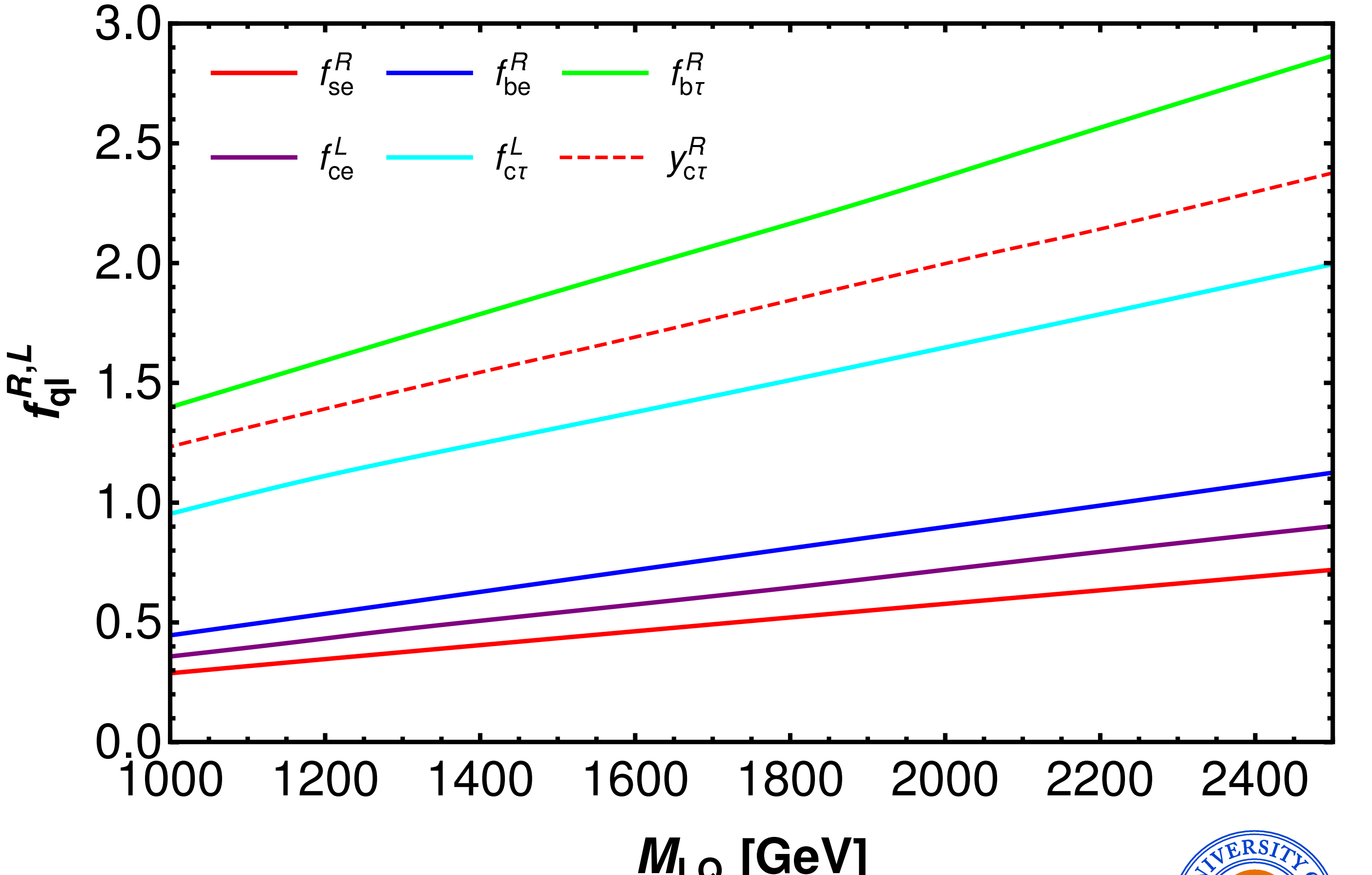
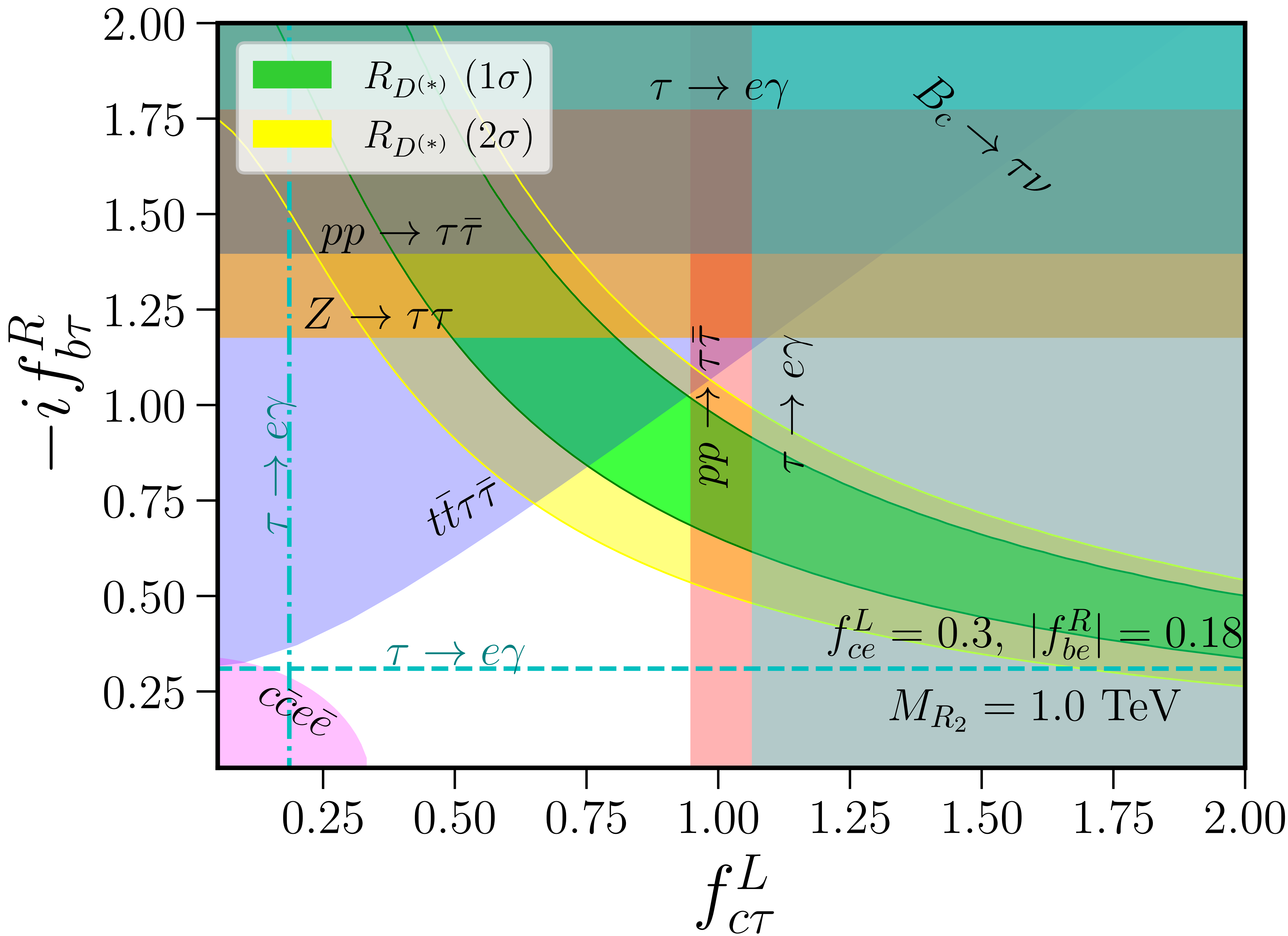


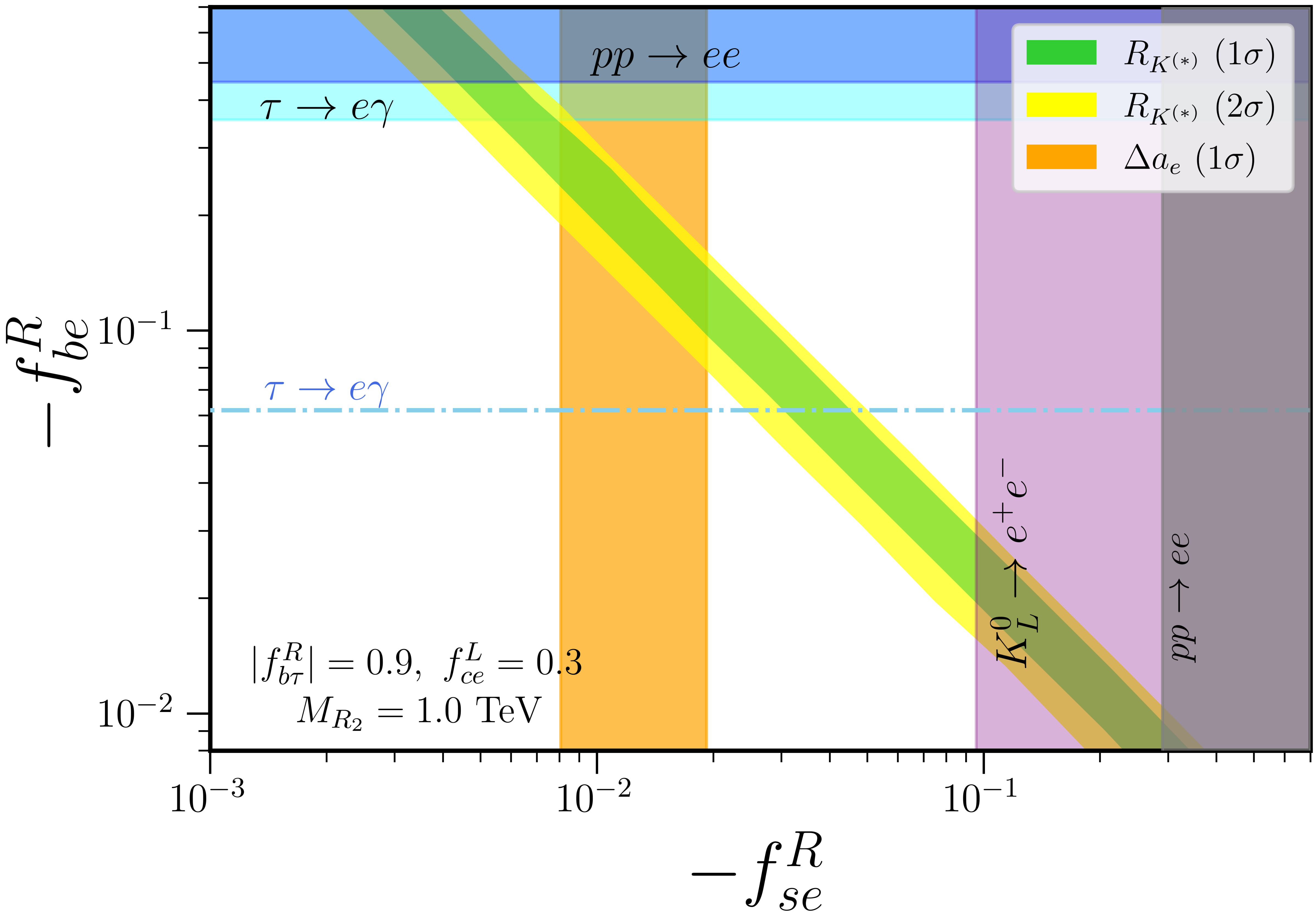


- Dilepton Bounds

Results: $R_D - R_{D^\star}$



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



Results: Numerical Fit

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

Oscillation parameters	**3σ range** NuFit5.1	**Model prediction** TX I (NH)	TX II (IH)
$\Delta m^2_{21} (10^{-5}\ \mathrm{eV}^2)$	6.82 - 8.04	7.41	7.39
$\Delta m^2_{23} (10^{-3}\ \mathrm{eV}^2)$(IH)	2.410 - 2.574	-	2.53
$\Delta m^2_{31} (10^{-3}\ \mathrm{eV}^2)$(NH)	2.43 - 2.593	2.53	-
$\sin^2\theta_{12}$	0.269 - 0.343	0.316	0.2986
$\sin^2\theta_{23}$ (IH)	0.410 - 0.613	-	0.534
$\sin^2\theta_{23}$ (NH)	0.408 - 0.603	0.506	-
$\sin^2\theta_{13}$ (IH)	0.02055 - 0.02457	-	0.0227
$\sin^2\theta_{13}$(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.