Testing Majorana (LFV) and Dirac Neutrino (ΔN_{eff}) Mass Models

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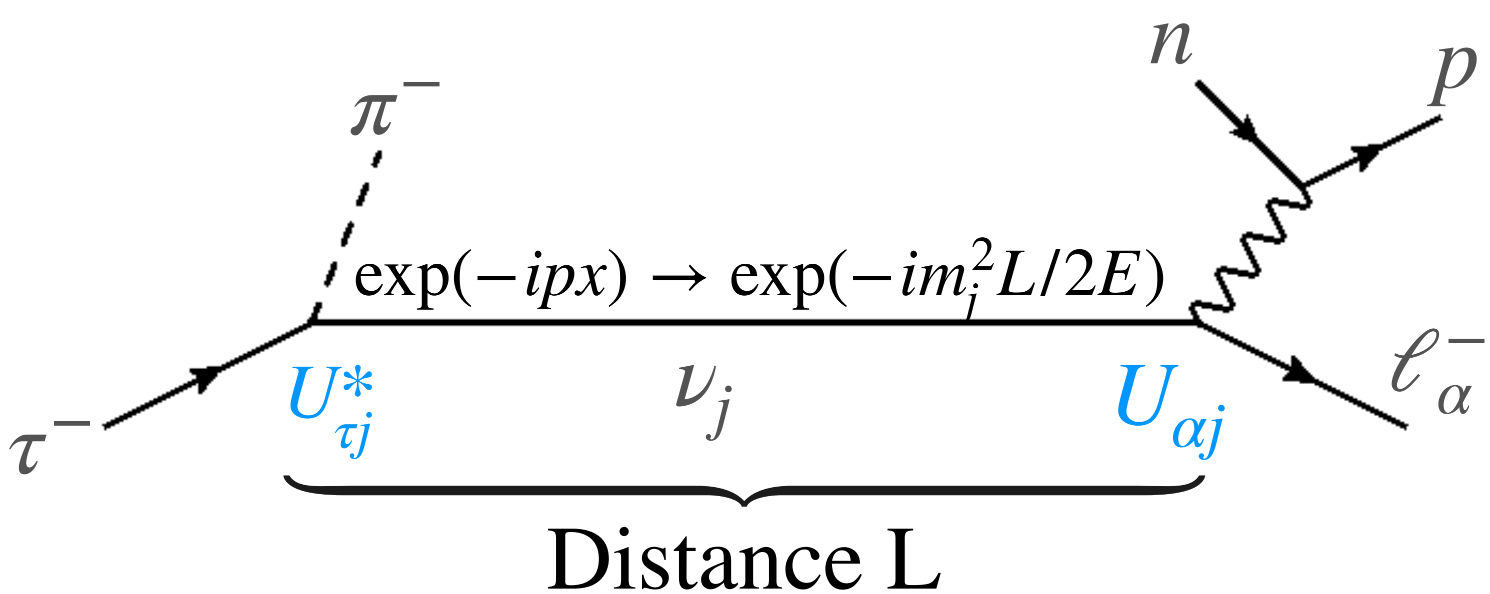
ν oscillation

In Standard Model: no ν_R ! $\Longrightarrow M_\nu = 0.$

$$|\nu_\alpha\rangle = \sum_{i=e,\mu,\tau} U_{i\alpha}|\nu_i\rangle \Longrightarrow M_\nu \neq 0$$



$$\mathrm{P}(\nu_\tau \to \nu_\alpha) = \left| \sum_j U^*_{\tau j} U_{\alpha j} \exp\left(-i\frac{m_j^2 L}{2E}\right) \right|^2$$

NuFIT 5.2 (2022)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{\mathrm{CP}}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

$\nu_\alpha \leftrightarrow \nu_\beta$ prove that SM global symmetry

$U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \Rightarrow U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$ is broken!

Lepton Flavor is definitely violated, so where is it?

Dirac vs Majorana

- Dirac neutrinos:

  Introduce ν_R to the SM ($SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$) allowing

  $$\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$$

  - $\nu = \nu_L + \nu_R \neq \bar{\nu}$
  - $U(1)_L$ conserved
  - $m_\nu = y_\nu \langle H \rangle \approx 0.1\text{eV}$, this means Yukawa coupling $y_\nu \sim 10^{-12}$!!

    $\Longrightarrow$ difficult to measure

  - ν_R only couples to Higgs

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  $\boxed{\nu_R \text{ is a SM gauge singlet } (1,1,0)}$

- Majorana neutrinos:
  - $\nu = \nu_L + \nu_L^c = \bar{\nu}$
  - $U(1)_L$ broken $\Longrightarrow$ neutrinoless double beta decay $0\nu\beta\beta$
  - Allow mass term $M \bar{\nu}_R^c \nu_R$ or add $SU(2)$ triplet Δ

Outline

- Majorana neutrinos test with lepton flavor violation

  Prediction requires flavor structure (ν oscillations) and new physics scale

Neutrino masses → New Particles → $(g-2)_\mu$, CDF anomaly, Flavor anomalies, Dark Matter → LFV

Radiative ν-models:

Zee Model, Extended Scotogenic Model, Flavor (LQ) Model

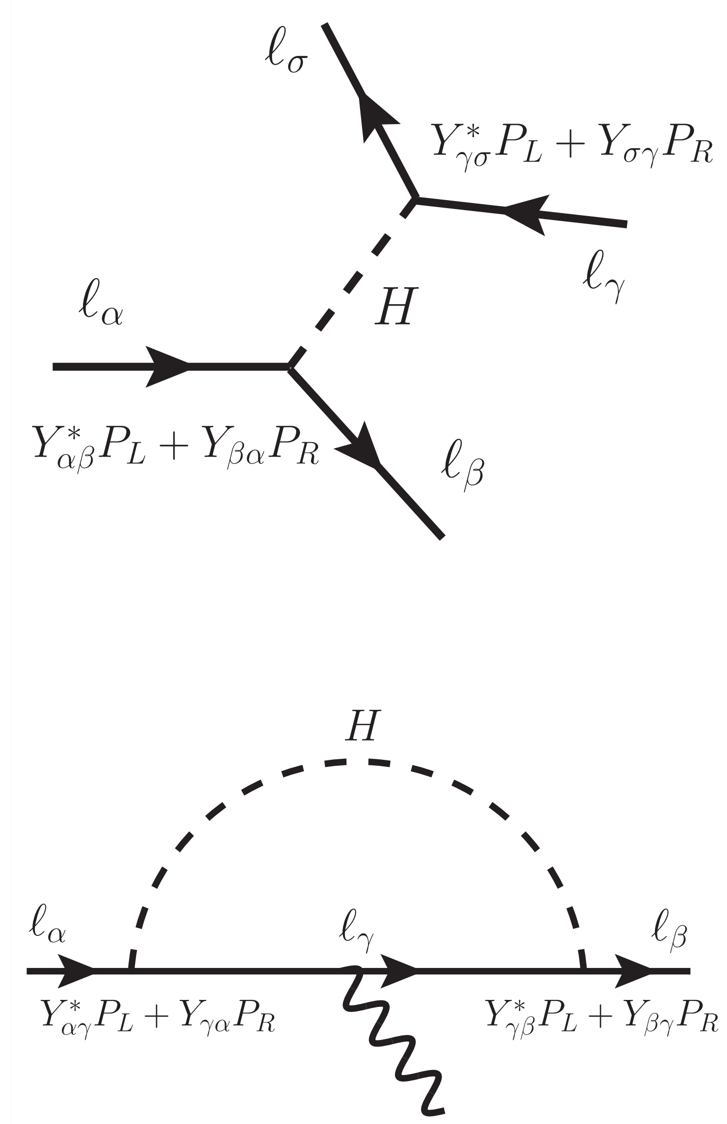
- Dirac neutrinos test with N_{eff}

Flavor violating decays

- $\mu \to e\gamma$ @ MEG, $\mu \to 3e$ @ Mu3e
- $\mu \leftrightarrow e$ conversion @ Mu2e
- $\tau \to \ell\gamma,\ \tau \to \mu\bar{\ell}\ell$ @ Belle II

	Present bound	Future sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}
$\tau \to e\gamma$	3.3×10^{-8}	9×10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	7×10^{-9}
$\mu \to eee$	1.0×10^{-12}	$\sim 10^{-16}$
$\tau \to eee$	2.7×10^{-8}	5×10^{-10}
$\tau \to \mu\mu\mu$	2.1×10^{-8}	3.5×10^{-10}
$\tau^- \to e^-\mu^+\mu^-$	2.7×10^{-8}	4.5×10^{-9}
$\tau^- \to \mu^-e^+e^-$	1.8×10^{-8}	3×10^{-10}
$\tau^- \to e^+\mu^-\mu^-$	1.7×10^{-8}	2.5×10^{-10}
$\tau^- \to \mu^+e^-e^-$	1.5×10^{-8}	2.2×10^{-10}
$e^-\mu^+ \leftrightarrow e^+\mu^-$	8.3×10^{-11}	2×10^{-14}
$\mu \leftrightarrow e$ conv. [Au]	7×10^{-13}	–
$\mu \leftrightarrow e$ conv. [Al]	–	6×10^{-17}

eg. LFV in 2HDM

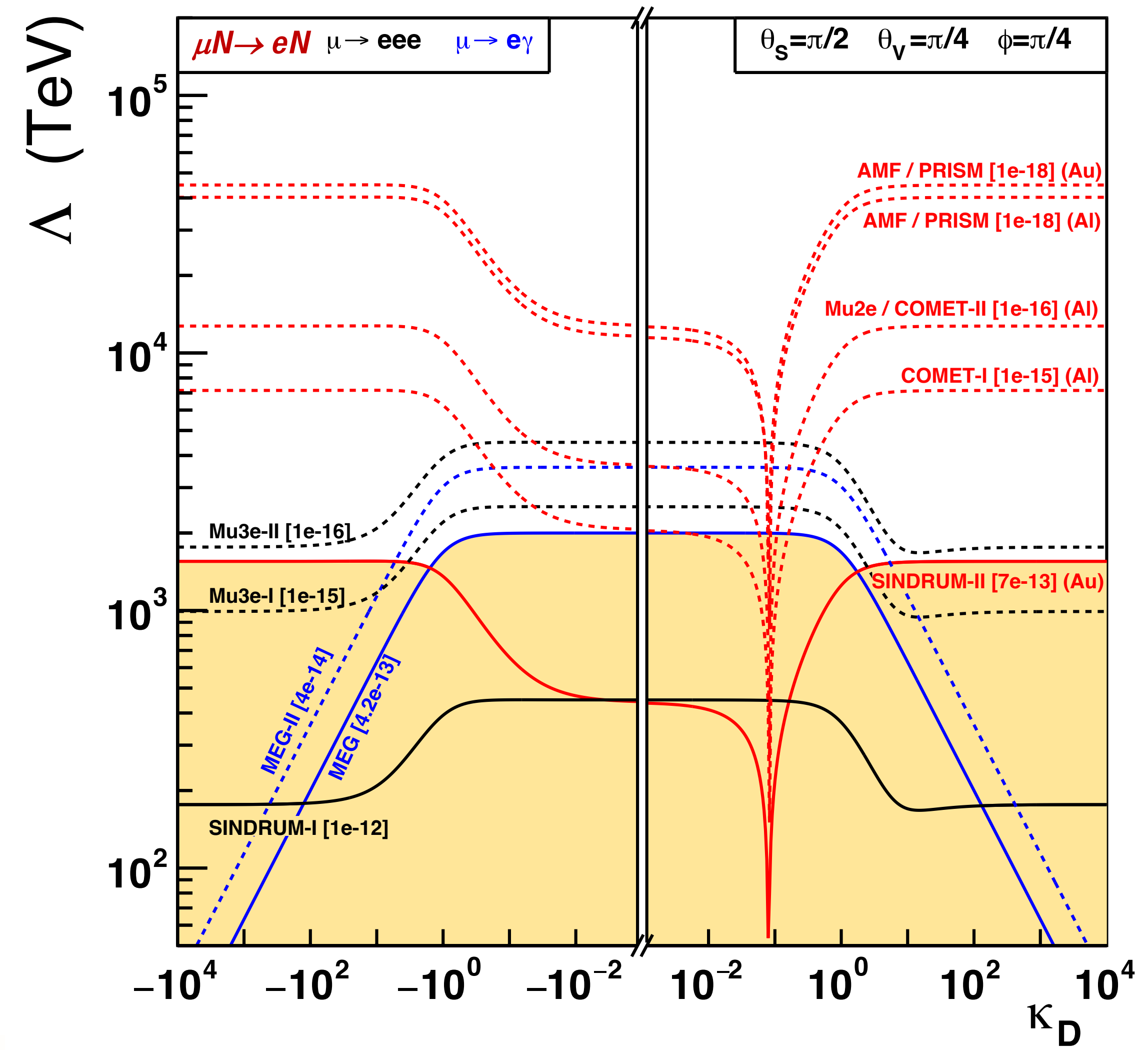


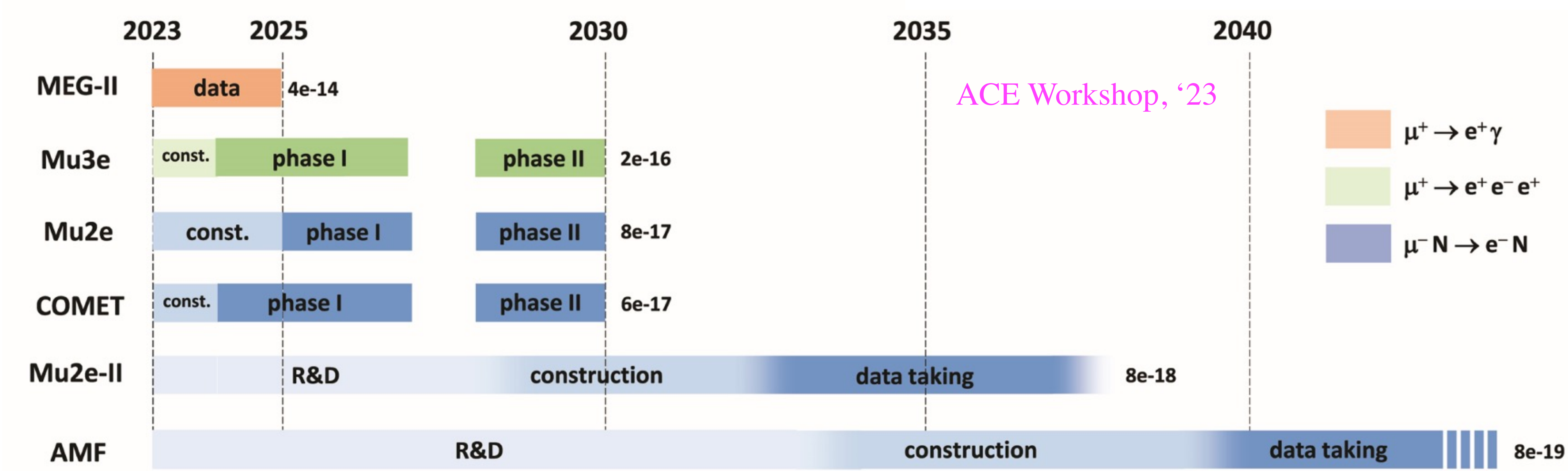
- LFV at colliders

- CLFV can prove masses $\mathcal{O}(10^3 - 10^4)$ TeV. Strongest constraints on many models.

- Mu2e will improve the current limit on conversion rate $R_{\mu e}$ by **four orders** of magnitude.

Davidson-Echenard 2204.00564

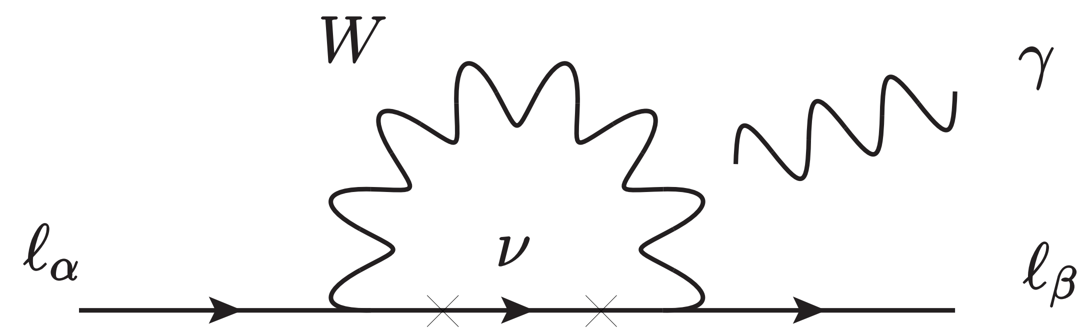




ACE Workshop, '23

$\boxed{\text{Neutrino Oscillation} \Longrightarrow \text{Flavor Violation}}$

- Dirac neutrinos: $\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$
  - $m_\nu = y_\nu \langle H \rangle \approx 0.1$ eV
  - Suppressed by Dirac mass, m_ν



$$A(\ell_\alpha \to \ell_\beta \gamma) \propto \frac{m_\nu^2}{m_W^2} < 10^{-24}!!$$

Neutrino Oscillation $\Longrightarrow$ Flavor Violation

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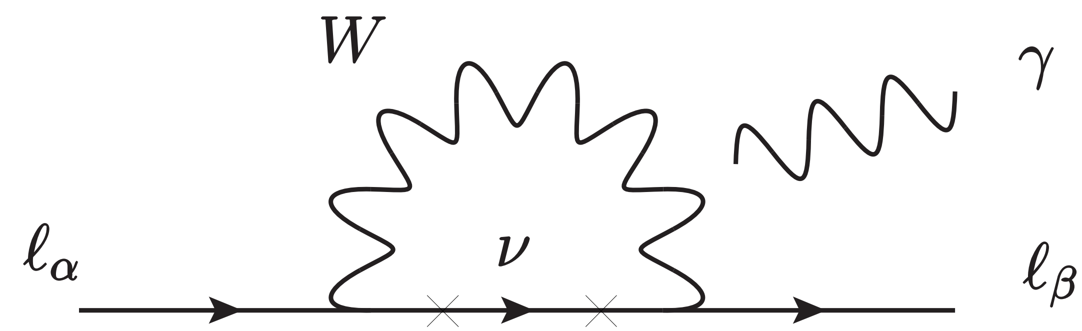
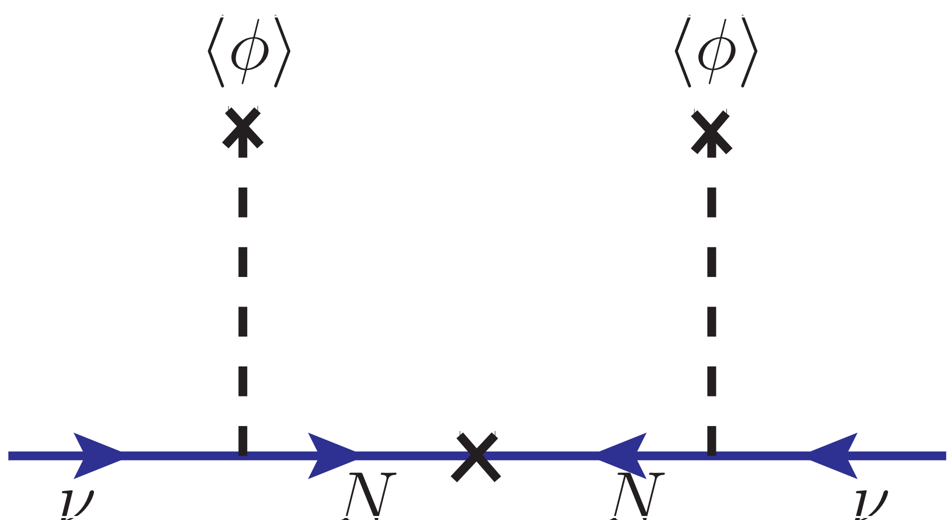


$$A(\ell_\alpha \to \ell_\beta \gamma) \propto \frac{m_\nu^2}{m_W^2} < 10^{-24}!!$$

- Seesaw mass: ν-mass is induced via Weinberg's dim-5 operator

$\mathscr{L}_Y : 1/2\ M_R \overline{N}_R^c N_R + m_D \bar{\nu}_L N_R + h.c.$



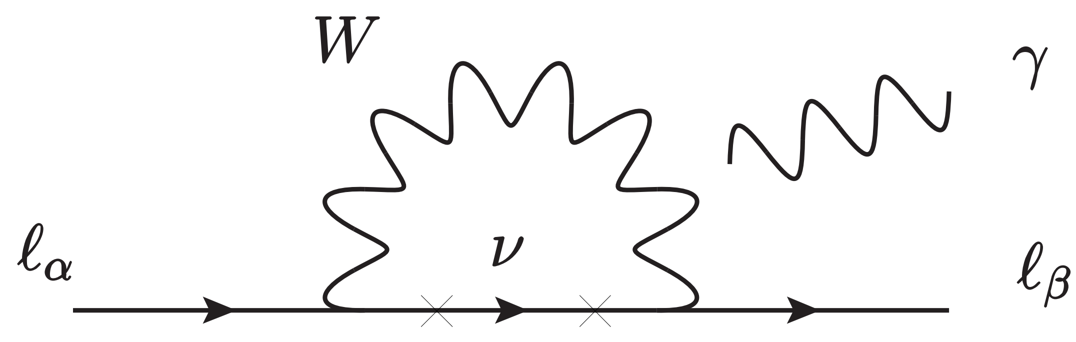
Type I / Type III : $m_\nu \sim m_D^2 / M_R$

$$\boxed{A(\ell_\alpha \to \ell_\beta \gamma) \propto (m_D M_R^{-2} m_D^\dagger)_{\alpha\beta} \simeq m_\nu / M_R}$$

Structure in m_D can give large effect

Neutrino Oscillation $\Longrightarrow$ Flavor Violation

- **Dirac neutrinos:** $\mathscr{L}_Y : y_\nu \bar{L} H \nu_R + h.c.$
  - $m_\nu = y_\nu \langle H \rangle \approx 0.1$ eV
  - Suppressed by Dirac mass, m_ν



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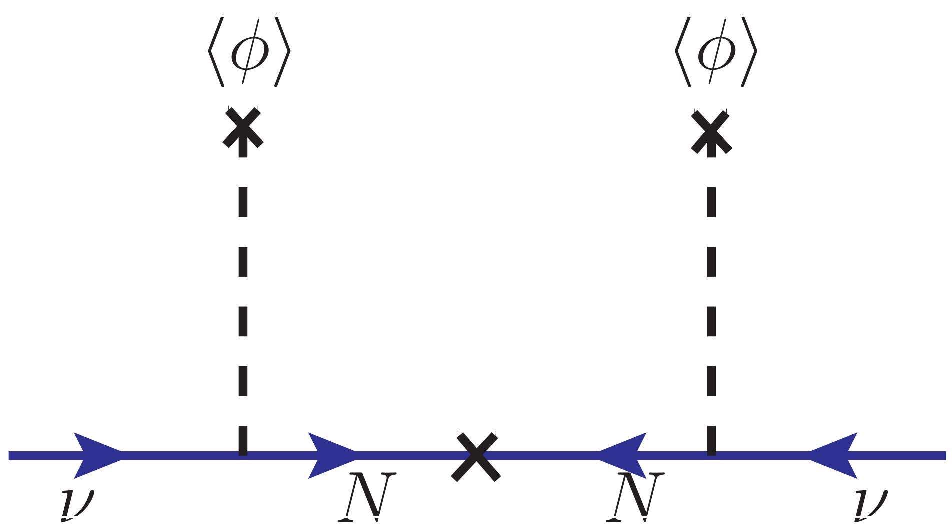
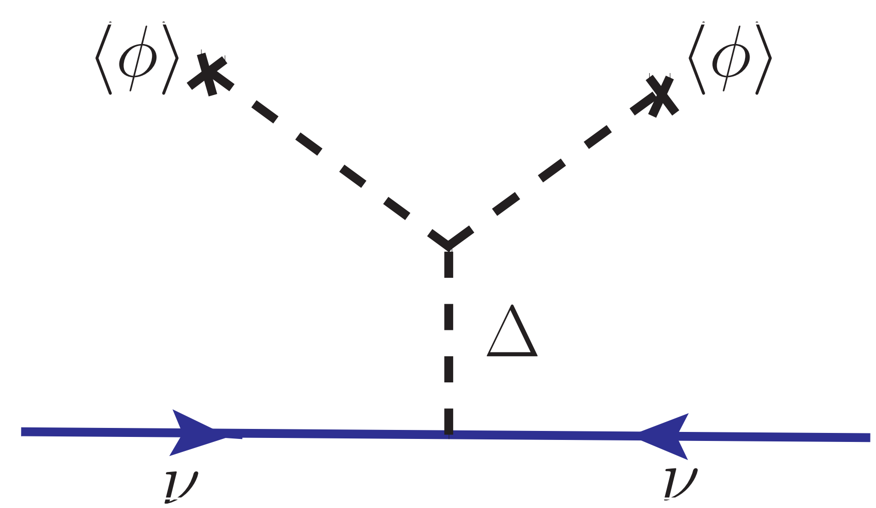


Type I / Type III : $m_\nu \sim m_D^2/M_R$

$\mathscr{L} : y\bar{L}^c \Delta L + \mu H \Delta H + h.c.$



Type II : $m_\nu \simeq y\langle\Delta\rangle$

$A(\ell_\alpha \to \ell_\beta \gamma) \propto (m_D M_R^{-2} m_D^\dagger)_{\alpha\beta} \simeq m_\nu / M_R$

Structure in m_D can give large effect

$\mathrm{BR}(\tau \to \mu\gamma) \simeq 23\mathrm{BR}(\tau \to e\gamma) \simeq 3.5\mathrm{BR}(\mu \to e\gamma)$

Prediction of LFV ratios via m_ν

What about radiative neutrino mass models?

— Each loop has $1/(16\pi^2)$ suppression

— Can tie to explain anomalies

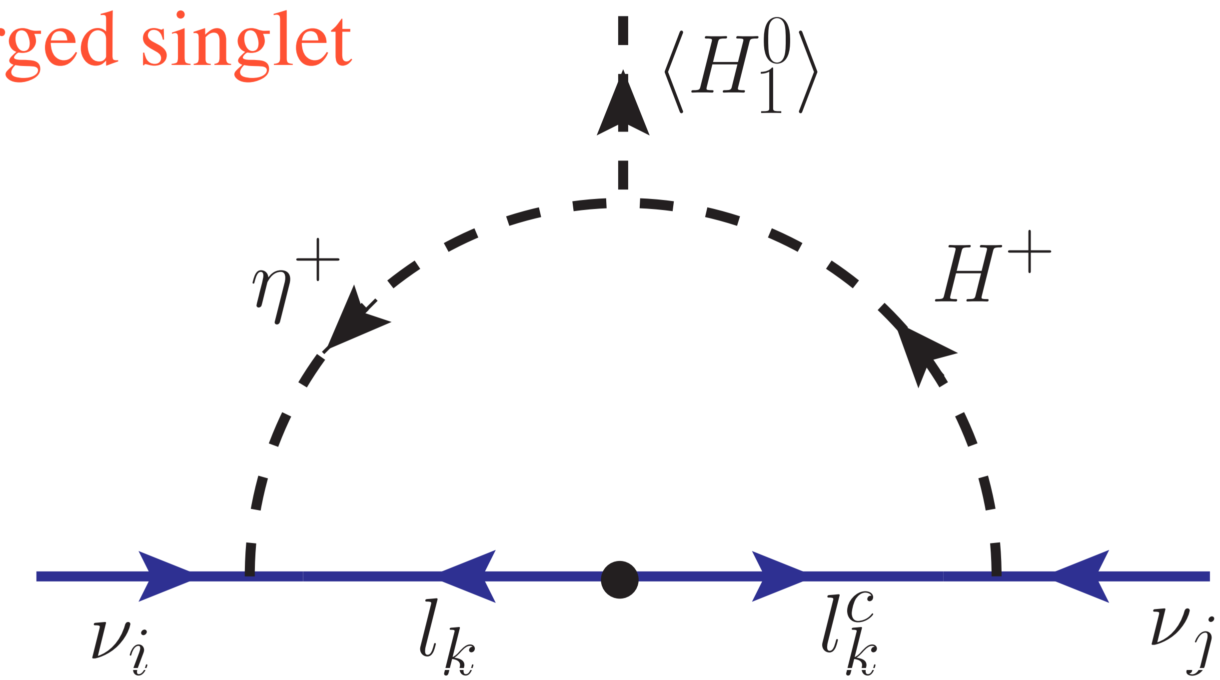
$(g-2)_\mu$, dark matter, B anomalies, … that fixes new physics scale.

$\boxed{\text{Prediction for LFV ?}}$

Zee Model, Extended Scotogenic Model, Flavor (LQ) Model

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 $\Longrightarrow$ Majorana Masses
- Simple realization: **Zee Model**, which has a second Higgs doublet and a charged singlet



$$H_1(1,2,1/2) = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}$$

$$H_2(1,2,1/2) = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

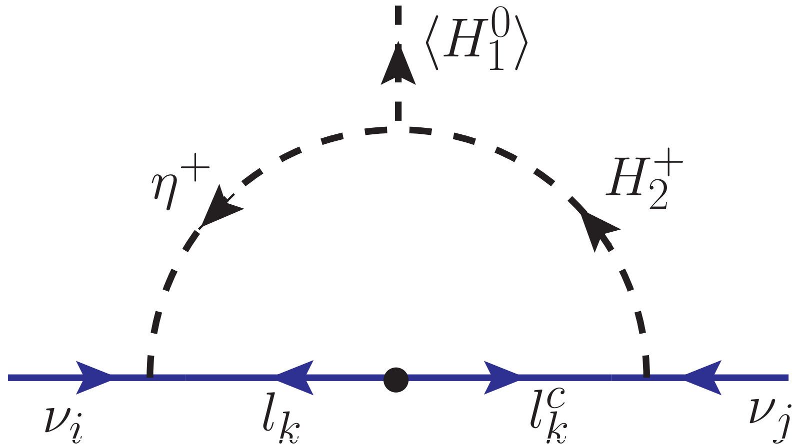
$$\eta^+(1,1,1)$$

- Smallness of neutrino mass is explained via loop and chiral suppression
- New physics in this framework may lie at the TeV scale; if connected to $(g-2)_\mu \Longrightarrow$ Prediction for LFV

Zee Model

- Gauge symmetry is same as the Standard Model

$$\boxed{-\mathscr{L} : \bar{L}^c f L \eta^+ + \bar{\ell}\tilde{Y} L \tilde{H}_1 + \bar{\ell} Y L \tilde{H}_2 - \mu H_1 H_2 \eta^-}$$



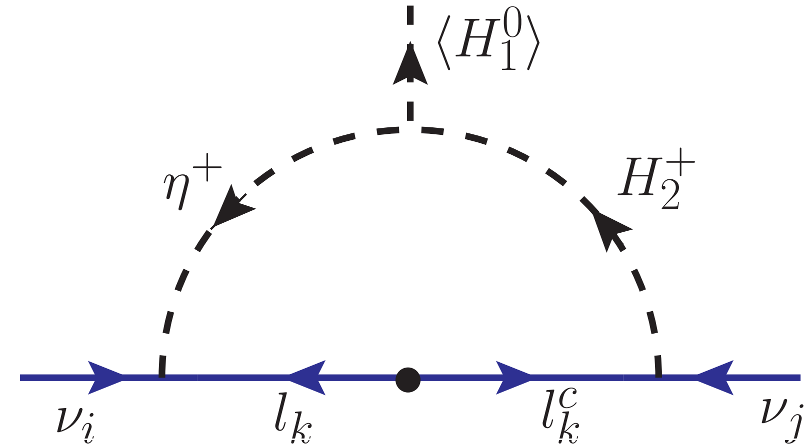
$$f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{e\tau} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

$$\boxed{\begin{aligned} M_\nu &= \kappa \left(f M_\ell Y + Y^T M_\ell f^T \right) \\ \kappa &= \frac{1}{16\pi^2} \sin 2\phi \log \left(\frac{m_{h^+}^2}{m_{H^+}^2} \right) \end{aligned}}$$

- If $Y \propto M_\ell$, which happens with a Z_2 , then the model is ruled out

[Wolfenstein '80]

Zee Model



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- If $Y \propto M_\ell$, which happens with a Z_2 , then the model is ruled out

[Wolfenstein '80]

- General Parameterization to solve for M_ν : $Y = \kappa^{-1} M_\ell^{-1} (Z + Q)$

$$Q \equiv \begin{pmatrix} 2q_4 - \frac{f_{\mu\tau}}{f_{e\tau}} q_1 & \frac{f_{\mu\tau}}{f_{e\tau}} (q_4 - q_2) & -\frac{2f_{\mu\tau}}{f_{e\mu}} q_4 - \frac{f_{\mu\tau}}{f_{e\tau}} q_3 \\ q_1 & q_2 + q_4 & \frac{2f_{e\tau}}{f_{e\mu}} q_4 + q_3 \\ -\frac{f_{e\mu}}{f_{e\tau}} q_1 & \frac{f_{e\mu}}{f_{e\tau}} (q_4 - q_2) & -\frac{f_{e\mu}}{f_{e\tau}} q_3 \end{pmatrix} \qquad Z \equiv \begin{pmatrix} -\frac{M^\nu_{e\tau}}{f_{e\tau}} & 0 & -\frac{M^\nu_{\tau\tau}}{2f_{e\tau}} \\ 0 & \frac{f_{e\mu} M^\nu_{\tau\tau} - 2 f_{e\tau} M^\nu_{\mu\tau}}{2 f_{e\tau} f_{\mu\tau}} & 0 \\ \frac{M^\nu_{ee}}{2f_{e\tau}} & \frac{M^\nu_{\mu\mu}}{2f_{\mu\tau}} & 0 \end{pmatrix}$$

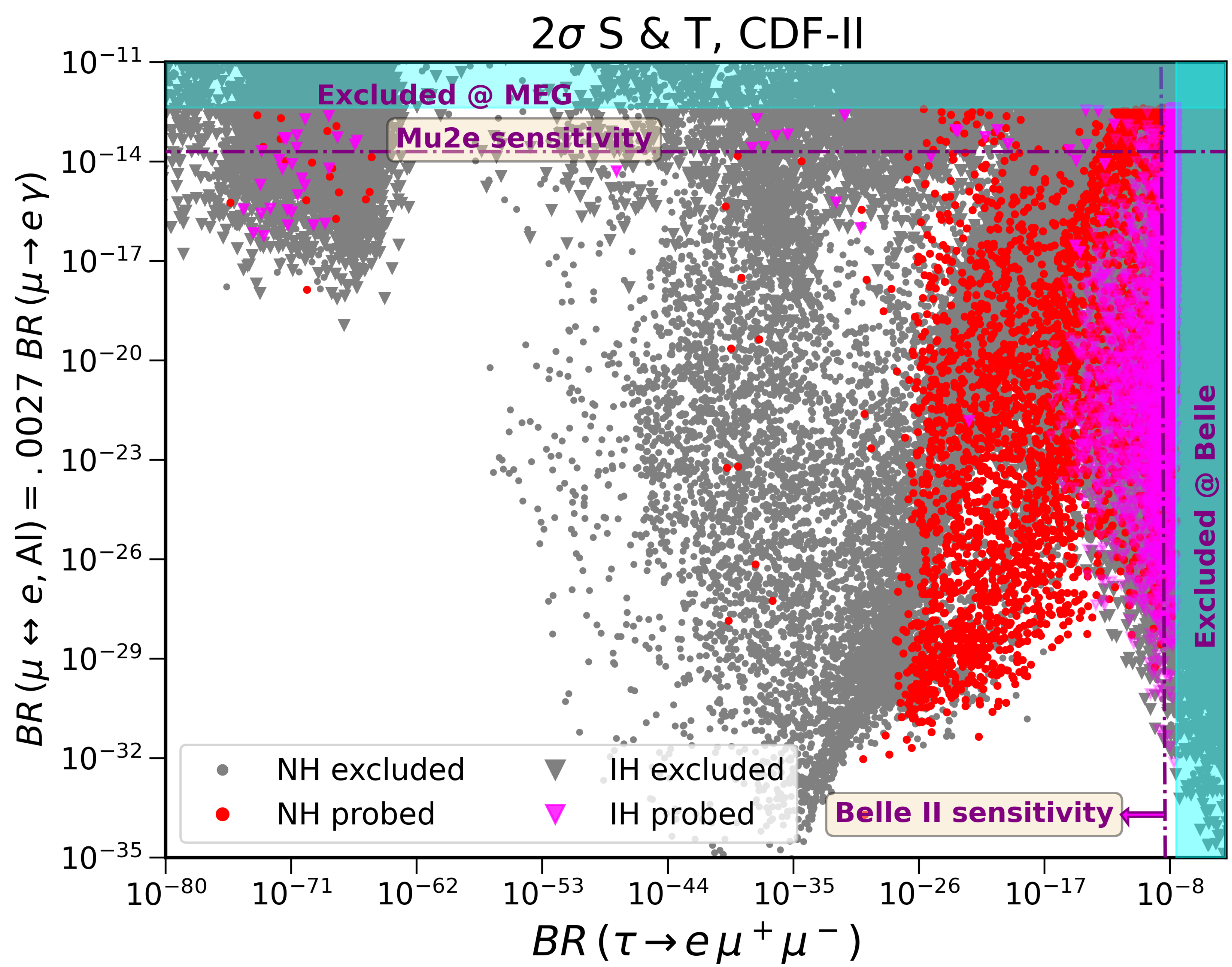
[Pleitez, et al. '17]

$$|q_1| < \sqrt{4\pi} m_\mu \kappa \qquad |q_2| < \sqrt{4\pi} \, |f_{e\tau}/f_{\mu\tau}| \, m_e \kappa + \sqrt{\pi} \, |f_{e\mu}/f_{e\tau}| \, m_\mu \kappa + \sqrt{\pi} m_\tau \kappa$$

$$|q_3| < \sqrt{4\pi} \, |f_{e\tau}/f_{e\mu}| \, m_\tau \qquad |q_4| < \sqrt{\pi} \, |f_{e\mu}/f_{e\tau}| \, m_\mu \kappa + \sqrt{\pi} m_\tau \kappa$$

Zee Model prediction for LFV

- $\nu_{aL} \leftrightarrow \nu_{bL} \Longrightarrow e, \mu, \tau$ number are violated
- Second Higgs to explain $(g-2)_\mu \Longrightarrow$ Prediction for LFV



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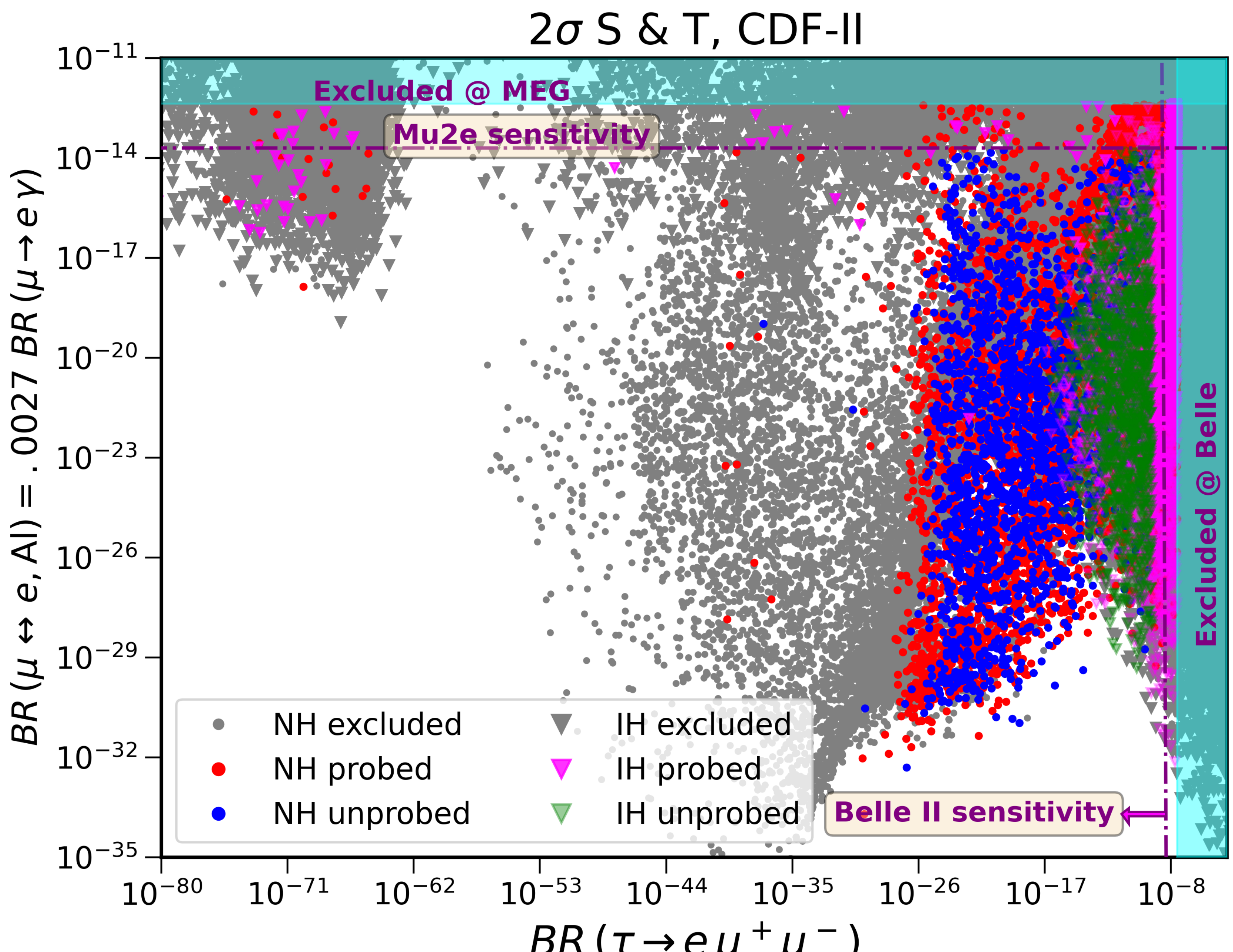
Blue and Green Points:

texture zero	ordering	$\sum_j m_j$/meV	$\langle m_{\beta\beta} \rangle$/meV
$M_{ee} = 0$	normal	$\in [60, 65]$	0
$M_{ee} = 0$	inverted	–	–
$M_{\mu\mu} = 0$	normal	> 150	> 41
$M_{\mu\mu} = 0$	inverted	> 98	> 15

[Heeck, **Thapa** '23]



Observation $\Longrightarrow$ new particles beyond SM and ν

Minimal texture $\Longrightarrow$ concrete Prediction

$$Y = \begin{array}{c} \begin{array}{ccc} \phantom{\frac{M^\nu_{ee}M^\nu_{\mu\mu}}{4f_{e\mu}m_\tau\kappa M^\nu_{\mu\tau}}} & (g-2)_\mu & \end{array} \\ \begin{pmatrix} 0 & \boxed{\dfrac{-M^\nu_{\mu\mu}}{2f_{e\mu}m_e\kappa}} & 0 \\ 0 & 0 & 0 \\ \dfrac{M^\nu_{ee}M^\nu_{\mu\mu}}{4f_{e\mu}m_\tau\kappa M^\nu_{\mu\tau}} & 0 & 0 \end{pmatrix} \end{array}$$

- Leads to $M^\nu_{e\tau} = M^\nu_{\tau\tau} = 0$ (texture-2 zero)

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NH : $m_\ell > 3.8$ meV, $m_{\beta\beta} > 0.15$ eV
$\delta_{CP} \simeq [266 - 269]$
$\alpha_1 \simeq [182 - 187]$, $\alpha_2 \simeq [177 - 179]$

IH : $m_\ell > 5.0$ meV, $m_{\beta\beta} > 0.48$ eV
$\delta_{CP} \simeq [270 - 271]$
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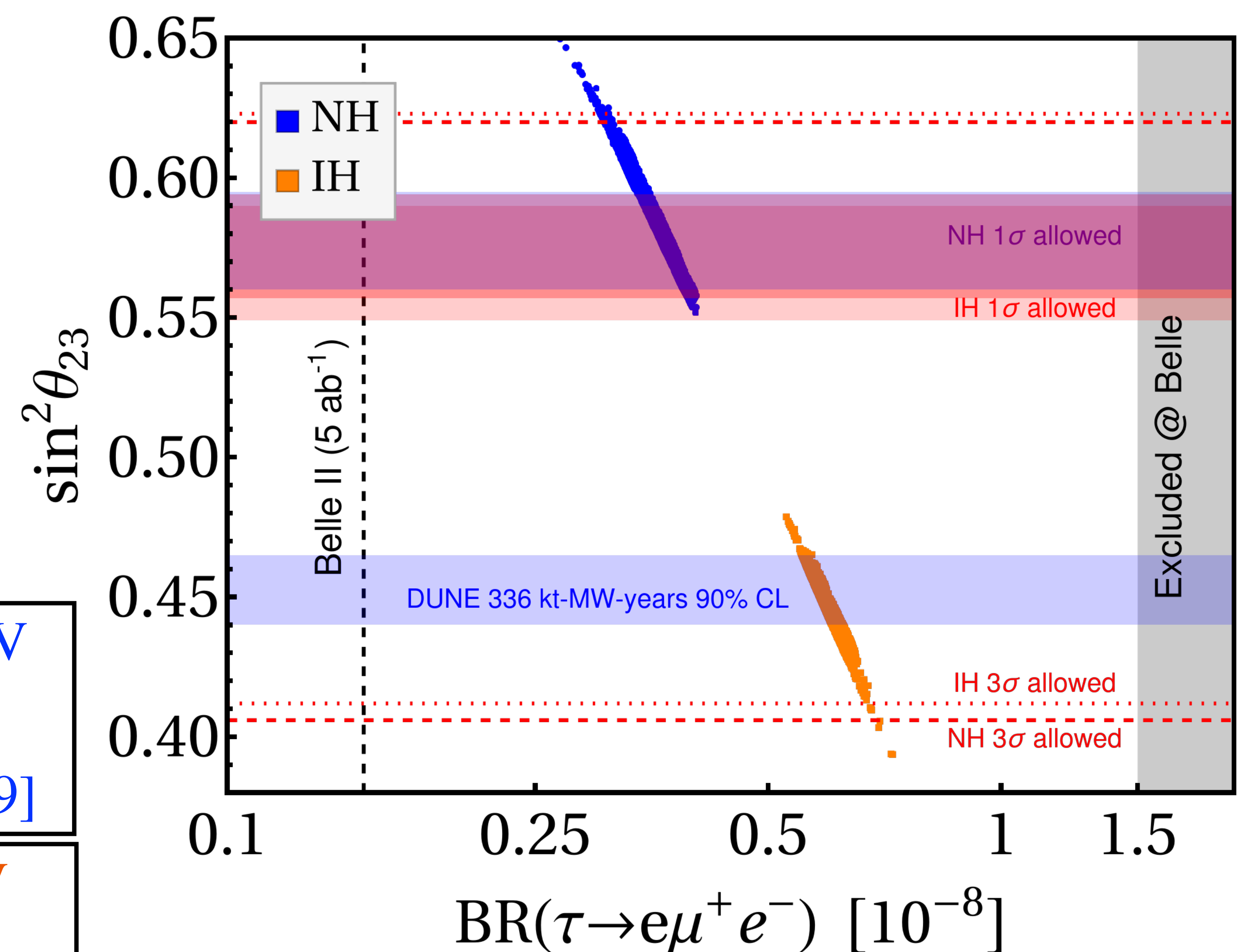

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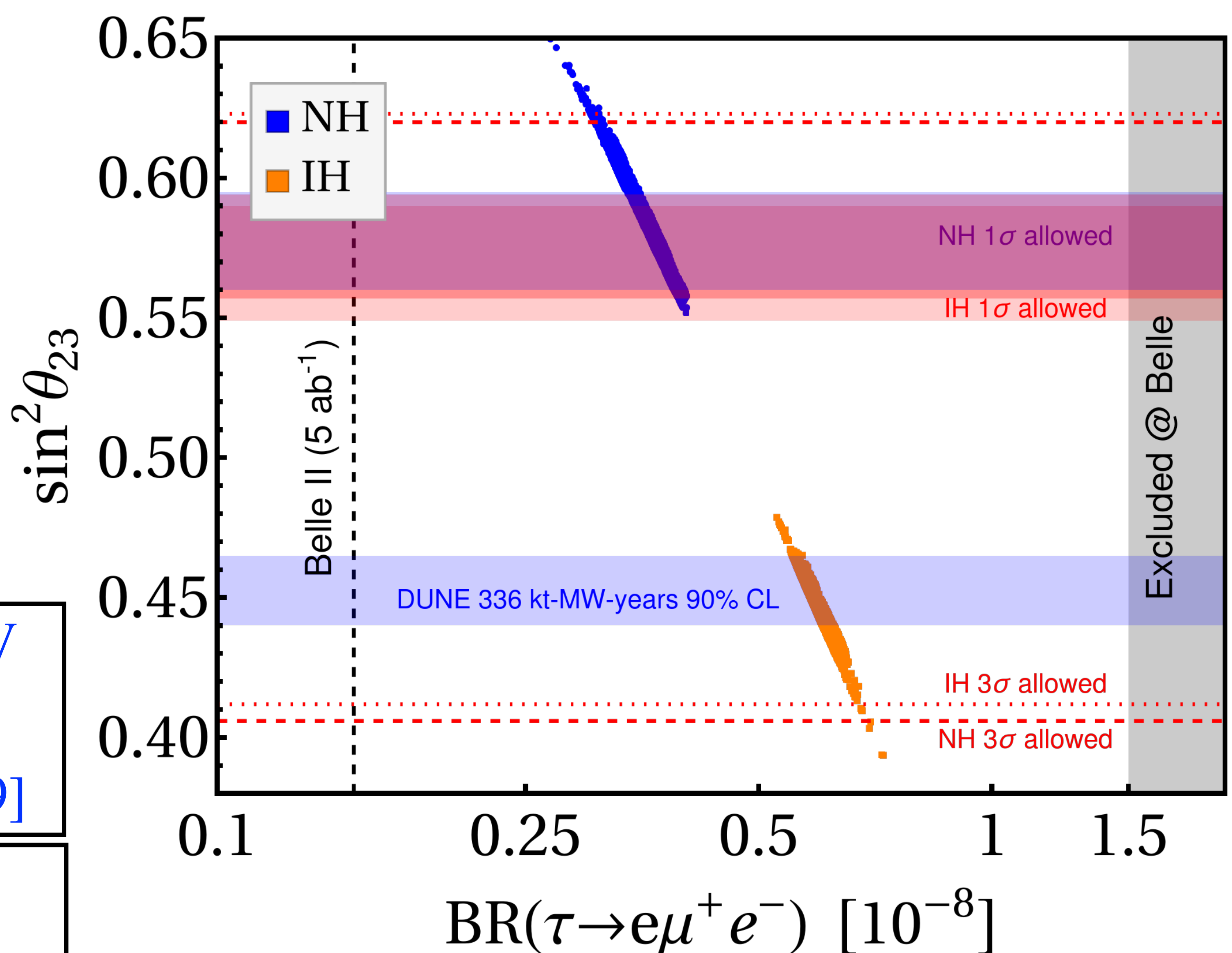
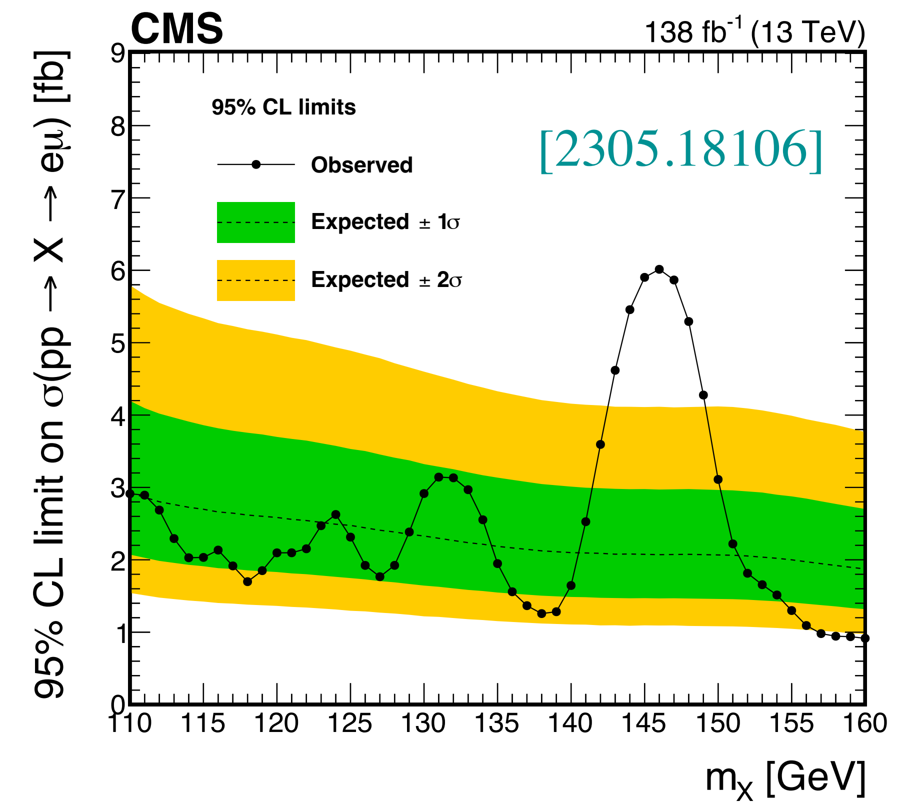


- Flavor violating Yukawa coupling $Y_{12} \equiv Y_{e\mu}$ can explain recent CMS excess (3.8σ local) in resonant $e\mu$ channel [Afik, Dev, **Thapa**, '23]

- CMS reported 3.8σ local (2.8σ global) excess in the resonant $e\mu$ search around 146 GeV, with a preferred cross-section of $3.89^{+1.25}_{-1.13}$ fb
- Use the lepton (PDF) of the proton to explain CMS excess! [Bertone et.al '15, Buonocore '20, Dreiner '21]



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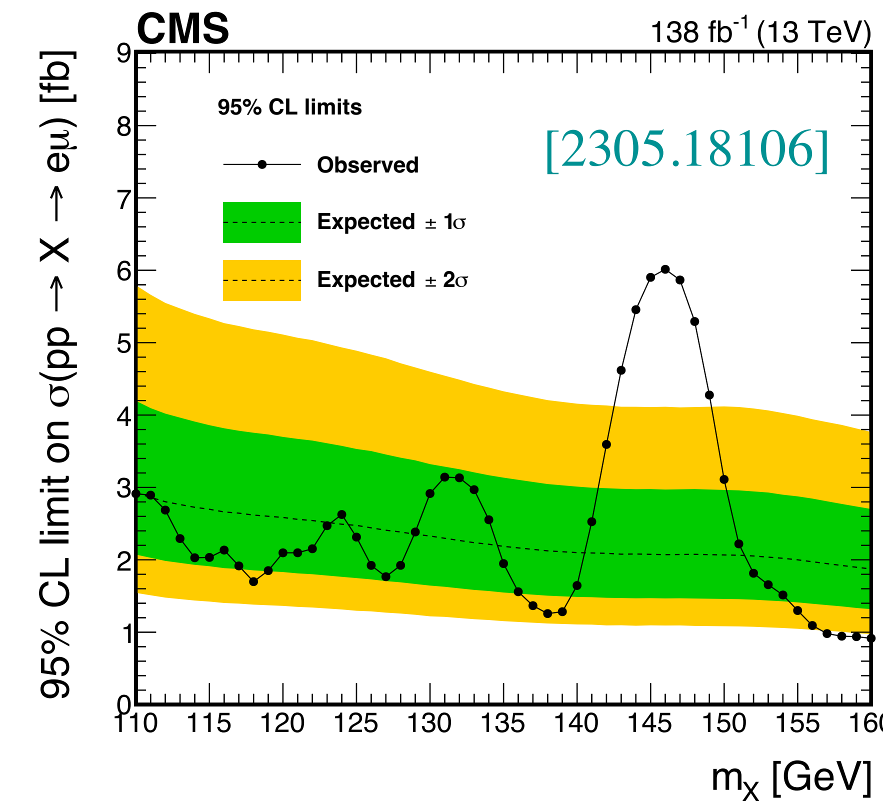

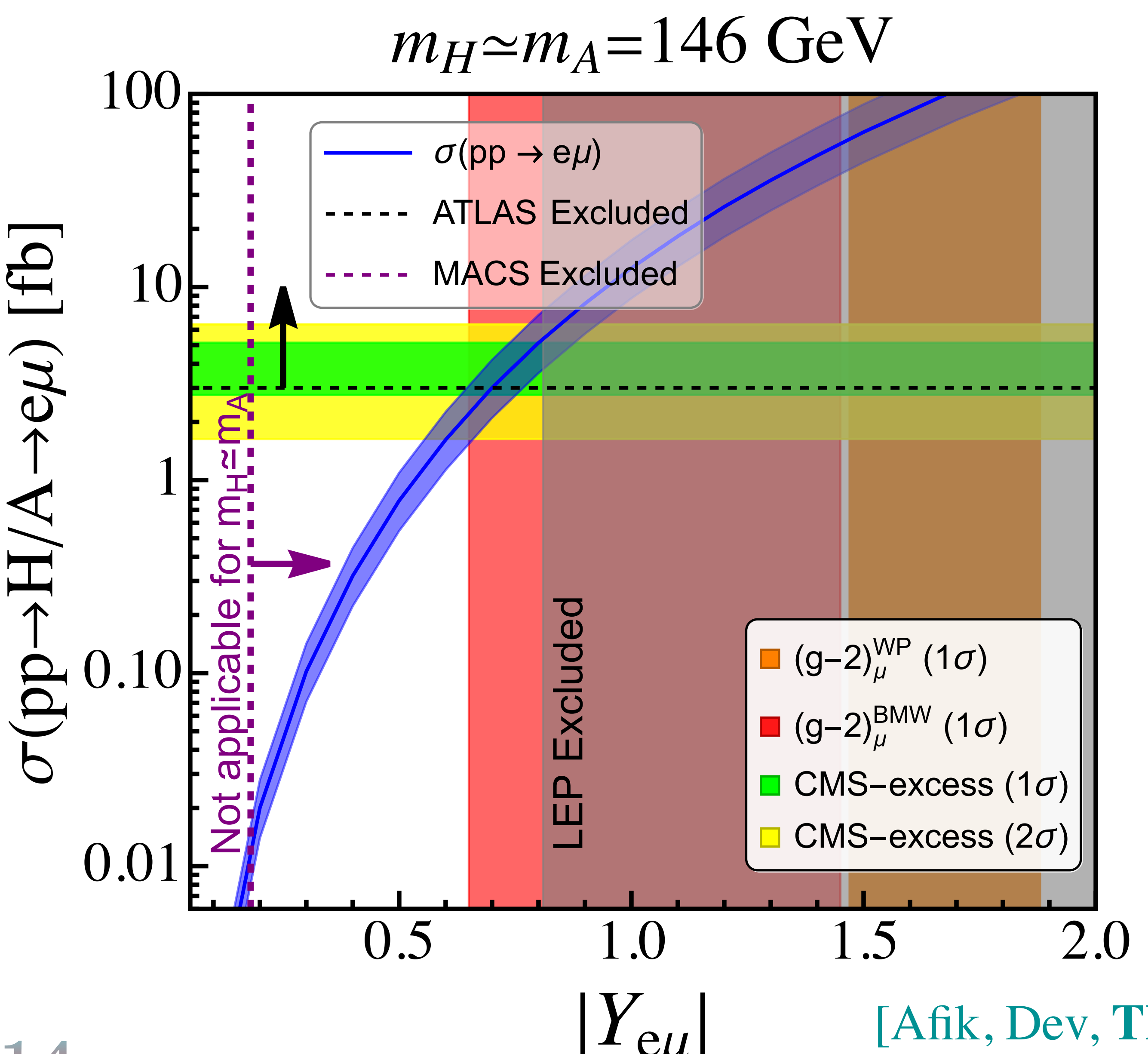

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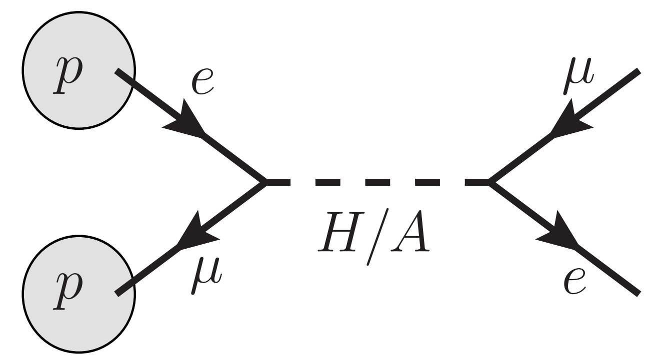

- Leptophilic neutral (pseudo) scalars with Yukawa coupling $Y_{e\mu} \sim 0.55 - 0.81$ gives right cross-section
- Same parameter space can explain $(g-2)_\mu$ as well as CDF W-boson mass anomaly

Radiative neutrino mass models

— Each loop has $1/(16\pi^2)$ suppression

— Can tie to explain anomalies

$(g-2)_\mu$, dark matter, B anomalies, … that fixes new physics scale.

$\boxed{\text{Prediction for LFV ?}}$

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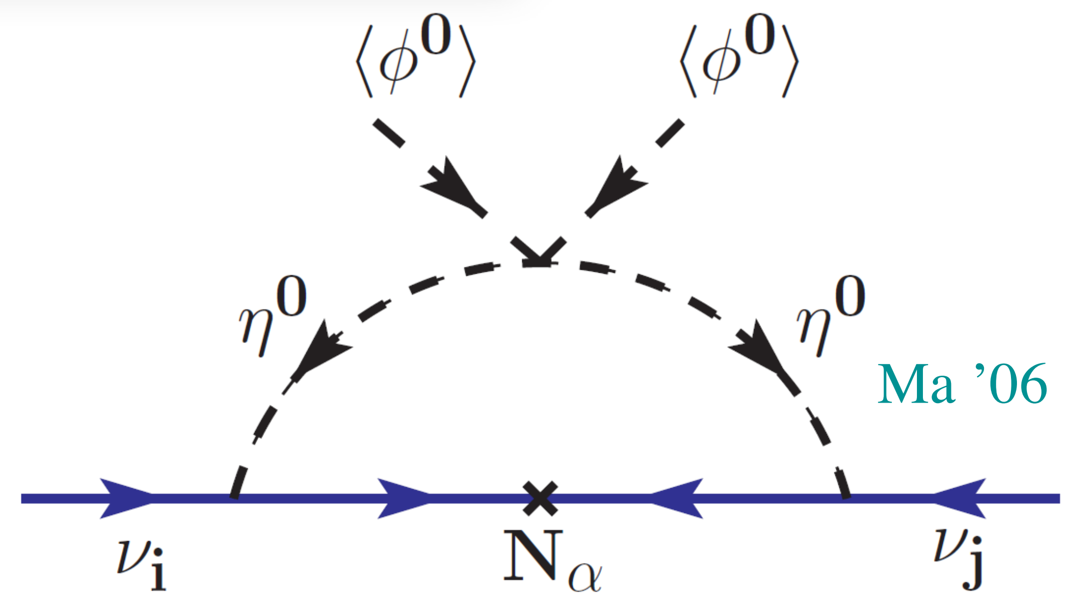
Scotogenic Model: Dark Matter

- No Standard Model particle inside the loop
- Neutrino mass has no chiral suppression; new scale can be large
- Z_2 symmetry forbids tree-level contribution to Dirac neutrino mass and gives rise to dark matter candidate. DM require TeV scale new physics

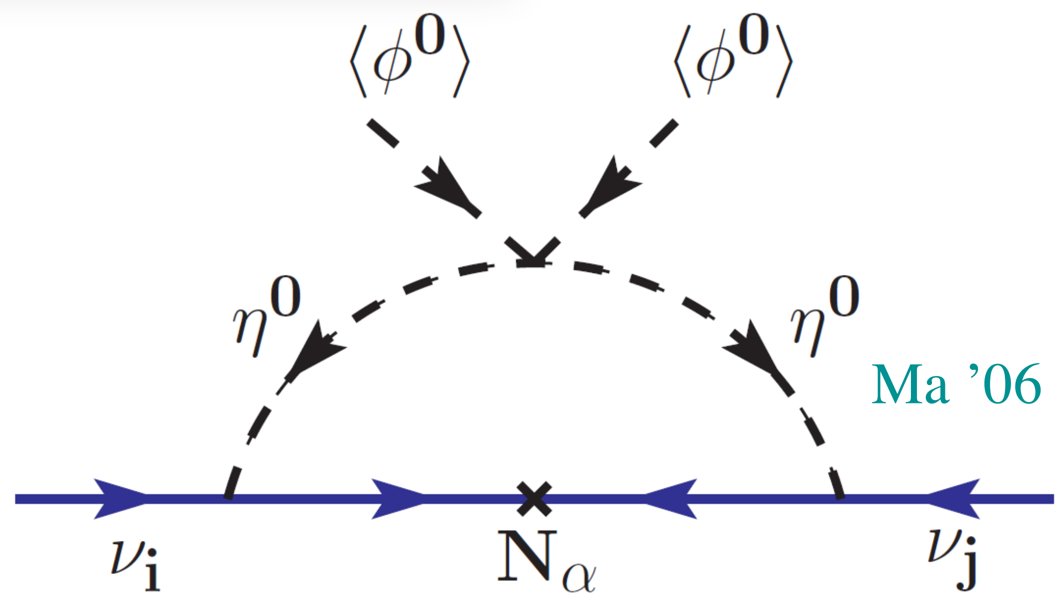


$$\eta(1,2,1/2,-) = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$$

$$N(1,1,0,-)$$

Scotogenic Model: Dark Matter

- No Standard Model particle inside the loop
- Neutrino mass has no chiral suppression; new scale can be large
- Z_2 symmetry forbids tree-level contribution to Dirac neutrino mass and gives rise to dark matter candidate. DM require TeV scale new physics



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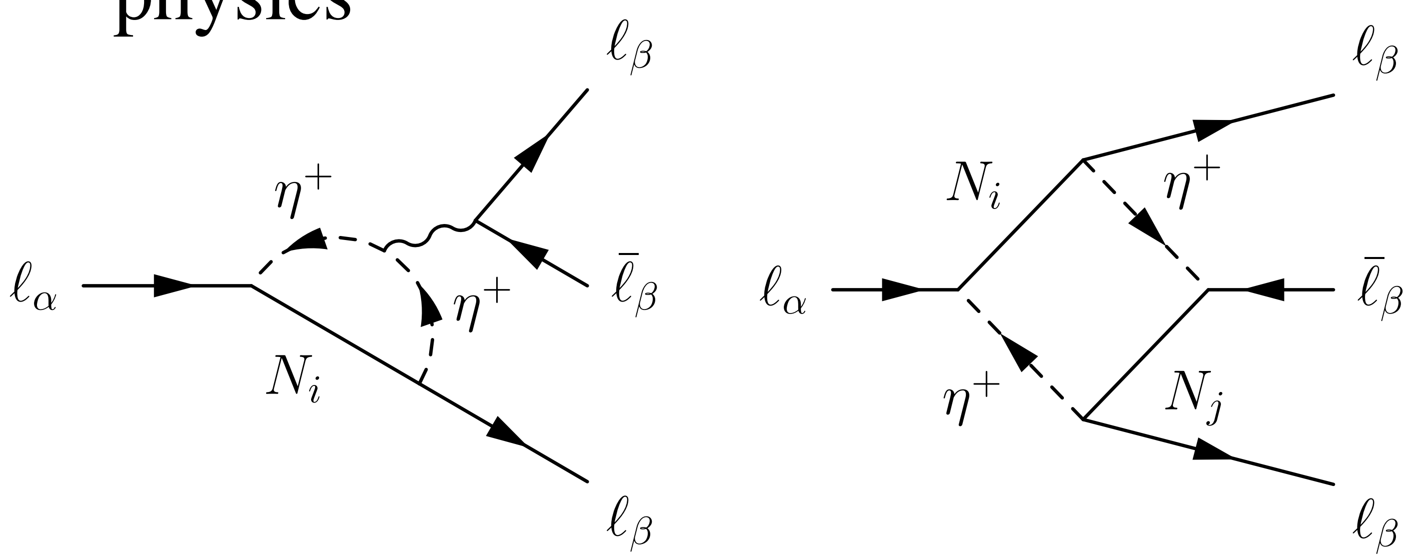
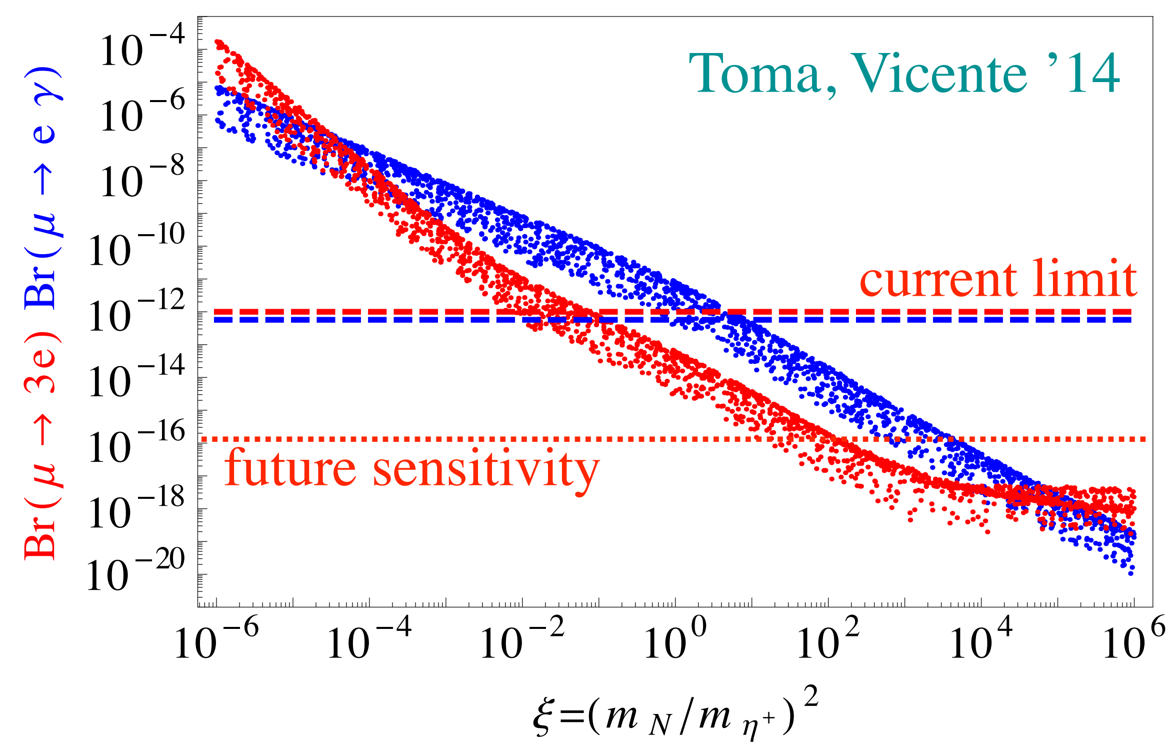




- Most parameters are probed but still difficult to have firm prediction!

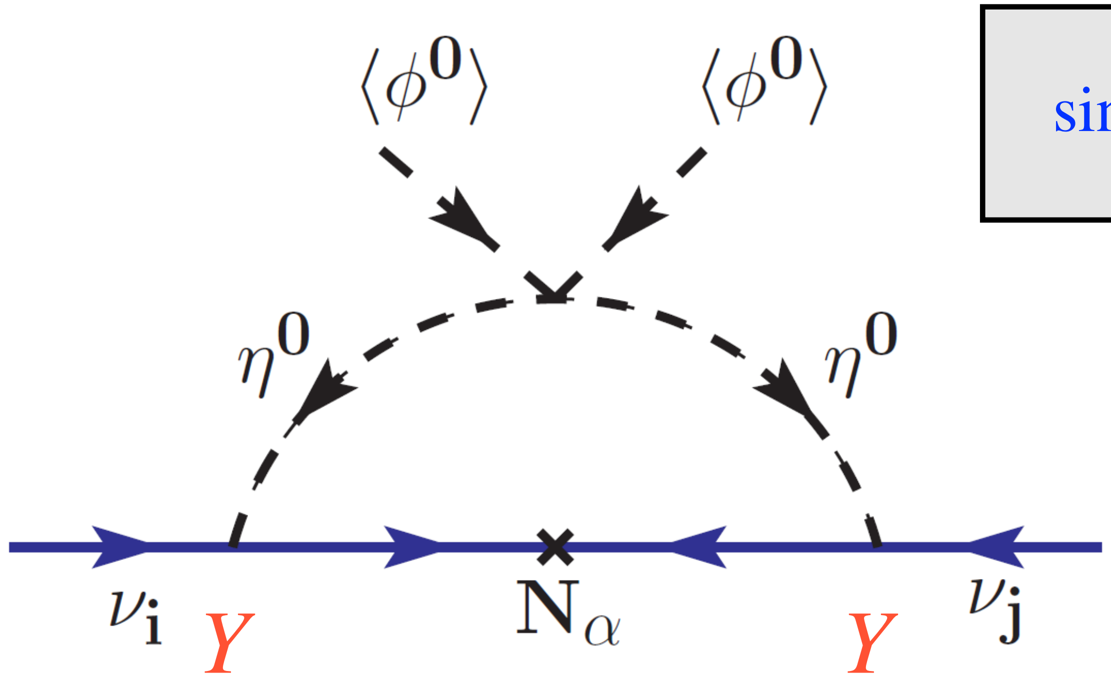
Can we do more!

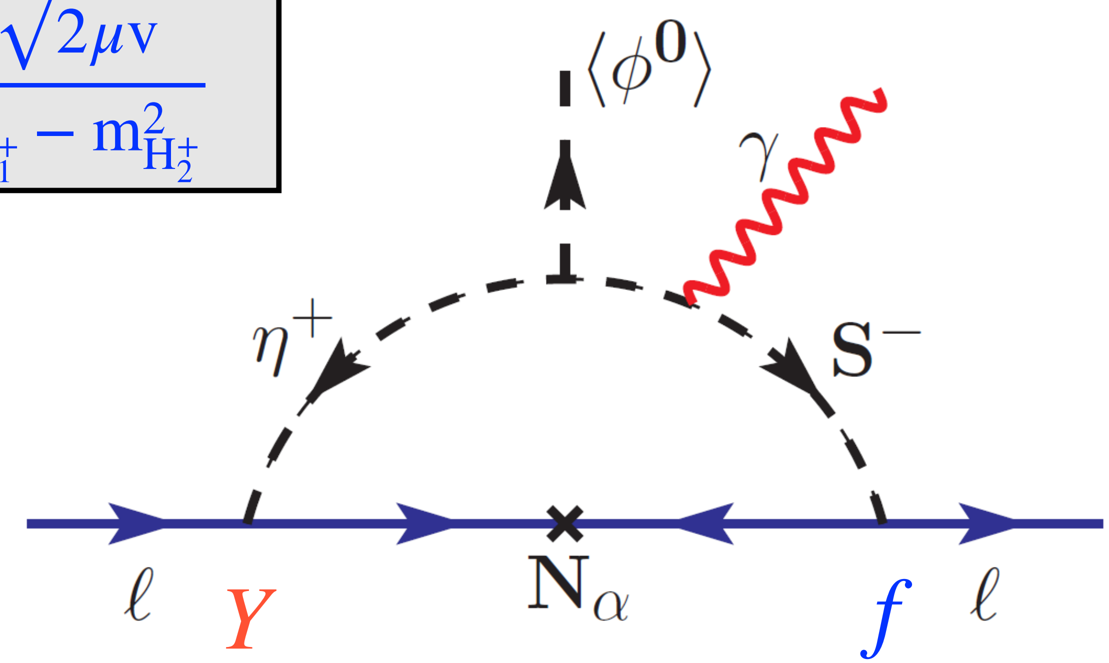
Can we do more!

- Extend scotogenic model with charged singlet $S^{-}(1,1,-1,-)$ that allows $f_{ij}\ \bar{\ell}_{R_i} S^{-} \bar{N}_{R_j}$

[Dcruz, **Thapa**, '22]

$$\sin 2\theta = \frac{-\sqrt{2}\mu v}{m^2_{H_1^+} - m^2_{H_2^+}}$$





$$M^{\nu}_{ij} = \sum_k Y_{ik}\Lambda_k Y^{*}_{kj}$$

$$\Lambda_k = \frac{M_{N_k}}{32\pi^2}\left[\frac{m_H^2}{m_H^2 - M_{N_k}^2}\log\frac{m_H^2}{M_{N_k}^2} - (m_H \leftrightarrow m_A)\right]$$

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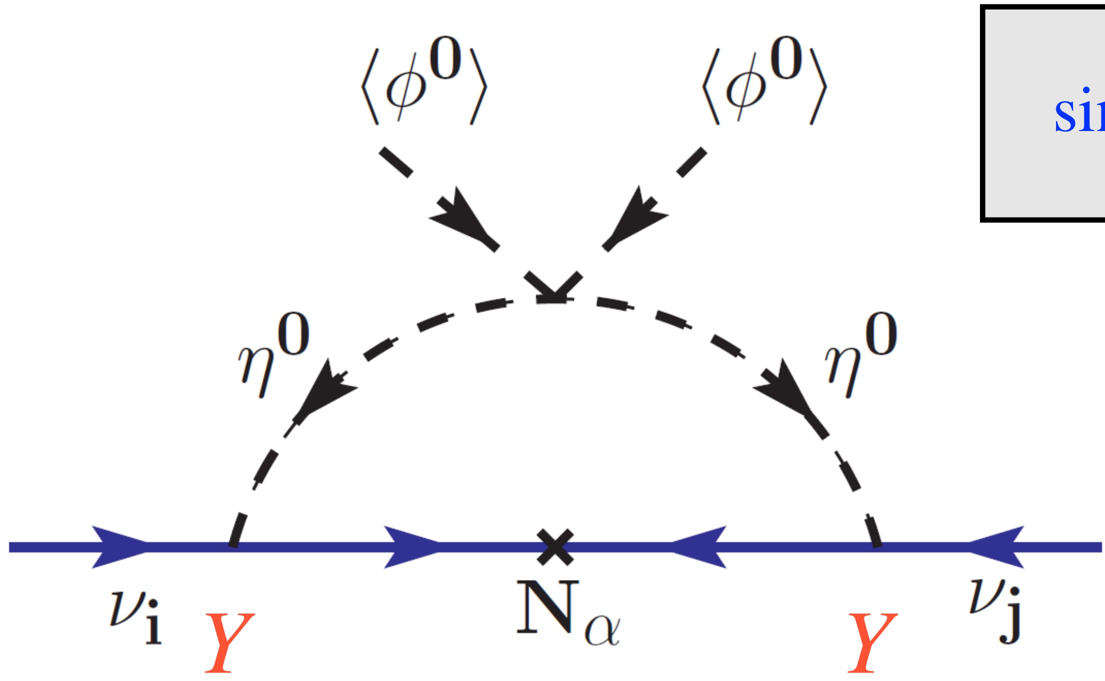

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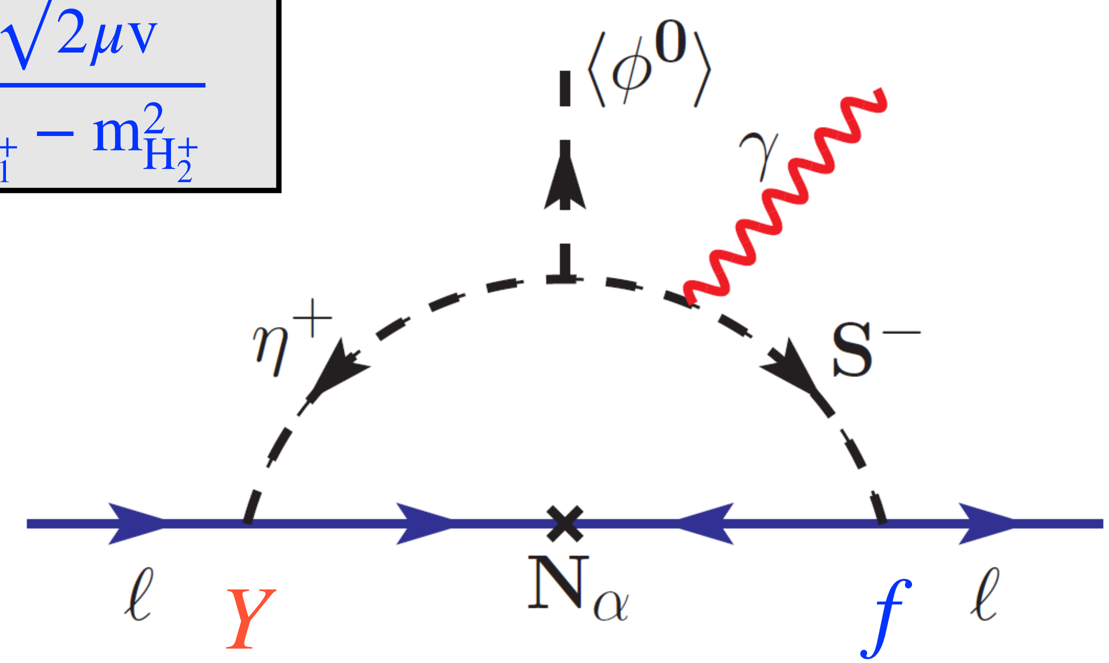

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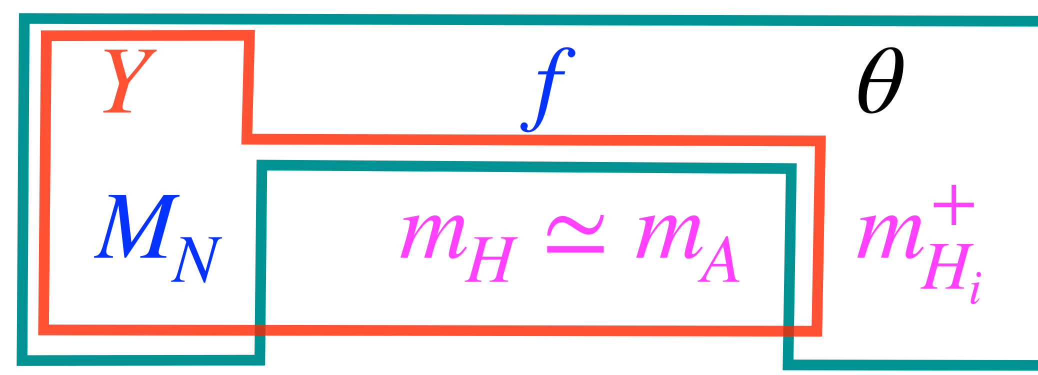
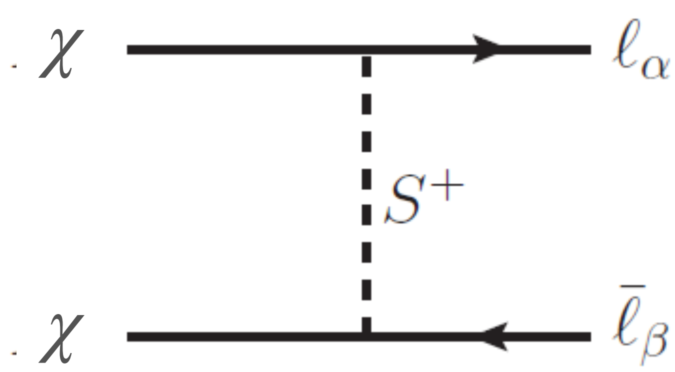
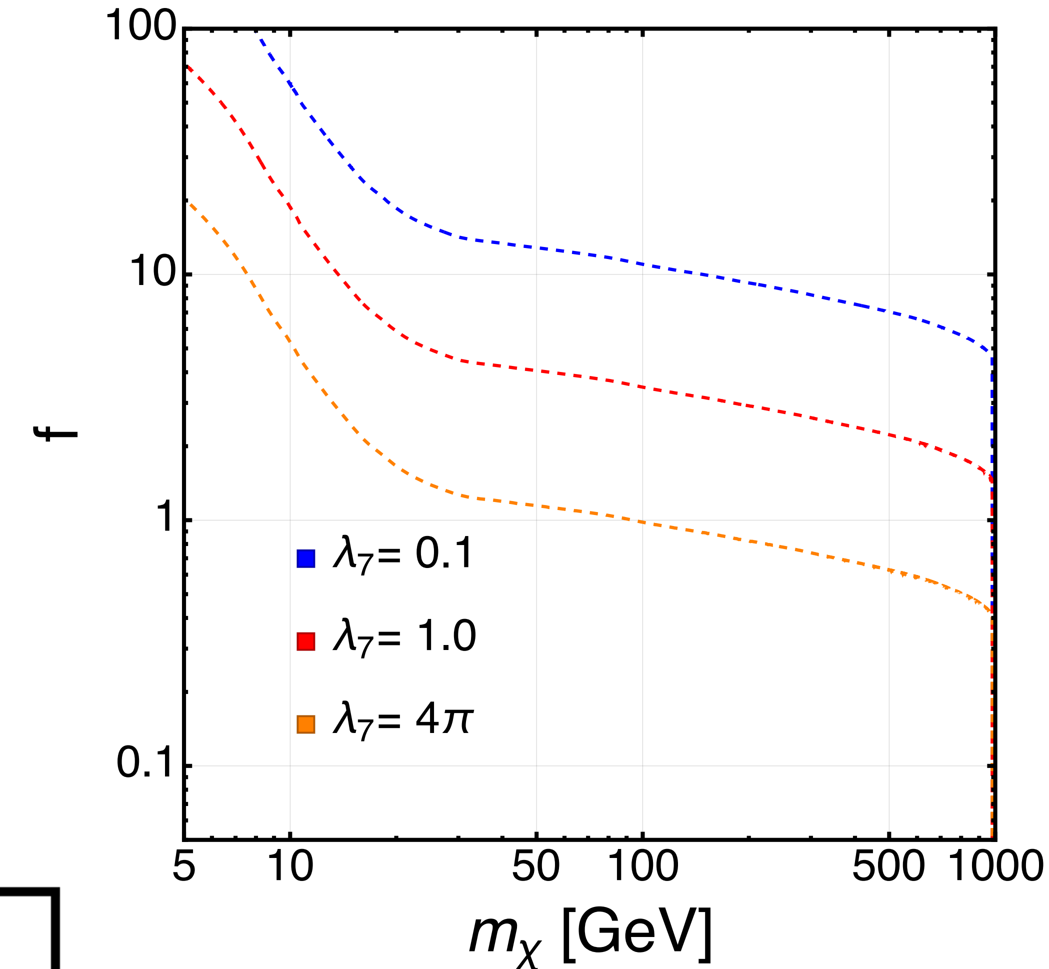


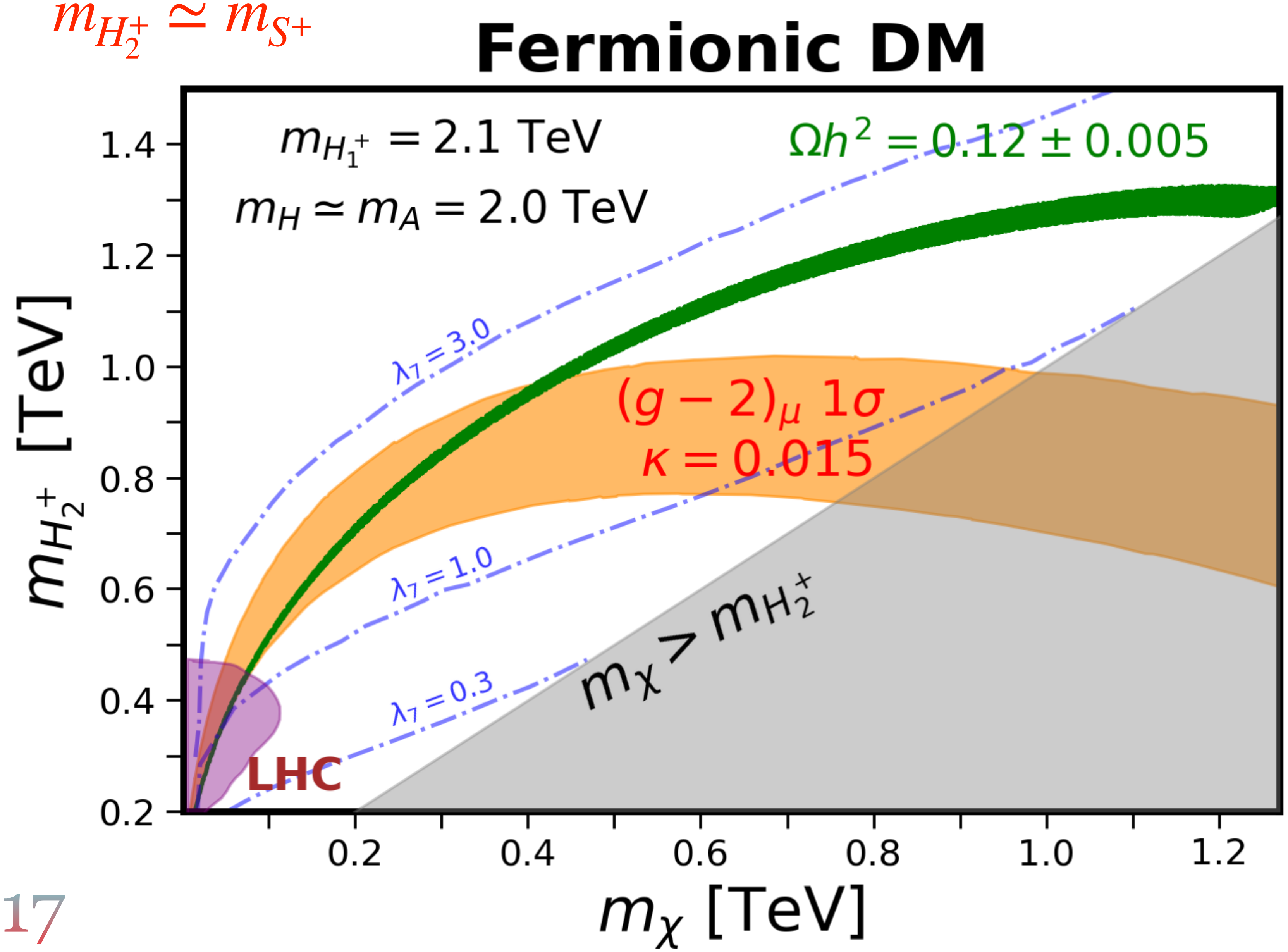
Neutrino mass, AMM, Scalar DM, Fermionic DM,
W-mass correction, LFV prediction

- The lightest of the right-handed neutrinos is the fermionic DM candidate.

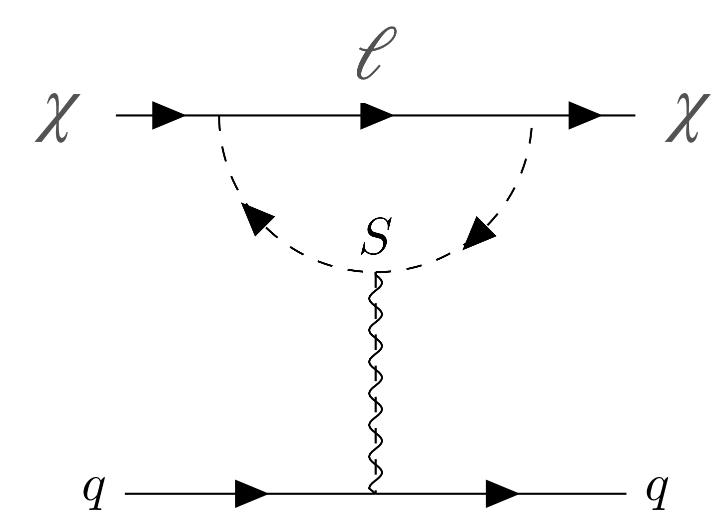




$m_{H_2^+} \simeq m_{S^+}$



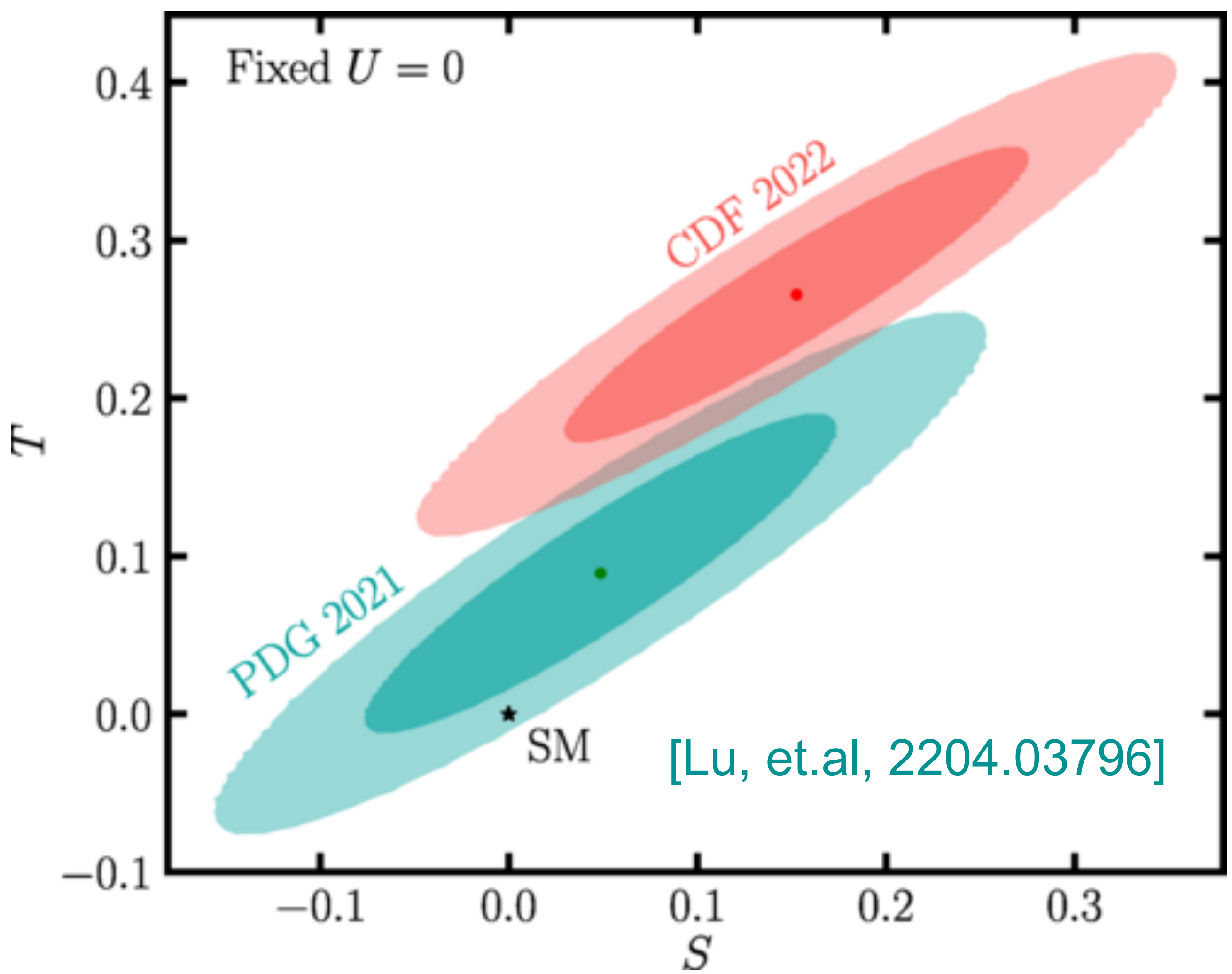
- The Higgs penguin diagram provide direct detection constraint.



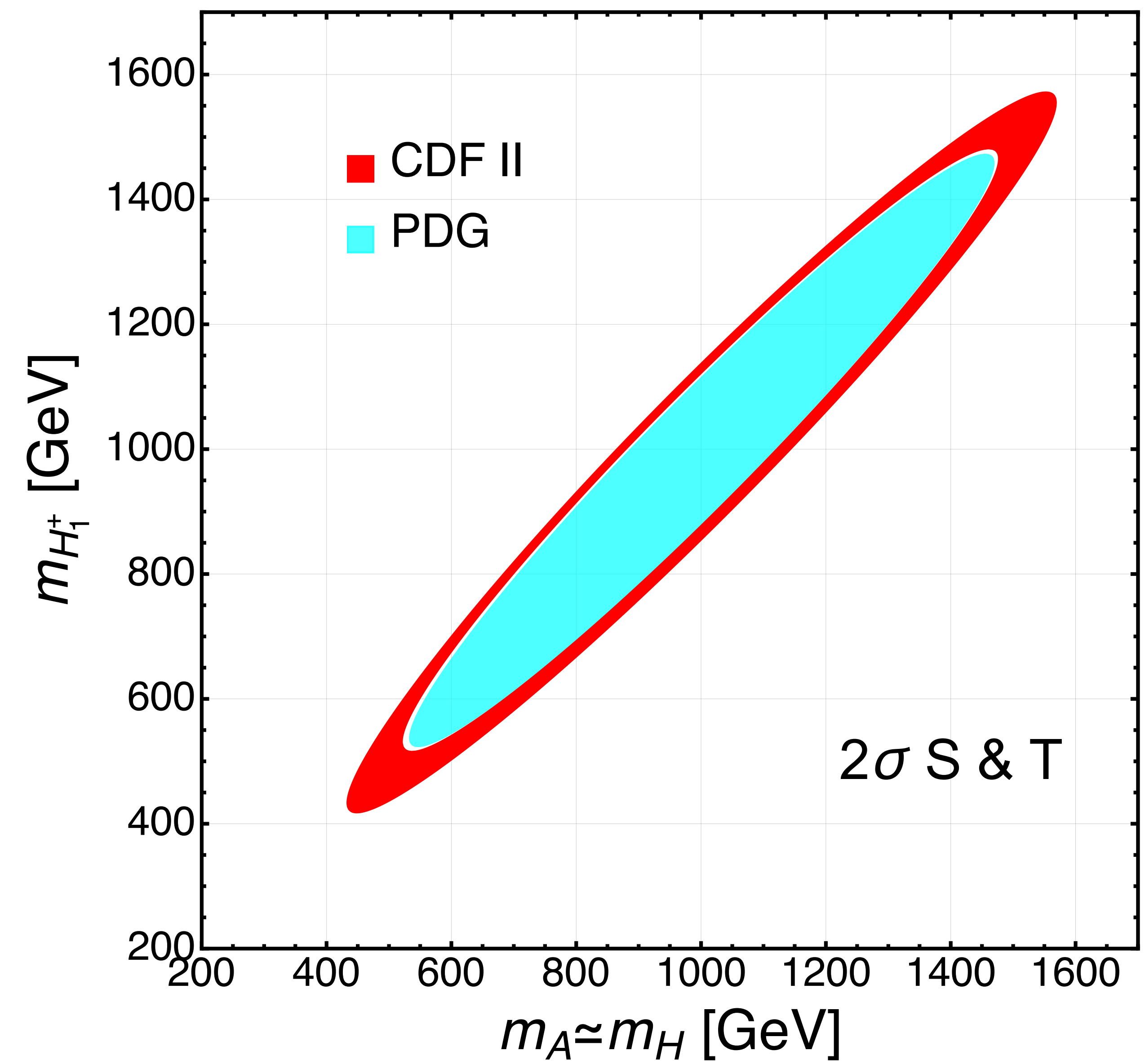
Y f θ

M_N $m_H \simeq m_A$ $m_{H_i}^+$

Neutrino mass, AMM, Scalar DM, Fermionic DM,
W-mass correction, LFV prediction



sin θ = 0.2, $m_{H_2^+}$ = 1000 GeV



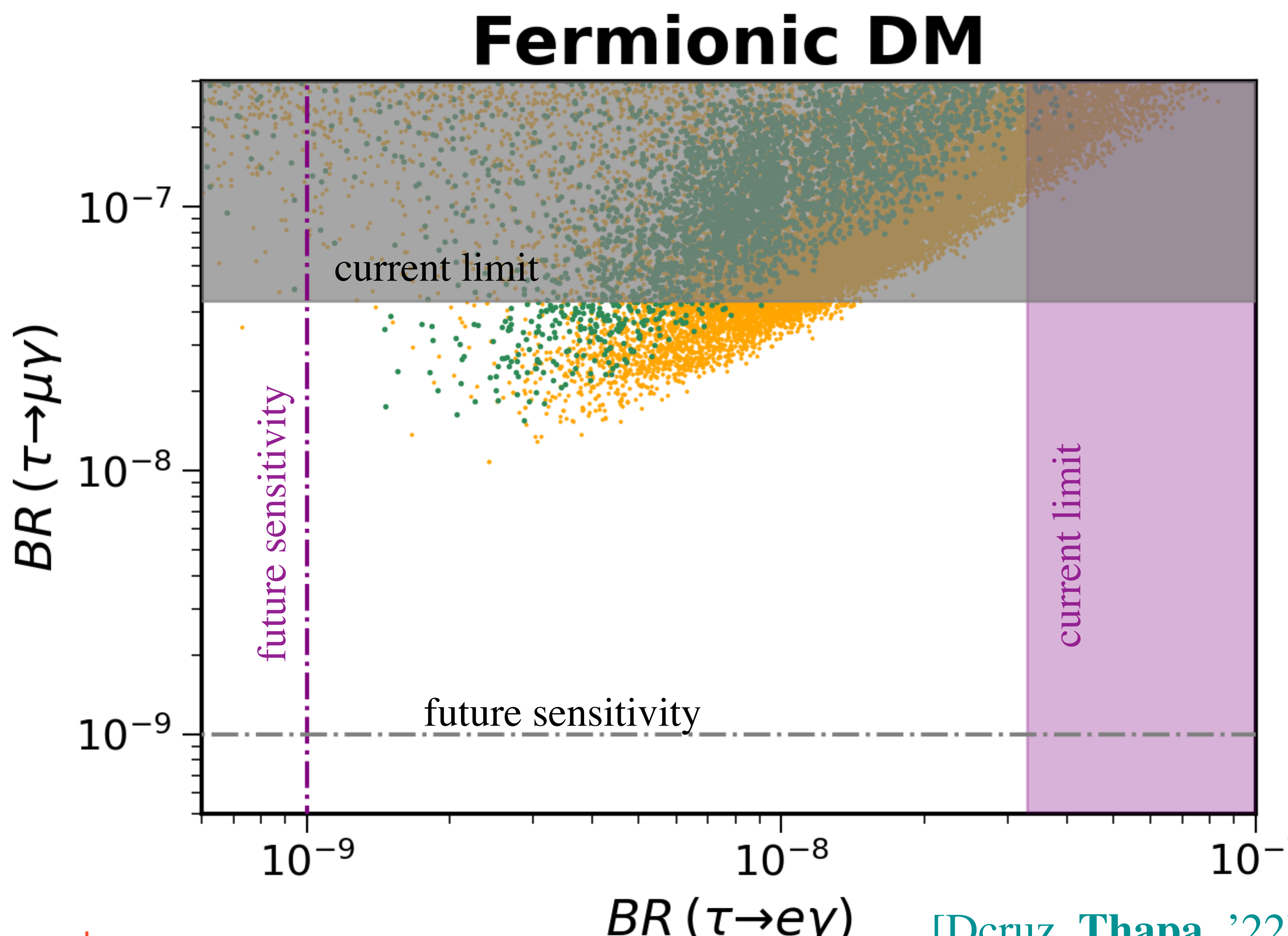
Prediction for LFV

$$Y = U_{\text{PMNS}} \sqrt{M_\nu^{\text{diag}}} R^\dagger \sqrt{\Lambda^{-1}}^\dagger$$

$$\Lambda_k = \frac{M_{N_k}}{16\pi^2}\left[\frac{m_H^2}{m_H^2 - M_{N_k}^2}\log\frac{m_H^2}{M_{N_k}^2} - (m_H \to m_A)\right]$$

[Casas, Ibarra '01]

- Data points satisfy
  - ν oscillation data
  - relic density
  - chisq CDF-II
  - $(g-2)_\mu$ (orange)
  - $(g-2)_{e,\mu}$ (green)



[Dcruz, **Thapa**, '22]

- $M_N < 15$ TeV, $m_{H_i}^+ < 6.5$ TeV
- Requires $m_H \simeq m_A$ for neutrino mass fit

Radiative neutrino mass models

— Each loop has $1/(16\pi^2)$ suppression

— Can tie to explain anomalies

$(g-2)_\mu$, dark matter, B anomalies, … that fixes new physics scale.

$\boxed{\text{Prediction for LFV ?}}$

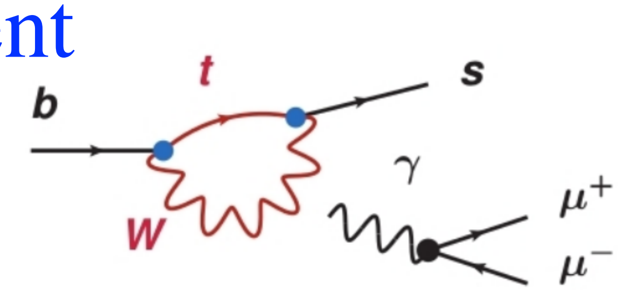
Zee Model, Extended Scotogenic Model, Flavor (LQ) Model

- SM is flavor universal $\Longrightarrow$ any deviation is key signature of physics beyond the SM
- Hints of deviations from SM in semileptonic B decays

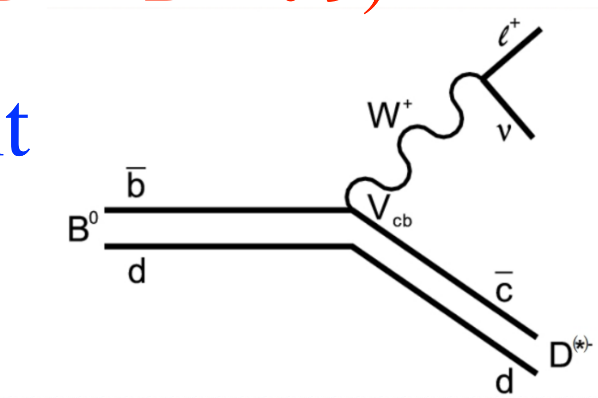
$$R_{K^{(\star)}} = \frac{\Gamma\left(\bar{B} \to \bar{K}^{(\star)}\mu^+\mu^-\right)}{\Gamma\left(\bar{B} \to \bar{K}^{(\star)}e^+e^-\right)}$$

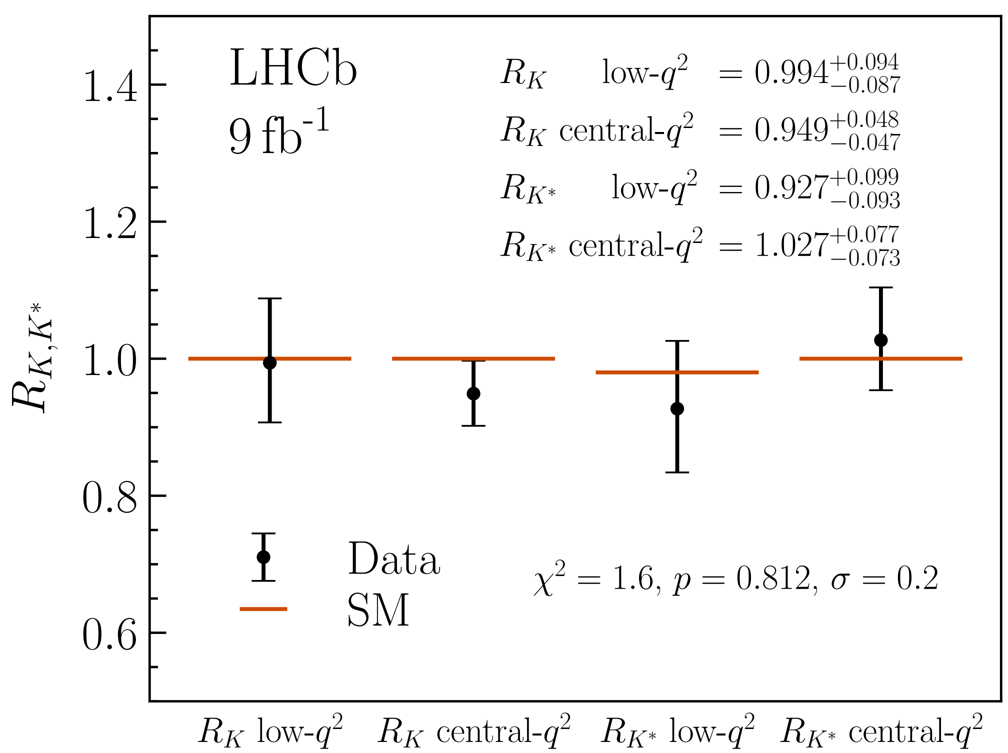
$$R_{D^{(\star)}} = \frac{\Gamma(\bar{B} \to D^{(\star)}\tau\nu)}{\Gamma(\bar{B} \to D^{(\star)}\ell\nu)}$$

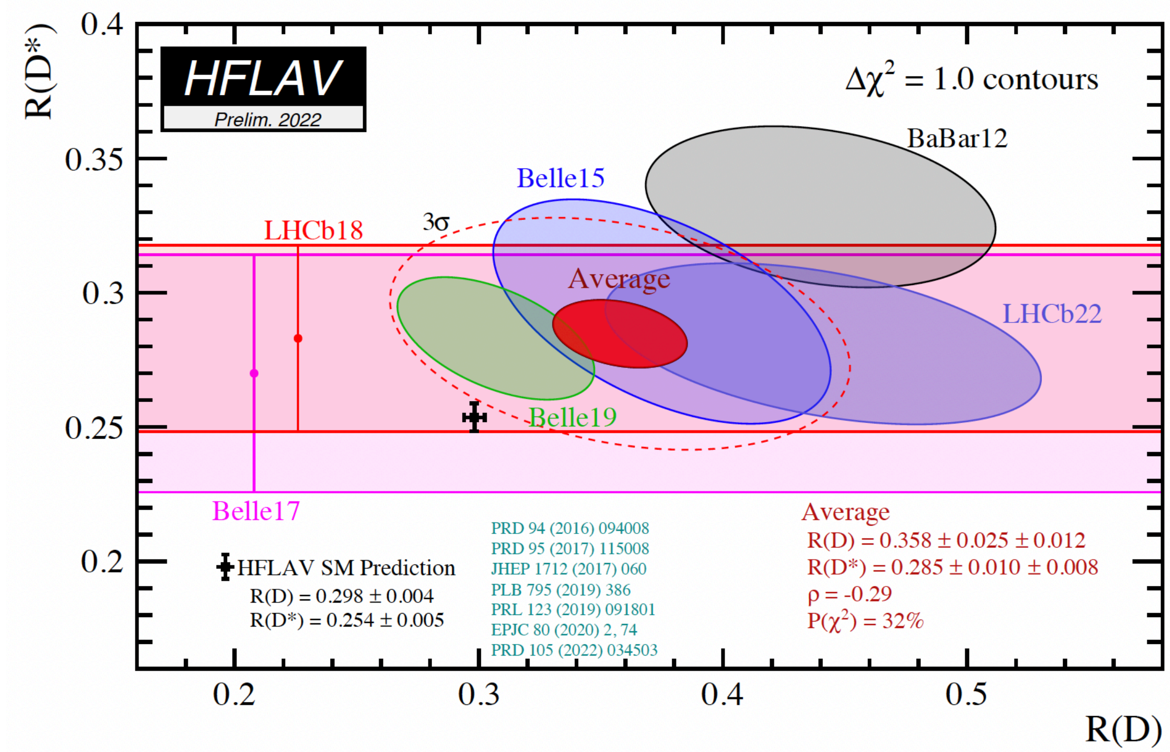
Neutral current



Charged current





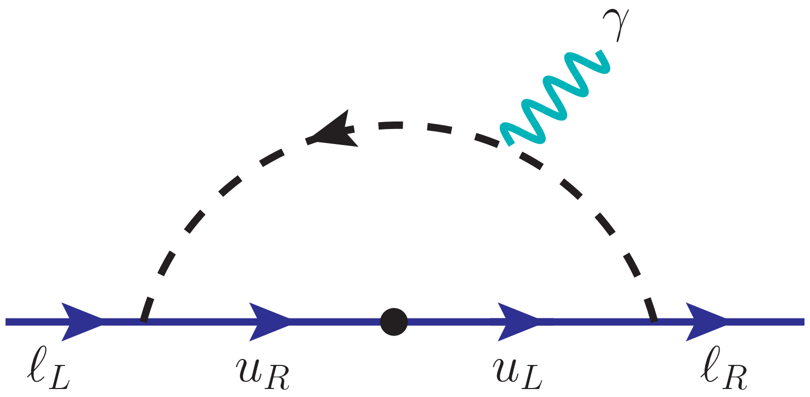


$\boxed{R_{K^{(*)}} \text{ anomaly is gone !}}$

$\boxed{\text{Tension with the SM at} \sim 3\sigma \text{ level}}$

$\boxed{\text{LFUV} \Longrightarrow \text{Neutrino mass} \Longrightarrow \text{LFV}}$

- Neutrino mass model to resolve B-anomalies [$R_2\,(3,2,7/6)$ or $S_1(\bar{3},1,1/3)$]
- The same R_2 and S_1 LQ also induce muon $(g-2)_\mu$
- Flavor structure is very constrained
- Framework can be tested at LHC as well as in processes such as $\tau \to e\gamma$



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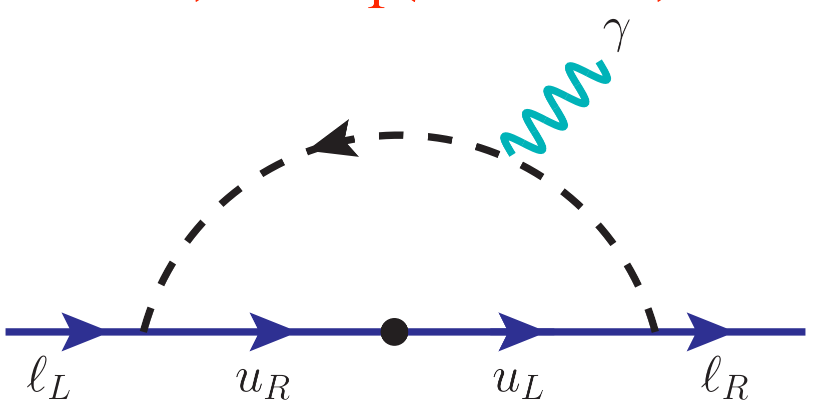
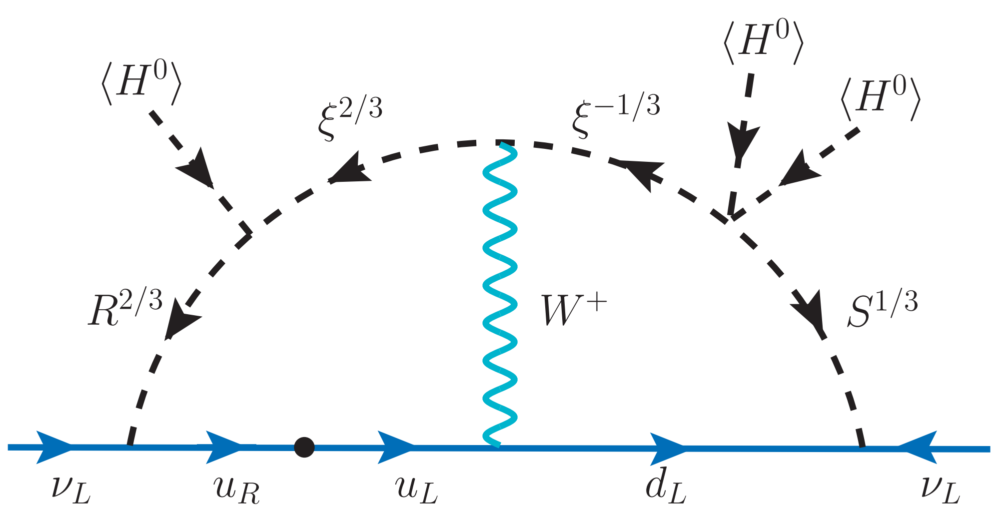
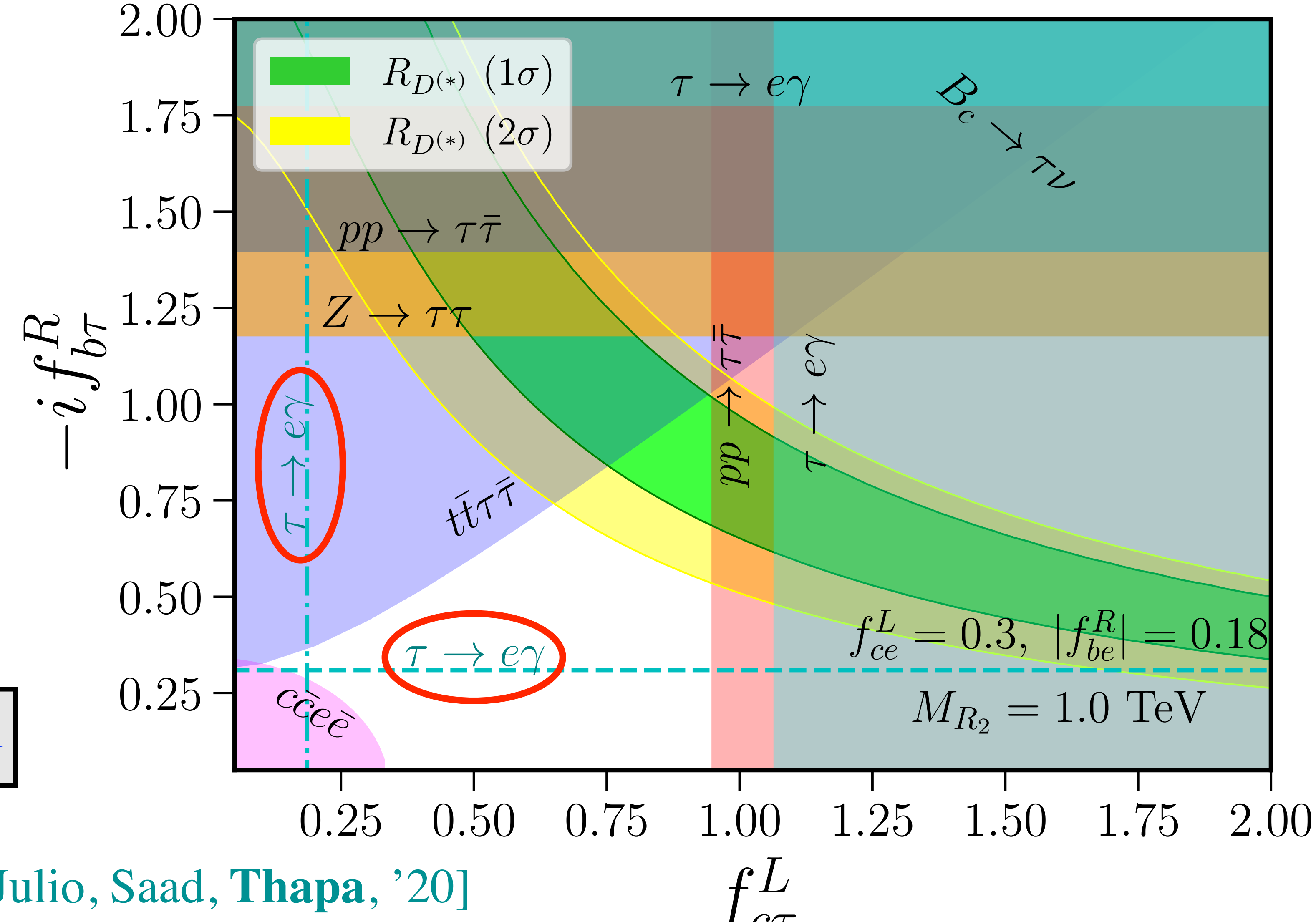


$$\mathscr{L}_Y = f^L \overline{u}_R R_2 L + f^R \overline{Q} R_2 \ell_R$$
$$+ y^L \overline{Q^c} L S_1 + y^R \overline{u^c}_R S_1 \ell_R$$



$$\boxed{M_\nu = m_0 I_0\ \{(y^L)^T M_u f^L + \text{transpose}\}}$$

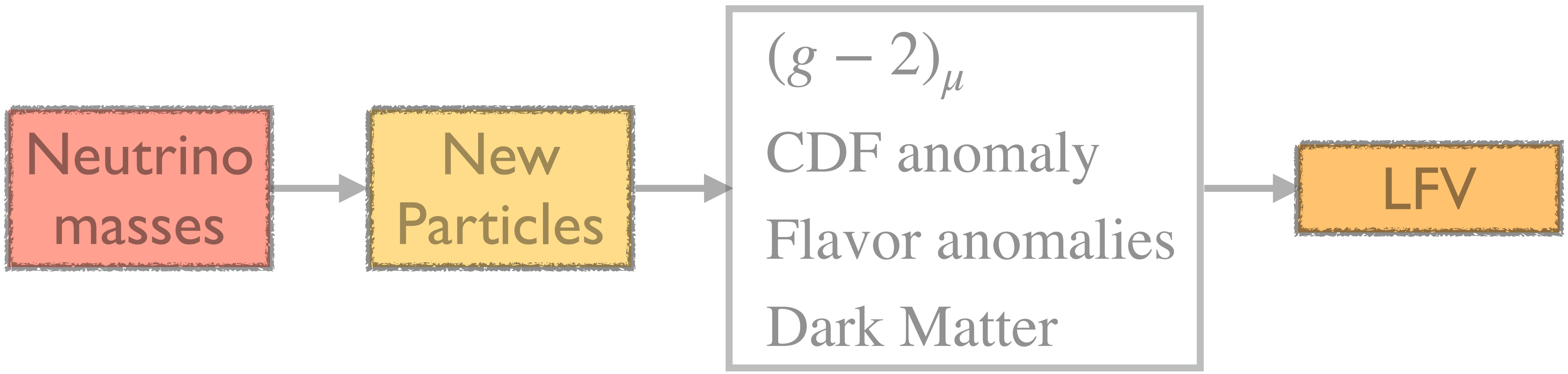


[Julio, Saad, **Thapa**, '20]

Outline

- Majorana neutrinos test with lepton flavor violation

  Prediction requires flavor structure (ν oscillations) and new physics scale



  Radiative ν-models:

  Zee Model, Extended Scotogenic Model, Flavor (LQ) Model

- Dirac neutrinos test with N_{eff}

- Neutrinos may well be Dirac particles $\Longrightarrow \Delta L = 0$

- Oscillation experiments cannot distinguish Dirac neutrinos from Majorana neutrinos

- If Dirac nature $\Longrightarrow$ important to understand the smallness of their masses

- Dirac leptogenesis to explain observed baryon asymmetry is an attractive feature [Dick, Lindner, Ratz, Wrig, '99]

- Dirac seesaw can be achieved in Mirror Models [Lee, Yang '56; Foot, Volkas '95; Berezhiani, Mohapatra '95, Silagadze '97]

Dirac Neutrinos from Left-Right Symmetry

$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

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- Fermion Representation:

$$Q_L(3,2,1,1/3) = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad Q_R(3,1,2,1/3) = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\psi_L(1,2,1,-1) = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \psi_R(1,1,2,-1) = \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

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- Vector-like fermion introduced to realize "universal seesaw" for charged fermion masses [Davidson, Wali '87]

$$P(3,1,1,4/3), \quad N(3,1,1,-2/3), \quad E(1,1,1,-2)$$

$$\boxed{M_u = \begin{pmatrix} 0 & y_u \kappa_L \\ y_u^\dagger \kappa_R & M_{P^0} \end{pmatrix} \qquad M_d = \begin{pmatrix} 0 & y_d \kappa_L \\ y_d^\dagger \kappa_R & M_{N^0} \end{pmatrix} \qquad M_\ell = \begin{pmatrix} 0 & y_\ell \kappa_L \\ y_\ell^\dagger \kappa_R & M_{E^0} \end{pmatrix}}$$

$$m_{u_i} \approx \frac{y_{u_i}^2 \kappa_L \kappa_R}{M_{P_i^0}}, \qquad m_{d_i} \approx \frac{y_{d_i}^2 \kappa_L \kappa_R}{M_{N_i^0}}, \qquad m_{\ell_i} \approx \frac{y_{\ell_i}^2 \kappa_L \kappa_R}{M_{E_i^0}}$$

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- Higgs Representation: $\boxed{\chi_L(1,2,1,1) = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}_L \quad \chi_R(1,2,1,1) = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}_R}$

$$SU(2)_L \times SU(2)_R \times U(1)_X \xrightarrow{\langle \chi_R^0 \rangle} SU(2)_L \times U(1)_Y \xrightarrow{\langle \chi_L^0 \rangle} U(1)_{\text{EM}}$$

- Higgs sector is very simple: $\chi_L(1,2,1,1) + \chi_R(1,1,2,1)$
- $W_L^+ \leftrightarrow W_R^+$ mixing is absent at tree-level
- $W_L^+ \leftrightarrow W_R^+$ mixing is induced at the loop level, which in turn induces two-loop Dirac masses for neutrino [Babu, He '89]

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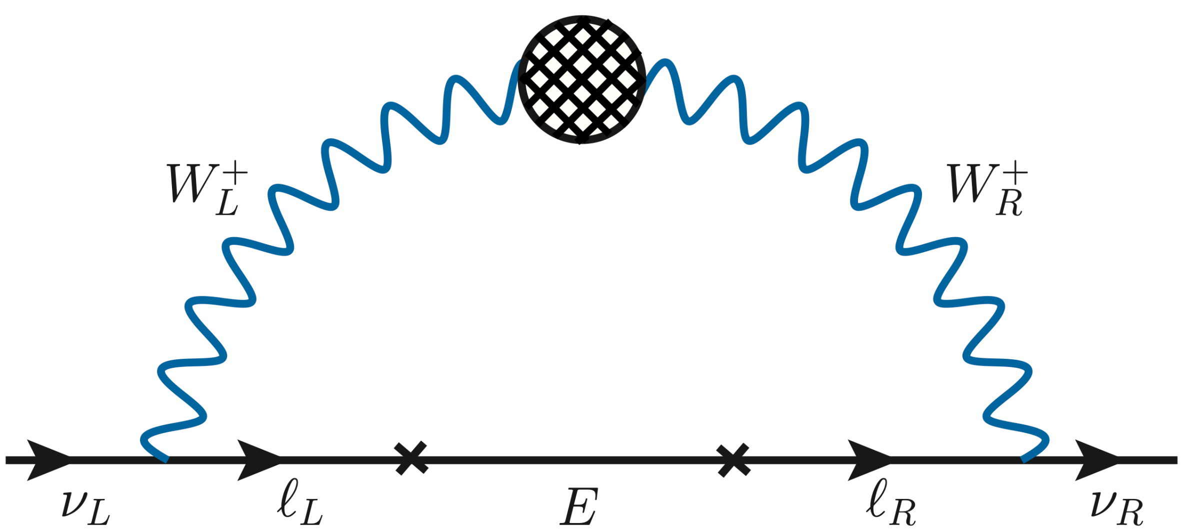
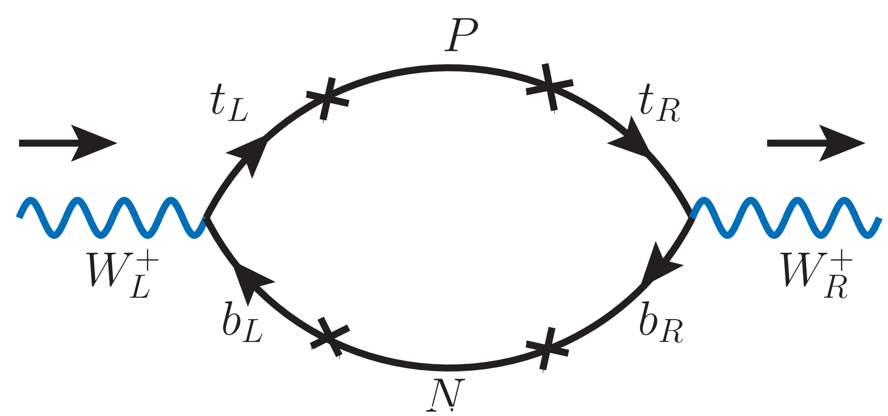




$$\boxed{\xi \approx \frac{\alpha}{4\pi \sin^2\theta_W}\frac{m_b m_t}{M_{W_R}^2}}$$

$$M_{\nu^D} = \frac{-g^4}{2} y_t^2 y_b^2 y_\ell^2 \kappa_L^3 \kappa_R^3 \frac{r\, M_P M_N M_{E_\ell}}{M_{W_L}^2 M_{W_R}^2}\, I_{E_\ell}$$

$$I_{E_\ell} = \int\!\!\int \frac{d^4k\, d^4p}{(2\pi)^8} \frac{3M_{W_L}^2 M_{W_R}^2 + (p^2 - M_{W_L}^2)(p^2 - M_{W_R}^2)}{k^2 (p+k)^2 (k^2 - M_N^2)((p+k)^2 - M_P^2) p^2 (p^2 - M_{E_\ell}^2)(p^2 - M_{W_L}^2)(p^2 - M_{W_R}^2)}$$

[Babu, He, Su, **Thapa** '22]

Testing Dirac Neutrinos with N_{eff}

- CMB is sensitive to extra radiation density arising from new extra degrees of freedom that were in thermal equilibrium with the SM plasma

- ν_R (ultra-light new particles, new degrees of freedom) couples to other particles and are produced in the early universe and contribute to additional radiation density in early universe !

- The effect of such light particles is parameterized as ΔN_{eff} and is measured in units of extra neutrino degrees of freedom

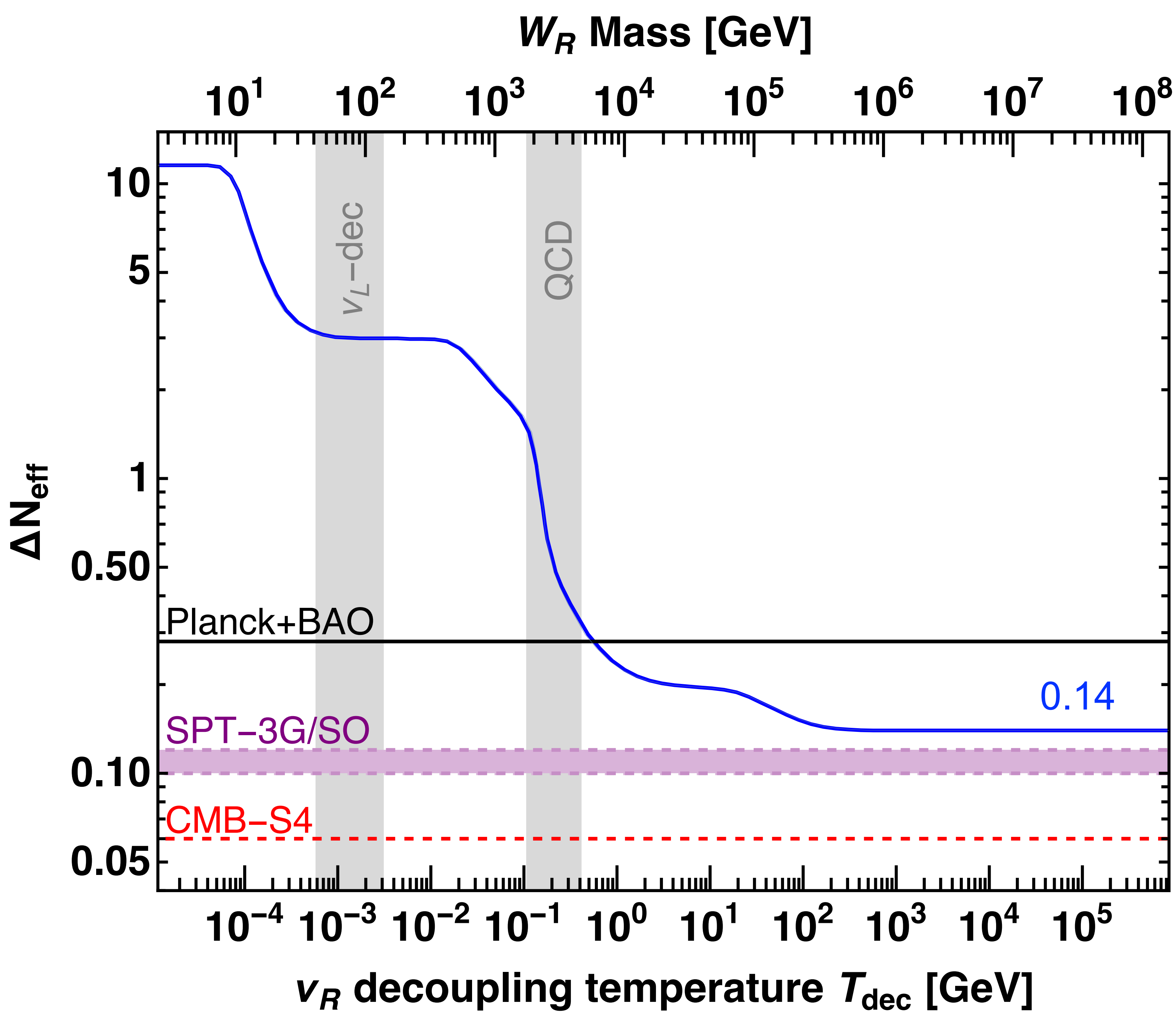
- Dirac neutrino modes of this type will modify N_{eff} by about 0.14

$$\Delta N_{\text{eff}} \simeq 0.027 \left(\frac{106.75}{g_\star\left(T_{\text{dec}}\right)} \right)^{4/3} g_{\text{eff}}$$

$$g_{\text{eff}} = (7/8) \times (2) \times (3) = 21/4$$

Dirac Neutrino in cosmology

- In SM $N_{\text{eff}} \simeq 3$
- Improvement on ΔN_{eff} in CMB-S4
- Valid for 3 ν_R in thermal equilibrium with SM
- This gives strong constraint for any (eg. LR model) Dirac neutrino mass model



[Heeck, Abazajian ’19; Babu, He, Su, **Thapa** ’22]

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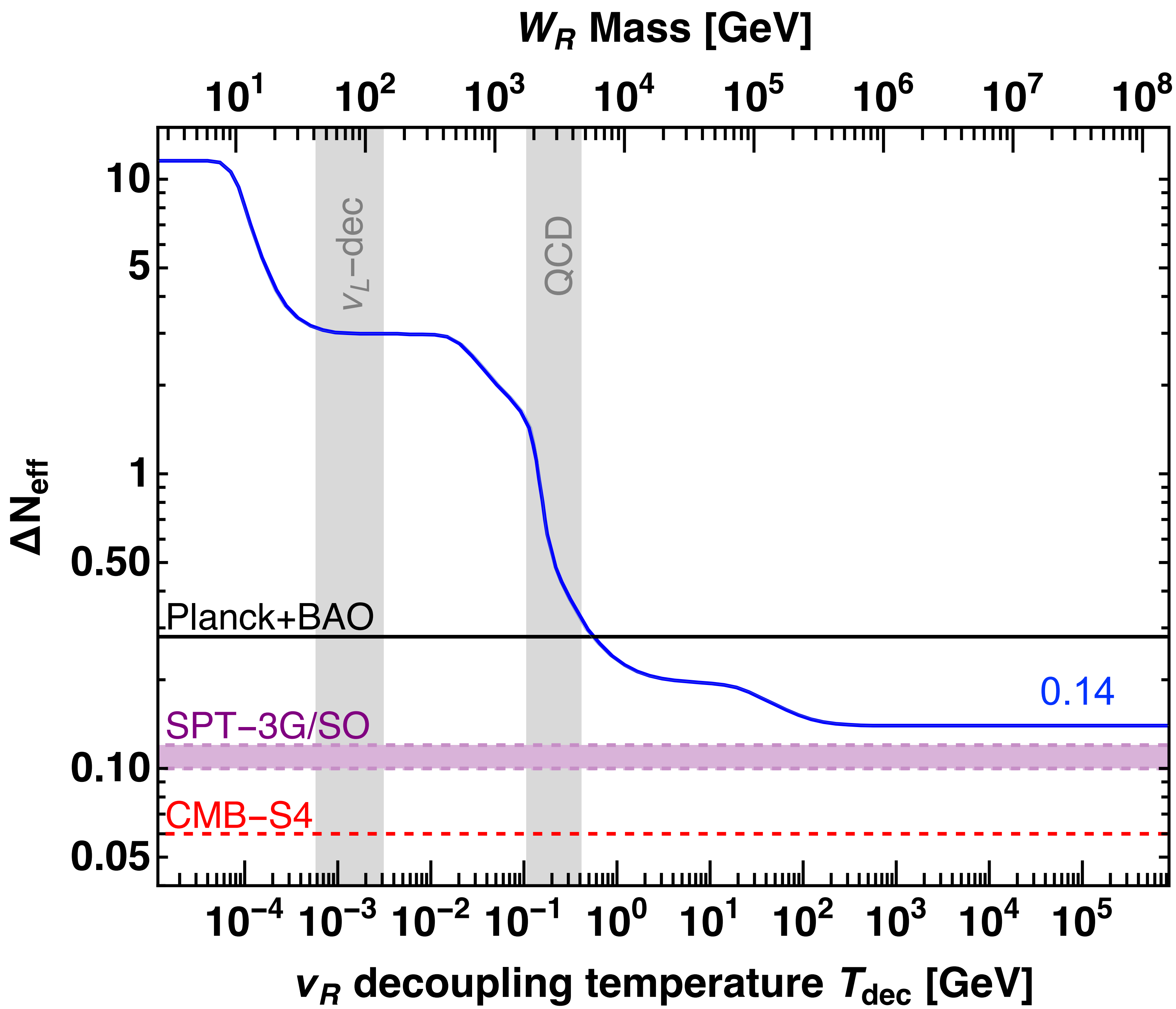

[Heeck, Abazajian '19; Babu, He, Su, **Thapa** '22]

Can we embed LR model into GUT ?

Embedding in $SU(5)_L \times SU(5)_R$

- The fermion spectrum of the model has a natural embedding in $SU(5)_L \times SU(5)_R$ unification

- All left-handed (right-handed) fermions of the SM fit into $\mathbf{10} + \bar{\mathbf{5}}$ of $SU(5)_L$ $(SU(5)_R)$

- The remaining vector-like quarks and leptons fill rest of the multiples

$$F_{L,R} = \begin{pmatrix} D_1^c \\ D_2^c \\ D_3^c \\ e \\ -\nu \end{pmatrix}_{L,R} \qquad T_{L,R} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & U_3^c & -U_2^c & u_1 & d_1 \\ -U_3^c & 0 & U_1^c & u_2 & d_2 \\ U_2^c & -U_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & E^c \\ -d_1 & -d_2 & -d_3 & -E^c & 0 \end{pmatrix}_{L,R}$$

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- Parity can be imposed under which $F_L \leftrightarrow F_R$ and $T_L \leftrightarrow T_R$

Gauge coupling Unification

- The evolution of the gauge couplings constants at one-loop level are governed by the following RGEs

$$\boxed{\alpha_i^{-1}(\mu) = \alpha_i^{-1}(\mu_0) - \frac{b_i}{2\pi}\, ln(\mu/\mu_0)}$$

$$\alpha_i = g_i^2/4\pi$$

At m_t (top quark mass):

$$g_1 = 0.3583\,,\ g_2 = 0.64779\,,\ g_3 = 1.1666$$

- With the SM particles, we obtain following beta function coefficients with properly normalized gauge couplings:

$$b_1 = \frac{41}{26}, \quad b_2 = -\frac{19}{6}, \quad b_3 = -\frac{7}{2}$$

- $SU(5) \times SU(5)$ group can directly break to the SM gauge group, where g_1, g_2, g_3 meet at a single value

$$\boxed{\alpha_{\rm GUT} = 2\ \alpha_3 = \alpha_2 = \frac{13}{3}\alpha_1}$$

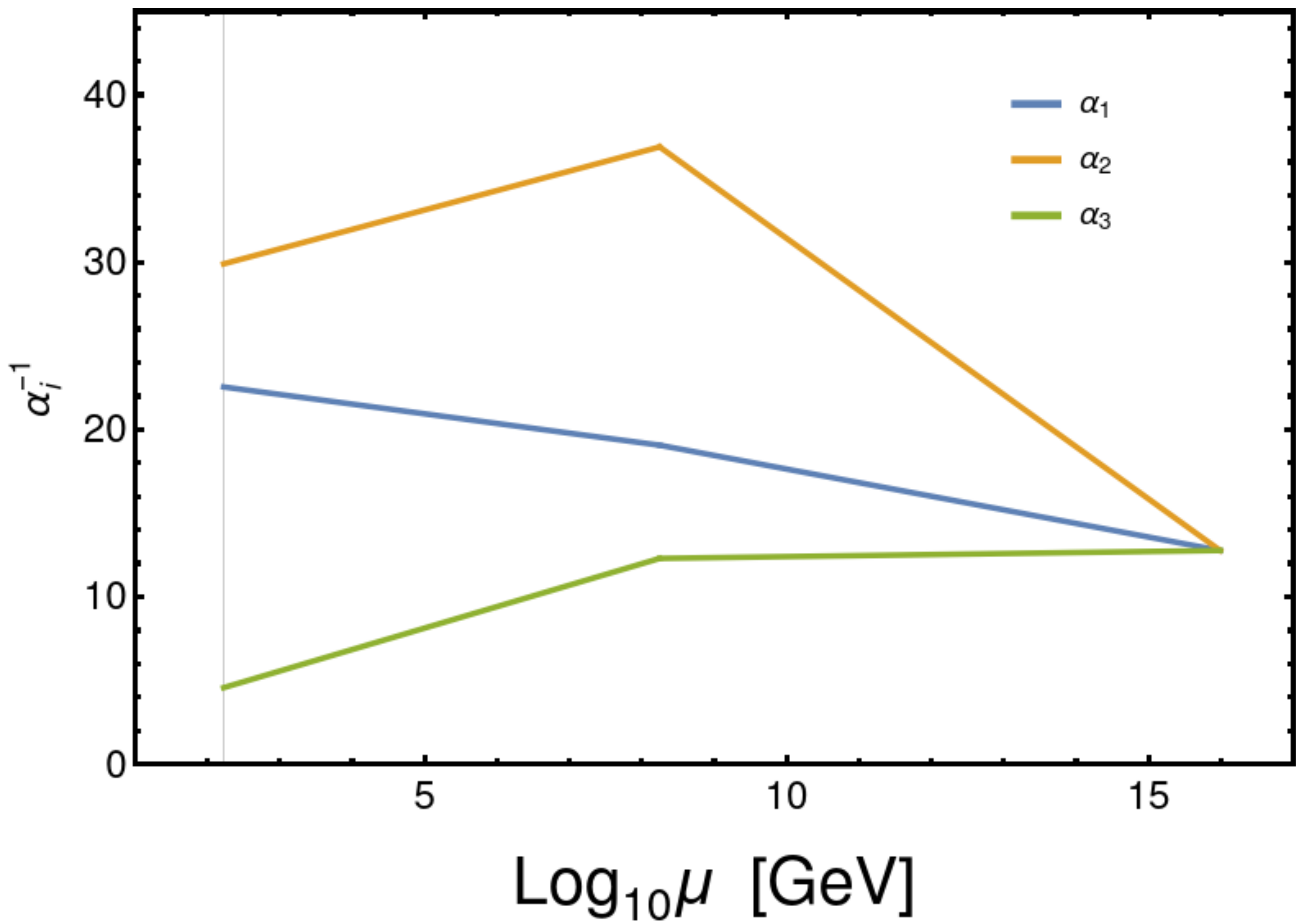
$\Longrightarrow$ $\sin^2\theta_W = 3/16$

$\Longrightarrow$ Cannot reconcile value measured at electroweak scale

- Add $(8,3,0)_F + 2\ (3,2,-5/6)_S$ fields at scale M

$$b_1 = \frac{173}{78}, \quad b_2 = \frac{17}{2}, \quad b_3 = \frac{-1}{6}$$

$$M_{\text{GUT}} = 9.50 \times 10^{15}\ \text{GeV}$$
$$\alpha_{\text{GUT}} = 0.078$$



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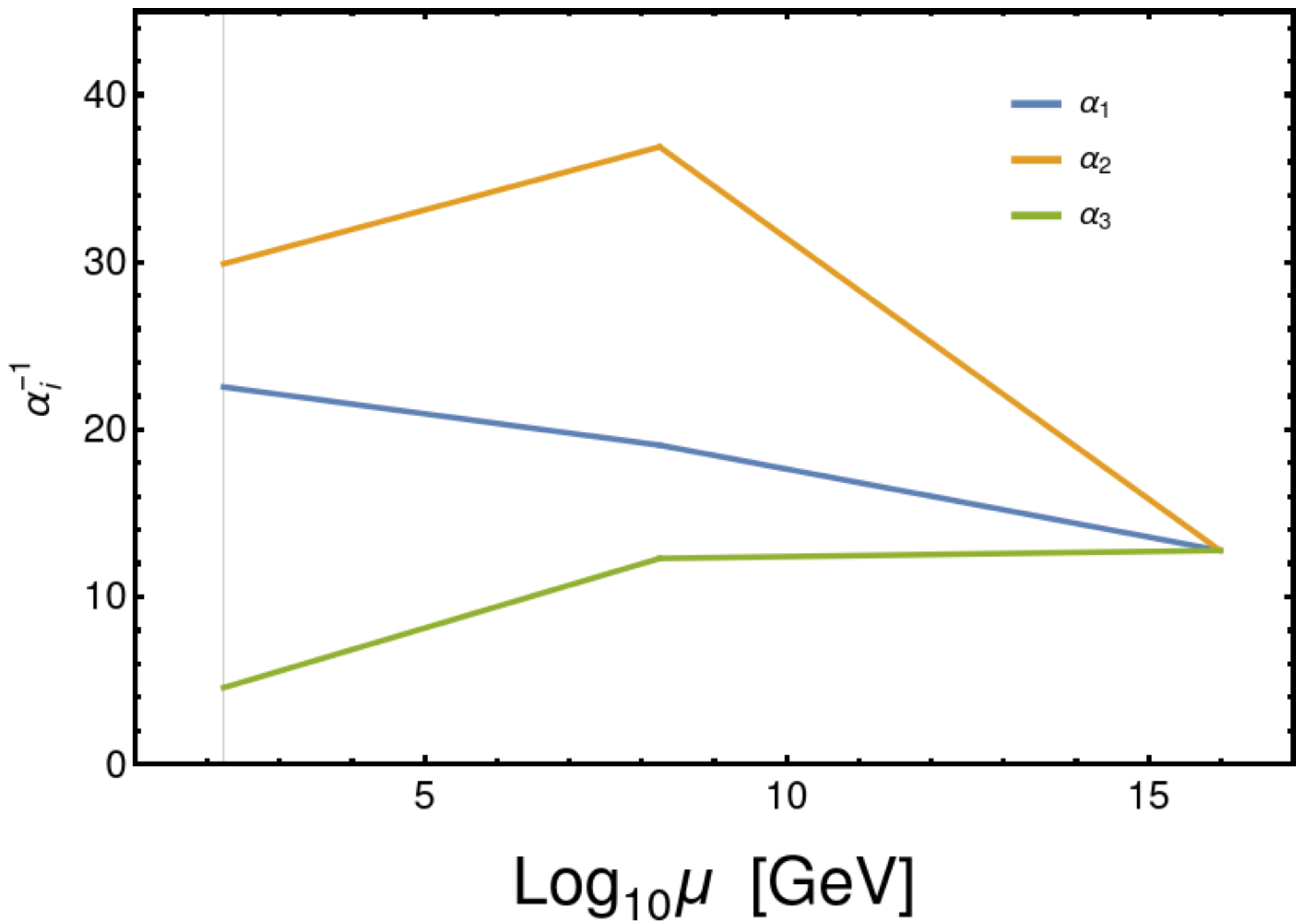

- Not the only breaking chain; some have many attractive features $\Longrightarrow$ predicts Dirac neutrinos, firm prediction on oscillation parameters, and can solve strong CP problem. [Babu, Mohapatra, **Thapa,** in preparation]

More on Dirac Neutrinos: Dirac Leptogenesis

- Dirac neutrinos: $y_\nu \bar{L} H \nu_R \Longrightarrow$ Higgs coupling strength $y_\nu \sim 10^{-12}!!$ $\Longrightarrow$ too feeble to ever thermalize ν_R in the early universe $\Longrightarrow$ Dirac Leptogenesis $\Longrightarrow$ matter/antimatter asymmetry [Dick, Lindner, Ratz, Wrig, '009]

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Idea: Take a new heavy particle X that decay out of equilibrium into a non-thermal ν_R and a SM particle.

Simple models:

Case	$SU(3)\times SU(2)\times U(1)$	spin	g_X	$(B-L)(X)$	Relevant Lagrangian terms that induce X decay	$\varepsilon_{\text{wave}}$	$\varepsilon_{\text{vertex}}$	ΔB
a	$(\mathbf{1},\mathbf{1},-1)$	0	1	-2	$\nu_R e_R \bar{X},\ LL\bar{X}$	✓	✗	0
b	$(\mathbf{1},\mathbf{2},1/2)$	0	2	0	$\bar{H}X,\ \bar{\nu}_R LX,\ \bar{L}e_R X,\ \bar{Q}_L d_R X,\ \bar{u}_R Q_L X,\ X^\dagger H^\dagger HH$	✓	✓or ✗	0
c	$(\mathbf{3},\mathbf{1},-1/3)$	0	3	$-2/3$	$d_R\nu_R X^\dagger,\ u_R e_R X^\dagger,\ Q_L L X^\dagger, u_R d_R X,\ Q_L Q_L X$	✓	✓or ✗	0 or 1
d	$(\mathbf{3},\mathbf{1},2/3)$	0	3	$-2/3$	$u_R\nu_R X^\dagger,\ d_R d_R X$	✓	✗	1
e	$(\mathbf{3},\mathbf{2},1/6)$	0	6	$4/3$	$\bar{Q}_L\nu_R X,\ \bar{d}_R L X$	✓	✗	0
f	$(\mathbf{1},\mathbf{2},-1/2)$	1/2	2	-1	$\bar{X}L,\ \bar{\nu}_R X H,\ \bar{X}e_R H$	✓	✓	0

[Heeck, Heisig, **Thapa, '23**]

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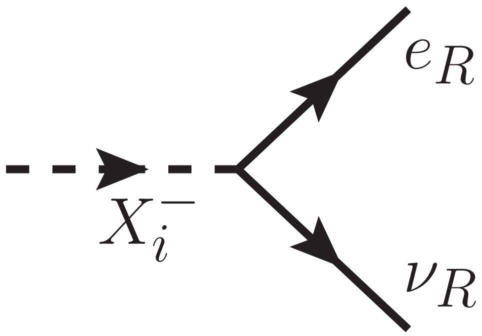
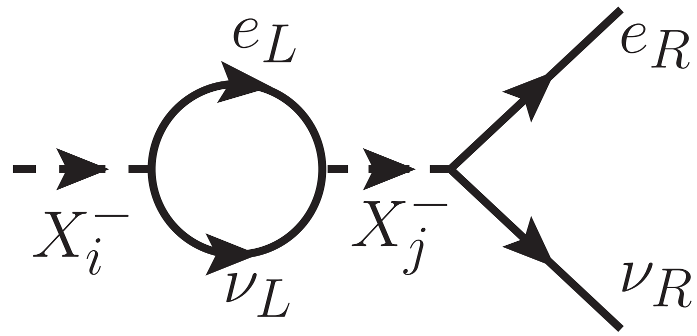
c	$(\mathbf{3}, \mathbf{1}, -1/3)$	0	3	$-2/3$	$d_R \nu_R X^\dagger,\ u_R e_R X^\dagger,\ Q_L L X^\dagger, u_R d_R X,\ Q_L Q_L X$	✓	✓or ✗	0 or 1
d	$(\mathbf{3}, \mathbf{1}, 2/3)$	0	3	$-2/3$	$u_R \nu_R X^\dagger,\ d_R d_R X$	✓	✗	1
e	$(\mathbf{3}, \mathbf{2}, 1/6)$	0	6	$4/3$	$\bar{Q}_L \nu_R X,\ \bar{d}_R L X$	✓	✗	0
f	$(\mathbf{1}, \mathbf{2}, -1/2)$	1/2	2	-1	$\bar{X}L,\ \bar{\nu}_R X H,\ \bar{X} e_R H$	✓	✓	0

[Heeck, Heisig, **Thapa, '23**]

Dirac Leptogenesis





$$\Sigma_A \equiv Y_A + Y_{\bar{A}} \qquad \Delta_A \equiv Y_A - Y_{\bar{A}}$$

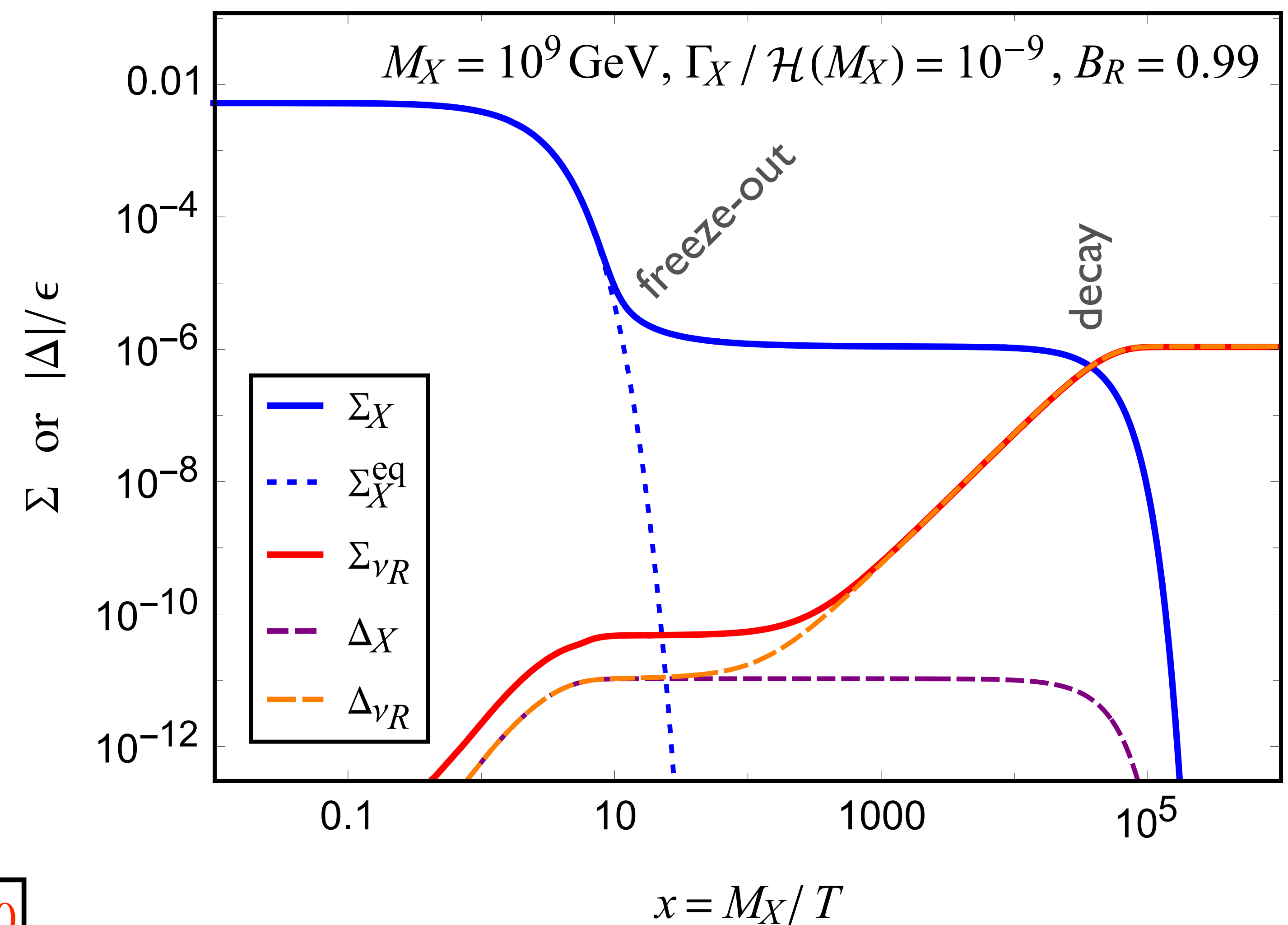
- *CP* asymmetry: opposite lepton asymmetries for left- and right-handed neutrinos with $\Delta L = 0$

$$\Delta\nu = \nu_L - \bar{\nu}_L = -(\nu_R - \bar{\nu}_R) \neq 0$$

- ν_R are out of equilibrium after X decays and are invisible to the sphalerons, only left handed asymmetry is converted into baryons.

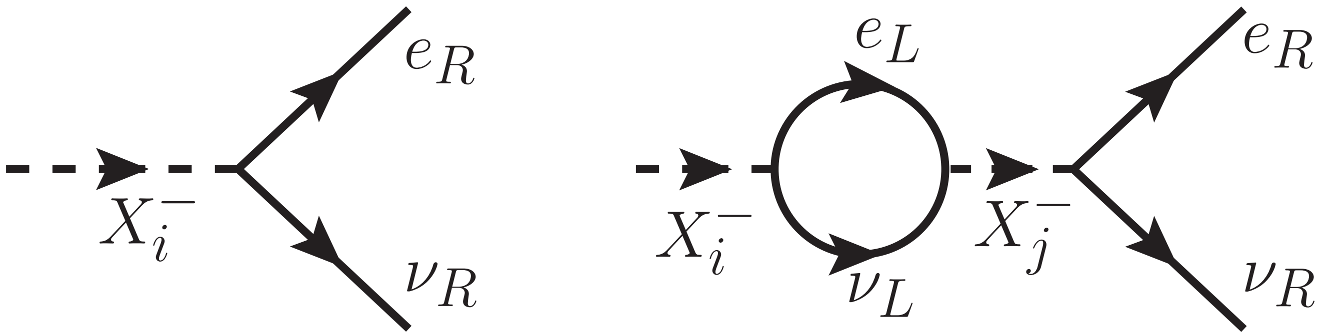
$$\boxed{Y_{\Delta B} = \simeq 10^{-3}\epsilon\eta \simeq 10^{-10}}$$

$\eta \simeq 2.1 \times 10^{-4}, \quad \Delta N_{\rm eff} \simeq 0.082$



[Heeck, Heisig, **Thapa,** '23]

Dirac Leptogenesis



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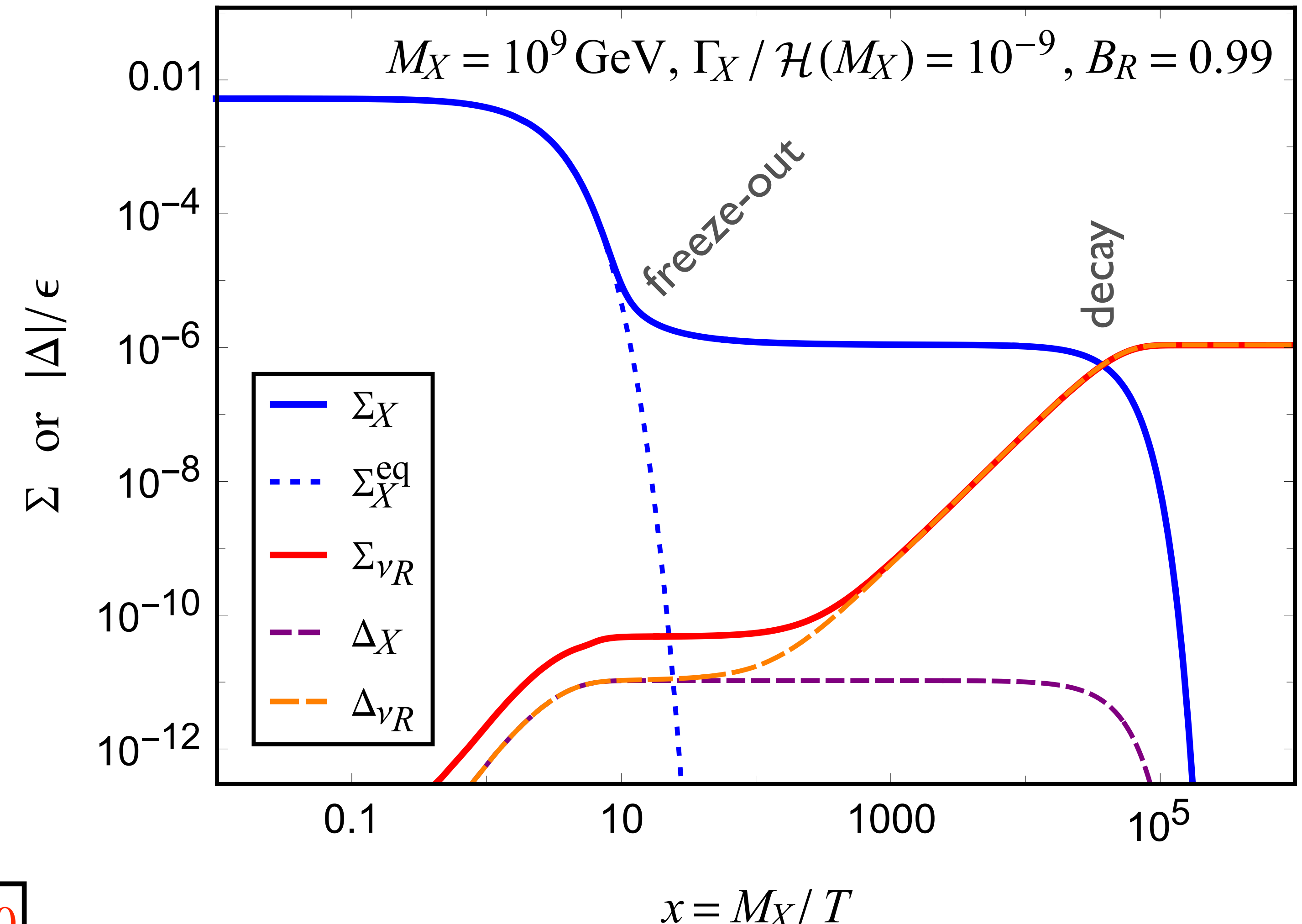

[Heeck, Heisig, **Thapa**, '23]

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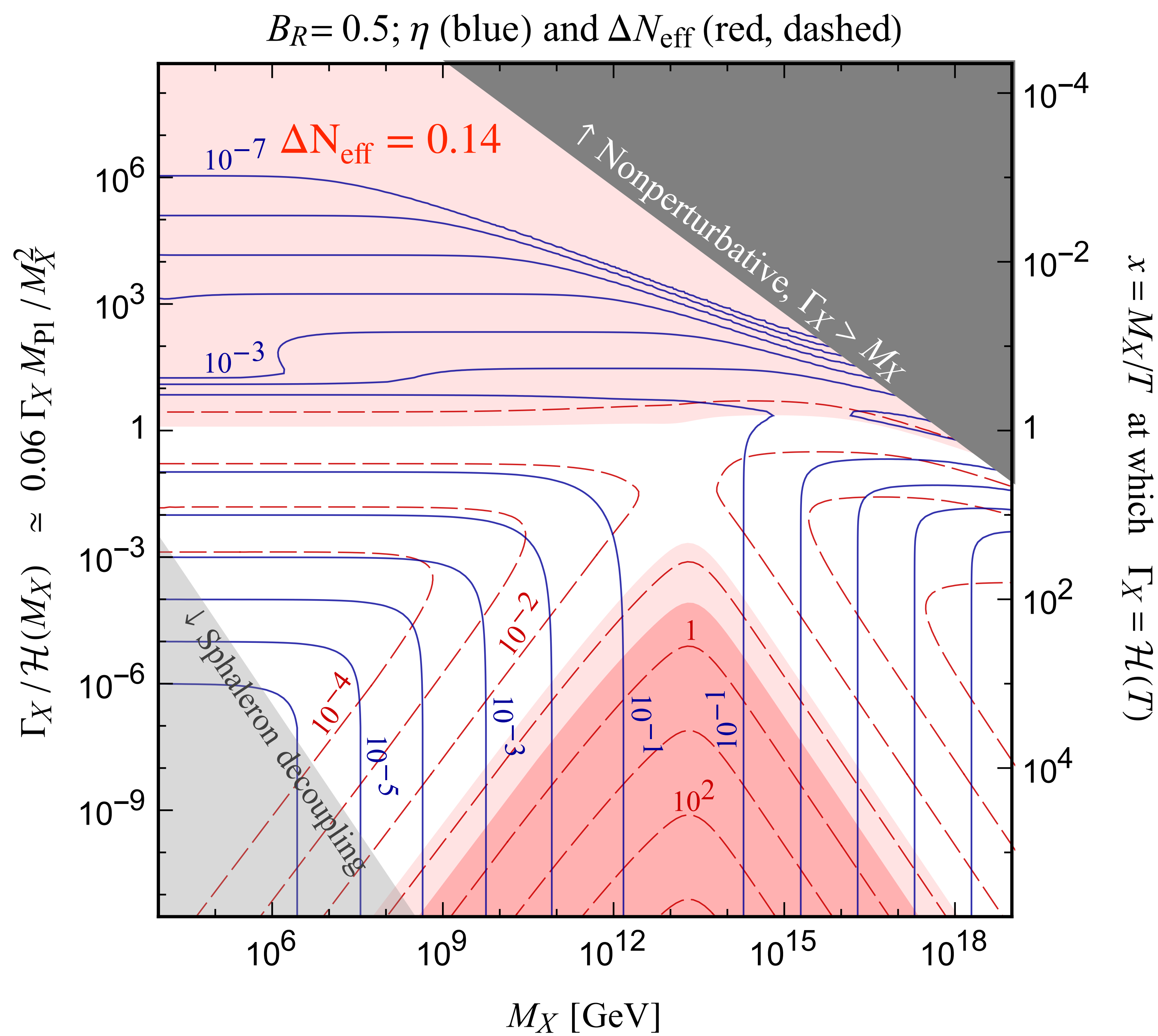
When X decays so late into $\nu_R \Longrightarrow$ shoots extremely highly relativistic ν_R with energy $\approx M_X/2 \Longrightarrow$ arbitrarily large N_{eff}

Dirac ν in the CMB

- X decays into high-energy ν_R
- Testable $\Delta N_{\rm eff}$!

$\Longrightarrow$ Large parameter space is already excluded (Red) and can be probed (lightRed)



[Heeck, Heisig, **Thapa**, '23]

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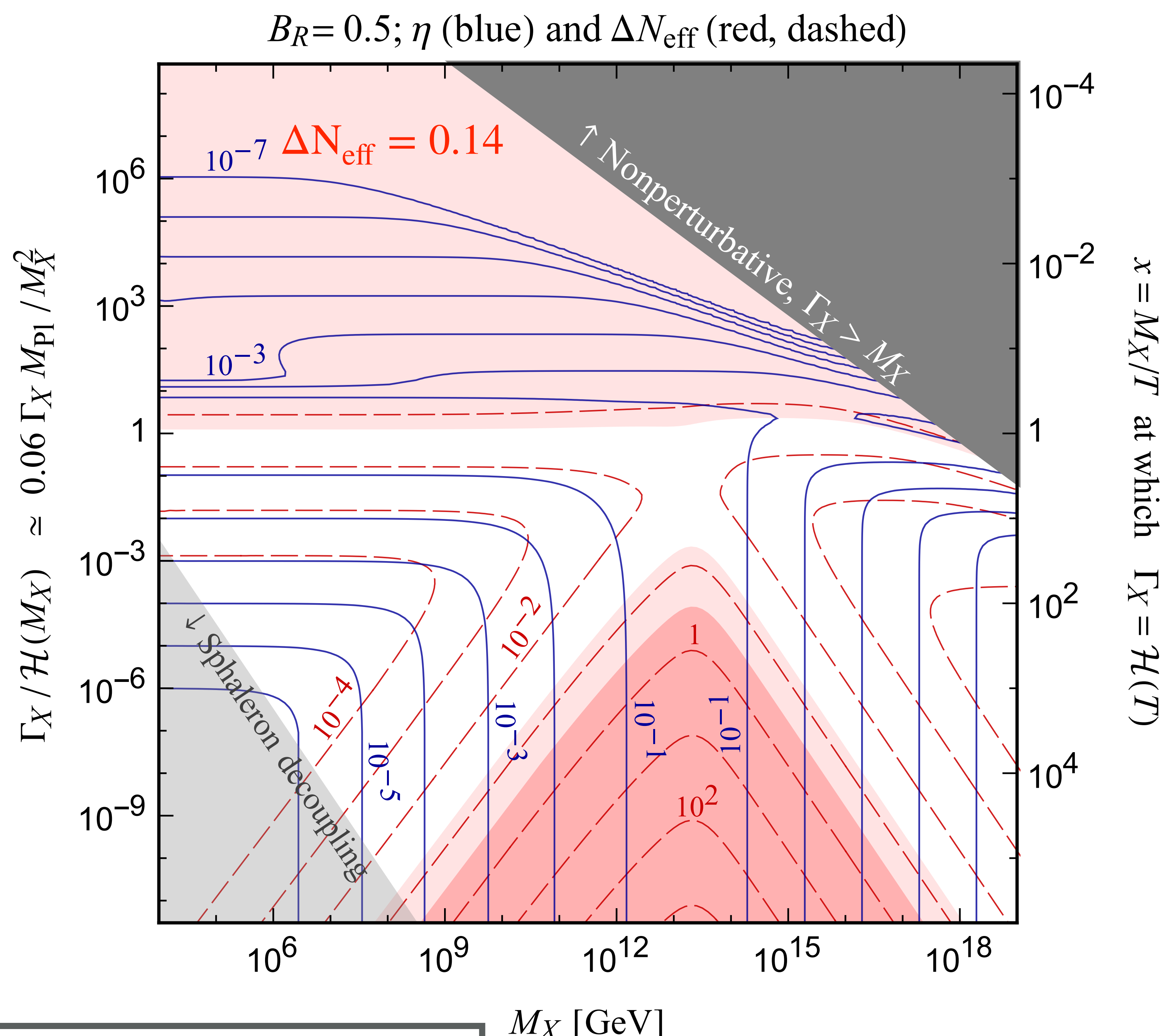


[Heeck, Heisig, **Thapa**, '23]

- Don't need sphalerons: can generate $\Delta B \neq 0$ directly with Leptoquarks
  $\Longrightarrow$ Predicts proton decay $p \to K^+ \bar{\nu}_R$

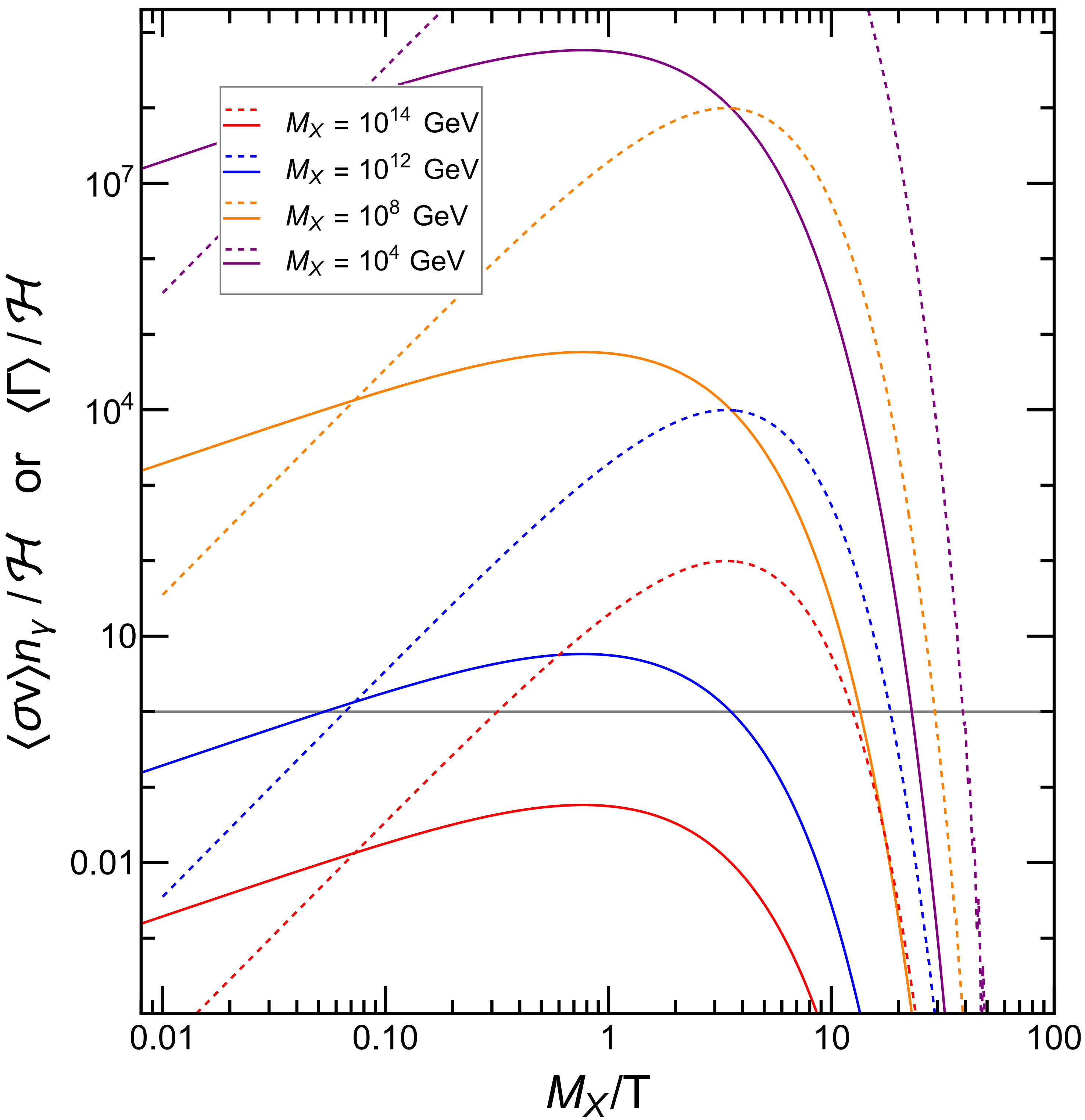
Conclusion

- Neutrino oscillations require extension of the SM.

- Models for both Majorana and Dirac neutrinos were discussed with some models to incorporate Dark Matter, Dirac leptogenesis, and various anomalies.

- Most of the models discussed can be probed through
  - LFV experiments ($\mu \to e\gamma, \tau \to \mu\gamma$),
  - N_{eff}
- Hope that anomalies are confirmed CDF, $(g-2)_\mu, R_D - R_{D*}$!

Thank you


$M_X = 10^{14}$ GeV
$M_X = 10^{12}$ GeV
$M_X = 10^{8}$ GeV
$M_X = 10^{4}$ GeV
$\langle\sigma v\rangle n_\gamma \,/\, \mathcal{H}$ or $\langle\Gamma\rangle \,/\, \mathcal{H}$
10^7
10^4
10
0.01
0.01
0.10
1
10
100
M_X/T

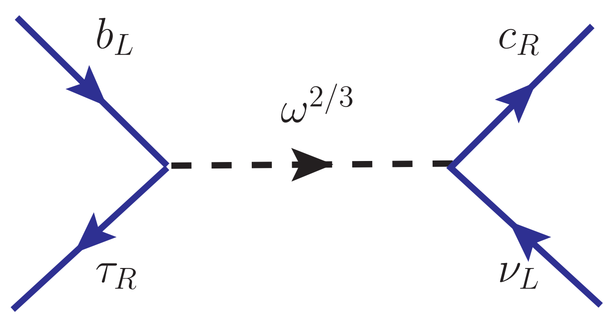
-1

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

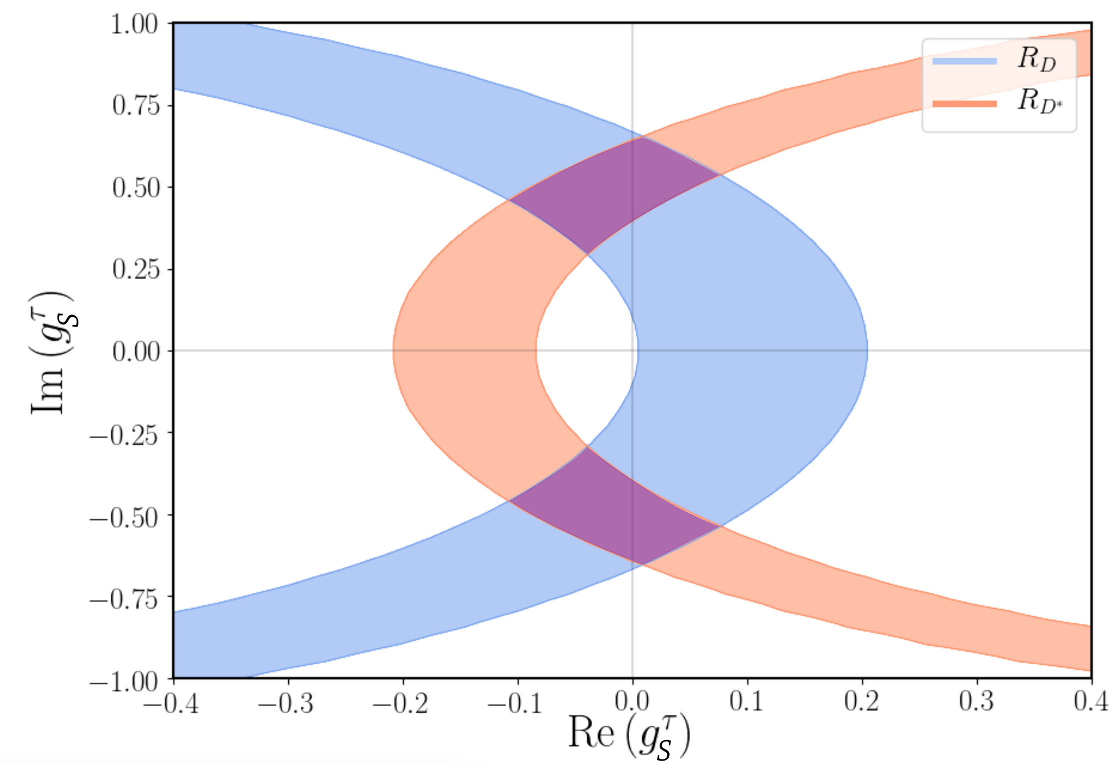
Category	**Model**	**Fields**	**Loop?**	**Ref.**
Class-I	Model-I	$S_1(\bar{3}, 1, 1/3)$ $\omega(\bar{6}, 1, 2/3)$	two-loop	[Babu, Leung, '01] [Kohda, Sachdeva, Waite, '19]
	Model-II	$S_3(\bar{3}, 3, 1/3)$ $\omega(\bar{6}, 1, 2/3)$	two-loop	[Babu, Leung, '01]
Class-II	Model-III	$S_1(\bar{3}, 1, 1/3)$ $\widetilde{R}_2(3, 2, 1/6)$	one-loop two-loop	[Dorsner, Fajfer, Košnik, '17] [Catà, Mannel, '19] [Babu, Julio, '10]
	Model-IV	$S_3(\bar{3}, 3, 1/3)$ $\widetilde{R}_2(3, 2, 1/6)$	one-loop	[Dorsner, Fajfer, Košnik, '17]
Class-III	Model-V	$R_2(3, 2, 7/6)$ $S_3(\bar{3}, 3, 1/3)$ $\chi(3, 1, 2/3)$	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]

Charged Current Anomaly: $R_{D^{(*)}}$: $R_2 \sim (3,2,7/6)$

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\ [(1+g_V)(\bar\tau_L\gamma^\mu\nu_L)\ (\bar c_L\gamma_\mu b_L)] + g_s\ (\bar\tau_R\nu_L)(\bar c_R b_L) + g_T\ (\bar\tau_R\sigma^{\mu\nu}\nu_L)\ (\bar c_R\sigma_{\mu\nu}b_L)$$

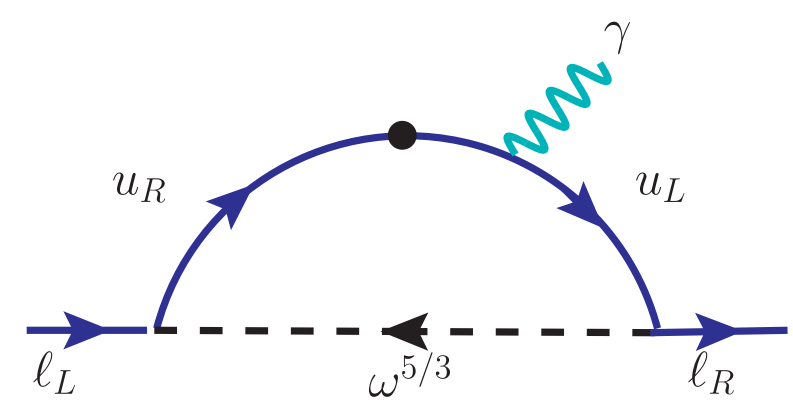


$$\boxed{g_S\left(\mu = m_{R_2}\right) = 4g_T\left(\mu = m_{R_2}\right) = \frac{f^L_{2\alpha}f^{R\star}_{33}}{4\sqrt{2}m^2_{R_2}G_F V_{cb}}}$$



Anomalous Magnetic Moment

$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f^R_{32} & 0 \end{pmatrix} \qquad f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f^R_{32} & 0 \end{pmatrix}$$



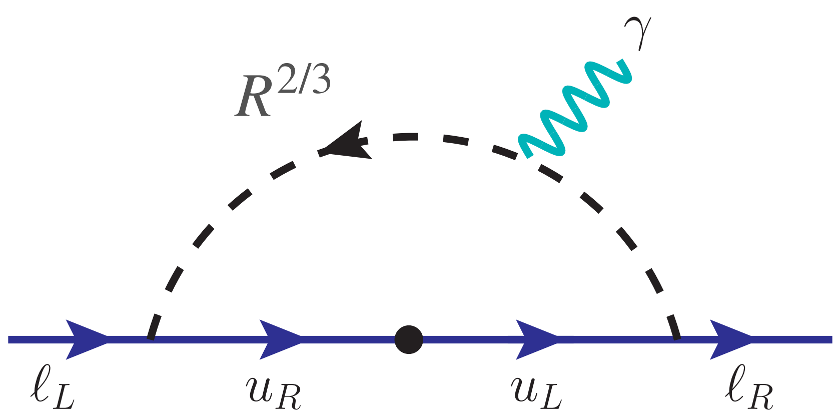
- For 1TeV LQ mass, the required product of Yukawa

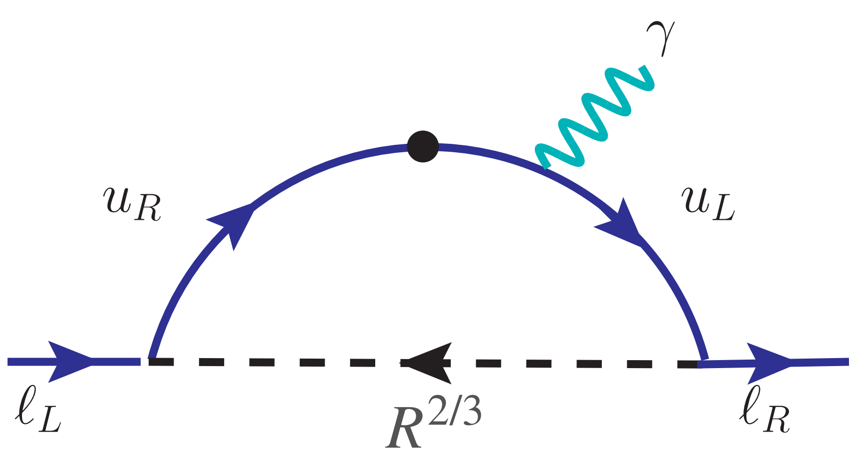
$$\boxed{(g-2)_\mu : \qquad f^L_{32}f^R_{32} = -0.0019}$$

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

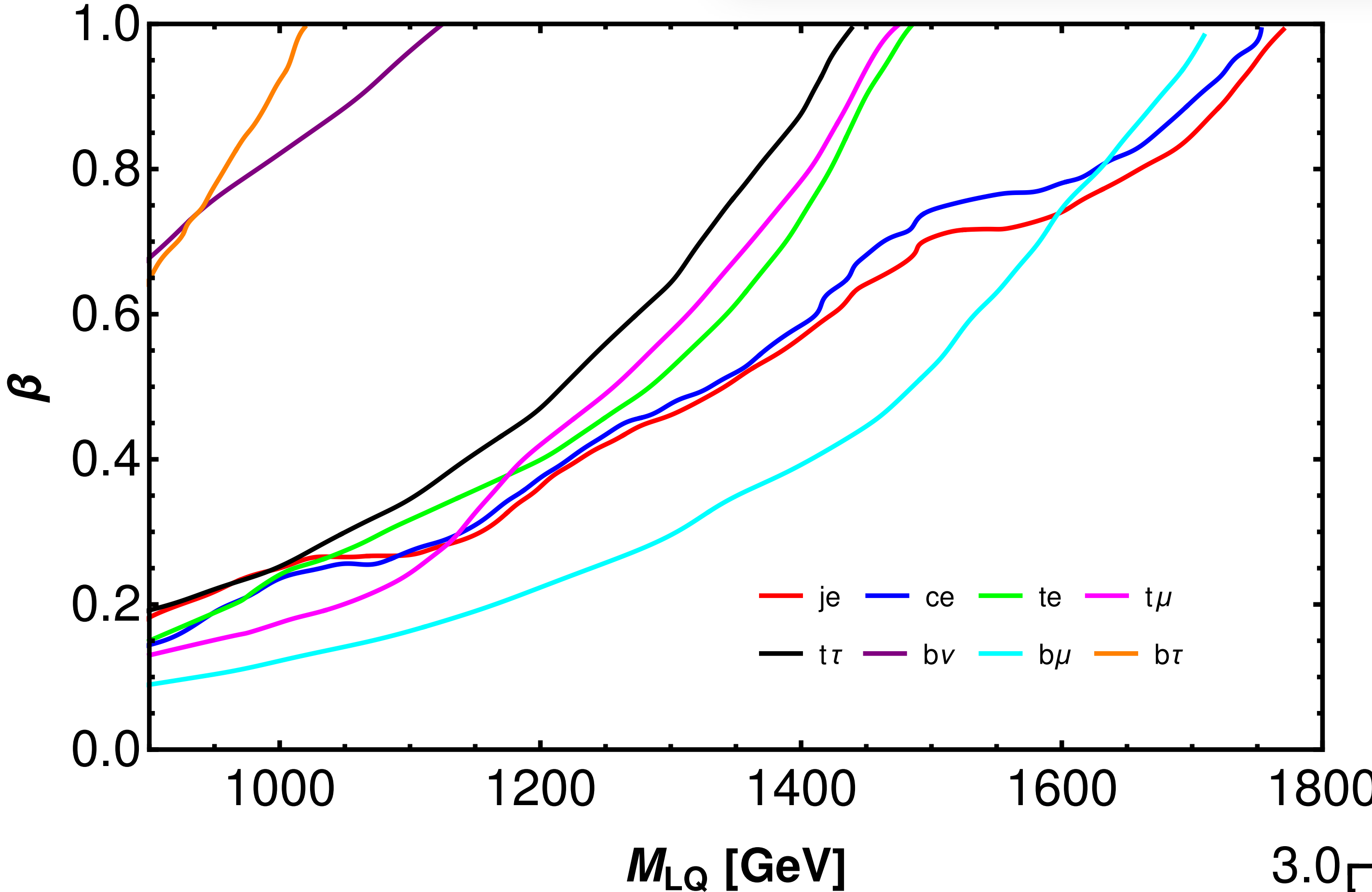


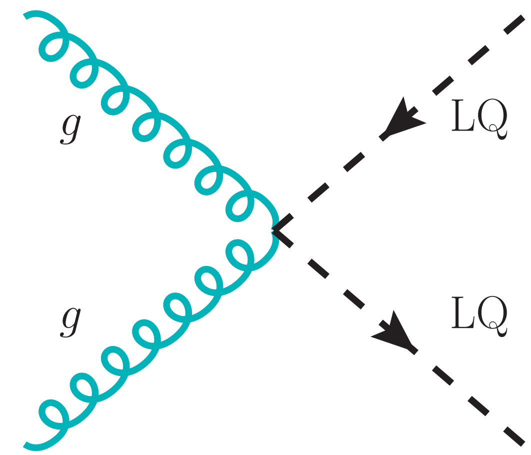


Bounds from kaons

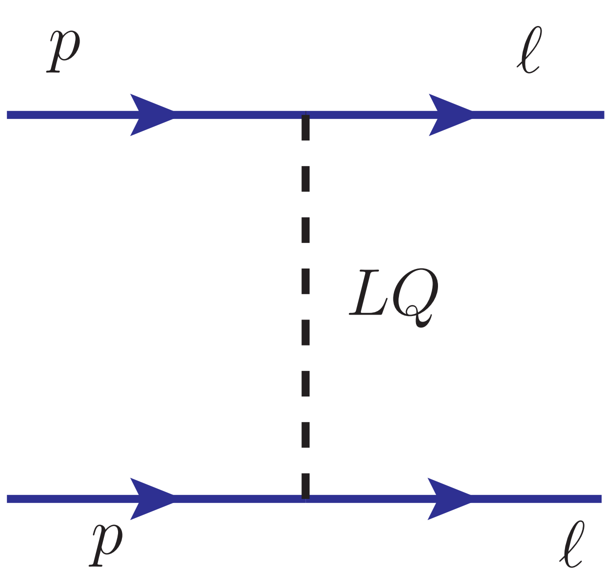
Process	**Constraints**
$K_L \to e^+ e^-$	$\lvert \hat{f}^R_{de} \hat{f}^{R*}_{se} \rvert \leq 2.0 \times 10^{-3} \left(\frac{M_{R_2}}{\text{TeV}} \right)^2$
$K^0_L \to e^\pm \mu^\mp$	$\lvert \hat{f}^R_{d\mu} \hat{f}^{R*}_{se} + \hat{f}^R_{s\mu} \hat{f}^{R*}_{de} \rvert \leq 1.9 \times 10^{-5} \left(\frac{M_{R_2}}{\text{TeV}}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

Collider Constraints

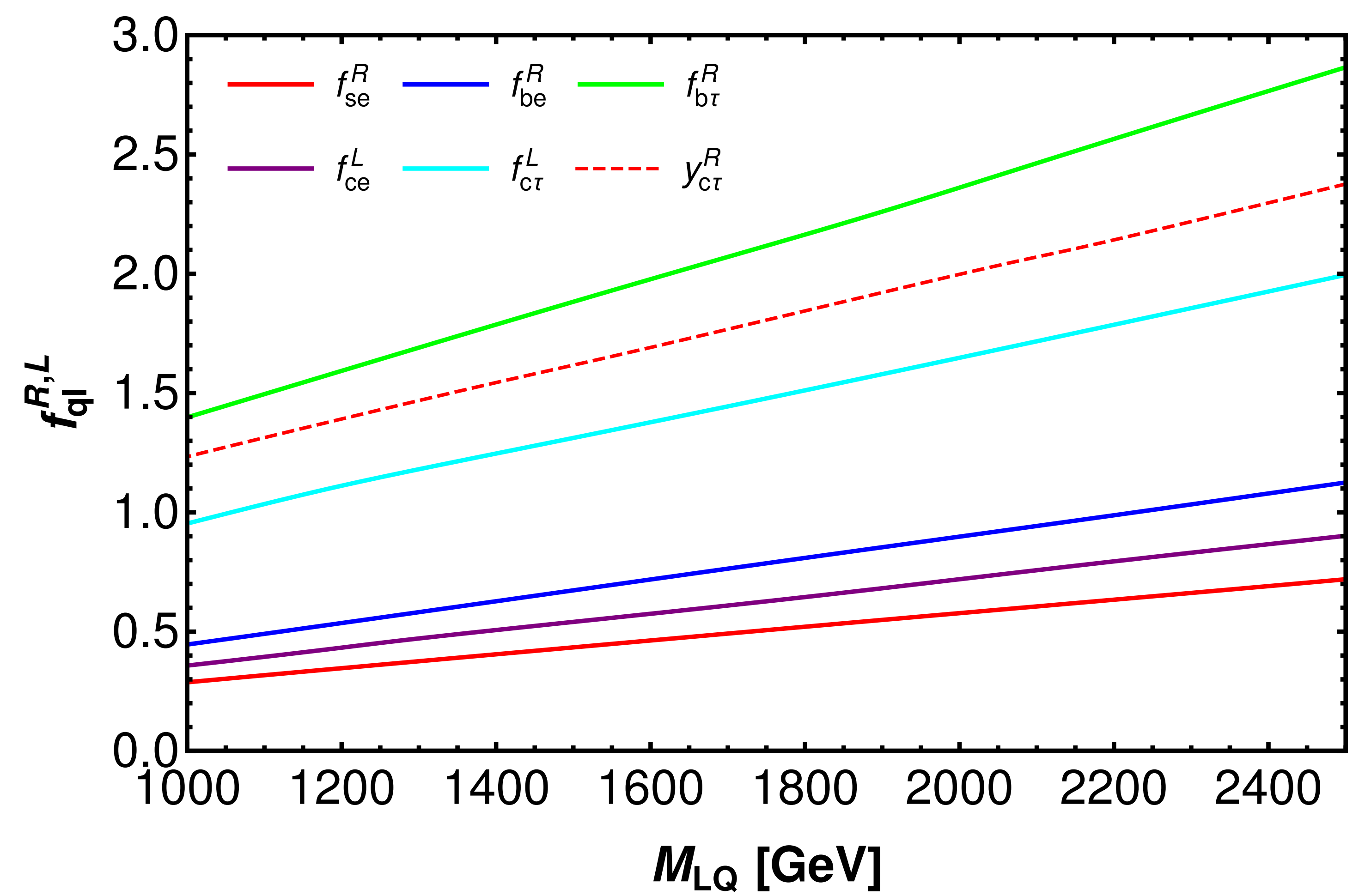




Pair-production Bounds



Dilepton Bounds



Fit to Oscillation Data

$$M_{\nu^D} = y_\ell M_E I_E y_\ell^\dagger$$

Oscillation parameters	**3σ range** `NuFit5.1` [51]	**Model prediction**			
		BP I (NH)	BP II (NH)	BP III (IH)	BP IV (IH)
$\Delta m^2_{21}(10^{-5}\ \text{eV}^2)$	6.82 - 8.04	7.42	7.38	7.35	7.35
$\Delta m^2_{23}(10^{-3}\ \text{eV}^2)$(IH)	2.410 - 2.574	-	-	2.48	2.52
$\Delta m^2_{31}(10^{-3}\ \text{eV}^2)$(NH)	2.43 - 2.593	2.49	2.51	-	-
$\sin^2\theta_{12}$	0.269 - 0.343	0.324	0.301	0.306	0.310
$\sin^2\theta_{23}$ (IH)	0.410 - 0.613	-	-	0.510	0.550
$\sin^2\theta_{23}$ (NH)	0.408 - 0.603	0.491	0.533	-	-
$\sin^2\theta_{13}$ (IH)	0.02055 - 0.02457	-	-	0.0219	0.0213
$\sin^2\theta_{13}$(NH)	0.02060 - 0.02435	0.0234	0.0213	-	-
δ_{CP} (IH)	192 - 361	-	-	236°	279°
δ_{CP} (NH)	105 - 405	199°	280°	-	-
m_{light} (10^{-3}) eV		0.66	2.04	14.1	8.50
M_{E_1}/M_{W_R}		917	45.5	1936	1990
M_{E_2}/M_{W_R}		0.650	0.43	0.12	0.11
M_{E_3}/M_{W_R}		0.019	0.029	0.015	0.012

[Babu, He, Su, **Thapa** '22]