Connection between neutrino mass models and muon experiments

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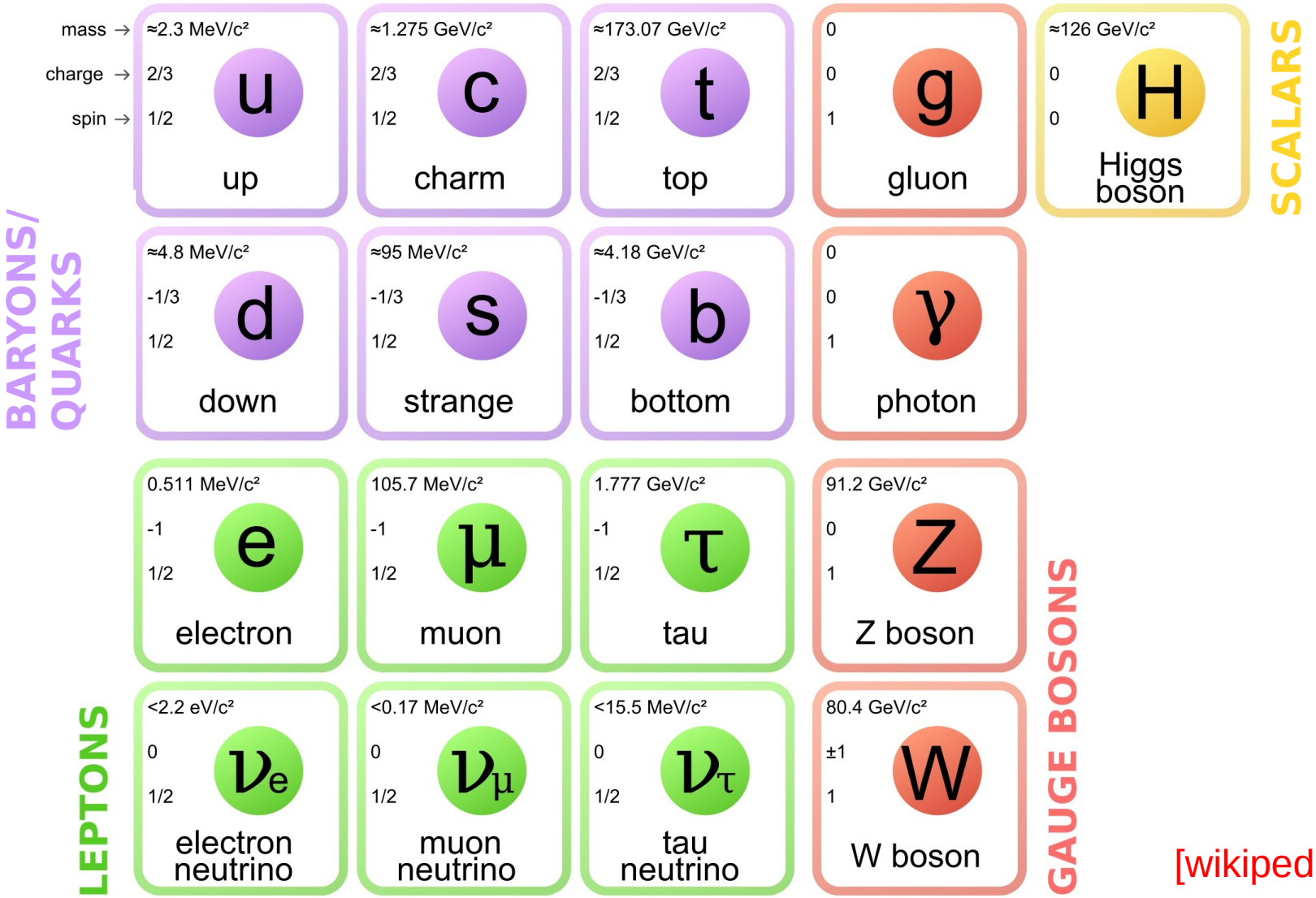
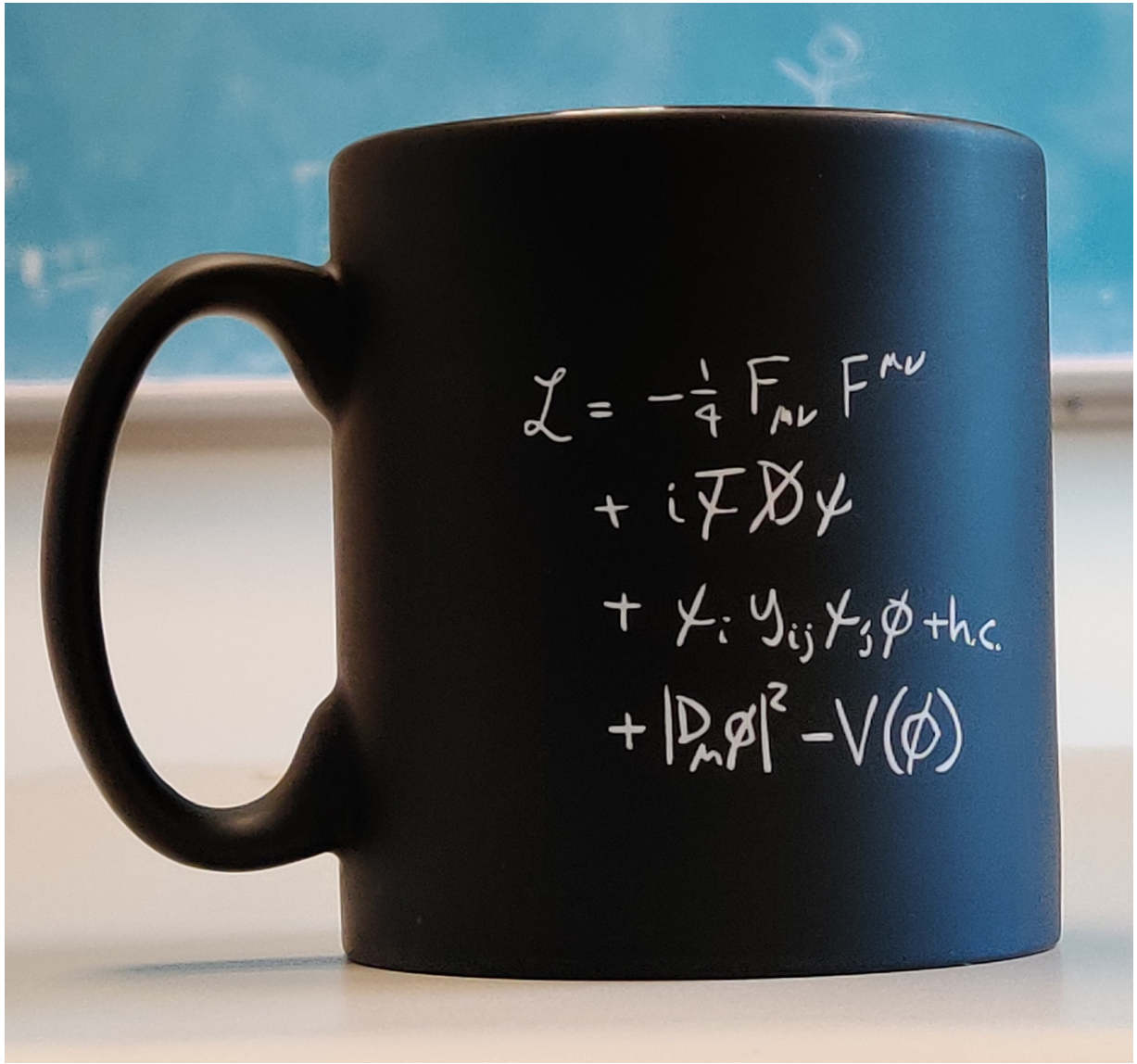
Elementary particles



[wikipedia]

The Standard Model



Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathrm{U}(1)_{\mathrm{B}} \times \mathrm{U}(1)_{\mathrm{L_e}} \times \mathrm{U}(1)_{\mathrm{L}_\mu} \times \mathrm{U}(1)_{\mathrm{L}_\tau}$$
$$=$$
$$\cancel{\mathrm{U}(1)}_{\mathrm{B+L}} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L_e}} \,.$$

- Broken non-perturbatively, but unobservable. ['t Hooft, PRL '76]

- True accidental global symmetry:

$$\boxed{\mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L_e}} \,.}$$

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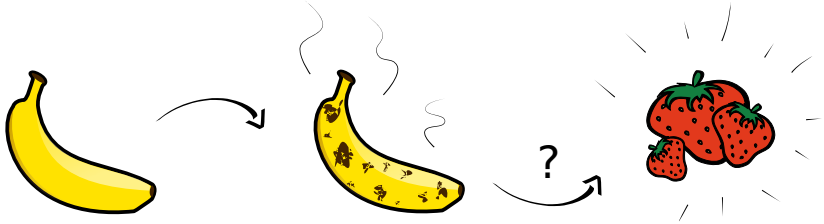
Lepton flavor conservation!

Prediction of Standard Model.

Flavor violating decays

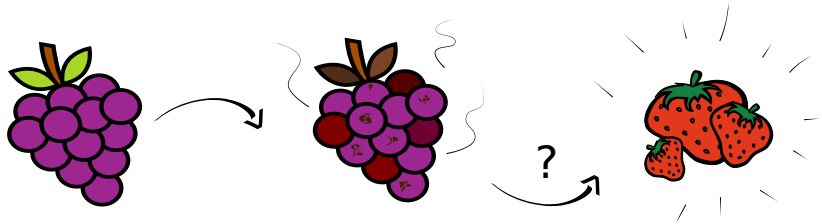


- Prime example: $\mu \to e\gamma$ @ MEG.
- Observation = new particles.
- $\mu \to e$ conversion @ Mu2e can probe scales up to 10^7 GeV.

See talks by Palo, Perrevoort, Group, Yamamoto, Dekkers, Papa, Lynch, Kriewald, Oksuzian.

LFV	process	current	future	exp
$\lvert\Delta L_\mu\rvert = 1$	$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}	MEG-II
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}	Mu3e
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-16}	Mu2e, COMET
$\lvert\Delta L_e\rvert = 1$	$h \to e\bar{\mu}$	6.1×10^{-5}	10^{-5}	LHC
	$Z \to e\bar{\mu}$	7.5×10^{-7}	10^{-10}	FCC-ee
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}	NA62

Flavor violating decays



- Produce tauons at B factories (BaBar, Belle (II), LHCb).
- Observation = new particles.
- $\tau^- \to e^- e^+ e^-$ @ Belle II will probe scales up to 2×10^4GeV.

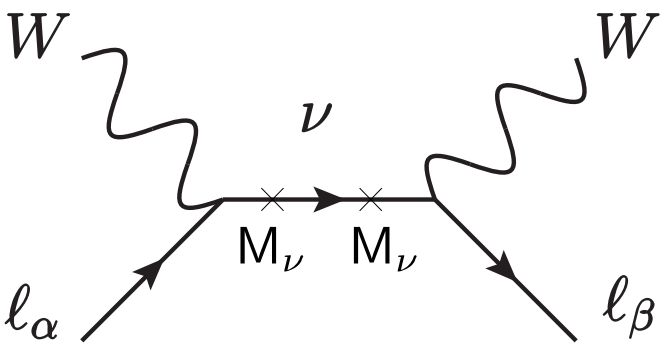
LFV	process	current	future	exp
$\lvert\Delta L_\tau\rvert = 1$	$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}	Belle II
	$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	10^{-9}	Belle II
	$\tau \to e\,\mathrm{had}$	$\mathcal{O}(10^{-8})$	10^{-9}	Belle II
$\lvert\Delta L_e\rvert = 1$	$h \to e\bar{\tau}$	4.7×10^{-3}	10^{-4}	LHC
	$Z \to e\bar{\tau}$	9.8×10^{-6}	10^{-9}	FCC-ee
	$\mathrm{had} \to e\bar{\tau}(\mathrm{had})$	$\mathcal{O}(10^{-6})$	–	Belle II

Neutrino oscillations = flavor violation

- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

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

  is broken!



- Amplitudes for *charged* lepton flavor violation are suppressed:

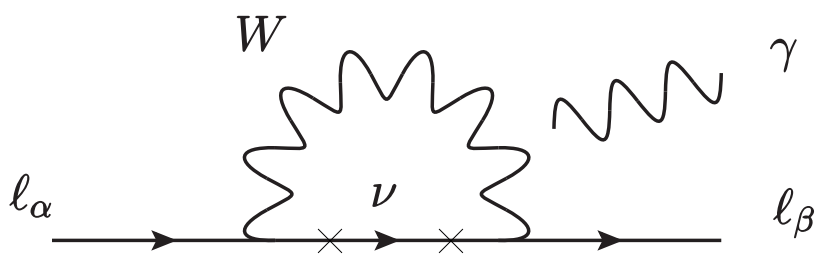
$$\mathcal{A}(\ell_\alpha^- \to \ell_\beta^-) \propto \frac{(M_\nu M_\nu^\dagger)_{\alpha\beta}}{M_W^2} < 10^{-24}\,.$$

Great goalpost for Snowmass 3000!

- Most (neutrino mass) models also generate CLFV rates unsuppressed by M_ν that could be observable.

Neutrino mass ⇒ charged LFV?

- SM + Dirac neutrinos: $\mathcal{L} = \mathcal{L}_{\rm SM} - \underbrace{(y\overline{L}H\nu_R + \text{h.c.})}_{} + i\overline{\nu}_R\partial\!\!\!/\nu_R$



$$m_\nu = y\langle H\rangle = U\,\mathrm{diag}(m_1, m_2, m_3)V_R \overset{!}{\lesssim} \text{eV}$$

- *All* CLFV is GIM suppressed:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta\gamma)}{\Gamma(\ell_\alpha \to \ell_\beta\nu_\alpha\overline{\nu}_\beta)} \simeq \frac{3\alpha_{\rm EM}}{32\pi}\left|\sum_{j=2,3} U_{\alpha j}\frac{\Delta m^2_{j1}}{M_W^2}U^\dagger_{j\beta}\right|^2 < 5\times 10^{-53}\,.$$

[‘77: Petcov; Bilenky, Petcov, Pontecorvo; Marciano, Sanda; Lee, Pakvasa, Shrock, Sugawara]

Seesaw mass ⇒ charged LFV?

- SM + seesaw neutrinos: $L = L_{SM} + i\overline{N}_R \partial\!\!\!/ N_R$

$$- \left(\tfrac{1}{2} M_R \overline{N}_R^c N_R + \underbrace{y\overline{L}HN_R}_{m_D \overline{\nu}_L N_R} + \text{h.c.}\right)$$

- Violates $\Delta L = 2$. For large M_R:

$$M_N \simeq M_R\,, \qquad M_\nu \simeq -m_D M_R^{-1} m_D^T = U^* \,\mathrm{diag}(m_1, m_2, m_3) U^\dagger .$$

- Majorana neutrinos!
- LFV:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{EM}}{8\pi} \underbrace{|(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}|^2}_{\mathcal{O}(M_\nu^4/m_D^4)} .$$

Not true with fine-tuning or structure in m_D.

Seesaw parameters

$$L = L_{SM} + i\overline{N}_R \partial\!\!\!/ N_R - (\tfrac{1}{2} M_R \overline{N}_R^c N_R + m_D \overline{\nu}_L N_R + h.c.)$$

$$\Rightarrow \quad M_\nu \simeq -m_D M_R^{-1} m_D^T \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \propto |(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}|^2.$$

- One to one correspondence

$$\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D M_R^{-2} m_D^\dagger\}.$$

[Broncano, Gavela, Jenkins, hep-ph/0210271]

- Or: unique d=6 operator $(y M_R^{-2} y^\dagger)(\overline{L}H)(i\partial\!\!\!/)(H^\dagger L)$.
- Gives LFV and non-unitary PMNS.

LFV *complementary* to M_ν!

EFT Seesaw

- One to one correspondence

$$\{m_D, M_R\} \leftrightarrow \{M_\nu \simeq -m_D M_R^{-1} m_D^T, m_D M_R^{-2} m_D^\dagger\}.$$

- Flavor structure of m_D to get large LFV and tiny M_ν:

$$m_D \propto \begin{pmatrix} 1 \\ z\sqrt{\frac{M_2}{M_1}} \\ \pm i\sqrt{1+z^2}\sqrt{\frac{M_3}{M_1}} \end{pmatrix} (\lambda_e \;\; \lambda_\mu \;\; \lambda_\tau) + \epsilon$$

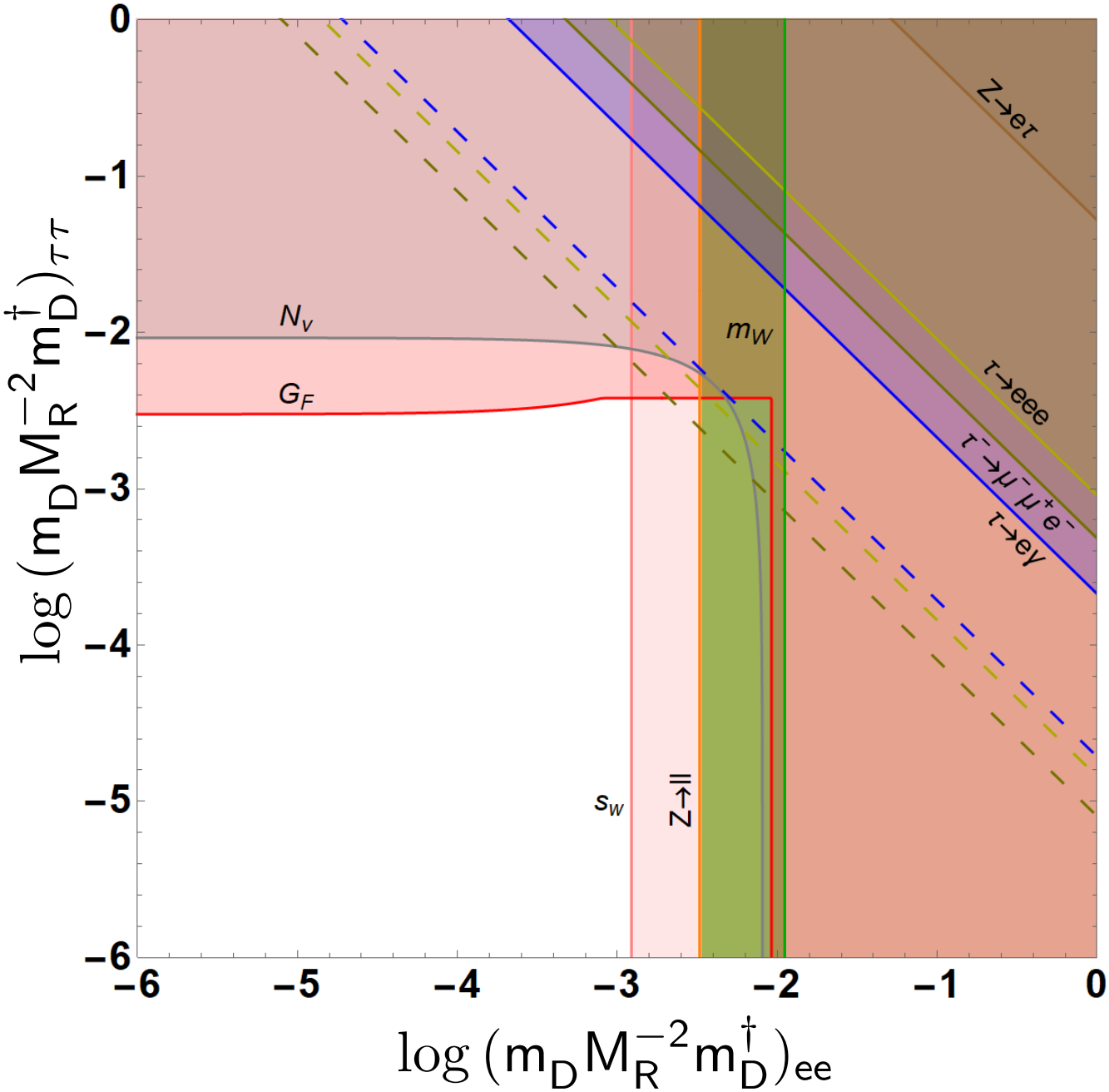
[Coy & Frigerio, 1812.03165;
See also Kersten & Smirnov '07]

- LFV matrix only has 3 real free parameters:

$$(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta} = \sqrt{(m_D M_R^{-2} m_D^\dagger)_{\alpha\alpha} (m_D M_R^{-2} m_D^\dagger)_{\beta\beta}}\,.$$

- Relation between LFV and non-LFV constraints.

$$(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta} = \sqrt{(m_D M_R^{-2} m_D^\dagger)_{\alpha\alpha}(m_D M_R^{-2} m_D^\dagger)_{\beta\beta}}\,.$$



[Coy & Frigerio, 1812.03165 & 2110.09126]

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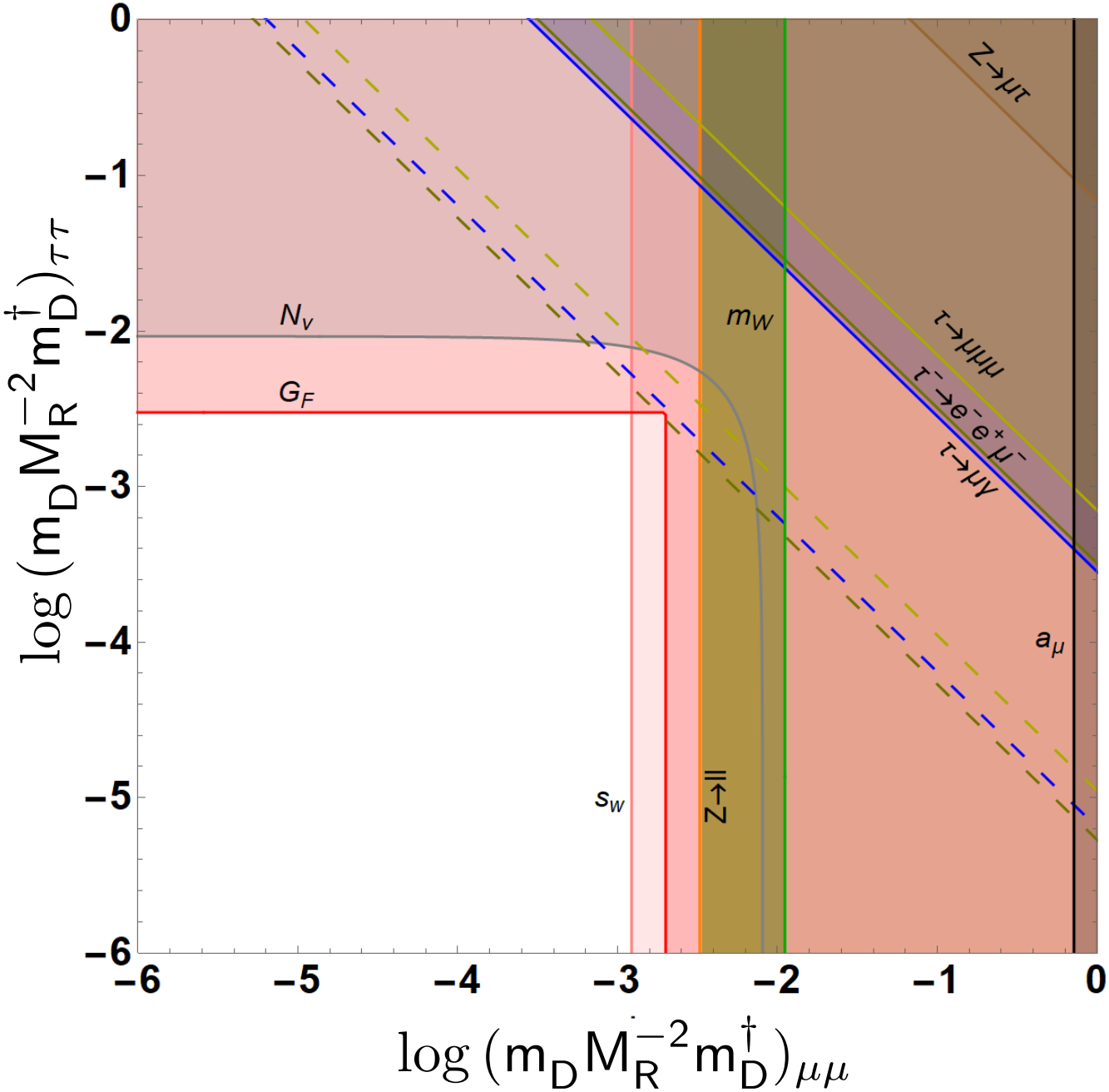

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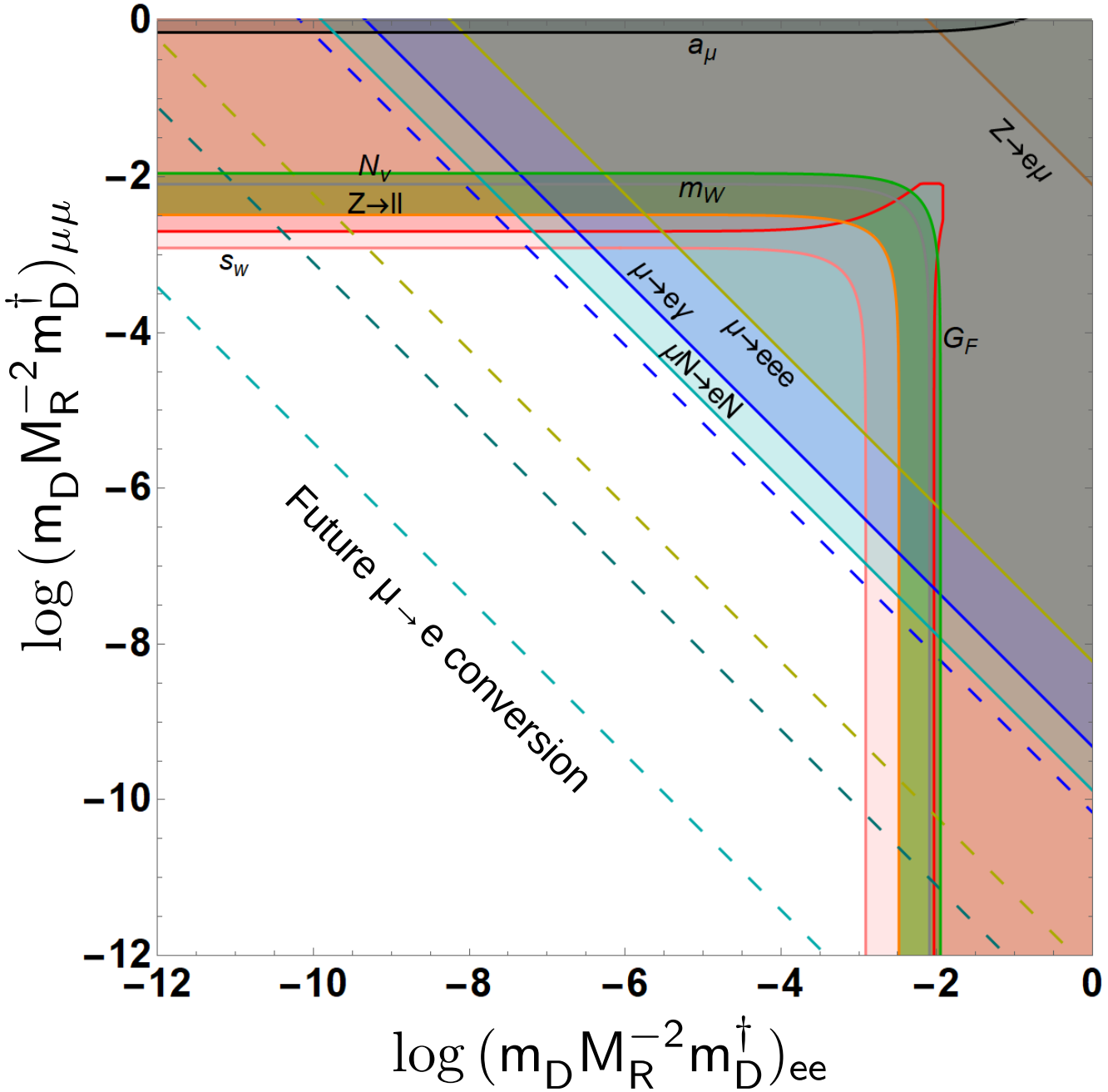

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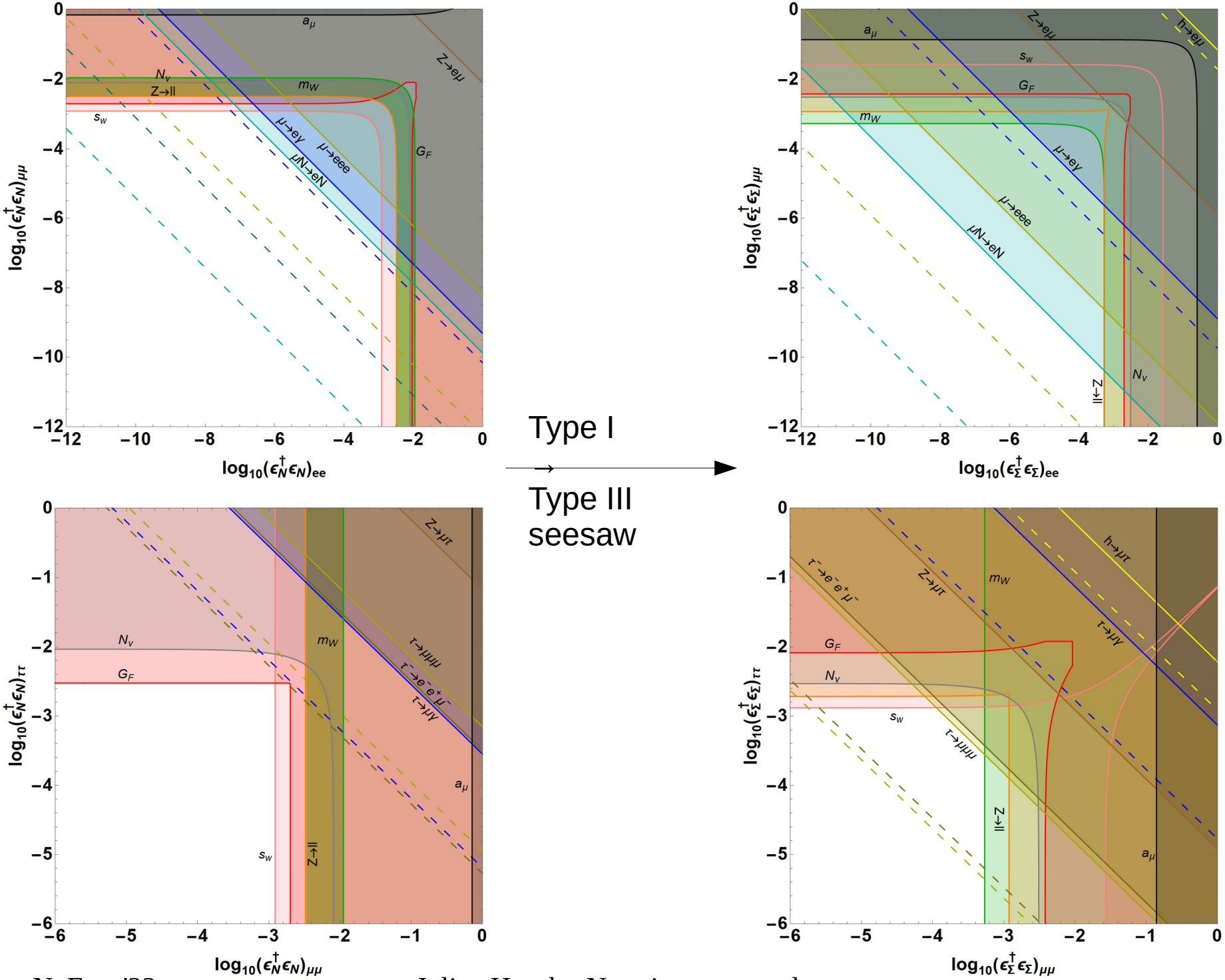
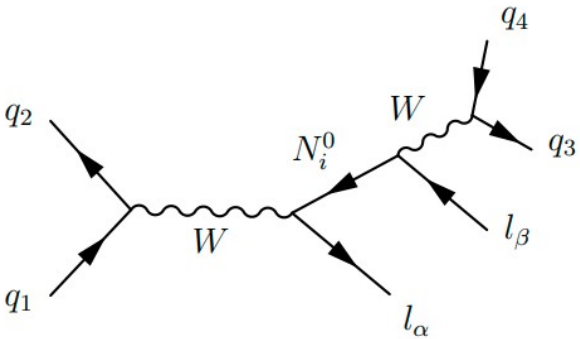


[Coy & Frigerio, 1812.03165 & 2110.09126]

Seesaw

- Interesting interplay of LFV and non-LFV observables.
- Type-I can get large rates for muon LFV, tauons difficult.
  [Crivellin, Kirk, Manzari, 2208.00020 find testable tau LFV though]
- Type-III seesaw can also give large tau LFV. [Coy & Frigerio '22]
- For "light" right-handed neutrinos EFT breaks down:
  - N_R can be emitted on-shell at colliders.



[Kersten & Smirnov '07]

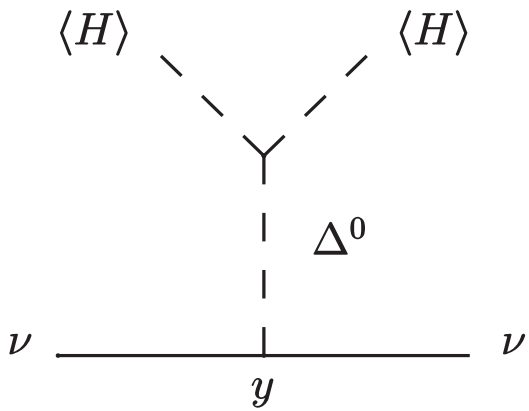
  - Allows better access to seesaw parameters.
    See talks by ATLAS & CMS later.

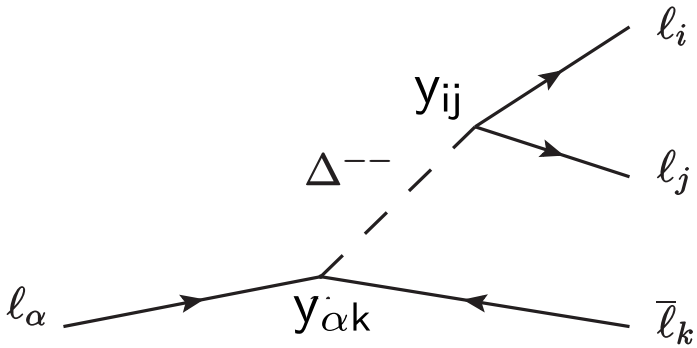
LFV *complementary* to M_ν!

Scalar-triplet (type-II) seesaw

[Konetschny & Kummer '77; Magg & Wetterich, '80; Schechter & Valle '80; Cheng & Li, '80; Mohapatra & Senjanovic, '81]

$$L = L_{SM} + |D_\alpha \Delta|^2 - (y_{\alpha\beta} \overline{L}^c_\alpha \Delta L_\beta + \mu H \Delta H + h.c.)$$





$$\Rightarrow \quad (M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta} \frac{2\mu v^2}{M_\Delta^2} \quad \& \quad BR(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |(M_\nu)_{\alpha k}|^2 |(M_\nu)_{ij}|^2.$$

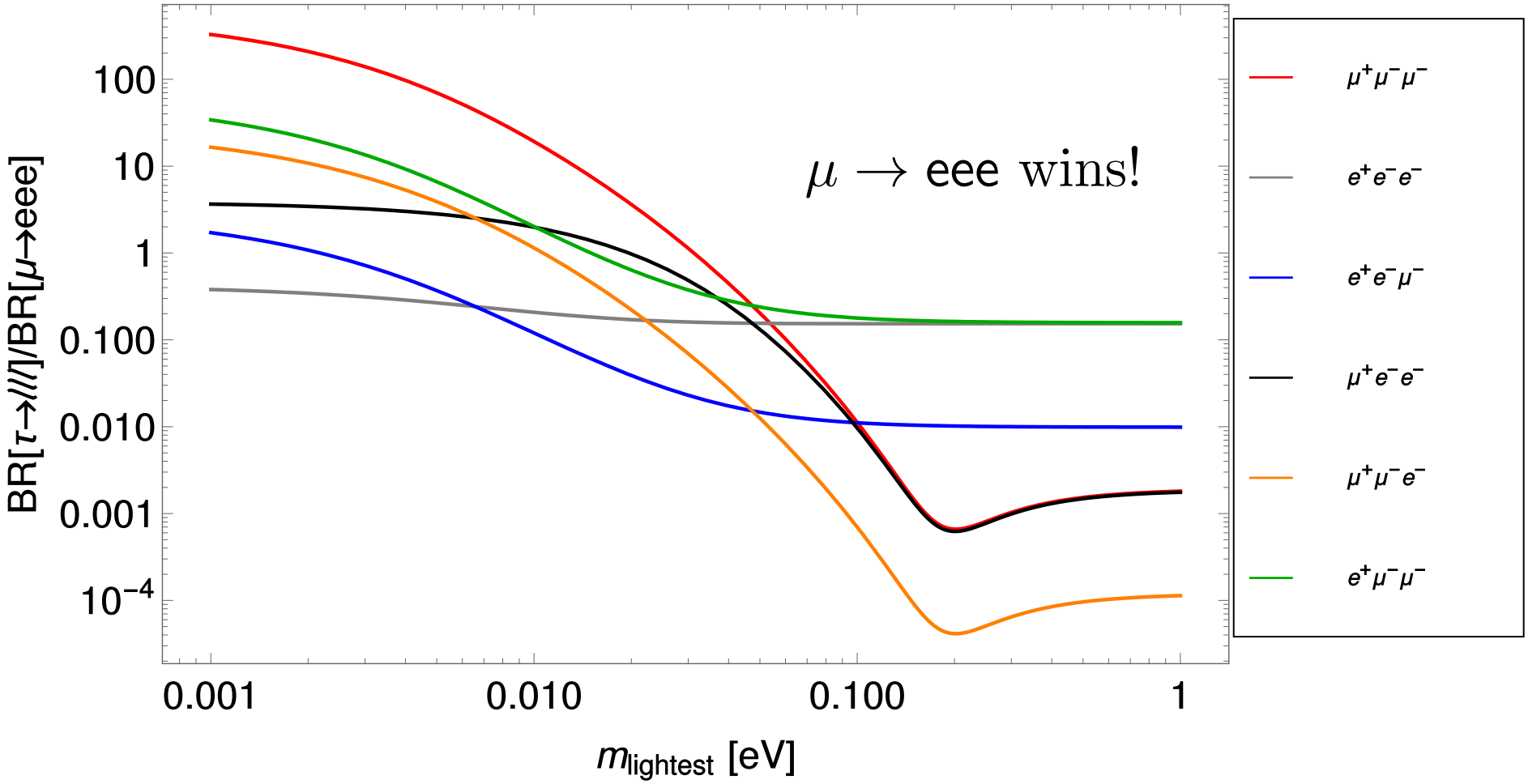
[Pich, Santamaria, Bernabeu, '84; Abada++, 0707.4058]

Prediction of LFV *ratios* via M_ν!

CDF's W-mass first hint for this triplet with O(100 GeV) mass? [Heeck, 2204.10274]

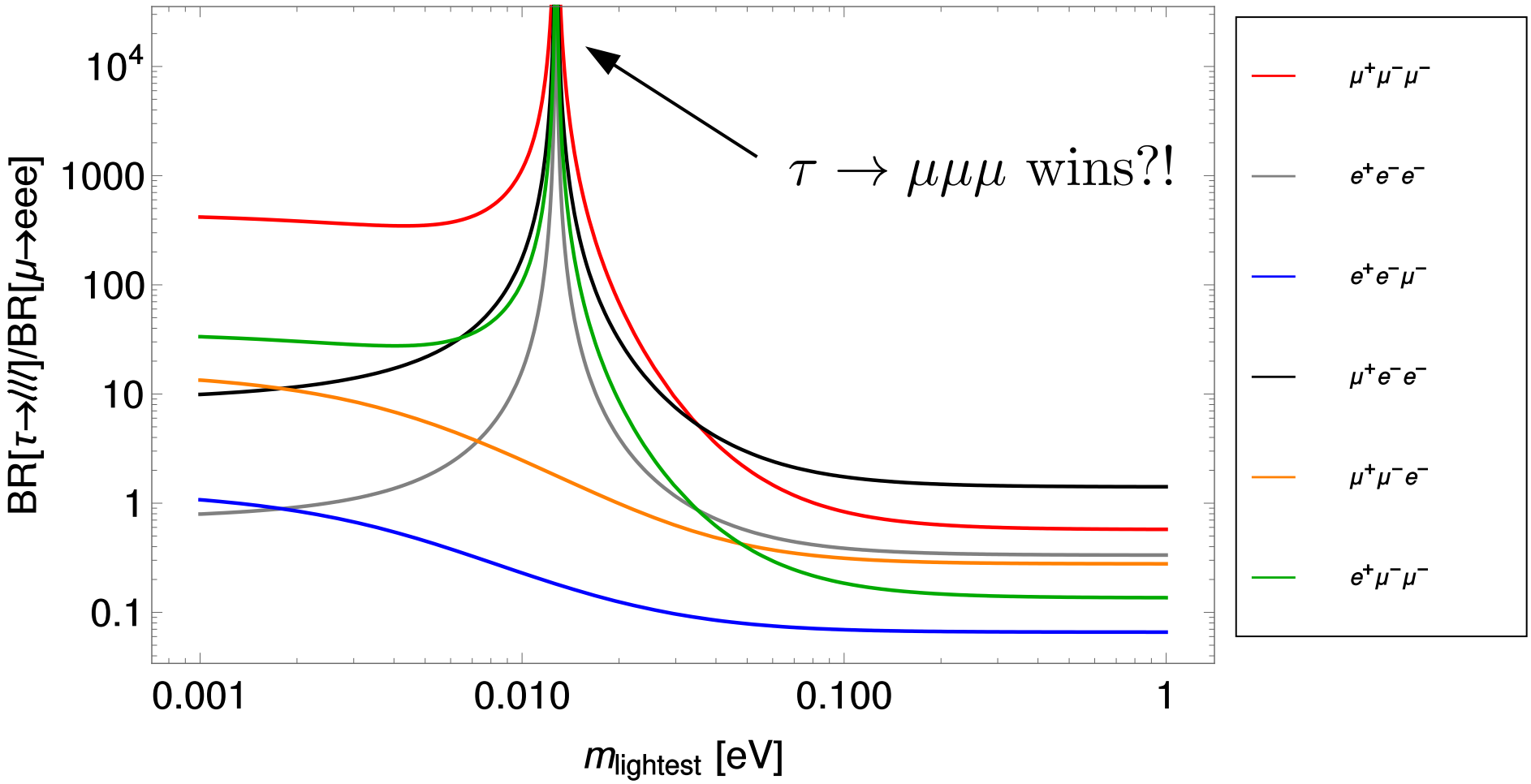
Majorana CP phases

Normal hierarchy, $\alpha_1 = \alpha_2 = 0\,.$



$$\Rightarrow \quad (\mathrm{M}_\nu)_{\alpha\beta} \simeq \mathrm{y}_{\alpha\beta}\frac{2\mu \mathrm{v}^2}{\mathrm{M}_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_\mathrm{i}\ell_\mathrm{j}\bar{\ell}_\mathrm{k}) \propto |(\mathrm{M}_\nu)_{\alpha\mathrm{k}}|^2|(\mathrm{M}_\nu)_{\mathrm{ij}}|^2.$$

Normal hierarchy, $\alpha_1,\ \alpha_2 : (M_\nu)_{e\mu} \sim 0\,.$

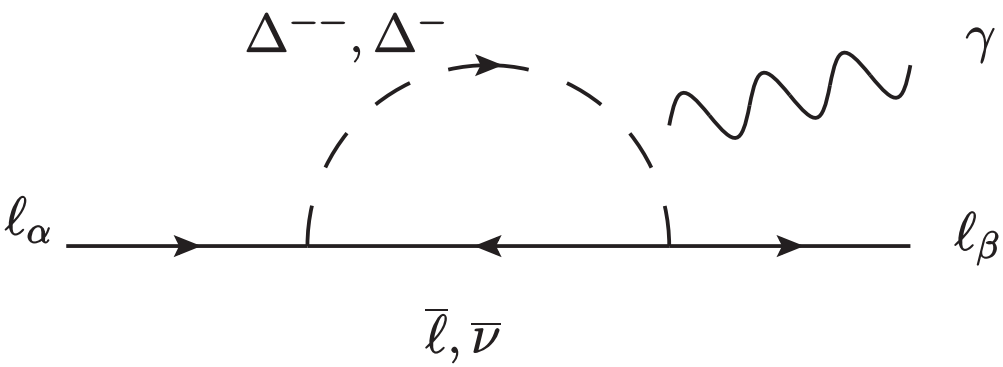


$$\Rightarrow \quad (M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta}\frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |(M_\nu)_{\alpha k}|^2 |(M_\nu)_{ij}|^2.$$

Scalar-triplet seesaw

$$(M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta}\frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |y_{\alpha k}|^2 |y_{ij}|^2 / M_\Delta^4 .$$

- But at loop level:



$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \propto \frac{|(y^\dagger y)_{\alpha\beta}|^2}{M_\Delta^4} .$$

[Pich, Santamaria, Bernabeu, '84]

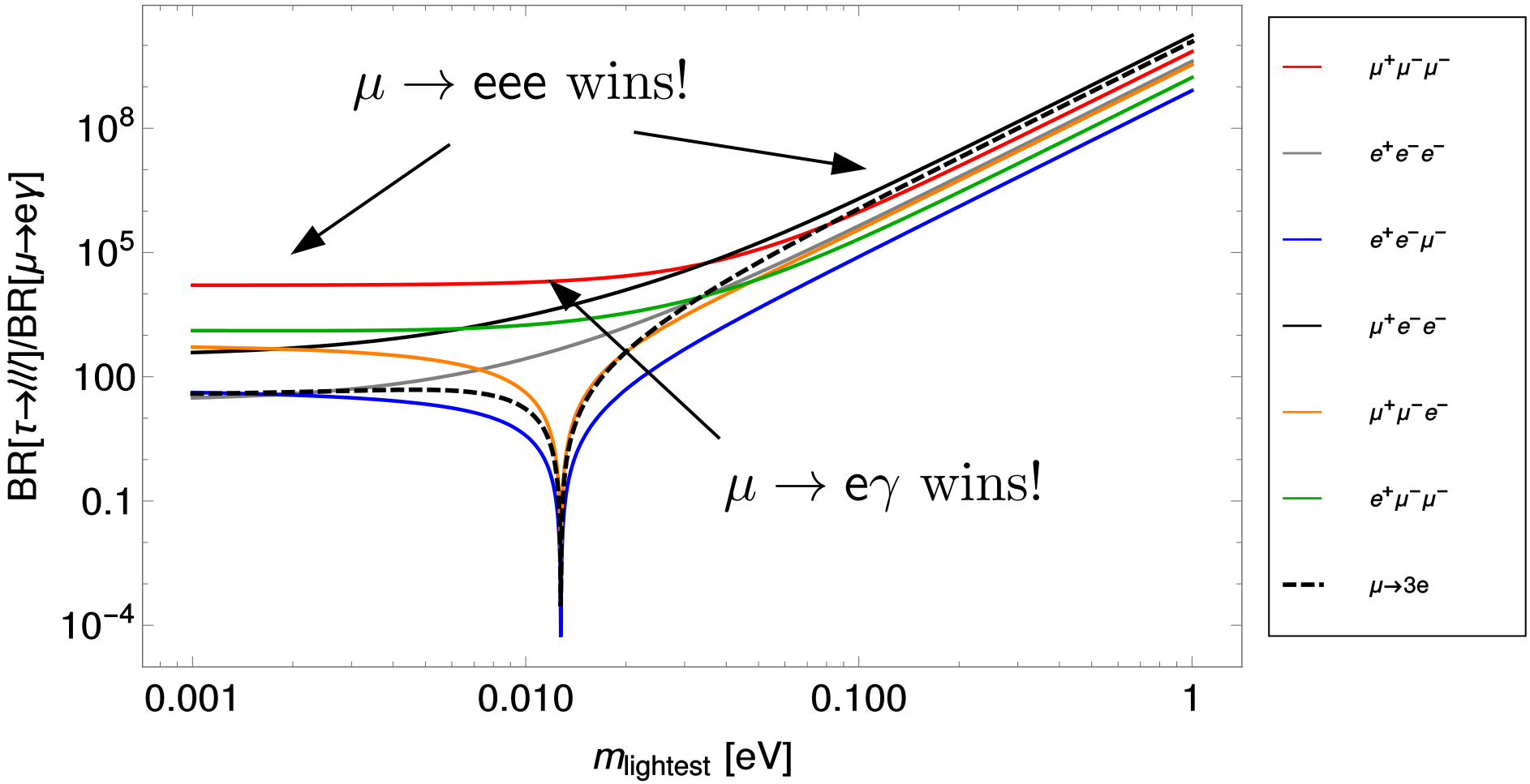
- $\mu \to 3e$ could be 0, but $\mu \to e\gamma$ cannot (since θ_{13}).

[Chakrabortty++, 1204.1000]

- Prediction:

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

Normal hierarchy, $\alpha_1, \alpha_2 : (M_\nu)_{e\mu} \sim 0$.



Prediction of LFV ratios via M_ν!

Seesaws and LFV

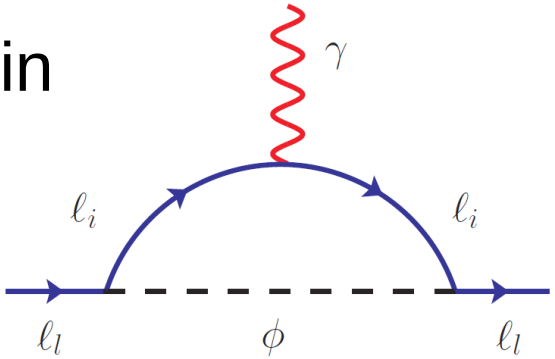
- Seesaws make different predictions for LFV *ratios*.

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3} - 0.3$	$0.1-10$
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$

[Calibbi & Signorelli, 1709.00294]

  - (Muon) LFV experiments could distinguish seesaws.
  - Could even access neutrino parameters (phases etc.).
  - Cannot explain $(g\text{-}2)_\mu$ (or give large muon EDM).

- $(g\text{-}2)_\mu$ surprisingly difficult, wrong sign also in scotogenic model & Zee-Babu model, and often killed by $\mu \to e\gamma$.

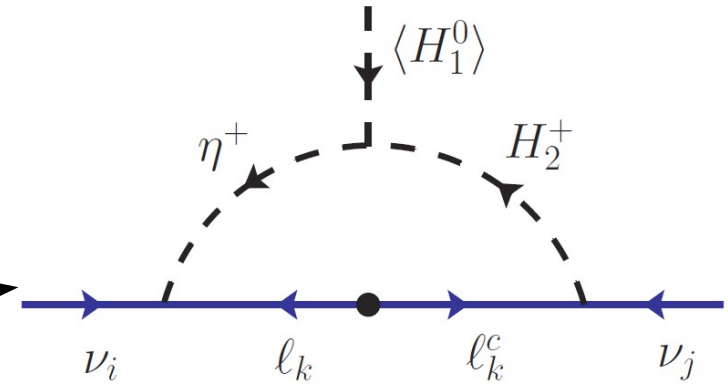


Zee model

- 2HDM plus charged singlet scalar η^+.

$$\mathcal{L} \supset f_{ij} L_i \epsilon L_j \eta^+ + \mu H_1 \epsilon H_2 \eta^- + \text{h.c.}$$

- Radiative neutrino mass:

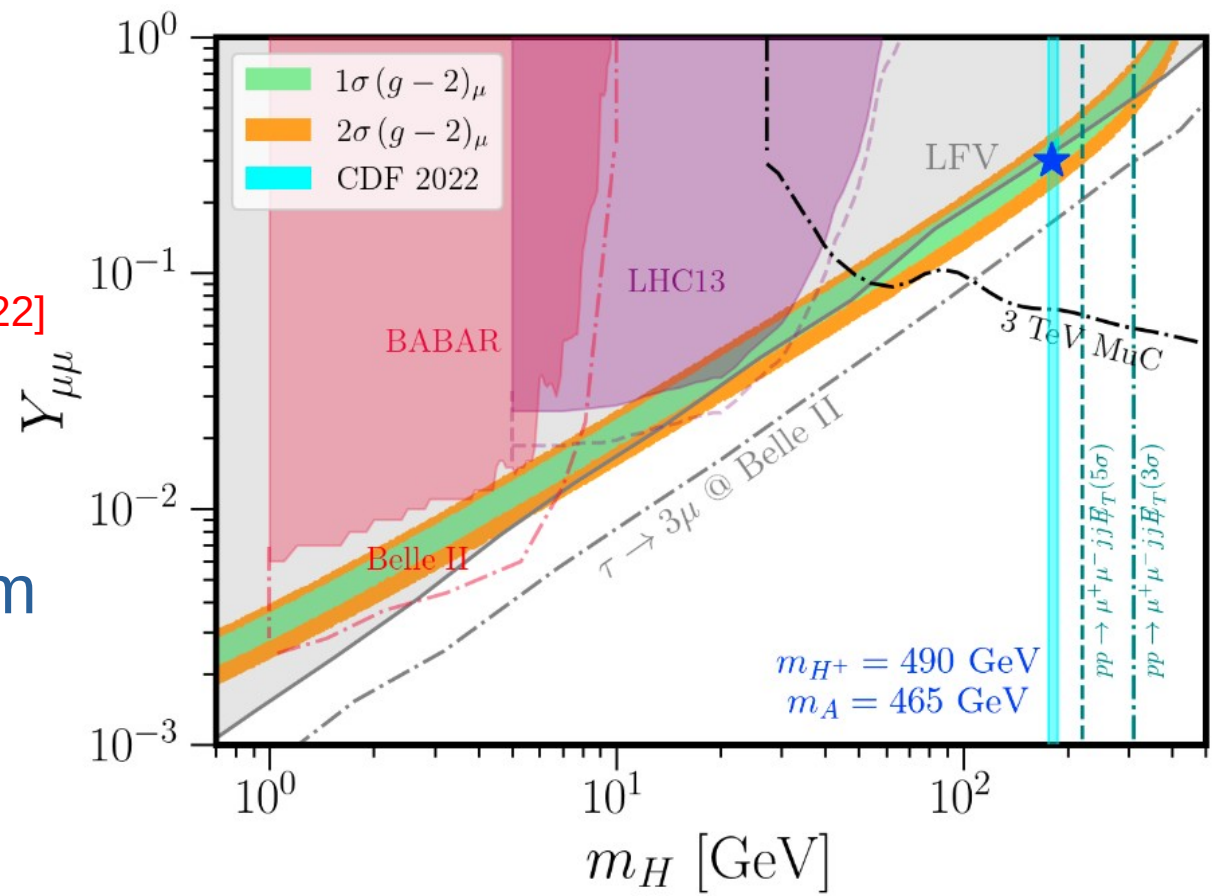


- Can explain $(g\text{-}2)_\mu$.
- Can also explain CDF's M_W!

  [Chowdhury, Heeck, Thapa, Saad, '22]

- Zee model can also yield testable muonium-antimuonium conversion!

  [Heeck & Thapa, in progress]



Majoronic seesaw

- SM + 3 singlets N_R + new scalar $\sigma = (f + \sigma^0 + iJ)/\sqrt{2}.$

Lepton number breaking scale Heavy scalar **Majoron**

[Chikashige, Mohapatra, Peccei, '81; Schechter, Valle, '82]

- Break $U(1)_L$ spontaneously:

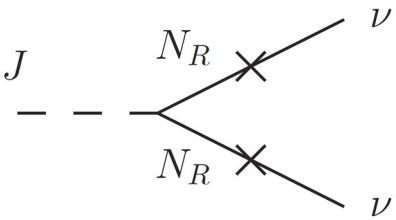
$$L = -\underbrace{\bar{L} y H}_{m_D = \frac{y}{\sqrt{2}} v} N_R - \frac{1}{2} \overline{N}_R^c \underbrace{\kappa \sigma}_{M_R = \frac{\kappa f}{\sqrt{2}}} N_R + h.c. \quad \longrightarrow \quad \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- For $M_R \gg m_D$: $M_\nu \simeq -m_D M_R^{-1} m_D^T$

$$\simeq 1\text{eV} \left(\frac{m_D}{100\text{GeV}} \right)^2 \left(\frac{10^{13}\text{GeV}}{M_R} \right).$$

Majoron couplings

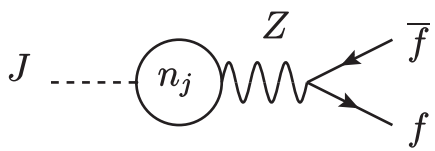
- Tree-level coupling only to neutrinos:



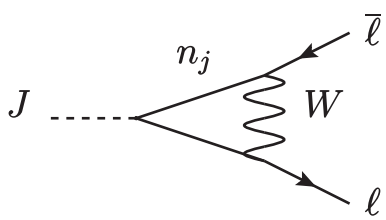
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 (m_D M_R^{-1} m_D^T)^*_{\alpha\beta}\nu_\beta = -\underbrace{\frac{iJ}{2f}\sum_k \overline{\nu}_k \gamma_5 m_k \nu_k}$$

Too small for lab

- One loop:



$$\frac{iJ}{f}\overline{f}\gamma_5 f \, \frac{m_f T_3^f}{8\pi^2 v^2} \, \mathrm{tr}\left(m_D m_D^\dagger\right)$$



$$\frac{iJ}{f}\overline{\ell}_\alpha \left(\frac{m_\beta}{8\pi^2 v^2}P_R - \frac{m_\alpha}{8\pi^2 v^2}P_L\right)\ell_\beta \left(m_D m_D^\dagger\right)_{\alpha\beta}$$

Off-diagonal!

[**JH**, Garcia-Cely, JHEP ‘17; see also Pilaftsis ‘94]

Properties

- Crucial observation: the two matrices are independent!

$$\{m_D,\, M_R\} \leftrightarrow \{M_\nu = -m_D M_R^{-1} m_D^T,\;\; m_D m_D^\dagger\}.$$

[Davidson, Ibarra, JHEP '01]

- $J\bar{\ell}\ell'$ coupling can be *large* and of arbitrary structure.
- Similar couplings arise for familons or flavor Z'.

[Wilczek, '82; Reiss, '82; Grinstein, Preskill, Wise, 85; ...]

- Experimental signature depends on J decay channel:

$$\ell \to \ell' J, \quad J \to \text{inv}\,, \ell''\ell''', \underbrace{\gamma\gamma}, \ldots$$

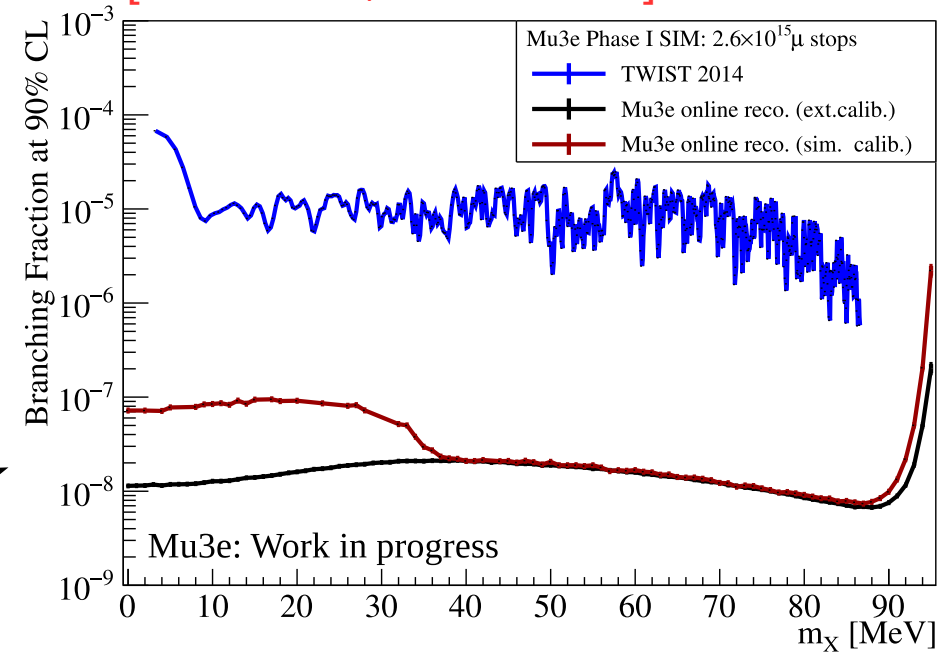
[**JH**, Rodejohann, PLB '18; Bauer et al., PRL '20; Cornella et al., JHEP '20; Cheung++, JHEP '21]

[$\mu \to e\, J$, $J \to \gamma\gamma$: MEG, 2005.00339]

$\mu \to e\ J$

See talk by Perrevoort.

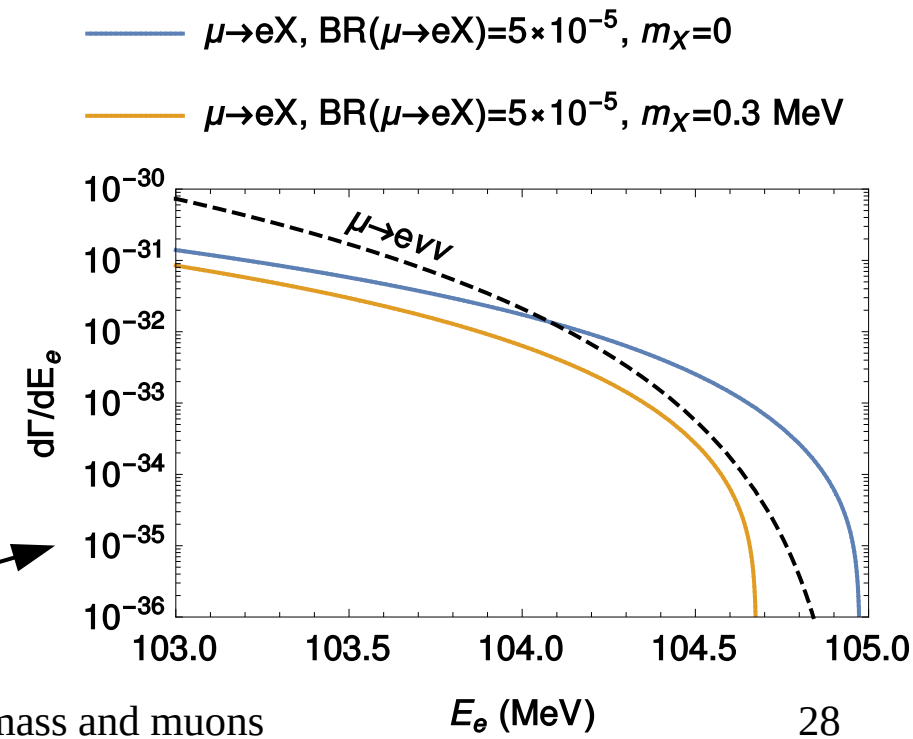
[Perrevoort, 1812.00741]

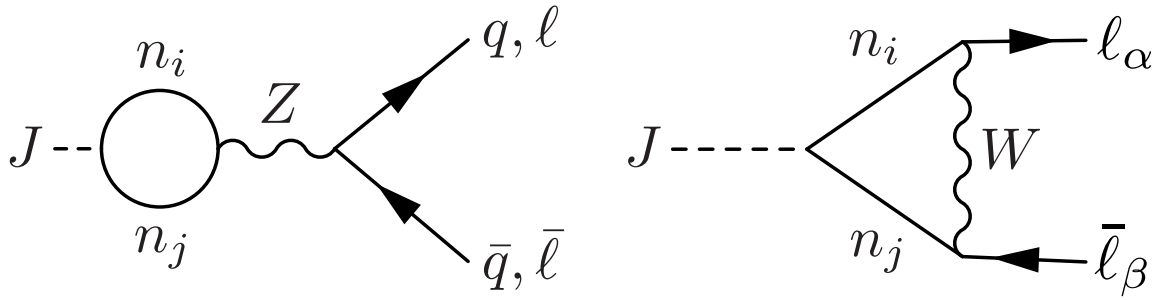


- Electron *line* on top of Michel spectrum.
- Good prospects @ Mu3e.
- In progress: signal in $\mu \to e$ conversion exps. COMET, Mu2e(-II).
  - Many muons!
  - Nuclear recoil: E_e up to m_μ.
  - Suppression of tail...

[Garcia i Tormo++, PRD '11; Uesaka, 2005.07894]

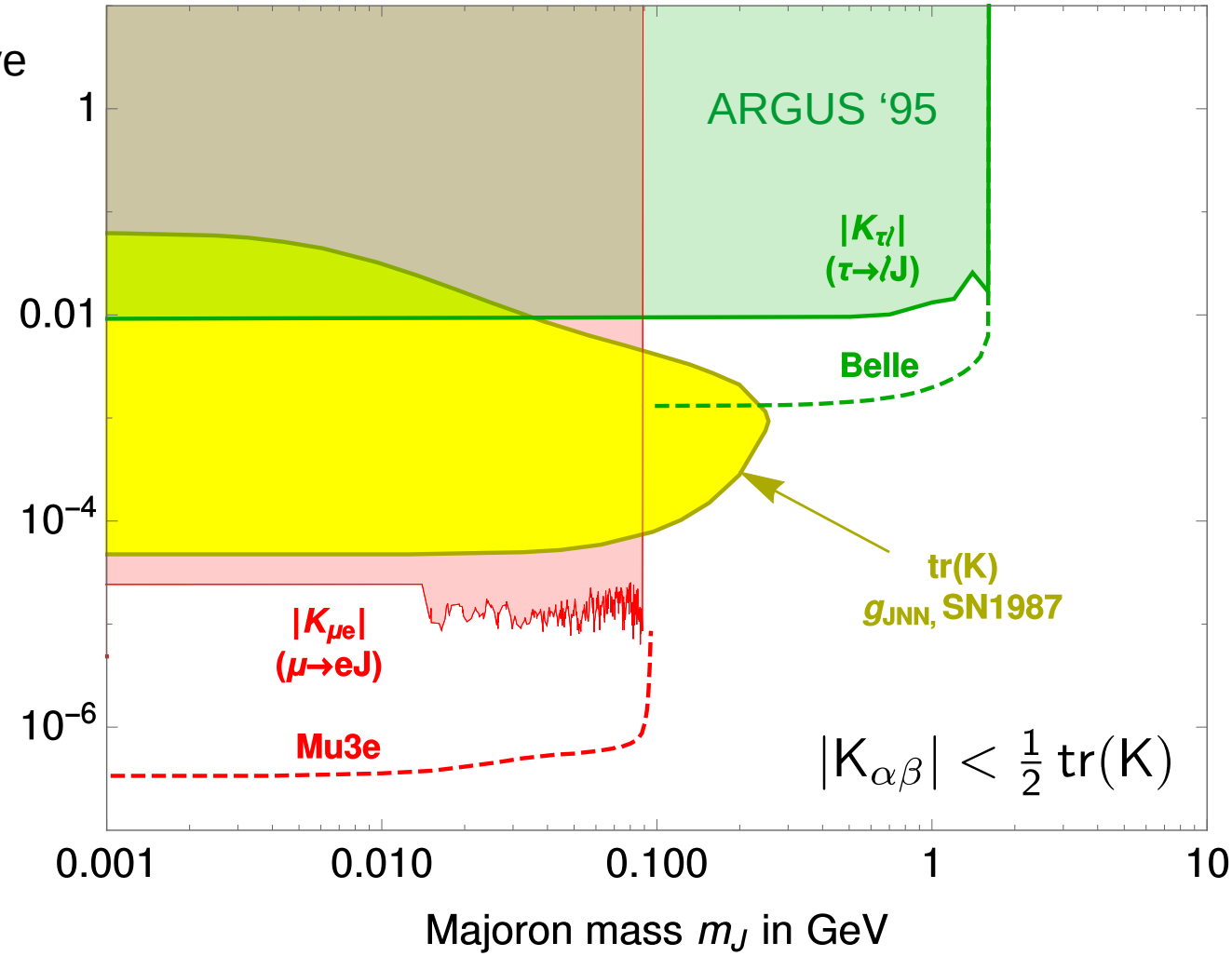
[**JH**++, Mu2e-II Snowmass LOI]





Limit on effective coupling

$$K \equiv \frac{m_D m_D^\dagger}{f\,v}$$



[**JH**, Garcia-Cely, JHEP '17]

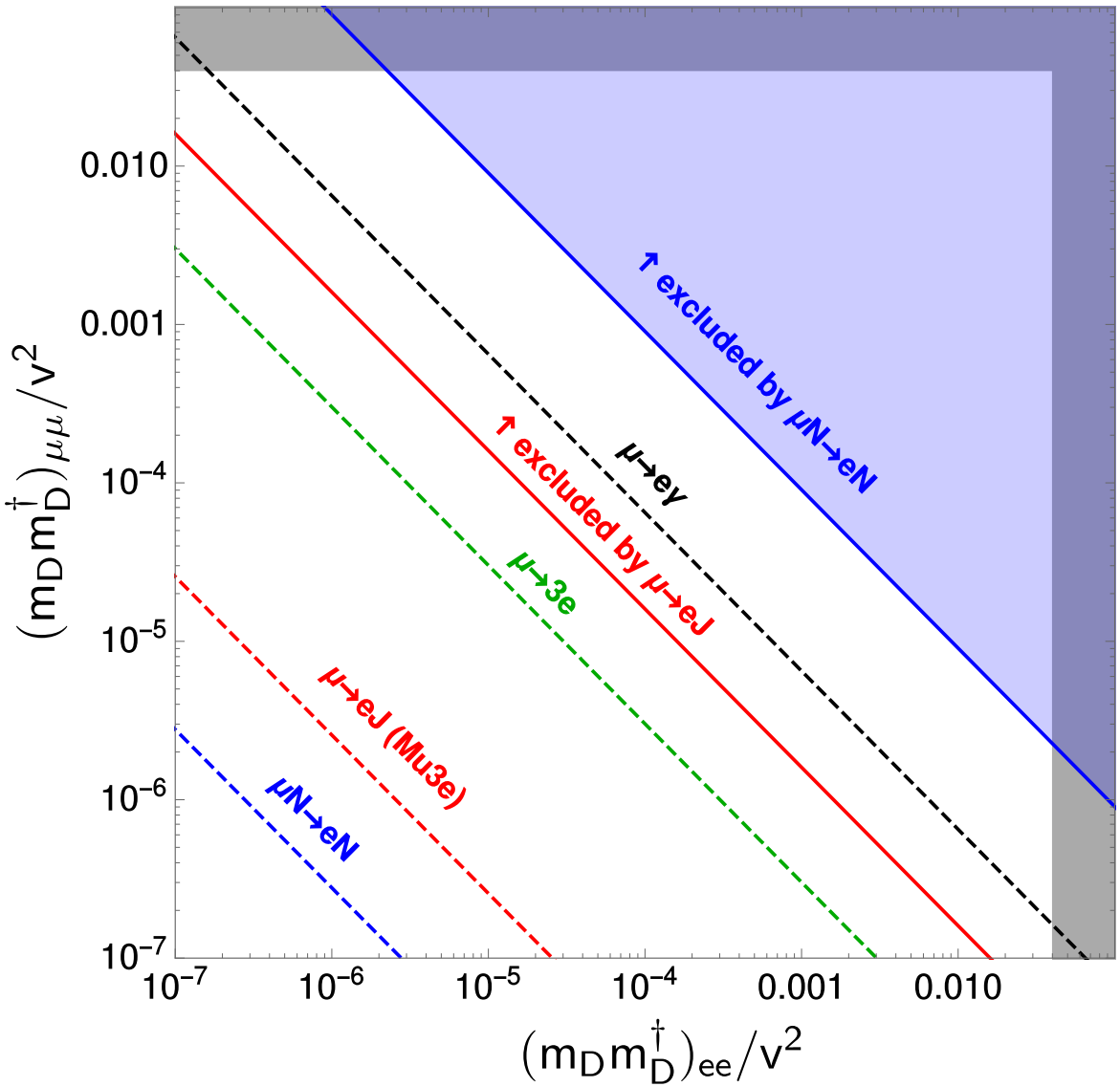
- Comparison of Majoron and non-Majoron limits.

  [from Coy & Frigerio, PRD '19]

- $m_D M_R^{-2} m_D^\dagger$ vs. $\frac{m_D m_D^\dagger}{f}$.
- Sterile neutrinos modify EWPD & LFV.
- $\frac{\Gamma(\ell \to \ell' \gamma)}{\Gamma(\ell \to \ell' J)} \simeq 2\pi\alpha \frac{m_\ell^2}{M_R^2} \frac{f^2}{M_R^2}$.
- Majoron wins for f ~ M_R.
- $\ell \to \ell' + J$ possible!
- Together with μ?

$M_R = f = 1\,\text{TeV}$

$(m_D m_D^\dagger)_{e\mu} = [(m_D m_D^\dagger)_{ee}(m_D m_D^\dagger)_{\mu\mu}]^{1/2}$



[**JH**, Patel, PRD '19]

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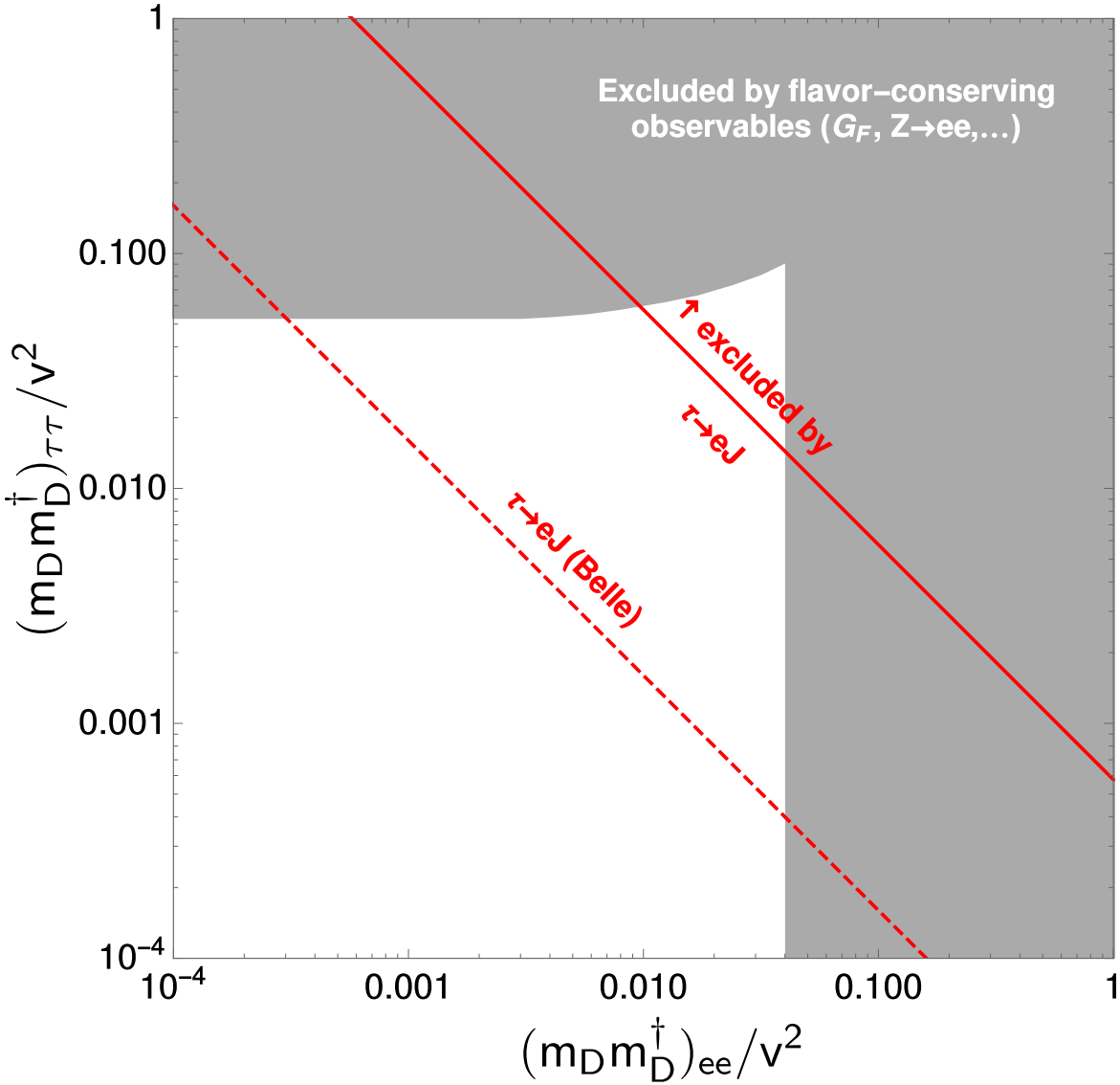
- Majoron wins for f ~ M_R.
- $\ell \to \ell' + J$ possible!
- Together with LFV in μ?

$$M_R = f = 1\,\text{TeV}$$

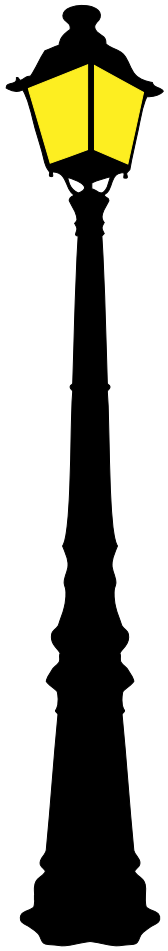
$$(m_D m_D^\dagger)_{e\tau} = [(m_D m_D^\dagger)_{ee}(m_D m_D^\dagger)_{\tau\tau}]^{1/2}$$



[**JH**, Patel, PRD '19]

Summary

- Neutrino mass models *qualitatively* predict CLFV, sometimes quantitative predictions of *ratios*.
- Expect first observations in muon experiments, channel ($\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$, $\bar{\mu}e \to \mu\bar{e}$, $\mu \to eJ$) depends on model.
- Observations complement neutrino experiments.
- Some models can explain $(g\text{-}2)_\mu$ anomaly.
- Light new physics open new avenues.



Explore every corner of our lamppost!

Backup

Effective field theory view

- SM symmetry: $G = U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$.
- Effective field theory with Majorana ν:

$$L = L_{SM} + \overbrace{\frac{LLHH}{\Lambda}}^{M_\nu} + \underbrace{\sum_j \frac{\mathcal{O}_j}{\Lambda^2} + \sum_j \frac{\mathcal{O}'_j}{\Lambda^3} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \dots}_{\text{could conserve G or subgroup}}$$

conserves G

violates G

⇒ ‘weird’ channels dominate!?

Upcoming CLFV

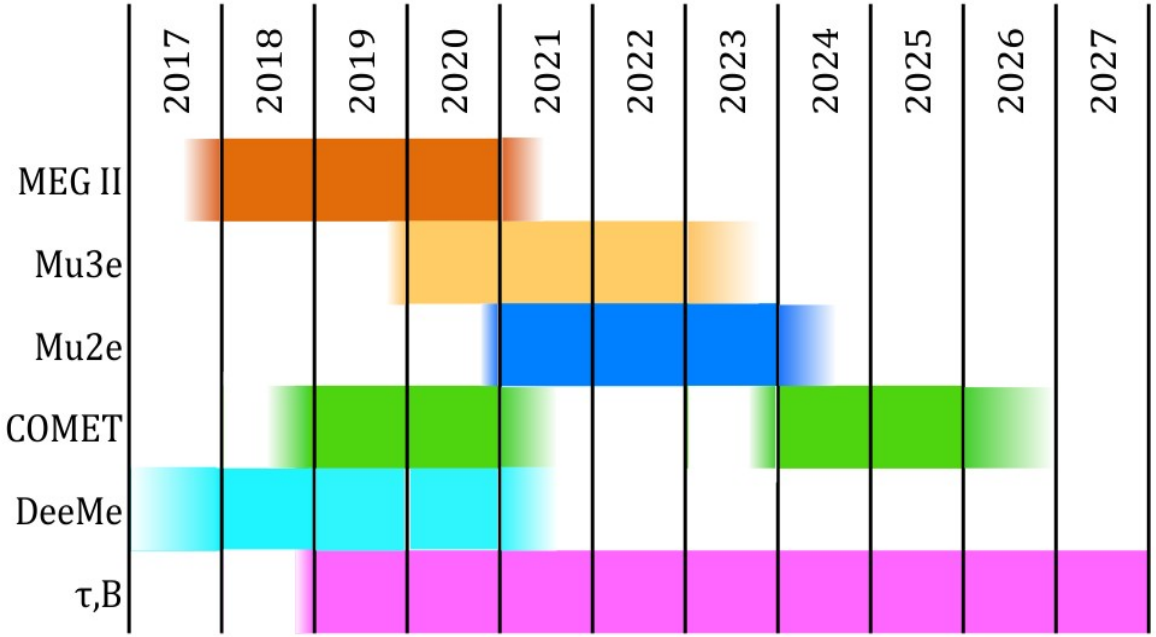
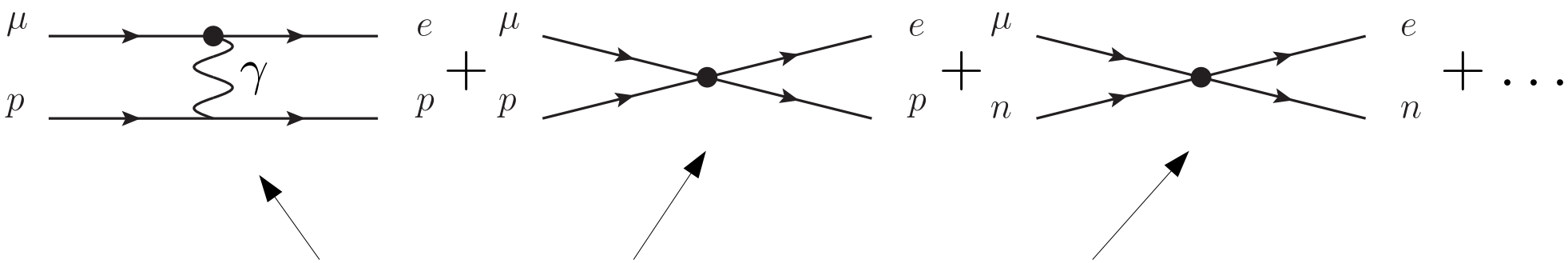


Figure 47. – Projected time lines for different projects searching for CLFV decays. MEG IIis expected to start data taking in 2018 after an engineering run in 2017; Mu3e magnet and detectors are expected at the end of 2019; Mu2e foresees three years of data taking starting in 2021; COMET Phase-I is expected to start commissioning and data taking in 2018 for two-three years, followed by a stop to develop and deploy the beamline and detectors for Phase-II; DeeMe is expected to start soon and take data with graphite and silicon carbide targets in sequence; Belle II is schedule to start data taking at end 2018.

[Calibbi & Signorelli, 1709.00294]

The inverse problem

- If we see CLFV, can we pin down the underlying operator?
  - In many cases: Yes! (e.g. $\mu \to e\gamma \leftrightarrow$ dipole)
  - $\mu \to e$ conversion in nucleus: No!

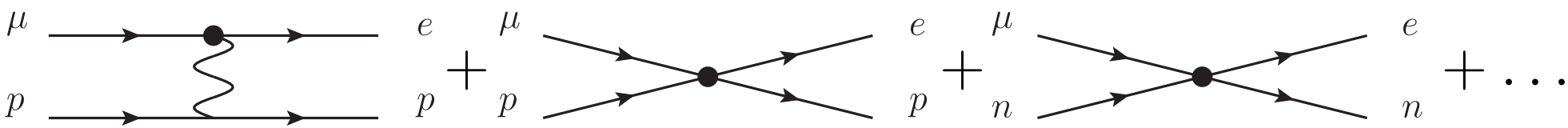


Relative contributions depend on nucleus: Z, N, spin!

- Need to observe $\mu \to e$ conversion in different nuclei!

[Kitano, Koike, Okada, PRD '07; Cirigliano++, PRD '09; Davidson++, '18]

μ → e conversion

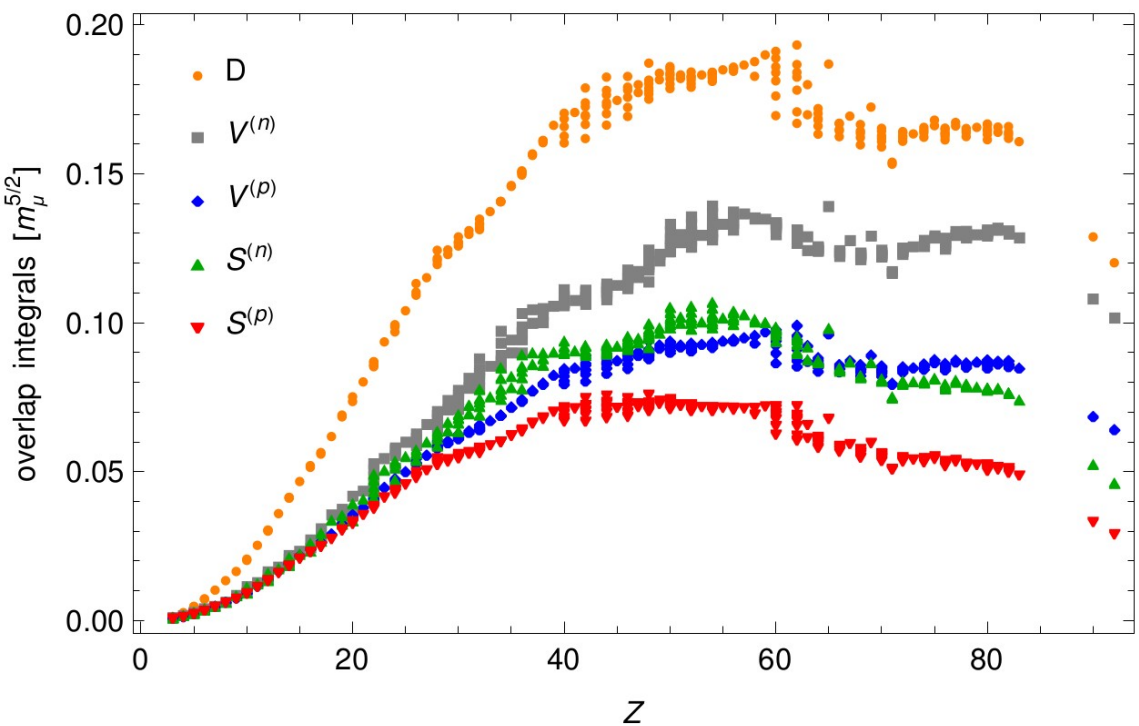


- Assuming spin-*independent* conversion:

$$\mathrm{BR}_{\mathrm{SI}} = \frac{32 G_F^2}{\Gamma_{\mathrm{capture}}} \left[|\boldsymbol{v} \cdot \boldsymbol{C}_L|^2 + |\boldsymbol{v} \cdot \boldsymbol{C}_R|^2 \right]$$

Overlap integrals Wilson coefficients

$$\boldsymbol{v} \equiv \left(\frac{D}{4}, V^{(p)}, S^{(p)}, V^{(n)}, S^{(n)} \right)$$

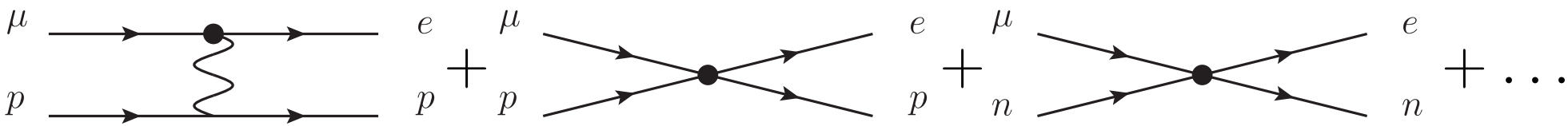


To measure the Wilson coefficients, use nuclei whose **v** are maximally misaligned.

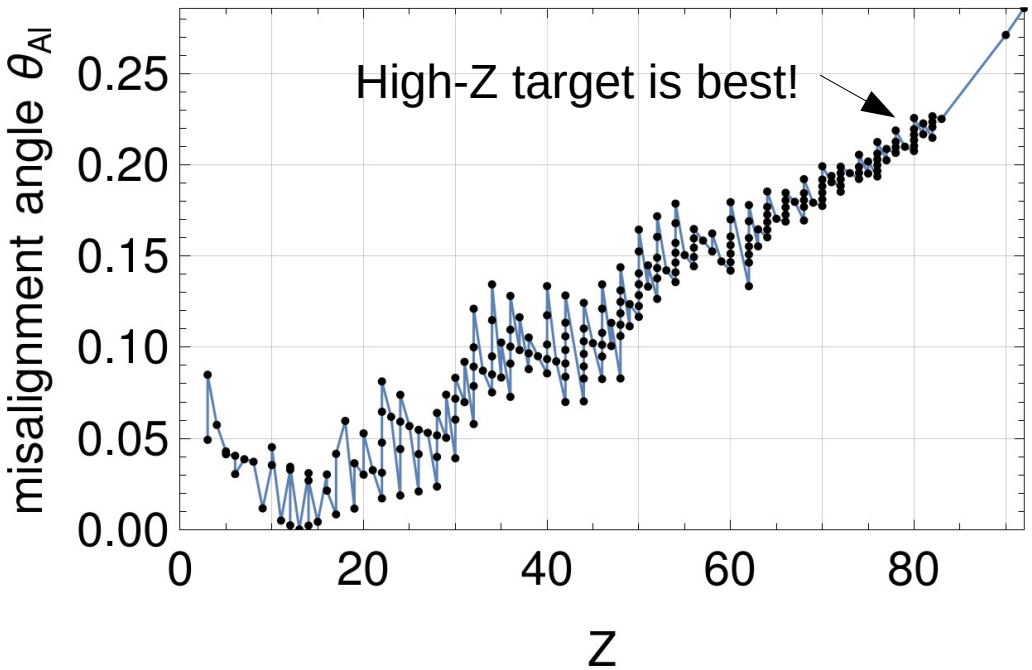
[Davidson, Kuno, Yamanaka, PLB '19]

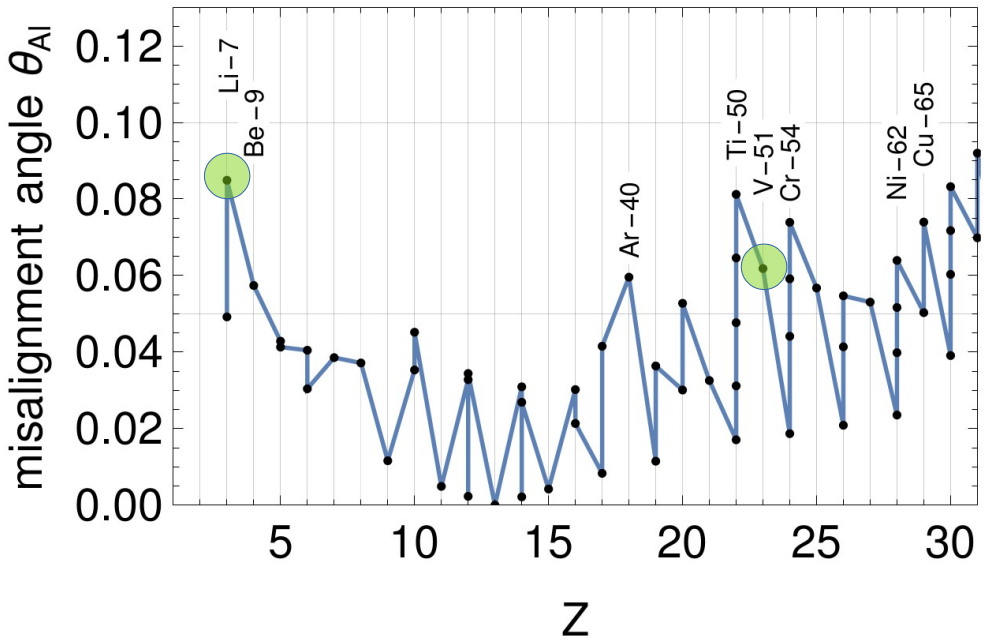
[Kitano, Koike, Okada, PRD '07; Heeck, Szafron, Uesaka, NPB '22]

μ → e conversion



- Misalignment with aluminium (target in COMET & Mu2e):





- At low Z, Li-7 and V-51 can distinguish proton/neutron.

[Davidson, Kuno, Yamanaka, PLB '19; Heeck, Szafron, Uesaka, NPB '22]

Pseudo-Goldstone

- Spontaneous global U(1) breaking gives $m_J = 0$.
- Non-zero mass from:
  - Breaking by gravity, e.g. wormholes,

$$m_J \sim M_{\rm Pl} \exp\left[-\mathcal{O}(M_{\rm Pl}/f)\right].$$

[Alonso, Urbano, 1706.07415]

  - Anomalies, e.g. if $U(1)_{B-L} = U(1)_{PQ}$.

[Mohapatra, Senjanovic '83; Langacker, Peccei, Yanagida '86; SMASH '16]

  - Explicit breaking, e.g. $\Delta V = \frac{1}{2} m_J^2 J^2$.