New Frontiers in Lepton Flavor

Phenomenology of Lepton Flavour Violation

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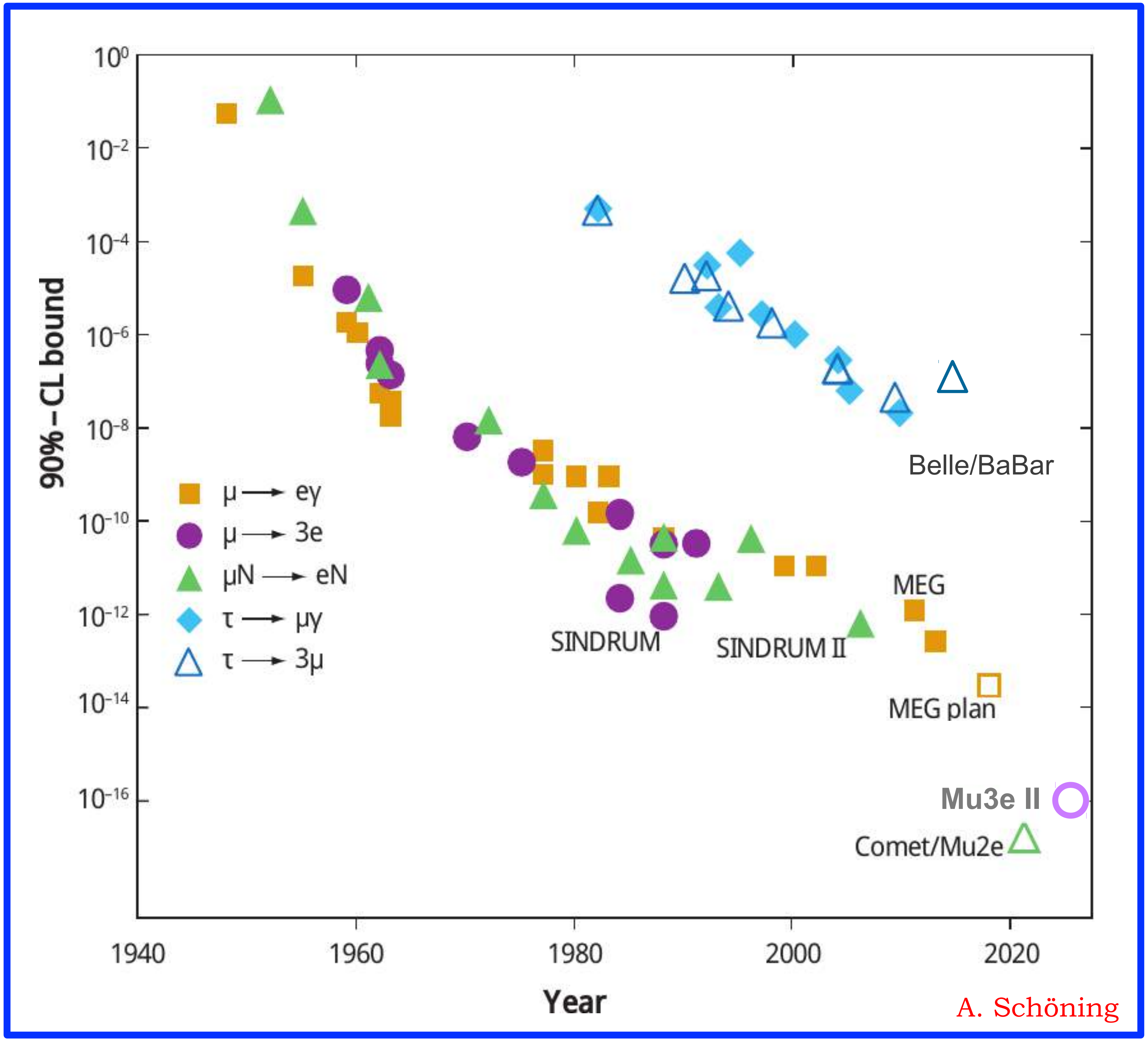
Neutrino masses/oscillations $\Longleftrightarrow \not{L}_e, \not{L}_\mu, \not{L}_\tau$

Lepton family numbers are not conserved

Why not *charged* lepton flavour violation (CLFV):

$$\mu \to e\gamma, \quad \tau \to \mu\gamma, \quad \mu \to eee, \ \text{etc.}\,?$$

CLFV has been sought for almost 80 years...



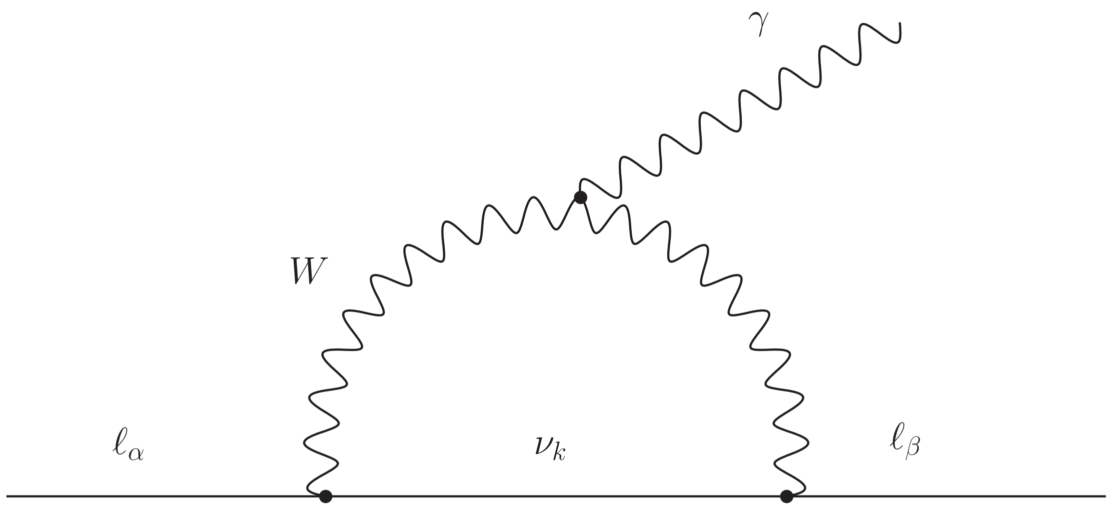
Why are we interested in CLFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!
(while they would be exact global symmetries, if neutrinos were massless)

- Neutrino mass eigenstates couple to charged leptons of different flavours through the PMNS

- In the SM + massive neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$



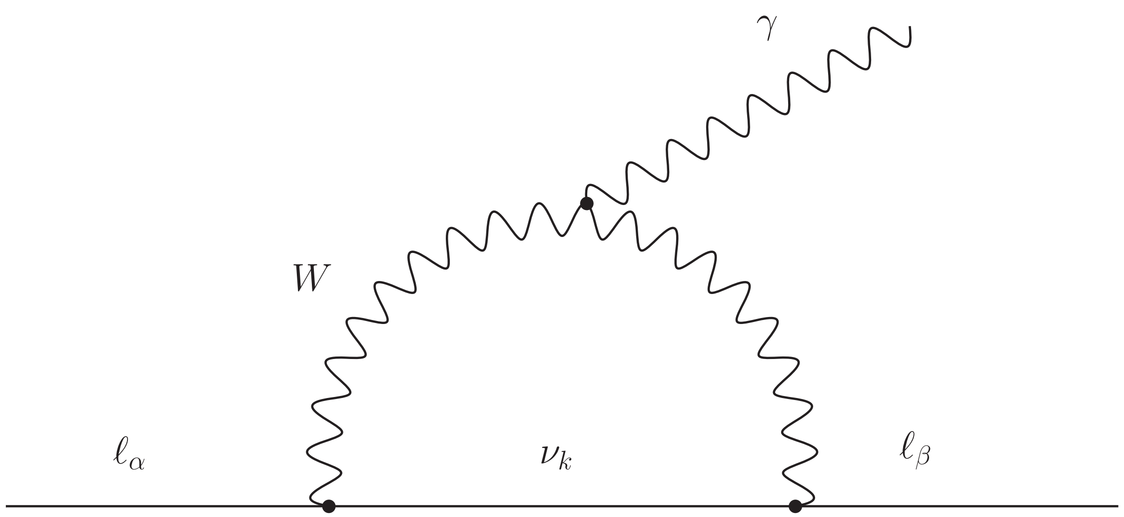
Cheng Li ’77, ’80; Petcov ‘77

⇒ $\mathrm{BR}(\mu \to e\gamma) \approx \mathrm{BR}(\tau \to e\gamma) \approx \mathrm{BR}(\tau \to \mu\gamma) = 10^{-55} \div 10^{-54}$

Large mixing, but huge suppression due to small neutrino masses

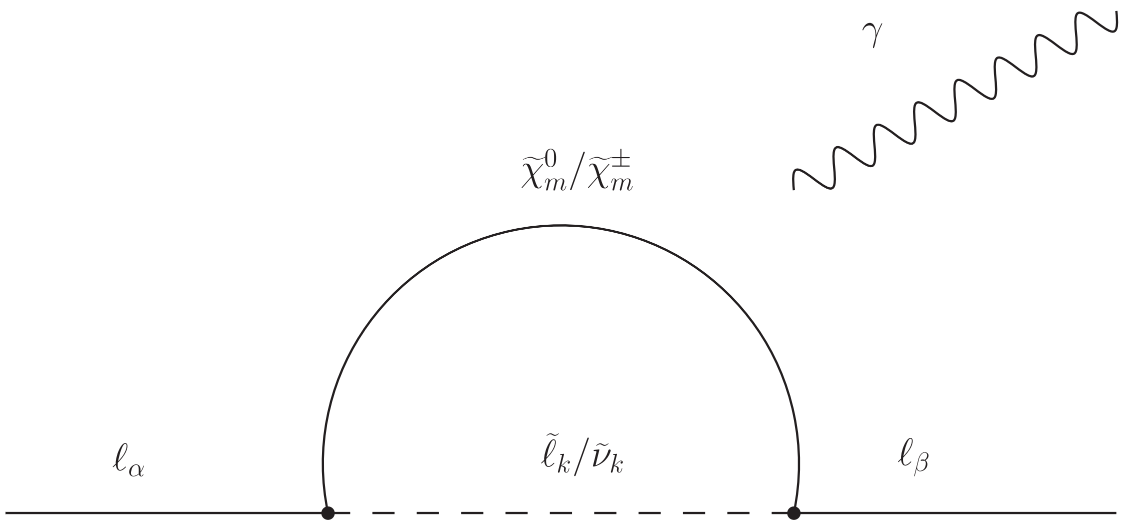
⇒ In presence of NP at the TeV we can expect large effects

Why are we interested in CLFV?



e.g. SUSY

Borzumati Masiero ‘86;
Hisano et al. ‘95



$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \sim \frac{|\delta_{\alpha\beta}|^2}{G_F^2\, m^4_{\text{SUSY}}}$$

- Unambiguous signal of New Physics
- Stringent test of NP coupling to leptons
- It probes scales far beyond the LHC reach

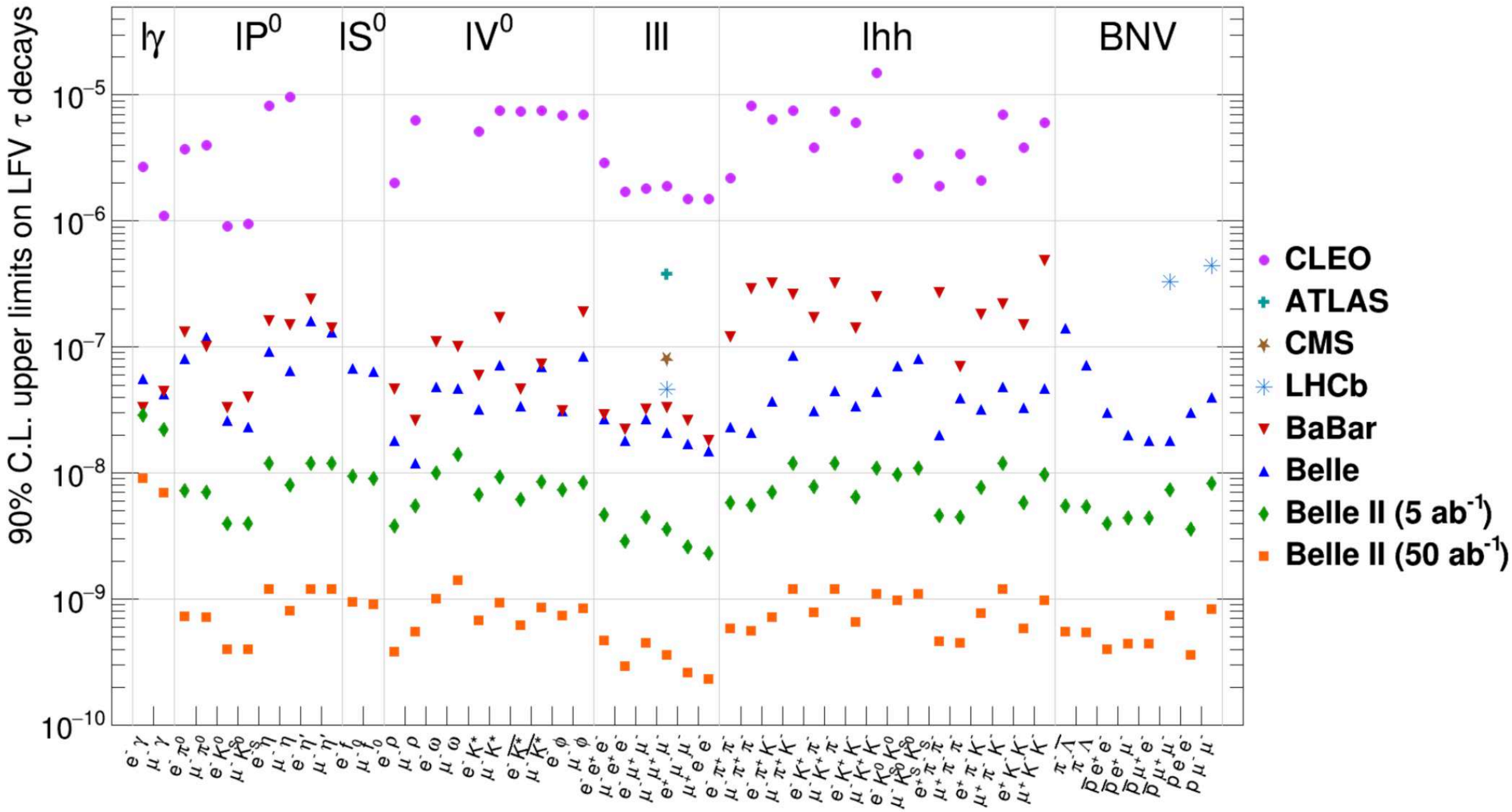
⇨ For a pedagogical introduction (exp + th) cf. LC and Signorelli ‘17

LFV observable	Present bounds		Expected future limits	
BR($\mu \to e\gamma$)	4.2×10^{-13}	MEG (2016) [28]	6×10^{-14}	MEG II [29]
BR($\mu \to eee$)	1.0×10^{-12}	SINDRUM (1988) [30]	10^{-16}	Mu3e [31]
CR($\mu \to e$, Au)	7.0×10^{-13}	SINDRUM II (2006) [32]		–
CR($\mu \to e$, Al)		–	6×10^{-17}	COMET/Mu2e [33, 34]
BR($Z \to e\mu$)	2.62×10^{-7}	ATLAS (2022) [35]	$10^{-8} - 10^{-10}$	FCC-ee/CEPC [36]
BR($\tau \to e\gamma$)	3.3×10^{-8}	BaBar (2010) [37]	9×10^{-9}	Belle II [25, 38]
BR($\tau \to eee$)	2.7×10^{-8}	Belle (2010) [39]	4.7×10^{-10}	Belle II [25, 38]
BR($\tau \to e\mu\mu$)	2.7×10^{-8}	Belle (2010) [39]	4.5×10^{-10}	Belle II [25, 38]
BR($\tau \to \pi e$)	8.0×10^{-8}	Belle (2007) [40]	7.3×10^{-10}	Belle II [25, 38]
BR($\tau \to \rho e$)	1.8×10^{-8}	Belle (2011) [41]	3.8×10^{-10}	Belle II [25, 38]
BR($Z \to e\tau$)	5.0×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]
BR($\tau \to \mu\gamma$)	4.2×10^{-8}	Belle (2021) [43]	6.9×10^{-9}	Belle II [25, 38]
BR($\tau \to \mu\mu\mu$)	2.1×10^{-8}	Belle (2010) [39]	3.6×10^{-10}	Belle II [25, 38]
BR($\tau \to \mu ee$)	1.8×10^{-8}	Belle (2010) [39]	2.9×10^{-10}	Belle II [25, 38]
BR($\tau \to \pi\mu$)	1.1×10^{-7}	Babar (2006) [44]	7.1×10^{-10}	Belle II [25, 38]
BR($\tau \to \rho\mu$)	1.2×10^{-8}	Belle (2011) [41]	5.5×10^{-10}	Belle II [25, 38]
BR($Z \to \mu\tau$)	6.5×10^{-6}	ATLAS (2021) [42]	10^{-9}	FCC-ee/CEPC [36]

Table 2: Present 90% CL upper limits (95% CL for the Z decays) and future expected sensitivities for the set of LFV transitions relevant for our analysis.

… and we have experiments!

LFV tau decays:



Belle II Snowmass, arXiv:2207.06307

CLFV from heavy new physics: the SM effective field theory

If NP scale $\mathbf{\Lambda} \gg m_W$: $$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

Dimension-6 effective operators that can induce CLFV

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

Grzadkowski et al. ’10; Crivellin Najjari Rosiek ‘13

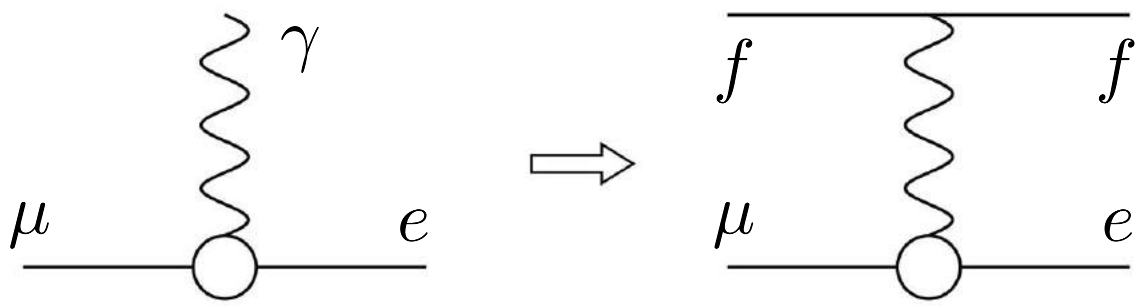
Probing very high-energy scales

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

	$\lvert C_a\rvert$ $[\Lambda = 1$ TeV$]$	Λ (TeV) $[\lvert C_a\rvert = 1]$	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \to e\gamma$
$C_{\ell e}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \to eee$
$C_{\ell\ell, ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
$C_{\ell e}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell q, \ell d, ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell u, eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{e\gamma}^{\tau\mu}$	2.7×10^{-6}	610	$\tau \to \mu\gamma$
$C_{e\gamma}^{\tau e}$	2.4×10^{-6}	650	$\tau \to e\gamma$
$C_{\ell\ell, ee}^{\mu\tau\mu\mu}$	7.8×10^{-3}	11.3	$\tau \to \mu\mu\mu$
$C_{\ell e}^{\mu\tau\mu\mu, \mu\mu\mu\tau}$	1.1×10^{-2}	9.5	$\tau \to \mu\mu\mu$
$C_{\ell\ell, ee}^{e\tau ee}$	9.2×10^{-3}	10.4	$\tau \to eee$
$C_{\ell e}^{e\tau ee, eee\tau}$	1.3×10^{-2}	8.8	$\tau \to eee$

Example: *only* dipole operators

$$\mathcal{L} \supset \frac{C_{e\gamma}^{e\mu}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{e}\,\sigma_{\mu\nu}P_R\,\mu\,F^{\mu\nu} + \frac{C_{e\gamma}^{\mu e}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{\mu}\,\sigma_{\mu\nu}P_R\,e\,F^{\mu\nu} + \text{h.c.},$$



$$\text{BR}(\mu\to e\gamma) \simeq \frac{m_\mu^3 v^2}{8\pi\Lambda^4\Gamma_\mu}\left(|C_{e\gamma}^{e\mu}|^2 + |C_{e\gamma}^{\mu e}|^2\right)$$

simple correlations among $\mu\to e$ modes!

$$\Rightarrow\quad \text{BR}(\mu\to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - \frac{11}{4}\right)\times \text{BR}(\mu\to e\gamma)$$

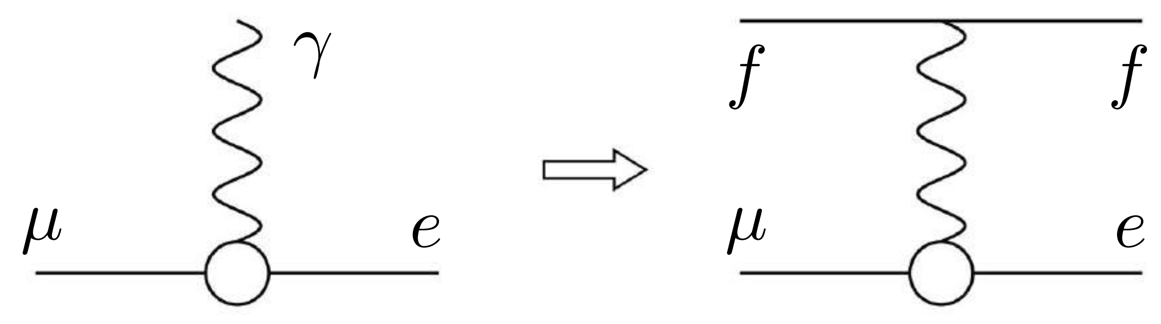
$$\text{CR}(\mu\,\text{N}\to e\,\text{N}) \simeq \pi D(\text{N})^2\frac{\Gamma_\mu}{\Gamma_{\text{capt}}(\text{N})}\times\text{BR}(\mu\to e\gamma) \approx \alpha\times\text{BR}(\mu\to e\gamma)$$

overlap integral between leptons and nucleus

rate of muon capture by the nucleus

Example: *only* dipole operators

$$\mathcal{L} \supset \frac{C_{e\gamma}^{e\mu}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{e}\,\sigma_{\mu\nu}P_R\,\mu\,F^{\mu\nu} + \frac{C_{e\gamma}^{\mu e}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{\mu}\,\sigma_{\mu\nu}P_R\,e\,F^{\mu\nu} + \text{h.c.},$$

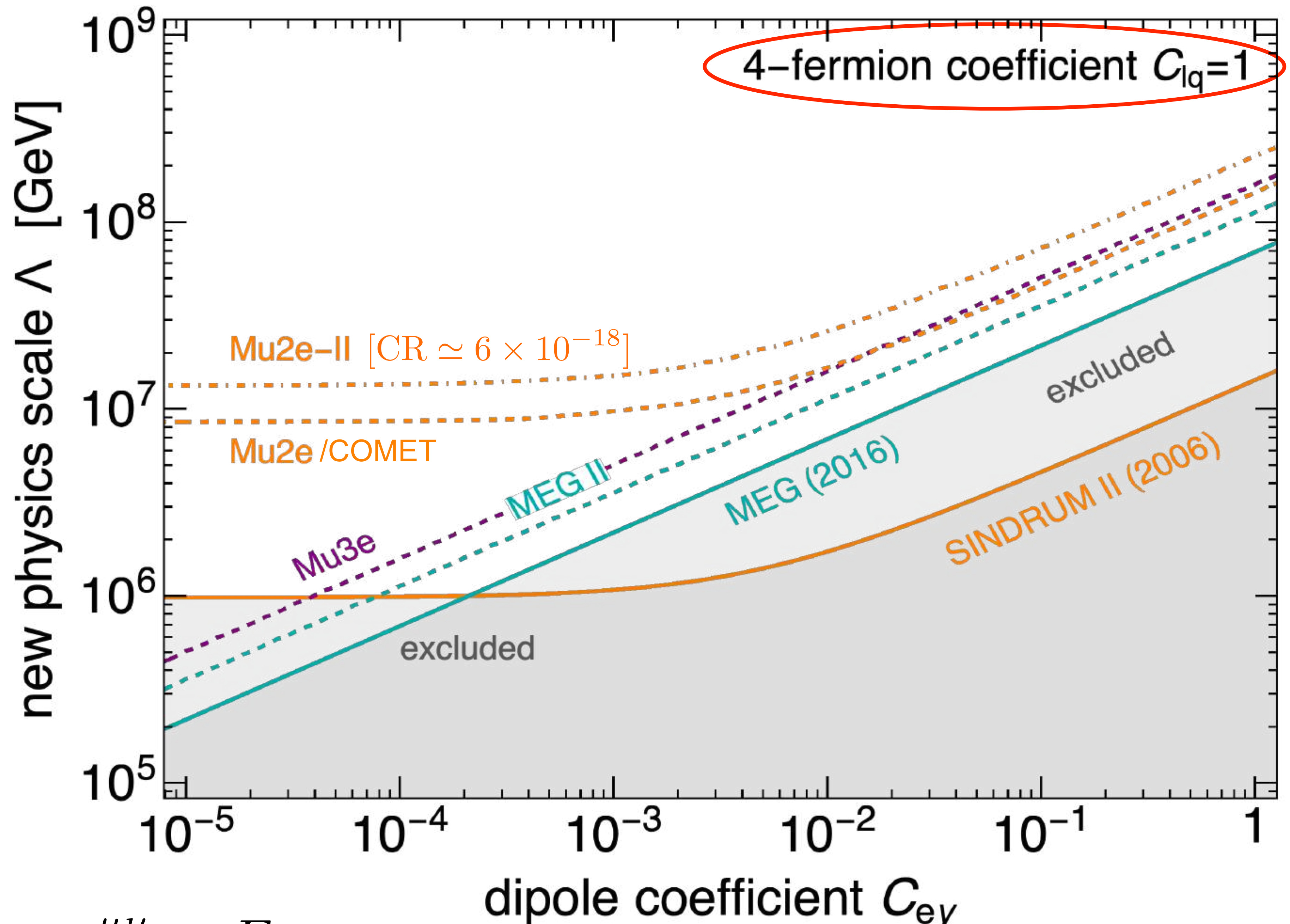


$$\text{BR}(\mu \to eee) \simeq 0.0067 \times \text{BR}(\mu \to e\gamma)$$
$$\text{CR}(\mu\,\text{Al} \to e\,\text{Al}) \simeq 0.0026 \times \text{BR}(\mu \to e\gamma)$$

- 10^{-15} (10^{-16}) sensitivity on $\mu\to eee$ / $\mu\to e$ conversion needed to test dipole operators beyond MEG (MEG II)
- Future $\mu\to e\gamma$ searches would require to reach (at least) a sensitivity < 10^{-14} to go beyond Mu3e/Mu2e/COMET

Example: dipole *and* 4-fermion operators

$$\frac{C_{\ell q}}{\Lambda^2}\,(\bar{e}_L\,\gamma^\mu\,\mu_L)\,(\overline{Q}\,\gamma_\mu Q)$$

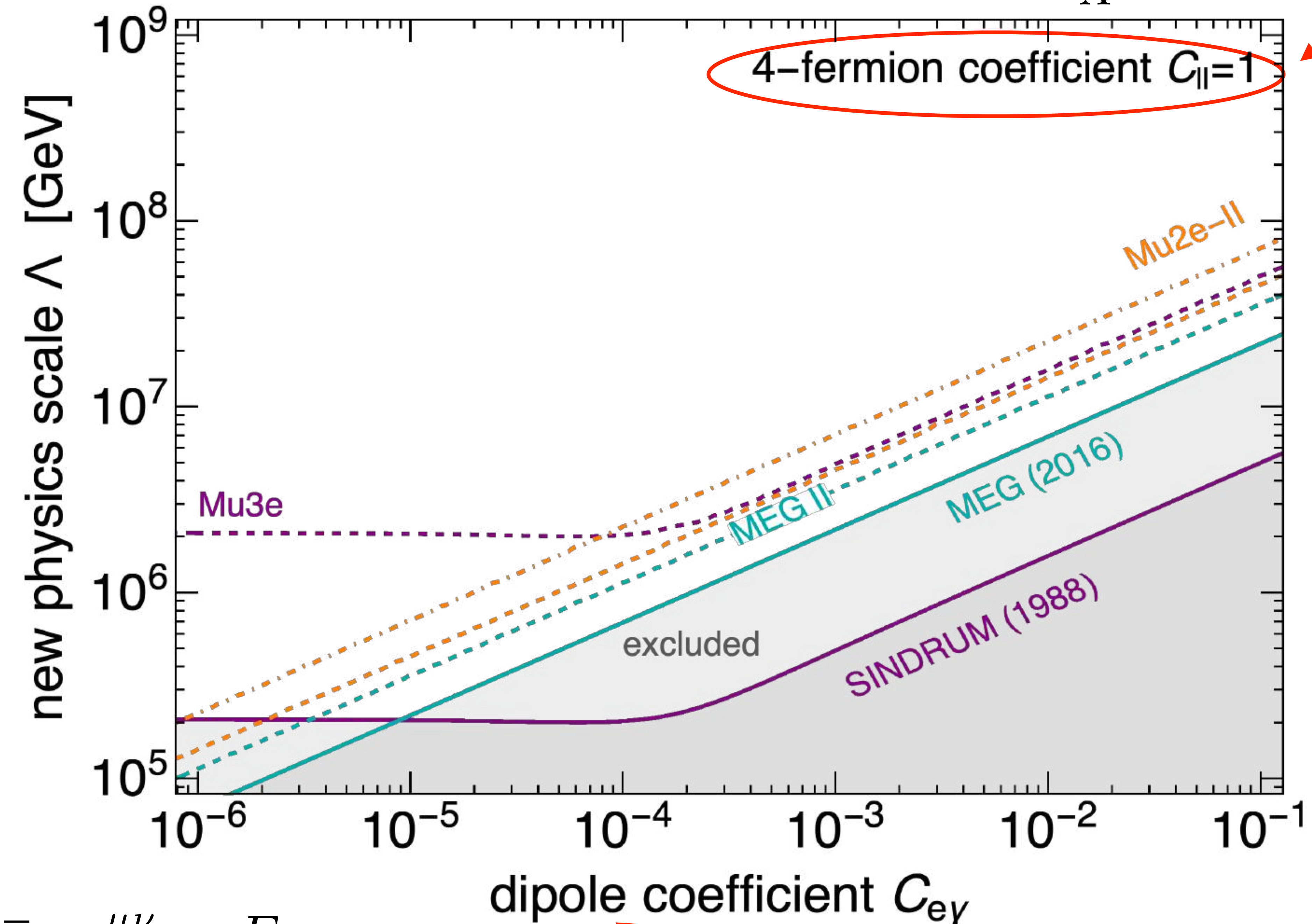


$$\frac{C_{e\gamma}}{\Lambda^2}\langle H\rangle\,\bar{e}_L\,\sigma^{\mu\nu}\,\mu_R\,F_{\mu\nu}$$

Mu2e-II Snowmass, arXiv:2203.07569

Example: dipole *and* 4-fermion operators

$$\frac{C_{\ell\ell}}{\Lambda^2}(\bar{e}_L\gamma^\mu\mu_L)(\bar{e}_L\gamma_\mu e_L)$$



$$\frac{C_{e\gamma}}{\Lambda^2}\langle H\rangle\,\bar{e}_L\,\sigma^{\mu\nu}\mu_R\,F_{\mu\nu}$$

Correlations in the μ-e sector

Searches for the different $\mu \to e$ modes are complementary tools in order to discriminate among different new physics models:

TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). Whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level is indicated; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to eqs.* (40), (41).

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	10^{-3}–10^{-2}
Type-I seesaw	Loop*	Loop*	3×10^{-3}–0.3	0.1–10
Type-II seesaw	Tree	Loop	$(0.1$–$3) \times 10^3$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^3$	$\mathcal{O}(10^3)$
LFV Higgs	Loop$^{(a)}$	Loop$^{*(a)}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	0.05–0.5	2–20

(a) A tree-level contribution to this process exists but it is subdominant.

LC Signorelli '17

If dipole operator dominates
(e.g. as in R-parity conserving SUSY)

Also colliders: LFV Higgs decays

In the SM Higgs couplings and masses aligned → flavour conserving

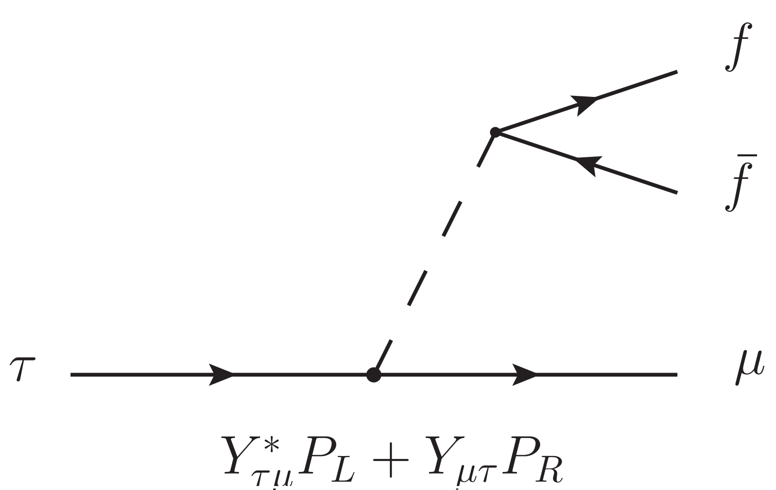
$$(m_f)_{ij} = \frac{v}{\sqrt{2}}(Y_f)_{ij}, \qquad -\mathcal{L}_{h\bar{f}f} = \frac{m_f}{v}\,\bar{f}_L f_R\, h + \text{h.c.}$$

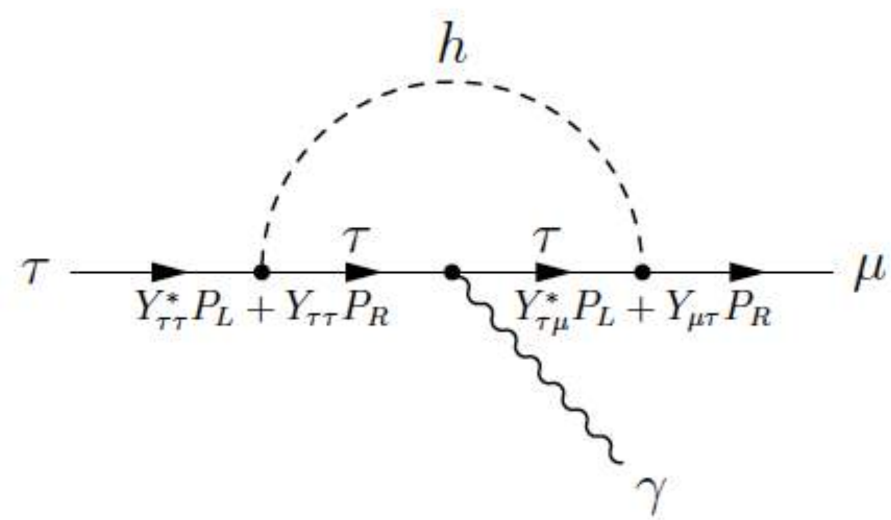
This is not the case if there is 2nd Higgs doublet or ops such as $\overline{L}_L e_R \Phi(\Phi^\dagger\Phi)$

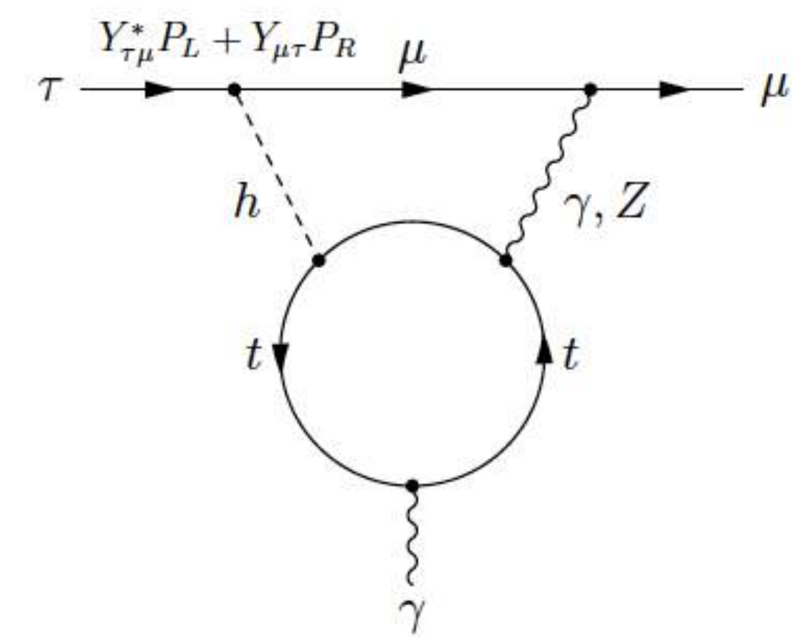
Useful parameterisation: $$-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + \text{h.c.}$$

Harnik Kopp Zupan '12

These couplings induce both LFV Higgs decays and low-energy processes:







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Harnik Kopp Zupan '12

Limits: $\text{BR}(h\to e\mu) < 4.4\times 10^{-5},\ \text{BR}(h\to e\tau) < 2.0\times 10^{-3},\ \text{BR}(h\to \mu\tau) < 1.8\times 10^{-3}$

ATLAS, CMS '23

Process	Coupling	Bound
$h\to\mu e$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2+\lvert Y^h_{e\mu}\rvert^2}$	$< 1.9\times 10^{-4}$
$\mu\to e\gamma$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2+\lvert Y^h_{e\mu}\rvert^2}$	$< 2.1\times 10^{-6}$
$\mu\to eee$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2+\lvert Y^h_{e\mu}\rvert^2}$	$\lesssim 3.1\times 10^{-5}$
$\mu\,\text{Ti}\to e\,\text{Ti}$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2+\lvert Y^h_{e\mu}\rvert^2}$	$< 1.2\times 10^{-5}$
$h\to\tau e$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2+\lvert Y^h_{e\tau}\rvert^2}$	$< 1.3\times 10^{-3}$
$\tau\to e\gamma$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2+\lvert Y^h_{e\tau}\rvert^2}$	< 0.014
$\tau\to eee$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2+\lvert Y^h_{e\tau}\rvert^2}$	$\lesssim 0.12$
$h\to\tau\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2+\lvert Y^h_{\mu\tau}\rvert^2}$	$< 1.2\times 10^{-3}$
$\tau\to\mu\gamma$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2+\lvert Y^h_{\mu\tau}\rvert^2}$	< 0.016
$\tau\to\mu\mu\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2+\lvert Y^h_{\mu\tau}\rvert^2}$	$\lesssim 0.25$

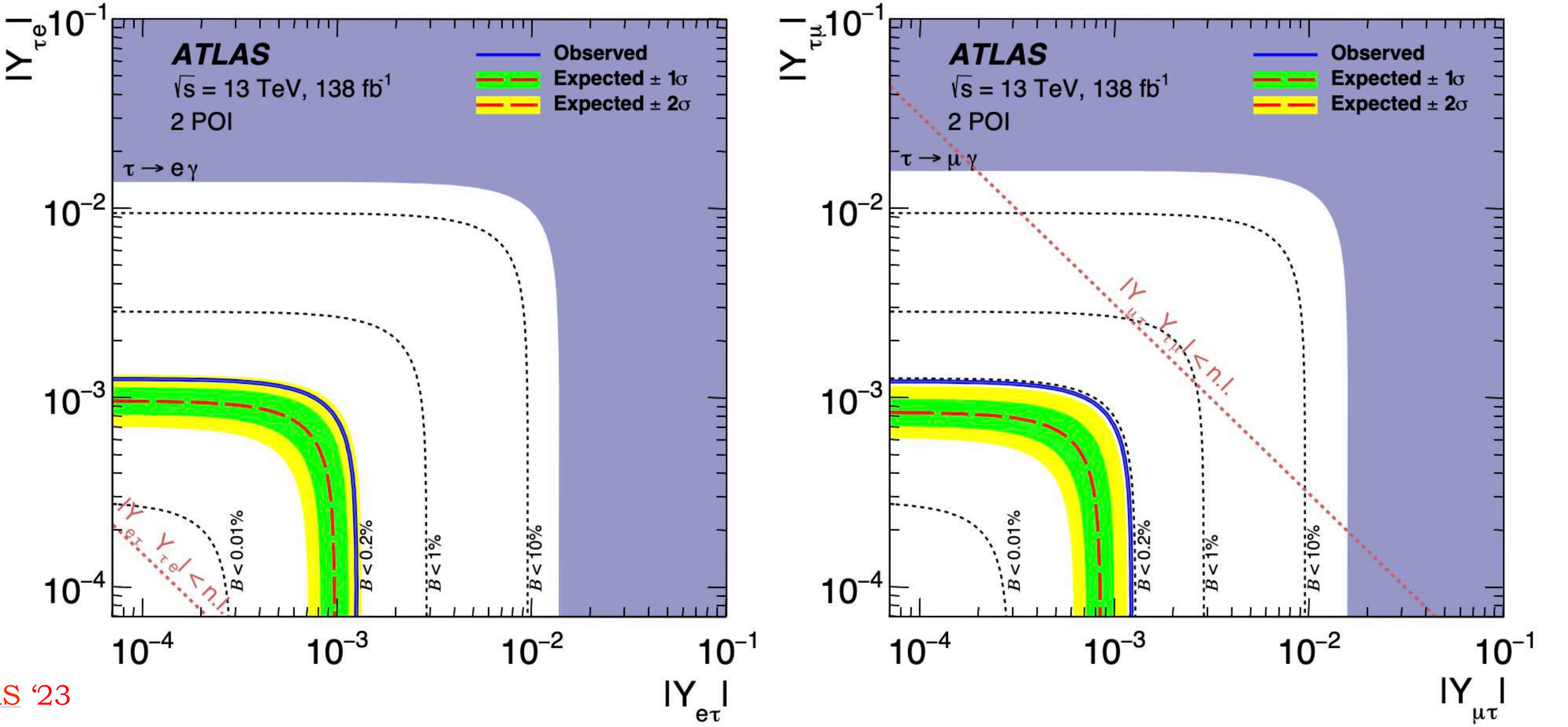
Also colliders: LFV Higgs decays

In the SM Higgs couplings and masses aligned → flavour conserving

$$(m_f)_{ij} = \frac{v}{\sqrt{2}}(Y_f)_{ij}, \qquad -\mathcal{L}_{h\bar{f}f} = \frac{m_f}{v}\,\bar{f}_L f_R\, h + \text{h.c.}$$

This is not the case if there is 2nd Higgs doublet or ops such as $\overline{L}_L e_R \Phi(\Phi^\dagger\Phi)$

Useful parameterisation: $-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + \text{h.c.}$



ATLAS ‘23

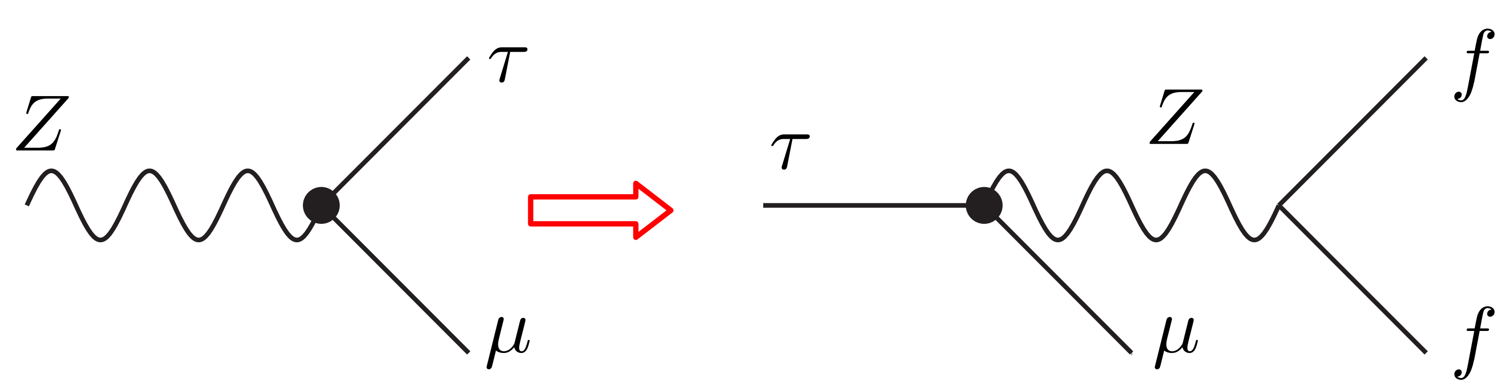
Also colliders: LFV Z decays at future circular e+e-

CEPC/FCC-ee Z-pole run: $O(10^{12})$ Z → M. Dam '18

Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee exp.
$\mathrm{BR}(Z \to \mu e)$	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
$\mathrm{BR}(Z \to \tau \mu)$	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$):
  max ~10 improvement can be expected at HL-LHC (3000/fb)
- A Tera Z factory can improve the present (future) bounds by 4 (3) orders of magnitude
- The question is: can we find new physics searching for these modes?
  Low-energy LFV decays are unavoidably induced, giving *indirect* bounds

e.g. :



$\tau \to \mu \ell\ell$

$\tau \to \mu \pi$

$\tau \to \mu \rho$

. . .

Model-independent indirect limits on Z LFV decays

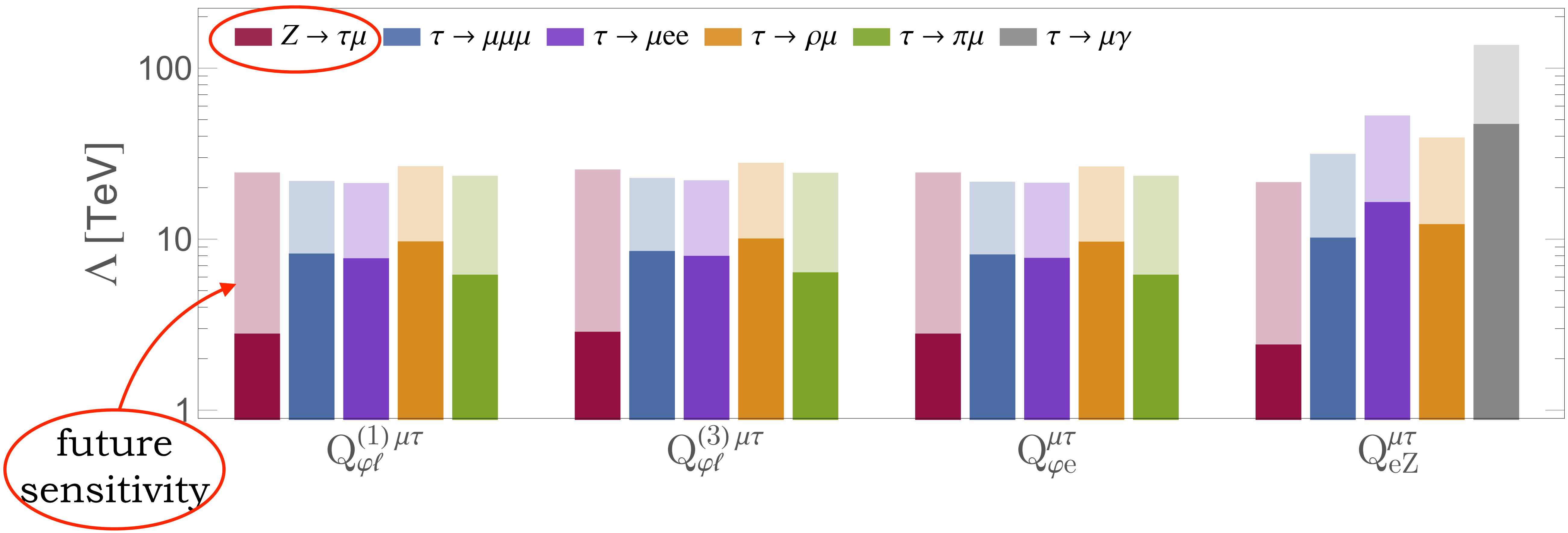
Observable	Operator	Indirect Limit on LFVZD	Strongest constraint
lepton-Higgs ops	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\mu}$	3.7×10^{-13}	$\mu \to e$, Au
$\mathrm{BR}(Z \to \mu e)$	$Q_{\varphi e}^{e\mu}$	9.4×10^{-15}	$\mu \to e$, Au
dipole ops	$Q_{eB}^{e\mu}$	1.4×10^{-23}	$\mu \to e\gamma$
	$Q_{eW}^{e\mu}$	1.6×10^{-22}	$\mu \to e\gamma$
$\mathrm{BR}(Z \to \tau e)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{\varphi e}^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{eB}^{e\tau}$	1.2×10^{-15}	$\tau \to e\gamma$
	$Q_{eW}^{e\tau}$	1.3×10^{-14}	$\tau \to e\gamma$
$\mathrm{BR}(Z \to \tau\mu)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{\varphi e}^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{eB}^{\mu\tau}$	1.5×10^{-15}	$\tau \to \mu\gamma$
	$Q_{eW}^{\mu\tau}$	1.7×10^{-14}	$\tau \to \mu\gamma$

LC Marcano Roy '21

Model-independent indirect limits on Z LFV decays

Observable	Operator	Indirect Limit on LFVZD	Strongest constraint
	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\mu}$	3.7×10^{-13}	$\mu \to e$, Au

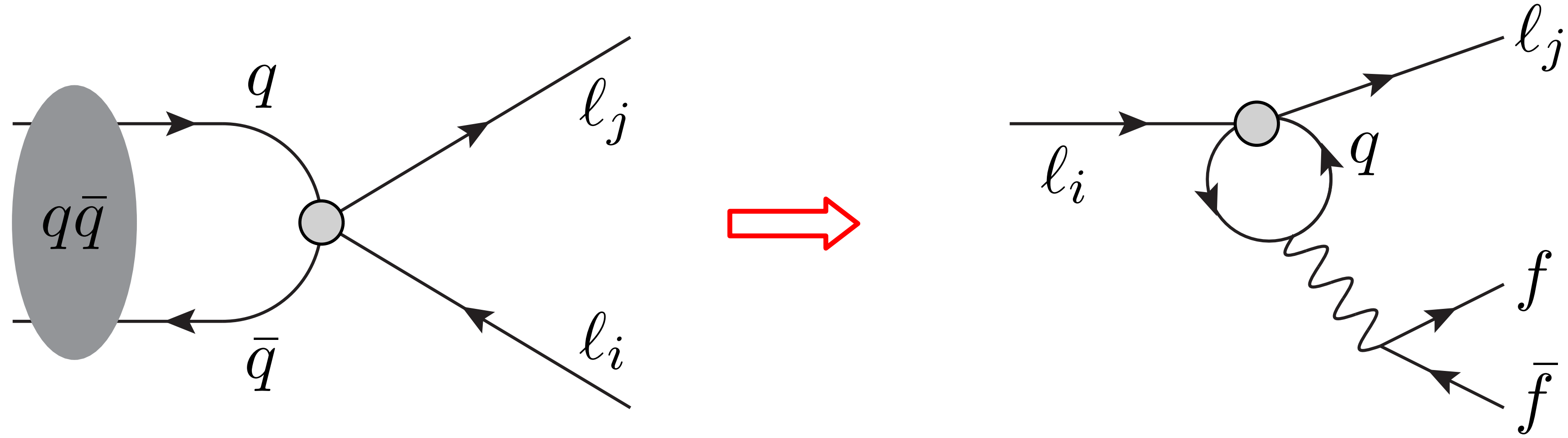
- A Tera Z can test LFV new physics scales searching for $Z \to \tau\, \ell$ at the level of what Belle II will do through LFV tau decays (or better)



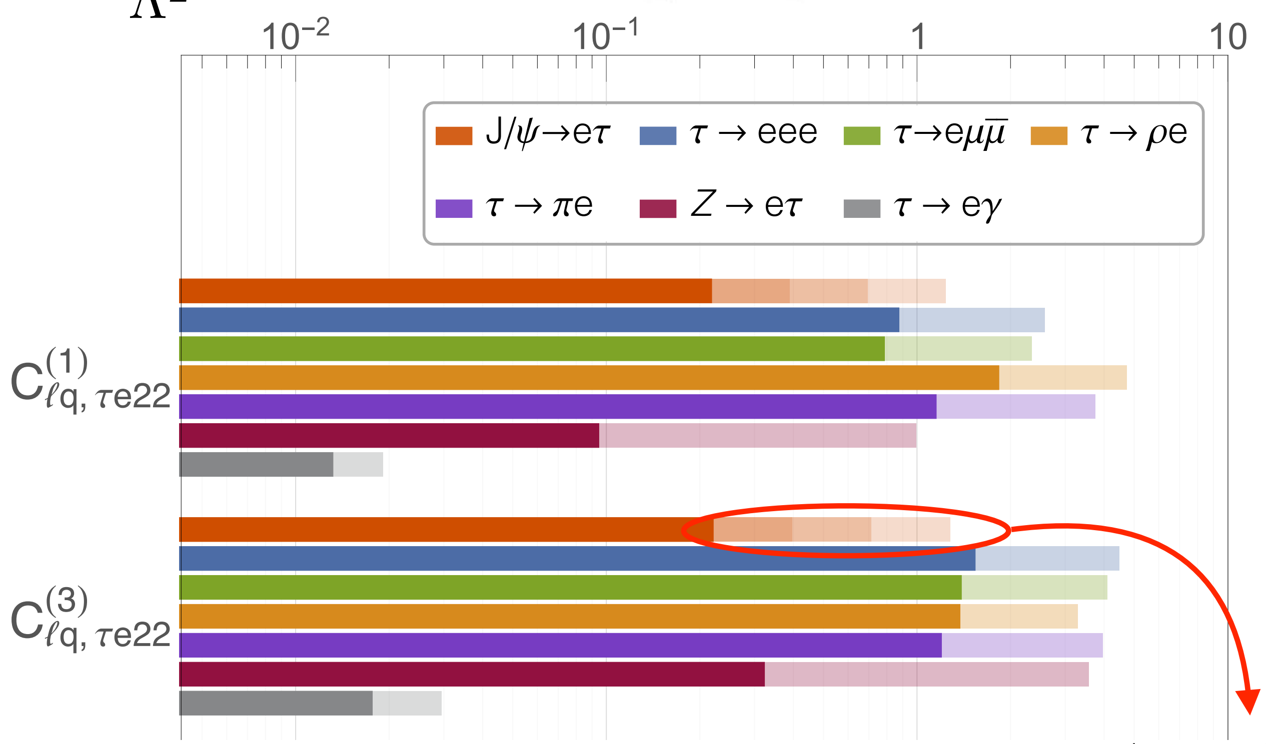
LC Marcano Roy '21

2 quarks - 2 lepton operators

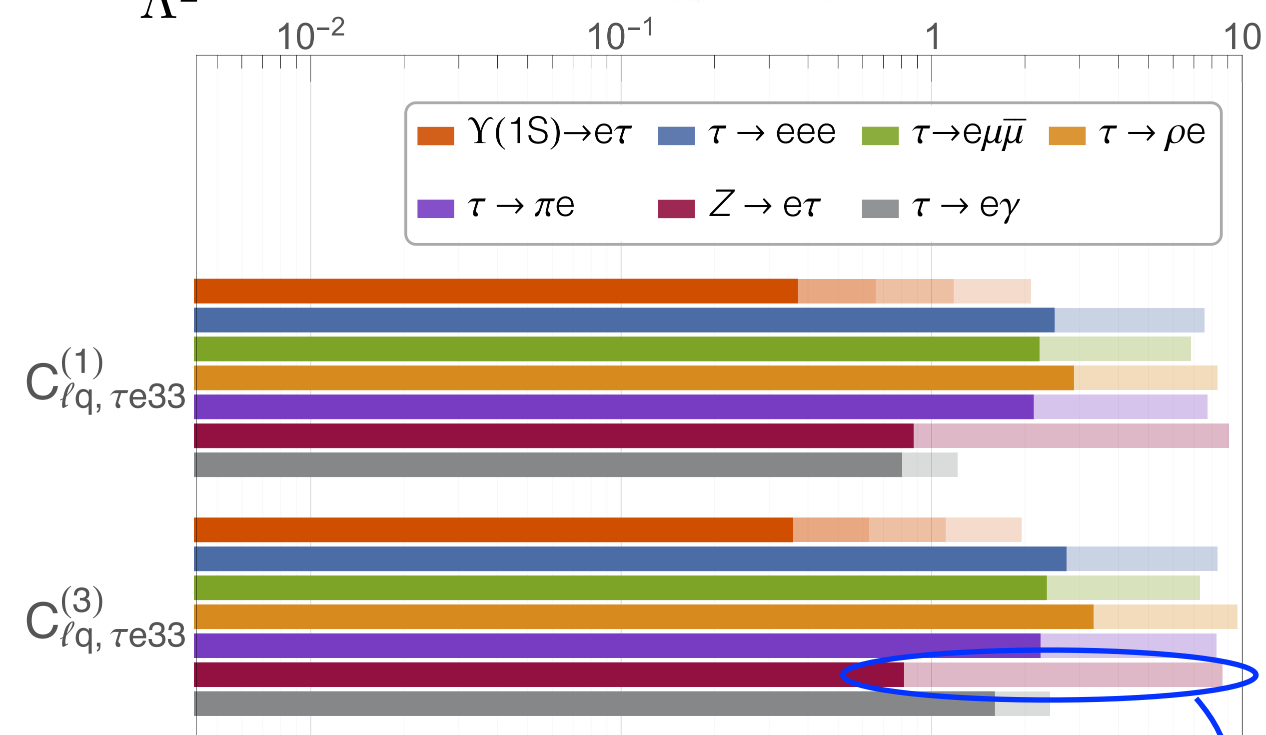
Low-energy CLFV and LFV Z decays are also sensitive to this kind of operators. Example involving heavy quark flavours:



$$\frac{C_X}{\Lambda^2}(\bar{c}\gamma_\mu c)(\bar{\tau}\gamma^\mu e)$$



$$\frac{C_X}{\Lambda^2}(\bar{b}\gamma_\mu b)(\bar{\tau}\gamma^\mu e)$$



LC Li Marcano Schmidt '22

$\{10^{-1}, 10^{-2}, 10^{-3}\}\times$ present limit

Z LFV

Assume there is a *light*, *invisible*, new particle "a"
with *flavour-violating couplings* to leptons

Light:

$$m_a \;<\; m_\mu\,,\; m_\tau$$

Invisible:

- Neutral
- Feebly coupled (long-lived)

CLFV modes would then be $\mu \to e\,a,\;\; \tau \to \mu\,a,\;\; \mu \to e\,\gamma\,a,\;$ etc.

Interesting interplay with cosmo/astro:

- DM candidate? (if long-lived enough)
- Bounds from star cooling/supernovae (if light and feeble enough)

Why should a be light and feebly-coupled?

That's natural, if it is the (pseudo) Nambu-Goldstone boson (PNGB) of a broken global U(1), *aka* an axion-like particle (ALP)

Examples:

Global symmetry:	PNGB:
• Lepton Number	Majoron
• Peccei-Quinn	Axion
• Flavour symmetry	Familon
...	

Wilczek '82
Pilaftsis '93
Feng et al. '97
LC Goertz Redigolo Ziegler Zupan '16
Di Luzio et al. '17, '19
...

Equivalent possibility: light Z' of a local U(1), e.g. L_i-L_j (with $g \ll 1$)

Heeck '16

General couplings to leptons:

Shift symmetry (PNGB!) → m_a from (small) explicit U(1) breaking

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij}\ \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij}\ \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

U(1)-breaking scale → coupling suppression

Where does *lepton flavour violation* come from?

- If lepton U(1) charges are flavour non-universal
  ⇨ naturally flavour-violating couplings
- Alternatively, loop-induced flavour-violating couplings

Explicit examples at the end...

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij}\ \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij}\ \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

This generic Lagrangian induces 2-body LFV decays such as:

$$\Gamma(\ell_i \to \ell_j\, a) = \frac{1}{16\pi} \frac{m^3_{\ell_i}}{F^2_{ij}} \left(1 - \frac{m_a^2}{m^2_{\ell_i}}\right)^2 \qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

Feng et al. '97

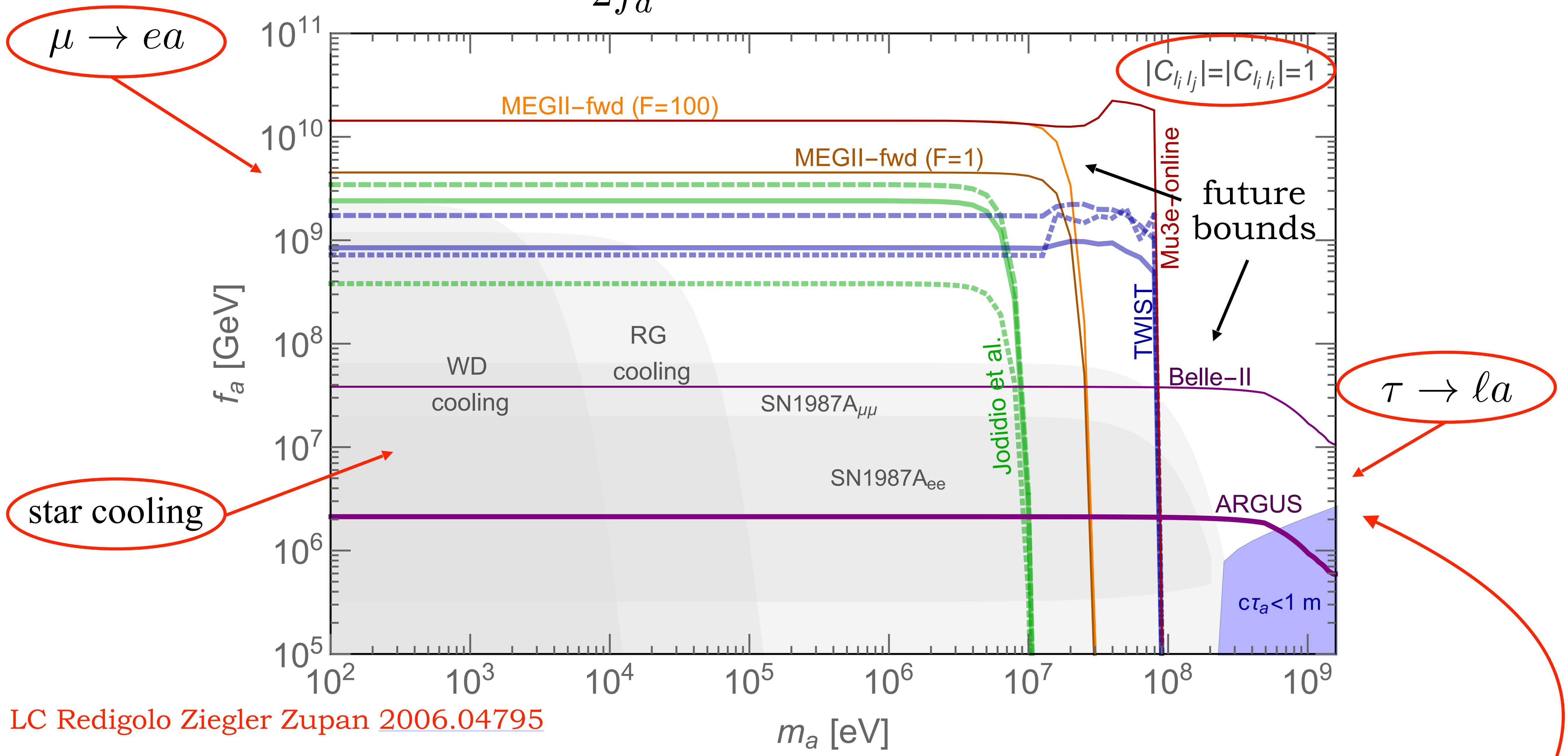
Goal: constrain the effective LFV scales F_{ij} using experimental data

- Which experiments?
- What are the future prospects?

→ D. Redigolo's talk

Lepton-flavour-violating invisible ALPs

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$



LC Redigolo Ziegler Zupan 2006.04795

Decays mediated by dim-5 operators: much larger NP scales can be reached
Essential interplay among μ decays, τ decays, and astrophysical bounds

- How generic is a PNGB with flavour-violating couplings to leptons?
- Can we test ALPs with LFV *beyond stars*?
- That is, how are FC and FV couplings related (F_{ee}, $F_{\mu e}$, etc.) ?

To answer these questions, we need to consider specific models

- LFV QCD axion:

QCD axion (DSFZ type) with leptons carrying non-universal PQ

- LFV axiflavon:

QCD axion obtained by identifying PQ = Froggatt-Nielsen U(1)
(FV axion-quark couplings suppressed by an additional flavour SU(2))

- Leptonic familon

PNGB from spontaneously broken Froggatt-Nielsen U(1) (acting on leptons only)

- Majoron

spontaneously broken lepton number (in the context of low-energy seesaw)

LFV QCD axion

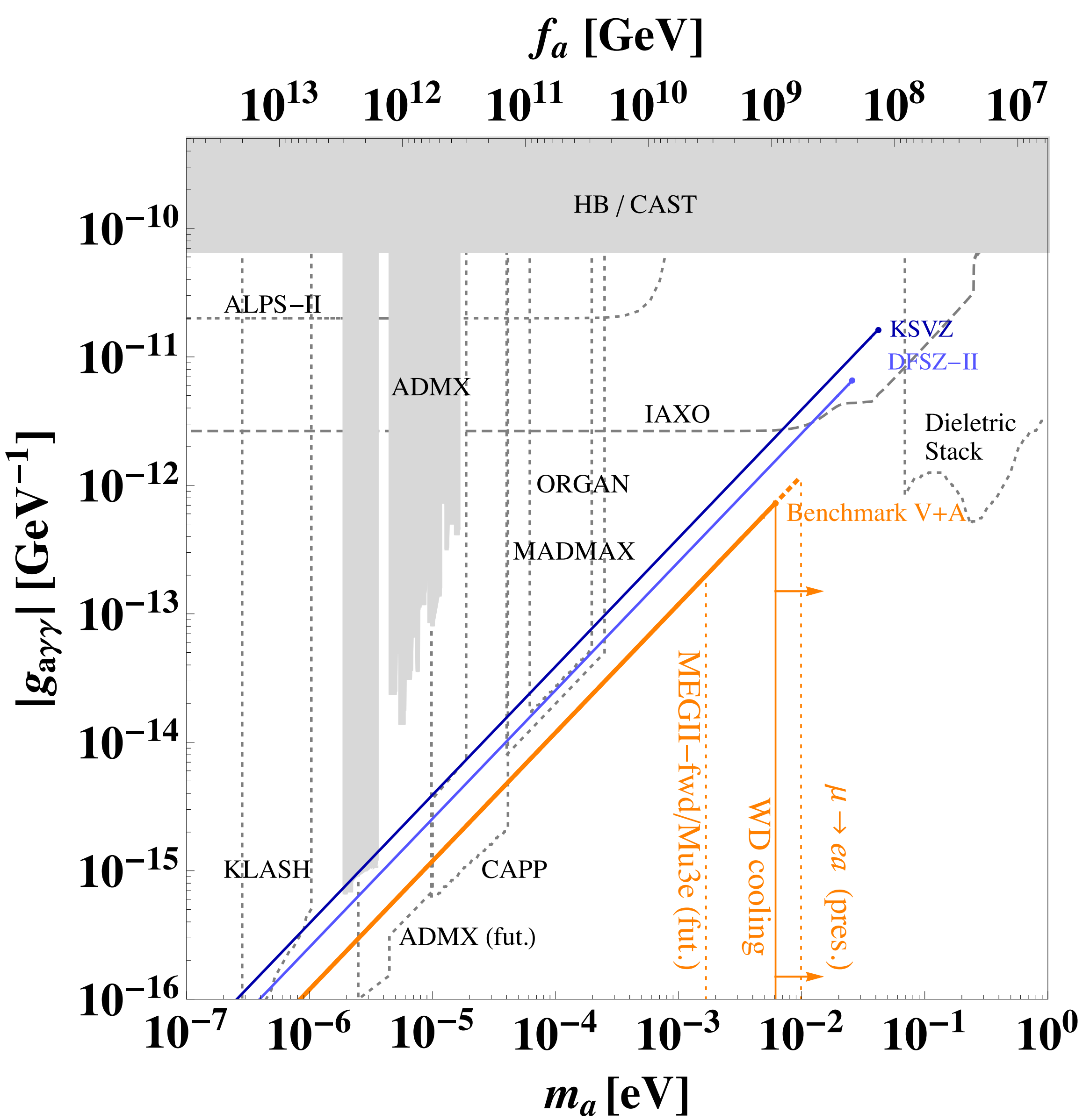
flavor non-universal charges
→ flavor-violating couplings

$$C^{V,A}_{f_i f_j} = \frac{1}{2N}\left(V_R^{f\,\dagger} X_{f_R} V_R^f \pm V_L^{f\,\dagger} X_{f_L} V_L^f\right)_{ij}$$

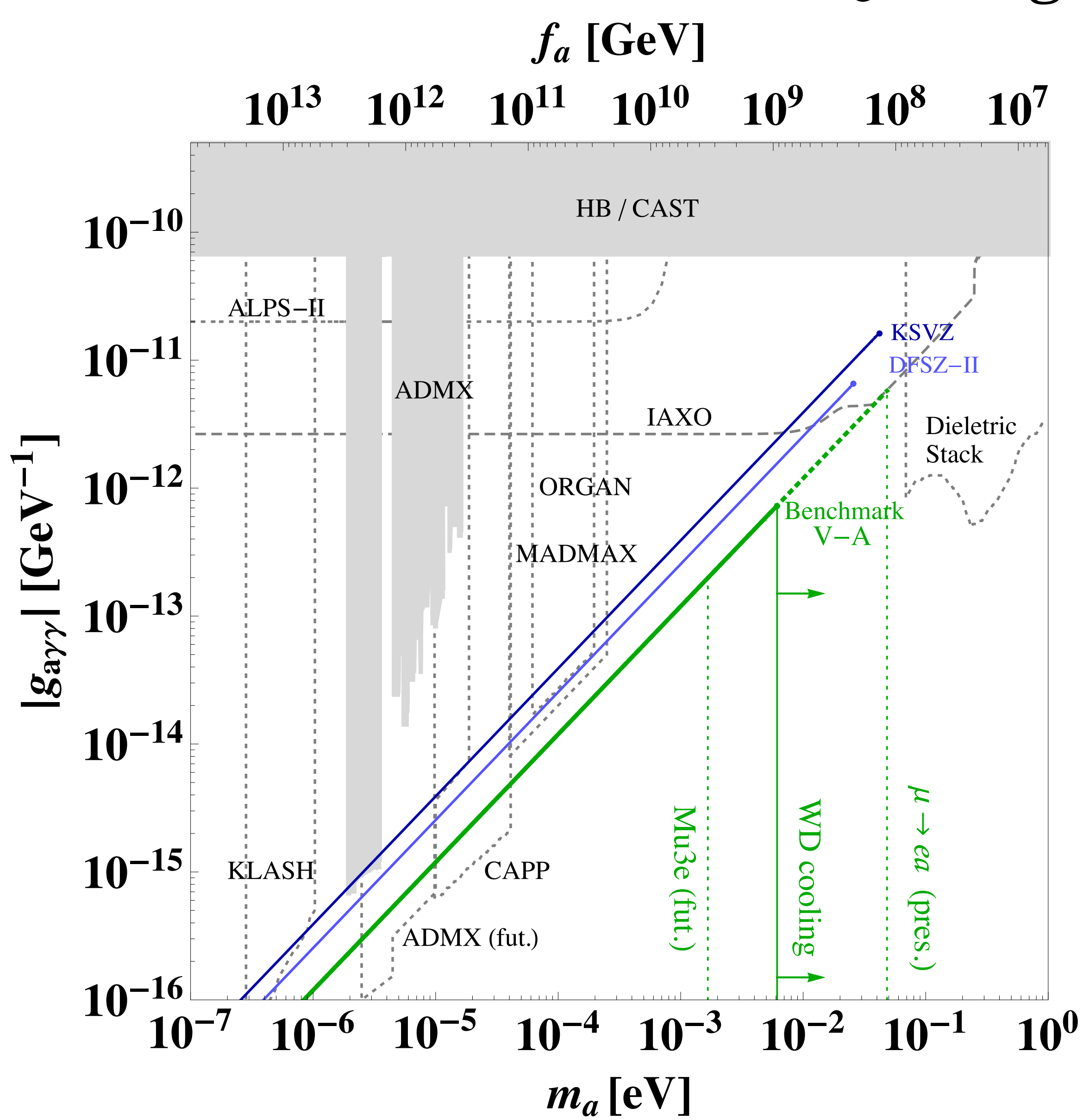
$$V_L^\dagger Y^e V_R = Y^e_{diag}$$

L and R unitary rotations to the lepton mass basis

matrices of PQ charges



V+A axion (large R rotations)



V-A axion (large L rotations)

LFV QCD axion

flavor non-universal charges
→ flavor-violating couplings

$$C^{V,A}_{f_i f_j} = \frac{1}{2N}\left(V_R^{f\,\dagger} X_{f_R} V_R^f \pm V_L^{f\,\dagger} X_{f_L} V_L^f\right)_{ij}$$

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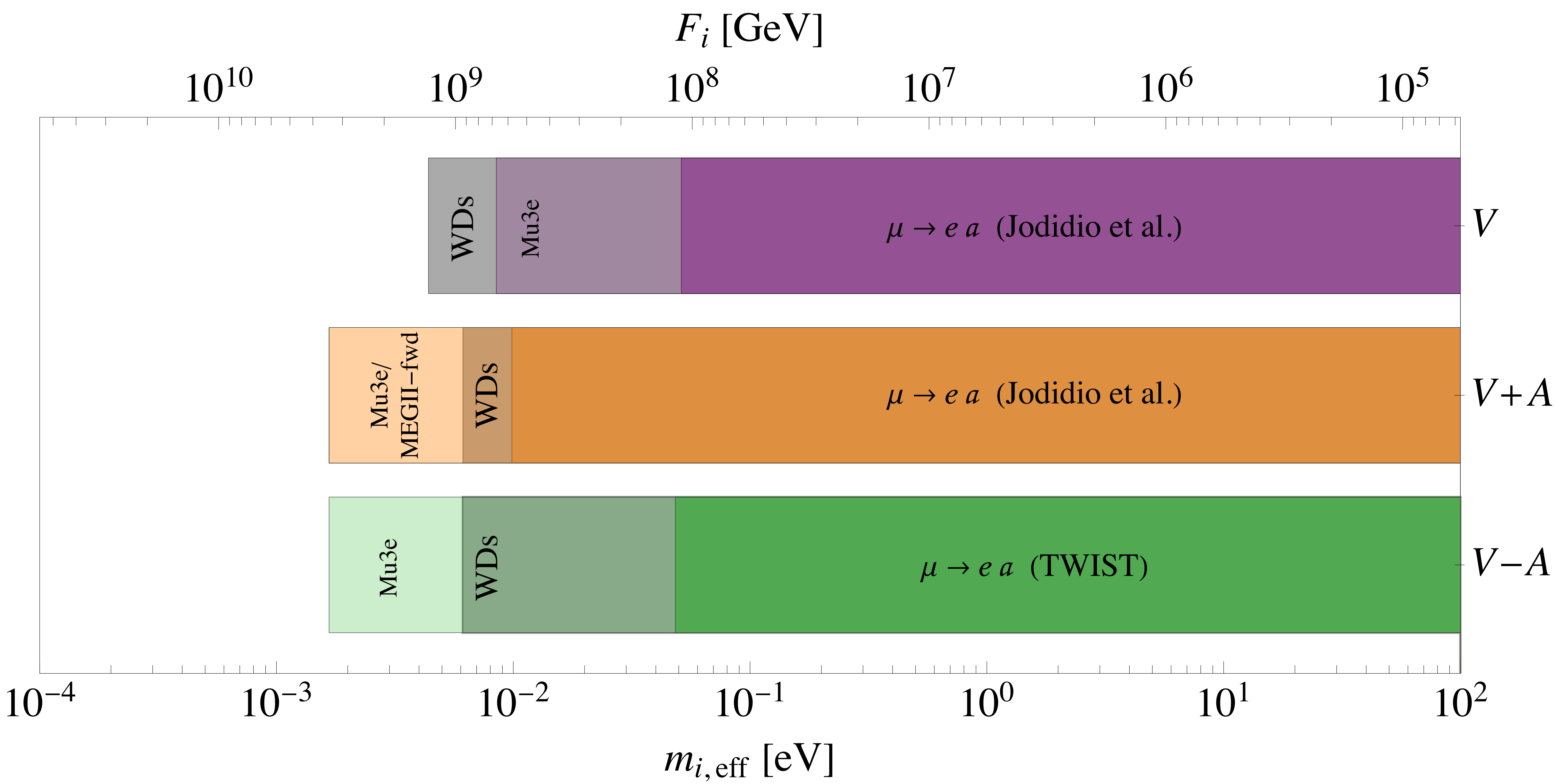


Type I seesaw: $\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}\partial\!\!\!/ N - \left(Y_N \overline{N} \widetilde{\Phi}^\dagger L + \frac{1}{2} M_N \overline{N} N^c + \text{h.c.} \right)$

L-breaking term

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_N^T v/\sqrt{2} \\ Y_N v/\sqrt{2} & M_N \end{pmatrix} \quad \overset{M_N \gg Y_N v}{\Longrightarrow} \quad m_\nu = -\frac{v^2}{2} Y_N^T M_N^{-1} Y_N$$

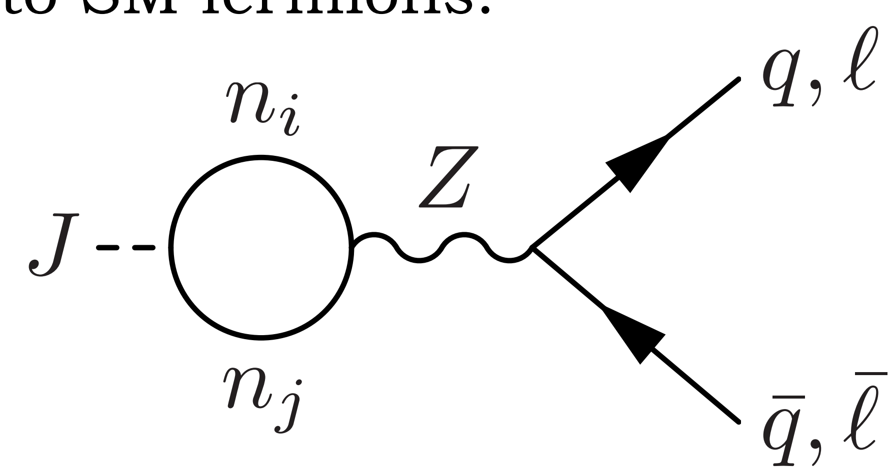
Spontaneous breaking of the lepton number:

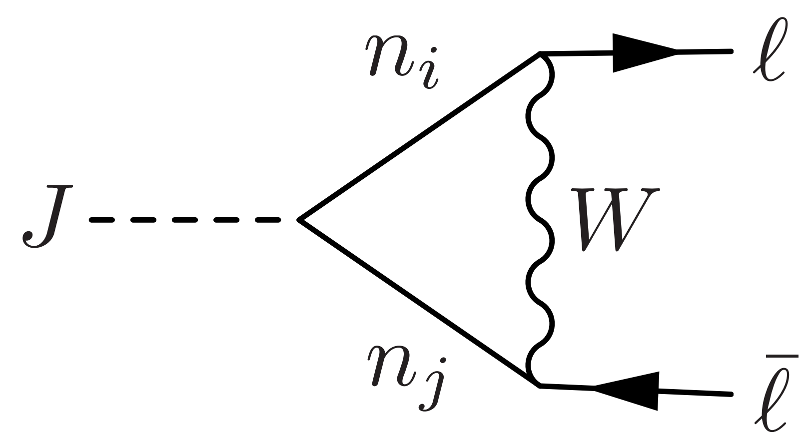
$$\frac{1}{2}\lambda_N\, \sigma \bar{N}^c N, \quad \sigma = \frac{f_N + \hat{\sigma}}{\sqrt{2}} e^{iJ/f_N} \quad \Longrightarrow \quad M_N = \lambda_N f_N/\sqrt{2}$$

PNGB: Majoron!

Chikashige Mohapatra Peccei ‘80

Couplings to SM fermions:





Majoron

Type I seesaw: $\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}\partial\!\!\!/ N - \left(Y_N \overline{N}\widetilde{\Phi}^\dagger L + \frac{1}{2} M_N \overline{N} N^c + \text{h.c.} \right)$

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PNGB: Majoron!

Chikashige Mohapatra Peccei ‘80

Couplings to SM fermions:

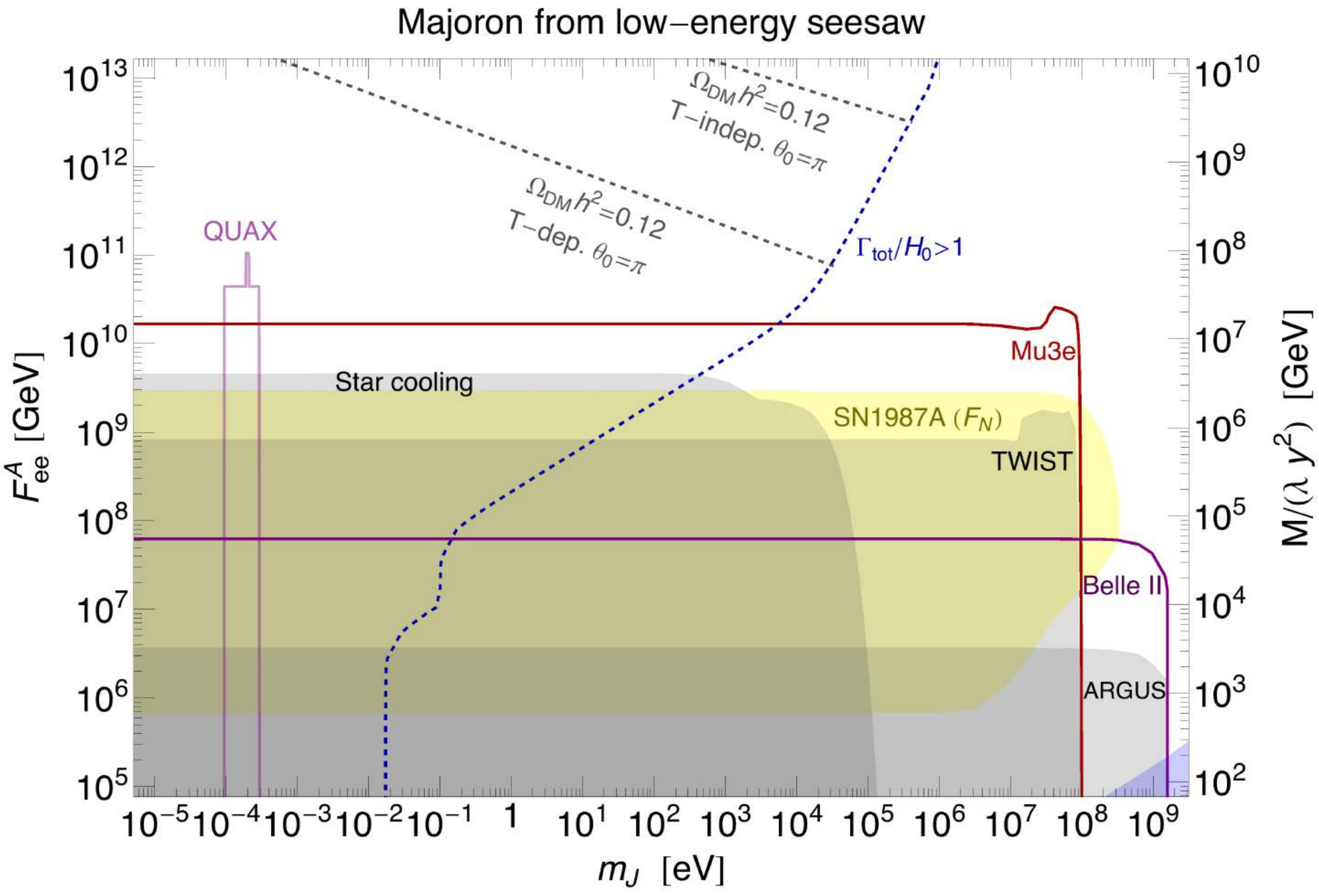
$$C^V_{q_i q_j} = 0\,, \qquad C^A_{q_i q_j} = -\frac{T_3^q}{16\pi^2}\delta_{ij}\,\text{Tr}\left(Y_N Y_N^\dagger\right)\,,$$

$$C^V_{\ell_i \ell_j} = \frac{1}{16\pi^2}\left(Y_N Y_N^\dagger\right)_{ij}\,, \qquad C^A_{\ell_i \ell_j} = \frac{1}{16\pi^2}\left[\frac{\delta_{ij}}{2}\,\text{Tr}\left(Y_N Y_N^\dagger\right) - (Y_N Y_N^\dagger)_{ij}\right]$$

Generically flavour-violating, (V-A)

Pilaftsis ’94
Garcia-Cely Heeck ‘17

Majoron



Lepton number anomaly free: suppressed coupling to photons ($E_{\rm UV}$=0)

$$\Gamma(a\to\gamma\gamma)=\frac{\alpha_{\rm em}^2 E_{\rm eff}^2}{64\pi^3}\frac{m_a^3}{f_a^2}, \qquad m_a \ll m_{\ell_i}:\; E_{\rm eff}\simeq E_{\rm UV} \qquad \mathcal{L}_{\rm eff}=E_{\rm UV}\frac{\alpha_{\rm em}}{4\pi}\frac{a}{f_a}F\tilde{F}$$

Summary

CLFV observables among the cleanest and most stringent tests of physics beyond the Standard Model

Future CLFV can test new physics up to very large scales: of the order of 10^7 — 10^8 GeV

Still plenty of room also to discover (tau) LFV at a Tera Z (and complementarity with B-factory searches)

ALPs from non-universal global U(1)s (or due to loop effects) give rise to lepton-flavour-violating decays

We have huge room for improvement over old limits: next generation experiments may discover axions in muon decays!

Grazie! Thanks! 谢谢!

Additional slides

Why no CLFV in the Standard Model?

In the SM fermion masses, thus the *flavour sector*, stems from the Yukawa interactions:

$$-\mathcal{L}_Y = (Y_u)_{ij}\, \overline{Q}_{L\,i}\, u_{R\,j}\, \widetilde{\Phi} + (Y_d)_{ij}\, \overline{Q}_{L\,i}\, d_{R\,j}\, \Phi + (Y_e)_{ij}\, \overline{L}_{L\,i}\, e_{R\,j}\, \Phi + h.c.$$

Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Unitary rotation matrices, couplings to photon and Z remain flavour-diagonal:

$$e\ \bar{f}\gamma_\mu f A^\mu \qquad\qquad (g_L\ \bar{f}_L\gamma_\mu f_L + g_R\ \bar{f}_R\gamma_\mu f_R) Z^\mu$$

Couplings to the Higgs are also flavour-conserving (aligned to the mass matrix):

$$\frac{m_f}{v}\, \bar{f}_L f_R\, h$$

No (tree-level) flavour-changing neutral currents

Why no CLFV in the Standard Model?

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Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Flavour violation occurs in charged currents only:

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\overline{u}_L \gamma^\mu (V_u^\dagger V_d) d_L + \overline{\nu}_L \gamma^\mu (V_\nu^\dagger V_e) e_L \right) W_\mu^+ + h.c.$$

$$V_{\rm CKM} \equiv V_u^\dagger V_d \qquad\qquad U_{\rm PMNS} \equiv V_\nu^\dagger V_e$$

However, if neutrinos are massless, we can choose:

$$V_\nu = V_e$$

No LFV (Y_e only ‘direction’ in the leptonic flavour space)

Z LFV in the SMEFT

The couplings of Z to leptons are protected by the SM gauge symmetry
→ LFV effects must be proportional to the EW breaking:

$$\mathrm{BR}(Z \to \ell\ell') \sim \mathrm{BR}(Z \to \ell\ell) \times C_{\mathrm{NP}}^2 \left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4$$

In the SM EFT, only 5 operators contribute at the tree level:

$$Q_{\Phi\ell}^{(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}_L \gamma^\mu \ell'_L), \qquad Q_{\Phi\ell}^{(3)} = (\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{\ell}_L \tau_I \gamma^\mu \ell'_L), \qquad Q_{\Phi e} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}_R \gamma^\mu \ell'_R)$$

$$Q_{eW} = (\bar{\ell}_L \sigma^{\mu\nu} \ell'_R) \tau_I \Phi \, W^I_{\mu\nu}, \qquad Q_{eB} = (\bar{\ell}_L \sigma^{\mu\nu} \ell'_R) \Phi \, B_{\mu\nu}$$

$$\mathrm{BR}\,(Z \to \ell_i \ell_j) = \frac{m_Z}{12\pi\Gamma_Z} \left\{ \left| g_{VR}\delta_{ij} + \delta g^{ij}_{VR} \right|^2 + \left| g_{VL}\delta_{ij} + \delta g^{ij}_{VL} \right|^2 + \frac{m_Z^2}{2} \left(\left| \delta g^{ij}_{TR} \right|^2 + \left| \delta g^{ij}_{TL} \right|^2 \right) \right\}$$

$$\mathcal{L}^Z_{\mathrm{eff}} = \Big[\left(g_{VR}\, \delta_{ij} + \delta g^{ij}_{VR} \right) \, \bar{\ell}_i \gamma^\mu P_R \ell_j \, + \, \left(g_{VL}\, \delta_{ij} + \delta g^{ij}_{VL} \right) \, \bar{\ell}_i \gamma^\mu P_L \ell_j \Big] Z_\mu \, + \\ \Big[\delta g^{ij}_{TR} \, \bar{\ell}_i \sigma^{\mu\nu} P_R \ell_j \, + \, g^{ij}_{TL} \, \bar{\ell}_i \sigma^{\mu\nu} P_L \ell_j \Big] Z_{\mu\nu} \, + \, h.c.\,,$$

Z LFV in the SMEFT

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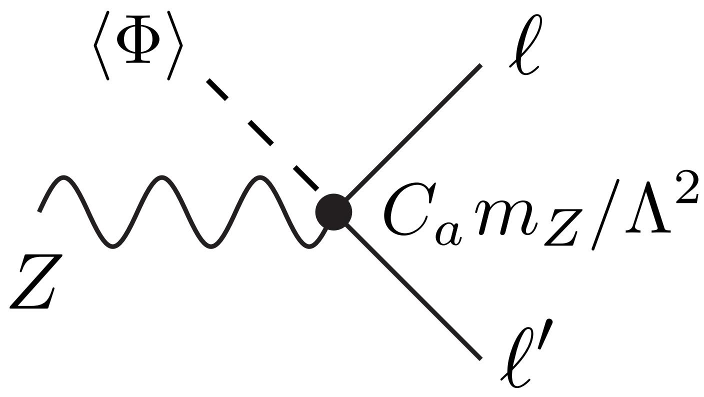
$$\mathrm{BR}\left(Z \to \ell_i \ell_j\right) = \frac{m_Z}{12\pi\Gamma_Z}\left\{ \left|g_{VR}\delta_{ij} + \delta g_{VR}^{ij}\right|^2 + \left|g_{VL}\delta_{ij} + \delta g_{VL}^{ij}\right|^2 + \frac{m_Z^2}{2}\left(\left|\delta g_{TR}^{ij}\right|^2 + \left|\delta g_{TL}^{ij}\right|^2\right)\right\}$$

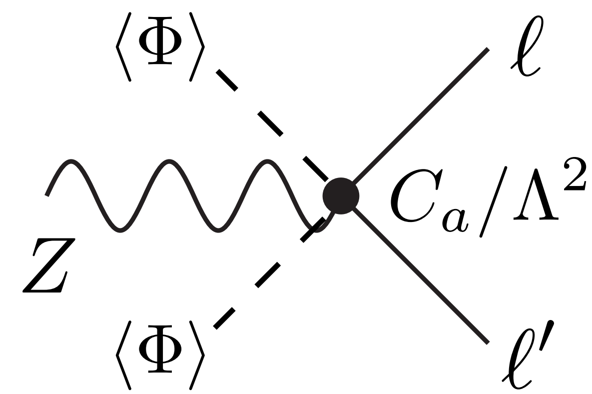
$$\delta g_{VR}^{ij} = -\frac{e v^2}{2 s_{\mathrm{w}} c_{\mathrm{w}} \Lambda^2} C_{\varphi e}^{ij}, \quad \delta g_{VL}^{ij} = -\frac{e v^2}{2 s_{\mathrm{w}} c_{\mathrm{w}} \Lambda^2}\left(C_{\varphi\ell}^{(1)\,ij} + C_{\varphi\ell}^{(3)\,ij}\right),$$

$$\delta g_{TR}^{ij} = \delta g_{TL}^{ji\,*} = -\frac{v}{\sqrt{2}\Lambda^2}\left(s_{\mathrm{w}} C_{eB}^{ij} + c_{\mathrm{w}} C_{eW}^{ij}\right),$$

Dipole operators:



Higgs-lepton operators:



$$Q^{(1)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar\ell_L \gamma^\mu \ell'_L), \qquad Q^{(3)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar\ell_L \tau_I \gamma^\mu \ell'_L), \qquad Q_{\Phi e} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar\ell_R \gamma^\mu \ell'_R)$$

$$Q_{eW} = (\bar\ell_L \sigma^{\mu\nu} \ell'_R)\tau_I \Phi\, W^I_{\mu\nu}, \qquad Q_{eB} = (\bar\ell_L \sigma^{\mu\nu} \ell'_R)\Phi\, B_{\mu\nu}$$

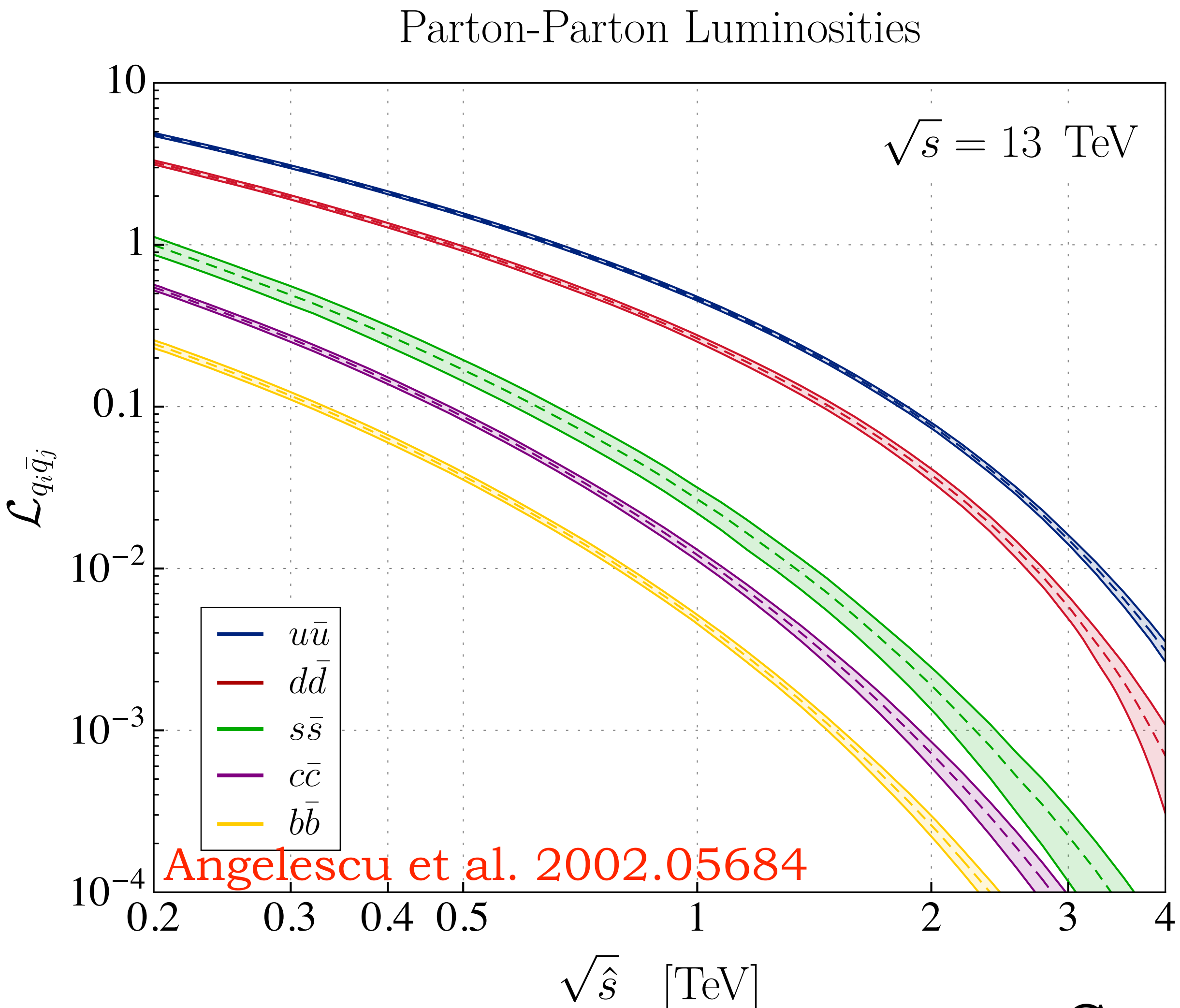
If a single operator dominates, $Z \to \ell\ell'$ constrain NP scales up to

$$C_a = 1: \quad \Lambda \gtrsim 5\ \text{TeV} \quad (\text{Z} \to \mu\text{e}), \quad \Lambda \gtrsim 3\ \text{TeV} \quad (\text{Z} \to \tau\ell)$$

$$\delta g^{ij}_{VR} = -\frac{ev^2}{2s_\text{w}c_\text{w}\Lambda^2} C^{ij}_{\varphi e}, \quad \delta g^{ij}_{VL} = -\frac{ev^2}{2s_\text{w}c_\text{w}\Lambda^2} \left(C^{(1)\,ij}_{\varphi\ell} + C^{(3)\,ij}_{\varphi\ell} \right),$$

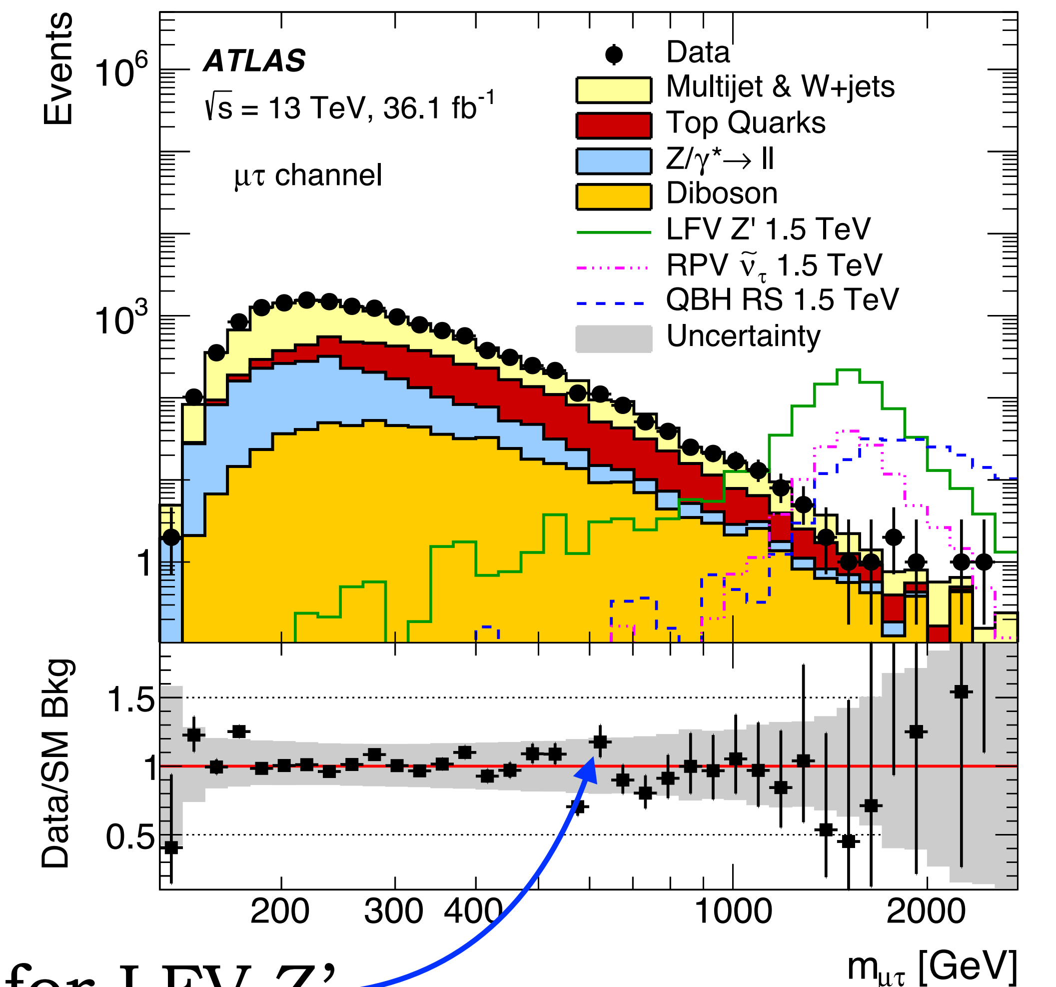
$$\delta g^{ij}_{TR} = \delta g^{ji\,*}_{TL} = -\frac{v}{\sqrt{2}\Lambda^2} \left(s_\text{w} C^{ij}_{eB} + c_\text{w} C^{ij}_{eW} \right),$$

Many $\bar{c}c$ scatterings in pp collisions at the LHC



Angelescu et al. 2002.05684

Di-lepton invariant mass



Search for LFV Z'

ATLAS 1807.06573

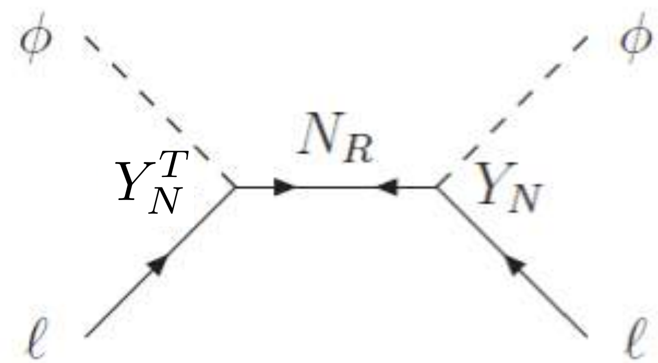
LHC di-lepton tails constrain $\bar{c}c\,\bar{\ell}_i \ell_j$ contact interactions up to Λ > 2-3 TeV

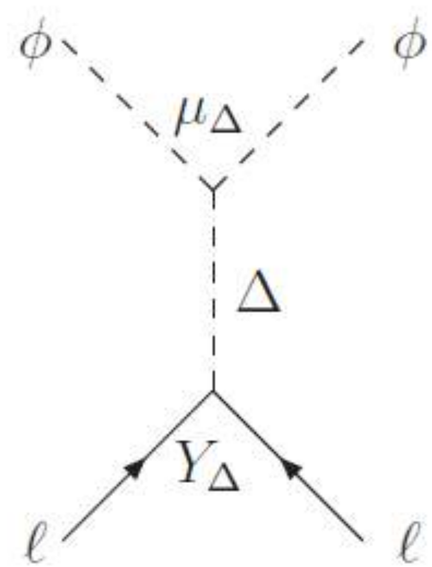
⇒ Indirect LHC bounds (if EFT is valid):

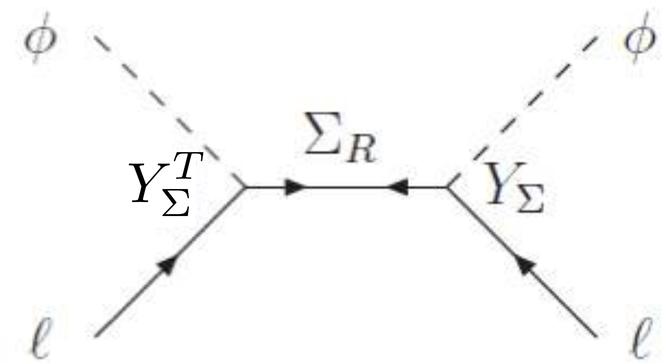
$$\mathrm{BR}(J/\psi \to e\mu) < 10^{-11}, \quad \mathrm{BR}(J/\psi \to e\tau) < 6 \times 10^{-11}, \quad \mathrm{BR}(J/\psi \to \mu\tau) < 7 \times 10^{-11}$$

Angelescu et al. 2002.05684

Three ways of generating the Weinberg operator at the tree level:







Type I

Heavy fermionic singlets (RH neutrinos)

Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, ...

Type II

Heavy scalar triplet

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, ...

Type III

Heavy fermionic triplets

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez, ...

Type I seesaw

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}\partial\!\!\!/ N - \left(Y_N \overline{N}\widetilde{\Phi}^\dagger L + \frac{1}{2} M_N \overline{N} N^c + \text{h.c.} \right)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_N^T v/\sqrt{2} \\ Y_N v/\sqrt{2} & M_N \end{pmatrix} \quad \Longrightarrow \quad m_\nu = -\frac{v^2}{2} Y_N^T M_N^{-1} Y_N$$

New contributions to CLFV processes:

- Light neutrinos contribution (non-unitary PMNS) $\quad \mathcal{U} = \left(1 - \frac{v^2}{2} Y_N^\dagger M_N^{-2} Y_N\right) U$

$$\frac{\Gamma(\ell_i \to \ell_j \gamma)}{\Gamma(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \mathcal{U}_{ik} \mathcal{U}^\dagger_{kj} F\left(\frac{m^2_{\nu_k}}{M_W^2}\right) + \sum_{k=1,N} U^{\nu N}_{ik} U^{\nu N \dagger}_{kj} F\left(\frac{M_k^2}{M_W^2}\right) \right|^2$$

$$F(x) = \frac{10}{3} - x + \mathcal{O}(x^2) \qquad\qquad F(x) \simeq \frac{1}{2}, \quad x \gg 1$$

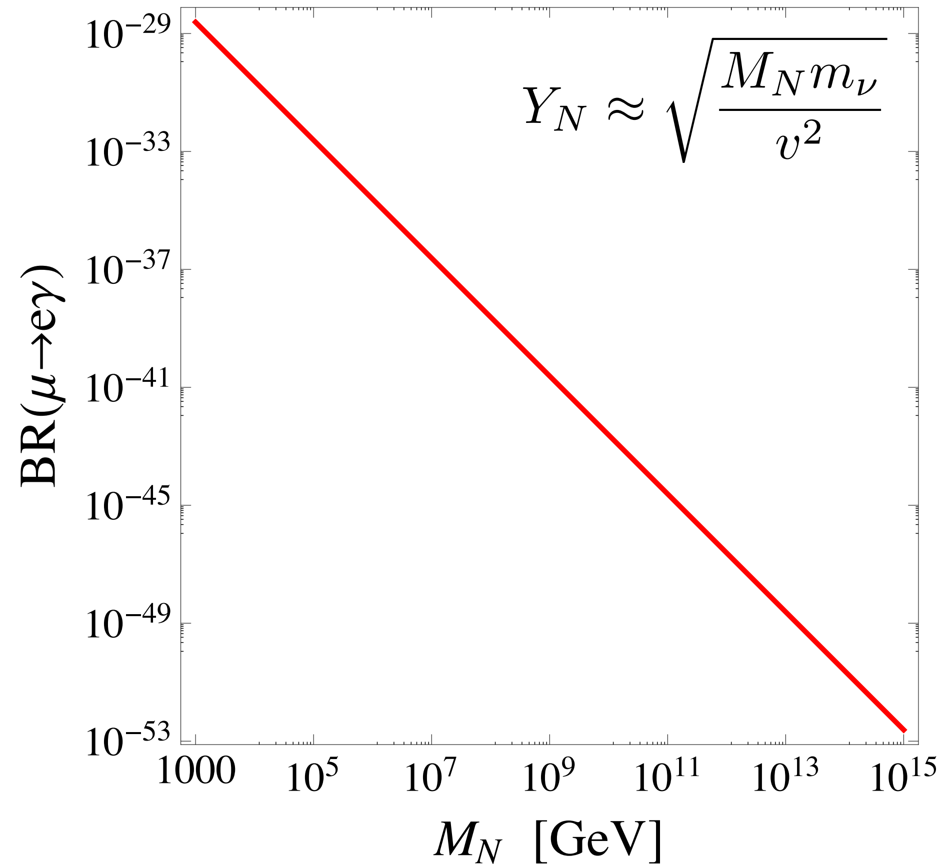
- Heavy neutrinos in the loop $\quad U^{\nu N} = \frac{v}{\sqrt{2}} Y_N^\dagger M_N^{-1}$

Ilakovac Pilaftsis '94

Can we have large CLFV rates fulfilling with $m_{\nu_i} \lesssim 0.1$ eV ?

Type I seesaw

Naive expectation for RH neutrinos at the same scale:



But that's not (necessarily) the end of the story:

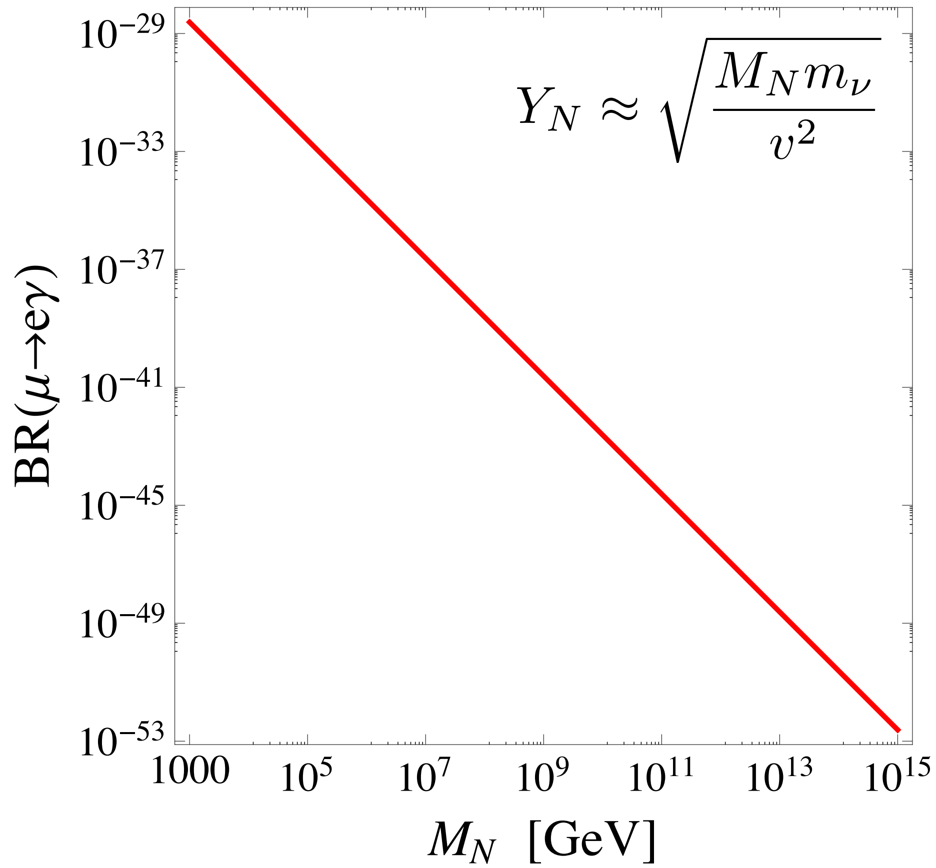
- Neutrino masses controlled by *L*-breaking dim-5 operator: $Y_N^T M_N^{-1} Y_N$
- CLFV controlled by *L*-conserving dim-6 operator: $Y_N^\dagger M_N^{-2} Y_N$

Broncano Gavela Jenkins '02

Can the dim-5 coefficient be small while the dim-6 one is large?
Yes! If the lepton number is approximately conserved…

Type I seesaw

Naive expectation for RH neutrinos at the same scale:



Observable effects possible for small breaking of lepton number, e.g.:

- Two almost degenerate RH neutrinos (pseudo-Dirac pair) Ibarra Molinaro Petcov '11
- Extended mass matrix (inverse seesaw, linear seesaw...)

$$\begin{array}{ccc} \nu_L & N\ (L=1) & S\ (L=-1) \end{array}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_N & 0 \\ \frac{v}{\sqrt{2}} Y_N & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix} \implies m_\nu = \frac{v^2}{2} Y_N^T \frac{\mu}{M_N^2} Y_N$$

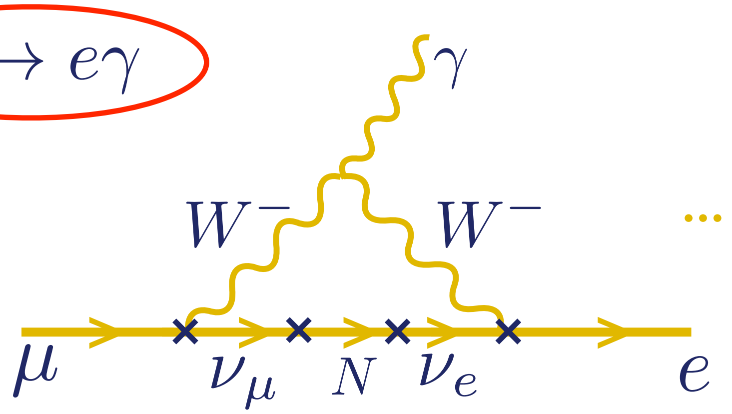
$\mu \ll M_N$

Mohapatra Valle '86

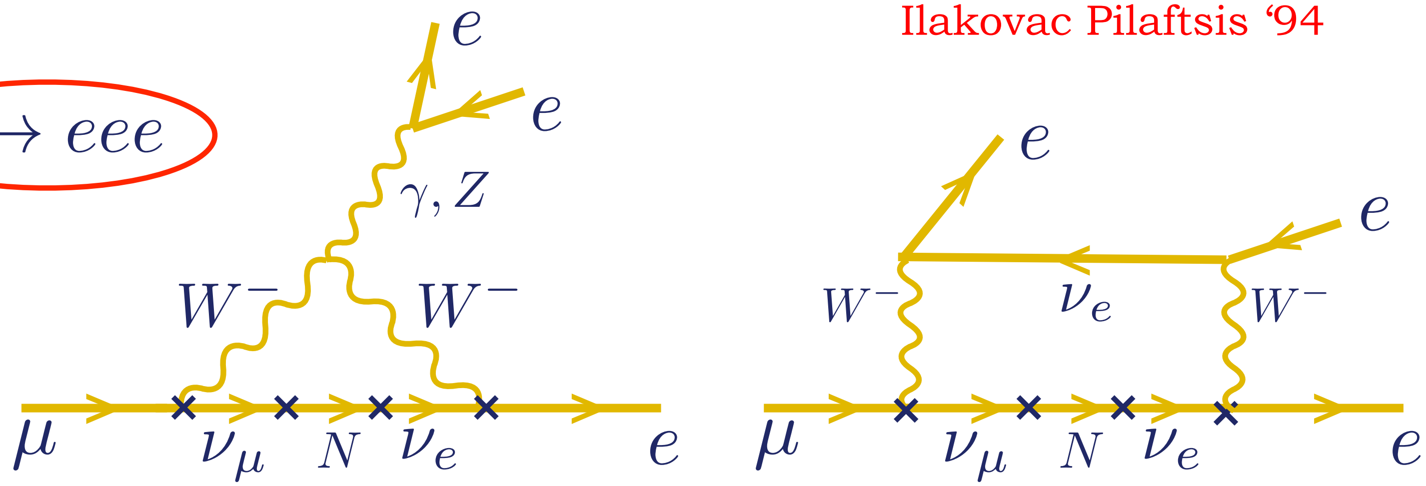
In type I seesaw, flavour-mixing occur only for neutral states

⇨ all CLFV modes arise at the loop level:

$\mu \to e\gamma$

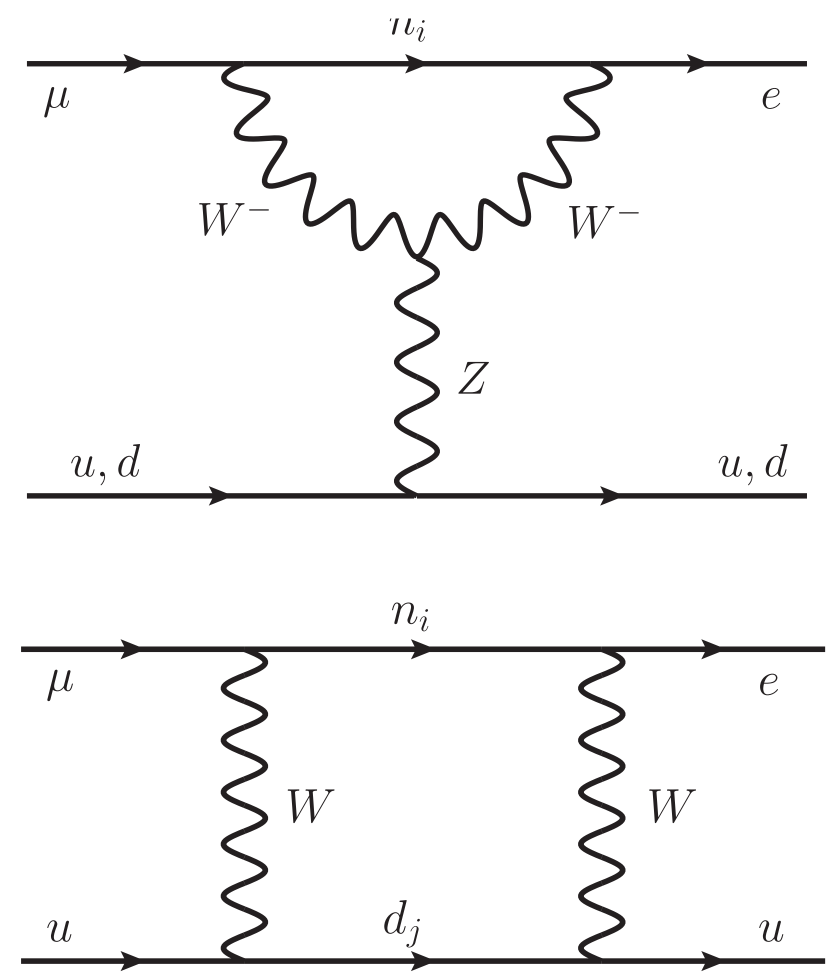


$\mu \to eee$



Ilakovac Pilaftsis '94

$\mu \to e$ in nuclei



Dinh Ibarra Molinaro Petcov '12
Alonso Dhen Gavela Hambye '12

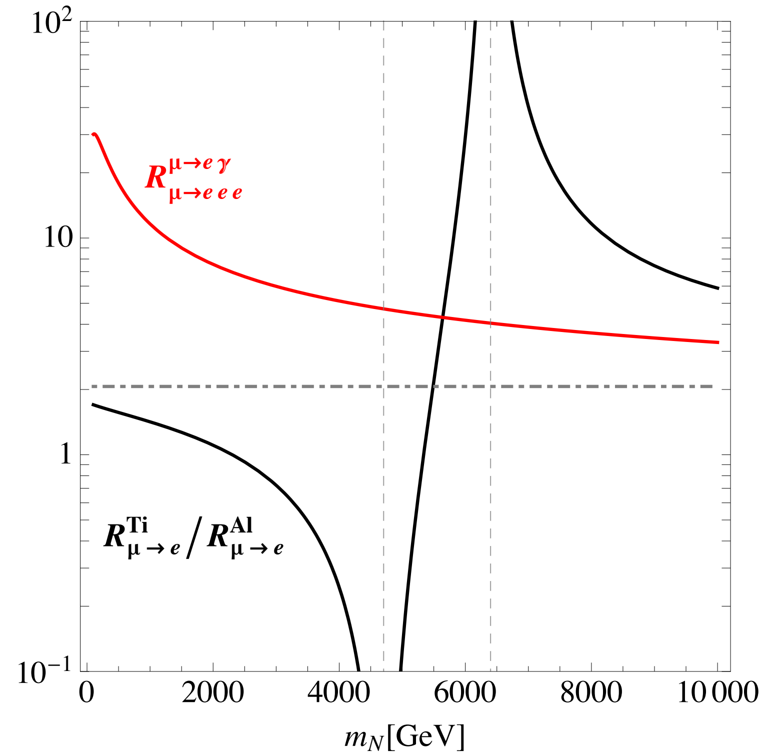
Type I seesaw

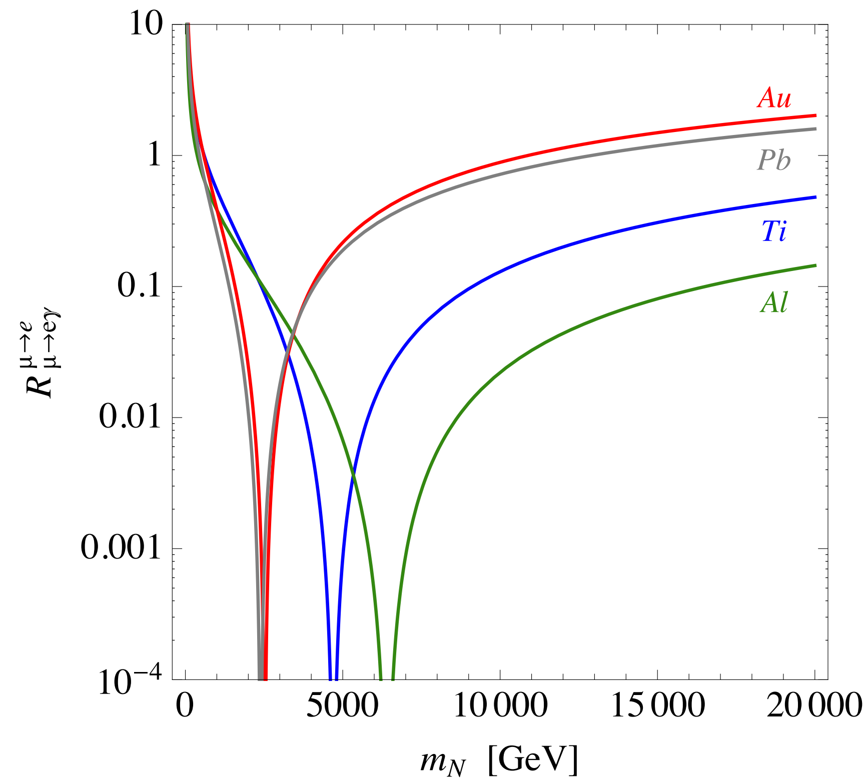
Type I

Chu Dhen Hambye '11
Dinh et al. '12, Alonso et al. '12

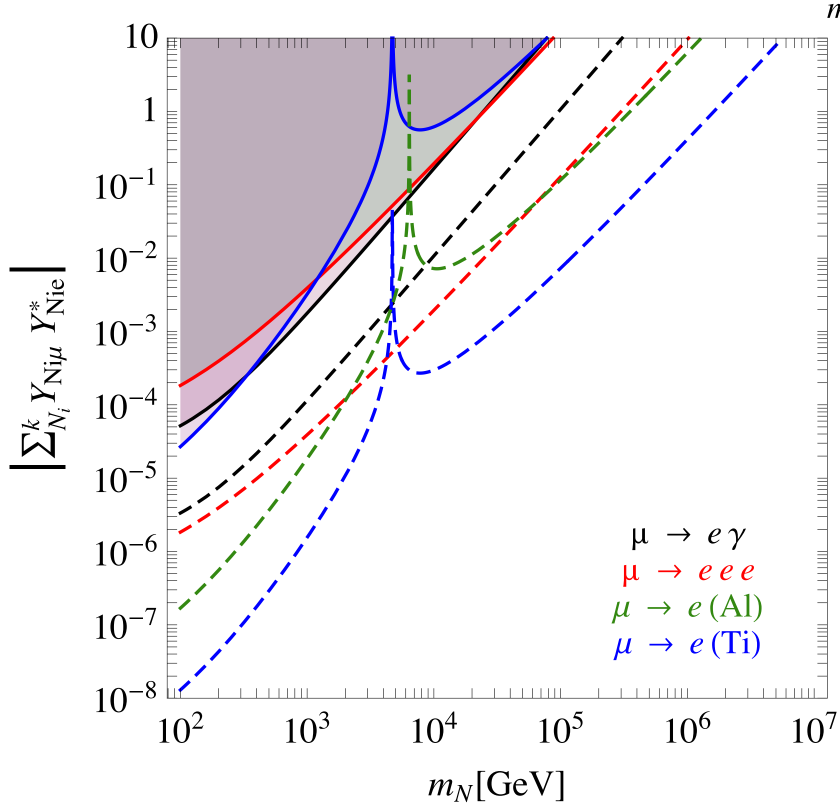
Quasi-degenerate RH neutrinos
dependence on Yukawa couplings drops in ratios of BRs:

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\mu \to eee)}$$





$$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$$



Future experiments can test RH neutrino masses up to:

$$m_N \approx 300\ \mathrm{TeV} \times \left(\frac{10^{-14}}{\mathrm{BR}(\mu \to e\gamma)}\right)^{\frac{1}{4}},\ m_N \approx 1000\ \mathrm{TeV} \times \left(\frac{10^{-16}}{\mathrm{BR}(\mu \to eee)}\right)^{\frac{1}{4}},$$

$$m_N \approx 1000\ \mathrm{TeV} \times \left(\frac{10^{-16}}{\mathrm{CR}(\mu\,\mathrm{Al} \to e\,\mathrm{Al})}\right)^{\frac{1}{4}},\ m_N \approx 6000\ \mathrm{TeV} \times \left(\frac{10^{-18}}{\mathrm{CR}(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti})}\right)^{\frac{1}{4}}$$

Alonso Dhen Gavela Hambye '12

Type II seesaw

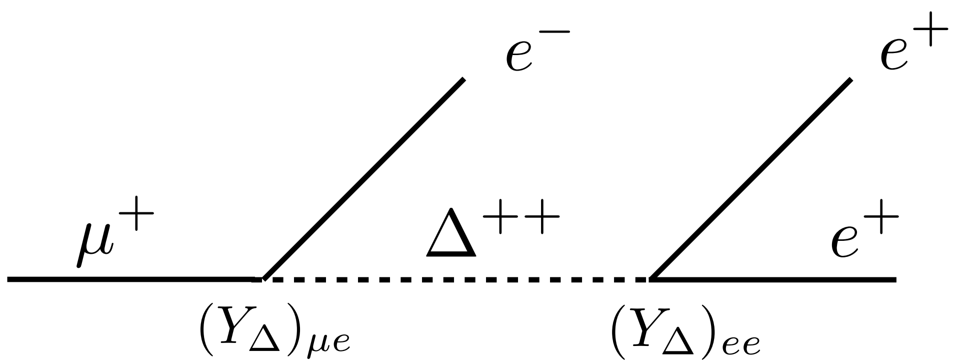
Type II

Scalar SU(2) triplet (Y=1): $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

L-breaking term

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}\left(D_\mu \Delta^\dagger\right)\left(D^\mu \Delta\right) - M_\Delta^2 {\rm Tr}\Delta^\dagger\Delta - \left(Y_\Delta L^T i\tau_2 \Delta L + \mu_\Delta \widetilde{\Phi}^T i\tau_2 \Delta \widetilde{\Phi} + {\rm h.c.}\right) \Rightarrow m_\nu = -2 Y_\Delta \frac{v^2 \mu_\Delta}{M_\Delta^2}$$

Concerning CLFV, the main difference wrt Type I is $\mu \to eee$ at the tree level:



$$\text{BR}(\mu \to eee) = \frac{|(Y_\Delta)_{\mu e}|^2 |(Y_\Delta)_{ee}|^2}{M_\Delta^4 G_F^2}$$

Abada et al. '07, '08

Present bound: $Y_\Delta = \mathcal{O}(1) \implies M_\Delta \gtrsim 300$ TeV

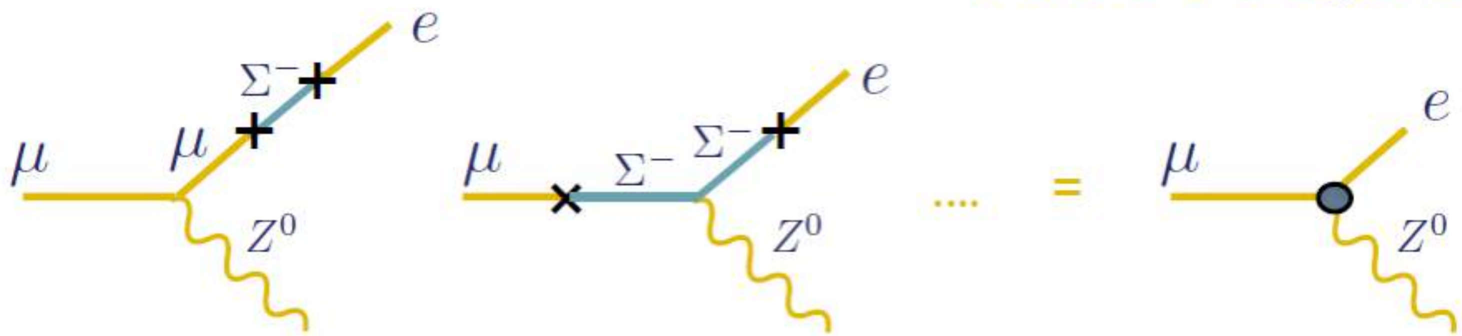
Mu3e sensitivity: $\text{BR}(\mu^+ \to e^+ e^+ e^-) \simeq 10^{-16} \Rightarrow M_\Delta \approx 3000$ TeV

Type III

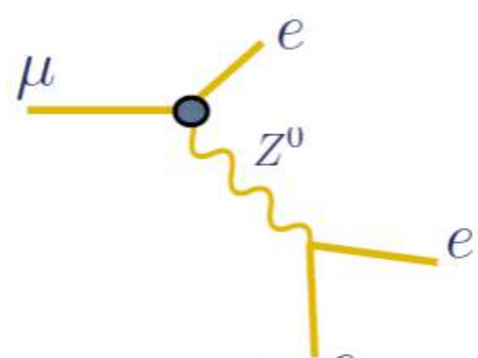
crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states

Hypercharge Y=0

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$



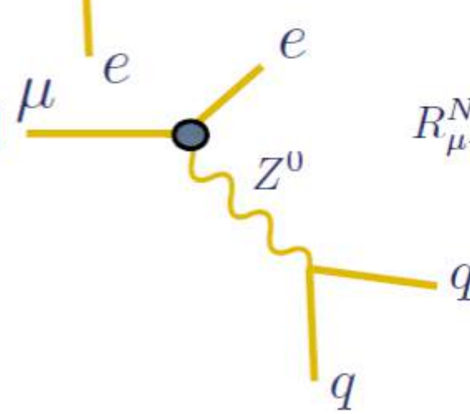
⇒ $\mu \to eee$: tree level



$$\Gamma(\mu \to eee) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot d^2$$

Abada, Biggio, Bonnet, Gavela, TH 07', 08'

$\mu \to e$ conversion : tree level



$$R^N_{\mu\to e} = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot (b^N)^2$$

$\mu \to e\gamma$: still at one loop

⇒ ratios of 2 processes with same flavour transition: totally fixed!

$$\mathrm{BR}(\mu \to e\gamma) = 1.3 \times 10^{-3} \times \mathrm{BR}(\mu \to eee) = 3.1 \times 10^{-4} \times \mathrm{CR}(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}),$$
$$\mathrm{BR}(\tau \to \mu\gamma) = 1.3 \times 10^{-3} \times \mathrm{BR}(\tau \to \mu\mu\mu) = 2.1 \times 10^{-3} \times \mathrm{BR}(\tau^- \to \mu^- e^+ e^-),$$
$$\mathrm{BR}(\tau \to e\gamma) = 1.3 \times 10^{-3} \times \mathrm{BR}(\tau \to eee) = 2.1 \times 10^{-3} \times \mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-).$$

borrowed from T. Hambye

$\mu \to e\, a$: signal and background

Signal: monochromatic positron with $p_e = \sqrt{\left(\frac{m_\mu^2 - m_a^2 + m_e^2}{2m_\mu}\right)^2 - m_e^2}$

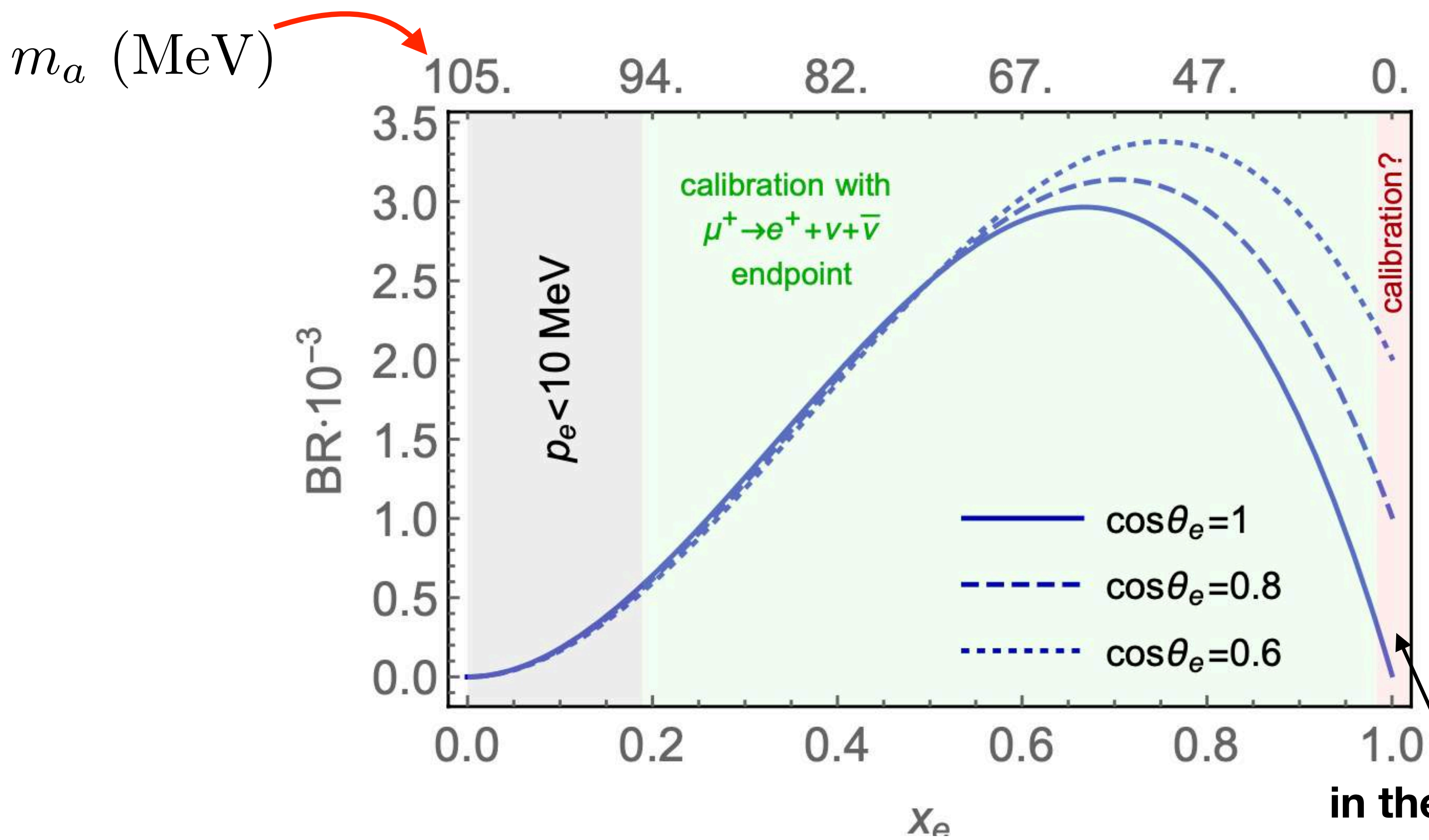
Differential decay rate: $\frac{\mathrm{d}\Gamma(\ell_i \to \ell_j\, a)}{\mathrm{d}\cos\theta} = \frac{m_{\ell_i}^3}{32\pi F_{\ell_i\ell_j}^2}\left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2 \left[1 + 2P_{\ell_i}\cos\theta \frac{C^V_{\ell_i\ell_j} C^A_{\ell_i\ell_j}}{(C^V_{\ell_i\ell_j})^2 + (C^A_{\ell_i\ell_j})^2}\right]$

signal depends on the chirality of the couplings

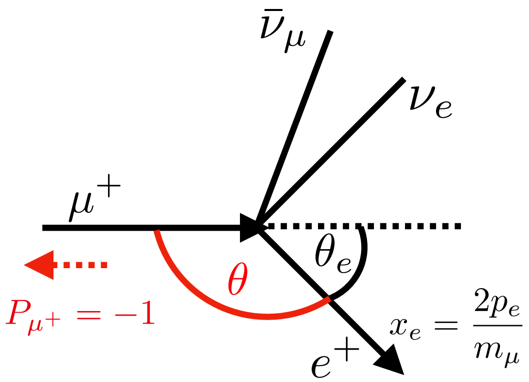
Michel spectrum: $\frac{\mathrm{d}^2\Gamma(\mu^+ \to e^+\, \nu_e\, \bar\nu_\mu)}{\mathrm{d}x_e\, \mathrm{d}\cos\theta} \simeq \Gamma_\mu \left((3 - 2x_e) - P_\mu (2x_e - 1)\cos\theta\right) x_e^2$ $\quad x_e = \frac{2p_e}{m_\mu}$

μ polarization

And "surface" muons are highly polarized (produced by pion decays at rest on the surface of the production target) → the SM background can be suppressed



the bkd goes to zero in the "forward" direction (the direction opposite to the muon polarization)



Future prospects: MEG II/Mu3e

Comparison in the case $m_a \approx 0$

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C_{ij}^V \, \bar{\ell}_i \gamma_\mu \ell_j + C_{ij}^A \, \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right) \qquad F_{ij}^{V,A} \equiv \frac{2 f_a}{C_{ij}^{V,A}} \qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C_{ij}^V|^2 + |C_{ij}^A|^2}}$$

Present best limits — LC Redigolo Ziegler Zupan 2006.04795

Process	BR Limit	Decay constant	Bound (GeV)	Experiment
$\mu \to e\, a$	$2.6 \times 10^{-6*}$	$F_{\mu e}$ (V or A)	4.8×10^{9}	Jodidio at al. [9]
$\mu \to e\, a$	$2.5 \times 10^{-6*}$	$F_{\mu e}$ ($V + A$)	4.9×10^{9}	Jodidio et al. [9]
$\mu \to e\, a$	$5.8 \times 10^{-5*}$	$F_{\mu e}$ ($V - A$)	1.0×10^{9}	TWIST [10]
$\mu \to e\, a\, \gamma$	$1.1 \times 10^{-9*}$	$F_{\mu e}$	$5.1 \times 10^{8\#}$	Crystal Box [47]

Expected future sensitivities

Process	BR Sens.	Decay constant	Sens. (GeV)	Experiment
$\mu \to e\, a$	$7.2 \times 10^{-7*}$	$F_{\mu e}$ (V or A)	9.2×10^{9}	MEGII-fwd*
$\mu \to e\, a$	$7.2 \times 10^{-8*}$	$F_{\mu e}$ (V or A)	2.9×10^{10}	MEGII-fwd**
$\mu \to e\, a$	$7.3 \times 10^{-8*}$	$F_{\mu e}$ (V or A)	2.9×10^{10}	Mu3e [42]

What about mu to e conversion experiments?