Charged Lepton Flavour Violation in Particle Physics and Cosmology

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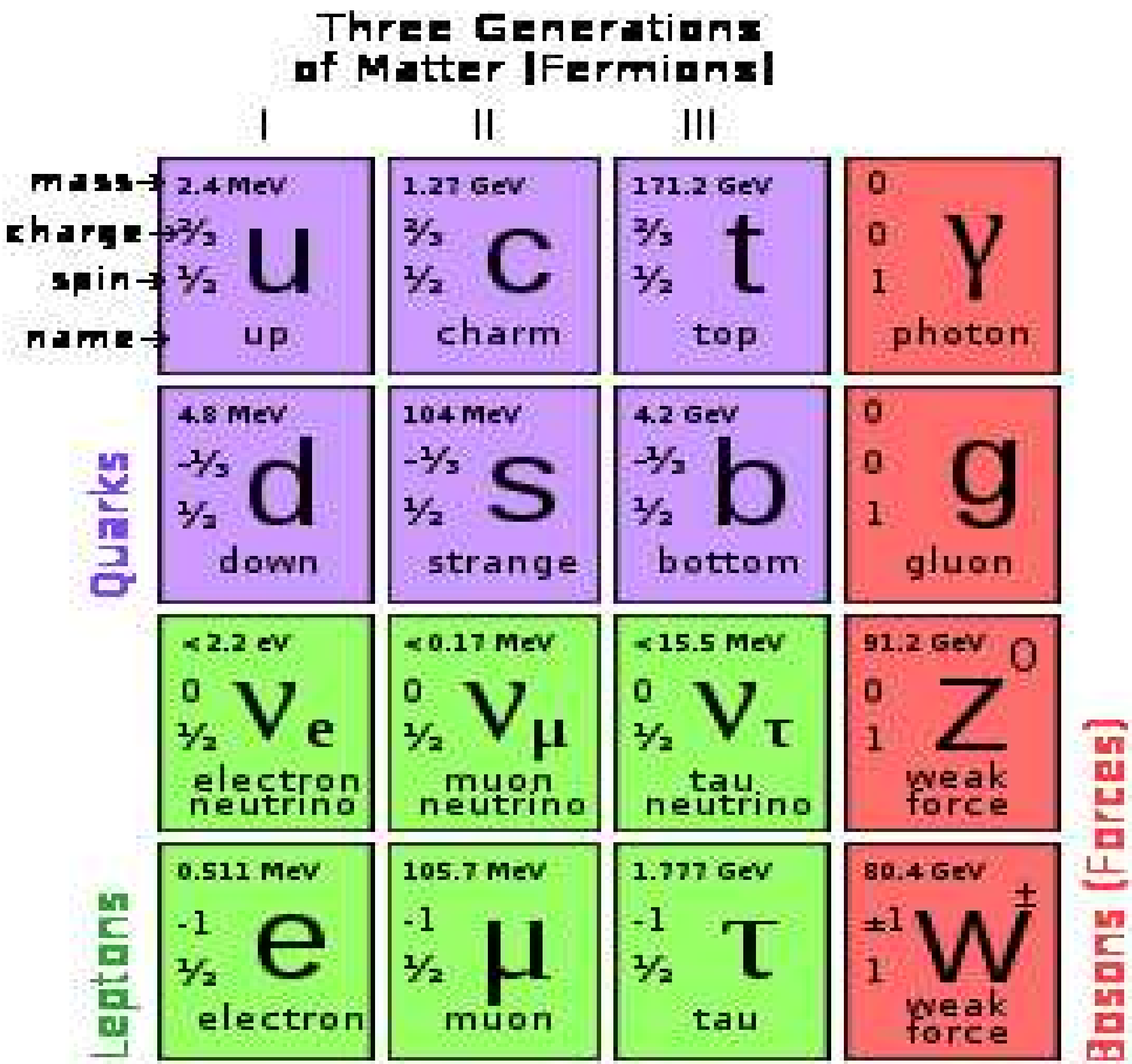
Plan of the talk

- **Neutrino Masses and Mixings**
- **The Seesaw and Non-Seesaw Paradigms**
- **Matter–AntiMatter Asymmetry**
- **Lepton Flavour and Number Violation at the LHC**
- **Lepton Flavour and Number Violation in Low-Energy Experiments**
- **Conclusions**

The Standard Model

[S.L. Glashow, NP 22 (1961) 579; S. Weinberg, PRL19 (1967) 1264; A. Salam, Eighth Nobel Symposium (1968).]



• Neutrino Masses and Mixings

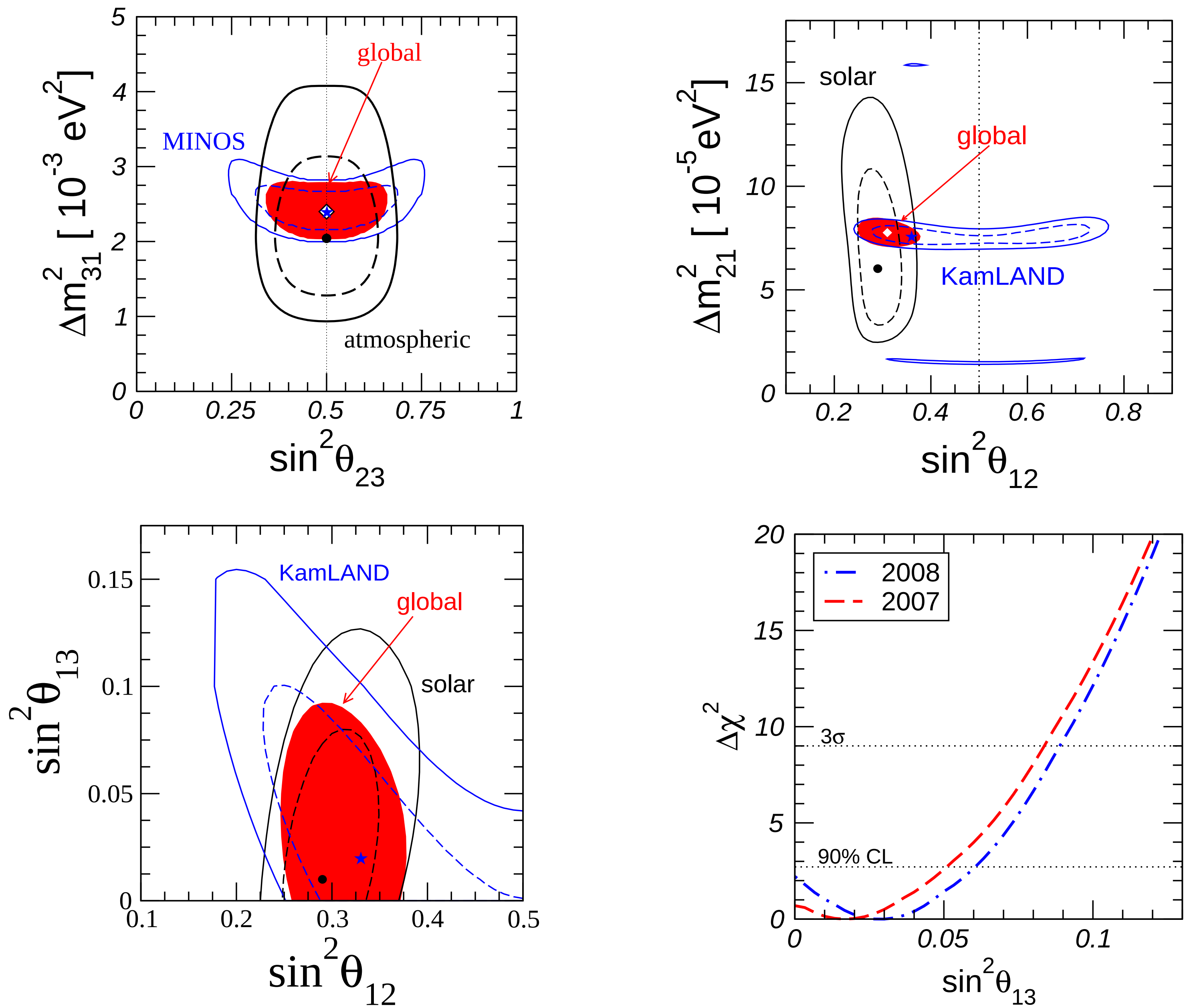
PMNS Mixing Matrix

[B. Pontecorvo, SPJETP7 (1958) 172;
Z. Maki, M. Nakagawa, S. Sakata, PTP28 (1962) 870.]

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} .$$

$$\begin{aligned} U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

[T. Schwetz, M. A. Tortola, J. W. F. Valle, arXiv:0808.2016v3, Feb 2010]



At the 3σ CL:

$$m^2_{\nu_2} - m^2_{\nu_1} \equiv \Delta m^2_\odot = (7.03 — 8.27) \times 10^{-5}\ \mathrm{eV}^2\,,$$
$$m^2_{\nu_3} - m^2_{\nu_2} \equiv \Delta m^2_{\rm atm} = (2.07 — 2.75) \times 10^{-3}\ \mathrm{eV}^2\,,$$
$$\sin^2\theta_{12} = 0.27 — 0.38\,, \qquad \sin^2\theta_{23} = 0.36 — 0.67\,, \qquad \sin^2\theta_{13} \leq 0.053\,,$$

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Cosmological and astronomical limits (WMAP + SDSS):

[M. Tegmark et al., PRD69 (2004) 103501]

$$\sum_{i=1}^{3} m_{\nu_i} \lesssim 1.74\ \mathrm{eV} \quad (95\%\ \mathrm{CL})\,.$$

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Mainz and Troitsk experiment $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$:

[E.W. Otten, C.Weinheimer, RPP 71 (2008) 086201]

$$m_{\nu_e} \lesssim 2.2\ \mathrm{eV} \quad (95\%\ \mathrm{CL})\ .$$

KATRIN sensitivity (start 2010): $\quad m_{\nu_e} \simeq 0.2$ eV.

• The Seesaw and Non-Seesaw Paradigms

– The Seesaw Paradigm

[P. Minkowski, PLB67 (1977) 421; T. Yanagida (1979) . . .]

$$\mathrm{SO}(10) \to \mathrm{SU}(4)_{\mathrm{PS}}\otimes\mathrm{SU}(2)_R\otimes\mathrm{SU}(2)_L \to \mathrm{SU}(3)_c\otimes\mathrm{SU}(2)_R\otimes\mathrm{SU}(2)_L\otimes\mathrm{U}(1)_{B-L}$$
$$\to \mathrm{SU}(3)_c\otimes\mathrm{SU}(2)_L\otimes\mathrm{U}(1)_Y \;\equiv\; \text{SM} + 3\,\nu_R\text{'s}$$

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix},\ \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix},\ \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}, \qquad e_R,\ \mu_R,\ \tau_R\,, \qquad \nu_{1R},\ \nu_{2R},\ \nu_{3R}\,.$$

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$$\mathcal{L}_{\mathrm{mass}} \ =\ -\frac{1}{2}\,(\bar{\nu}_L\,,\ \bar{\nu}_R^C)\,\underbrace{\begin{pmatrix} 0 & \mathbf{m}_D \\ \mathbf{m}_D^T & \mathbf{m}_M \end{pmatrix}}_{:6\times 6\ \mathrm{matrix}}\begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix}\ +\ \mathrm{H.c.}$$

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Seesaw approximation: $(\mathbf{m}_M \gg \mathbf{m}_D \sim m_t)$

$$\mathbf{m}_N^{\mathrm{heavy}} \approx m_M\mathbf{1}_3 \sim 10^{15}\ \mathrm{GeV} \quad\leftarrow\quad \text{3 heavy neutrinos}$$

$$\mathbf{m}_\nu^{\mathrm{light}} \approx -\mathbf{m}_D\frac{1}{\mathbf{m}_M}\mathbf{m}_D^T \sim 4\times 10^{-2}\ \mathrm{eV} \quad\leftarrow\quad \text{3 light neutrinos}$$

$$\theta_{\nu N} \approx (\mathbf{m}_D\,\mathbf{m}_M^{-1})_{\nu N} \approx \sqrt{m_\nu^{\mathrm{light}}/m_N^{\mathrm{heavy}}} \sim 10^{-12}$$

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– The Non-Seesaw Paradigm

[A.P., PRL95 (2005) 081602 [hep-ph/0408103];
based on A.P., ZPC55 (1992) 275;
D. Wyler, L. Wolfenstein, NPB218 (1983) 205;
R.N. Mohapatra, J.W.F. Valle, PRD34 (1986) 1642.]

Break SO(3) and $U(1)_l$ flavour symmetries:

$$\mathrm{SO(3)} \ \xrightarrow{\sim h_\tau}\ \mathrm{SO(2)} \simeq \mathrm{U(1)}_l \ \xrightarrow{\sim h_e}\ \mathbf{I}$$

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U$_l$(1)-broken Yukawa sector:

$$\mathbf{m}_D = \frac{v_{\rm SM}}{\sqrt{2}} \begin{pmatrix} \varepsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \varepsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \varepsilon_\tau & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix},$$

with $a \sim b \sim 10^{-2} \sim h_\tau$, $c \lesssim 10^{-4}$ & $|\varepsilon_l| \sim 10^{-7} \sim h_e$.

$$\Longrightarrow \quad \mathbf{m}_\nu^{\rm light} \sim \frac{\varepsilon_l^2\, v_{\rm SM}^2}{m_N} \sim 0.1~{\rm eV} \quad \Longrightarrow \quad m_N \sim 100 - 500~{\rm GeV}$$

$\Longrightarrow$ 3 nearly degenerate heavy Majorana neutrinos.

• Matter–AntiMatter Asymmetry

$$\eta_B^{\rm CMB} \ = \ \frac{n_B}{n_\gamma} \ = \ 6.1^{+0.3}_{-0.2} \times 10^{-10} \qquad (\eta_B^{\rm BBN} \ = \ 3.4\text{–}6.9 \times 10^{-10}, \text{ at 95\% CL})$$

Sakharov's conditions for generating the BAU:

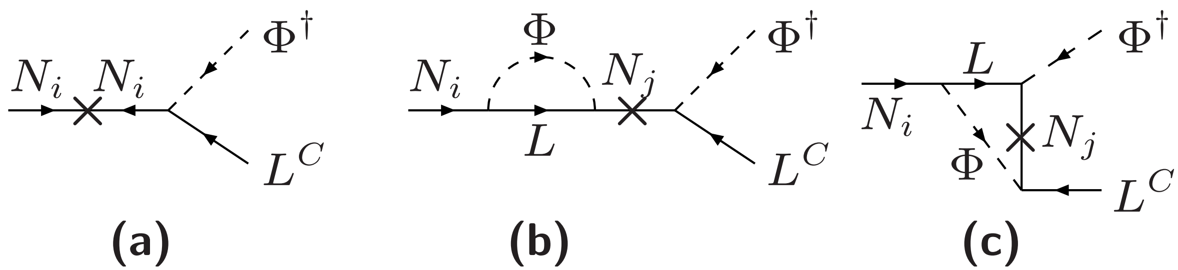
[A.D. Sakharov, JETP Lett. 5 (1967) 24.]

- B-violating interactions
- C and CP violation
- Out-of-equilibrium dynamics

$\Longrightarrow$ Baryogenesis through Leptogenesis

Out-of-equilibrium L-violating decays of heavy Majorana neutrinos produce a net lepton asymmetry, converted into the BAU through $(B+L)$-violating sphaleron interactions.

[M. Fukugita, T. Yanagida, PLB174 (1986) 45.]



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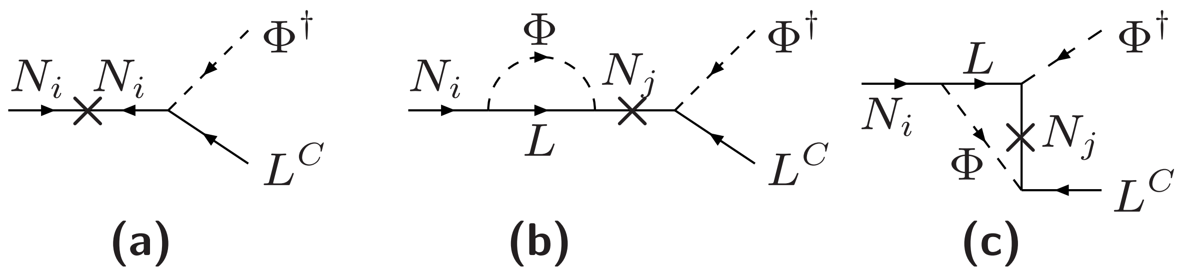

$\Longrightarrow$ Resonant Leptogenesis

Resonant conditions for $O(1)$ leptonic asymmetries:

[A.P., PRD56 (1997) 5431;
A.P., T. Underwood, NPB692 (2004) 303.]

$$\Rightarrow \qquad m_{N_2} - m_{N_1} \ \sim\ \tfrac{1}{2}\,\Gamma_{N_{1,2}}$$

$$\Rightarrow \qquad \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}} \ \sim\ 1$$

• The Flavourdynamics of Leptogenesis

BAU can be generated from and protected in a single lepton flavour:

$$\frac{1}{3}B - L_{e,\mu,\tau} .$$

[e.g. J.A. Harvey, M.S. Turner, PRD42 (1990) 3344;
H. Dreiner, G.G. Ross, NPB410 (1993) 188;
J.M. Cline, K. Kainulainen, K.A. Olive, PRD49 (1994) 6394.]

Two sources of flavour effects:

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Two sources of flavour effects:

- Charged-lepton Yukawa couplings $h_{e,\mu,\tau}$

[R. Barbieri, P. Creminelli, A. Strumia, N. Tetradis, NPB575 (2000) 61;
A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001;
E. Nardi, Y. Nir, J. Racker, E. Roulet, JHEP0601 (2006) 068;
A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada, A. Riotto, JCAP0604 (2006) 004.]

Modify BAU predictions by up to 1-order of magnitude.

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  Modify BAU predictions by up to 1-order of magnitude.

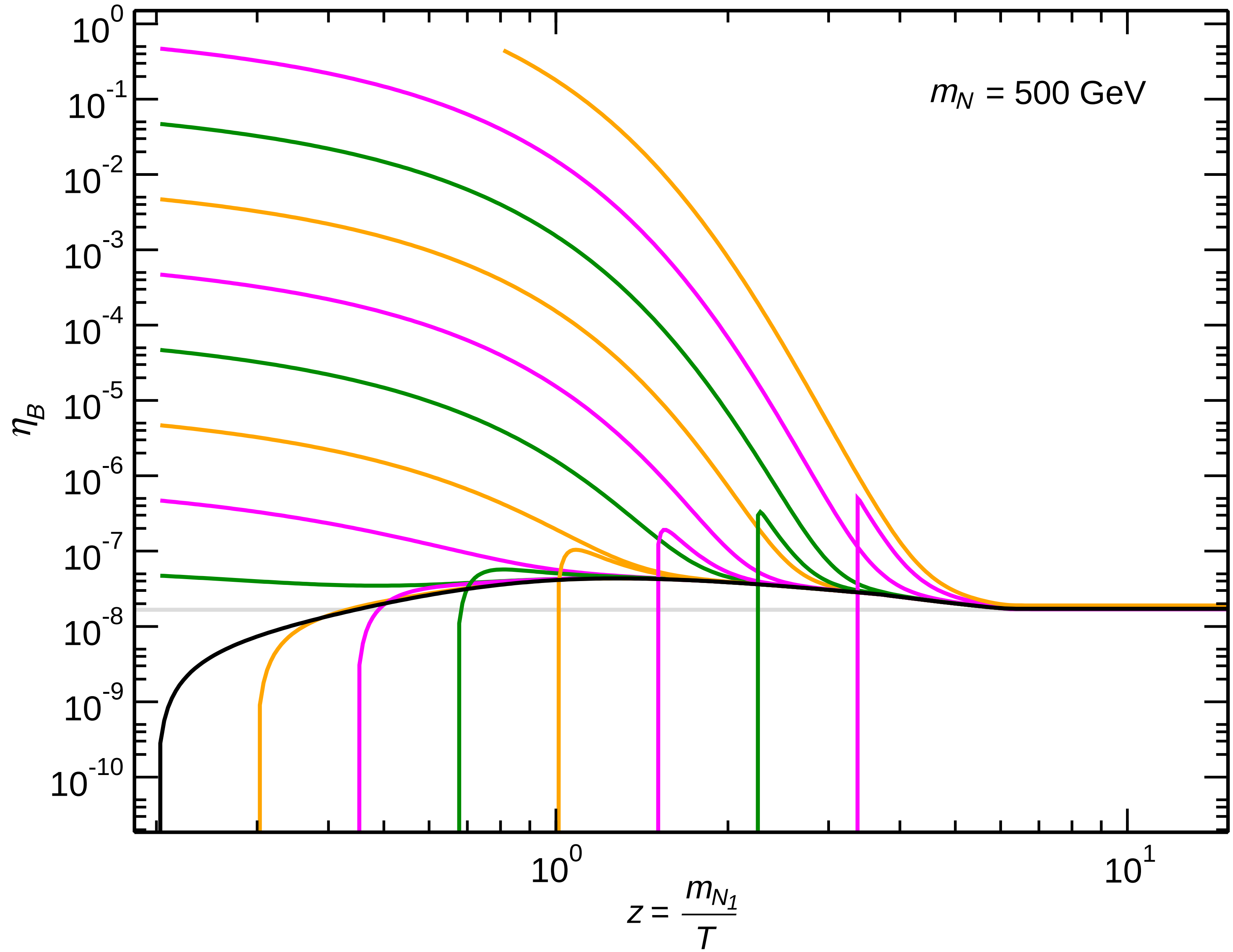
- Heavy-neutrino Yukawa couplings $h^{\nu}_{l\alpha}$

  [A. Pilaftsis, PRL95 (2005) 081602 [hep-ph/0408103];
  T. Endoh, T. Morozumi and Z. h. Xiong, PTP111 (2004) 123;
  A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001;
  O. Vives, PRD73 (2006) 073006.]

  Modify BAU predictions by many orders of magnitude, e.g. $> \; 10^6$!

Resonant τ-Leptogenesis

[A.P., T. Underwood, PRD72 (2005) 113001.]



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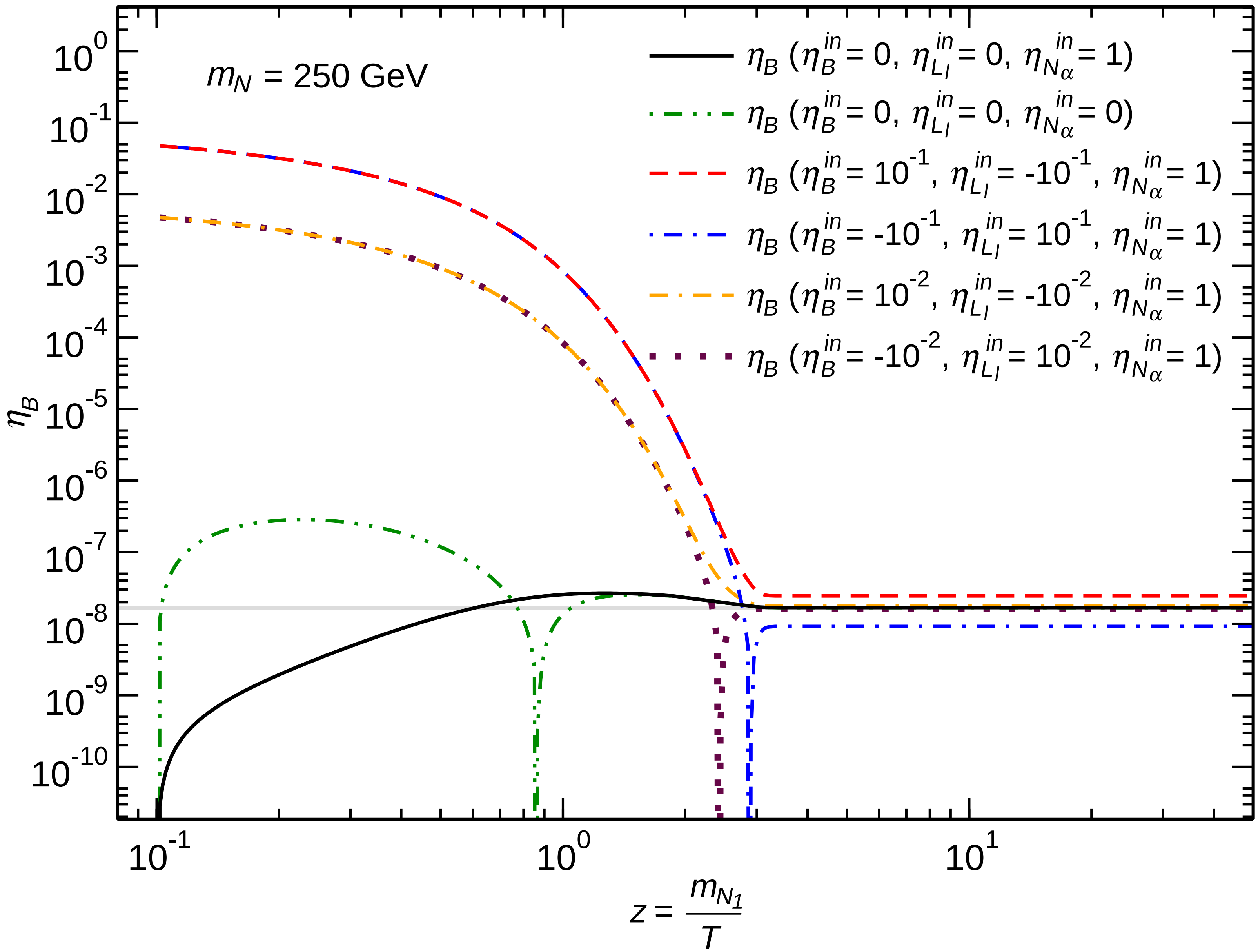

• Lepton Flavour and Number Violation at the LHC

• Lepton Flavour and Number Violation at the LHC

- **Heavy Majorana Neutrino Production at the LHC**

[A.P., ZPC55 (1992) 275; A. Datta, M. Guchait, A.P., PRD50 (1994) 3195;
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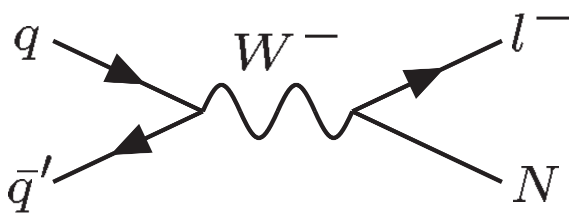

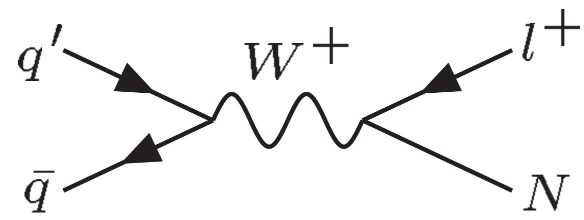

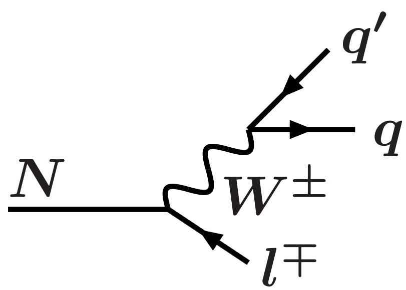

Signal: 2 leptons + 2 jets + no $\not{p}_T$

- **LNV signatures:** $pp \to e^+e^+,\ e^+\mu^+,\ e^-e^-,\ e^-\mu^-, e^-\tau^- \ldots$

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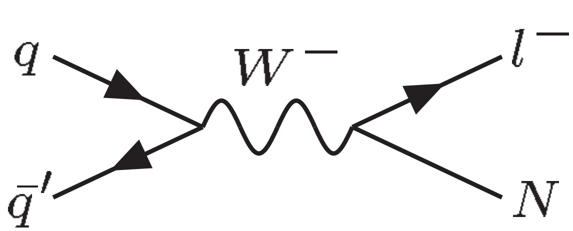

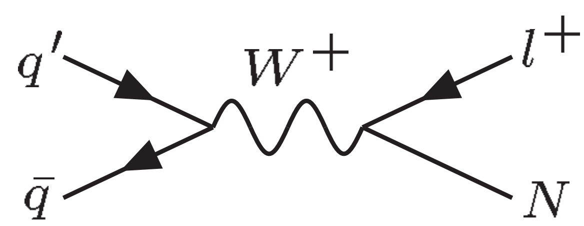

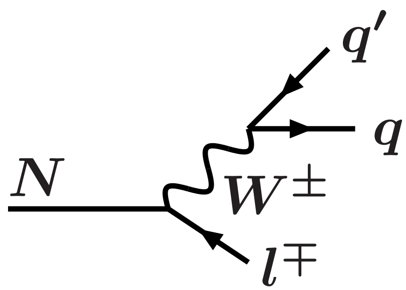

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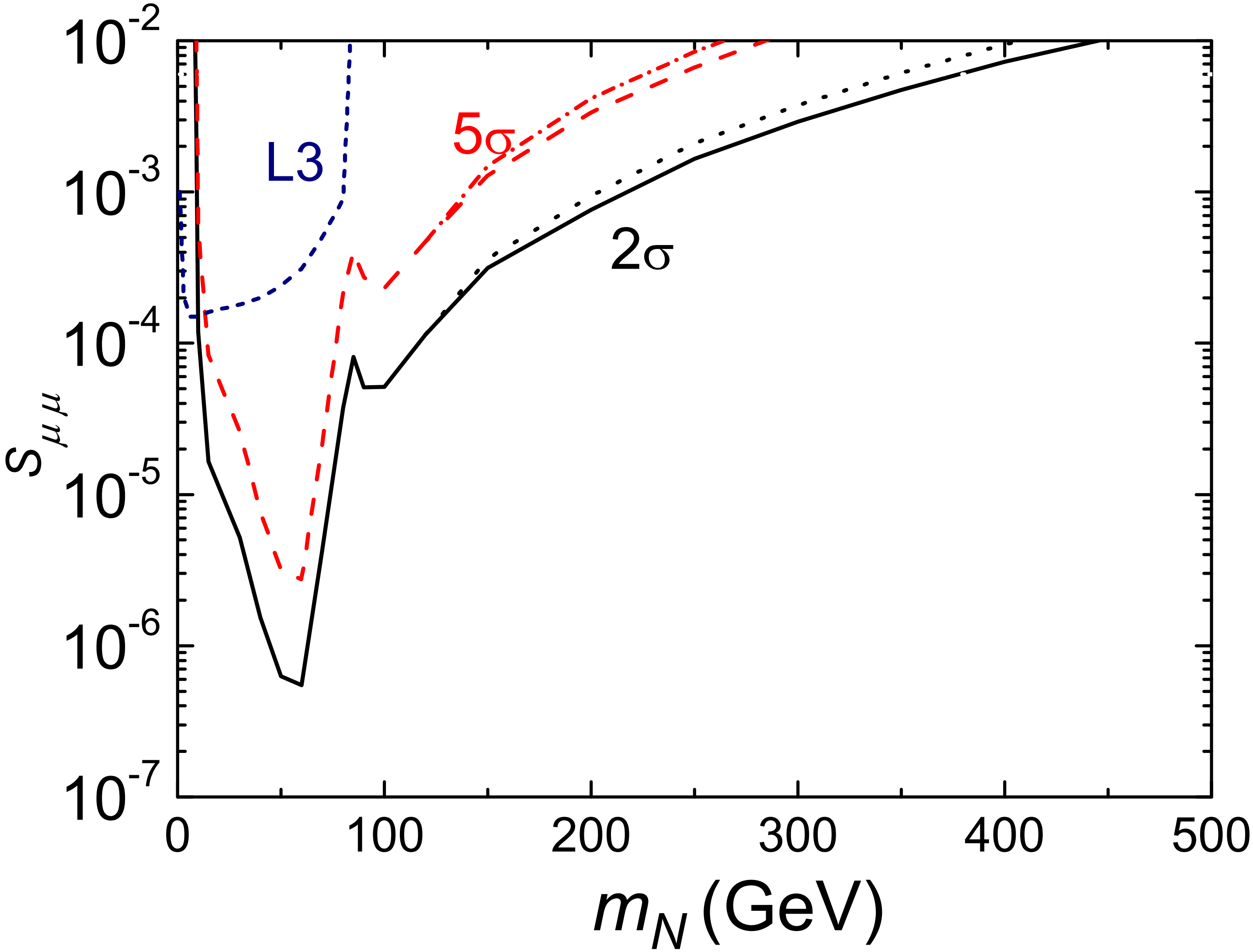
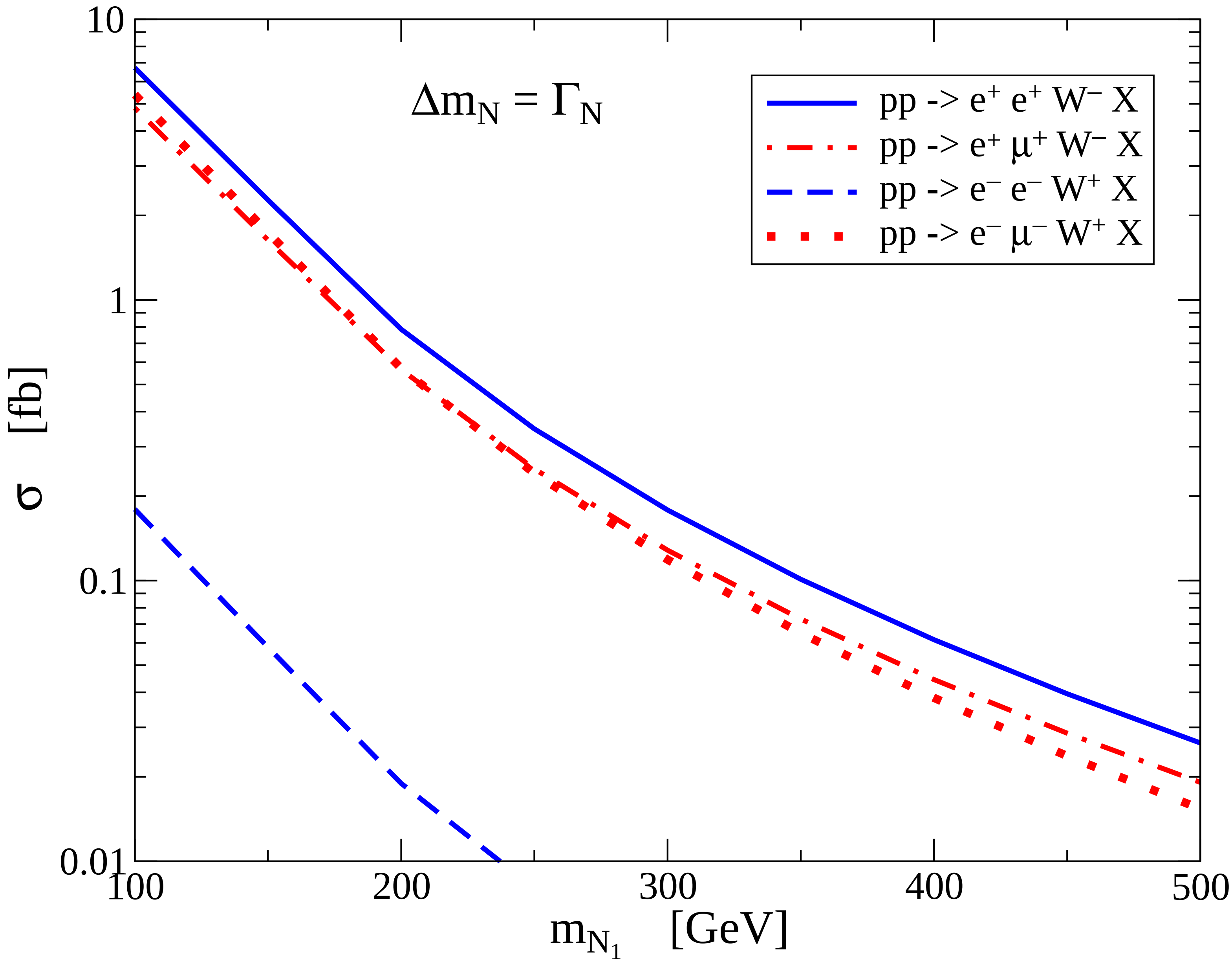
- **CP Asymmetries**

[S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]

LHC sensitivity with 100 fb^{-1}



[T. Han, B. Zhang, PRL97 (2006) 171804;
Manchester–ATLAS Group, work in progress.]



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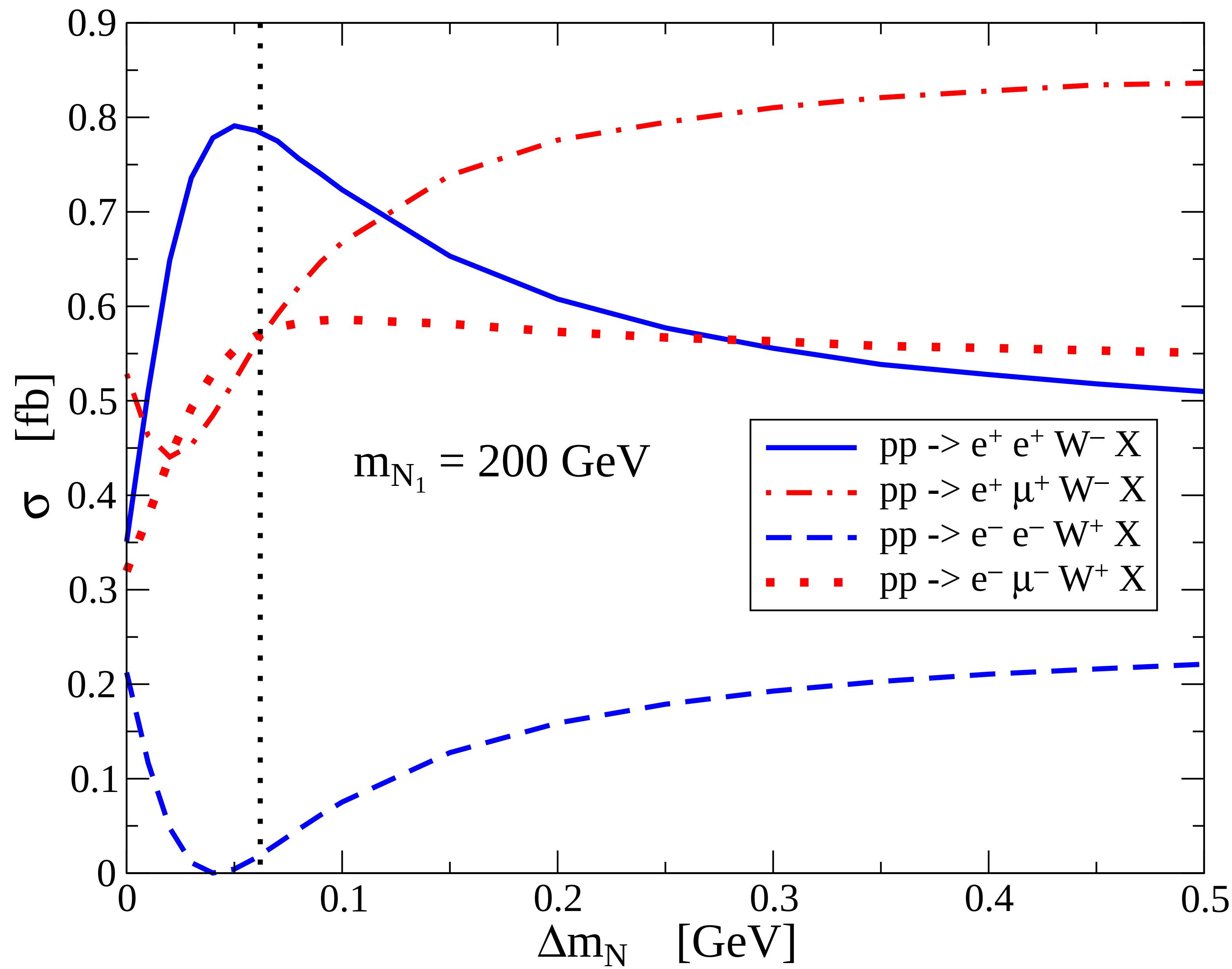

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$$A_{\rm CP}({\rm LNV1}) \;=\; \frac{\sigma(pp\to e^+e^+W^-X) - K\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^+e^+W^-X) + K\sigma(pp\to e^-e^-W^+X)}\,,$$

$$A_{\rm CP}({\rm LNV2}) \;=\; \frac{\sigma(pp\to e^+\mu^+W^-X) - K\sigma(pp\to e^-\mu^-W^+X)}{\sigma(pp\to e^+\mu^+W^-X) + K\sigma(pp\to e^-\mu^-W^+X)}\,,$$

$$R_{\rm CP}({\rm LNV}) \;=\; \frac{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} - \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} + \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}\,.$$

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$$A_{\rm CP}({\rm LNV1}) = \frac{\sigma(pp\to e^+e^+W^-X) - K\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^+e^+W^-X) + K\sigma(pp\to e^-e^-W^+X)},$$

$$A_{\rm CP}({\rm LNV2}) = \frac{\sigma(pp\to e^+\mu^+W^-X) - K\sigma(pp\to e^-\mu^-W^+X)}{\sigma(pp\to e^+\mu^+W^-X) + K\sigma(pp\to e^-\mu^-W^+X)},$$

$$R_{\rm CP}({\rm LNV}) = \frac{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} - \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} + \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}.$$

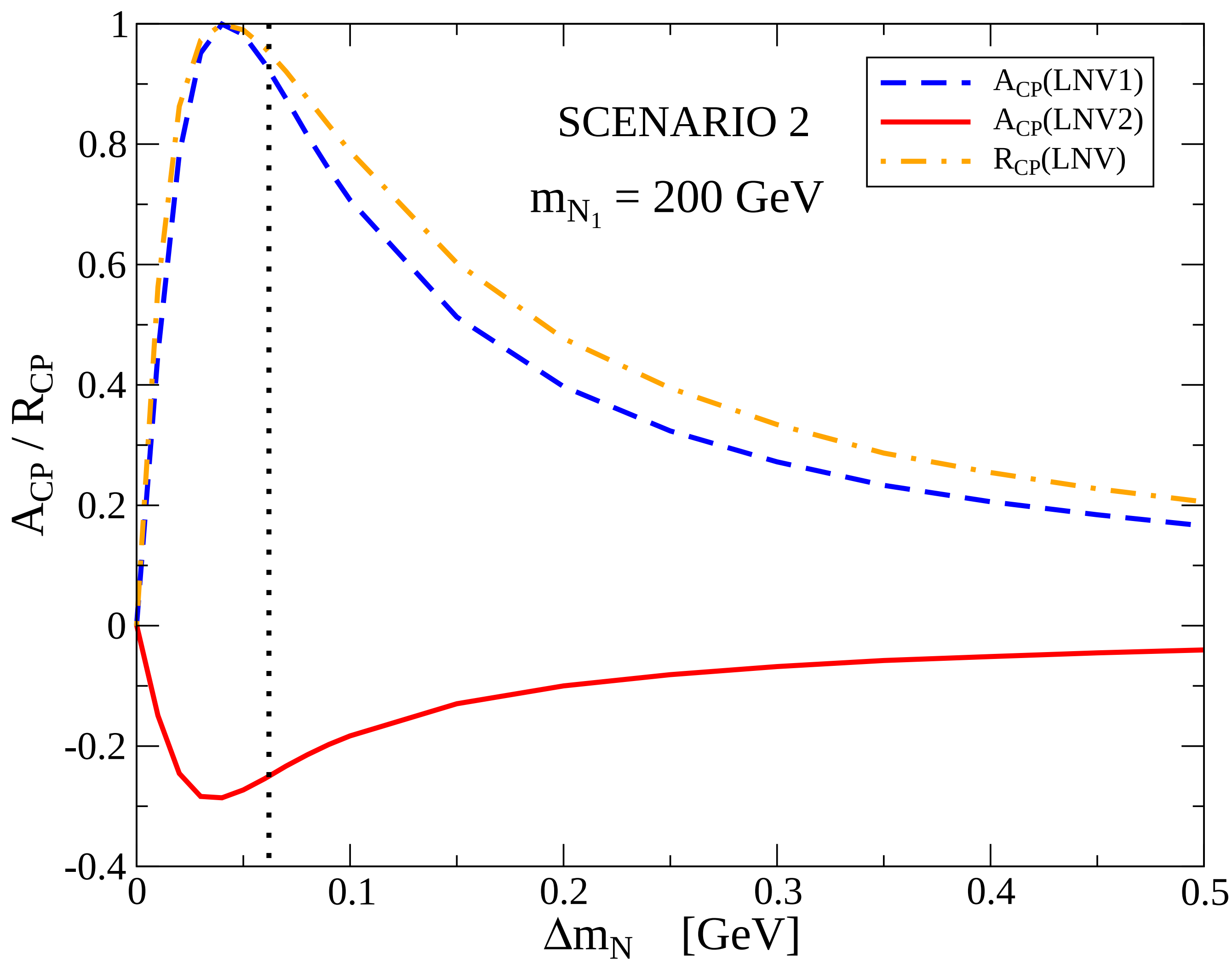
- **Lepton Flavour Violation:**

$$A_{\rm CP}({\rm LNC}) = \frac{\sigma(pp\to e^+\mu^-W^\pm X) - \sigma(pp\to e^-\mu^+W^\pm X)}{\sigma(pp\to e^+\mu^-W^\pm X) + \sigma(pp\to e^-\mu^+W^\pm X)},$$

$$R_{\rm CP}({\rm LNC}) = \frac{\frac{\sigma(pp\to e^+\mu^-W^\pm X)}{\sigma(pp\to e^-\mu^+W^\pm X)} - \frac{\sigma(pp\to e^-\mu^+W^\pm X)}{\sigma(pp\to e^+\mu^-W^\pm X)}}{\frac{\sigma(pp\to e^+\mu^-W^\pm X)}{\sigma(pp\to e^-\mu^+W^\pm X)} + \frac{\sigma(pp\to e^-\mu^+W^\pm X)}{\sigma(pp\to e^+\mu^-W^\pm X)}}.$$

Resonant CP Violation through Mixing of Heavy Majorana Neutrinos

[A.P., NPB504 (1997) 61;
S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]



• Lepton Flavour and Number Violation in Low-Energy Experiments

• $0\nu\beta\beta$ Decay

$$ {}^{A}_{Z}X \ \rightarrow\ {}^{A}_{Z+2}X \ +\ 2e^- \ . $$

Half-life for $0\nu\beta\beta$ decay:

$$ [T^{0\nu\beta\beta}_{1/2}]^{-1} \ =\ \frac{|\langle m\rangle|^2}{m_e^2}\, |\mathcal{M}_{0\nu\beta\beta}|^2\, G_{01}\ . $$

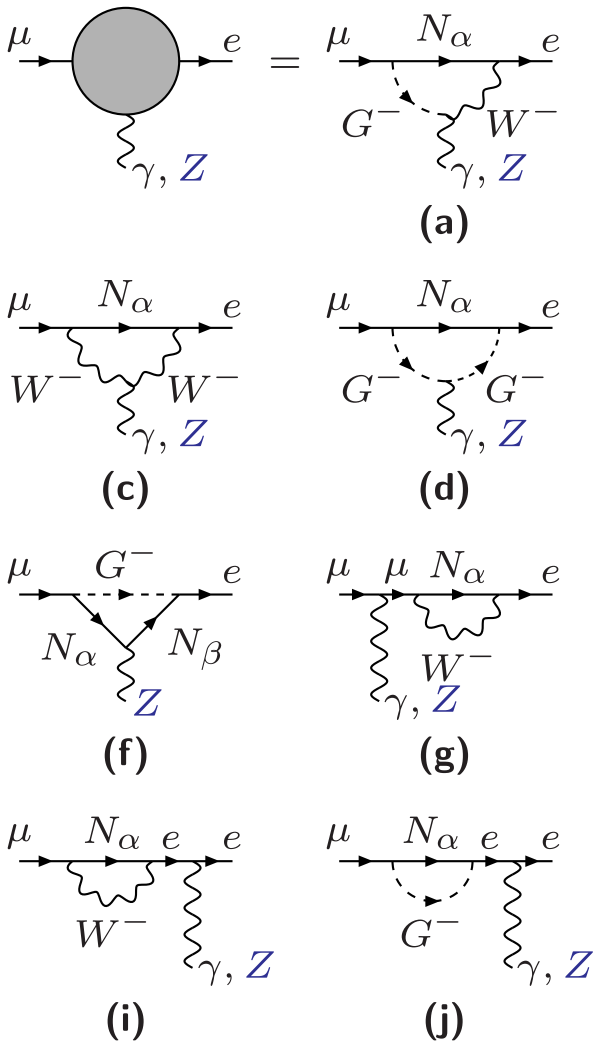
RτL with inverted light-neutrino hierarchy:

$$ |\langle m_{0\nu\beta\beta}\rangle| \ =\ |(\mathbf{m}^\nu)_{ee}| \ =\ \frac{v^2}{2m_N}\,\Big|\,\frac{\Delta m_N}{m_N}\,a^2 \ -\ \varepsilon_e^2\,\Big| \ \approx\ 0.013\ \mathrm{eV}\ . $$

Future $0\nu\beta\beta$ experiments will be sensitive to $|\langle m\rangle| \sim$ 0.01–0.05 eV, such as SuperNEMO . . .

• $\mu \to e\gamma$

[T.P. Cheng, L.F. Li, PRL45 (1980) 1908;
J.G. Körner, A.P., K. Schilcher, PLB300 (1993) 381.]



$a = b = 8 \times 10^{-3}$;
$m_N = 250$ GeV:

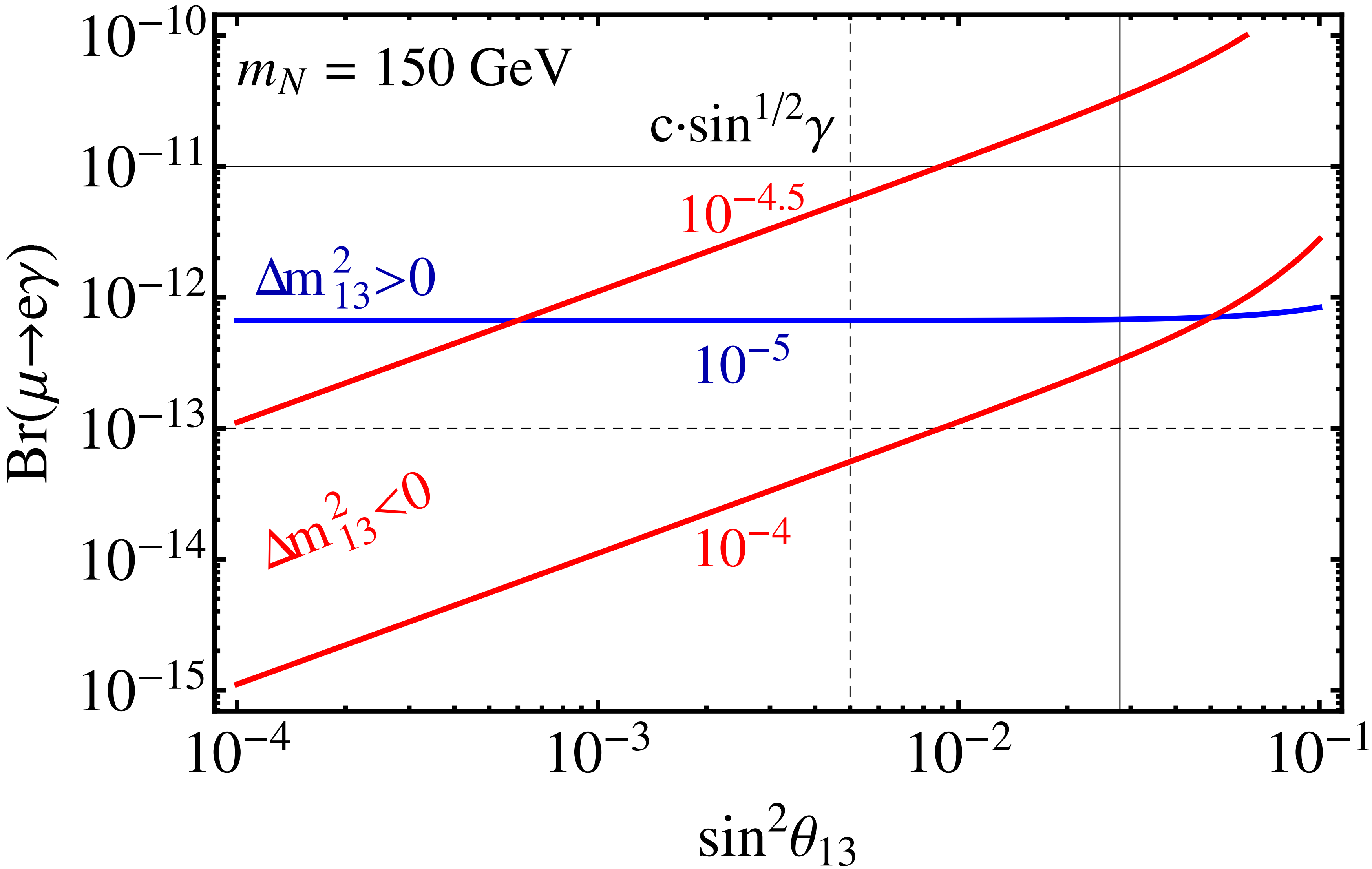
$$B(\mu \to e\gamma) \sim 7 \cdot 10^{-4} \times \frac{(ab)^2\, v_{\rm SM}^4}{m_N^4} \sim 10^{-12}\,.$$

$B^{\rm exp}(\mu \to e\gamma) \; < \; 1.2 \times 10^{-11}$

MEG sensitivity:
$B(\mu \to e\gamma) \sim 10^{-13}$–$10^{-14}$.

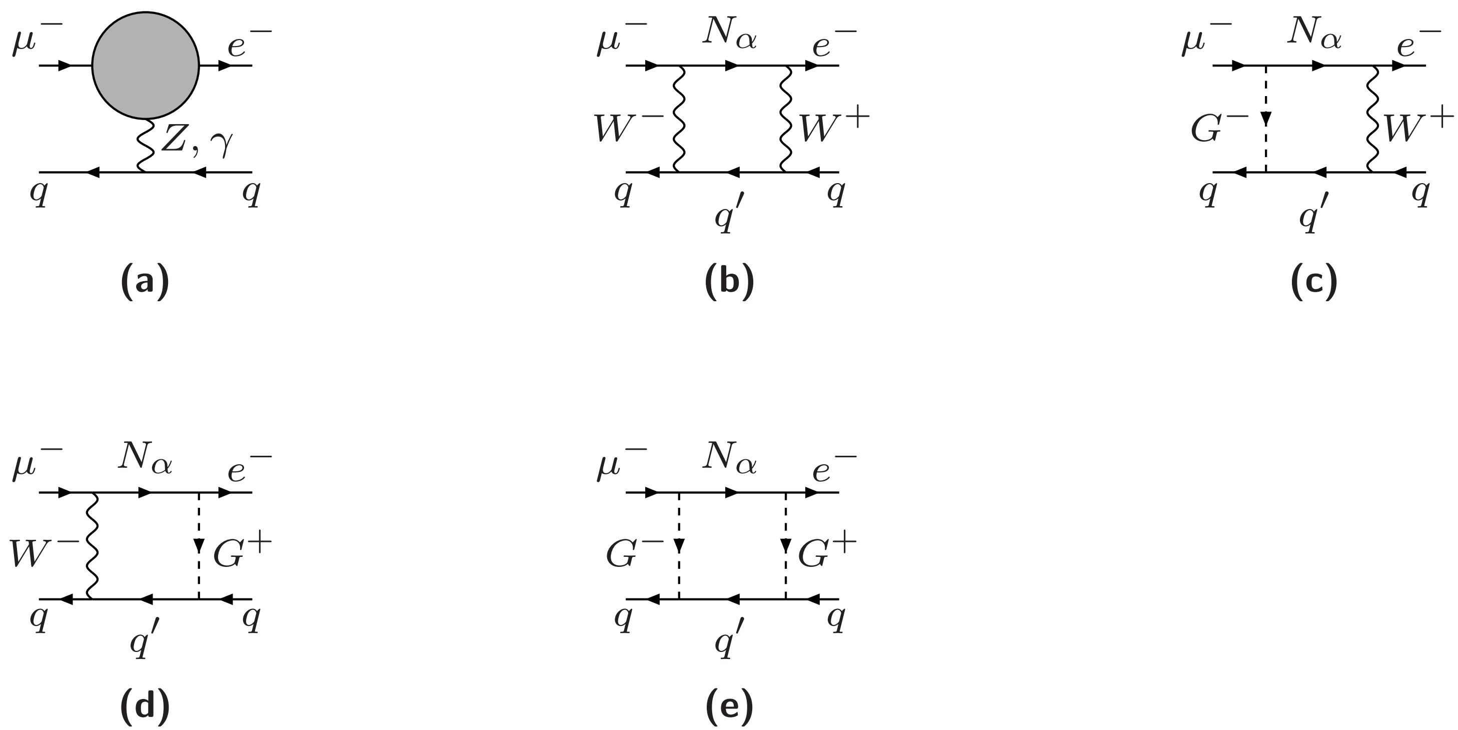
- $\mu \longrightarrow e\gamma$

[F. Deppisch, A.P., **PRELIMINARY**.]



• Coherent $\mu \to e$ Conversion in Nuclei ($^{48}_{22}$Ti, $^{197}_{79}$Au)

[A.P., T. Underwood, PRD72 (2005) 113001]



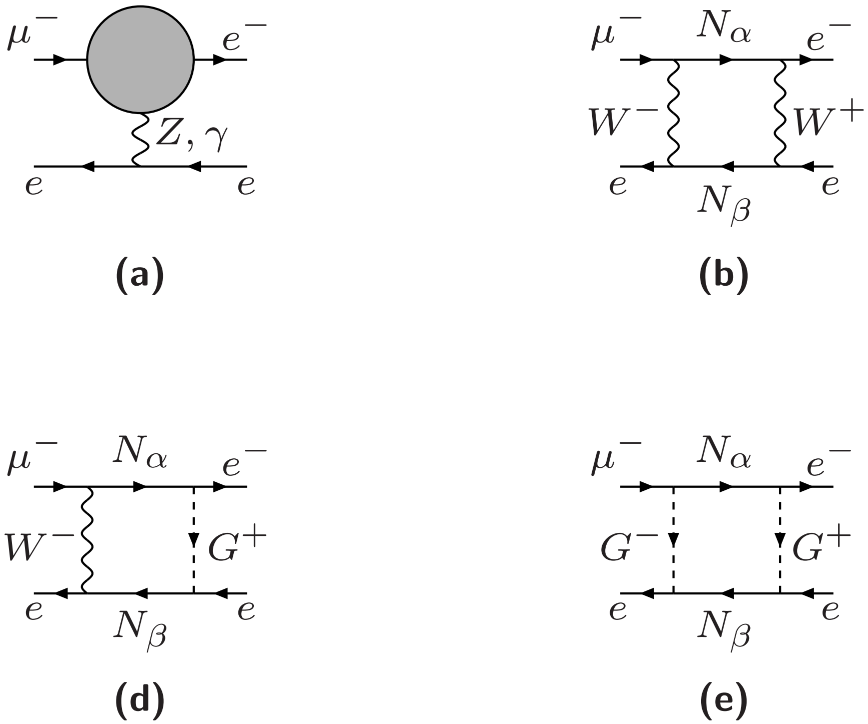
$m_N = 250$ GeV: $\quad B_{\rm Ti}(\mu \to e) \;\approx\; 0.5 \times B(\mu \to e\gamma) \;\sim\; 5 \times 10^{-13}$.

$$B^{\rm exp}_{\rm Ti}(\mu \to e) \;<\; 4.3 \times 10^{-12}\,, \qquad B^{\rm exp}_{\rm Au}(\mu \to e) \;<\; 7 \times 10^{-13}\,.$$

COMET/PRISM sensitivity: $\quad B^{\rm exp}_{\rm Ti}(\mu \to e) \;\sim\; 10^{-13} - 10^{-18}$.

• $\mu \longrightarrow eee$

[A. Ilakovac, A.P., NPB437 (1995) 491.]

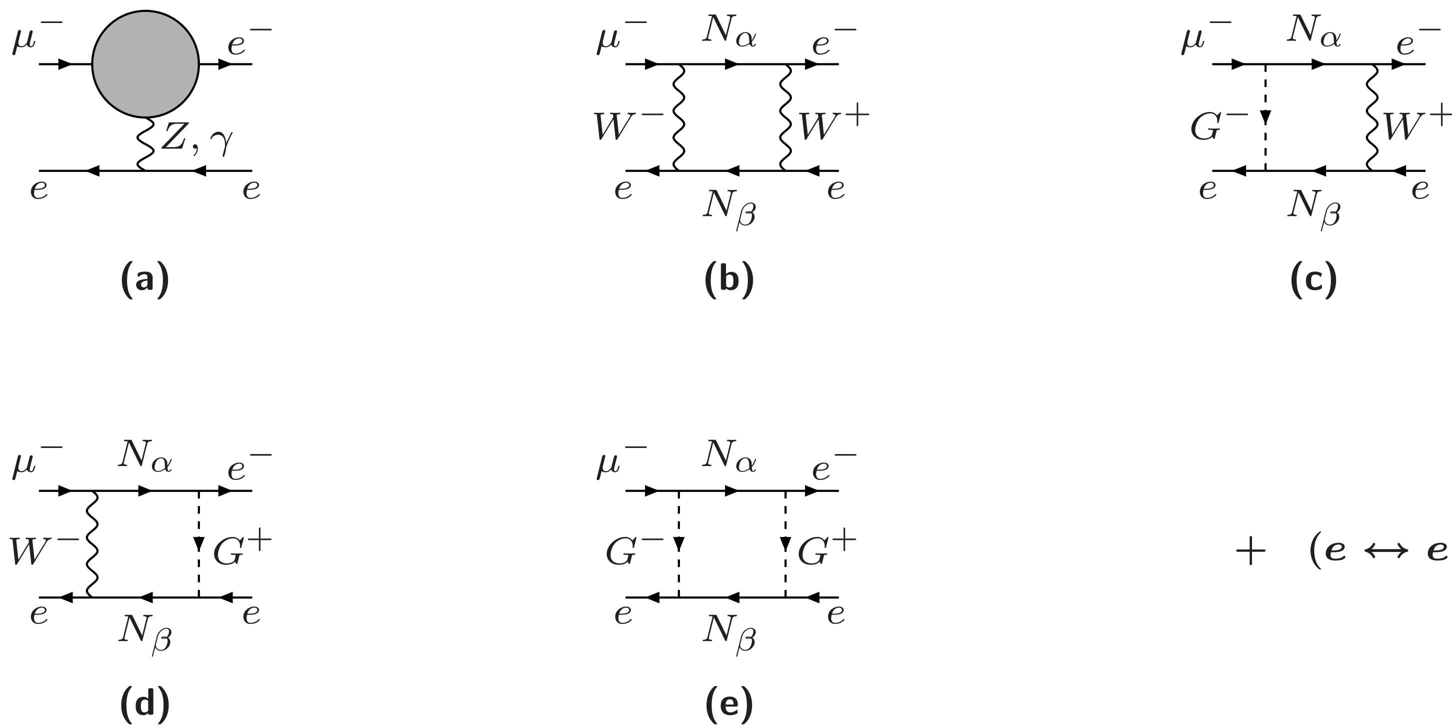


$+ \quad (e \leftrightarrow e^-)$

$\boldsymbol{m_N = 250}$ GeV: $\quad B(\mu \to eee) \approx 1.4{\cdot}10^{-2} \times B(\mu \to e\gamma) \sim 1.4 \times 10^{-14}$.

• $\mu \longrightarrow eee$

[A. Ilakovac, A.P., NPB437 (1995) 491.]



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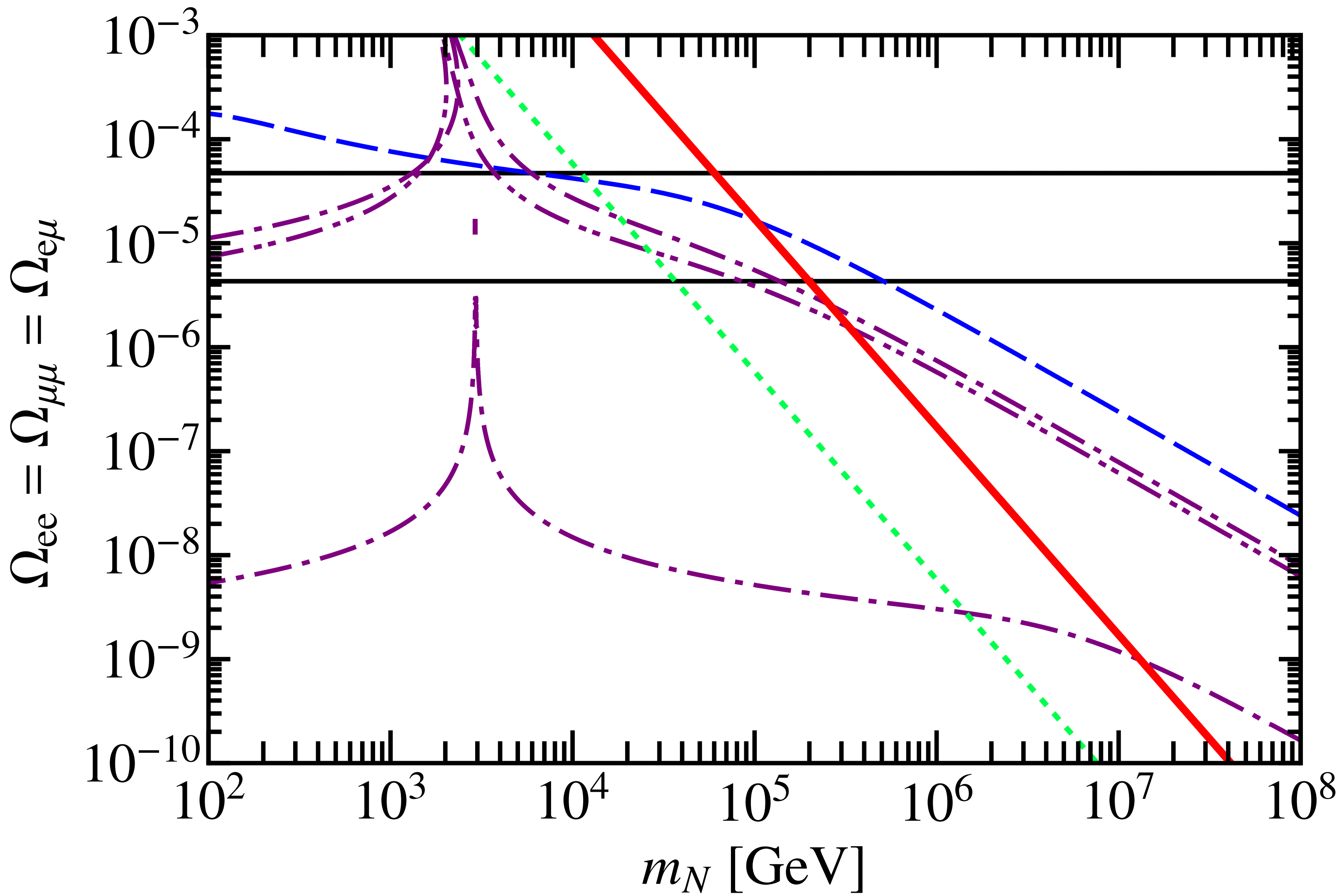
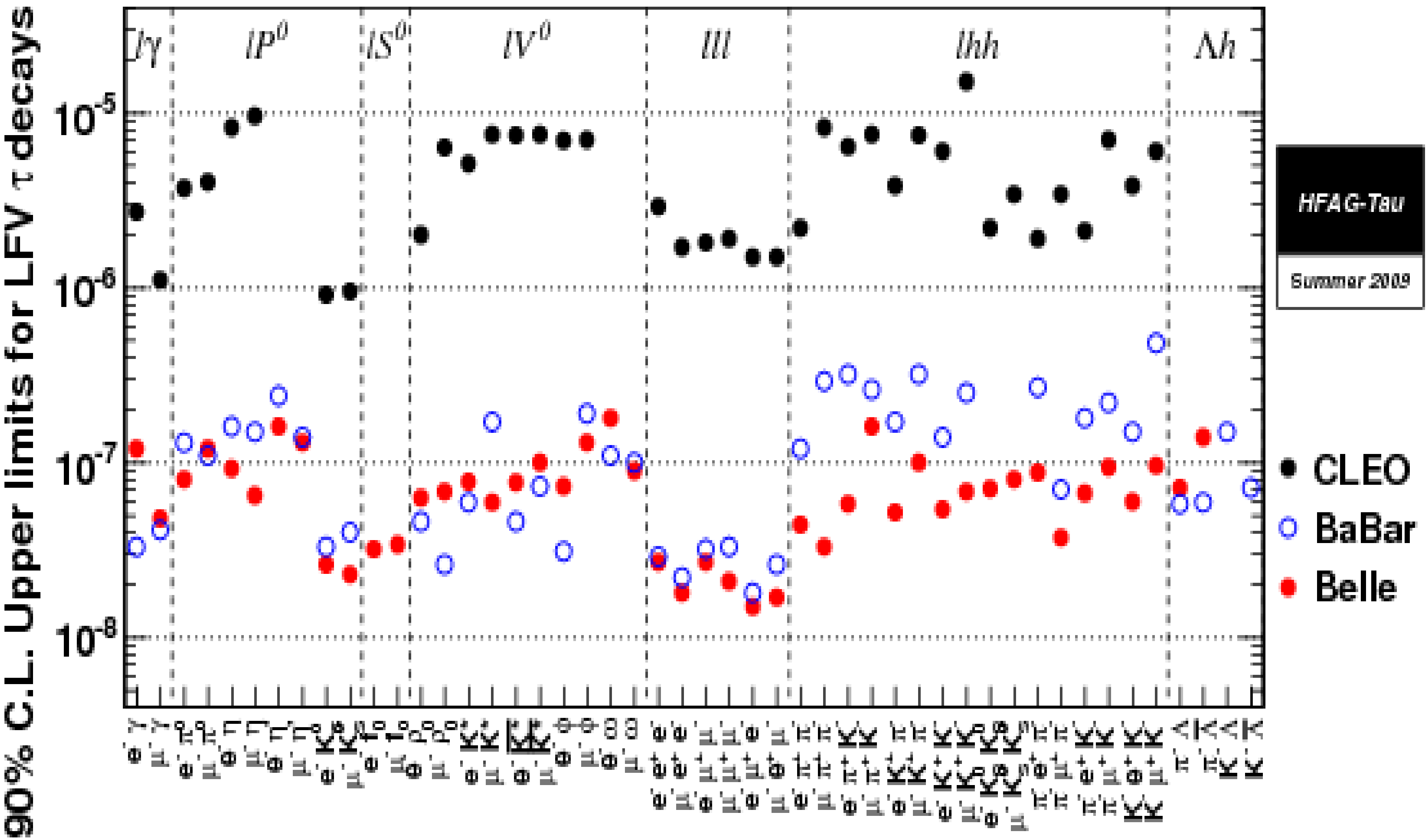
$B^{\rm exp}(\mu \to eee) \; < \; 10^{-12}\;,$ **new improved experiment needed!**

- $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$ conversion

[A. Ilakovac, A.P., PRD80 (2009) 091902.]

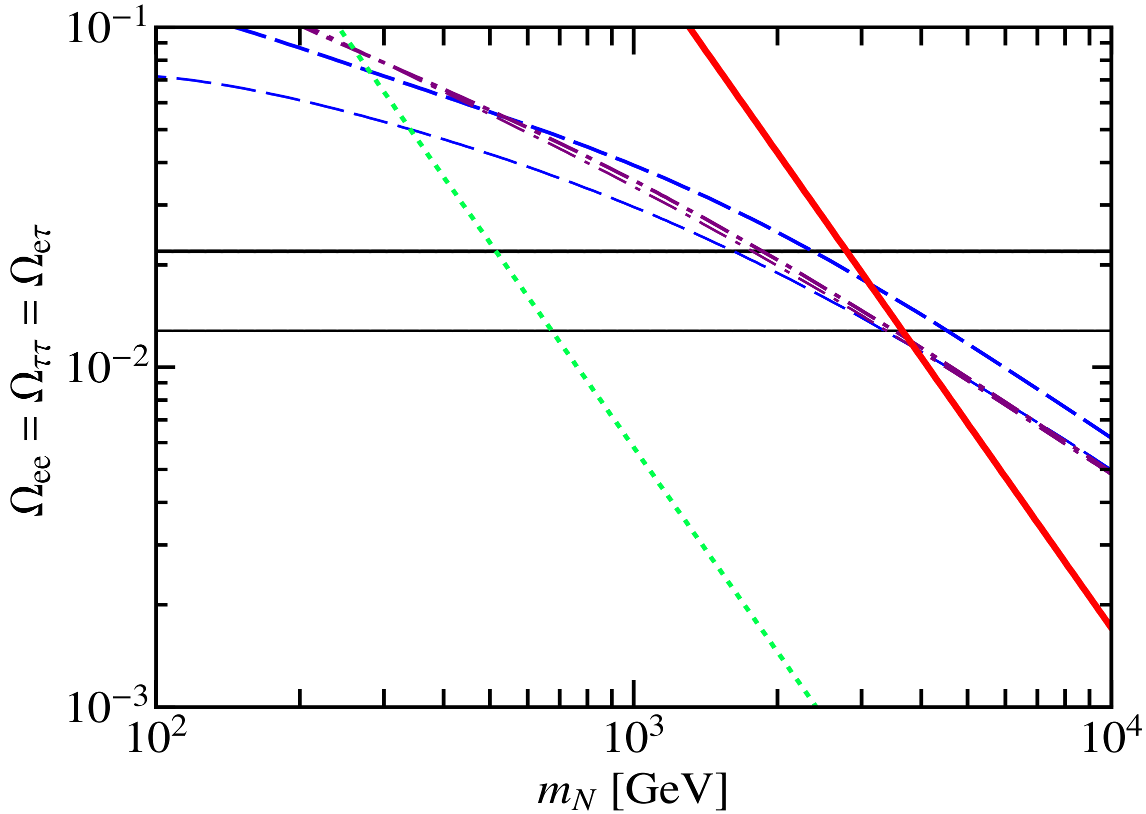


• **Charged Lepton Flavour Violation in τ-Decays** [See talks in this conference.]



LFV in the τ Sector: $\boldsymbol{\Omega}_{\tau e} = \boldsymbol{\Omega}_{ee} = \boldsymbol{\Omega}_{\tau\tau}$, other $\boldsymbol{\Omega}_{\ell\ell'} = 0$

[A. Ilakovac, A.P., NPB437 (1995) 491; PRD80 (2009) 091902]



Upper Bounds: [C. Amsler et al., PLB 667 (2008) 1]

$$
\begin{array}{lcl}
B(\tau^- \to e^-\gamma) & < & 1.1 \times 10^{-7} \\
B(\tau^- \to e^-e^-e^+) & < & 3.6 \times 10^{-8} \\
B(\tau^- \to e^-\mu^-\mu^+) & < & 3.7 \times 10^{-8}
\end{array}
$$

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- $B(\mu \to e\gamma) \sim 10^{-13}$ + successful leptogenesis $\Longrightarrow$ large θ_{13} for models with inverted light neutrino hierarchy.
- Strong correlations among the predictions for LFV and LNV at the observable level ($m_N = 250$ GeV):

$$\begin{aligned} B(\mu \to e\gamma) &\sim 10^{-13}, \\ B(\mu \to e) &\approx 0.5 \times B(\mu \to e\gamma), \\ B(\mu \to eee) &\approx 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma), \\ |\langle m_{0\nu\beta\beta} \rangle| &\approx 0.01 \text{ eV}. \end{aligned}$$