NEUTRINO THEORY

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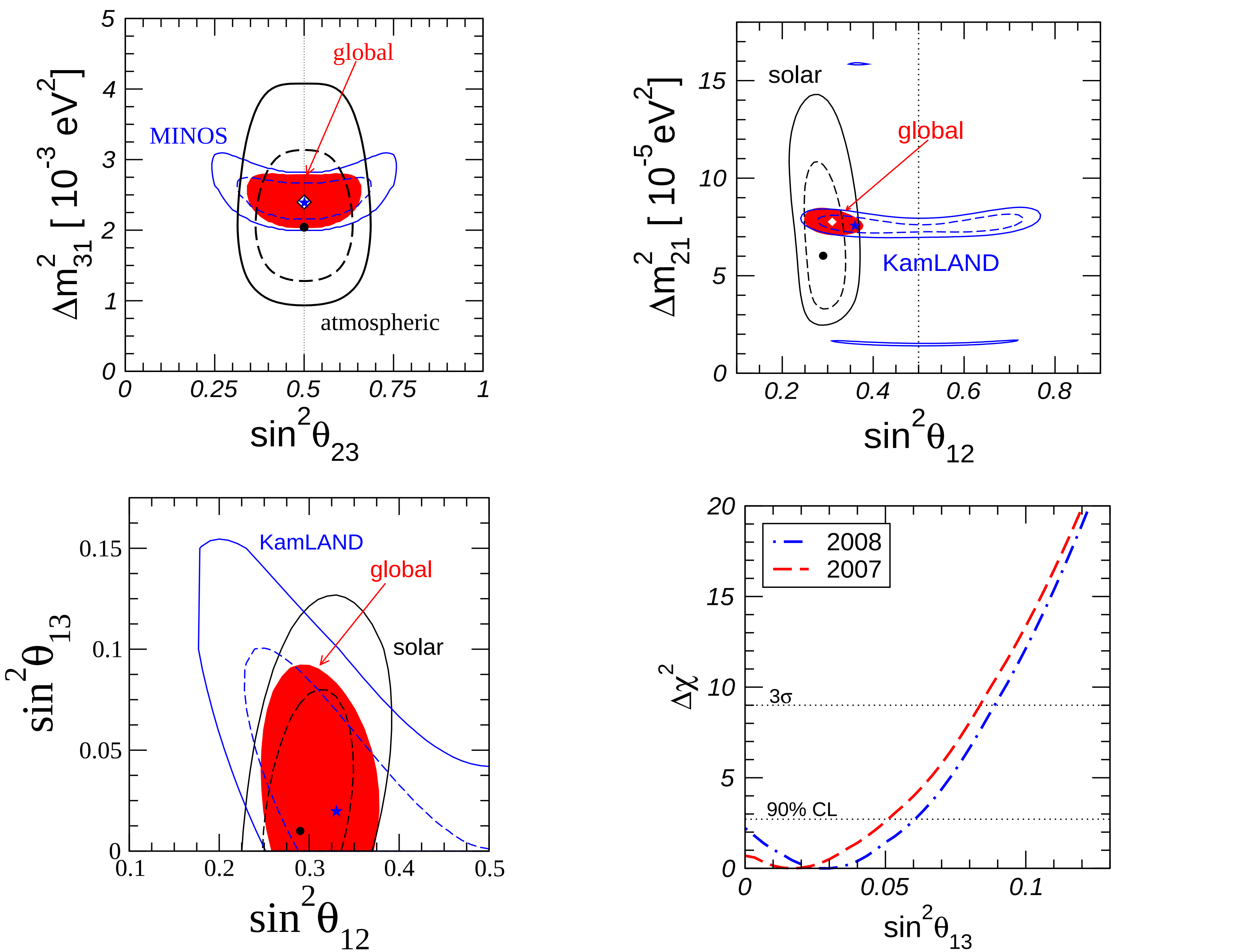
Plan of the talk

- 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

• Neutrino Masses and Mixings

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



At the 3σ CL:

$$\begin{aligned}
\Delta m^2_{\odot}\ [10^{-5}\mathrm{eV}^2] &= 7.03 - 8.27\,, \\
\Delta m^2_{\mathrm{atm}}\ [10^{-3}\mathrm{eV}^2] &= 2.07 - 2.75\,, \\
\sin^2\theta_{12} &= 0.27 - 0.38\,, \\
\sin^2\theta_{23} &= 0.36 - 0.67\,, \\
\sin^2\theta_{13} &\leq 0.053\,,
\end{aligned}$$

with $\Delta m^2_{\odot} = m^2_{\nu_2} - m^2_{\nu_1}$ and $\Delta m^2_{\mathrm{atm}} = m^2_{\nu_3} - m^2_{\nu_1}$.

Cosmological and astronomical limits (WMAP + SDSS):

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

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

• The Seesaw and Non-Seesaw Paradigms

– The Seesaw Paradigm

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

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

$$\begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_i , \quad l_{iR}\,, \quad \nu_{iR}\,; \qquad i = 1,2,3 = e,\mu,\tau$$

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

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Seesaw approximation: $(m_M \gg m_D \sim m_t)$

$$m_N^{\text{heavy}} \approx m_M \sim 10^{15}\ \text{GeV} \quad \leftarrow \quad 3 \text{ heavy neutrinos}$$

$$m_\nu^{\text{light}} \approx -m_D \frac{1}{m_M} m_D^T \sim 4 \times 10^{-2}\ \text{eV} \quad \leftarrow \quad 3 \text{ light neutrinos}$$

$$\theta_{\nu N} \approx m_D\, m_M^{-1} \approx \sqrt{m_\nu^{\text{light}}/m_N^{\text{heavy}}} \sim 10^{-12}$$

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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:

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

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$U_l(1)$-broken Yukawa sector:

$$m_D \;=\; \frac{v}{\sqrt{2}} \begin{pmatrix} \varepsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \varepsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \varepsilon_\tau & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix} ,$$

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

$$\Longrightarrow \quad m_\nu^{\rm light} \ \sim\ \frac{m_e^2}{m_N} \sim\ 0.1\ \mathrm{eV} \quad \Longrightarrow \quad m_N \ \sim\ 100 - 500\ \mathrm{GeV}$$

$\Longrightarrow$ 3 nearly degenerate heavy Majorana neutrinos.

Light neutrino-mass spectrum:

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

$$m_\nu^{\rm light} \;=\; \frac{v^2}{2m_N} \begin{pmatrix} \frac{\Delta m_N}{m_N}\,a^2 - \varepsilon_e^2 & \frac{\Delta m_N}{m_N}\,ab - \varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}\,ac - \varepsilon_e\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}\,ab - \varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N}\,b^2 - \varepsilon_\mu^2 & \frac{\Delta m_N}{m_N}\,bc - \varepsilon_\mu\varepsilon_\tau \\ \frac{\Delta m_N}{m_N}\,ac - \varepsilon_e\varepsilon_\tau & \frac{\Delta m_N}{m_N}\,bc - \varepsilon_\mu\varepsilon_\tau & \frac{\Delta m_N}{m_N}\,c^2 - \varepsilon_\tau^2 \end{pmatrix} ,$$

where

$$\Delta m_N \;=\; 2(\Delta m_M)_{23} + i[(\Delta m_M)_{33} - (\Delta m_M)_{22}], \quad \frac{b}{a} \;=\; \frac{19}{50} ,$$

and (in $\sim 10^{-7}$ units)

$$\sqrt{\frac{\Delta m_N}{m_N}}\,a \;=\; 2\,, \quad \varepsilon_e \;=\; 2 + \frac{21}{250}\,, \quad \varepsilon_\mu \;=\; \frac{13}{50}\,, \quad \varepsilon_\tau \;=\; -\frac{49}{128}\,.$$

Prediction: inverted mass hierarchy, $m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$, with

$$m_{\nu_2}^2 - m_{\nu_1}^2 \;=\; 7.54\times 10^{-5}\ {\rm eV}^2\,, \qquad m_{\nu_1}^2 - m_{\nu_3}^2 \;=\; 2.45\times 10^{-3}\ {\rm eV}^2\,,$$

$$\sin^2\theta_{12} \;=\; 0.36\,, \qquad \sin^2\theta_{23} \;=\; 0.35\,, \qquad \sin^2\theta_{13} \;=\; 0.047\,.$$

• 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:

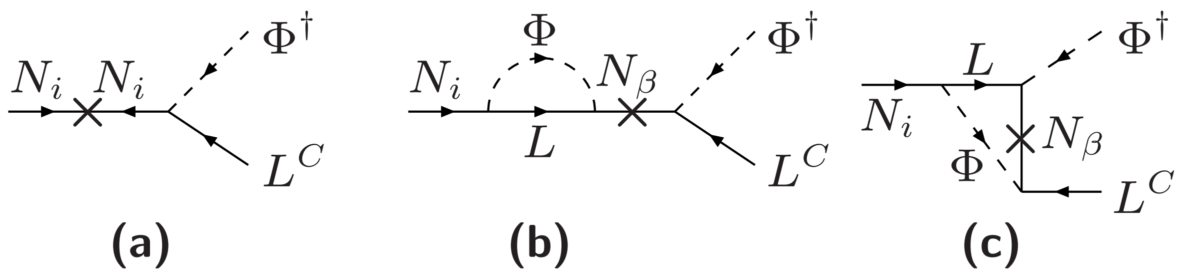
[A.D. Sakharov, JETP Lett. 5 (1967) 24.]

- 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 and T. Yanagida, PLB174 (1986) 45.]



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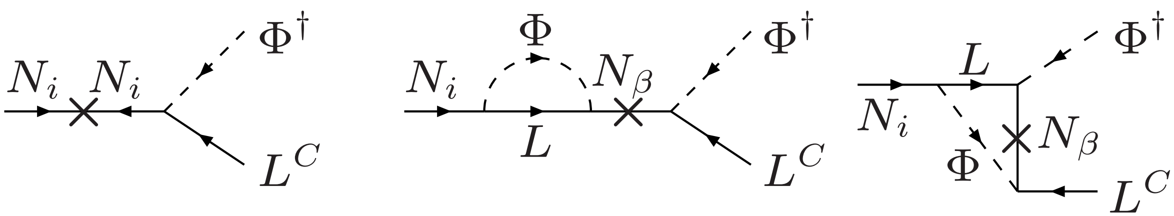


(a) (b) (c)

$\Longrightarrow$ Resonant Leptogenesis

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

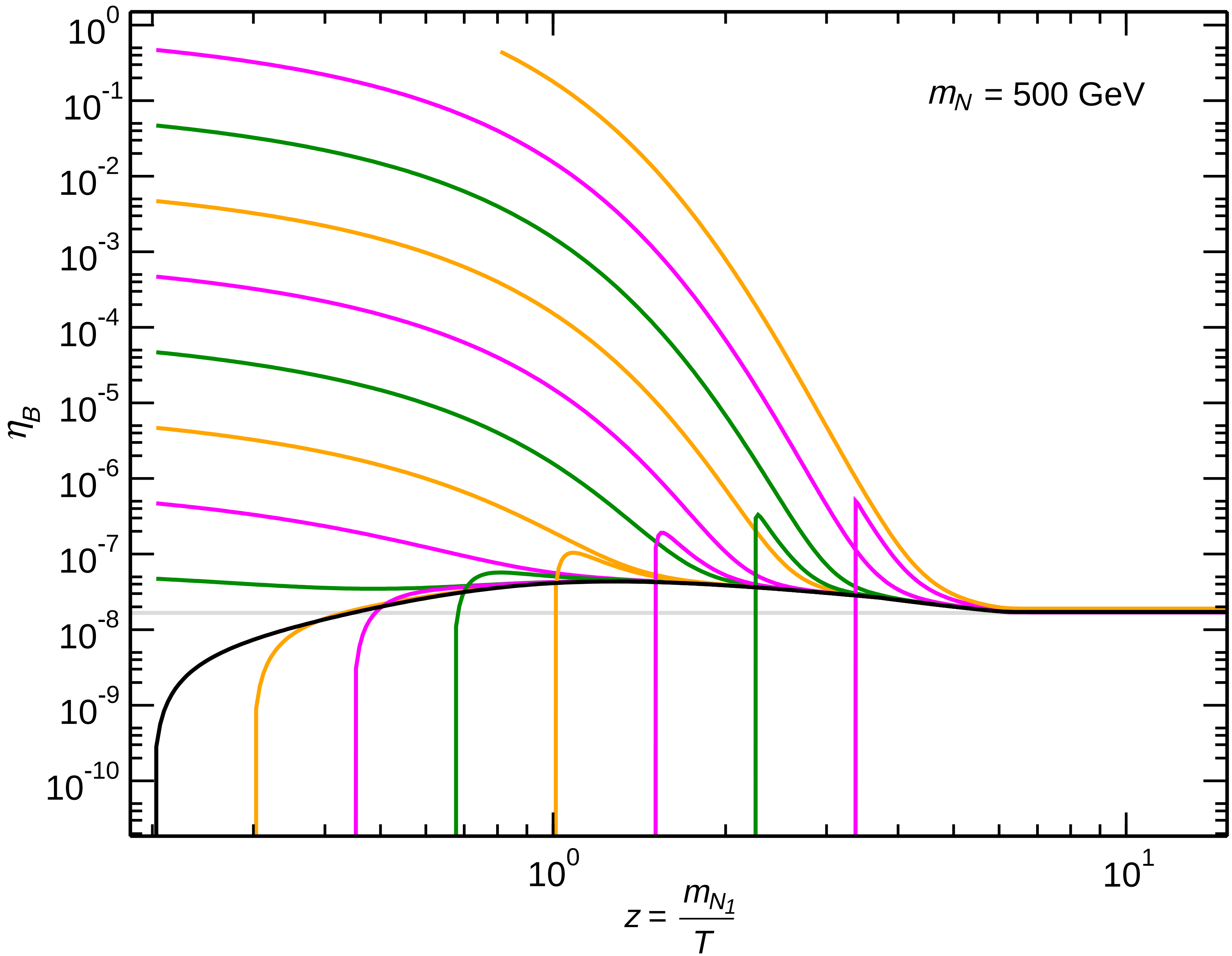
[A.P., PRD56 (1997) 5431.]

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

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

Resonant Leptogenesis

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



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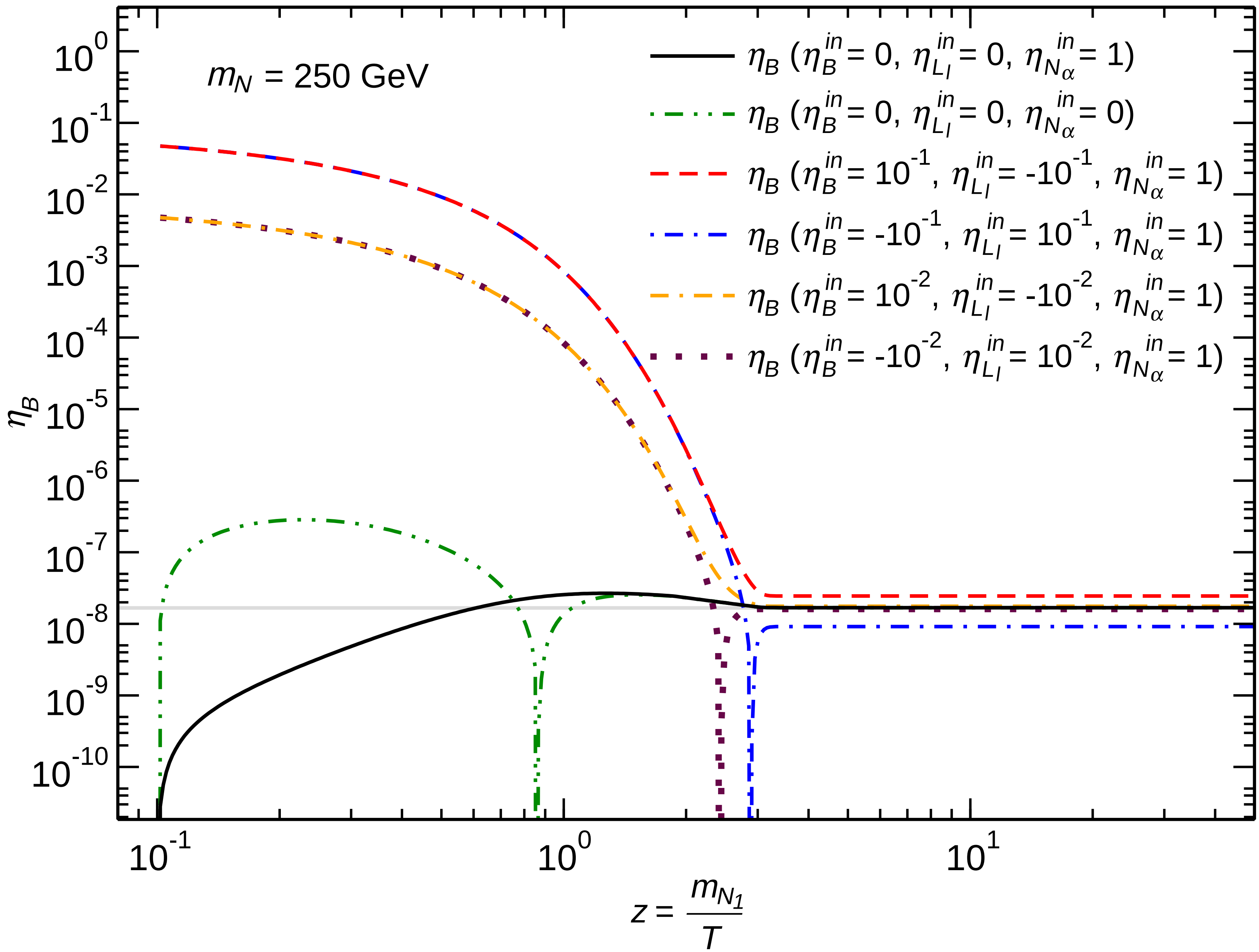
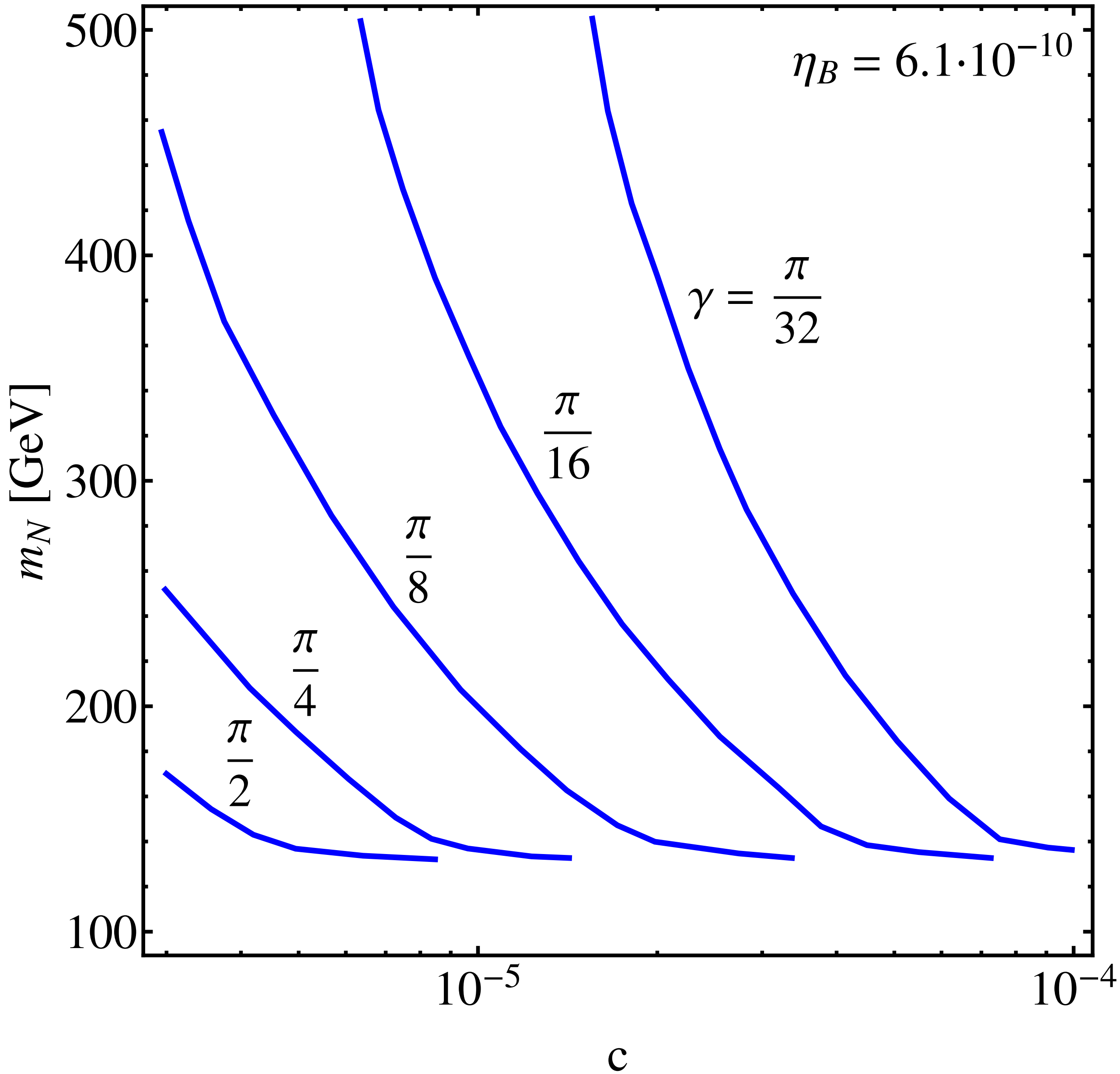


Resonant τ-Leptogenesis

[A.P., PRL95 (2005) 081602;
F. Deppisch, A.P., **PRELIMINARY**.]

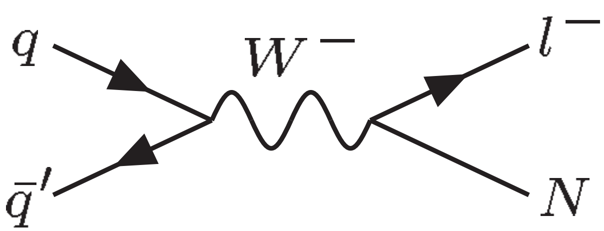


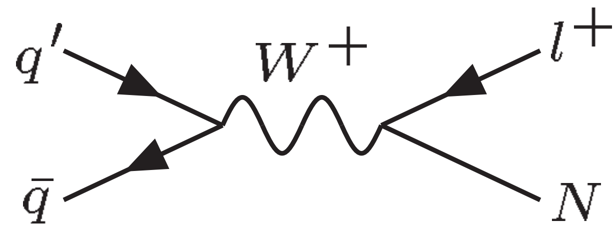
• Lepton Flavour and Number Violation at the LHC

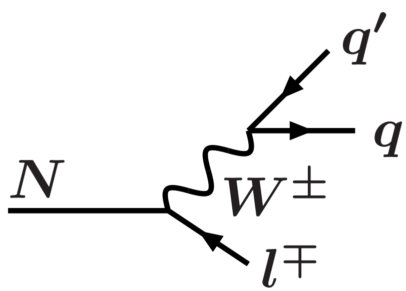
• Lepton Flavour and Number Violation at the LHC

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

[A.P., ZPC55 (1992) 275; A. Datta, M. Guchait, A.P., PRD50 (1994) 3195;
T. Han, B. Zhang, PRL97 (2006) 171804;
F. del Aguila, J. A. Aguilar-Saavedra, R. Pittau, JHEP0710 (2007) 047.]







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

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

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

• Lepton Flavour and Number Violation at the LHC

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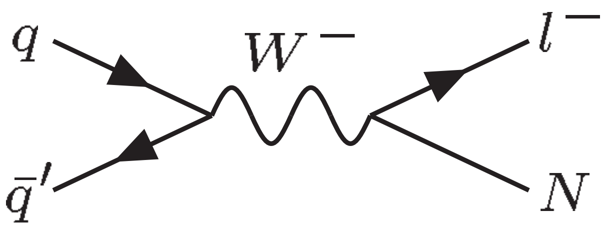

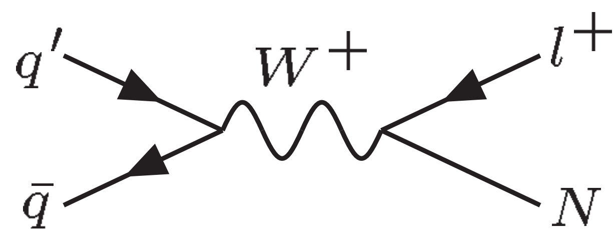

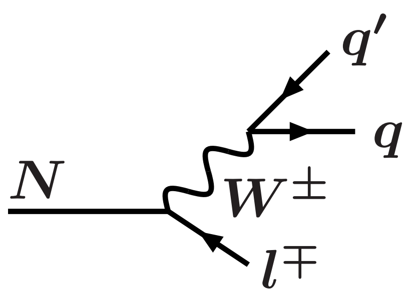

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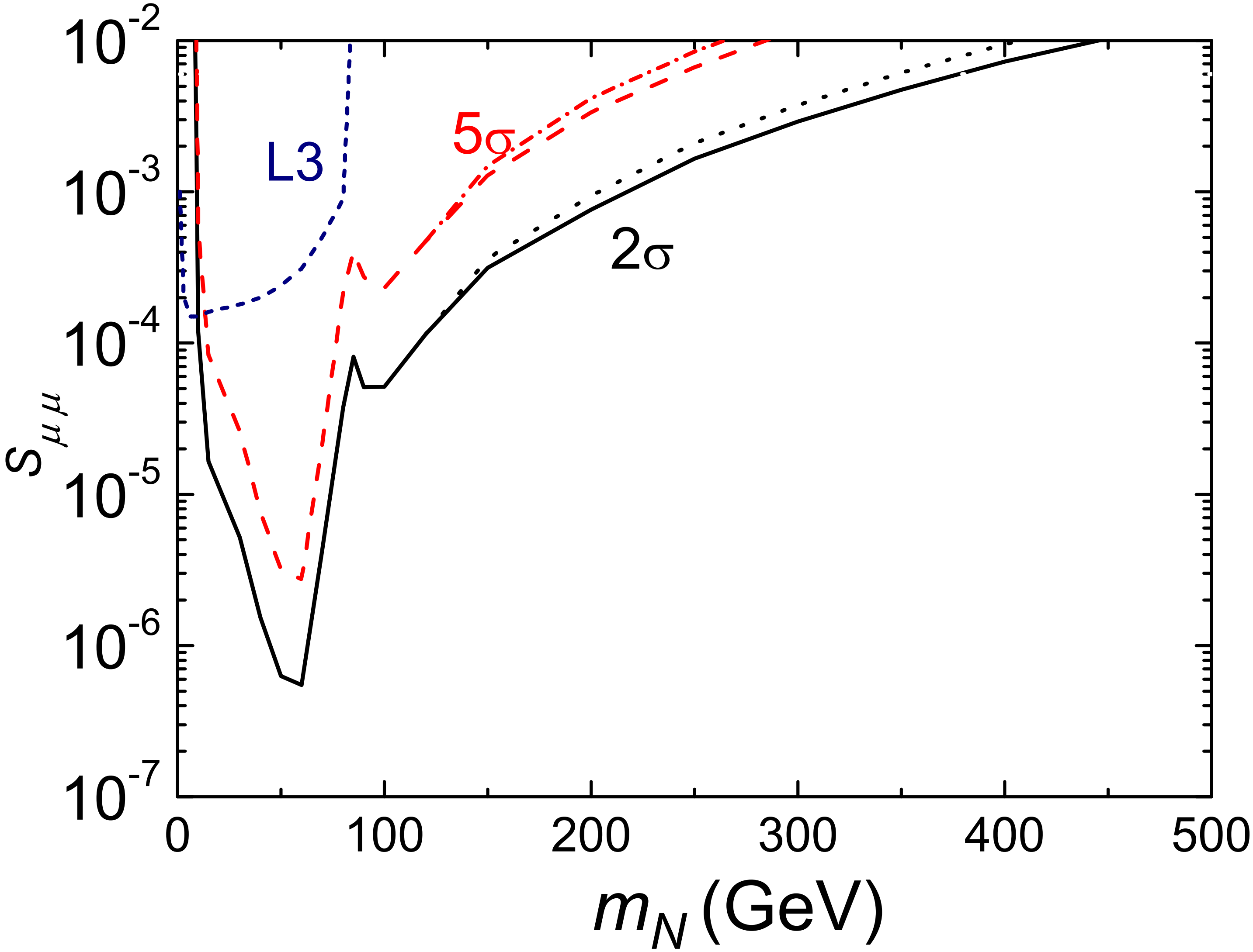
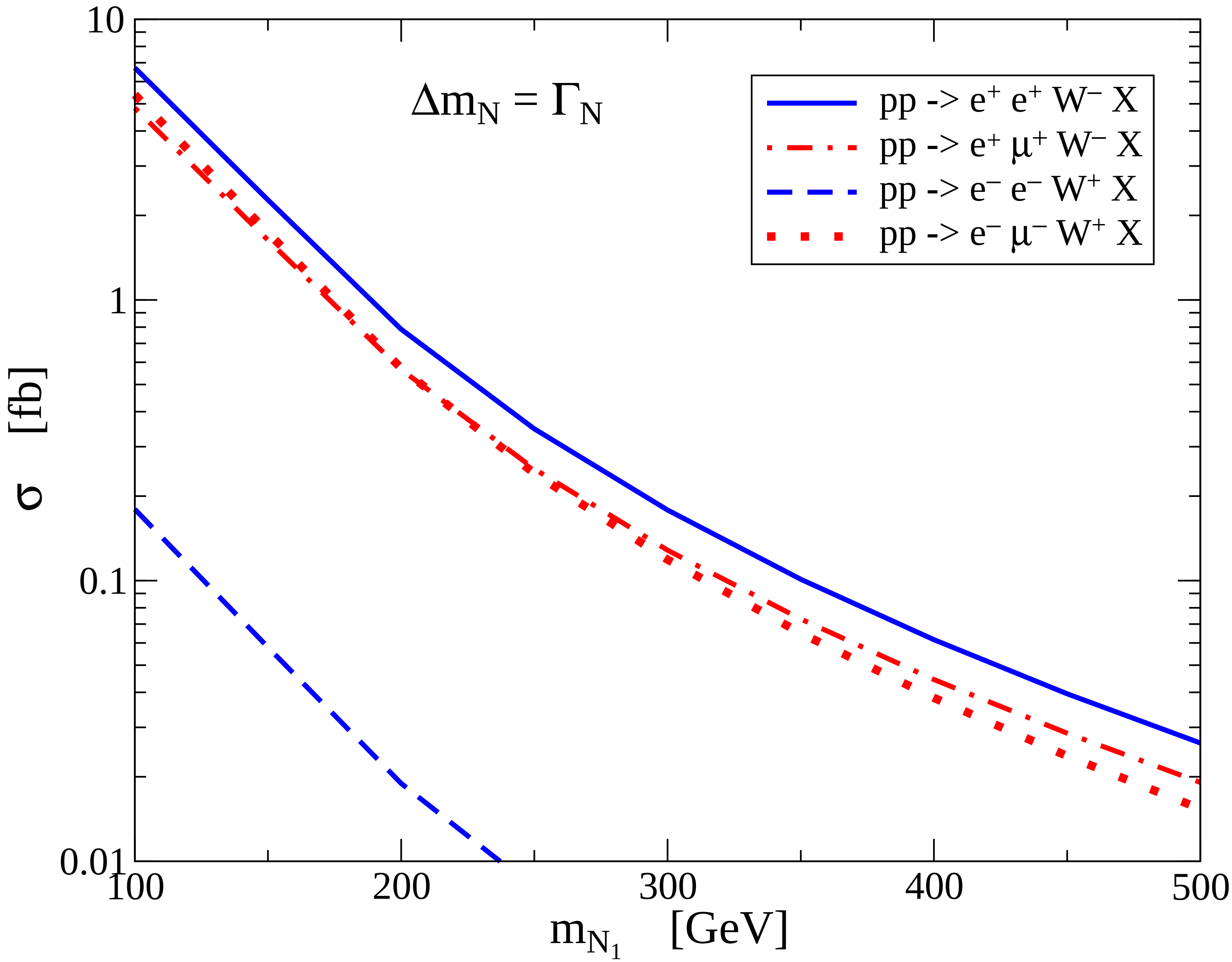
- **CP Asymmetries**

[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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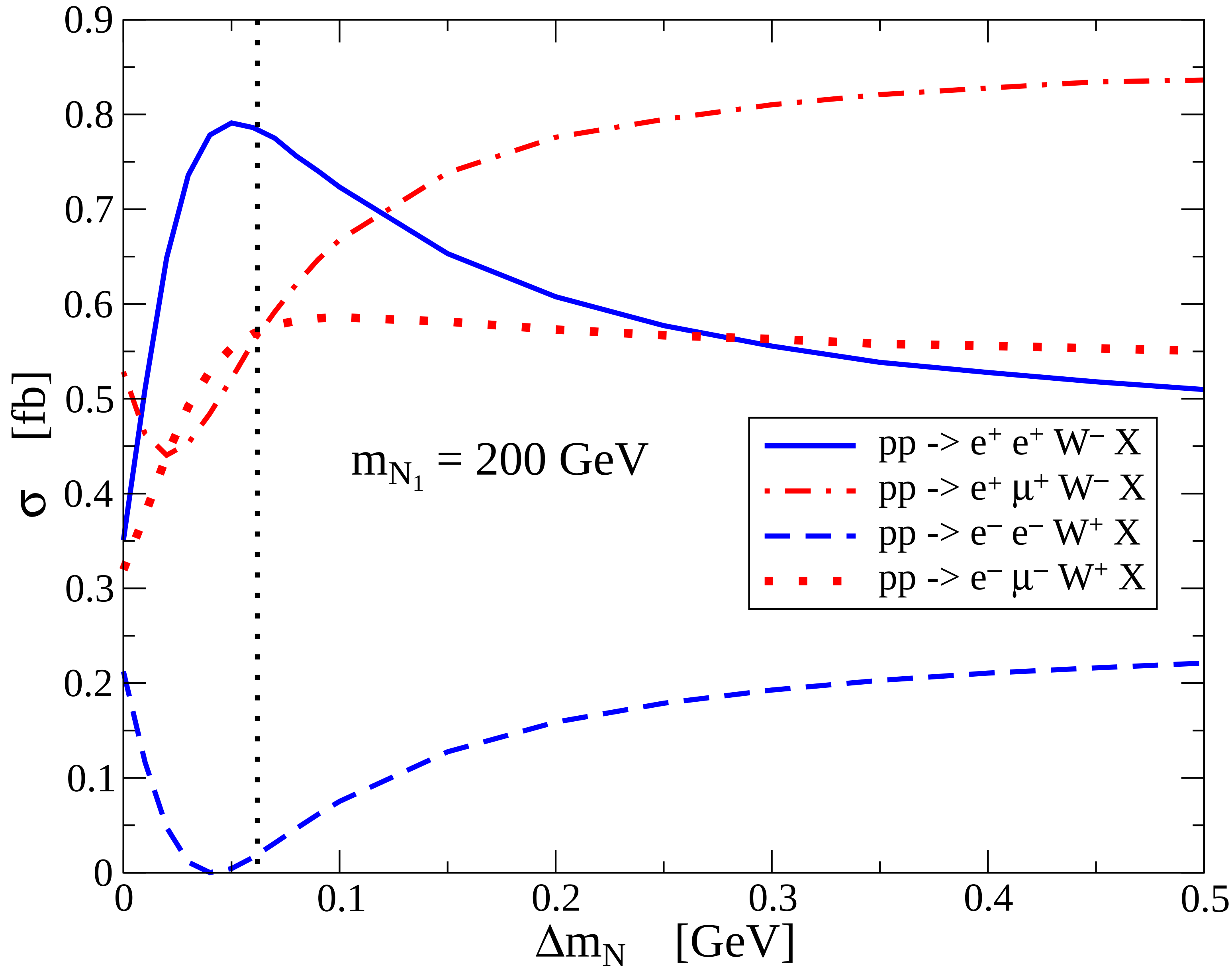

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CP Asymmetries

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- **Lepton Number Violation:**

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

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

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

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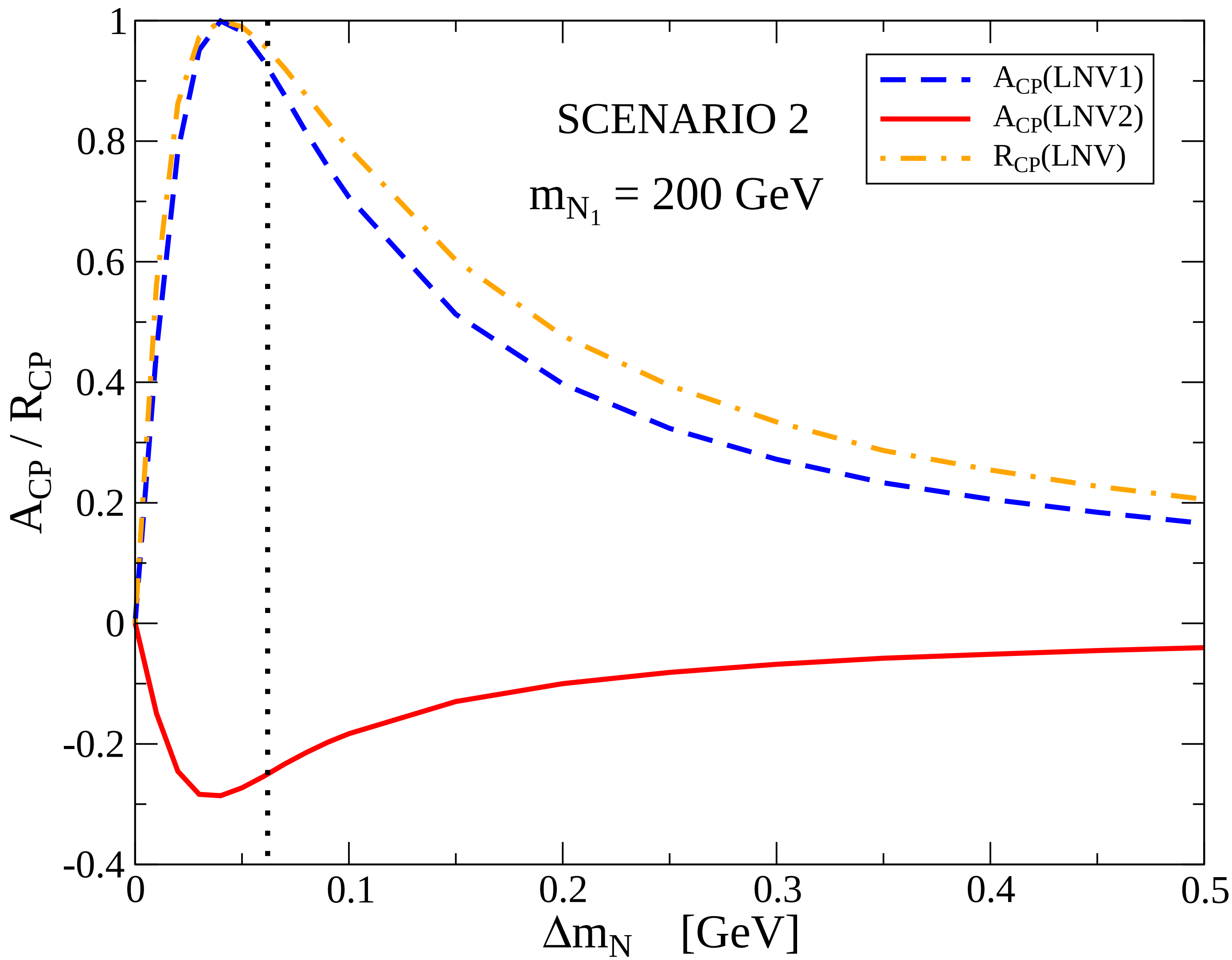
- **Lepton Flavour Violation:**

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

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

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

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

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

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

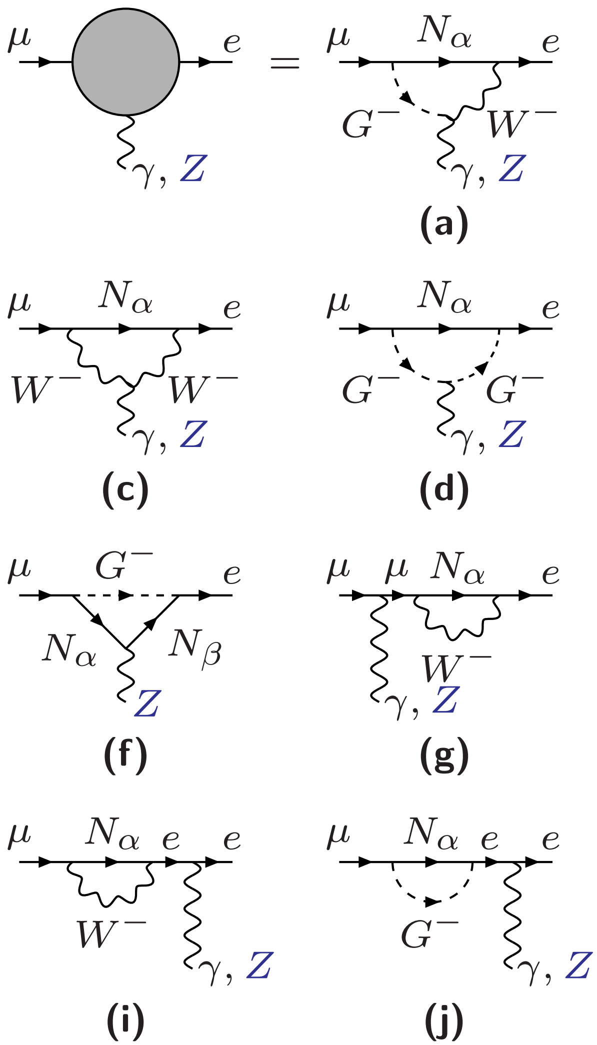
RτL realize inverted light-neutrino hierarchy, with:

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

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

• $\mu \longrightarrow e\gamma$

[T.P. Cheng, L.F. Li, PRL45 (1980) 1908;
A. Ilakovac, A.P., NPB437 (1995) 491]



For $h^{\nu}_{eN_{2,3}} = h^{\nu}_{\mu N_{2,3}} = 8 \times 10^{-3}$ and $m_N = 250$ GeV:

$$B(\mu \to e\gamma)$$

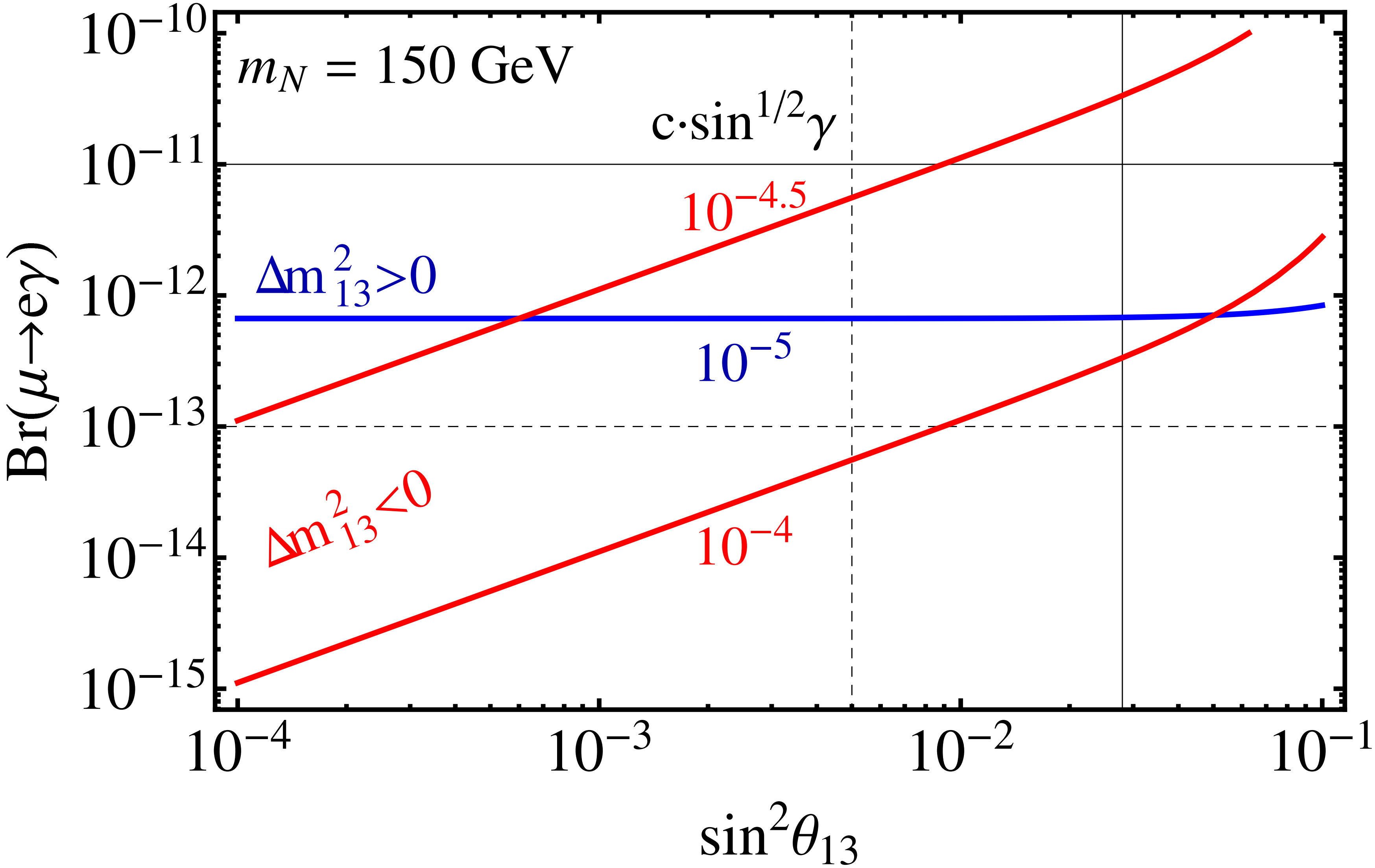
$$\sim \; 7 \cdot 10^{-4} \times \frac{(h^{\nu}_{eN} h^{\nu}_{\mu N})^2 v^4}{m_N^4}$$

$$\sim 10^{-12} \; .$$

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

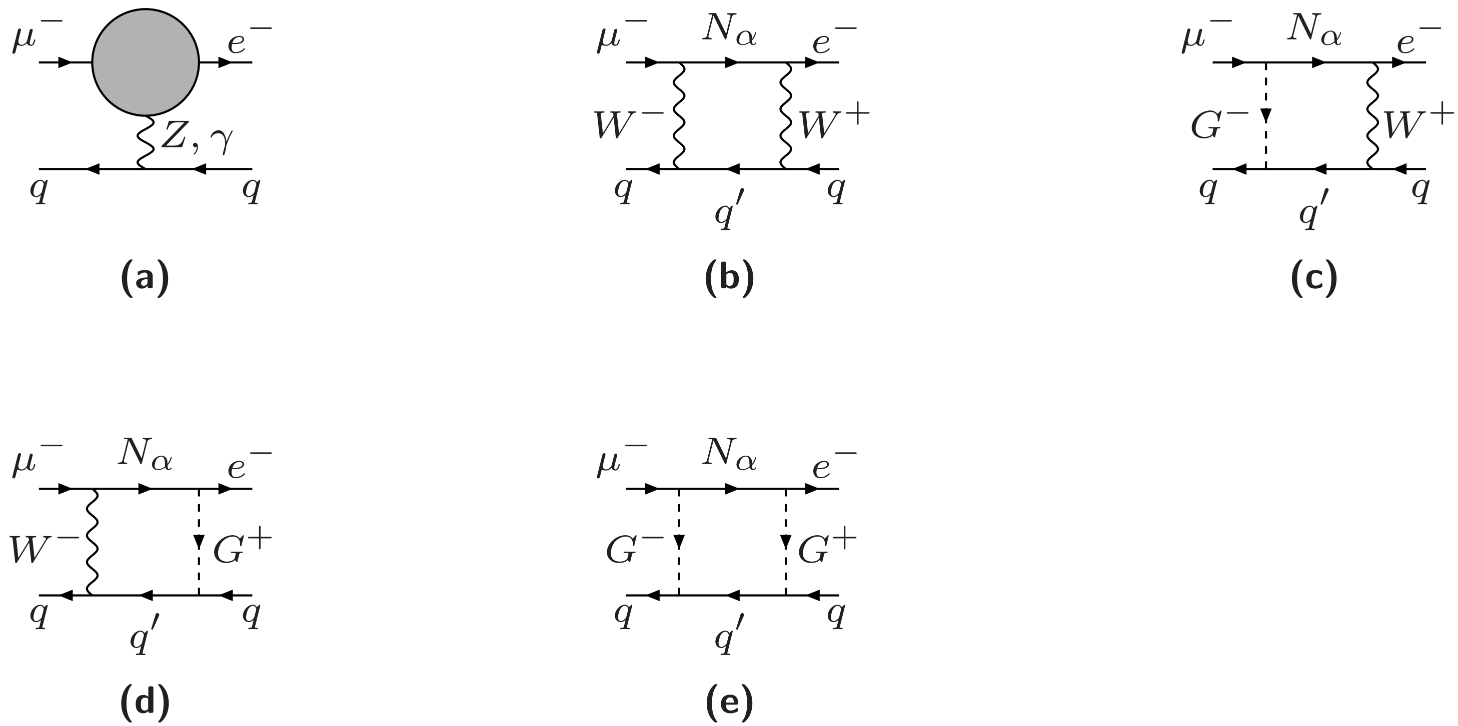
• $\mu \longrightarrow e\gamma$

[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]



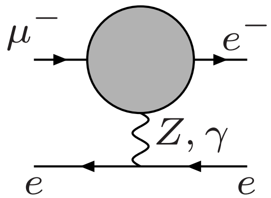
$\boldsymbol{m_N = 250}$ GeV:

$$B(\mu \to e) \;\approx\; 0.5 \times B(\mu \to e\gamma) \;\sim\; 5 \times 10^{-13}\ .$$

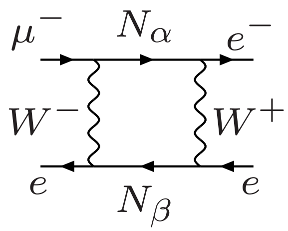
COMET/PRISM will be sensitive to $B(\mu \to e) \;\sim\; 10^{-13}$–$10^{-18}$.

• $\mu \longrightarrow eee$

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



(a)



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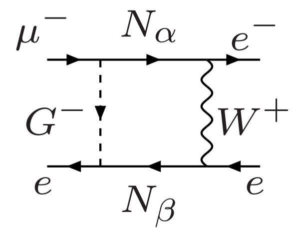
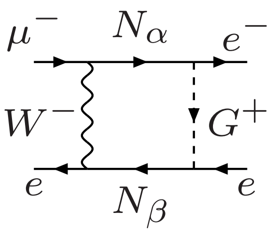


(c)



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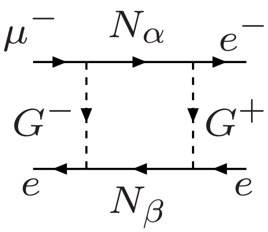

(e)

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

$m_N = 250$ GeV:

$$B(\mu \to eee) \;\approx\; 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma) \;\sim\; 1.4 \times 10^{-14}\ .$$

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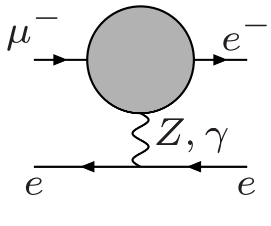

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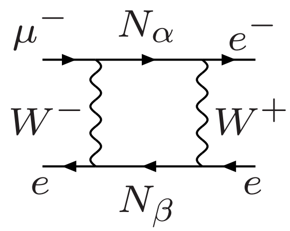

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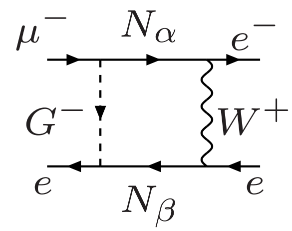
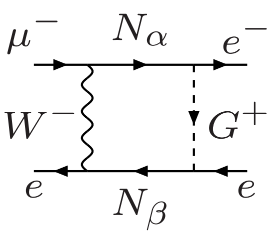


(c)



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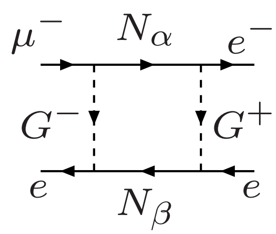

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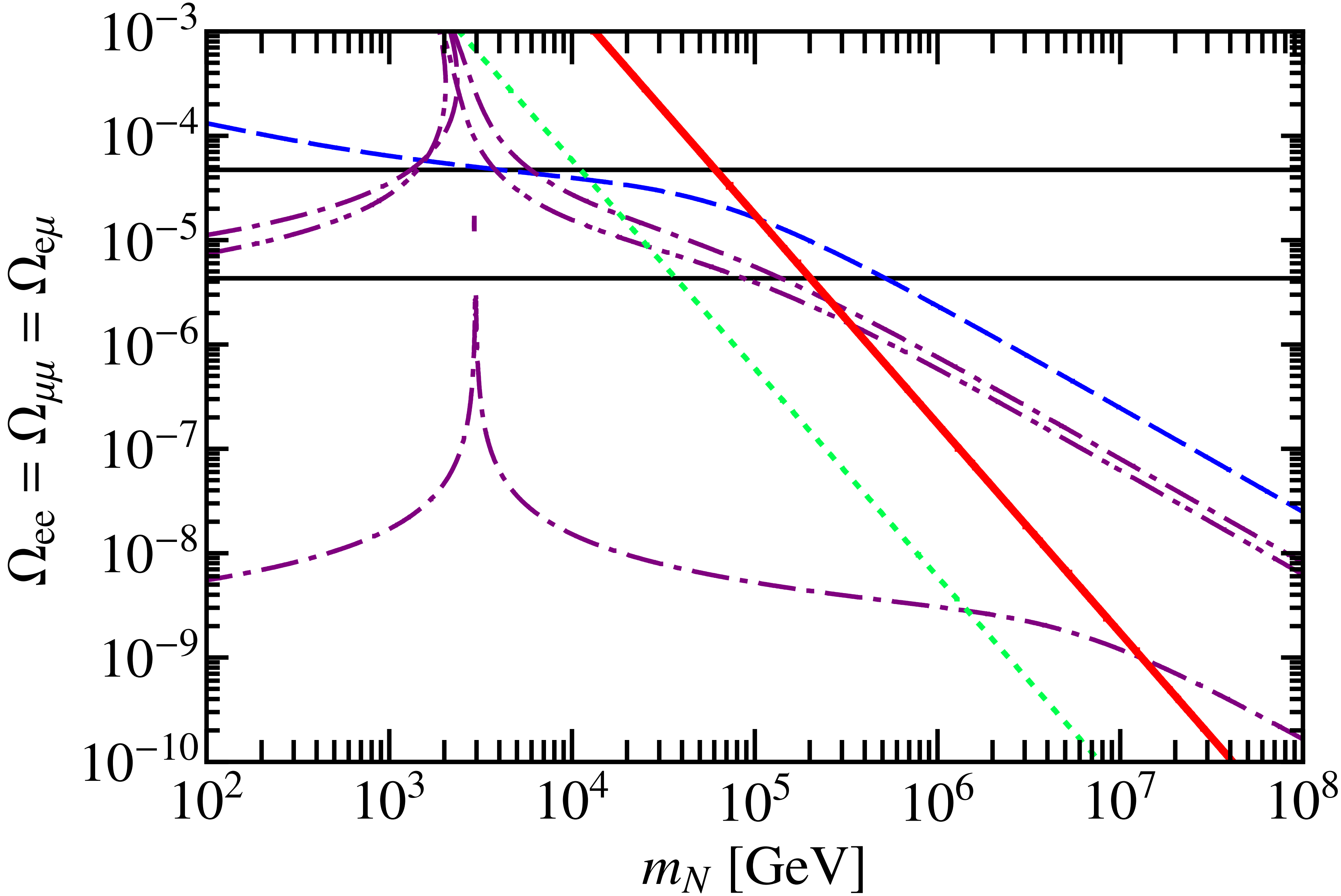
No new experiment proposed yet!

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

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



- **Conclusions**

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- **Strong correlations among the predictions for LFV and LNV at the observable level** ($m_N = 250$ **GeV**):

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