# Leptogenesis: Recent Developments

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# Plan of the talk

- **Matter–AntiMatter Asymmetry**
- **Models of Leptogenesis**
- **Lepton Flavour and Number Violation at the LHC**
- **Lepton Flavour and Number Violation in Low-Energy Experiments**
- **Conclusions**

## • Matter–AntiMatter Asymmetry

[E. Komatsu *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **192** (2011) 18.]

$$\eta_B^{\rm CMB} = \frac{n_B}{n_\gamma} \approx 6.2 \times 10^{-10} \qquad (\eta_B^{\rm BBN} = 3.4\text{–}6.9 \times 10^{-10}, \text{ at 95\% CL})$$

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

## Popular Scenarios for Baryogenesis:

- **Baryogenesis through the decay of a heavy particle**
  Out-of-equilibrium, $B$-violating decay of a heavy GUT particle, e.g. in SO(10).

  [M. Yoshimura, PRL**41** (1978) 281; S. Dimopoulos and L. Susskind, PR**D18** (1978) 4500; . . .
  K. S. Babu and R. N. Mohapatra, PRL**109** (2012) 091803.]

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- **Baryogenesis at the electroweak phase transition**
  BAU generated by $(B+L)$-violating sphaleron interactions at $T \sim T_c \approx 140$ GeV, through a 1st order phase transition.

  [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PLB155 (1985) 36;
  MSSM: M. Carena, M. Quirós, C. Wagner '96; K. Rummukainen, M. Laine '98 . . . ]

  MSSM parameter space squeezed by EDMs and direct LHC searches:

  [T. Cohen, D. E. Morrissey and A. Pierce, PRD86 (2012) 013009;

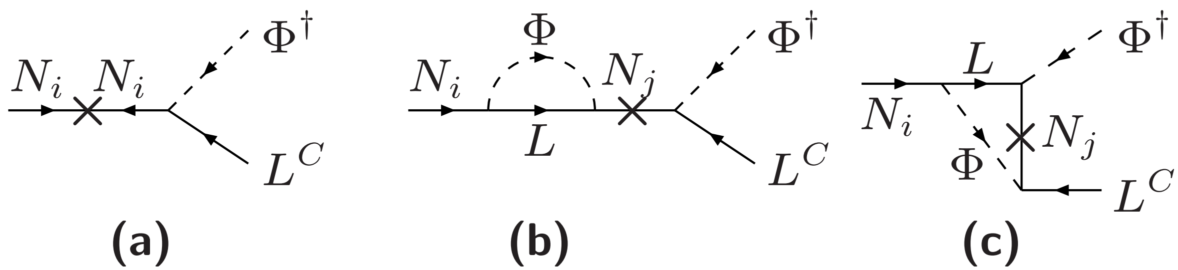
  M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, arXiv:1207.6330;

  M. Laine, G. Nardini and K. Rummukainen, arXiv:1211.7344.]

## $\Longrightarrow$ **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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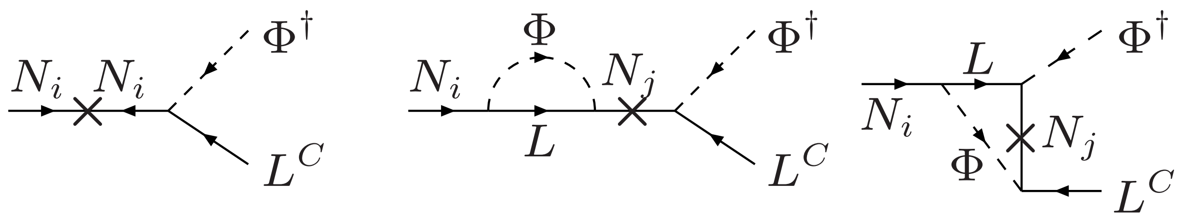


**(a)** **(b)** **(c)**

# Neutrino Physics as a Portal to Leptogenesis

## • Models of Leptogenesis

- **Hierarchical Leptogenesis** [M. Fukugita, T. Yanagida, PLB174 (1986) 45.]

  Lower mass bound on $m_{N_1} \gtrsim 10^9 - 10^6$ GeV

  [S. Davidson, A. Ibarra, PLB535 (2002) 25;
  W. Buchmüller, P. Di Bari, M. Plümacher, Annals Phys. **315** (2005) 305;
  J. Racker, M. Pena and N. Rius, JCAP **1207** (2012) 030.]

- **Resonant Leptogenesis** [this talk.]

- **Dirac Leptogenesis** [K. Dick, M. Lindner, M. Ratz, D. Wright, PRL84 (2000) 4039.]

- **Other scenarios:** Non-thermal leptogenesis, Affleck–Dine, spontaneous leptogenesis, CPT-Violating Leptogenesis . . .

  [For a review, see, M. Dine and A. Kusenko, Rev. Mod. Phys. **76** (2004) 1;
  N. Mavromatos and S. Sarkar, arXiv:1211.0968.]

## • 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.]

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- 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 Leptogenesis

Importance of self-energy effects (when $|m_{N_1} - m_{N_2}| \ll m_{N_{1,2}}$)

[J. Liu, G. Segré, PRD48 (1993) 4609;
M. Flanz, E. Paschos, U. Sarkar, PLB345 (1995) 248;
L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169.]

Importance of the heavy-neutrino width effects $\Gamma_{N_i}$

[A.P., PRD56 (1997) 5431; A.P. and T. Underwood, NPB692 (2004) 303;
inspired by the $K^0\bar{K}^0$ system: T.D. Lee, R. Oehme, C.N. Yang, PR106 (1957) 340.]

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**Several variants:**

- **Soft RL**

[Y. Grossman, T. Kashti, Y. Nir, E. Roulet, PRL91 (2003) 251801;
G. D'Ambrosio, G. F. Giudice, M. Raidal, PLB575 (2003) 75.]

- **Radiative RL**

[R. Gonzalez Felipe, F. R. Joaquim and B. M. Nobre, PRD70 (2004) 085009;
G. C. Branco, A. J. Buras, S. Jager, S. Uhlig, A. Weiler, JHEP0709 (2007) 004;
G. C. Branco, R. Gonzalez Felipe, M. N. Rebelo and H. Serodio, PRD79 (2009) 093008.]

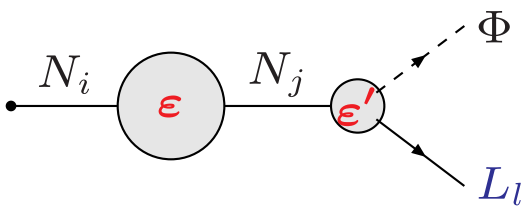
- **Coherent RL** (via sterile neutrino oscillations)

[E. K. Akhmedov, V. A. Rubakov, A. Y. Smirnov, PRL81 (1998) 1359;
T. Asaka, M. Shaposhnikov, PLB620 (2005) 17;
M. E. Shaposhnikov, JHEP0808 (2008) 008.]

## • The Field-Theory of Resonant Leptogenesis:

LSZ-type formalism for mixing and decay of heavy Majorana neutrinos

[A.P., PRD56 (1997) 5431; NPB504 (1997) 61.]




$$\times\ [S_{ii}(\not p)]^{-1}\, u_{N_i}(p)\ \equiv\ \mathcal{T}^{\rm eff}(N_i \to L_l \Phi)$$

2-$N$ Mixing Model:

$$S_{ij}(\not p)\ =\ \left( \begin{array}{cc} \not p - m_{N_1} + \Sigma_{11}(\not p) & \Sigma_{12}(\not p) \\ \Sigma_{21}(\not p) & \not p - m_{N_2} + \Sigma_{22}(\not p) \end{array} \right)^{-1}$$

[For 3-$N$ mixing, see, A.P., T. Underwood, NPB692 (2004) 303.]

## Effective (Resummed) Neutrino Yukawa Couplings:

$$\mathcal{T}^{\rm eff}(N_i \to L_l \Phi) \; = \; \overline{\mathbf{h}}^{\nu}_{li}\, \bar{u}_l\, P_R\, u_{N_i}$$

For 2-$N$ mixing:

$$\overline{\mathbf{h}}^{\nu}_{li} \;=\; h^{\nu}_{li} + iB_{li} - \frac{ih^{\nu}_{lj}\, m_{N_i}\,(m_{N_i} A_{ij} \;+\; m_{N_j} A_{ji})}{m^2_{N_i} - m^2_{N_j} + 2i\, A_{jj}\, m^2_{N_i}}$$

$$\overline{\mathbf{h}}^{\nu C}_{li} \;=\; h^{\nu *}_{li} + iB^{*}_{li} - \frac{ih^{\nu *}_{lj}\, m_{N_i}\,(m_{N_i} A^{*}_{ij} \;+\; m_{N_j} A^{*}_{ji})}{m^2_{N_i} - m^2_{N_j} + 2i\, A_{jj}\, m^2_{N_i}}$$

## Lepton Flavour Asymmetries

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

$$\delta_{il} \;\equiv\; \frac{\Gamma_{il} \;-\; \Gamma^{C}_{il}}{\sum\limits_{l=e,\mu,\tau} (\Gamma_{il} \;+\; \Gamma^{C}_{il})} \;=\; \frac{|\overline{\mathbf{h}}^{\nu}_{li}|^2 \;-\; |\overline{\mathbf{h}}^{\nu C}_{li}|^2}{(\overline{\mathbf{h}}^{\nu\dagger}\, \overline{\mathbf{h}}^{\nu})_{ii} \;+\; (\overline{\mathbf{h}}^{\nu C\dagger}\, \overline{\mathbf{h}}^{\nu C})_{ii}}$$

$\varepsilon'$-type CP violation :

$$\varepsilon'_{N_i} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}}\,\left(\frac{\Gamma_{N_j}}{m_{N_j}}\right)\,f\left(\frac{m^2_{N_j}}{m^2_{N_i}}\right),$$

where

$$\Gamma_{N_j} \;=\; \frac{(h^{\nu\dagger}\,h^{\nu})_{jj}}{8\pi}\,m_{N_j}$$

$\varepsilon$-type CP violation :

$$\varepsilon_{N_i} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}}\,\frac{(m^2_{N_i}-m^2_{N_j})\,m_{N_i}\,\Gamma_{N_j}}{(m^2_{N_i}-m^2_{N_j})^2\,+\,m^2_{N_i}\Gamma^2_{N_j}}$$

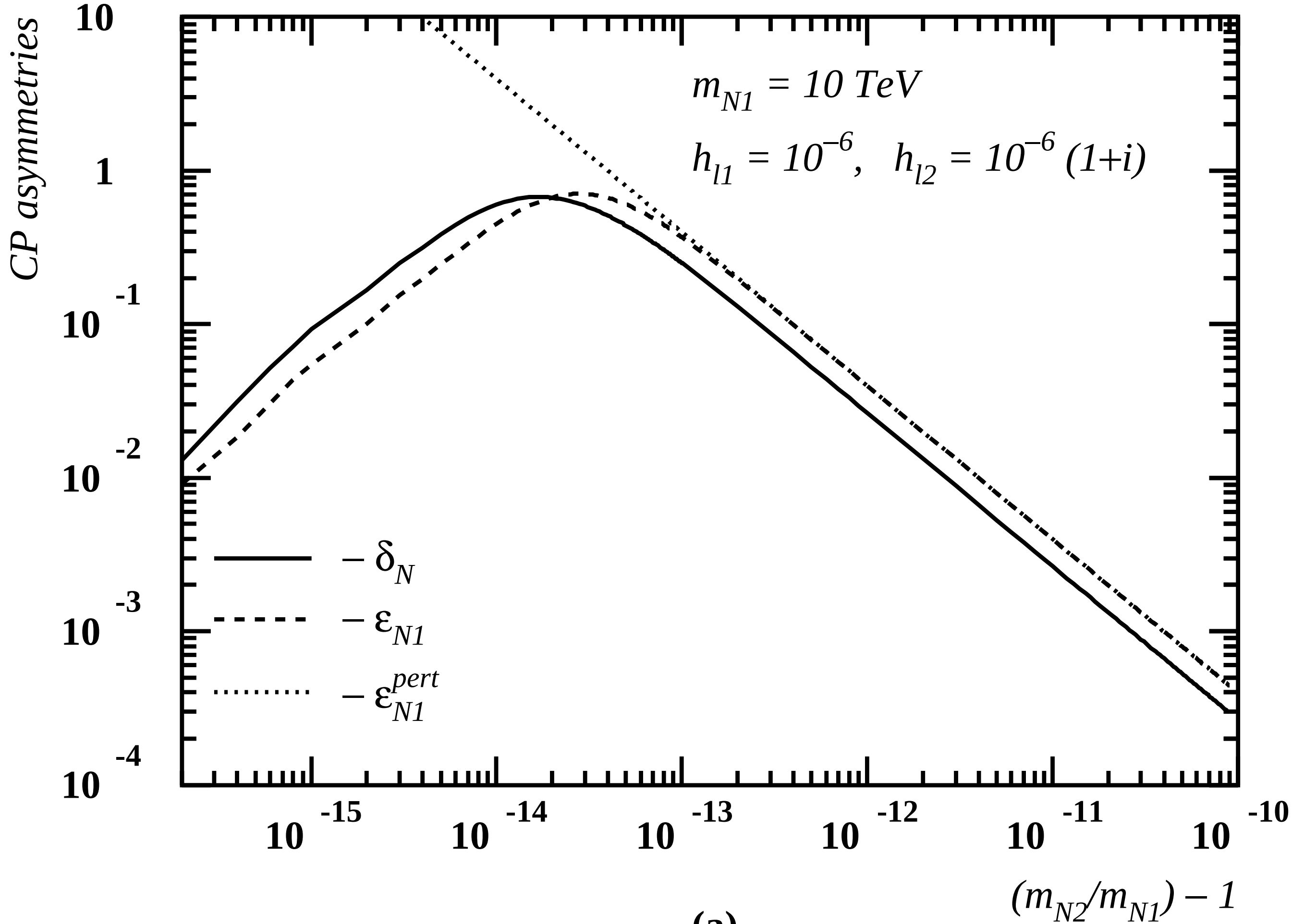
Note that $\varepsilon_{N_{1,2}}$ are of the same sign!

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

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

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

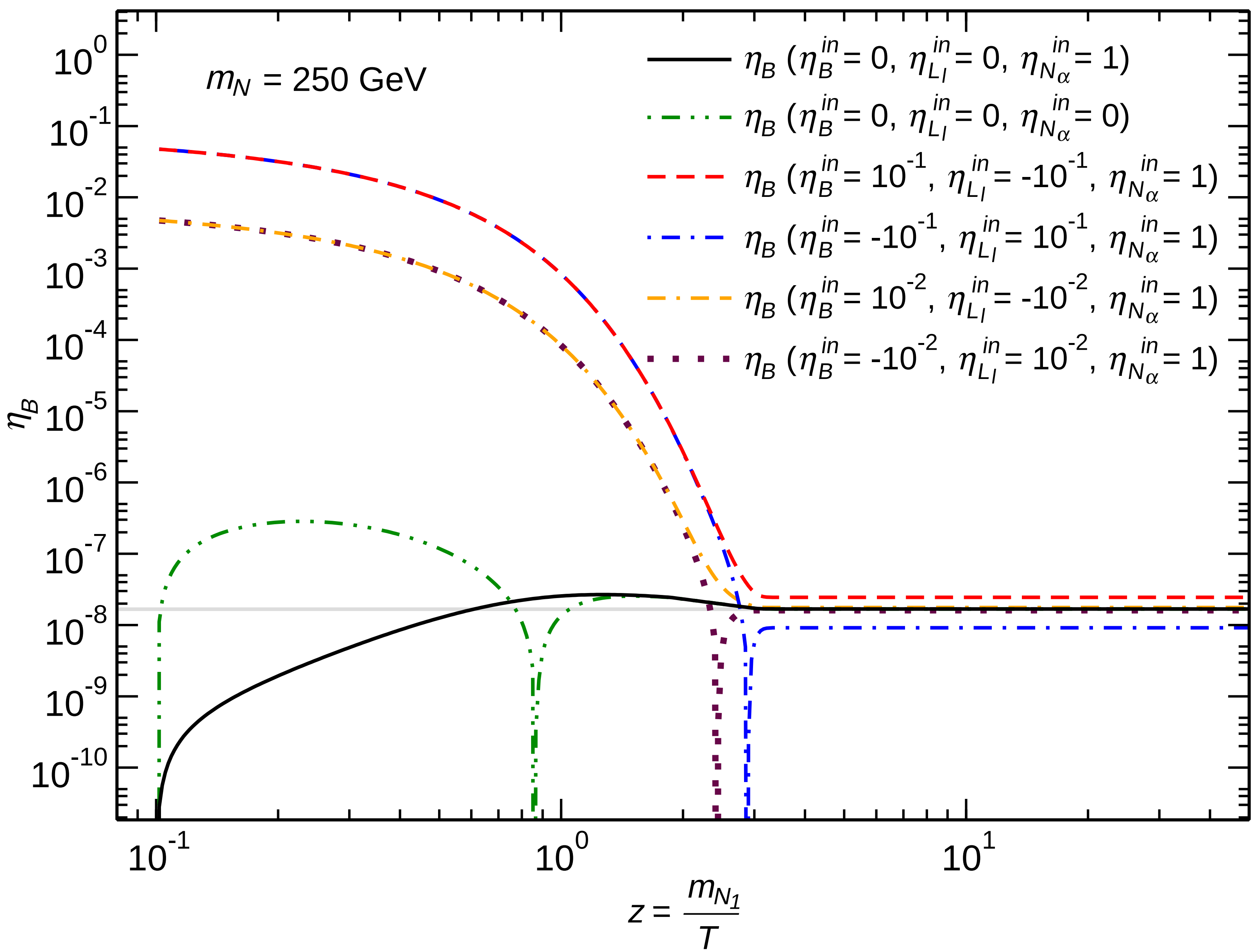
$$\Rightarrow \quad \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{ij}}{(h^{\nu\dagger}\,h^{\nu})_{ii}\,(h^{\nu\dagger}\,h^{\nu})_{jj}} \sim 1$$




**(a)**

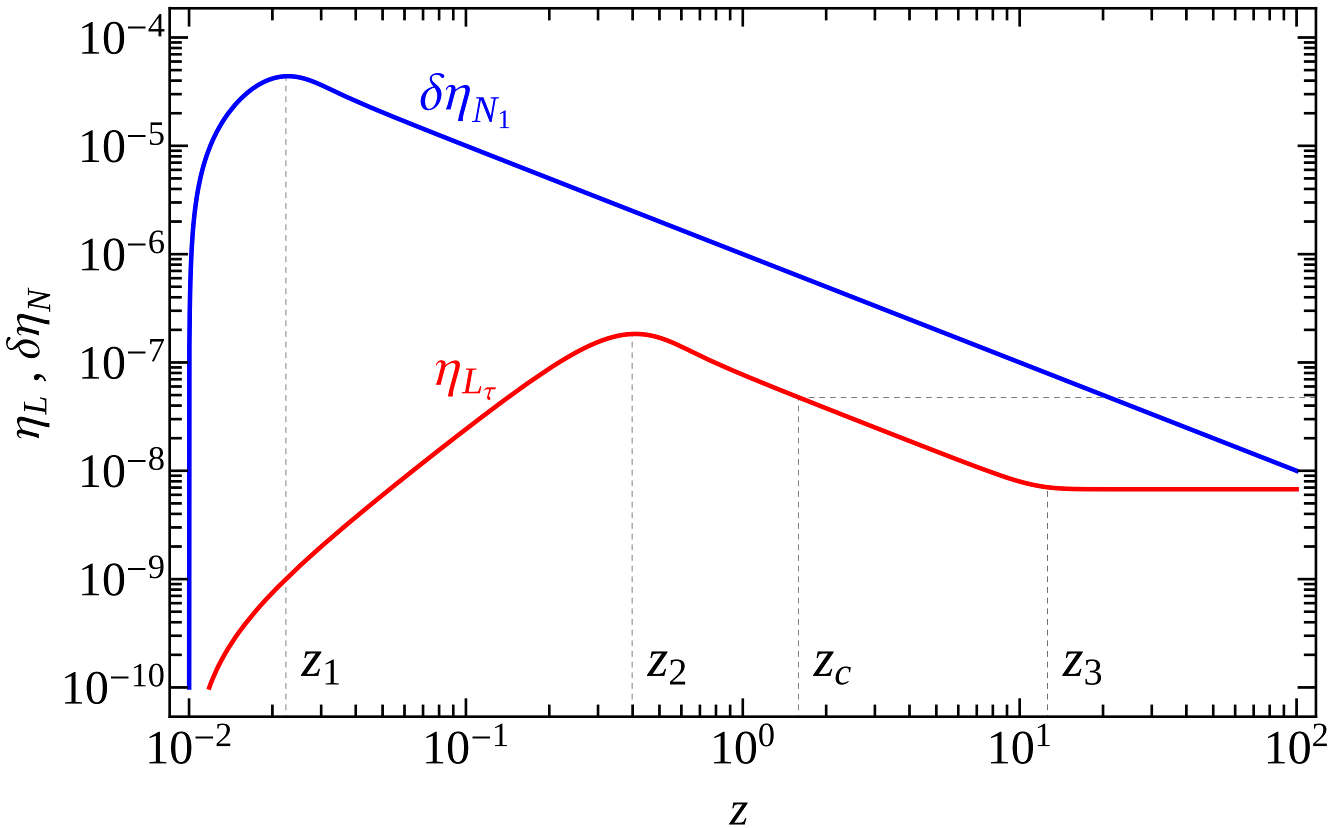
## Resonant $\tau$-Genesis

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



## Resonant $\tau$-Genesis

[F. Deppisch, A.P., PRD83 (2011) 076007.]




$z = m_N/T$, $m_N = 220$ GeV, $T_c = 130$ GeV, $\delta_\tau = 10^{-6}$, $K_\tau^{\rm eff} = 100$.

$$\eta_B \ \sim \ -\, 3\cdot 10^{-2} \sum_{l=e,\mu,\tau} \frac{\delta_l}{K_l^{\rm eff}\, \min[m_N/T_c\,,\ 1.25\ln(25K_l^{\rm eff})]}\ .$$

## • Comparison with Other Methods: $\varepsilon_{N_1}$ [F. Deppisch, A.P., PRD83 (2011) 076007.]

Consider a simple Inverse Seesaw-like Model $(1L + 2\nu_R)$:

[R. N. Mohapatra, PRL56 (1986) 561;
R. N. Mohapatra, J. W. F. Valle, PRD34 (1986) 1642;
P. S. B. Dev and A.P., arXiv:1209.4051.]

$$M_\nu \;=\; \begin{pmatrix} 0 & vy & 0 \\ vy & \mu_1 & M \\ 0 & M & \mu_2 e^{i\alpha} \end{pmatrix}$$

Heavy neutrino masses:

$$M_{1,2} \;\approx\; M \;\mp\; \frac{\mu}{2}\,, \quad \text{with } \mu \;=\; |\mu_1 + \mu_2 e^{i\alpha}|$$

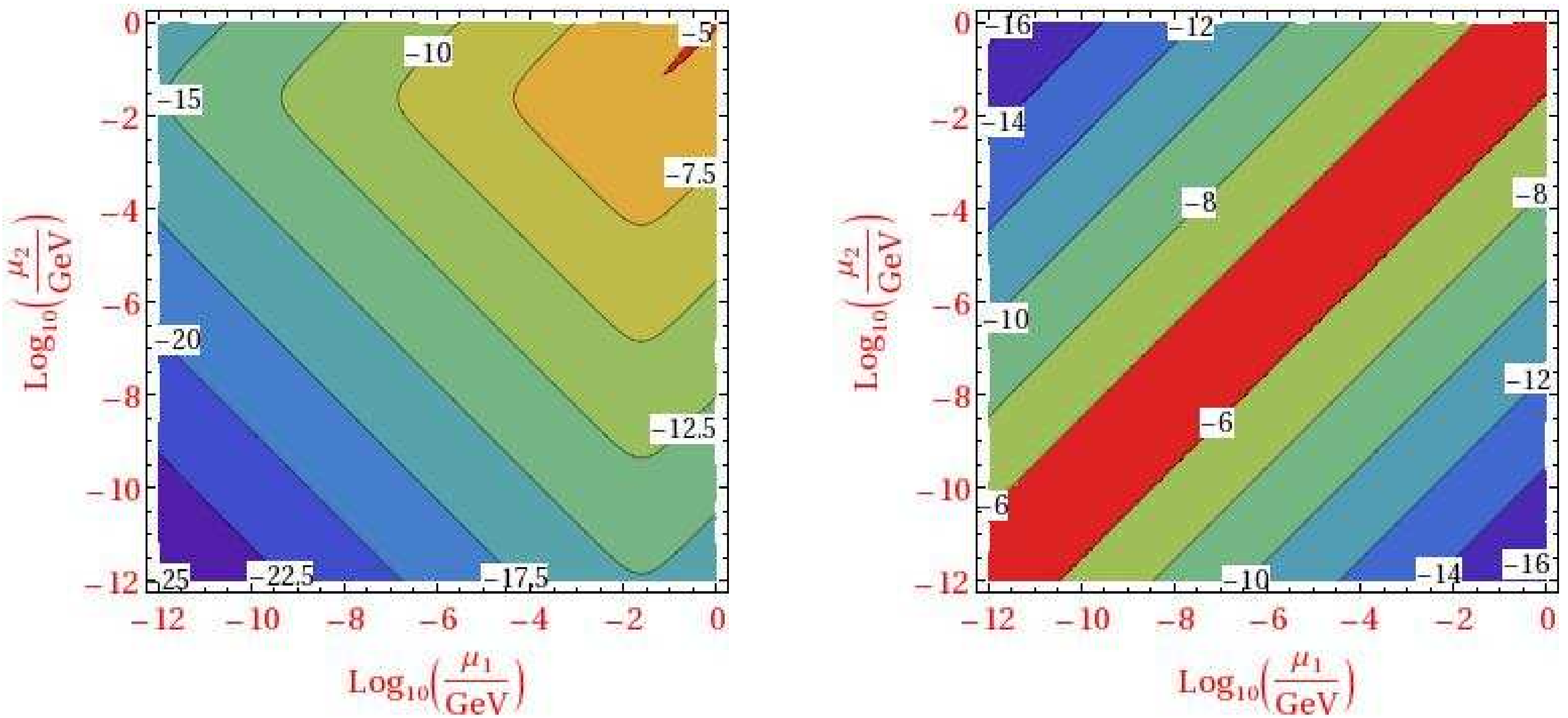
Lepton asymmetry $\varepsilon_{N_1}$:

$$\varepsilon_{N_1} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\, h^{\nu})^2_{12}}{(h^{\nu\dagger}\, h^{\nu})_{11}\,(h^{\nu\dagger}\, h^{\nu})_{22}}\; f_{\mathrm{reg}}$$

$\Longrightarrow \quad \varepsilon_{N_1} \to 0,$ when $\mu_{1,2} \to 0.$

## $L$-conserving limits of $\varepsilon_{N_1}$

[Plots: courtesy of P.S. Bhupal Dev]




Singular regulator:

[W. Buchmüller and M. Plümacher, PLB431 (1998) 354.]

$$f_{\rm reg}^{\rm BP} \;=\; \frac{|m_{N_1}^2 - m_{N_2}^2|\, m_{N_1}\, \Gamma_{N_2}}{(m_{N_1}^2 - m_{N_2}^2)^2 \,+\, (m_{N_1}\Gamma_{N_1} - m_{N_2}\Gamma_{N_2})^2}$$

## Thermal QFT Effects

G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia,
Towards a complete theory of thermal leptogenesis in the SM and MSSM,
Nucl. Phys. B685 (2004) 89.

A. De Simone and A. Riotto,
Quantum Boltzmann equations and leptogenesis, JCAP 0708 (2007) 002.

M. Garny, A. Hohenegger, A. Kartavtsev and M. Lindner,
Systematic approach to leptogenesis in nonequilibrium QFT: self-energy contribution to the CP-violating parameter, Phys. Rev. D81 (2010) 085027.

M. Beneke, B. Garbrecht, C. Fidler, M. Herranen and P. Schwaller,
Flavoured leptogenesis in the CTP formalism, Nucl. Phys. B843 (2011) 177.

A. Anisimov, W. Buchmüller, M. Drewes and S. Mendizabal,
Quantum leptogenesis I, Annals Phys. 326 (2011) 1998.

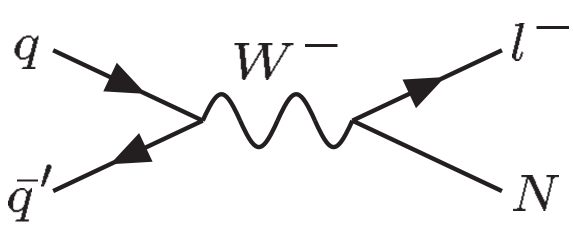
Perturbative Non-Equilibrium Thermal Field Theory,
P. Millington and A.P., arXiv:1211.3152 (101 pages) [PM, this conference]

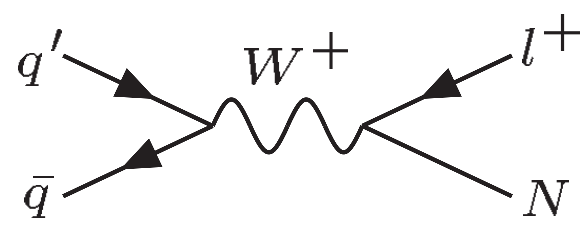
## • Lepton Flavour and Number Violation at the LHC

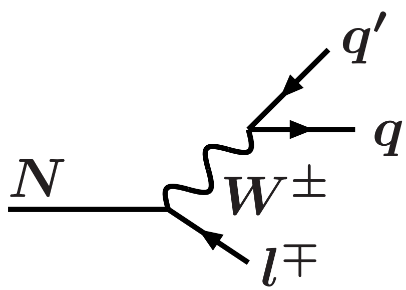
## • Lepton Flavour and Number Violation at the LHC

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

[A.P., ZPC55 (1992) 275; A. Datta, M. Guchait, A.P., PRD50 (1994) 3195;
J. Kersten, A. Y. Smirnov, PRD76 (2007) 073005;
F. del Aguila, J. A. Aguilar-Saavedra, R. Pittau, JHEP0710 (2007) 047.]




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

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

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

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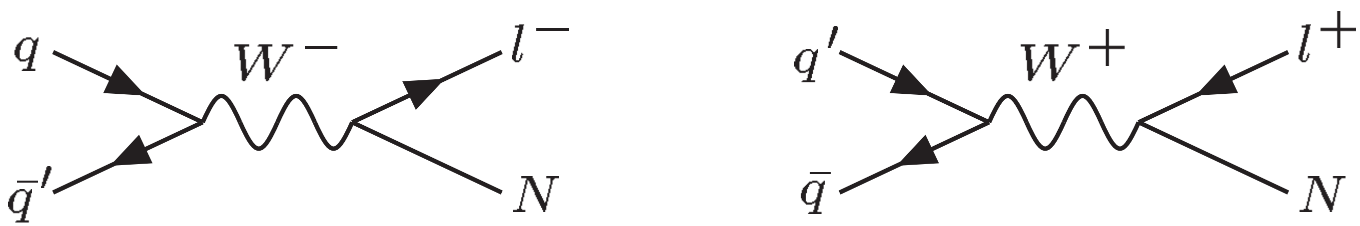


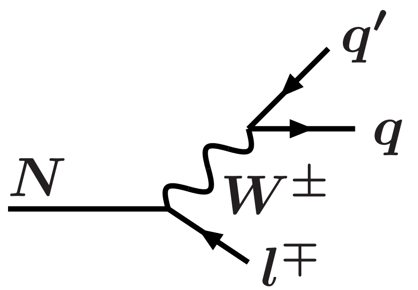


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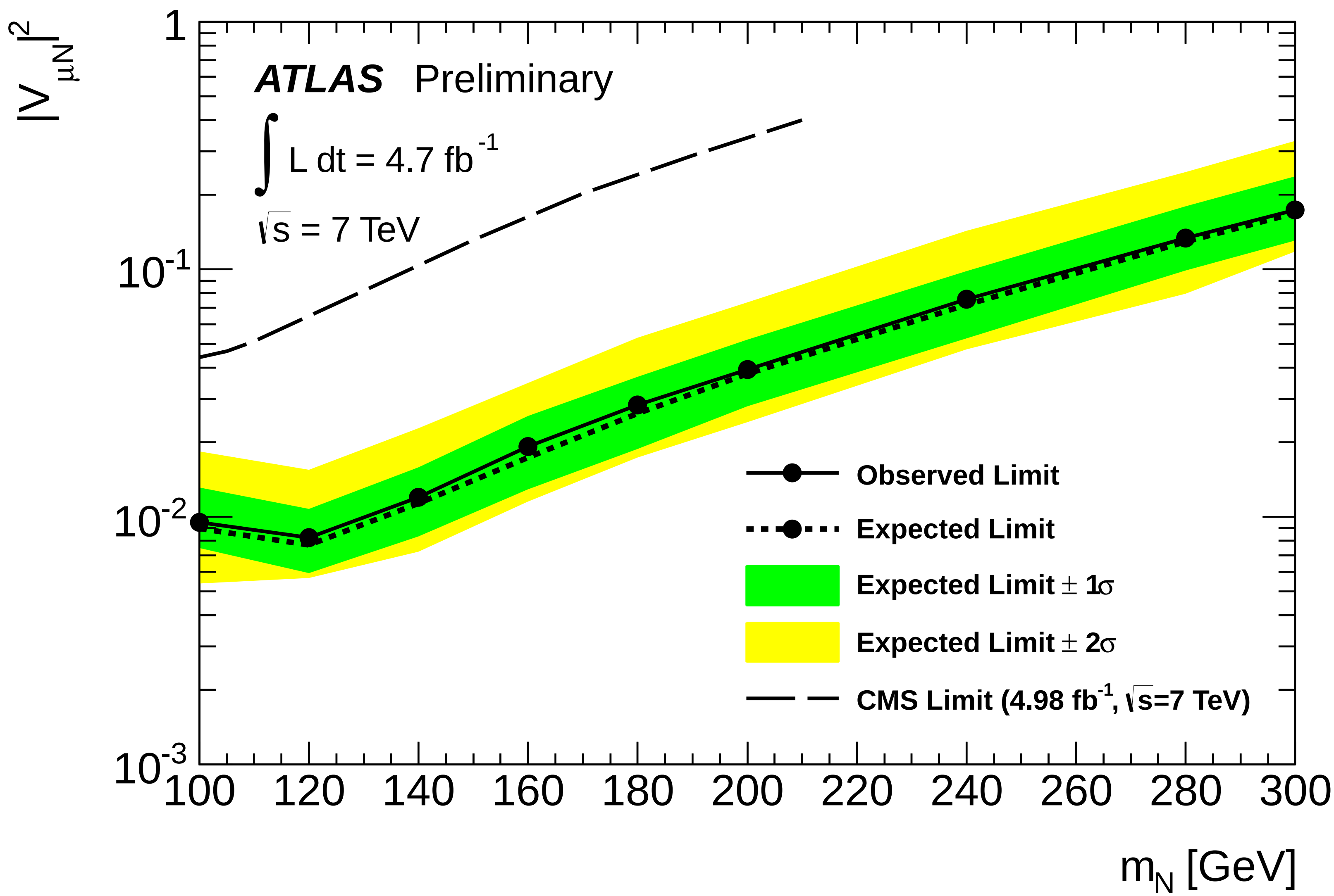
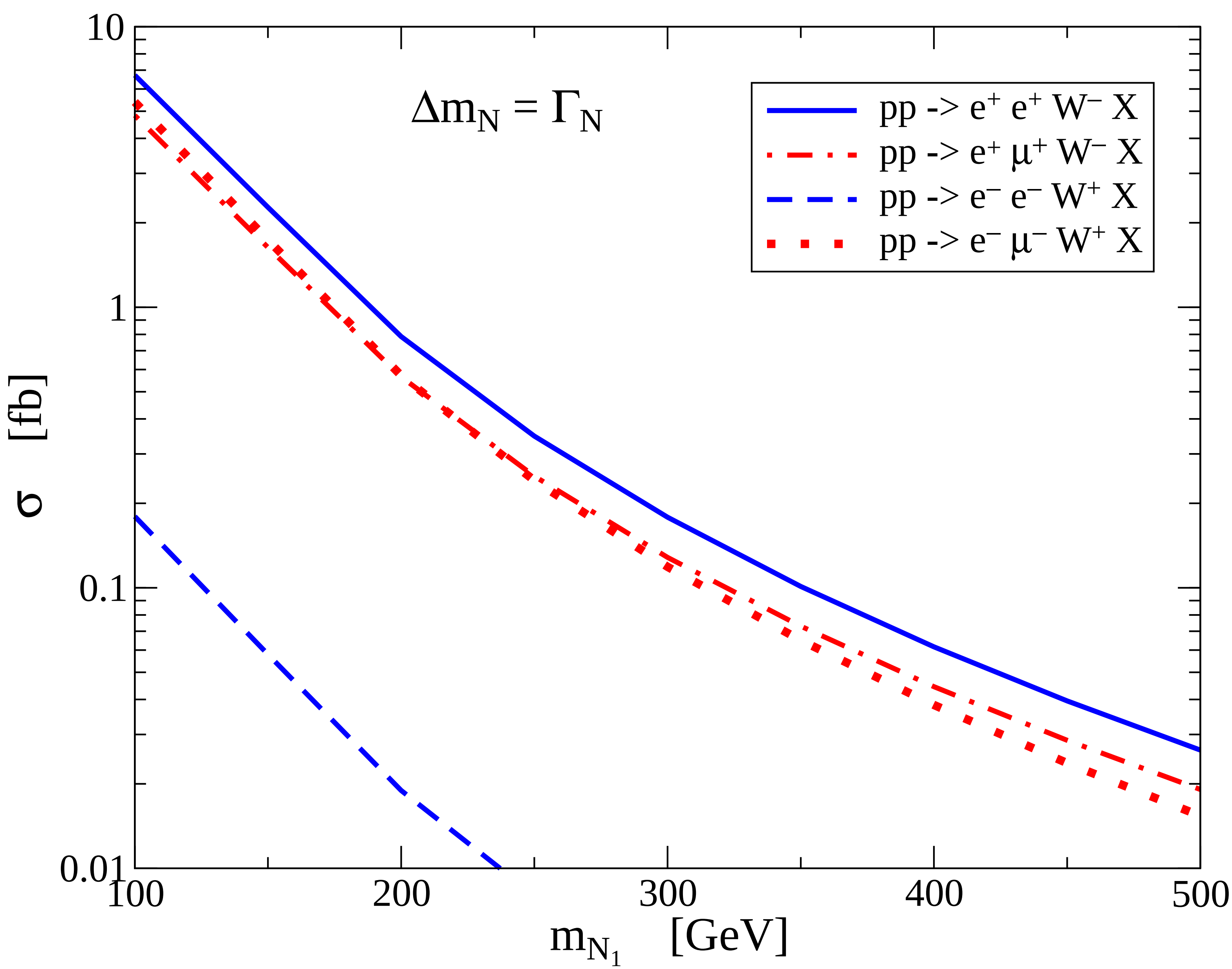
- **CP Asymmetries** [S. Bray, J.S. Lee, A.P., NPB786 (2007) 95.]

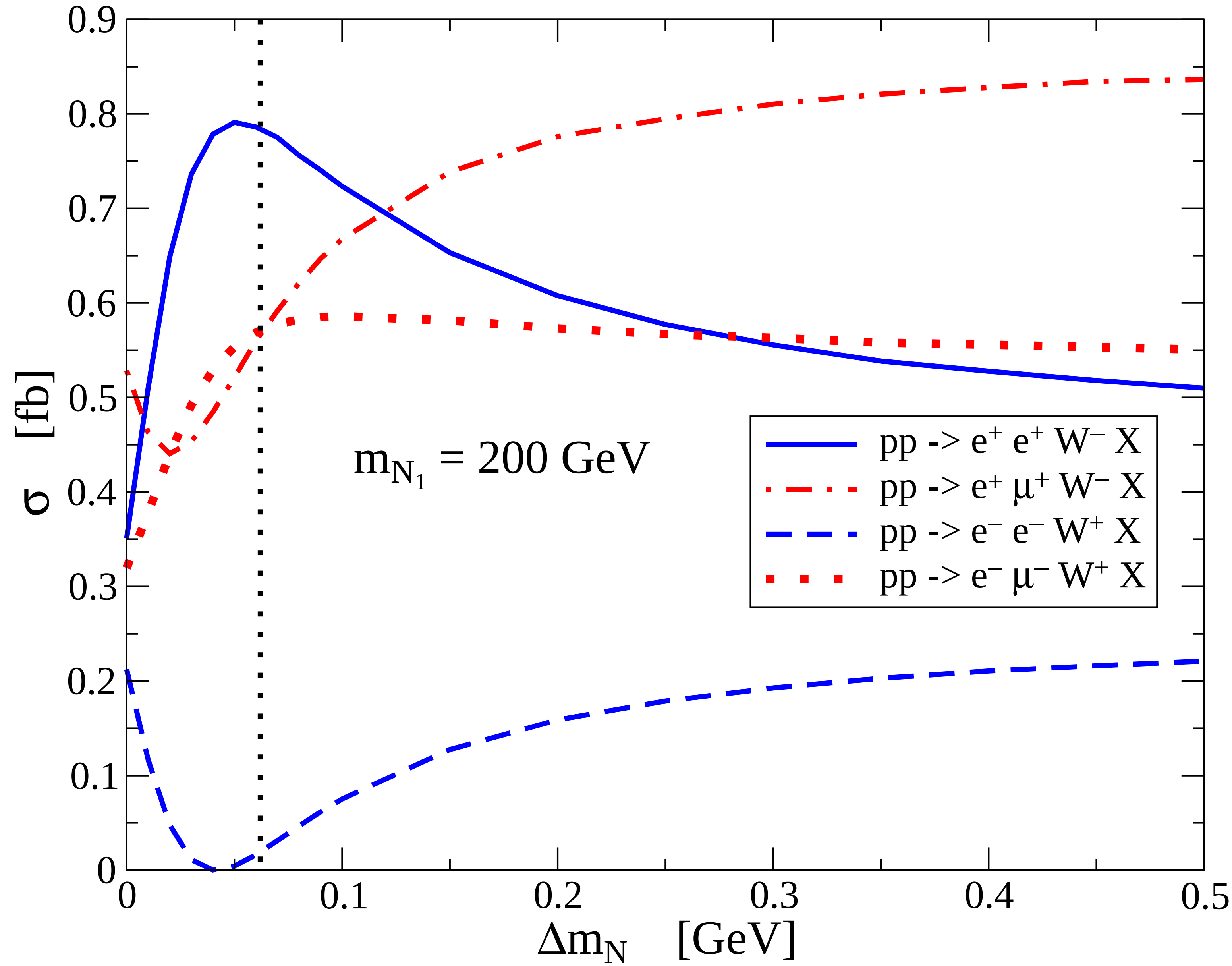
# LHC Constraints with 4.7 $\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV

[U.-K. Yang, J. Almond (Manchester–ATLAS Group), ATLAS-CONF-2012-139.]






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




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

## CP Asymmetries

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- **Lepton Number Violation:**

$$
\begin{aligned}
A_{\rm CP}({\rm LNV1}) &= \frac{\sigma(pp\to e^+e^+W^-X) - K\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^+e^+W^-X) + K\sigma(pp\to e^-e^-W^+X)}\,,\\
A_{\rm CP}({\rm LNV2}) &= \frac{\sigma(pp\to e^+\mu^+W^-X) - K\sigma(pp\to e^-\mu^-W^+X)}{\sigma(pp\to e^+\mu^+W^-X) + K\sigma(pp\to e^-\mu^-W^+X)}\,,\\
R_{\rm CP}({\rm LNV}) &= \frac{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} - \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}{\frac{\sigma(pp\to e^+e^+W^-X)}{\sigma(pp\to e^+\mu^+W^-X)} + \frac{\sigma(pp\to e^-e^-W^+X)}{\sigma(pp\to e^-\mu^-W^+X)}}\,.
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$$A_{\rm CP}({\rm 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)},$$

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

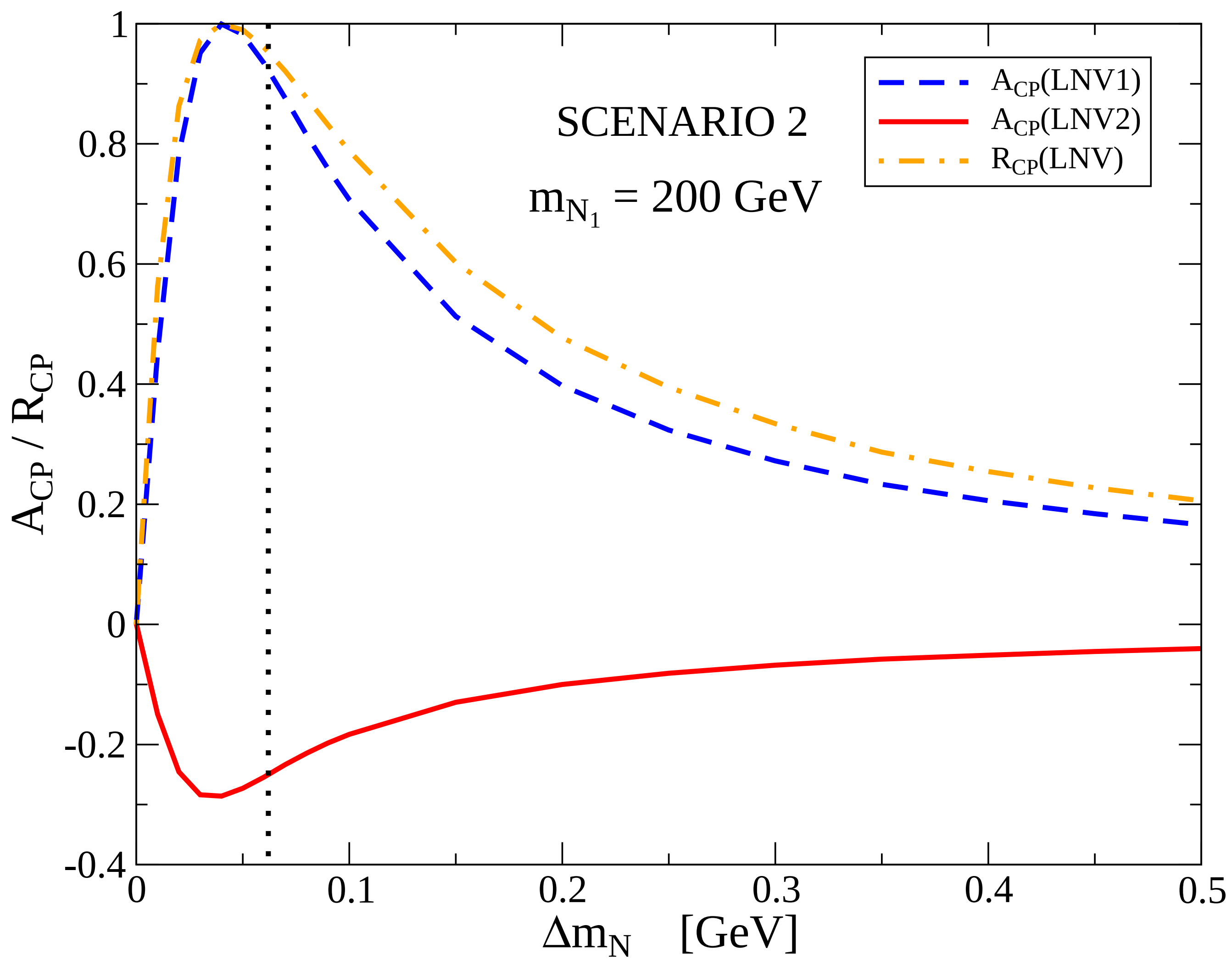
- **Lepton Flavour Violation:**

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

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

## 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

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

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

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

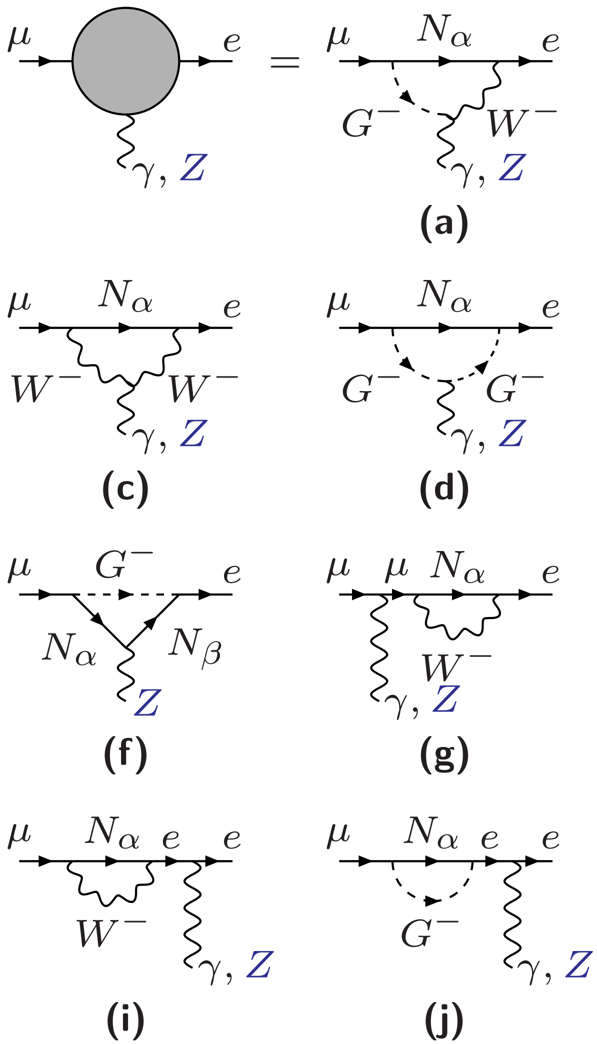
R$\tau$L with inverted light-neutrino hierarchy:

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

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

• $\mu \longrightarrow e\gamma$

[T.P. Cheng, L.F. Li, PRL45 (1980) 1908;
J.G. Körner, A.P., K. Schilcher, PLB300 (1993) 381;
J. Bernabéu, J.G. Körner, A.P., K. Schilcher, PRL71 (1993) 2695.]



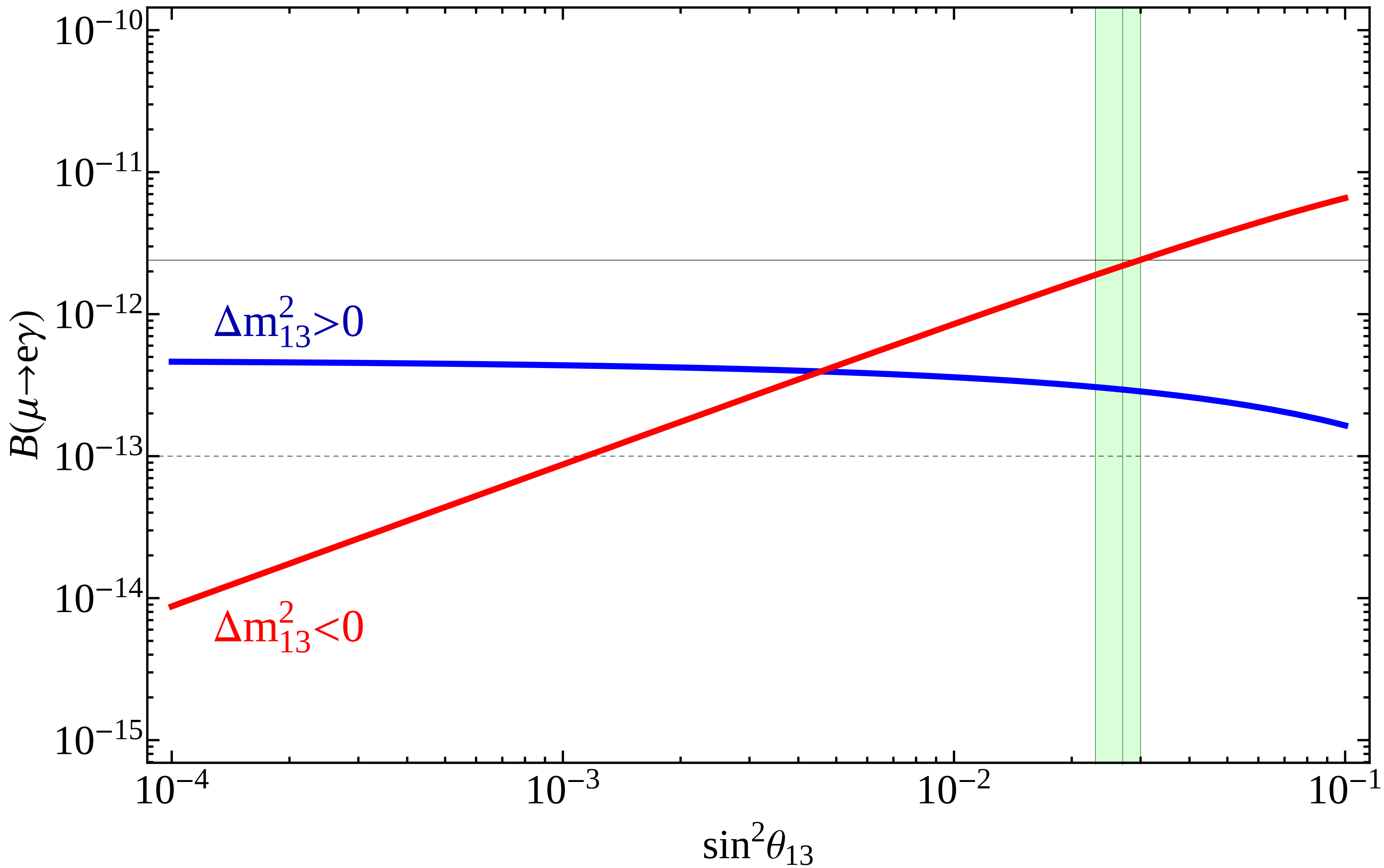

$a = b = 8 \times 10^{-3}$;
$m_N = 250$ GeV:

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

$$B^{\rm exp}(\mu \to e\gamma) \; < \; 2.4 \times 10^{-12}$$

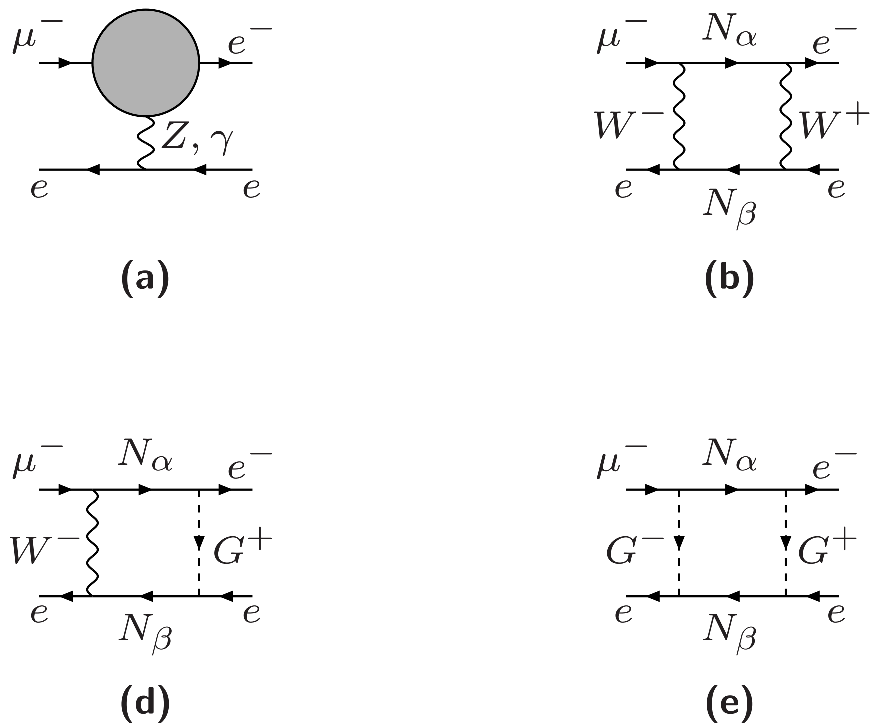
MEG sensitivity:
$B(\mu \to e\gamma) \sim 10^{-13}$–$10^{-14}$.

• $\mu \longrightarrow e\gamma$ in the Minimal R$\tau$G [F. Deppisch, A.P., PRD83 (2011) 076007.]



## • $\mu \longrightarrow eee$

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




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

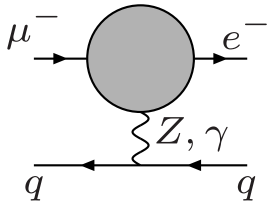
$$m_N = 250 \text{ GeV}: \quad B(\mu \to eee) \approx 1.4{\cdot}10^{-2} \times B(\mu \to e\gamma) \sim 1.4 \times 10^{-14}\,.$$

Current experimental limit: $B^{\exp}(\mu \to eee) < 10^{-12}$

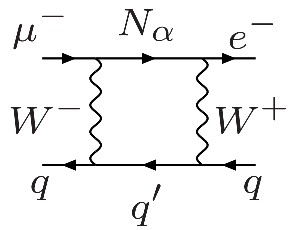
[J. L. Hewett et al, arXiv:1205.2671 [hep-ex].]

Future proposed sensitivity: $B^{\exp}(\mu \to eee) \sim 10^{-16}$

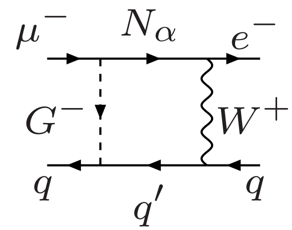
## • Coherent $\mu \to e$ Conversion in Nuclei ($^{48}_{22}$Ti, $^{197}_{79}$Au)




**(a)**

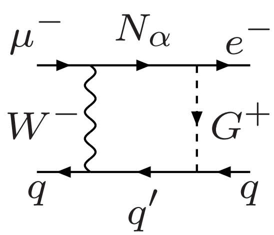



**(b)**

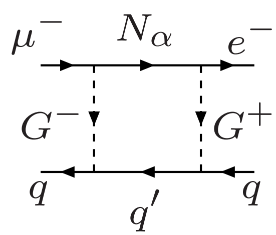



**(c)**

[A. Ilakovac, A.P., PRD80 (2009) 091902;
R. Alonso, M. Dhen, M. B. Gavela, T. Hambye, arXiv:1209.2679.]




**(d)**




**(e)**

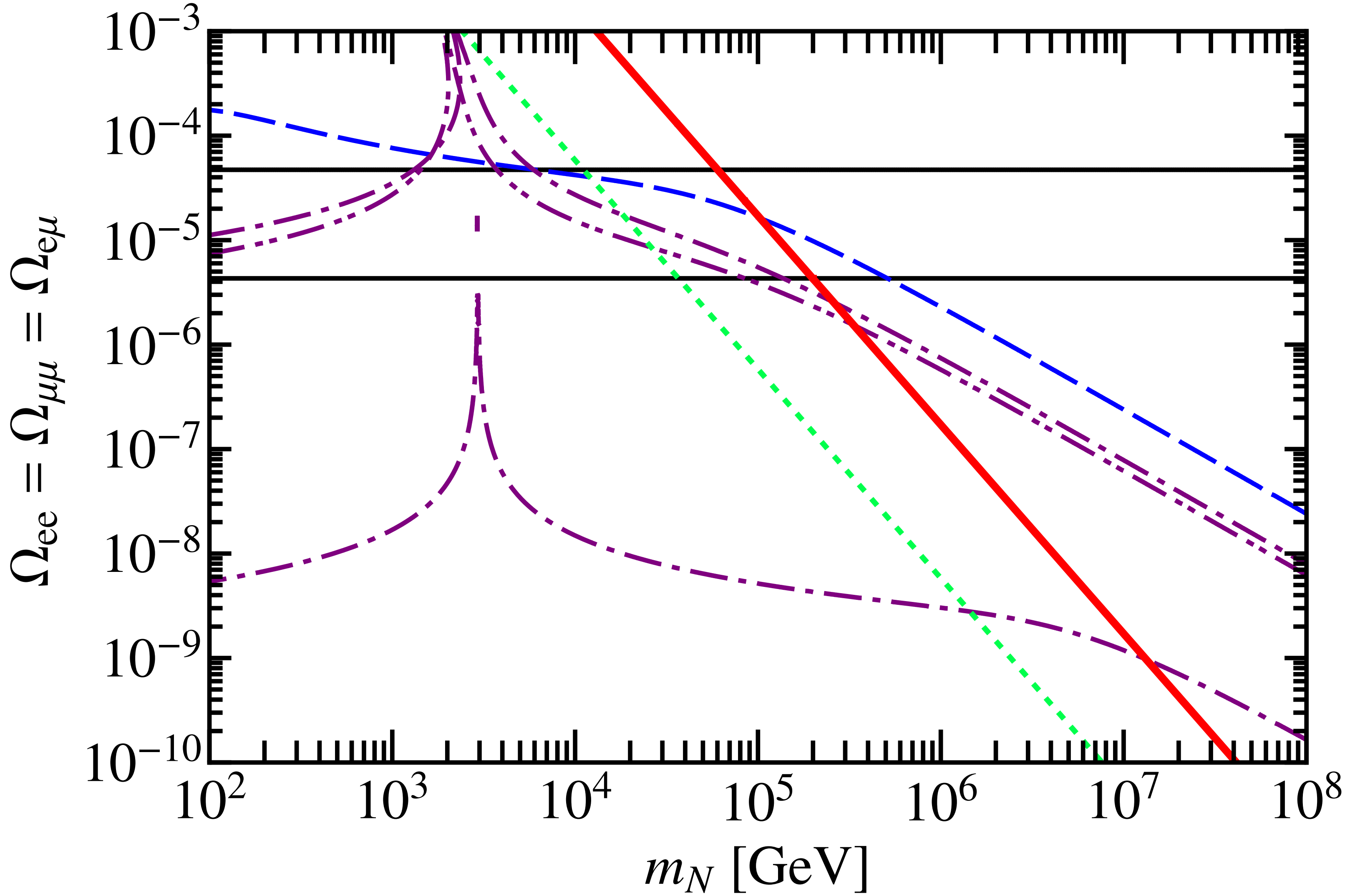
$\boldsymbol{m_N = 250}$ GeV: $\quad B_{\rm Ti}(\mu \to e) \;\approx\; 5 \times B(\mu \to e\gamma).$

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

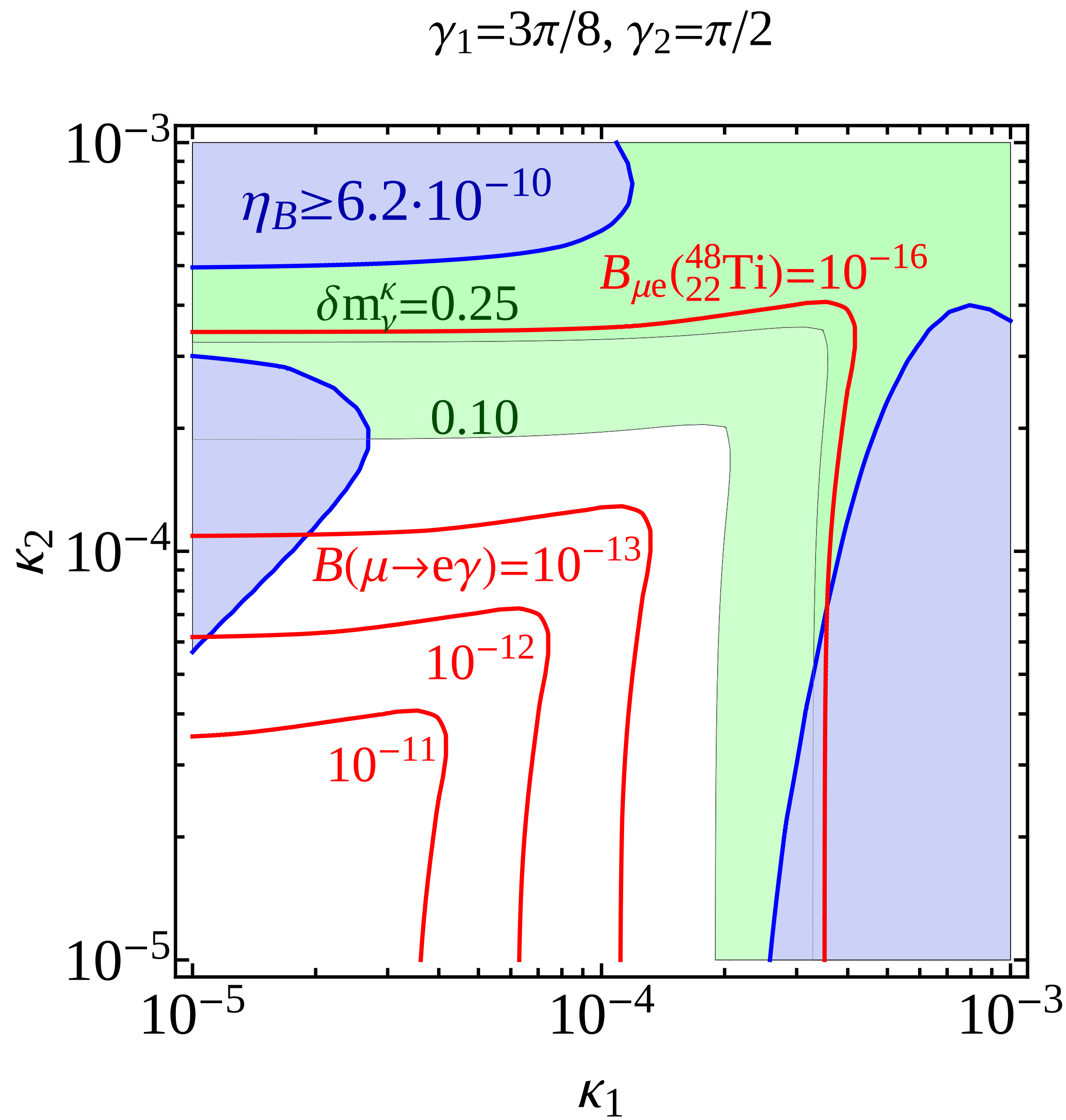
**COMET/PRISM sensitivity:** $\quad B^{\rm exp}_{\rm Ti}(\mu \to e) \;\sim\; 10^{-13} - 10^{-18}\,.$

• $\mu \longrightarrow e\gamma$, $\mu \longrightarrow eee$ and $\mu \longrightarrow e$ conversion

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



• **Resonant $\tau$-Genesis** $(m_N = 120\ \text{GeV})$ [F. Deppisch, A.P., PRD83 (2011) 076007.]



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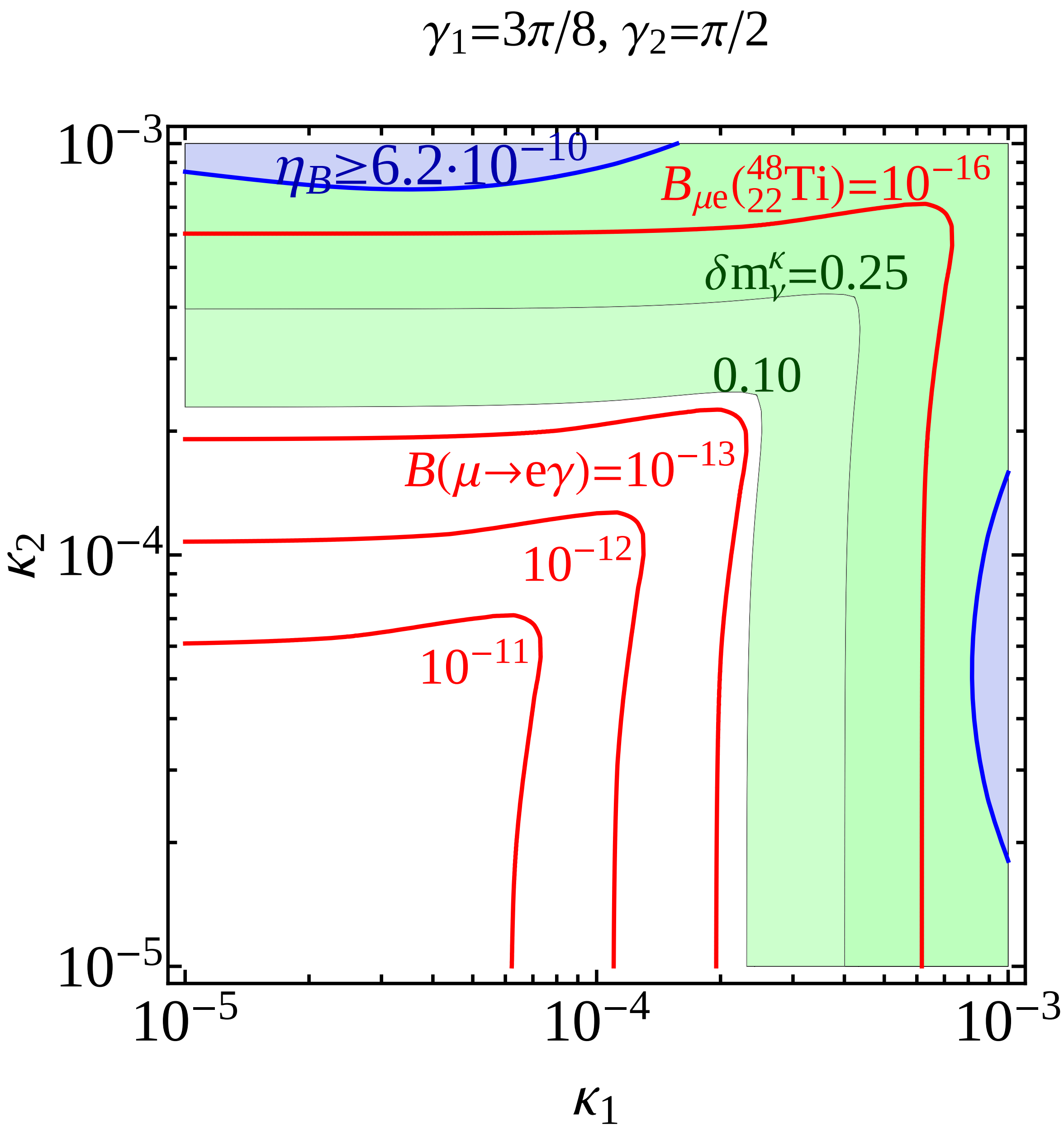

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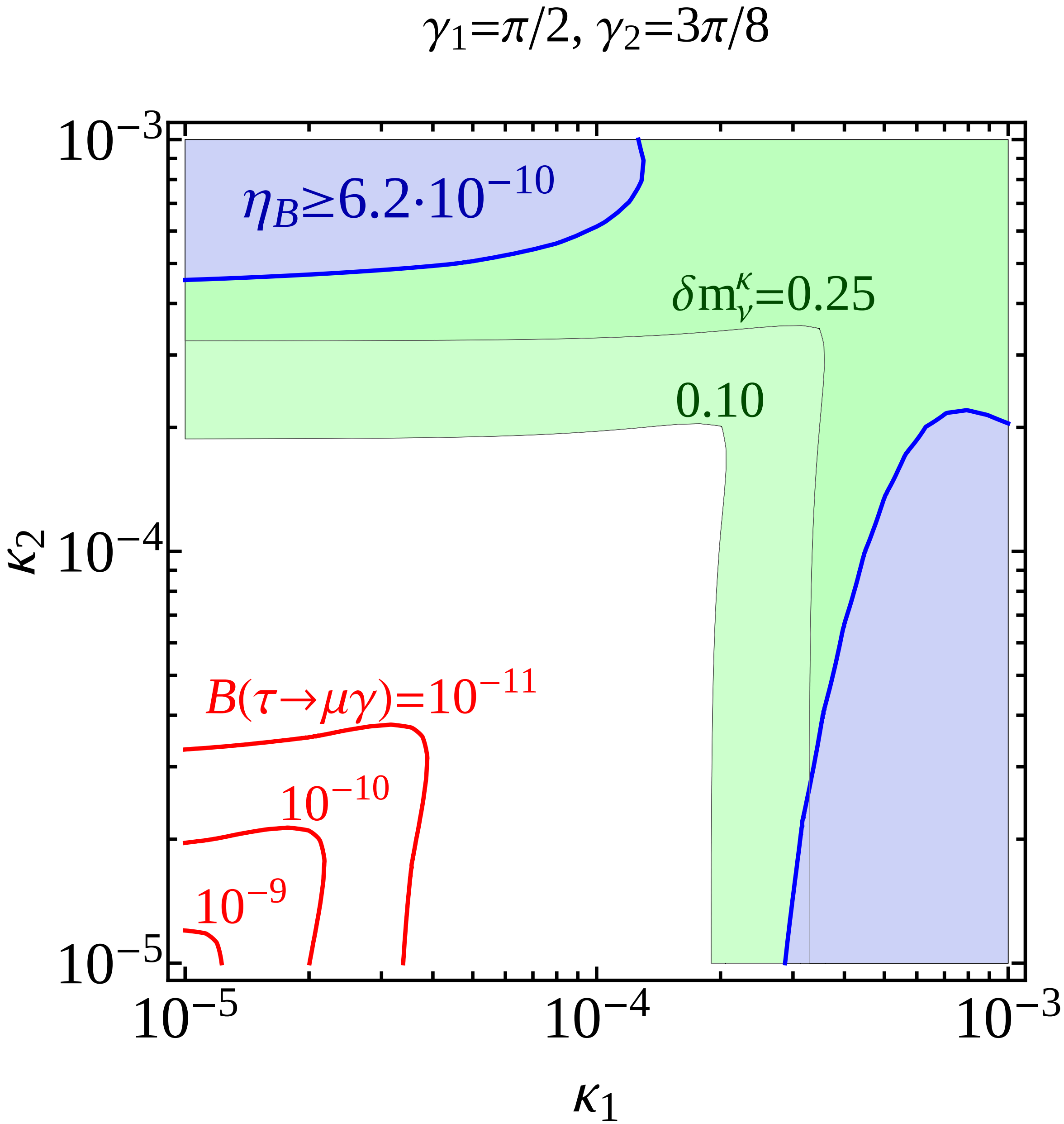

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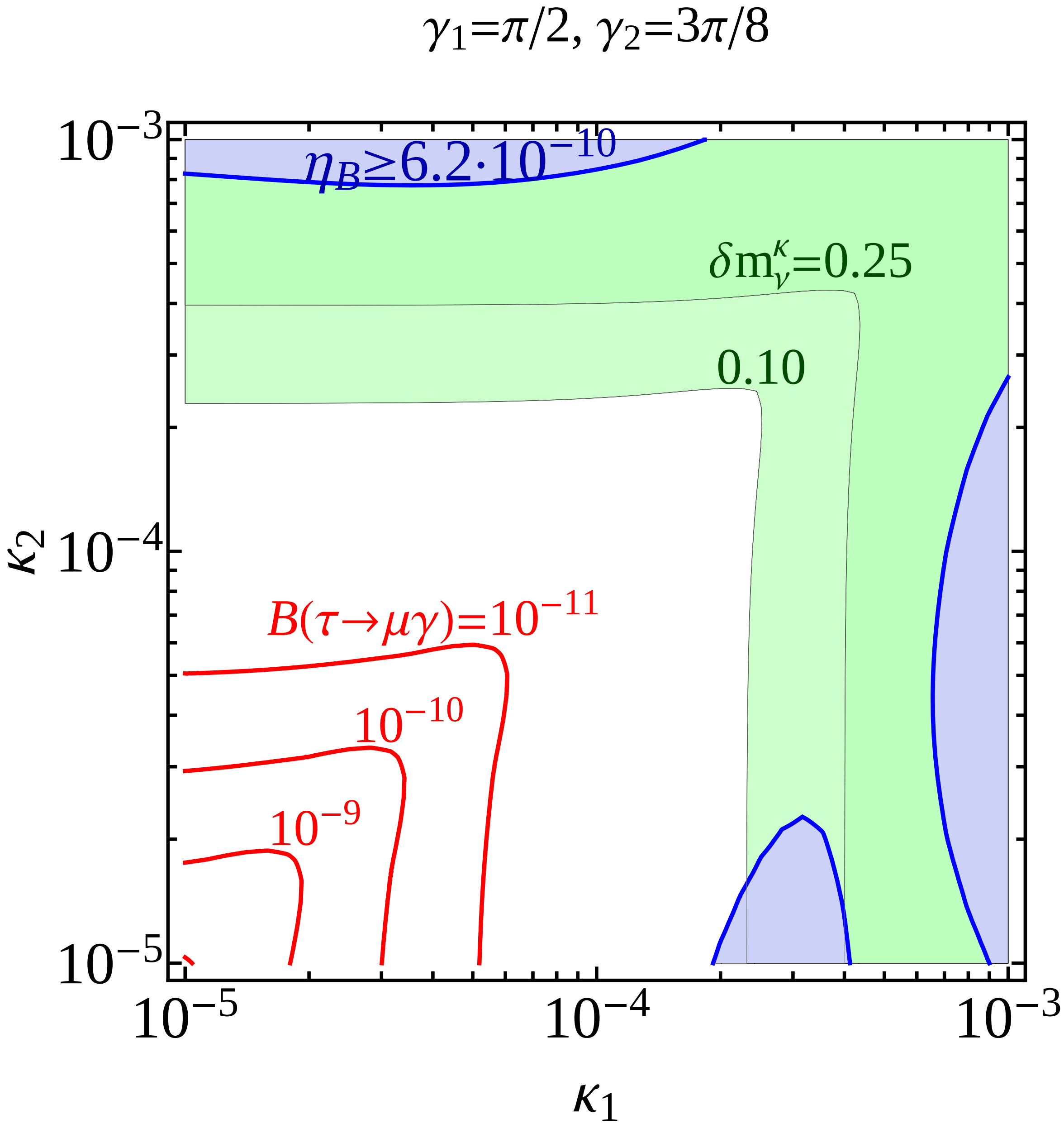

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  $\Longrightarrow \quad \geq$ 3 RHNs + Non-trivial Flavour Effects.

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

$$
\begin{aligned}
B(\mu \to e\gamma) &\sim 10^{-13}, \\
B(\mu \to e) &\approx 5 \times B(\mu \to e\gamma), \\
B(\mu \to eee) &\approx 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma), \\
|\langle m_{0\nu\beta\beta} \rangle| &\approx 0.01 \text{ eV}.
\end{aligned}
$$