Non-Unitary Lepton Mixing Matrix, Low Energy CP Violation and Leptogenesis

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Outline

- Non-Unitarity
  - Example: Sterile Neutrinos
  - Non-Unitarity from See-Saw Mechanism
  - Implications of Non-Unitarity for NuFacts
- Leptogenesis and Low Energy CP Violation: Standard Picture
- Leptogenesis and Low Energy CP Violation: Non-Unitarity

W.R., arXiv:0903.4590 [hep-ph]

Unitarity

Per definition: $U = U_\ell^\dagger \, U_\nu =$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{R_{23}(\theta_{23})} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\tilde{R}_{13}(\theta_{13};\delta)} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{R_{12}(\theta_{12})}$$

is unitary

$$U\, U^\dagger = U^\dagger U = \mathbb{1}$$

evident from

$$U_\nu^T \, m_\nu \, U_\nu = \text{diag}\;, \quad \text{where } m_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

Sterile Neutrinos and Non-Unitarity

suppose one (or more) sterile neutrino(s) present

$$\tilde{U}^T \, m_\nu \, \tilde{U} = \mathrm{diag}~, \quad \text{where } m_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} & m_{es} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} & m_{\mu s} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} & m_{\tau s} \\ m_{es} & m_{\mu s} & m_{\tau s} & m_{ss} \end{pmatrix}$$

$\tilde{U}$ is unitary, but "active" 3×3 part is not...

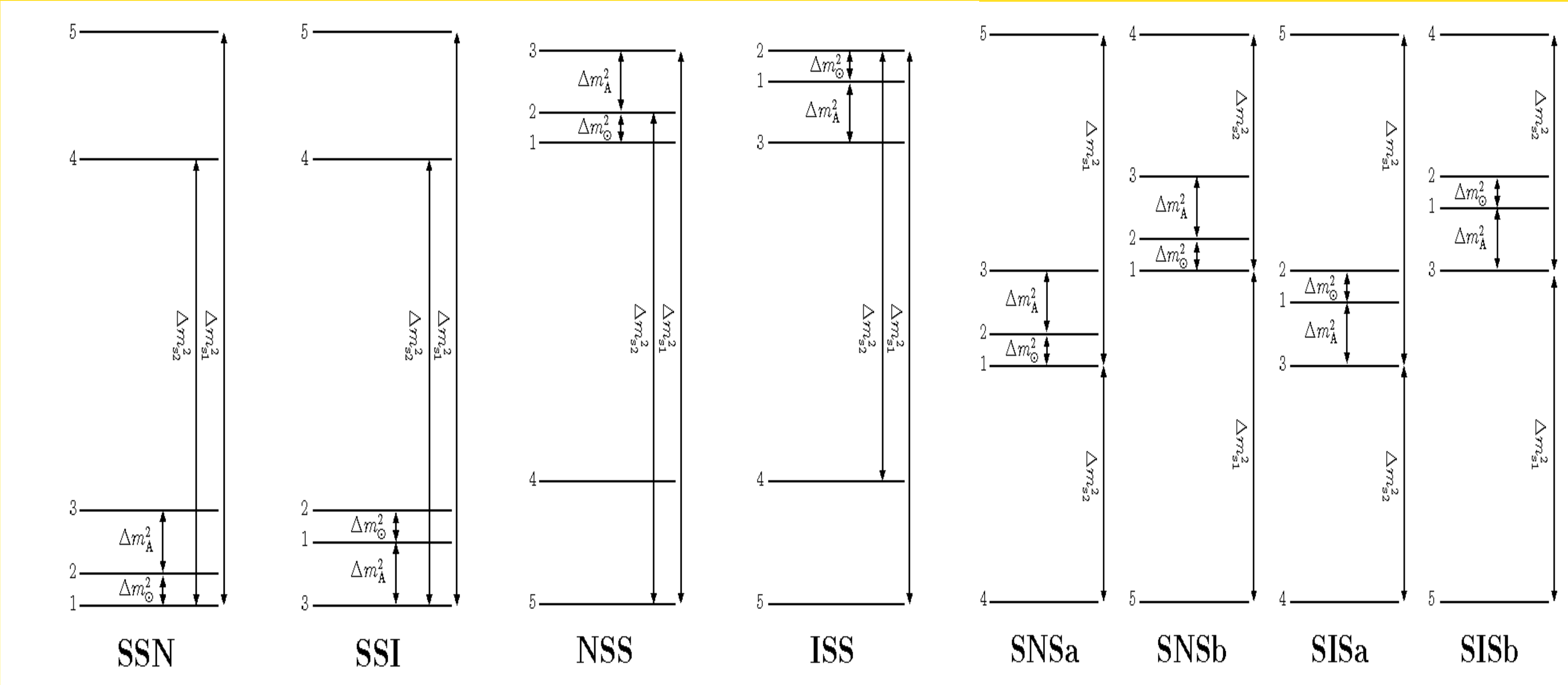
$$\tilde{U} = \begin{pmatrix} & N_{3\times 3} & & U_{es} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$\Rightarrow$ inconsistency when "unitary triangles" are constructed

$$N^\dagger N = \mathbb{1}_3 + \mathcal{O}(|U_{\alpha s}|^2)$$

Sterile Neutrinos

Take full 4×4 (or 5×5) matrix into account and try to reconstruct



mass-related observables ($0\nu\beta\beta$, KATRIN, cosmology) more useful

Goswami, W.R., JHEP **0710**, 073 (2007)

Note: SBL 3+2 fits in literature are only for SSN or NSS...

See-Saw Mechanism leads to Non-Unitarity!!

6×6 mass matrix $\mathcal{M}_\nu$

$$\mathcal{L} = \frac{1}{2} \left(\overline{\nu_L^c} \, , \; \overline{N_R} \right) \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} + h.c.$$

diagonalized by unitary matrix $\mathcal{U}^T \, \mathcal{M}_\nu \mathcal{U} = \text{diag}$

$$\begin{pmatrix} N & S \\ T & V \end{pmatrix}^T \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} N & S \\ T & V \end{pmatrix} = \begin{pmatrix} m_\nu^{\text{diag}} & 0 \\ 0 & M_R^{\text{diag}} \end{pmatrix}$$

S, T are of order m_D / M_R

$$\boxed{N^T \, m_D^T \, M_R^{-1} \, m_D \, N = m_\nu^{\text{diag}}}$$

with $N^\dagger N = \mathbb{1}_3 - S^\dagger S = \mathbb{1}_3 + \mathcal{O}(m_D^2 / M_R^2)$

`Xing, arXiv:0902.2469 [hep-ph]`

Sources of Non-Unitarity

- sterile neutrinos
- mixing with SUSY particles
- NSIs ($\leftrightarrow$ zero-distance effect $P(\nu_\alpha \to \nu_\beta, L \to 0) \neq 0$)
- see-saw mechanism(s)

useful parametrization: $\boxed{N = (\mathbb{1} + \eta)\, U_0}$

$$|\eta| \leq \begin{pmatrix} 5.5 \cdot 10^{-3} & 3.5 \cdot 10^{-5} & 8.0 \cdot 10^{-3} \\ \cdot & 5.0 \cdot 10^{-3} & 5.1 \cdot 10^{-3} \\ \cdot & \cdot & 5.1 \cdot 10^{-3} \end{pmatrix}$$

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP **0610**, 084 (2006)

<u>3 CP phases unconstrained!</u>

Sources of Non-Unitarity

$$U = U_\ell^\dagger \, U_\nu$$

source of non-unitarity: basically always U_ν

Why not U_ℓ?

For instance, $SU(2)$ singlet charged leptons in E_6 models...

CP phases from Non-Unitarity

Czakon, Gluza, Zralek, Acta Phys. Polon. B **32**, 3735 (2001); Bekman, Gluza, Holeczek, Syska, Zralek, Phys. Rev. D **66**, 093004 (2002); Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, Phys. Lett. B **649**, 427 (2007); Goswami, Ota, Phys. Rev. D **78**, 033012 (2008); Altarelli, Meloni, Nucl. Phys. B **809**, 158 (2009); Antusch, Blennow, Fernandez-Martinez, Lopez-Pavon, arXiv:0903.3986 [hep-ph]

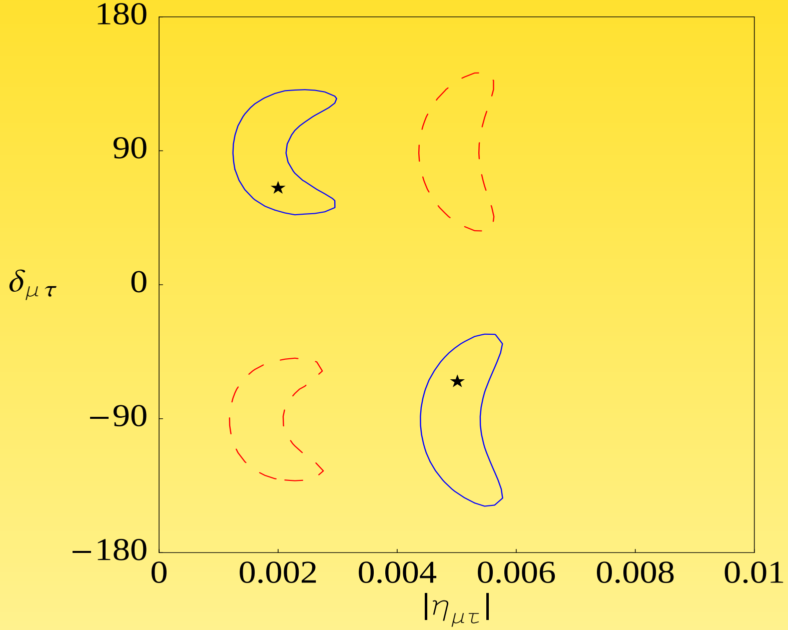
μ-τ channel at neutrino factory excellent probe

choose here: $E_\mu = 50$ GeV, $L = 130$ km, 5kt Opera-like detector

constraints on new CP phases possible for

$$|\eta_{\mu\tau}| \leq \text{few} \times 10^{-4}$$

CP phases from Non-Unitarity



Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, Phys. Lett. B **649**, 427 (2007)

CP phases from Non-Unitarity

consider asymmetries

$$A_{\alpha\beta} = \frac{P_{\alpha\beta} - P_{\overline{\alpha}\overline{\beta}}}{P_{\alpha\beta} + P_{\overline{\alpha}\overline{\beta}}}$$

With $E_\mu = 50$ GeV, $L = 130$ km, $\Delta_{ij} = \Delta m^2_{ij} \frac{L}{2E}$

$$P^{\rm SM}_{\mu\tau} \simeq \sin^2 \frac{\Delta_{31}}{2} - \left(\frac{1}{3} \sin \Delta_{31} - \frac{2\sqrt{2}}{3} \sin^2 \frac{\Delta_{31}}{2} \, |U_{e3}| \, \sin\delta \right) \Delta_{21}$$

$$P^{\rm SM}_{\overline{\mu}\overline{\tau}} \simeq \sin^2 \frac{\Delta_{31}}{2} - \left(\frac{1}{3} \sin \Delta_{31} + \frac{2\sqrt{2}}{3} \sin^2 \frac{\Delta_{31}}{2} \, |U_{e3}| \, \sin\delta \right) \Delta_{21}$$

$$\Rightarrow \boxed{A^{\rm SM}_{\mu\tau} \simeq \tfrac{2\sqrt{2}}{3} \, \Delta_{21} \, |U_{e3}| \, \sin\delta}$$

- doubly suppressed
- smaller than 10^{-4} for $|U_{e3}| = 0.1$

CP phases from Non-Unitarity

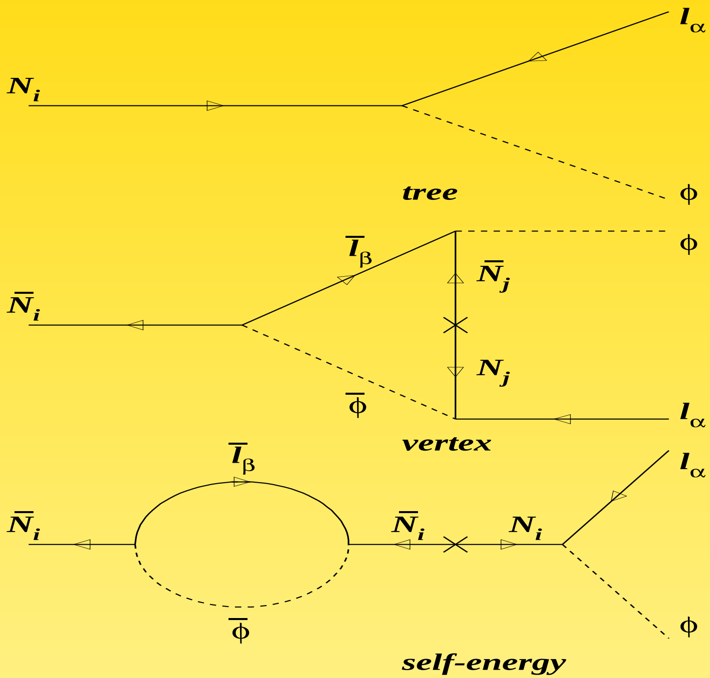
Same experimental configuration in non-unitarity case:

$$P^{\rm NU}_{\mu\tau} \simeq P^{\rm SM}_{\mu\tau} - 2\,\sin\Delta_{31}\,|\eta_{\mu\tau}|\,\sin\Phi_{\mu\tau}$$
$$P^{\rm NU}_{\overline{\mu\tau}} \simeq P^{\rm SM}_{\overline{\mu\tau}} + 2\,\sin\Delta_{31}\,|\eta_{\mu\tau}|\,\sin\Phi_{\mu\tau}$$

$$\Rightarrow \boxed{A^{\rm NU}_{\mu\tau} \simeq -4\cot\frac{\Delta_{31}}{2}\,|\eta_{\mu\tau}|\,\sin\Phi_{\mu\tau}}$$

- can be 0.1 even for $|\eta_{\mu\tau}| \simeq 10^{-4}$
- *linear in* $|\eta_{\mu\tau}|$

Leptogenesis



Baryon Asymmetry proportional to

$$\varepsilon_1 = \frac{1}{8\pi\, v^2} \frac{1}{(m_D m_D^\dagger)_{11}} \sum_{j=2,3} \mathrm{Im}\left\{ (m_D m_D^\dagger)^2_{1j} \right\} f(M_j^2/M_1^2)$$

"Unflavored Leptogenesis"

Leptogenesis: "no connection theorem"

$$Y_B \propto \mathrm{Im}\left\{(m_D m_D^\dagger)_{1j}^2\right\}$$

insert Casas-Ibarra parametrization

$$m_D = i\,\sqrt{M_R}\,R\,\sqrt{m_\nu^{\rm diag}}\,U^\dagger \quad \text{where} \quad RR^T = \mathbb{1}$$

The relevant quantity for leptogenesis is then

$$m_D m_D^\dagger = \sqrt{M_R}\,R\,\sqrt{m_\nu^{\rm diag}}\;\underbrace{U^\dagger\,U}_{=\mathbb{1}}\;\sqrt{m_\nu^{\rm diag}}\,R^\dagger\,\sqrt{M_R}$$

Does not depend on U because U is unitary!

Branco, Morozumi, Nobre, Rebelo; Rebelo; Pascoli, Petcov, W.R.

(if R is real: no leptogenesis!)

Leptogenesis

But now U is not unitary (and called N)

$$\boxed{m_D = i\,\sqrt{M_R}\,R\,\sqrt{m_\nu^{\rm diag}}\,N^\dagger}$$

and thus for leptogenesis

$$m_D m_D^\dagger = \sqrt{M_R}\,R\,\sqrt{m_\nu^{\rm diag}}\;\underbrace{N^\dagger N}_{\mathbb{1} + 2\,U_0^\dagger\,\eta\,U_0 \neq \mathbb{1}}\;\sqrt{m_\nu^{\rm diag}}\,R^\dagger\,\sqrt{M_R}$$

- depends on low energy phases!
- if R complex, suppressed by smallness of η
- $\Rightarrow$ switch off phases in R, i.e., no leptogenesis in standard case

Leptogenesis

Flavored leptogenesis:

$$\varepsilon_i^\alpha \propto \mathrm{Im}\Big\{ \big(m_D\big)_{i\alpha} \big(m_D^\dagger\big)_{\alpha j} \big(m_D m_D^\dagger\big)_{ij} \Big\}$$

- depends also in standard case on low energy phases
- now depends also on non-standard phases

Leptogenesis and Non-Unitarity

$N = (\mathbb{1} + \eta)\, U_0$ with U_0 tri-bimaximal, η only $\mu\tau$ element and normal hierarchy:

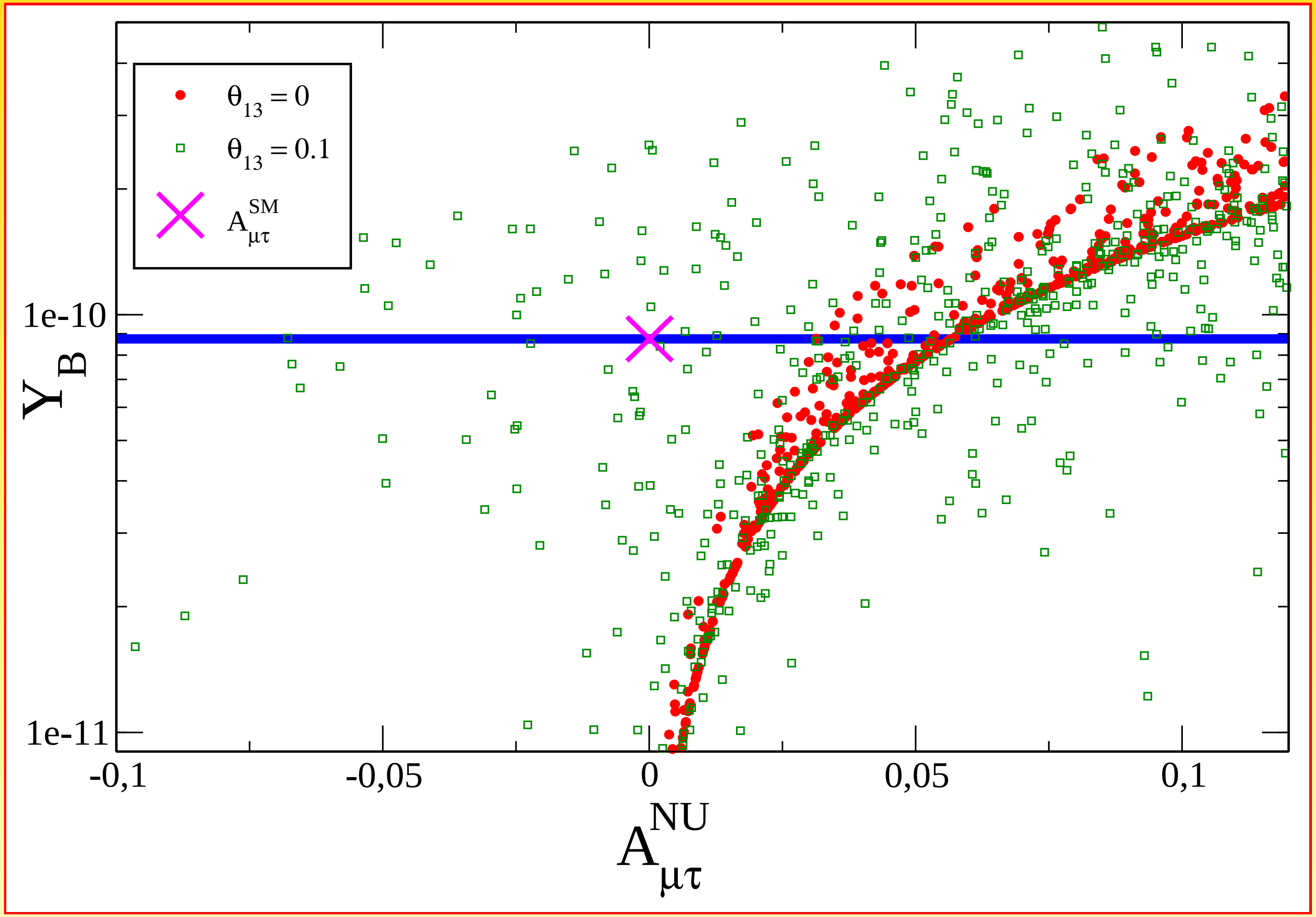
$$\varepsilon_1 \simeq \sqrt{\frac{3}{8\pi^2\, v^4}}\, \frac{M_1\, \sqrt{m_2\, m_3}}{v^2}\, \frac{(m_2 - m_3)\, c_{13}^R\, s_{12}^R\, s_{13}^R}{m_2\, R_{12}^2 + m_3\, R_{13}^2} |\eta_{\mu\tau}|\, \sin\phi_{\mu\tau}$$
$$\sim -10^{-4}\, |\eta_{\mu\tau}|\, \sin\phi_{\mu\tau}$$

and Baryon Asymmetry

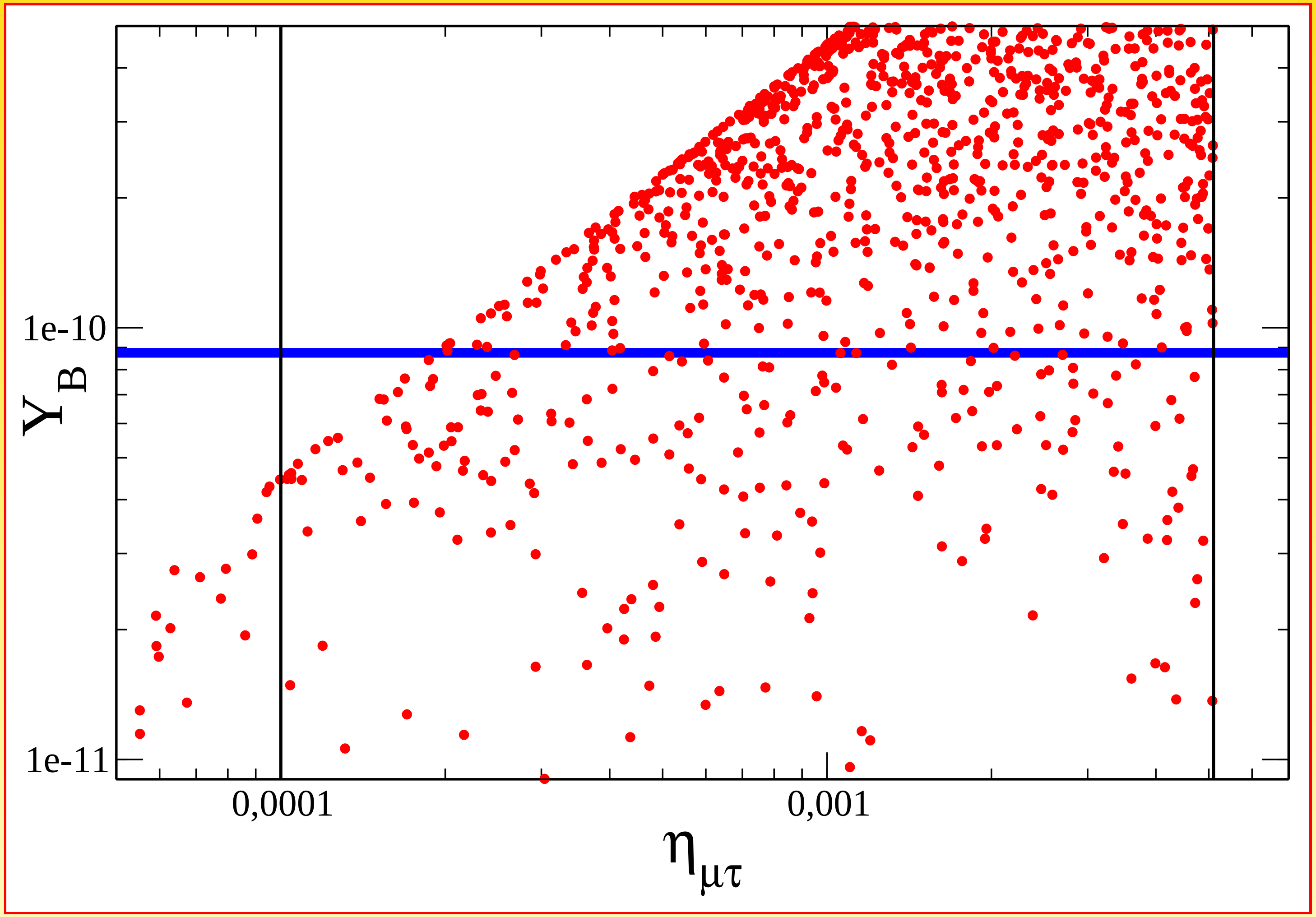
$$Y_B \simeq 1.27 \times 10^{-3}\, \varepsilon_1\, \eta(\tilde{m}_1) \stackrel{!}{=} (8.75 \pm 0.23) \times 10^{-11}$$

linear in $|\eta_{\mu\tau}|$, just as $A_{\mu\tau}^{\mathrm{NU}}$

Leptogenesis and Non-Unitarity



Leptogenesis and Non-Unitarity



See-Saw Variant (see also Valle *et al.*; Ohlsson *et al.*; Ma)

$$\mathcal{L} = \frac{1}{2}\,(\overline{\nu_L^c}\,,\ \overline{N_R}\,,\ \overline{X}) \begin{pmatrix} 0 & m_D^T & m^T \\ m_D & M_R & 0 \\ m & 0 & M_S \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \\ X^c \end{pmatrix} + h.c.$$

diagonalized by $\mathcal{U} = \begin{pmatrix} N & S & A \\ T & V & D \\ B & E & W \end{pmatrix}$ $\quad S, T = \mathcal{O}(m_D/M_R)$, $\quad A, B = \mathcal{O}(10^{-2})$

- N_R do not couple to new guys: leptogenesis unchanged
- $m = \mathcal{O}(10^{-13})$ GeV and $M_S = \mathcal{O}(10^{-15})$ GeV
- contribution to m_ν of order $m \times (A, B) \ll m_D^2/M_R$
- $N^T\, m_D^T\, M_R^{-1}\, m_D\, N = m_\nu^{\rm diag}$, with $N N^\dagger + A A^\dagger + S S^\dagger \simeq N N^\dagger + A A^\dagger = \mathbb{1}$
- $N = (\mathbb{1} + \eta)\, U_0$ gives $2\eta = -A A^\dagger$

Variant of Texture

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & m^T \\ m_D & M_R & 0 \\ m & 0 & M_S \end{pmatrix}$$

now with m_D, $m = \mathcal{O}(\mathrm{MeV})$, $M_R = \mathcal{O}(\mathrm{TeV})$ and $M_S = \mathcal{O}(10^2)$ eV

sequential mass matrix in scenarios with extra compact spacelike dimensions:

$$\mathcal{M}_\nu^{\mathrm{KK}} = \begin{pmatrix} 0 & m^{(0)} & m^{(-1)} & m^{(1)} & m^{(-2)} & \cdots \\ m^{(0)} & \varepsilon & 0 & 0 & 0 & \cdots \\ m^{(-1)} & 0 & \varepsilon - \frac{1}{R} & 0 & 0 & \cdots \\ m^{(1)} & 0 & 0 & \varepsilon + \frac{1}{R} & 0 & \cdots \\ m^{(-2)} & 0 & 0 & 0 & \varepsilon - \frac{2}{R} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Bhattacharya, Dey, Mukhopadhyay, arXiv:0907.0099 [hep-ph]

Summary

- non-unitarity general property of many extensions of standard 3-neutrino picture
- not from usual high-scale see-saw $\Rightarrow$ observation of non-unitarity rules out standard high scale see-saw
- rich phenomenology possible
- can evade "no-connection theorem" in leptogenesis