Leptogenesis in left-right symmetric theories

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ν masses and mixing, Les Houches
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- Motivation
- Model + Strategy
- Results on Y_B
- ~~CP~~ phases and $0\nu\beta\beta$
- Conclusion + Outlook

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hep-ph/0104228
hep-ph/0105175

MOTIVATION

- Baryogenesis in SM does not work

- Neutrino oscillation needs non SM physics
  ↓
  Model predicts heavy neutrinos

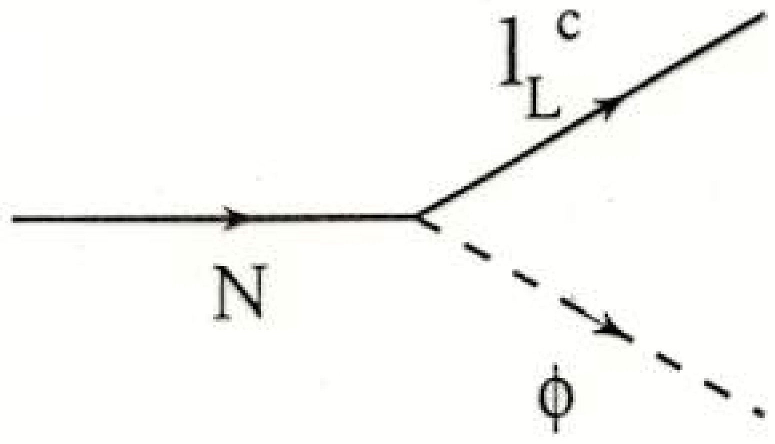
- Leptogenesis explains $Y_B \sim 10^{-10}$ through decay of heavy neutrinos

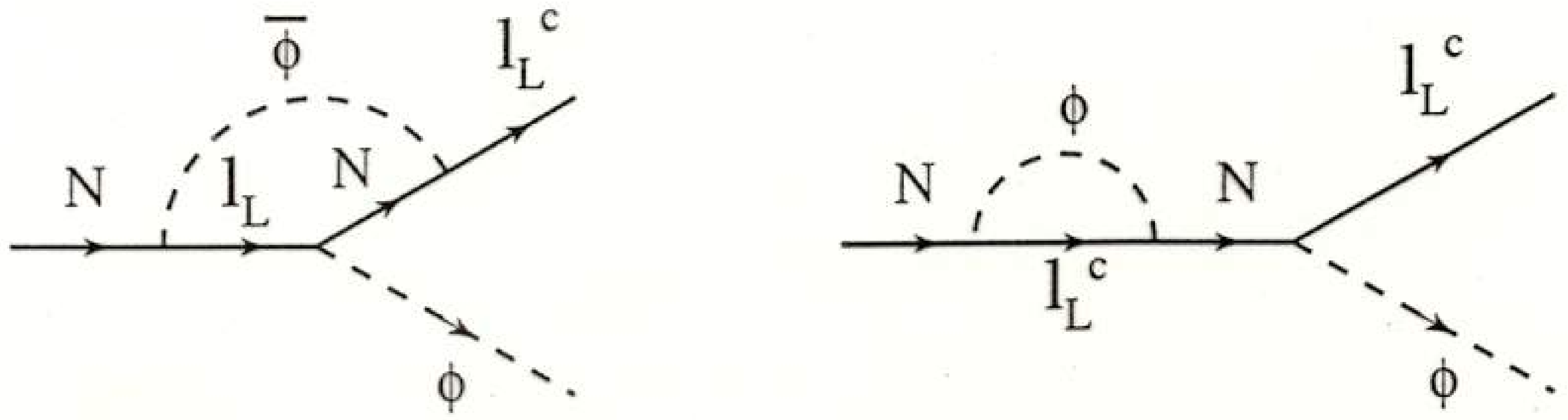
? Does your model for neutrino mass also produce correct baryon asymmetry ?

Ellis, Lola, Nanopoulos 99 / Berger + Brahmachari 99 / Lazarides, Vlachos 99 / Barbieri et al 99 / Berger 00 / Buchmüller, Plümacher 99 / Jeannerat, Khalil, Lazarides 00 / Kang, Kang Sarkar 00 / Goldberg 00 / Nezri + Orloff 00 / Falcone, Tramontano 01 / Nielsen, Takanishi 01 / Buchmüller + Yanagida 98 / Hirsch + King 01

Leptogenesis á la Fukugita + Yanagida:

Radiative corrections create lepton asymmetry





$$\varepsilon_1 = \frac{\Gamma(N_1 \rightarrow \ell^c \Phi) - \Gamma(N_1 \rightarrow \ell \Phi^+)}{+}$$

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

where $f\left(M_j^2 / M_1^2 \right) \simeq \frac{3}{2} \frac{M_1}{M_j}$ for $M_j^2 >> M_1^2$

<u>from coupling:</u>

$$-\mathcal{L} = \overline{\ell_{\alpha L}} \frac{\Phi}{\langle \Phi \rangle} m_{D\alpha\beta} N_{\beta R}$$

$$Y_B = a\, Y_L = a \frac{1}{g^*} \varkappa\, \varepsilon_1 \qquad \text{where}$$

- $$a = \frac{c}{c-1} \simeq -0.55$$

$$c = \frac{8N_f + 4N_H}{22N_f + 13N_H} \simeq 0.35 \quad \text{for} \quad \begin{array}{l} N_f = 3 \\ N_H = 1, 2 \end{array}$$

Fraction of lepton asymmetry Y_L converted into baryon asymmetry Y_B (sphaleron)

- $g^* \simeq 110$

\# massless degrees of freedom @ $T = M_1$

- $\varkappa$: Dilution factor

$$\ell^c \phi \longrightarrow \ell \phi^+ \longleftrightarrow N_1 \longrightarrow \ell^c \phi$$

$$\varkappa \simeq \begin{cases} \sqrt{0.1k}\, \exp\left\{-\frac{4}{3} \sqrt[4]{0.1k}\right\} & k \gtrsim 10^6 \\ \frac{0.3}{k(\ln k)^{0.6}} & 10 \lesssim k \lesssim 10^6 \\ \frac{1}{2\sqrt{k^2+9}} & 0 \lesssim k \lesssim 10 \end{cases}$$

$$k = \frac{\Gamma_1}{H(T=M_1)} = \frac{(m_D^+ m_D)_{11} M_1}{8\pi v^2} \frac{M_{Pl}}{1.66\sqrt{g^*} M_1^2} \lesssim 10$$

Leptogenesis and Neutrino mixing

1) $m_\nu = m_L - \tilde{m}_D M_R^{-1} \tilde{m}_D^T$

$\simeq - \tilde{m}_D^T M_R^{-1} \tilde{m}_D$ (in most works)

left-handed triplet neglected !?

2) m_ν light left-handed $\longleftrightarrow$ Oscillation

M_R heavy right-handed $\longleftrightarrow$ Leptogenesis

Is there a connection?

→ Left-Right Symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$\psi_L : (2,1,-1)$ lepton doublet

$\psi_R : (1,2,-1)$ lepton doublet

$\Phi : (2,2,0)$ Higgs bi-doublet $\tilde{m}_D$

$\Delta_R : (1,3,2)$ Higgs triplet M_R

$\Delta_L : (3,1,2)$ Higgs triplet m_L

$$-\mathcal{L} = \overline{\psi_{\alpha L}}\, h_{\alpha\beta}\, \Phi\, \psi_{\beta R} + f_{\alpha\beta}\left[\overline{\psi^c_{\alpha L}}\, \varepsilon\, \vec{\Delta}_L \vec{\tau}\, \psi_{\beta L} + (L \leftrightarrow R)\right]$$

SSB: $\langle \Phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$ $\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$

$\kappa^2 + \kappa'^2 = v^2$ and $\frac{\kappa}{\kappa'} \simeq \frac{m_t}{m_b} \longrightarrow \kappa \simeq v$

Mass matrix $\begin{pmatrix} v_L f & v h \\ v h^T & v_R f \end{pmatrix}$ See-saw: $v_R \gg v_L, v$

In general: $\boxed{v_L v_R = \gamma M_W^2}$ where $\gamma = \mathcal{O}(1)$

Strategy:

$$m_\nu = m_L - \tilde{m}_D M_R^{-1} \tilde{m}_D^T$$

$v_L f = m_L \qquad v_R f = M_R$

$v_L v_R = \gamma M_W^2$

$$m_\nu = f\left(v_L - \tilde{m}_D \frac{f^{-1}}{\gamma M_W^2} \tilde{m}_D^T\right)$$

- LMA or SMA or QVO
- hierarchical m_i
- $\tilde{m}_D = m_{up}, m_{down}, m_{lepton}$

$$v_R f = M_R$$

Diagonalize

$$Y_B$$

Free parameters: $\alpha, \beta \longrightarrow (m_\nu)_{ee}$: $0\nu\beta\beta$

$\delta \longrightarrow \cancel{CP}$: Oscillation

(m_1)

„type II see-saw":

$$m_\nu = m_L - \tilde{m}_D M_R^{-1} \tilde{m}_D^T$$

$$R_{max} = \frac{|\tilde{m}_D M_R^{-1} \tilde{m}_D^T|}{|m_L|} = \frac{m^2/v_R}{v_L} = \frac{m^2}{\gamma M_W^2}$$

$$\simeq \begin{cases} \mathcal{O}(1) & \text{for } \tilde{m}_D = m_{up} \\ 0 & \text{for } \tilde{m}_D = m_{down}, m_{lepton} \end{cases}$$

1. $\tilde{m}_D = m_{up}$ hep-ph/0104228

SO(10)

$$M_R = \frac{v_R}{v_L} \overline{m_\nu}$$

where $$(\overline{m_\nu})_{ij} = \begin{cases} (m_\nu)_{ij} & (i,j) \neq (3,3) \\ (m_\nu)_{33} + S & i = j = 3 \end{cases}$$

$$S \sim \frac{M_W m_t}{v_R} \sim 10^{-2}\, eV$$

2. $\tilde{m}_D = m_{down}, m_{lepton}$ hep-ph/0105175

SU(5)

$$M_R = \frac{v_R}{v_L} m_\nu$$

i.e. m_L dominates m_ν

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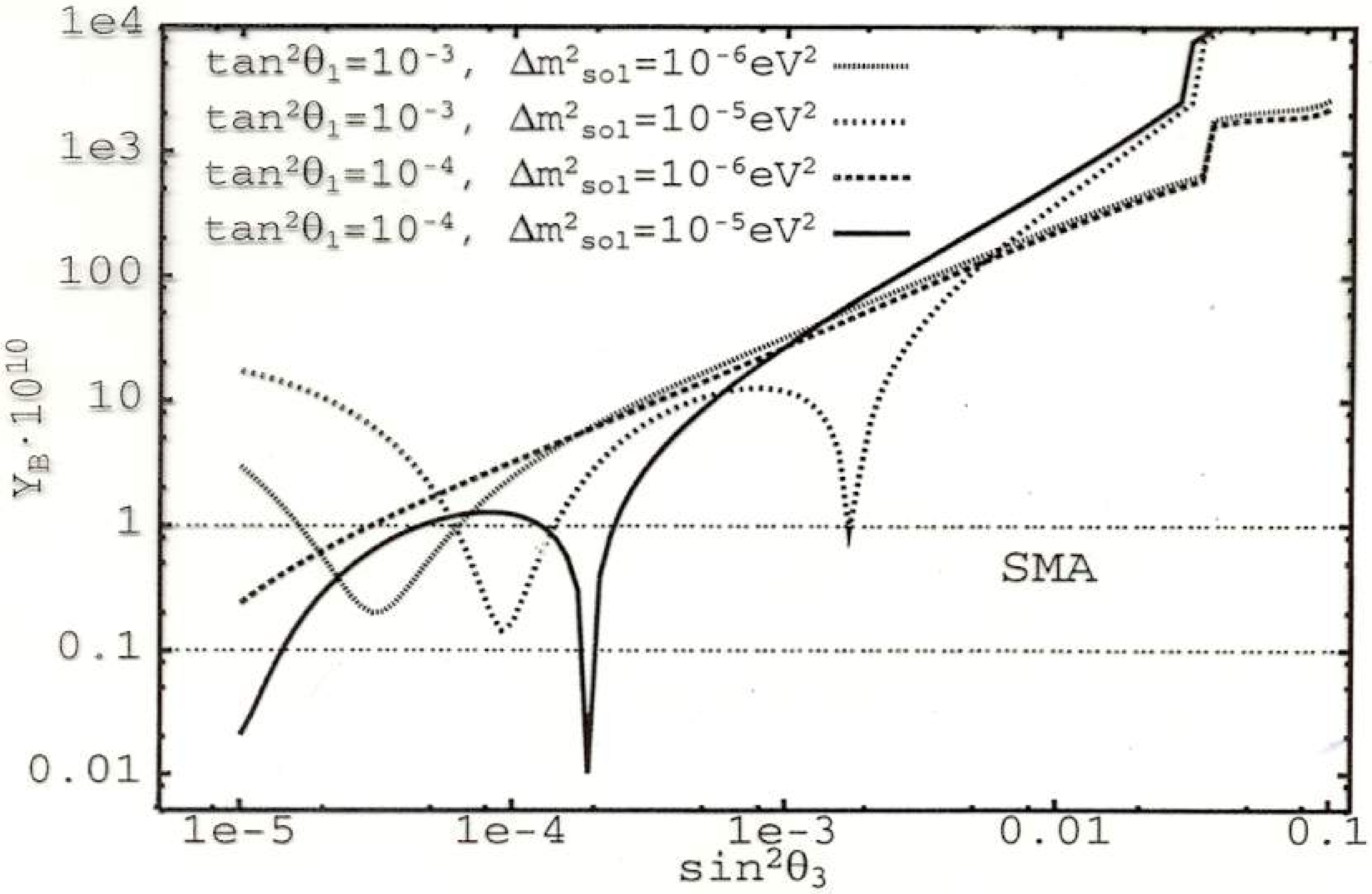
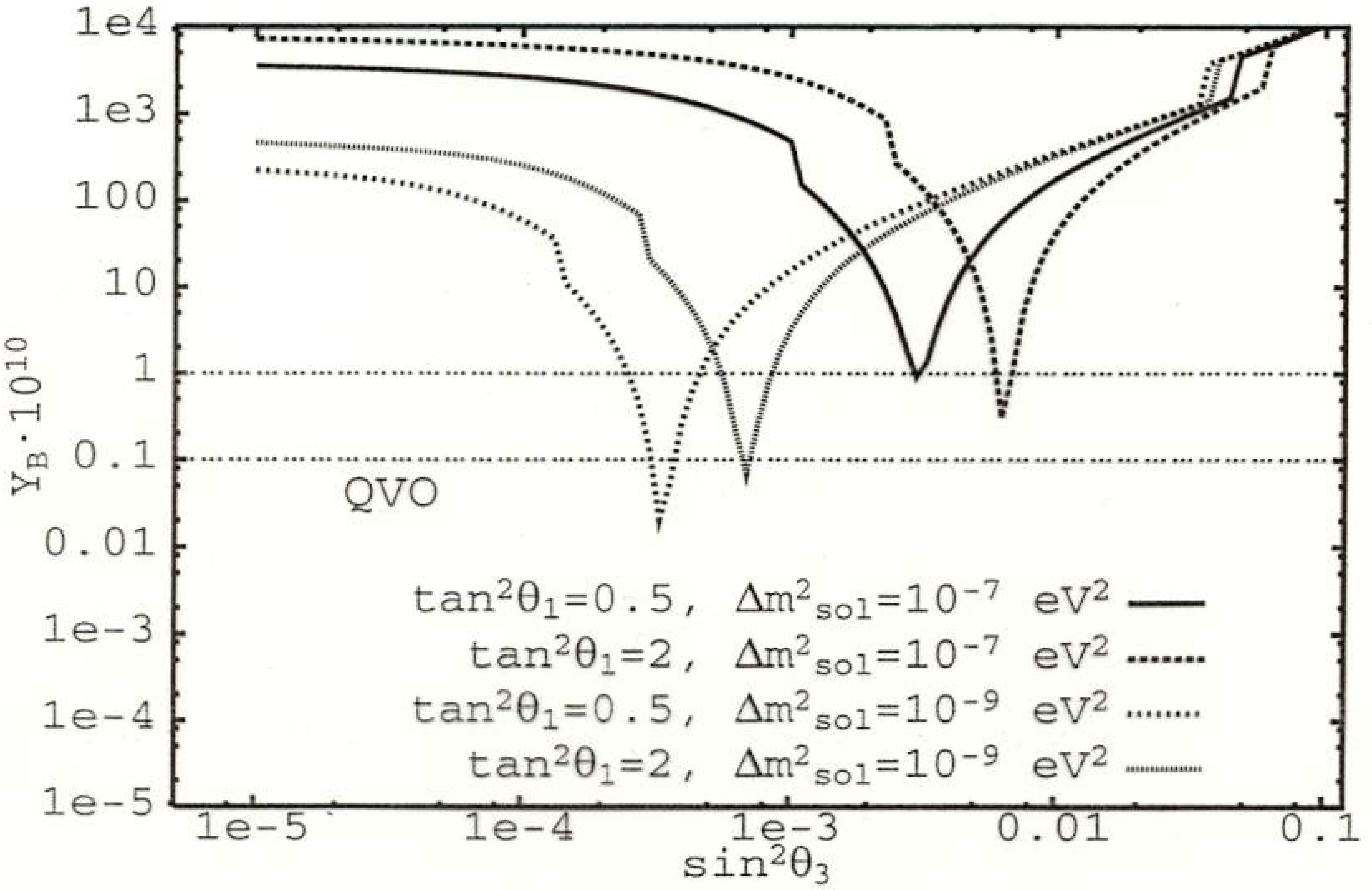
HIERARCHICAL SCHEME

DIRAC = up quark

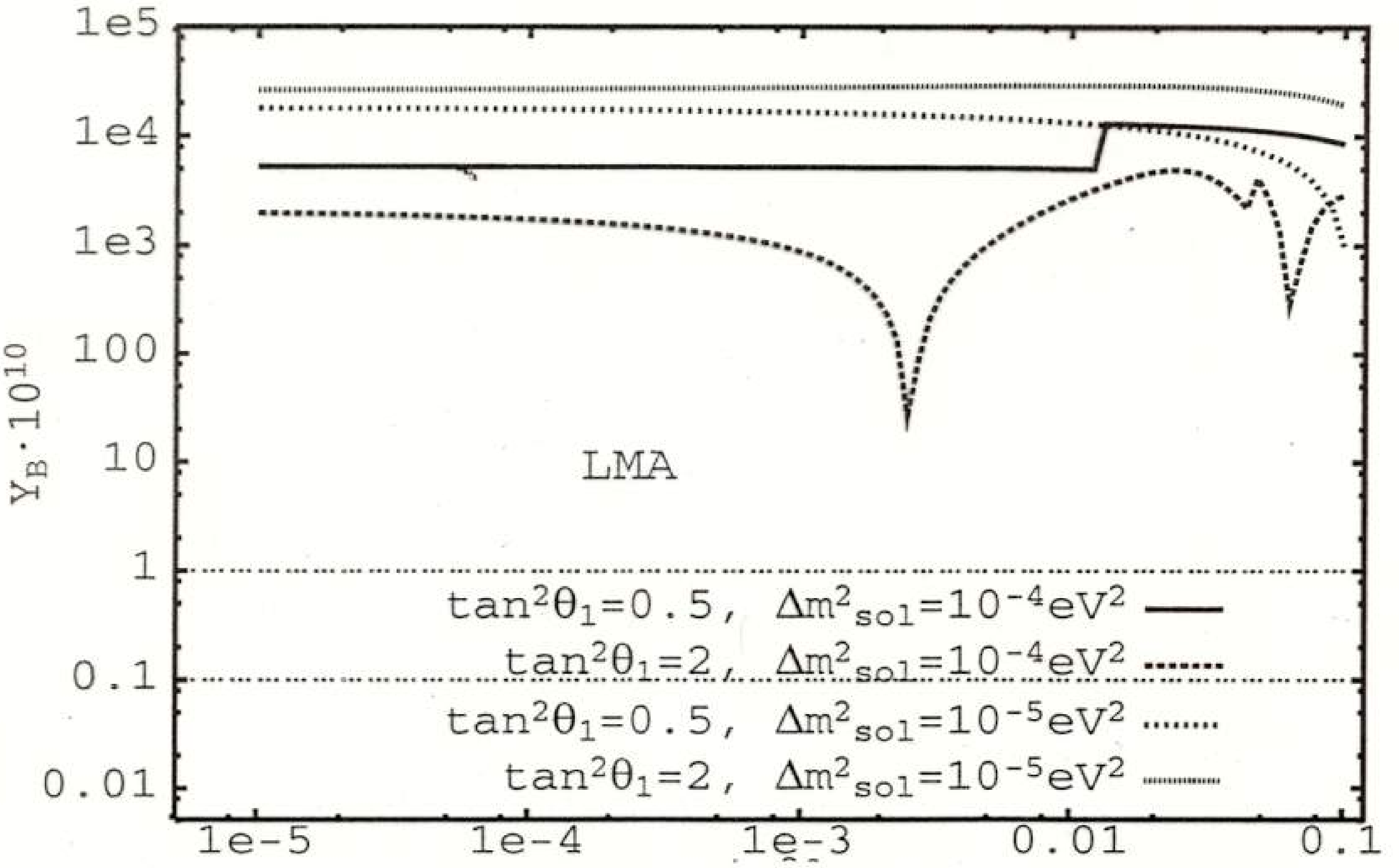
$3\alpha = 4\beta = 6\delta = \pi$



$5\alpha = 4\beta = 6\delta = \pi$



$5\alpha = 6\beta = 3\delta = \pi$



$\tilde{m}_D = m_u \simeq \mathrm{diag}(0,0,m_t)$ $\quad v_R = 10^{15}$ GeV $\quad \gamma = 1$

② Dirac = down quark
charged lepton

$M_R = \frac{v_R}{v_L} m_\nu$

$$U_L = \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 e^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 e^{i\delta} & c_1 c_2 - s_1 s_2 s_3 e^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 e^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix} P$$

$$P = \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)})$$

$$\Rightarrow P(\nu_\alpha \to \nu_\beta) = P(\nu_\alpha \to \nu_\beta, \delta)$$

$$\langle m \rangle = \langle m \rangle (\alpha, \beta)$$

$$U_L \simeq \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & s_3 e^{-i\delta} \\ -\frac{1}{2}(1 + s_3 e^{i\delta}) & \frac{1}{2}(1 - s_3 e^{i\delta}) & 1/\sqrt{2} \\ \frac{1}{2}(1 - s_3 e^{i\delta}) & -\frac{1}{2}(1 + s_3 e^{i\delta}) & 1/\sqrt{2} \end{pmatrix} P$$

for LMA, QVO

$$U_L \simeq \begin{pmatrix} 1 & 0 & s_3 e^{-i\delta} \\ -\frac{1}{2} s_3 e^{i\delta} & 1/\sqrt{2} & 1/\sqrt{2} \\ -\frac{1}{2} s_3 e^{i\delta} & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} P$$

for SMA

With approximate forms of $U_L = U_R$:

$$K \simeq 1.5 \left(\frac{10^{-6}\,eV}{m_1}\right)\left(\frac{10^{15}\,GeV}{v_R}\right)^2 \gamma \left(\frac{m}{GeV}\right)^2 \begin{cases} 1-2\,s_3\,c_\delta & \text{LMA QVO} \\ s_3^2 & \text{SMA} \end{cases}$$

Fulfilled for typical parameters; use $\mathcal{H} \lesssim 1/6$:

$$\boxed{Y_B \cdot 10^{10} \lesssim 4.1 \left(\frac{m}{GeV}\right)^2 \frac{1}{1-2s_3c_\delta}\left\{(s_{2\alpha}+4s_3\,s_\delta\,c_{2\alpha})\frac{m_1}{\sqrt{\Delta m^2_\odot}} + 2\left(s_{2(\beta+\delta)}-2s_3\,s_{2\beta+\delta}\right)\frac{m_1}{\sqrt{\Delta m^2_A}}\right\}}$$

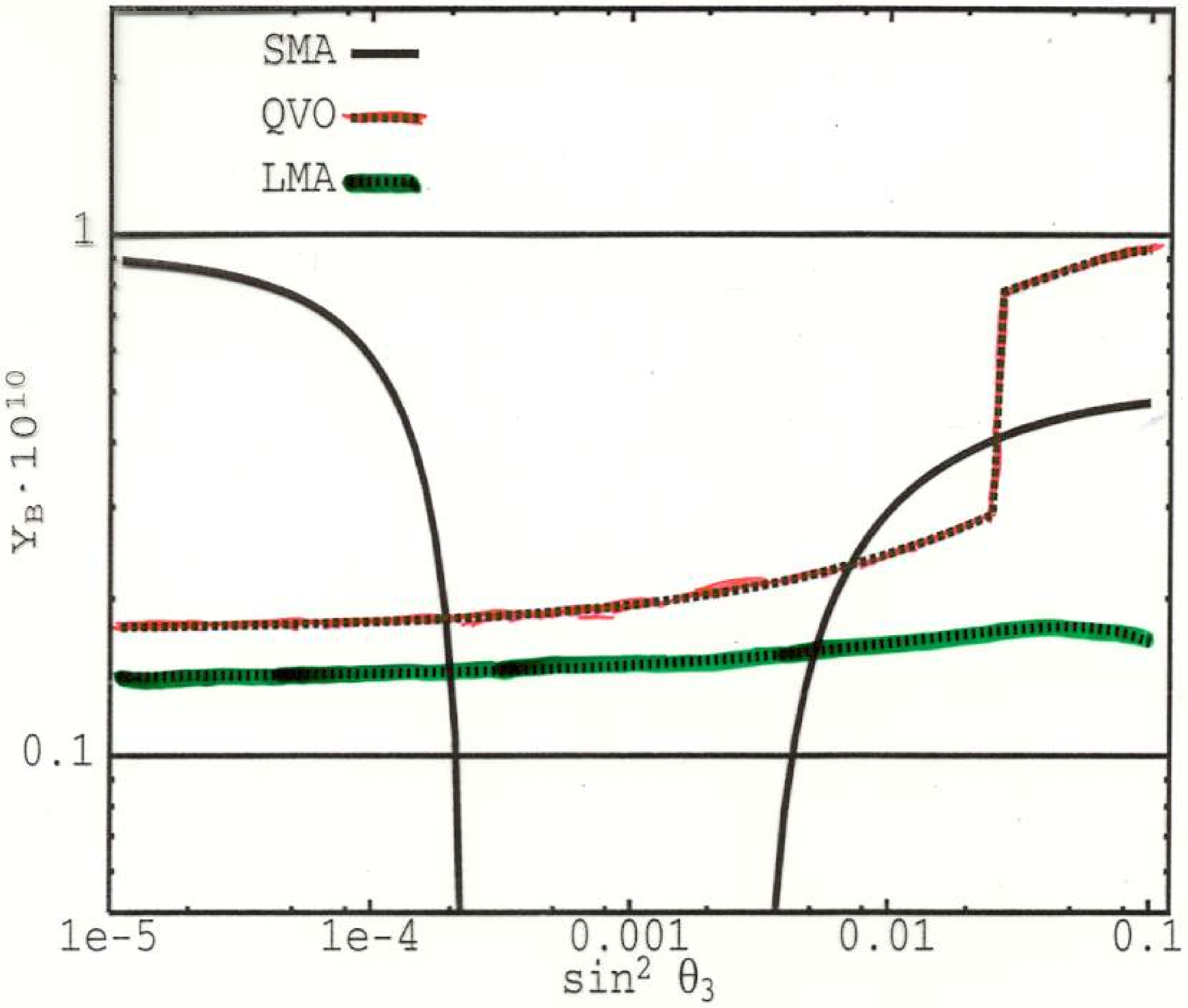
LMA QVO

$$\boxed{Y_B \cdot 10^{10} \lesssim 8.2 \left(\frac{m}{GeV}\right)^2 \left\{s_{2(\alpha-\delta)}\frac{m_1}{\sqrt{\Delta m^2_\odot}} + s_{2\beta}\frac{m_1}{\sqrt{\Delta m^2_A}}\right\}}$$

SMA

- Term proportional to $\sqrt{\frac{1}{\Delta m^2_\odot}}$ contributes most
- $Y_B \propto m^2 \cdot m_1$
- If $\alpha = \beta = \delta = 0$: $Y_B = 0$

(2) DIRAC = down quark
charged lepton



$\Delta m_A^2 = 3 \cdot 10^{-3}\ eV^2 \quad , \Theta_2 = \pi/4$

$\Delta m_\odot^2 = 5 \cdot 10^{-6}\ eV^2 \quad , \tan^2 \Theta_1 = 5 \cdot 10^{-4} \quad , m_1 = 10^{-5}\, eV$

$\Delta m_\odot^2 = 5 \cdot 10^{-5}\ eV^2 \quad , \tan^2 \Theta_1 = 1 \quad , m_1 = 10^{-5}\, eV$

$\Delta m_\odot^2 = 10^{-8}\ eV^2 \quad , \tan^2 \Theta_1 = 1 \quad , m_1 = 2 \cdot 10^{-6}\, eV$

$3\alpha = 5\beta = 6\delta = \pi$

$$\tilde{m}_D = \begin{pmatrix} 0 & \sqrt{m_d m_s} & 0 \\ \sqrt{m_d m_s} & m_s & \sqrt{m_b m_s} \\ 0 & \sqrt{m_b m_s} & m_b \end{pmatrix}$$

Maximal value for Y_B:

$$0.1 \leq Y_B \cdot 10^{10} \leq \begin{cases} 0.6 \left(\frac{m_1}{10^{-5}\,eV}\right) & SMA \\ 1.4 \left(\frac{m_1}{10^{-6}\,eV}\right) & LMA \\ 2.1 \left(\frac{m_1}{10^{-7}\,eV}\right) & QVO \end{cases}$$

$\rightarrow$ m_1 not smaller than

$$\boxed{\begin{array}{lll} 10^{-6}\ eV & \text{for} & SMA \\ 10^{-7}\ eV & \text{for} & LMA \\ 10^{-8}\ eV & \text{for} & QVO \end{array}}$$

Lower limit

Connection to $0\nu\beta\beta$

...rdical scheme has highest $\langle m \rangle$ for LMA

- High $\langle m \rangle = \sum_i U_{Lei}^2 m_i$ and correct Y_B ?

$\longrightarrow$ Random scan: $\Delta m_\odot^2 = 10^{-5} \ldots 10^{-3}\,\mathrm{eV}^2$

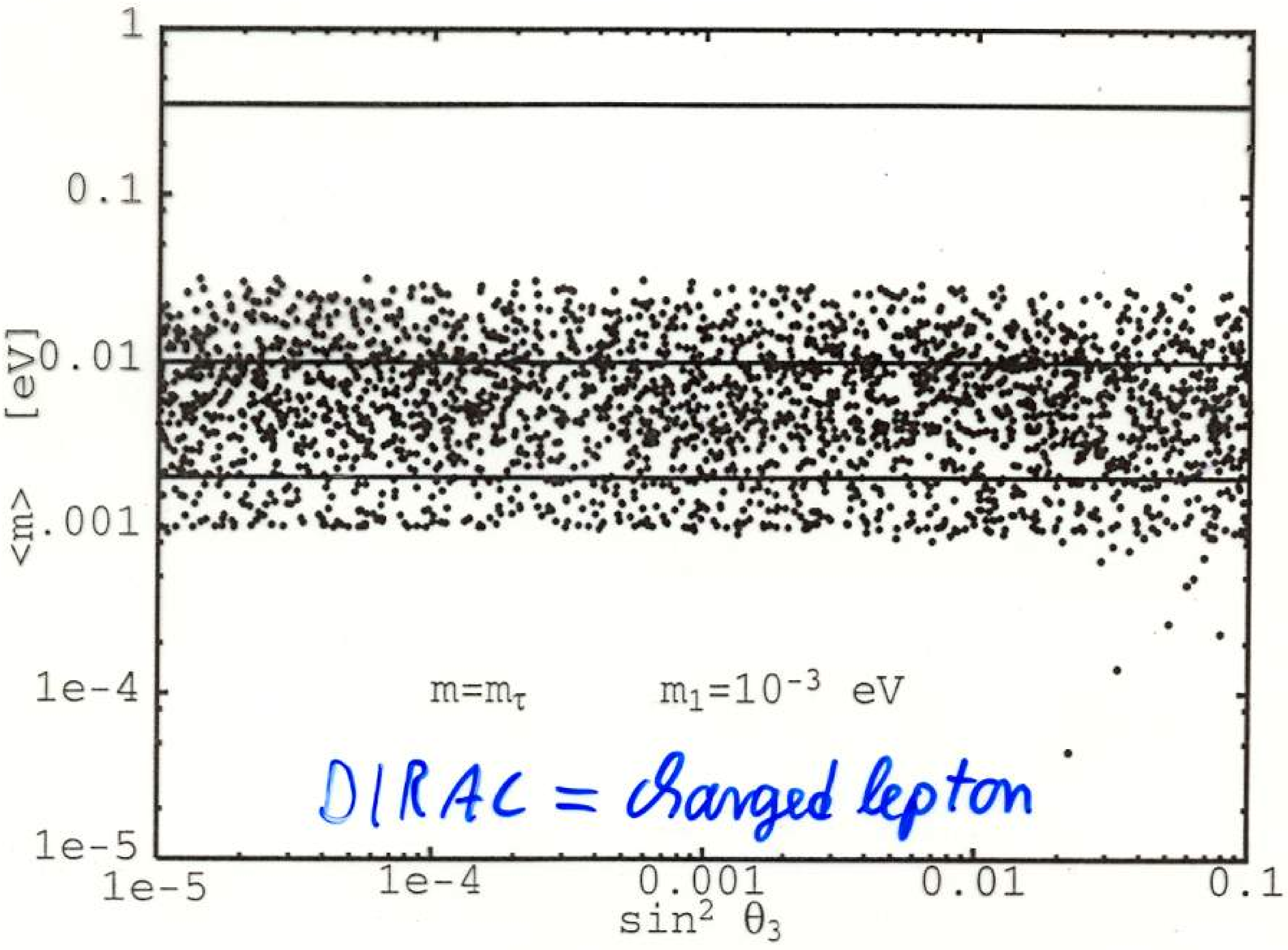
$\tan^2\Theta_1 = 0.1 \ldots 4$

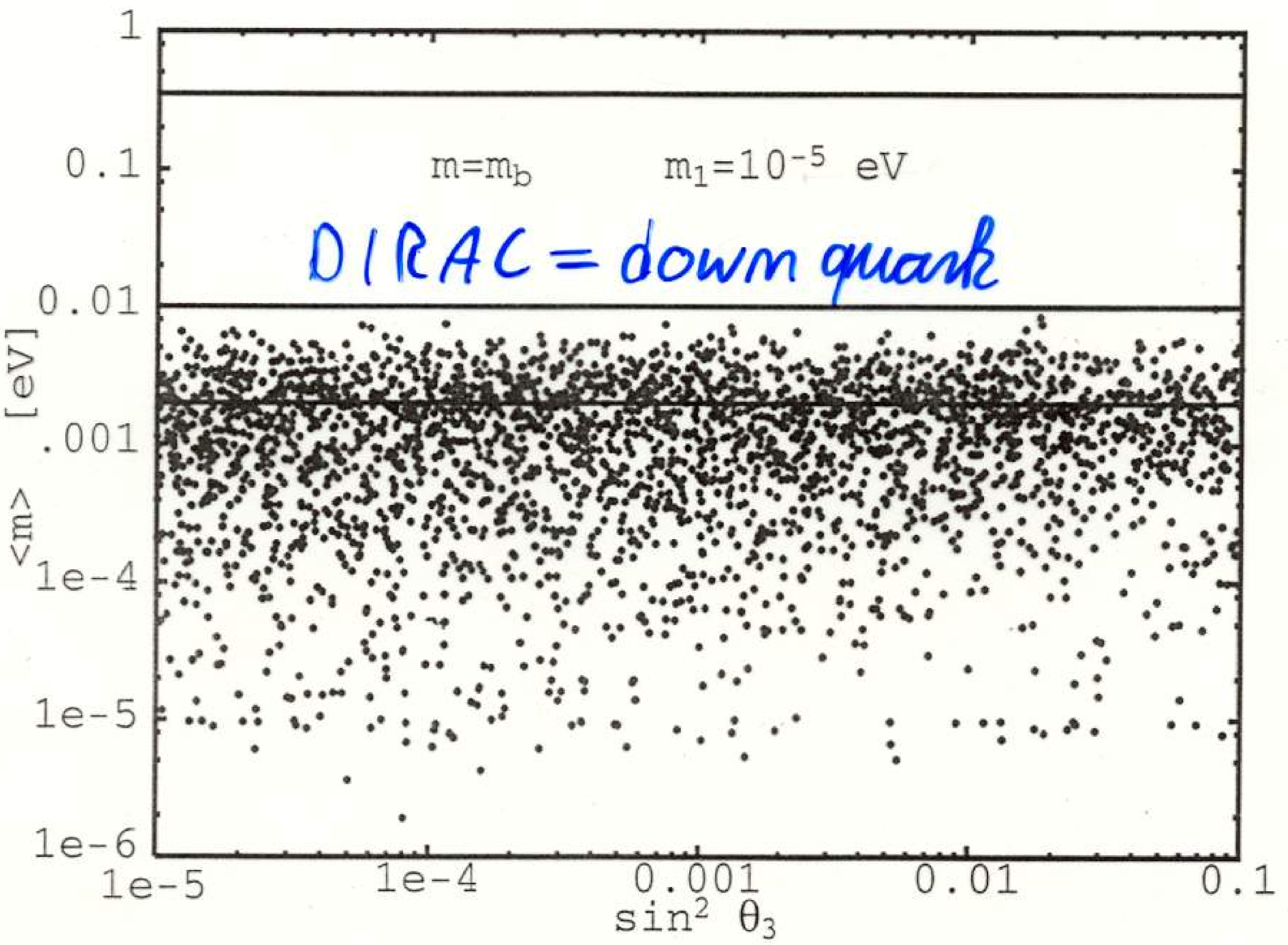
$\alpha, \beta, \delta = 0, \ldots, 2\pi$

	correct Y_B	$\langle m \rangle \geq 2 \cdot 10^{-3}\,\mathrm{eV}$
...own $= 10^{-3}\,\mathrm{eV}$	5 %	4 %
...own $= 10^{-5}\,\mathrm{eV}$	27 %	7 %
...pton $= 10^{-3}\,\mathrm{eV}$	35 %	30 %
...lepton ...$_1 = 10^{-5}\,\mathrm{eV}$	1 %	$\leq$ 1 %

Phase δ equally distributed ($s_3 e^{-i\delta}$)

Parameter sets giving correct Y_B





Summary

- LR symmetry + Leptogenesis
  - $$\begin{tikzcd} \text{light } \nu_L \arrow[r, leftrightarrow] \arrow[d, leftrightarrow, "LR"'] & \text{Oscillation} \arrow[d, leftrightarrow] \\ \text{heavy } N_R \arrow[r, leftrightarrow] & \text{Leptogenesis} \end{tikzcd}$$
  - type II see-saw, m_L dominates
  - lower limit on m_1
  - $\tilde{m}_D = m_{up} \longrightarrow$ No LMA (SNO), No $0\nu\beta\beta$

    $\tilde{m}_D = m_{down} \longrightarrow$ All solar solutions, No $0\nu\beta\beta$

    $\tilde{m}_D = m_{lepton} \longrightarrow$ All solar solutions, $0\nu\beta\beta$ if $m_1 \gtrsim 10^{-3}\,eV$

- Future
  - Inverse + Degenerate scheme
  - δ, α, β and ~~CP~~
  - Analyze full LR leptogenesis (Triplet-decay, γ, ...)