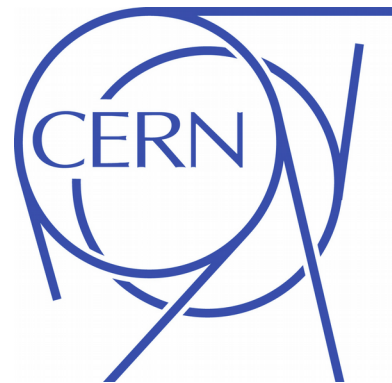# Testable leptogenesis scenarios and phenomenological implications
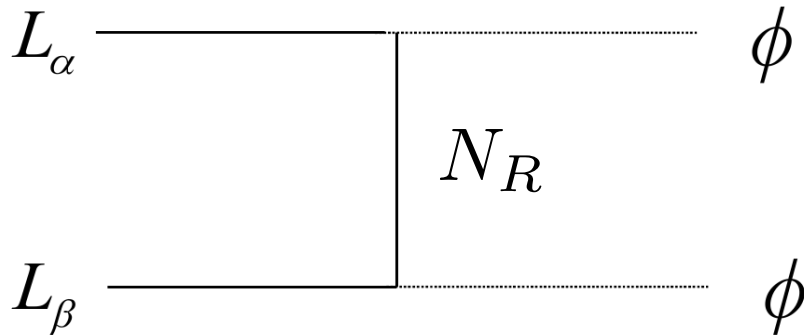
Jacobo López-Pavón

CERN

53rd Rencontres de Moriond-EW 2018
La Thuile
March 10- March 17 2018

Minimal Seesaw Model

Heavy fermion singlet: N_R. Type I *seesaw*.
Minkowski 77; Gell-Mann, Ramond, Slansky
79; Yanagida 79; Mohapatra, Senjanovic 80.

We will focus on the simplest extension of SM able to account for neutrino masses:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_K - \frac{1}{2}\overline{N_i}M_{ij}N_j - Y_{i\alpha}\overline{N_i}\widetilde{\phi}^\dagger L_\alpha + h.c.$$

Minimal Seesaw Model

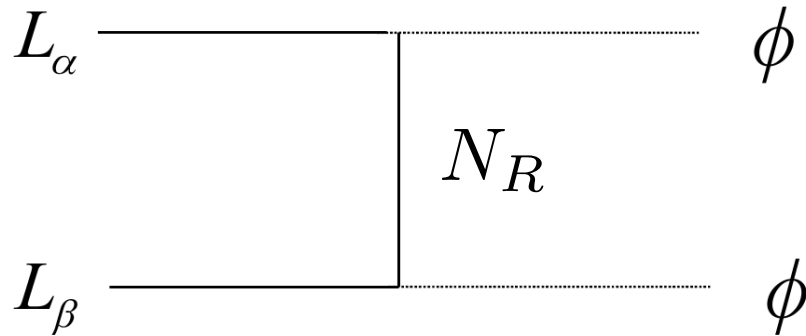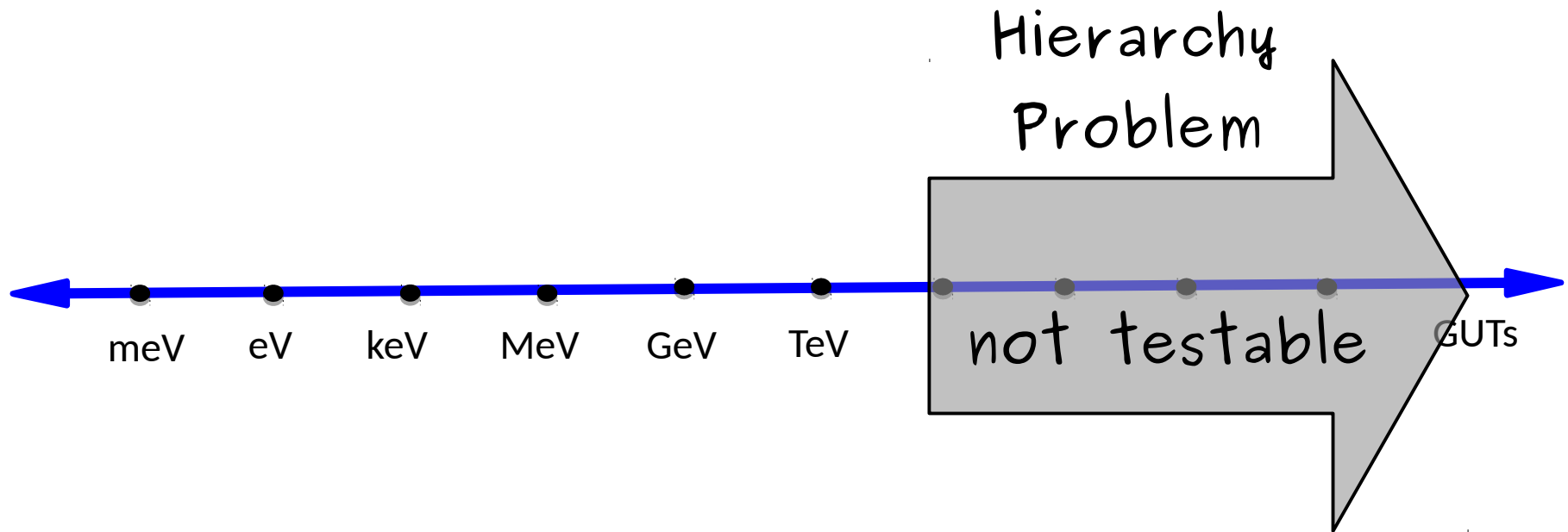L_α ──────── ϕ

N_R

L_β ──────── ϕ

Heavy fermion singlet: N_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky
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We will focus on the simplest extension of SM able to account for neutrino masses:
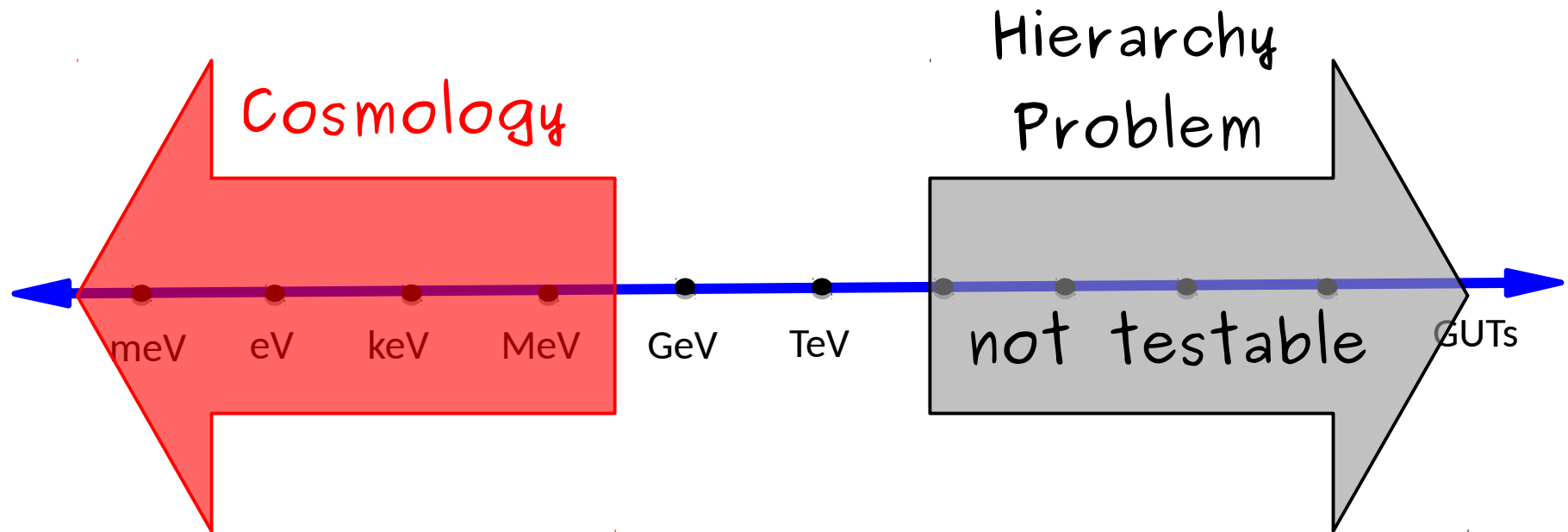
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i}M_{ij}N_j - Y_{i\alpha}\overline{N_i}\widetilde{\phi}^\dagger L_\alpha + h.c.$$

New Physics Scale $(m_\nu \sim Y^2 v^2 / M)$

The New Physics Scale

meV eV keV MeV GeV TeV

Hierarchy Problem

not testable

GUTs

The New Physics Scale
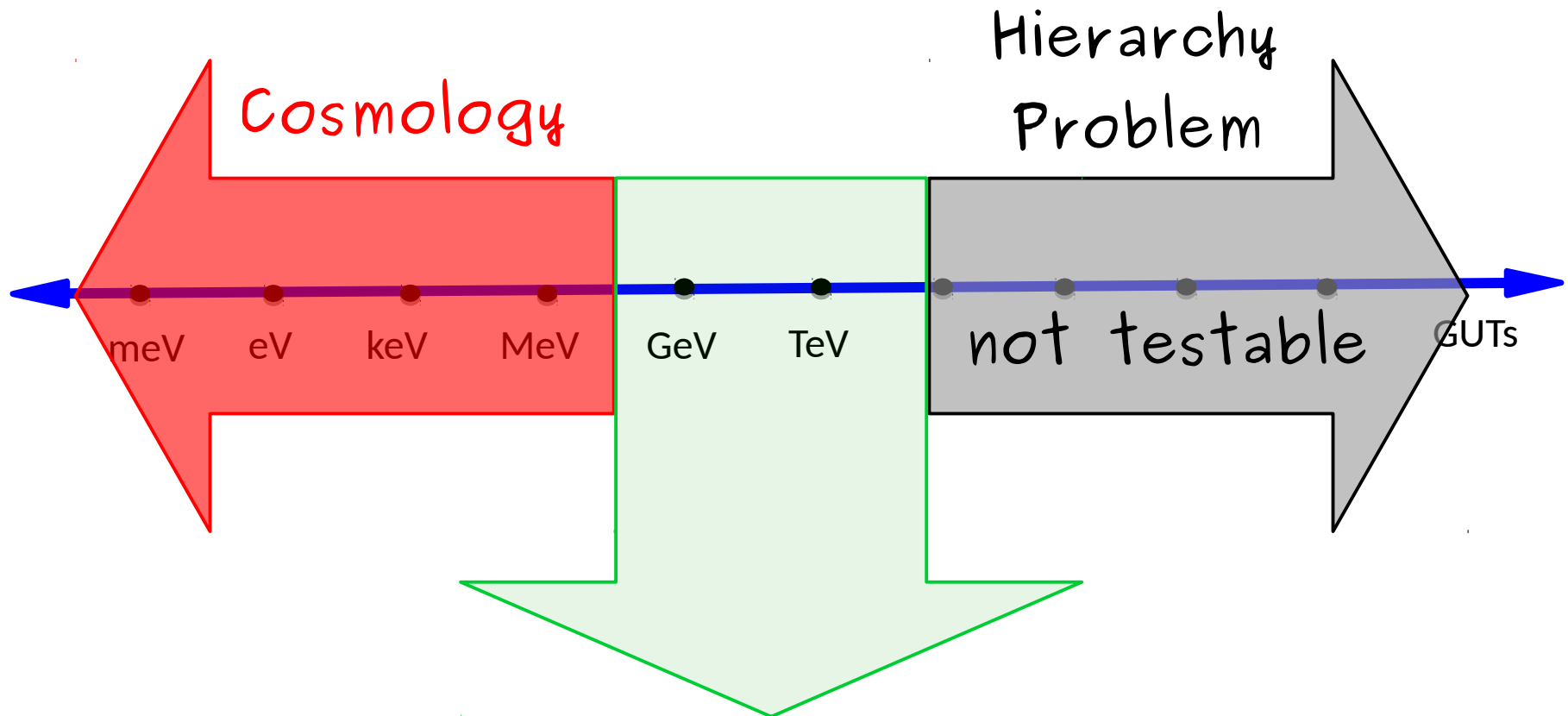

- Minimal Type-I seesaw with **N$_R$=2**

CMB+BBN data ➡ M$_R$ >100 MeV

(or Type-I seesaw with **N$_R$=3**
& $m_{lightest} \gtrsim 10^{-3} eV$)

P. Hernandez, M. Kekic, JLP 1311.2614;1406.2961

The New Physics Scale

Cosmology

Hierarchy Problem

meV eV keV MeV GeV TeV **not testable** GUTs

- Resonant Leptogenesis M>100GeV
  Pilaftsis

- Leptogenesis via Oscillations M=0.1-100GeV
  Akhmedov, Rubakov, Smirnov (ARS); Asaka, Shaposnikov (AS)

GeV Scale Leptogenesis

Hernandez, Kekic, JLP, Racker, Rius 1508.03676;
Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

See also talks by Valerie **Domcke** and Juraj **Klaric**

Asaka, Shaposhnikov;Shaposhnikov; Asaka, Eijima, Ishida; Canetti, Drewes, Frossard, Shaposhnikov;Drewes, Garbrecht; Shuve, Yavin; Abada, Arcadi, Domcke, Lucente...
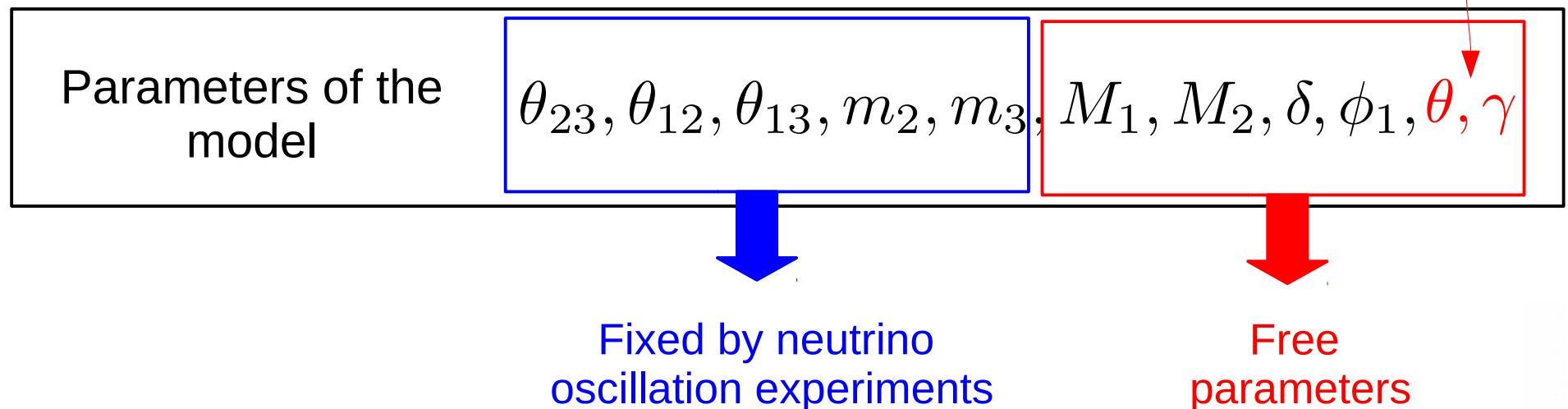
Full parameter space exploration N_R=2

$$Y_B^{\mathrm{exp}} \simeq 8.65(8) \times 10^{-11}$$

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

$$\log \mathcal{L} = -\frac{1}{2} \left(\frac{Y_B(t_{\mathrm{EW}}) - Y_B^{\mathrm{exp}}}{\sigma_{Y_B}} \right)^2 .$$

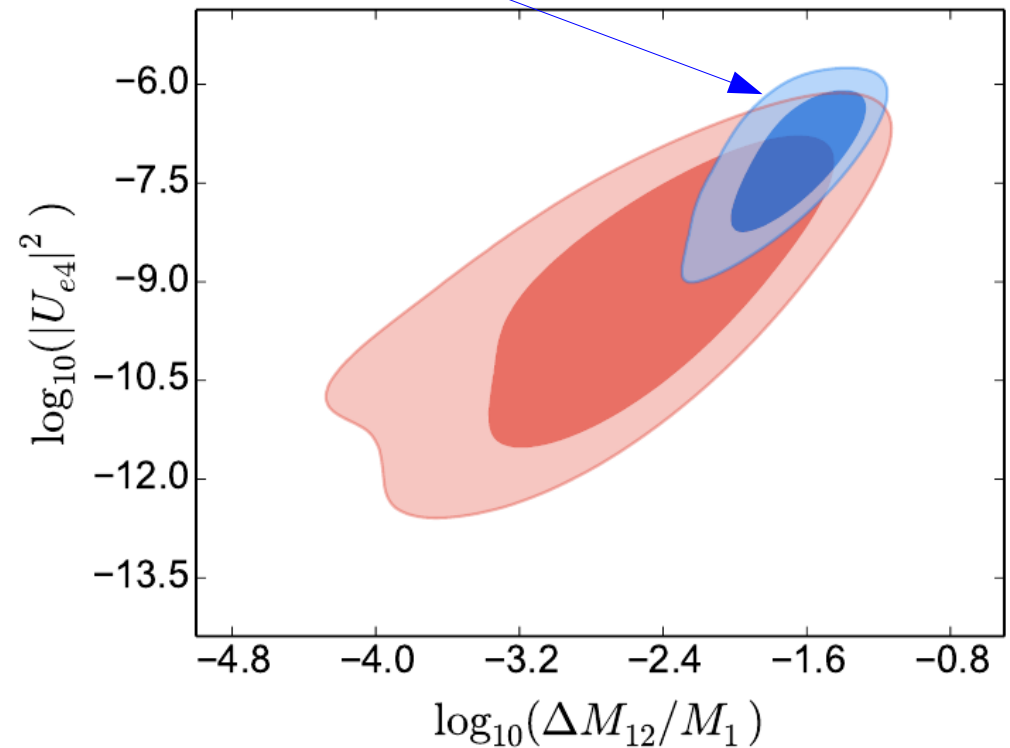Casas-Ibarra
$$R\left(\theta + i\gamma\right)$$

Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3,$	$M_1, M_2, \delta, \phi_1, \theta, \gamma$

Fixed by neutrino oscillation experiments

Free parameters

Leptogenesis in Minimal Model NR=2

Non degenerated solutions

Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 2016
arXiv:1606.06719

Leptogenesis in Minimal Model N$_R$=2

Non very degenerate solutions

PRESENT BOUND

FUTURE SENSITIVITY

Inverted light neutrino ordering (IH)
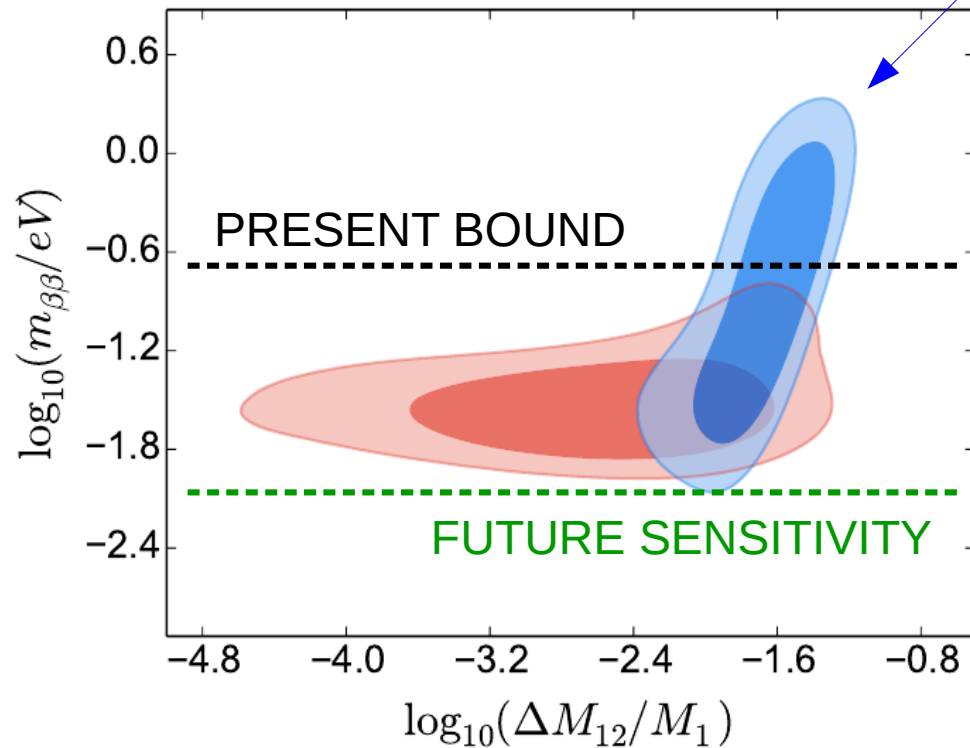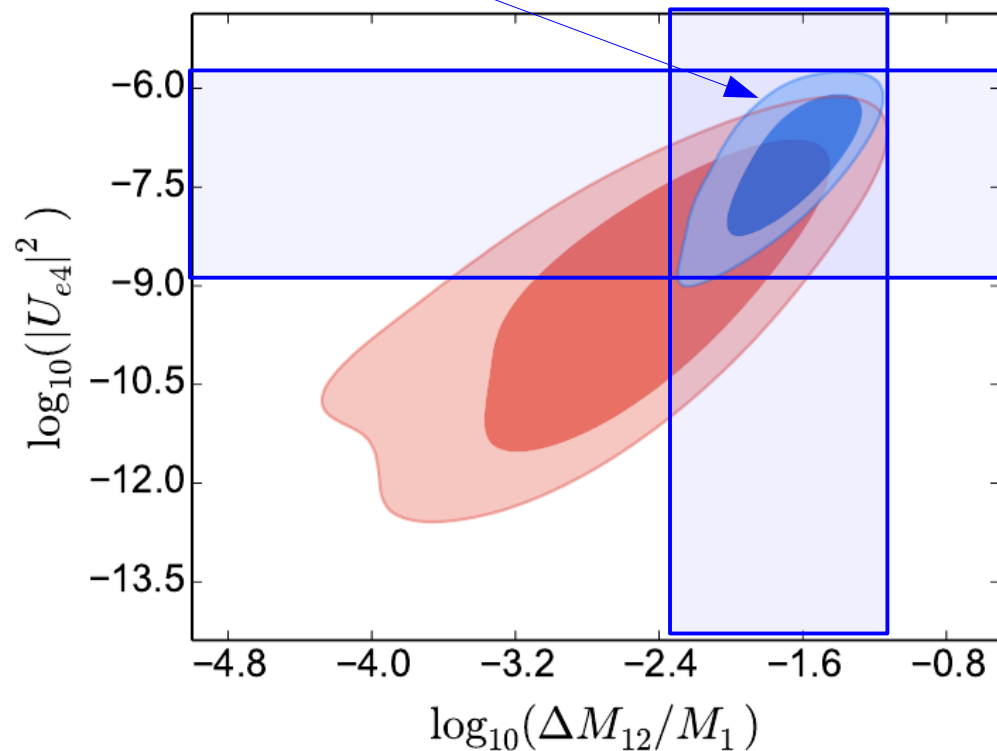
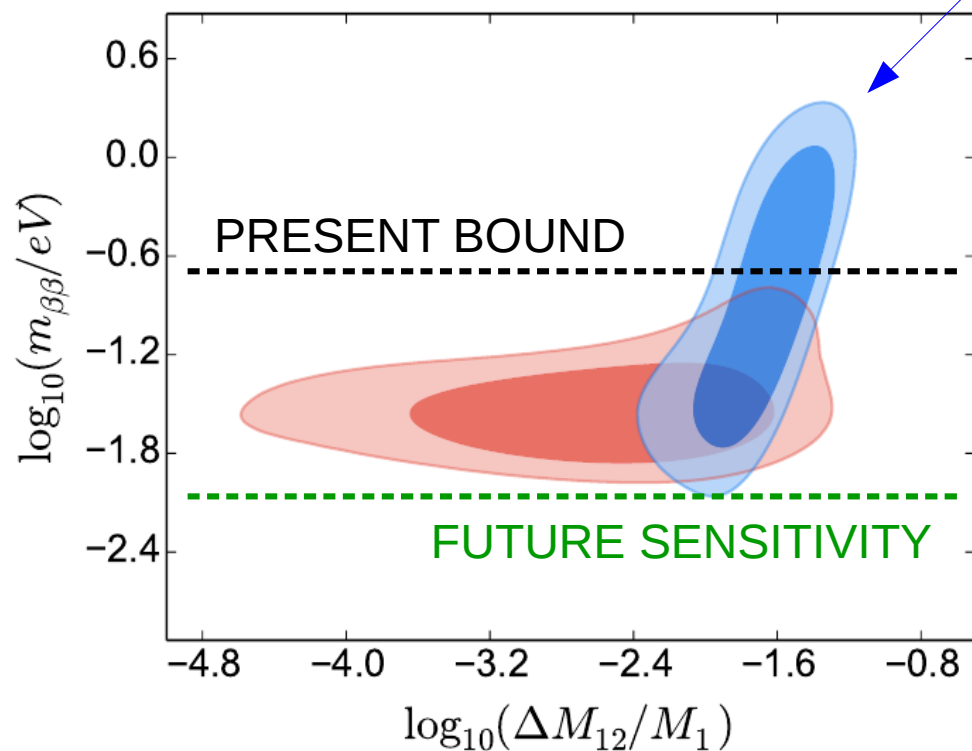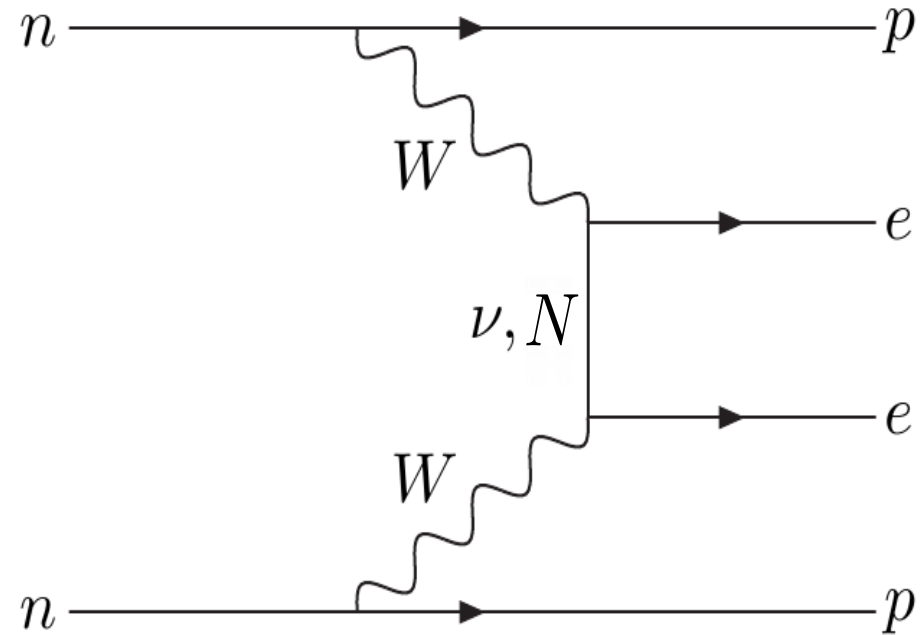# Leptogenesis in Minimal Model N_R=2

Non very degenerate solutions

Inverted light neutrino ordering (IH)
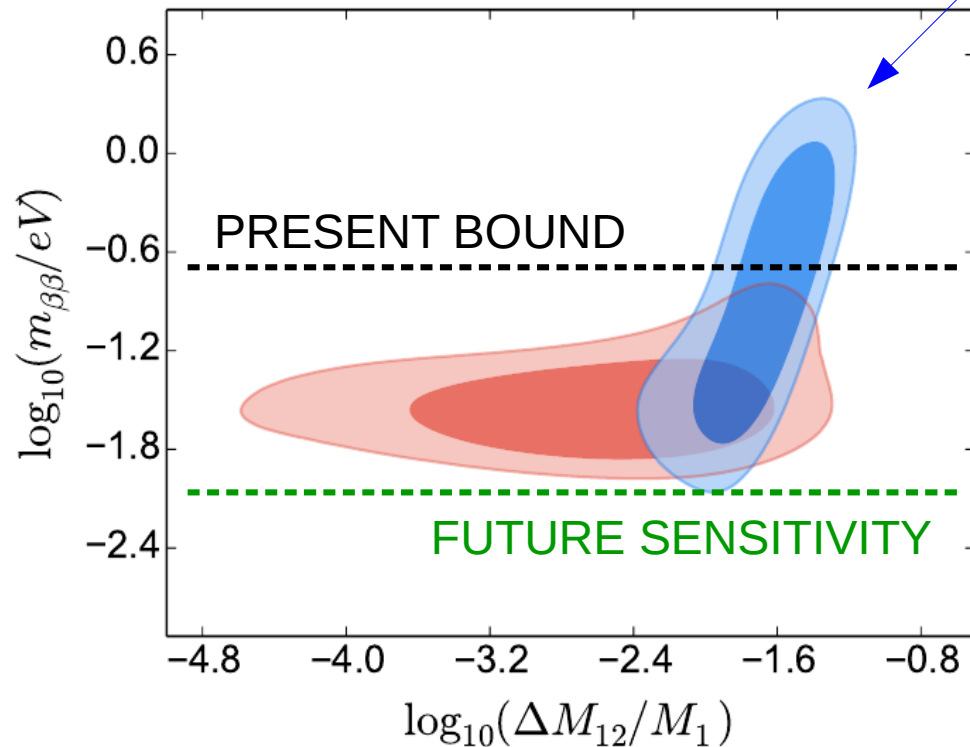
Hernandez, Kekic, JLP, Racker, Salvado 2016
arXiv:1606.06719

Leptogenesis in Minimal Model NR=2
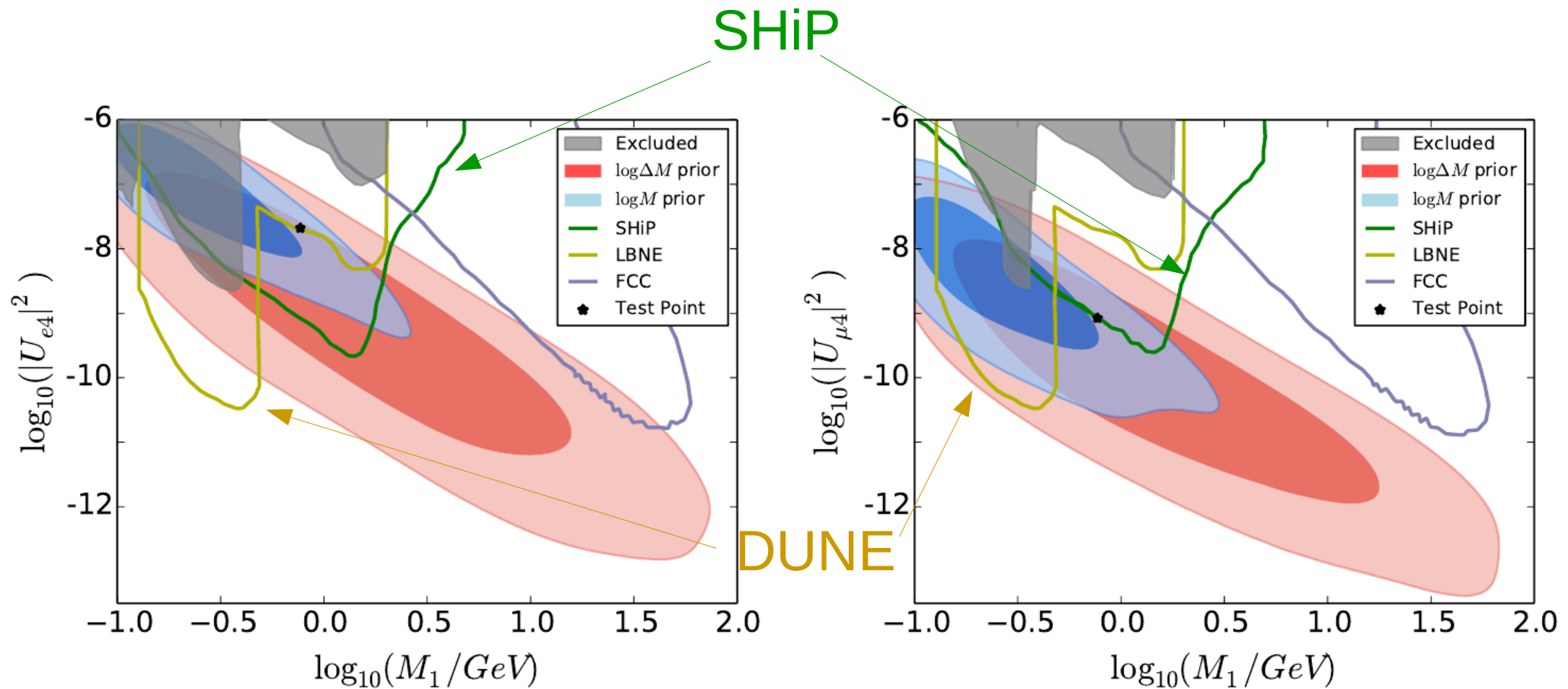
Inverted light neutrino ordering

What if the N_R are within reach of SHiP?

Can we estimate Y_B from the experiments?

Predicting Y_B in minimal model $N_R=2$

- **Baryon asymmetry depends on all the unknown parameters**

- **SHiP sensitivity** $\iff |U_{\alpha j}^2| \gg m_\nu/M \iff R_{ij} \gg 1 \iff e^\gamma \gg 1$

$$(U_{\alpha j})^2 \propto e^{-2\theta i}\, e^{2\gamma} f\left(\delta, \phi_1, M_j\right)$$

Hernandez, Kekic, JLP, Racker, Salvadò 2016

Predicting Y_B in minimal model $N_R=2$

- **Baryon asymmetry depends on all the unknown parameters**

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SHiP sensitive to $|U_{\alpha j}|(\delta, \phi_1, \gamma), \, M_j$

$$(U_{\alpha j})^2 \propto e^{-2\theta i} \boxed{e^{2\gamma} f(\delta, \phi_1, M_j)}$$

Predicting Y_B in minimal model $N_R=2$

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SHiP sensitive to $|U_{\alpha j}|(\delta, \phi_1, \gamma), \, M_j$

$$(U_{\alpha j})^2 \propto \boxed{e^{-2\theta i}} \boxed{e^{2\gamma} f(\delta, \phi_1, M_j)}$$

Neutrinoless double beta decay sensitive to θ through
interference between light and heavy contribution

Predicting Y_B in minimal model N_R=2
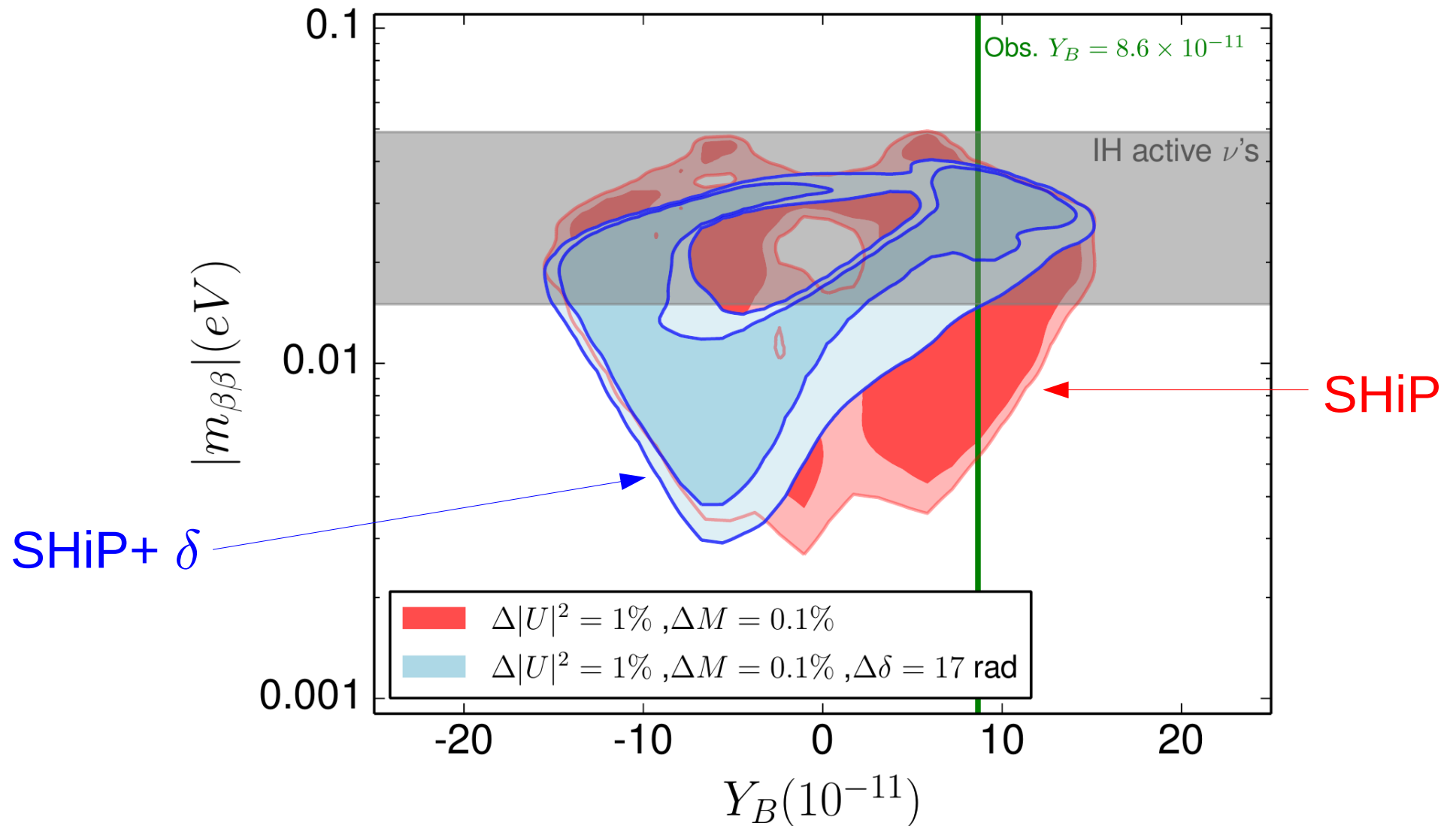
$$Y_B = 8.6 \times 10^{-11}$$ Obs.

IH active ν's

SHiP

SHiP+ δ

(red)	$\Delta|U|^2 = 1\%$, $\Delta M = 0.1\%$
(light blue)	$\Delta|U|^2 = 1\%$, $\Delta M = 0.1\%$, $\Delta\delta = 17$ rad

$|m_{\beta\beta}|(eV)$

$Y_B(10^{-11})$

Predicting Y_B in minimal model $N_R=2$

Legend:
- $\Delta|U|^2 = 1\%$, $\Delta M = 0.1\%$
- $\Delta|U|^2 = 1\%$, $\Delta M = 0.1\%$, $\Delta\delta = 17$ rad

Axes: $|m_{\beta\beta}|\,(eV)$ versus $Y_B(10^{-11})$

Annotations: SHiP, SHiP$+\delta$

Predicting Y_B in minimal model $N_R=2$

Hernandez, Kekic, JLP, Racker, Salvado 2016 arXiv:1606.06719
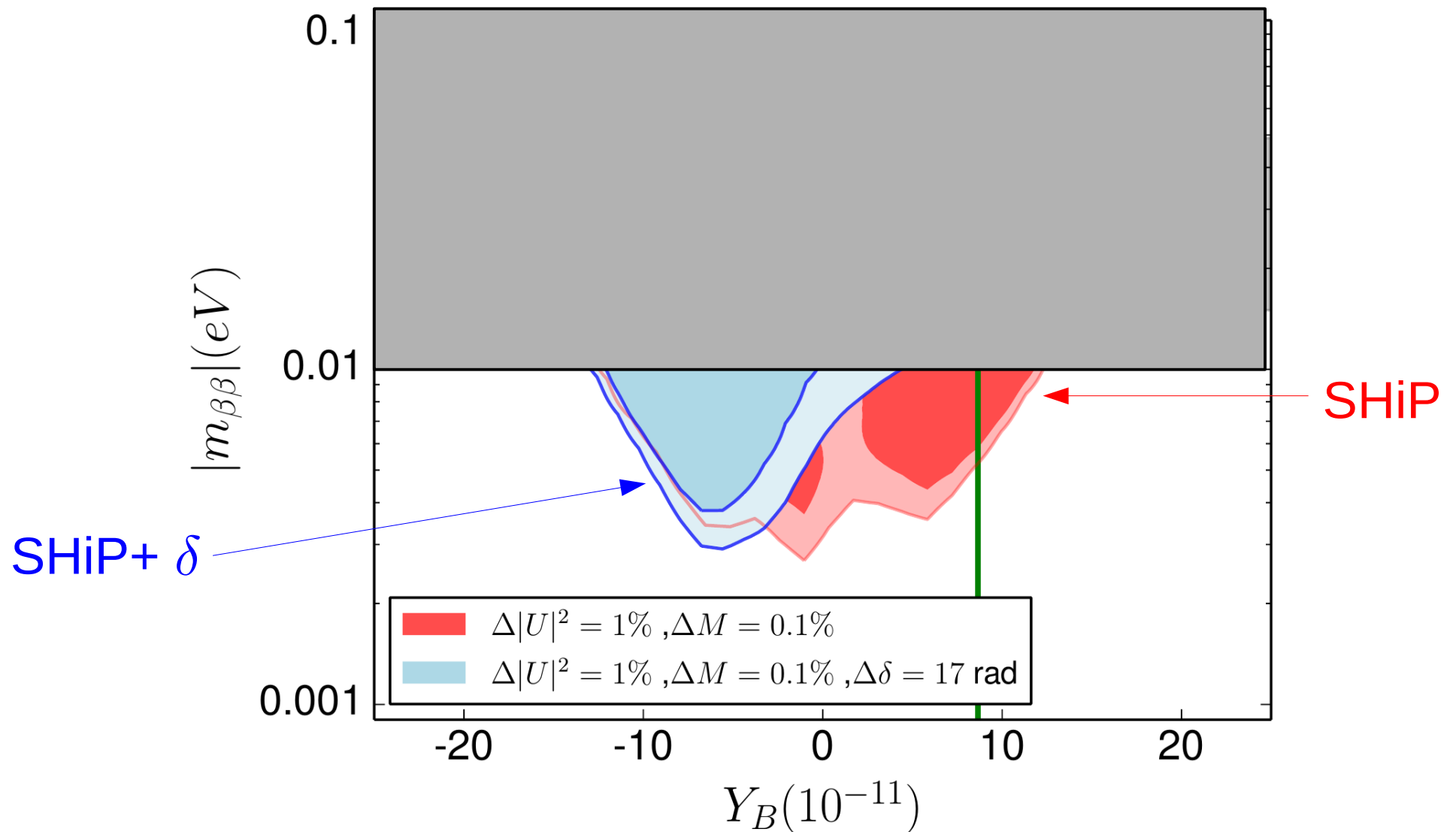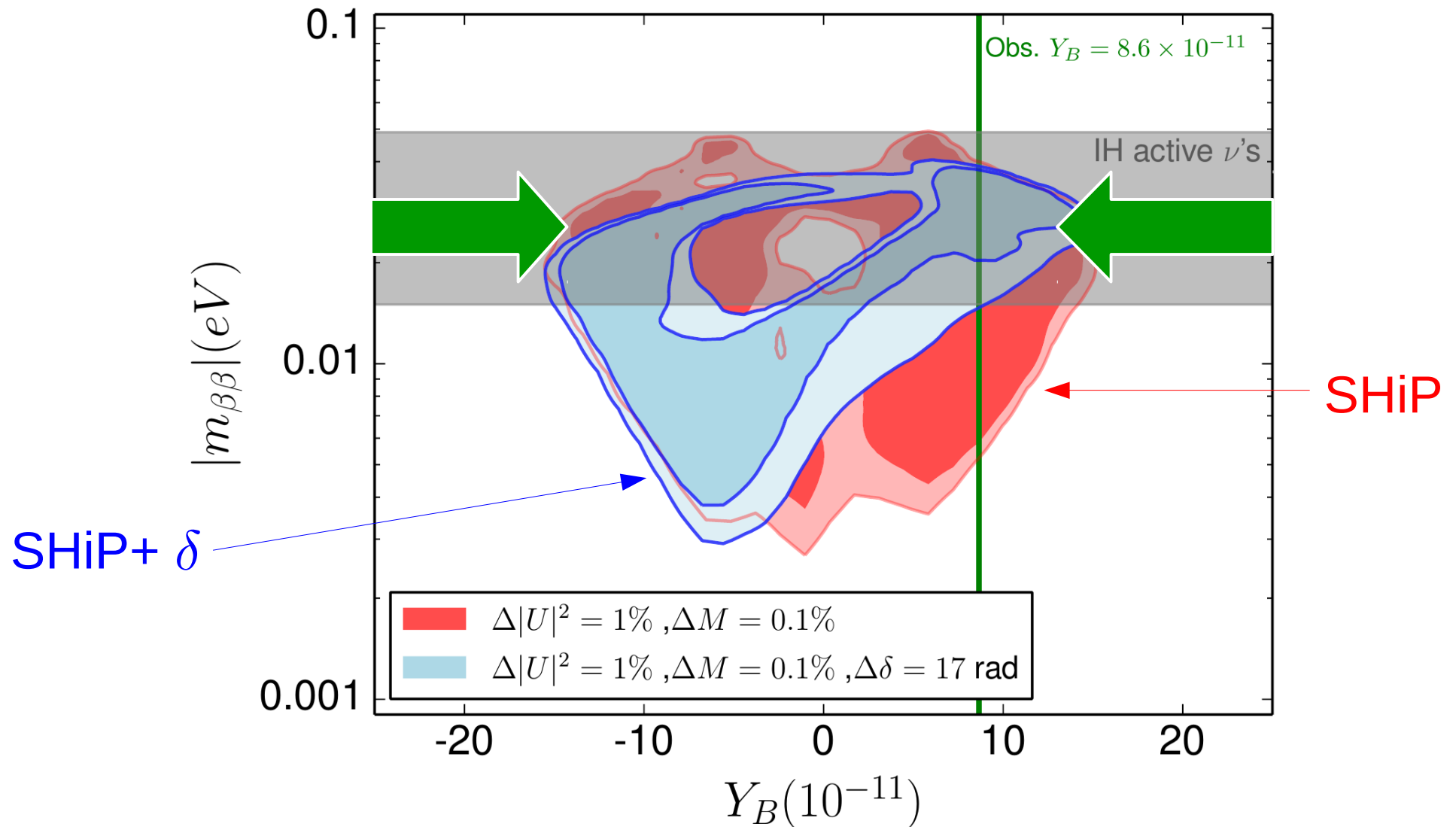
CP-violation in Minimal Model

Measurment of PMNS phases from FCC-ee and SHiP?

Caputo, Hernandez, Kekic, JLP, Salvado
arXiv:1611.05000

CP-violation in minimal model

- **SHiP and FCC-ee** can measure:

$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu4}|, |U_{\mu5}|$$

Sensitivity to PMNS CP-phases! δ, ϕ_1
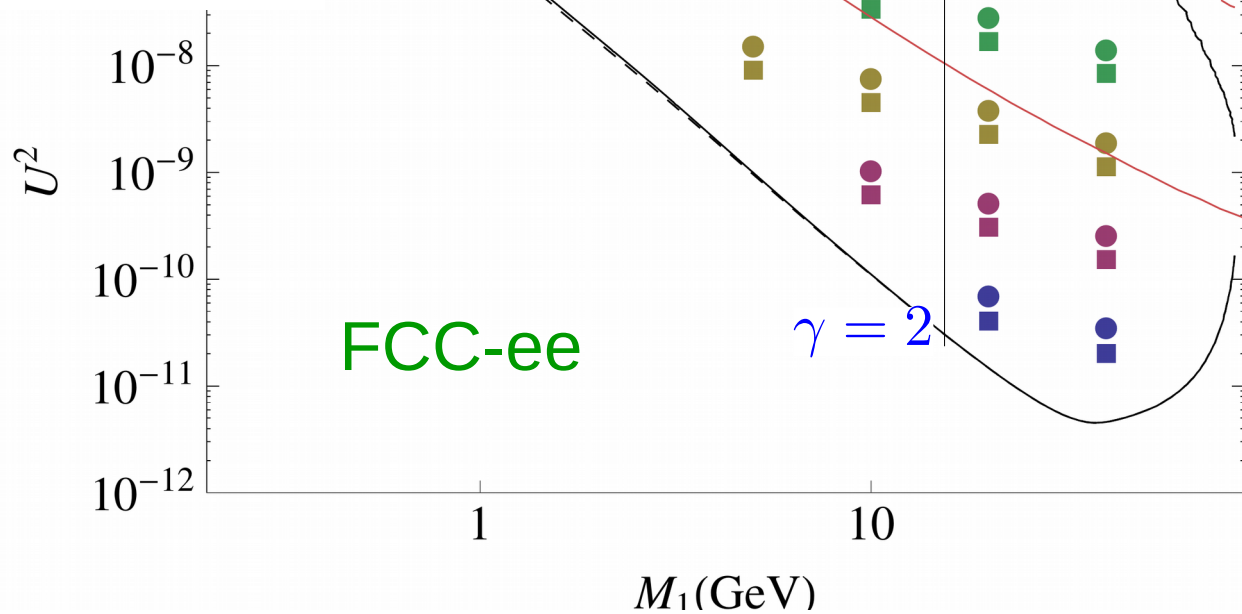
- $|U_{e4}|^2/|U_{\mu4}|^2 \simeq |U_{e5}|^2/|U_{\mu5}|^2 \simeq$

$$\frac{(1 + s_{\phi_1}\sin 2\theta_{12})(1 - \theta_{13}^2) + \frac{1}{2}r^2 s_{12}(c_{12}s_{\phi_1} + s_{12})}{\left(1 - \sin 2\theta_{12}s_{\phi_1}\left(1 + \frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}\right)c_{23}^2 + \theta_{13}(c_{\phi_1}s_\delta - \cos 2\theta_{12}s_{\phi_1}c_\delta)\sin 2\theta_{23} + \theta_{13}^2(1 + \sin 2\theta_{12})s_{23}^2 s_{\phi_1}}$$

- $|U_{e4}|^2, |U_{\mu4}|^2, |U_{e5}|^2, |U_{\mu5}|^2 \propto e^{2\gamma}$

γ

CP-violation in minimal model
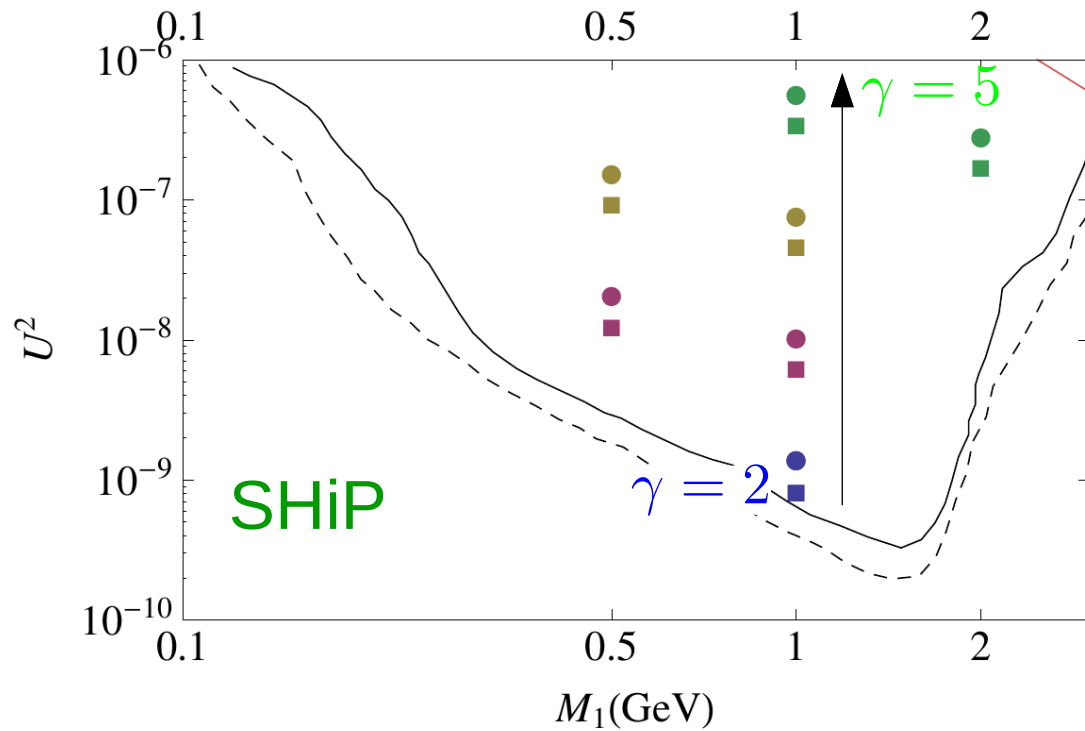
5σ discovery CP-violation

Previous predictions rely
to a large extent on
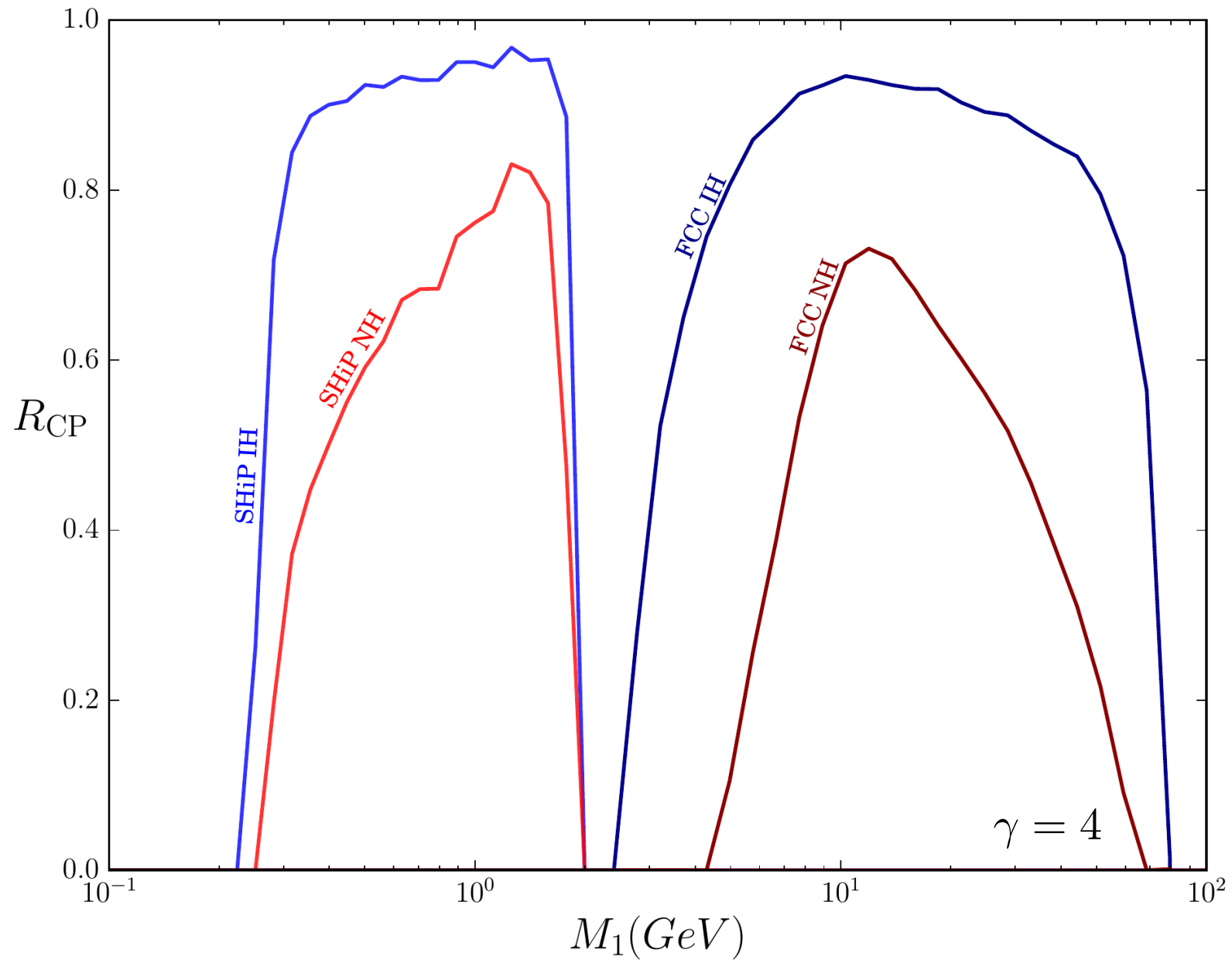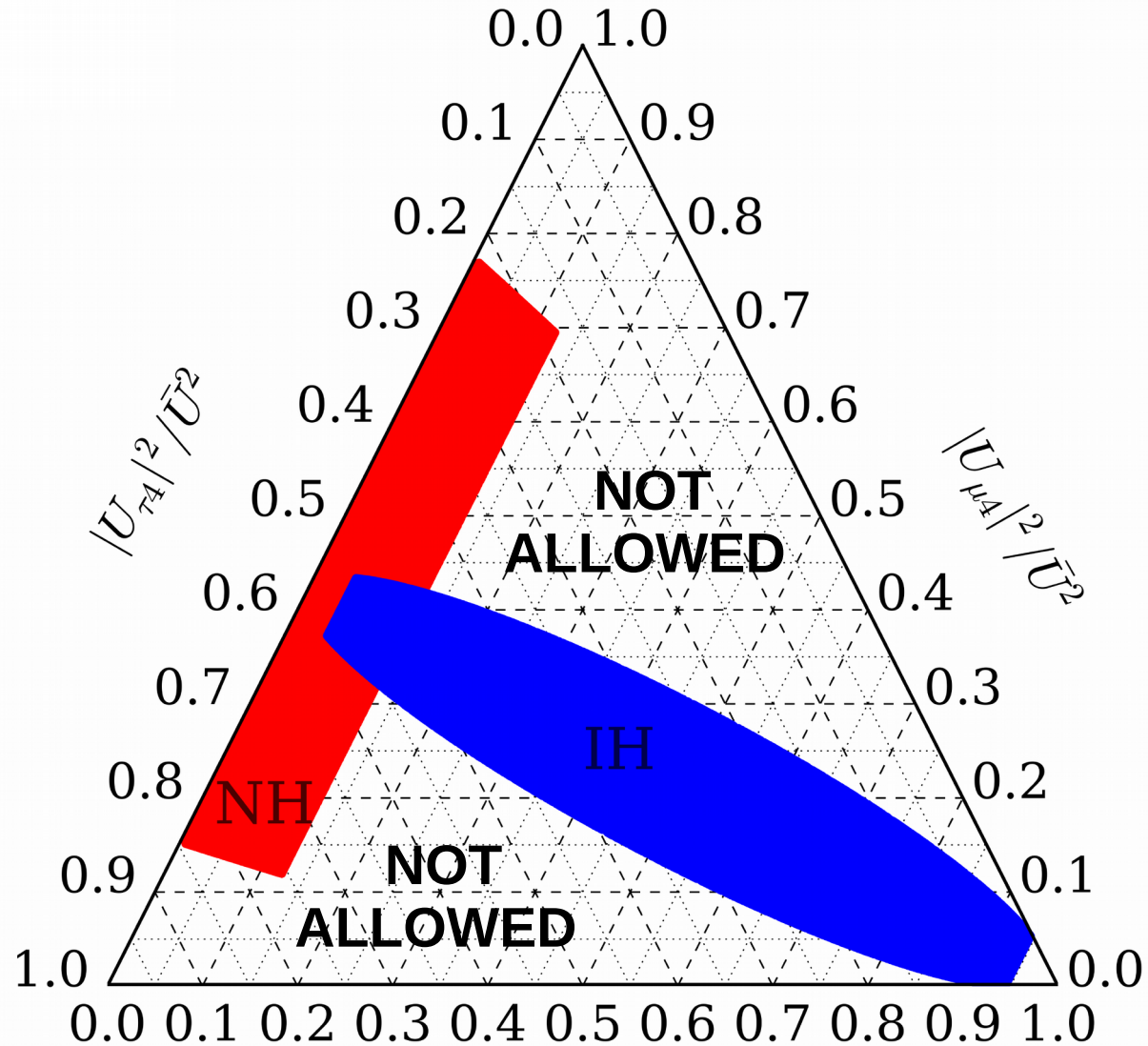the minimality

Caputo, Hernandez, JLP, Salvado
arXiv:1704.08721

Minimal Model

Conclusions: Minimal Model

- HIGH PREDICTIVITY!!

- Successful baryogenesis is possible with a mild heavy neutrino degeneracy in the minimal model.

- These less fine-tuned solutions prefer smaller masses M ≤ 1GeV (target region of SHiP) and significant non-standard contributions to neutrinoless double beta decay.

- If O(GeV) heavy neutrinos would be discovered in SHiP and the neutrino ordering is inverted, predicting the baryon asymmetry looks in principle viable, in contrast with previous beliefs.

- 5σ measurement of leptonic CP violation from SHiP and FCC-ee would be possible in a very significant fraction of parameter space! (regardless the baryon asymmetry generation).

Thank you!

To what extent can the predictions be modified in the presence of additional New Physics?

Caputo, Hernandez, JLP, Salvado
arXiv:1704.08721

Model Independent Approach: EFT

- The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi} \Phi^\dagger L_\beta^c + h.c.,$$

$$\mathcal{O}_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N}_i N_j^c \Phi^\dagger \Phi + h.c.,$$

$$\mathcal{O}_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \overline{N}_i \sigma_{\mu\nu} N_j^c B_{\mu\nu} + h.c.$$

Graesser 2007; del Aguila, Bar-Shalom, Soni, Wudka 2009;
Aparici, Kim, Santamaria, Wudka 2009.

Model Independent Approach: EFT

• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi}\Phi^\dagger L_\beta^c + h.c.,$$

- Generates a third light neutrino mass and a new Majorana CP-phase

$$\frac{v^2 \alpha_W}{\Lambda} \sim \mathcal{O}(1) m_{1(3)}$$

- Modification of the heavy neutrino mixing flavour structure controlled by the magnitude of the lightest neutrino mass generated.

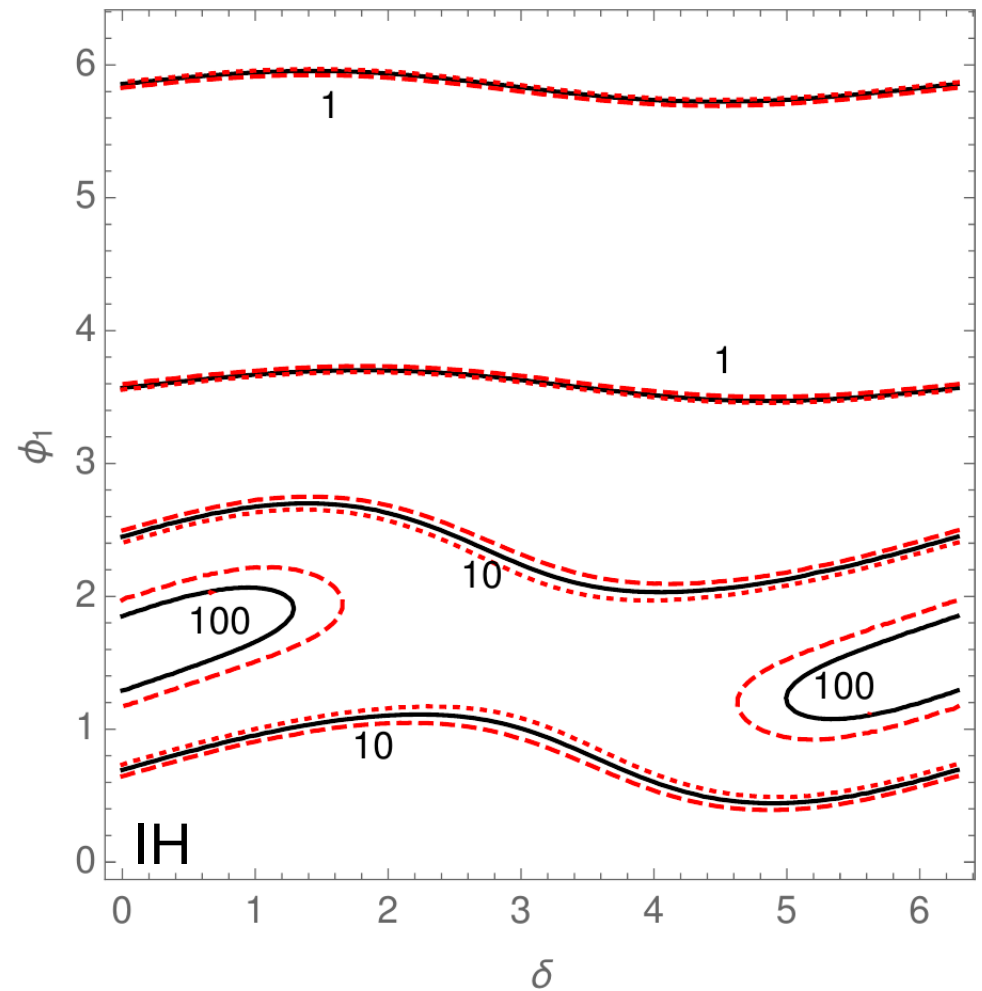# Contours of constant ratio $|U_{es}|^2/|U_{\mu s}|^2$

Minimal Model

$\mathcal{O}(m_3/\sqrt{\Delta m_{atm}^2})$

NH

0.05

0.5

0.05

IH

1

1

10

100

10

100
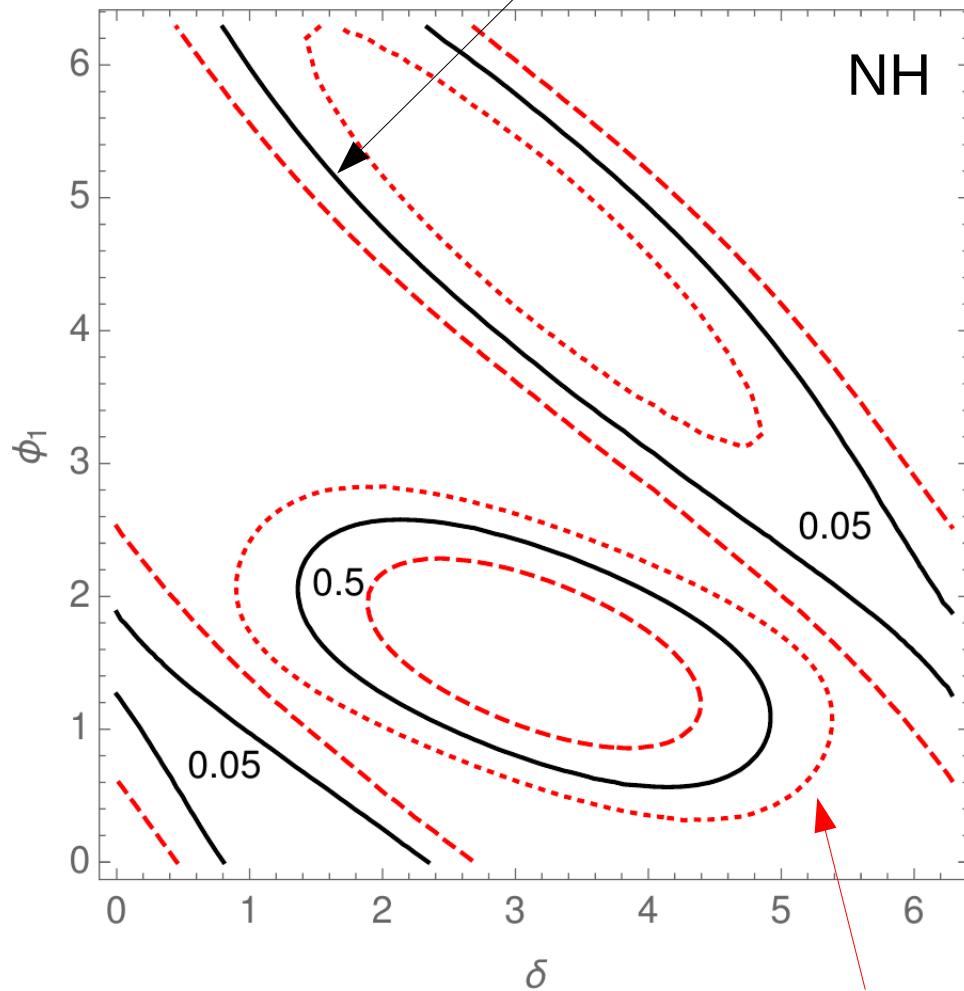
$\mathcal{O}(m_1/\sqrt{\Delta m_{sol}^2})$

Minimal Model + NP

$m_{1(3)} = 0.1\sqrt{\Delta m_{sol}^2}$

Model Independent Approach: EFT

• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

- The higgs can decay to a pair of long-lived heavy neutrinos!
(**powerful signal of two displaced vertices**)

$$\mathcal{O}_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N}_i N_j^c \Phi^\dagger \Phi + h.c.,$$

Accomando, Delle Rose, Moretti, Olaiya, Shepherd-Themistocleous 2017
Caputo, Hernandez, JLP, Salvado 2017

Seesaw Portal
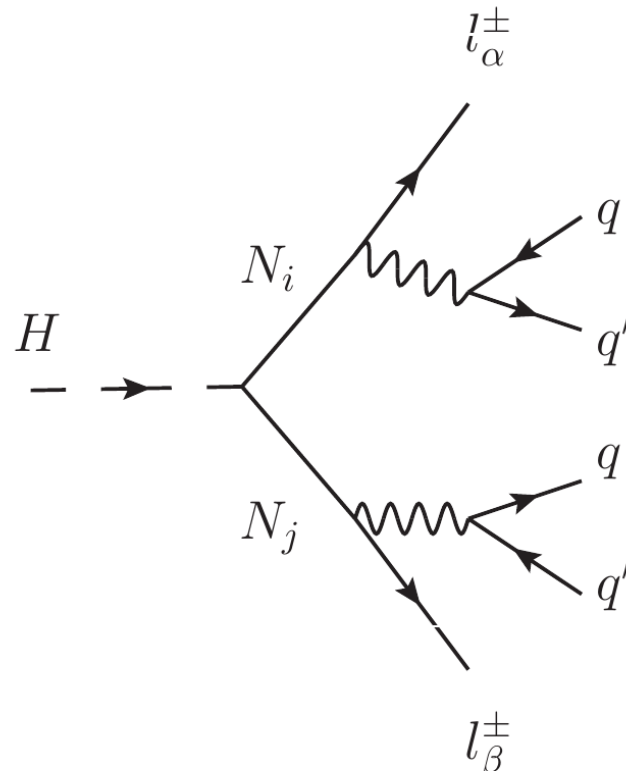
i) Search of displaced tracks in the inner tracker where at least one displace lepton, e or μ, is reconstructed from each vertex.

ii) Search for displaced tracks in the muon chambers and outside the inner tracker, where at least one μ is reconstructed from each vertex.

Accomando, Delle Rose, Moretti, Olaiya, Shepherd-Themistocleous 2017
CMS Collaboration 1411.6977, CMS-PAS-EXO-14-012

Seesaw Portal

Inner Tracker (NH)

Muon Chamber (NH)

Mathusla (14 TeV, 3000 fb⁻¹)
Chou, Curtin, Lubatti 2017

IH

$M_1 = 20\,GeV$

$M_1 = 35\,GeV$

$(\delta, \phi) = (0, \pi/2)$

$\mathrm{Br}(H \to N_1 N_1)$

$\dfrac{M_H}{2\,M}\, c\,\tau\,(m) \sim \gamma c \tau (m)$

LHC (13 TeV, 300 fb⁻¹)
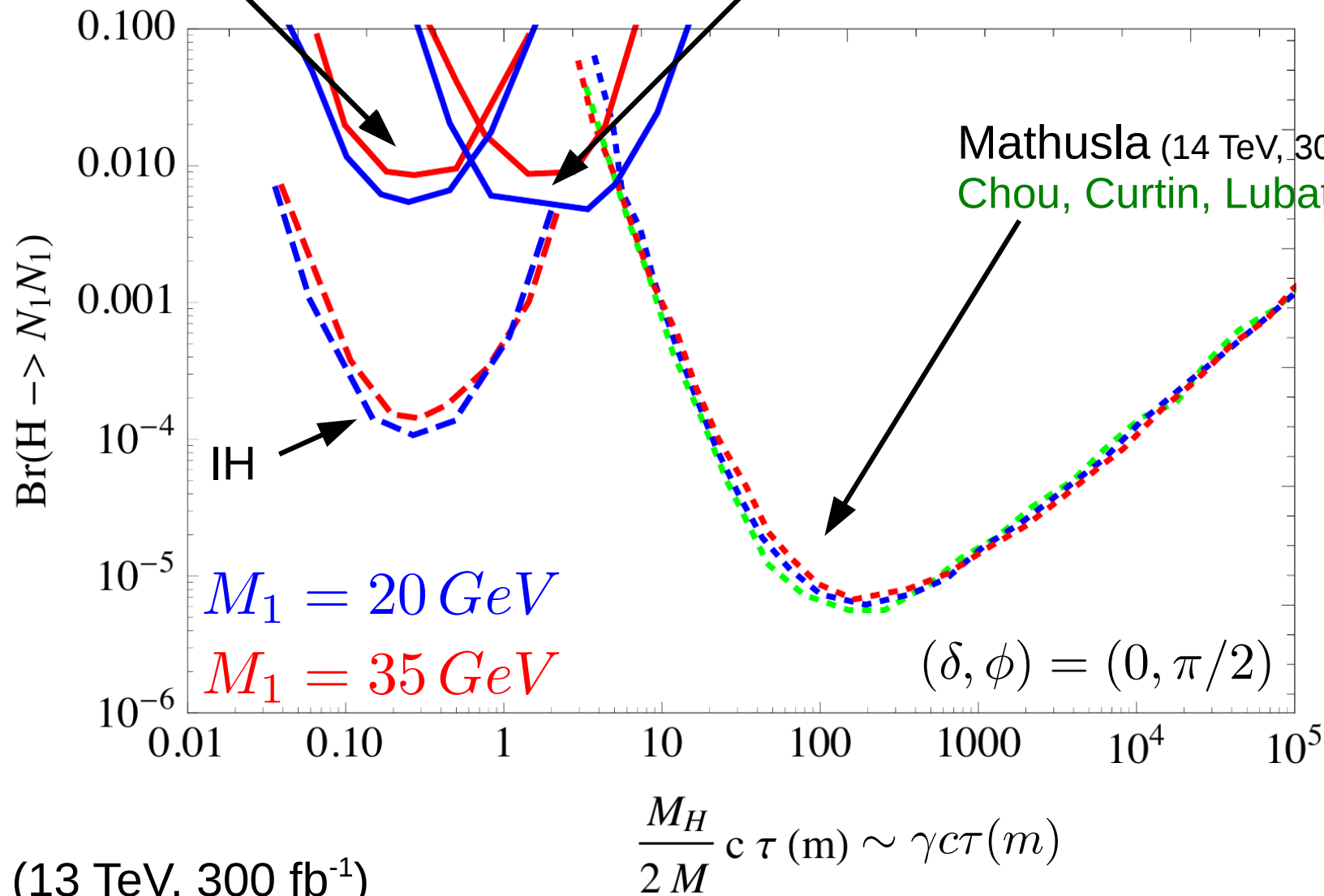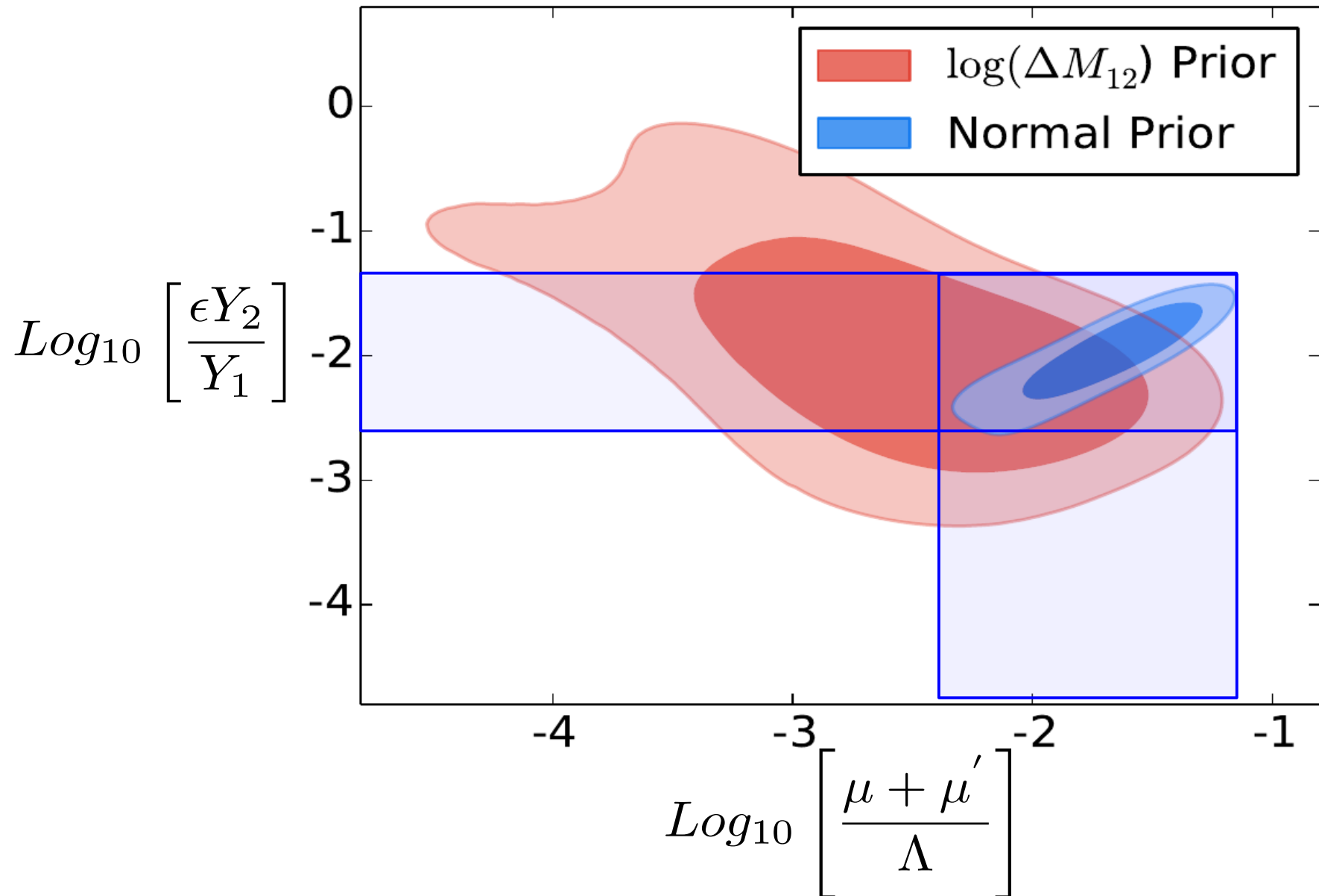
Approximated LNC

Approximated LNC

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \textcolor{red}{\epsilon Y_2^T} v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \textcolor{red}{\mu'} & \Lambda \\ \textcolor{red}{\epsilon Y_2} v/\sqrt{2} & \Lambda & \textcolor{red}{\mu} \end{pmatrix}$$

Mohapatra 1986; Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Malinsky, Romao, Valle 2005...

- Light nu masses suppressed with LNV parameters

$$m_\nu = \textcolor{red}{\mu} \frac{v^2}{2\Lambda^2} Y_1^T Y_1 + \frac{v^2}{2\Lambda} \textcolor{red}{\epsilon Y_2^T} Y_1 + \frac{v^2}{2\Lambda} Y_1^T \textcolor{red}{\epsilon Y_2}$$

- Quasi-Dirac heavy neutrinos:

$$M_2 \approx M_1 \approx \Lambda \qquad \Delta M \approx \textcolor{red}{\mu' + \mu}$$

Conclusions: Minimal Model + NP

- Previous predictions relay to a large extent on its minimality. We studied the impact of NP encoded on d=5 effective operators

- If coefficients are of the same order, strongest bounds come from the bounds on the lightest neutrino mass:

$$\frac{v^2 \alpha_W}{\Lambda} \sim \mathcal{O}(1) m_{lightest} \leq 0.2 \, eV \leftrightarrow \frac{\alpha_W}{\Lambda} \leq 3 \cdot 10^{-9} \, TeV^{-1}$$

In order to keep the minimal model predictions on flavour mixing the bound should be much stronger (at least one order of magnitude)

$$\frac{v^2 \alpha_W}{\Lambda} \lesssim 0.1 \sqrt{\Delta m_{sol}^2} \sim 10^{-3} eV$$

Conclusions: Minimal Model + NP

- Previous predictions relay to a large extent on its minimality.
  We studied the impact of NP encoded on d=5 effective operators

- In the presence, instead, of large hierarchies:

$$\alpha_W \ll \alpha_{N\Phi} \sim \alpha_{NB}$$

which could be protected by global symmetries $(U_L(1), \, MFV)$

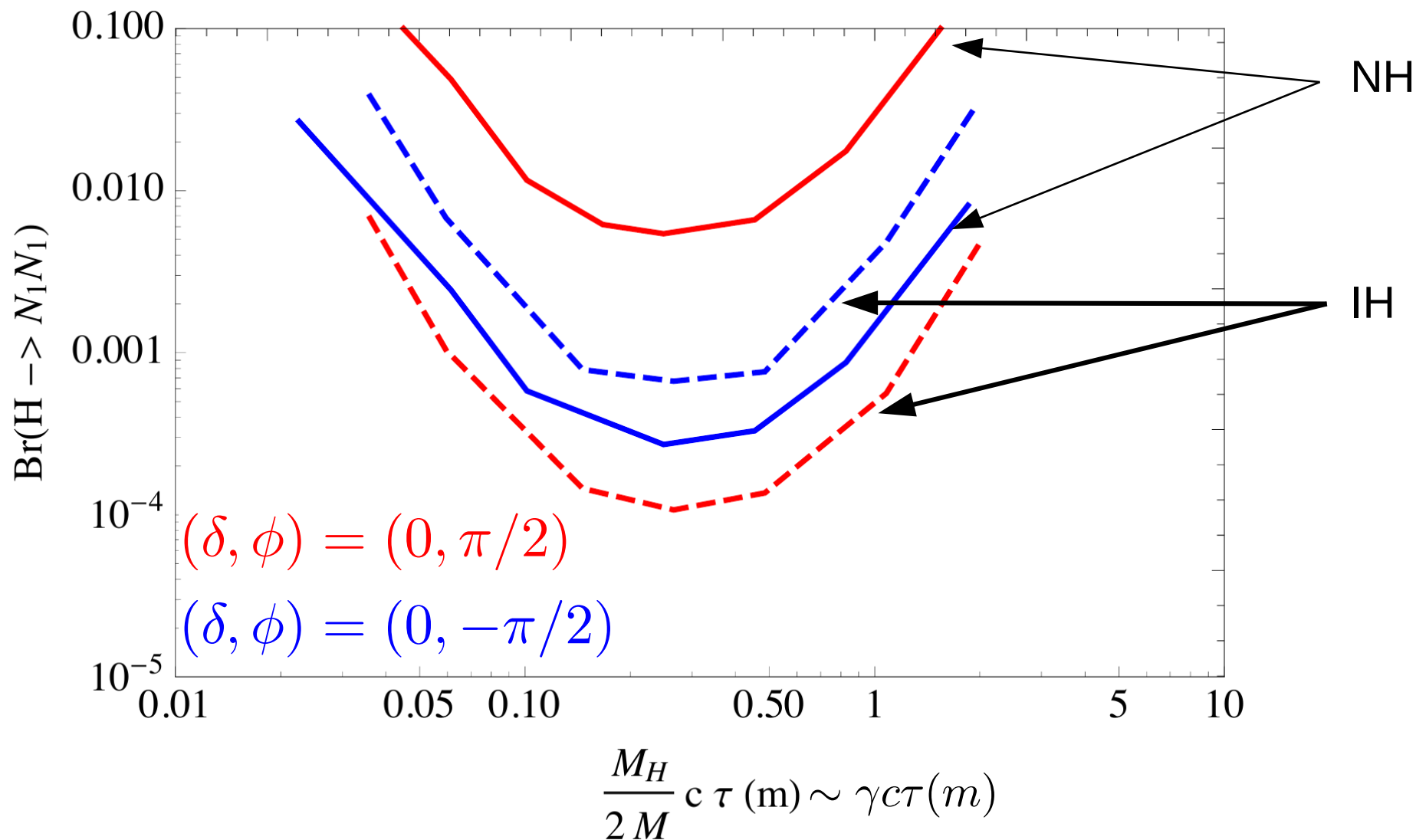LHC: $\quad \dfrac{\alpha_{N\Phi}}{\Lambda} \leq 6 \times \left(10^{-3} - 10^{-2}\right) TeV^{-1}$

Caputo, Hernandez, JLP, Salvado 2017

$$\dfrac{\alpha_{NB}}{\Lambda} < 10^{-2} - 10^{-1} \, TeV^{-1}$$

Aparici, Kim, Santamaria, Wudka 2009.

Seesaw Portal

LHC (13 TeV, 300 fb⁻¹)

$M_1 = 20\,GeV$

Production Branching Ratio

$$g_{N\Phi} \equiv \frac{v \alpha_{N\Phi}}{\sqrt{2}\Lambda}$$

Legend:
- $M_N = 50$ GeV
- $M_N = 35$ GeV
- $M_N = 20$ GeV
- $M_N = 10$ GeV
- $M_N = 5$ GeV

y-axis: $\mathrm{Br}(H \rightarrow N_1 N_1)$

x-axis: $g_{N\Phi}$
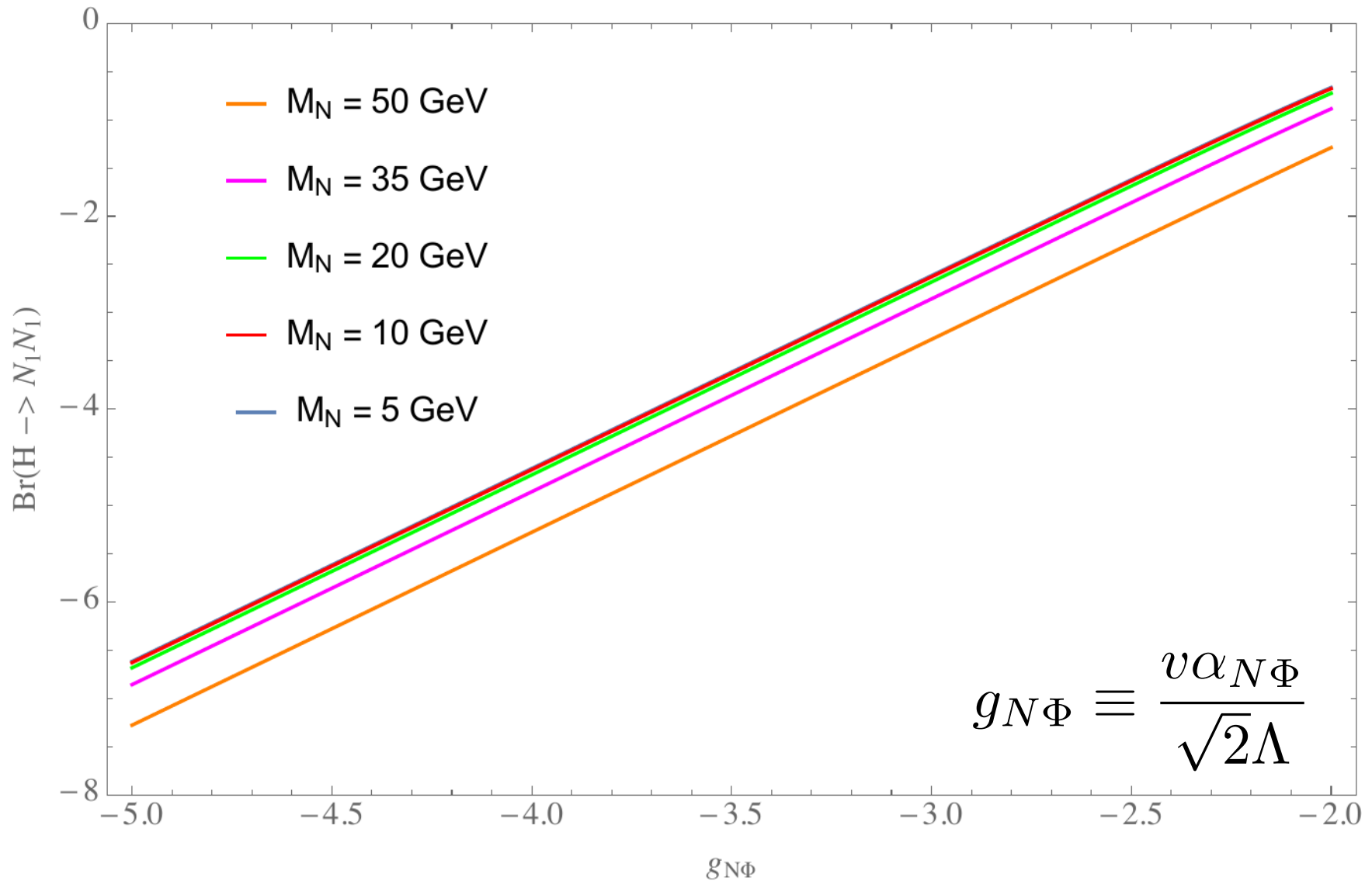
Production Cross Section
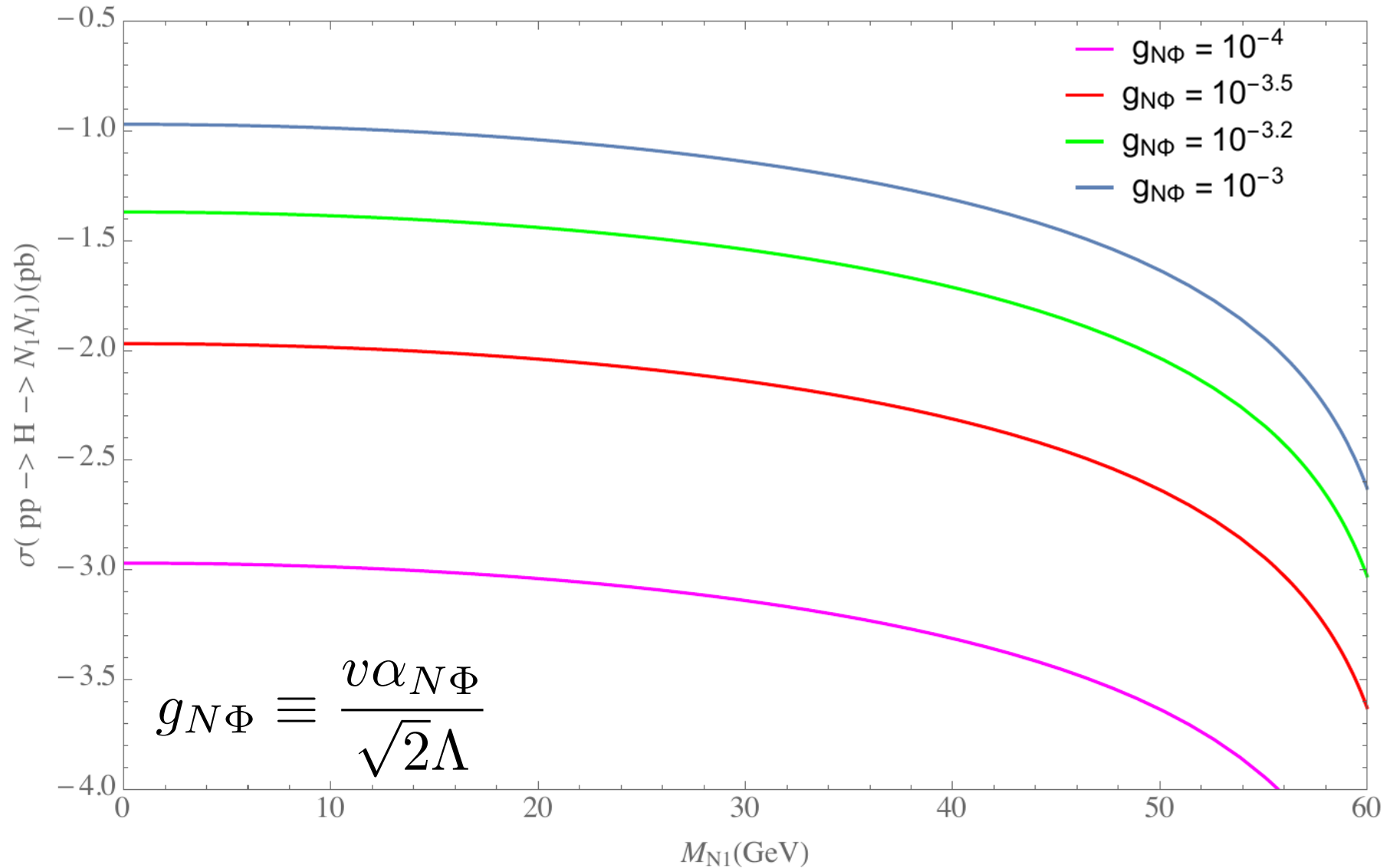
Predicting Y_B in minimal model N_R=2

- Neutrinoless double beta decay effective mass in the IH case

$$|m_{\beta\beta}|_{IH} \simeq$$

LIGHT NEUTRINO
contribution

$$\simeq \quad \sqrt{\Delta m^2_{atm}} \left| c^2_{13} \left(c^2_{12} + e^{2i\phi_1} s^2_{12} \left(1 + \frac{r^2}{2} \right) \right) \right.$$

$$- \left. f(A) e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2 e^{i\delta} s_{23} \theta_{13}) \frac{(0.9\,\text{GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right) \right|$$

$$\theta$$

HEAVY NEUTRINO
contribution

- Heavy neutrino contribution can be sizable for $M \sim O\left(GeV\right)$ ✅

Mitra, Senjanovic, Vissani 2011
JLP, Pascoli, Wong 2012

In order to quantify the discovery CP potential we consider that SHiP or FCC-ee will measure the number of electron and muon events in the decay of one of the heavy neutrino states (without loss of generality we assume to be that with mass M_1), estimated as explained in the previous section. We will only consider statistical errors.

The test statistics (TS) for leptonic CP violation is then defined as follows:

$$\Delta\chi^2 \equiv -2 \sum_{\alpha=\text{channel}} N_\alpha^{\text{true}} - N_\alpha^{CP} + N_\alpha^{\text{true}} \log\left(\frac{N_\alpha^{CP}}{N_\alpha^{\text{true}}}\right)$$
$$+ \left(\frac{M_1 - M_1^{\min}}{\Delta M_1}\right)^2. \tag{10}$$

where $N_\alpha^{\text{true}} = N_\alpha(\delta, \phi_1, M_1, \gamma, \theta)$ is the number of events for the true model parameters, and $N_\alpha^{CP} = N_\alpha(CP, \gamma^{\min}, \theta^{\min}, M_1^{\min})$ is the number of events for the CP-conserving test hypothesis that minimizes $\Delta\chi^2$ among the four CP conserving phase choices $CP = (0/\pi, 0/\pi)$ and over the unknown test parameters. ΔM_1 is the uncertainty in the mass, which is assumed to be 1%.
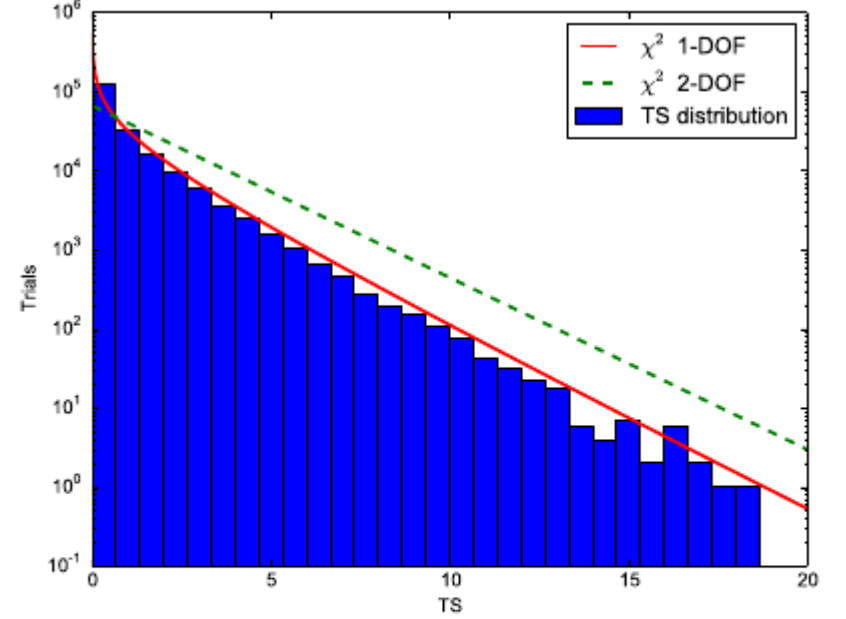
Fig. 4 Distribution of the test statistics for $\mathcal{O}(10^7)$ number of experimental measurements of the number of events for true values of the phases $(\delta, \phi_1) = (0,0)$ for IH and $(\gamma, \theta, M_1) = (3.5, 0, 1)$ GeV, compared to the χ^2 distribution for 1 or 2 degrees-of-freedom.

Kinematical Cuts

$$p_T(l) > 26 \text{ GeV}, \quad |\eta| < 2, \quad \Delta R > 0.2, \quad \cos\theta_{\mu\mu} > -0.75.$$

ee	$M_1 = 10\text{GeV}$	$M_1 = 20\text{GeV}$	$M_1 = 30\text{GeV}$	$M_1 = 40\text{GeV}$
p_T	6.4%	7.0%	5.6%	4.5%
η	4.2%	4.8%	4%	2.9%
ΔR	4.2%	4.8%	4%	2.9%

Table 1. Signal efficiciencies after consecutive cuts on p_T, η and ΔR for the ee channel in the inner tracker, for various heavy neutrino masses.

(Independent of U)

$\mu\mu$	$M_1 = 10\text{GeV}$	$M_1 = 20\text{GeV}$	$M_1 = 30\text{GeV}$	$M_1 = 40\text{GeV}$
p_T	7.0%	6.8%	6.0%	4.7 %
η	4.7%	4.9%	4%	3.2%
ΔR	4.7%	4.9%	4%	3.2%
$\cos\theta_{\mu\mu}$	3.2%	3.6%	3.0%	2.7%

Table 2. Signal efficiciencies after consecutive cuts on p_T, η and ΔR for the $\mu\mu$ channel in the muon chamber for various heavy neutrino masses.

Cuts associated to displaced tracks

- Inner tracker (IT):

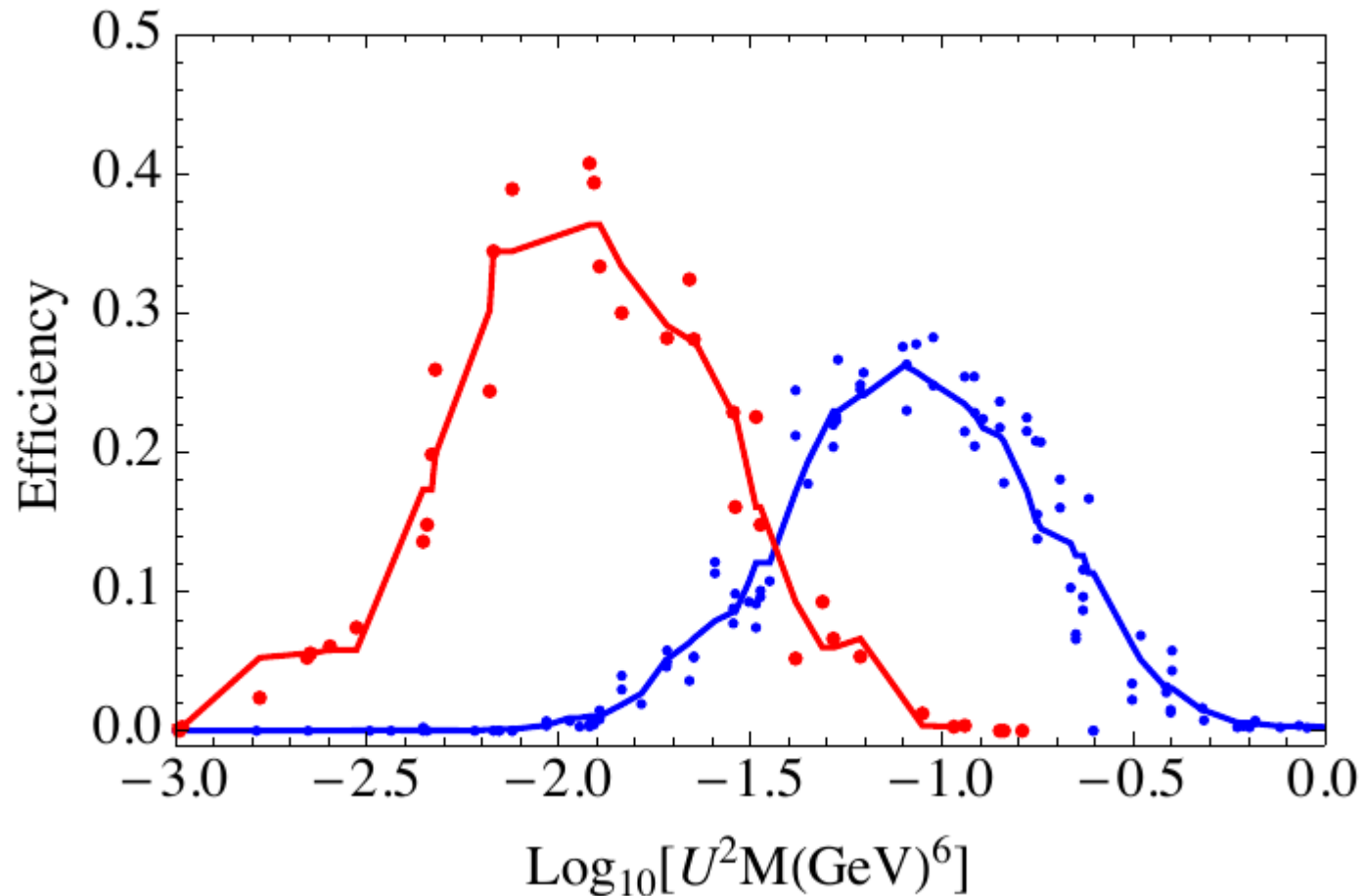$$10\text{cm} < |L_{xy}| < 50\text{cm}, \quad |L_z| \leq 1.4\text{m}, \quad d_0/\sigma_d^t > 12,$$

where $\sigma_d^t \simeq 20\mu\text{m}$ is the resolution in the tracker.

- Muon chambers (MC):

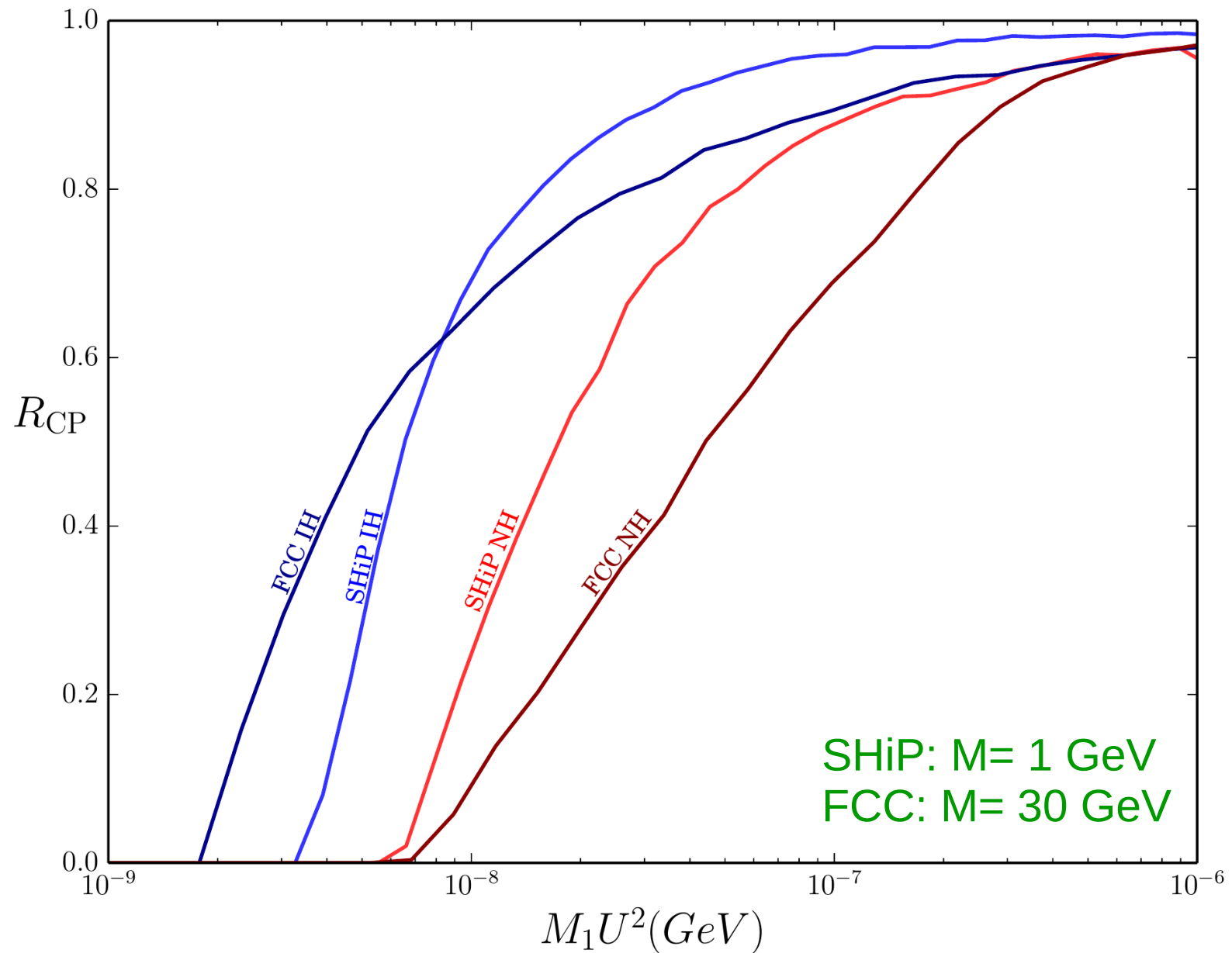$$|L_{xy}| \leq 5\text{m}, \quad |L_z| \leq 8m, \quad d_0/\sigma_d^\mu > 4,$$

where the impact parameter resolution in the chambers is $\sigma_d^\mu \sim 2\text{cm}$.

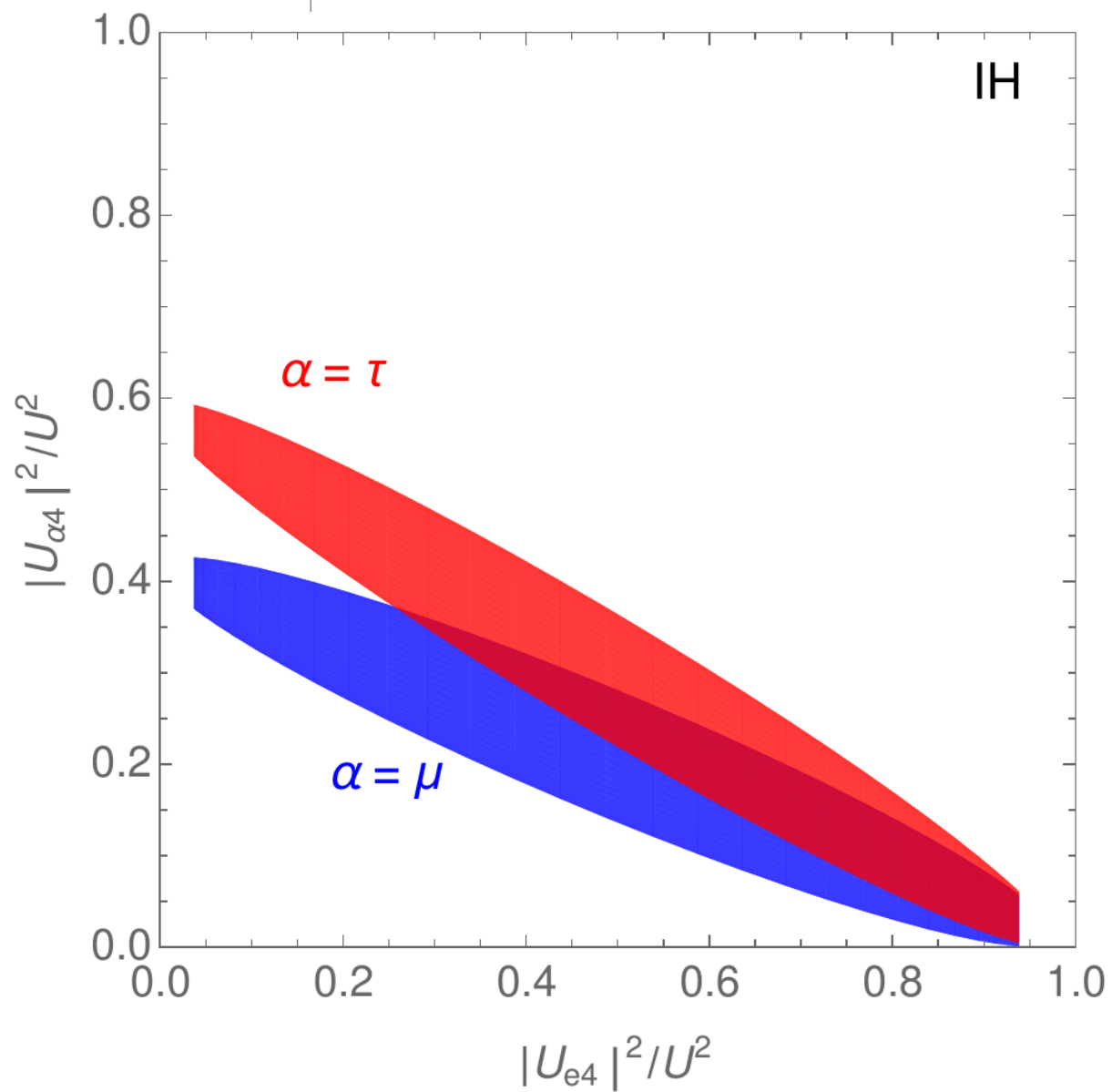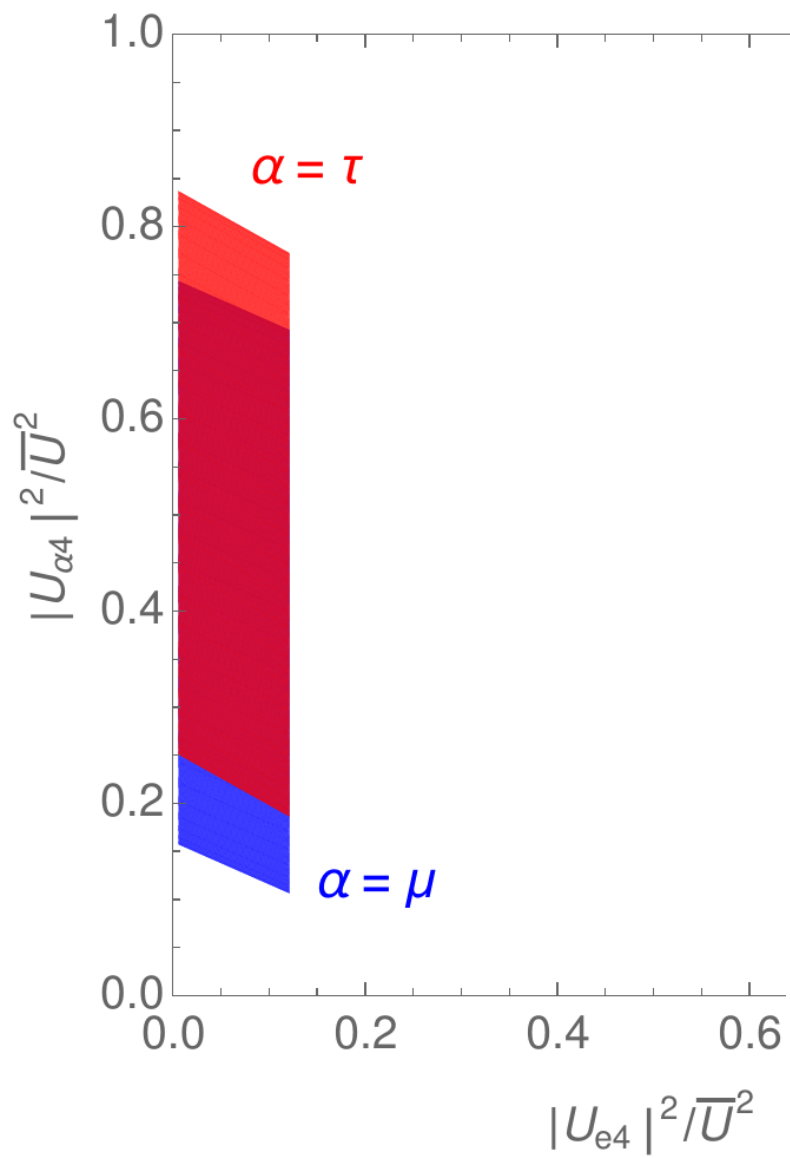# Cuts associated to displaced tracks

$$< L^{-1} > \propto U^2 M^6$$

5σ discovery CP-violation

R_{CP} vs $M_1 U^2 (GeV)$

FCC IH, SHiP IH, SHiP NH, FCC NH
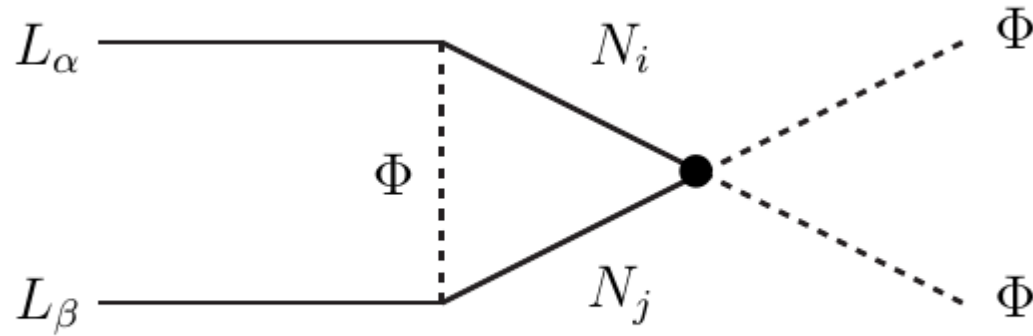
SHiP: M= 1 GeV
FCC: M= 30 GeV

Predicting Y_B in minimal model $N_R=2$

- **Baryon asymmetry** for IH and in the weak wash out regime:

$$[Y_B]_{IH} \propto e^{4\gamma} \frac{(\Delta m^2_{atm})^{3/2}}{4v^6} M_1 M_2 (M_1 + M_2)$$

$$\left[(\sin 2\theta \cos 2\theta_{12} - \cos \phi_1 \cos 2\theta \sin 2\theta_{12}) \left(\sin^2 2\theta_{23} + (4 + \cos 4\theta_{23}) \sin \phi_1 \sin 2\theta_{12} \right) \right.$$

$$\left. + \mathcal{O}(\epsilon) \right]$$

- Baryon asymmetry depends on all the unknown parameters (also on δ at $\mathcal{O}(\epsilon)$)

1-loop contribution of $\mathcal{O}_{N\Phi}$ to nu masses

$$\frac{\alpha_{N\phi}}{\Lambda} \lesssim \frac{2 \cdot 10^{13}}{\log \frac{\mu^2}{M^2}} \left(\frac{10^{-6}}{\theta^2}\right) \left(\frac{\text{GeV}}{M}\right)^2 \frac{\alpha_W}{\Lambda}$$

Kinematic Equations

We have solved the equations for the density matrix in the Raffelt-Sigl formalism

$$\frac{d\rho_N(k)}{dt} = -i[H, \rho_N(k)] - \frac{1}{2}\left\{\Gamma_N^a, \rho_N\right\} + \frac{1}{2}\left\{\Gamma_N^p, 1 - \rho_N\right\}$$

- Fermi-Dirac or Bose-Einstein statistics is kept throughout

- Collision terms include 2 ↔ 2 scatterings at tree level with top quarks and gauge bosons, as well as 1 ↔ 2 scatterings, including the resummation of scatterings mediated by soft gauge bosons

- Leptonic chemical potentials are kept in all collision terms to linear order

- Include spectator processes
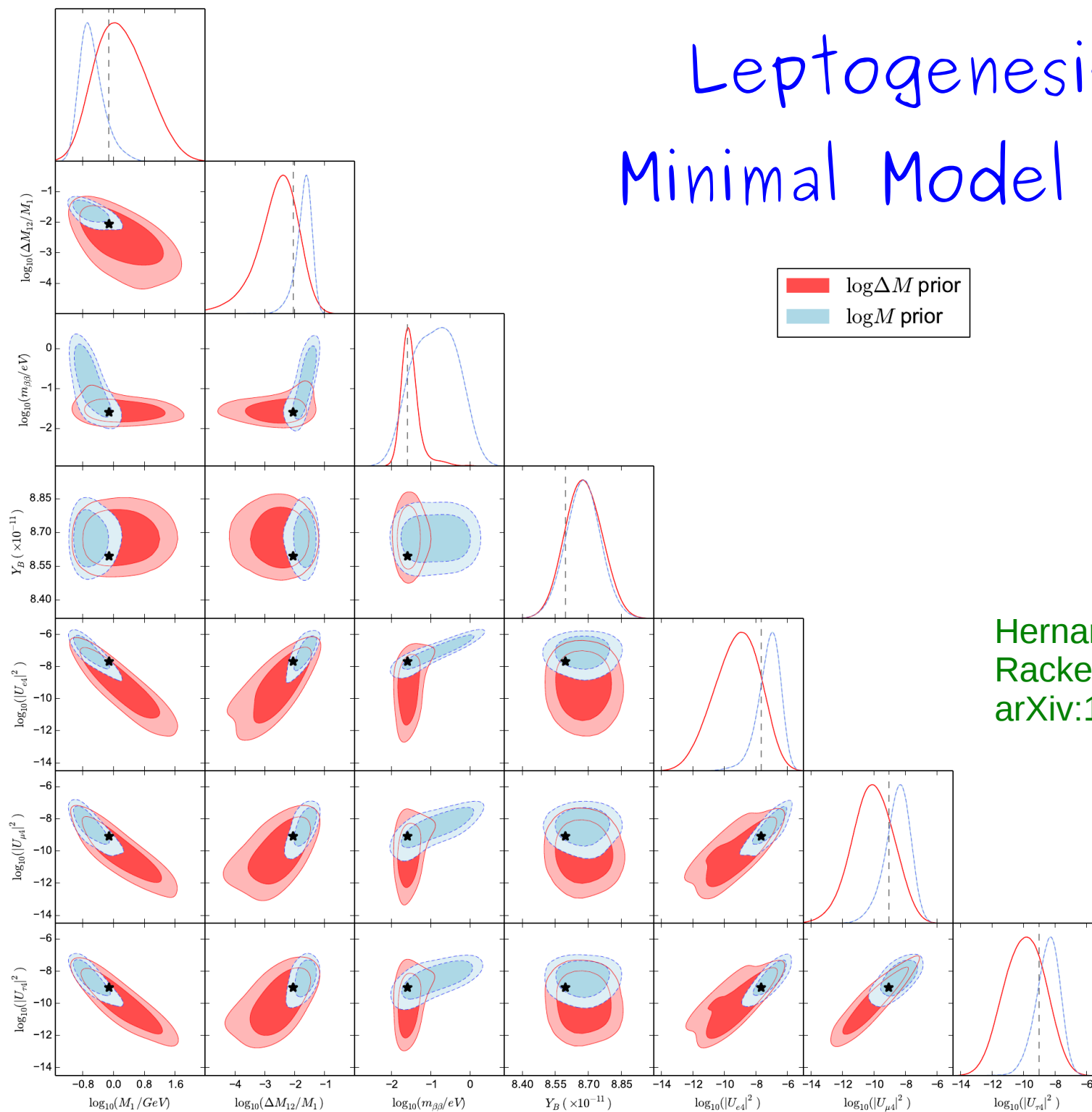
Kinematic Equations

We have solved the equations for the density matrix in the Raffelt-Sigl formalism using the code SQuIDS

Arguelles Delgado, Salvado, Weaver 2015
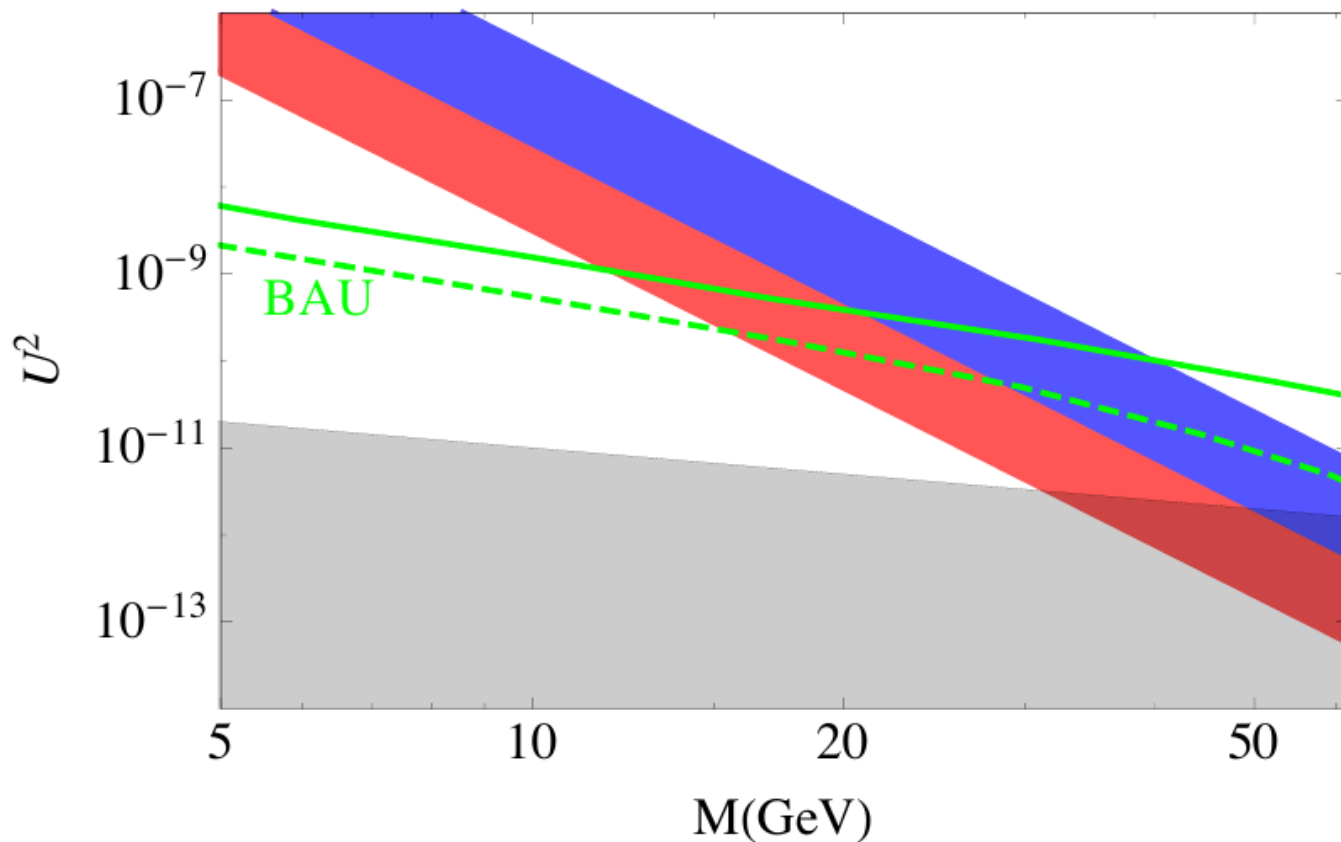https://github.com/jsalvado/SQuIDS

$$xH_u\frac{dr_+}{dx} = -i[\langle H_{\rm re}\rangle, r_+] + [\langle H_{\rm im}\rangle, r_-] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{{\rm Re}[Y^\dagger Y], r_+ - 1\}$$

$$+i\langle\gamma_N^{(1)}\rangle{\rm Im}[Y^\dagger\mu Y] - i\frac{\langle\gamma_N^{(2)}\rangle}{2}\{{\rm Im}[Y^\dagger\mu Y], r_+\} - i\frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{{\rm Im}[Y^\dagger Y], r_-\right\},$$

$$xH_u\frac{dr_-}{dx} = -i[\langle H_{\rm re}\rangle, r_-] + [\langle H_{\rm im}\rangle, r_+] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{{\rm Re}[Y^\dagger Y], r_-\}$$

$$+\langle\gamma_N^{(1)}\rangle{\rm Re}[Y^\dagger\mu Y] - \frac{\langle\gamma_N^{(2)}\rangle}{2}\{{\rm Re}[Y^\dagger\mu Y], r_+\} - i\frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{{\rm Im}[Y^\dagger Y], r_+ - 1\right\},$$

$$\frac{d\mu_{B/3-L_\alpha}}{dx} = \frac{\int_k \rho_F}{\int_k \rho_F'}\left\{\langle\gamma_N^{(0)}\rangle{\rm Tr}[r_-{\rm Re}(Y^\dagger I_\alpha Y) + ir_+{\rm Im}(Y^\dagger I_\alpha Y)]\right.$$

$$\left. + \mu_\alpha\left(\langle\gamma_N^{(2)}\rangle{\rm Tr}[r_+{\rm Re}(Y^\dagger I_\alpha Y)] - \langle\gamma_N^{(1)}\rangle{\rm Tr}[YY^\dagger I_\alpha]\right)\right\},$$

$$\mu_\alpha = -\sum_\beta C_{\alpha\beta}\mu_{B/3-L_\beta},$$

Leptogenesis in Minimal Model N_R=2

Hernandez, Kekic, JLP,
Racker, Salvado 2016
arXiv:1606.06719

IH

Legend:
- $\log \Delta M$ prior (red)
- $\log M$ prior (light blue)

Figure 11. Regions on the plane (M, U^2) where LHC displaced track selection efficiency (eq. (3.20) and (3.21)) is above 10% in the IT (blue band) and MC (red band). The grey shaded region cannot explain the light neutrino masses and the green lines correspond to the upper limits of the 90%CL bayesian region for successful baryogenesis in the minimal model for NH (solid) and IH (dashed), taken from [13].

Model Independent Approach: EFT

• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j
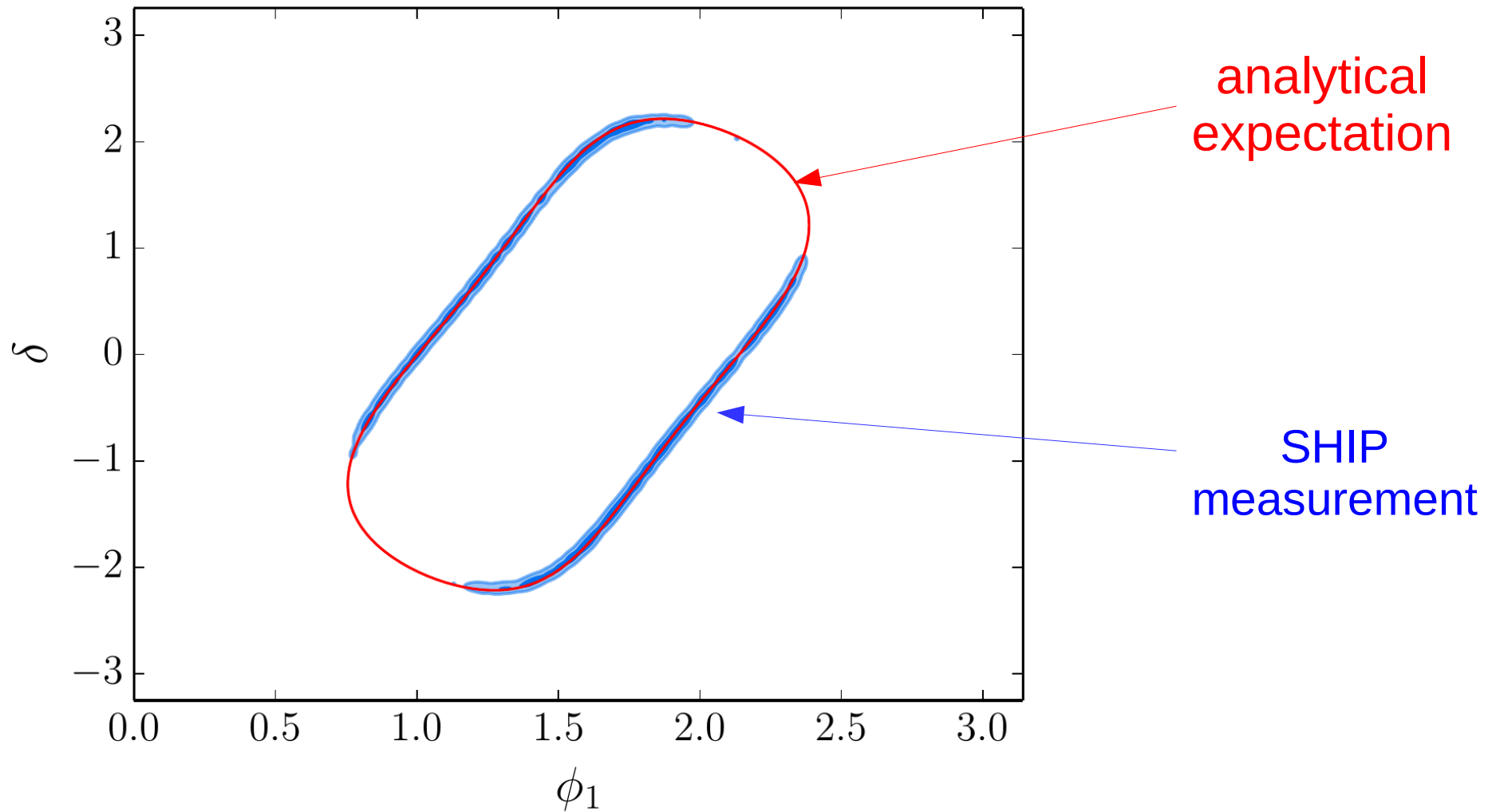
- Electroweak moment N_j couplings. $\dfrac{\alpha_{NB}}{\Lambda} < 10^{-2} - 10^{-1} TeV$

- Generated only at the 1-loop level (suppression with respect to other operators expected)

$$\mathcal{O}_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \overline{N}_i \sigma_{\mu\nu} N_j^c B_{\mu\nu} + h.c.$$
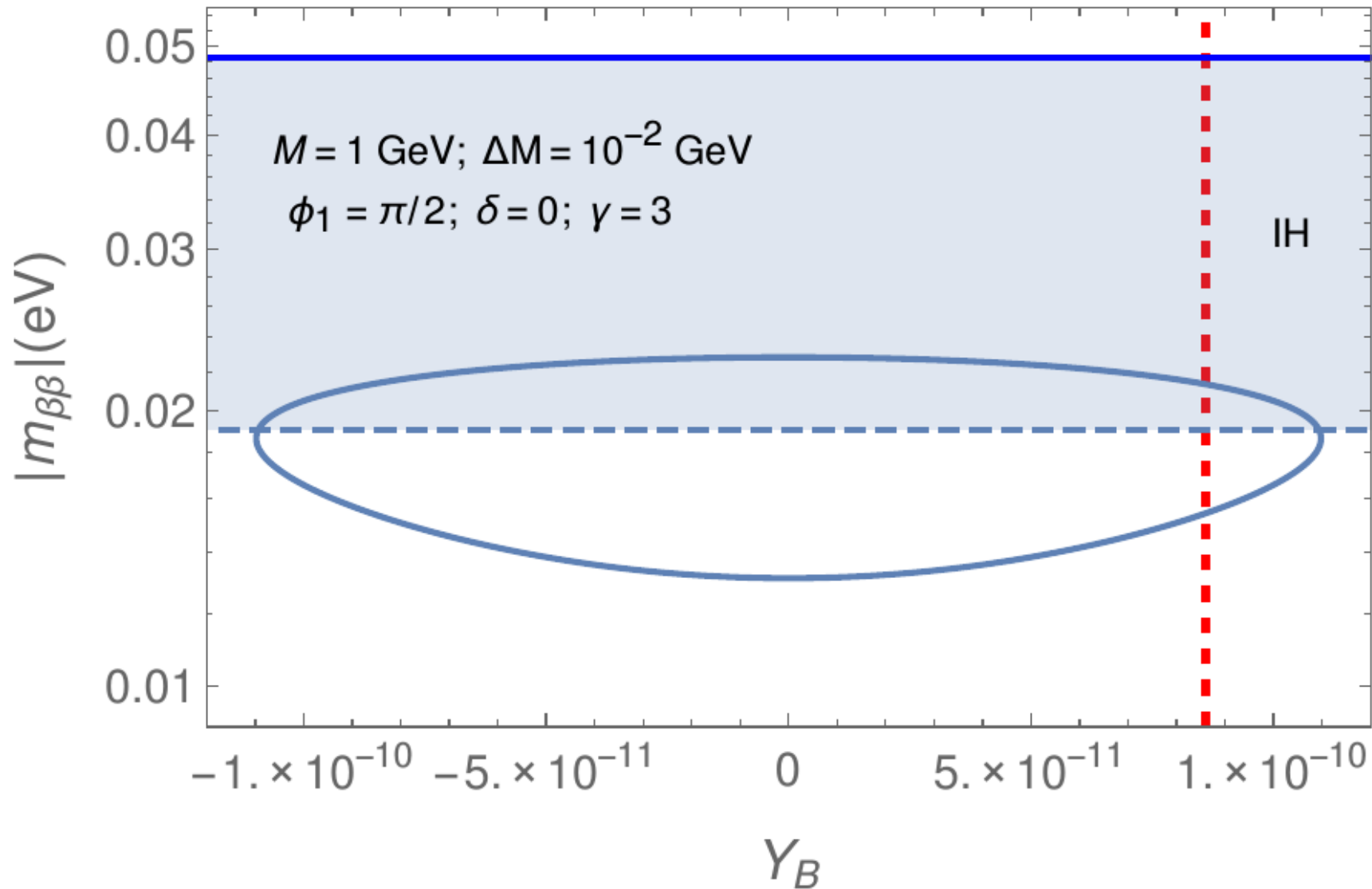
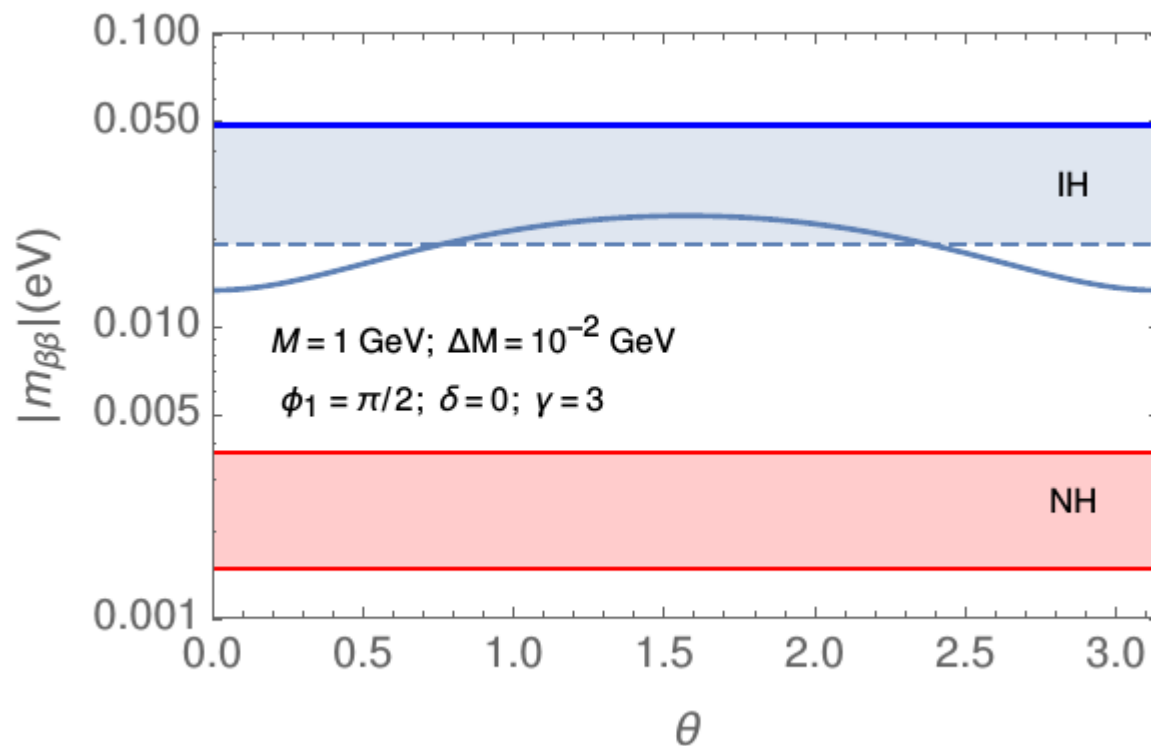Aparici, Kim, Santamaria, Wudka 2009.

SHIP sensitive to PMNS CP phases

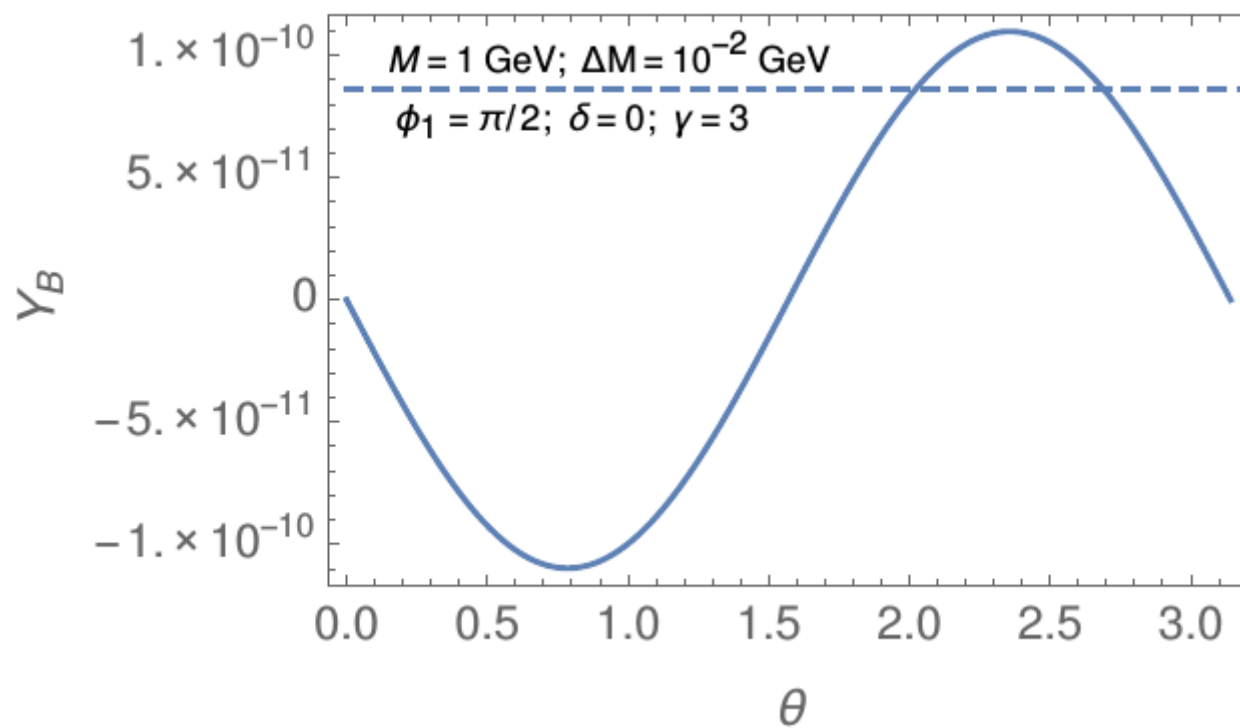Recall, neutrino oscillation experiments sensitive to δ

Predicting Y_B in minimal model $N_R=2$

$M = 1$ GeV; $\Delta M = 10^{-2}$ GeV

$\phi_1 = \pi/2$; $\delta = 0$; $\gamma = 3$

IH

Leptogenesis
in
Minimal Model

Plot 1: $|m_{\beta\beta}|$ (eV) vs θ with $M = 1$ GeV; $\Delta M = 10^{-2}$ GeV; $\phi_1 = \pi/2$; $\delta = 0$; $\gamma = 3$. Regions labeled IH and NH.

Plot 2: Y_B vs θ with $M = 1$ GeV; $\Delta M = 10^{-2}$ GeV; $\phi_1 = \pi/2$; $\delta = 0$; $\gamma = 3$.

Hernandez, Kekic, JLP,
Racker, Salvadò 2016
ArXiv:1606.06719