Testable Models for Leptogenesis

Jacobo López-Pavón

Invisibles18

3- 7 September 2018

Outline

- Minimal Seesaw Model. New Physics Scale.

- **Testable Leptogenesis.**

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

- CP violation in the minimal model.

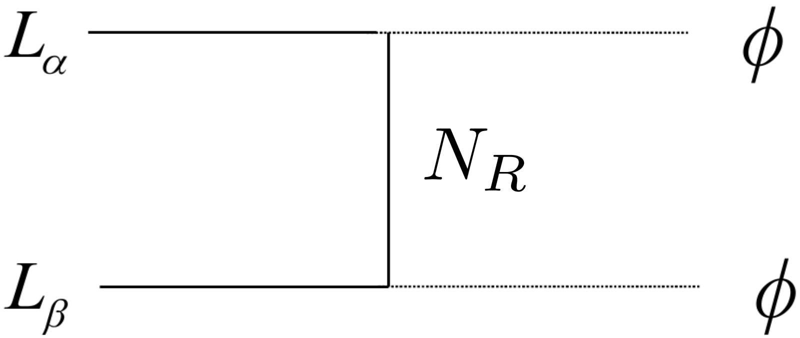
  Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

- Modifications of the minimal model predictions from Higher energy New Physics effects.

  Caputo, Hernandez, JLP, Salvado 1704.08721

- Conclusions

Minimal Seesaw Model (n_R=2)

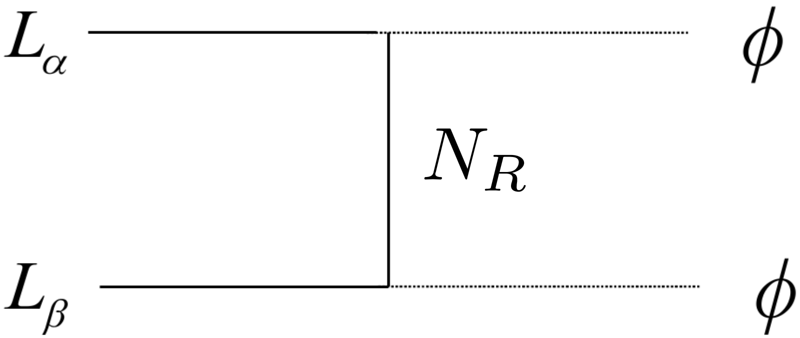


Heavy fermion singlet: N_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

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

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

Minimal Seesaw Model ($n_R=2$)



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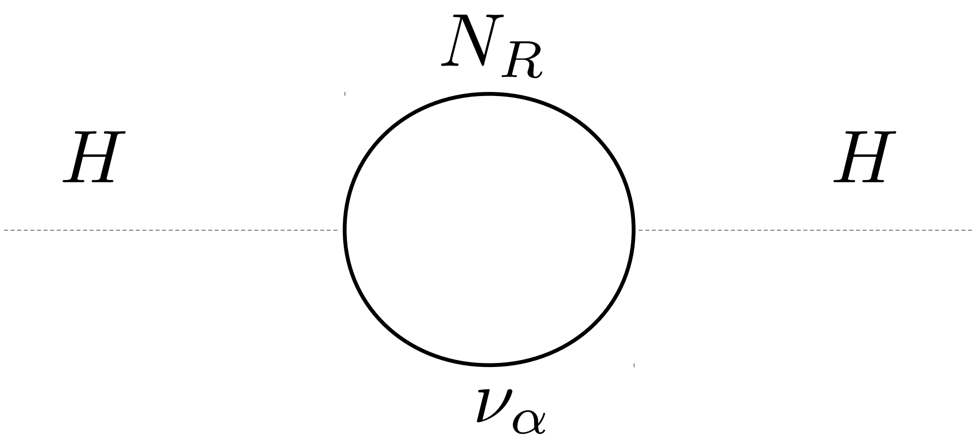
New Physics Scale $\quad (m_\nu \sim Y^2 v^2/M)$

The New Physics Scale

- Contrary to the high scale models, a low Majorana scale does not worsen the Higgs mass hierarchy problem.



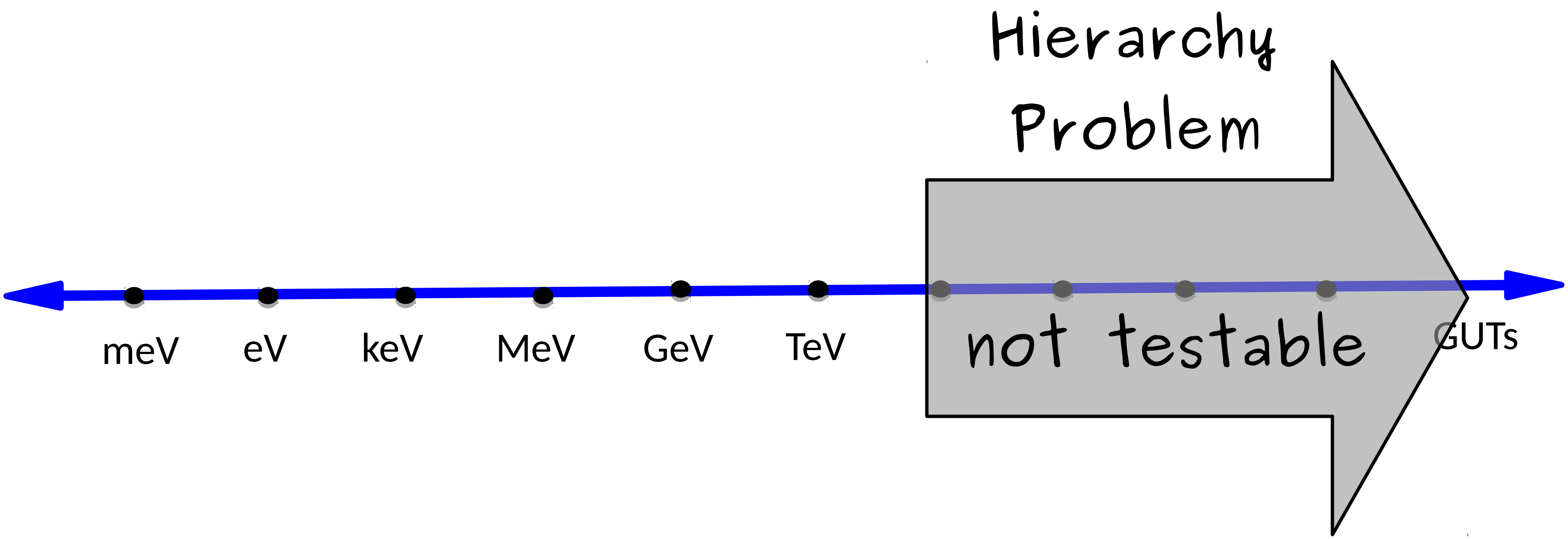
$$[\delta M_H^2]_{N_R} \propto M^2$$

Vissani 1998

- In principle, a small M requires $Y \ll 1$.

$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T \lesssim \mathcal{O}\,(1\,\mathrm{eV})$$

The New Physics Scale



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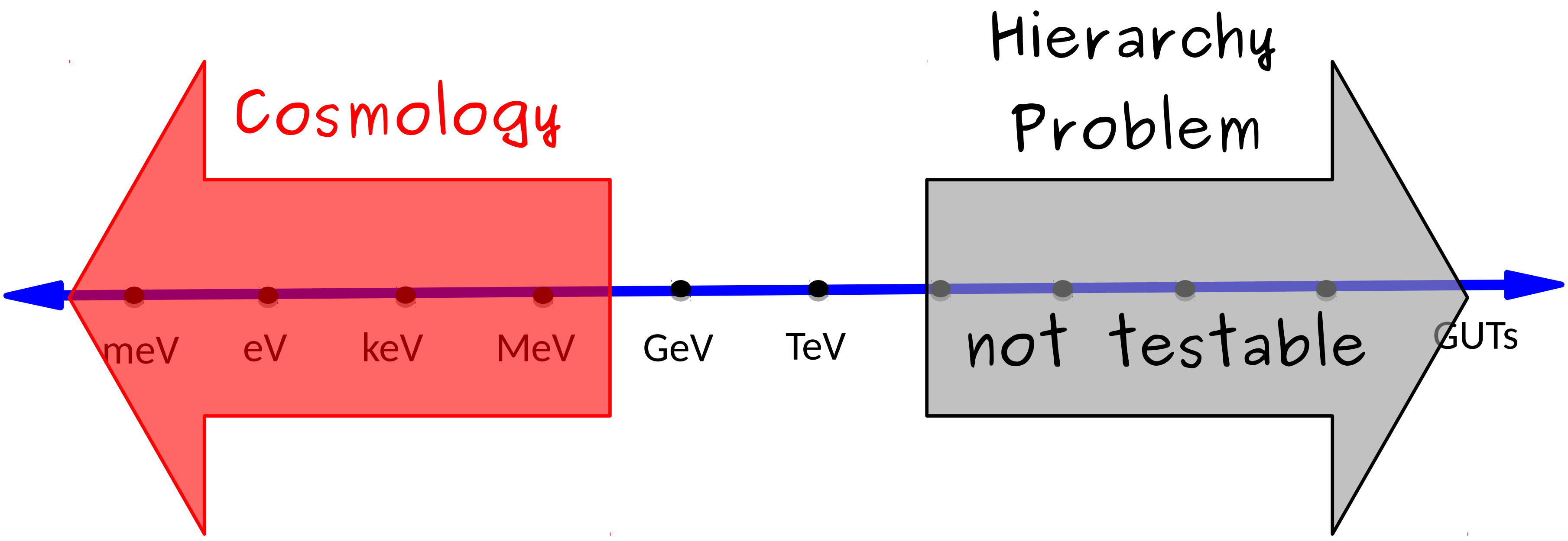
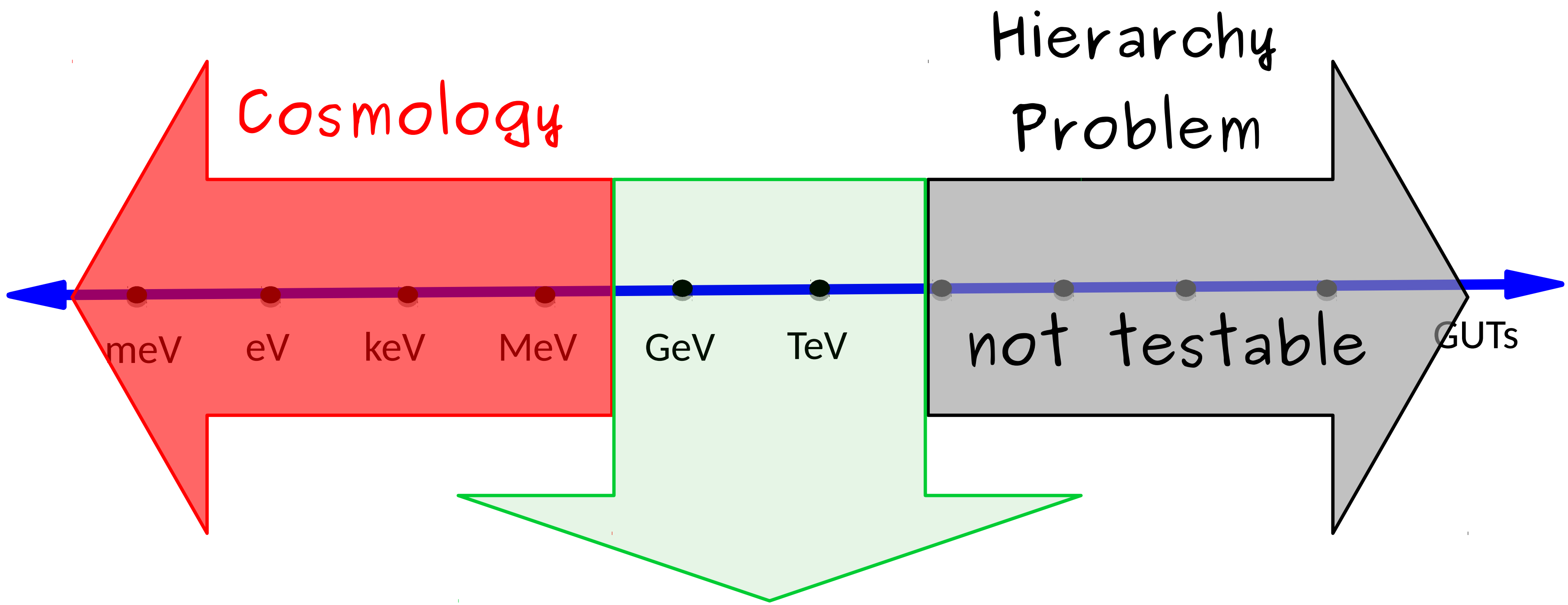


P. Hernandez, M. Kekic, JLP 1311.2614;1406.2961

The New Physics Scale



- $0\nu\beta\beta$ decay

LFV, SHiP, LHC

FCC...

See talks by
Stefan Antusch (colliders) &
Xabier Marcano ($0\nu\beta\beta$)

- Leptogenesis

via Oscillations

M=0.1–100GeV

Akhmedov, Rubakov, Smirnov (ARS)
Asaka, Shaposnikov (AS)

- Resonant

Leptogenesis

M>100GeV

Pilaftsis

Low Scale Leptogenesis
(ARS)

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

Asaka, Shaposhnikov ;Shaposhnikov; Asaka, Eijima, Ishida; Canetti, Drewes, Frossard, Shaposhnikov;Drewes, Garbrecht; Shuve, Yavin; Abada, Arcadi, Domcke, Lucente...

Kinematic Equations

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

$$\frac{d\rho_N(k)}{dt} = -i[H, \rho_N(k)] - \frac{1}{2}\{\Gamma^a_N, \rho_N\} + \frac{1}{2}\{\Gamma^p_N, 1 - \rho_N\}$$

- Fermi-Dirac or Bose-Einstein statistics is kept throughout
- Collision terms include $2 \leftrightarrow 2$ scatterings at tree level with top quarks and gauge bosons, as well as $1 \leftrightarrow 2$ 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

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

Leptogenesis in Minimal Model $n_R=2$

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

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

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

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

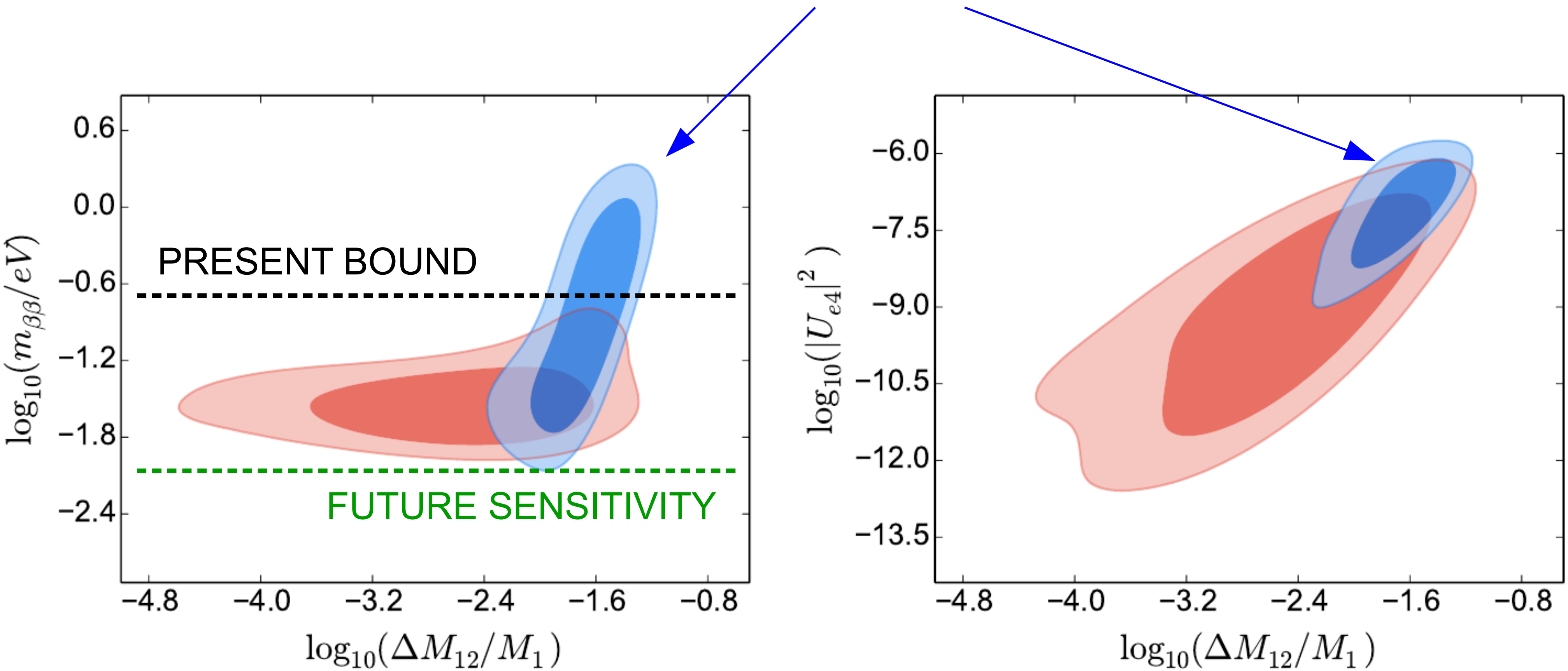
Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3$	$M_1, M_2, \delta, \phi_1, \theta, \gamma$

Fixed by neutrino oscillation experiments

Free parameters

Leptogenesis in Minimal Model $n_R=2$

Non very degenerate solutions



Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $n_R=2$

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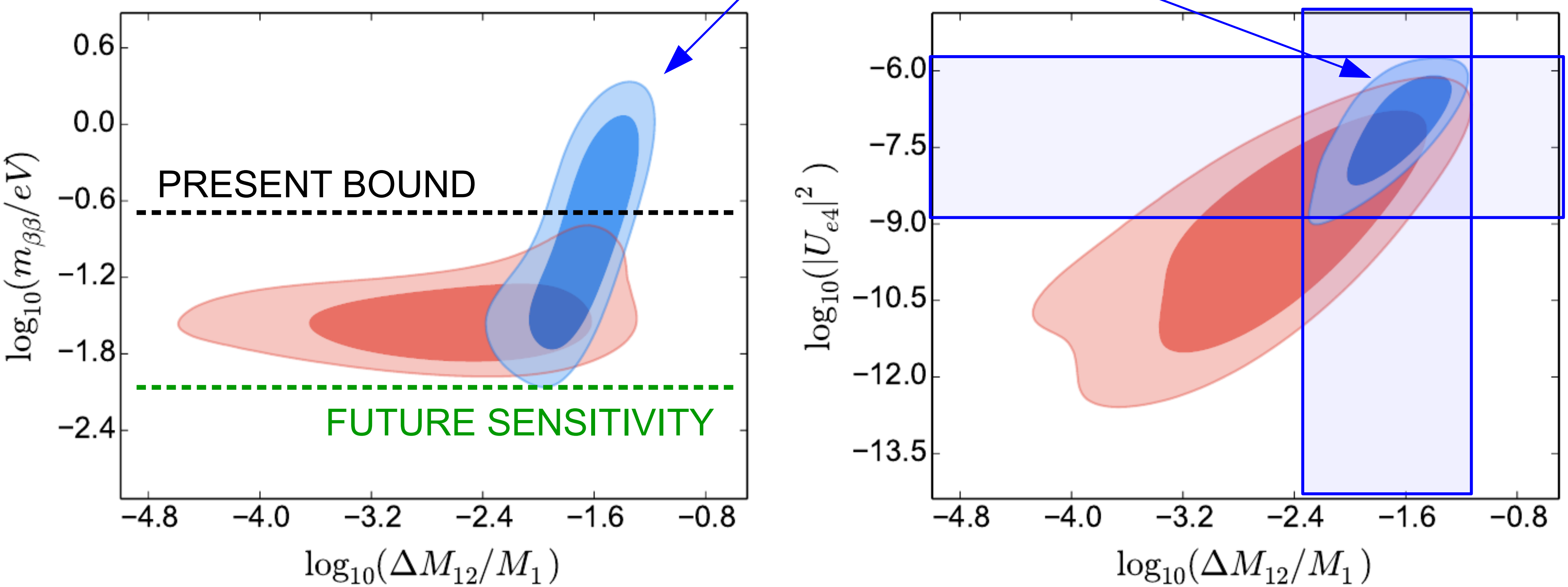

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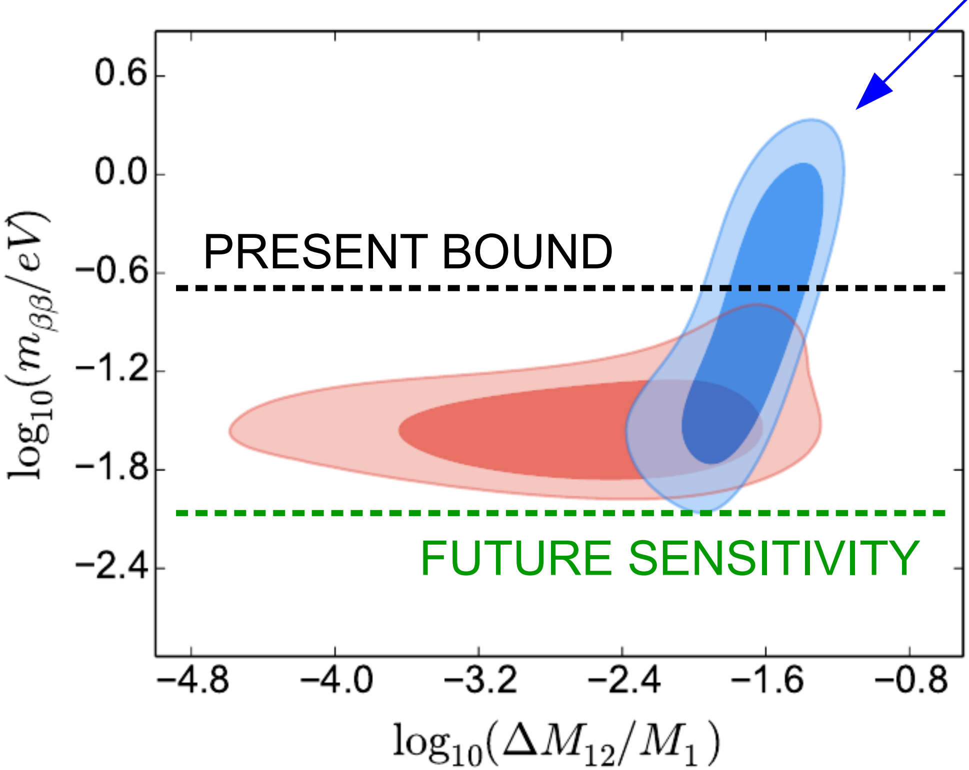
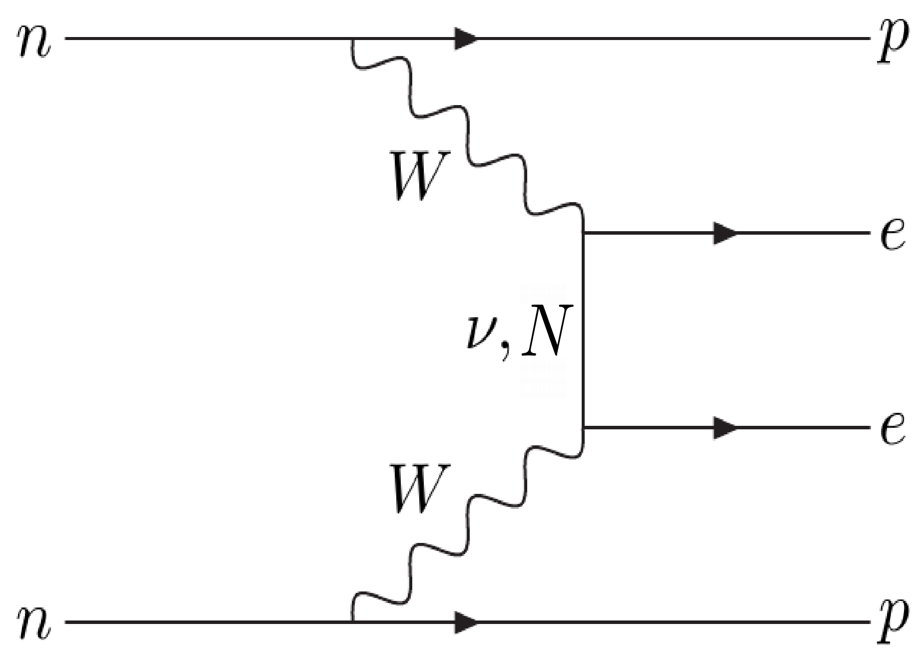


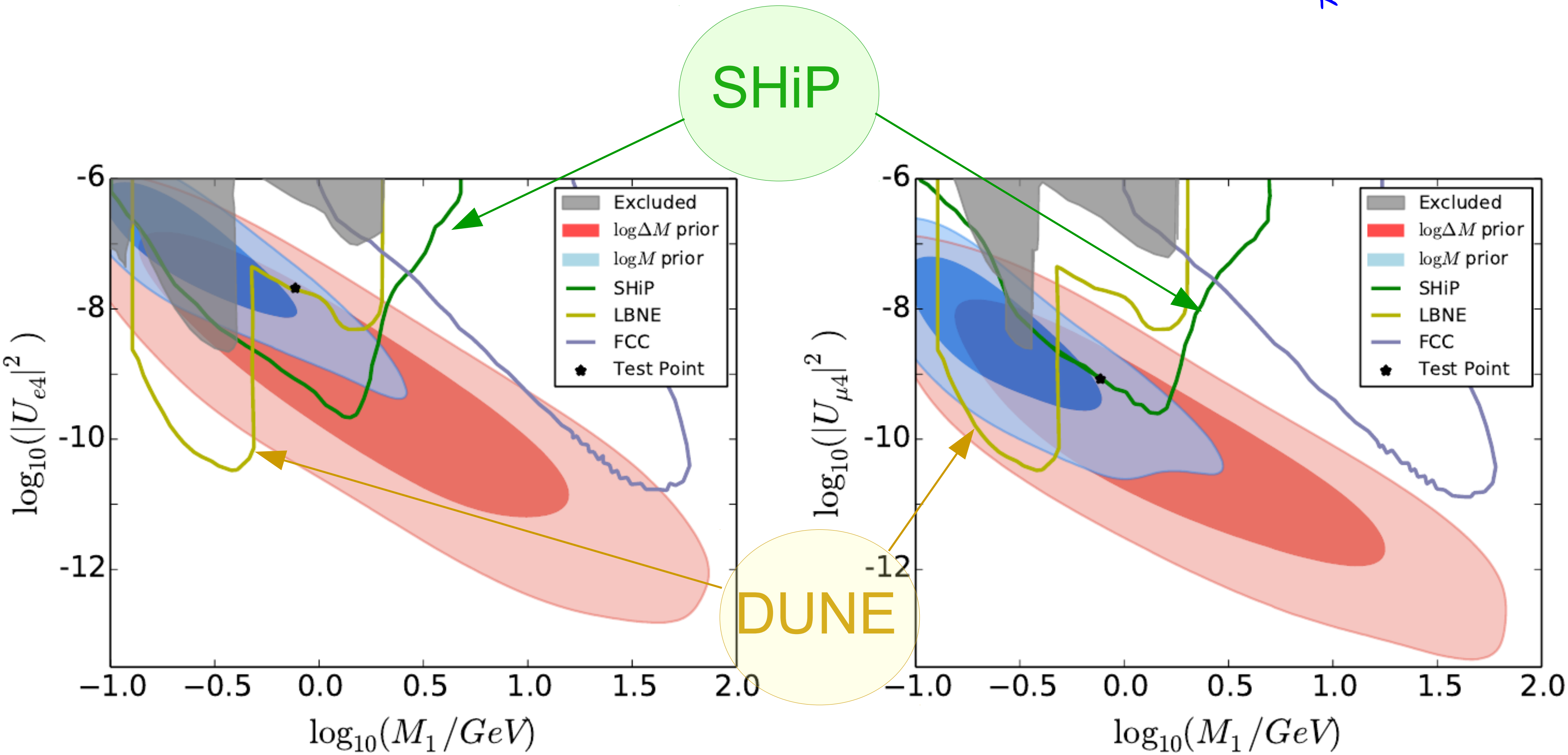


See talk by Chiara Brofferio
(experimental review)

Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $n_R=2$



Inverted light neutrino ordering

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

What if the N_R are within reach of SHiP?

Can we estimate Baryon asymmetry from the experiments?

Predicting Y_B in minimal model $N_R=2$

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

- **SHiP sensitivity** $\Longleftrightarrow |U^2_{\alpha j}| \gg m_\nu/M \Longleftrightarrow \boldsymbol{R_{ij} \gg 1} \Longleftrightarrow \boldsymbol{e^\gamma \gg 1}$

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

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

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

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

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

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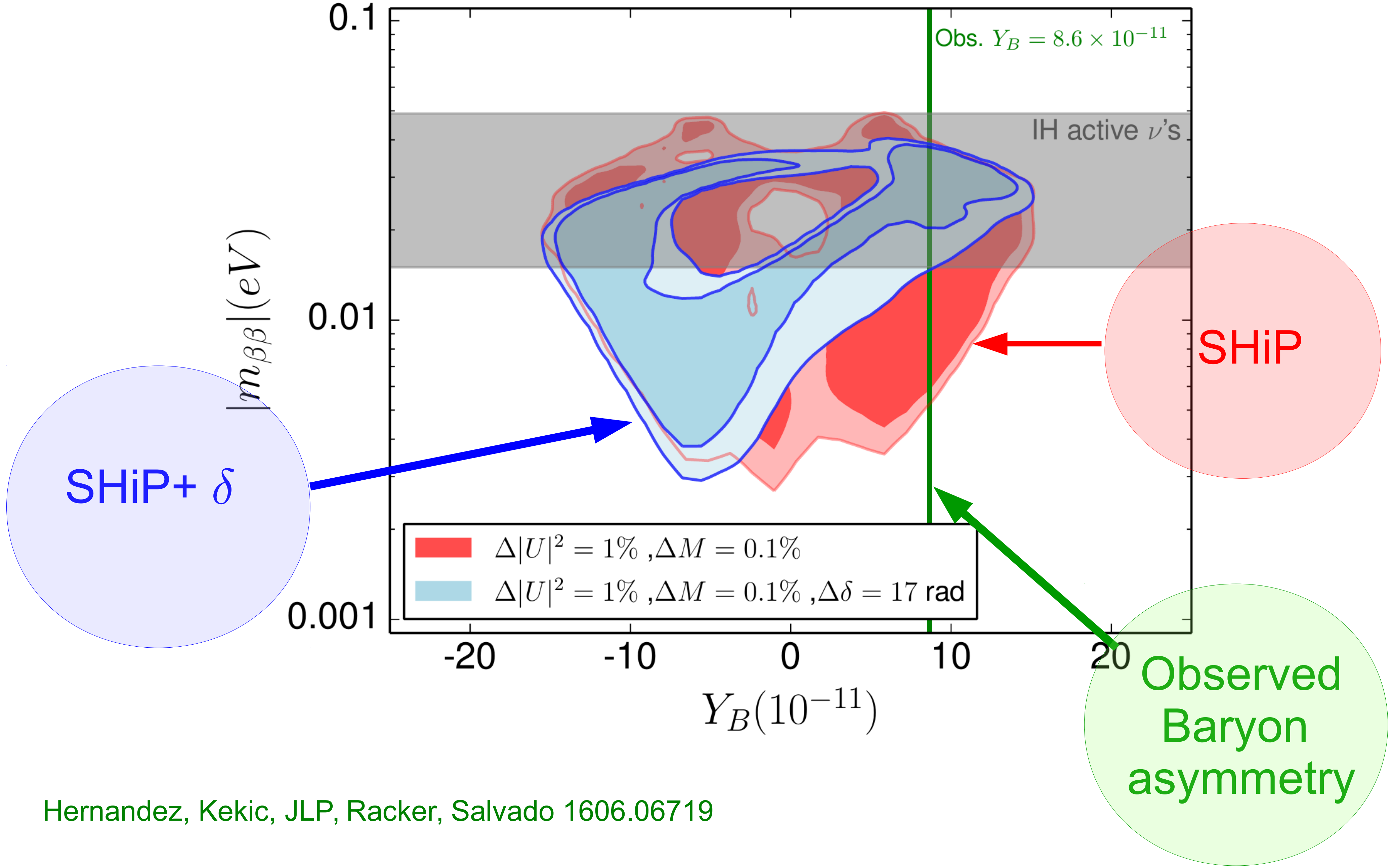
Neutrinoless double beta decay sensitive to θ through interference between light and heavy contribution

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Predicting Y_B in minimal model $N_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

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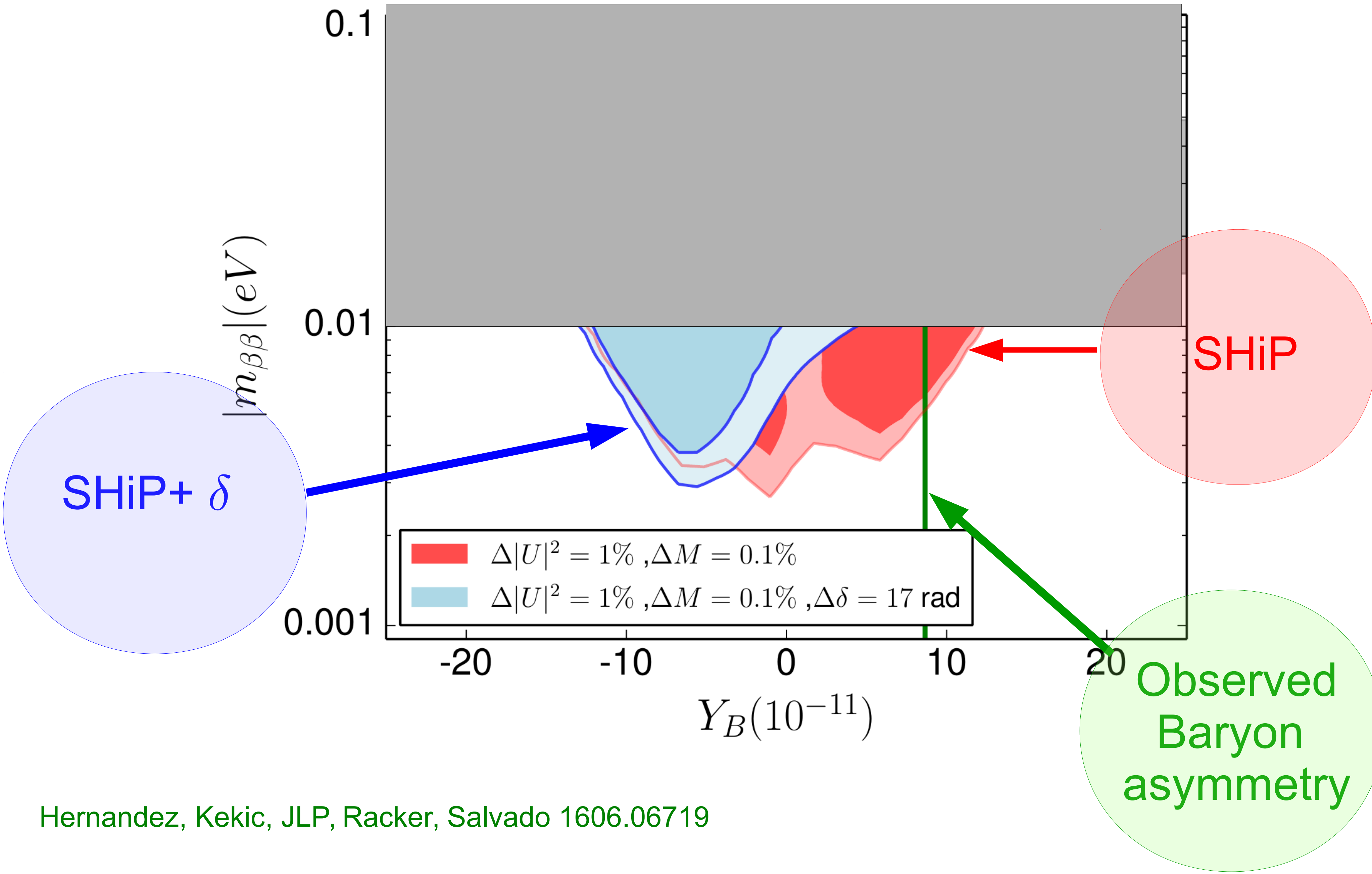
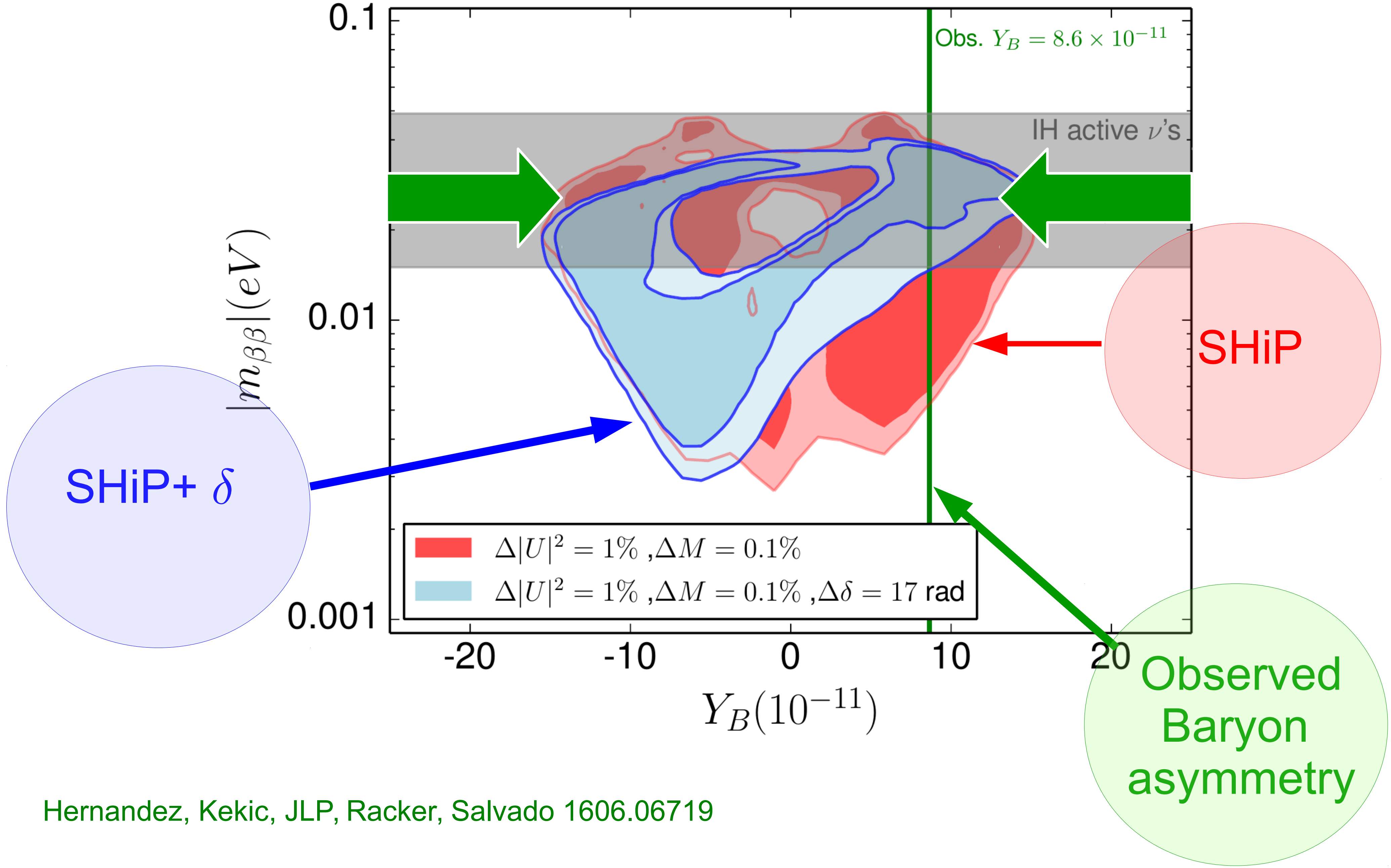


Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Predicting Y_B in minimal model $N_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

CP-violation in Minimal Model

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

CP-violation in minimal model

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

$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu 4}|, |U_{\mu 5}|$$

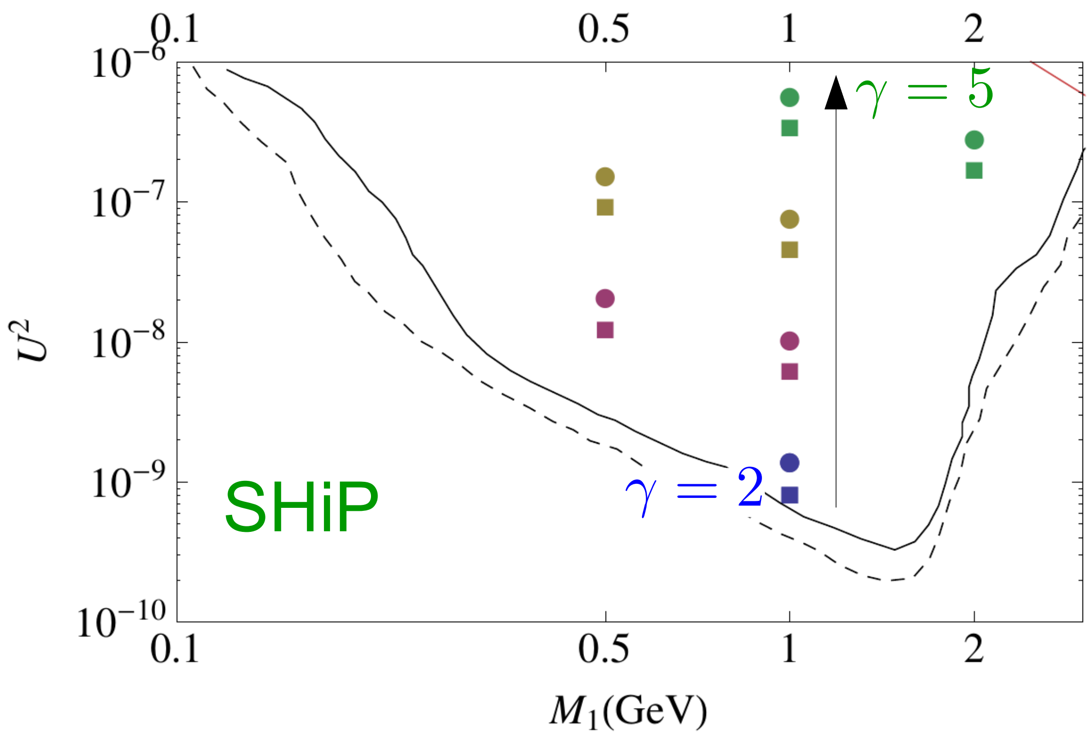
Sensitivity to PMNS CP-phases! δ, ϕ_1

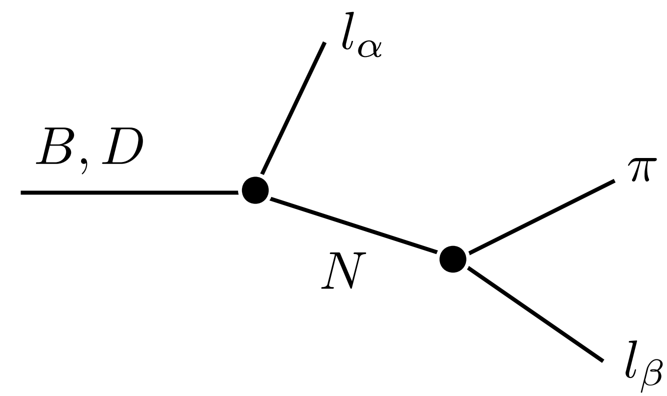
- $|U_{e4}|^2/|U_{\mu 4}|^2 \simeq |U_{e5}|^2/|U_{\mu 5}|^2 \simeq$

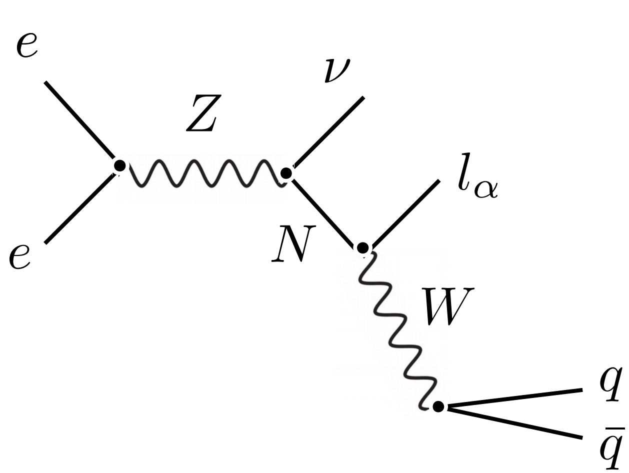
$$\frac{(1 + s_{\phi_1}\sin 2\theta_{12})(1-\theta_{13}^2) + \frac{1}{2}r^2 s_{12}(c_{12}s_{\phi_1} + s_{12})}{\left(1 - \sin 2\theta_{12} s_{\phi_1}\left(1+\frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}\right)c_{23}^2 + \theta_{13}(c_{\phi_1}s_\delta - \cos 2\theta_{12} s_{\phi_1} c_\delta)\sin 2\theta_{23}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

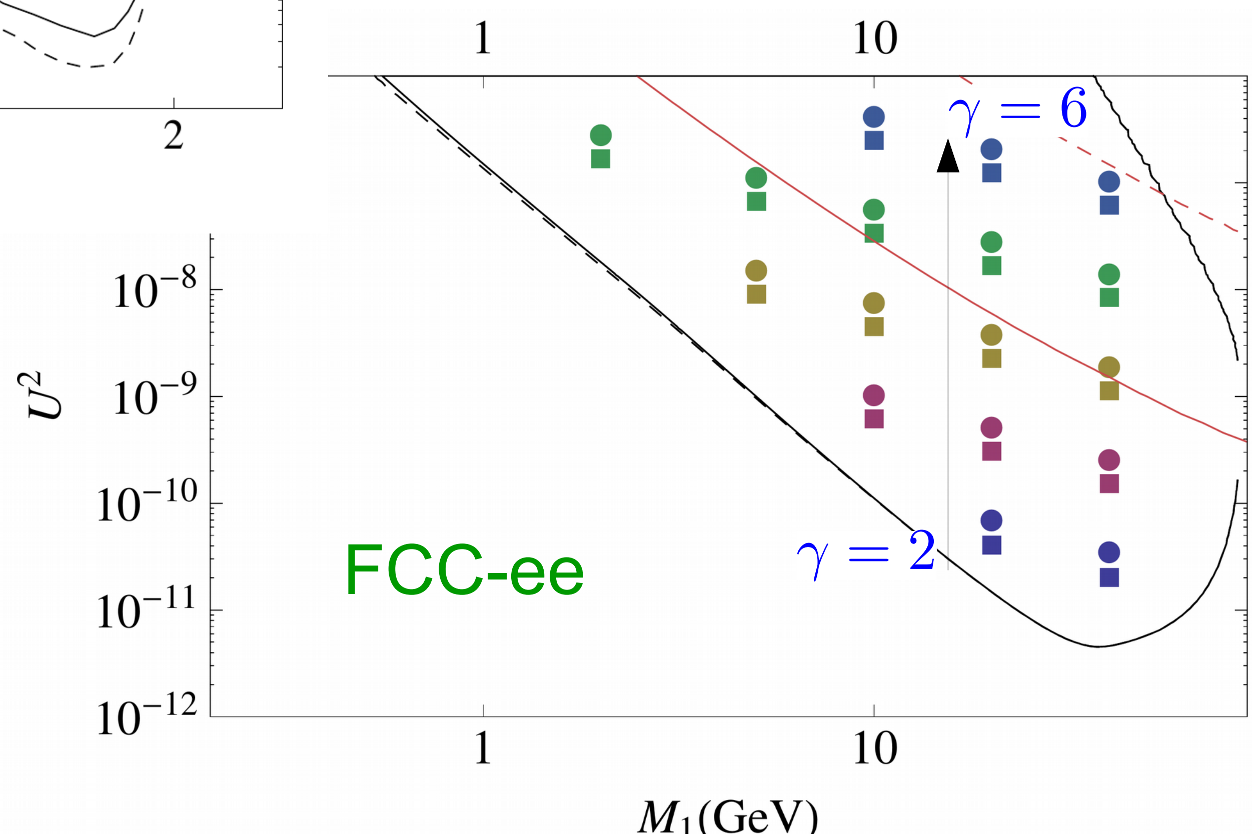
- $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{e5}|^2, |U_{\mu 5}|^2 \propto \frac{e^{2\gamma}}{M}$ → γ

CP-violation in minimal model

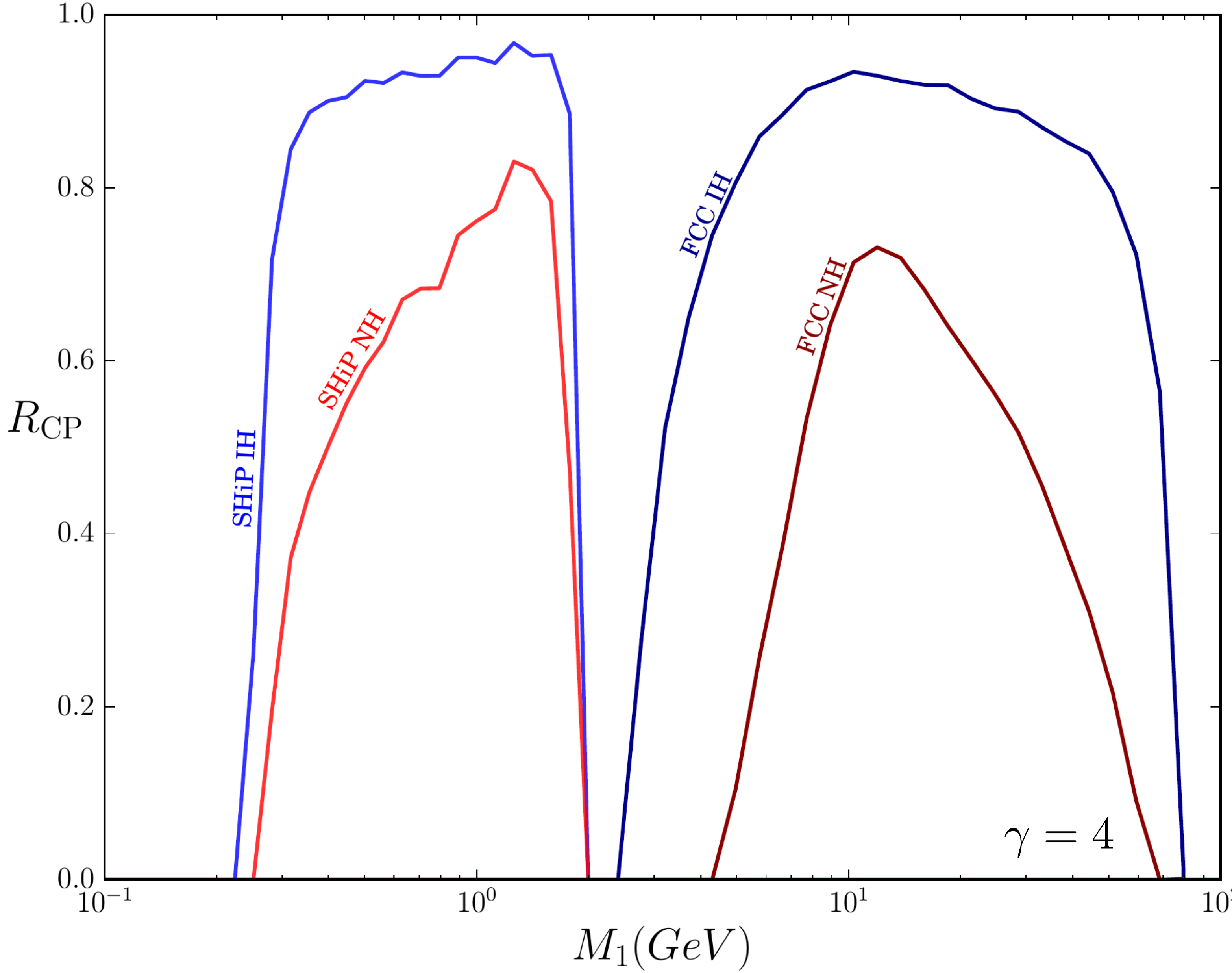








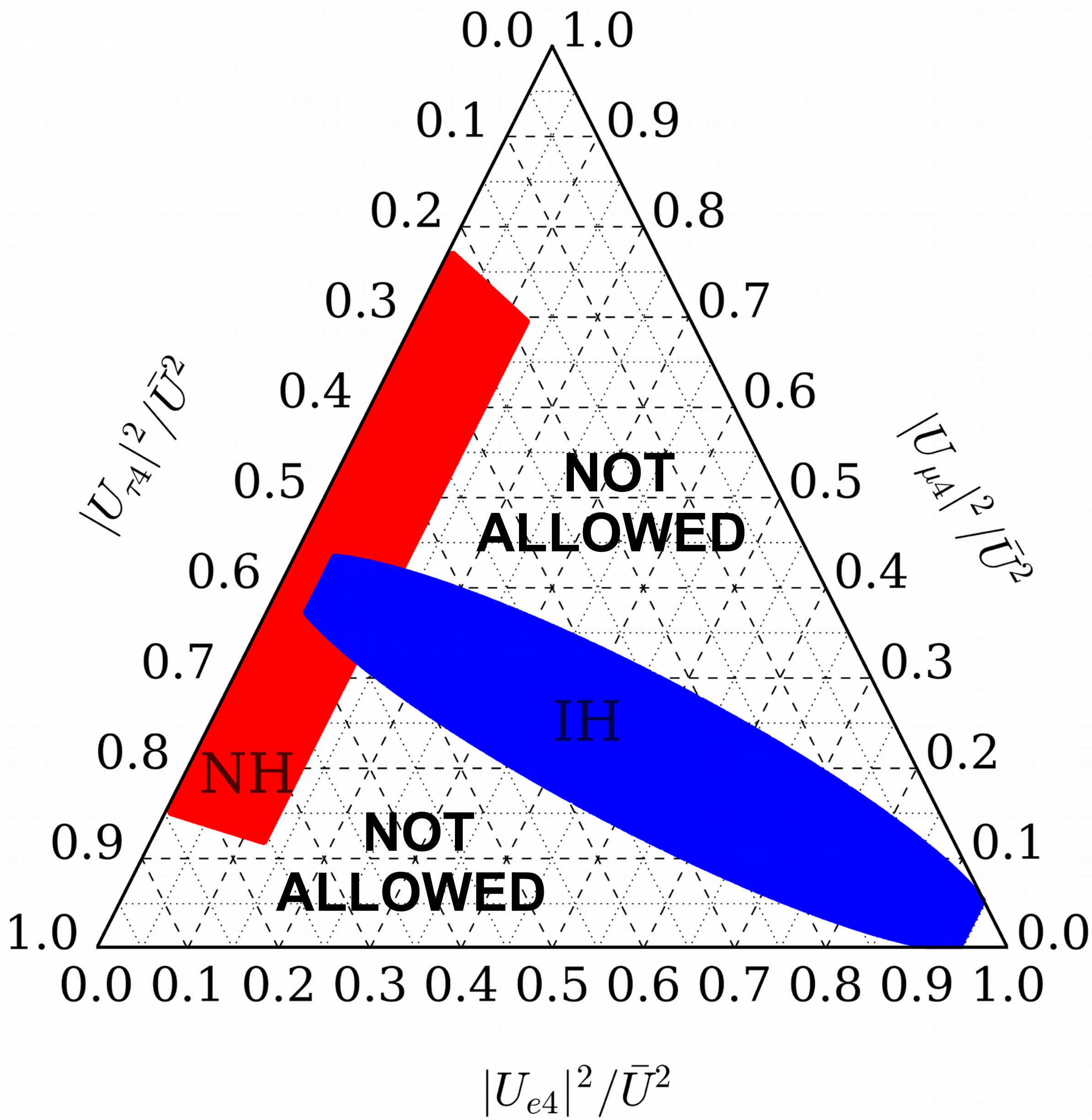
5σ discovery CP-violation



Previous predictions rely to a large extent on the minimality

Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

Minimal Model: Flavor Structure



To what extent can they 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

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

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

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

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

Model Independent Approach: EFT

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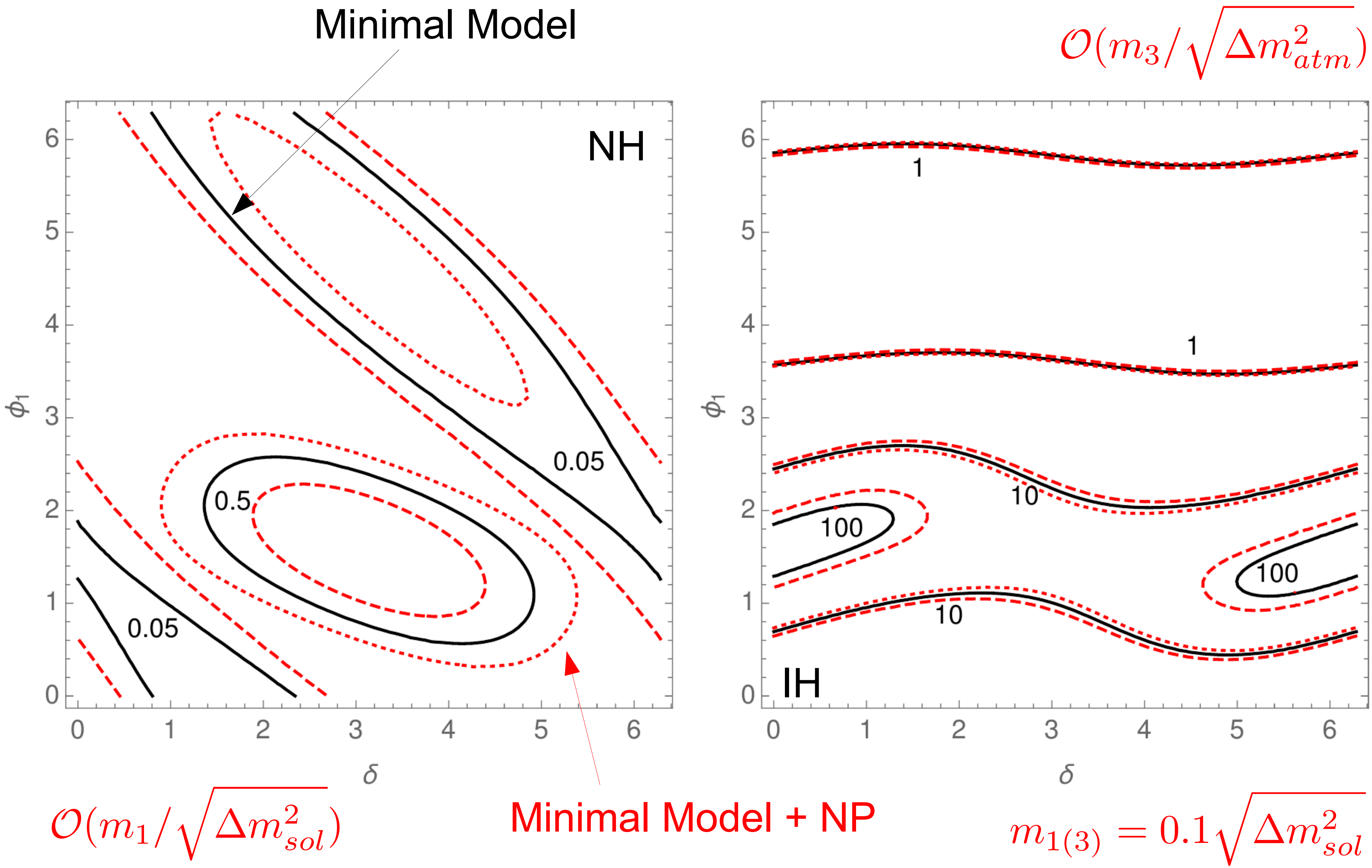
$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi}\Phi^\dagger L^c_\beta + h.c.,$$

- 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 $|U_{es}|^2/|U_{\mu s}|^2$



Model Independent Approach: EFT

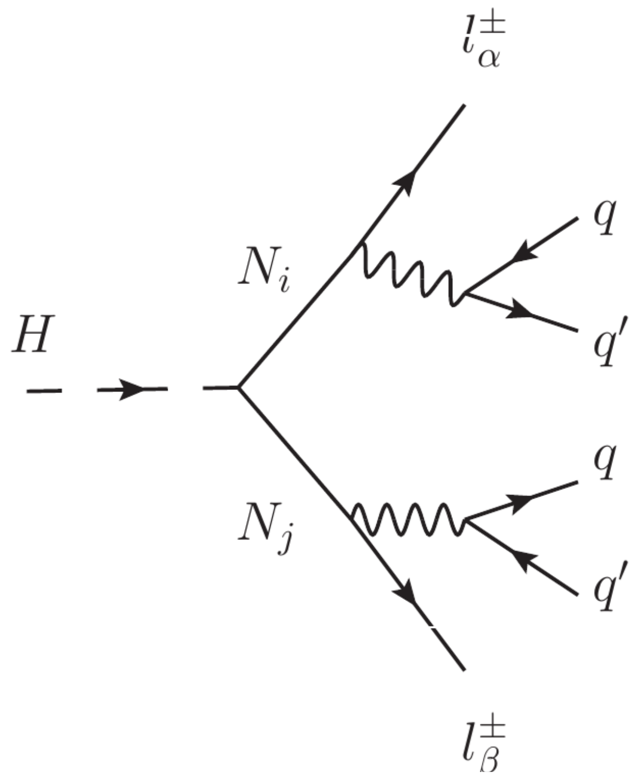
• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

- 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

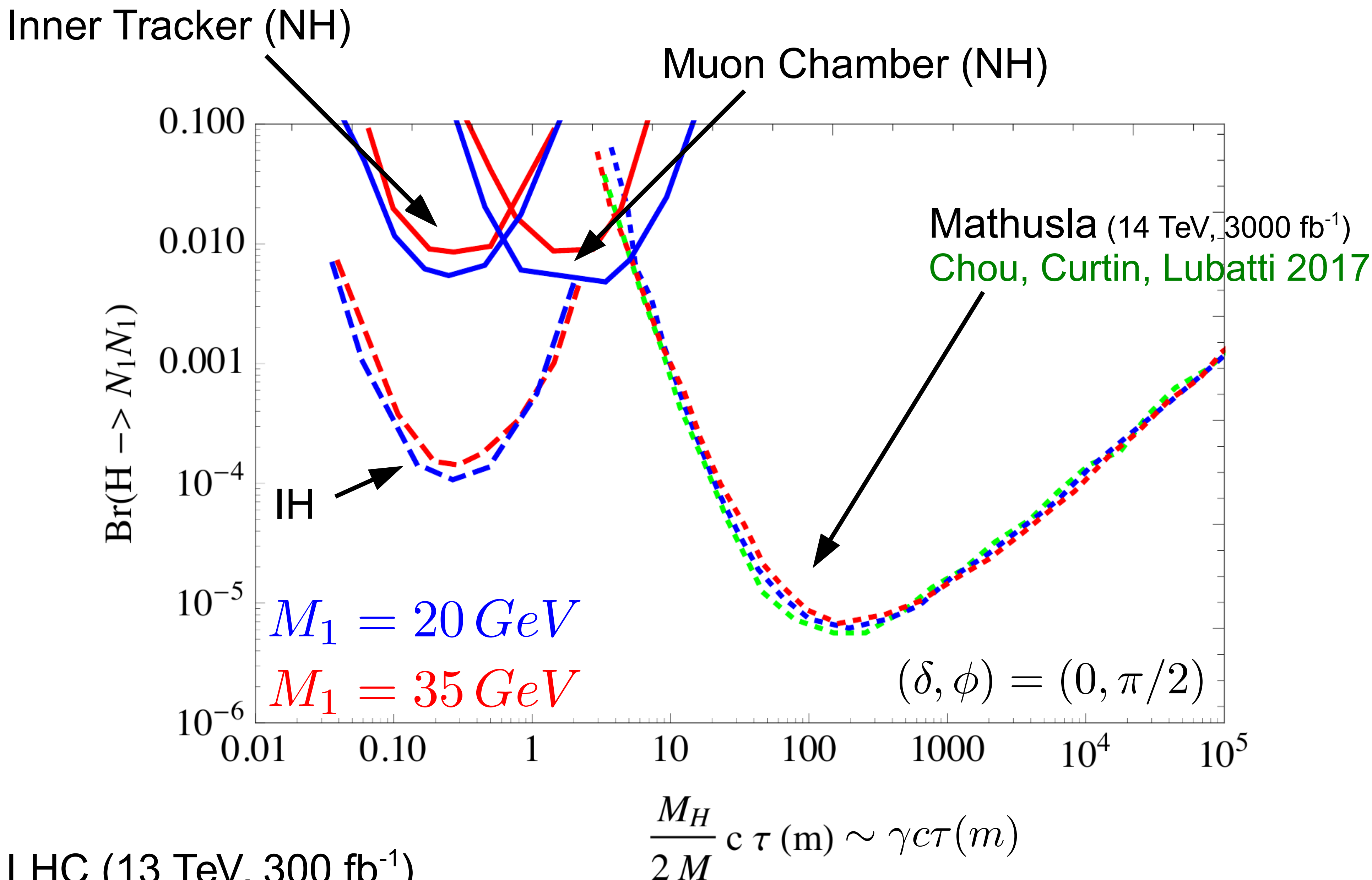


i) Search of displaced tracks in the inner tracker where at least one displace lepton, e or μ, is reconstructed from each vertex.

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



LHC (13 TeV, 300 fb^{-1})

Conclusions: Minimal Model

- Low Scale Minimal models are testable and highly predictive

- Successful baryogenesis is possible with a mild heavy neutrino degeneracy, small N_R masses M~O(GeV), and significant N_R 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**.

- Extremely **constrained flavor structure** which shows a strong correlation with the PMNS CP-phases.

- **New window to** determine **PMNS CP violating phases** (both the Dirac and Majorana phases).

- Precise measurement of flavor ratios will be essential in establishing the connection between the observed heavy states and neutrino masses.

Conclusions: Minimal Model + heavy NP

- We studied the impact of NP encoded on d=5 effective operators.
  At tree level two d=5 operators can be generated:

(i) Modification of flavor structure controlled by the lightest neutrino mass generated by Weinberg operator. Prediction kept if

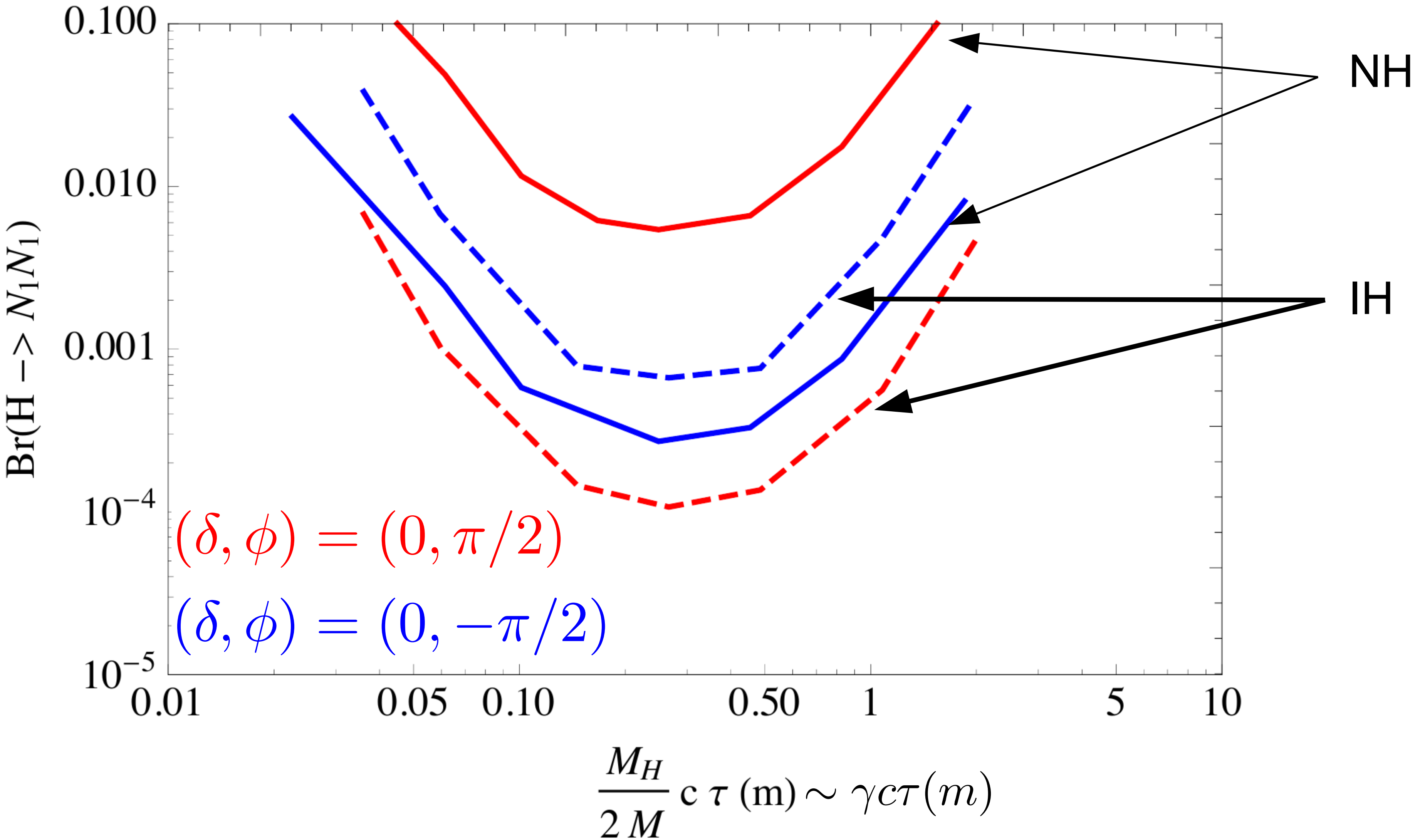
$$\frac{v^2\alpha_W}{\Lambda} \leq 0.1\sqrt{\Delta m^2_{sol}} \sim 10^{-3} eV$$

(ii) Higgs can decay to a pair of long-lived heavy neutrinos. Powerful signal of two displaced vertices.

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

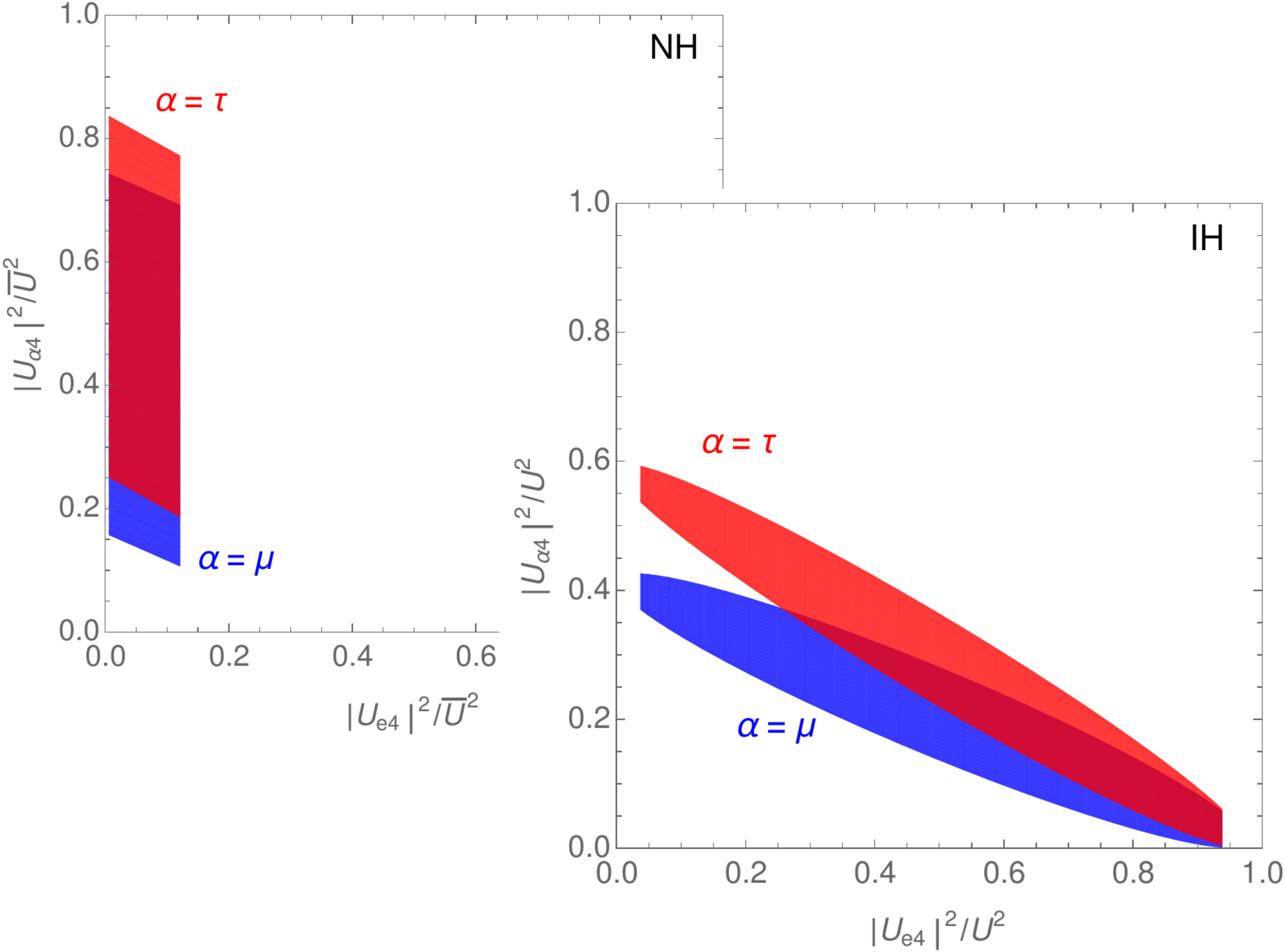
Danke!

Seesaw Portal



LHC (13 TeV, 300 fb^{-1})

$M_1 = 20\,GeV$



NH
$\alpha = \tau$
$\alpha = \mu$
$|U_{\alpha 4}|^2/\overline{U}^2$
$|U_{e4}|^2/\overline{U}^2$
IH
$\alpha = \tau$
$\alpha = \mu$
$|U_{\alpha 4}|^2/U^2$
$|U_{e4}|^2/U^2$

Approximated LNC

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

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

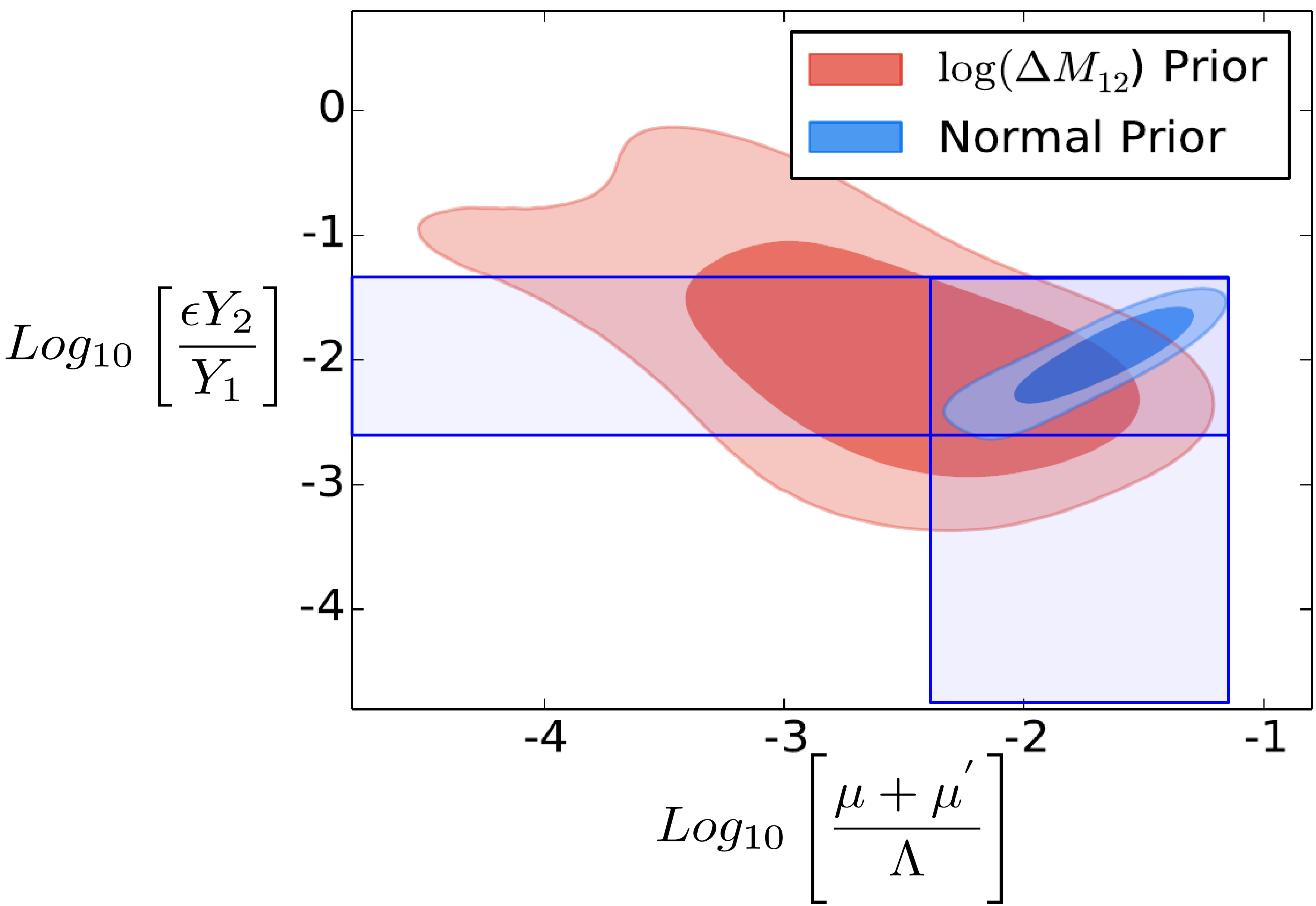
- Light nu masses suppressed with LNV parameters

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

- Quasi-Dirac heavy neutrinos:

$$M_2 \approx M_1 \approx \Lambda \qquad \Delta M \approx \mu' + \mu$$

Approximated LNC



Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO contribution

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

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

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

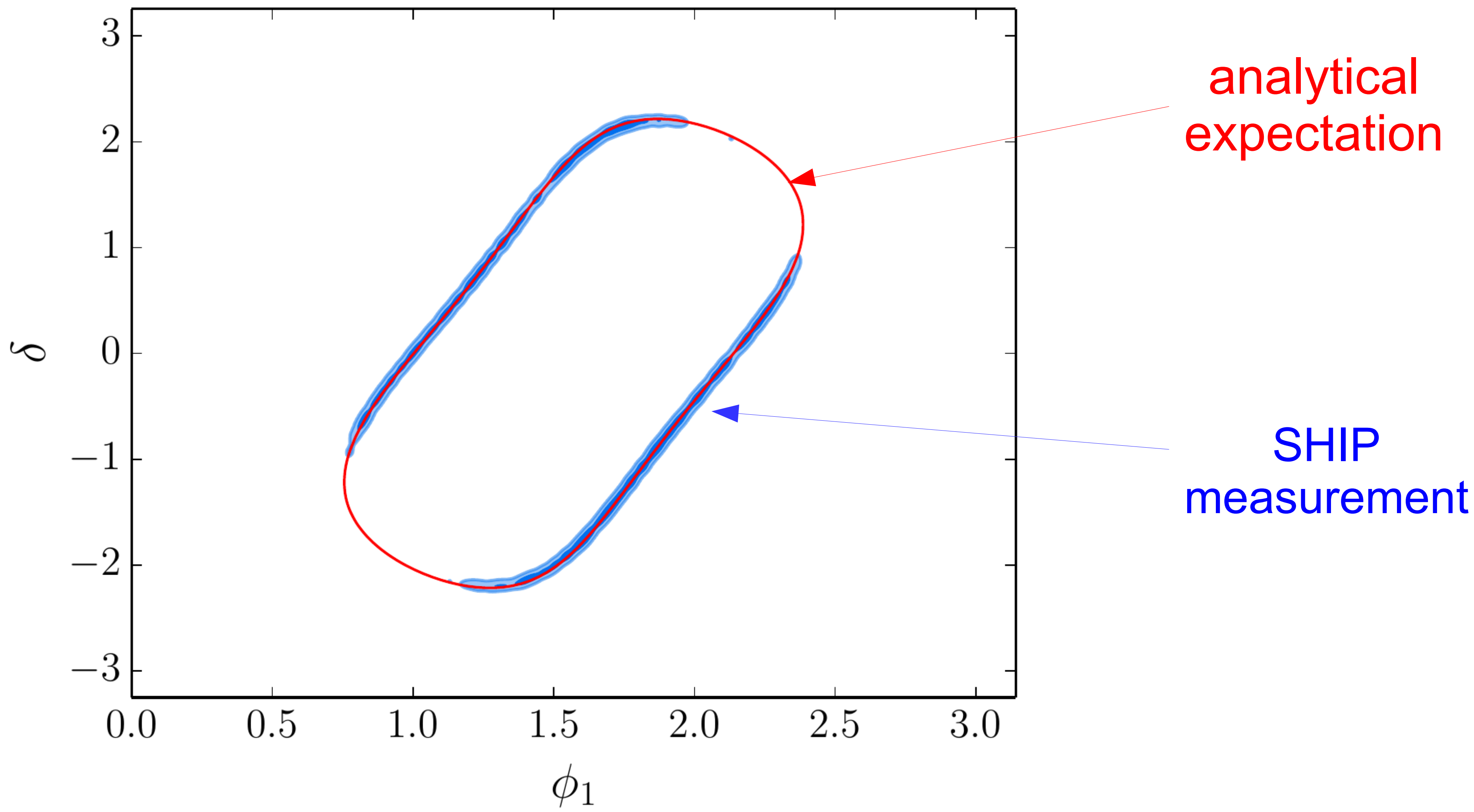
θ

HEAVY NEUTRINO contribution

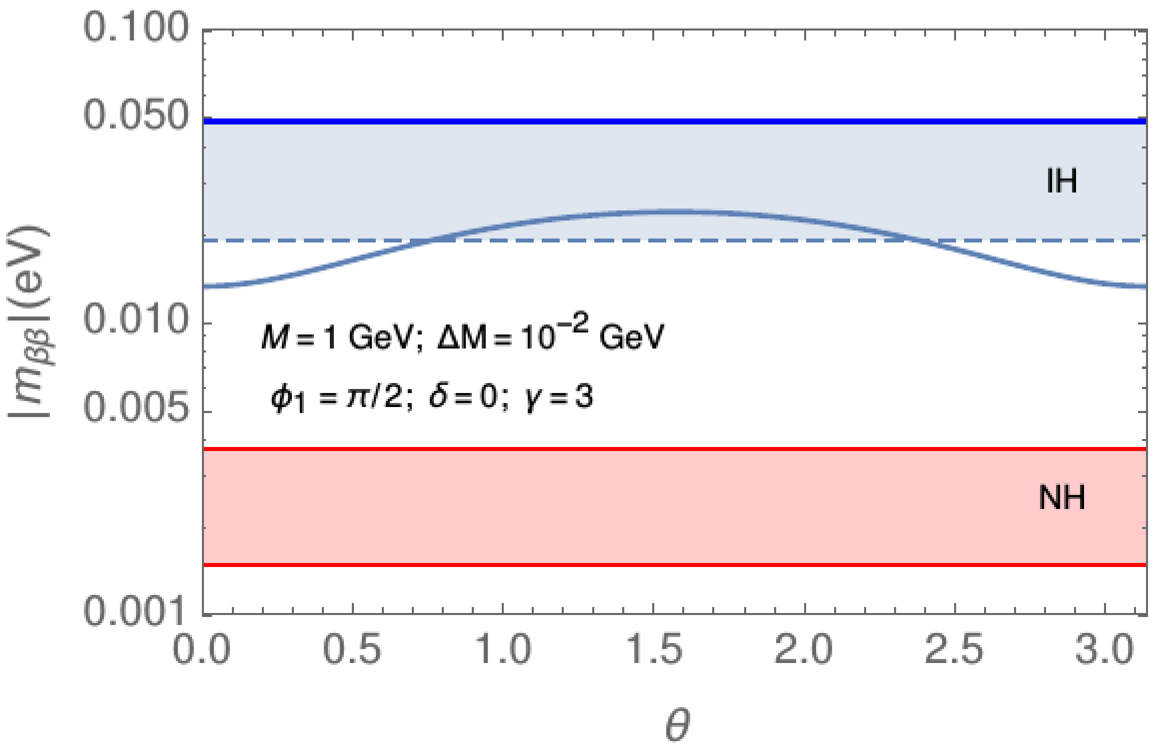
- Heavy neutrino contribution can be sizable for $M \sim O\,(GeV)$

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

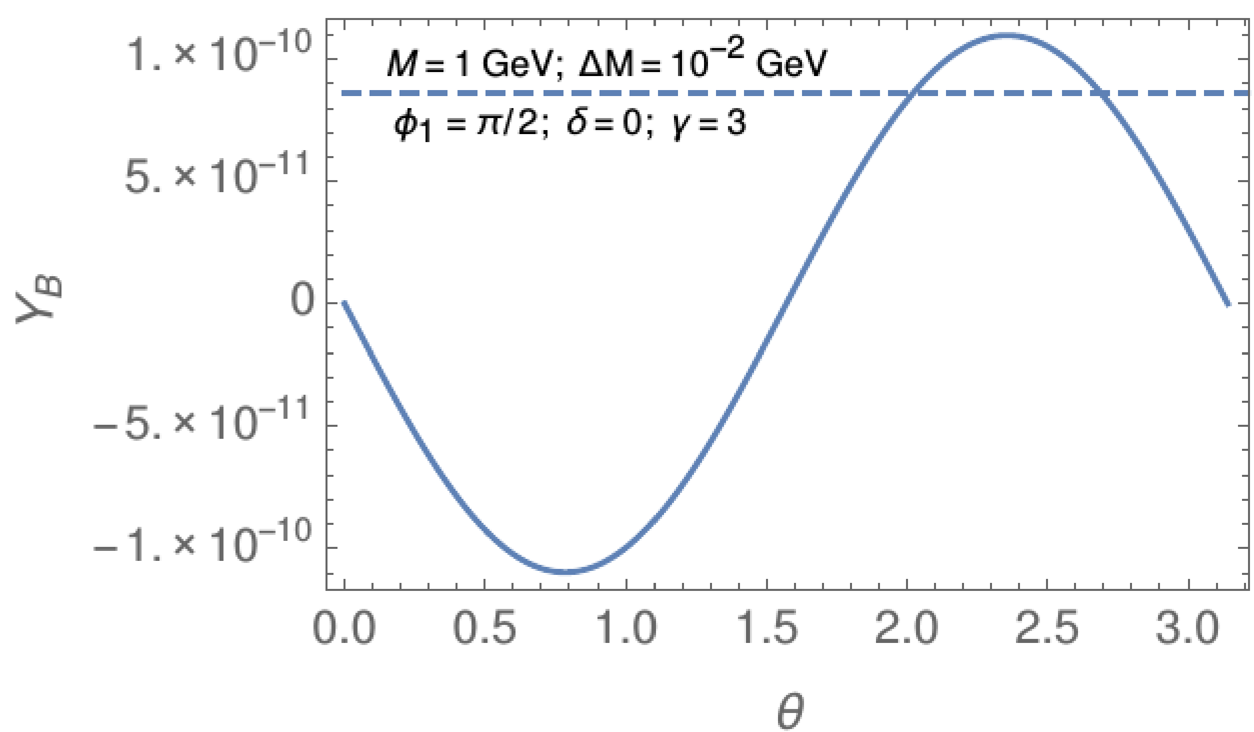
SHIP sensitive to PMNS CP phases



Recall, neutrino oscillation experiments sensitive to δ



Leptogenesis in Minimal Model



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

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:

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

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 $N_\alpha^{CP} = N_\alpha(CP, \gamma^{\text{min}}, \theta^{\text{min}}, M_1^{\text{min}})$ 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%.

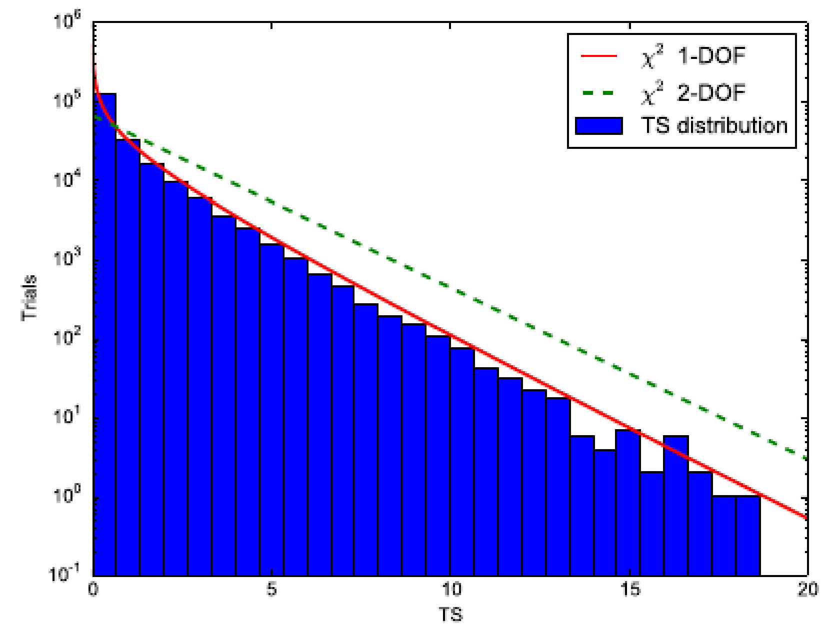
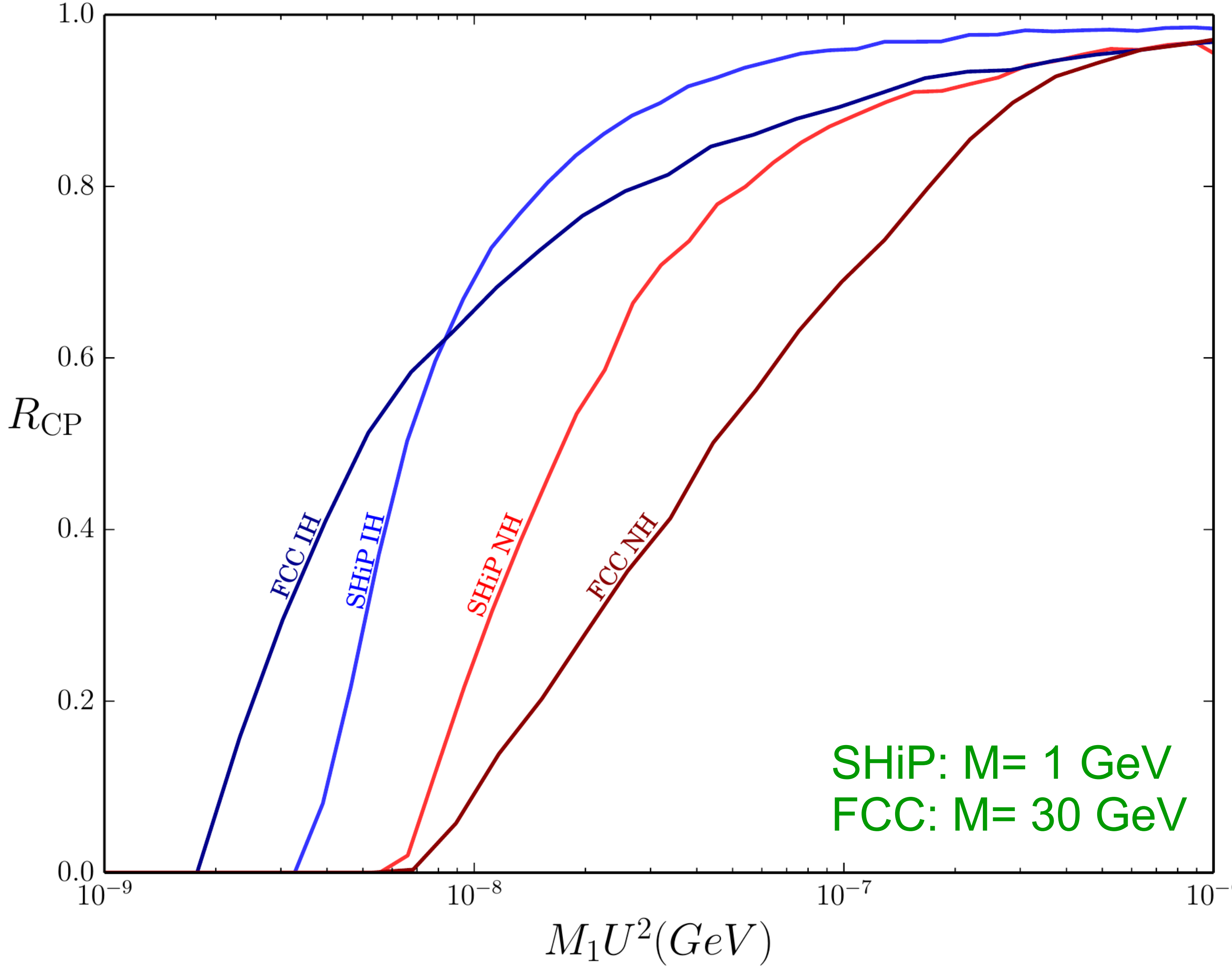
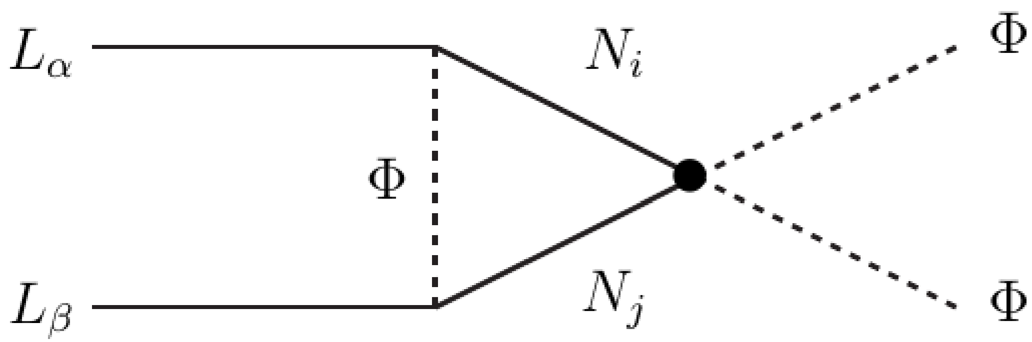


Fig. 4 Distribution of the test statistics for $\mathscr{O}(10^7)$ number of experimental measurements of the number of events for true values of the phases $(\delta, \phi_1) = (0, 0)$ for IH and $(\gamma, \theta, M_1) = (3.5, 0, 1)$ GeV, compared to the χ^2 distribution for 1 or 2 degrees-of-freedom.

5σ discovery CP-violation

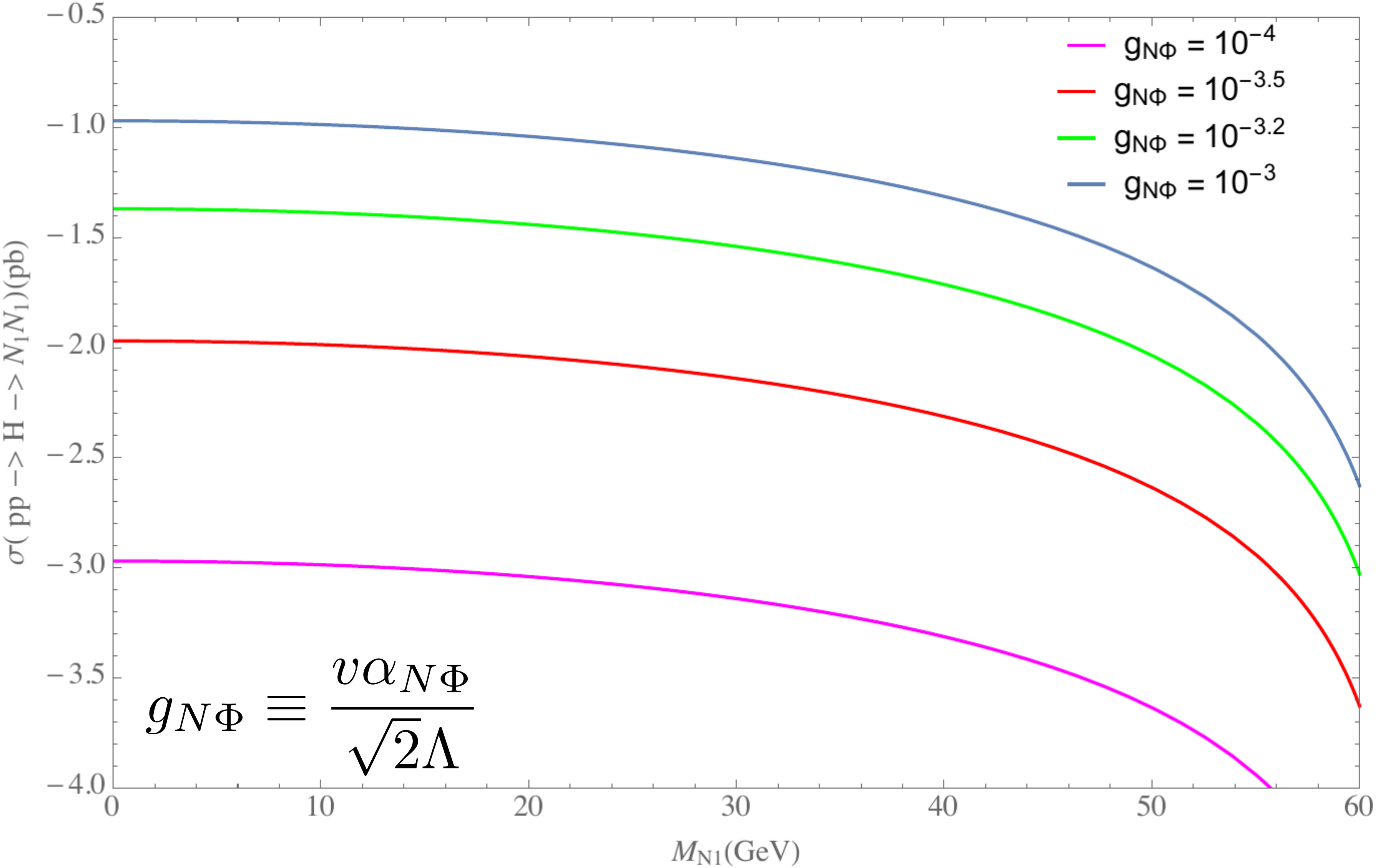


1-loop contribution of $\mathcal{O}_{N\Phi}$ to nu masses

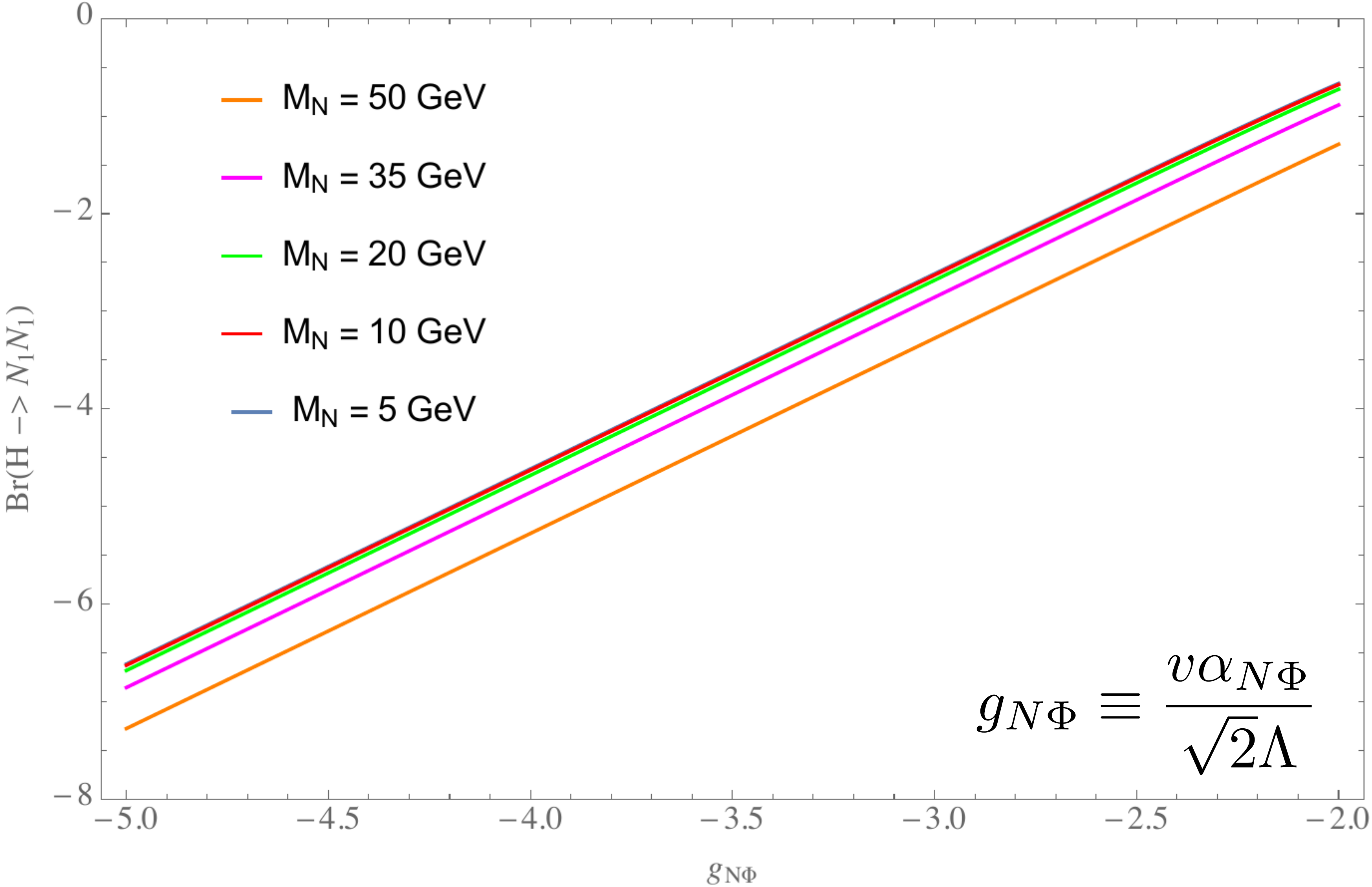


$$\frac{\alpha_{N\phi}}{\Lambda} \lesssim \frac{2 \cdot 10^{13}}{\log \frac{\mu^2}{M^2}} \left(\frac{10^{-6}}{\theta^2}\right) \left(\frac{\text{GeV}}{M}\right)^2 \frac{\alpha_W}{\Lambda}$$

Production Cross Section



Production Branching Ratio



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 eficiciencies 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 eficiciencies 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):

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

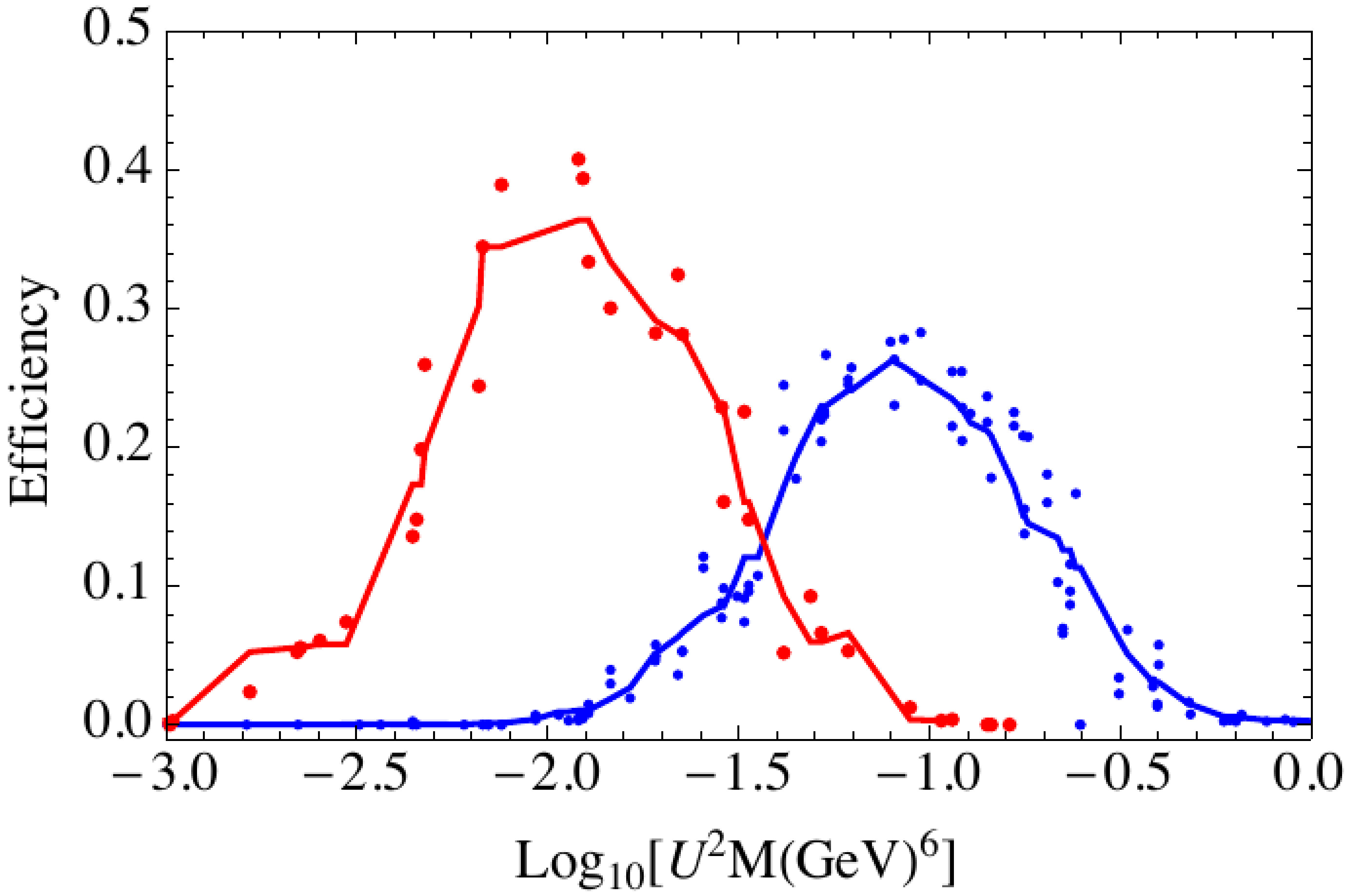
where $\sigma_d^t \simeq 20\mu$m is the resolution in the tracker.

- Muon chambers (MC):

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

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

Cuts associated to displaced tracks



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

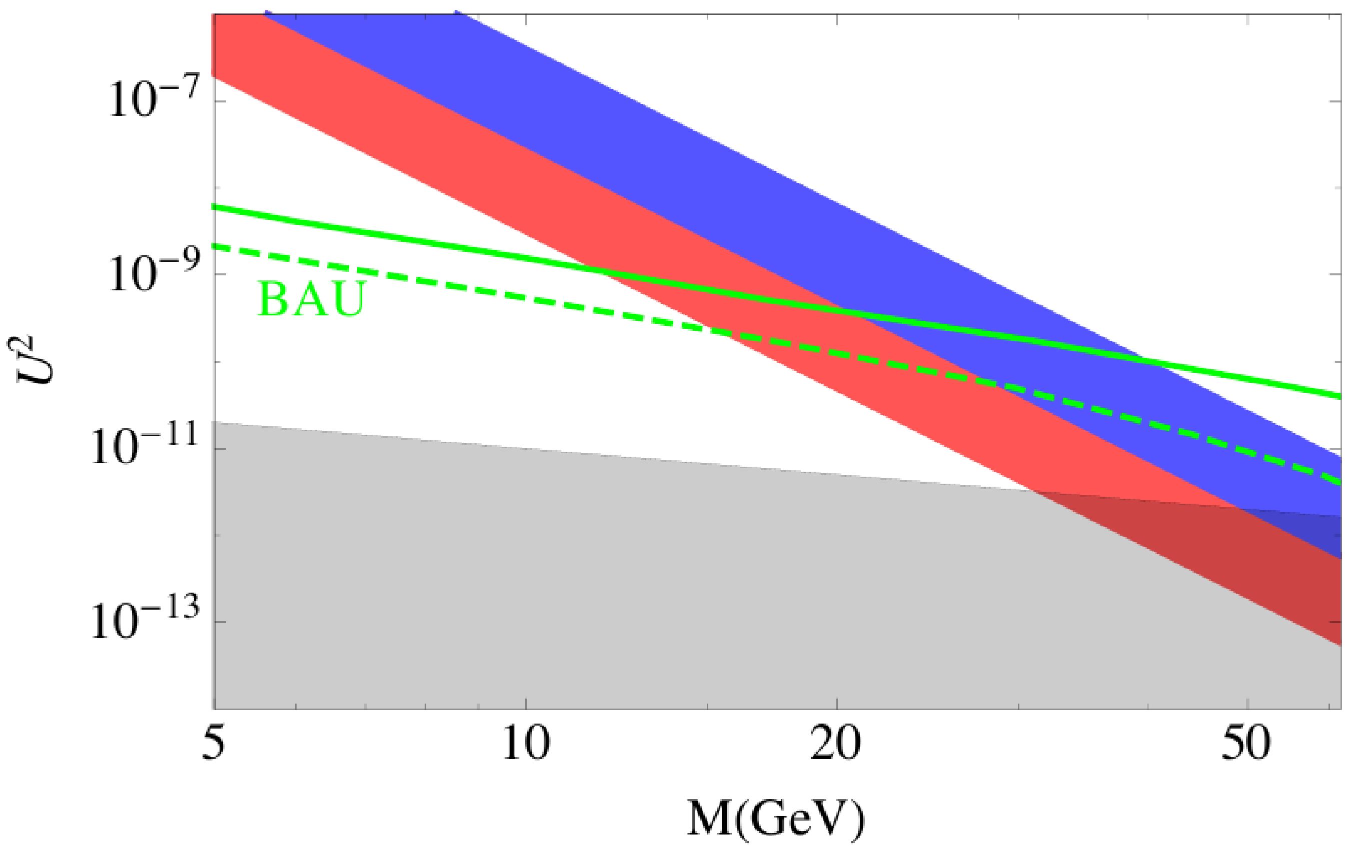


Figure 11. Regions on the plane (M, U^2) where LHC displaced track selection efficiency (eq. (3.20) and (3.21)) is above 10% in the IT (blue band) and MC (red band). The grey shaded region cannot explain the light neutrino masses and the green lines correspond to the upper limits of the 90%CL bayesian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

Kinematic Equations

We have computed and 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

$$
\begin{aligned}
xH_u \frac{dr_+}{dx} &= -i[\langle H_{\rm re}\rangle, r_+] + [\langle H_{\rm im}\rangle, r_-] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{\mathrm{Re}[Y^\dagger Y], r_+ - 1\} \\
&\quad + i\langle\gamma_N^{(1)}\rangle \mathrm{Im}[Y^\dagger \mu Y] - i\frac{\langle\gamma_N^{(2)}\rangle}{2}\{\mathrm{Im}[Y^\dagger \mu Y], r_+\} - i\frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{\mathrm{Im}[Y^\dagger Y], r_-\right\}, \\
xH_u \frac{dr_-}{dx} &= -i[\langle H_{\rm re}\rangle, r_-] + [\langle H_{\rm im}\rangle, r_+] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{\mathrm{Re}[Y^\dagger Y], r_-\} \\
&\quad + \langle\gamma_N^{(1)}\rangle \mathrm{Re}[Y^\dagger \mu Y] - \frac{\langle\gamma_N^{(2)}\rangle}{2}\{\mathrm{Re}[Y^\dagger \mu Y], r_+\} - i\frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{\mathrm{Im}[Y^\dagger Y], r_+ - 1\right\}, \\
\frac{d\mu_{B/3-L_\alpha}}{dx} &= \frac{\int_k \rho_F}{\int_k \rho'_F}\Big\{\langle\gamma_N^{(0)}\rangle \mathrm{Tr}[r_- \mathrm{Re}(Y^\dagger I_\alpha Y) + i r_+ \mathrm{Im}(Y^\dagger I_\alpha Y)] \\
&\quad + \mu_\alpha \left(\langle\gamma_N^{(2)}\rangle \mathrm{Tr}[r_+ \mathrm{Re}(Y^\dagger I_\alpha Y)] - \langle\gamma_N^{(1)}\rangle \mathrm{Tr}[Y Y^\dagger I_\alpha]\right)\Big\}, \\
\mu_\alpha &= -\sum_\beta C_{\alpha\beta}\mu_{B/3-L_\beta},
\end{aligned}
$$

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. $\frac{\alpha_{NB}}{\Lambda} < 10^{-2} - 10^{-1} TeV$

- 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.

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)

$$\frac{v^2 \alpha_W}{\Lambda} \leq 0.1 \sqrt{\Delta m^2_{sol}} \sim 10^{-3} eV$$