Low Scale
Testable Leptogenesis

Jacobo López-Pavón

Neutrino Physics at the High Energy Frontier
ACFI, 18-20 July 2017

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.

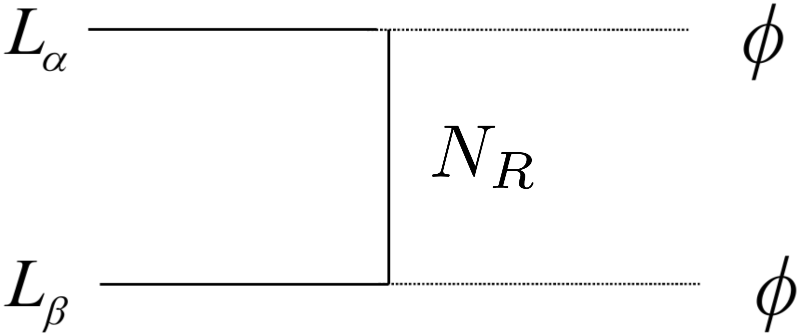
  Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

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

  Caputo, Hernandez, JLP, Salvado 1704.08721

- Conclusions

Minimal Model: Seesaw Model

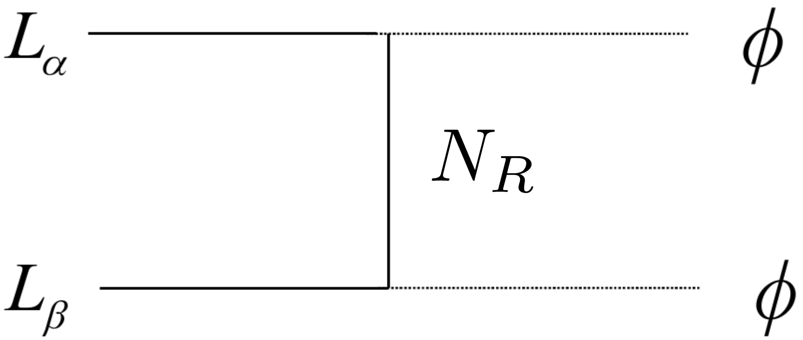


Heavy fermion singlet: ν_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

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

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

Minimal Model: Seesaw Model



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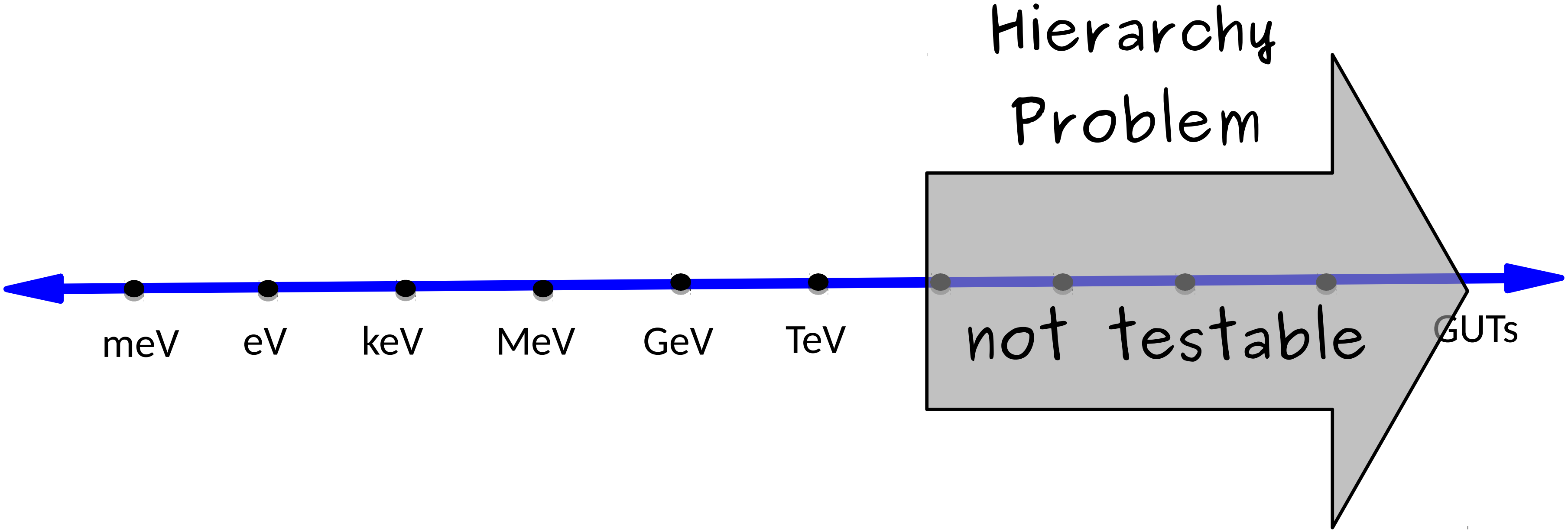
New Physics Scale $(m_\nu \sim Y^2 v^2 / M)$

The New Physics Scale



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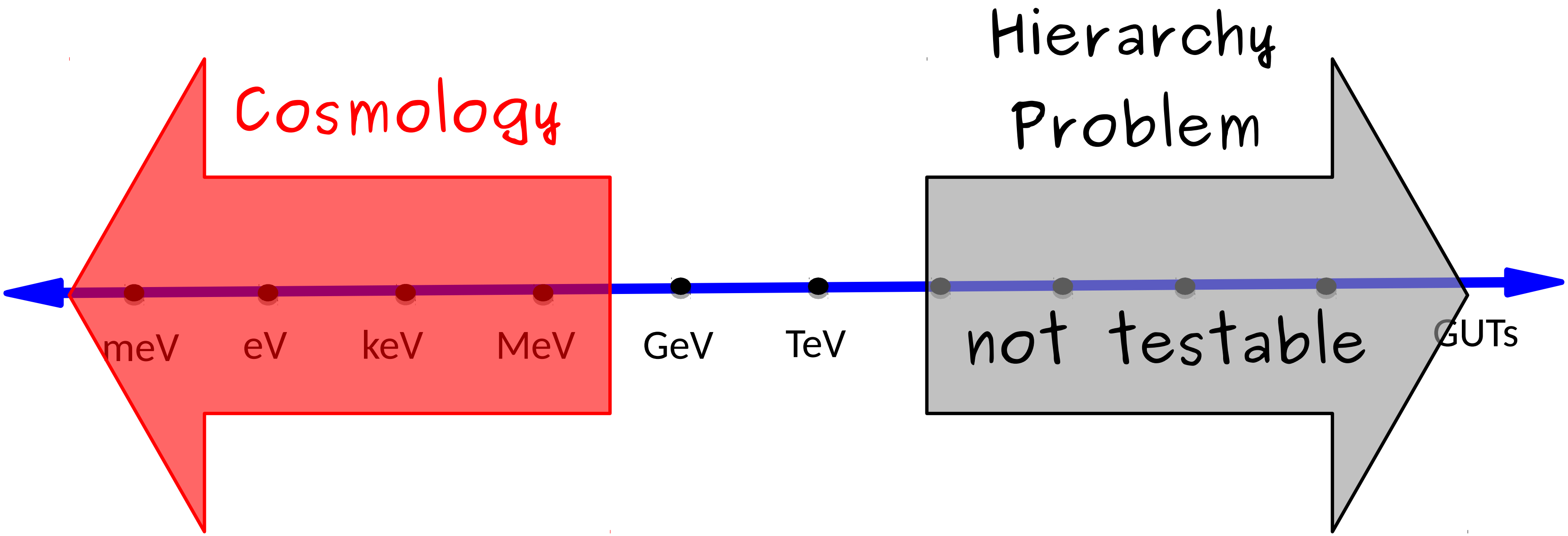


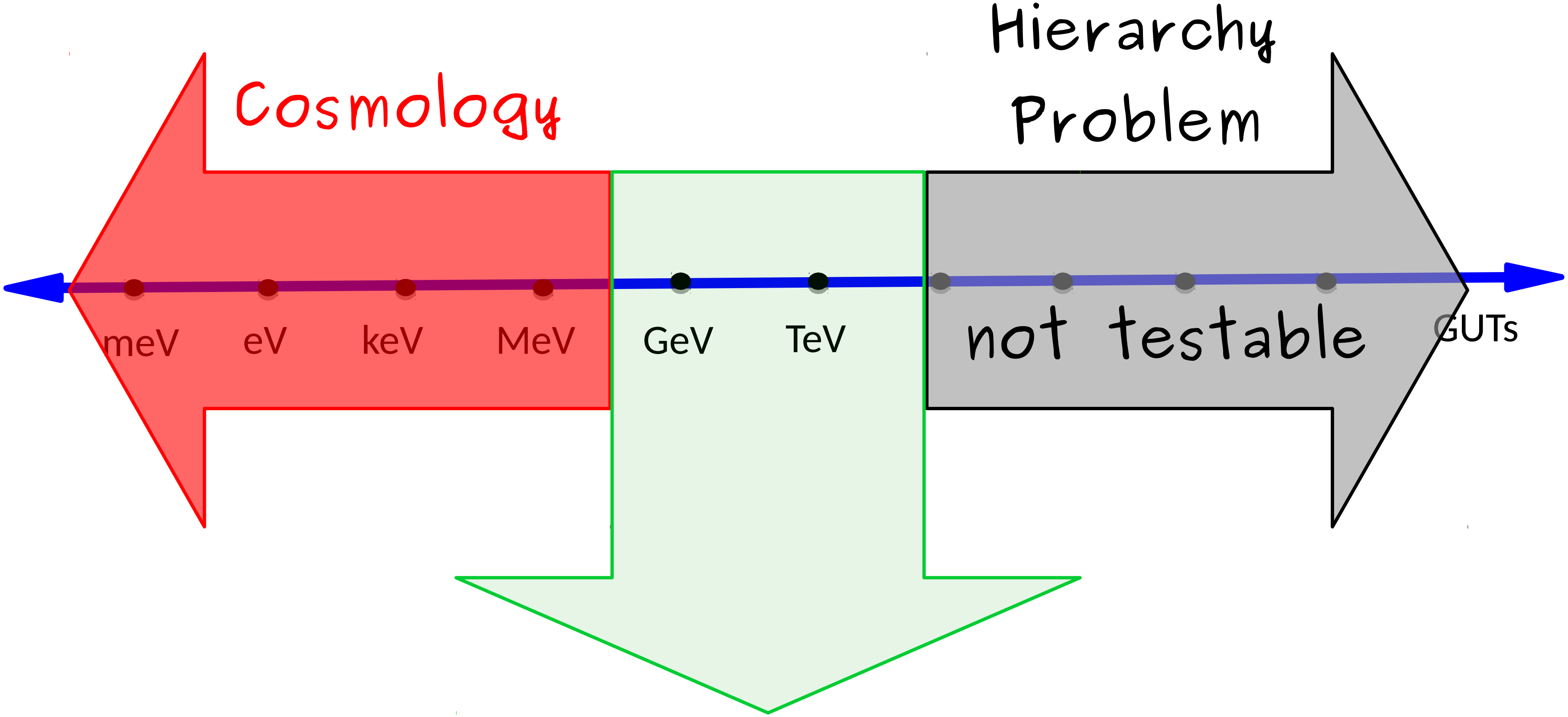
- Minimal Type-I seesaw with **N$_R$=2** (or Type-I seesaw with **N$_R$=3** & $m_{lightest} \gtrsim 10^{-3} eV$)

CMB+BBN data ➡ M$_R$ >100 MeV

- Type-I seesaw with **N$_R$=3** & $m_{lightest} \lesssim 10^{-3} eV$ $\left\{ \begin{array}{l} \text{M}_2\text{, M}_3\text{>100 MeV} \\ \text{M}_1 \text{ unbounded} \end{array} \right.$

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

The New Physics Scale



- Resonant Leptogenesis M>100GeV

  Pilaftsis

see talk by **Bhupal Dev**

- 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

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

Kinematic Equations

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

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

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

- Collision terms include 2 ↔ 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

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

Full parameter space exploration $N_R=2$

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

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

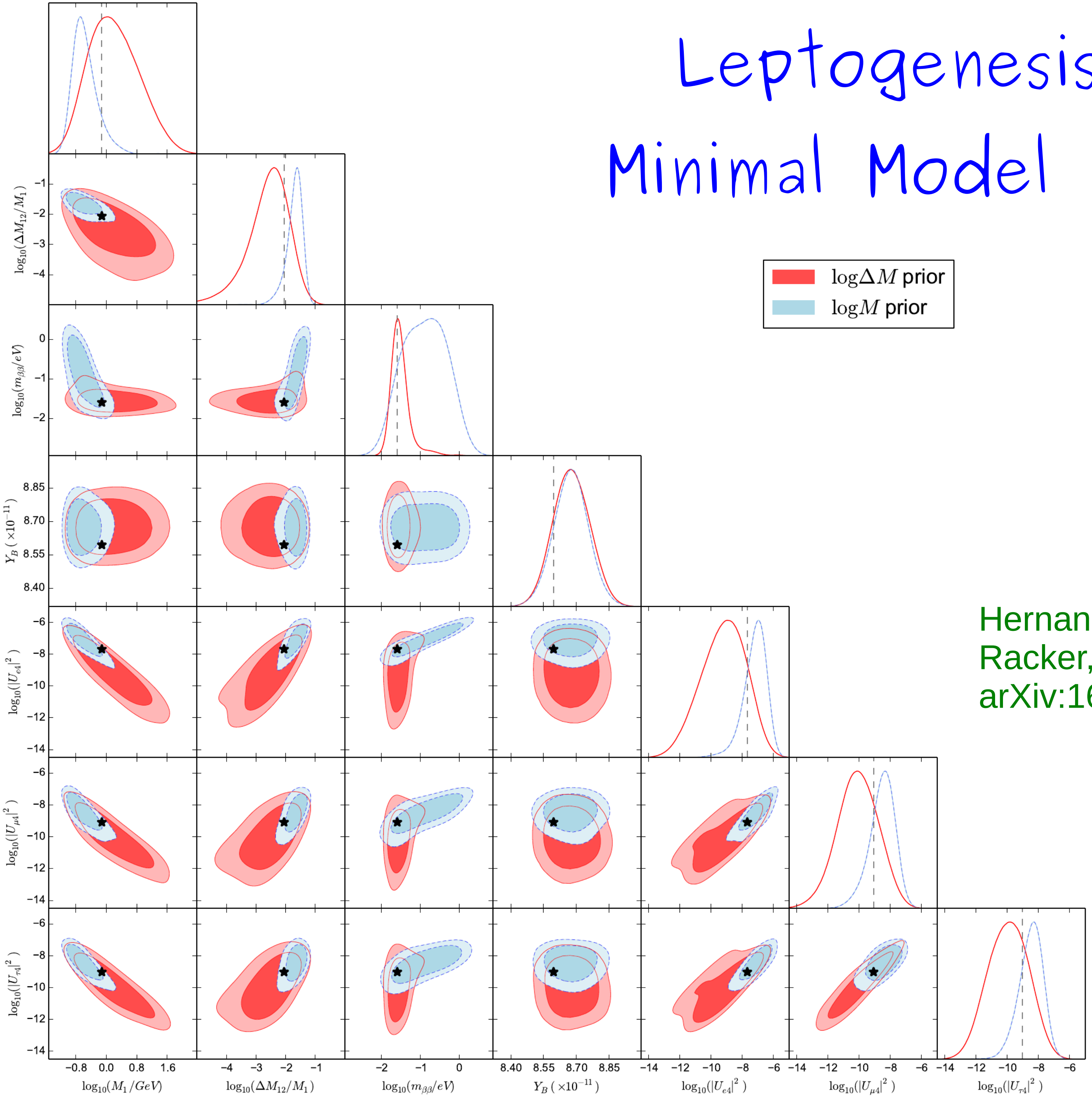
$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3,$

$M_1, M_2, \delta, \phi_1, \theta, \gamma$

Fixed by neutrino oscillation experiments

Free parameters

Leptogenesis in Minimal Model $N_R=2$

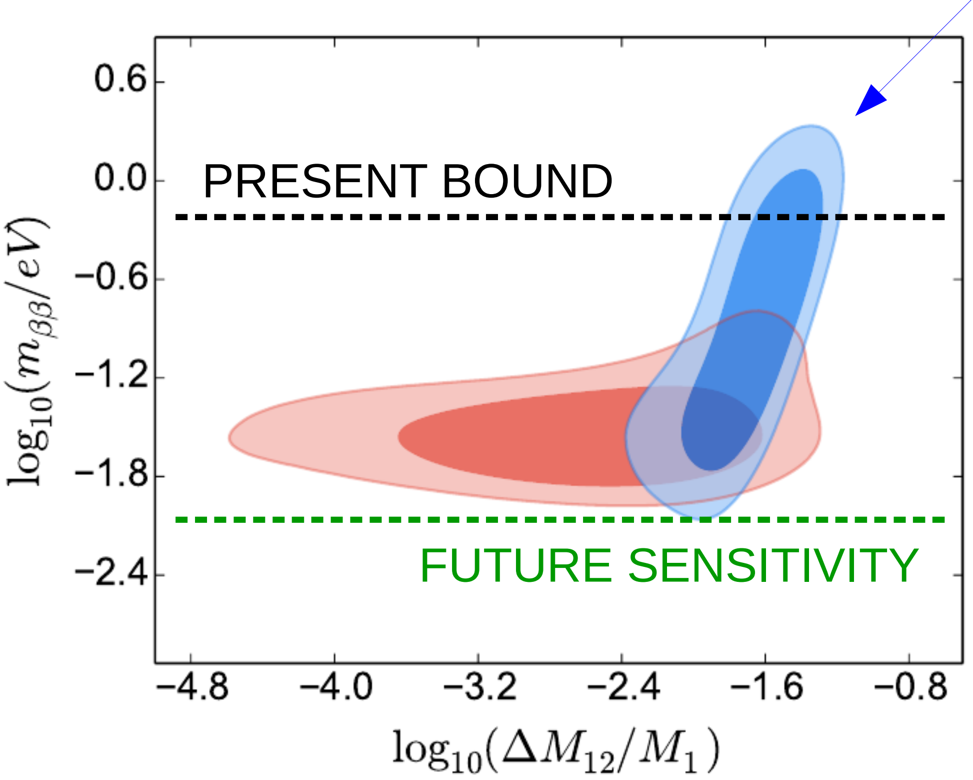


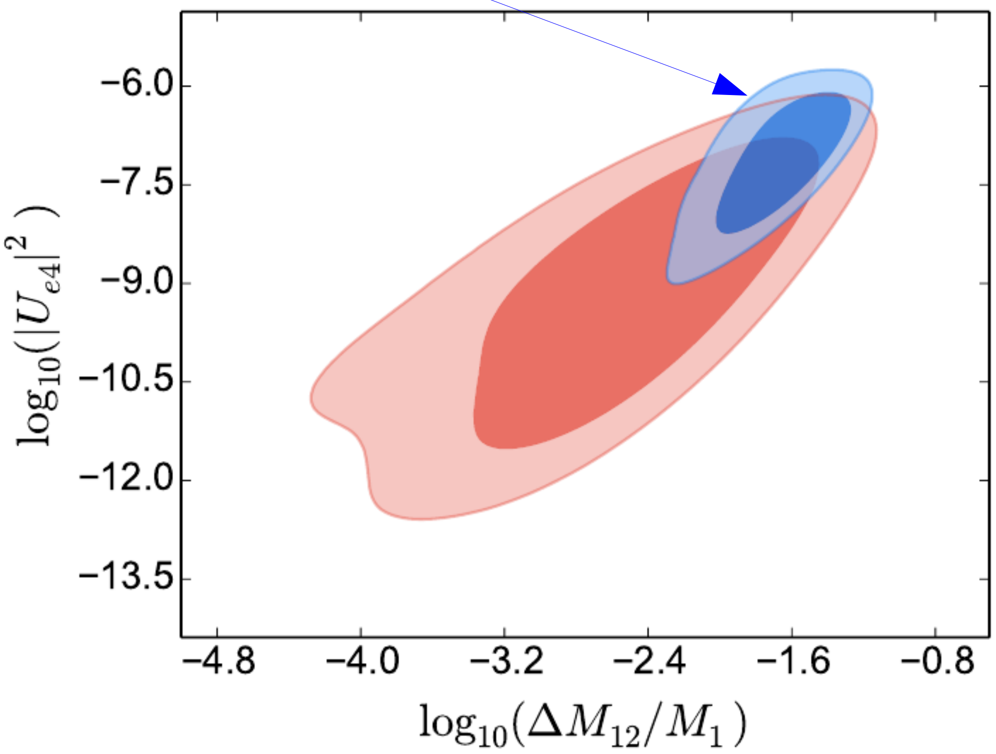
Hernandez, Kekic, JLP, Racker, Salvado 2016
arXiv:1606.06719

IH

Leptogenesis in Minimal Model $N_R=2$

Non degenerated solutions

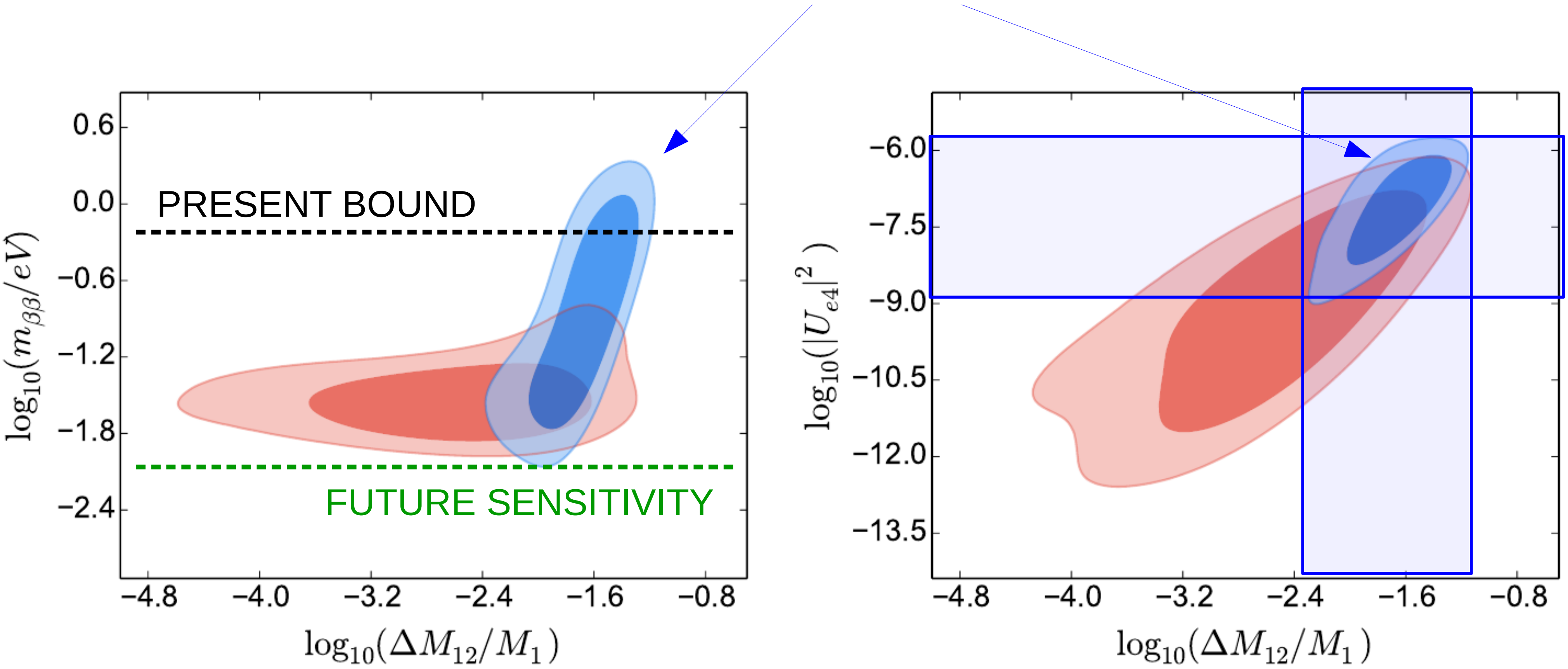




Inverted light neutrino ordering (IH)

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

Leptogenesis in Minimal Model $N_R=2$



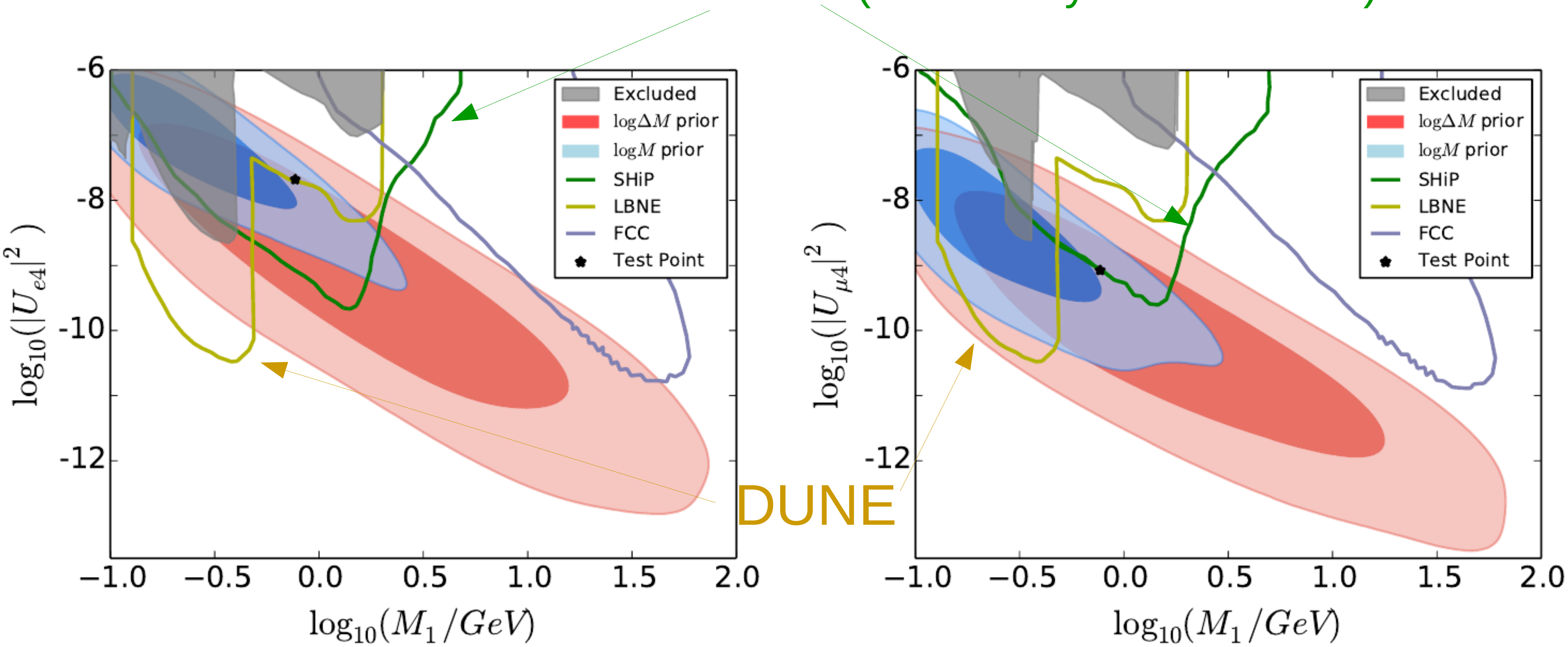
Non very degenerate solutions

Inverted light neutrino ordering (IH)

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

Leptogenesis in Minimal Model $N_R=2$

SHiP (see talk by **Nicola Serra**)



DUNE

Inverted light neutrino ordering

Hernandez, Kekic, JLP, Racker, Salvadò 2016
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What if the sterile ν are within reach of SHiP?

Can we estimate Y_B from the experiments?

Predicting Y_B in minimal model $N_R=2$

- **SHiP** sensitive to sterile neutrinos ⟺ $\left\{ \begin{array}{c} |U^2_{\alpha j}| \gg m_\nu/M \\ \text{(large } R_{ij} \leftrightarrow e^{\gamma} \gg 1 \text{)} \end{array} \right.$

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

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

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

$$+ \mathcal{O}(\epsilon) \Big]$$

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$$+ \mathcal{O}(\epsilon) \Big]$$

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

Predicting Y_B in minimal model $N_R=2$

- **SHiP** can measure (if sterile states not too degenerate)

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

Predicting Y_B in minimal model $N_R=2$

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SHiP sensitive to
PMNS CP-phases!
δ, ϕ_1

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

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

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

γ

Predicting Y_B in minimal model $N_R=2$

- SHiP sensitive to $M_1,\ M_2,\ \phi_1,\ \delta,\ \gamma$ ✓

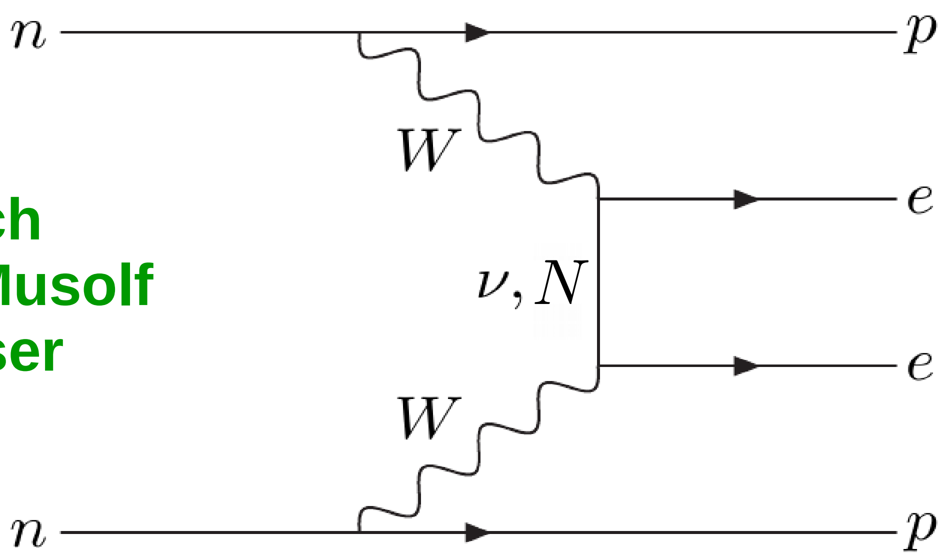
- Great but…

  ...how about θ which is essential to predict Y_B?

Neutrinoless double beta decay

$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

see talks by
Frank **Deppisch**
Michael **Ramsey-Musolf**
Michael **Graesser**
Julia **Harz**



$$m_{\beta\beta} = \sum_i \underline{m_i} \, \underline{U_{ei}^2} \, \overline{\mathcal{M}}(m_i)$$

NMEs

mass of propagating neutrino

mixing

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

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

$$\begin{aligned}\simeq \quad & \sqrt{\Delta m^2_{atm}}\left|c^2_{13}\left(c^2_{12}+e^{2i\phi_1}s^2_{12}\left(1+\frac{r^2}{2}\right)\right)\right. \\ - \quad & \left. f(A)\,e^{2i\theta}e^{2\gamma}(c_{12}-ie^{i\phi_1}s_{12})^2(1-2e^{i\delta}s_{23}\theta_{13})\frac{(0.9\,\mathrm{GeV})^2}{4M_1^2}\left(1-\left(\frac{M_1}{M_1+\Delta M_{12}}\right)^2\right)\right|\end{aligned}$$

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

$$\begin{aligned} \simeq &\quad \sqrt{\Delta m^2_{atm}} \left| \boxed{c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right)} \right. \\ - &\quad \left. f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23}\theta_{13}) \frac{(0.9\,\mathrm{GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right) \right| \end{aligned}$$

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO
contribution

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

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

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

HEAVY NEUTRINO
contribution

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

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

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

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

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

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

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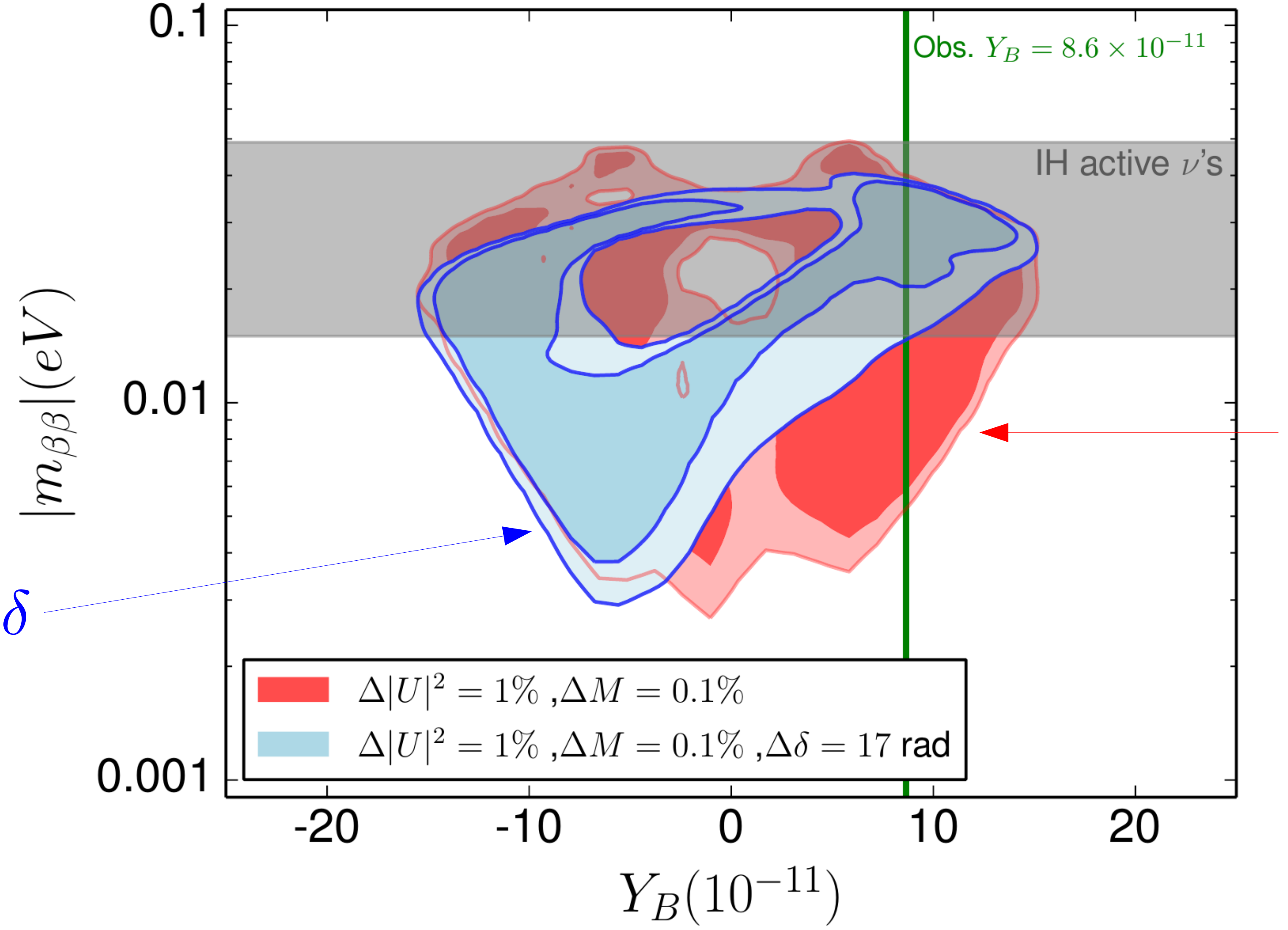
Predicting Y_B in minimal model $N_R=2$

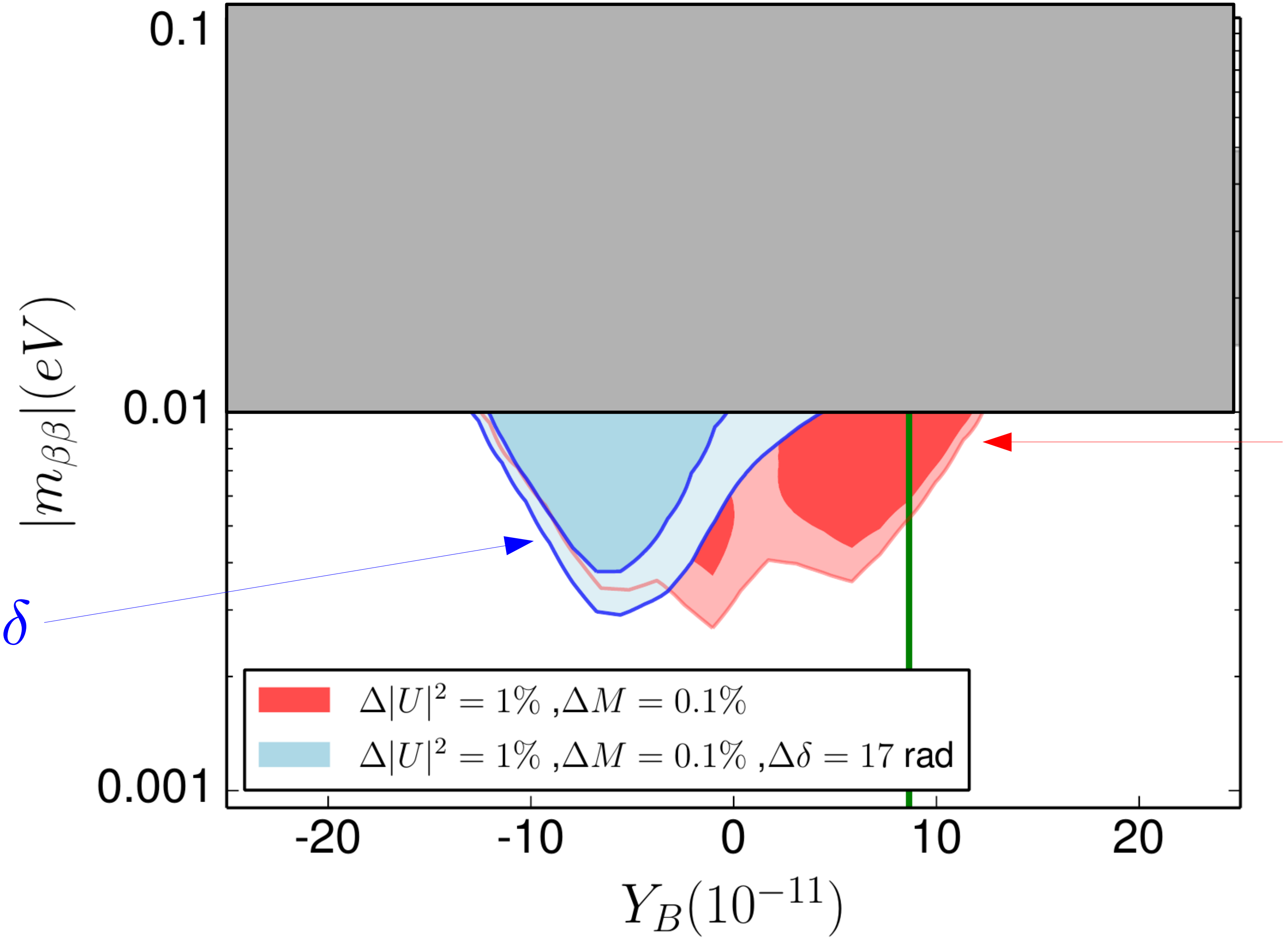


SHiP

SHiP+ δ

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

Predicting Y_B in minimal model $N_R=2$



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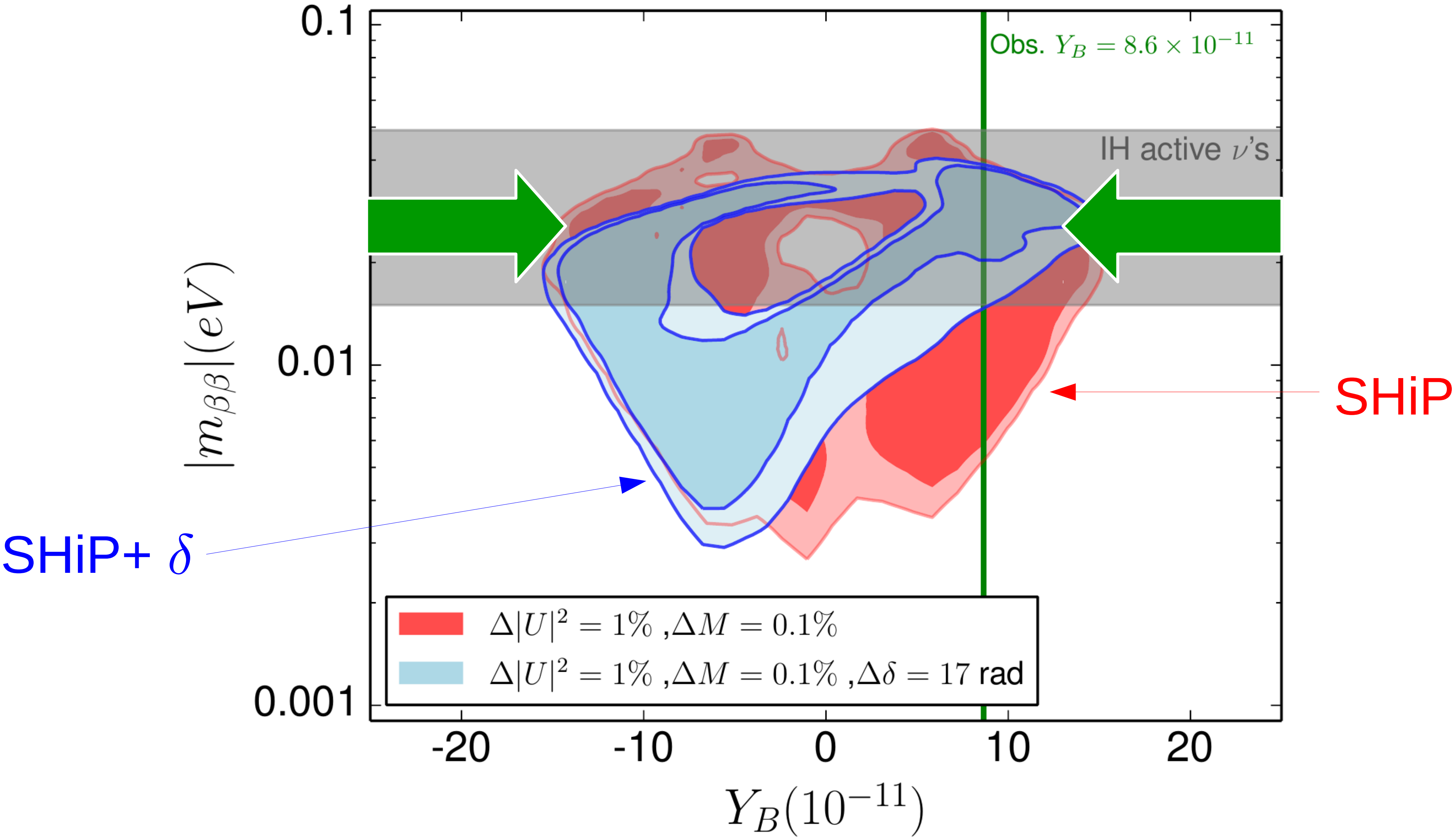


Hernandez, Kekic, JLP, Racker, Salvadò 2016 arXiv:1606.06719

Are these less fine tuned solutions protected by any symmetry?

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

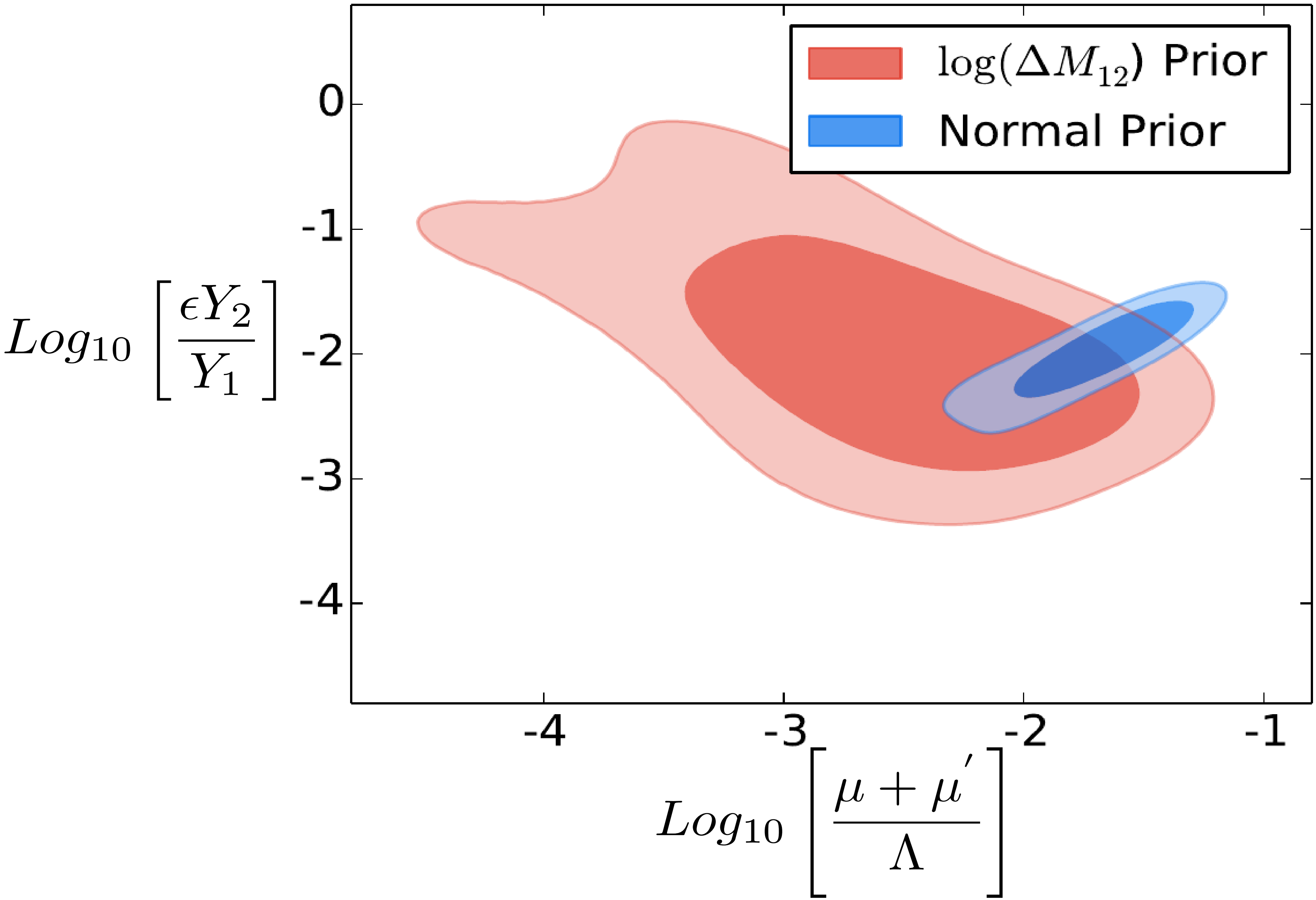
- Light nu masses suppressed with LNV parameters

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

- Quasi-Dirac heavy neutrinos:

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

Approximated LNC



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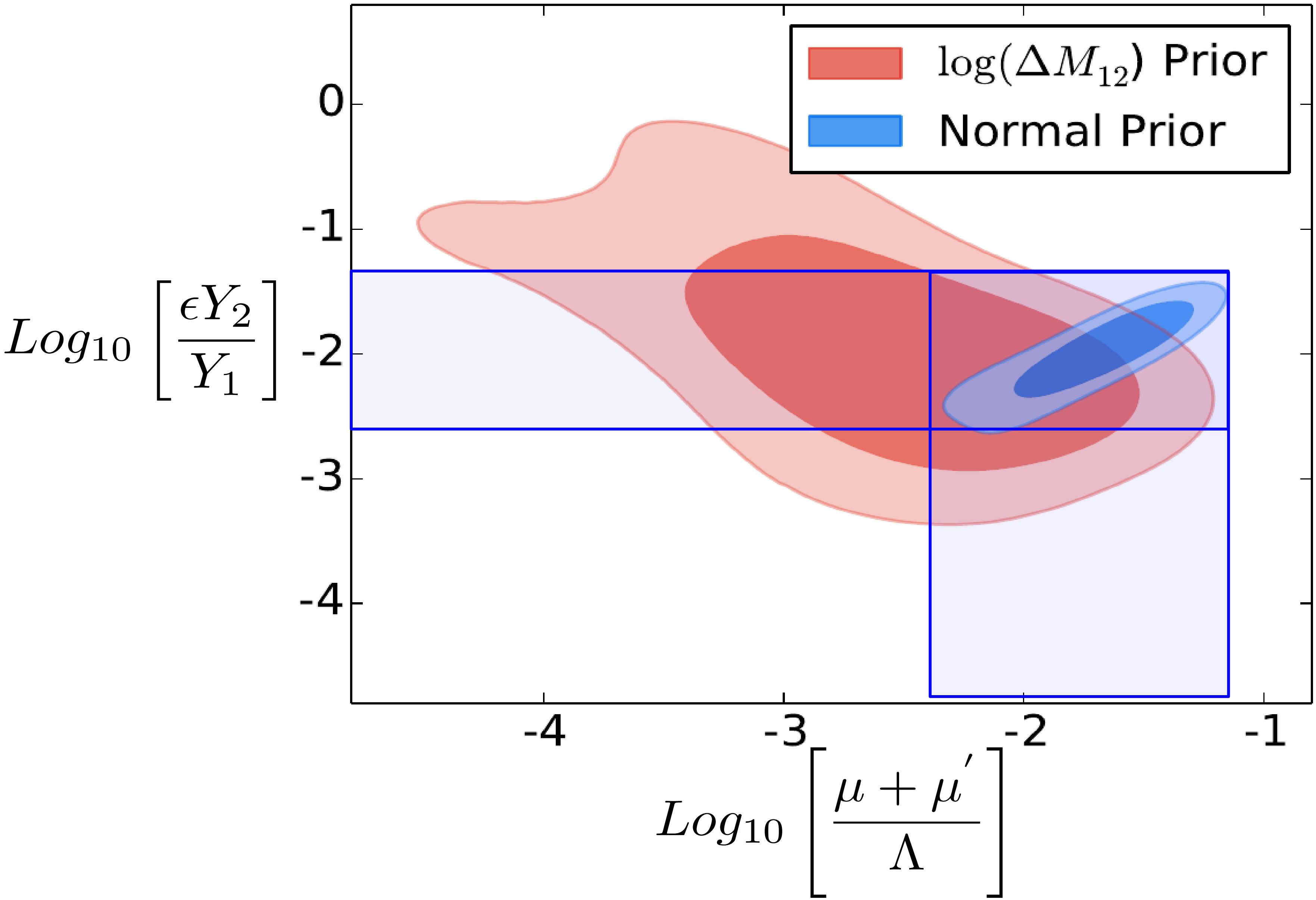


CP-violation in Minimal Model

Measurment of PMNS phases from FCC and ShiP?

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

CP-violation in minimal model

- **SHiP and FCC** can measure:

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

Sensitivity to
PMNS CP-phases!
δ, ϕ_1

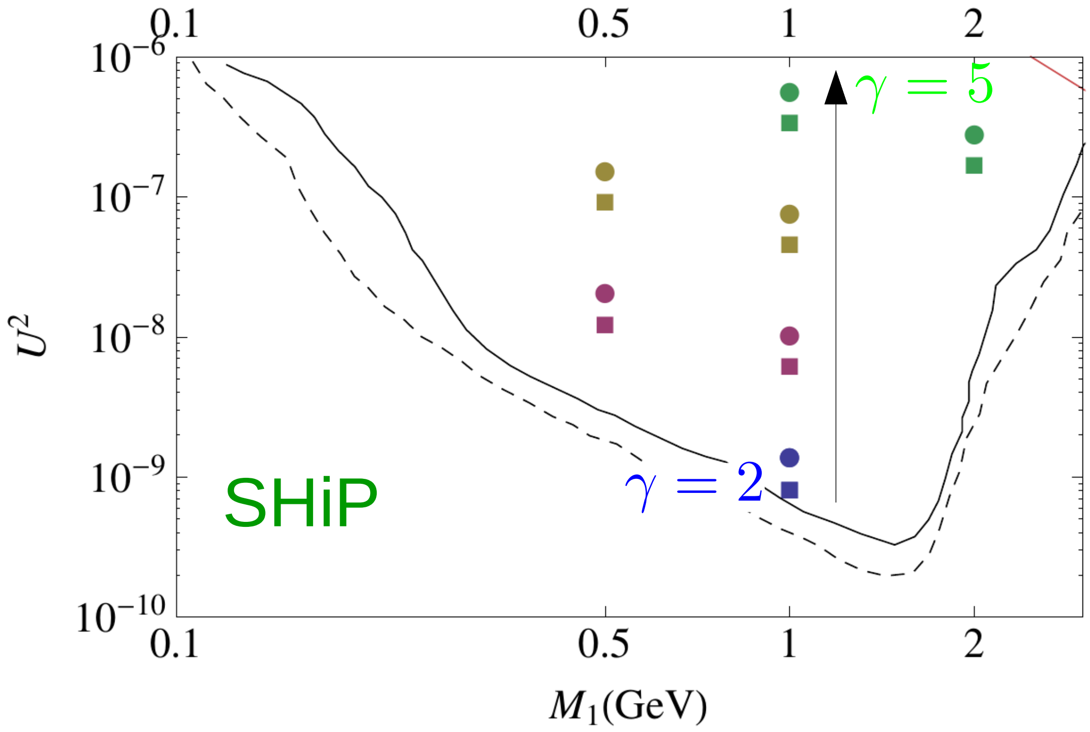
- $|U_{e4}|^2/|U_{\mu4}|^2 \simeq |U_{e5}|^2/|U_{\mu5}|^2 \simeq$

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

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

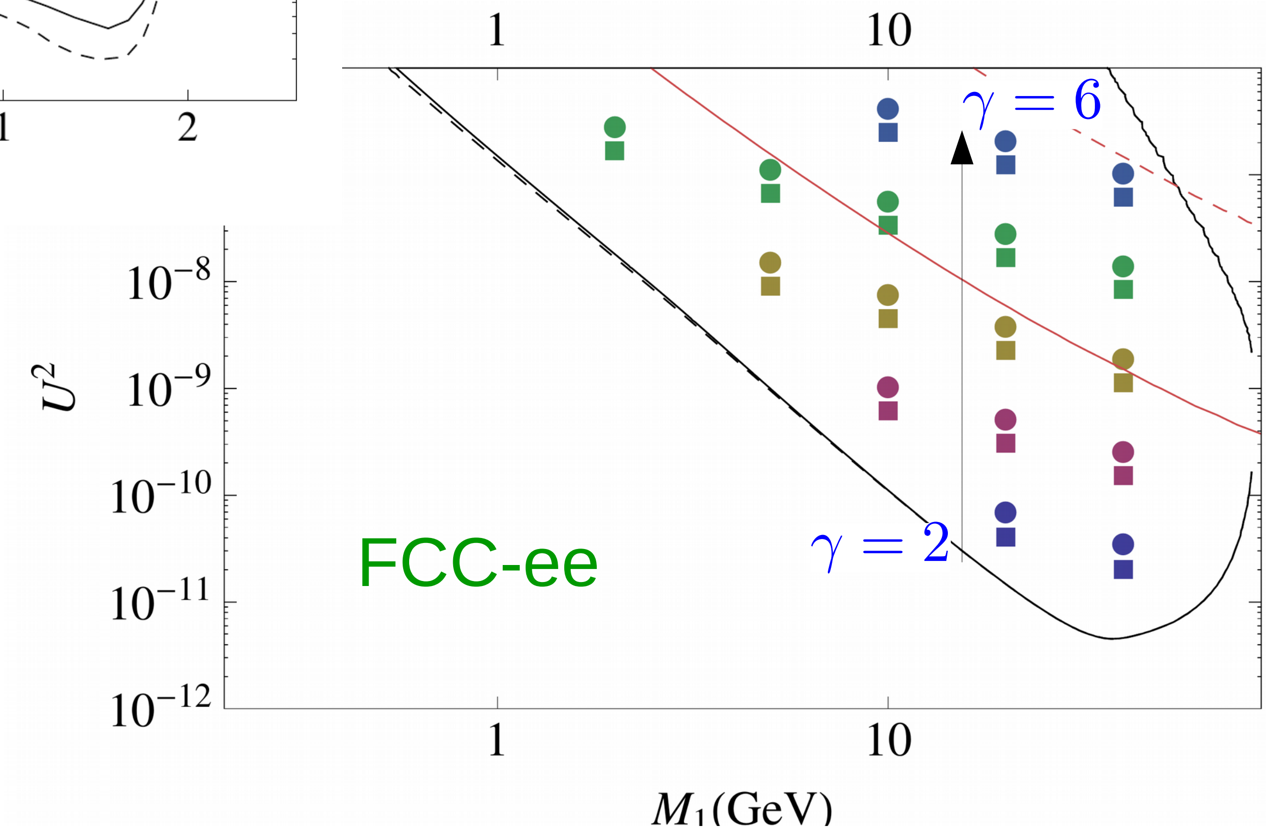
γ

CP-violation in minimal model

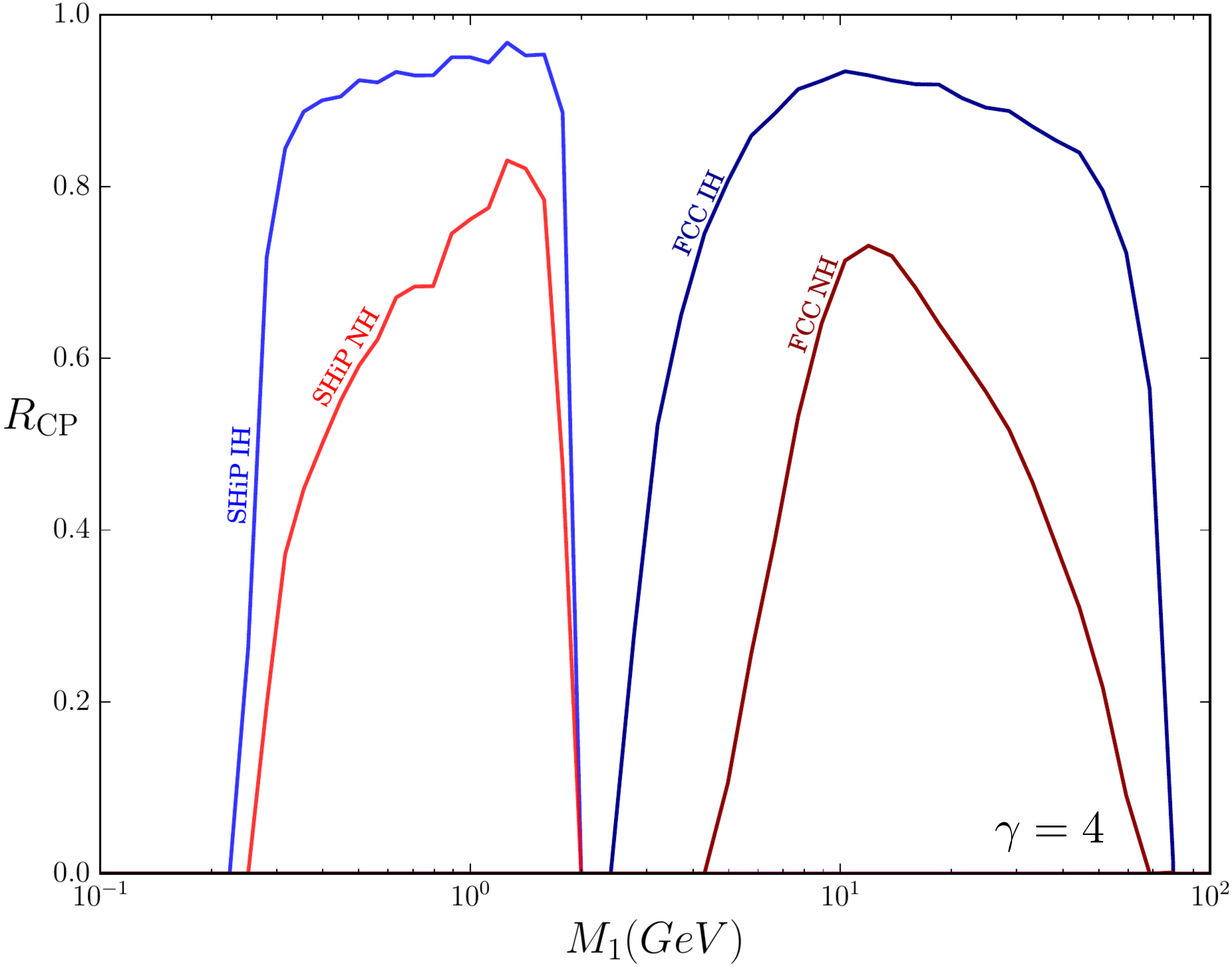


see talk by
Nicola Serra

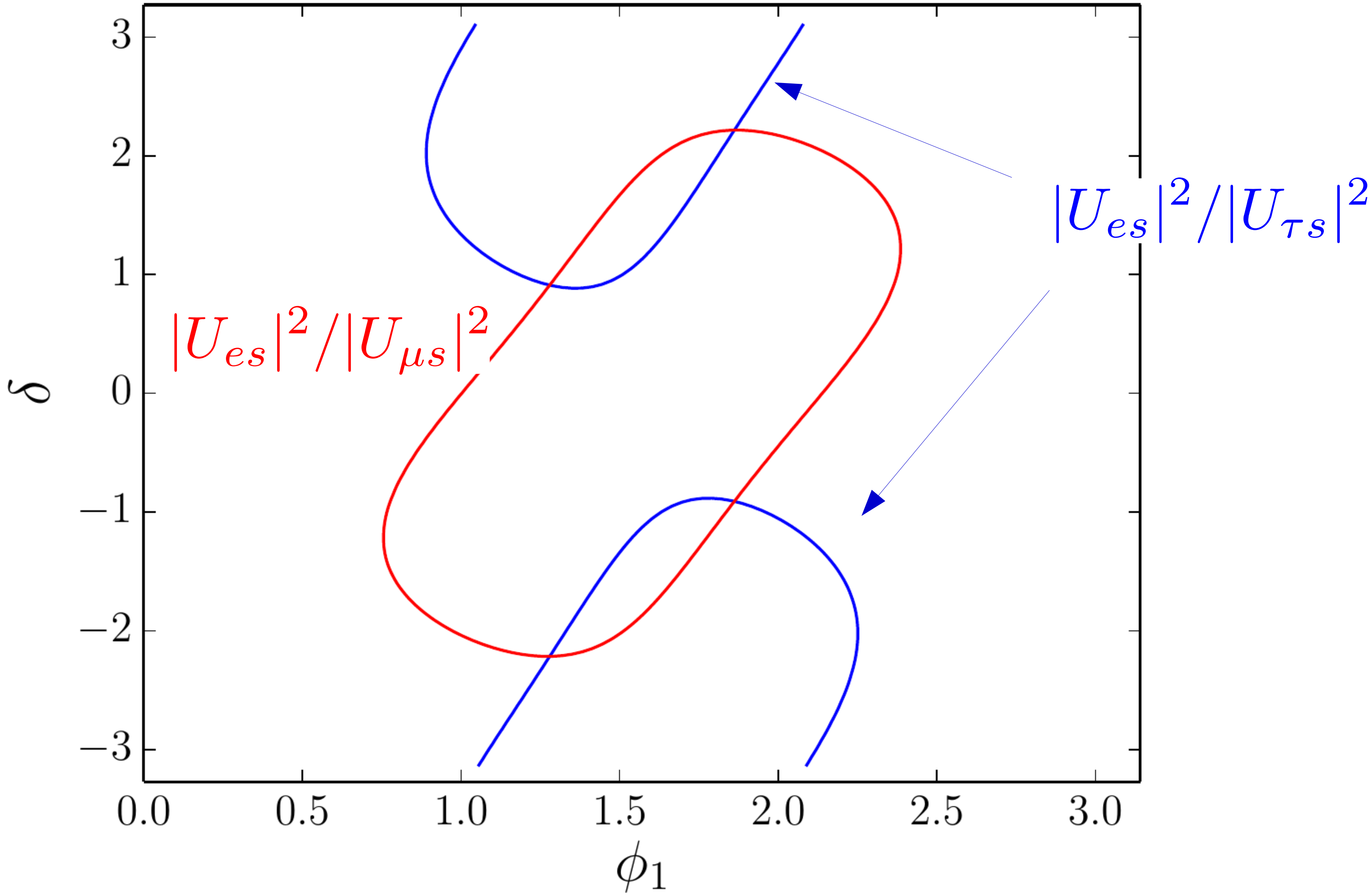
see talks by
Oliver **Fischer**
Marcin **Chrzaszcz**



5σ discovery CP-violation



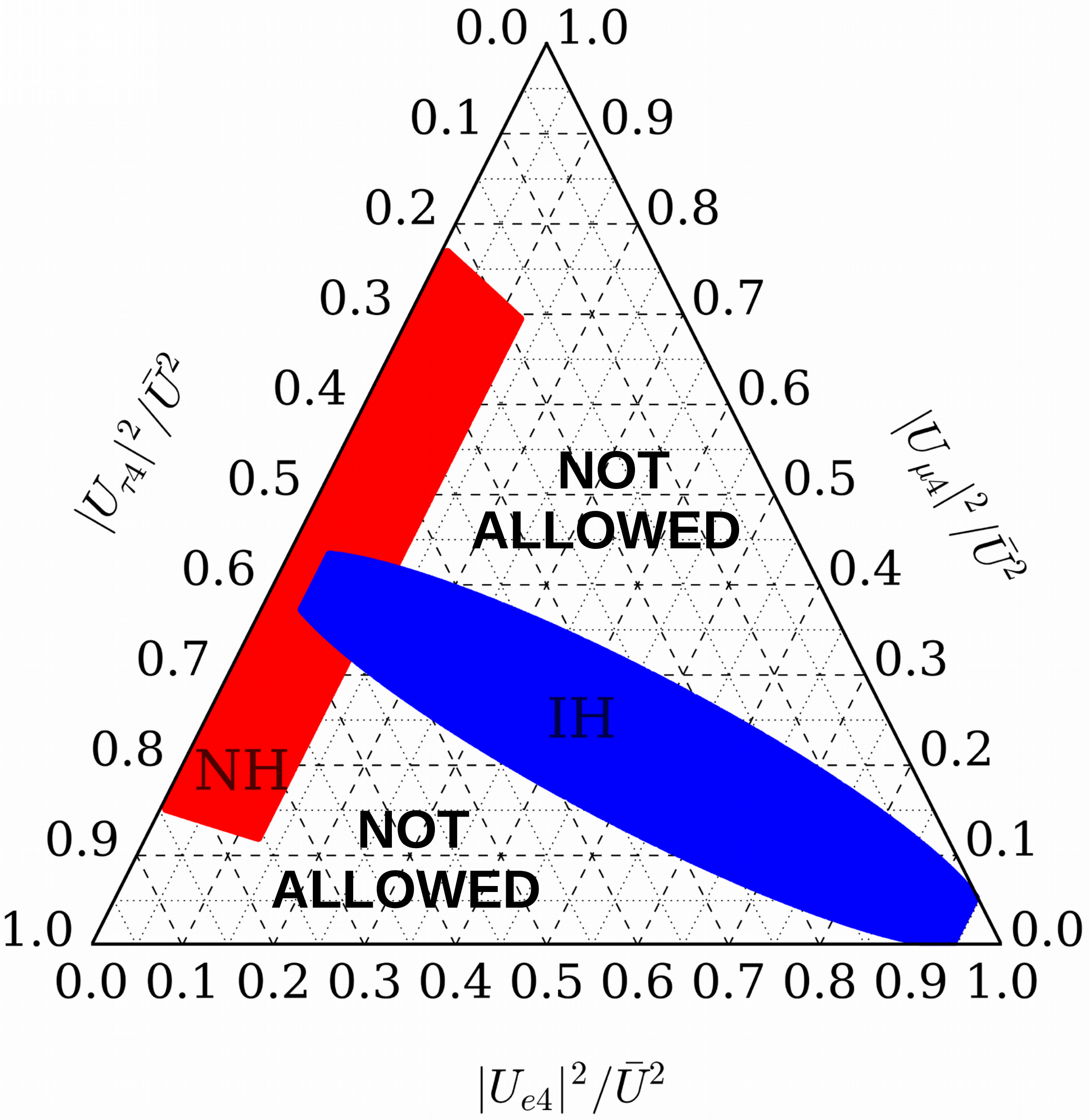
Tau detection



Previous predictions rely to a large extent on the minimality

Caputo, Hernandez, JLP, Salvado
arXiv:1704.08721

Minimal Model



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

- 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

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

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

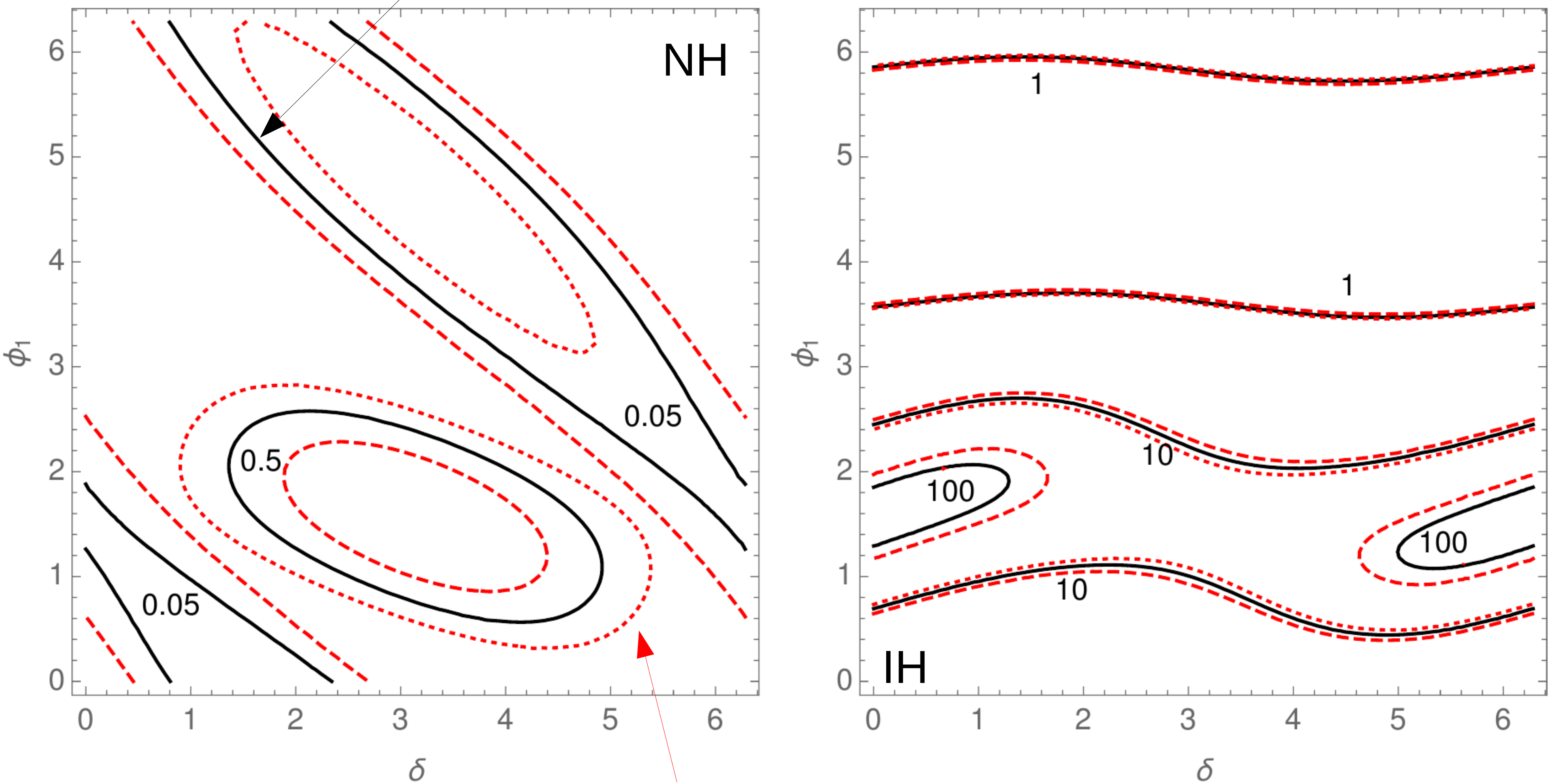
$$\frac{v^2 \alpha_W}{\Lambda} \sim \mathcal{O}(1) m_{1(3)}$$

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

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

Minimal Model

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



$\mathcal{O}(m_1/\sqrt{\Delta m^2_{sol}})$

Minimal Model + NP

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

Model Independent Approach: EFT

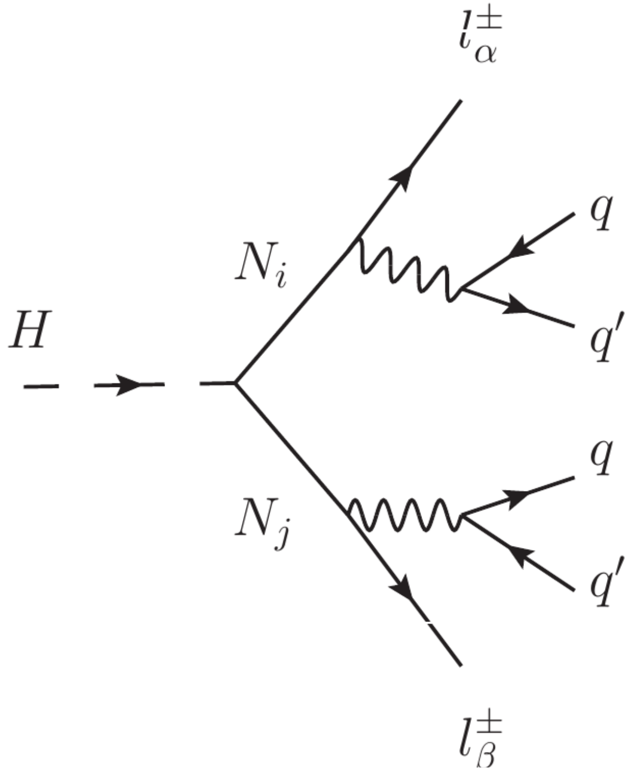
- The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

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

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

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

Seesaw Portal



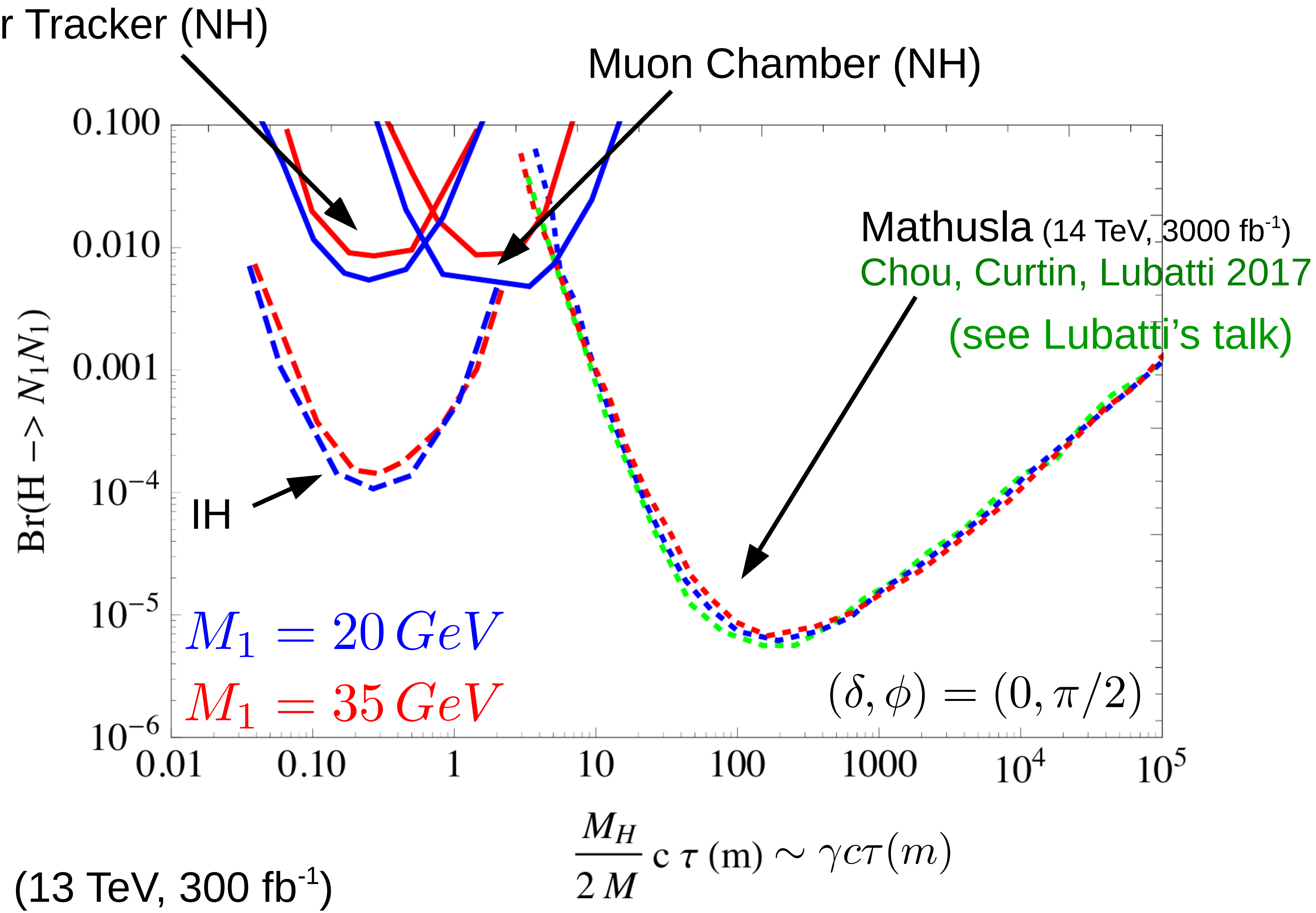
similar to
$\Delta \to NN$
(talk by **Miha Nemevšek**)

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

(see Lubatti's talk)

IH

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

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 would be possible in a very significant fraction of parameter space! (regardless the baryon asymmetry generation).

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)

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

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

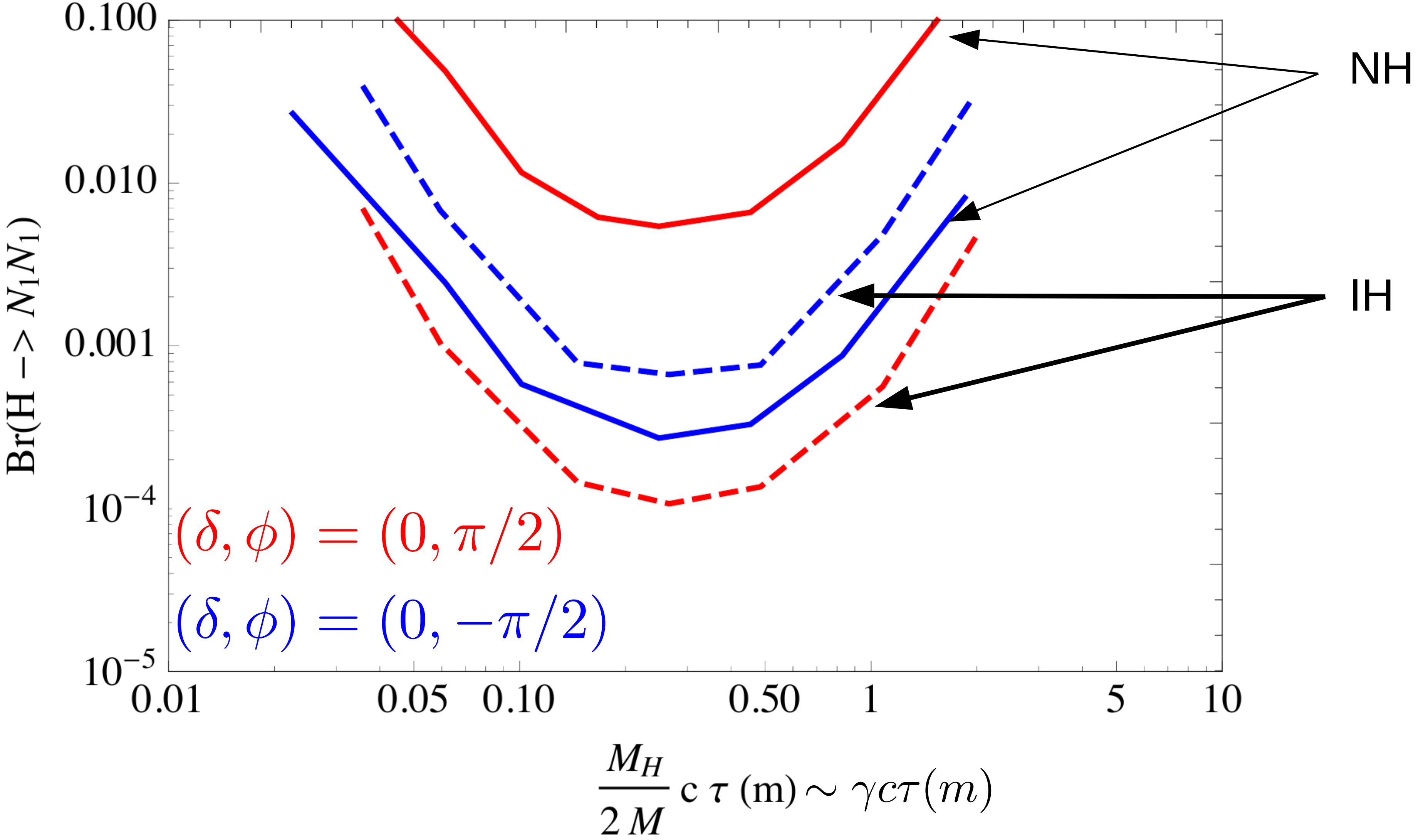
Caputo, Hernandez, JLP, Salvado 2017

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

Aparici, Kim, Santamaria, Wudka 2009.

Thanks!

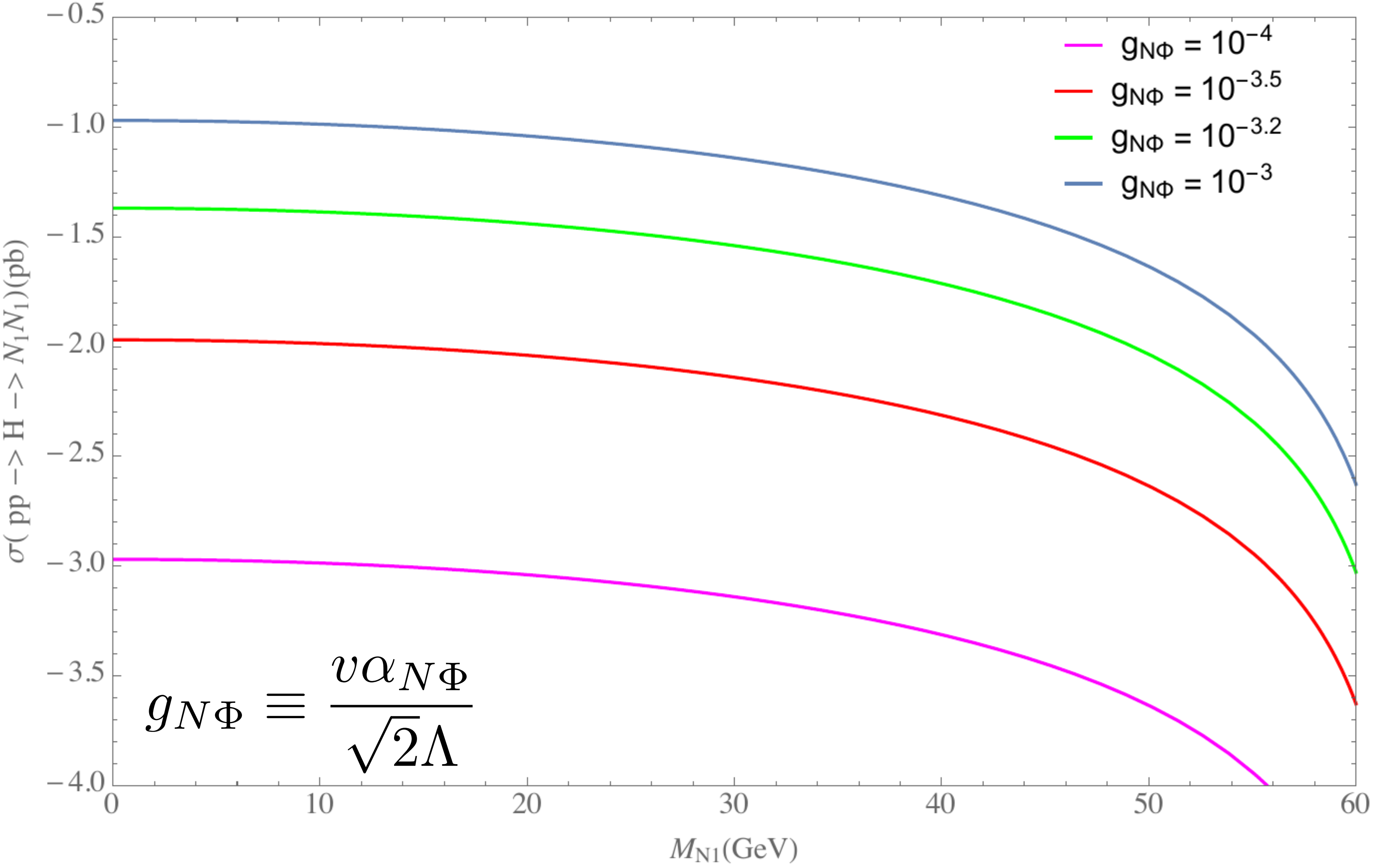
Seesaw Portal



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

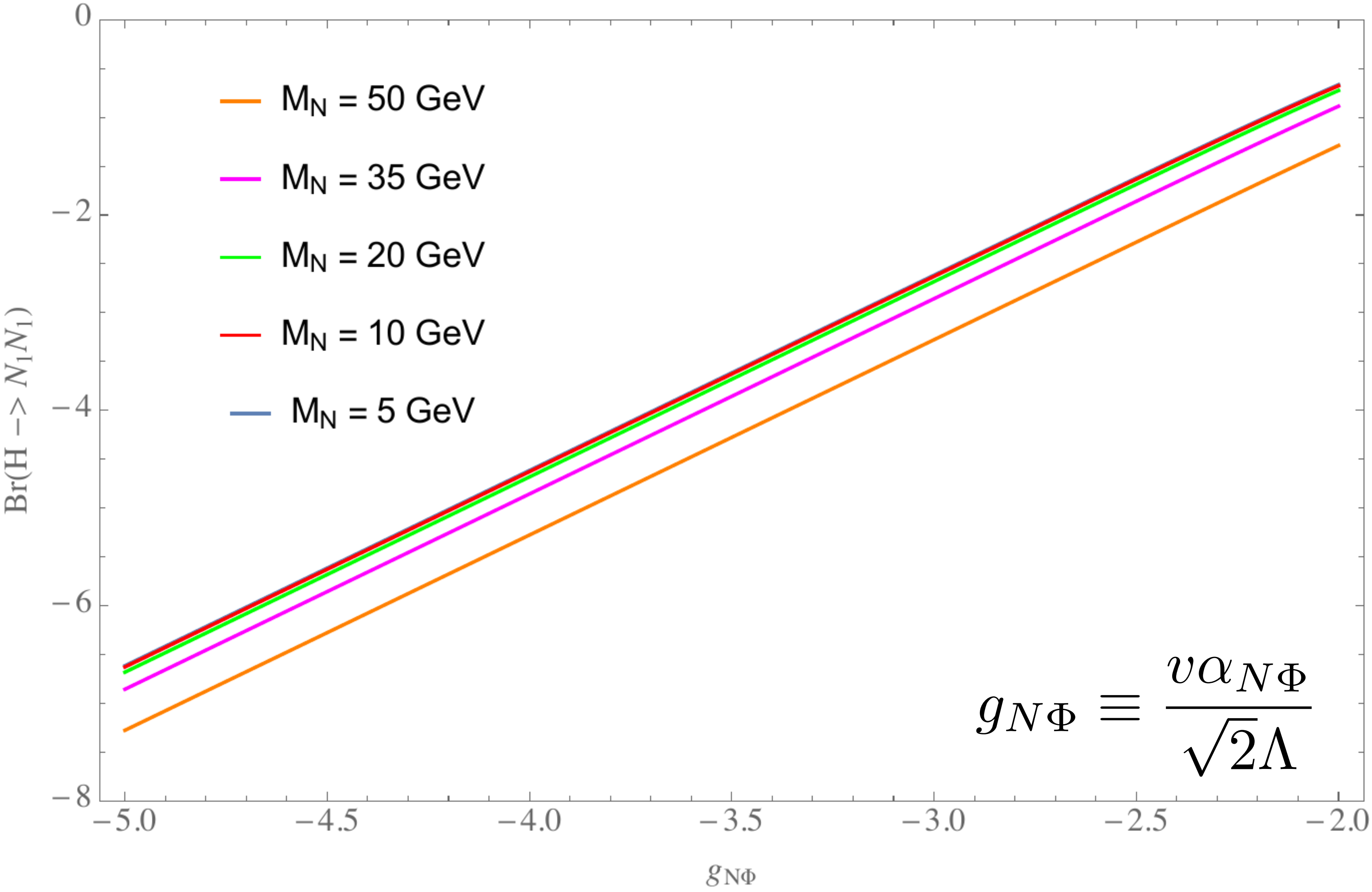
$M_1 = 20\,GeV$

Production Cross Section



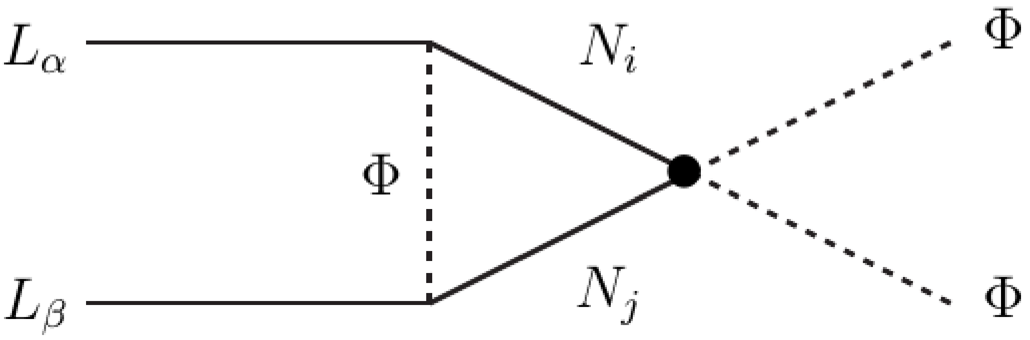
$$g_{N\Phi} \equiv \frac{v\alpha_{N\Phi}}{\sqrt{2}\Lambda}$$

Production Branching Ratio

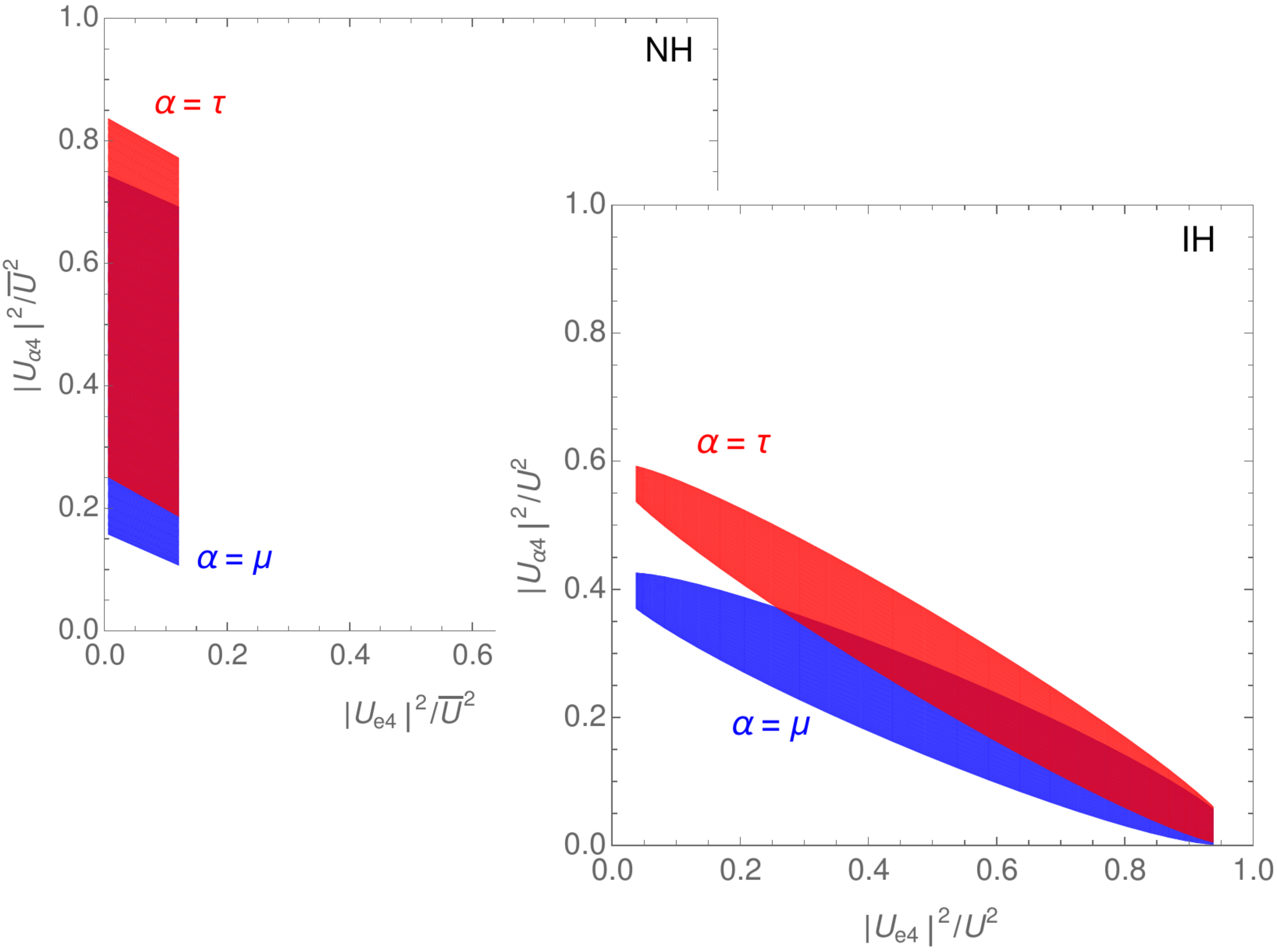


$$g_{N\Phi} \equiv \frac{v\alpha_{N\Phi}}{\sqrt{2}\Lambda}$$

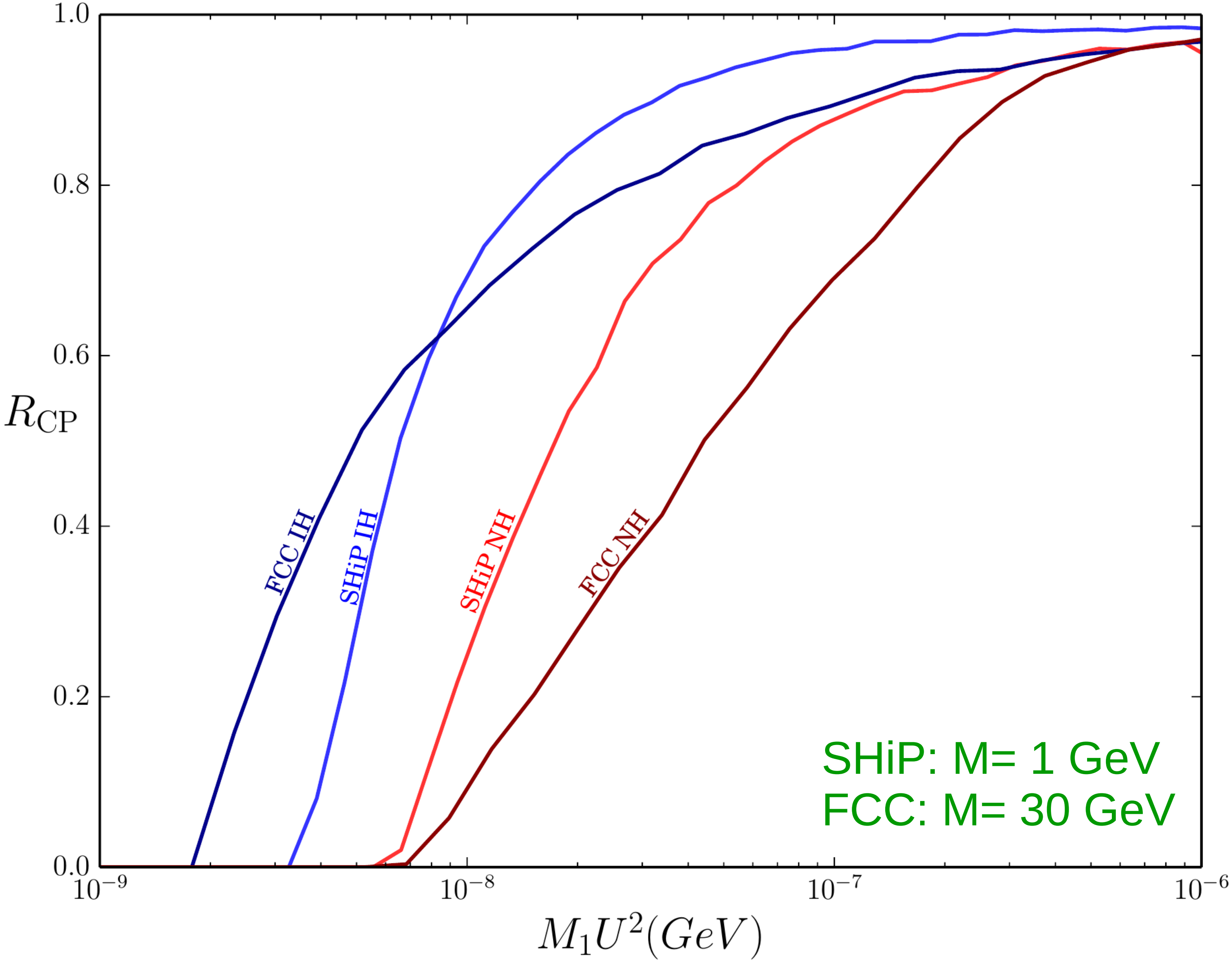
1-loop contribution of $\mathcal{O}_{N\Phi}$ to nu masses



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


NH
$\alpha = \tau$
$\alpha = \mu$
$|U_{\alpha 4}|^2/\overline{U}^2$
$|U_{e4}|^2/\overline{U}^2$
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
IH
$\alpha = \tau$
$\alpha = \mu$
$|U_{\alpha 4}|^2/U^2$
$|U_{e4}|^2/U^2$
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

5σ discovery CP-violation



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:

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

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

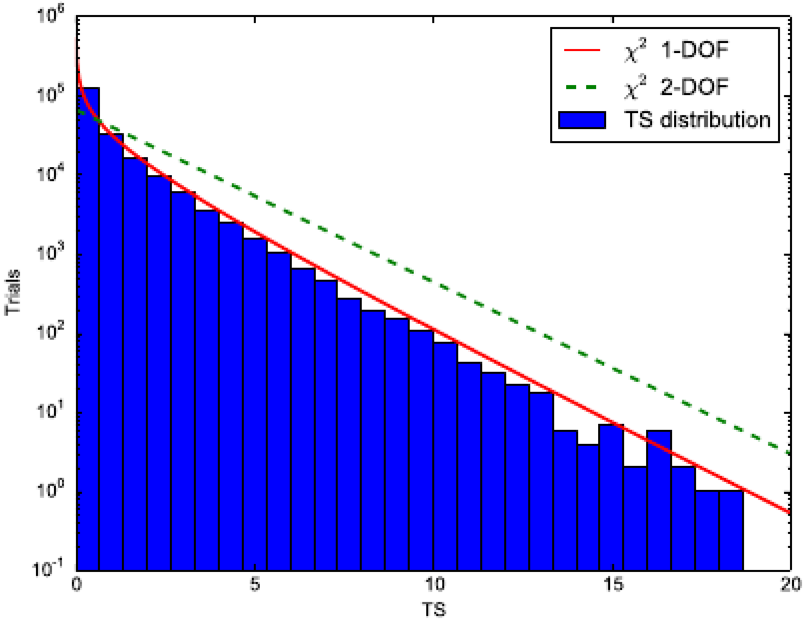


Fig. 4 Distribution of the test statistics for $\mathscr{O}(10^7)$ number of experimental measurements of the number of events for true values of the phases $(\delta, \phi_1) = (0, 0)$ for IH and $(\gamma, \theta, M_1) = (3.5, 0, 1)$ GeV, compared to the χ^2 distribution for 1 or 2 degrees-of-freedom.

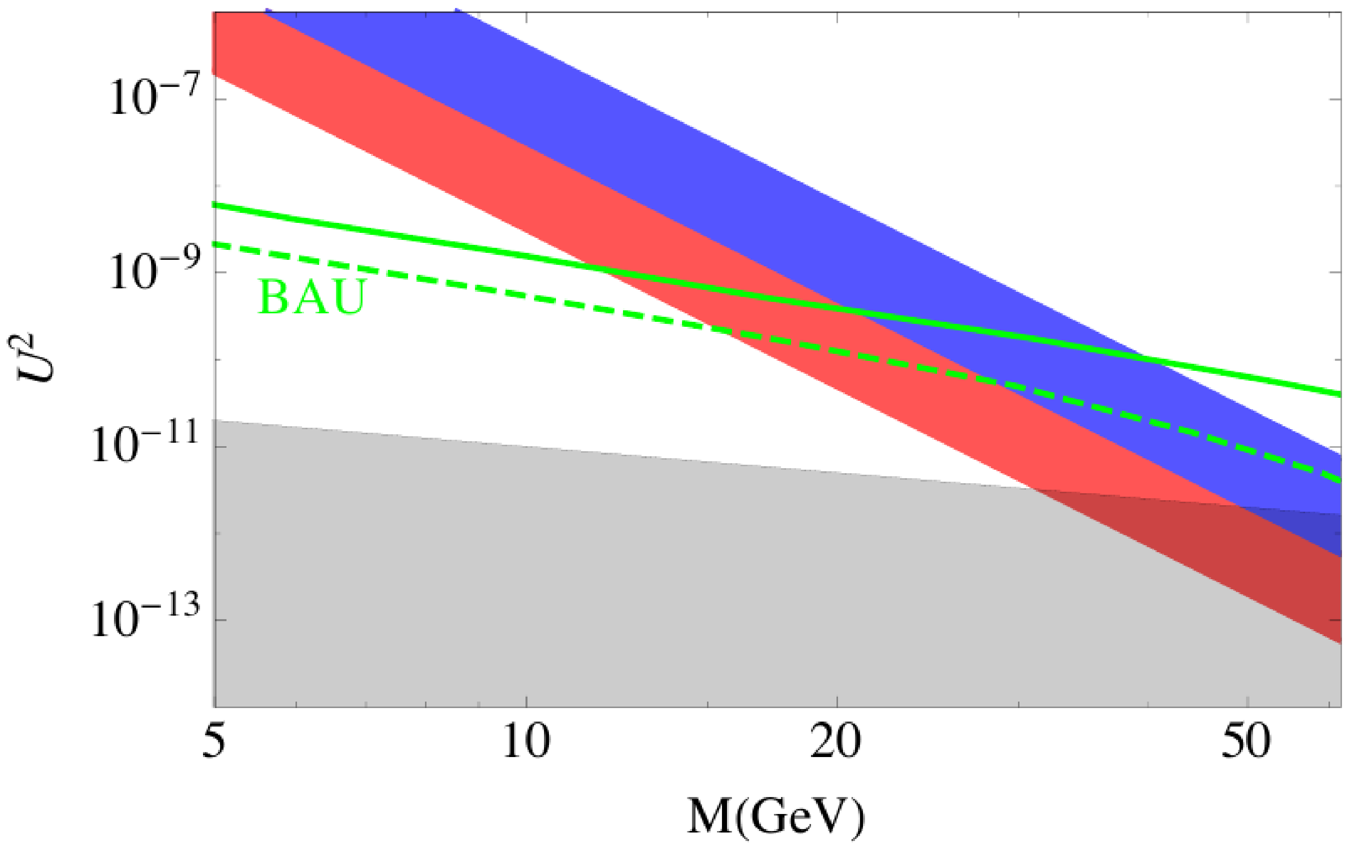


Figure 11. Regions on the plane (M, U^2) where LHC displaced track selection efficiency (eq. (3.20) and (3.21)) is above 10% in the IT (blue band) and MC (red band). The grey shaded region cannot explain the light neutrino masses and the green lines correspond to the upper limits of the 90%CL bayesian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

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):

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

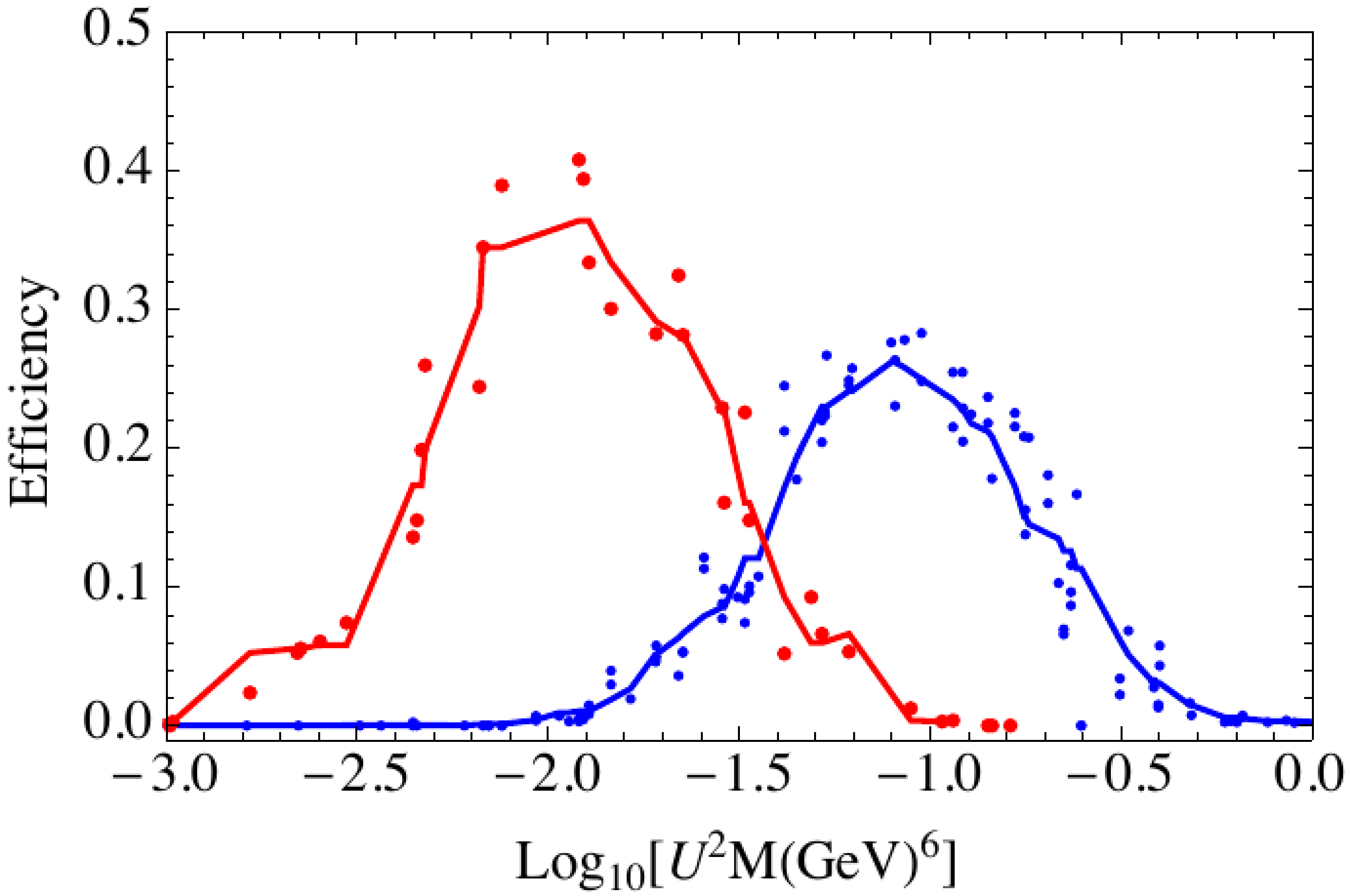
where $\sigma_d^t \simeq 20\mu\text{m}$ is the resolution in the tracker.

- Muon chambers (MC):

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

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

Cuts associated to displaced tracks



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

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

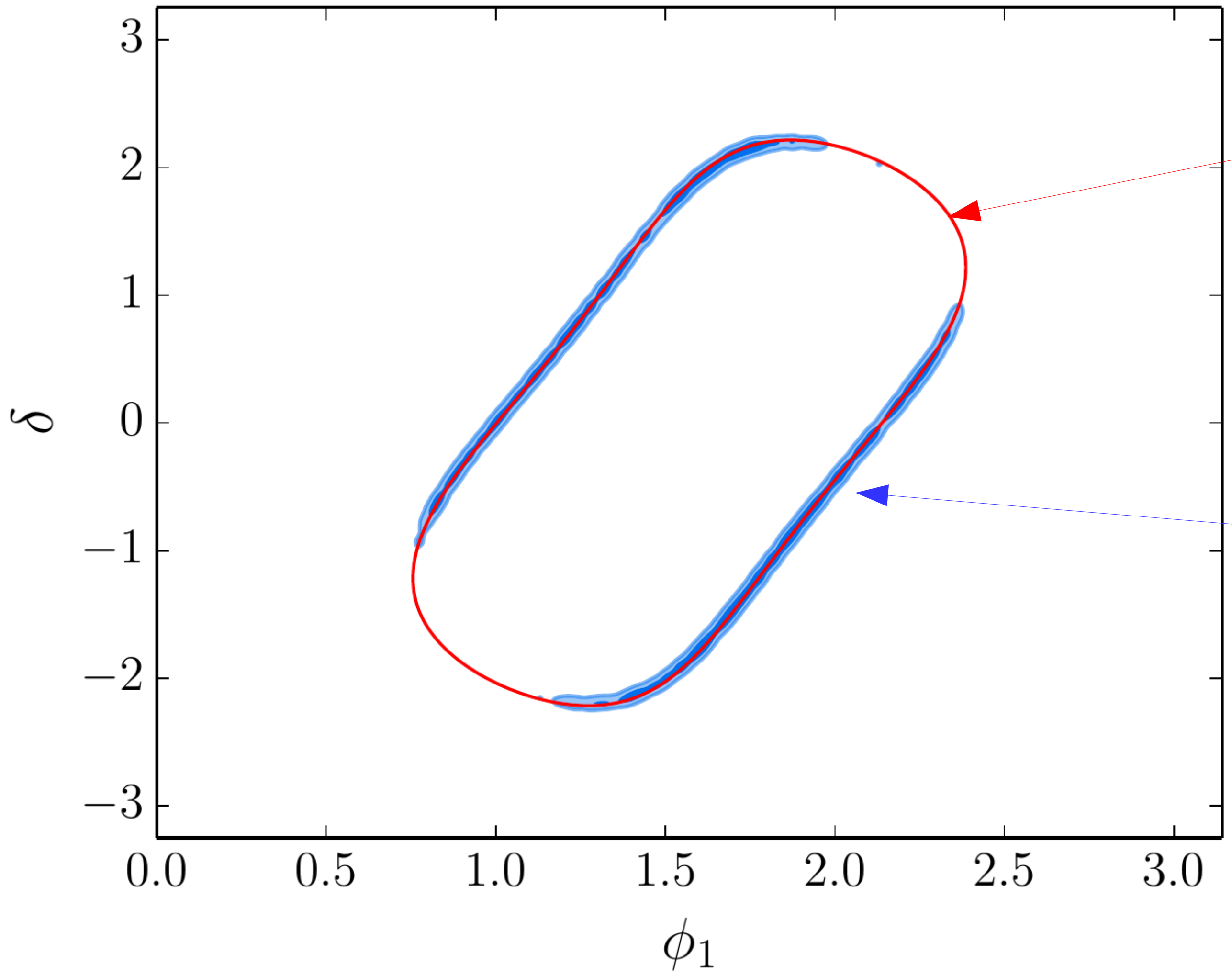
- Electroweak moment N_j couplings. $\frac{\alpha_{NB}}{\Lambda} < 10^{-2} - 10^{-1} TeV$

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

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

Aparici, Kim, Santamaria, Wudka 2009.

SHIP sensitive to PMNS CP phases

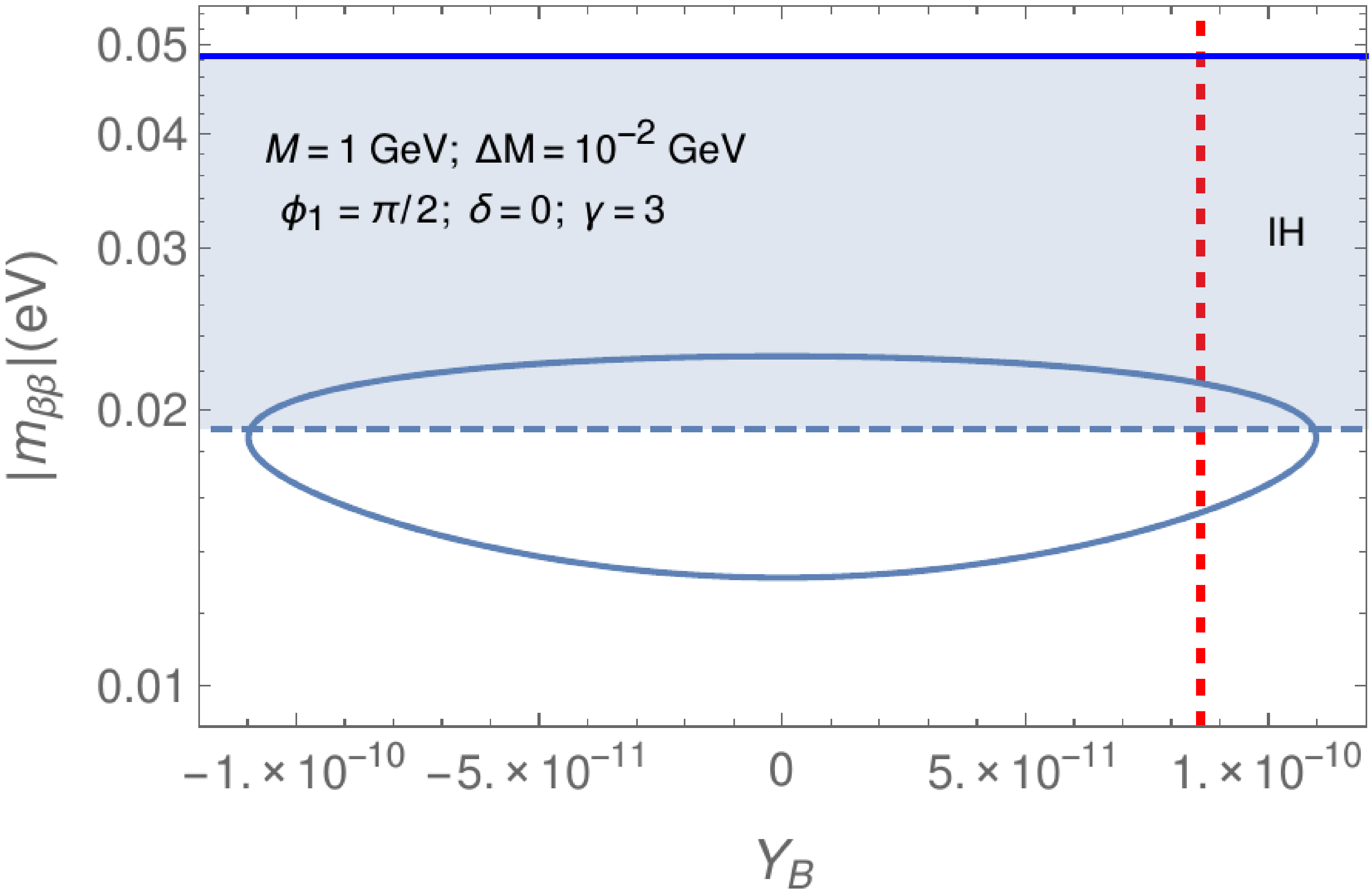


analytical expectation

SHIP measurement

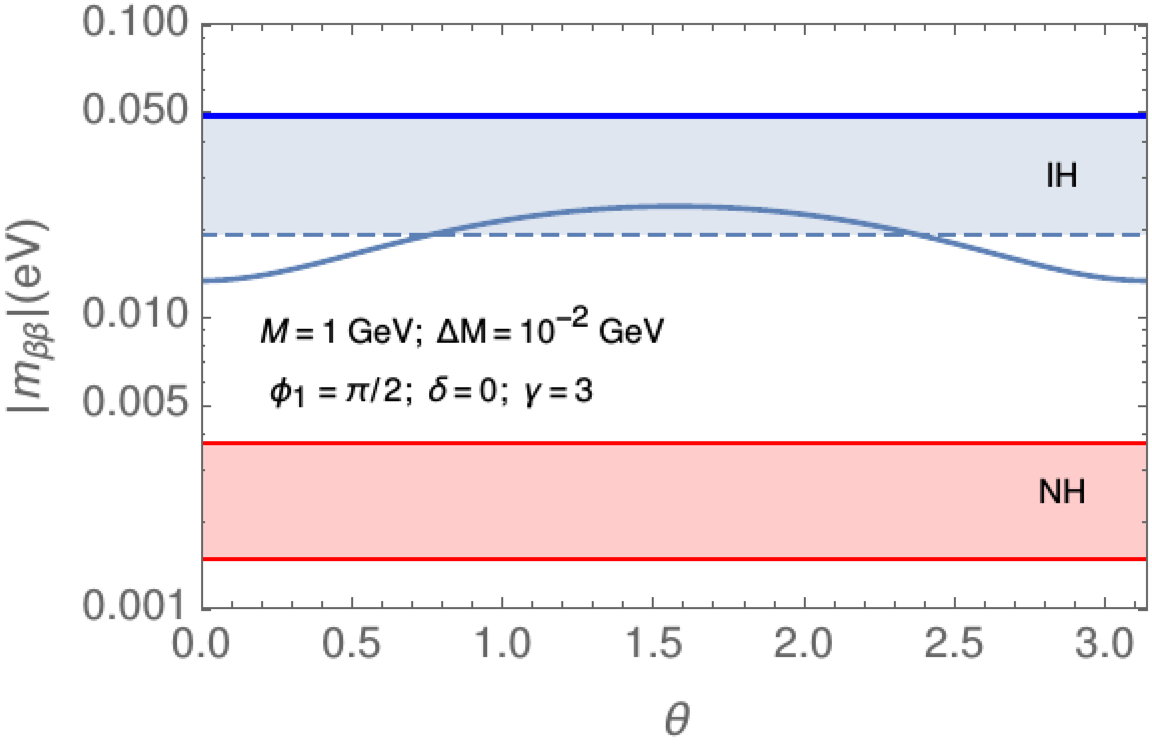
Recall, neutrino oscillation experiments sensitive to δ

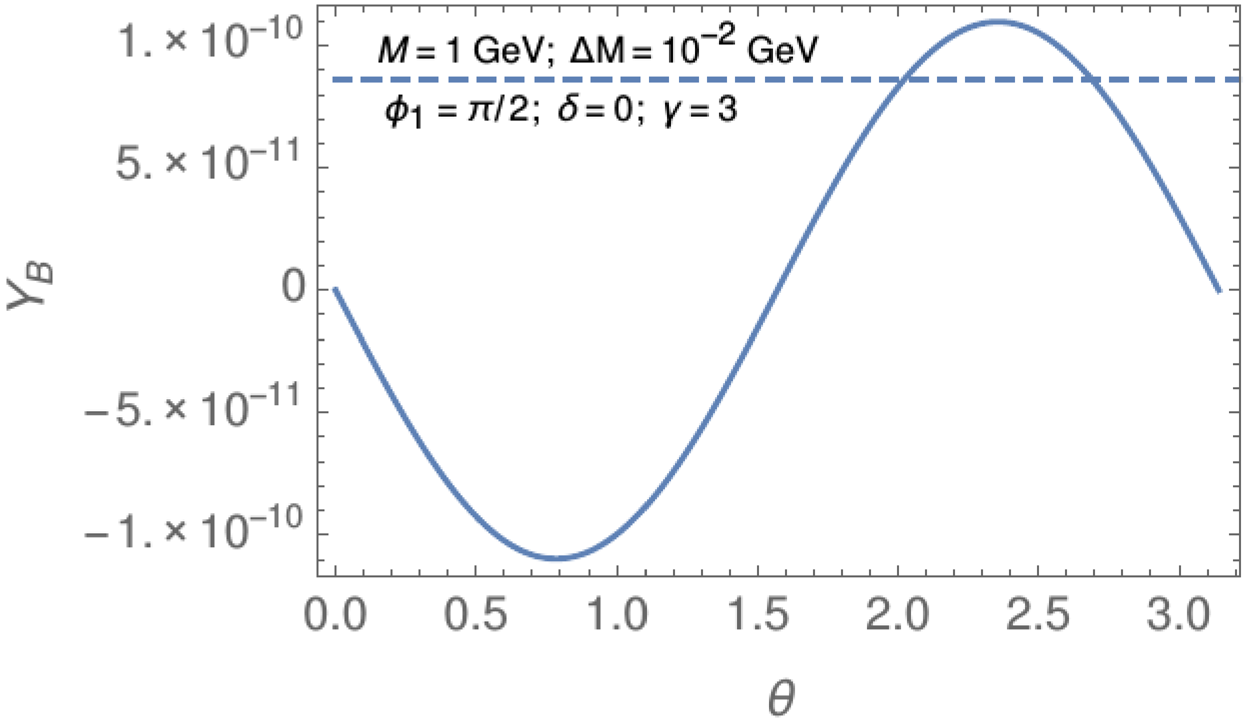
Predicting Y_B in minimal model $N_R=2$



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

Leptogenesis in Minimal Model





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

CP invariants

- The lepton assymetry should be proportional to a combination of the following 4 independent CP-invariants

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \\ I_1^{(3)} &= \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \\ I_2^{(3)} &= \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}] \end{aligned}\right\}$$

CP phases from V & W
(UPMNS & R)

$$\left. J_W = -\mathrm{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \right\}$$

CP phases from W
(only R)

$$Y = V^\dagger \mathrm{Diag}\{y_1, y_2, y_3\} W$$

CP invariants

- The lepton assymetry should be proportional to a combination of the following 4 independent CP-invariants

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[W^*_{12}V_{11}V^*_{21}W_{22}] \\ I_1^{(3)} &= \mathrm{Im}[W^*_{12}V_{13}V^*_{23}W_{22}] \end{aligned}\right\} \qquad N_R \geqslant 2$$

$$\left.\begin{aligned} I_2^{(3)} &= \mathrm{Im}[W^*_{13}V_{12}V^*_{22}W_{23}] \\ J_W &= -\mathrm{Im}[W^*_{23}W_{22}W^*_{32}W_{33}] \end{aligned}\right\} \qquad N_R \geqslant 3$$

$$Y = V^\dagger \mathrm{Diag}\left\{y_1, y_2, y_3\right\} W$$

CP invariants

- The lepton assymetry should be proportional to a combination of the following 4 independent CP-invariants

$$\left.\begin{array}{l} I_1^{(2)} = -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \\ \\ I_1^{(3)} = \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \end{array}\right\} \qquad AS \;\; \nu MSM$$

$$I_2^{(3)} = \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}]$$

$$\left. J_W = -\mathrm{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \right\} \qquad ARS$$

$$Y = V^\dagger \mathrm{Diag}\left\{y_1, y_2, y_3\right\} W$$

CP invariants

- The lepton assymetry should be proportional to a combination of the following 4 independent CP-invariants

$$I_1^{(2)} = -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \simeq \theta_{12}\bar{\theta}_{12} \sin\psi_1$$

$$I_1^{(3)} = \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \simeq \theta_{12}\bar{\theta}_{13}\bar{\theta}_{23} \sin\left(\bar{\delta} + \psi_1\right)$$

$$I_2^{(3)} = \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}]] \simeq \bar{\theta}_{12}\theta_{13}\theta_{23} \sin\left(\delta - \psi_1\right)$$

$$J_W = -\mathrm{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \simeq \theta_{12}\theta_{13}\theta_{23} \sin\delta$$

$$Y = V^\dagger \mathrm{Diag}\left\{y_1, y_2, y_3\right\} W$$

$$Y_B \simeq 1.3 \times 10^{-3} \sum_\alpha \mu_{B/3-L_\alpha}$$