GeV Neutrinos at SHIP and FCC

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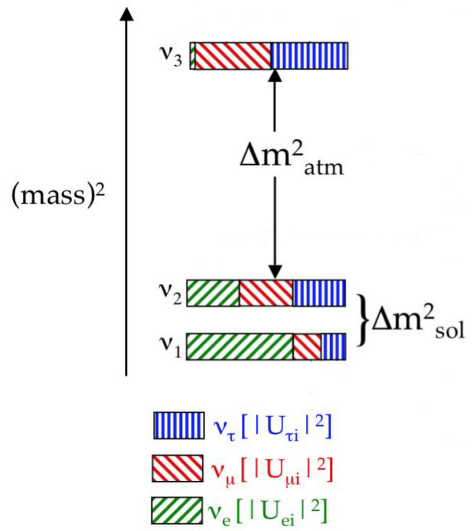
Neutrinos: the quest for a new physics scale

CERN 2017

Talk based on A. Caputo, P. Hernandez, M. Kekic, J. Lopez-Pavon, J.S. (arXiv:1611.05000)

Neutrinos are massive



$$\Delta m^2_{\rm sol} = 7.50 \times 10^{-5} {\rm eV}^2$$

$$|\Delta m^2_{\rm atm}| = 2.534 \times 10^{-3} {\rm eV}^2$$

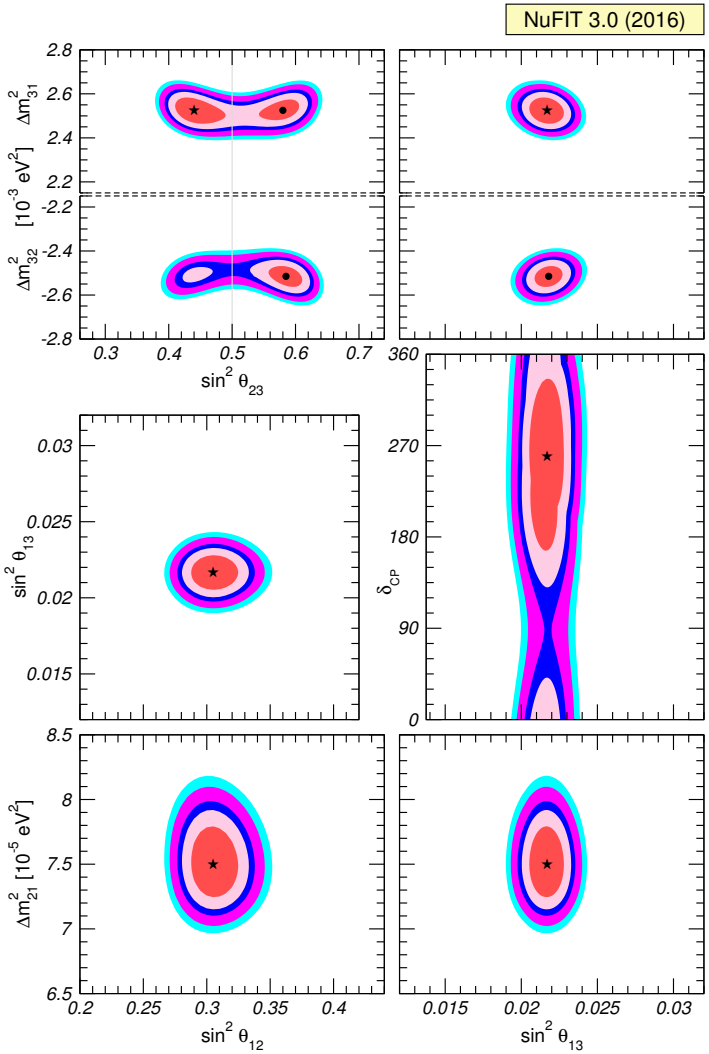
NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

[B. Kayser, hep-ph/0506165 (2004)]

[M.C. Gonzalez-Garcia et. al. JHEP 01 (2017) 087 www.nu-fit.org]

M.C. Gonzalez-Garcia Talk



Seesaw Type-I

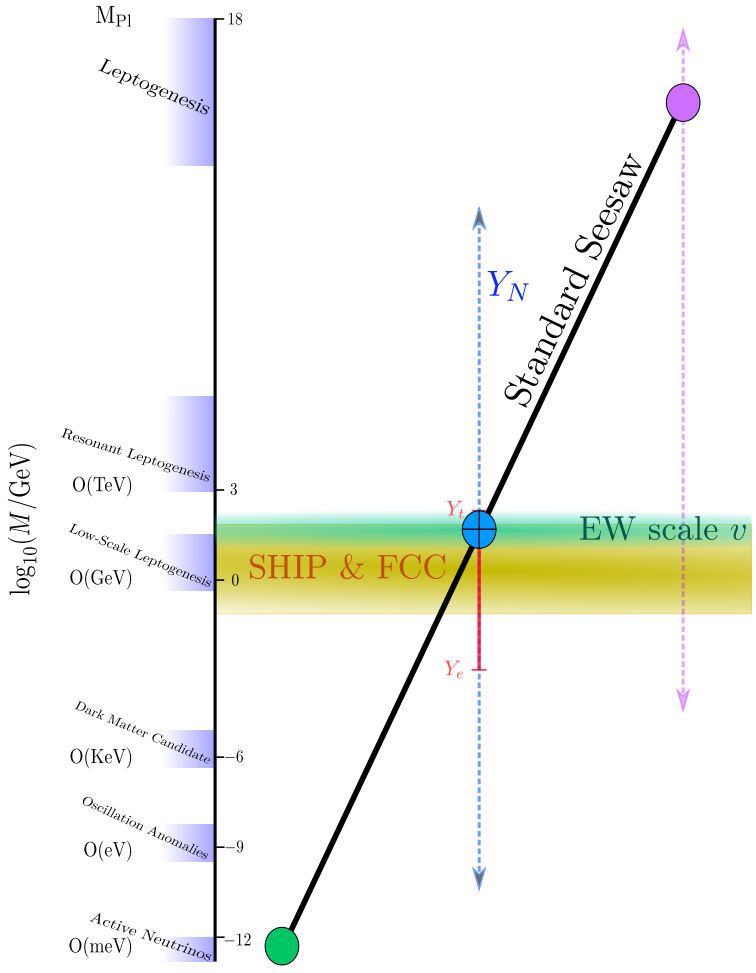
$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{3} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c..$$

- Neutrino Masses suggest a NEW PHYSICS scale.
- We focus in the simplest model type-I seesaw
- $Y_N = O(1) \rightarrow$ Hierarchy problem and not testable.

$$m_\nu = Y_N^T \frac{v^2}{M_N} Y_N$$

Minkowski; Yanagida; Glashow; Gell-Mann,

Ramond Slansky; Mohapatra, Senjanovic...



Low-Scale Seesaw

- Testable in collider (SHIP and FCC)
- Interesting cosmological implications

(Akhmedov, Rubakov, Smirnov)

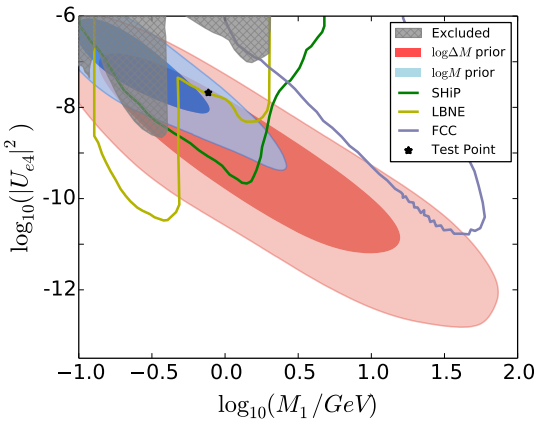
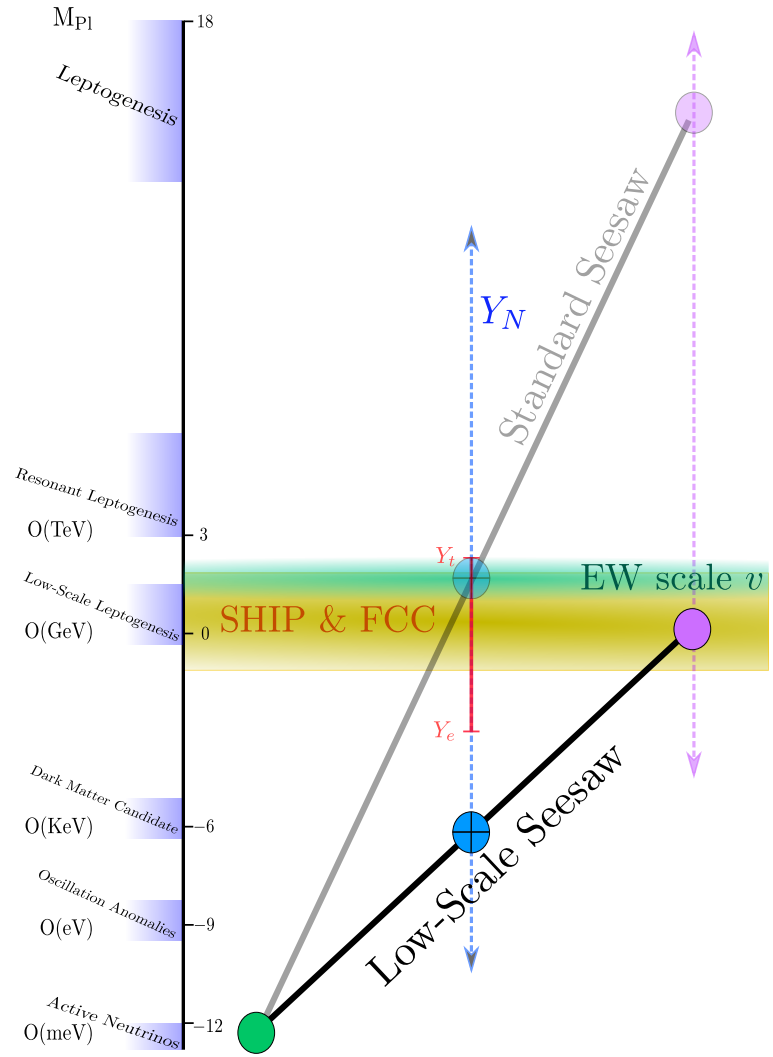


Figure from: P.Hernández, M.Kekic , J.López-Pavón J. Racker, J.S. arXiv:1606.06719 Talk by Juan Racker

- Potential implications in neutrino-less double β decay.
- Small Yukawas, but not so far from the SM.

$$m_\nu = Y_N^T \frac{v^2}{M_N} Y_N$$



Parametrization of the Model

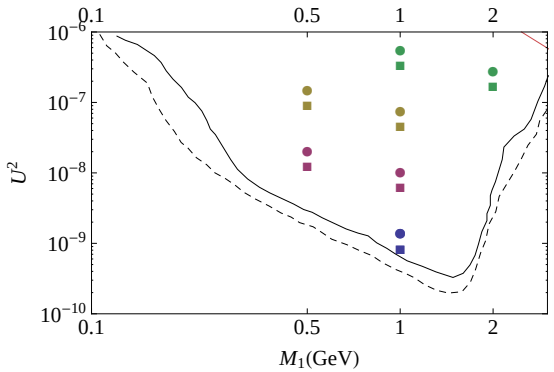
- We set the minimal models with 2 heavy sterile neutrinos.
- Casas-Ibarra parametrization helps us to parametrize the model easily imposing what we know about the light sector.

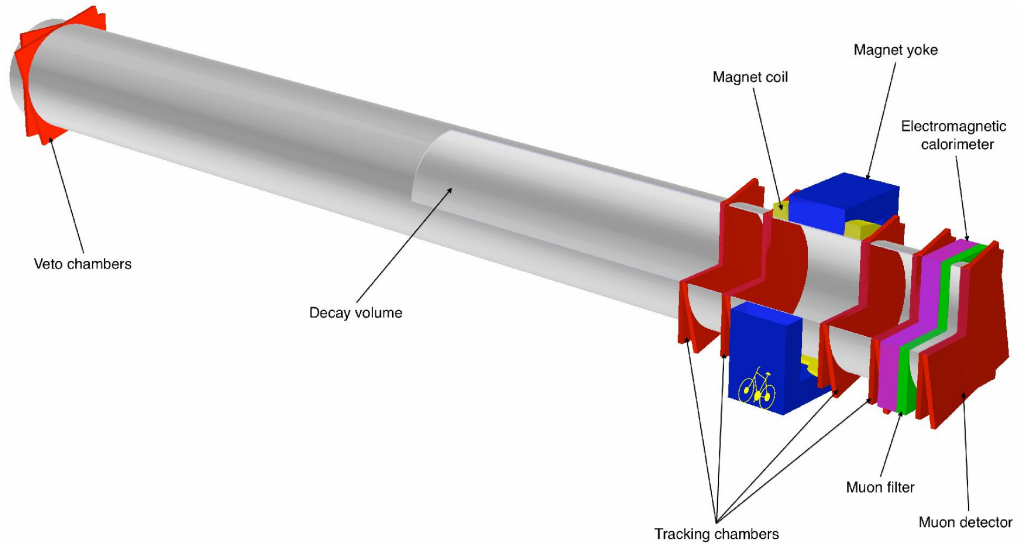
$$U_{\alpha h} = i U_{\mathrm{PMNS}} \sqrt{m_l}\ R^{\dagger}(z) M^{-1/2}$$

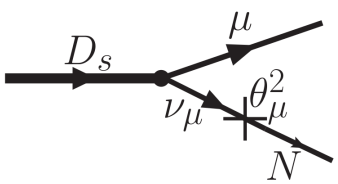
- We set U_{PMNS} angles and m_l square differences to the current best fit(NOT the PHASE, ORDERING).

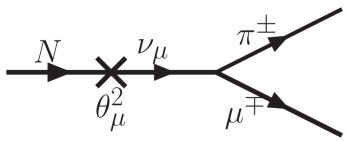
$$\{\delta, \phi_1, \gamma, \theta, M_1, M_2\}$$

SHIP (Search for Hidden Particles)





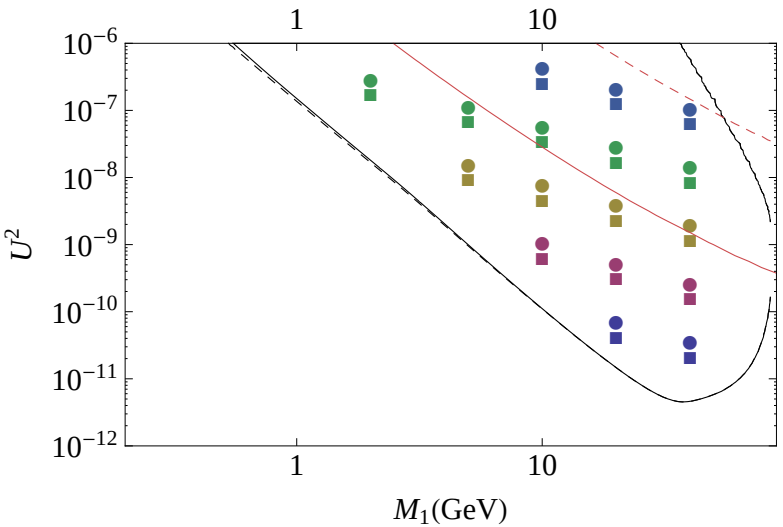




SHiP
Search for Hidden Particles

- Search for heavy sterile neutrinos from meson decays.
- Using the expected background and the sensitivity we can reconstruct the expected number of events $N_\alpha(M_i) \propto |U_{\alpha i}|^2 U^2$
- 3 Body $N \to l^-_\alpha l^+_\beta \nu_\beta$ negligible.

FCC-ee Future Circular Collider



- Produced in the Z decay, $10^{12} - 10^{13}$ decays at rest per year.
- Since we are interested in e and μ independently some of the channels give more information.
- We also include the hadronic channels, $N \to l_\alpha + q + \bar{q}'$

$$N_{\text{total}} = N_Z \, \text{BR}(Z \to N\nu)\text{BR}(N \to \text{leptonic})\left(e^{-l_{\min}/\gamma_L c\tau_N} - e^{-l_{\max}/\gamma_L c\tau_N}\right)$$

Production Decay Geometry

$l_{\min} = 0.1mm, \;\; l_{\max} = 5m$

GOAL: CP discovery potential

Assumptions:

1. SHiP or FCC measures one of the steriles.
2. The steriles are the main contribution in generating the light neutrino masses by the low scale seesaw.

Goal:

- Quantify the potential to exclude any of the CP conserving points(NULL HYPOTHESIS):

$$(\delta, \phi_1) = \{(0,0), (0,\pi), (\pi,0), (\pi,\pi)\}$$

Statistics definition

- Using the estimated number of events we construct the TS:

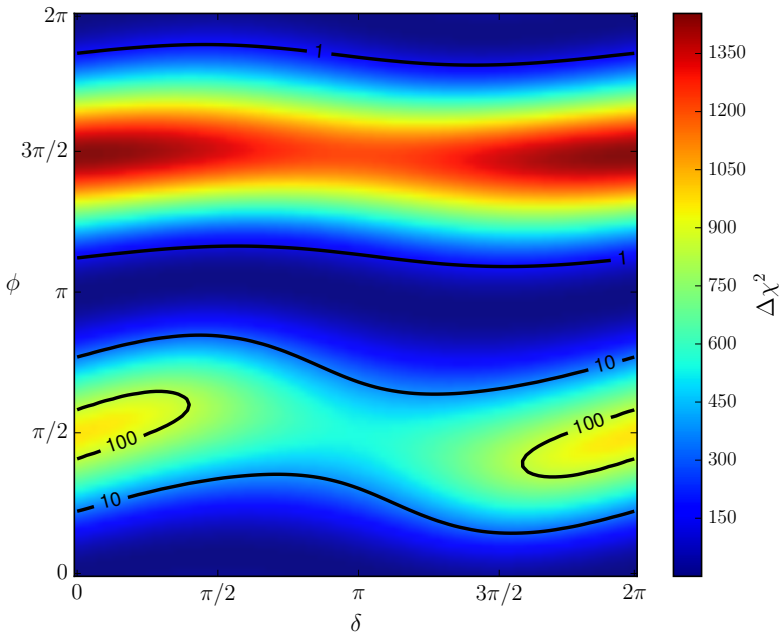
$$\Delta\chi^2 \equiv -2 \sum_{\alpha=\text{channel}} N_\alpha^{\text{true}} - N_\alpha^{CP} + N_\alpha^{\text{true}} \log\left(\frac{N_\alpha^{\text{CP}}}{N_\alpha^{\text{true}}}\right) + \left(\frac{M_1 - M_1^{\text{min}}}{\Delta M_1}\right)^2$$

- $N_\alpha^{\text{true}} = N_\alpha(\delta, \phi_1, M_1, \gamma, \theta)$, number of events for the true value.
- $N_\alpha^{CP} = N_\alpha(CP_{NULL}, M_1^{min}, \gamma^{min}, \theta^{min})$
- $M_1^{min}, \gamma^{min}, \theta^{min}$ are the values that minimize the TS
- We put 1% error to M_1

Statistics definition

- TS surface:

IH



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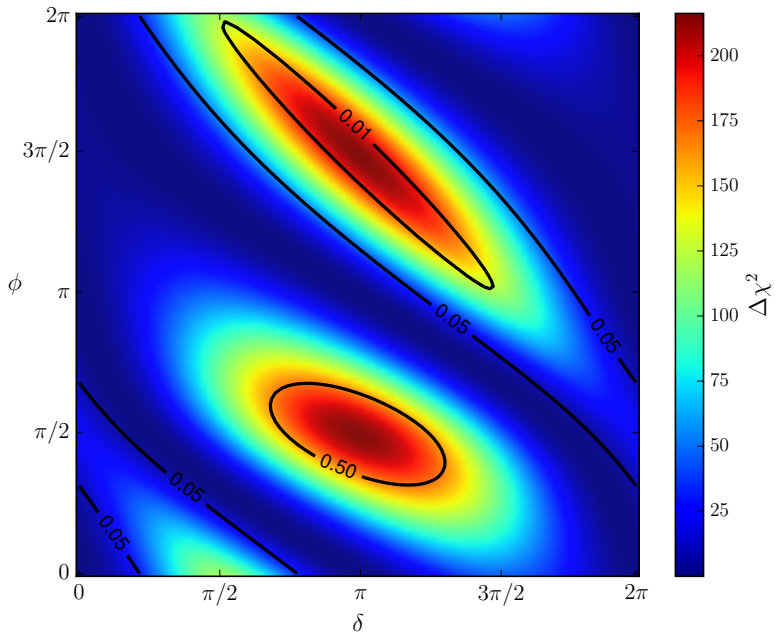
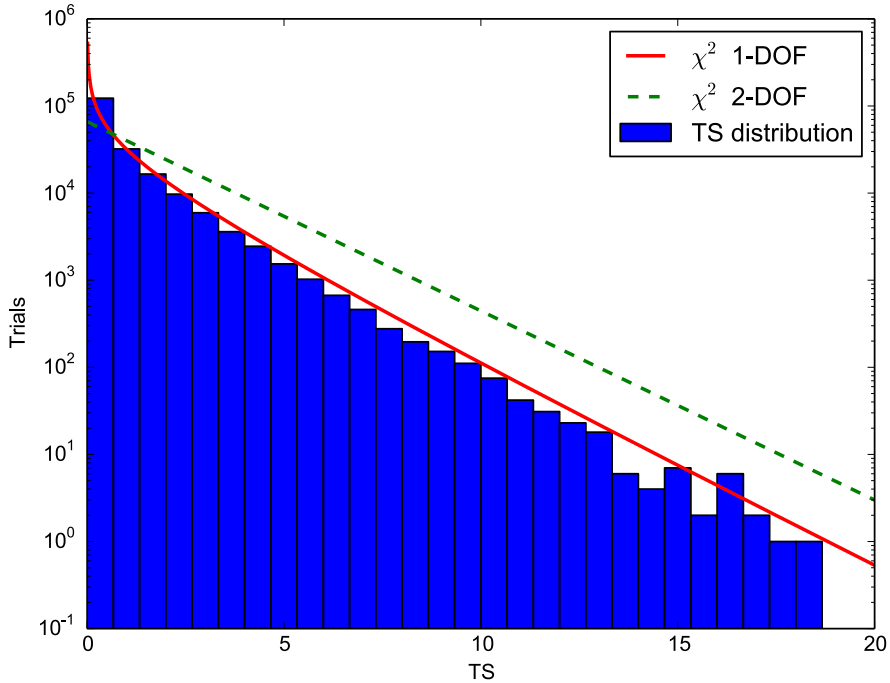


- Surface plots of $\Delta\chi^2$ for $(\gamma, \theta, M_1) = (3.5, 0, 1\ \text{GeV})$
- And constant e-μ ratios from approximated analytic formulas.

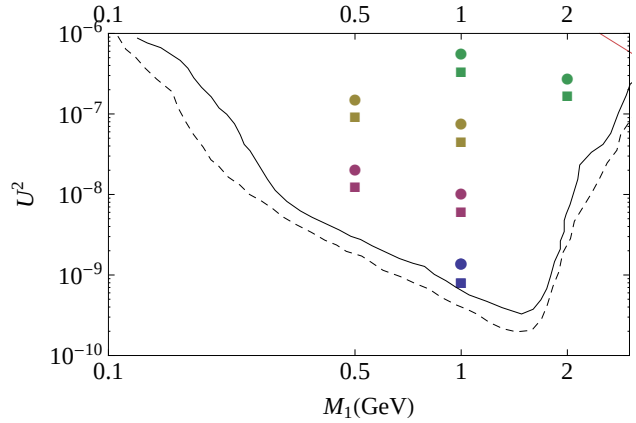
From the TS to the p-value

- We test the TS distribution sampling realizations of the experimental result for the Null Hypothesis.
- Due to the strong correlation between the phases the TS distributes like χ^2_{1-dof}



From the TS to the p-value

- 5-σ exclusion region:



$\gamma = 2, 3, 4, 5$

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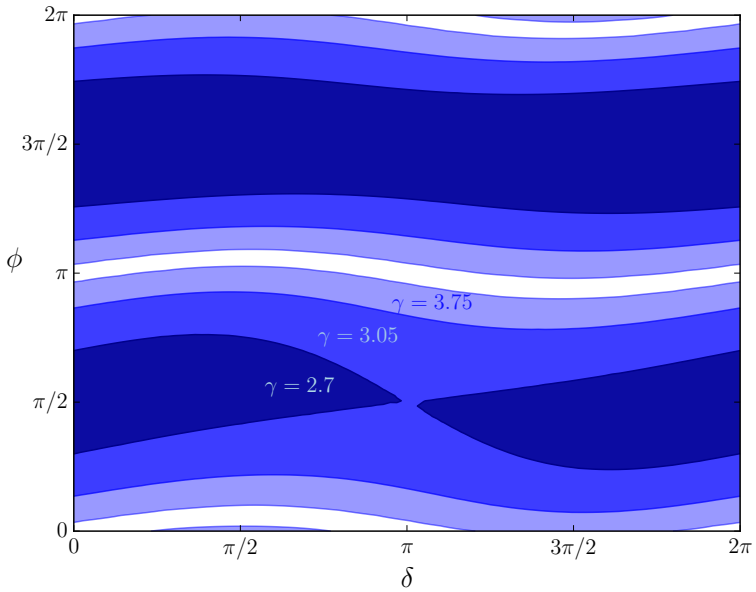

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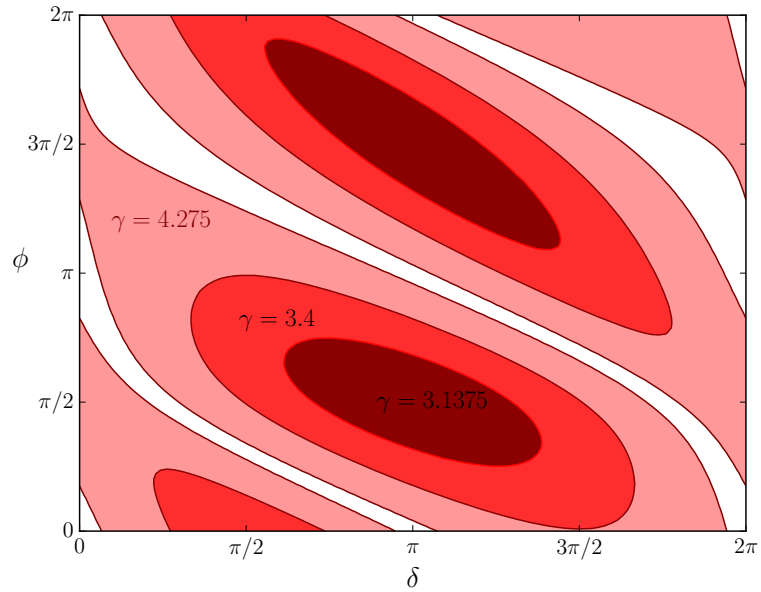
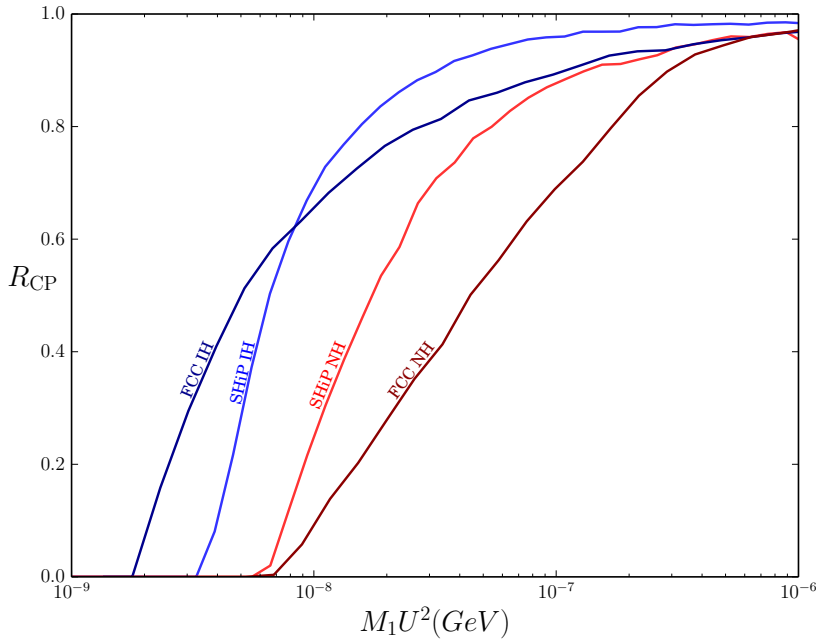


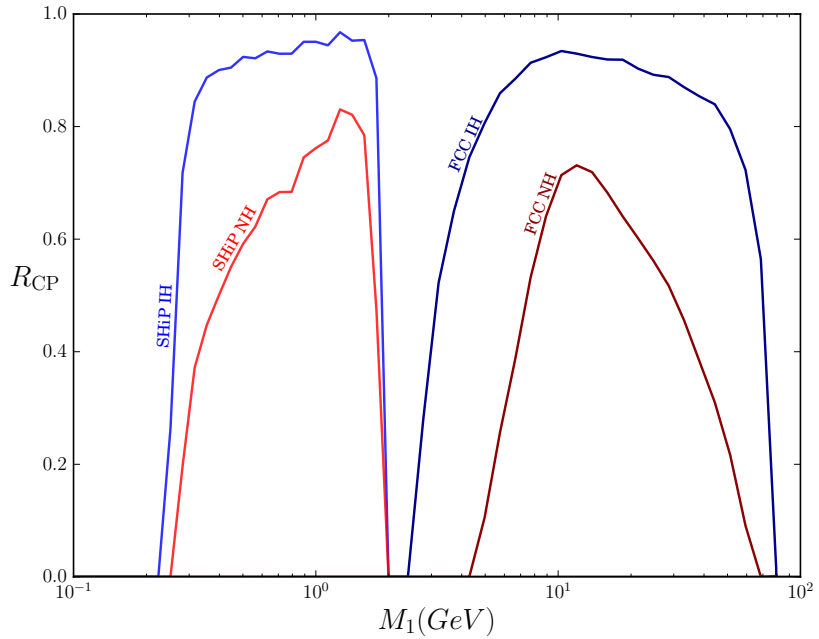
- SHiP 5-sigma exclusion regions in δ, ϕ_1 for $(\theta, M_1) = (0, 1$ GeV) and different values of γ

5σ real values space fraction

- In analogy to what is done in LBL for the Dirac phase δ, we can define R_{CP}:
  Fraction of the real parameters space $\delta, \phi_1 \in [0, 2\pi]$ *that excludes the null hypothesis at* $5\text{-}\sigma$

5σ ratio





- R_{CP} in terms of $M_1U^2 \propto \gamma$ and M_1 for SHiP and FCC-ee
- (left) $M_1^{SHiP} = 1$GeV and $M_1^{FCC-ee} = 30$GeV
- (right) $\gamma = 4$

Conclusions

- SHiP and FCC-ee may look for the sterile neutrinos in the range $10^{-1} - 10^{2}$GeV.
- We explore what can we learn about CP-violation in the Leptonic sector form a positive measure.
- The measure of the e-μ ratio is very sensible to CP-violation
- The exclusion at 5-σ of the CP-conserving values is very likely in a large part of the region to be explored.