The seesaw path to leptonic CP violation

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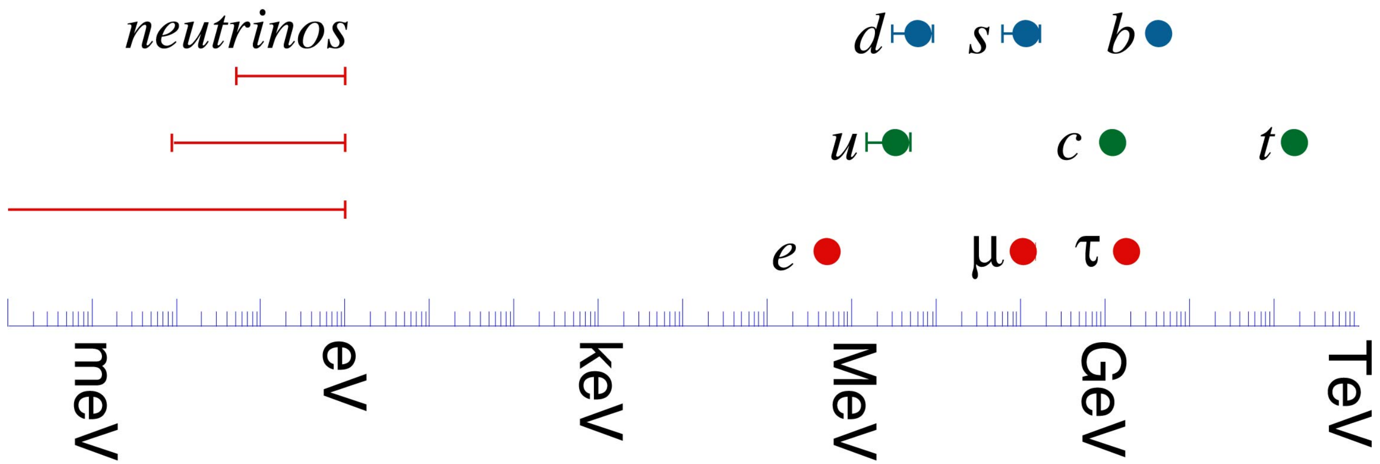
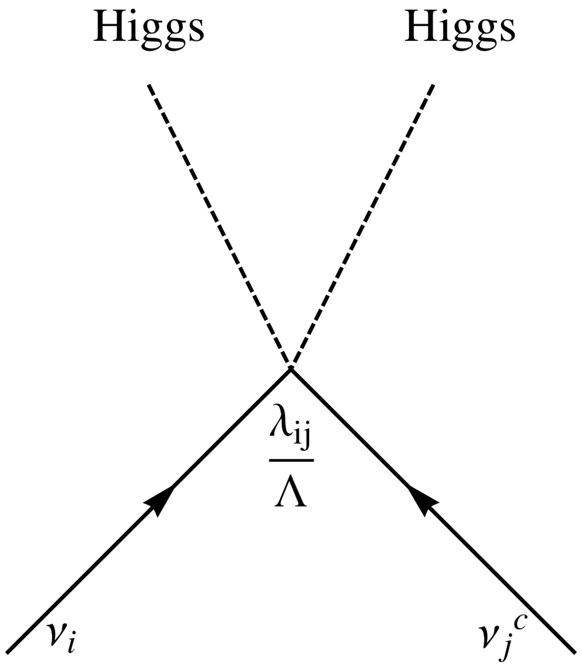
Caputo, PH, Kekic, Lopez-Pavón, Salvado arXiv:1611.05000

For the time being the only BSM signal: neutrino masses



Strongly suggests the existence of a new physics scale

Fermi-era of neutrino physics



Weinberg operator

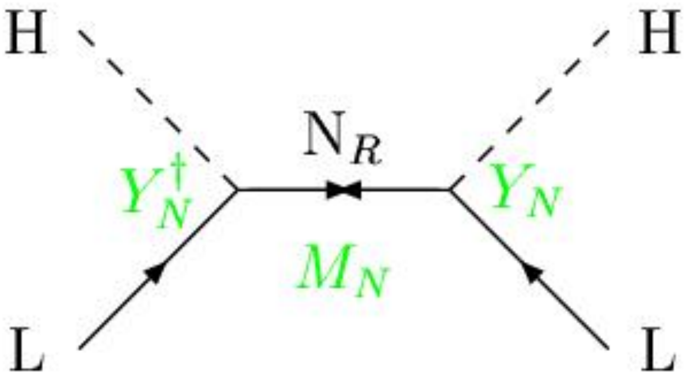
Neutrino masses = first higher dimensional operator

Why the seesaw ?

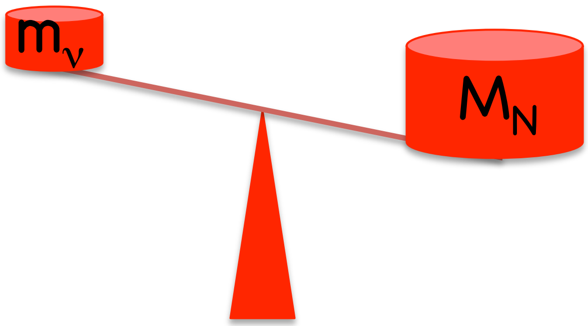
Minimality: SM+right-handed neutrinos

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

$$n_R \geq 2$$



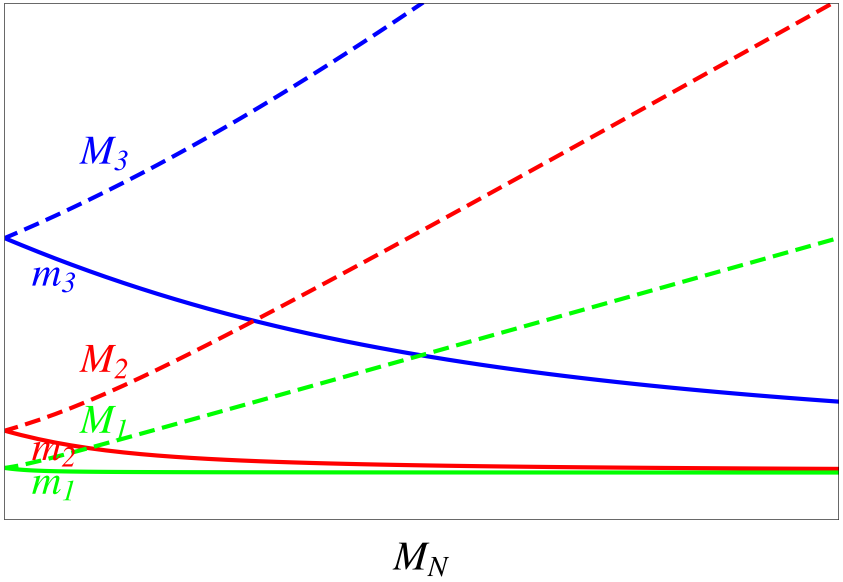
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$



Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...

Type I seesaw models

$n_R = 3$: 18 free parameters (6 masses+6 angles+6 phases) out of which we have measured 2 masses and 3 angles…

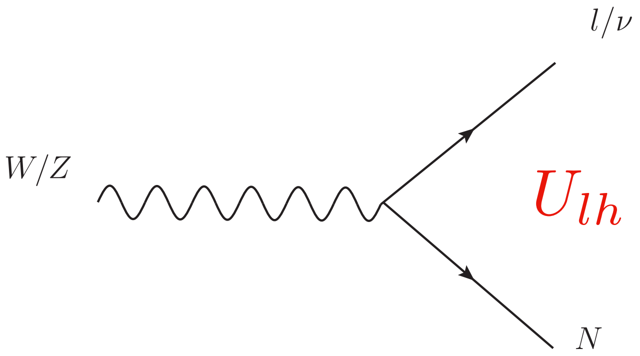


Type I seesaw models

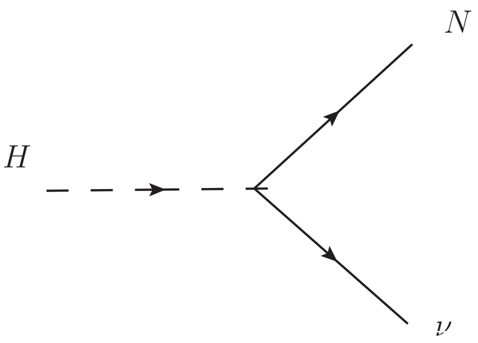
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{ll} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + U_{lh} \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

Type I seesaw models



$$U_{lh}$$



$$U_{lh}\frac{\sqrt{2}M_h}{v}$$

$$U_{lh} \simeq i U_{\mathrm{PMNS}}\sqrt{m_l}\,R\,\frac{1}{\sqrt{M_h}}$$

Casas-Ibarra

R: general orthogonal complex matrix (contains all the parameters we cannot measure in neutrino experiments)

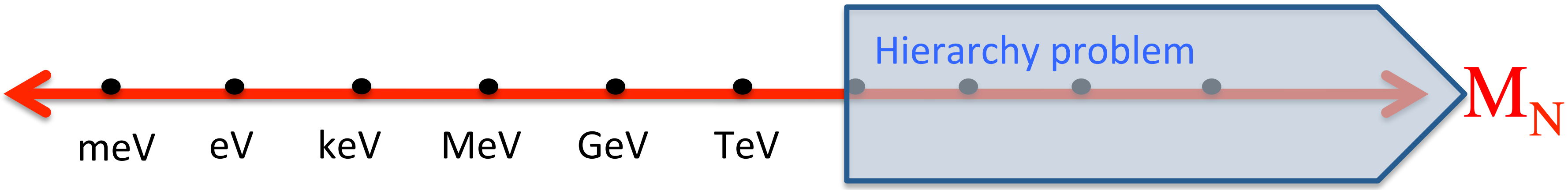
Strong correlation between active-heavy mixing and neutrino masses, but the naïve scaling ($|U_{lh}|^2 \sim m_l/M_h$) too naïve...

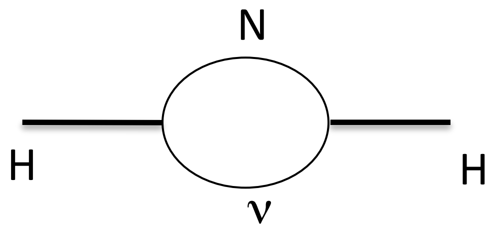
Why low-scale seesaw ?

$$M_N \leq v$$

To avoid fine-tunning

The new scale is stable under radiative corrections due to Lepton Number symmetry but the EW is not!





$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

Vissani

$M_N \gg m_H$ not natural in the absence of SUSY

Testability

eg. leptogenesis in the low-scale minimal model $n_R=2$

PH, Kekic, López-Pavón, Racker, Salvadó 1606.06719

Bayesian posterior probabilities (using nested sampling Montecarlo Multinest)

$$\mathcal{L} = -\left(\frac{Y_B(\text{param}) - Y_B^{\text{obs}}}{\sigma_{Y_B}}\right)^2$$

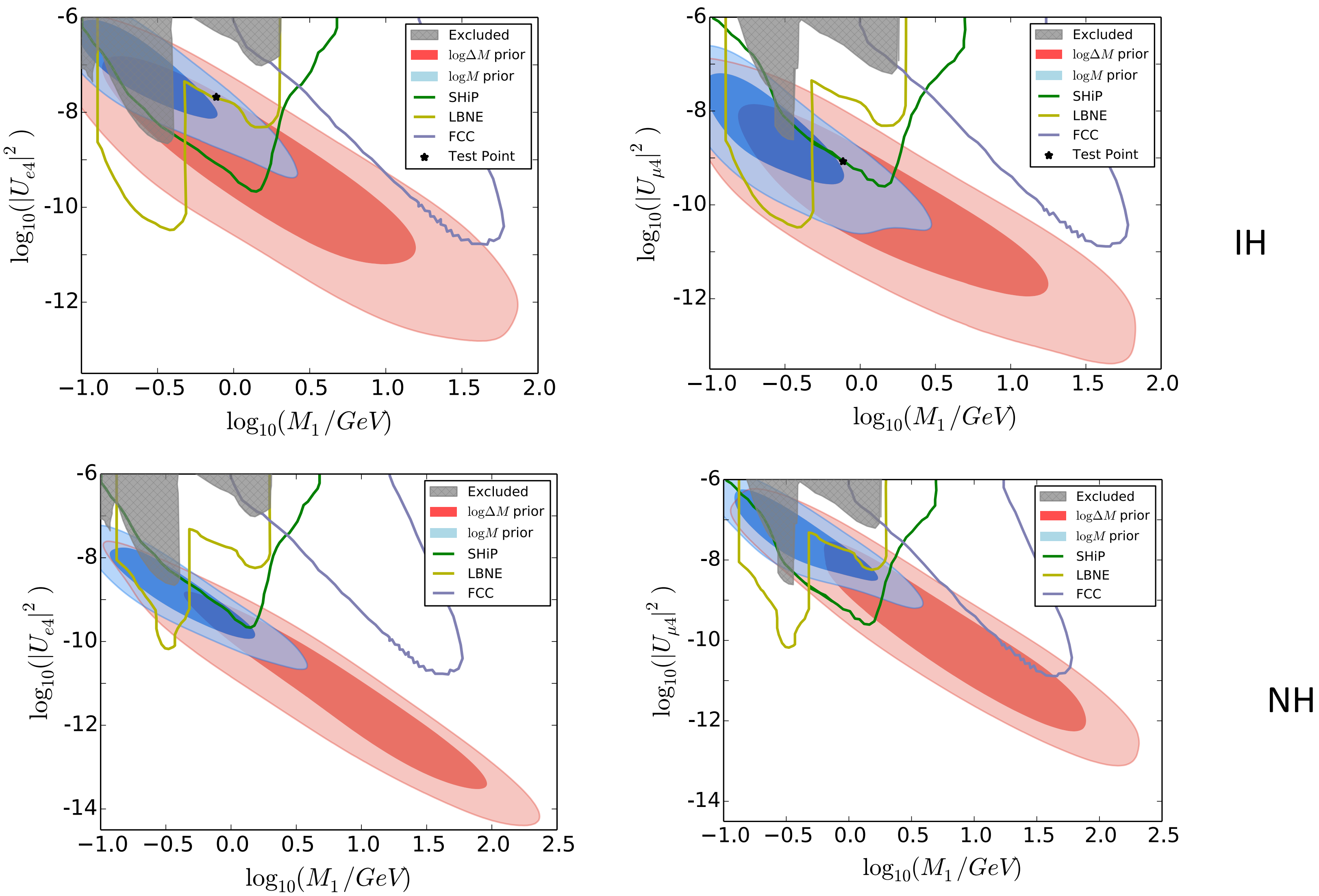
Use Casas-Ibarra parametrization: fix light neutrino masses and mixings to the best fit oscillation points (IH/NH) and vary

$$R(\theta + i\gamma);\; U_{PMNS}(\delta, \phi_1); M_1, M_2$$

Flat priors in:

$$\theta = [0,\pi]; \delta = [0, 2\pi]; \phi_1 = [0, 2\pi]; \gamma = [-9, 9];$$
$$\log_{10} M_1 \;\text{ and }\; \log_{10} M_2 / \log_{10}(M_2 - M_1)$$

Full exploration of the minimal model n_R=2



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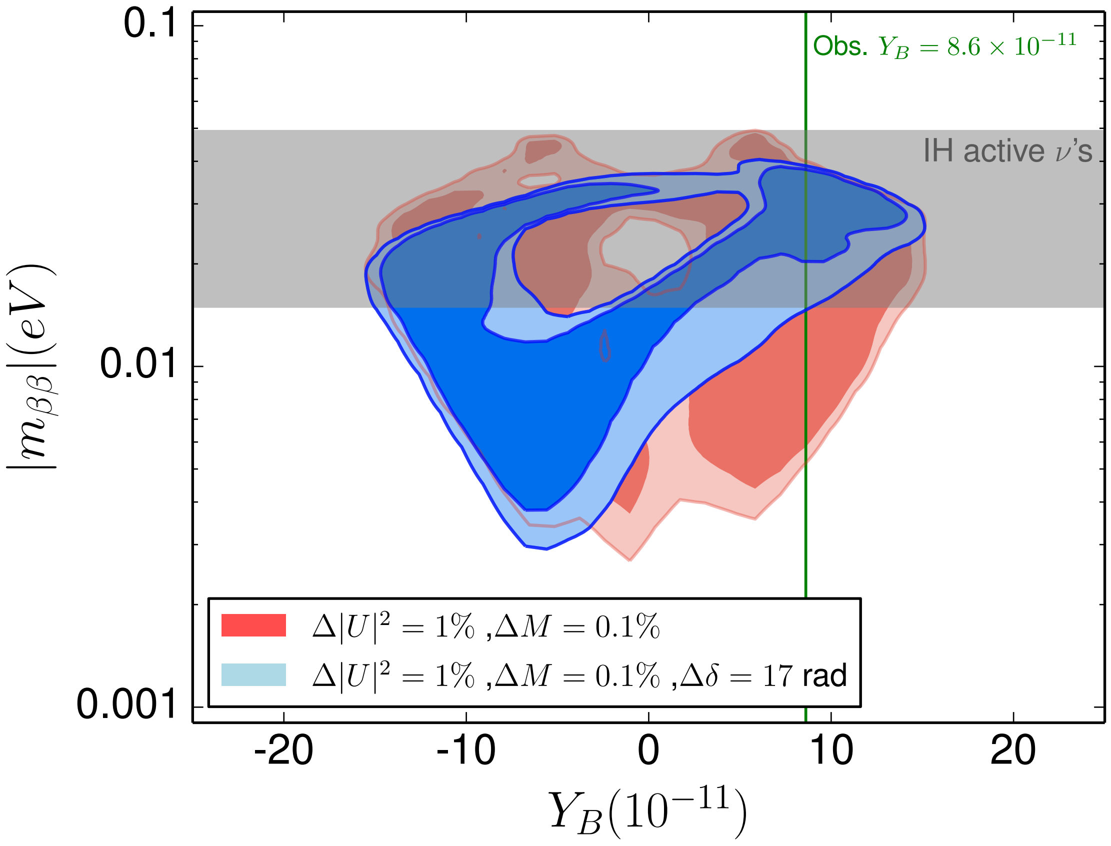
Predicting Y_B in the minimal model n_R=2 (IH)



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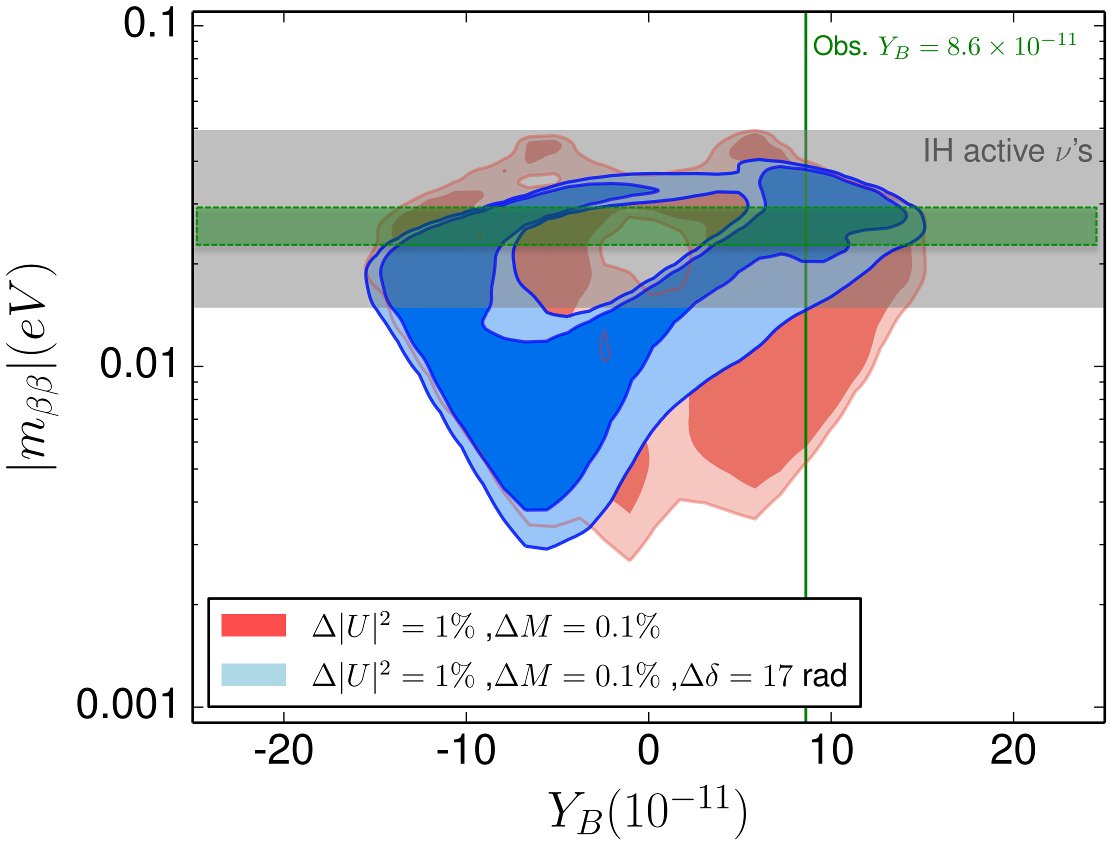
The GeV-miracle: the measurement of the mixing to e/μ of the sterile states, neutrinoless double-beta decay and δ in neutrino oscillations have a chance to give a prediction for Y_B

Predicting Y_B in the minimal model n_R=2 (IH)



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The GeV-miracle: the measurement of the mixing to e/μ of the sterile states, neutrinoless double-beta decay and δ in neutrino oscillations have a chance to give a prediction for Y_B

Leptonic CP violation

(whether Y_B or not)

In the regime of sensitivity of SHIP/FCC-ee , the flavour structure of the heavy mixings is strongly correlated with that of the U_{PMNS} matrix.

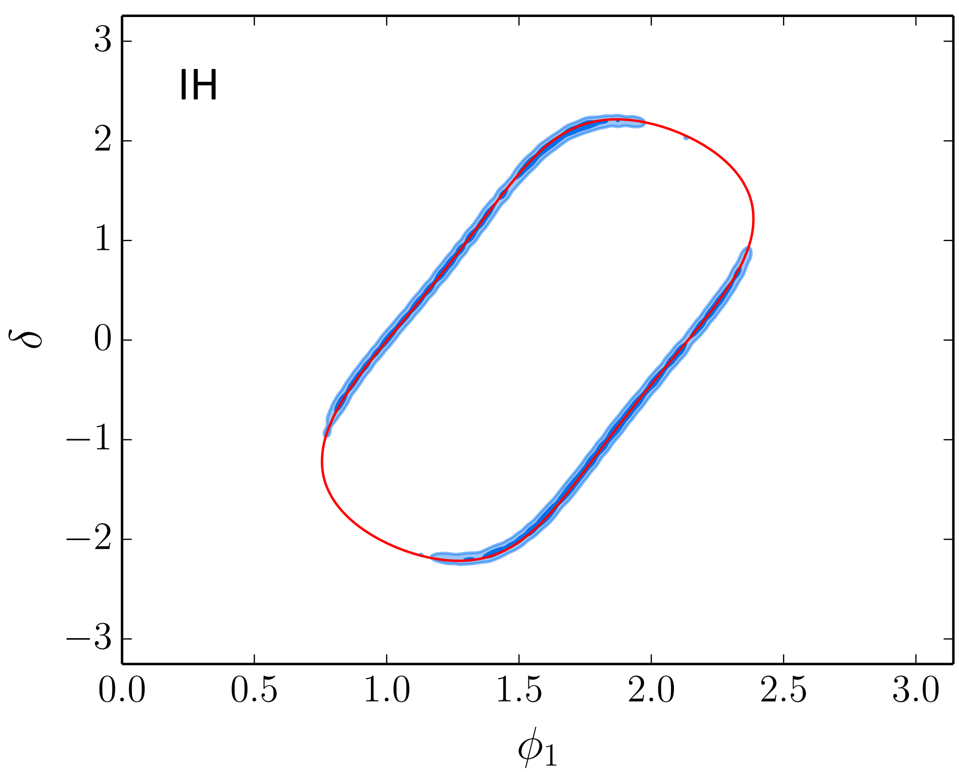
$$|U_{e4}|^2 M_1 \simeq |U_{e5}|^2 M_2 \simeq A\left[(1+\sin\phi_1 \sin 2\theta_{12})(1-\theta_{13}^2) + \frac{1}{2}x^2 s_{12}(c_{12}\sin\phi_1 + s_{12}) + \mathcal{O}(\epsilon^3)\right],$$

$$\begin{aligned}|U_{\mu 4}|^2 M_1 \simeq |U_{\mu 5}|^2 M_2 \simeq A\Bigg[&\left(1-\sin\phi_1 \sin 2\theta_{12}\left(1+\frac{1}{4}x^2\right)+\frac{1}{2}x^2 c_{12}^2\right)c_{23}^2 \\ &+\theta_{13}(\cos\phi_1 \sin\delta - \sin\phi_1 \cos 2\theta_{12}\cos\delta)\sin 2\theta_{23} \\ &+\theta_{13}^2(1+\sin\phi_1 \sin 2\theta_{12})s_{23}^2 + \mathcal{O}(\epsilon^3)\Bigg],\end{aligned}$$

$$\epsilon \sim e^{-\gamma} \sim \theta_{13} \sim x \equiv \sqrt{\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}}$$

$$A \equiv \frac{e^{2\gamma}\sqrt{\Delta m^2_{atm}}}{4},$$

For $n_R=2$ the ratio of e/μ mixings depends on the two phases of the U_{PMNS} matrix: δ, ϕ_1



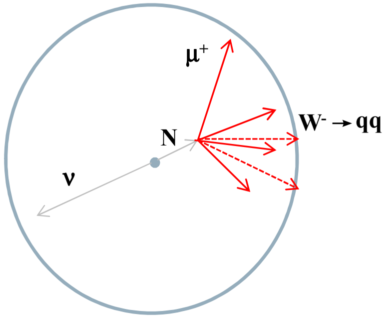
From a measurement of the ratio $\dfrac{|U_{eh}|^2}{|U_{\mu h}|^2}$

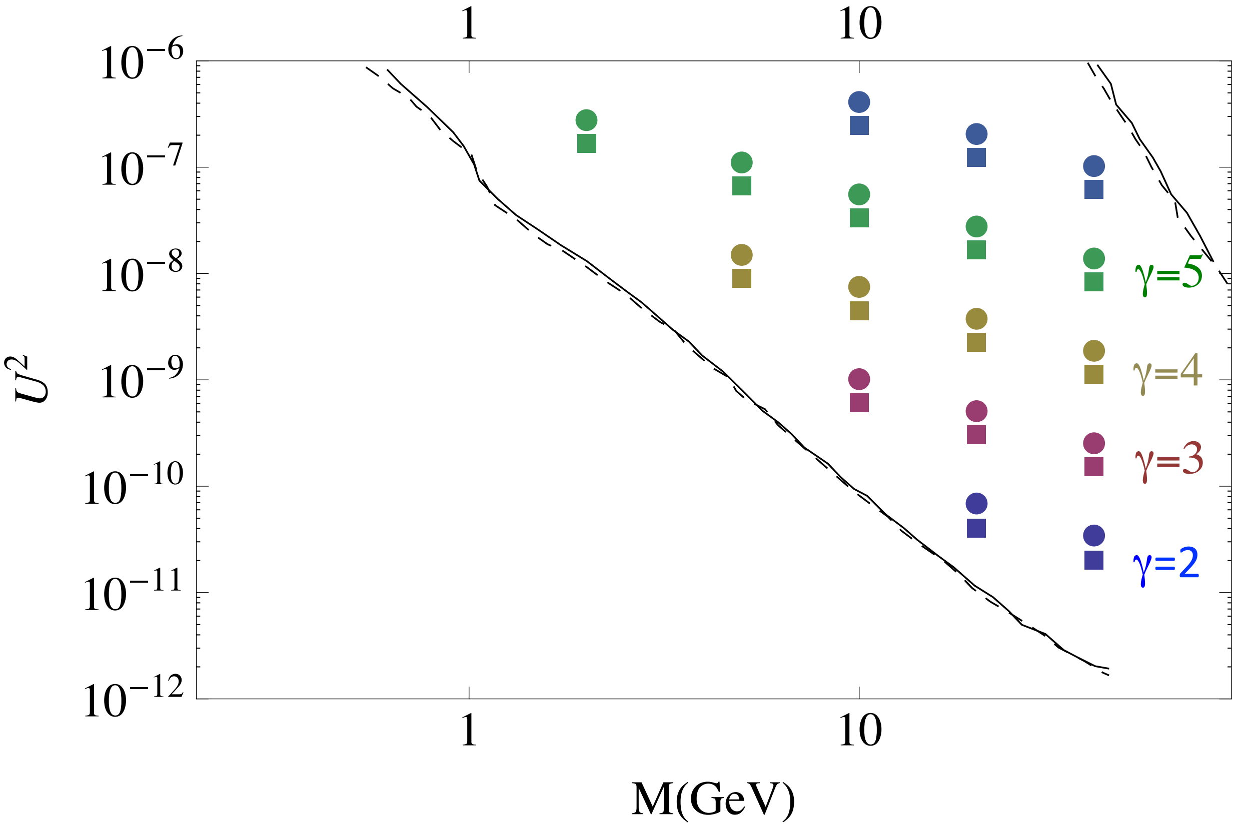
If SHIP/FCC-ee measures the heavy neutrinos and their mixings to e/μ:

Can we exclude a real U_{PMNS} matrix ie.
discover leptonic CP violation in mixing ?

$$(\delta, \phi_1) \neq (0/\pi, 0/\pi)$$

FCC-ee sensitivity region (10^{13} Z's, 0.1mm-5m DV search)





Blondel, Graverini, Serra, Shaposhnikov, FCC-ee study Team Collaboration, arXiv:1411.5230;
A. Abada et al arXiv:1412.6322; S. Antusch and O. Fischer arXiv:1502.05915

-> Talk by O. Fischer

Test statistics (shown to be distributed like χ^2 (1dof))

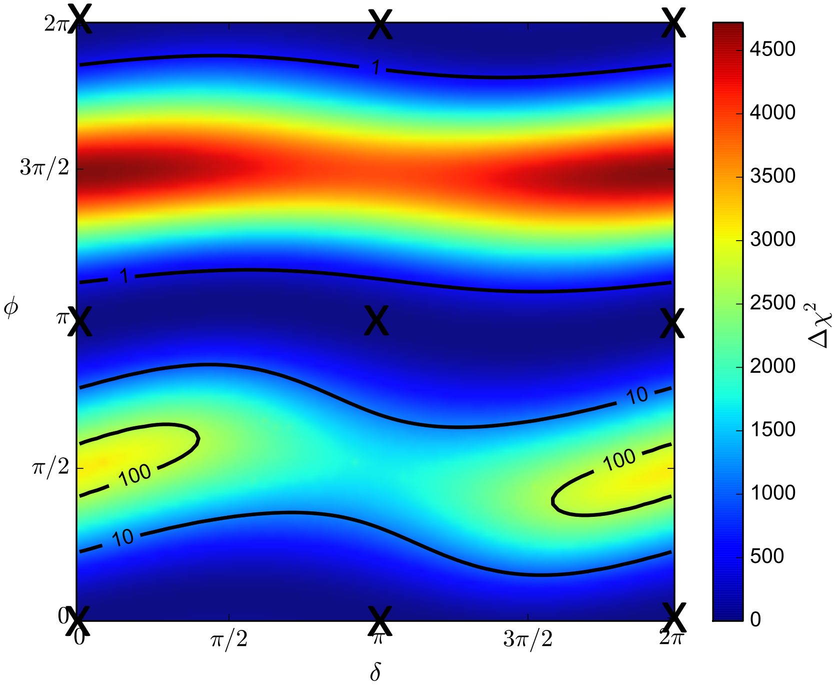
$$\Delta\chi^2 \equiv -2 \sum_{\alpha=e,\mu} N_\alpha^{\text{true}} - N_\alpha^{CP} + N_\alpha^{\text{true}} \log\left(\frac{N_\alpha^{\text{CP}}}{N_\alpha^{\text{true}}}\right)$$
$$+\left(\frac{M_1 - M_1^{\text{min}}}{\Delta M_1}\right)^2 .$$

$N^{\text{true}}_\alpha(\gamma,\theta,M_1,\delta,\phi)$ = # events for true parameters

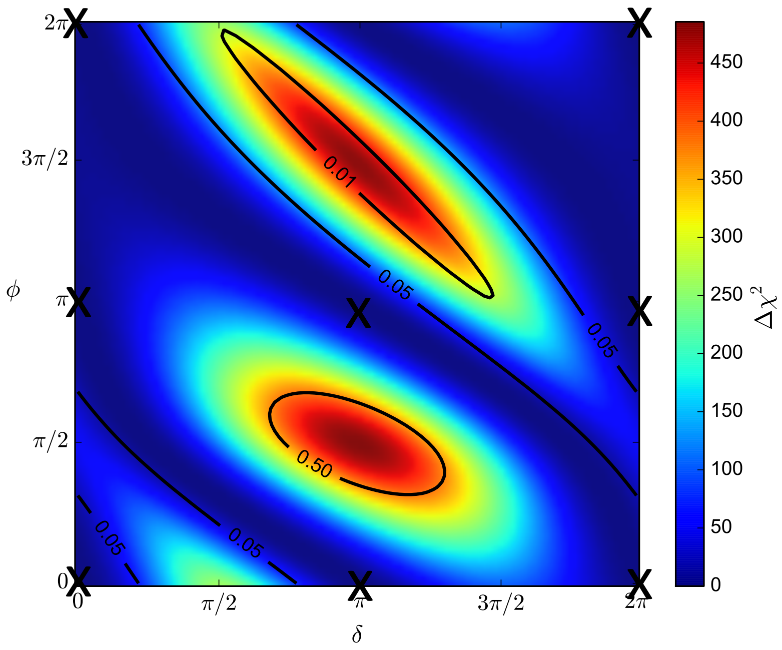
N^{CP}_α= # events for best fit CP conserving hypothesis

CP: $(\delta,\phi)=(0/\pi,0/\pi)$ any γ, θ, M_1

Assumed the neutrino ordering is known:

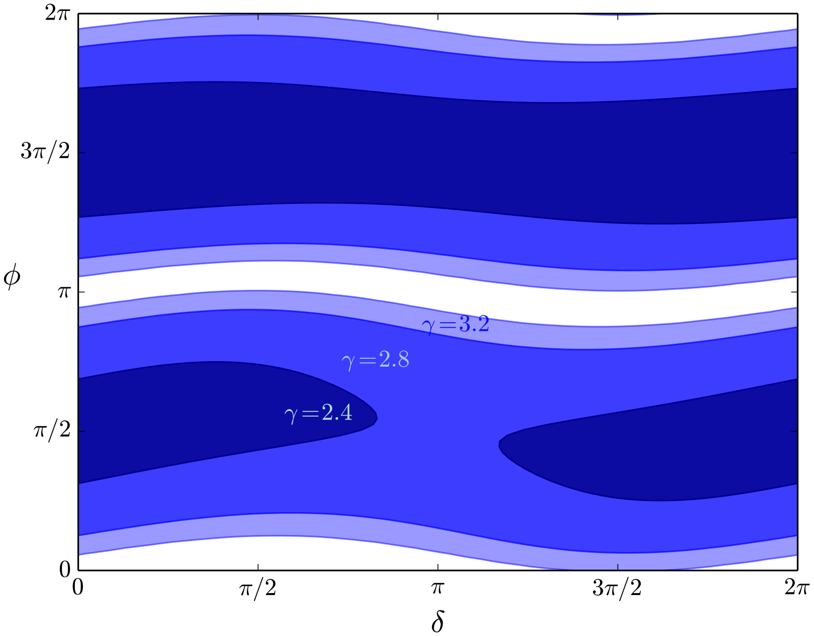


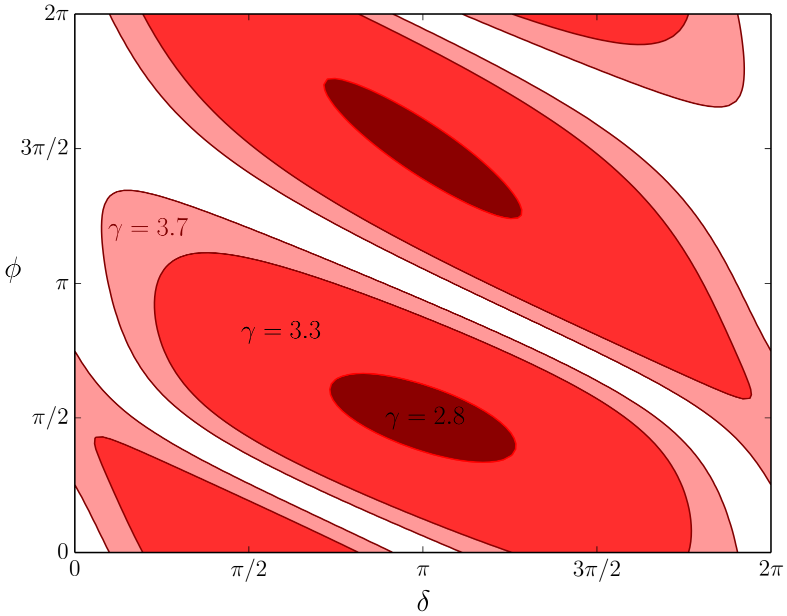
IH



NH

Leptonic CP violation 5σ CL discovery regions

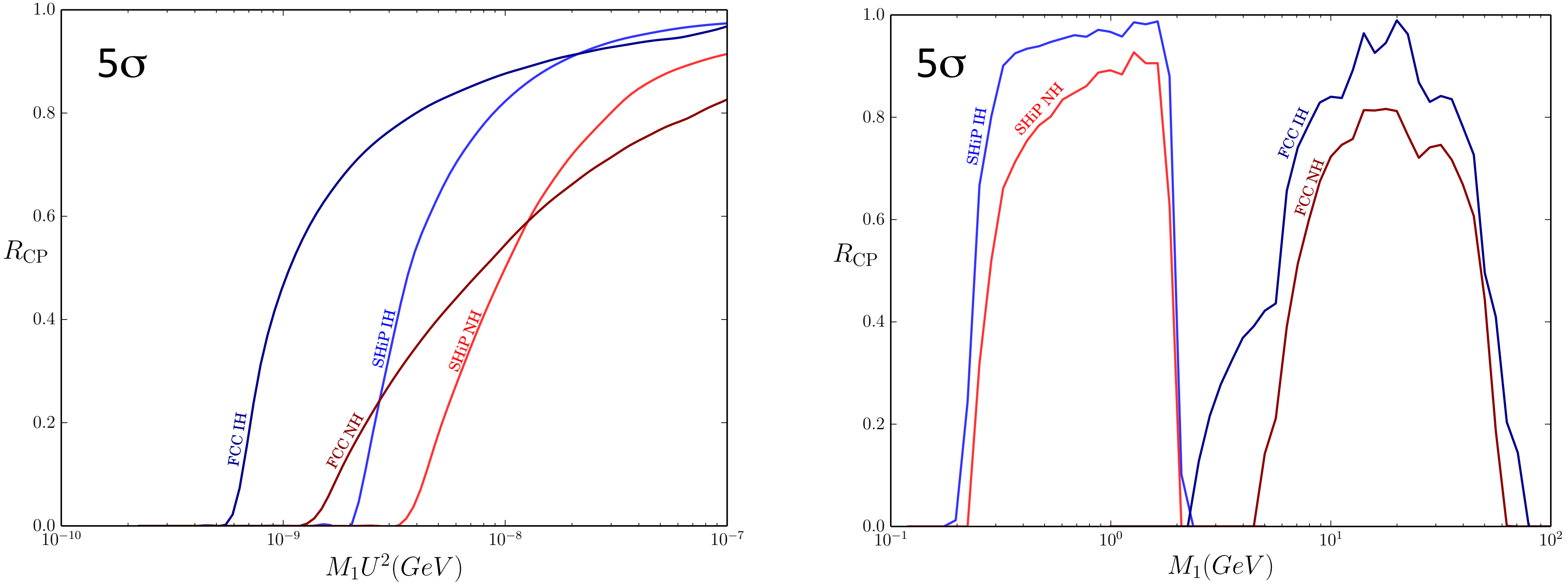




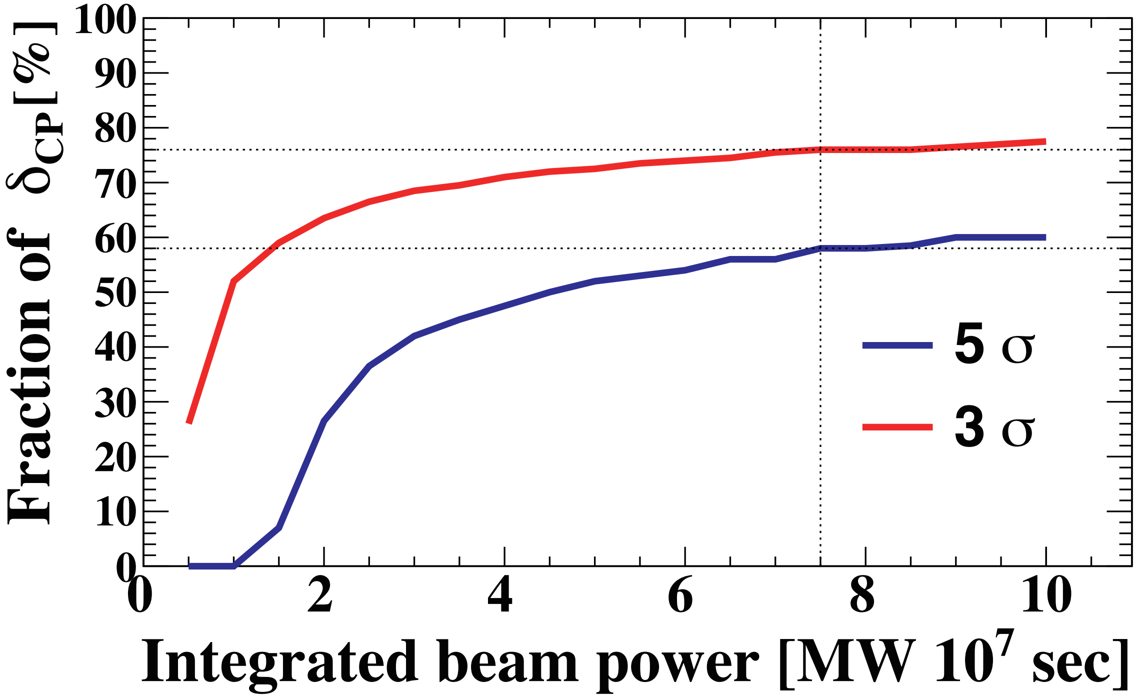
(no systematic error included)

R_{CP}=5σ CP-fraction =
fraction of the area of the CP rectangle which is colored

Discovery potential for leptonic CP violation in mixing



CP fraction of δ from future neutrino oscillation experiments:



HyperKamiokande LOI

BACKUPS

Testability: Leptogenesis

$$\Gamma_s(T) \sim y^2 T \sim \frac{M_N m_\nu}{v^2} T \qquad H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_P}$$

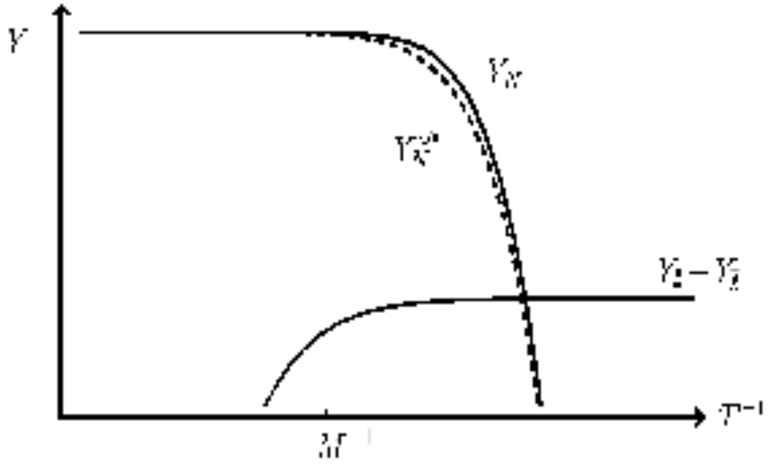
$$\frac{\Gamma_s(T_{EW})}{H(T_{EW})} \sim 5 \left(\frac{M}{1\mathrm{GeV}} \right) \left(\frac{m_\nu}{0.05\mathrm{eV}} \right)$$

CP asymmetries arise in production of sterile states that can seed the baryon asymmetry

Akhmedov, Rubakov,Smirnov

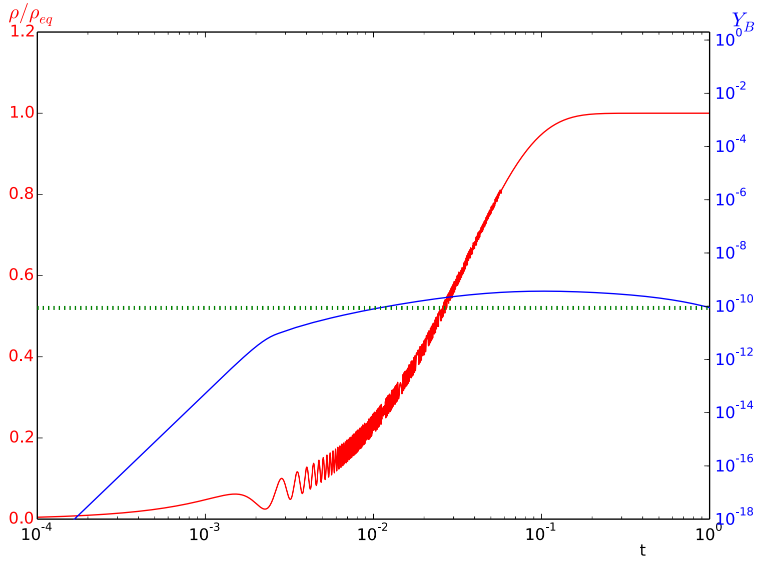
High-scale leptogenesis

$$M_N \gg v$$



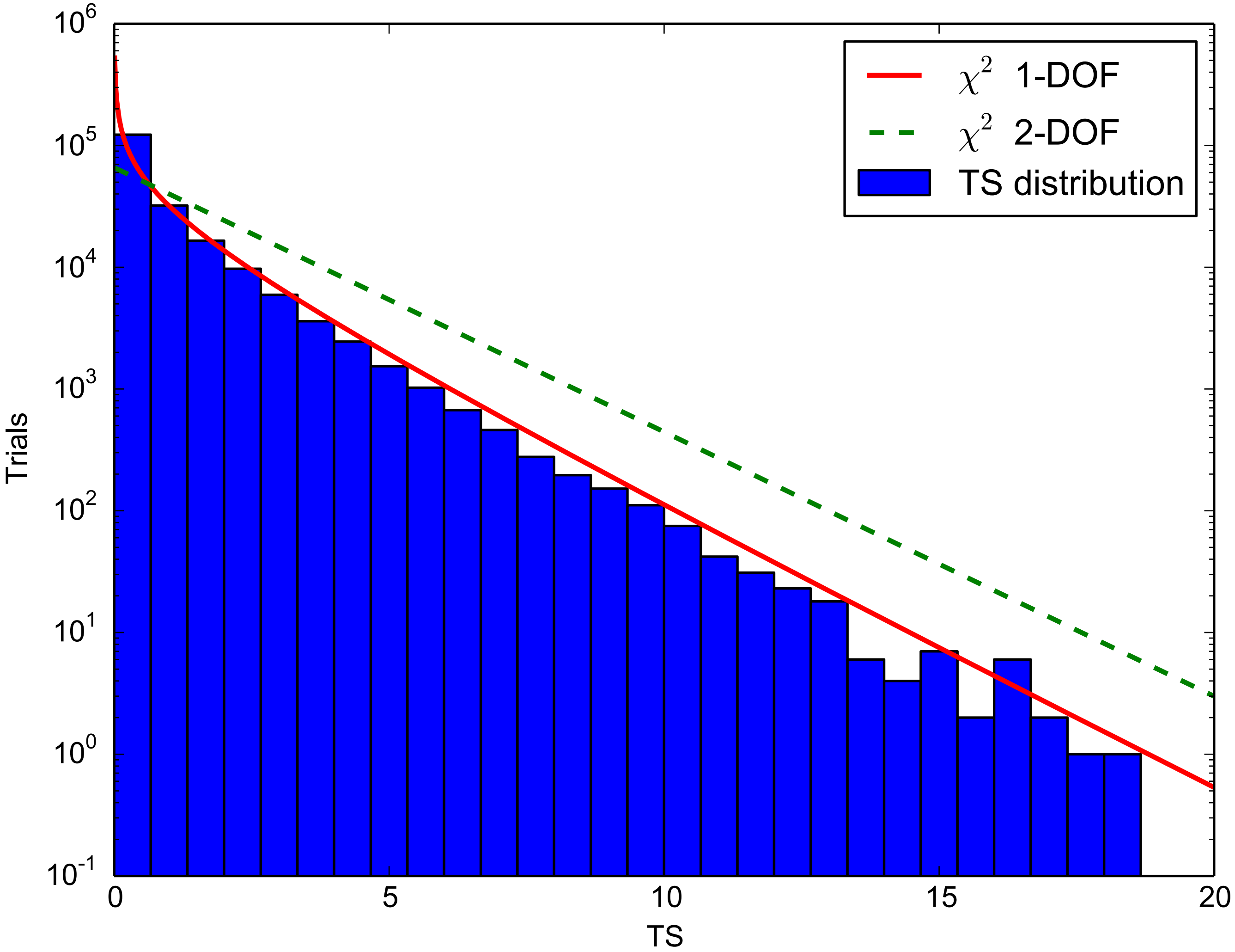
Low-scale leptogenesis

$$M_N \sim v$$



T_{EW}

Courtesy of M. Kekic


χ^2 1-DOF
χ^2 2-DOF
TS distribution
Trials
TS
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
5
10
15
20

Adding information from tau mixings