LEPTOGENESIS & CP

P. HERNÁNDEZ (IFIC,U. VALENCIA & CSIC)

SM+3 massive neutrinos

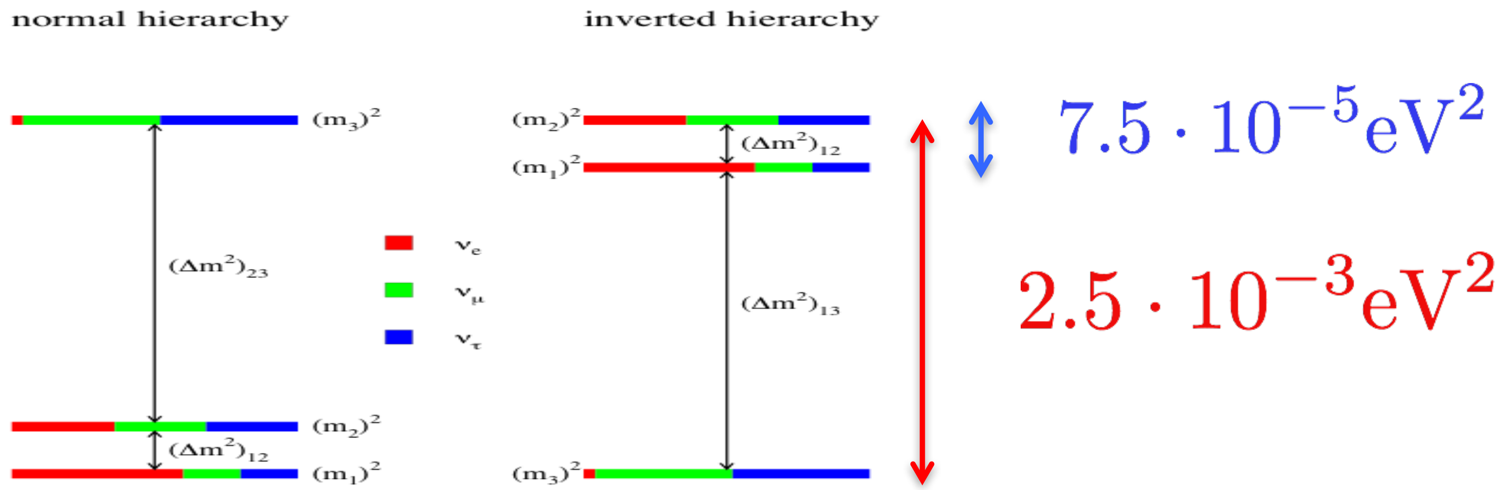
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \sim 34°$

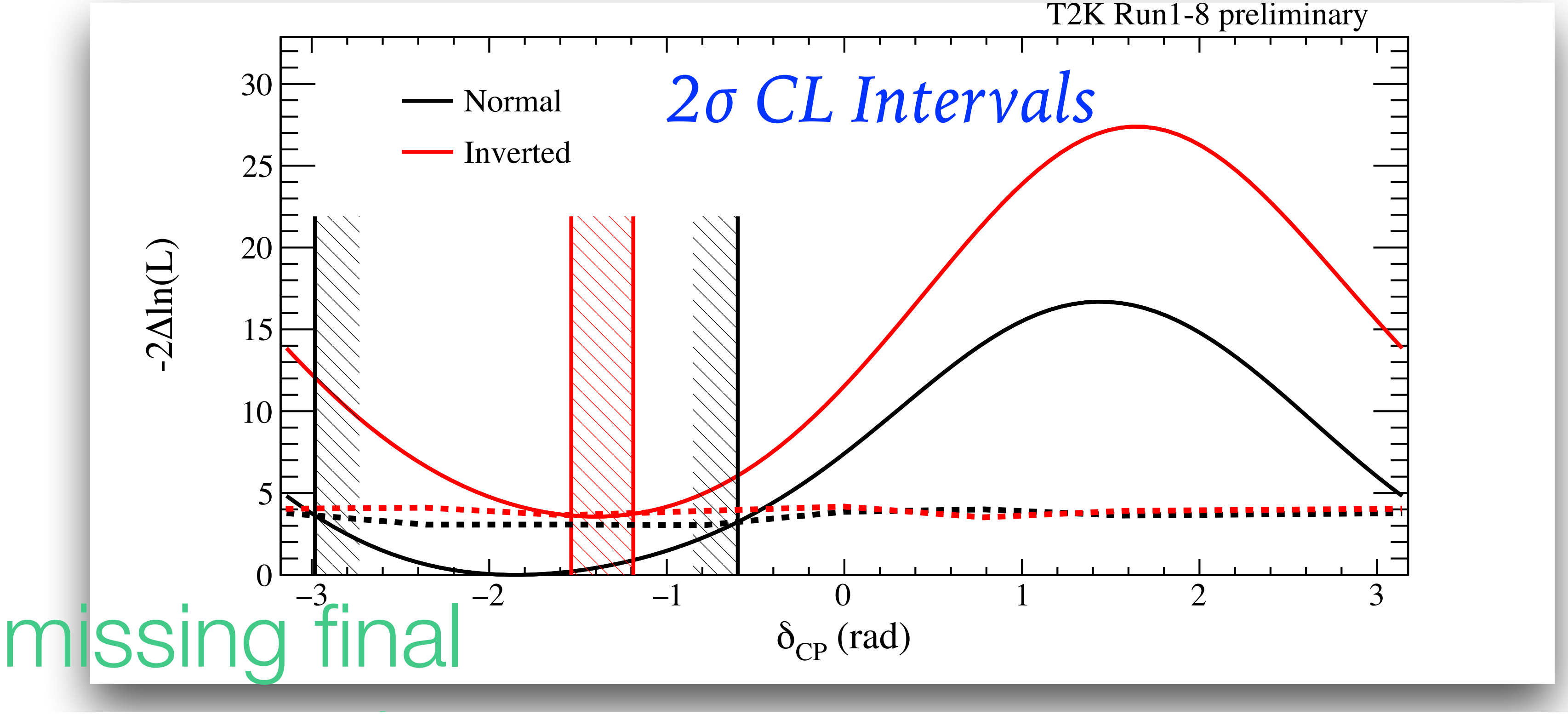
$\theta_{23} \sim 42°$ o $48°$

$\theta_{13} \sim 8.5°$

$\delta \sim\ ?$



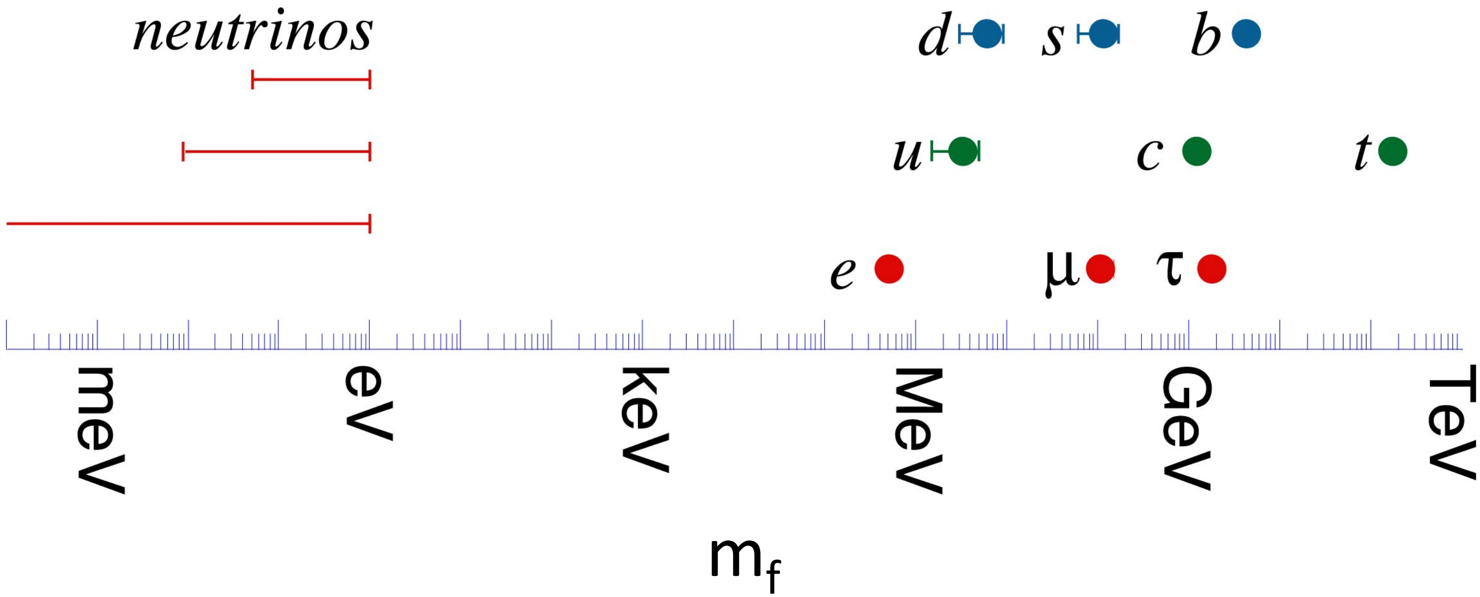
New results from T2K



δ=0, π excluded at 2σ

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



Why so different mixing ?

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PDG

PMNS

$$|U|^{\rm LID}_{3\sigma} = \begin{pmatrix} 0.798 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\ 0.232 \to 0.520 & 0.445 \to 0.697 & 0.617 \to 0.789 \\ 0.249 \to 0.529 & 0.462 \to 0.708 & 0.597 \to 0.773 \end{pmatrix}$$

NuFIT 2016

Why so different mixing ?

CKM

$$V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PMNS

$$|V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Harrison, Perkings, Scott

A new physics scale ?

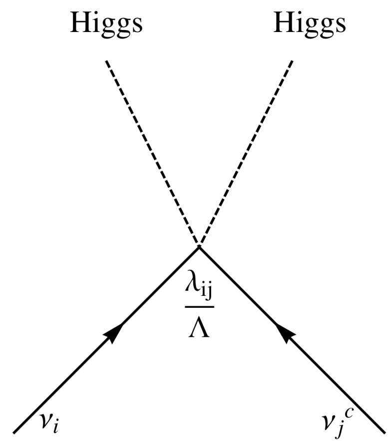
Neutrinos are different…they can have majorana masses:

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi}\;\alpha\;\tilde{\Phi}L^c + h.c.$$

Weinberg

$$[\alpha] = -1$$

$$\alpha = \frac{\lambda}{\Lambda}$$

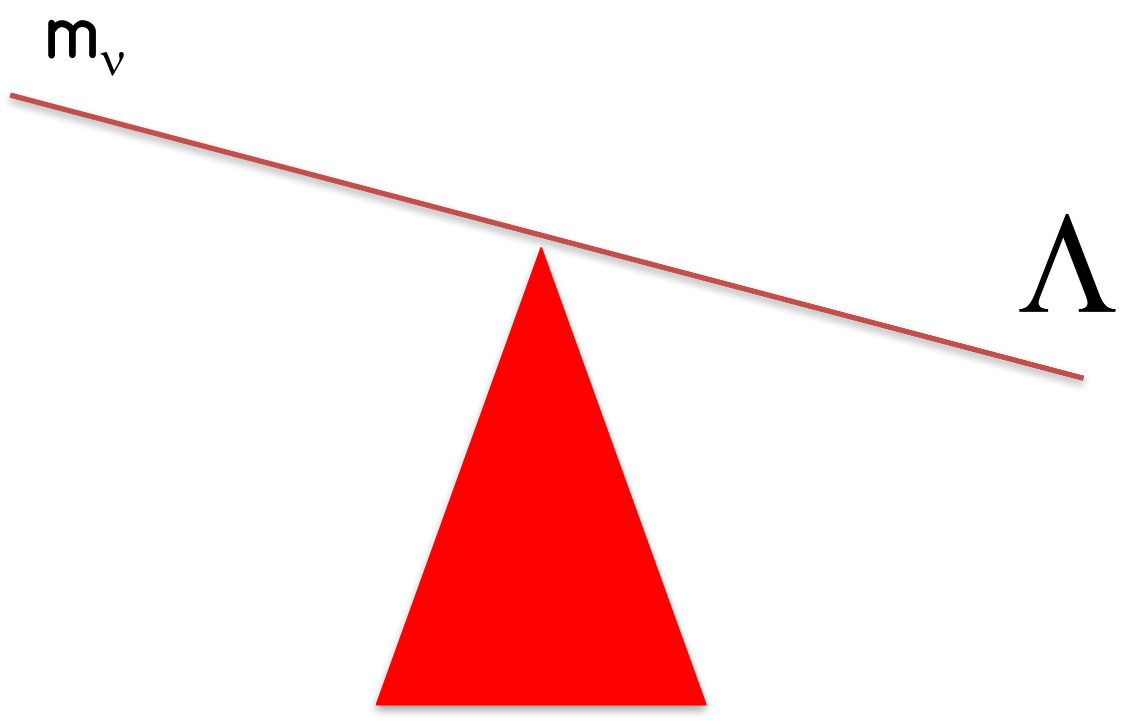


$$m_\nu = \lambda \frac{v^2}{\Lambda}$$

Scale at which new particles will show up
(mass of the neutrino mass mediators)

Seesaw mechanism:

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



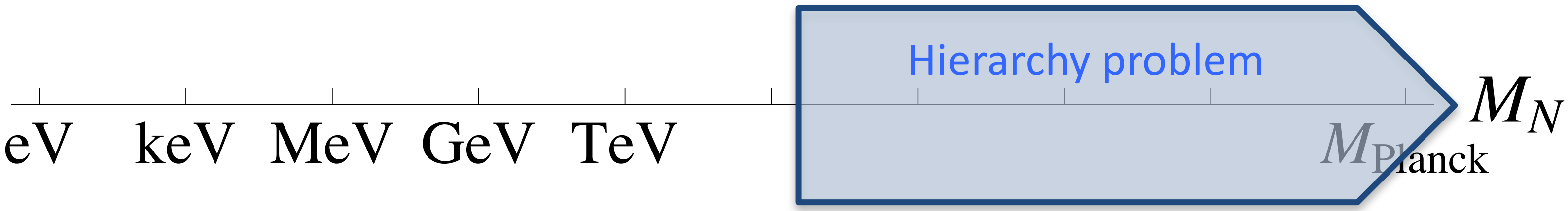
What originates the neutrino mass ?

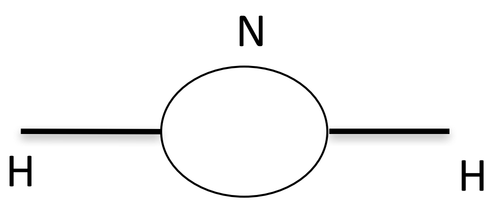
Could be $\Lambda >> v$... the standard lore (theoretical prejudice ?)

$$\left.\begin{array}{l} \Lambda = M_{\rm GUT} \\ \lambda \sim \mathcal{O}(1) \end{array}\right\} \quad m_\nu \ \surd$$

Hierarchy problem ?

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



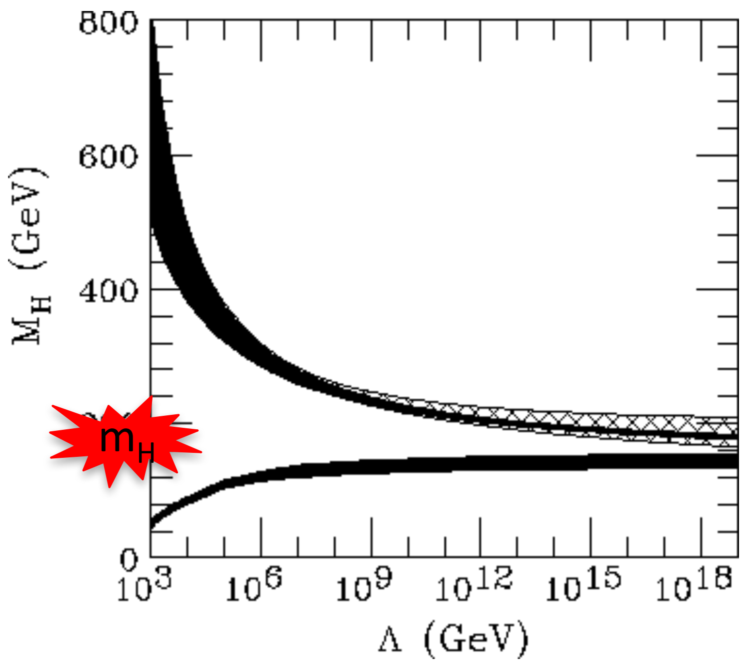


$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

Vissani

$M_N \gg m_H$ not natural in the absence of SUSY/other solution to the hierarchy problem

The Standard Model is healthy as far as we can see…



Could be naturally $\Lambda \sim v$?

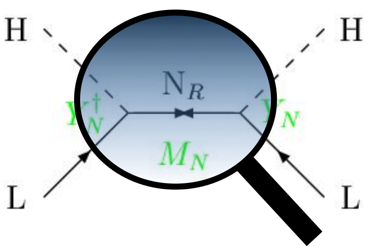
Yes !

λ in front of neutrino mass operator must be small…

Resolving the neutrino mass operator at tree level

E. Ma

Type I see-saw:
a heavy singlet scalar

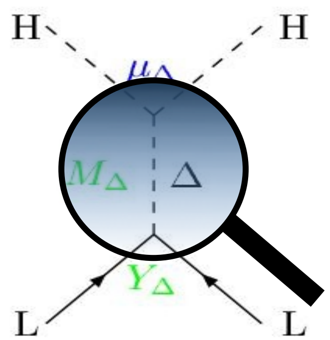


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

$\lambda \sim O(Y^2)$

Type II see-saw:
a heavy triplet scalar

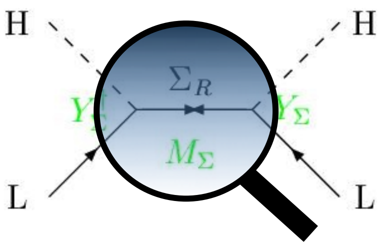


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Konetschny, Kummer;
Cheng, Li;
Lazarides, Shafi, Wetterich ...

$\lambda \sim O(Y\,\mu/M_\Delta)$

Type III see-saw:
a heavy triplet fermion

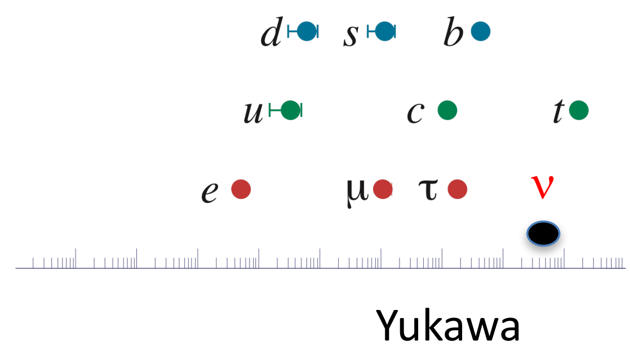


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

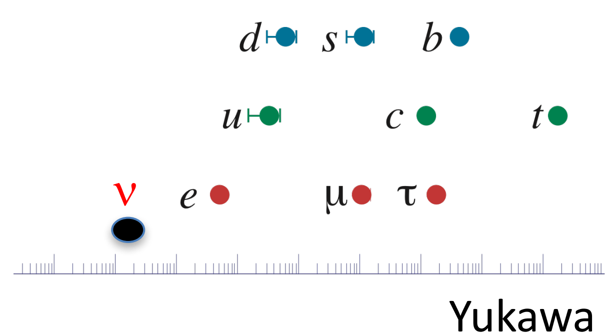
Foot et al; Ma;
Bajc, Senjanovic...

$\lambda \sim O(Y^2)$

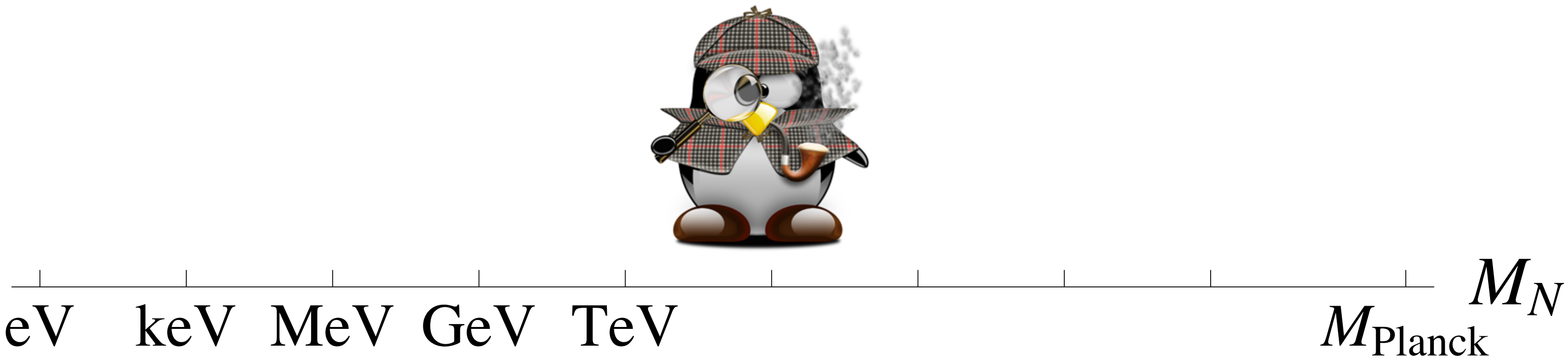
$M_N \sim$ GUT



$M_N \sim \nu$



Where is the new scale ?



"Once you eliminate the impossible, whatever remains, no matter how improbable/unnatural, must be the truth."

Where is the new scale ?

Generic predictions

- ➢ there is neutrinoless double beta decay at some level ($\Lambda > 100$MeV)

  model independent contribution from the neutrino mass

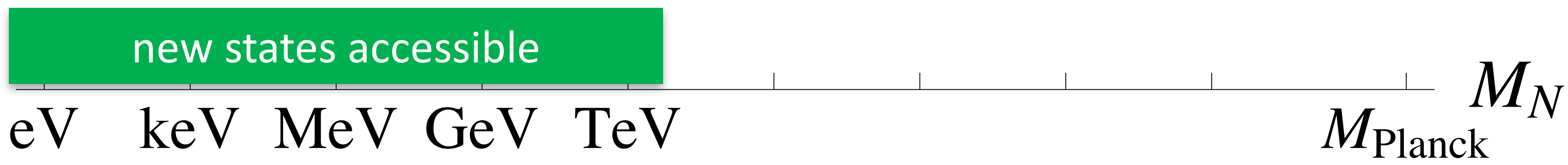
Where is the new scale ?

Generic predictions:

➢ a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis

model dependent...

Where is the new scale ?



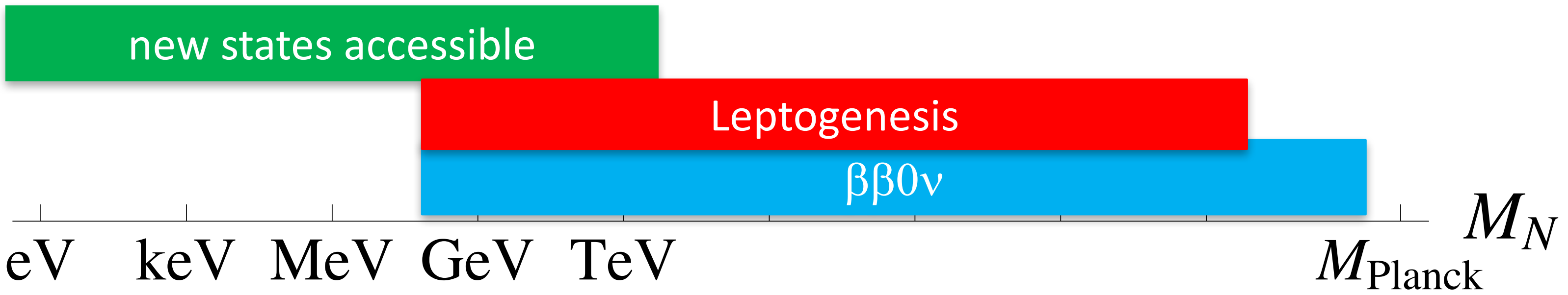
Generic predictions:

➢ there are other states out there at scale Λ: new physics beyond neutrino masses

potential impact in cosmology, EW precision tests, LHC, rare searches, ββ0ν, ...

model dependent...

Where is the new scale ?

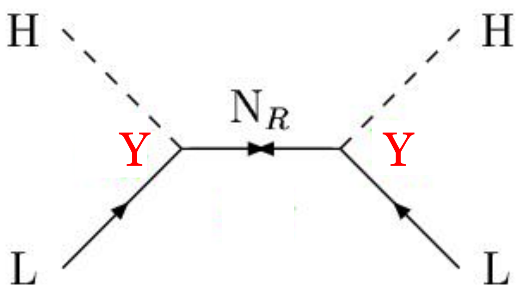


The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be tested !

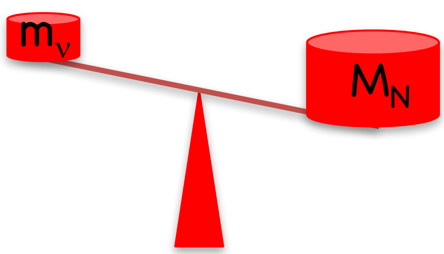
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

$$\mathcal{L}_\nu = -\bar{l} Y \tilde{\Phi} N_R - \frac{1}{2} \bar{N}_R M N_R + h.c.$$



$$n_R \geq 2$$

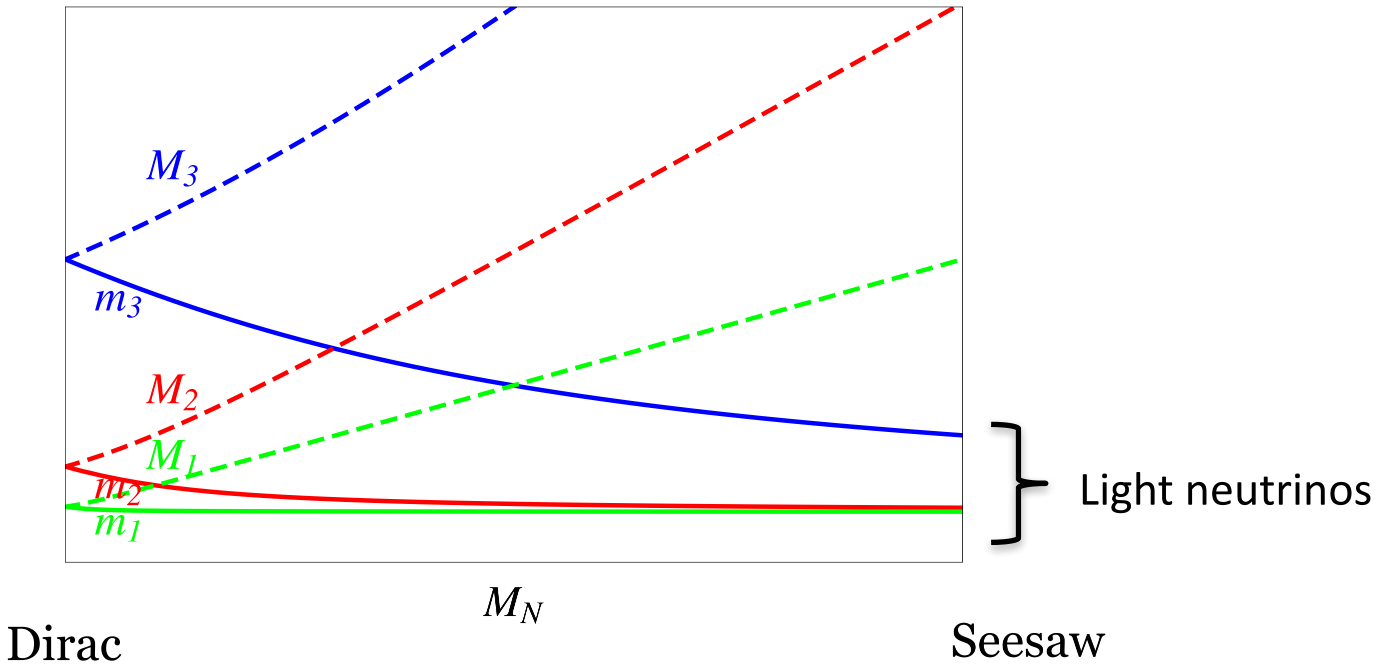


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

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…

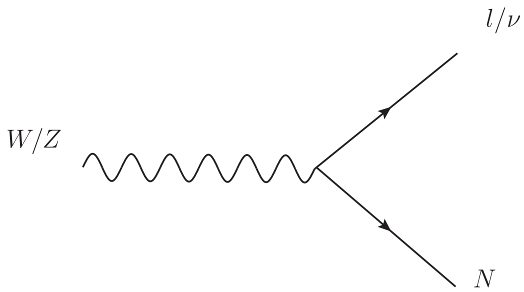


Type I seesaw models

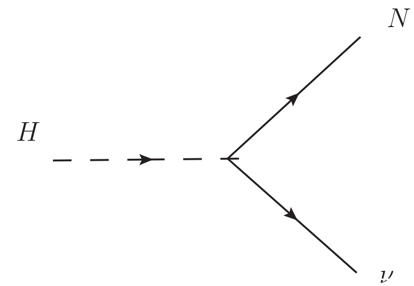
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

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

Type I seesaw models



U_{lh}



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

$$U_{lh} \simeq \underbrace{iU_{\rm PMNS}\sqrt{m_l}}_{\text{light param}}\underbrace{R\frac{1}{\sqrt{M_h}}}_{\text{heavy param}}$$

Casas-Ibarra

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

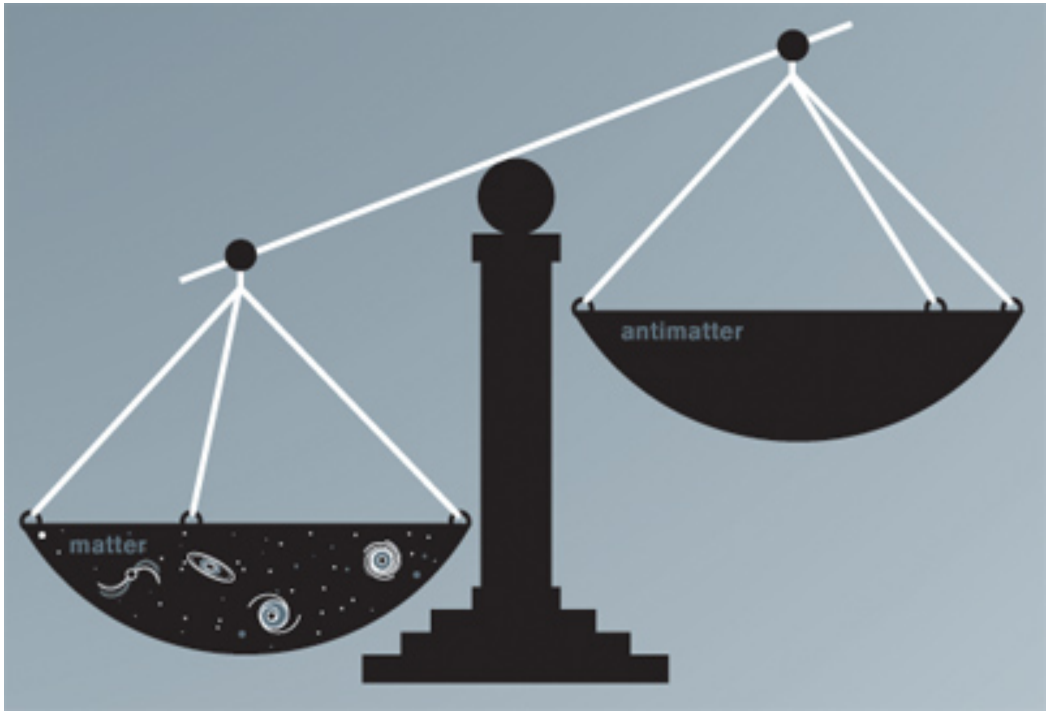
Strong correlation between active-heavy mixing and neutrino masses:

$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

(but naive scaling too naive for n_R >1...)

Baryon asymmetry

The Universe seems to be made of matter



$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$$

Baryon asymmetry

Can it arise from a symmetric initial condition with same matter & antimatter ?

Sakharov's necessary conditions for baryogenesis

- ✓ Baryon number violation (B+L violated in the Standard Model)
- ✓ C and CP violation (both violated in the SM)
- ✓ Deviation from thermal equilibrium (at least once: electroweak phase transition)

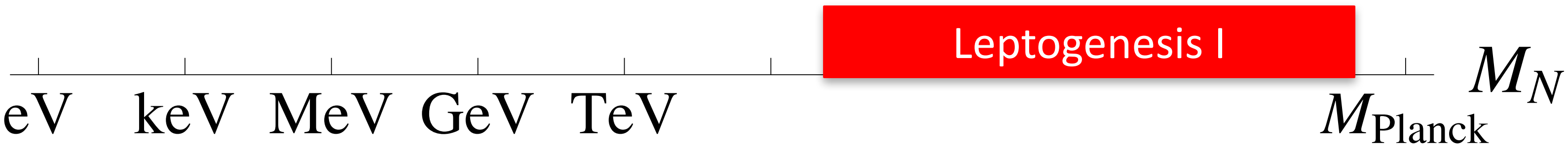
It does not seem to work in the SM with massless neutrinos …

CP violation too small ✘
EW phase transition too weak ✘

Massive neutrinos provide new sources of CP violation and non-equilibrium conditions

Leptogenesis

Models with massive neutrinos generically lead to generation of lepton and therefore baryon asymmetries



Standard leptogenesis in out-of-equilibrium decay $M_N > 10^7$GeV

Fukuyita, Yanagida

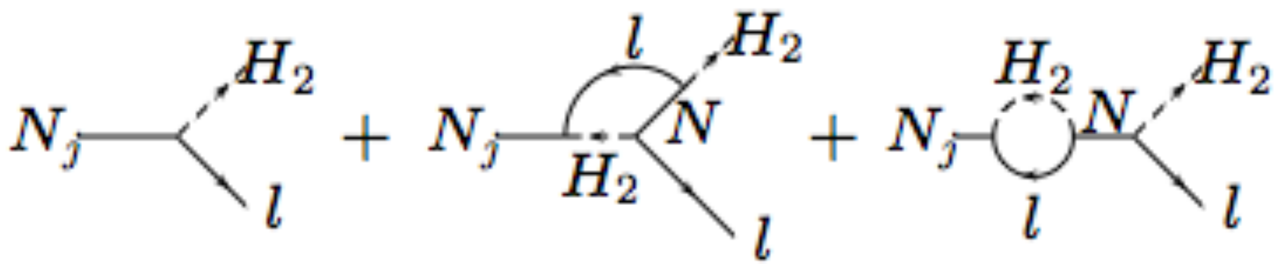
Can be extended to lower scales at the expense of a extreme degeneracy of the heavy states: resonant leptogenesis

Pilaftsis,...

High–scale leptogenesis

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana ν

Fukuyita, Yanagida

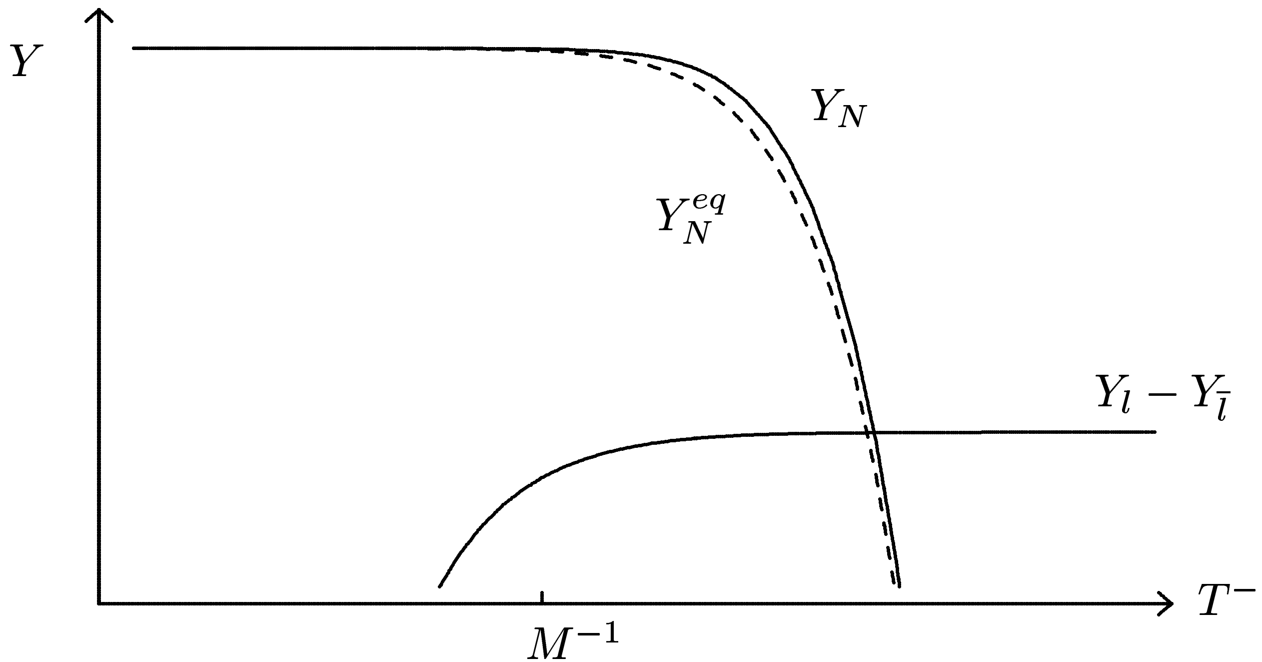


$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

$$Y_B = 4 \times 10^{-3} \overbrace{\epsilon_1}^{\mathrm{CP-asym}} \overbrace{\kappa}^{\mathrm{eff.\ factor}}$$

Generic and robust feature of see-saw models for large enough scales $M_N > 10^7$-10^9 GeV (unless an extreme degeneracy exits)

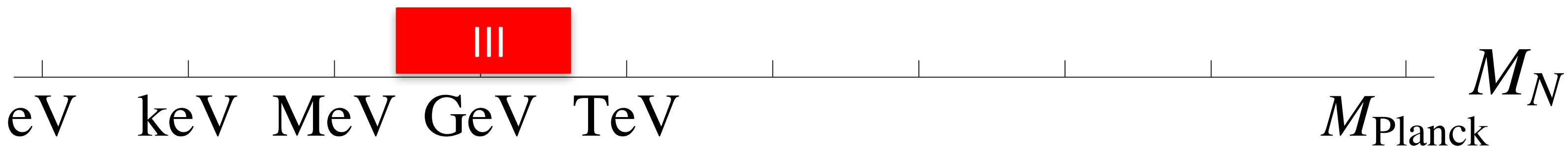
High-scale leptogenesis



$$\Gamma_N \leq H(M_N)$$

(decay rate < hubble expansion)

Leptogenesis

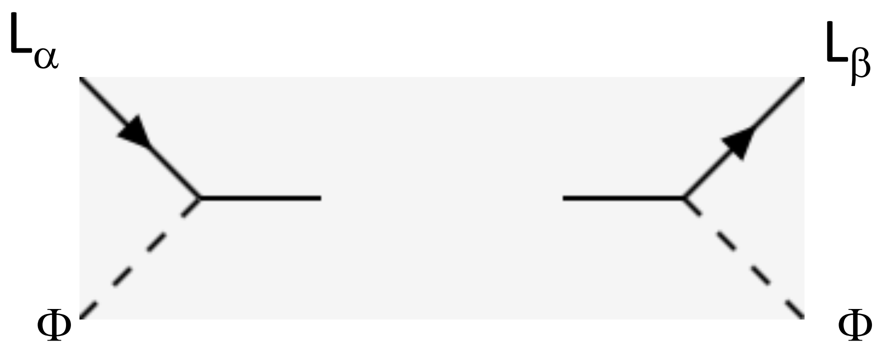


Leptogenesis from neutrino oscillations
0.1GeV <M < 100GeV

Akhmedov, Rubakov, Smirnov;
Asaka, Shaposhnikov,...

Low-scale Leptogenesis

CP asymmetries arise in production of sterile states oscillations

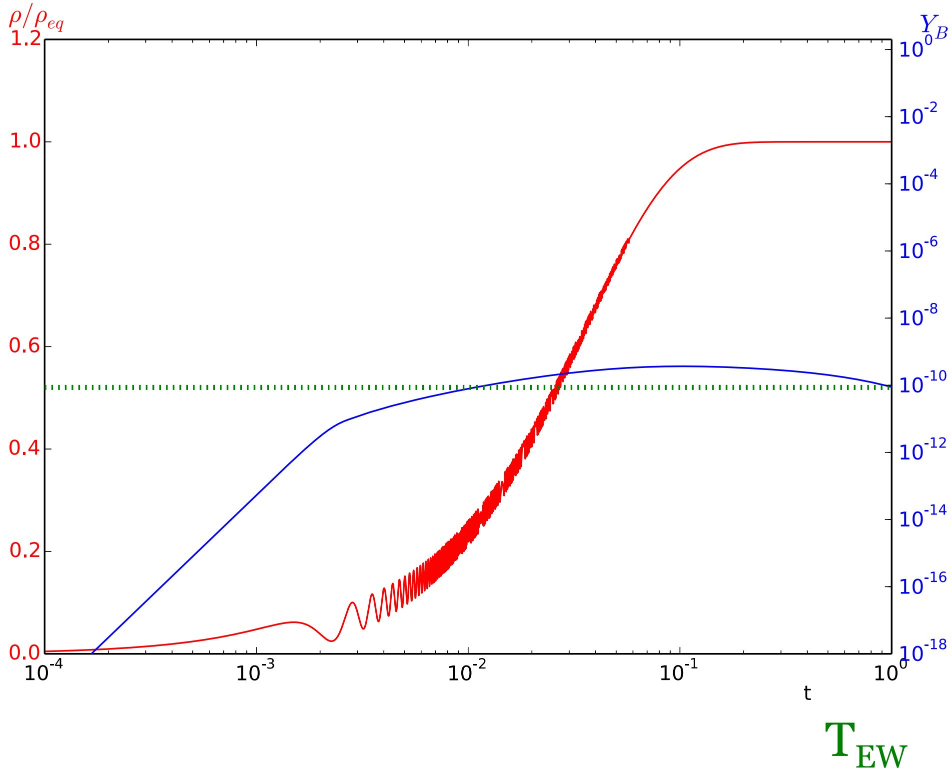


$$L_\alpha \to L_\beta \neq \bar{L}_\alpha \to \bar{L}_\beta$$

$$\sum_\alpha \Delta^\alpha_{CP} = 0 \qquad\qquad Y_B \propto \sum_\alpha \Delta^\alpha_{CP}\eta_\alpha$$

Different flavours different efficiency in transfering it to the baryons

Low-scale leptogenesis



$$\Gamma_s(T_{EW}) \leq H(T_{EW})$$

(scattering rate < hubble expansion)

Testability/predictivity ?

- Y_B cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:

High-scale scenarios: very difficult for $M_N > 10^7$ GeV

Low-scale scenarios: N's can be produced in the lab
and could be in principle detectable !

Full exploration of the minimal model N=2

Bayesian posterior probabilities (using nested sampling Montecarlo Multinest)

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

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

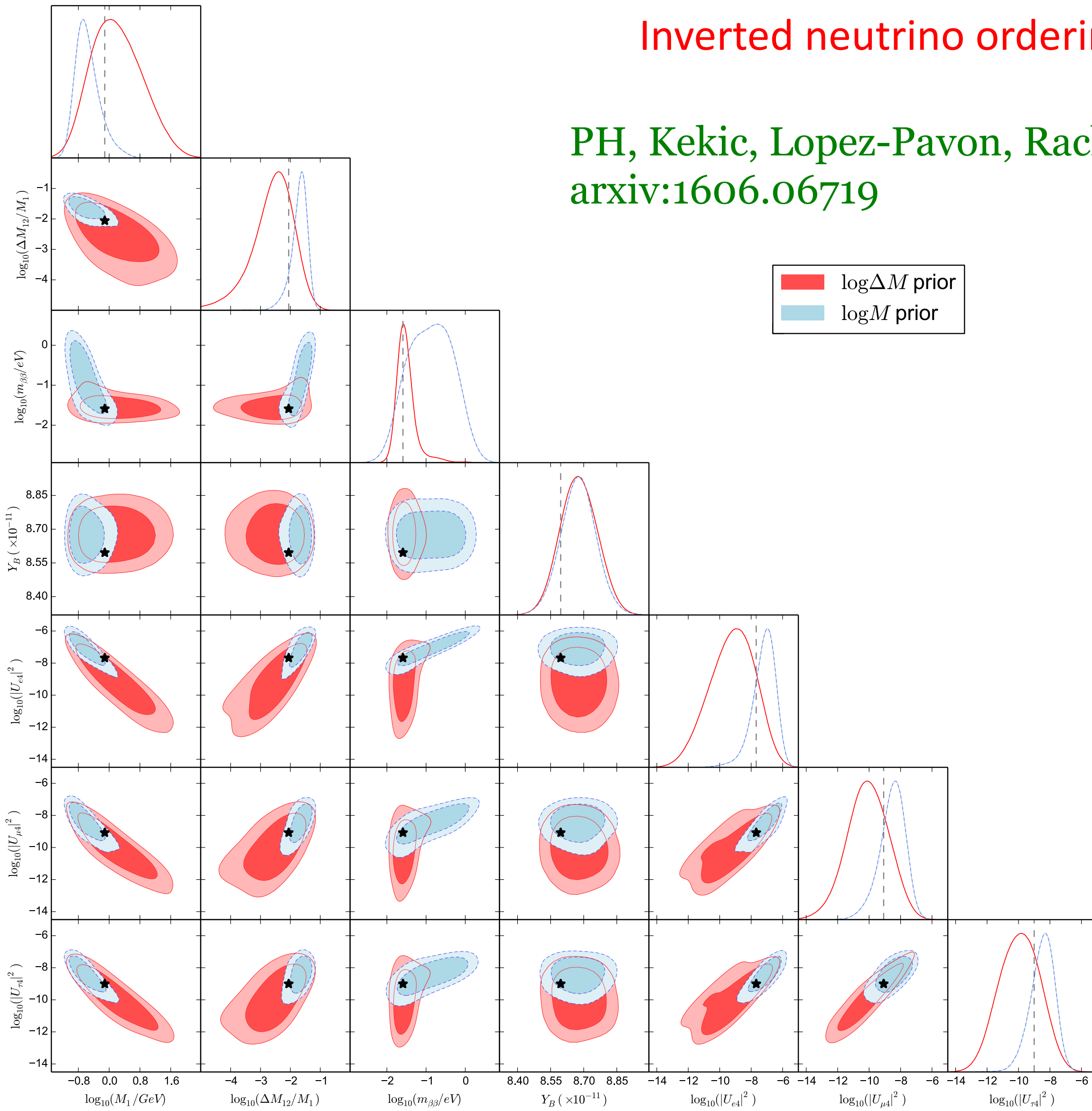
$$R(\theta + i\gamma);\; U_{PMNS}(\delta, \phi_1); M_1, M_2$$

Flat priors in:

$$\theta = [0, \pi]; \delta = [0, 2\pi]; \phi_1 = [0, 2\pi]; \gamma = [-9, 9];$$

$$\log_{10} M_1 \;\text{ and }\; \log_{10} M_2 / \log_{10}(M_2 - M_1)$$

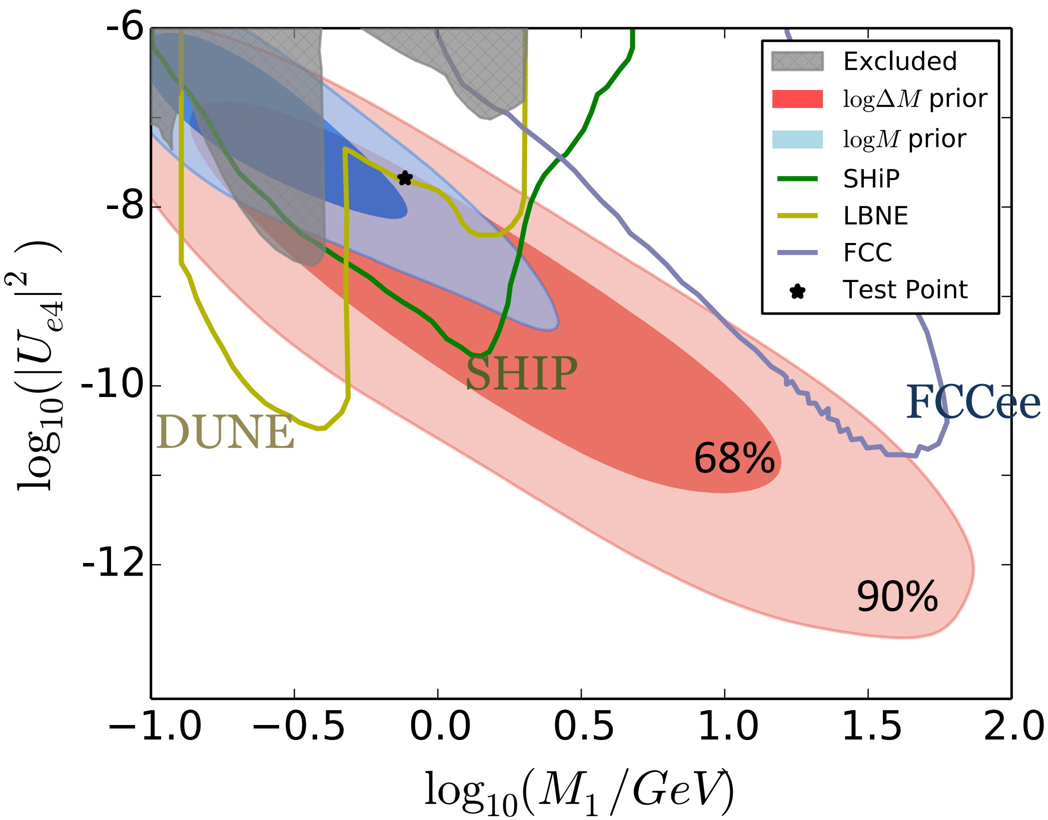
Full exploration of the minimal model N=2



Inverted neutrino ordering (IH)

PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719

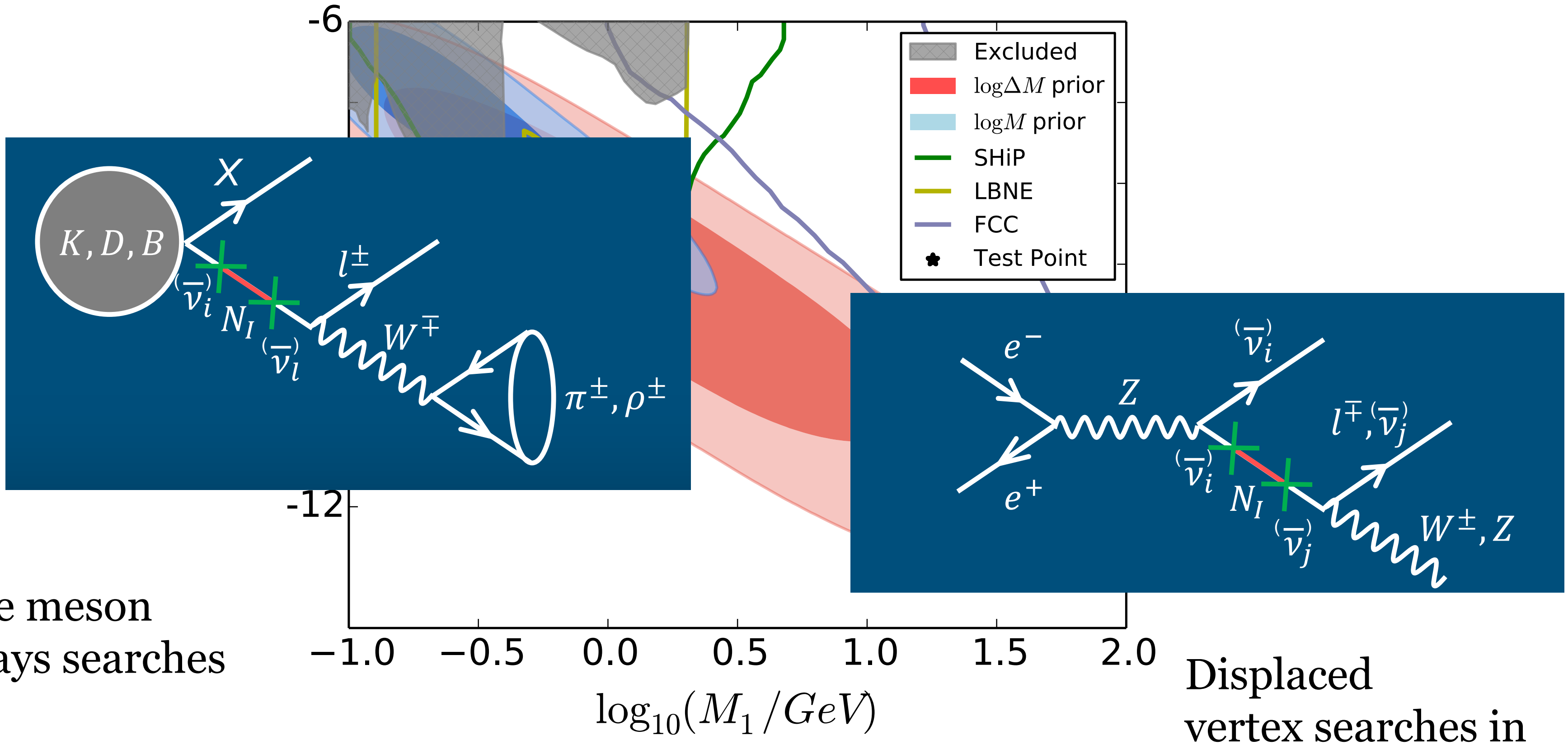
In the minimal model with just n_R=2 neutrinos (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719

Colored regions: posterior probabilities of successful Y_B

In the minimal model with just n_R=2 neutrinos (IH)



Rare meson decays searches

Displaced vertex searches in Z decays

Predicting Y_B in the minimal model n_R=2 ?

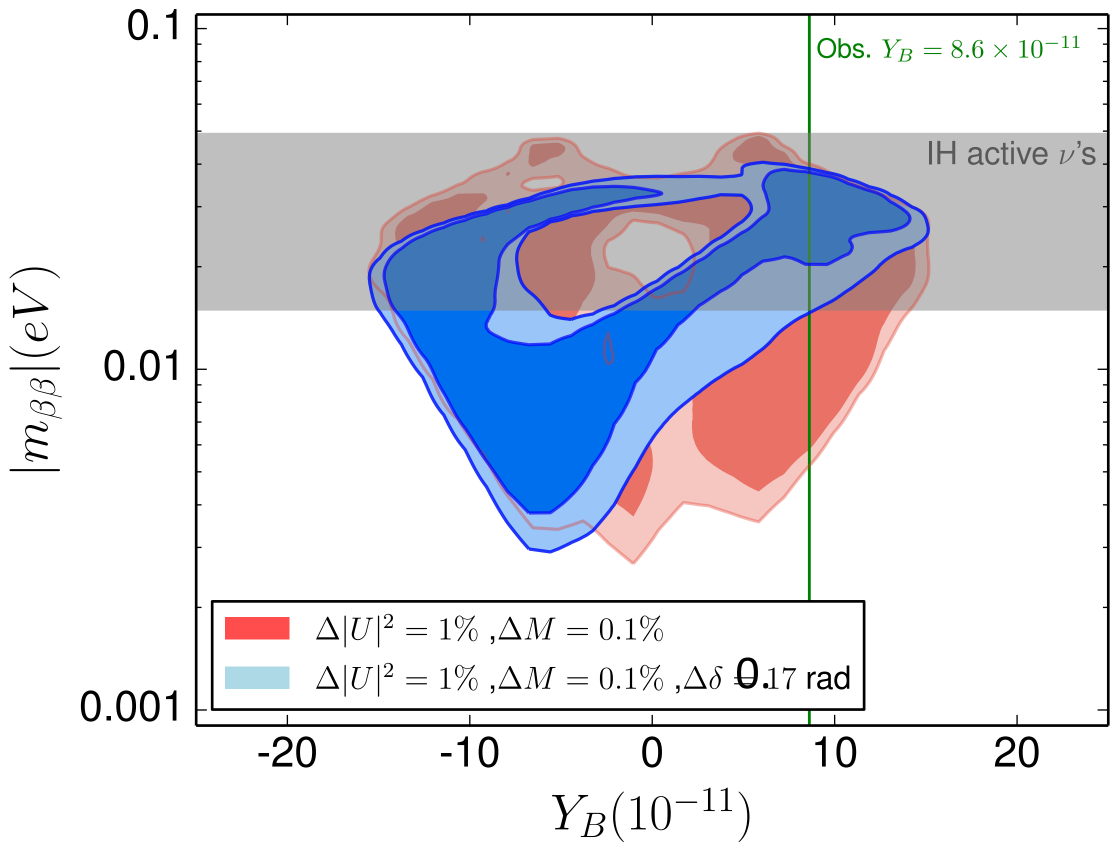
Assume a point within SHIP reach that gives the right baryon asymmetry

- SHIP measurement could provide (if states not too degenerate)

  $M_1, M_2, |U_{e1}|^2, |U_{\mu1}|^2, |U_{e2}|^2, |U_{\mu2}|^2$

- Future neutrino oscillations: δ phase in the U_{PMNS}

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

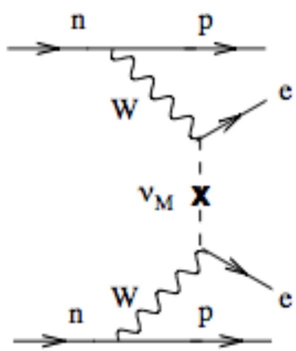


PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719

- Grey band: standard light neutrino contribution to $m_{\beta\beta}$ for IH
- Significant interference between light/heavy neutrino contributions to $m_{\beta\beta}$

Predicting Y_B in the minimal model n_R=2

Heavy states also contribute to the ββ0ν amplitude…



$$m_{\beta\beta} = \underbrace{\sum_{i=1}^{3} \left[(U_{PMNS})_{ei}\right]^2 m_i}_{\text{Light states}} + \underbrace{\sum_{i=j}^{3} U_{ej}^2 M_j \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)}}_{\text{Heavy states}}$$

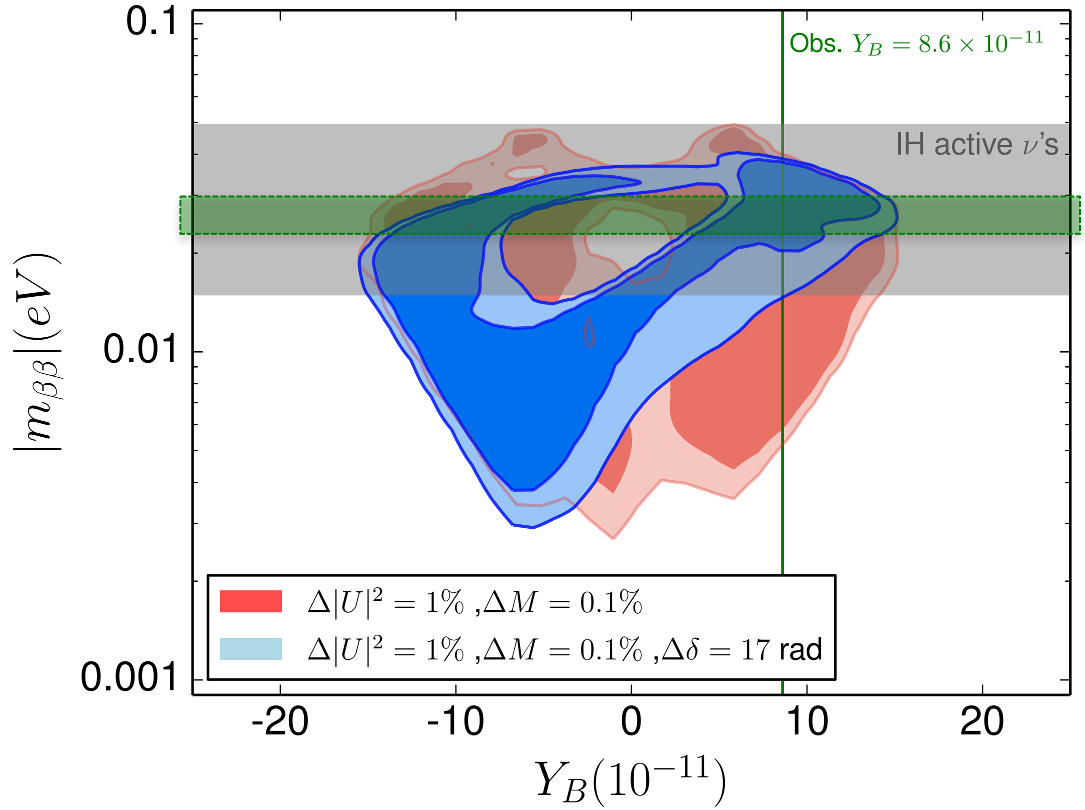
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100\ \text{MeV}}{M_j}\right)^2$$

the heavy contribution is sizeable for M_i of O(GeV)

Blennow,Fernandez-Martinez, Lopez-Pavon, Menendez;
Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

The non standard contributions bring essential information of some CP phases
and other unknown parameters

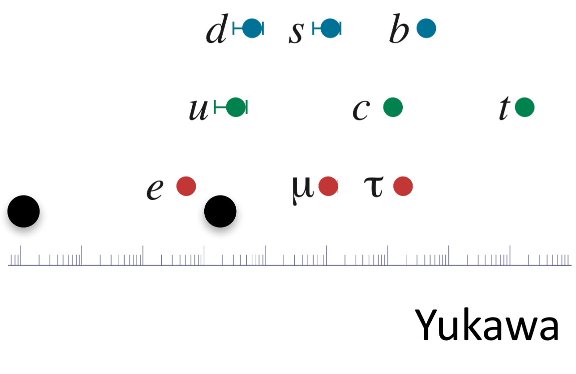
Predicting Y_B in the minimal seesaw model M~GeV



PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719

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

Sample point



$\delta = 234^o$ $\alpha = 254^o$

$M_1 \sim M_2 \sim 0.77$ GeV , $\Delta M/M \sim 10^{-2}$

How fine-tunned is the range of parameters for successful leptogenesis ?

The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al….many others

$L(N_1)= +1$, $L(N_2) = -1$

$$-\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L}\tilde{\Phi} N_1 + h.c.$$

$$\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

Degenarate heavy neutrinos and massless light neutrinos…

How natural is the range of parameters for successful Leptogenesis ?

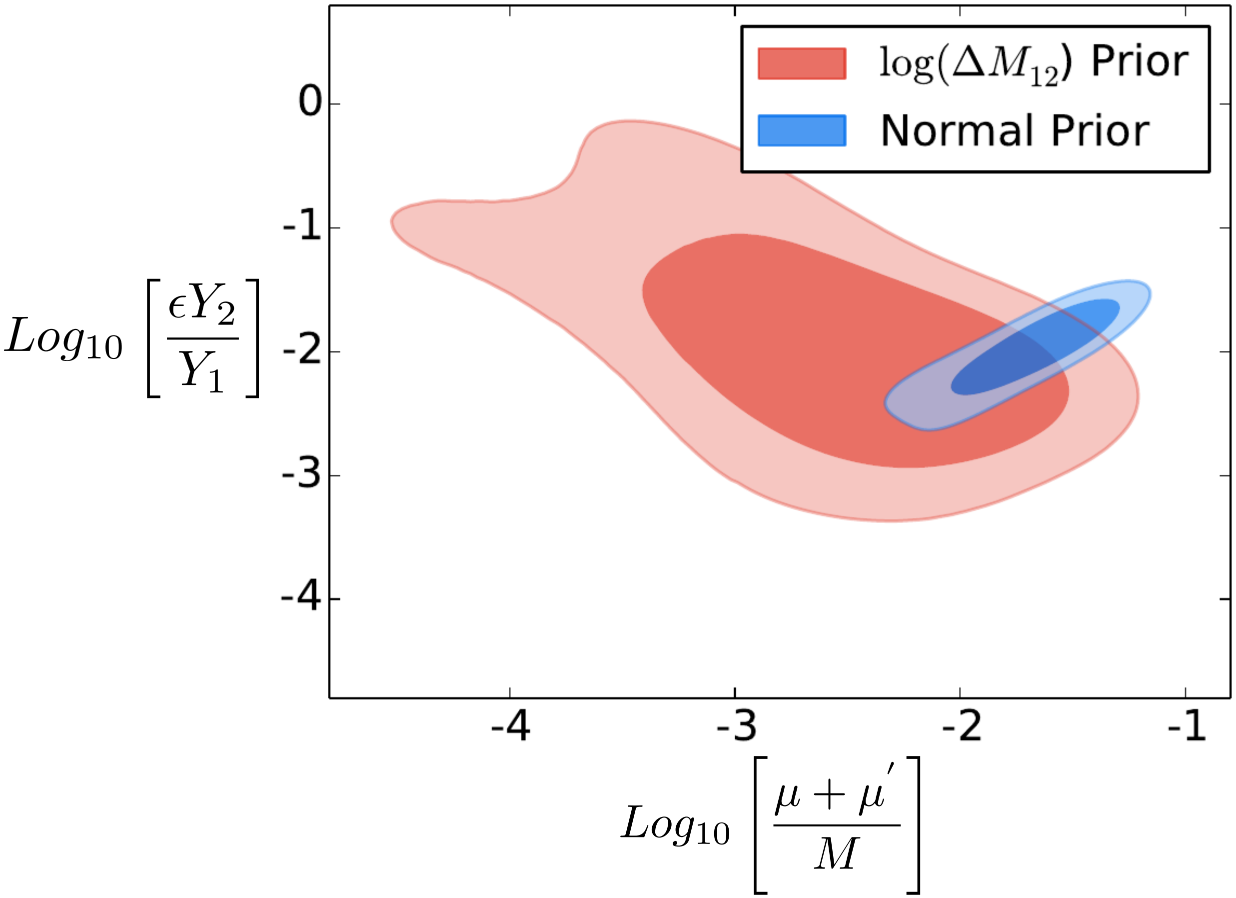
The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al....many others

$$\begin{pmatrix} 0 & Y_1 v & \epsilon Y_2 v \\ Y_1 v & \mu' & M_N \\ \epsilon Y_2 v & M_N & \mu \end{pmatrix}$$

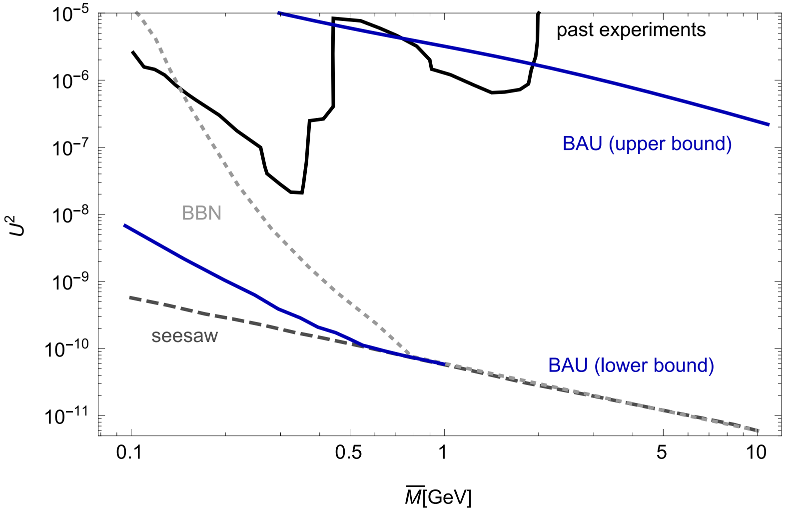
- How small must the small entries be ?

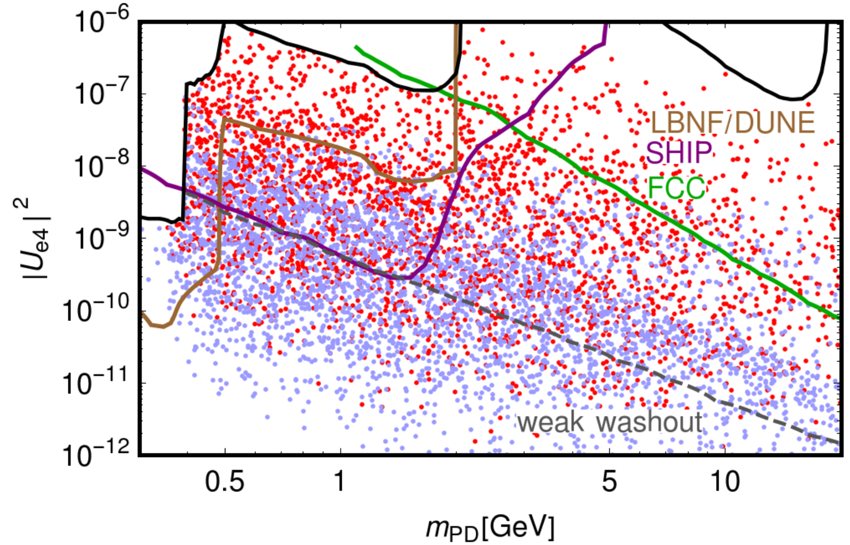
How natural is the range of parameters for successful ARS leptogenesis ?



- Blue region prefers a mild hierarchy in all $U(1)_L$ breaking terms
- Red region points requires μ, μ′ entries significantly smaller than ε

How large can the mixing be (even if less probable) and still have successful baryogenesis ?



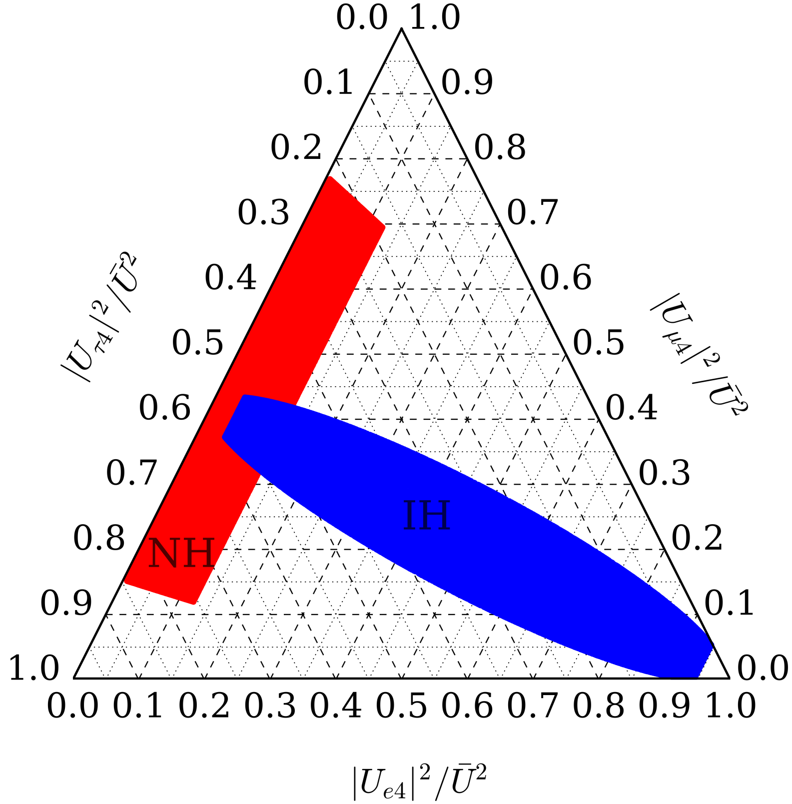


Drewes, Garbrecht,Gueter, Klaric
arxiv: 1606.06690

Abada, Arcadi, Domcke, Lucente
arxiv: 1709.00415

The seesaw path to leptonic CP violation:
flavour ratios of heavy lepton mixings strongly correlated with ordering, U_{PMNS} matrix: δ, ϕ_1

In minimal model:



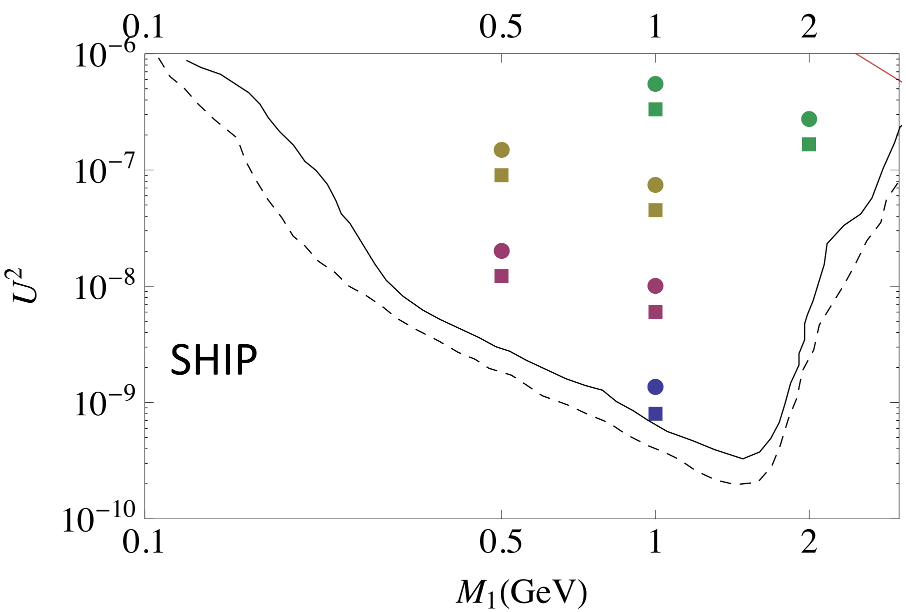
Caputo, PH, Lopez-Pavon, Salvado arxiv:1611.05000

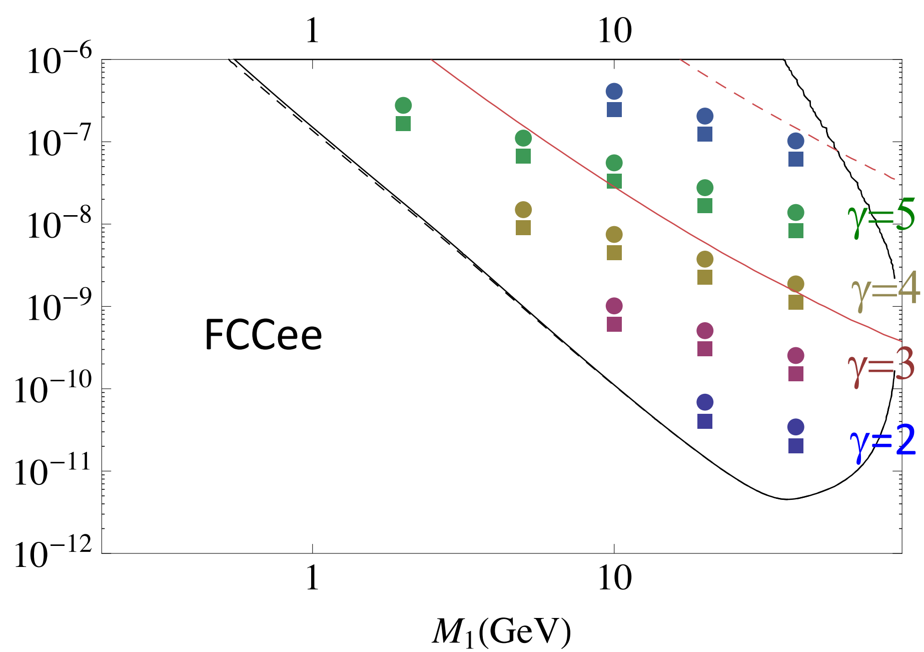
Superb sensitivity to Majorana CP phases: complementary to oscillations

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 ?

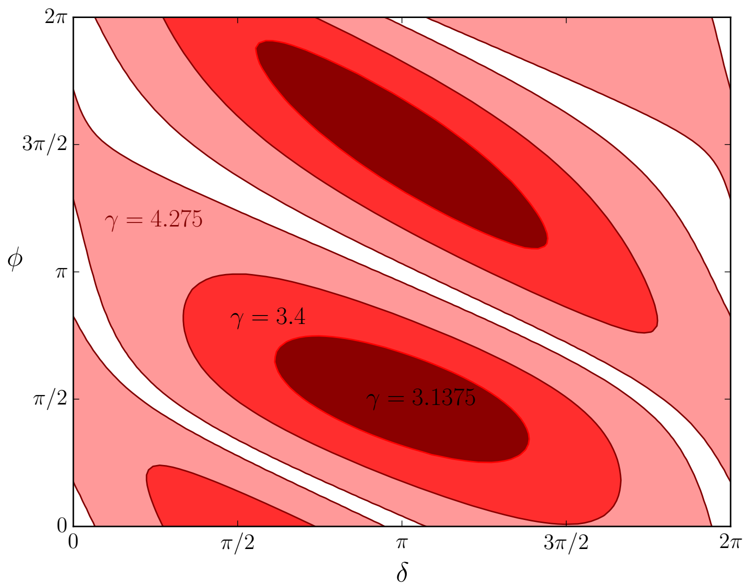
$(\delta, \phi_1) \neq (0/\pi, 0/\pi)$



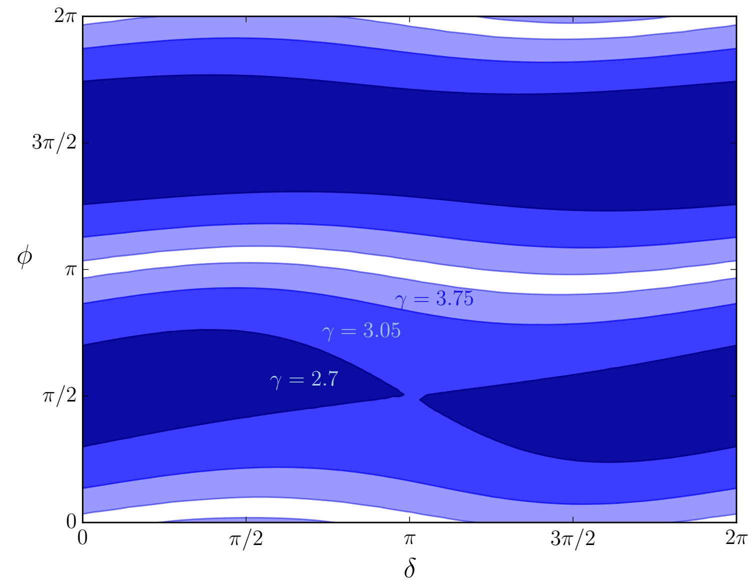


Leptonic CP violation 5σ CL discovery regions (SHIP)

Normal Hierarchy



Inverted Hierarchy



(no systematic error included)

Caputo, PH, Lopez-Pavon, Salvado arxiv:1611.05000

R_{CP}=5σ CP-fraction =

fraction of the area of the CP rectangle which is colored

Beyond the minimal model

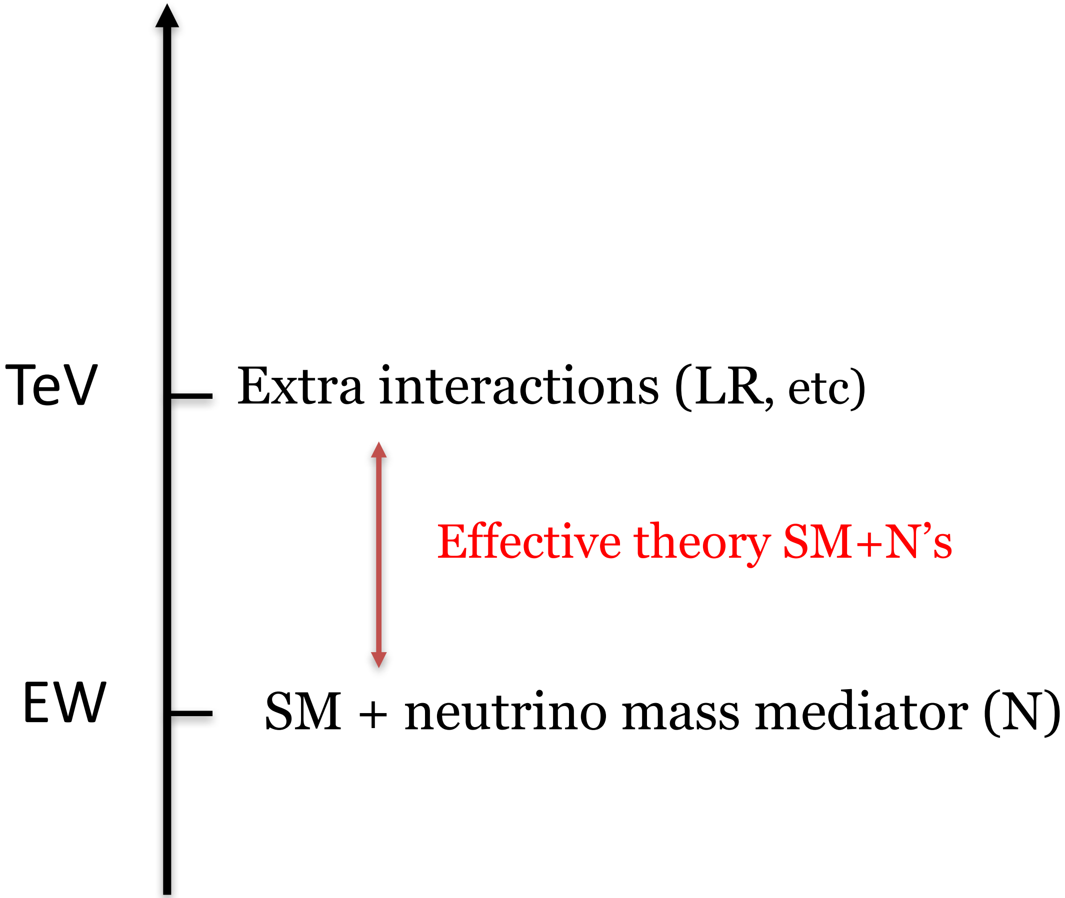
Many possibilities:

Examples: type I +W’, Z’,
left-right symmetric models
GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic;
Ferrari et al + many recent refs…

- Generically gauge interactions can enhanced the production in colliders
- But they make leptogenesis more challenging (out-of-equilibrium condition harder to meet)

Interesting possibility:



Model independent approach: EFT

$$\mathcal{L}_{BSM} = \mathcal{L}_{\rm mSS} + \sum_{d,i} \frac{1}{\Lambda^{d-4}} O_i^{(d)}$$

The seesaw portal to BSM:

d=5

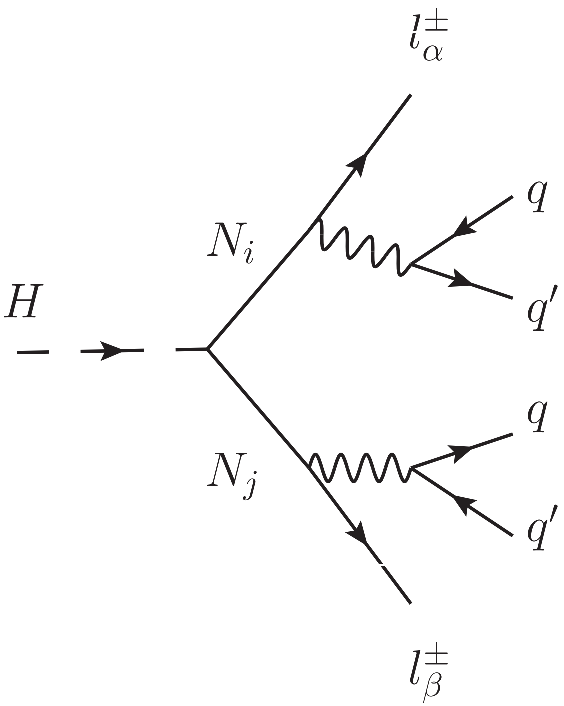
$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi} \Phi^\dagger L^c_\beta + h.c.,$$

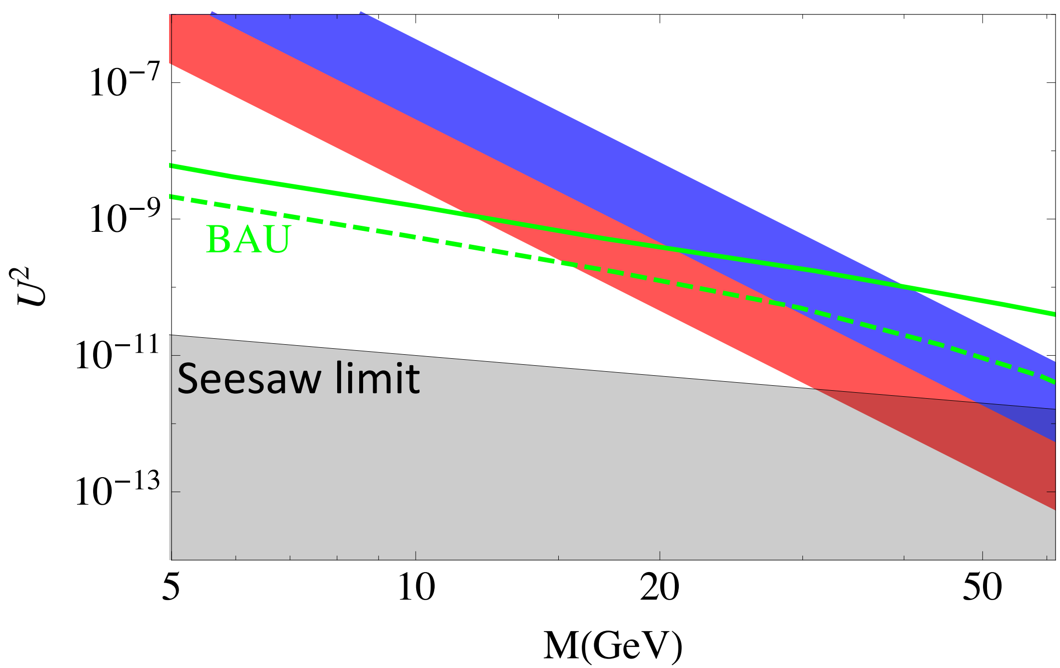
$$\mathcal{O}_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N}_i N^c_j \Phi^\dagger \Phi + h.c.,$$

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

S. Weinberg ’79; M. Graesser ’07; F. Del Aguila et al ’09; Aparici et al, ‘09; Caputo et al ‘17

$\mathcal{O}_{N\Phi}$ could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)



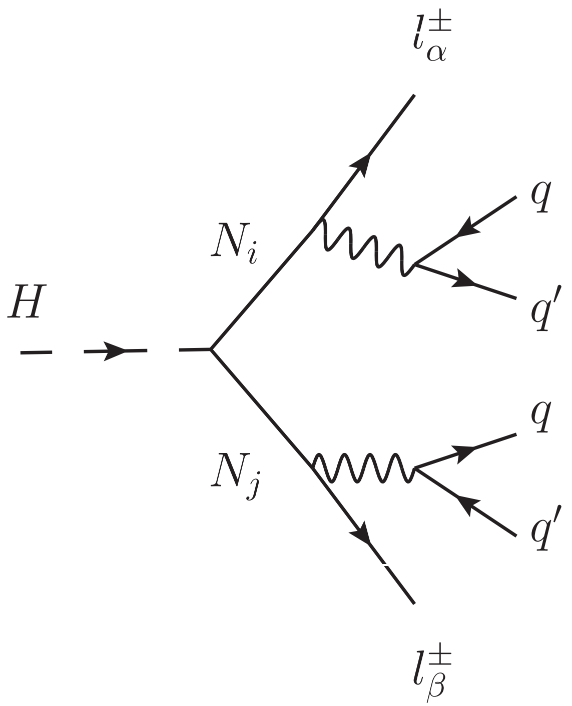


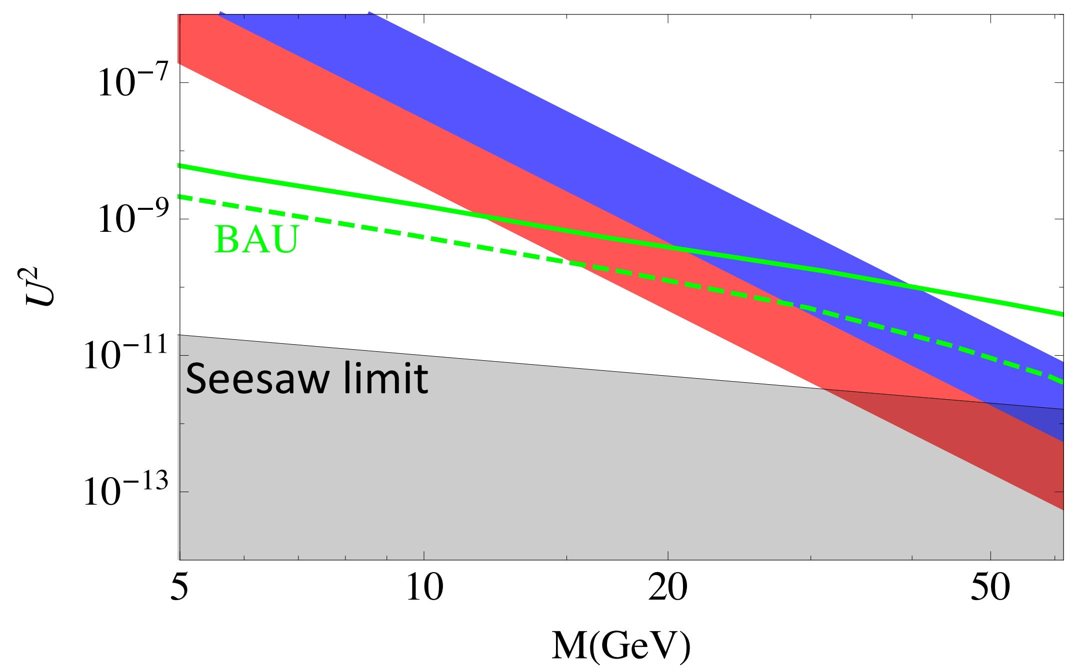
Caputo, PH, LopezPavon, Salvado, arxiv:1704.08721

LHC: 300 fb^{-1}, 13TeV

$$\left|\frac{\alpha_{N\Phi} v}{\sqrt{2}\Lambda}\right| \leq 10^{-3} - 10^{-2} \rightarrow \frac{\alpha_{N\Phi}}{\Lambda} \leq 6 \times (10^{-3} - 10^{-2})\mathrm{TeV}^{-1}.$$

$\mathcal{O}_{N\Phi}$ could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)





Caputo, PH, LopezPavon, Salvado, arxiv:1704.08721

A large hierarchy between the coefficients would be needed since the Weinberg operator is much more strongly suppressed: technically natural with $U(1)_L$

Conclusions

- Exploring the EW-> TeV region for NP related to neutrino masses is very well motivated

- A minimal model of neutrino masses with a new scale near GeV can explain the baryon asymmetry and might do so in a testable way (IH more promising)

- Testability in simplest model will require the contribution of very different type of experiments:

  SHIP/FCCee: masses and mixings of the heavy neutrino states

  DUNE/HyperK: CP violation ν neutrino oscillations

  $\beta\beta 0\nu$: non-standard contributions from heavy sector

- Flavour mixings of the heavy states high sensitivity to CP phases in U_{PMNS} (in particular Majorana phases!)

- Mediators of neutrino mass at the EW provide a new portal to BSM physics