# *Higgs couplings in extensions of low scale seesaw*

A.Caputo

University of Valencia and CSIC

Talk based on A.C, P. Hernandez, J. Lopez-Pavon, J. Salvado

“The seesaw portal in testable models of neutrino masses” JHEP 1706 (2017) 112

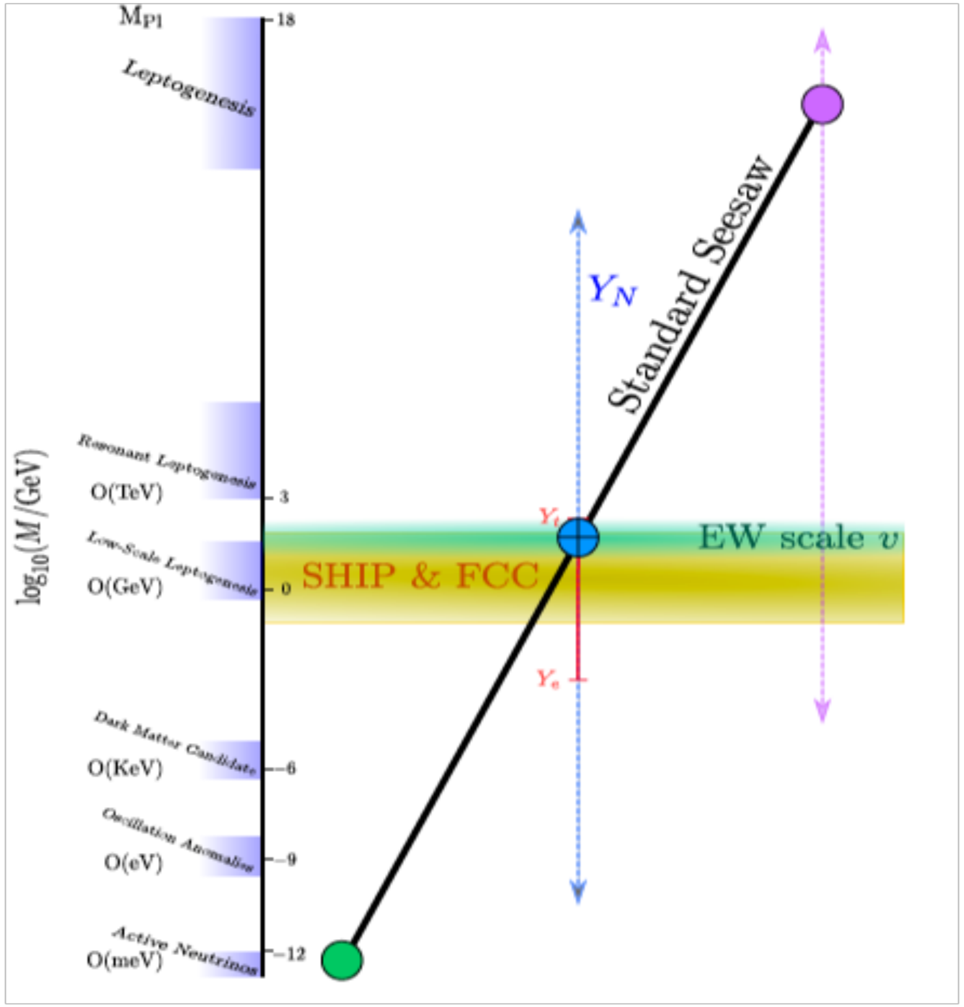
Higgs Coupling 2017

# Motivation

- $\mathcal{L}_{seesaw} = \mathcal{L}_{SM} - \sum_{\alpha,i} \overline{L_\alpha} Y^{\alpha,i} \tilde{\phi} N_i - \sum_{i,j=1}^{2} \frac{1}{2} \overline{N_i^C} M_N^{i,j} N_i + h.c$

P. Minkowski(1977), M. Gell-Mann, P. Ramond and R. Slansky (1979), T. Yanagida (1979), R.N. Mohapatra and G. Senjanovic (1980)

- Observed neutrino masses
- Explain Matter-Antimatter asymmetry via neutrino oscillations if $M_N \in [1, 10^2] GeV$
- Testable scenario in beam dump experiments and future colliders



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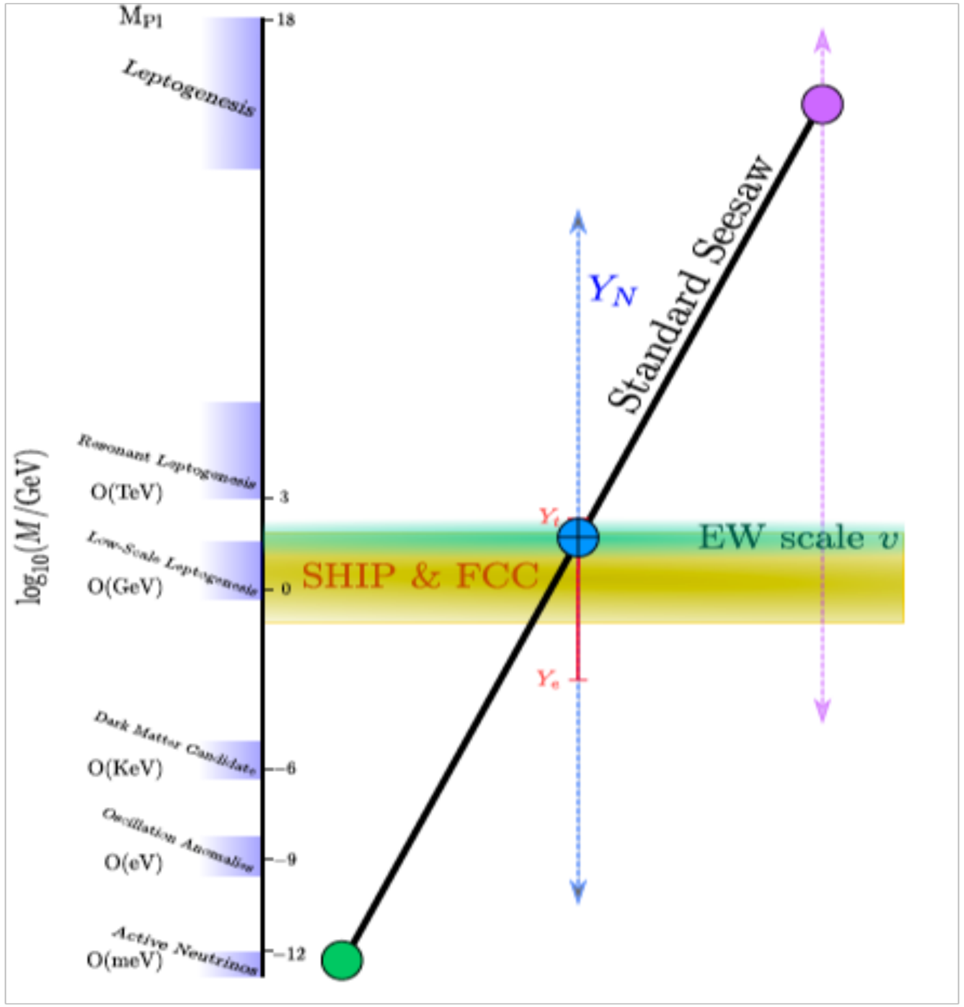

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E.K.Akhmedov, V.Rubakov, A.Y. Smirnov
Asaka, Shaposhnikov

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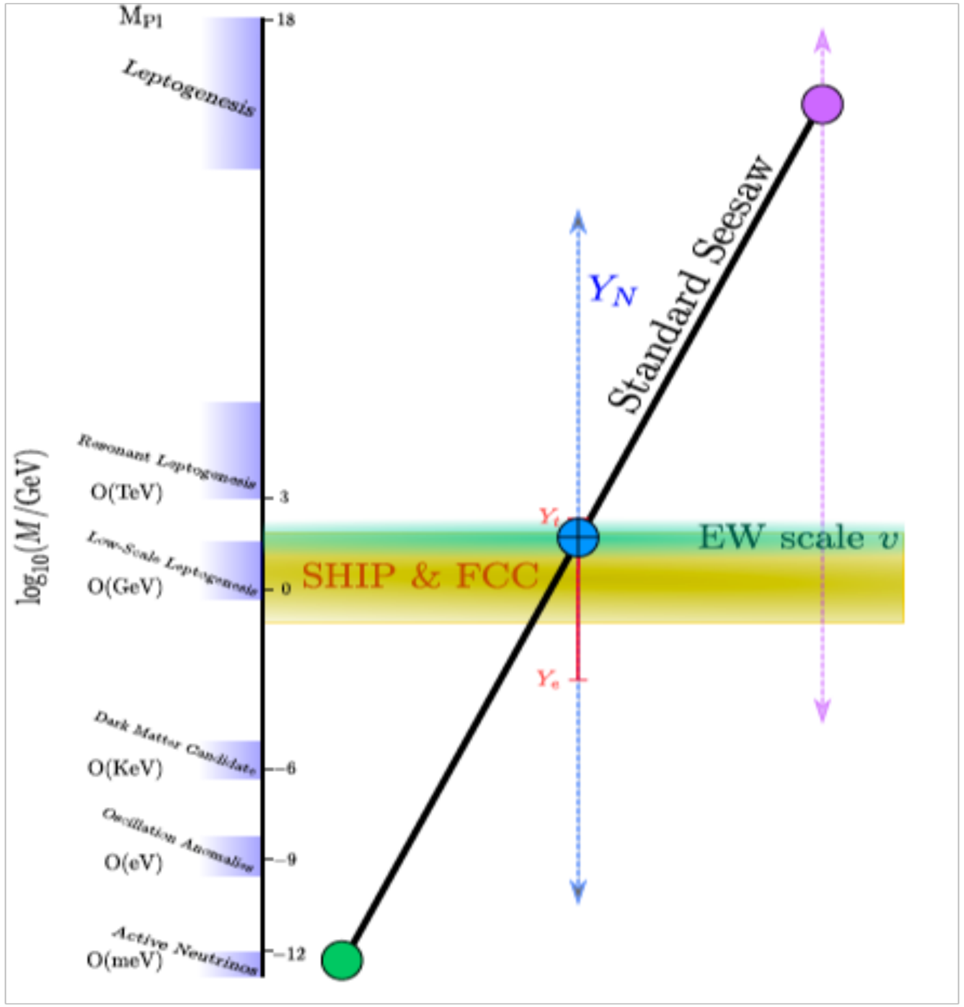

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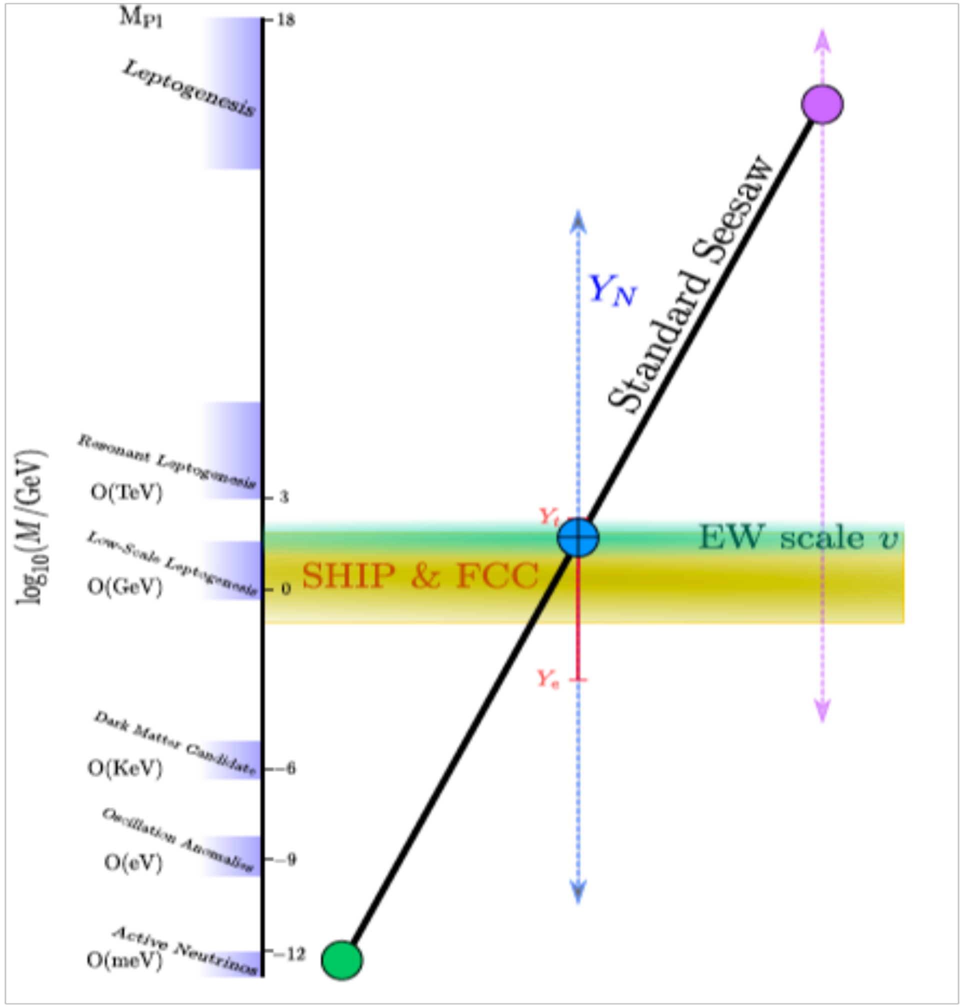
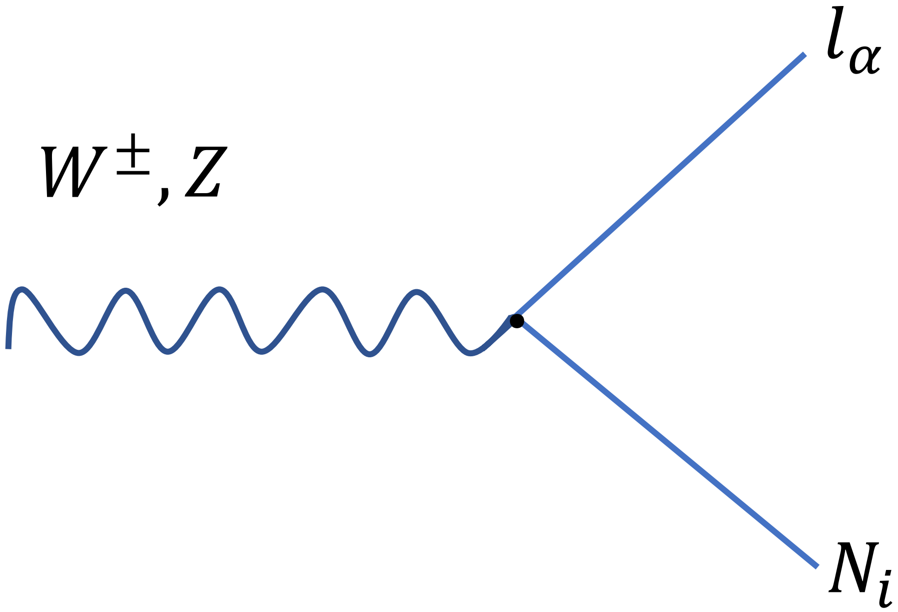


- light neutrinos masses

$$m_\nu \approx -\frac{v^2}{2} Y \frac{1}{M} Y^T$$

- two heavy states with mass M



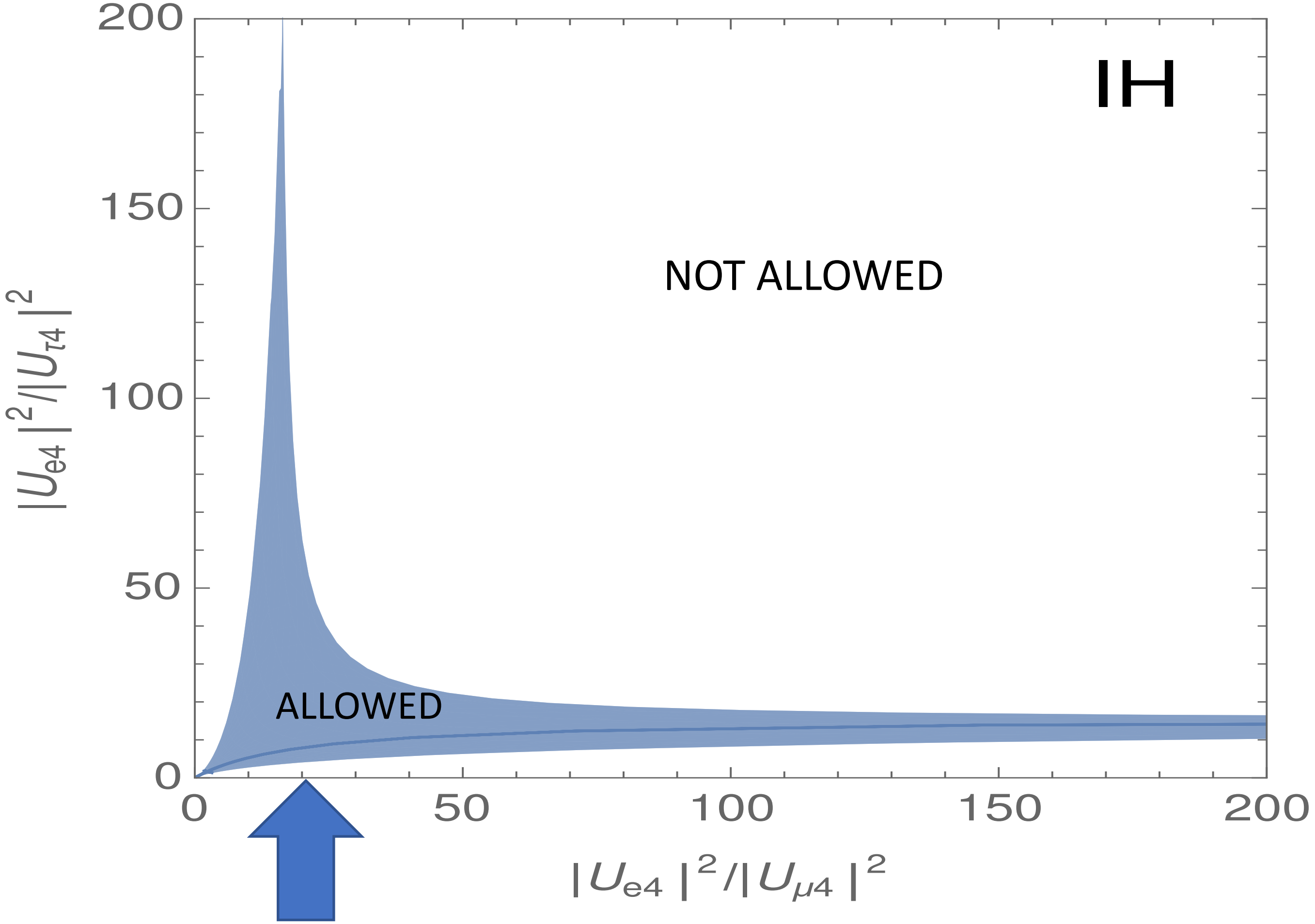

$\propto U_{\alpha i}$ *mixing between leptons and sterile neutrinos*

$$U_{\alpha i} = \frac{v}{\sqrt{2}} Y M^{-1} \approx \sqrt{\frac{m_\nu}{M}}$$

Strongly correlated to the light neutrino masses!!

# High Predictivity

Flavour ratios of mixings

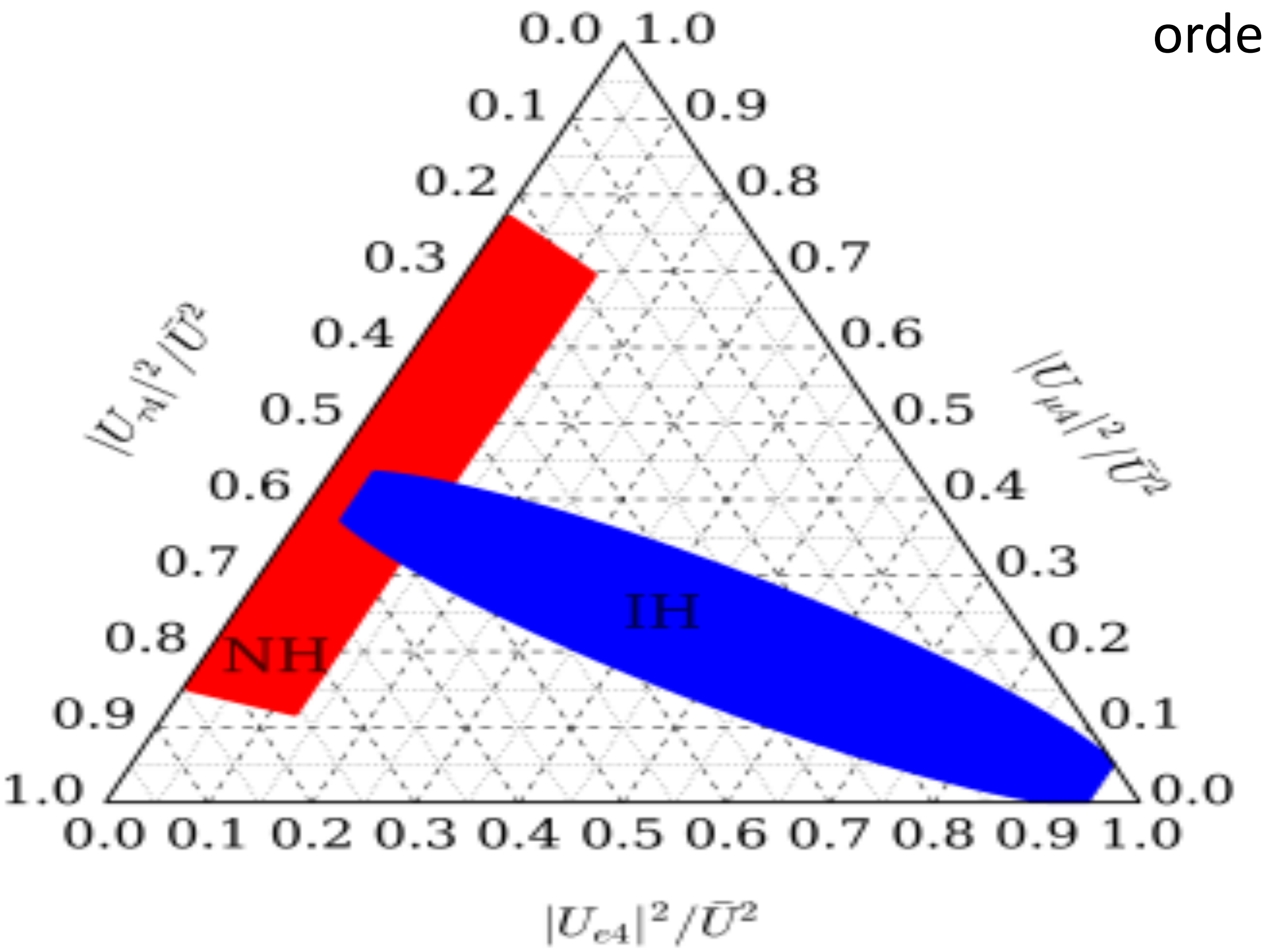



Varying
CP Phases $(\delta, \phi)$

Strong constraints from light neutrinos masses and mixings

A.C, P. Hernandez, J.Lopez-Pavon, M. Kekic, J.Salvado, 1611.05000

# High Predictivity



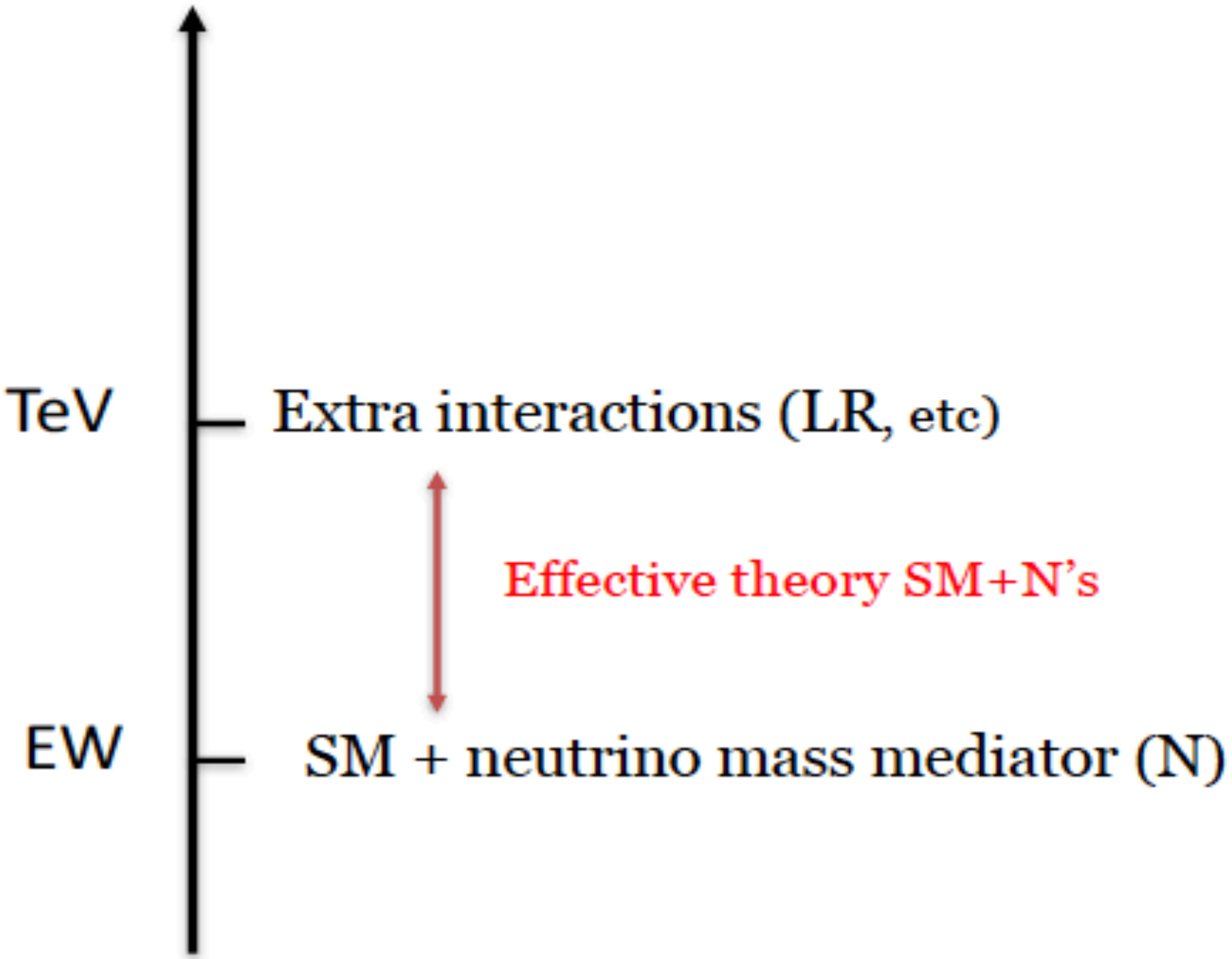

Flavour ratios strongly correlated with ordering and $U_{PMNS}$ $matrix$ $(\phi, \delta)$

Superbe sensitivity to Majorana CP phases: complementary to oscillations

These predictions rely to a large extent on the minimality of the model

To what extent can they be modified in the presence of additional new physics?

# Model independent approach: EFT



# Model independent approach: EFT

d=5 operators

- $O_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha,\beta}}{\Lambda} \overline{L_\alpha} \tilde{\phi} \phi^\dagger L_\beta^C$

- $O_{N\phi} = \sum_{i,j} \frac{(\alpha_{N\phi})_{i,j}}{\Lambda} \overline{N_i} N_j^C \phi^\dagger \phi$

- $O_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{i,j}}{\Lambda} \overline{N_i} \sigma_{\mu\nu} N_j^C B^{\mu\nu}$

S.Weinberg, Phys.Rev.Lett, 43(1979) 1566-1570
M.Graesser, Phys.Rev.D76 (2007) 075006
F. Del Aguila, S.Bar-Shalom, A.soni and J.Wudka, Phys. Lett. B670 (2009)

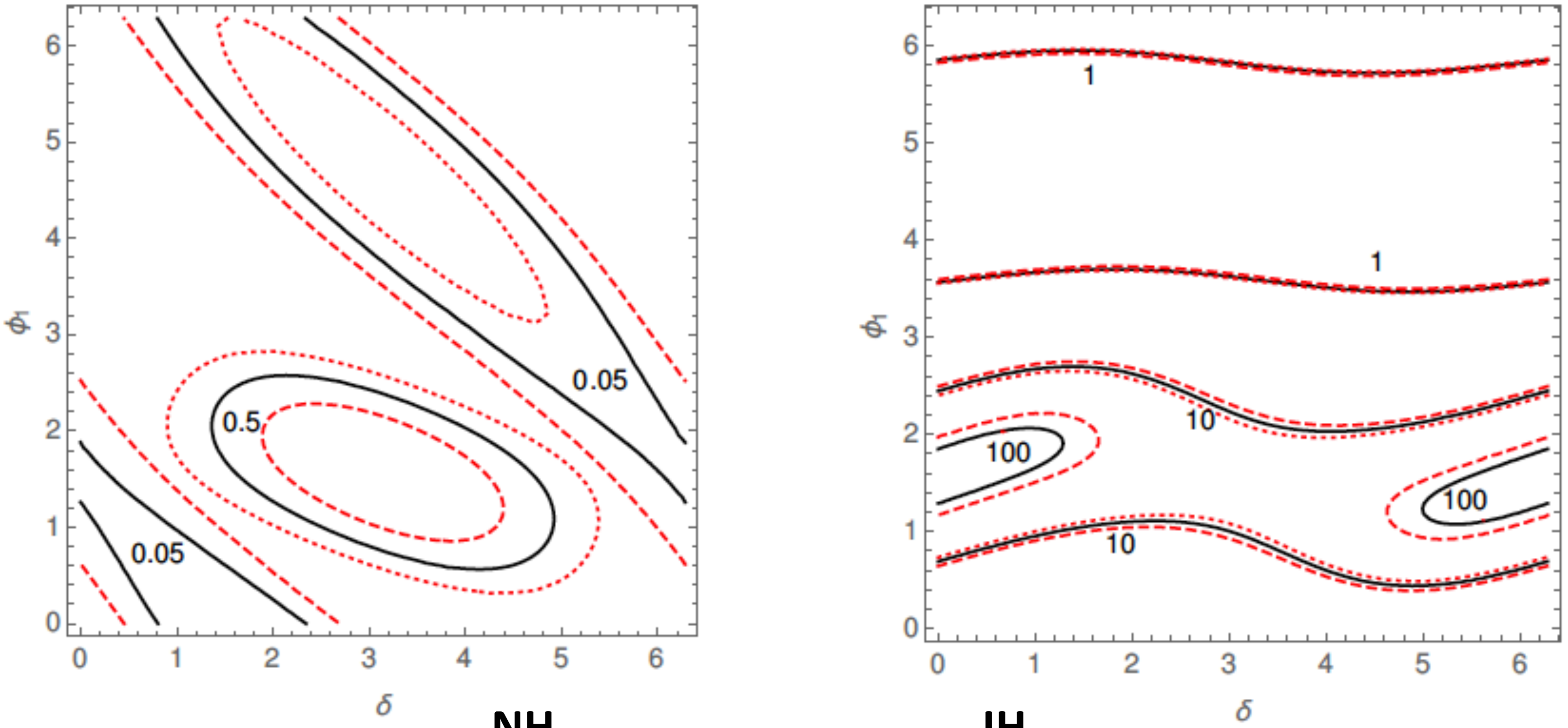
# Model independent approach: EFT

- $O_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha,\beta}}{\Lambda} \overline{L_\alpha} \tilde{\phi} \phi^\dagger L_\beta^C$ ⇒

Additional contribution to the light neutrino masses.
It can modify the predictions

# Model independent approach: EFT

- $O_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha,\beta}}{\Lambda} \overline{L_\alpha} \tilde{\phi} \phi^\dagger L^C_\beta$




**NH** **IH**

Leading order in the non-standard contribution

$$\delta_{\alpha\beta} = \frac{(\alpha_W)_{\alpha\beta} v^2}{\Lambda} \sim O(1) m_{1,3}$$

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

# Model independent approach: EFT

- $O_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{i,j}}{\Lambda} \overline{N_i} \sigma_{\mu\nu} N_j^C B^{\mu\nu}$

→ Magnetic moment

Bounds from Red Giants and Supernova cooling

A.Aparici, K.Kim, A.Santamaria and J.Wudka, Phys. Rev. D80(2009) 013010

# Model independent approach: EFT

- $O_{N\phi} = \sum_{i,j} \frac{(\alpha_{N\phi})_{i,j}}{\Lambda} \overline{N_i} N_j^C \phi^\dagger \phi$

→ New coupling to the Higgs

M.Graesser, Phys.Rev.D76 (2007) 075006

# Higgs coupling

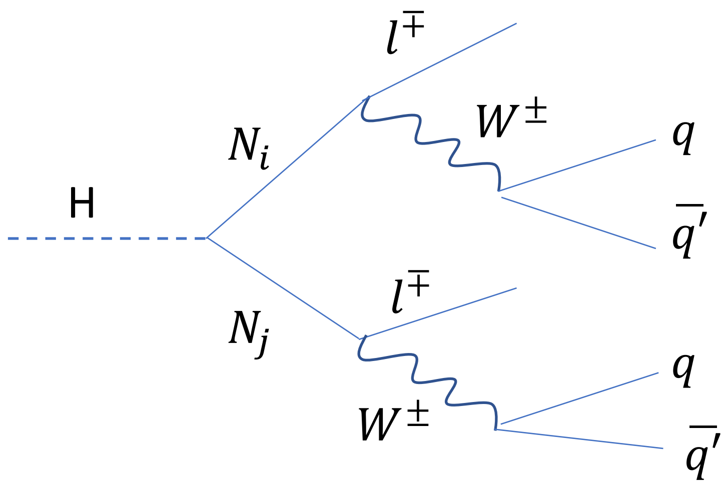
$$L \supset -\frac{v}{\sqrt{2}\Lambda} H \overline{N}^c \alpha_{N\phi} N + h.c.$$

$M_i \leq \frac{M_H}{2}$ →

*Spectacular signal at LHC, pair of* *__displaced vertices__ (DVs)*

*MadGraph5*, parton-level
Monte Carlo analysis

$$E_{C.M} = 13\ TeV, \mathcal{L} = 300\ fb^{-1}$$




*semileptonic decays only*

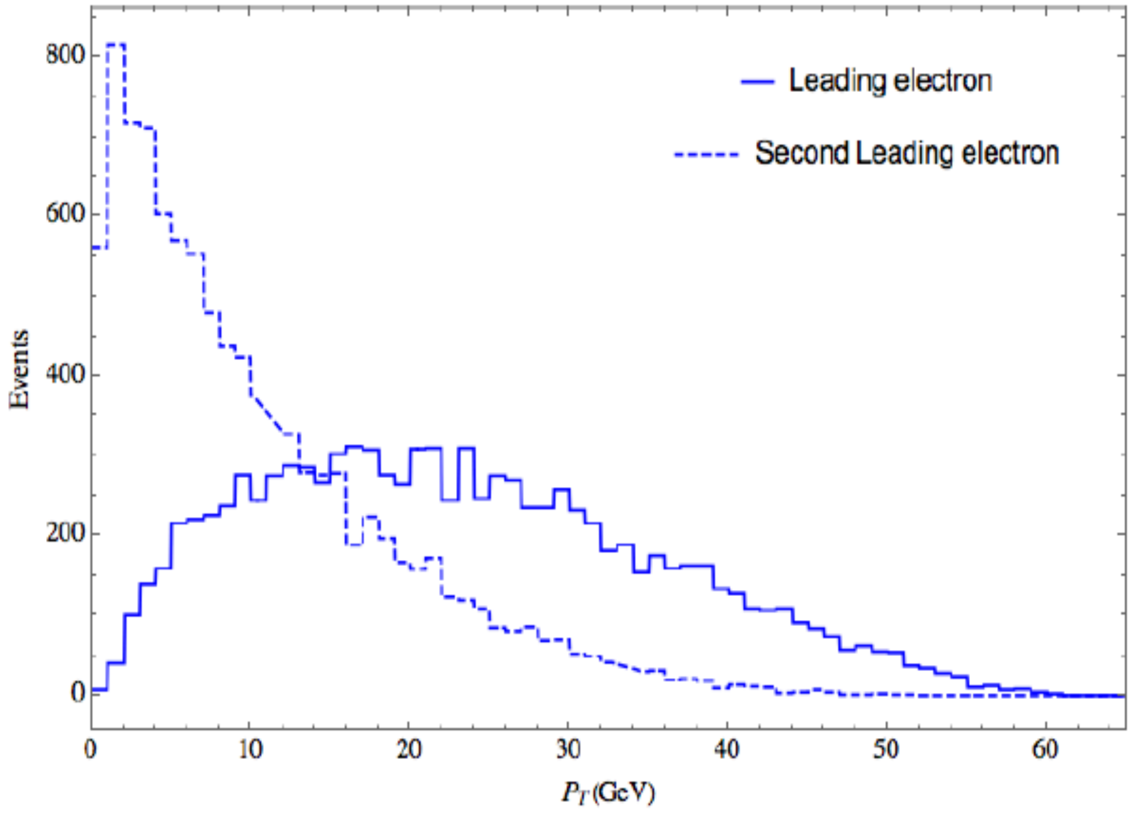
1. Search of displaced tracks in the inner tracker where at least one displaced lepton, $e$ or $\mu$, is reconstructed from each vertex

2. Search for displaced tracks in the muon chambers and outside the inner tracker, where at least one μ is reconstructed from each vertex


E.Accomando, L. Delle Rose, S.Moretti, E.Olaiya, C.Sheperd-Themistocleous (1612.05977)
CMS Collaboration, 1411.6977, CMS-PAS-EXO-14-012

Kinematical cuts:

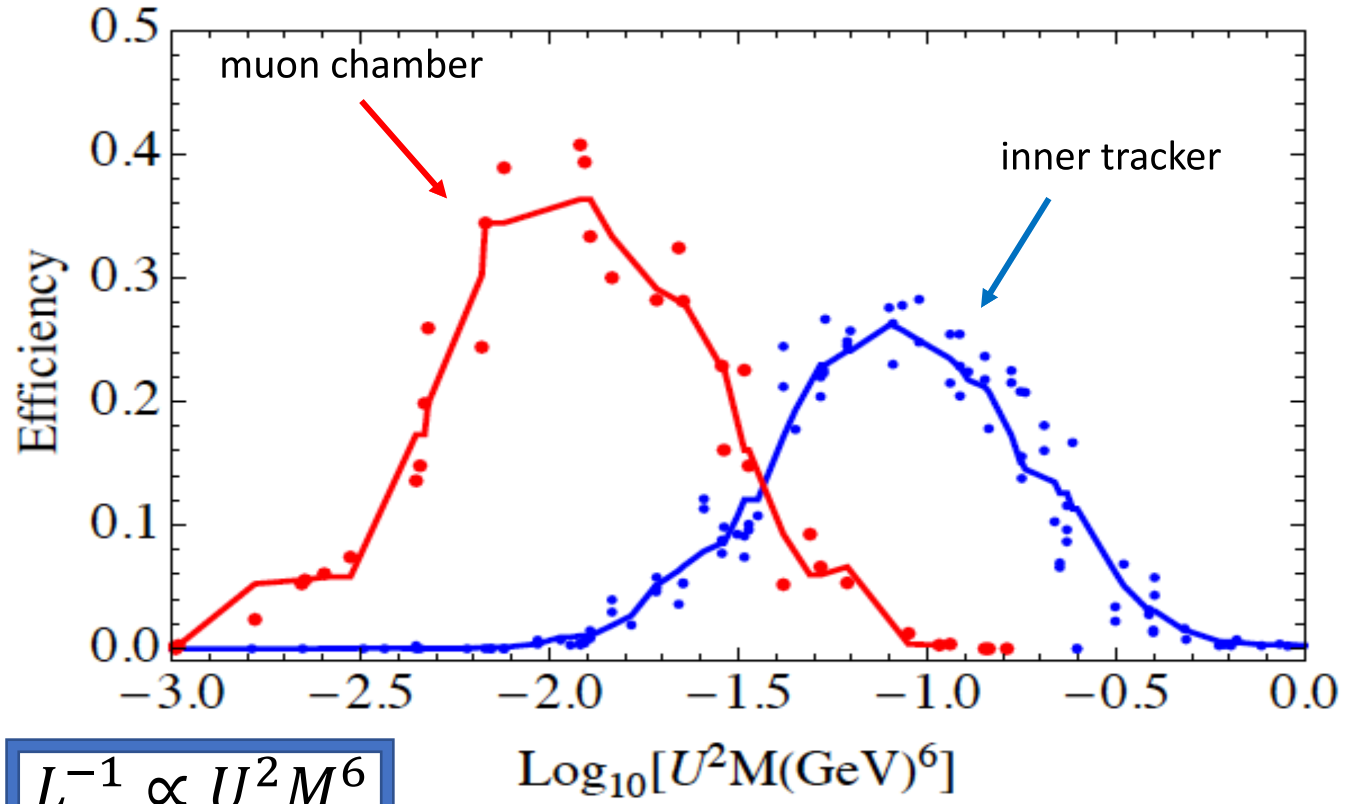
- $p_T(l) > 26GeV$
- $|\eta| < 2$
- $\Delta R > 0.2$
- $\cos\theta_{\mu\mu} > -0.75$




Cuts associated to displaced tracks:

1. $10cm < |L_{xy}| < 50cm, |L_z| \leq 1.4m, \frac{d_0}{\sigma_d^t} > 12 (\sigma_d^t \approx 20\mu m)$ Inner Tracker (IT)

2. $|L_{xy}| < 5m, |L_z| \leq 8m, \frac{d_0}{\sigma_d^\mu} > 4 \left(\sigma_d^\mu \approx 2cm\right)$ Muon Chambers (MC)




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

NH, InnerTracker

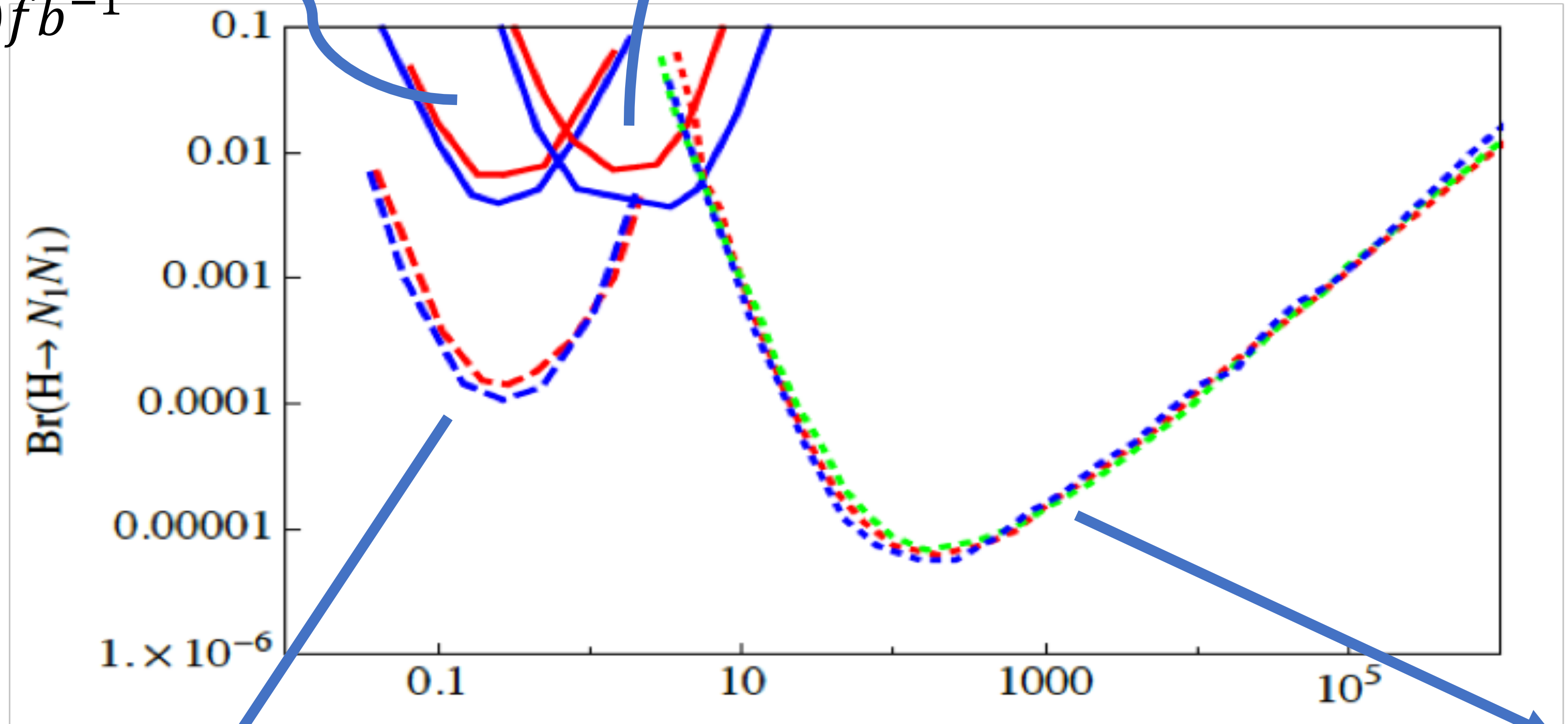
$\mathcal{L} = 300 fb^{-1}$

NH, Muon Chamber

M=20GeV

M=35GeV

$(\delta, \phi) = \left(0, +\frac{\pi}{2}\right)$

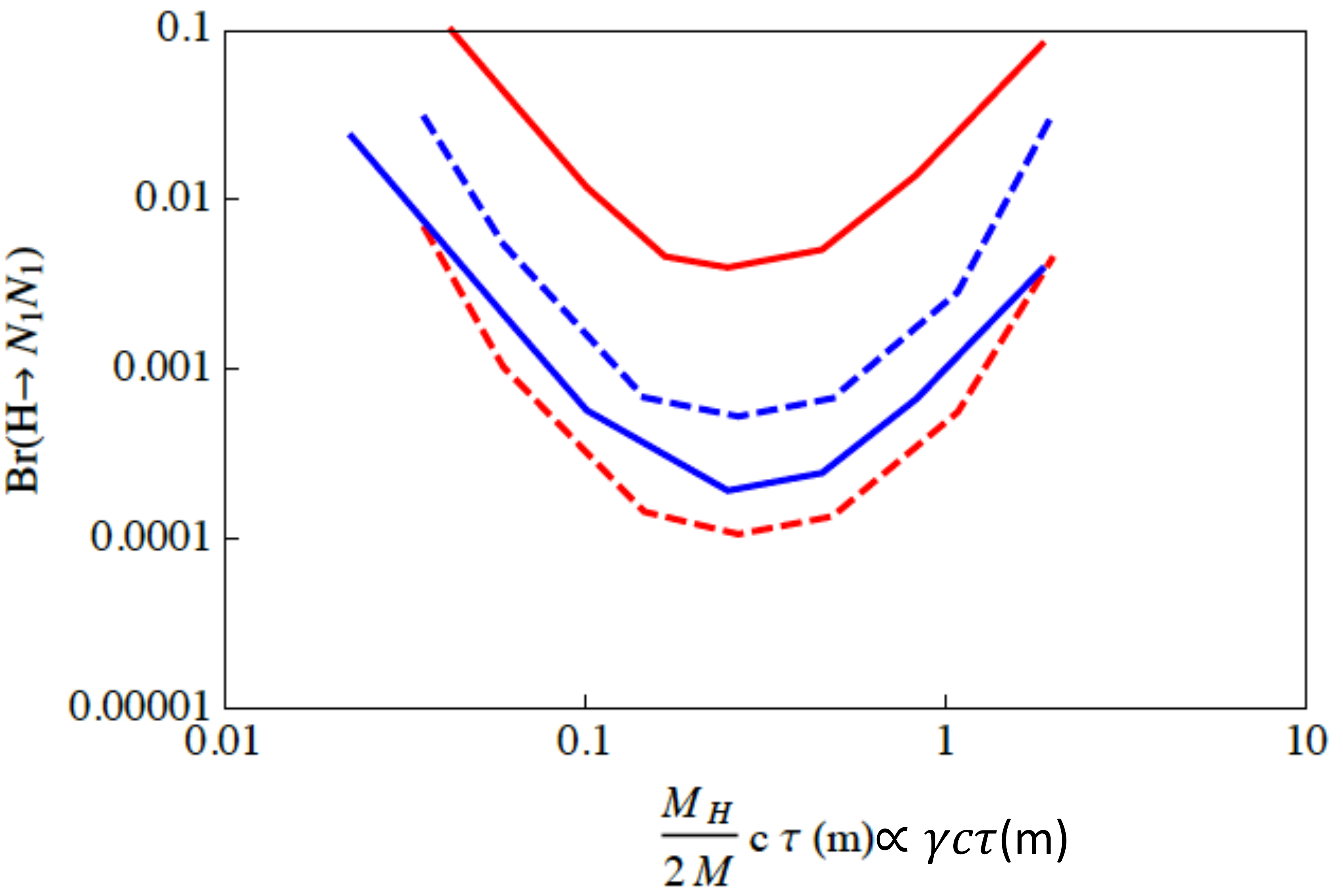



$\frac{M_H}{2M} c\,\tau\,(\mathrm{m}) \propto \gamma c\tau(m)$

IH

Mathusla (J.P. Chou, D.Curtin and H.J.Lubatti, Phys.Lett.B767(2017) 29-36)

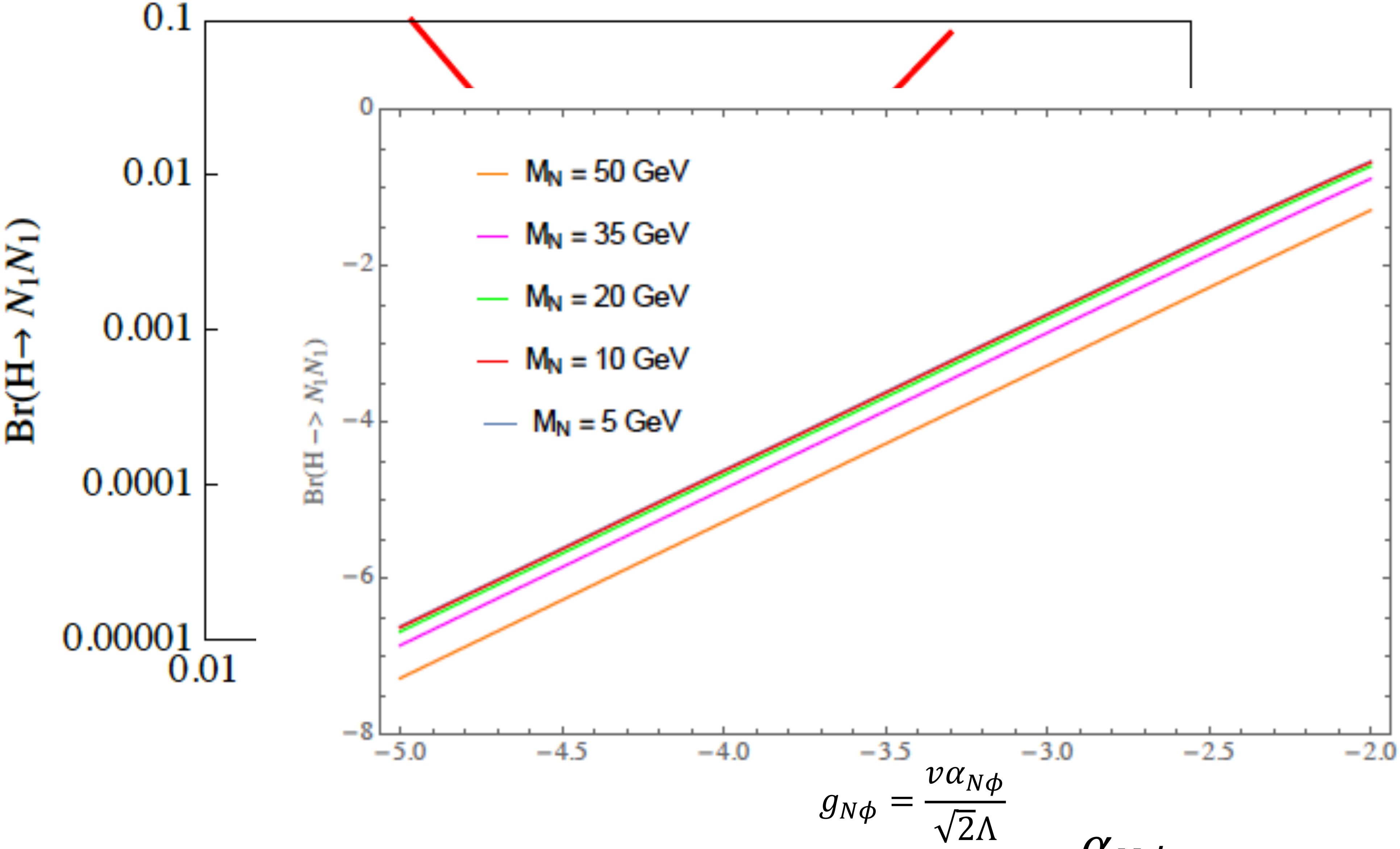
$\mathcal{L} = 3000 fb^{-1}$




$M_N = 20GeV$

$Solid \rightarrow NH$
$Dashed \rightarrow IH$

$Blue \rightarrow (\delta, \phi) = \left(0, -\frac{\pi}{2}\right)$
Red $\rightarrow (\delta, \phi) = \left(0, +\frac{\pi}{2}\right)$




$0GeV$

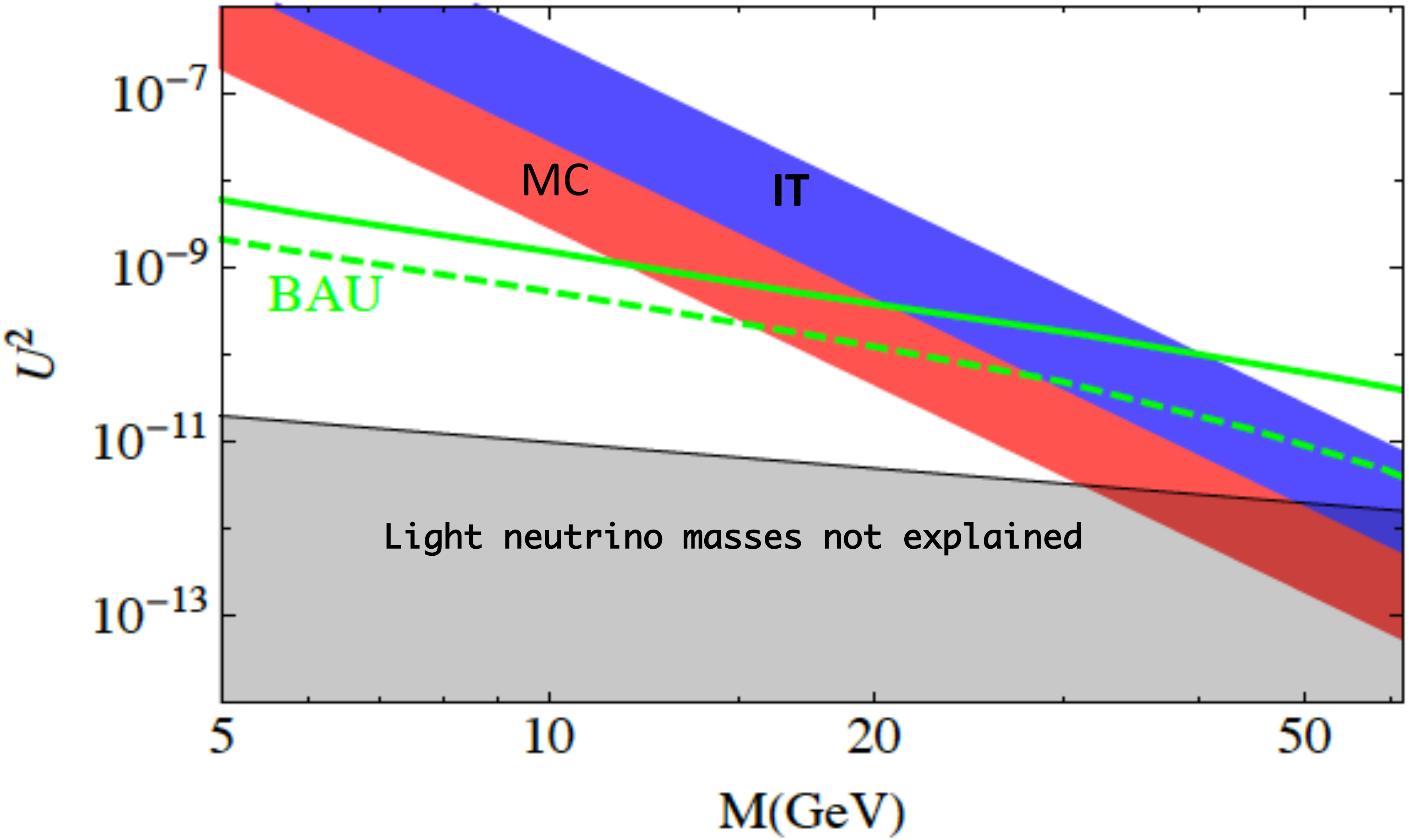
$NH$

$\rightarrow IH$

$(\delta, \phi) = \left(0, -\frac{\pi}{2}\right)$

$\delta, \phi) = \left(0, +\frac{\pi}{2}\right)$

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




Region of the $(M, U^2)$ plane where LHC displaced track selection efficiency is above 10% in the IT (blue band) and MC (red band)

# Conclusion

- If the coefficients of the d=5 operators are all of the same order, the strongest bounds come from the bound on the lightest neutrino mass:

$$\left|\frac{\alpha_W v^2}{2\Lambda}\right| \leq O(1) m_{lightest} \leq 0.2eV \rightarrow \frac{\alpha_W}{\Lambda} \leq 6\times10^{-9} TeV^{-1}$$

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- If we want the predictions on flavour mixings not to be lost, the bounds are even stronger

$$\left|\frac{\alpha_W v^2}{2\Lambda}\right| \leq \sqrt{\Delta m_{sol}^2}$$

In the presence, instead, of large hierarchies $\alpha_W \ll \alpha_{N\phi} \sim \alpha_{NB}$ (that could be protected by global symmetries: $U(1)_L, MFV$)

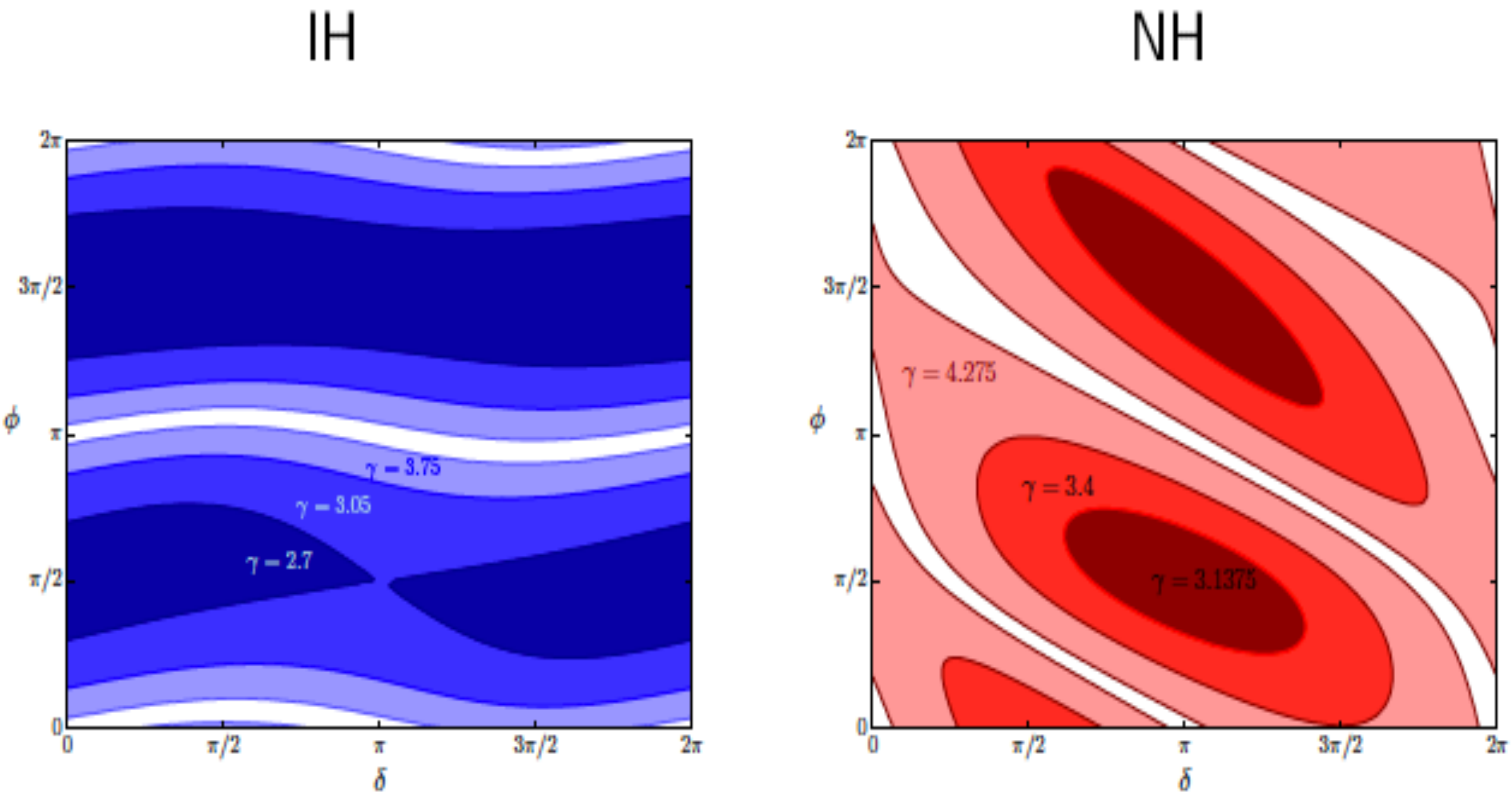
LHC ➡ $$\left|\frac{\alpha_{N\phi} v^2}{\sqrt{2}\Lambda}\right| \leq 10^{-3} - 10^{-2} \rightarrow \frac{\alpha_{N\phi}}{\Lambda} \leq 6\times(10^{-3} - 10^{-2}) TeV^{-1}$$

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

A.Aparici, K.Kim, A.Santamaria and J.Wudka, Phys. Rev. D80(2009) 013010

# Thanks for your attention

# High Predictivity

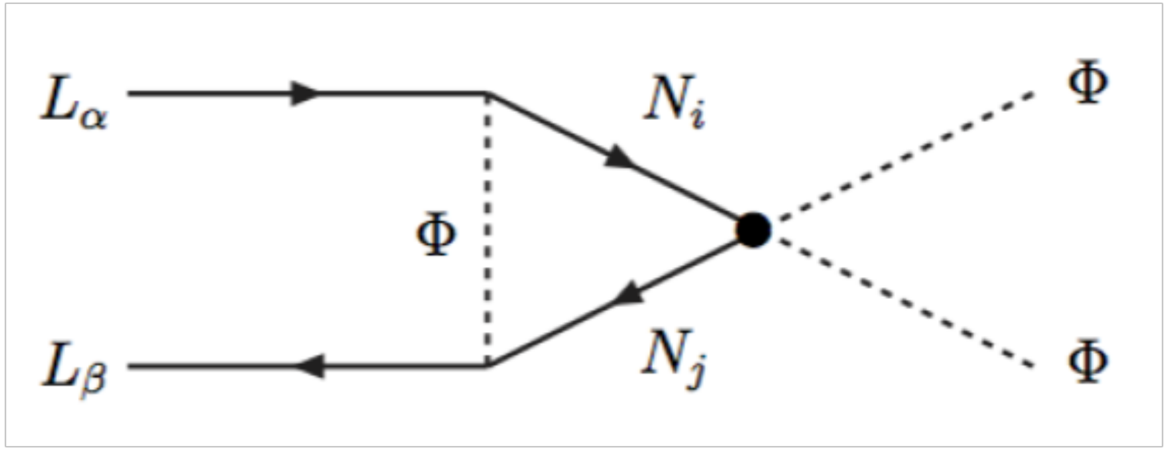



$5\sigma$ CP violation SHiP discovery on the plane $(\delta, \phi)$

$M = 1GeV$

A.C, P. Hernandez, J.Lopez-Pavon, M. Kekic, J.Salvado, 1611.05000

# Radiative corrections




$$\delta\left(\frac{\alpha_W}{\Lambda}\right) \propto \frac{1}{4\pi^2}\frac{Y^2}{4}\frac{\alpha_{N\Phi}}{\Lambda}\log\frac{\mu^2}{M^2}$$

This contribution has to be equal or smaller than the tree-level contribution

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