Testing the origin of neutrino masses and baryon asymmetry

Jacobo López-Pavón

New ν Physics: From Colliders to Cosmology
11 April 2025, IPPP (Durham University)

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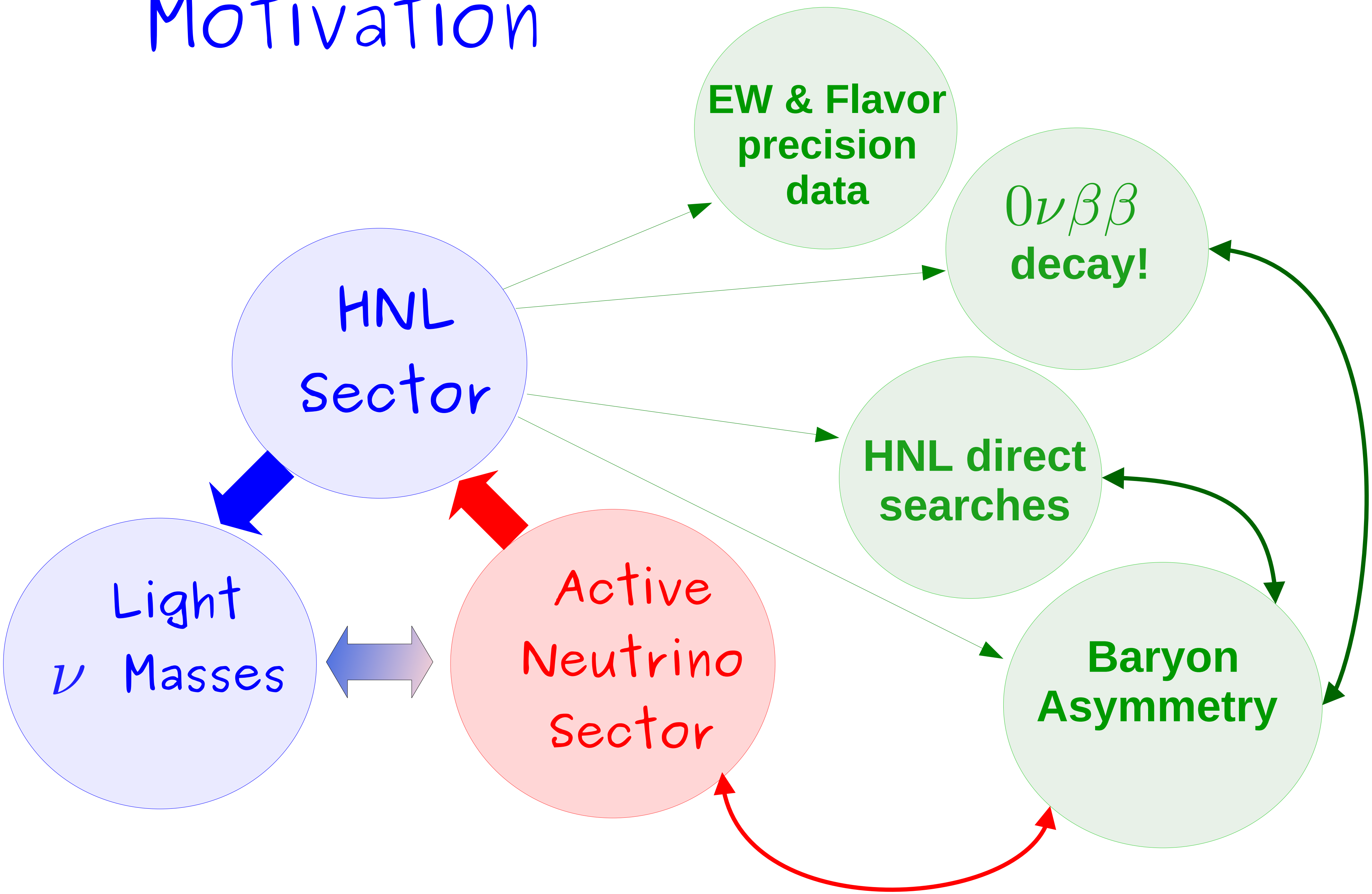
Motivation

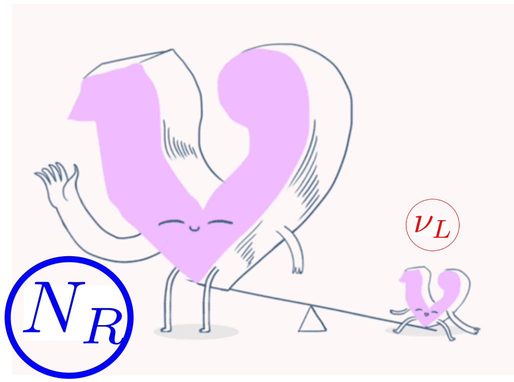

EW & Flavor precision data
$0\nu\beta\beta$ decay!
HNL Sector
HNL direct searches
Light ν Masses
Active Neutrino Sector
Baryon Asymmetry

Minimal model: Seesaw Model

- Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_i) to the SM field content:

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

Light Neutrino Masses



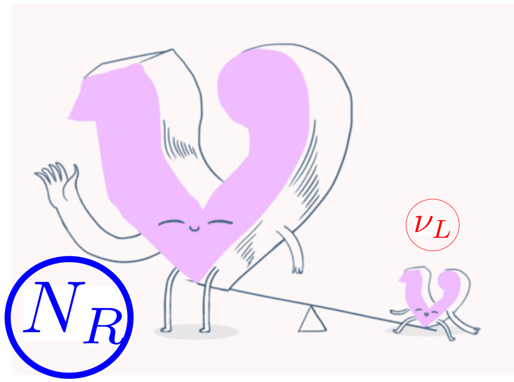
Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80

Mass Matrix

$$
\begin{array}{cccc}
 & \overline{\nu^c} & \overline{N} & \\
M_\nu = & \left(\begin{array}{c} 0 \\ Y v/\sqrt{2} \end{array} \right. & \left. \begin{array}{c} Y^T v/\sqrt{2} \\ M \end{array} \right) & \begin{array}{c} \nu \\ N^c \end{array}
\end{array}
$$

$$
\begin{pmatrix} \boxed{\frac{v^2}{2} Y^T M^{-1} Y} & 0 \\ 0 & M \end{pmatrix}
$$

Light Neutrino Masses



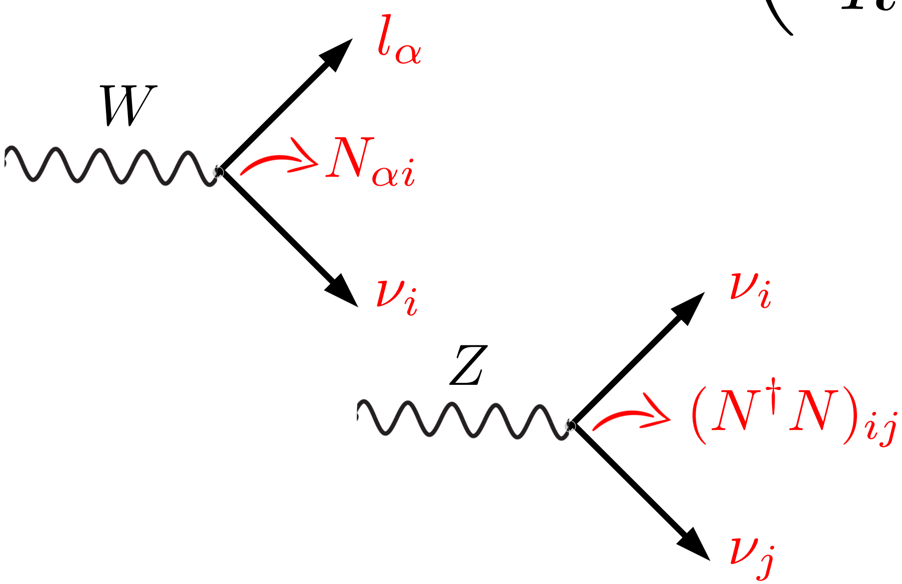
Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80

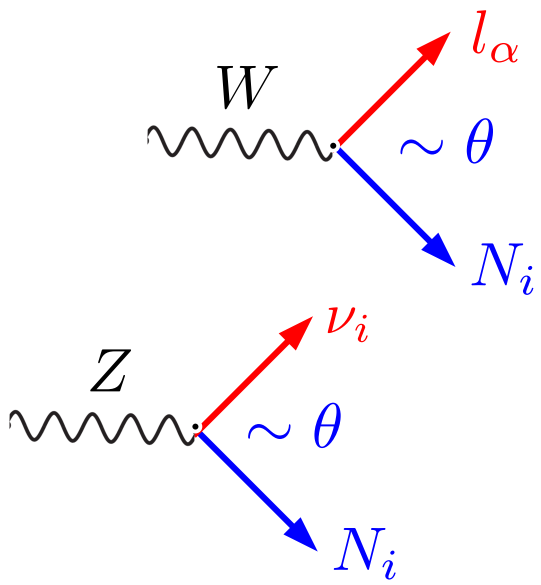
Mixing

$\nu_i - \nu_\alpha$
mixing

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

$N_i - \nu_\alpha$
mixing





Non unitary PMNS matrix

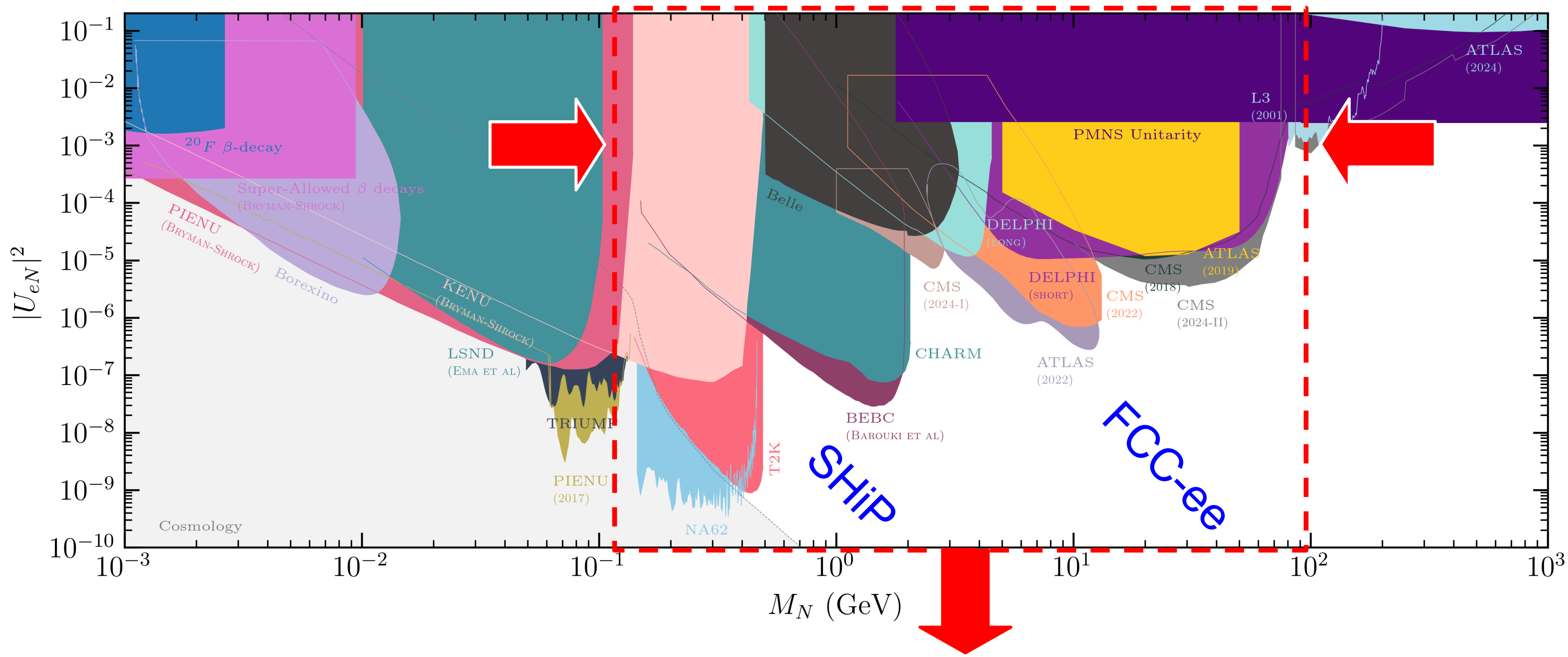
- Constraints from *EW and CLFV precision data*

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006
Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

"Direct" Searches

- *Sterile neutrino oscillations, kinks in beta decays & peak searches in semileptonic meson decays, beam-dump experiments, colliders...*

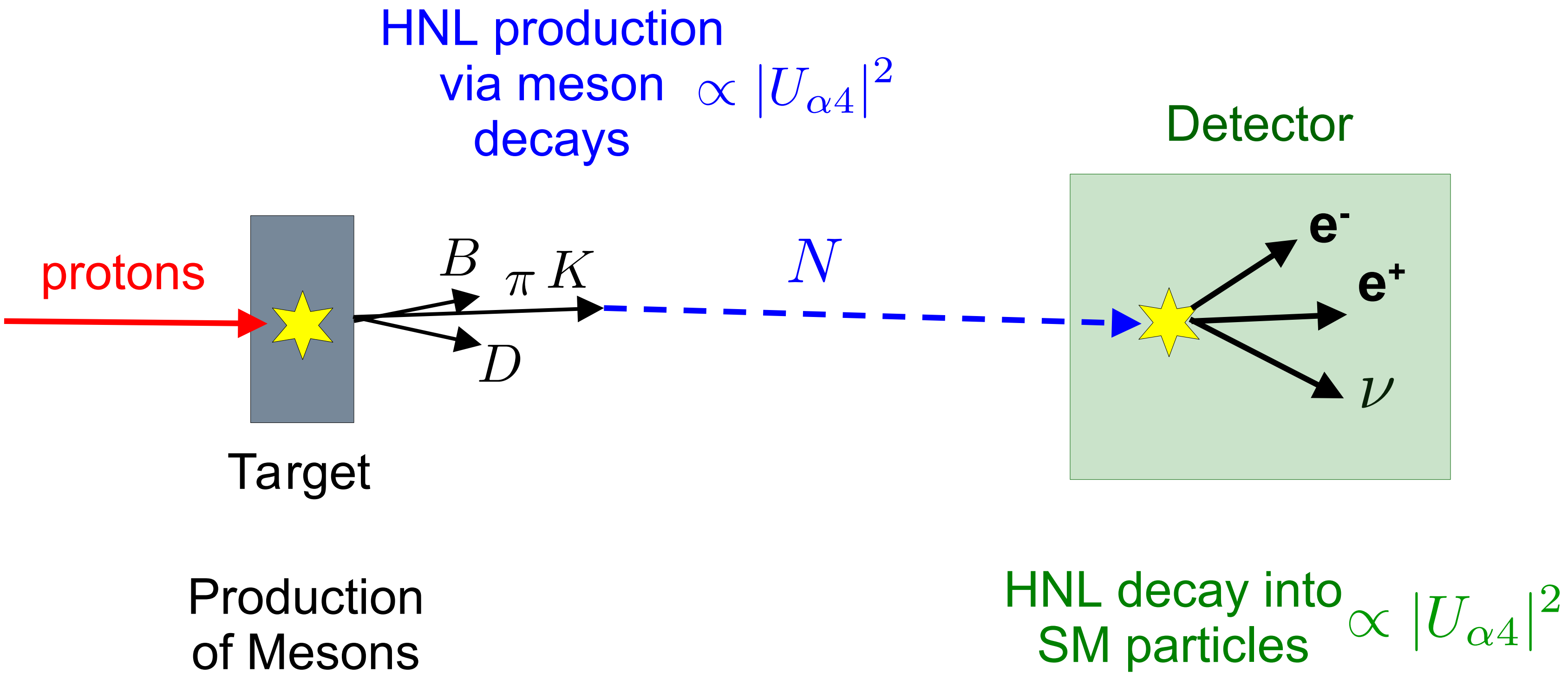
Current Constraints

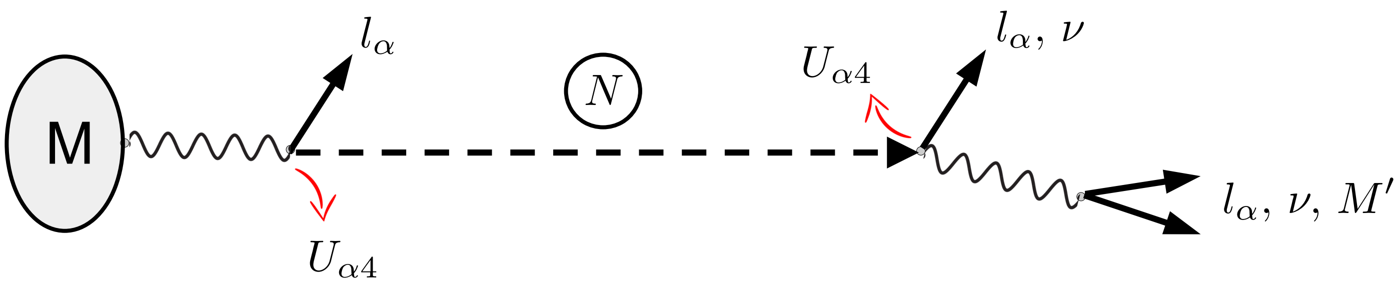


ARS Leptogenesis

https://github.com/mhostert/Heavy-Neutrino-Limits
Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2304.06772
See also talks by Lyon, Saimpert, Silva, Kretz, Mitra, Lutz and Sfar.

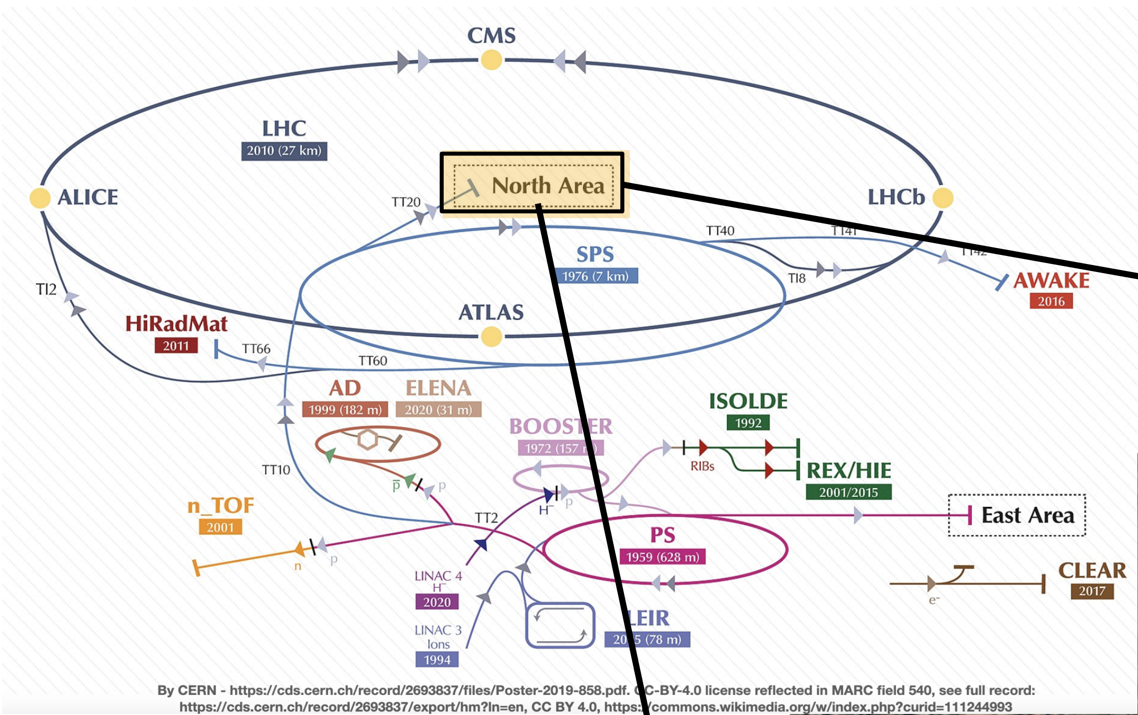
ProtoDUNE in beam dump configuration?

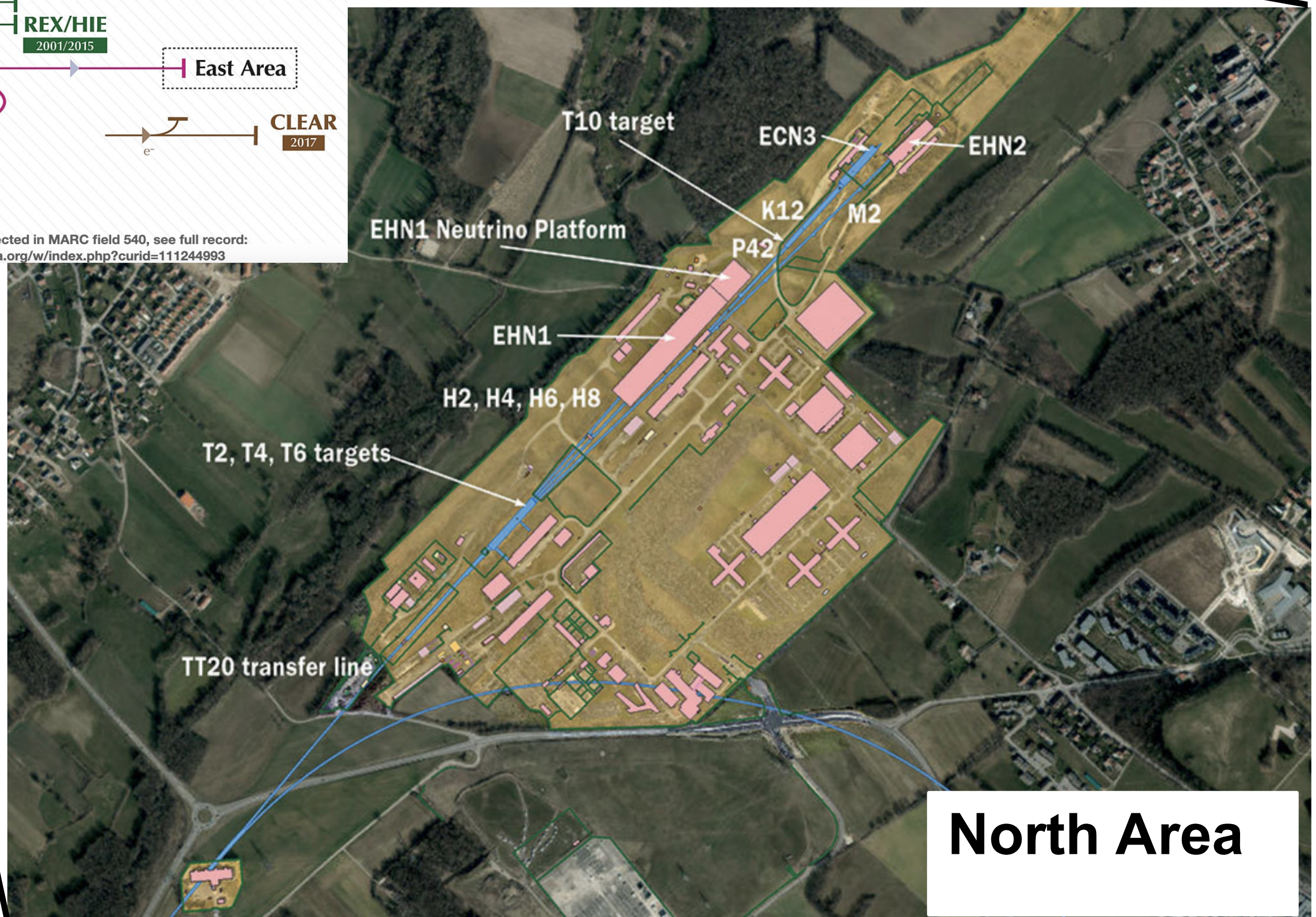




See talk by Jelle Groot for other beam dump searches

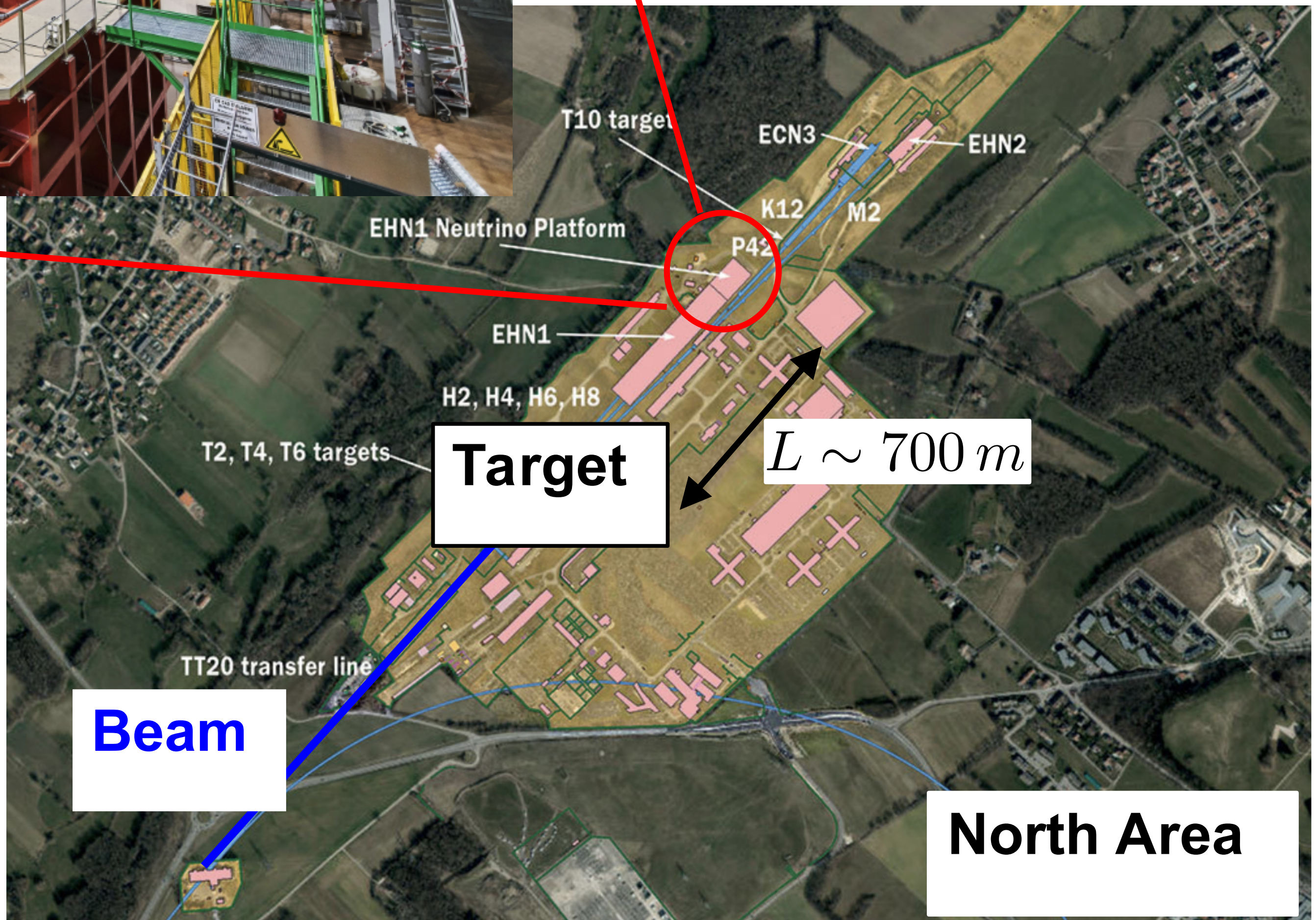
North Area & SPS accelerator @CERN





North Area & SPS accelerator @CERN

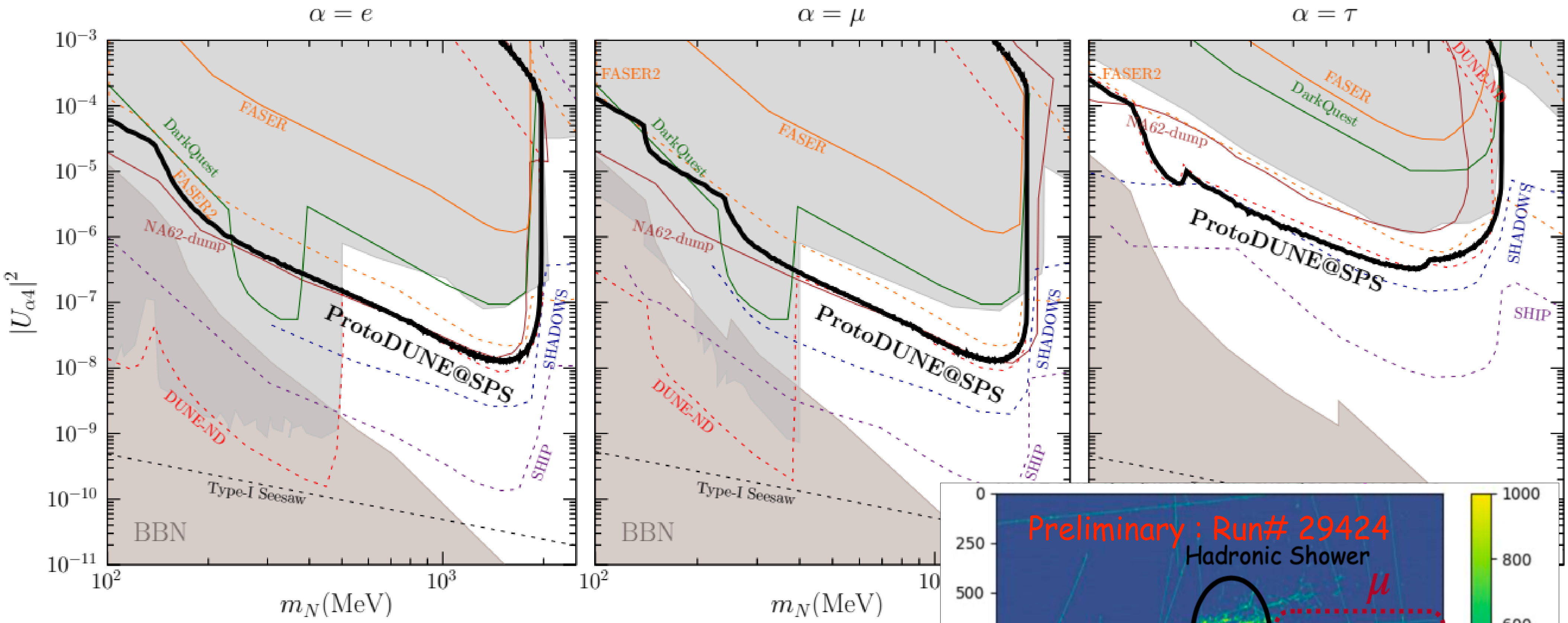
CERN Neutrino Platform
(**ProtoDUNE** detectors)



ProtoDUNE detectors
(already located at CERN)

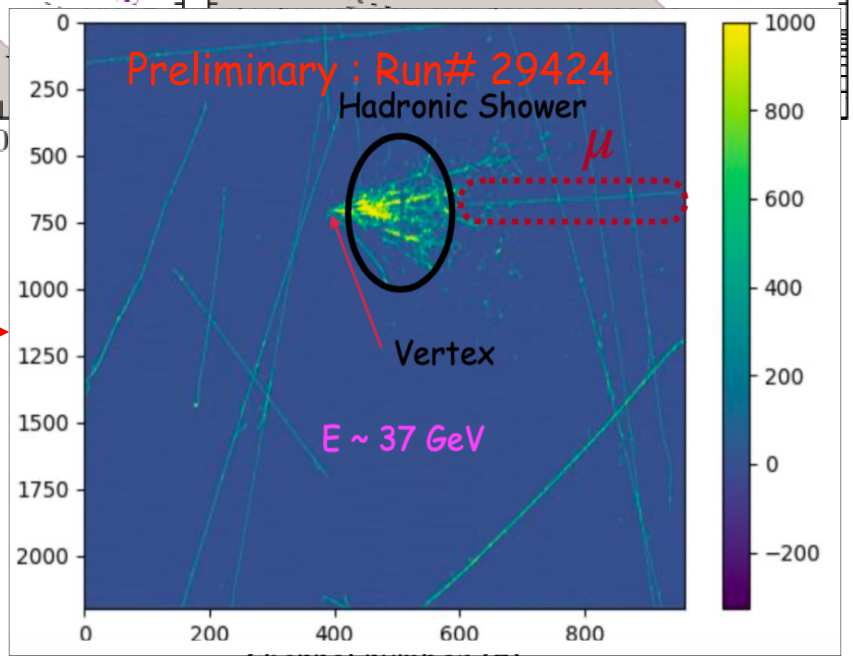
Two kiloton-scale liquid Argon Time Projection Chambers (LArTPCs) constructed to prototype and consolidate the technology of the DUNE Far Detector.

ProtoDUNE in beam dump configuration?

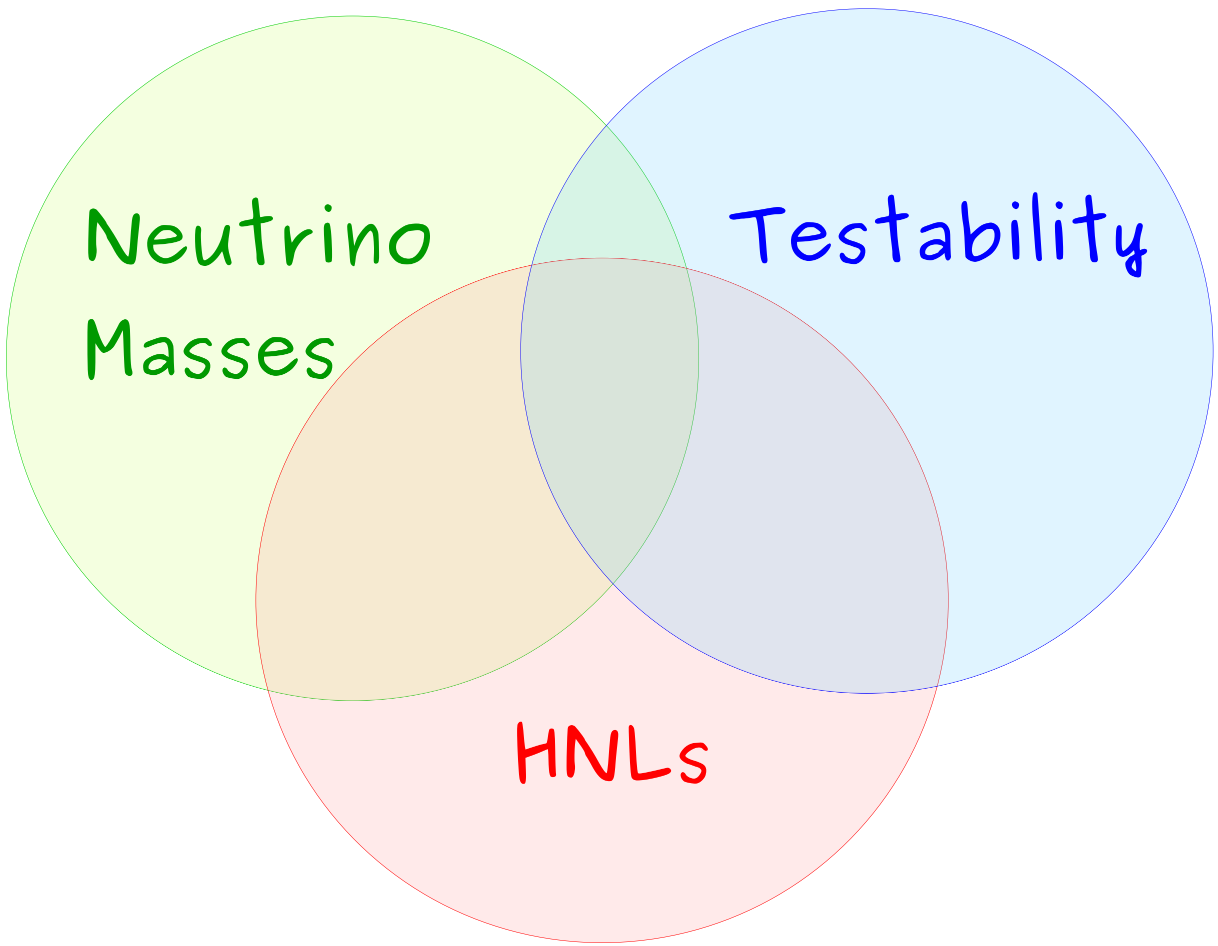


Coloma, JLP, Molina-Bueno, Urrea 2304.06765

Neutrino candidate detected during test in summer 2024

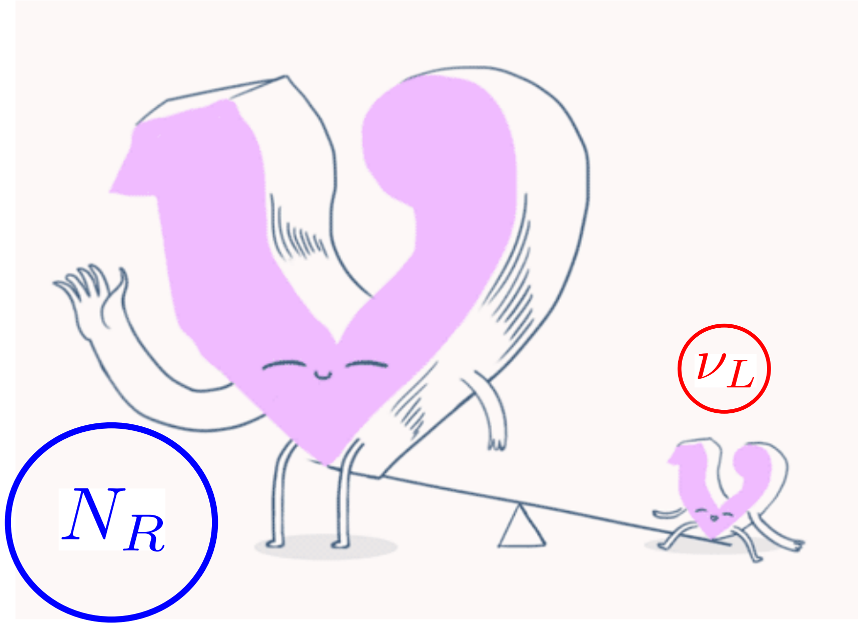


H. Amar, A. Chatterjee, C. Hasnip, W. Ketchum, L. Molina Bueno, D. Pullia, DUNE-DAQ...
https://indico.cern.ch/event/1460367/contributions/6240613/attachments/3001559/5289608/BSM@protoDUNE_NeutrinoWkshp_Animesh.pdf
https://indico.cern.ch/event/1381368/contributions/5963281/attachments/2888251/5062517/molina_LLP2024_2072024_v2.pdf


Neutrino
Masses
Testability
HNLs

Constraint on HNL mixing from active sector

- Generation of light neutrino masses imposes **constraints on mixing between HNLs and active neutrinos from *active neutrino sector***

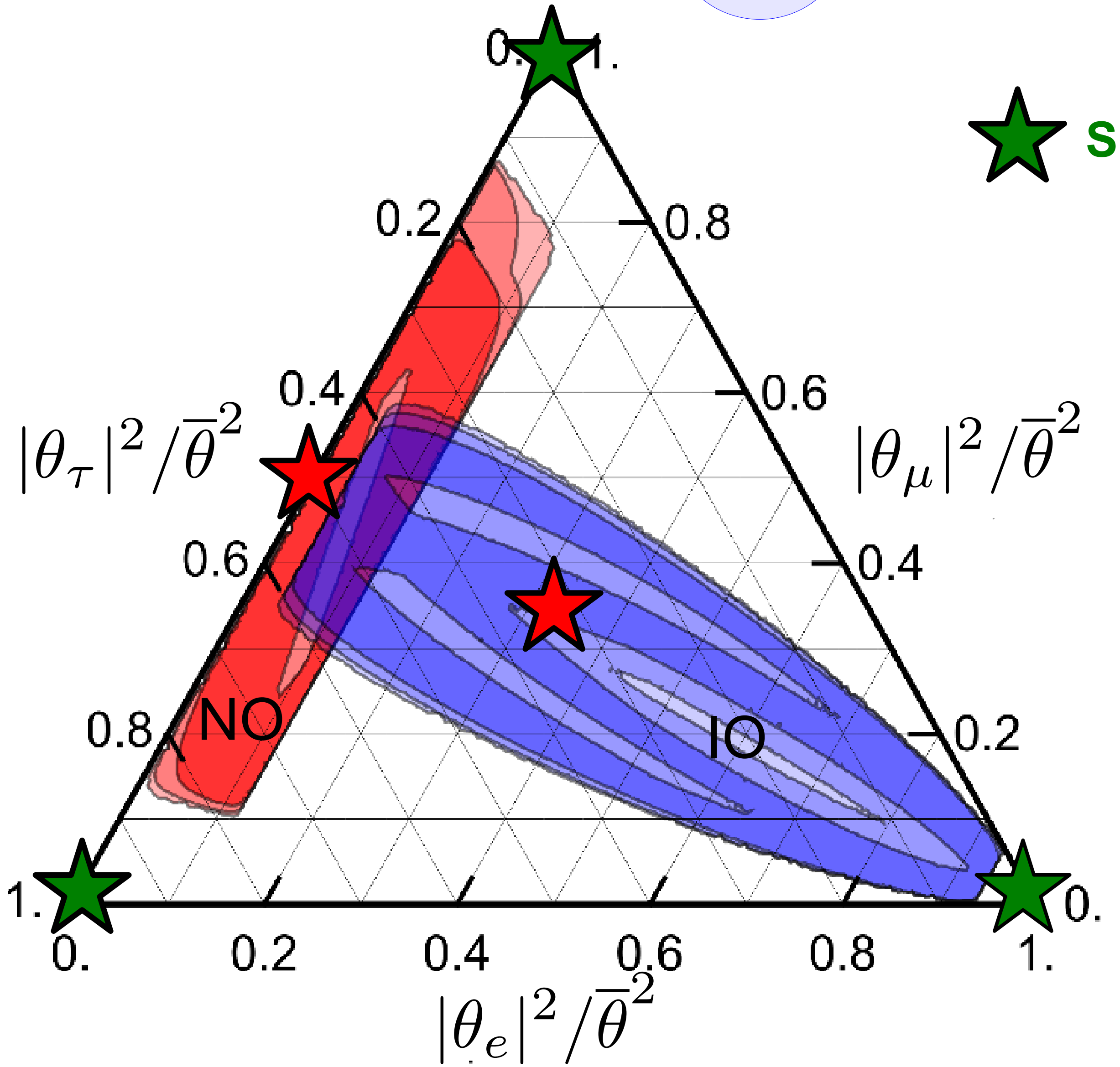


$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \boxed{\theta\, M\, \theta^T} = \boxed{U\, m\, U^T}$$

HNL sector

Light-active neutrino sector

Minimal model $n_R=2$: Flavor Structure

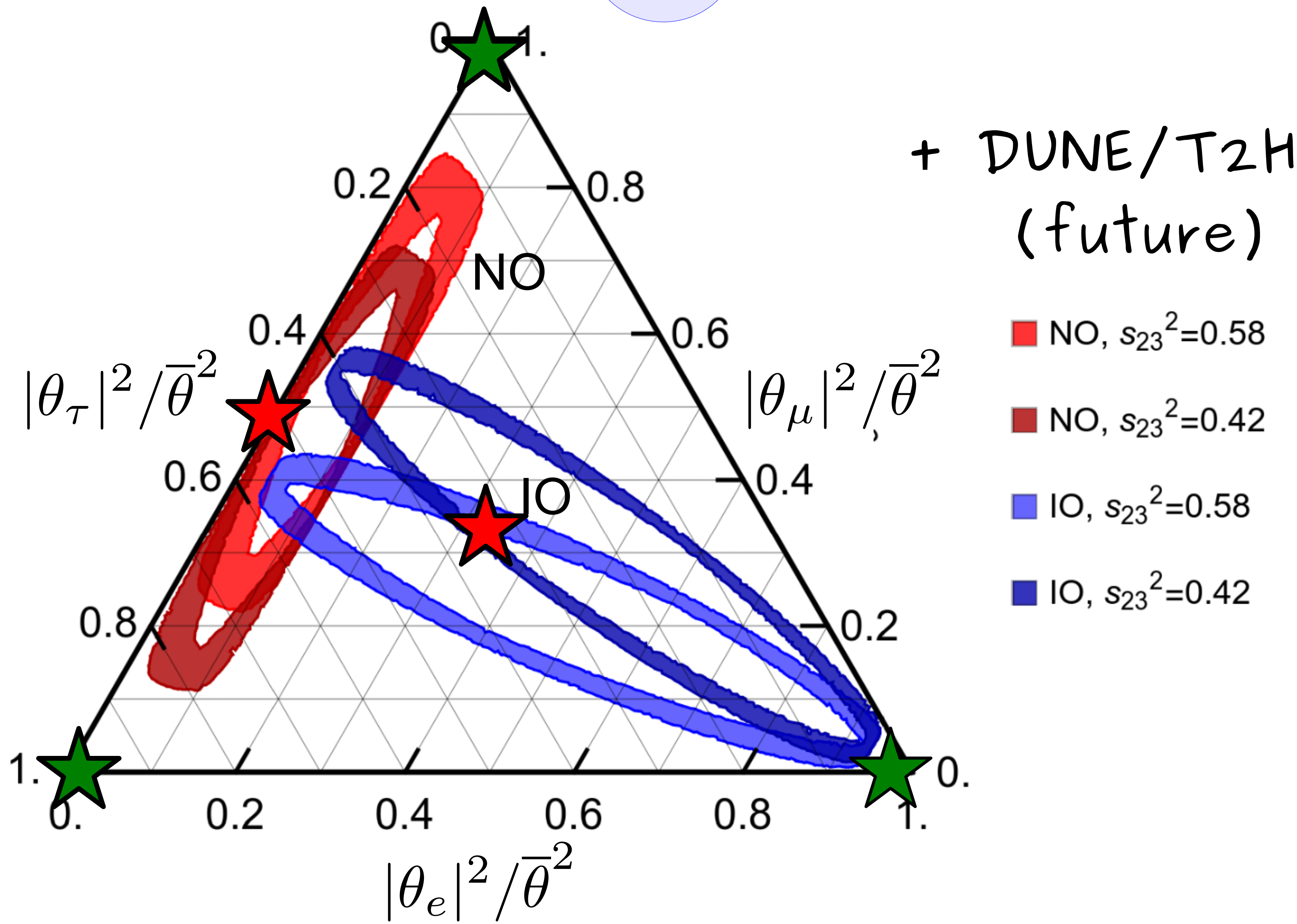


Single flavored benchmarks
(1,0,0), (0,1,0), (0,0,1)

NEW 2021
(0, 1/2, 1/2)
(1/3, 1/3, 1/3)

Abdullahi et al 2203.08039
Drewes, Klaric, JLP 2207.02742
Caputo, Hernandez, JLP, Salvado, 1704.08721

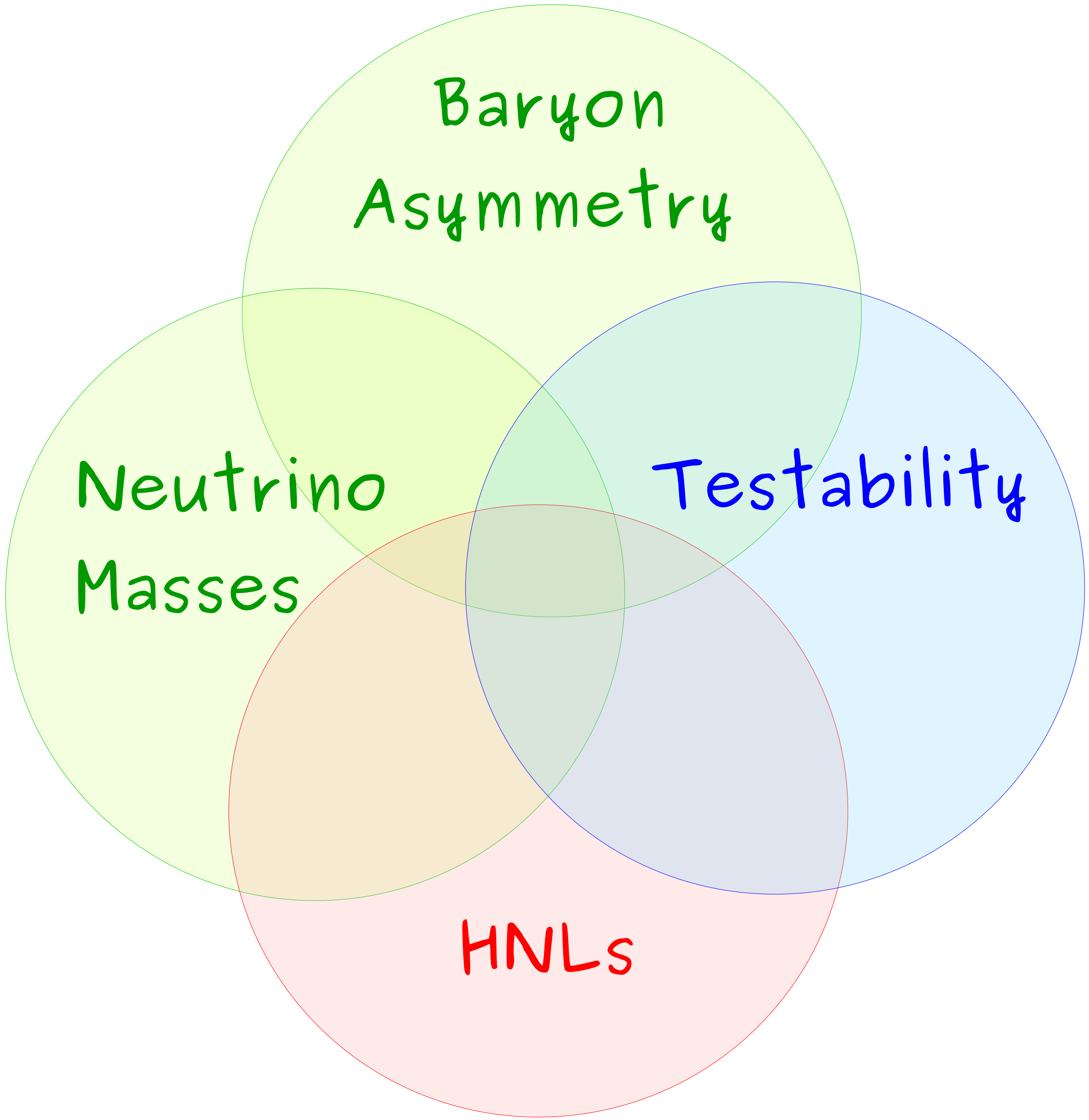
Minimal model $n_R=2$: Flavor Structure



+ DUNE/T2HK…
(future)

DUNE forecast assuming $\delta = -\pi/2$

Abdullahi et al 2203.08039
Drewes, Klaric, JLP 2207.02742



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719
Hernandez, JLP, Rius, Sandner 2207.01651
Hernandez, JLP, Rius, Sandner 2305.14427

Sakharov conditions

1 **Baryon number violation**

Sphalerons translate lepton asymmetry into baryon asymmetry.

2 **C and CP violation**

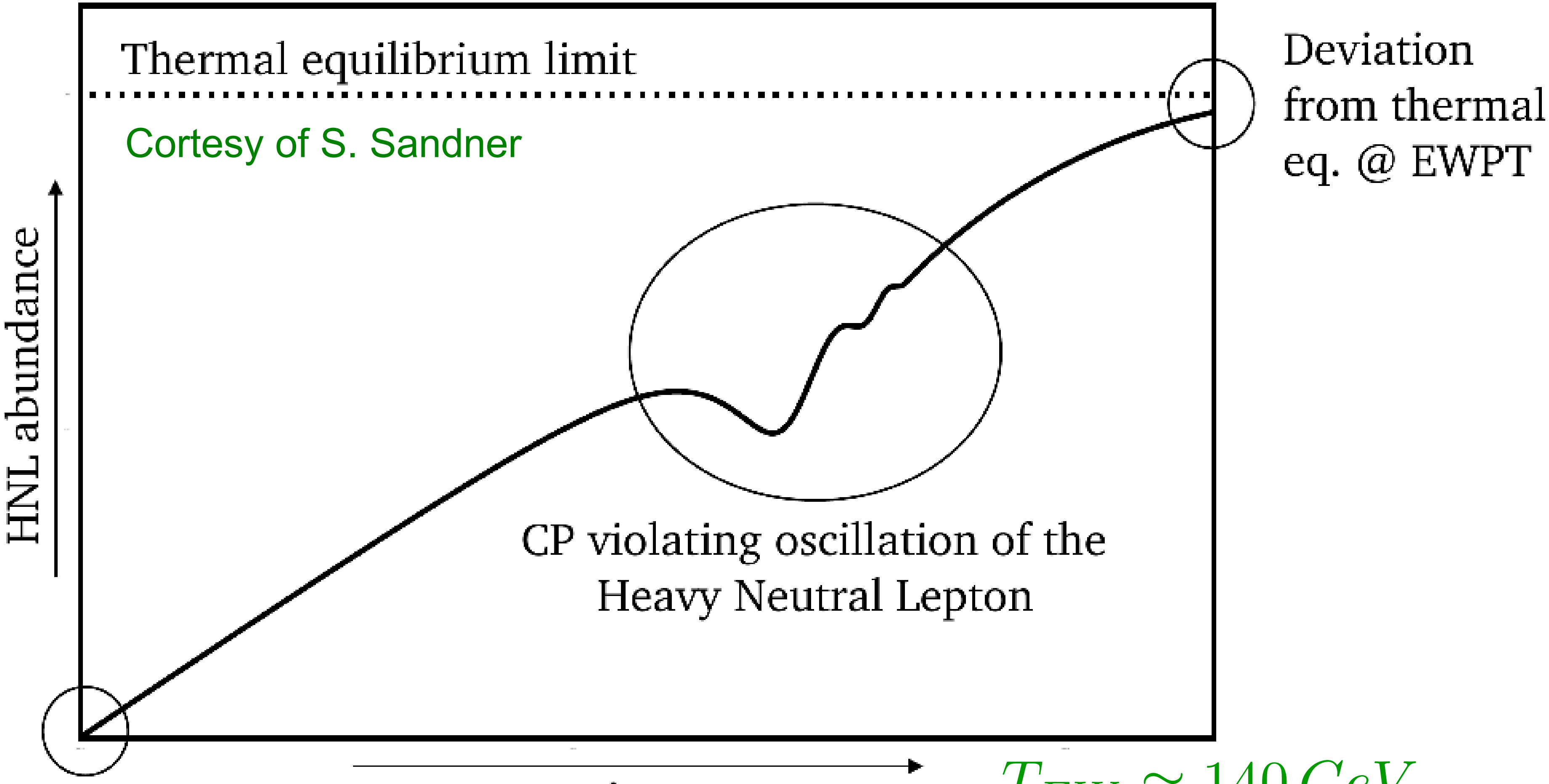
New sources of CP violation in lepton *sector encoded in the Yukawa couplings* (not enough $\cancel{CP}$ in quark sector)

(Gavela, Hernandez Orloff, Pene, Quimbay 1994)

3 **Departure from thermal equilibrium**

$$\Gamma_N \leq H(T) \qquad T > T_{EW}$$

Low Scale Leptogenesis (ARS)



Initial 0 abundance

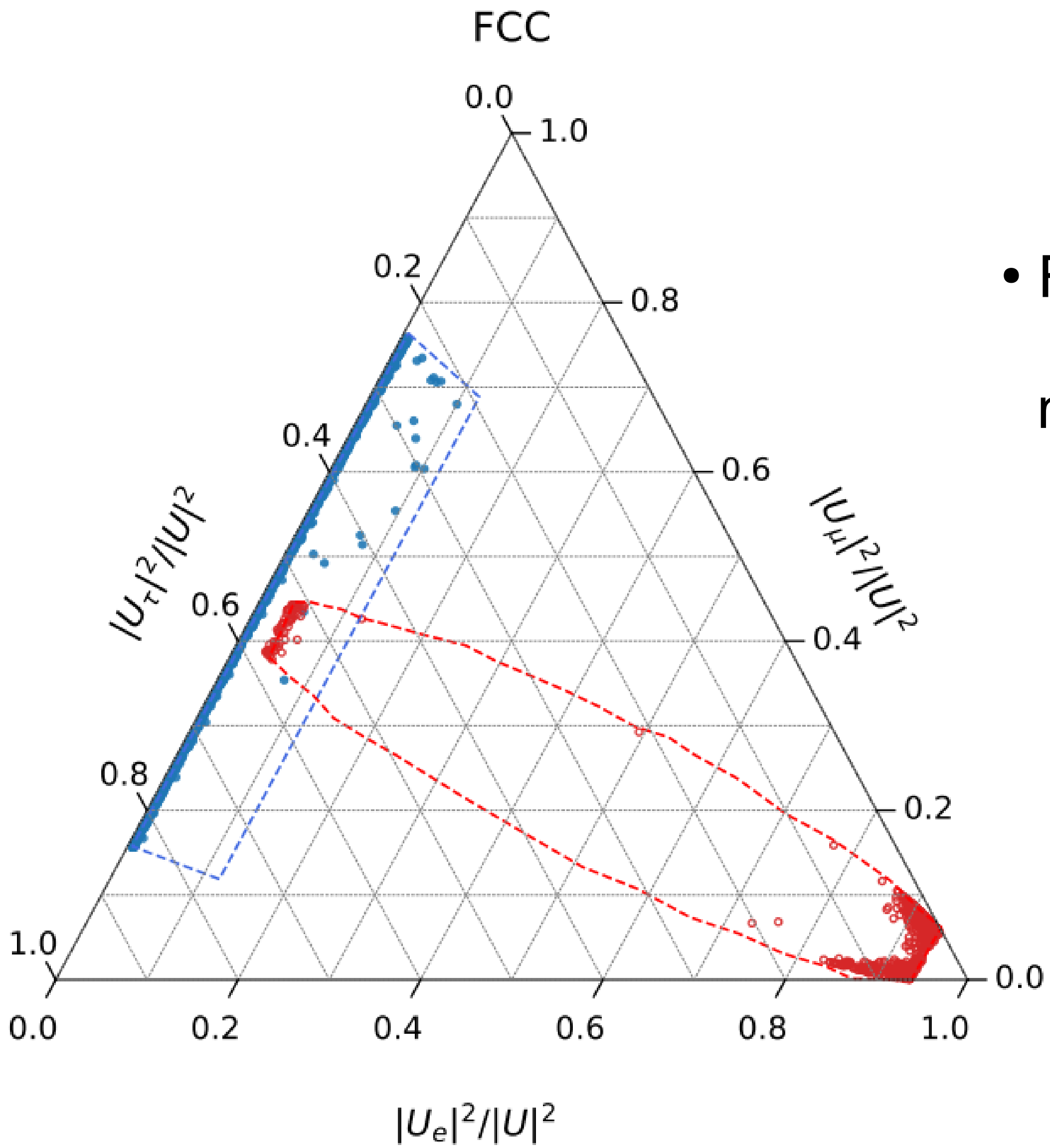
=> freeze-in

$$T_{EW} \approx 140\,GeV$$

$L \neq 0$ → $B-L=0$ → $B \neq 0$

Akhmedov, Rubakov, Smirnov (ARS)
Asaka, Shaposnikov (AS)

Baryon asymmetry: flavor structure

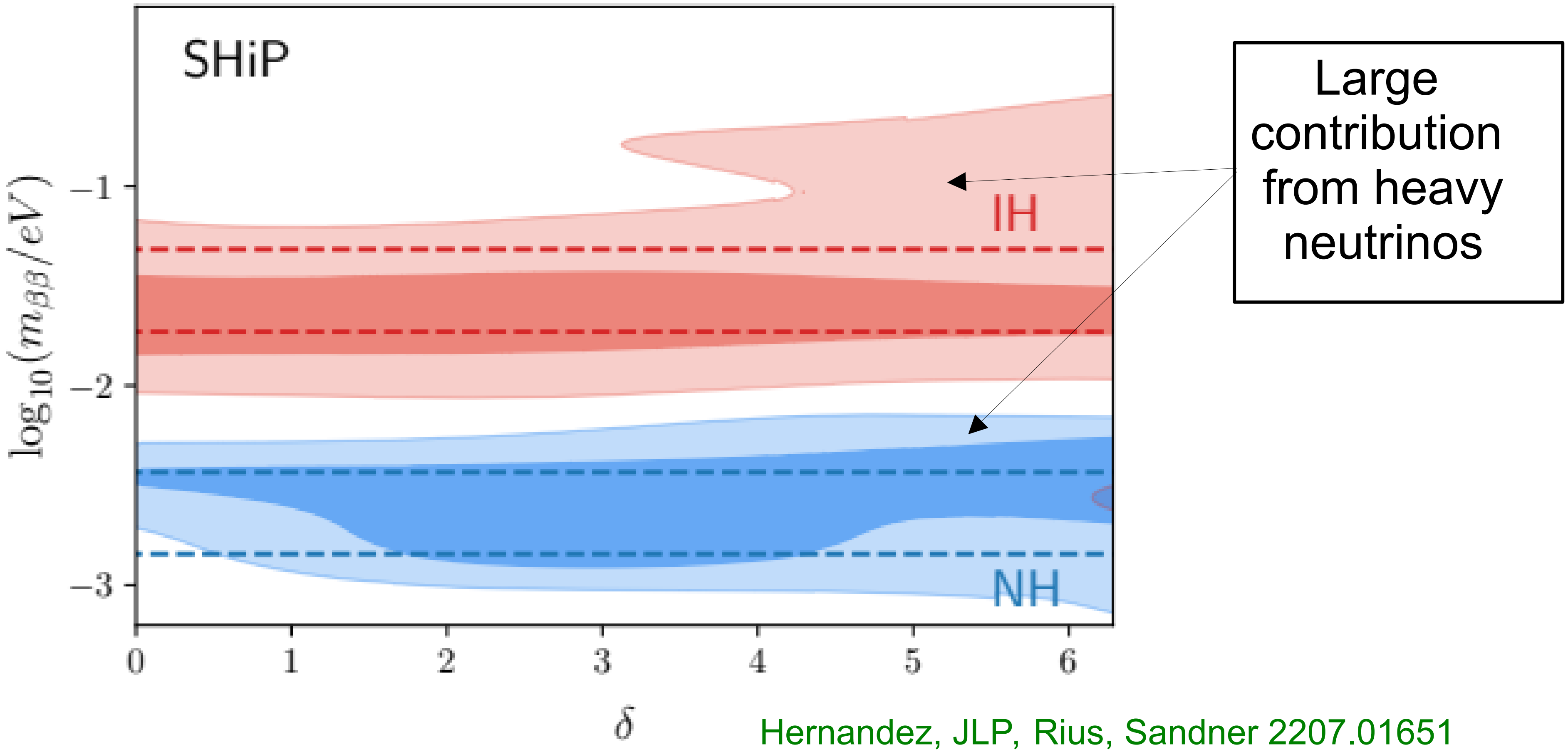


- Flavor correlations implied by reproducing observed matter-antimatter asymmetry in the region of parameter space that can be covered by FCC-ee for

$$\Delta M/M = 10^{-2}$$

Hernandez, JLP, Rius, Sandner 2207.01651

Baryon asymmetry: 0νββ decay



Hernandez, JLP, Rius, Sandner 2207.01651

- Correlation with neutrinoless decay rate implied by reproducing observed baryon asymmetry in region of parameter space that can be probed by SHiP for

$$\Delta M/M = 10^{-2}$$

See also talk by Vaisakh Plakkot and Jelle Groot

Predicting Y_B in minimal model $n_R=2$

- **Baryon asymmetry depends on all the unknown parameters**

SHiP & FCC-ee sensitive to $|\theta_\alpha|,\ M,\ \Delta M$

$$(\theta_\alpha)^2 \propto \boxed{e^{-i\beta}}\ \boxed{y^2 f\left(\delta, \phi, M, \Delta M\right)}$$

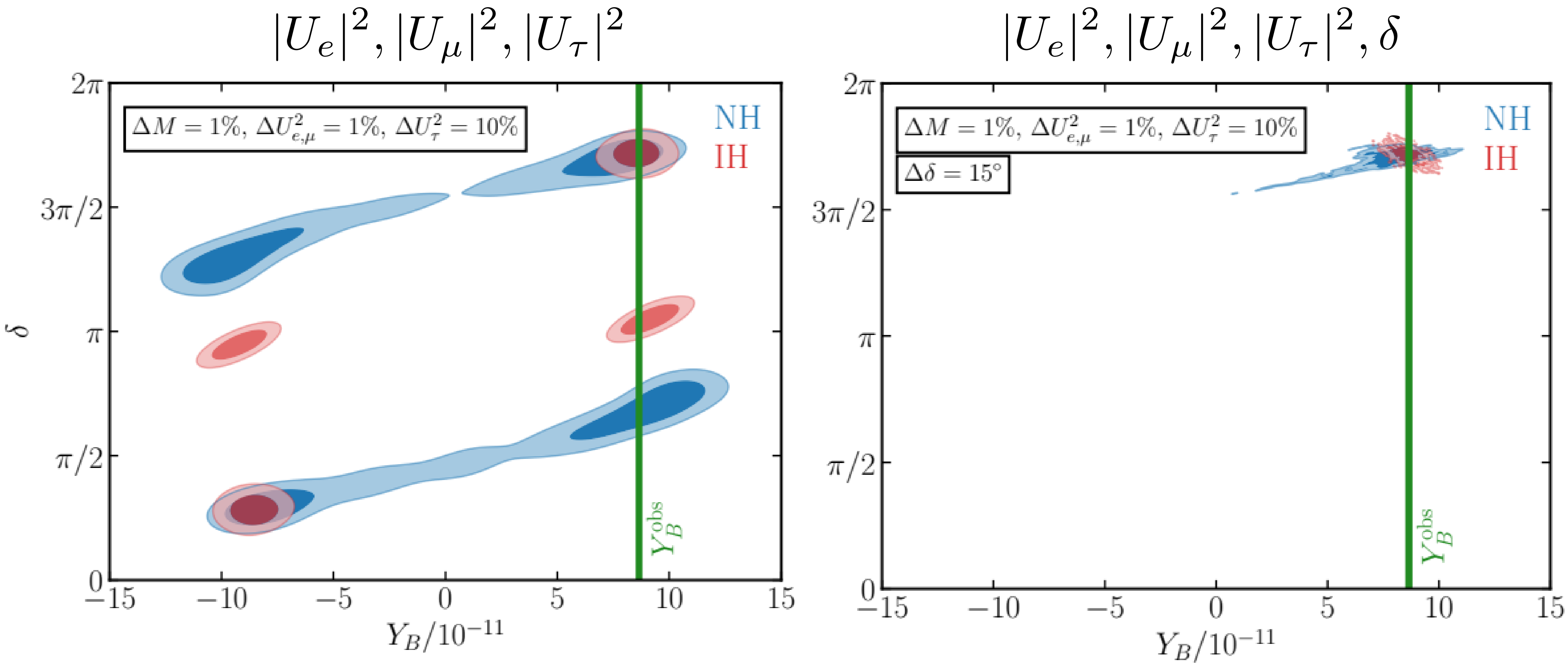
Neutrinoless double beta decay sensitive to β through interference between light and heavy contribution

Non physical phase if HNLs are degenerate

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Simplest scenario: degenerate HNLs

- Measurement of CP violation in neutrino oscillations, HNL mass and mixing with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry.



	$M^{\rm true}/{\rm GeV}$	$(U_e^2)_{\rm true}$	$(U_\mu^2)_{\rm true}$	$(U_\tau^2)_{\rm true}$	$\delta^{\rm true}/{\rm rad}$
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

FCC-ee + DUNE/T2HK

Hernandez, JLP, Rius, Sandner 2305.14427

Conclusions

- Introducing HNLs allows to explain the origin of neutrino masses and baryon asymmetry of our universe

- **Low Scale Minimal Seesaw Models** are testable and highly predictive: ***mechanisms generating neutrino masses and Baryon asymmetry can be potentially tested***

- Strong complementarity among different observables as neutrino oscillations, cosmology, neutrinoless double beta decay and HNLs direct searches.

- In non minimal models HNLs may present new interactions and thus a different phenomenology (Left-Right symmetric models, dark U(1) extensions, etc).
  See also talks by Ruiz, Groot, Mitra and Lutz

- Low energy effects of additional new physics at higher energies can be studied via an extension of the SMEFT including the HNLs as building blocks
  Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040
  See also talks by Titov and Bates

Thank you!

Project CNS2022-136013 funded by MICIU/AEI/10.13039/501100011033
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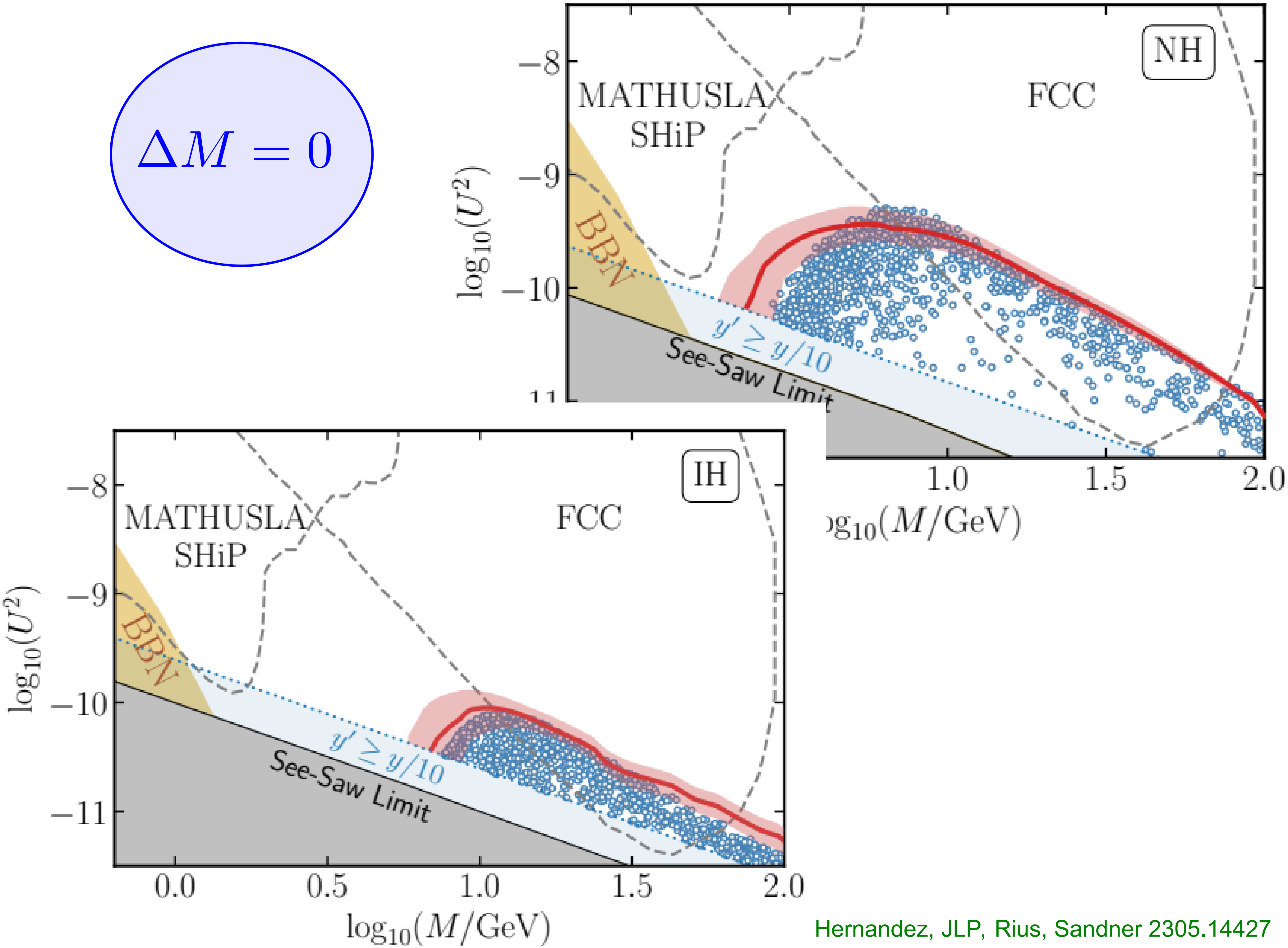
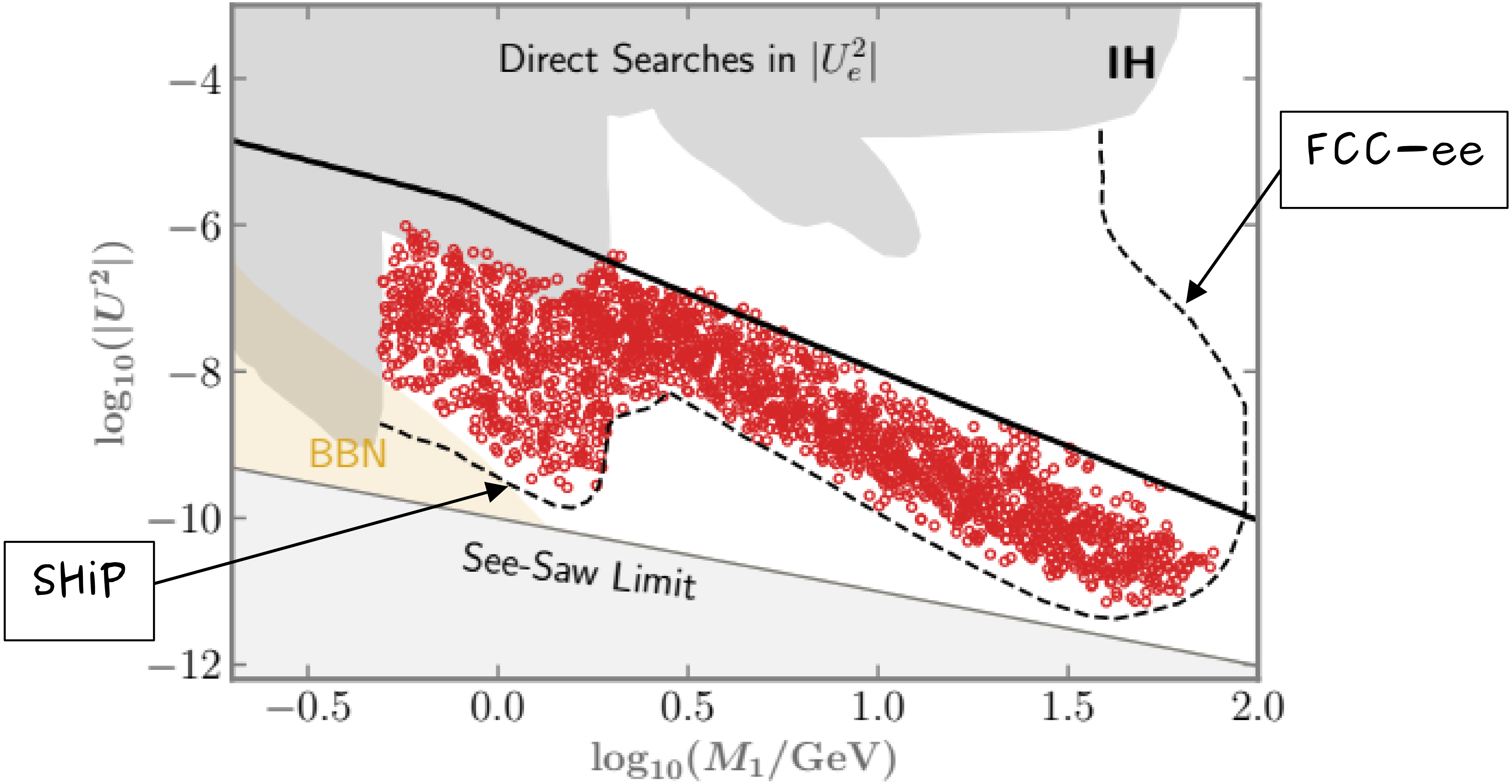
$\Delta M = 0$



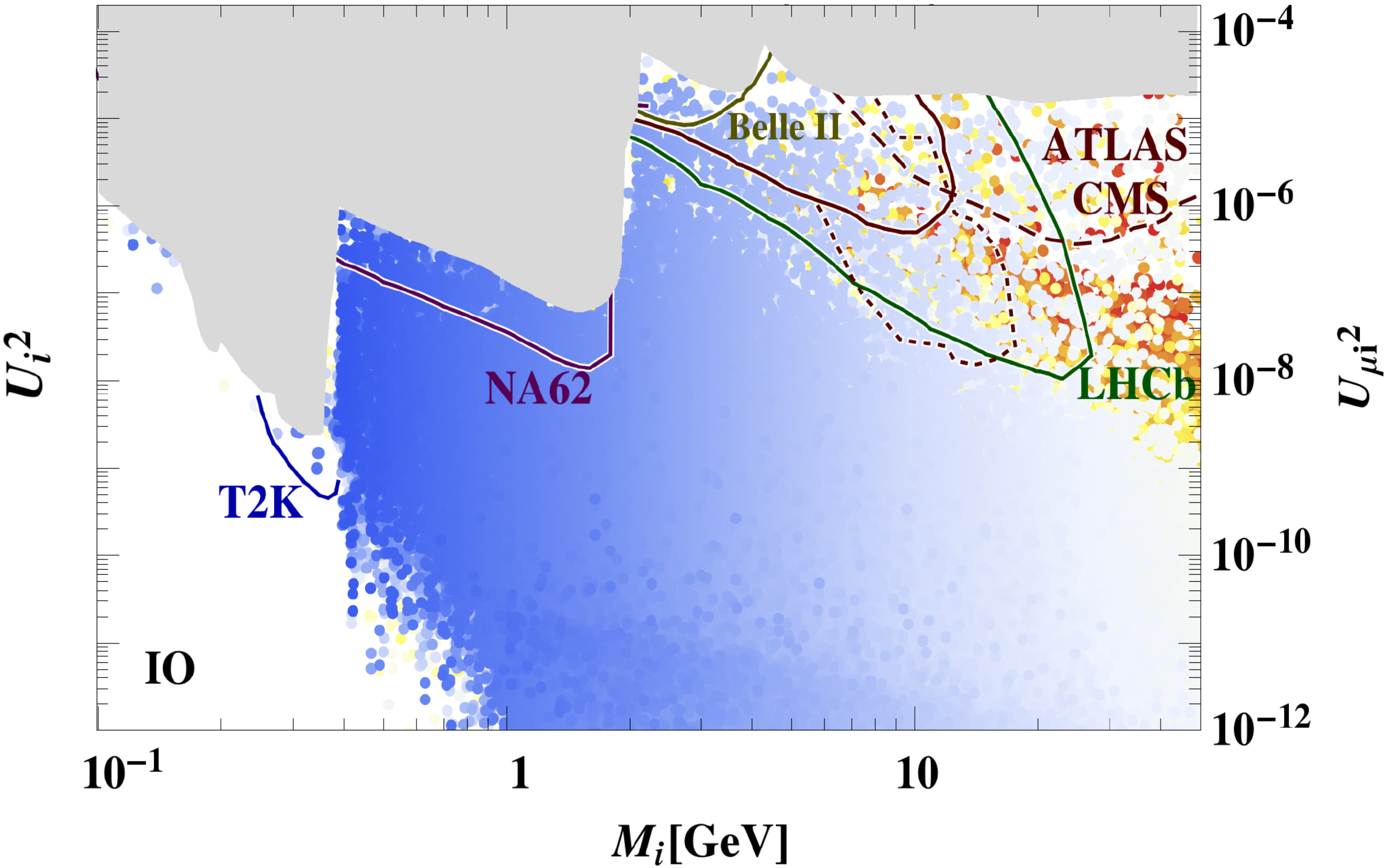
Hernandez, JLP, Rius, Sandner 2305.14427

Potentially Testable $n_R=2$



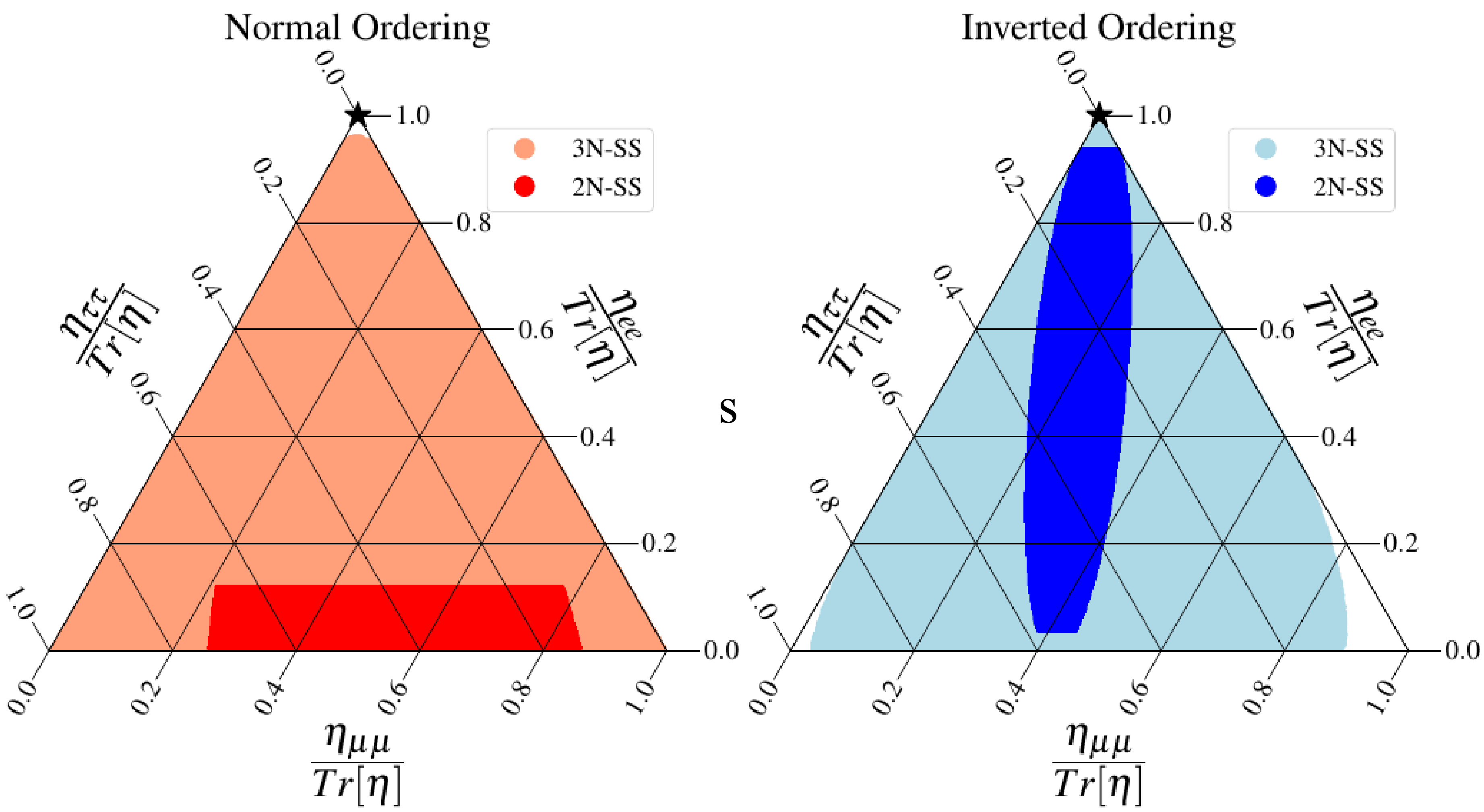
Hernández, JLP, Rius, Sandner 2207.01651

Potentially Testable $n_R=3$



Abada,Arcadi, Domcke, Drewes, Klaric, Lucente 1810.12463

Neutrino oscillation bounds on Flavor structure



Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Direct searches of HNLs

- Direct detection requires:

$$\theta_{\alpha i} \gg \sqrt{m/M} \Longleftrightarrow \boldsymbol{R_{ij} \gg 1}$$

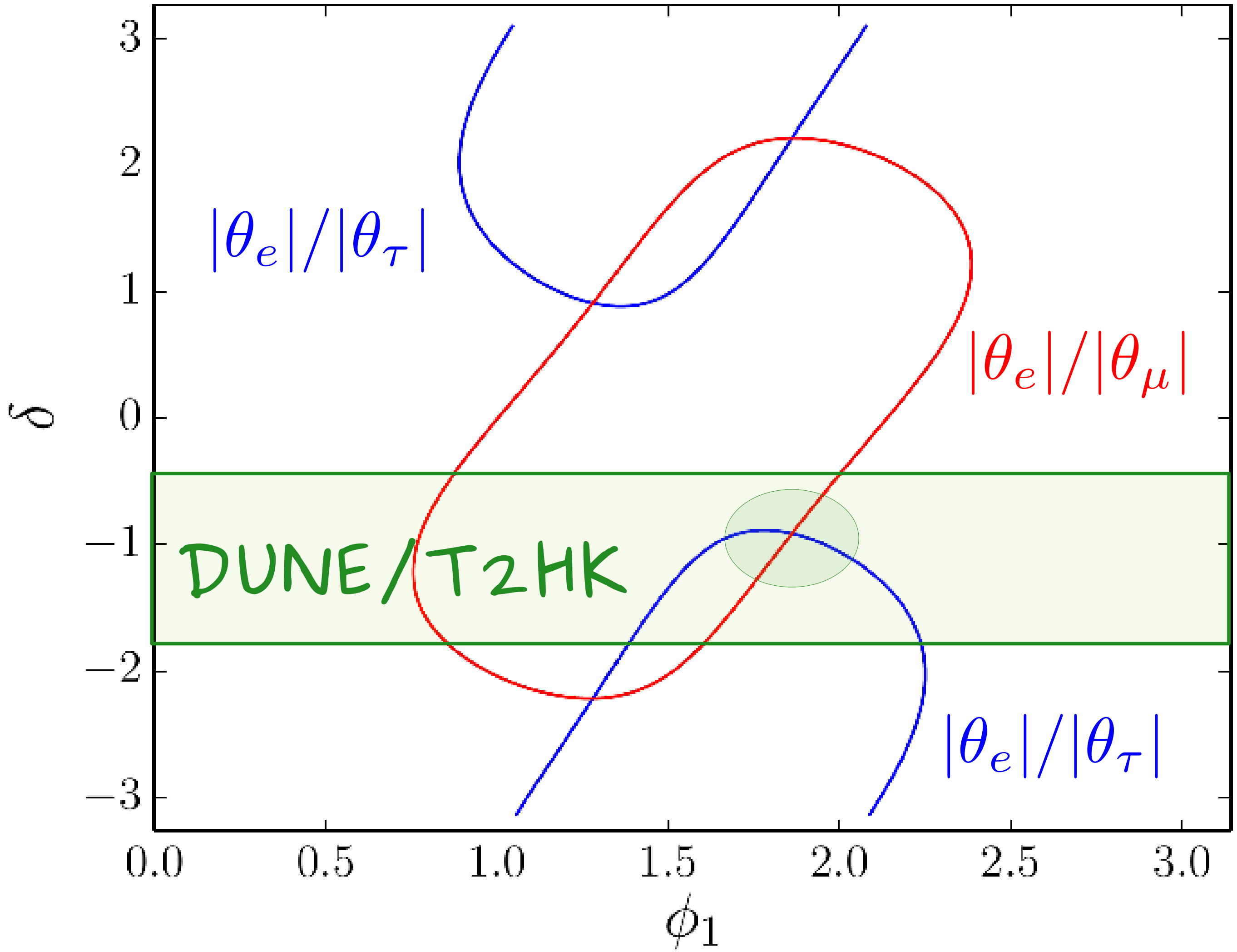
$$\Longleftrightarrow \theta^2_{\alpha i} \propto e^{-2\theta i} \boxed{e^{2\gamma} f\left(\delta, \phi_1, M_j\right)}$$

Sensitivity to PMNS CP-phases! δ, ϕ_1

- $|\theta_{e1}|^2/|\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2/|\theta_{\mu 2}|^2 \simeq$

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

PMNS CP-phases from HNLs searches

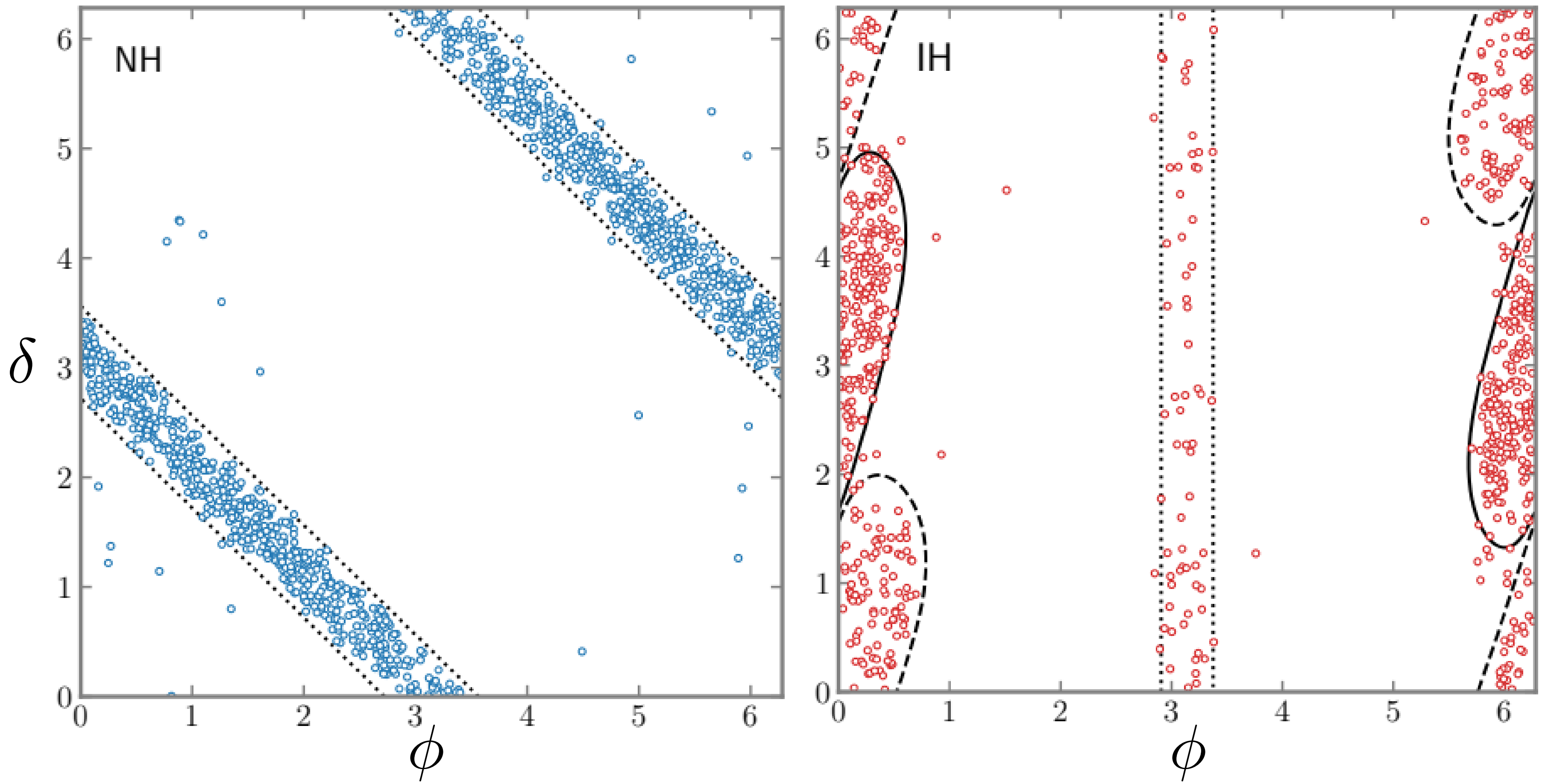


$n_R = 2$

- **Potential determination of the PMNS Majorana phase!**

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719
Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

Baryon asymmetry: PMNS CP phases

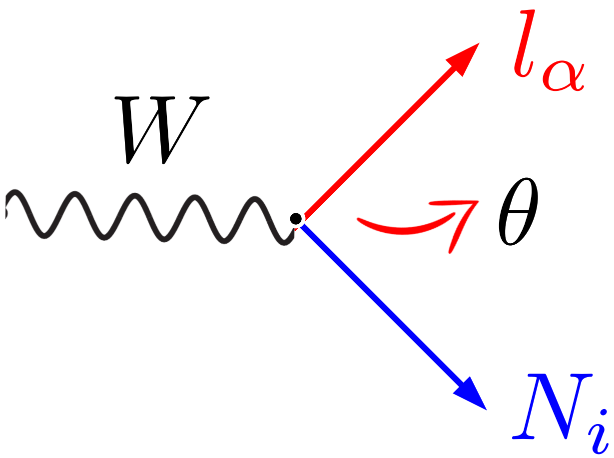


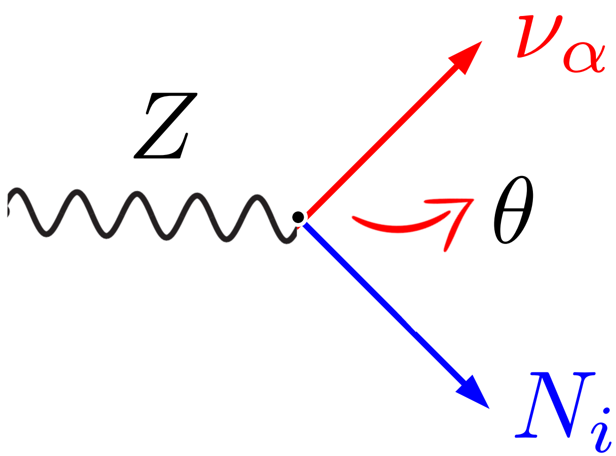
• PMNS CP-phase correlations implied by reproducing observed baryon asymmetry in region of parameter space that can be covered by FCC-ee for

$$\Delta M/M = 10^{-2}$$

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Constraint on HNL mixing from active sector





Casas-Ibarra

$$\theta = \boxed{iU\, m^{1/2}}\,\boxed{R^\dagger M^{-1/2}}$$

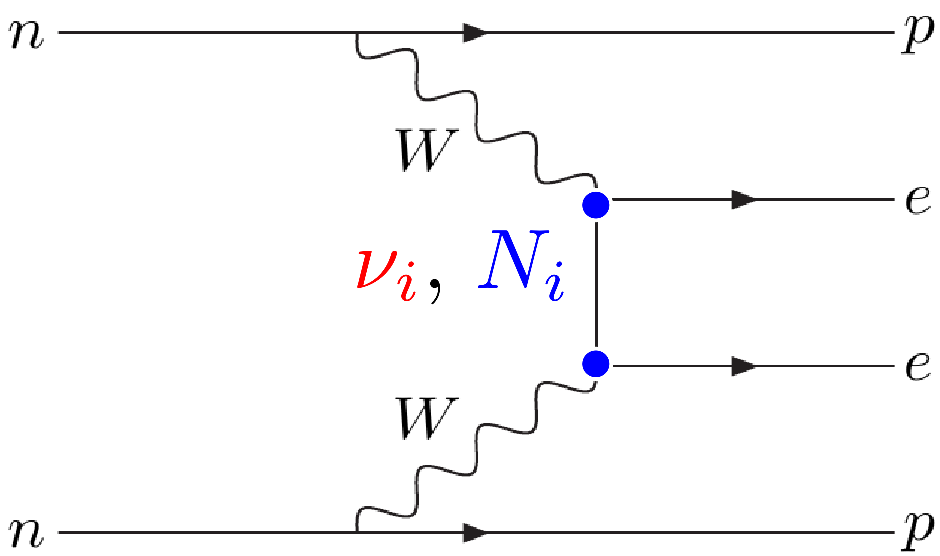
Active Sector

- 3x3 PMNS mixing matrix
- light neutrino masses

HNL Sector

- Complex $3 \times n_R$ orthogonal matrix
- HNL masses

Neutrinoless double beta decay



$$m_{\beta\beta} = \sum_{i=light} U_{ei}^2 m_i + \sum_{i=heavy} \overbrace{\underbrace{\frac{\mathcal{M}^{0\nu\beta\beta}(M_i)}{\mathcal{M}^{0\nu\beta\beta}(0)}}}^{\text{NMEs}} \theta_{ei}^2 M_i$$

$$M_i \gg 100\, MeV : \quad \sim 1/M_i^2$$

$$M_i \ll 100\, MeV : \quad \sim 1$$

Predicting Y_B in minimal model $n_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO
contribution

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

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

$$\left. \boxed{- \quad f(A)\, e^{2i\beta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 \frac{(0.9\,\mathrm{GeV})^2}{2M_1^2} \frac{\Delta M}{M_1}} \right|$$

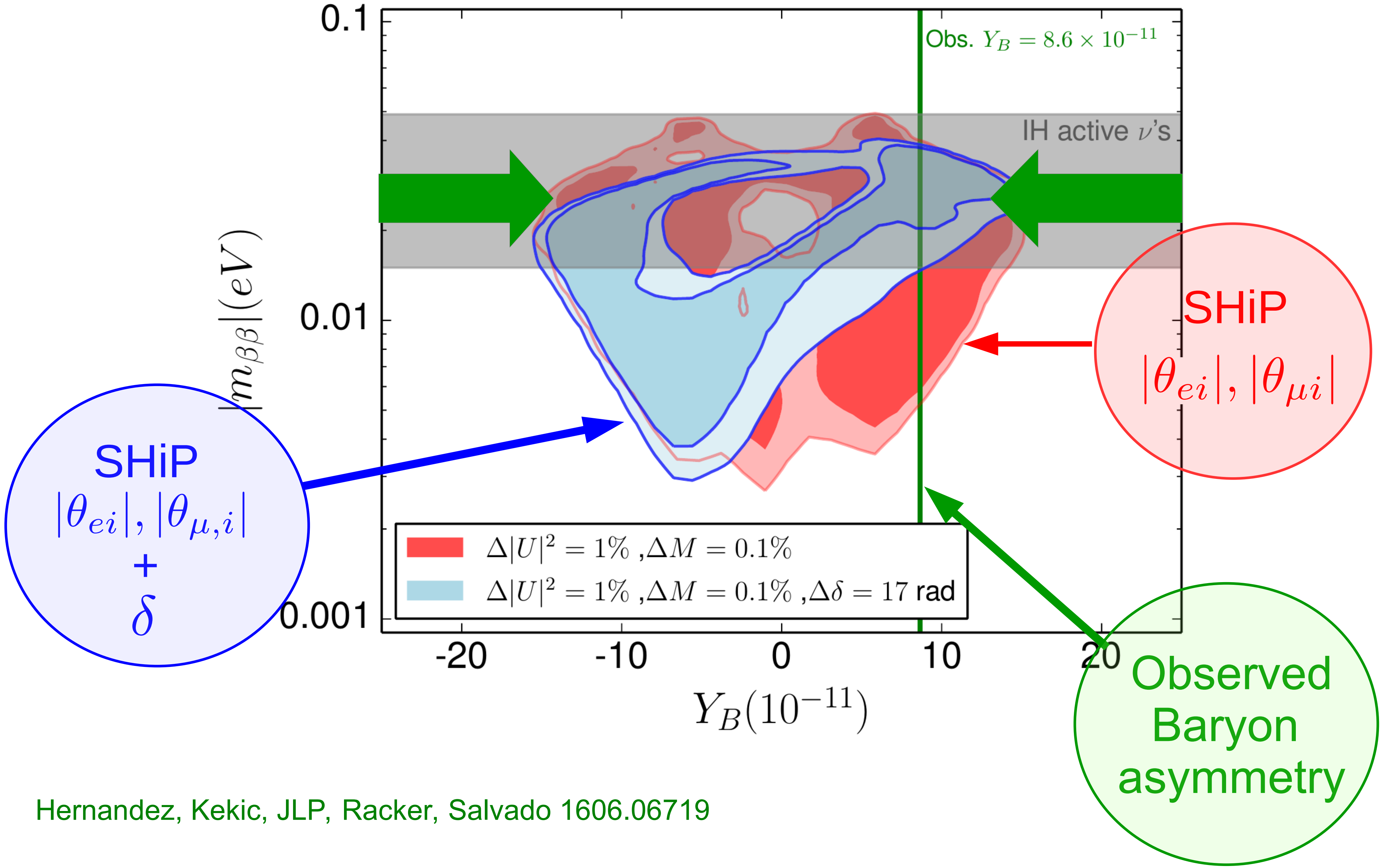
β

HEAVY NEUTRINO
contribution

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

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

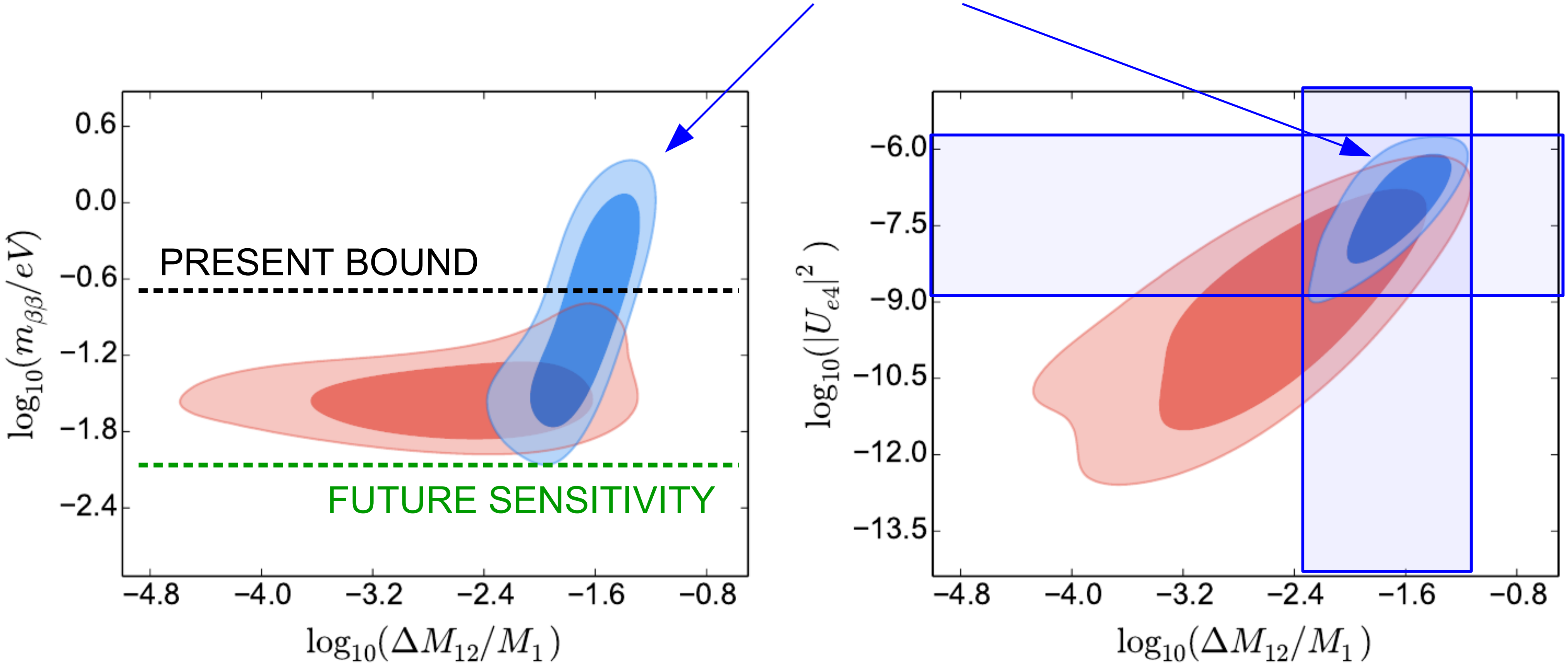
GeV Scale Leptogeneis $n_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $n_R=2$

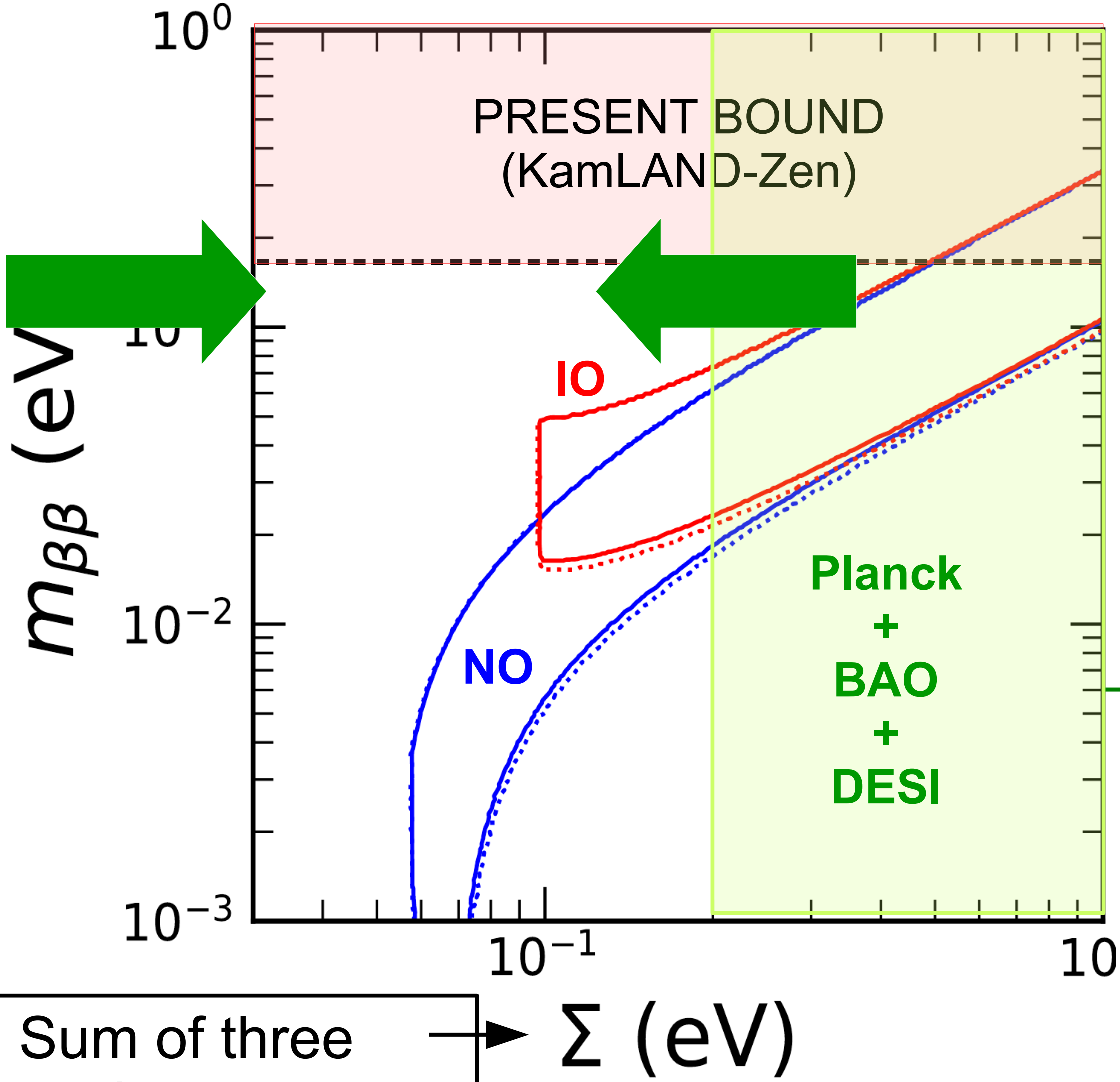
Non very degenerate solutions



Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Neutrinoless double beta decay signal?



Sum of three neutrino masses

- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

- *Extremely relevant input in order to probe New Physics models responsible for ν mass generation.*

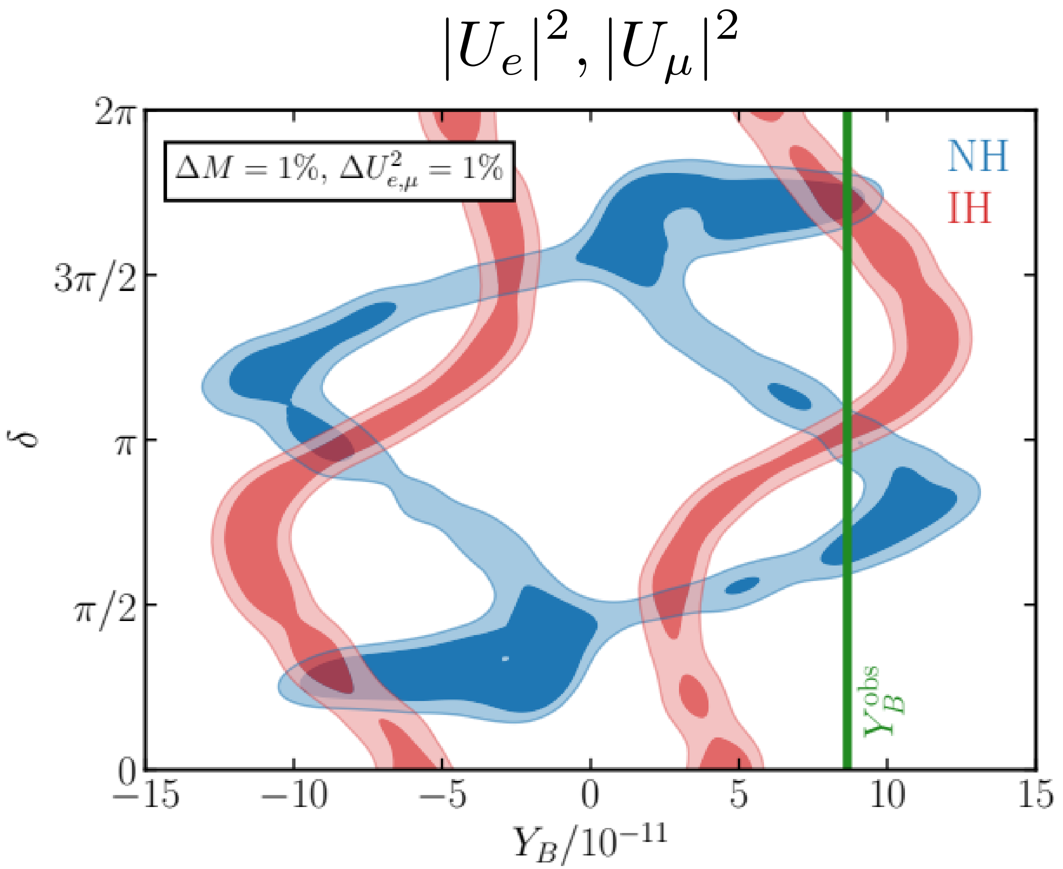
Posibilities:

- Dominated by New Physics as HNL contribution

- Cosmological bound could be relaxed. For instance, if neutrinos decay (new interactions required) Escudero, JLP, Rius, **Sandner** 2007.04994

Simplest scenario: degenerate HNLs

- Measurement of CP violation in neutrino oscillations, HNL mass and mixing with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry.



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IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

FCC−ee

Hernandez, JLP, Rius, Sandner 2305.14427

Minimal Model with approximated LNC

$$
\begin{array}{cccccc}
 & \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 & & \\
 & 1 & -1 & 1 & L & \\
M_\nu = & \left(\begin{array}{ccc} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & M \\ \epsilon Y_2 v/\sqrt{2} & M & \mu \end{array} \right. & & \left. \right) & \begin{array}{c} 1 \\ -1 \\ 1 \end{array} & \begin{array}{c} \nu \\ N_1^c \\ N_2^c \end{array}
\end{array}
$$

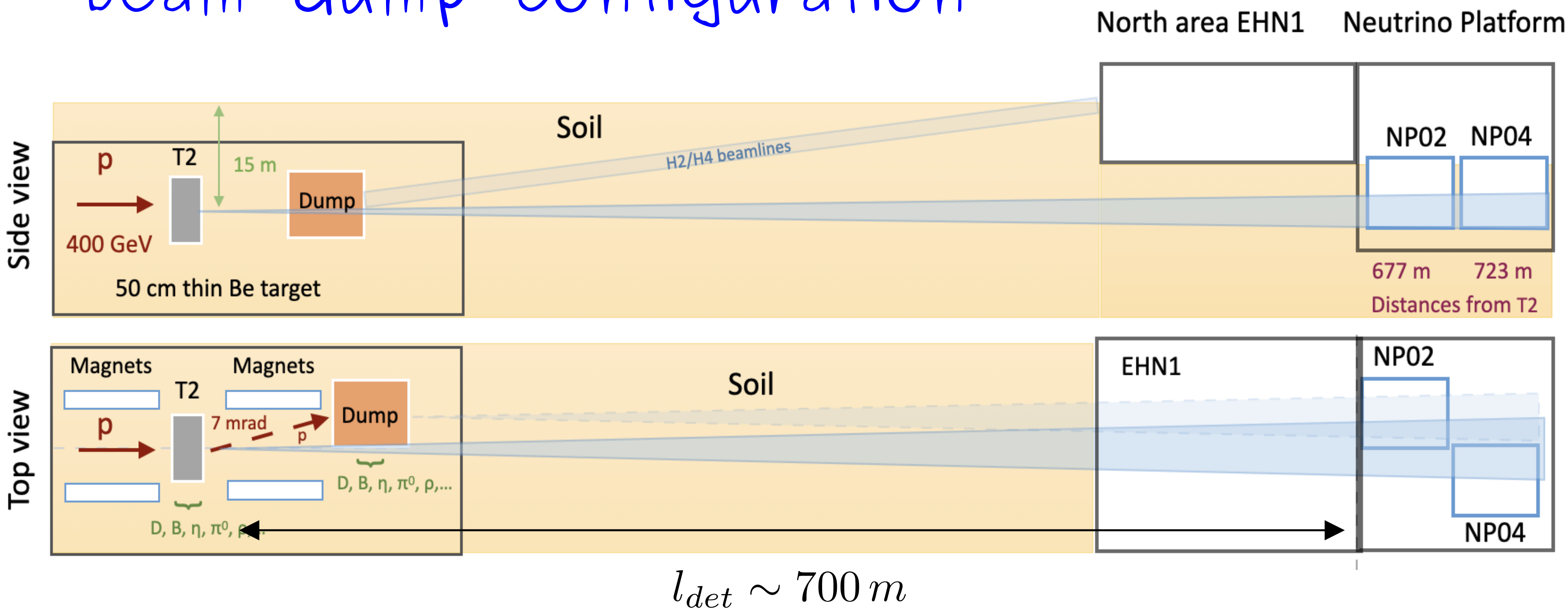
- Light nu masses suppressed with LNV parameters

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

- Quasi-Dirac heavy neutrinos with large mixing:

$$
M_2 \approx M_1 \approx M \qquad \Delta M \approx \mu' + \mu \qquad U_{\nu N} \sim Y_1 v/M
$$

Beam dump configuration

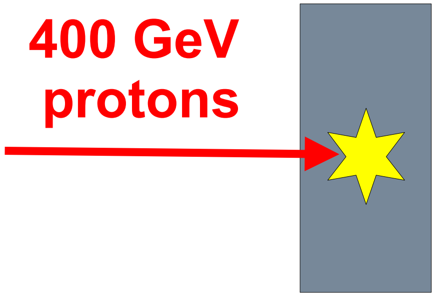


- Proton energy: 400 GeV (instead of 80-120 GeV as in neutrino experiments)
- ~5-7x10^{12} protons/spill with a spill duration of 4.8 s →3-5x10^{18}PoT/year
- *No decay volume*
- *ProtoDUNE detectors:* Liquid Argon Time Projection Chambers with large fiducial volume and excellent imaging capabilities to identify decay products
- Detectors at the surface.

Production

NEW

Full Simulation
H. Sieber



Meson production yield Y_M (normalised per PoT)

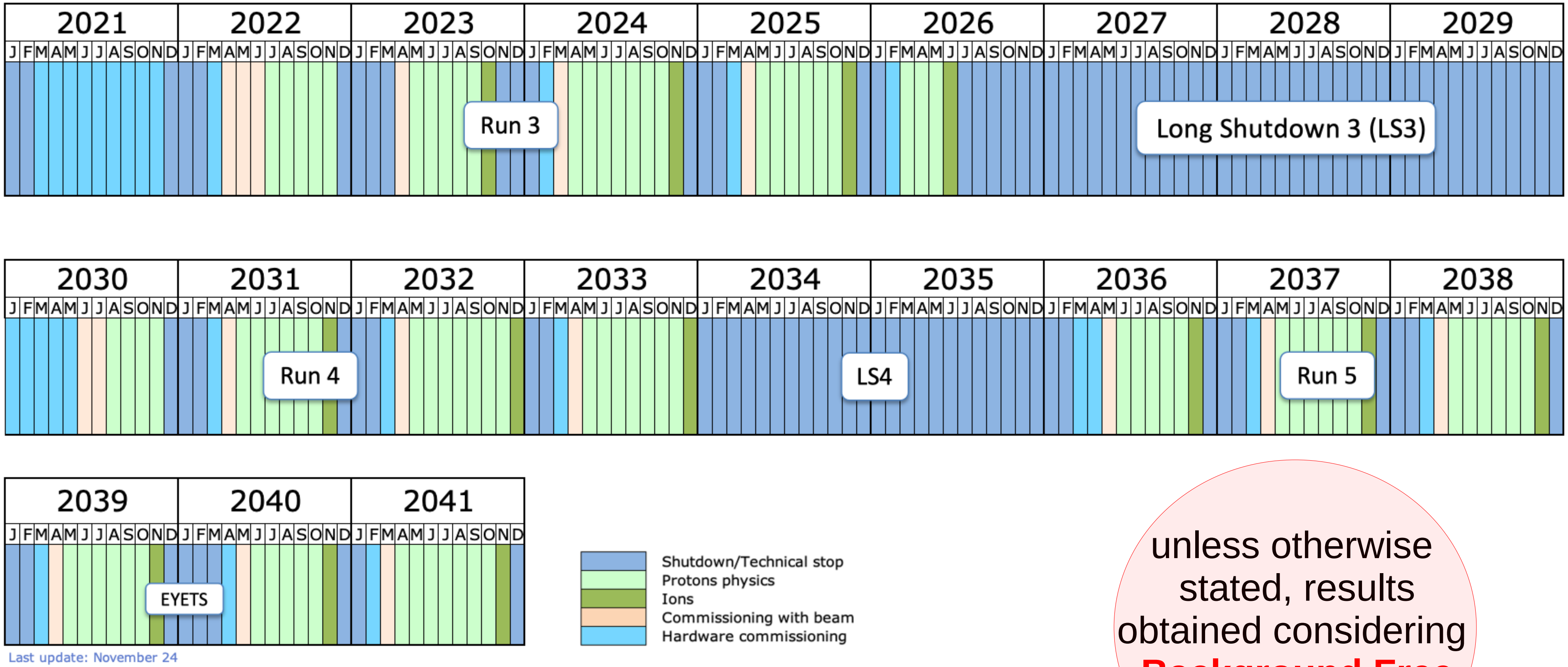
π^+	π^-	π^0	K^+	K^-	K^0_S
1.12	1.13	4.03	0.216	0.0856	2.93
K^0_L	η	η'	D^+	D^+_s	τ
0.0680	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
ρ	ω	ϕ	J/ψ	B^+	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

From Pythia
S.Urrea

- Implementation of heavy meson production? Production of BSM particles fom D decays extremely relevant.

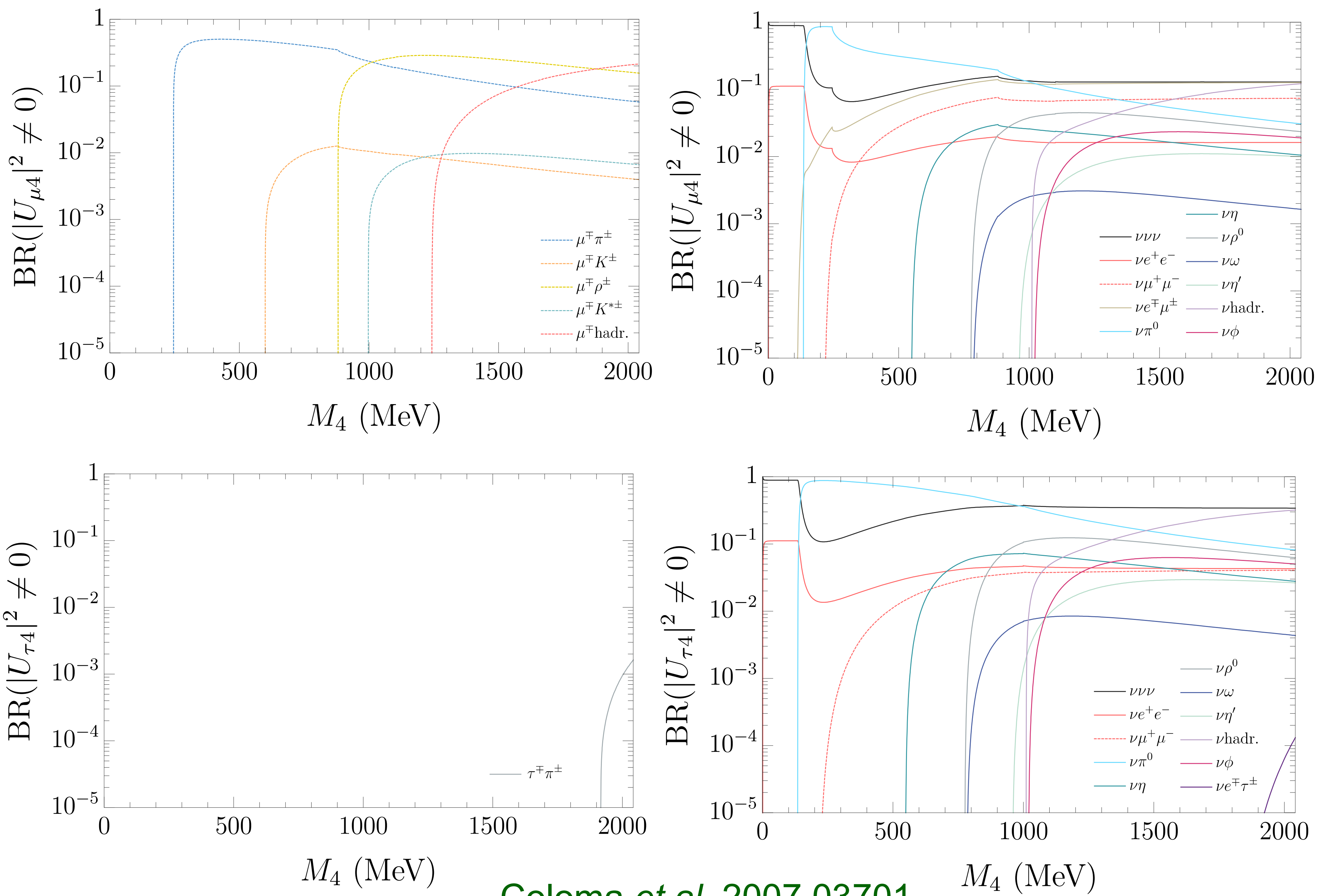
Time Scale & Statistics

- In our pheno analysis we assume **5 years** of data taking and **3.5x10^{18}PoT/year** (~5-7x10^{12} protons/spill with a spill duration of 4.8 s). **This could be done before LS4**.

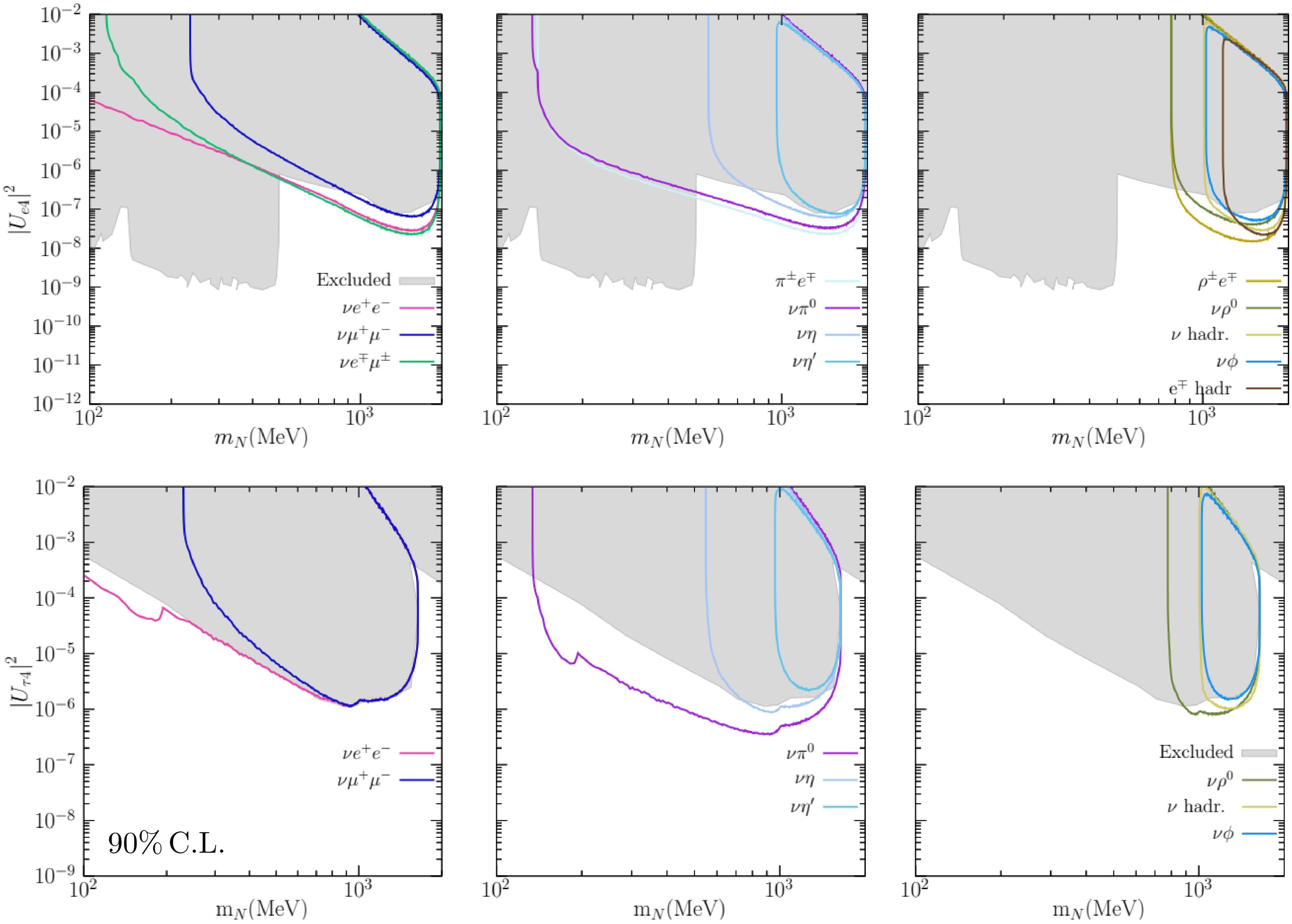


unless otherwise stated, results obtained considering **Background Free** scenario

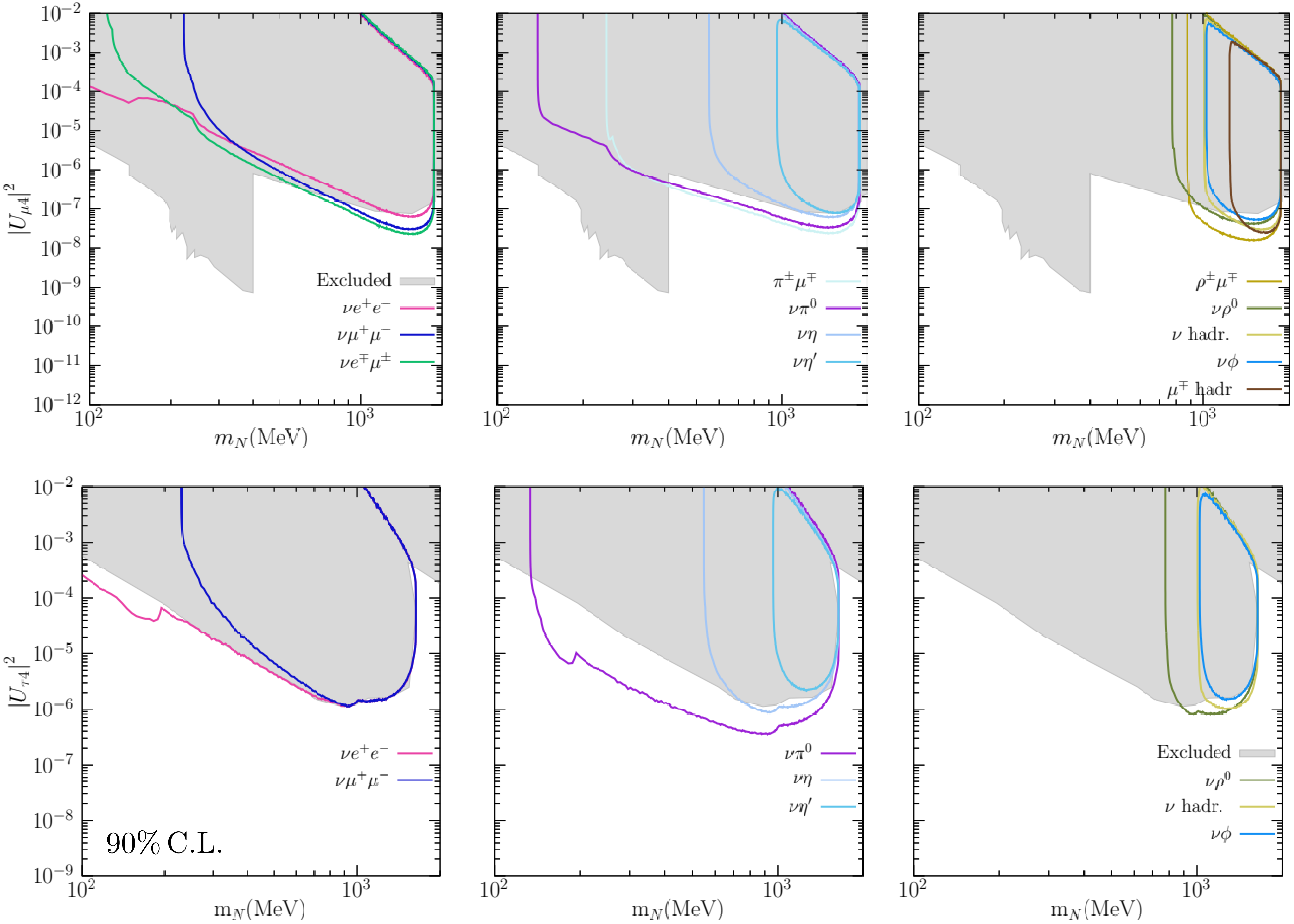
HNL decays



Coloma *et al.* 2007.03701



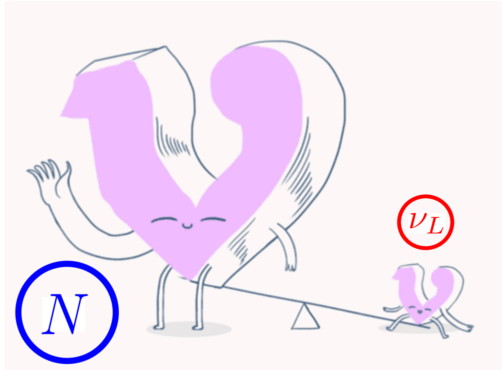
$|U_{e4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm e^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm e^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
$e^\mp$ hadr
$|U_{\tau4}|^2$
m$_N$(MeV)
90% C.L.



$|U_{\mu 4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm\mu^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm\mu^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
$\mu^\mp$ hadr
$|U_{\tau 4}|^2$
m$_N$(MeV)
90% C.L.

1) LLPs: Heavy Neutral Leptons

HNLs arising in low-scale seesaw models can accommodate **the origin of neutrino masses** and **baryon asymmetry**



$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}U^*_{\alpha 4}\gamma^\mu l_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}U^*_{\alpha 4}\gamma^\mu \nu_{L\alpha}Z_\mu$$

NEW

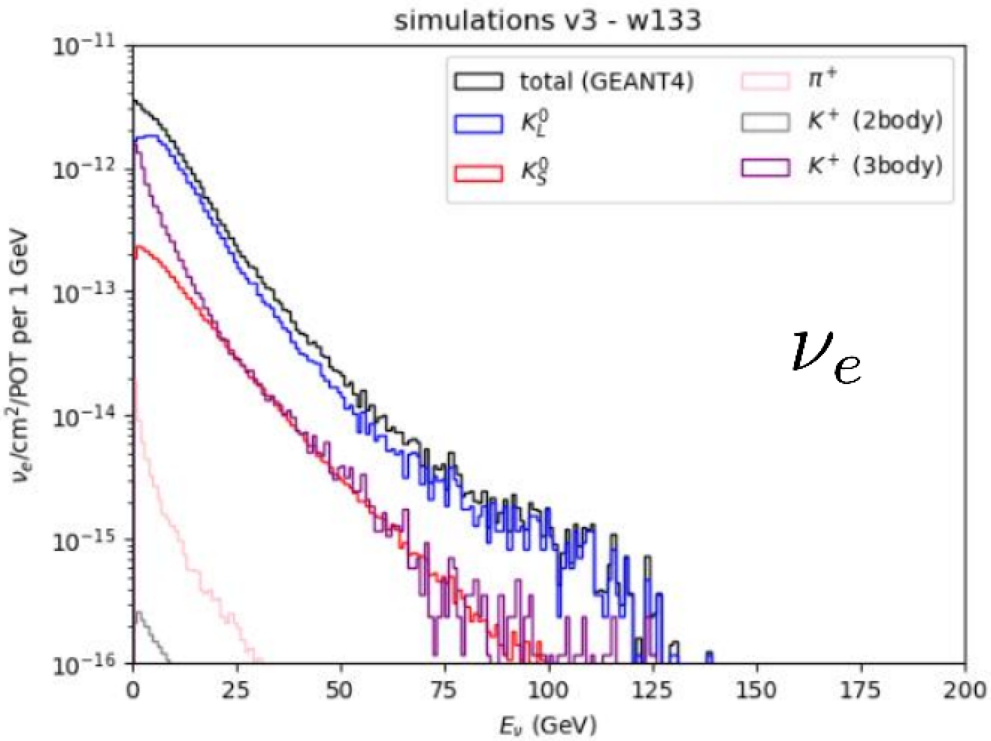
Parent	2-body decay	3-body decay
$\pi^+ \to$	e^+N_4	—
	μ^+N_4	
$K^+ \to$	e^+N_4	$\pi^0 e^+ N_4$
	μ^+N_4	$\pi^0 \mu^+ N_4$
$\tau^- \to$	$\pi^- N_4$	$e^- \overline{\nu} N_4$
	$\rho^- N_4$	$\mu^- \overline{\nu} N_4$

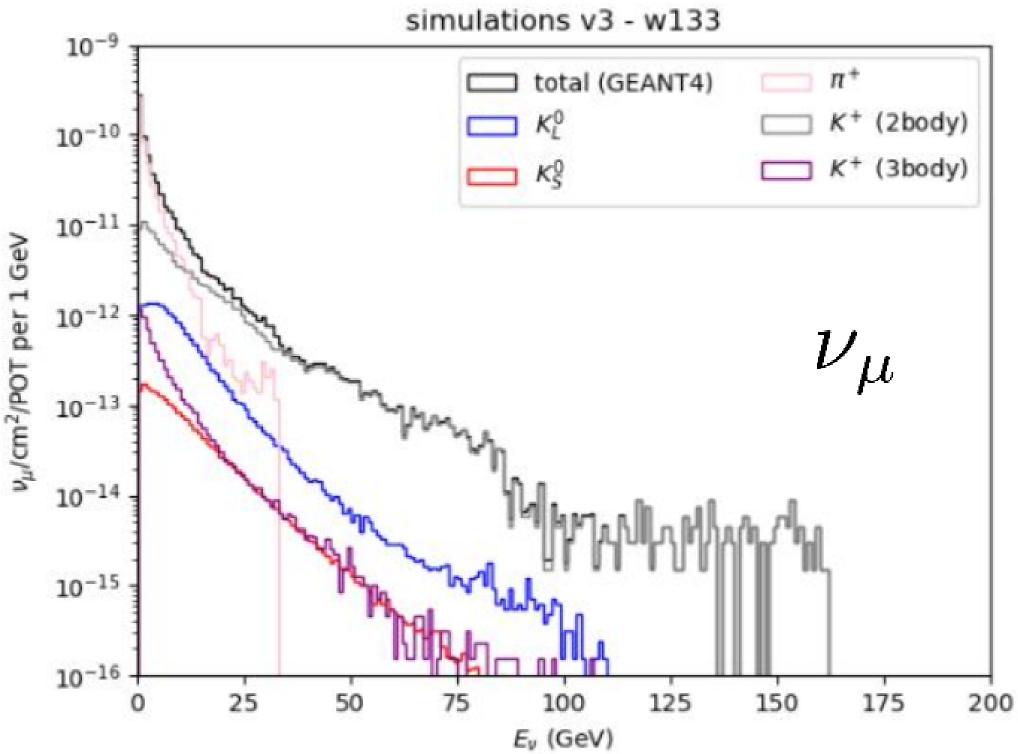
Parent	2-body decay	3-body decay
$D^+ \to$	e^+N_4	$e^+\overline{K^0}N_4$
	μ^+N_4	$\mu^+\overline{K^0}N_4$
	τ^+N_4	
$D_s^+ \to$	e^+N_4	—
	μ^+N_4	
	τ^+N_4	

HNL production branching ratios and decay widths from Coloma *et al.* 2007.03701

Work in progress: courtesy of S. Urrea

- A Geant4 implementation of the target, dump, and magnets has been used to validate our results and compute the possible neutrino flux and HNL signal.

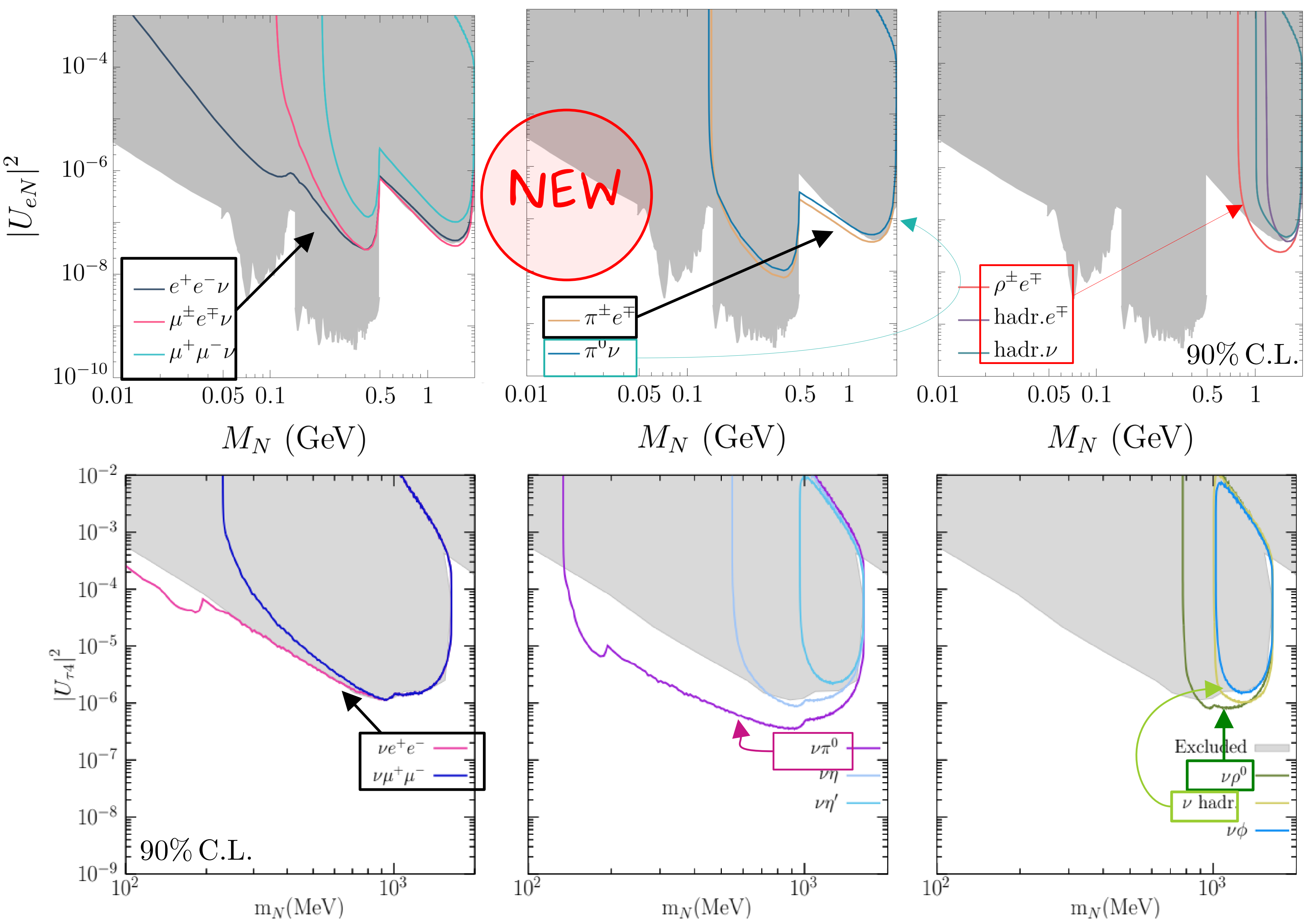




More details in:
https://indico.cern.ch/event/1460367/contributions/6240613/attachments/3001559/5289608/BSM@protoDUNE_NeutrinoWkshp_Animesh.pdf
https://indico.cern.ch/event/1381368/contributions/5963281/attachments/2888251/5062517/molina_LLP2024_2072024_v2.pdf

H. Sieber, J. Hernandez Garcia, C. Hasnip, J. Martin-Albo, P. Sajitha, L. Molina Bueno, S. Urrea

J. Hernández-García, S. Urrea



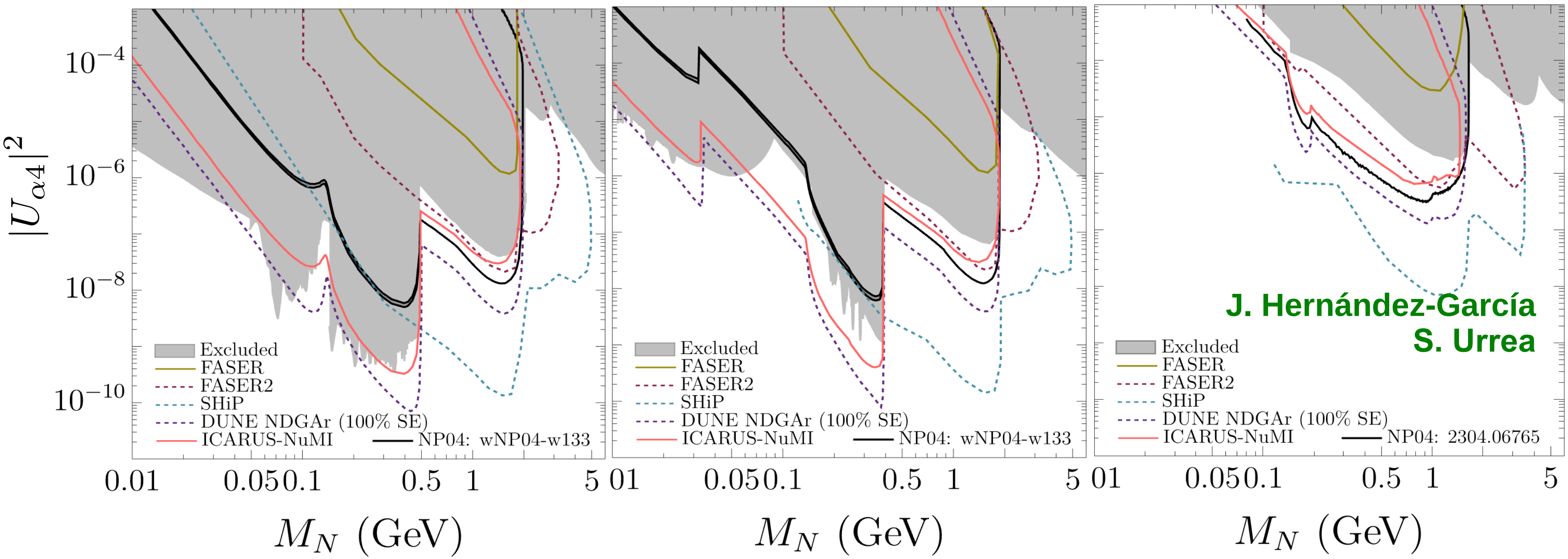
1) LLPs: Heavy Neutral Leptons

HNLs arising in low-scale seesaw models can accommodate **the origin of neutrino masses** and **baryon asymmetry**

NEW

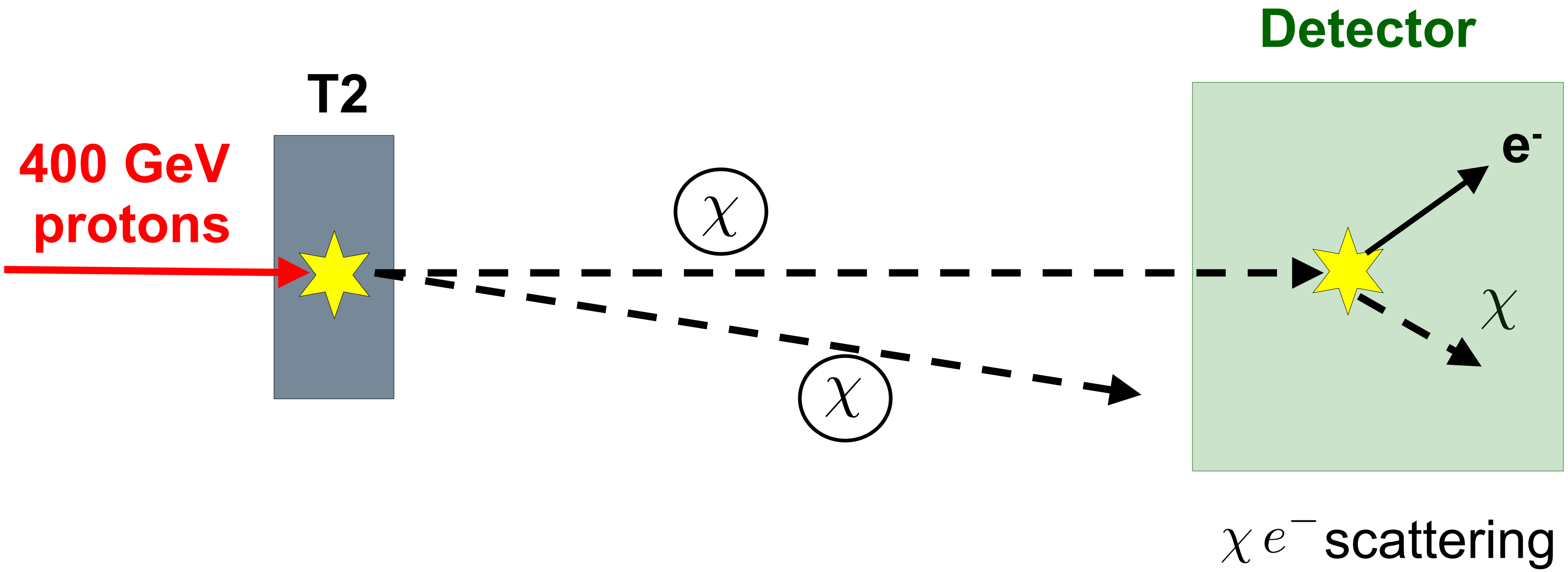
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}U^*_{\alpha 4}\gamma^\mu l_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}U^*_{\alpha 4}\gamma^\mu \nu_{L\alpha}Z_\mu$$

e *(BC6)* μ *(BC7)* τ *(BC8)*



No background considered for any of the lines. We need a realistic background estimation.

2) Stable Particles: Millicharged Particles

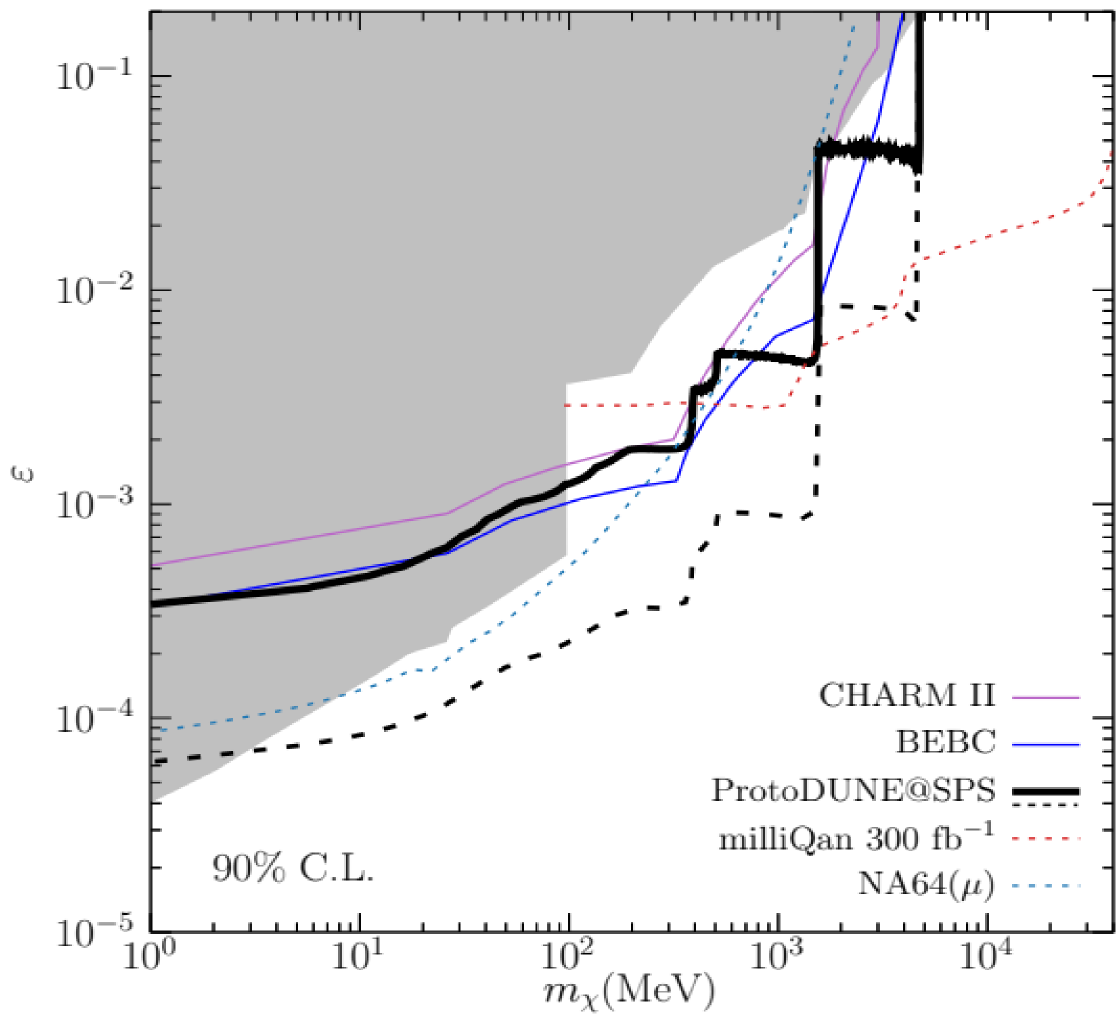


- **Millicharged particles (MCPs)**: fermions with an effective charge **eε,** arising from the mixing of the SM photon and a massless Dark Photon

$$\frac{d\sigma}{dT} = \pi\alpha^2\varepsilon^2 \frac{2E_\chi^2 m_e + T^2 m_e - T\left(m_\chi^2 + m_e\left(2E_\chi + m_e\right)\right)}{T^2\left(E_\chi^2 - m_\chi^2\right) m_e^2}$$

Harnik, Liu, and Palamar 1902.03246

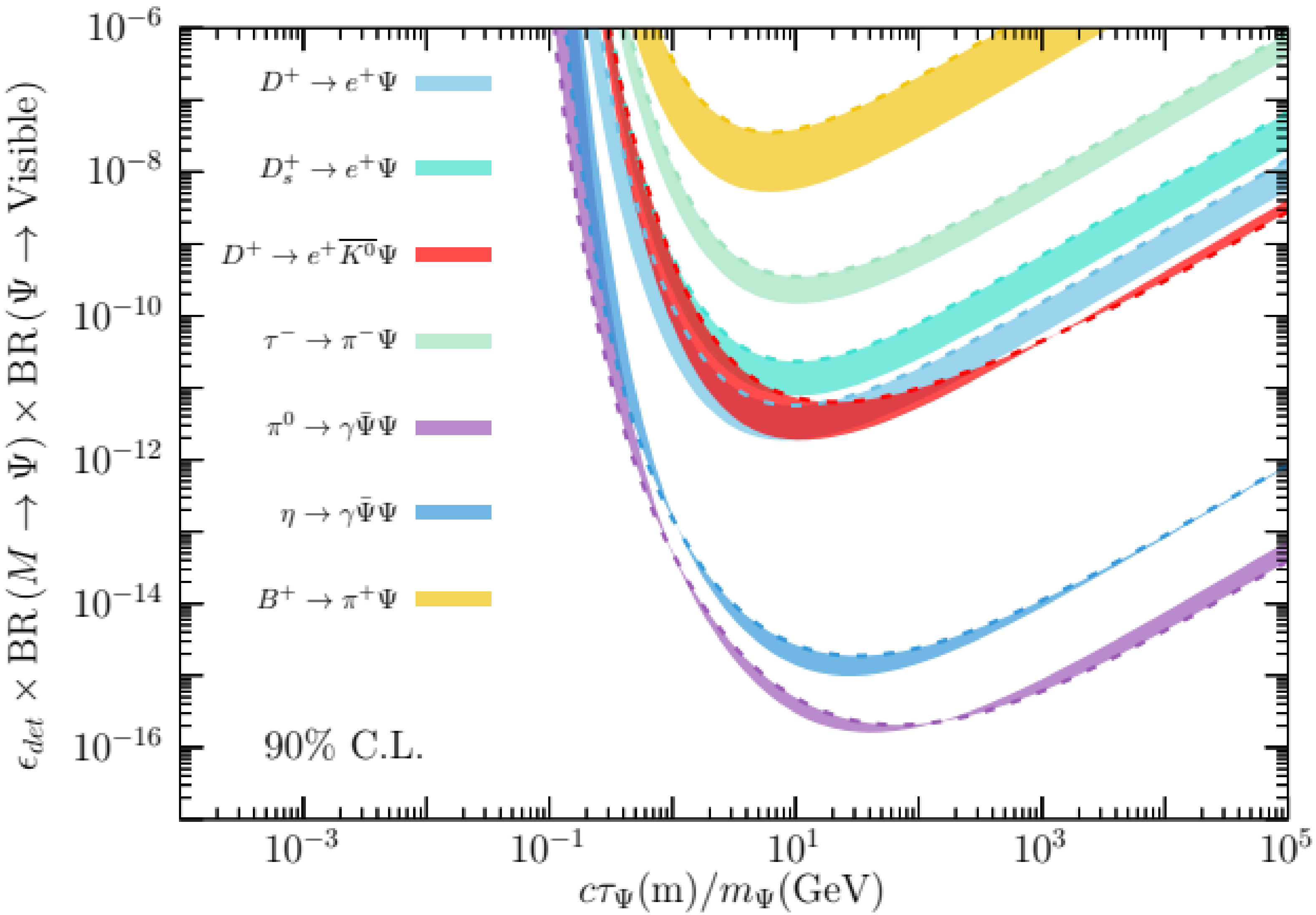
2) Stable Particles: Millicharged Particles



Coloma, JLP, Molina-Bueno, Urrea 2304.06765

1) LLPs: Model independent approach

$$N_{dec} = N_{dec}\left(\mathrm{BR}\left(M \to \Psi\right)\mathrm{BR}\left(\Psi \to visible\right)\epsilon_{det}, c\tau_\Psi/m_\Psi\right)$$



Leptogenesis: Kinetic Equations

- Equations for the density matrix in the Raffelt-Sigl formalism

Ghiglieri,Laine '17

$$\frac{d\rho_N(k)}{dt} = -\boxed{i[H, \rho_N(k)]} - \boxed{\frac{1}{2}\{\Gamma_N^a, \rho_N\} + \frac{1}{2}\{\Gamma_N^p, 1 - \rho_N\}}$$

Oscillations Scattering

$$\bar{\rho}_N \; (H \to H^*)$$

$$\frac{d\mu_{B/3-L_\alpha}}{dt} = f\left(\rho_N, \bar{\rho}_N, \mu_{B/3-L_\alpha}\right)$$

Leptogenesis: Kinetic Equations

$$
\begin{aligned}
xH_u \frac{\mathrm{d}r_N}{\mathrm{d}x} &= -i[\langle H \rangle, r_N] - \frac{\langle \gamma_N^{(0)} \rangle}{2}\{Y^\dagger Y, r_N - 1\} - x^2 \frac{\langle s_N^{(0)} \rangle}{2}\{MY^T Y^* M, r_N - 1\} \\
&+ \langle \gamma_N^{(1)} \rangle Y^\dagger \mu Y - x^2 \langle s_N^{(1)} \rangle M Y^T \mu Y^* M \\
&- \frac{\langle \gamma_N^{(2)} \rangle}{2}\{Y^\dagger \mu Y, r_N\} + x^2 \frac{\langle s_N^{(2)} \rangle}{2}\{MY^T \mu Y^* M, r_N\}, \\
xH_u \frac{\mathrm{d}r_{\bar{N}}}{\mathrm{d}x} &= -i[\langle H^* \rangle, r_{\bar{N}}] - \frac{\langle \gamma_N^{(0)} \rangle}{2}\{Y^T Y^*, r_{\bar{N}} - 1\} - x^2 \frac{\langle s_N^{(0)} \rangle}{2}\{MY^\dagger Y M \\
&- \langle \gamma_N^{(1)} \rangle Y^T \mu Y^* + x^2 \langle s_N^{(1)} \rangle M Y^\dagger \mu Y M \\
&+ \frac{\langle \gamma_N^{(2)} \rangle}{2}\{Y^T \mu Y^*, r_{\bar{N}}\} - x^2 \frac{\langle s_N^{(2)} \rangle}{2}\{MY^\dagger \mu Y M, r_{\bar{N}}\}, \\
xH_u \frac{\mathrm{d}\mu_{B/3-L_\alpha}}{\mathrm{d}x} &= \frac{\int_k \rho_F}{\int_k \rho'_F}\Bigg[\frac{\langle \gamma_N^{(0)} \rangle}{2}(Y r_N Y^\dagger - Y^* r_{\bar{N}} Y^T) - x^2 \frac{\langle s_N^{(0)} \rangle}{2}(Y^* M r_N M Y^{\cdot} \\
&- \mu_\alpha \left(\langle \gamma_N^{(1)} \rangle Y Y^\dagger + x^2 \langle s_N^{(1)} \rangle Y M^2 Y^\dagger \right) + \frac{\langle \gamma_N^{(2)} \rangle}{2} \mu_\alpha (Y r_N Y^\dagger + Y \\
&+ x^2 \frac{\langle s_N^{(2)} \rangle}{2} \mu_\alpha \left(Y M r_{\bar{N}} M Y^\dagger + Y^* M r_N M Y^T \right) \Bigg]_{\alpha\alpha},
\end{aligned}
$$

- *Stiff non-linear system with several relevant time scales: very hard to numerically explore parameter space.*

Leptogenesis: parameter scan

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

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

$$\log \mathcal{L} = -\frac{1}{2}\left(\frac{Y_B(t_{\rm EW}) - Y_B^{\rm exp}}{\sigma_{Y_B}}\right)^2 .$$

Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3,$	$\delta, \phi, M, \Delta M/M, \beta, y$

Fixed by neutrino oscillation experiments

Free parameters

Leptogenesis: Kinetic Equations

Hernandez, JLP, Rius, **Sandner**; arXiv:2207.01651

- AMIQS: publicly available software developed by **Stefan Sandner** introduced relevant optimizations that allows a faster scan.

https://github.com/stefanmarinus/amiqs
10.5281/zenodo.6866454

- Dependence on the parameters of the model and correlation between the baryon asymmetry and other observables not easy to understand just from a numerical scan.

- Our ultimate goal is to study this connection with future experimental measurements in order to be able to test leptogenesis.

Analytical understanding required

Towards analytical understanding

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

- Identify the different non-thermal regimes and characteristic time-scales
- Set up a perturbative approximation of the equations $(\epsilon \ll 1,\ \mu/M \ll 1)$
- Identify the CP invariants that control the flavour parameter dependencies

$$I_0 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y\, M^\dagger M Y^\dagger {Y_l}^\dagger Y\right]\right)$$

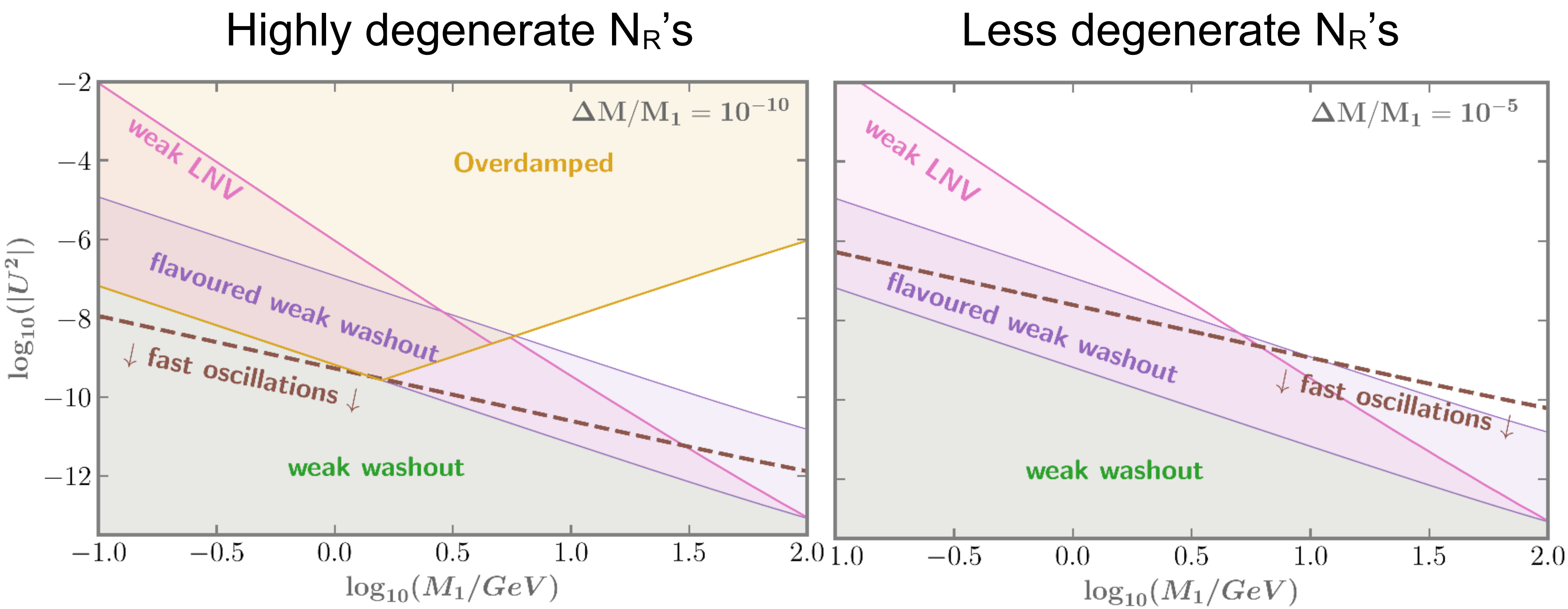
$$\equiv \sum_\alpha y_{l_\alpha}^2\, \Delta_\alpha\left(\delta, \phi, \Delta m^2_{\rm atm}, \Delta m^2_{\rm sol}, U^2, M, \theta\right)$$

$$I_1 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y\, M^\dagger M M^* (Y^\dagger Y)^* M\right]\right)$$

$$\equiv \sum_\alpha \Delta_\alpha^M\left(\delta, \phi, \Delta m^2_{\rm atm}, \Delta m^2_{\rm sol}, U^2, M, \theta\right)$$

- Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

Non thermal equilibrium regimes



Overdamped regime: $\Gamma_{\rm osc}^{\rm slow} = \epsilon^2 \Gamma$ $\quad \epsilon \equiv \frac{\Gamma_{osc}}{\Gamma}$ $\quad \Gamma_{\rm osc}(T) \propto \frac{M_2^2 - M_1^2}{T}$

Flavoured: $y_\alpha \ll y_\beta$ $\quad \Gamma_\alpha \propto (YY^\dagger)_{\alpha\alpha} T$

wLNV: $M \ll T$ $\quad \Gamma_M^{\rm slow} \propto \left(\frac{M_i}{T}\right)^2 \Gamma$

Example: overdamped regime (NH)

$$\left(\sum_\alpha \mu_{B/3-L_\alpha}\right)^{\rm ov-wLNV} \simeq \frac{\kappa x^2}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\frac{c_H M_P^*}{T_{EW}^3}\boxed{\left(\Delta_{\rm LNC}^{\rm ov}-\frac{24}{5}\frac{s_0 x^3}{T_{\rm EW}^2}\Delta_{\rm LNV}^{\rm ov}\right)}$$

$$\boxed{\Delta_{\rm LNC}^{\rm ov}} = \frac{1}{\left[{\rm Tr}\,(Y^\dagger Y)\right]^2}\sum_\alpha \frac{\Delta_\alpha}{(YY^\dagger)_{\alpha\alpha}} \approx \boxed{-(M_2^2-M_1^2)\frac{v^2\sqrt{\Delta m_{\rm atm}^2}}{8M^3U^4}s_\theta}$$

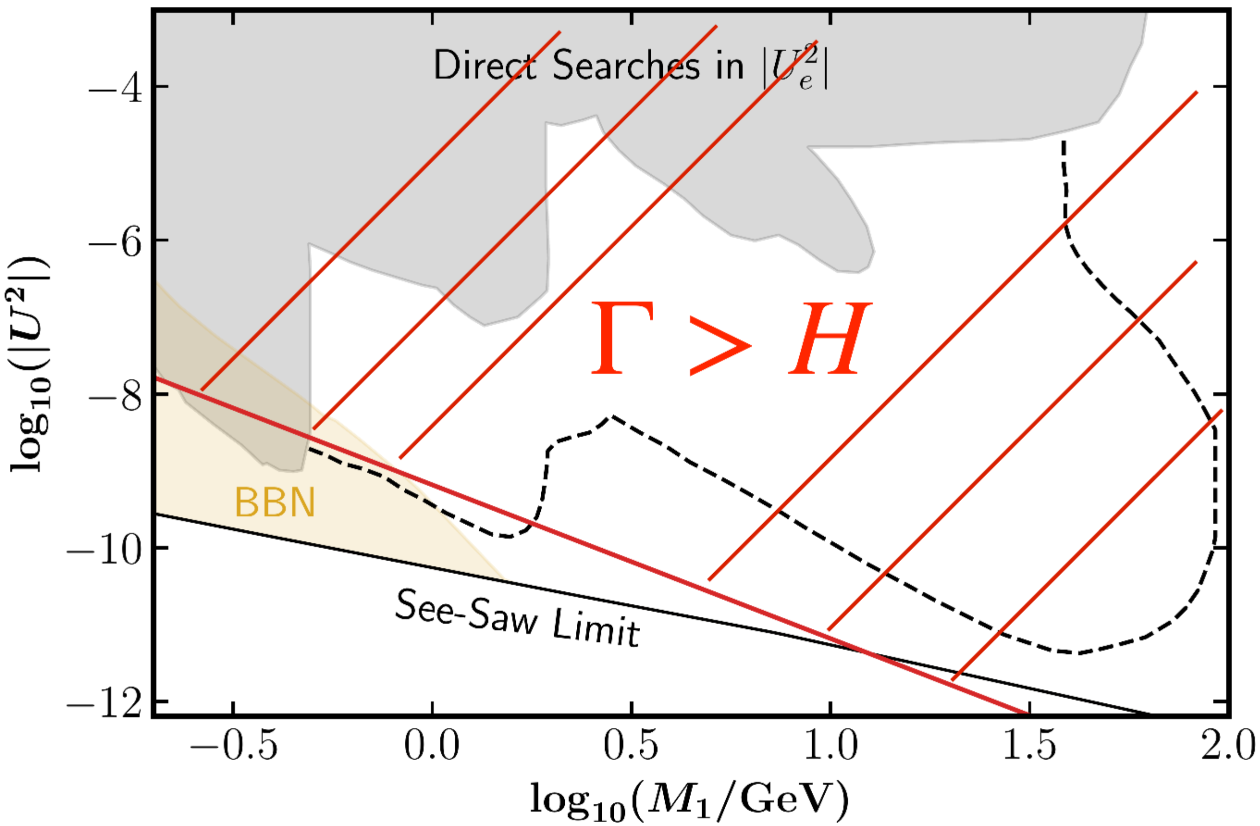
$$\left(\sum_\alpha \Delta_\alpha = 0,\;\; \Delta_{\rm LNC}^{\rm ov}\propto\sum_\alpha\frac{\Delta_\alpha}{\Gamma_\alpha}\right)$$

$$\boxed{\Delta_{\rm LNV}^{\rm ov}} = \frac{1}{\left[{\rm Tr}\,(Y^\dagger Y)\right]^2}\sum_\alpha \Delta_\alpha^M \approx \boxed{-M_1M_2(M_2^2-M_1^2)\frac{\sqrt{\Delta m_{\rm atm}^2}}{4MU^2}s_\theta}$$

$$\left(\sum_\alpha \Delta_\alpha^M \neq 0\right)$$

Non thermal equilibrition

In principle, $\Gamma(T_{\rm EW}) < H(T_{\rm EW})$ is required $\quad (\Gamma \propto Tr\left[Y^\dagger Y\right] T)$



BUT *approximate L symmetry and flavour effects can lead to* **slow modes**.

Non thermal equilibrium regimes $\Delta M = 0$

- "Thermal oscillation rate"

$$\Gamma^{\rm thm}_{\rm osc} \sim \rho y y' T$$

- LN symmetry

$$\Gamma^{\rm slow}_{\rm LN} \propto y'^2 T$$

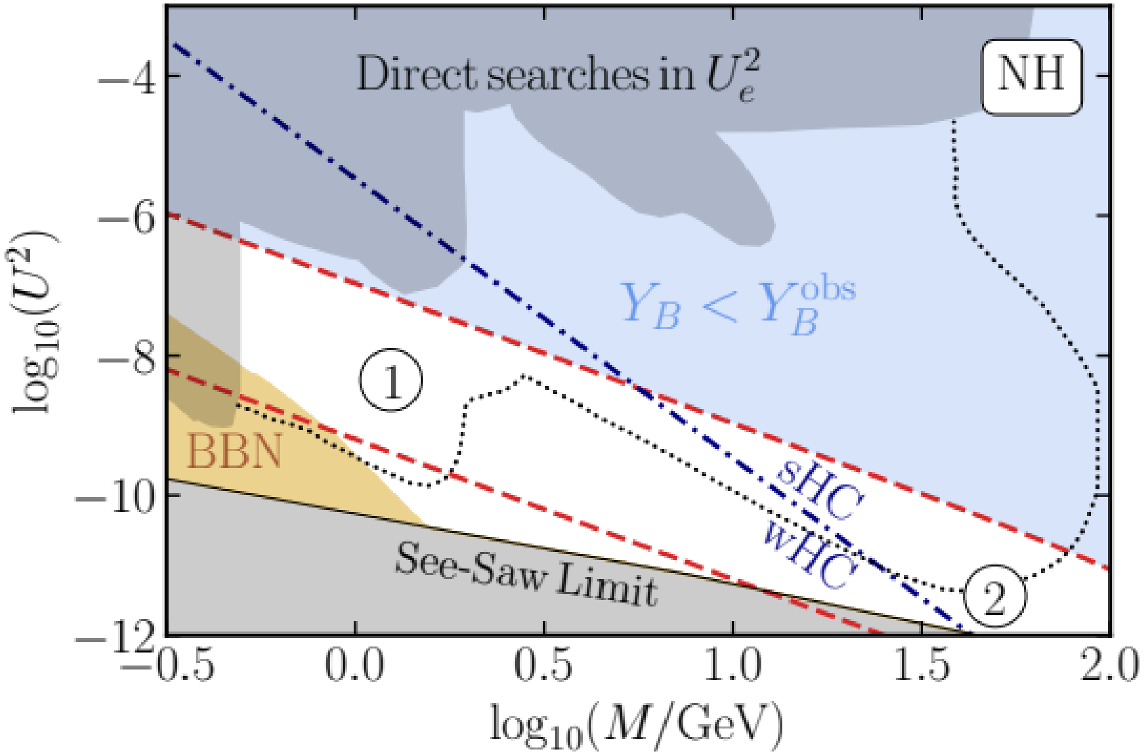
- Flavor

$$\Gamma_\alpha(T) \propto \epsilon_\alpha \Gamma(T), \quad \epsilon_\alpha \equiv \frac{(YY^\dagger)_{\alpha\alpha}}{{\rm Tr}[YY^\dagger]} = \frac{y_\alpha^2}{y^2} + \mathcal{O}\left(y'^2/y^2\right)$$

- wHC

$$\Gamma^{\rm slow}_M \propto \left(\frac{M}{T}\right)^2 \Gamma \leq \Gamma$$

Non thermal equilibrium: degenerate N's



- Regime 1 – **Flavoured with wHC**.

$$\Gamma_{\rm LN}(T_{\rm EW}), \Gamma_M(T_{\rm EW}), \Gamma_\alpha(T_{\rm EW}) < H_u(T_{\rm EW}) < \Gamma(T_{\rm EW}).$$

- Regime 2 – **Flavoured with sHC**.

$$\Gamma_{\rm LN}(T_{\rm EW}), \Gamma_\alpha(T_{\rm EW}) < H_u(T_{\rm EW}) < \Gamma_M(T_{\rm EW}), \Gamma(T_{\rm EW}).$$

Analytical understanding $\Delta M = 0$

- Identify the different non-thermal regimes and characteristic time-scales
- Set up a perturbative approximation of the equations $(\epsilon \ll 1,\ \mu/M \ll 1)$
- Identify the CP invariants that control the flavor parameter dependencies

$$\tilde{I}_0 \equiv \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger Y_l Y_l^\dagger Y\right]\right) \equiv \sum_\alpha y_{l_\alpha}^2 \Delta_\alpha$$

$$\equiv \sum_\alpha y_{l_\alpha}^2\, \Delta_\alpha\left(\delta, \phi, \Delta m^2_{\mathrm{atm}}, \Delta m^2_{\mathrm{sol}}, U^2, M,\right)$$

- Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

Hernandez, JLP, Rius, Sandner 2305.14427

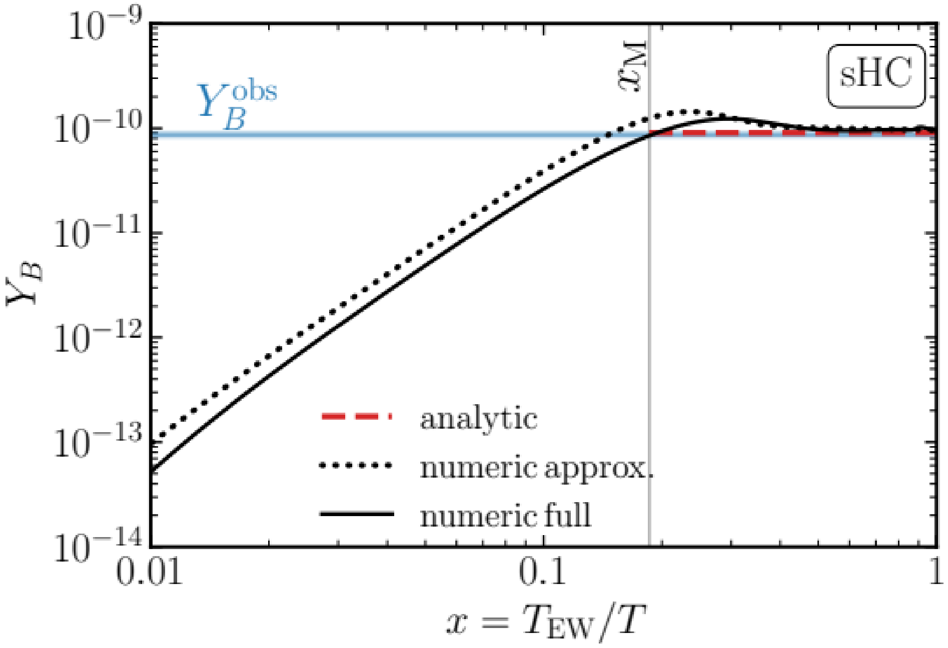
Example $\Delta M = 0$: Regime 2

$$\sum_\alpha \mu_{B-L_{\alpha/3}} = -x_M^3 \frac{1}{T_{\mathrm{EW}}^2} \frac{8\gamma_0\kappa^2(\gamma_1 s_0 + \gamma_0 s_1)(s_0\omega + \gamma_0\omega_M)}{6(4\gamma_0 s_0 + \gamma_1 s_0\kappa + \gamma_0 s_1\kappa)(\gamma_0^2 + 4\omega^2)} \boxed{\Delta_\alpha^{\mathrm{fw}}}$$

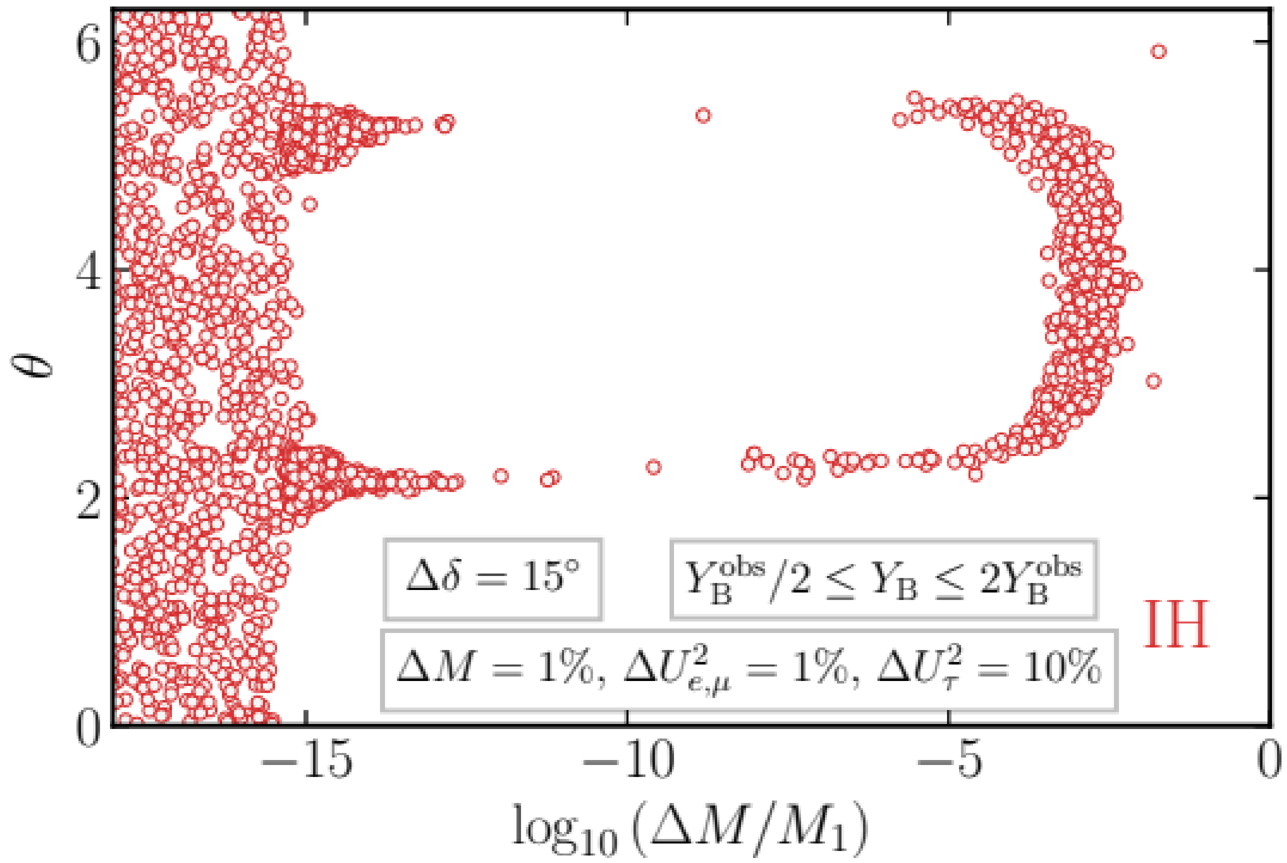
NO

$$\Delta_e^{\mathrm{fw}} = -\frac{M^2 \Delta m_{\mathrm{atm}}^2 \sqrt{r}}{2U^2 v^2} \theta_{13} s_{12} \sin(\delta + \phi)$$

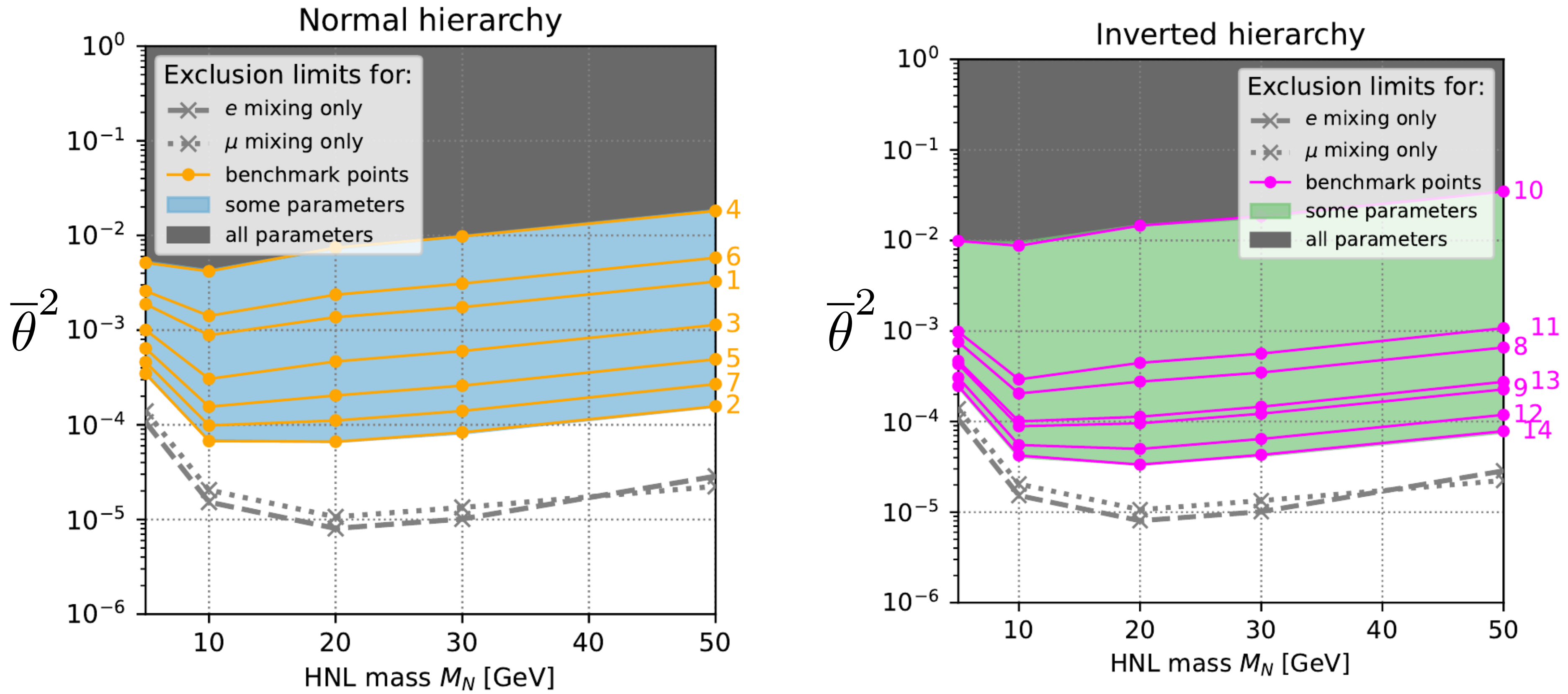
$$\Delta_\mu^{\mathrm{fw}} = -\Delta_\tau^{\mathrm{fw}} = -\frac{M^2 \Delta m_{\mathrm{atm}}^2 \sqrt{r}}{4U^2 v^2} c_{12} \sin\phi\,,$$



Degenerate vs Non Degenerate case



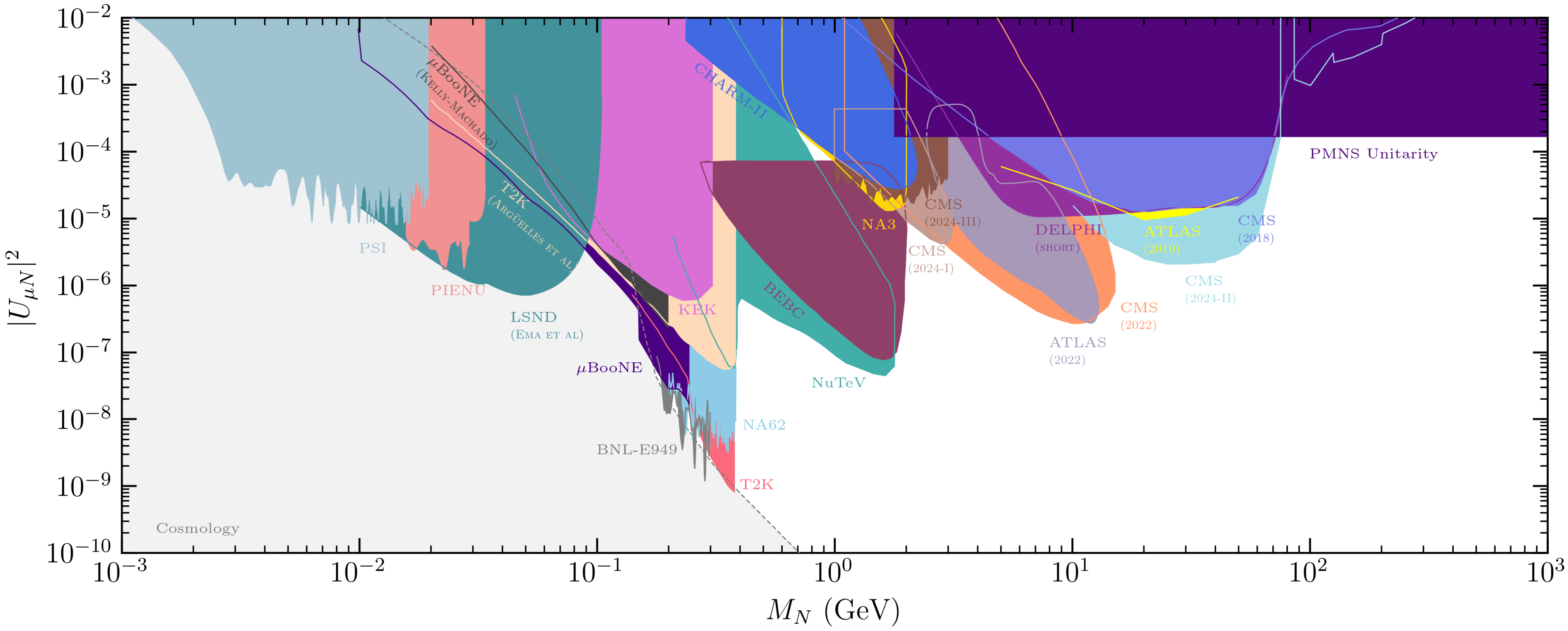
Flavor pattern vs sensitivity



- Interpretation of ATLAS data depends on assumptions about "flavor mixing pattern" Tastet, Ruchayskiya, Timiryasov 2107.12980

- Same conclusion applies to other experimental searches.

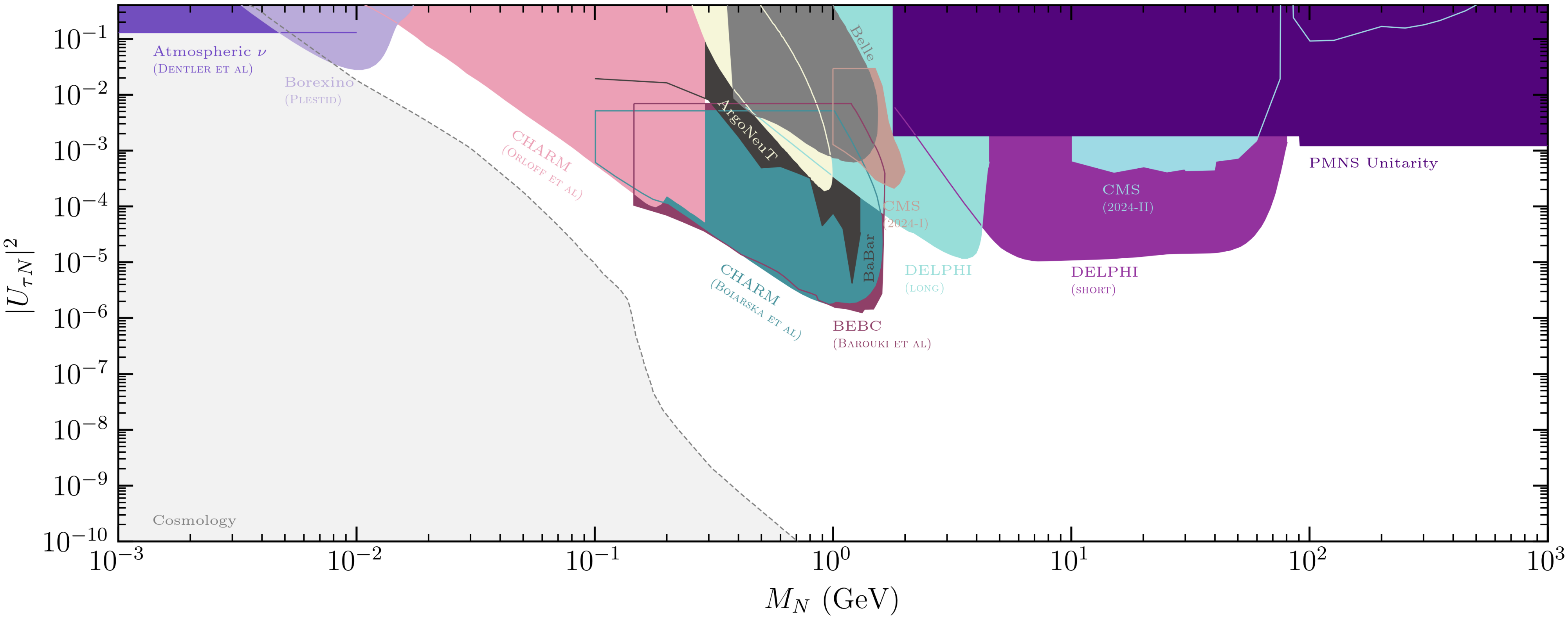
The New Physics Scale



https://github.com/mhostert/Heavy-Neutrino-Limits

Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

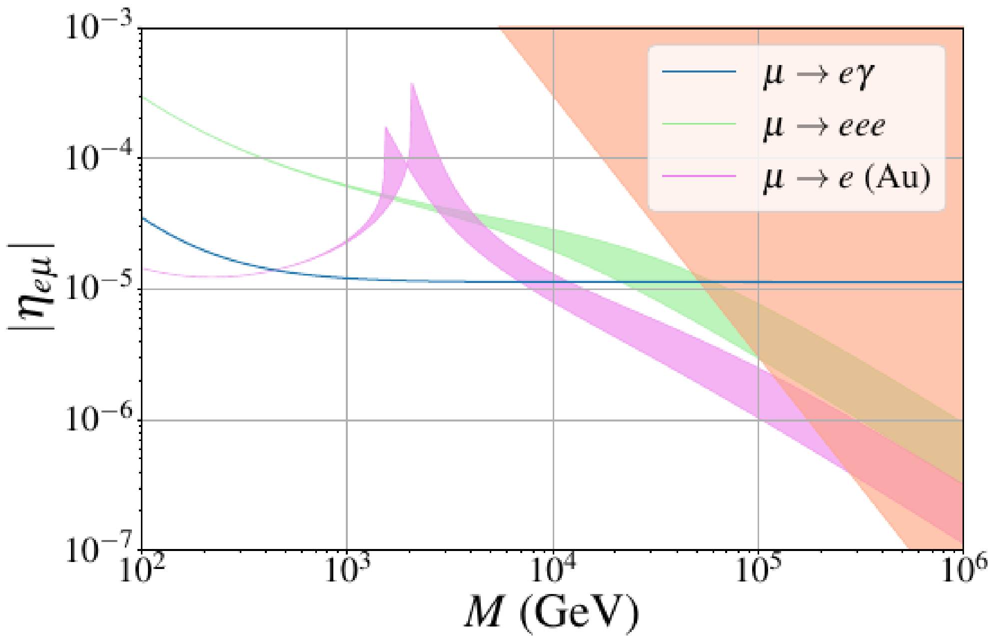
The New Physics Scale

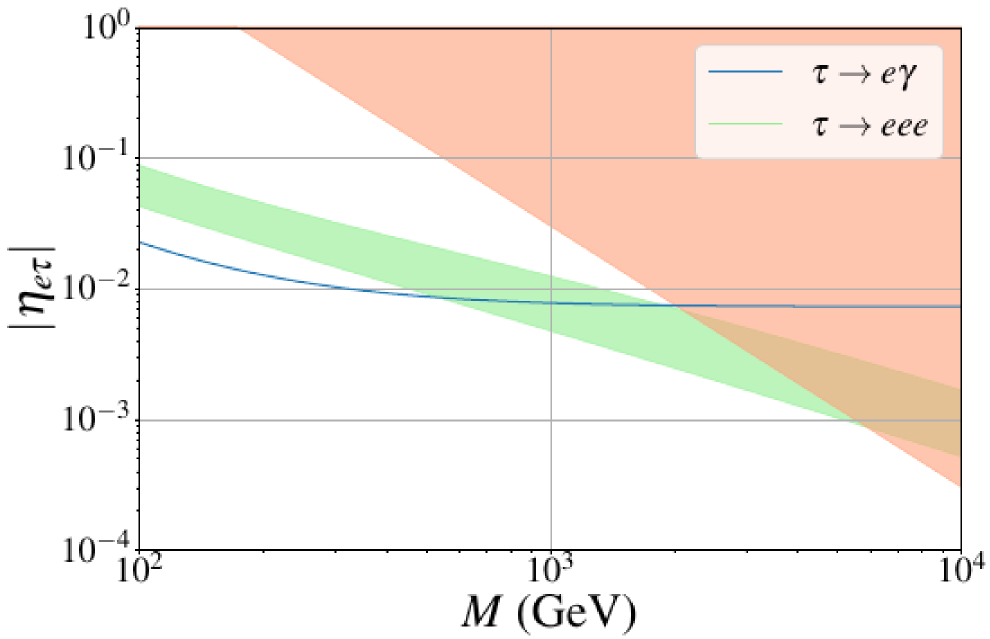


https://github.com/mhostert/Heavy-Neutrino-Limits

Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

Bounds from CLFV





Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Global bounds: EW and CLFV precision data

2N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4 \cdot 10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$6.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5 \cdot 10^{-5}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$1.6 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e\theta_\mu^*\rvert}{2}$	$8.3 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e\theta_\tau^*\rvert}{2}$	$1.5 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu\theta_\tau^*\rvert}{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Global bounds: EW and CLFV precision data

2N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4 \cdot 10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$6.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5 \cdot 10^{-5}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$1.6 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e\theta_\mu^*\rvert}{2}$	$8.3 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e\theta_\tau^*\rvert}{2}$	$1.5 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu\theta_\tau^*\rvert}{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

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Global bounds: EW and CLFV precision data

3N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\|\theta_e\|^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$[0.31, 1.0] \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{\|\theta_\mu\|^2}{2}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\|\theta_\tau\|^2}{2}$	$[0.3, 3.9] \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$1.7 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$
$\mathrm{Tr}\,[\eta] = \frac{\|\theta\|^2}{2}$	$[0.35, 1.3] \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$[0.33, 1.0] \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$\|\eta_{e\mu}\| = \frac{\|\theta_e \theta_\mu^*\|}{2}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
$\|\eta_{e\tau}\| = \frac{\|\theta_e \theta_\tau^*\|}{2}$	$[1.3, 5.1] \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$
$\|\eta_{\mu\tau}\| = \frac{\|\theta_\mu \theta_\tau^*\|}{2}$	$5.0 \cdot 10^{-6}$	$5.7 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$

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Global bounds: EW and CLFV precision data

G-SS	LFC Bound		LFV Bound	
	68%CL	95%CL	68%CL	95%CL
η_{ee}	$[0.33, 1.0] \cdot 10^{-3}$	$[0.081, 1.4] \cdot 10^{-3}$	-	-
$\eta_{\mu\mu}$	$1.5 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	-	-
$\eta_{\tau\tau}$	$1.6 \cdot 10^{-4}$	$8.9 \cdot 10^{-4}$	-	-
$\mathrm{Tr}\,[\eta]$	$[0.28, 1.2] \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	-	-
$\lvert\eta_{e\mu}\rvert$	$1.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$	$\mathbf{8.4 \cdot 10^{-6}}$	$\mathbf{1.2 \cdot 10^{-5}}$
$\lvert\eta_{e\tau}\rvert$	$\mathbf{4.2 \cdot 10^{-4}}$	$\mathbf{8.8 \cdot 10^{-4}}$	$5.7 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$
$\lvert\eta_{\mu\tau}\rvert$	$\mathbf{9.4 \cdot 10^{-6}}$	$\mathbf{1.8 \cdot 10^{-4}}$	$6.6 \cdot 10^{-3}$	$9.4 \cdot 10^{-3}$

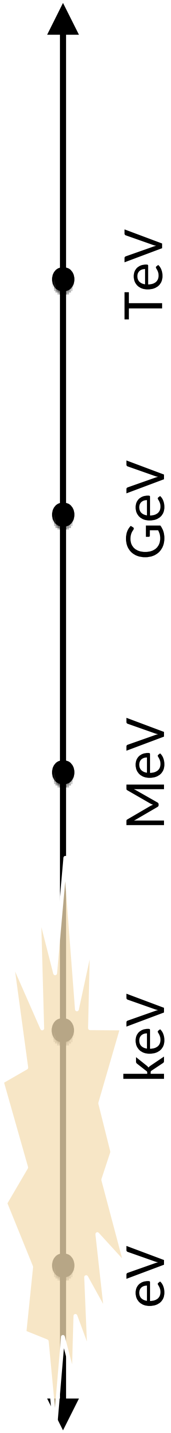
$$|\mathbb{I} - \alpha| = \begin{pmatrix} [0.081, 1.4] \cdot 10^{-3} & 0 & 0 \\ < 2.4 \cdot 10^{-5} & < 1.4 \cdot 10^{-4} & 0 \\ < 1.8 \cdot 10^{-3} & < 3.6 \cdot 10^{-4} & < 8.9 \cdot 10^{-4} \end{pmatrix}$$

Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Observable	SM prediction	Experimental value	
$M_W \simeq M_W^{\rm SM}\left(1+0.20\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	80.356(6) GeV	80.373(11) GeV	-
$s^{2\ \rm Tev}_{\rm eff} \simeq s^{2\ \rm SM}_{\rm eff}\left(1-1.40\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	0.23154(4)	0.23148(33)	[76]
$s^{2\ \rm LHC}_{\rm eff} \simeq s^{2\ \rm SM}_{\rm eff}\left(1-1.40\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	0.23154(4)	0.23129(33)	[76]
$\Gamma^{\rm LHC}_{\rm inv} \simeq \Gamma^{\rm SM}_{\rm inv}\left(1-0.33\left(\eta_{ee}+\eta_{\mu\mu}\right)-1.33\eta_{\tau\tau}\right)$	0.50145(5) GeV	0.523(16) GeV	[77]
$\Gamma_Z \simeq \Gamma_Z^{\rm SM}\left(1+1.08\left(\eta_{ee}+\eta_{\mu\mu}\right)-0.27\eta_{\tau\tau}\right)$	2.4939(9) GeV	2.4955(23) GeV	[76]
$\sigma^0_{\rm had} \simeq \sigma^{0\ \rm SM}_{\rm had}\left(1+0.50\left(\eta_{ee}+\eta_{\mu\mu}\right)+0.53\eta_{\tau\tau}\right)$	41.485(8) nb	41.481(33) nb	[76]
$R_e \simeq R_e^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	20.733(10)	20.804(50)	[76]
$R_\mu \simeq R_\mu^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	20.733(10)	20.784(34)	[76]
$R_\tau \simeq R_\tau^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$	20.780(10)	20.764(45)	[76]
$R^\pi_{\mu e} \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$	1	1.0010(9)	[78]
$R^\pi_{\tau\mu} \simeq \left(1-\left(\eta_{\tau\tau}-\eta_{\mu\mu}\right)\right)$	1	0.9964(38)	[78]
$R^K_{\mu e} \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$	1	0.9978(18)	[78]
$R^\tau_{\mu e} \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$	1	1.0018(14)	[78]
$R^\tau_{\tau\mu} \simeq \left(1-\left(\eta_{\tau\tau}-\eta_{\mu\mu}\right)\right)$	1	1.0010(14)	[78]

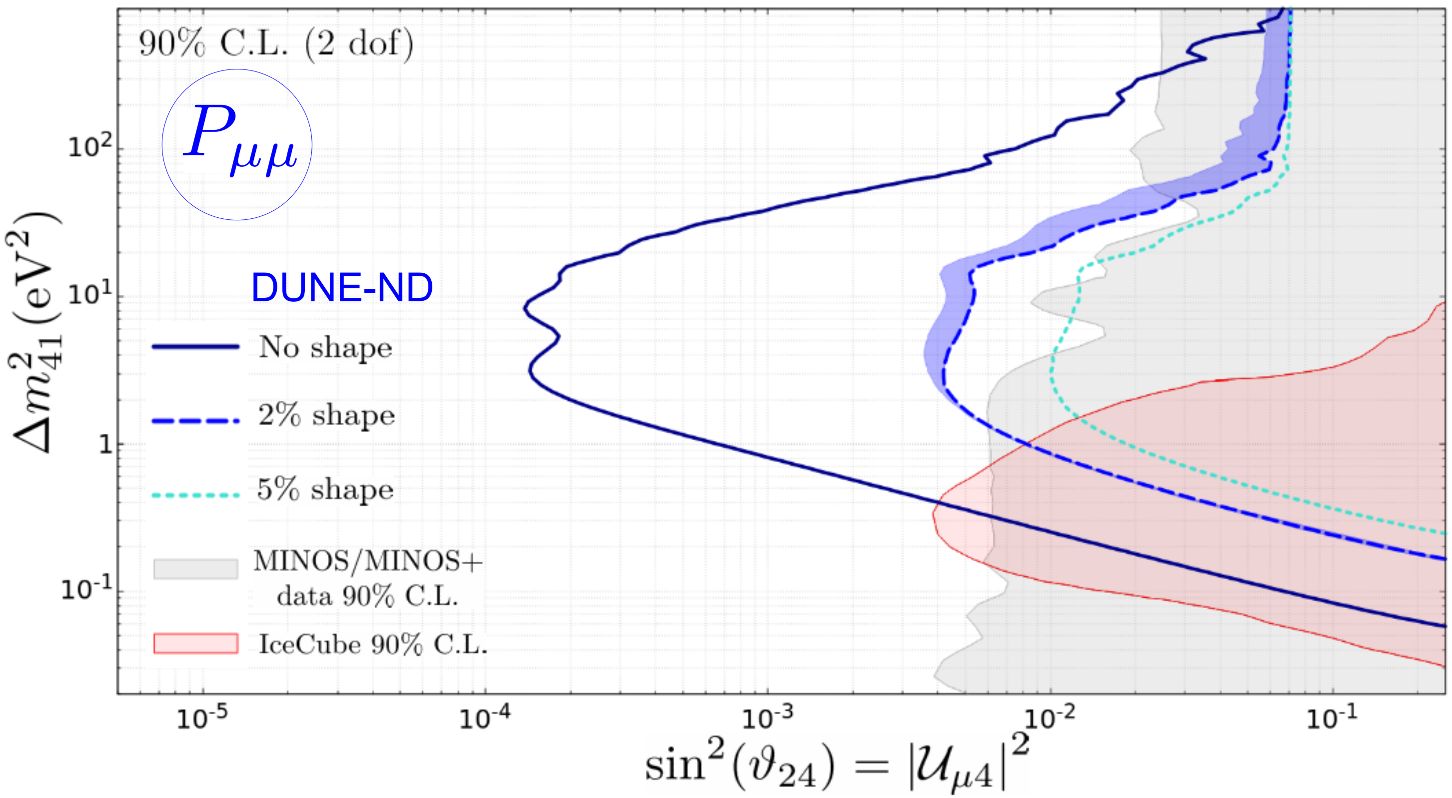
$\left\|V_{ud}^{\beta}\right\| \simeq \sqrt{1-\|V_{us}\|^2}\,(1+\eta_{\mu\mu})$	$\sqrt{1-\|V_{us}\|^2}$	0.97373(31)	[76]
$\left\|V_{us}^{\tau\to K\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{ee}+\eta_{\mu\mu}-\eta_{\tau\tau})$	$\|V_{us}\|$	0.2236(15)	[79]
$\left\|V_{us}^{\tau\to K,\pi}\right\| \simeq \|V_{us}\|\,(1+\eta_{\mu\mu})$	$\|V_{us}\|$	0.2234(15)	[76]
$\left\|V_{us}^{K_L\to\pi e\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{\mu\mu})$	$\|V_{us}\|$	0.2229(6)	[76]
$\left\|V_{us}^{K_L\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{ee})$	$\|V_{us}\|$	0.2234(7)	[76]
$\left\|V_{us}^{K_S\to\pi e\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{\mu\mu})$	$\|V_{us}\|$	0.2220(13)	[76]
$\left\|V_{us}^{K_S\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{ee})$	$\|V_{us}\|$	0.2193(48)	[76]
$\left\|V_{us}^{K^\pm\to\pi e\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{\mu\mu})$	$\|V_{us}\|$	0.2239(10)	[76]
$\left\|V_{us}^{K^\pm\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\,(1+\eta_{ee})$	$\|V_{us}\|$	0.2238(12)	[76]
$\left\|\frac{V_{us}}{V_{ud}}\right\|^{K,\pi\to\mu\nu} \simeq \frac{\|V_{us}\|}{\sqrt{1-\|V_{us}\|^2}}$	$\frac{\|V_{us}\|}{\sqrt{1-\|V_{us}\|^2}}$	0.23131(53)	[76]

The New Physics Scale

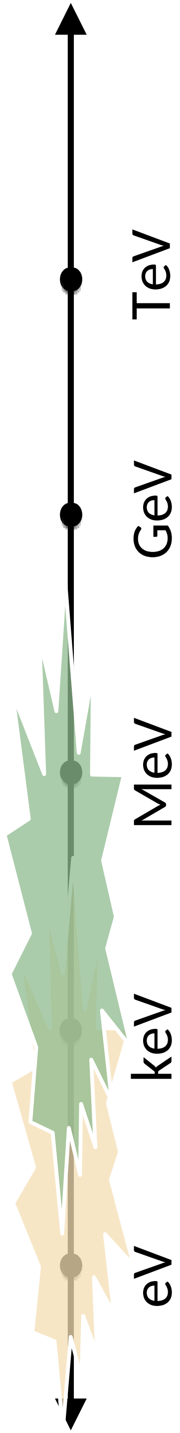


- For very light scales M, HNLs (in this regime usually called sterile neutrinos) participate in **neutrino oscillations**. In simplified 3+1 scenario:

Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

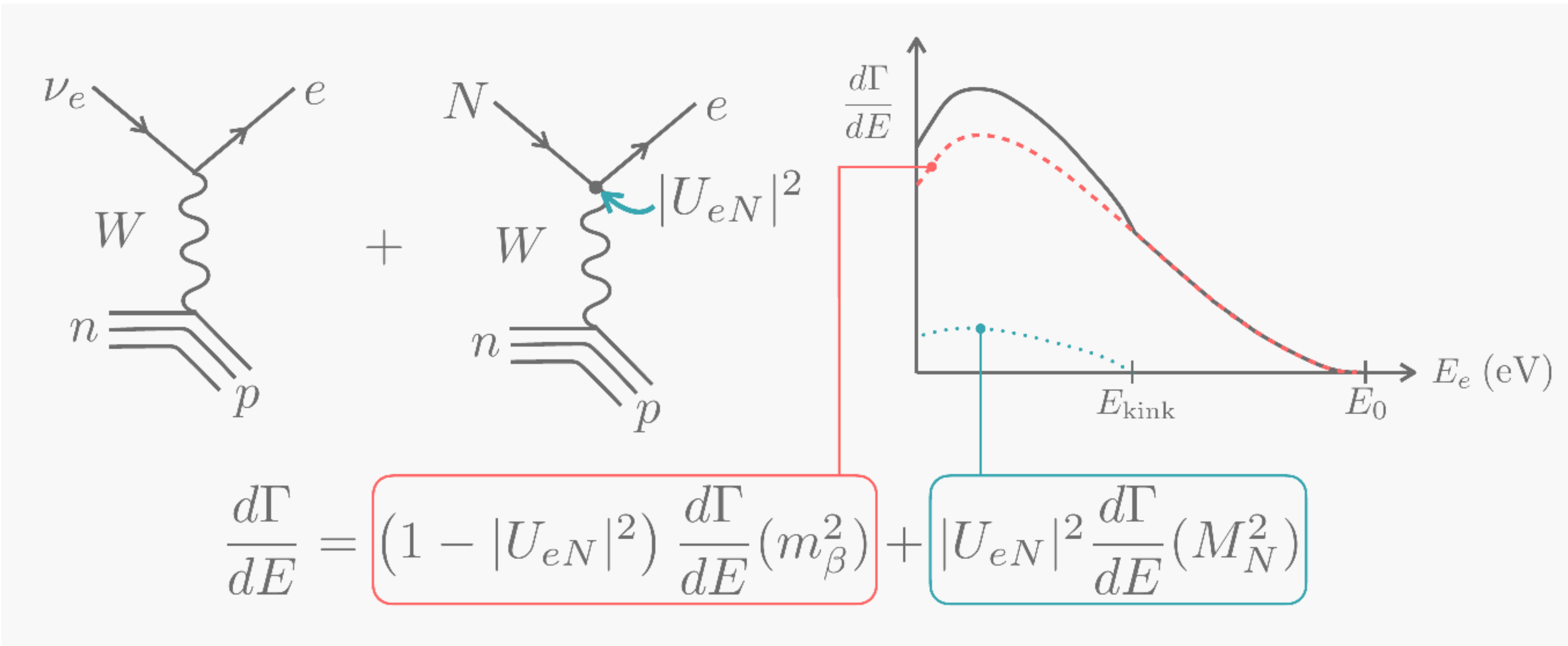


Dasgupta, Kopp 2106.05913;
Dentler, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz 1803.10661
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637;
...



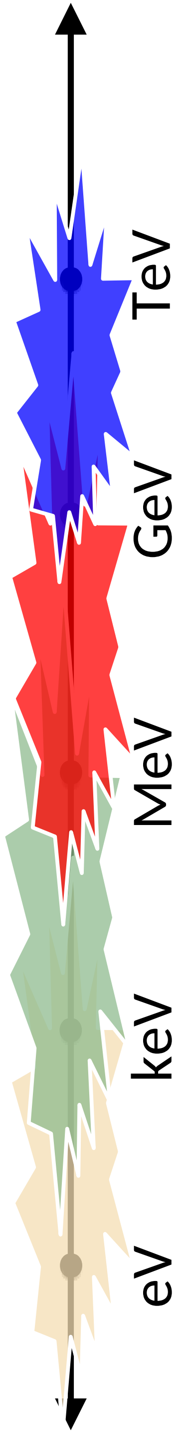
The New Physics Scale

- Search for **kinks in beta decays & peak searches in semileptonic meson decays** (pion & kaon decays)



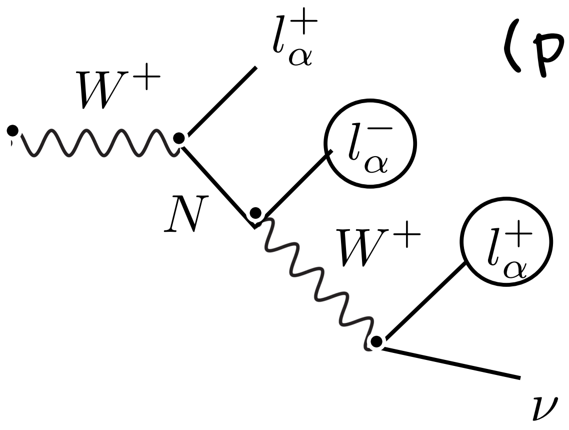
Cortesy of J. Hernandez-Garcia

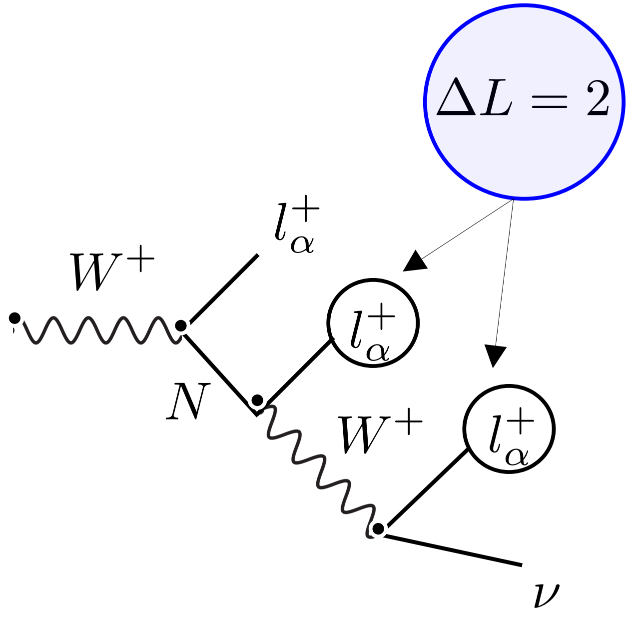
The New Physics Scale

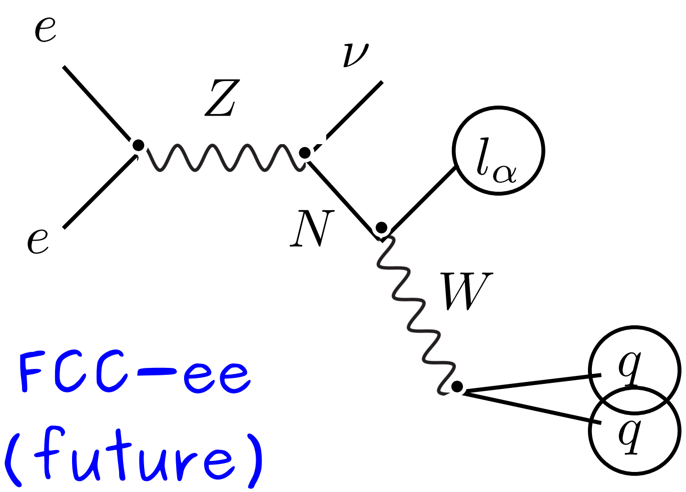


- **Colliders**

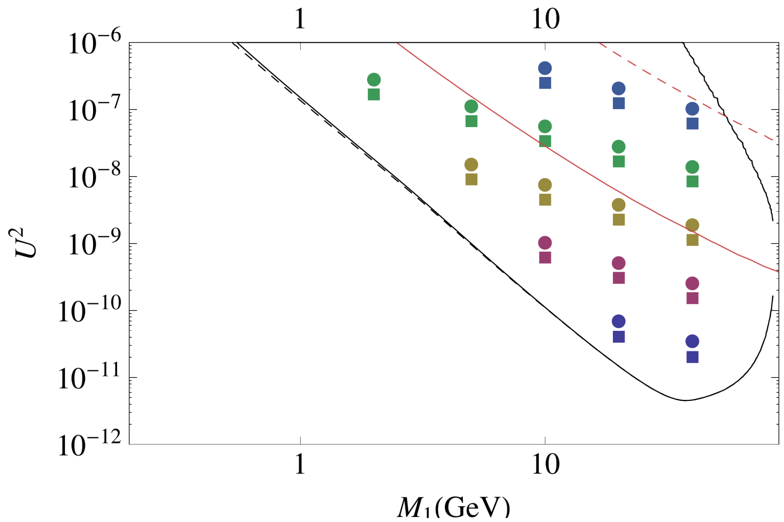
LHC
(present)



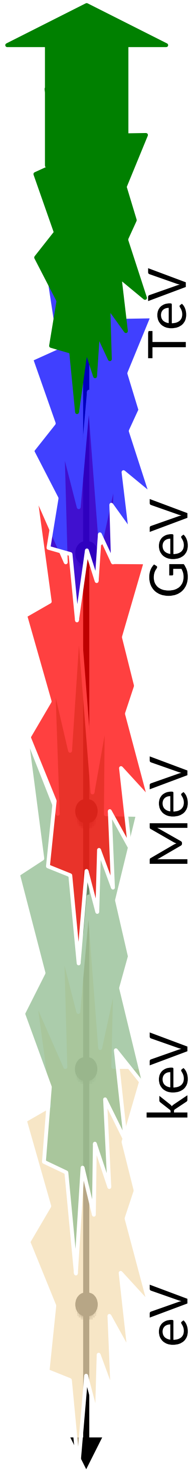




FCC-ee
(future)

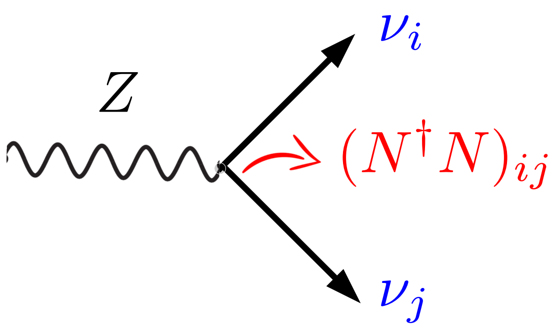


Caputo, Hernandez, Kekic, JLP, Salvado arXiv:1611.05000
Blondel, Graverini, Serra, Shaposhnikov 1411.5230



The New Physics Scale

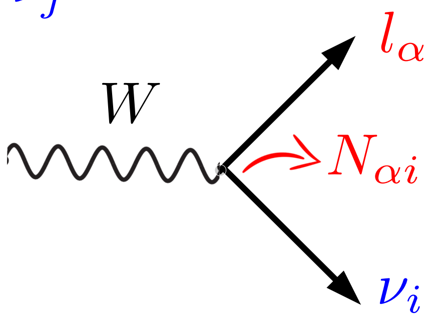
- **CLFV and EW precision data**



$$N = (1-\eta)\,U_{PMNS}$$

$$\eta = \frac{1}{2}\Theta^\dagger \boxed{\Theta}$$

HNL mixing

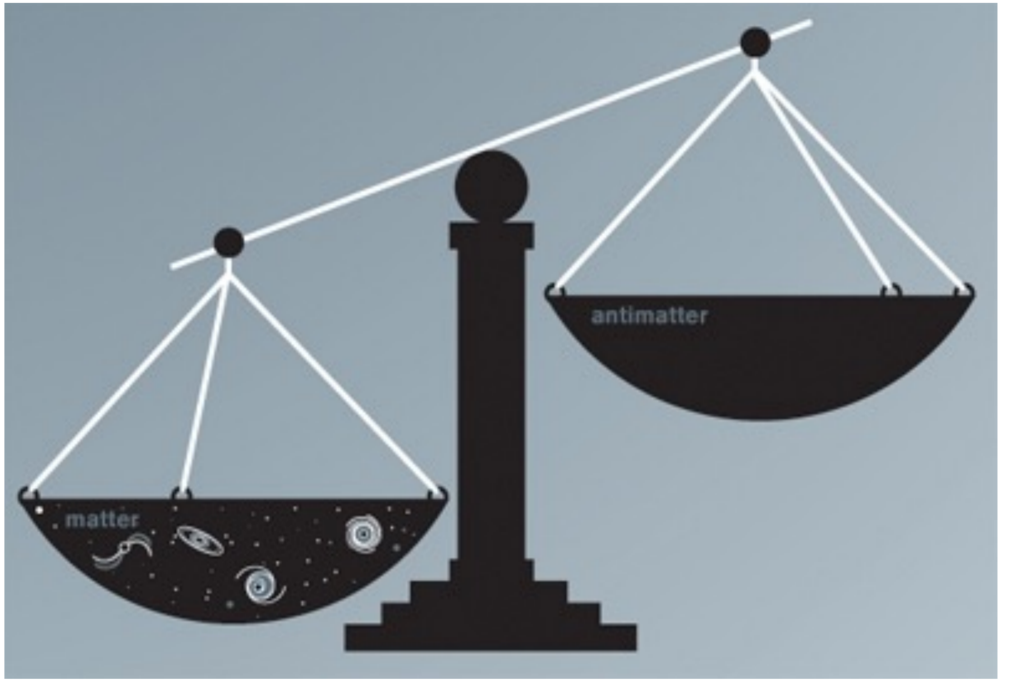


- *Many EW and CLFV processes affected:* determination of G_F via muon decay, W boson mass, weak mixing angle, ratios of Z fermionic decays, invisible width of the Z, ratios of weak decays constraining EW universality, weak decays constraining CKM unitarity, CLFV decays...

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006
Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Baryon asymmetry

- **After the Big-Bang same amount of matter and antimatter generated, but observed universe mainly made out of matter only!**



$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.13 \pm 0.04) \times 10^{-10}$$

Sakharov conditions

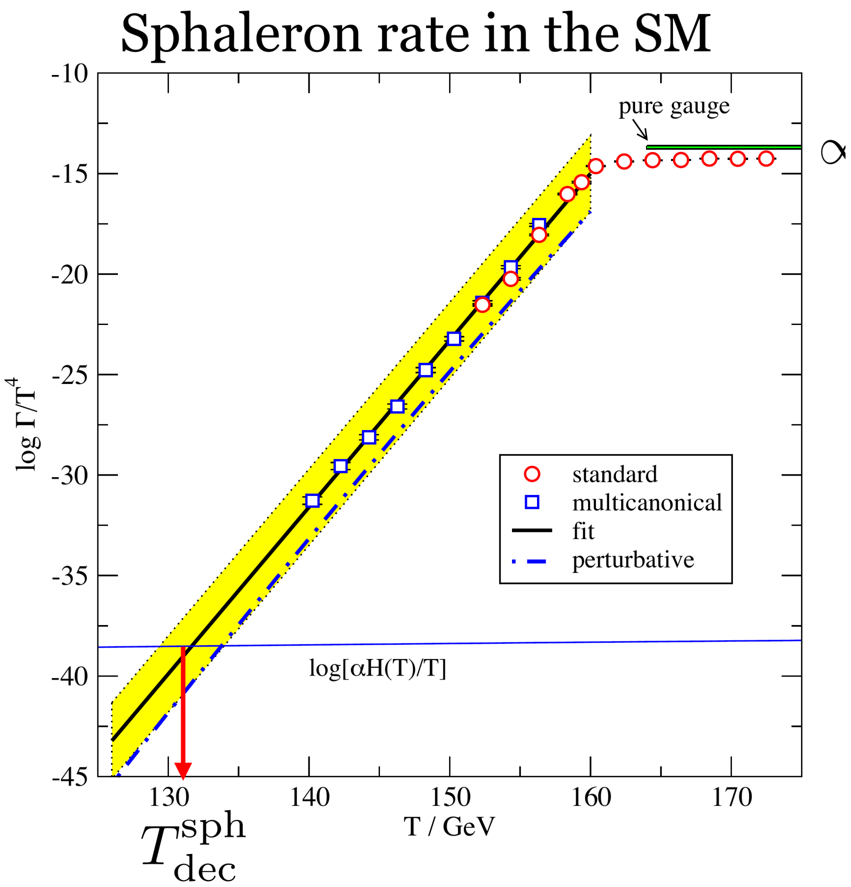
1 Baryon number violation

If baryon number is conserved, no baryon asymmetry can be generated

- Symmetry is broken by quantum effects: anomaly

- Only B-L is conserved!

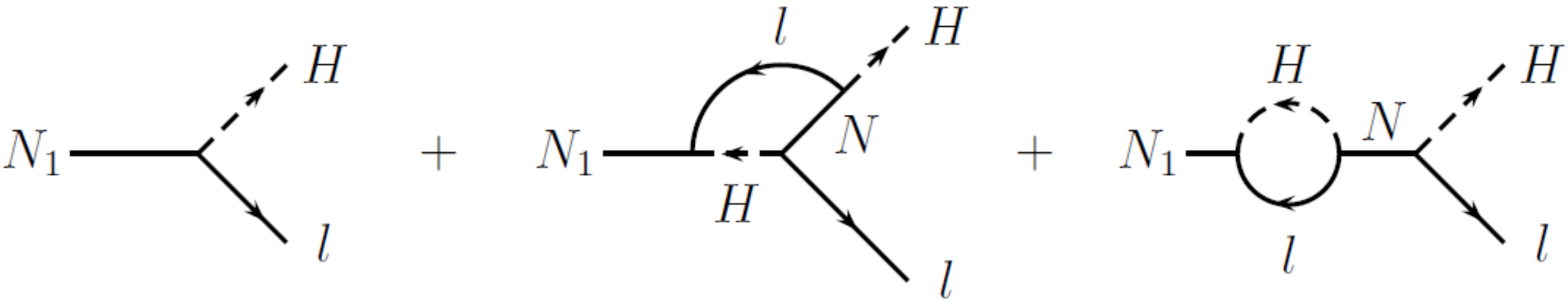
Sphalerons @T<140GeV



D'onofrio, Rummukainen, Trangberg 2014

Leptogenesis: Sakharov conditions

2 C and CP violation



At one loop: CP asymmetry generated via interference effects

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to l^c H^c)}{\Gamma(N \to lH) + \Gamma(N \to l^c H^c)} \propto Im(Y^\dagger Y)^2_{ij}$$