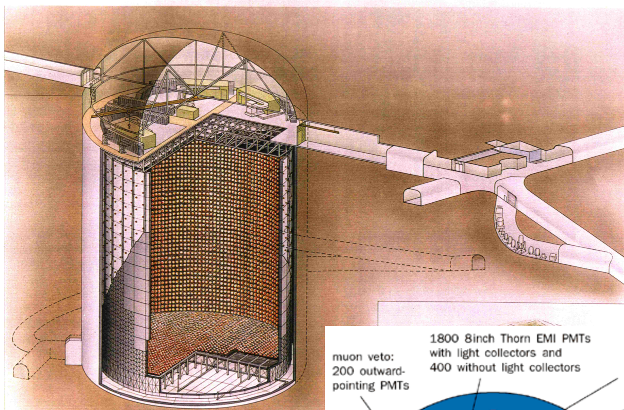
Neutrinos: Theory

Pilar Hernández
IFIC University of Valencia

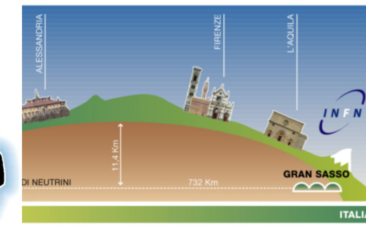
Particles and Nuclei International Conference

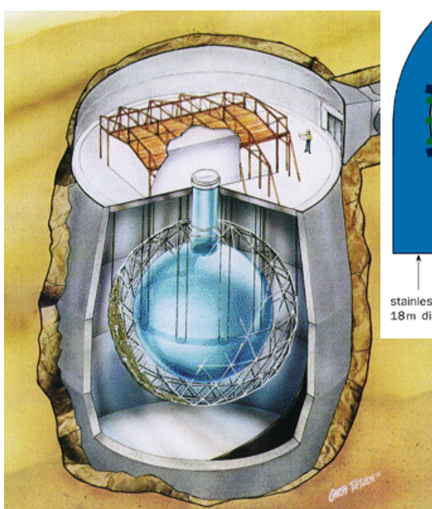
>20 years of revolutionary neutrino experiments have revealed neutrino masses and a new flavour sector, which does not quite fit in the Standard Model

SuperKamiokande

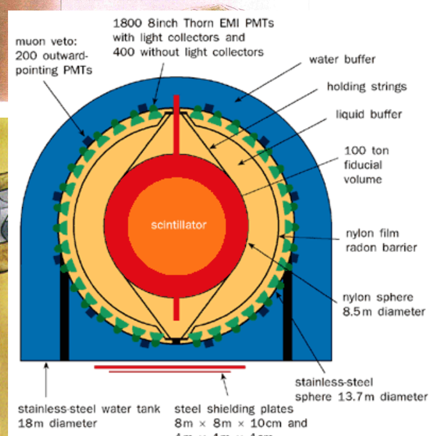


MINOS, Opera





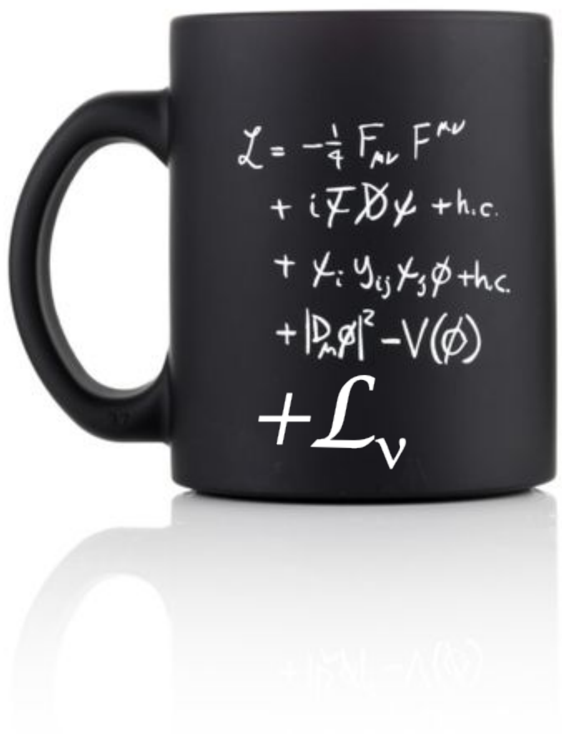
SNO



Borexino

...and more

Neutrino Theory: νSM in the making

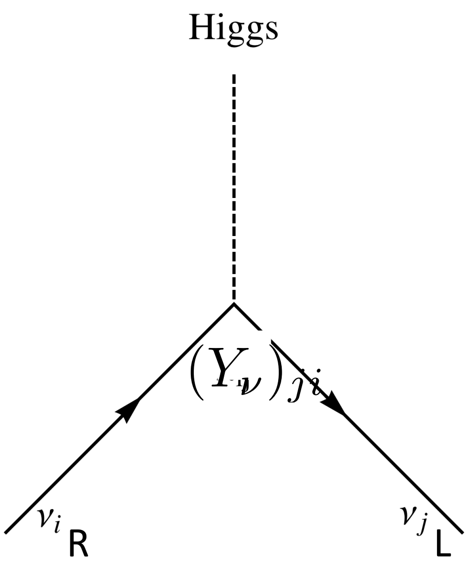


The Standard Model+massive ν

$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{1})_{0}$
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i\\ d^i\end{pmatrix}_L$	e_R	u^i_R	d^i_R	ν_R^1
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R	ν_R^2
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R	ν_R^3

The Standard Model+massive ν

With arbitrary choice: global L $\nu_R^i \rightarrow e^{i\alpha}\nu_R^i$



$$-\mathcal{L}_{\rm SM} \supset Y_{\nu ij}\bar{L}_i\tilde{\phi}\,\nu_{Rj}$$

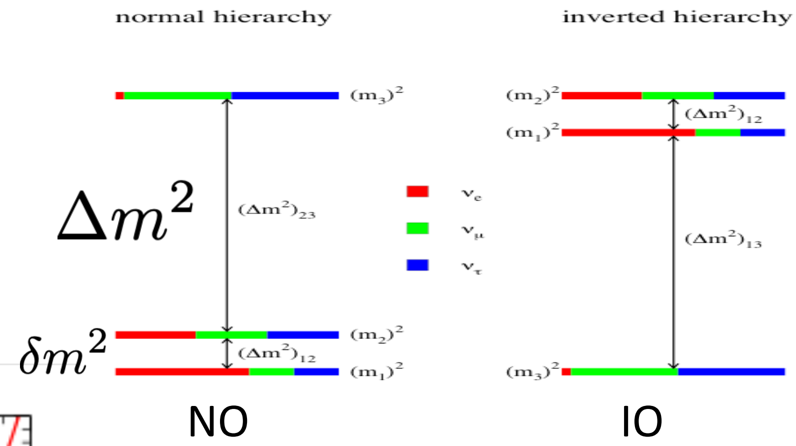
$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

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

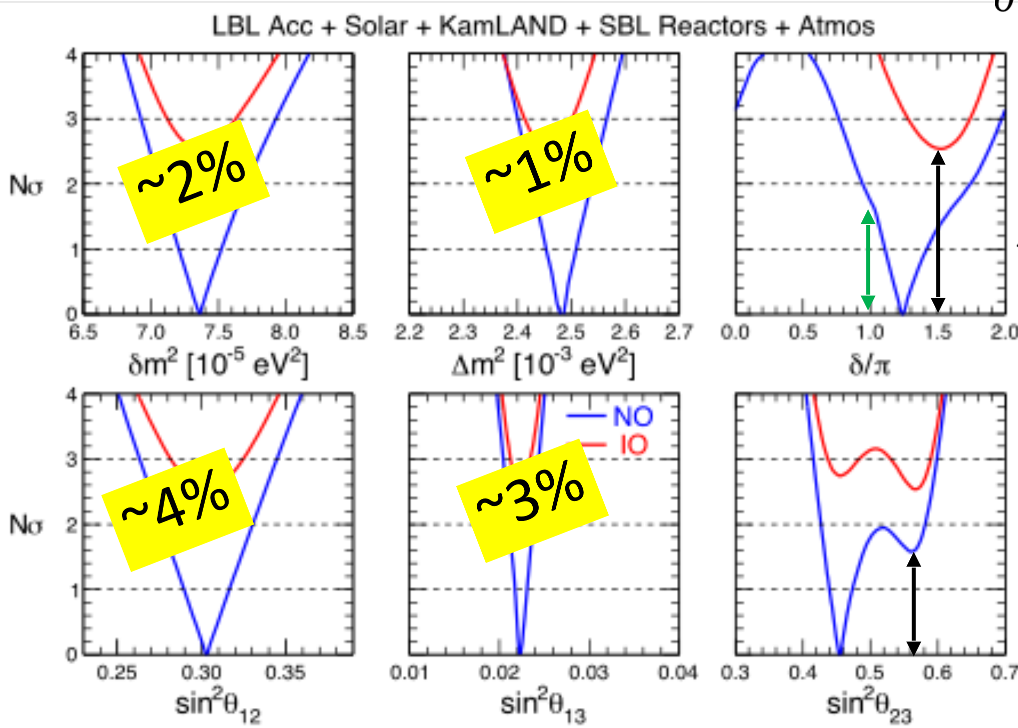
- No insight into family structure/parity breaking/lepton-quark complementarity…
- Less predictivity (7 more free parameters): 3 masses, 3 mixing angles, 1 CP phase

SM+3 massive neutrinos: Global Fits

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



Capozzi et al 2107.00532



$$\chi^2(\mathrm{IO}) - \chi^2(\mathrm{NO}) \sim 2.5\sigma$$

$$\chi^2(\delta = 0/\pi) - \chi^2(\delta_{\mathrm{BF}}) < 2\sigma$$

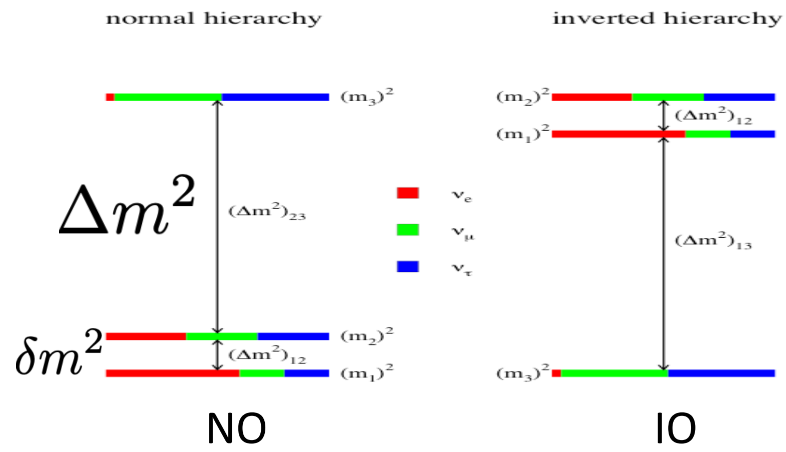
$$\chi^2(\text{2nd oct}) - \chi^2(\text{1st oct}) < 2\sigma$$

Also Esteban, et al '20; Salas et al, '20

-> See Tortola's talk

SM+3 massive neutrinos: Global Fits

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

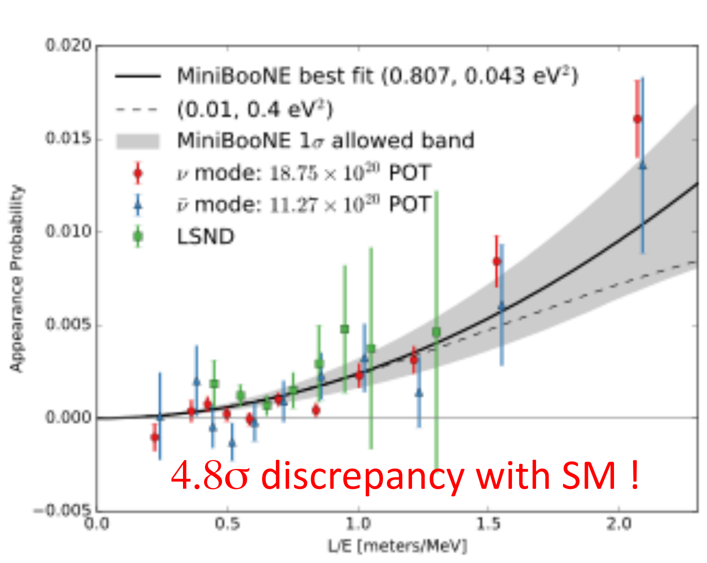


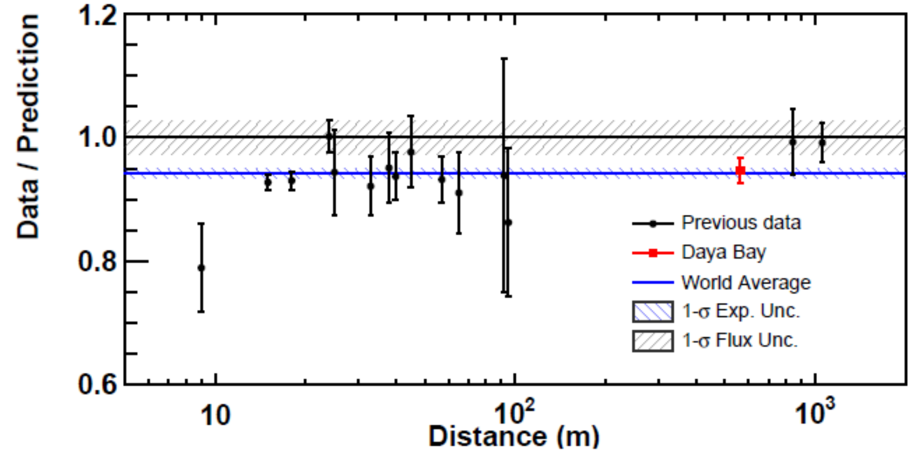
Hints for hierarchy/octant/CP violation still not robust

- Some tensions in the data (eg. NOVA vs T2K)
- $\Delta\chi^2$ look different when subsets of data are considered...
- Rich experimental programme ahead will pin these unknowns

-> See Tortola's talk

Outliers: LSND+MiniBOONE+Gallium+Reactor





➢ Not fully robust against systematics (neutrino cross sections/reactor neutrino fluxes)

➢ Still confusing experimental situation, intense experimental programme ongoing

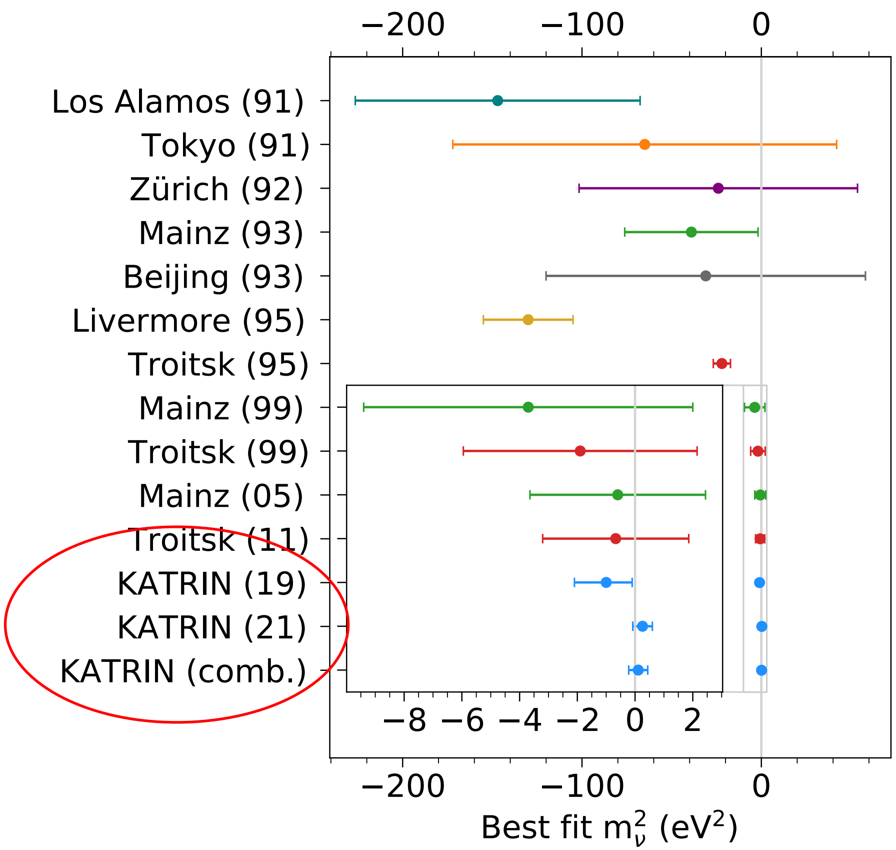
➢ Many highly constrained phenomenological models, but no baseline scenario

-> See Lasserre's Talk

Neutrino Mass Scale

$H^3 \rightarrow^3 He + e^- + \bar{\nu}_e$

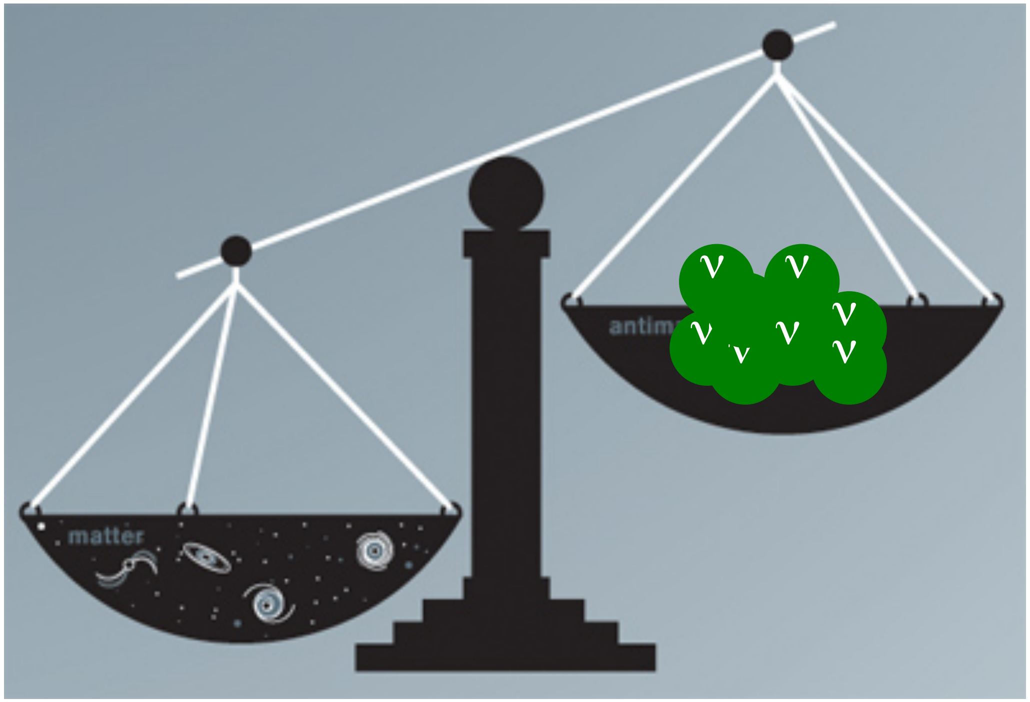
Kinematic effect of neutrino mass m_β



$m_\nu < 0.8\,\text{eV}$ (90 % CL)

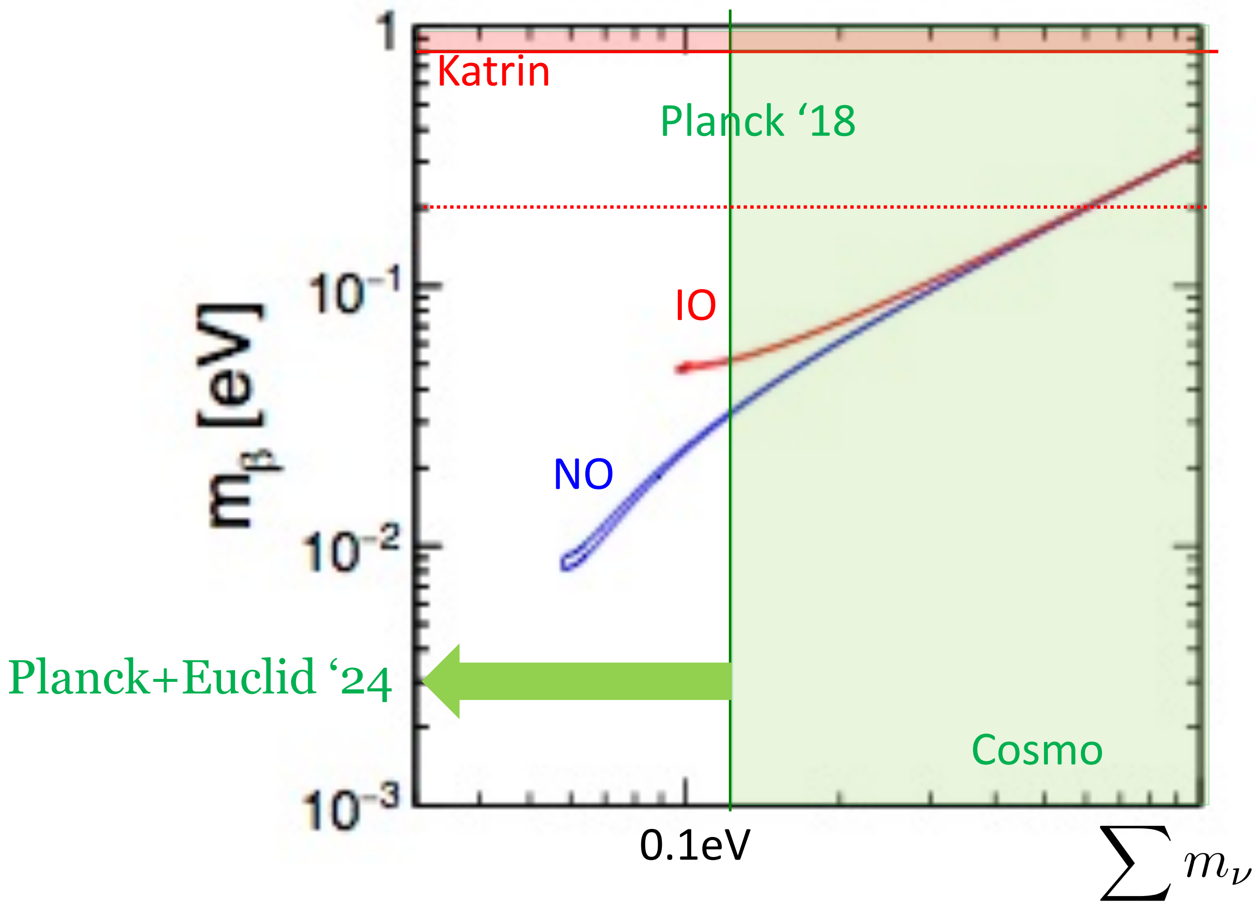
Neutrino Mass Scale

$\sum m_\nu$ strongly constrained by cosmology (LSS, CMB)



Planck '18 $\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Absolute ν mass scale

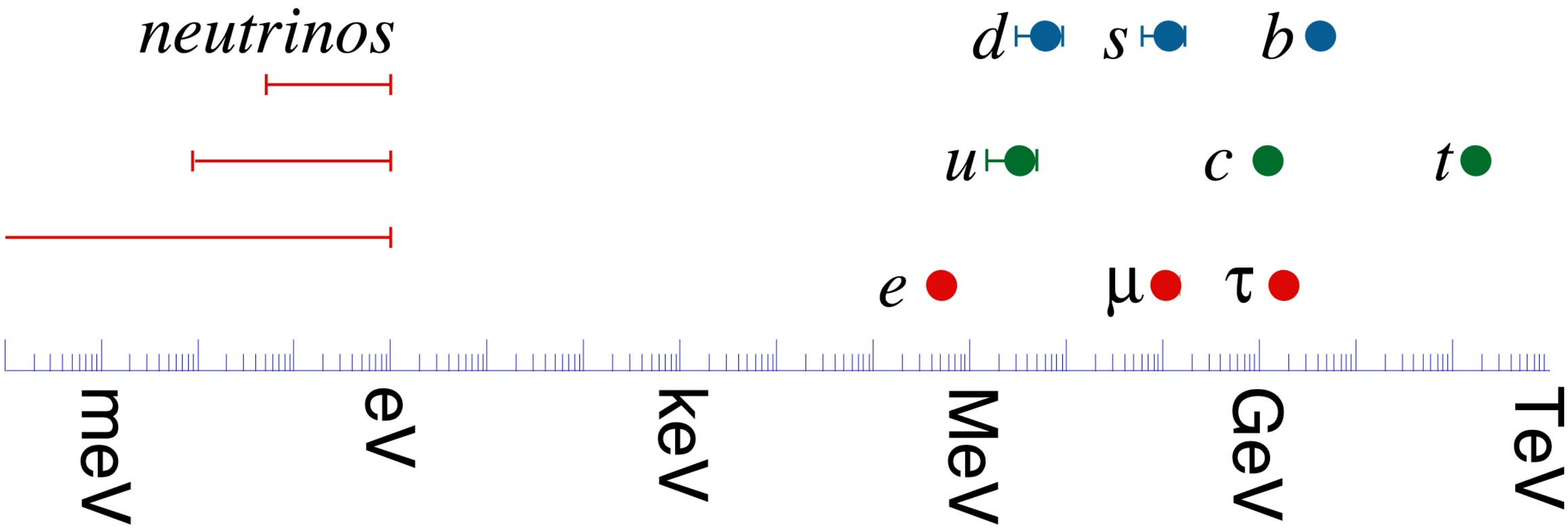


➢ Some tensions in cosmo data, alternative analysis not including incompatible data relaxed limits ~0.8eV Capozzi et al 2107.00532

➢ Cosmo bounds very sensitive to non-standard neutrino properties and cosmology
Chacko et al 1909.05275; 2002.08401; Escudero et al 2007.04994; Barenboim et al 2011.01502; Lorenz et al 2102.13618 ; Esteban, Salvado 2101.05804 ;....

Massive neutrinos: a new flavour perspective

Why are neutrinos so much lighter ?



Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$J = (3.18 \pm 0.15) \times 10^{-5}$

PMNS

NuFIT 5.0 (2020)

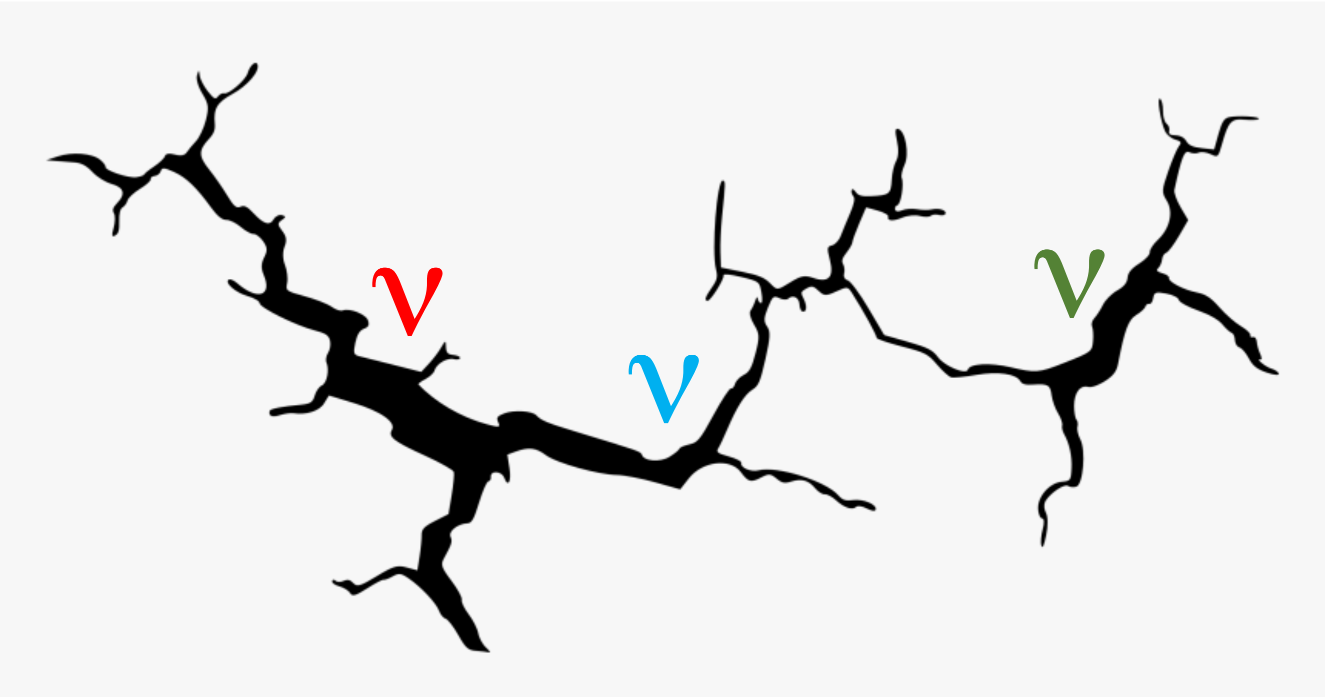
$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

$J \simeq 0.033 \sin\delta$

Many new ideas: Flavour symmetries, Modular invariance,...

-> Talk Ding

Are Neutrinos cracking the SM ?



Revealing a new physics scale mass of neutrino mass mediators ?

SM + high scale BSM = SMEFT

What if there is new physics (ie. new fields with mass Λ >> v)?

E

$$\mathcal{L}_{\mathrm{SM}}[\phi] + \mathcal{L}_{\mathrm{BSM}}[\phi, \Phi]$$

$$(g_3, g_2, g_1, y_q, y_l, \lambda, \mu^2, \ldots)$$

Λ

$$\mathcal{L}'_{\mathrm{SM}}[\phi] + \mathcal{L}_{\mathrm{SMEFT}}[\phi]$$

$$(g'_3, g'_2, g'_1, y'_q, y'_l, \lambda', \mu'^2, \ldots)$$

$$\mathcal{L}_{\mathrm{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

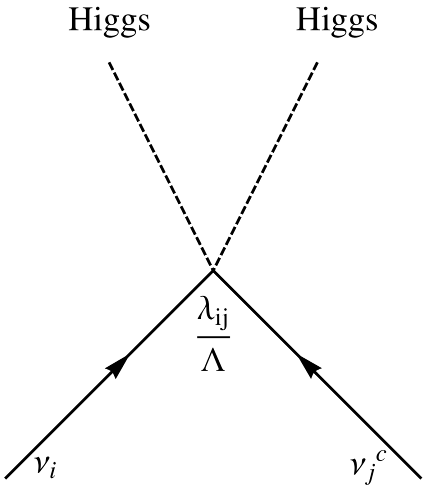
$$\mathcal{O}\left(\frac{E}{\Lambda}\right)^{d-4}$$

SMEFT @ d=5

RIP

$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}}_{\text{1 operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}}_{\text{2499 operators(59 B,L,FC)}} + \ldots$$

$\Delta L = 2$



$$\mathcal{O}^{(5)} = \frac{c_{ij}^{(5)}}{\Lambda}\bar{L}_i H (H L_j)^c + h.c. \rightarrow \overline{\nu}_L \frac{m_\nu}{2}\nu_L^c + h.c.$$

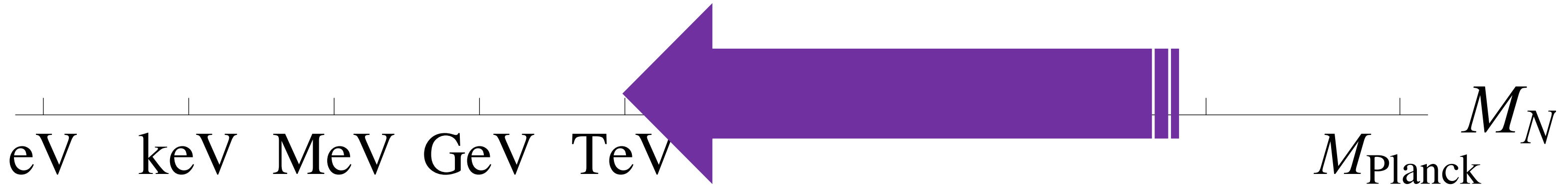
$$\frac{c^{(5)}}{\Lambda} = \frac{m_\nu}{v^2} \sim \mathcal{O}\left(\frac{1}{10^{15}\ \text{GeV}}\right)$$

Neutrino-mass mediator scale ?

Degeneracy between c and Λ !

$c_i^{(d)} \propto (\text{couplings})^{\#}$

$c_i^{(d)} \leq 1$ gives an upper bound on Λ



Neutrino-mass mediator scale ?

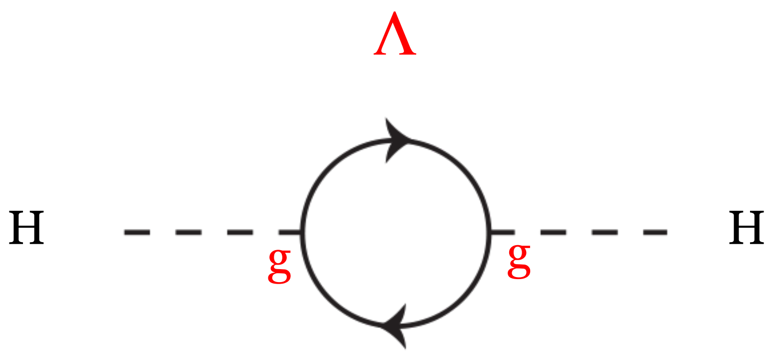
12 order of magnitude of possibilities that can explain why neutrinos are “naturally” special

Eg: Type I seesaw models

$$c^{(5)} \in [Y_e^2, 1]$$

SMEFT and hierarchy problem

Fine-tunning ?



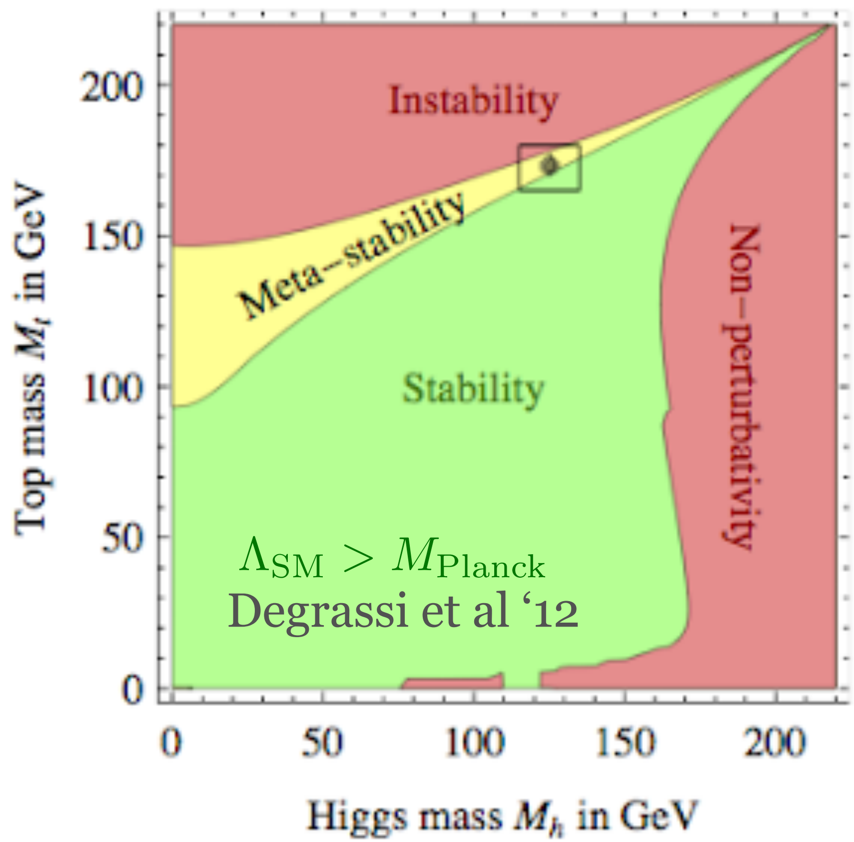
$$\mu'^2 = \mu^2 + \frac{g^2}{16\pi^2}\Lambda^2$$

If there are heavy new particles, the Higgs mass should know about them…

LHC news:

➢ No yet sign of a solution to the hierarchy problem (SUSY, compositeness,etc)

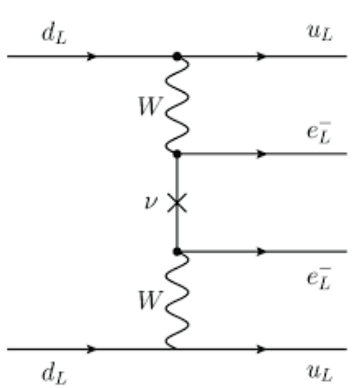
➢ The SM cutoff could be beyond M_{planck}



Neutrino-mass mediator scale ?

I Generic prediction

➢ there is neutrinoless double beta decay at some level (Λ > 100MeV)



model independent contribution

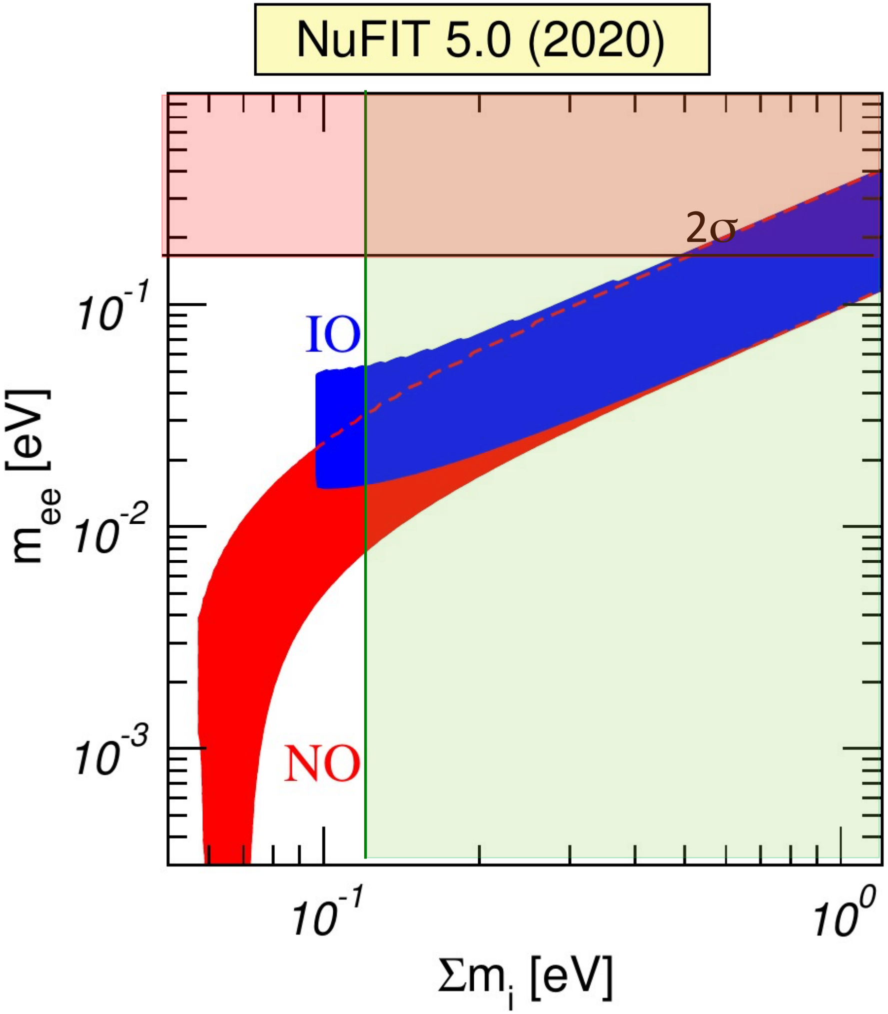
from the neutrino mass 😊

-> talk Lindner's

Majorana nature: ββ0ν

Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, MAJORANA, CUORE, NEXT, …

-> Talks Pertoldi,Dompè, Schonert



Next generation of experiments @Ton scale to cover the IO region

Neutrino-mass mediator scale ?

II Generic prediction

➢ a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis and sufficient out-of-equilibrium

details model dependent…

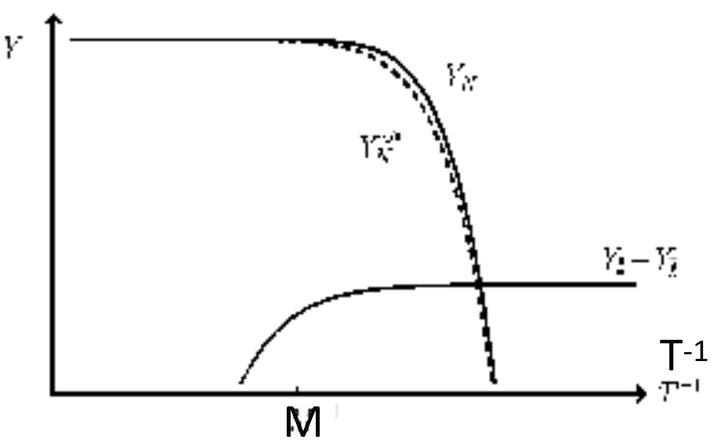
Sakharov conditions generically satisfied

✔ CP violation (≥ 3 CP phases)

✔ B+L violation from sphalerons $T > T_{EW}$

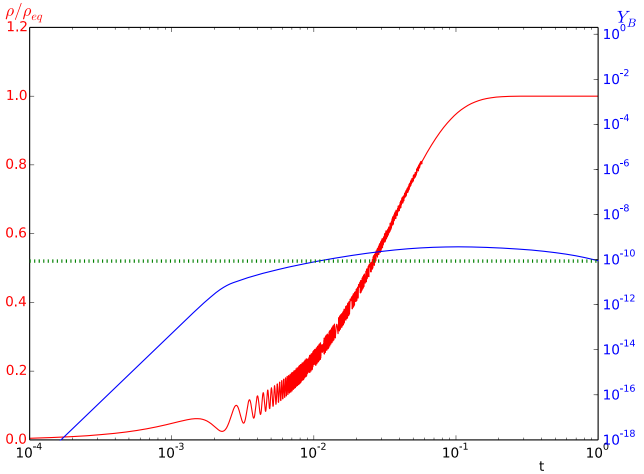
✔ New out of equilibrium condition from the neutrino mass mediators

Freeze-out leptogenesis
(larger couplings/scales)
Fukugita,Yanagida



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

Freeze-in leptogenesis
(smaller couplings/scales)
Akhmedov, Rubakov, Smirnov



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

New scale (if dynamical) could lead to new/modified PT

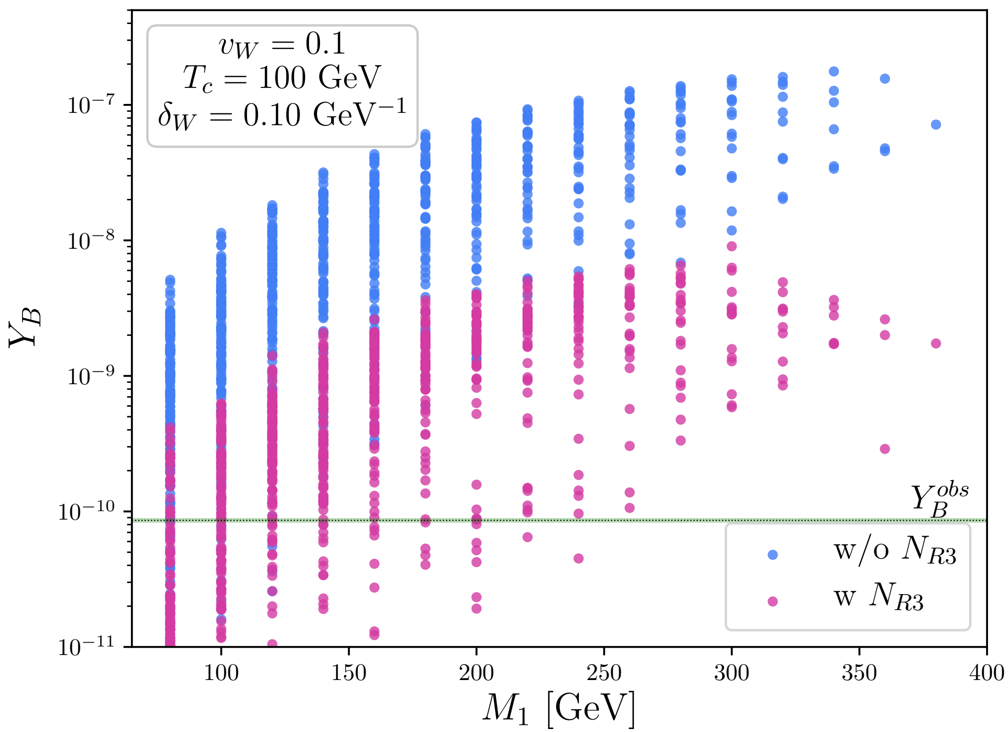
$$\Lambda = \langle \Phi \rangle$$

- @EW:

EWPT first order

+Leptonic CP violation

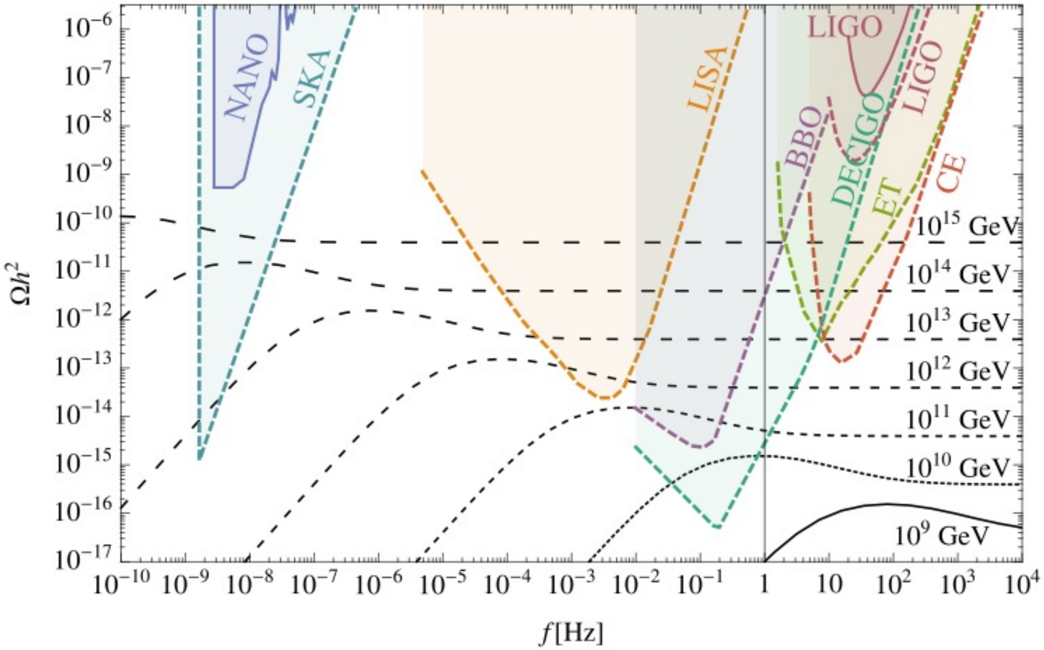
EW Baryogenesis by neutrinos ?



PH, Rius '96;Fernández-Martínez et al 2007.11008

New scale (if dynamical) could lead to new/modified PT

➢ ~ GUT cosmic strings -> stochastic background of Gravity Waves ?



Buchmuller et al 1305.3392 &1912.03695;Dror et al 1908.03227; King et al 2005.13549, 2106.15634

Neutrino-mass mediator scale ?

III Generic prediction

New interactions beyond d=5

$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}}_{1\ \text{operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}}_{2499\ \text{operators}(59\ \text{B,L,FC})} + \ldots$$

$c_i^{(6)}$ can modify the SM couplings and generate new ones including eg NSI that can be best constrained by neutrino oscillation/interaction physics

$$\mathcal{L}_{\text{SMEFT}} \supset \quad \mathcal{L}_{NC}^{NSI} = -\frac{G_F}{\sqrt{2}}\left(\epsilon_{pr}^{fL}\left[\bar{\nu}_p\gamma^\mu(1-\gamma_5)\nu_r\right]\left[\bar{f}\gamma_\mu(1-\gamma_5)f\right] + \epsilon_{pr}^{fR}\left[\bar{\nu}_p\gamma^\mu(1-\gamma_5)\nu_p\right]\left[\bar{f}\gamma_\mu(1+\gamma_5)f\right]\right),$$

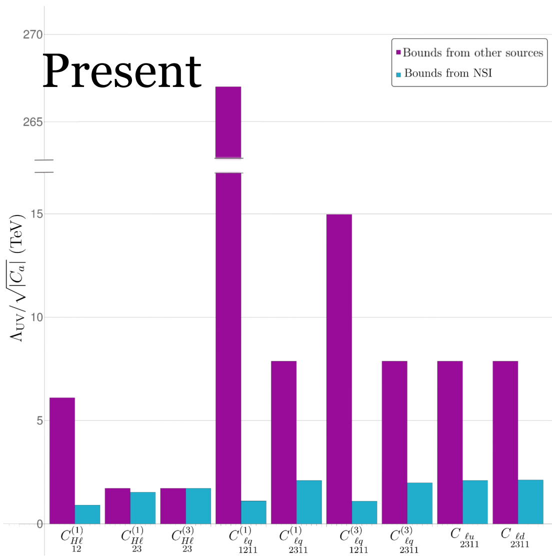
SMEFT (beyond $O_{d=5}$) from Neutrino Physics ?

➢ Updated and prospective NSI constraints from various experiments: reactors, LBL, solar, atmospheric, CEνNS, FASERnu, SND@LHC…

-> Talks Scholbert, Miranda, De Gouvea

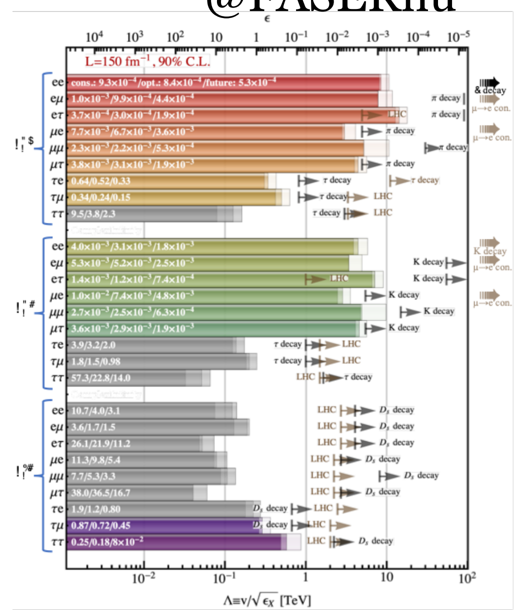
➢ Bounds not competitive within SMEFT ($\Lambda > v$) but can be relevant in the case of light mediators ($\Lambda << v$) or cancellations

Altmannshofer et al 1812.02778;Falkowski et al 1901.04555 &1910.02971; Bischer et al 1905.08699; Davidson, Gorbahn 1909.07406 ; Escrihuela et al 2105.06484; Y. Du et al 2106.15800;…



Terol-Calvo et al 1912.09131

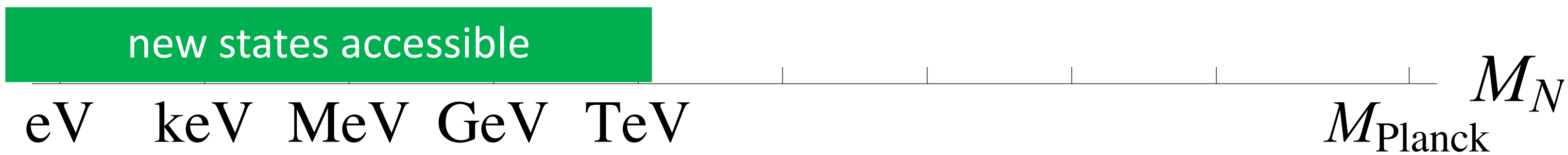
@FASERnu



Falkowski et al 2105.12136

Neutrino- mass mediator scale ?

IV Generic prediction

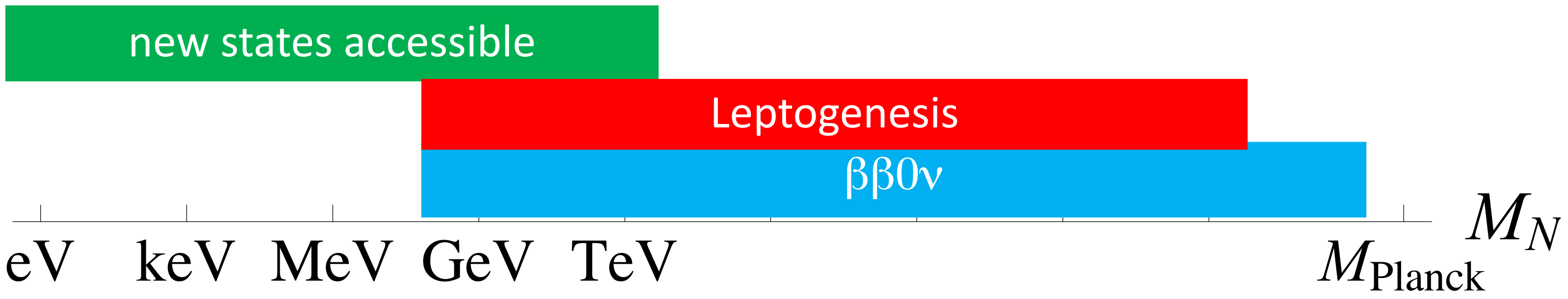


- new states can be kinematically produced

potential impact in cosmology (DM, baryogenesis), EW precision tests, collider, rare searches, $\beta\beta0\nu$, ...

model dependent...

Neutrino-mass mediator scale ?

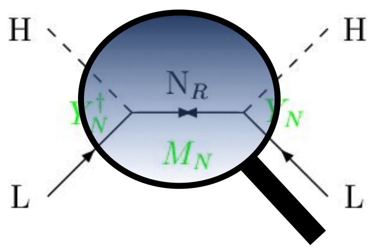


The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be predicted & tested !

Resolving the neutrino mass operator at tree level

E. Ma

Type I see-saw:
a heavy singlet scalar

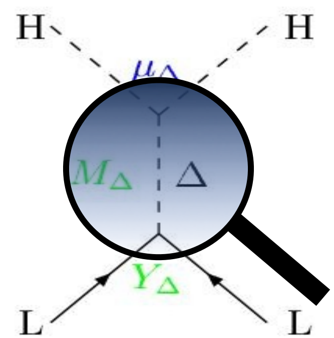


$$m_\nu = \frac{c v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

$c \sim O(Y^2)$

Type II see-saw:
a heavy triplet scalar

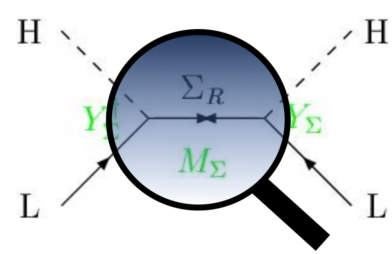


$$m_\nu = \frac{c v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

$c \sim O(Y \mu/M_\Delta)$

Type III see-saw:
a heavy triplet fermion



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

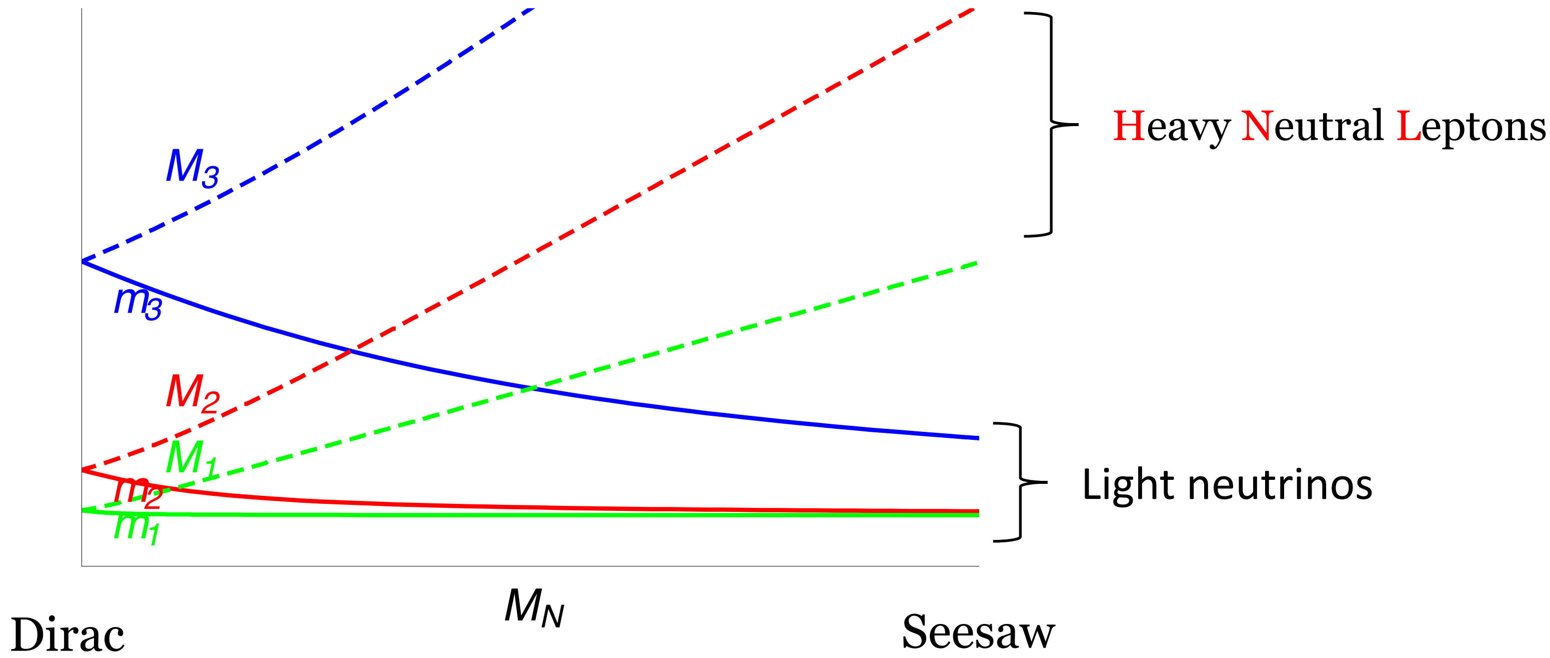
Foot et al; Ma;
Bajc, Senjanovic...

$c \sim O(Y^2)$

Type I seesaw models ($n_R \geq 2$)

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

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

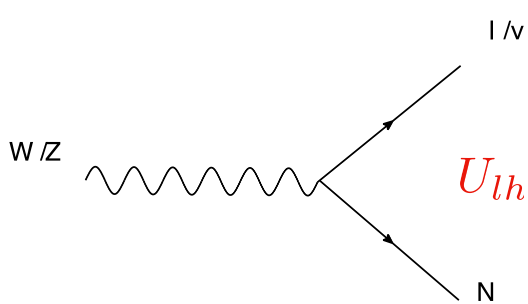


SM+NHLs

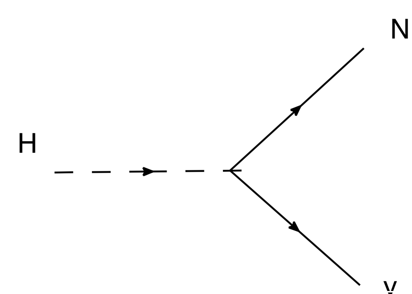
Type I seesaw models

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

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



U_{lh}



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

Seesaw correlations

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

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:

$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$ ($n_R = 1$)

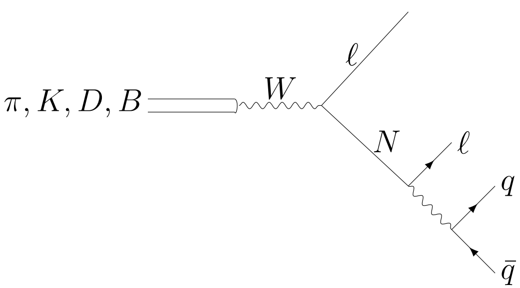
$$|U_{\alpha i}|^2 \gg \frac{m_\nu}{M_i} \leftrightarrow R \gg 1$$ ($n_R \geq 2$)

Natural approx Lepton number -> Pseudo-Dirac HNL

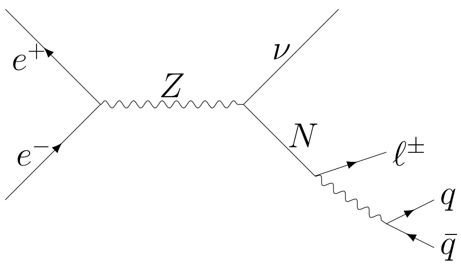
Searches for HNL's

@Laboratory (fixed target, colliders) and cosmic rays

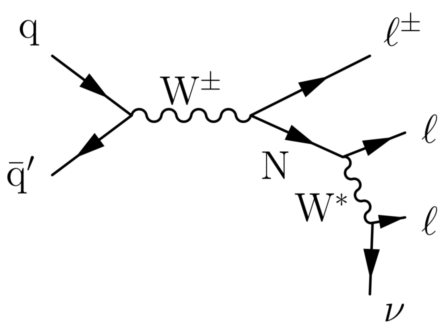
Meson decays



e+e-@Z peak



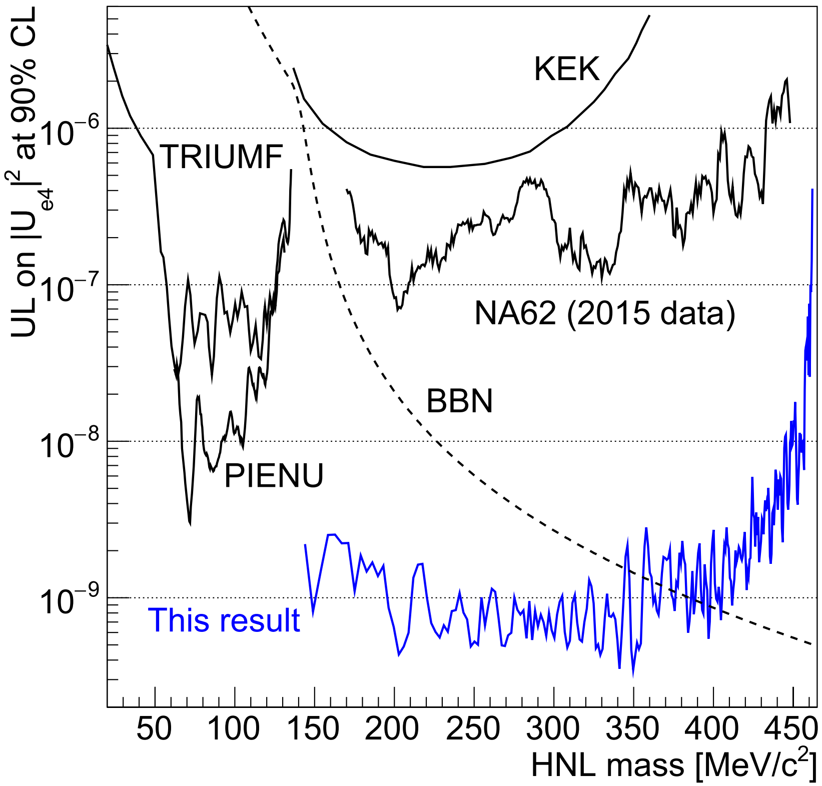
Hadron colliders



- ➢ New or updated constraints from LHC, NA62, T2K, atmospheric (SuperK, Icecube), CHARM

Cortina-Gil et al (NA62) 1712.00297, Abe et al (T2K) 1902.07598, Bryman, Schrock 1909.11198, Coloma et al, 1911.09129, Atkinson et al 2105.09357; Boyarska et al 2107.14685

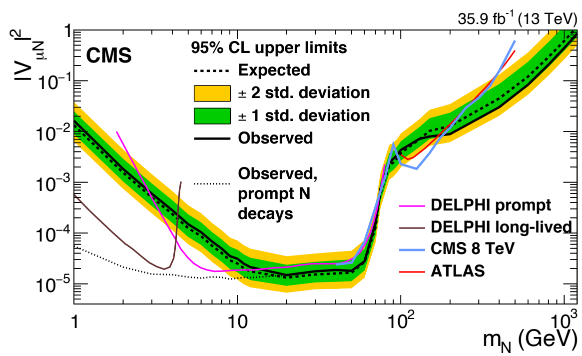
HNL searches at NA62

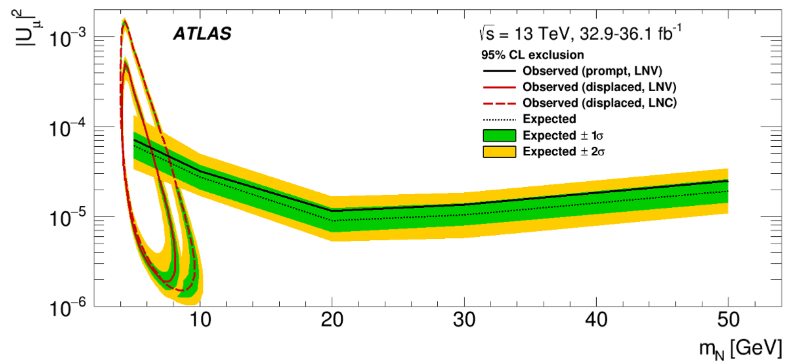


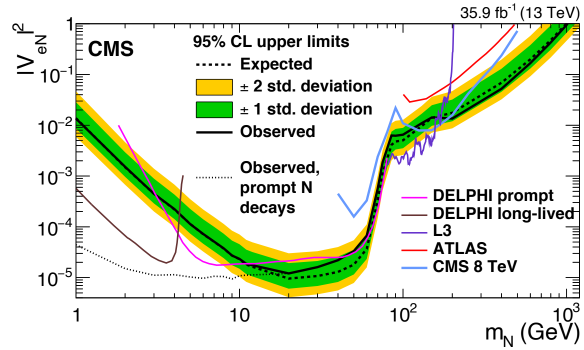
NA62 coll. 2005.09575

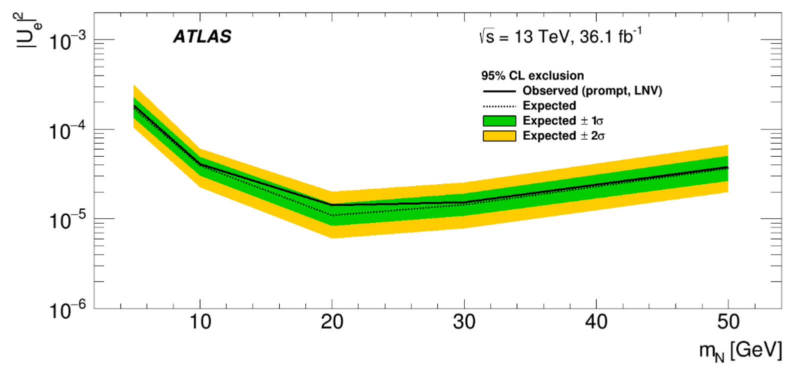
HNL's searches at LHC by prompt and displaced signatures

Helo et al, 1312.2900; Izaguirre, Shuve 1504.02470; Gago et al, 1505.05880; Dib, Kim 1509.05981; Cottin et al 1801.02734 & 1806.051891; Cvetic et al 1805.00070; Abada et al 1807.10024; Boiarska et al 1902.04535;Drewes, Hajer 1903.06100; Liu et al 1904.01020









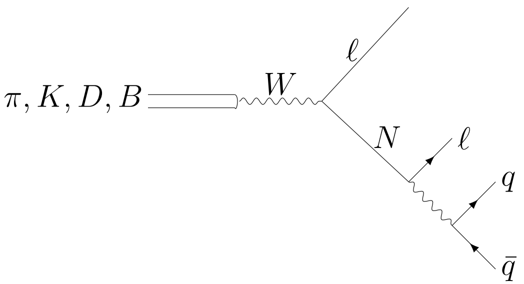
CMS collaboration 1802.02965

ATLAS collaboration 1905.09787

Searches for HNL's

@Laboratory (fixed target, colliders) and cosmic rays

Meson decays



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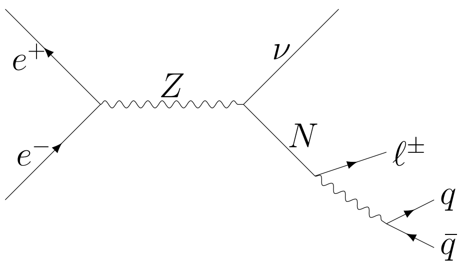
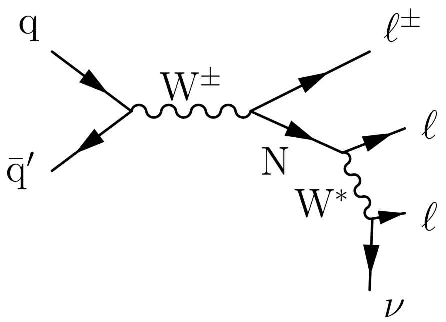


Hadron colliders



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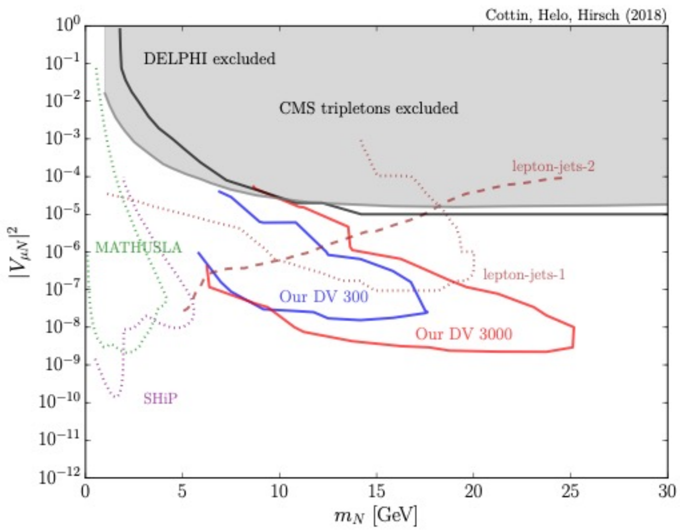
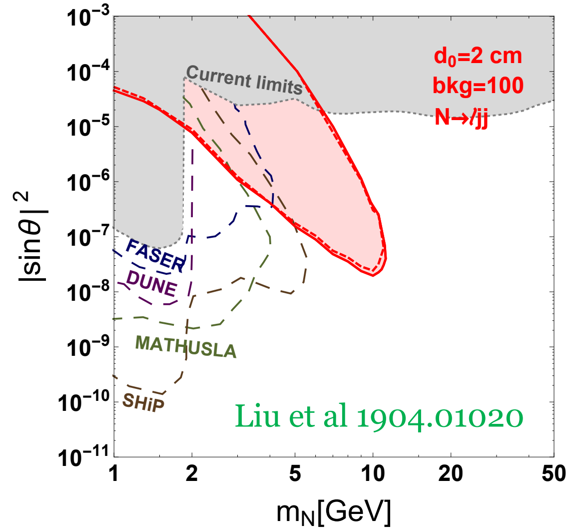
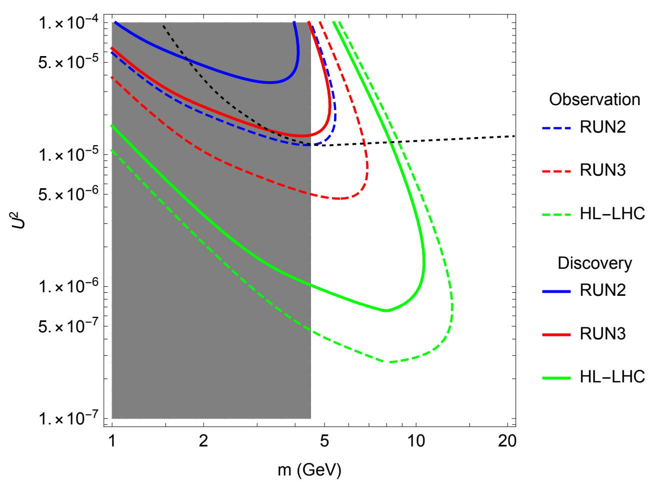
➢ Prospects at future facilities DUNE, HL-LHC, FASER, e+e- Higgs factories (ILC, FCC-ee)

High Mass region ($M_N > M_B$): HL-LHC can significantly improve HNL's searches

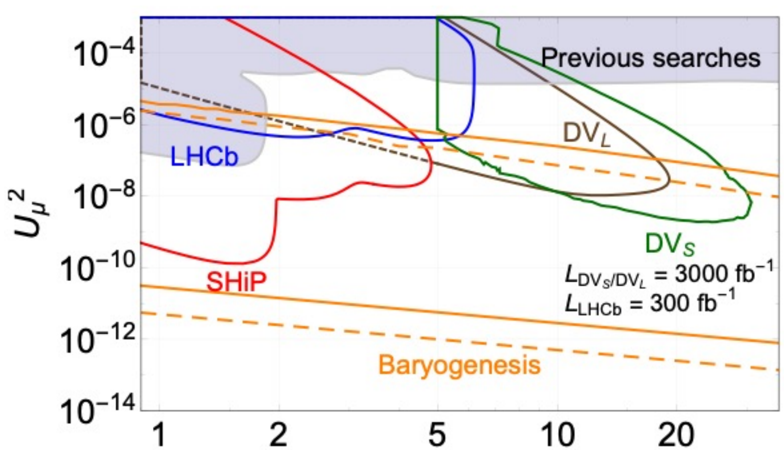




Dib et al 1904.01020

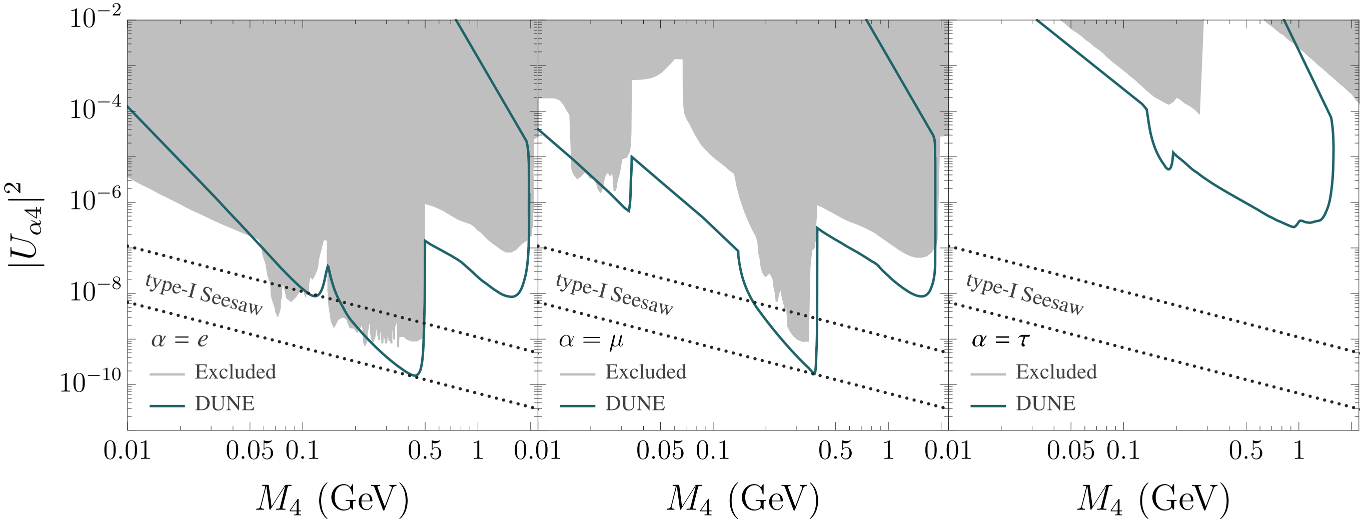


Boiarska et al 1902.04535



Low mass region: DUNE searches HNL's

Coloma et al, 2007.03701

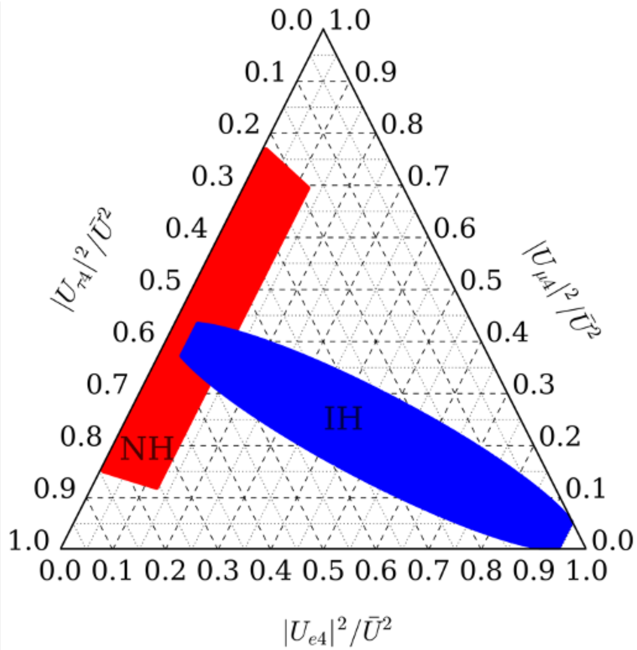


See also Krasnov, 1902.06099;Ballet et al, 1905.00284; Berryman et al, 1912.07622; Coloma 2105.09357

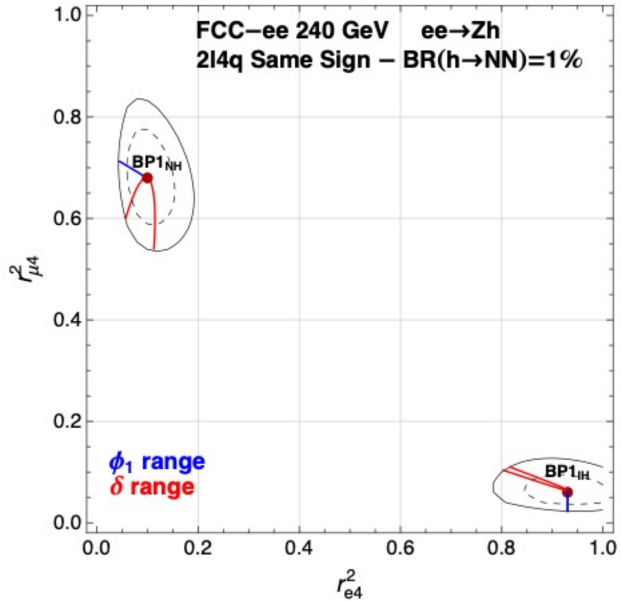
Seesaw correlations:

flavour ratios of heavy lepton mixings strongly correlated with ordering and CP phases of the U_{PMNS} matrix: δ, ϕ_1

n_R=2:



Caputo, PH, Lopez-Pavon, Salvado 1704.08721



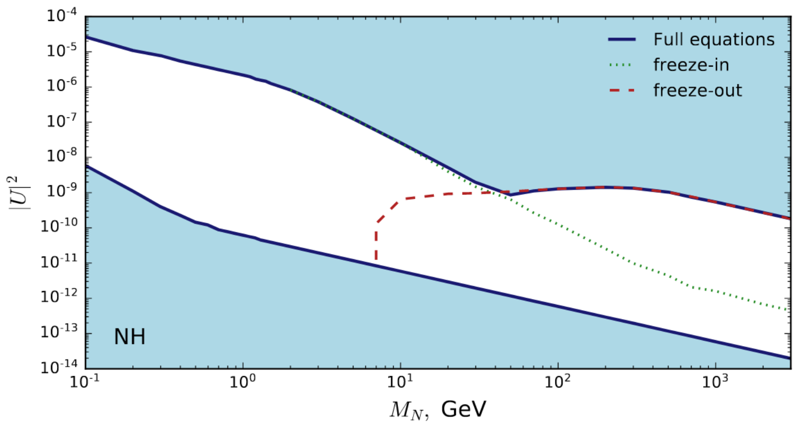
$$3.69 \le \phi_1 \le 5.57$$

$$0.78 \le \delta \le 1.85 \;\cup\; 4.47 \le \delta \le 5.55$$

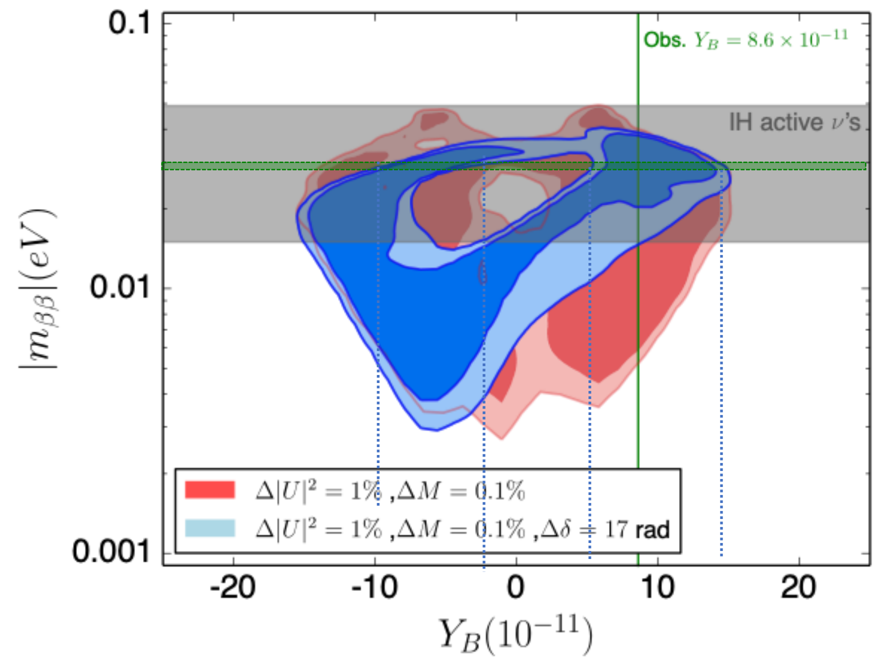
Barducci et al 2011.04725

Predicting Y_B in the minimal seesaw model M~GeV

Relevant region for Y_B



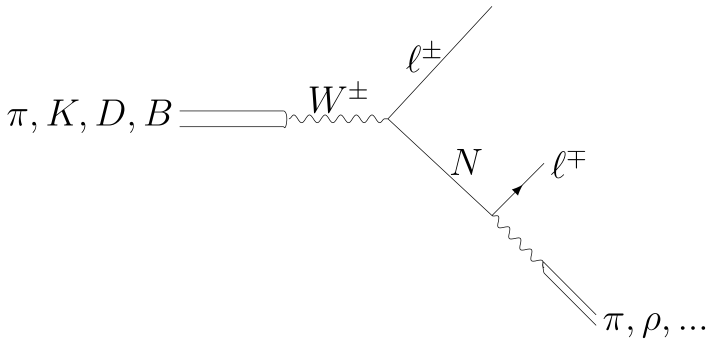
Klaric et al 2008.13771

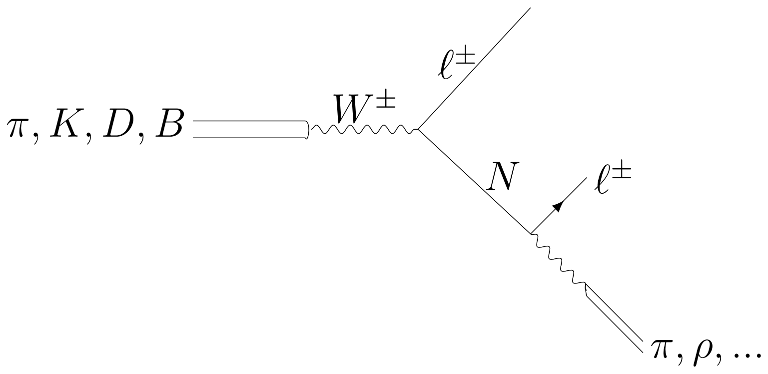


PH, Kekic, Lopez-Pavon, Racker, Salvado '16

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

Majorana vs Dirac

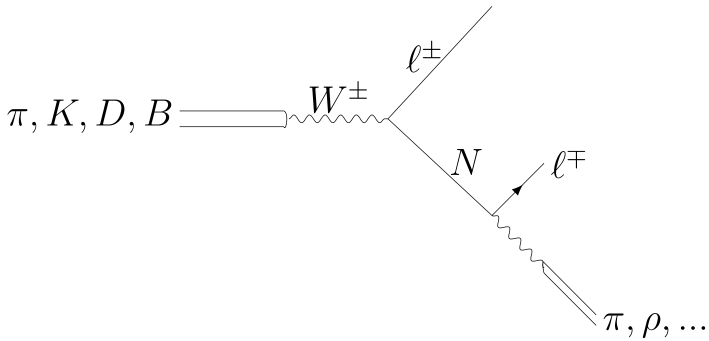




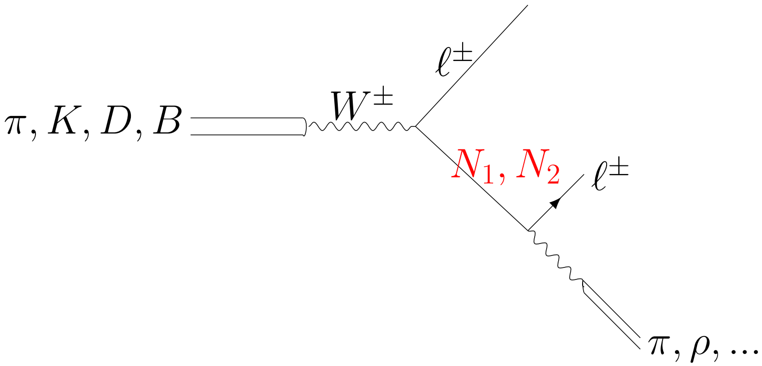
Lepton # conserving
(Dirac & Majorana)

Lepton # violating
(Majorana)

Majorana vs pseudo-Dirac



Lepton # conserving
(Dirac & Majorana)



Lepton # violating
(Majorana)

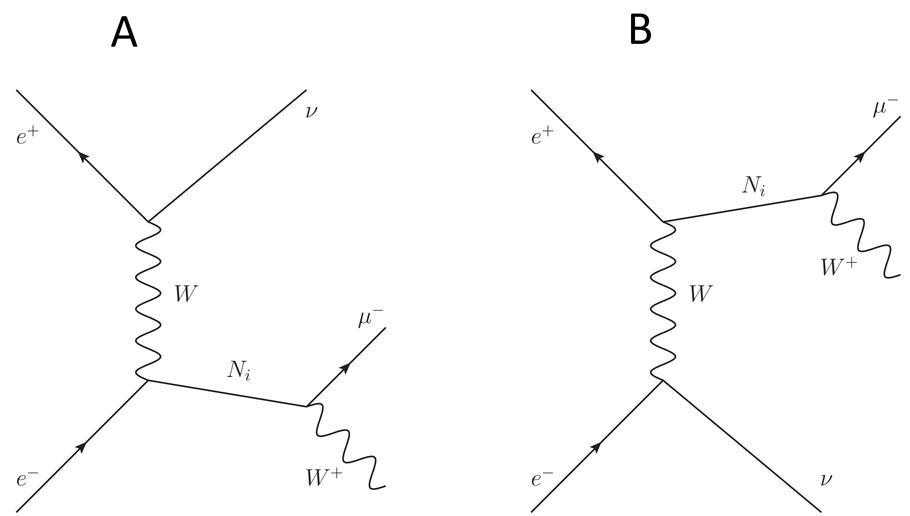
Observable effects in colliders only possible in regions with approximate lepton number <-> HNL's come in pseudo-Dirac pairs

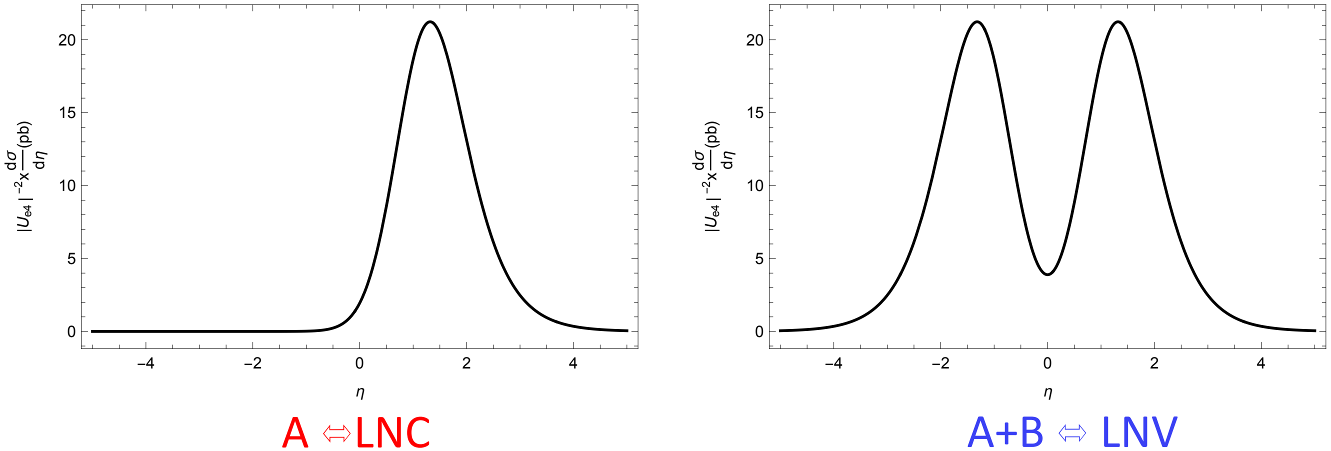
- If HNL are off-shell LNV processes strongly suppressed
- If HNL are on-shell LNV unsuppressed provided $|M_1 - M_2| \gg \Gamma_{1,2}$
- Quantum coherence effects (oscillations) $|M_1 - M_2| \simeq \Gamma_{1,2}$

Anamiati et al 1607.05641

Majorana vs pseudo-Dirac @ e+e-

In some processes lepton charges cannot distinguish, but angular distributions can ...

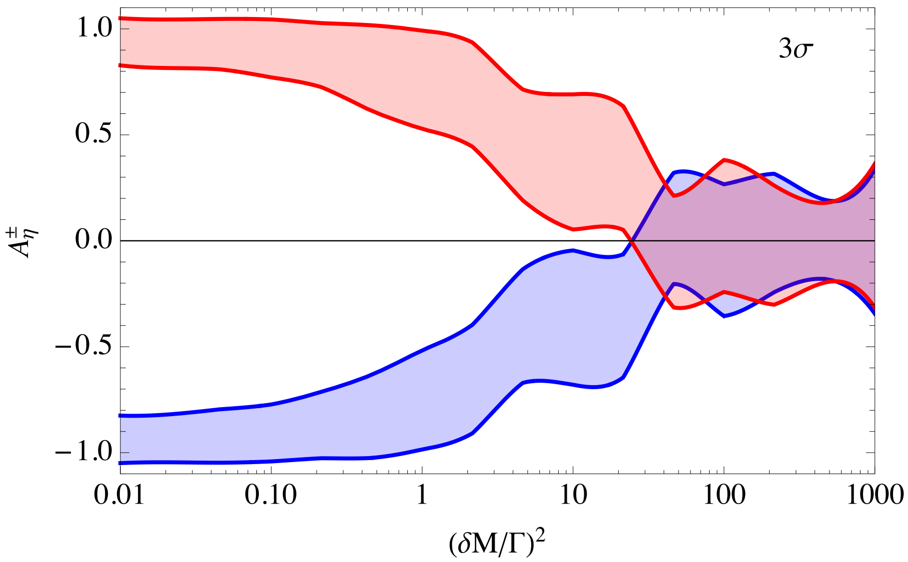




Also: beam dump when primary lepton not observed, purely leptonic decays,...

Majorana vs pseudo-Dirac @ e+e-

ILC, 250GeV, $2ab^{-1}$



$$A_\eta^\pm = \frac{N^\pm(\eta > 0) - N^\pm(\eta < 0)}{N_{\rm tot}^\pm} \,,$$

PH, Jones-Pérez, Suárez-Navarro 1810.07210

See also Del Aguila, Aguilar-Saavedra 0503026; Cvetic et al 1203.0573; Arbeláez et al, 1712.08704; Dib et al, 1703.01934; Balantekin et al 1808.10518; Tastet, Timiryasov 1912.05520; Blondel et al 2105.06576

Beyond the minimal model

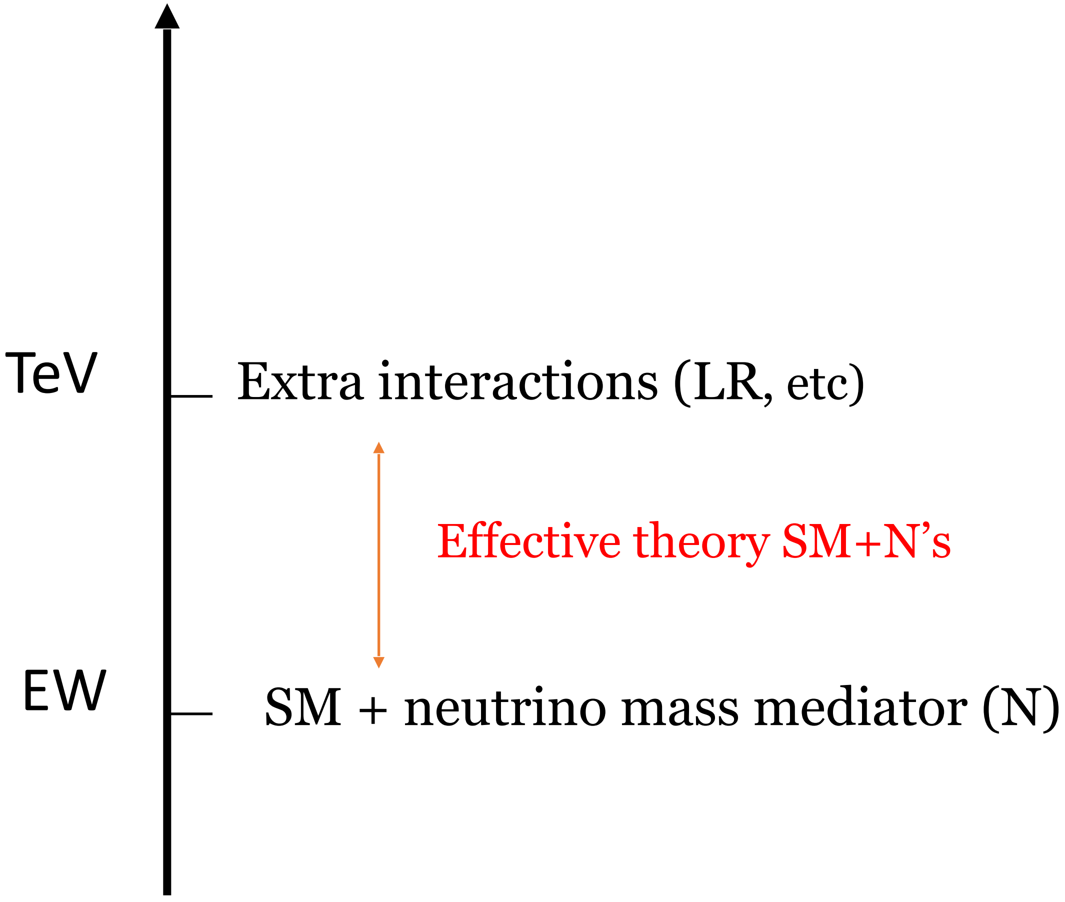
Many concrete possibilities: type I + extra Z'/scalars
left-right symmetric models
GUTs
radiative models

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic; Ferrari et al; Zee, Babu + many recent refs...

- Generically new gauge interactions can enhance the production in colliders: richer phenomenology
- But also make leptogenesis more challenging (out-of-equilibrium condition harder to meet)
- Can incorporate dark matter candidate or address other anomalies (eg B-anomalies, g-2)

Hati et al 1806.10146; Babu et al 2009.01771; Nomura, Okada 2104.03248;...

A more generic possibility:



Model independent approach: EFT

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

The seesaw portal to BSM:

d=5

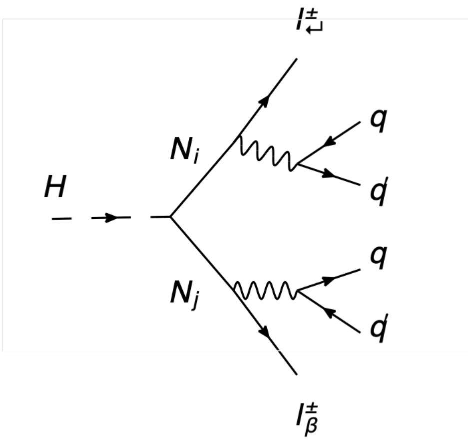
$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi} \Phi^\dagger L^c_\beta + h.c.,$$

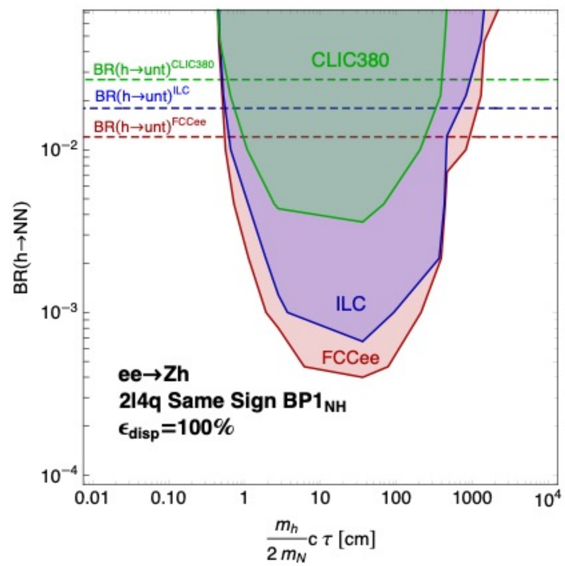
$$\mathcal{O}_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N}_i N^c_j \Phi^\dagger \Phi + h.c.,$$

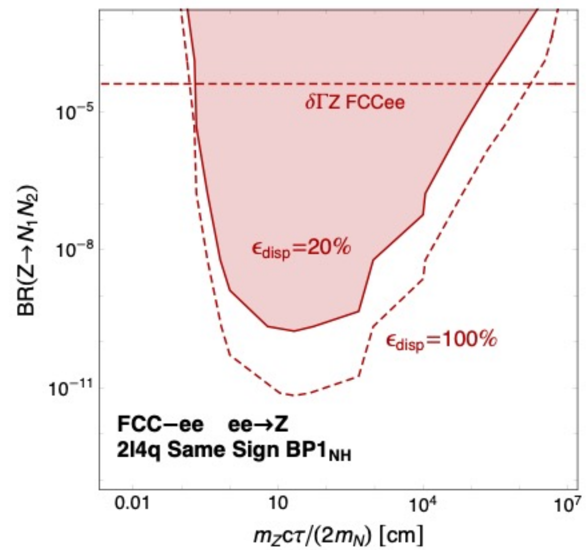
$$\mathcal{O}_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \overline{N}_i \sigma_{\mu\nu} N^c_j B_{\mu\nu} + h.c.$$

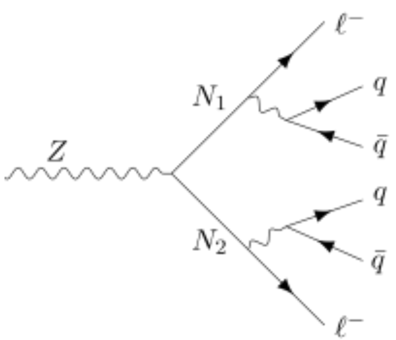
M. Graesser ’07; F. Del Aguila et al ’09; Aparici et al, ‘09; Bhattacharya, Wudka ’15; Liao, Ma ‘16

$\mathcal{O}_{NH}, \mathcal{O}_{NB}$ could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs/Z decays (production independent of mixing)









Barducci et al 2011.04725

Many recent studies d=6 present and future colliders, meson decays, CEνNS, ββ0ν...

Caputo et al 1704.08721; Alcaide et al 1905.11375; Butterworth et al 1909.04665; Han et al 2004.13869; Li et al 2005.01543 & 2007.15408; Biekotter et al 2007.00673; De Vries et al 2010.07305; Barducci et al 2003.08391 & 2011..04725; Cottin et al 2105.13851,...

Conclusions

- The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

- Many fundamental questions remain to be answered however: Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ? Lepton vs quark flavour ?

- A rich experimental neutrino programme lies ahead, that will answer some of these important questions

- Neutrino physics is an area of synergy where most hep experiments (colliders, neutrino exp, astroparticle exp) and cosmology are providing essential inputs