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Heavy neutrino production at the FCC-ee: Dirac or Majorana?

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Bologna

For the informal working group
Long-lived particles at the FCC-ee

Heavy Neutral Leptons (HNLs)

Why should we search for HNLs?

- HNLs represent one of the renormalisable "portals" to a BSM sector (e.g. "dark sector")
- Predicted by many extensions of the SM (left-right-symmetry, SO(10) GUT, …)
- Can address various shortcomings of the SM: e.g. MaD 1303.6912 , Abdullahi et al 2203.08039
  - Neutrino masses: seesaw mechanism
  - Baryogenesis via leptogenesis
  - Dark matter
  - Oscillation anomalies
  - …
- Low scale seesaw models exist and are testable at colliders

e,.g. Deppisch et al 1502.06541, Cai et al 1711.02180 , Argawal et al 2102.12143, Abdullahi et al 2203.08039

Why should we care if they are Dirac or Majorana (or something in between)?

- Symmetries of nature
- Identify underlying neutrino mass model
- Connection to baryogenesis/leptogenesis

Heavy Neutral Leptons (HNLs)

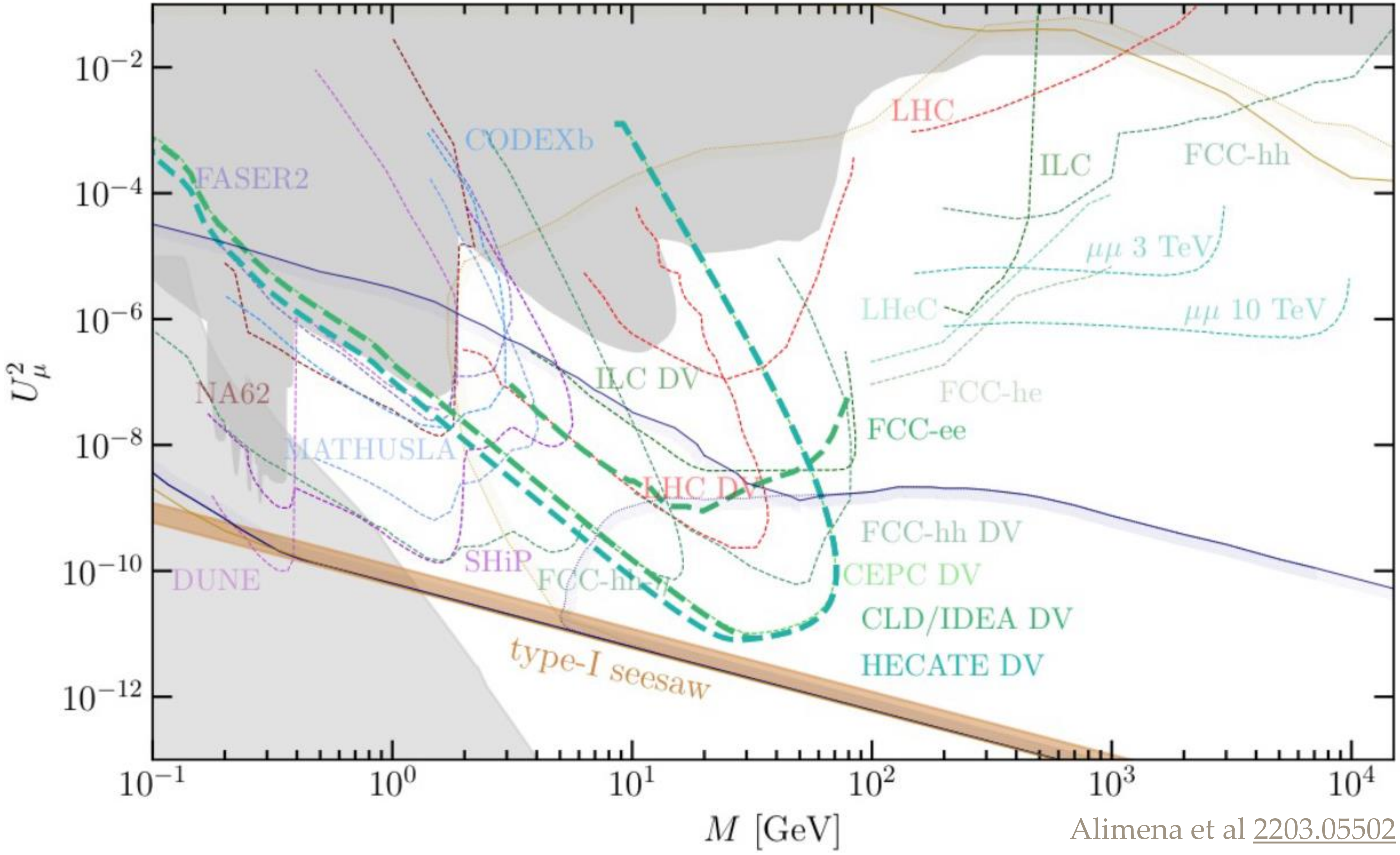
Common phenomenological description:

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu\nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

- One flavour of HNLs N
- Couples to SM only through mixing θ_a with SM neutrinos, where a = e, μ, τ
- Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}.
- **R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) N decays; $R_{ll} = 1$ for Majorana N and $R_{ll} = 0$ for Dirac N.**

This is not a realistic model of neutrino mass, but can effectively capture the pheno of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}.

Why Search with FCC-ee?



Alimena et al 2203.05502

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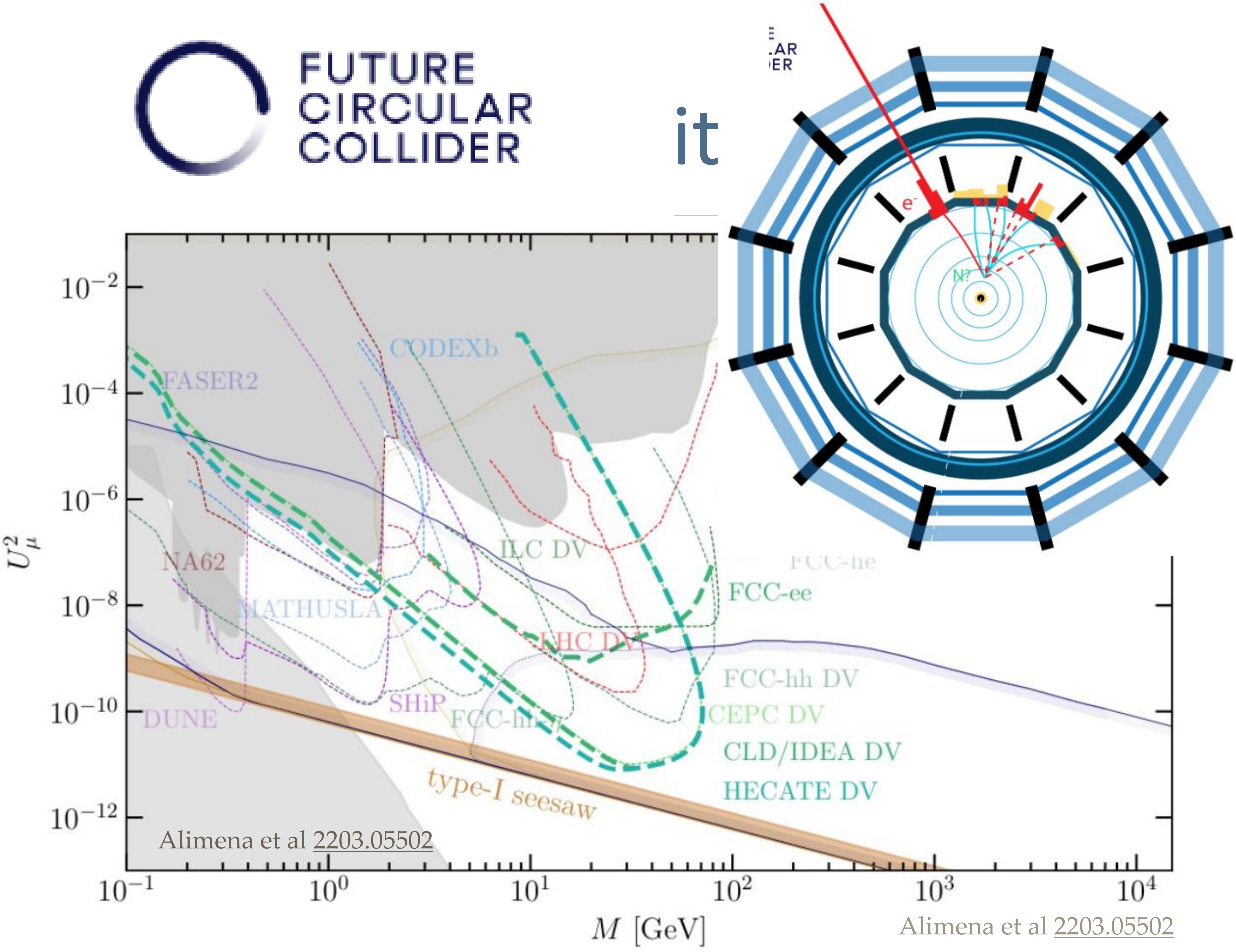

Alimena et al 2203.05502

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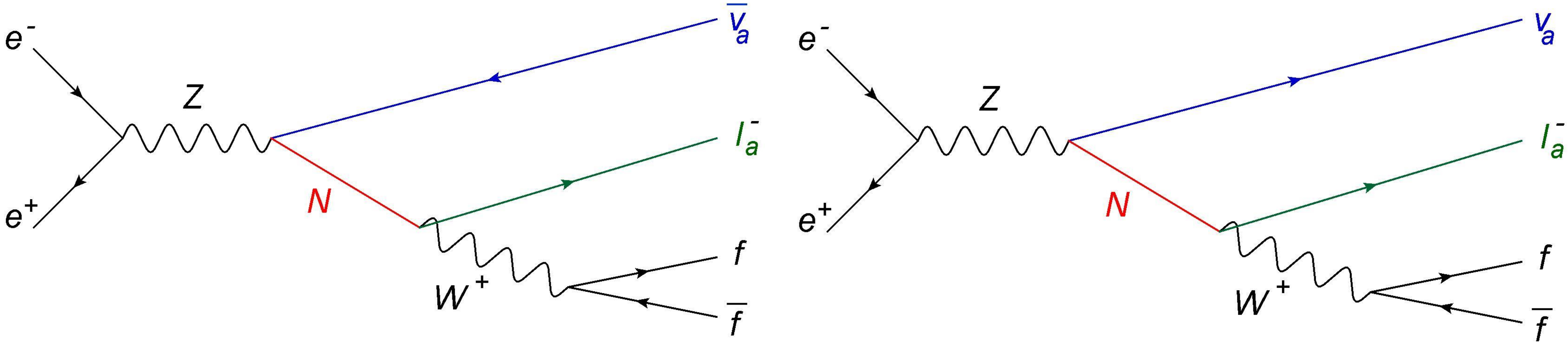
LNV at Lepton Colliders



- Largest event numbers: displaced vertices in Z-pole run

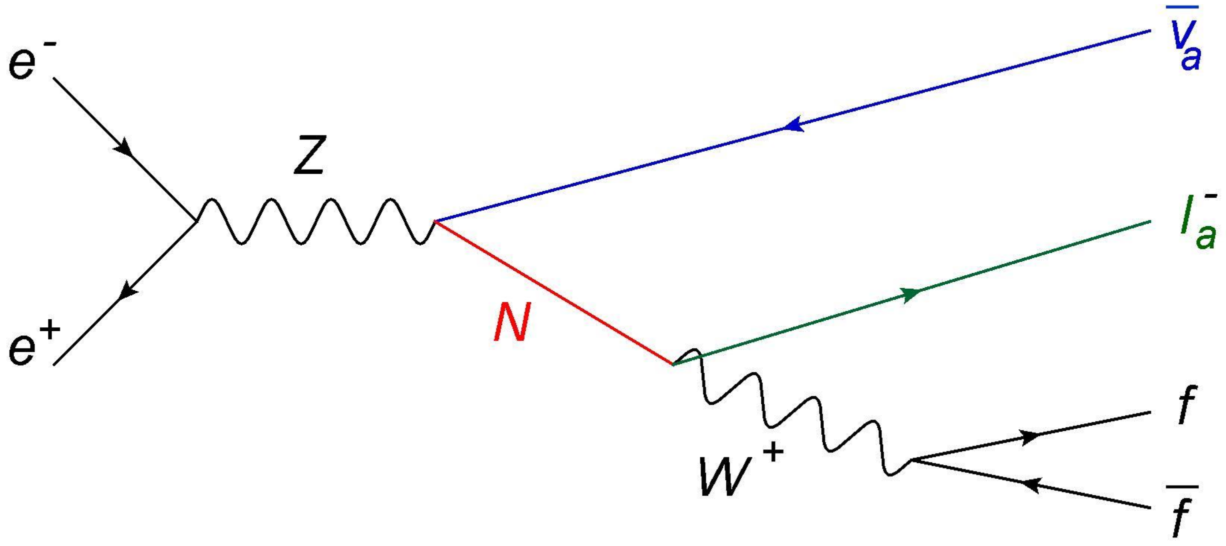
Blondel et al 1411.5230

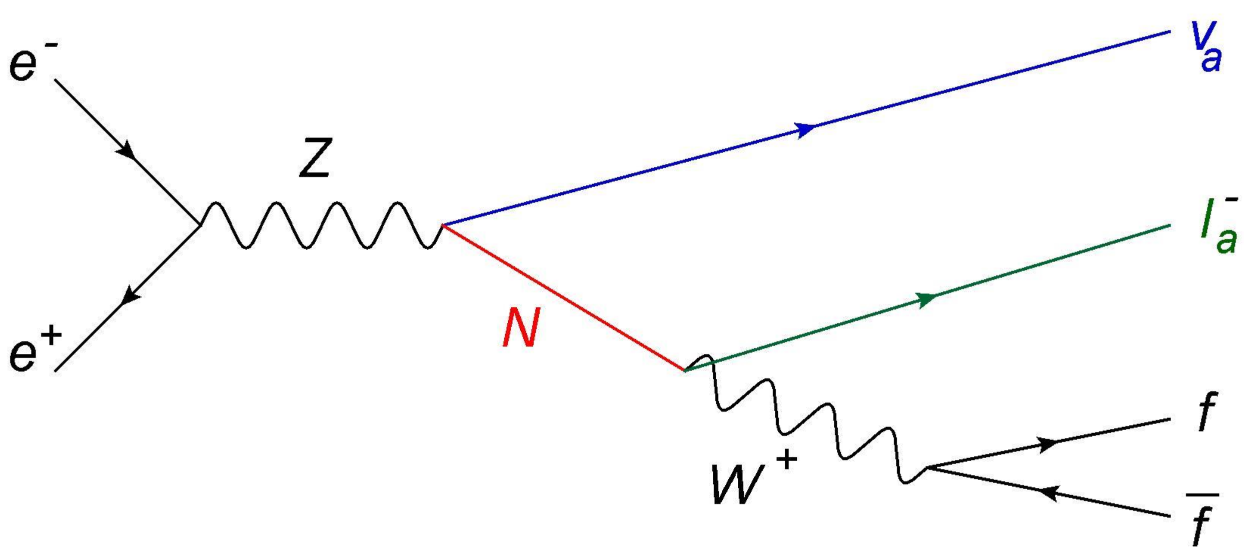
- Neutrino in final state unobservable
- Rely on indirect methods 2) – 4)
- 4-momentum of N can still be fully reconstructed

How to practically distinguish Dirac from Majorana *N*?

1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N

LNV at Lepton Colliders





Z-bosons are polarised due to P-violation of weak interaction:

$$g_R = 2\sin^2\theta_W \qquad g_L = (1 - 2\sin^2\theta_W) \qquad P_Z = \frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)} \simeq -0.15$$

- Chiral nature of weak interaction correlates charge, spin, and momenta of observable final state particles to spin of initial Z-boson
- This correlation depends on whether HNLs are Dirac or Majorana

e.g. Blondel et al 2105.06576

Observables:

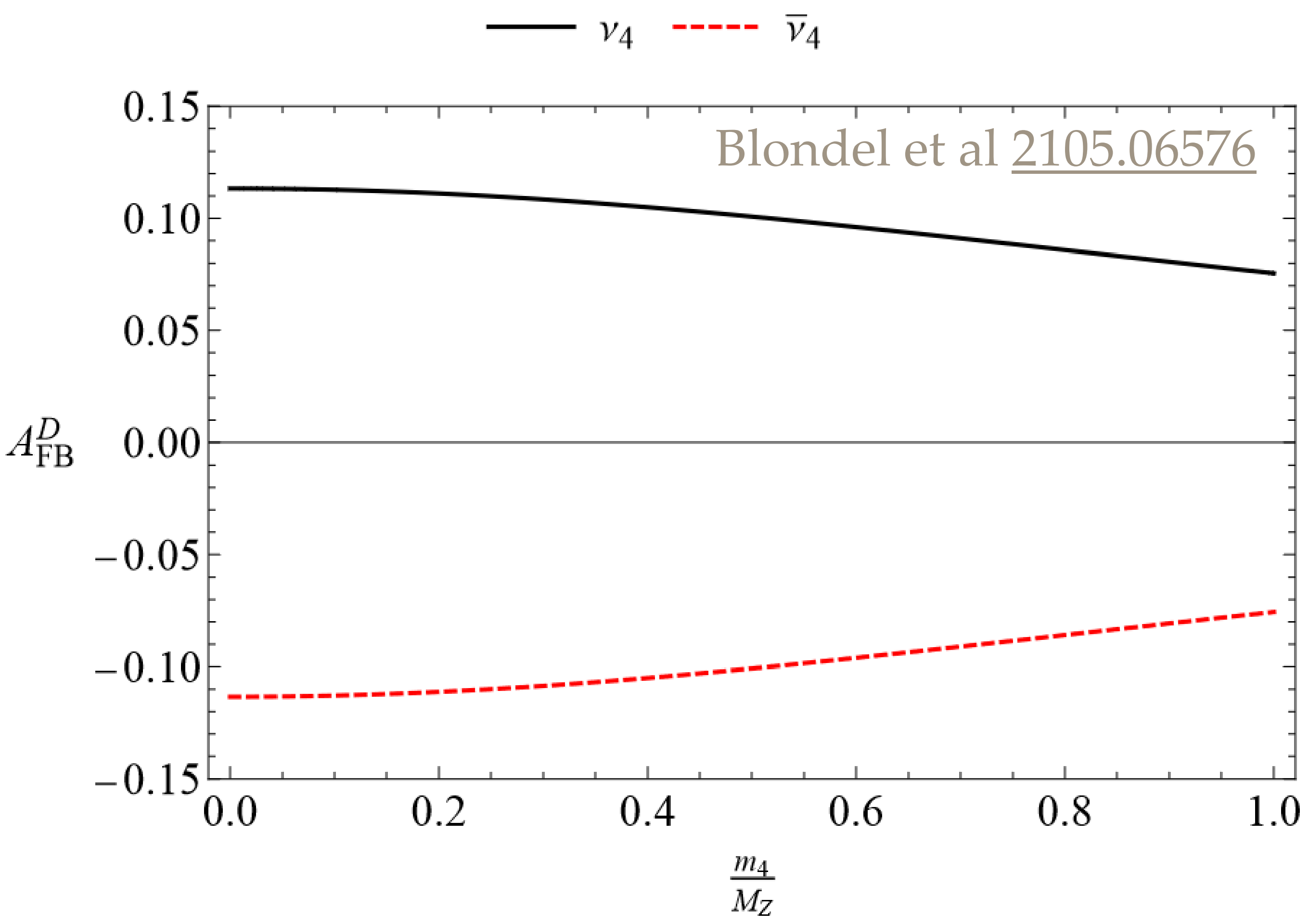
- **Forward-backward asymmetry of charged leptons**: vanishes in Majorana case, is proportional to Z-polarisation in Dirac case
- **Energy distribution of charged leptons**: Dirac N and anti-N are highly polarised, while Majorana H are only mildly polarised, leading to different charged lepton spectra

Forward-Backward Asymmetry

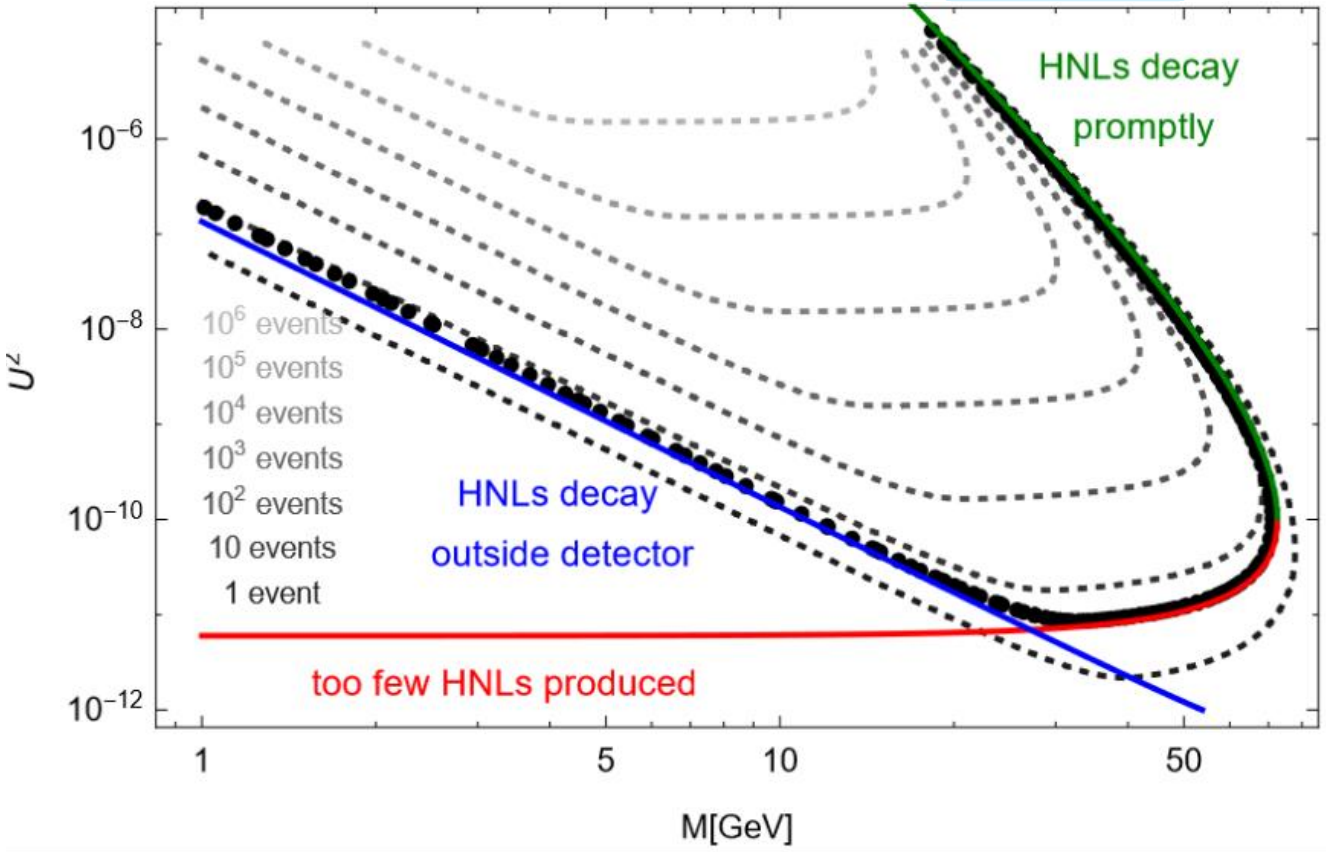
$$A_{\mathrm{FB}} = \frac{1}{\sigma}\left[\int_0^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta - \int_{-1}^0 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta\right]$$

$$A^D_{\mathrm{FB}}(\nu_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\frac{(g_L^2-g_R^2)}{(g_L^2+g_R^2)},$$

$$A^D_{\mathrm{FB}}(\bar{\nu}_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\frac{(g_R^2-g_L^2)}{(g_L^2+g_R^2)}$$



Blondel et al 2105.06576



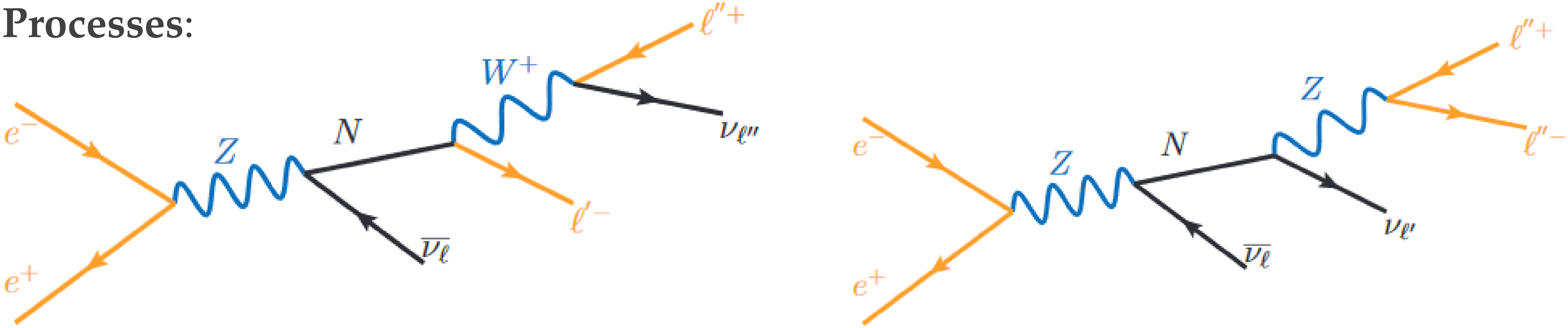
- Forward-backward asymmetry ~10%
- Needs hundreds of events for 2σ exclusion
- Estimate: doable for $U^2 > 10^{-9}$ at FCC-ee

Simulated Angular Distribution

Simulation:

MadGraph5_aMC@NLO with HeavyN / HeavyN_Dirac UFO
Pythia v8.303
DELPHES v3.4.2 with IDEA detector card

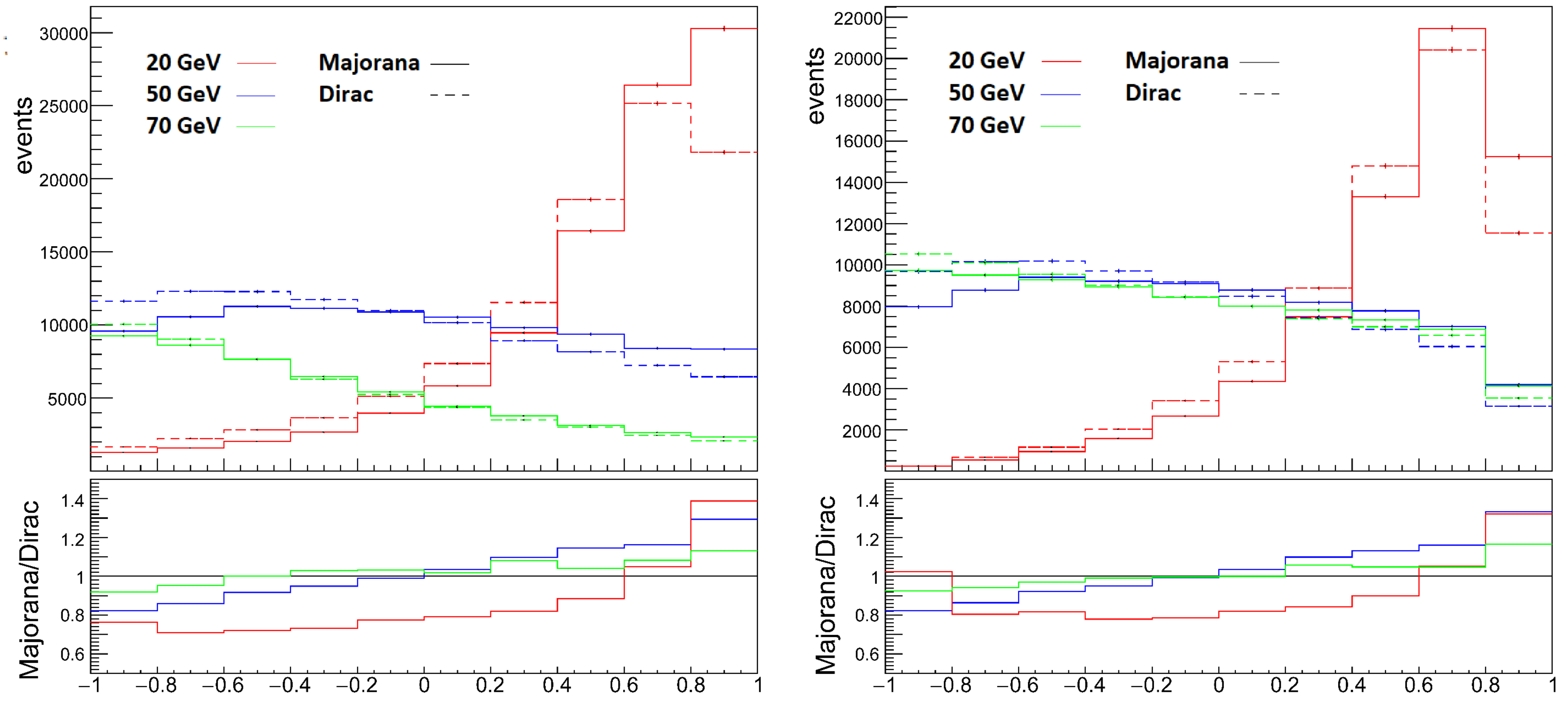
Processes:



$$\textbf{Majorana } N : e^+e^- \to Z \to N\nu_e + N\overline{\nu_e}, \quad \text{with} \quad N \to e^+e^-\nu_e + e^+e^-\overline{\nu_e},$$

$$\textbf{Dirac } N : e^+e^- \to Z \to N\overline{\nu_e} + \overline{N}\nu_e, \quad \text{with} \quad N\ (\overline{N}) \to e^+e^-\nu_e\ (\overline{\nu_e}),$$

Simulated Angular Distribution



Alimena et al 2203.05502

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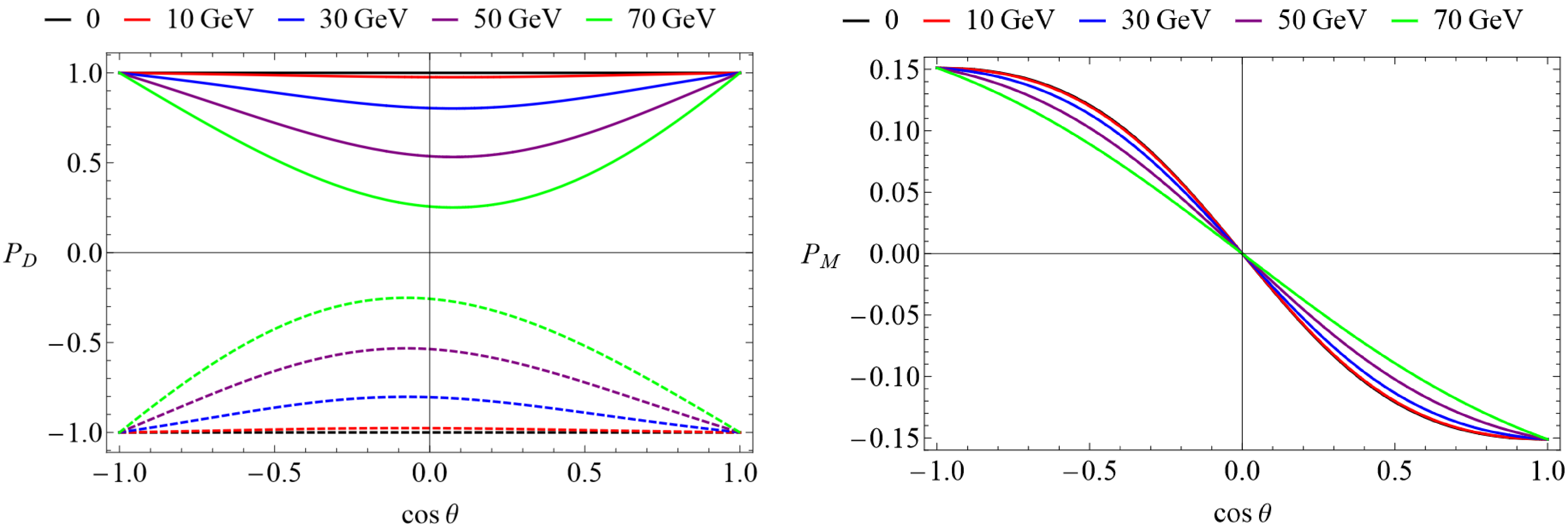
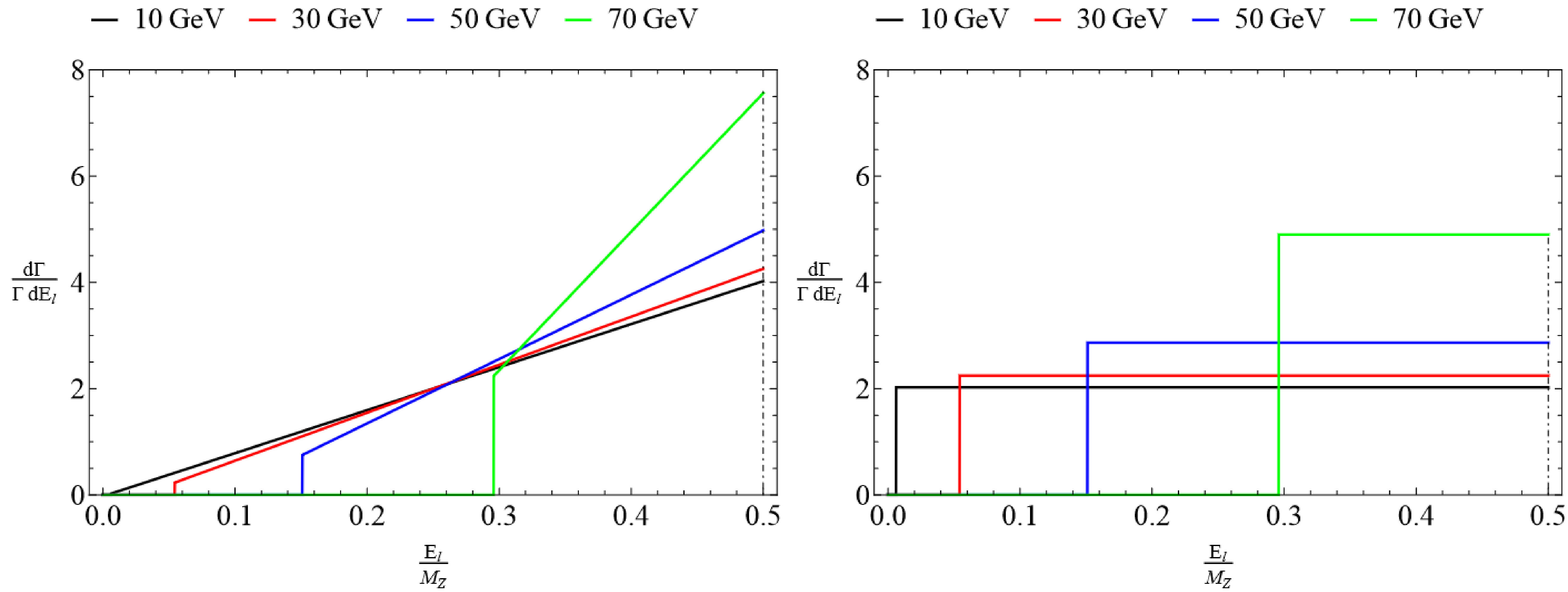
HNL Polarisation



- **Dirac** N and anti-N *individually* are highly polarised, can only decay into lepton or anti-lepton, respectively
- **Majorana** N are only mildly polarised and decay into leptons of either charge

Blondel et al 2105.06576

Polarisation Impact on Lepton Spectrum



- **Dirac** N and anti-N *individually* are highly polarised, can only decay into lepton or anti-lepton, respectively
- **Majorana** N are only mildly polarised and decay into leptons of either charge
- Lepton spectrum in HNL decay depends on polariations, e.g. decay into pion+lepton:

$$\frac{1}{\Gamma(\ell^{\pm})}\frac{d\Gamma(\ell^{\pm})}{dE_{\ell}} = \frac{4}{\left(1-\frac{M^2}{m_Z^2}\right)^2}\left[\frac{(1\mp P)}{2} - \frac{M^2}{m_Z^2}\frac{(1\pm P)}{2} \pm 2P\frac{E_{\ell}}{m_Z}\right]$$

Blondel et al 2105.06576

Constraining *R$_{ll}$* from HNL Lifetime

- HNL production cross section is same for Dirac and Majorana:

$$\mathrm{BR}(Z\to\nu N)=\frac{2}{3}|U_N|^2\,\mathrm{BR}(Z\to\text{invisible})\left(1+\frac{{m_N}^2}{2{m_Z}^2}\right)\left(1-\frac{{m_N}^2}{{m_Z}^2}\right)$$

- HNL decay rate differs:
  Dirac: : *C$_{MD}$ = 1*
  Majorana: *C$_{MD}$* = 2

$$\Gamma_N=\frac{1}{c\tau_N}\simeq C_0C_{MD}|U_N|^2\left(\frac{m_N}{50\mathrm{GeV}}\right)^5\times\left(\frac{3.10^9}{1\ \mathrm{cm}}\right)$$

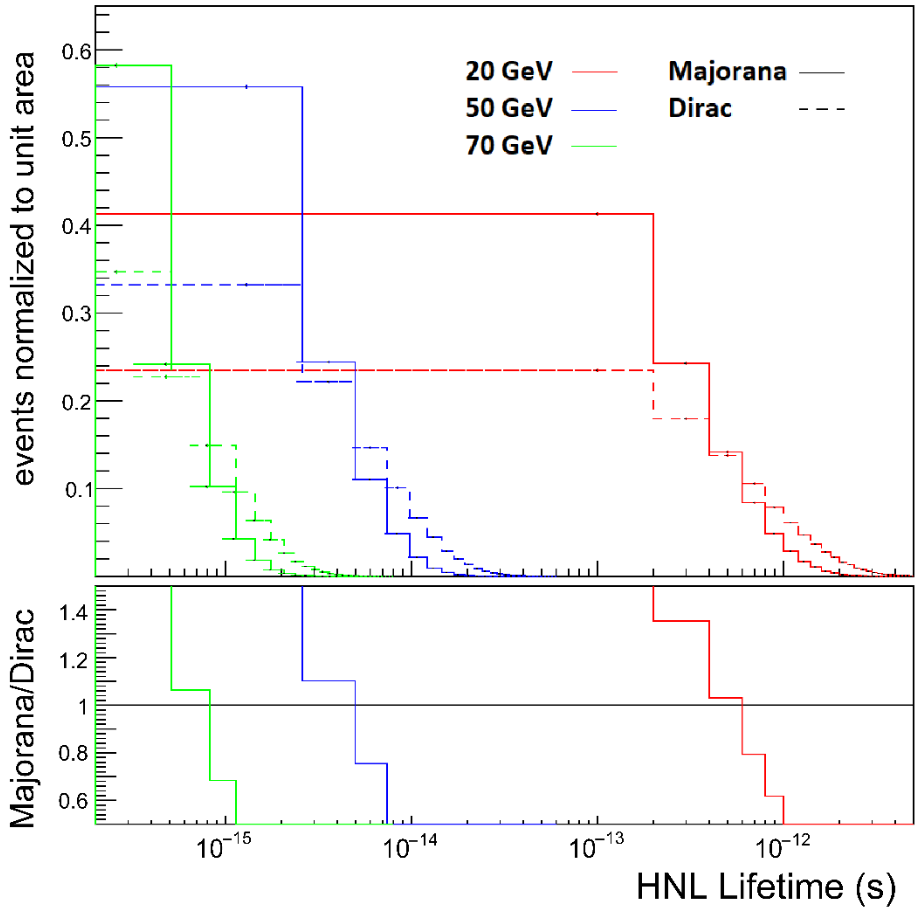
- HNL mass extracted from full 4-momentum reconstruction or from time-of-flight

➢ **Extract *U$_a$^{2}* from total # decays ,**
C$_{MD}$ from # decays between displacement *l$_0$, l$_1$*

$$N_{\mathrm{obs}}\simeq L\sigma_N\left[\exp\left(-\frac{l_0}{\lambda_N}\right)-\exp\left(-\frac{l_1}{\lambda_N}\right)\right]$$

$$\lambda_N=\beta\gamma/\Gamma_N\qquad\beta\gamma=(m_Z^2-M^2)/(2m_ZM)$$

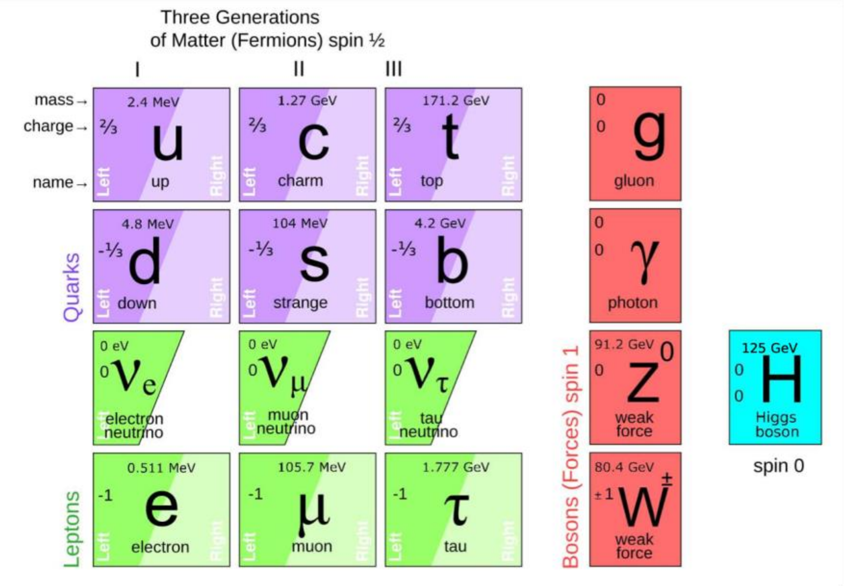
- Caveat: Dirac-HNL may be "faked" by pair of Majorana HNLs



Alimena et al 2203.05502

The Seesaw Mechanism (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$-\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$



 # massive SM neutrinos ≤ #RH neutrino flavours

- minimal model with $m_{\text{lightest}} = 0$ has two RHN
- if all SM neutrinos are massive, three RHN flavours are needed

three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

Neutrino masses vs collider searches

neutrino masses are small (sub eV) $m_\nu^{\rm tree} = -v^2 F M_M^{-1} F^T = -\theta M_M \theta^T$.

➢ **Suggests that active-sterile mixing angle θ must be small**

Problem!

colliders rely on branching ratio σ ~ θ

➢ **mixing angle θ must be sizeable**

Solution

approximate B-L conservation

Shaposhnikov 0605047 Kersten/Smirnov 0705.3221

- HNLs come in pairs with quasi degenerate masses and Yukawas
- This *symmetry protected type-I seesaw* resembles pheno of inverse seesaw, linear seesaw, etc.

$$\mathrm{M}_M = \begin{pmatrix} M(1-\mu) & 0 \\ 0 & M(1+\mu) \end{pmatrix}$$

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) \end{pmatrix}$$

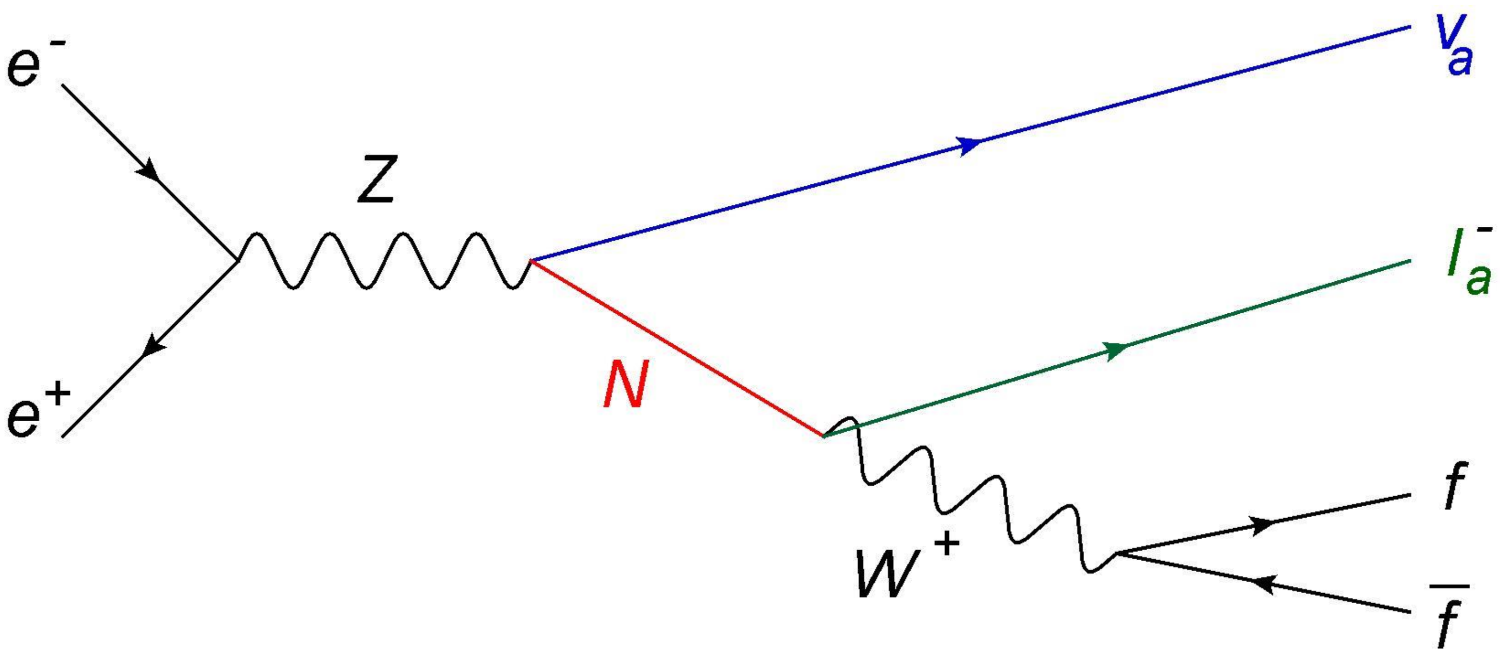
Majorana nature of HNLs: Can LNV decay be observed?

B-L symmetry: destructive interference amongst different HNL flavours

But: B-L is broken to generate neutrino mass. Is this enough???

In colliders:

HNL oscillations in detector can destroy coherence and make LNV observable!



- **Quasi-degenerate HNLs kinmeatically indistinguishable, behave like one particle with non-integer R_{ll}!**

e.g. Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$

- **Cases $R_{ll} = 0$ and $R_{ll} = 1$ nevertheless represent useful benchmarks**

MaD et al 2207.02742

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367, 2012.05763

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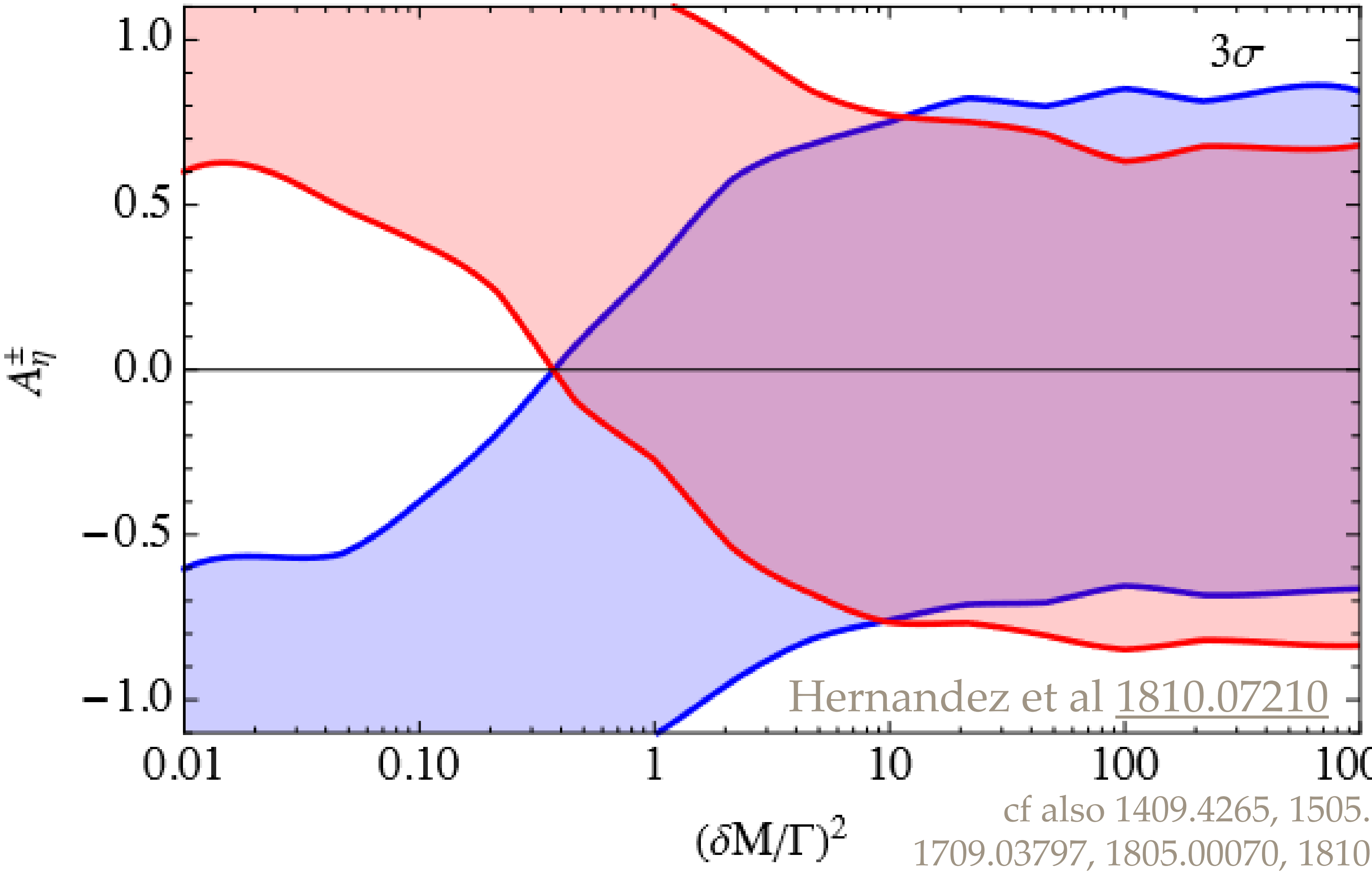

Hernandez et al 1810.07210

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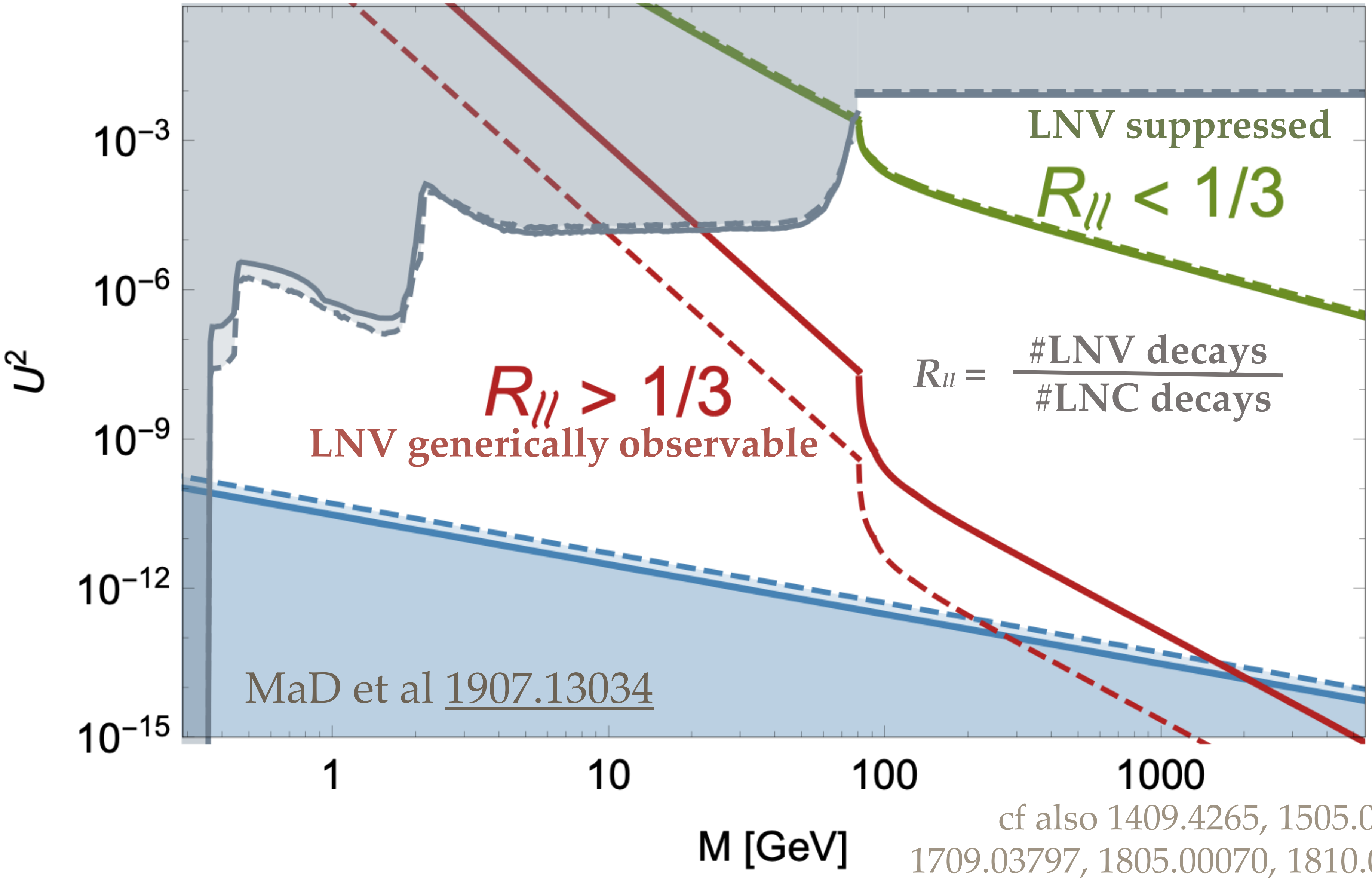

MaD et al 1907.13034

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- **Does neutrino osc. data allow for this without fine tuning? It depends**

MaD/Klaric/Klose 1907.13034

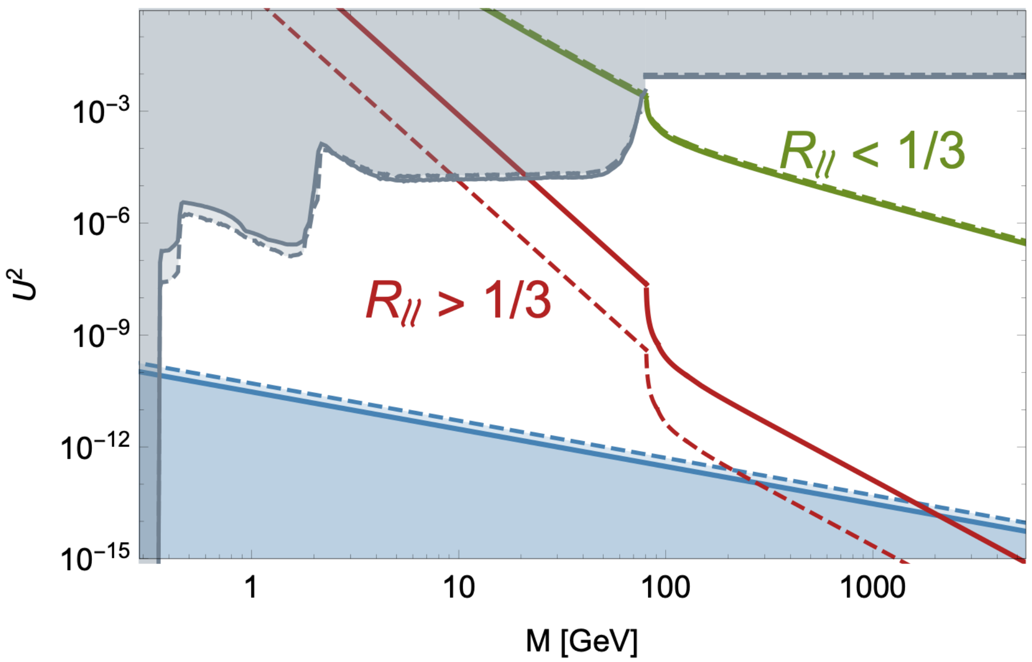
cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367, 2012.05763

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$

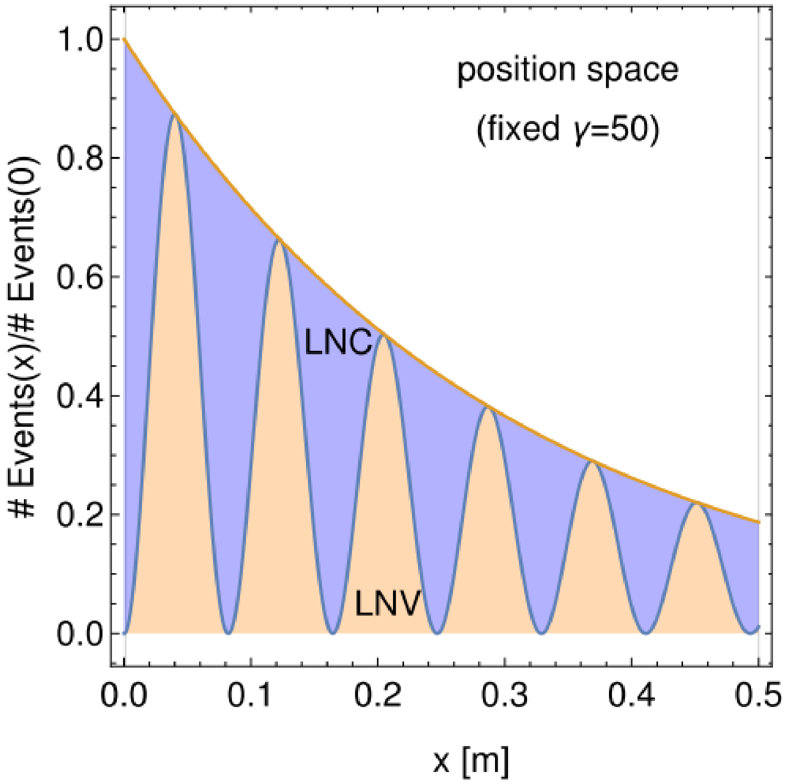
Anamiati et al 1607.05641

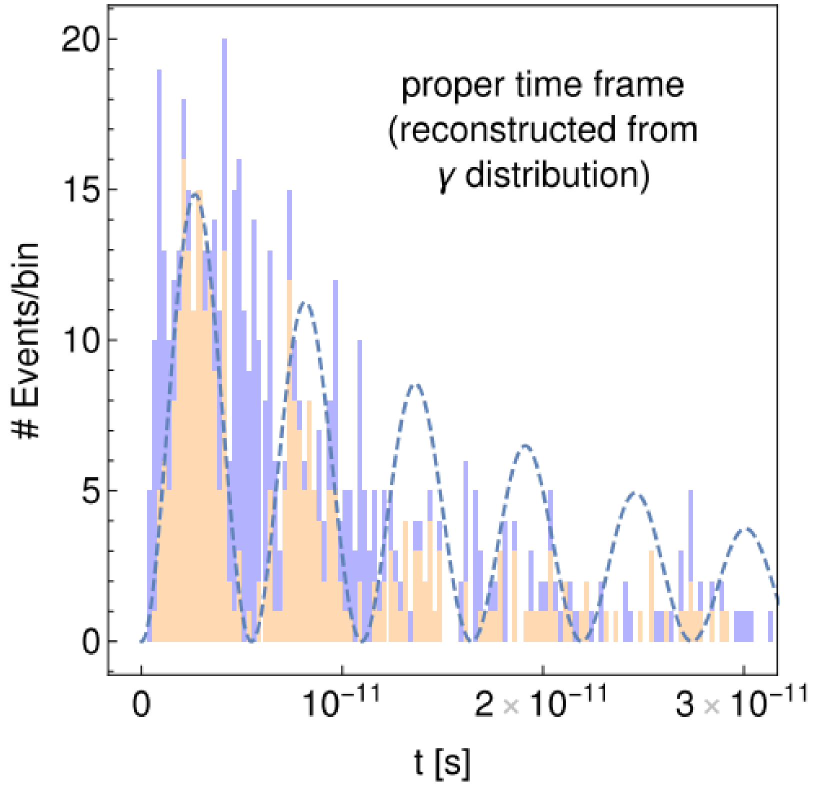


MaD/Klaric/Klose 1907.13034

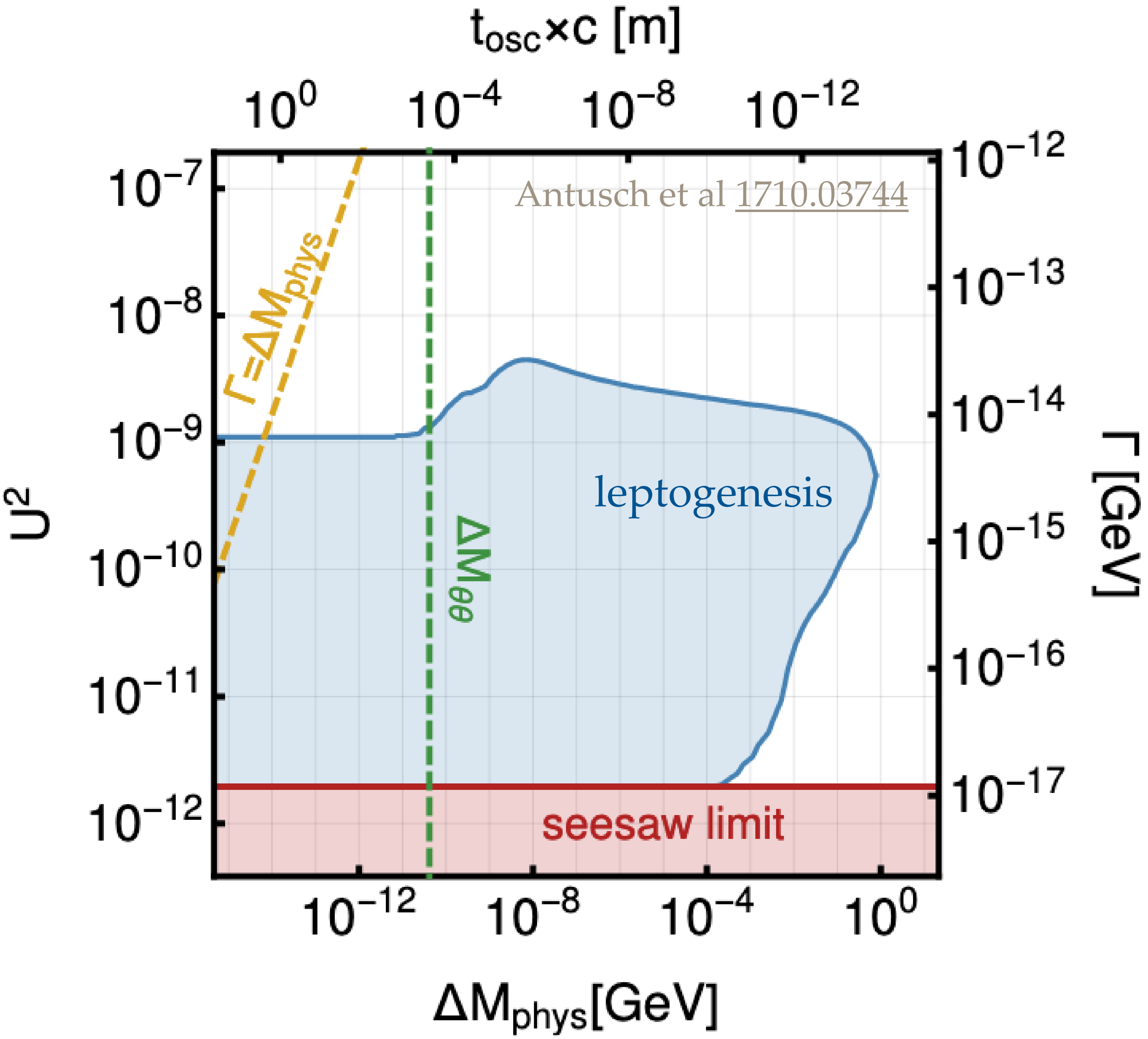
spatially resolving this ratio gives more information!

Antusch et al 1709.03797





Testing Leptogenesis



Antusch et al 1710.03744

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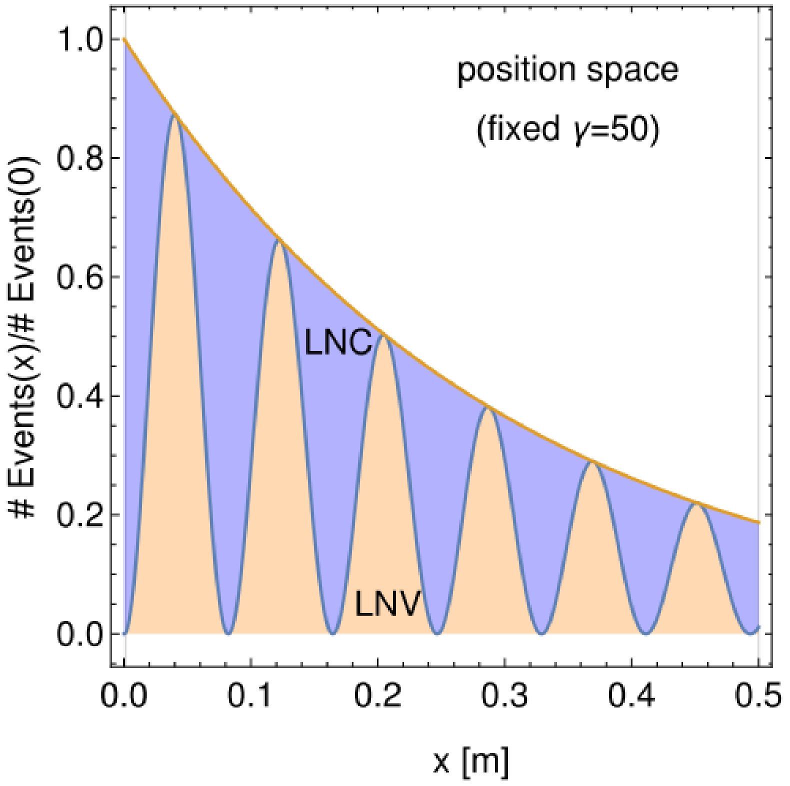

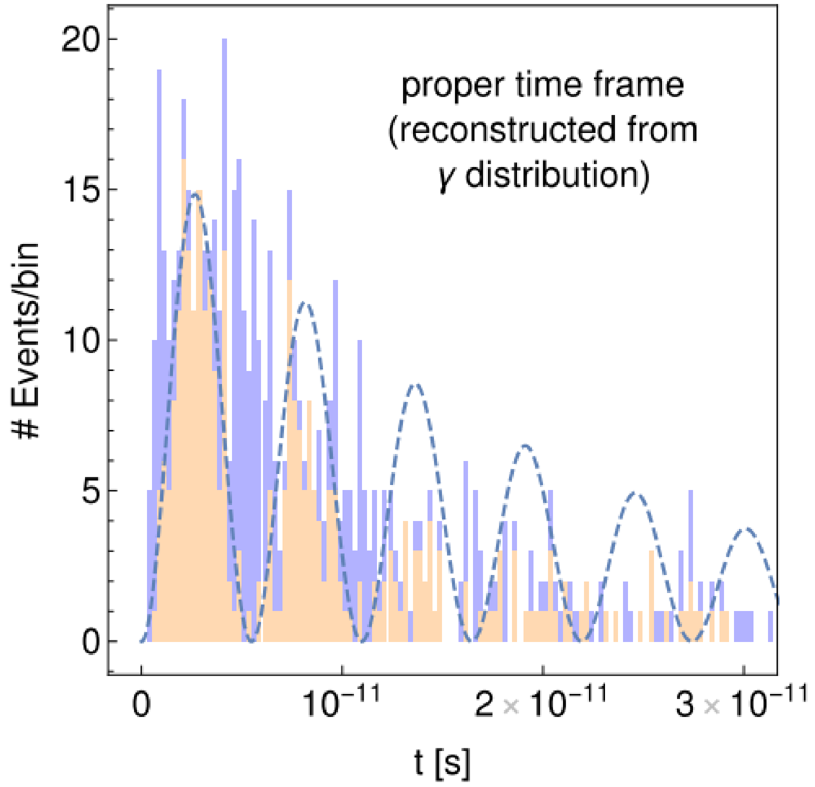

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Conclusions

- HNLs appear in many a well-motivated extensions of the SM, can be a portal to a “hidden sector”, …
- HNLs can explain neutrino masses and cosmological problems (leptogenesis, DM,…)
- HNLs in realistic neutrino mass model can phenomenologically behave like Dirac-particles, Majorana-particles, or something in between… (“pseudo Dirac”, “inverse seesaw”, “symmetry protected seesaw” …)
- Spectrum of possibilities can practically be modelled with continuous parameter $0 \leq R_{ll} \leq 1$
- Cases $R_{ll} = 0$ and $R_{ll} = 1$ represent useful benchmarks
- R_{ll} can be constrained in different ways at FCC-ee:
  - Forward-backward asymmetry in charged leptons from HNL decay
  - Spectrum of charged leptons
  - Comparing HNL lifetime to production cross sections
- Requires good measurement of M and the individual U_a^2

Backup Slides

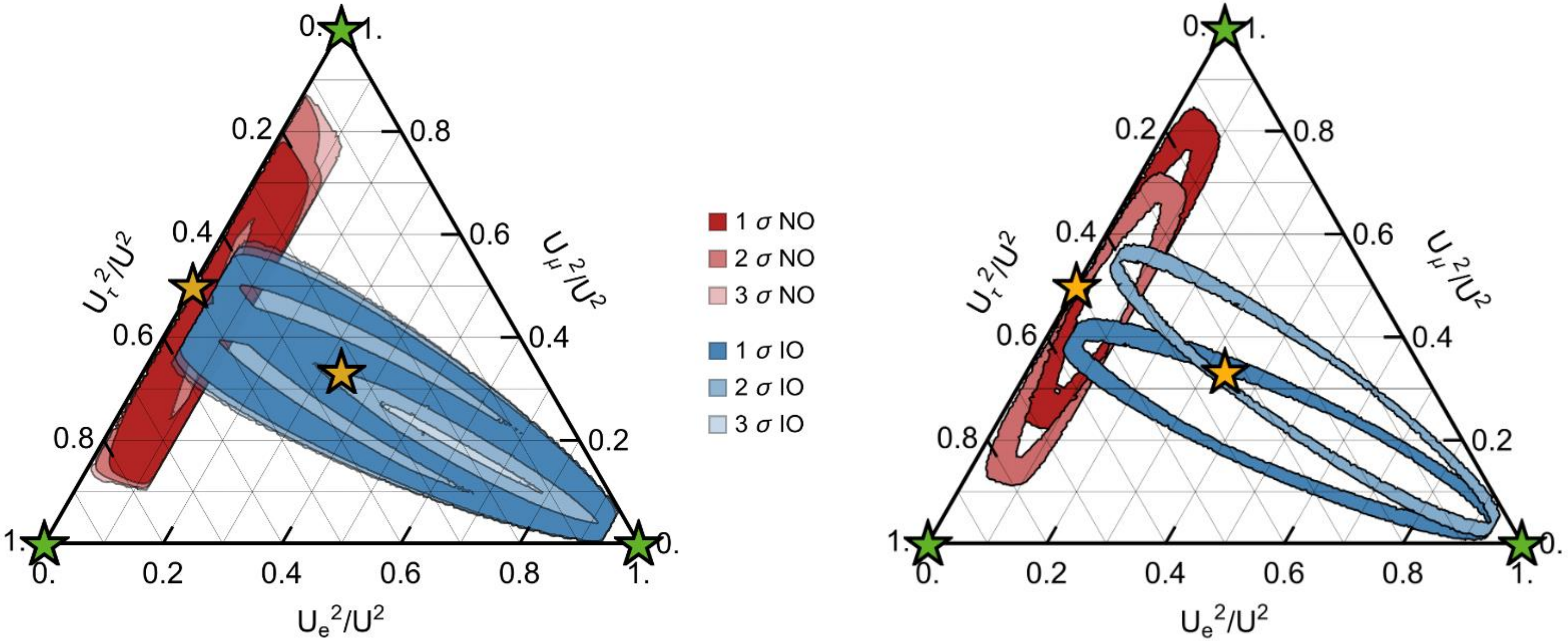
PBC Benchmark Recommendations

Benchmarks for LNV decay ratio:

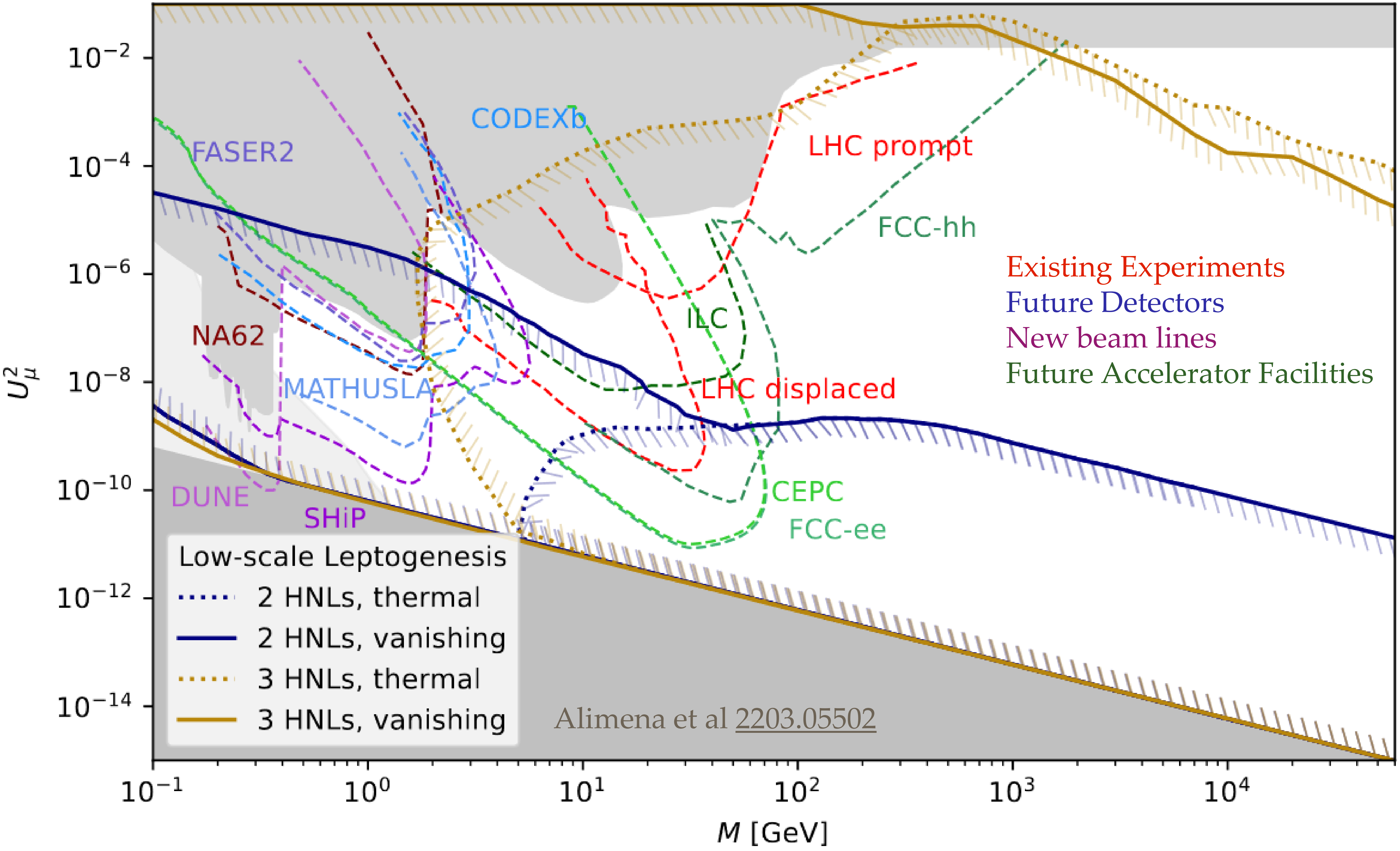
MaD/Klaric/Lopez-Pavon 2207.02742

- $R_{ll} = 0$ [one Dirac HNL]
- $R_{ll} = 1$ [one Majorana HNL]

Benchmarks for flavor mixing pattern:

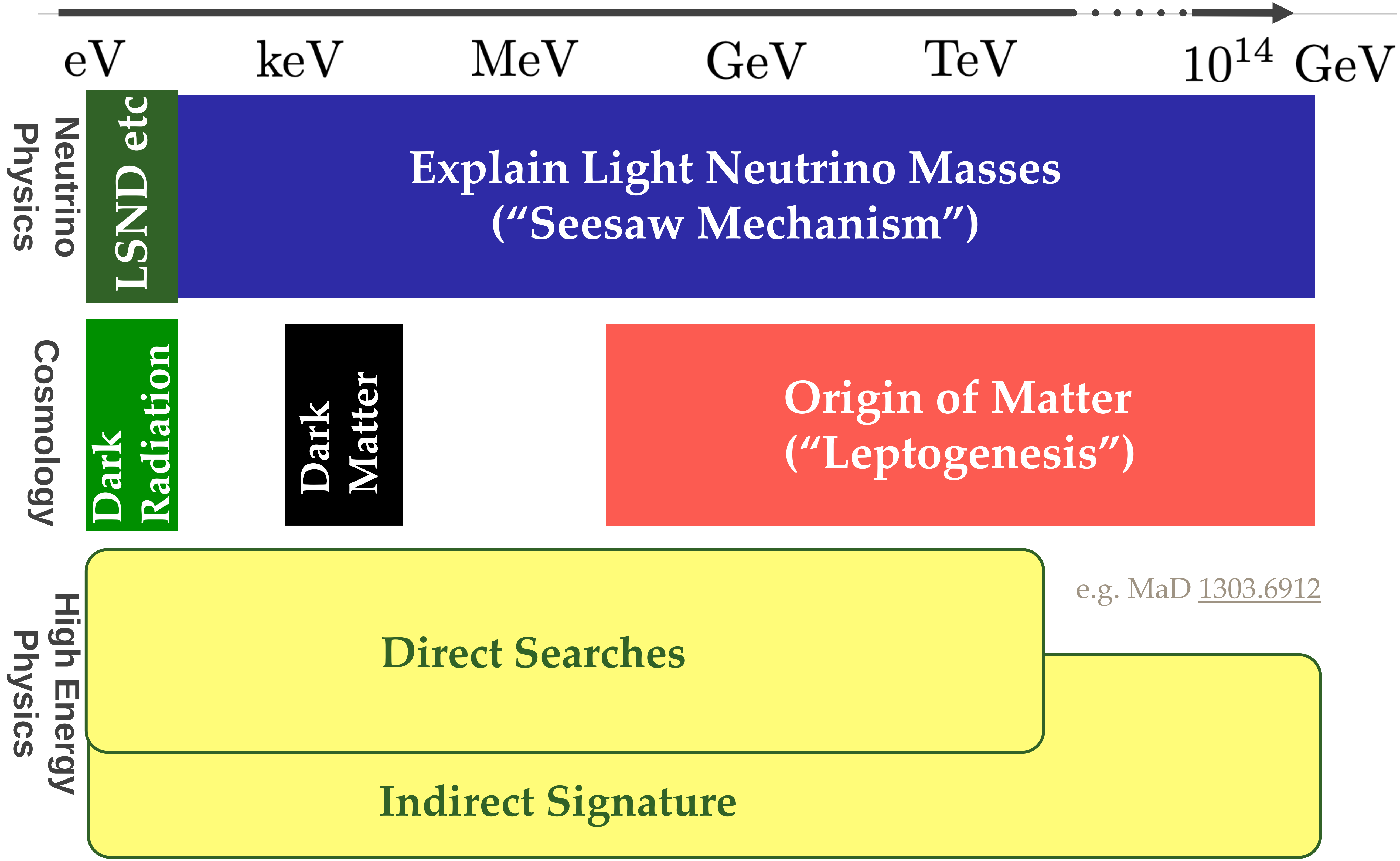


Leptogenesis



Alimena et al 2203.05502

Heavy Neutrino Mass Scale



eV keV MeV GeV TeV 10^{14} GeV

Neutrino Physics

LSND etc

Explain Light Neutrino Masses
(“Seesaw Mechanism”)

Cosmology

Dark Radiation

Dark Matter

Origin of Matter
(“Leptogenesis”)

High Energy Physics

Direct Searches

Indirect Signature

e.g. MaD 1303.6912

HNL Angular Distribution

Z-bosons are polarised due to P-violation of weak interaction:

$$g_R = 2\sin^2\theta_W \qquad g_L = (1 - 2\sin^2\theta_W) \qquad P_Z = \frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)} \simeq -0.15.$$

Dirac N particles and antiparticles have different angular distributions:

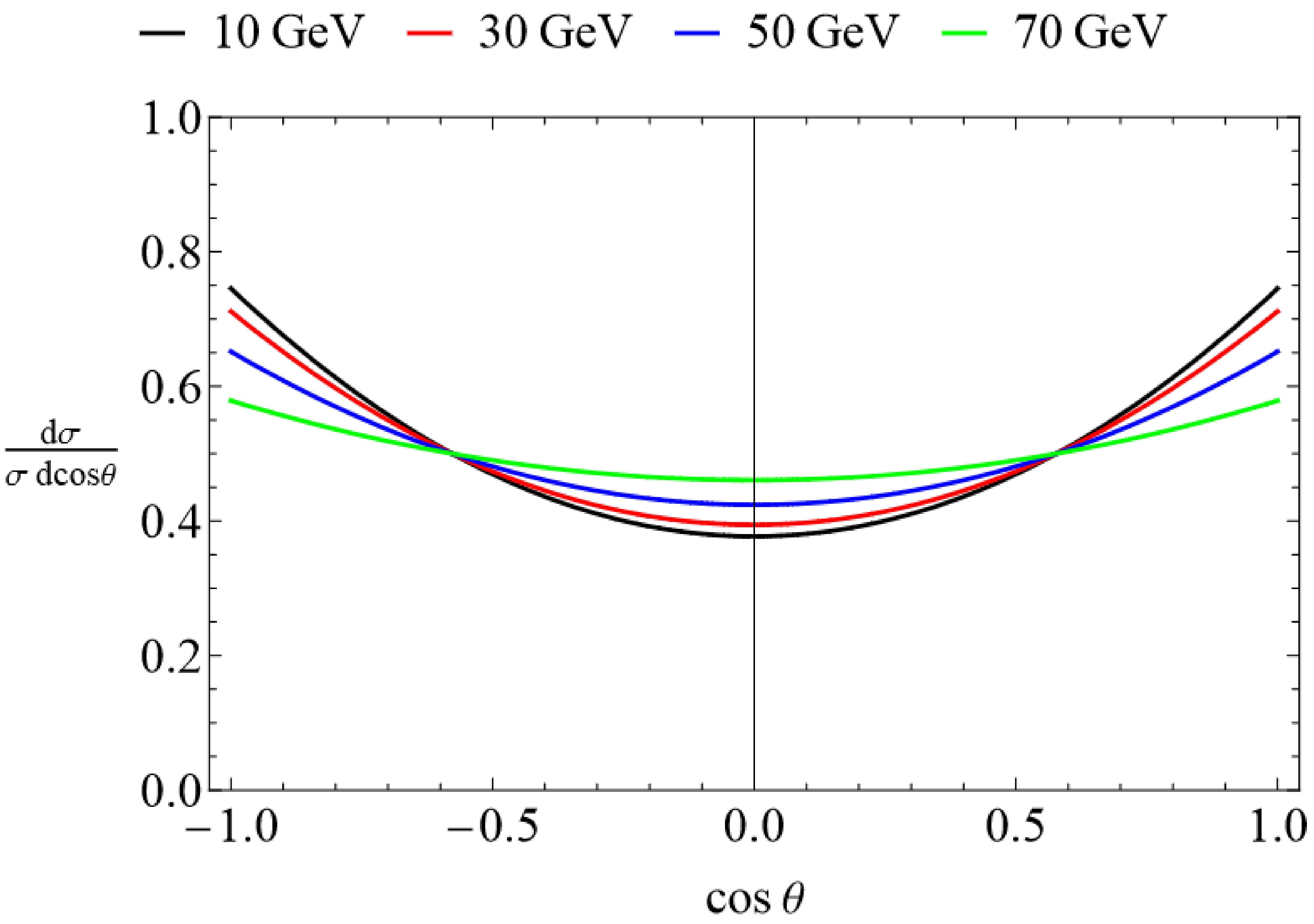
$$\frac{1}{\sigma_D(\nu_4)}\frac{\mathrm{d}\sigma_D(\nu_4)}{\mathrm{d}\cos\theta} = \frac{3}{4(g_R^2+g_L^2)}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\left(g_R^2(1-\cos\theta)^2 + g_L^2(1+\cos\theta)^2 + \frac{m_4^2}{M_Z^2}(g_R^2+g_L^2)\sin^2\theta\right)$$

$$\frac{1}{\sigma_D(\bar{\nu}_4)}\frac{\mathrm{d}\sigma_D(\bar{\nu}_4)}{\mathrm{d}\cos\theta} = \frac{3}{4(g_R^2+g_L^2)}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\left(g_R^2(1+\cos\theta)^2 + g_L^2(1-\cos\theta)^2 + \frac{m_4^2}{M_Z^2}(g_R^2+g_L^2)\sin^2\theta\right)$$

For Majorana N there is only one distribution:

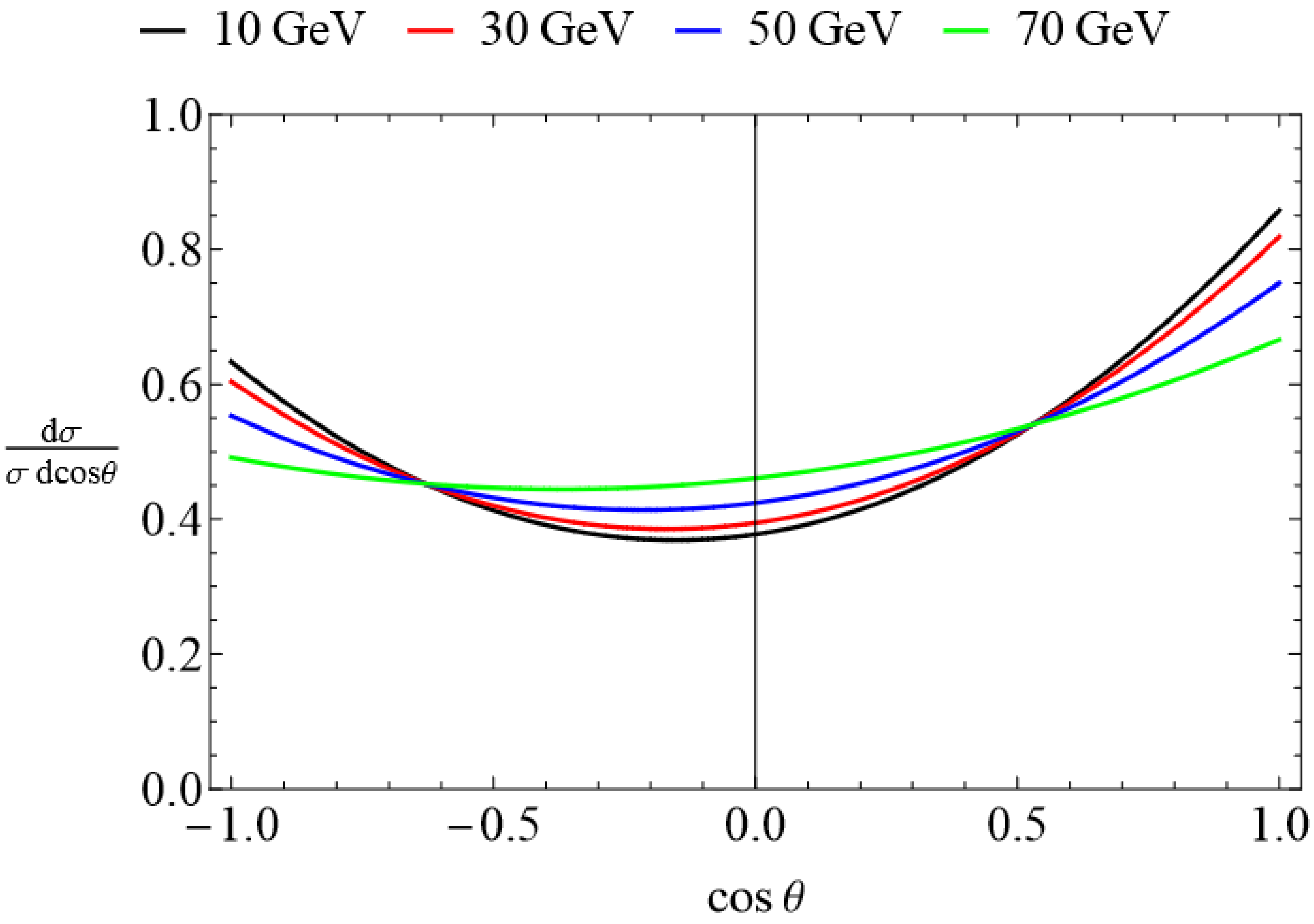
$$\frac{1}{\sigma_M(\nu_4)}\frac{\mathrm{d}\sigma_M(\nu_4)}{\mathrm{d}\cos\theta} = \frac{3}{4}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\left(1+\cos^2\theta + \frac{m_4^2}{M_Z^2}\sin^2\theta\right)$$

HNL Angular Distribution



Blondel et al 2105.06576

HNL Angular Distribution



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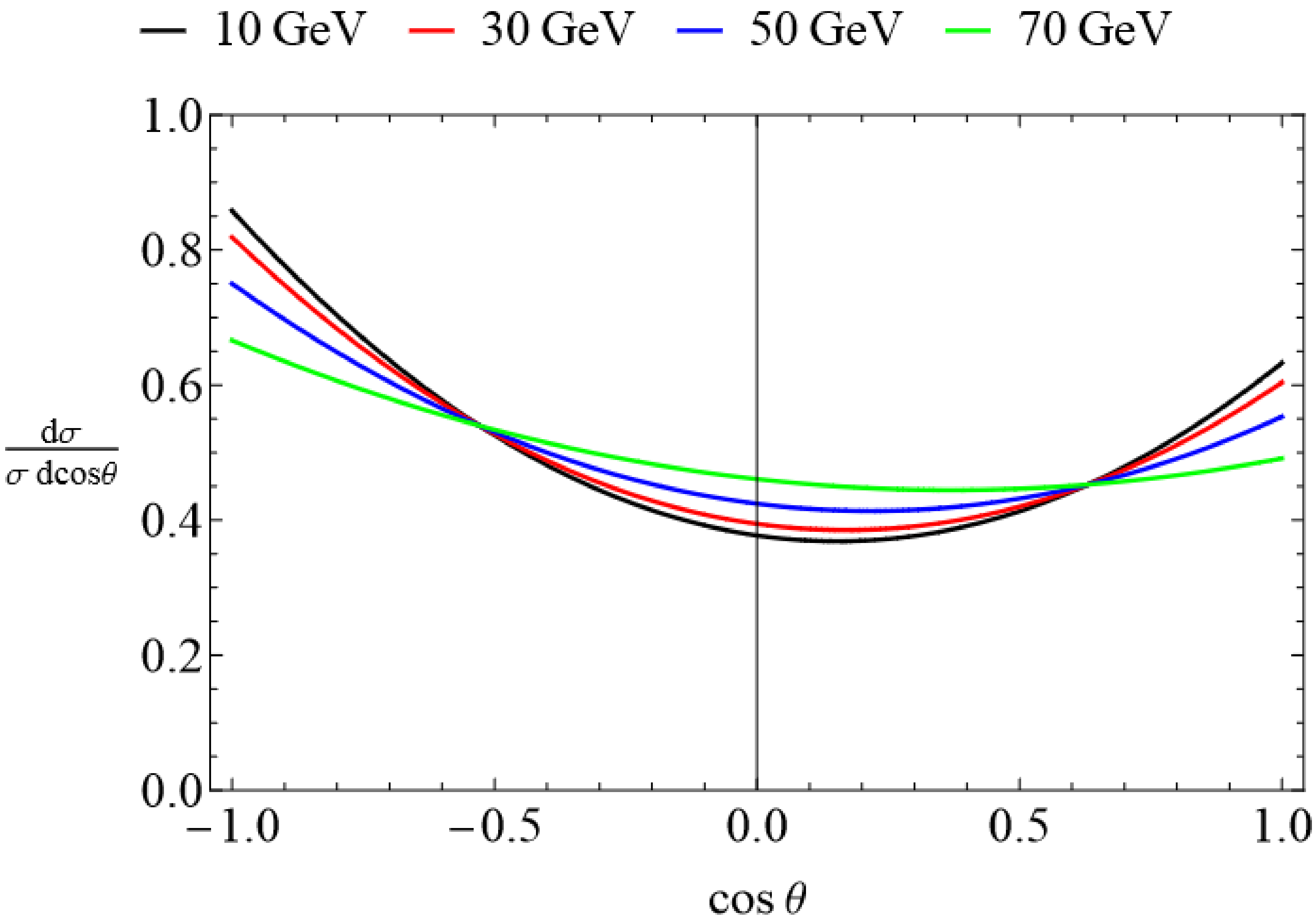


Blondel et al 2105.06576

Backgrounds

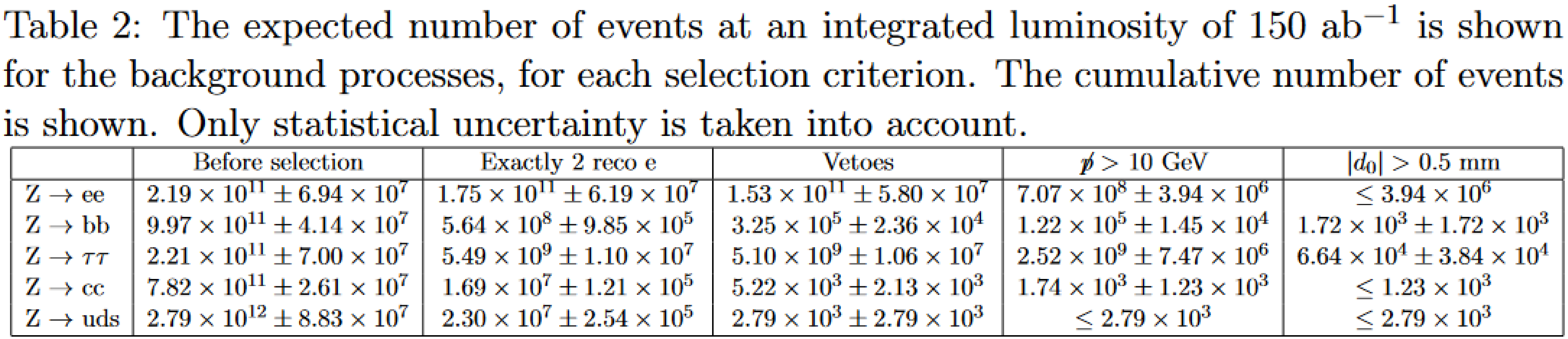


Table 2: The expected number of events at an integrated luminosity of 150 ab^{-1} is shown for the background processes, for each selection criterion. The cumulative number of events is shown. Only statistical uncertainty is taken into account.

	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$Z \to ee$	$2.19 \times 10^{11} \pm 6.94 \times 10^{7}$	$1.75 \times 10^{11} \pm 6.19 \times 10^{7}$	$1.53 \times 10^{11} \pm 5.80 \times 10^{7}$	$7.07 \times 10^{8} \pm 3.94 \times 10^{6}$	$\leq 3.94 \times 10^{6}$
$Z \to bb$	$9.97 \times 10^{11} \pm 4.14 \times 10^{7}$	$5.64 \times 10^{8} \pm 9.85 \times 10^{5}$	$3.25 \times 10^{5} \pm 2.36 \times 10^{4}$	$1.22 \times 10^{5} \pm 1.45 \times 10^{4}$	$1.72 \times 10^{3} \pm 1.72 \times 10^{3}$
$Z \to \tau\tau$	$2.21 \times 10^{11} \pm 7.00 \times 10^{7}$	$5.49 \times 10^{9} \pm 1.10 \times 10^{7}$	$5.10 \times 10^{9} \pm 1.06 \times 10^{7}$	$2.52 \times 10^{9} \pm 7.47 \times 10^{6}$	$6.64 \times 10^{4} \pm 3.84 \times 10^{4}$
$Z \to cc$	$7.82 \times 10^{11} \pm 2.61 \times 10^{7}$	$1.69 \times 10^{7} \pm 1.21 \times 10^{5}$	$5.22 \times 10^{3} \pm 2.13 \times 10^{3}$	$1.74 \times 10^{3} \pm 1.23 \times 10^{3}$	$\leq 1.23 \times 10^{3}$
$Z \to uds$	$2.79 \times 10^{12} \pm 8.83 \times 10^{7}$	$2.30 \times 10^{7} \pm 2.54 \times 10^{5}$	$2.79 \times 10^{3} \pm 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$

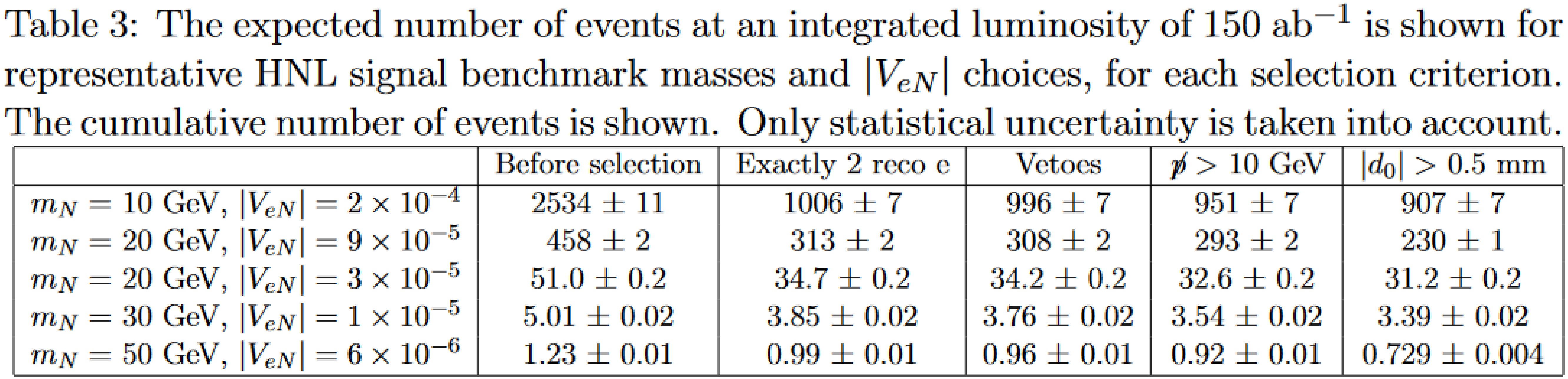


Table 3: The expected number of events at an integrated luminosity of 150 ab^{-1} is shown for representative HNL signal benchmark masses and $|V_{eN}|$ choices, for each selection criterion. The cumulative number of events is shown. Only statistical uncertainty is taken into account.

	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$m_N = 10$ GeV, $\lvert V_{eN} \rvert = 2 \times 10^{-4}$	2534 ± 11	1006 ± 7	996 ± 7	951 ± 7	907 ± 7
$m_N = 20$ GeV, $\lvert V_{eN} \rvert = 9 \times 10^{-5}$	458 ± 2	313 ± 2	308 ± 2	293 ± 2	230 ± 1
$m_N = 20$ GeV, $\lvert V_{eN} \rvert = 3 \times 10^{-5}$	51.0 ± 0.2	34.7 ± 0.2	34.2 ± 0.2	32.6 ± 0.2	31.2 ± 0.2
$m_N = 30$ GeV, $\lvert V_{eN} \rvert = 1 \times 10^{-5}$	5.01 ± 0.02	3.85 ± 0.02	3.76 ± 0.02	3.54 ± 0.02	3.39 ± 0.02
$m_N = 50$ GeV, $\lvert V_{eN} \rvert = 6 \times 10^{-6}$	1.23 ± 0.01	0.99 ± 0.01	0.96 ± 0.01	0.92 ± 0.01	0.729 ± 0.004

B-L Charge Assignment

charge assignment in Lagrangian

spinor	$\bar{L}$-charge
$\nu_{Rs} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
$\nu_{Rw} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} - i\nu_{R2})$	-1
ν_{R3}	0

approximately conserved helicity charges during leptogenesis

spinors	$\widetilde{L}$-charge
$P_+N_i, \quad \bar{N}_iP_+$	$+1$
$P_-N_i, \quad \bar{N}_iP_-$	-1

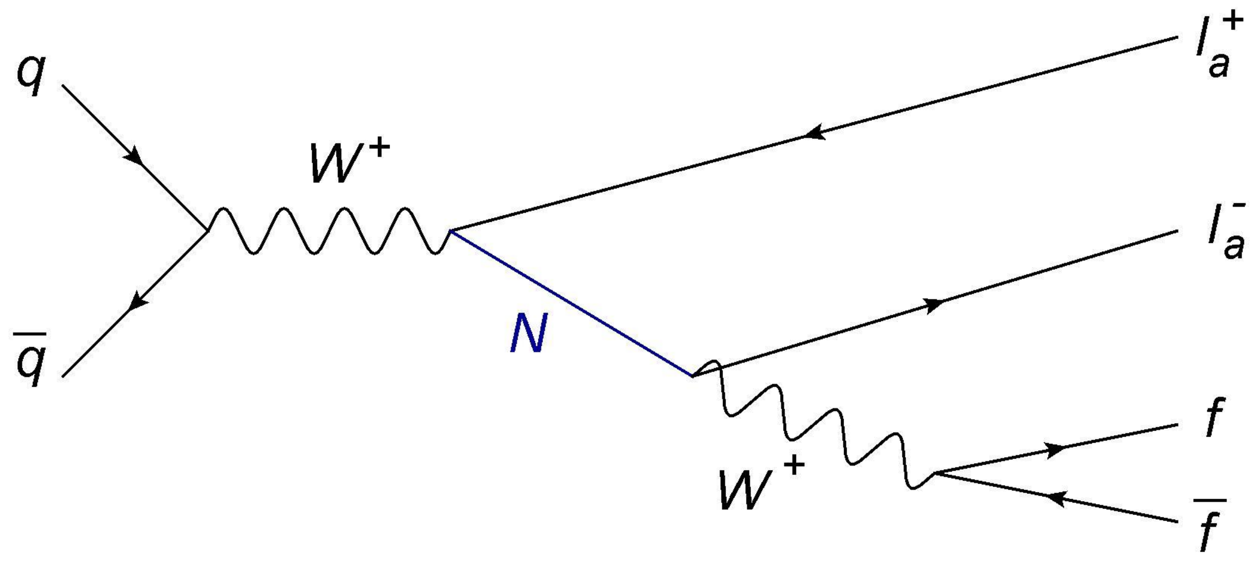
$$\psi_N = (\nu_{Rs} + \nu_{Rw}^c)$$

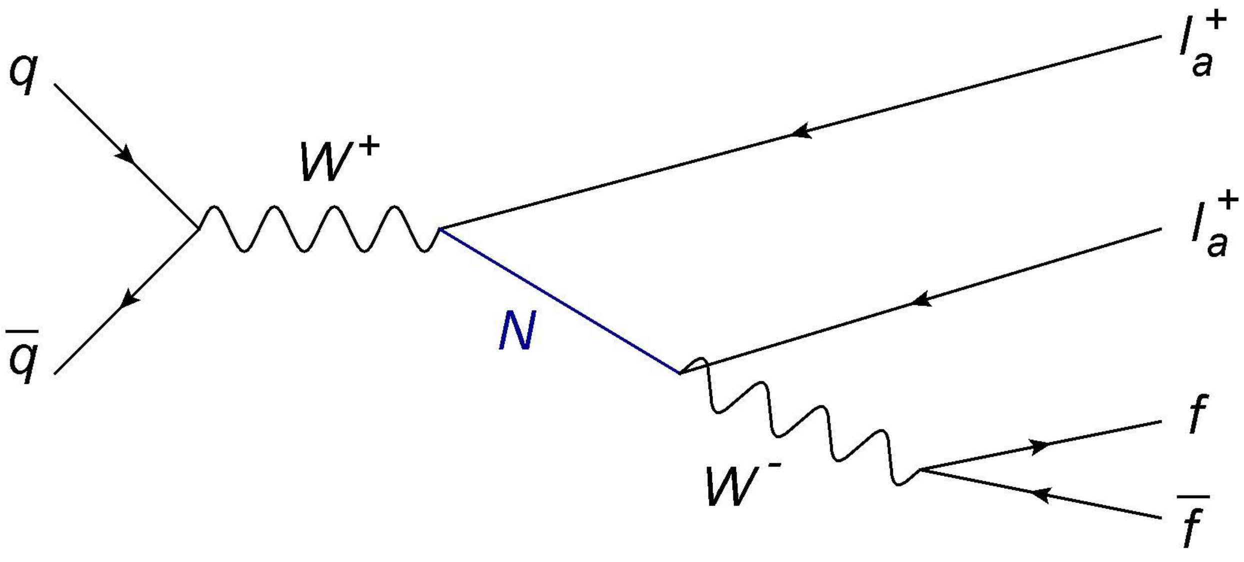
***B-L* violating parameters** $\mu, \; \epsilon, \; \epsilon'$

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} &+ \overline{\psi_N}(\mathrm{i}\partial\!\!\!/ - \bar{M})\psi_N + \overline{\nu_{R3}}\mathrm{i}\partial\!\!\!/\nu_{R3} - F_a^*\overline{\psi_N}\phi^T\varepsilon^\dagger\ell_{La} - F_a\bar{\ell}_{La}\varepsilon\phi^*\psi_N \\ &-\epsilon_a^*F_a^*\overline{\psi_N^c}\phi^T\varepsilon^\dagger\ell_{La} - \epsilon_aF_a\bar{\ell}_{La}\varepsilon\phi^*\psi_N^c - \epsilon_a'F_a\overline{\ell_{La}}\varepsilon\phi^*\nu_{R3} - \epsilon_a'^*F_a^*\overline{\nu_{R3}}\phi^T\varepsilon^\dagger\ell_{La} \\ &-\mu\bar{M}\frac{1}{2}\left(\overline{\psi_N^c}\psi_N + \overline{\psi_N}\psi_N^c\right) - \mu'\bar{M}\overline{\nu_{R3}^c}\nu_{R3}\,,\end{aligned}$$

Shaposhnikov 06
Kersten/Smirnov 07

LNV at the LHC





- At the LHC there exist fully reconstructable final states
- Direct observation of LNV (e.g. same sign dilepton) is possible
- Other methods are complementary

How to practically distinguish Dirac from Majorana *N*?

1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N