**Marco Drewes, Université catholique de Louvain**

# Searches for long-lived HNL at FCC

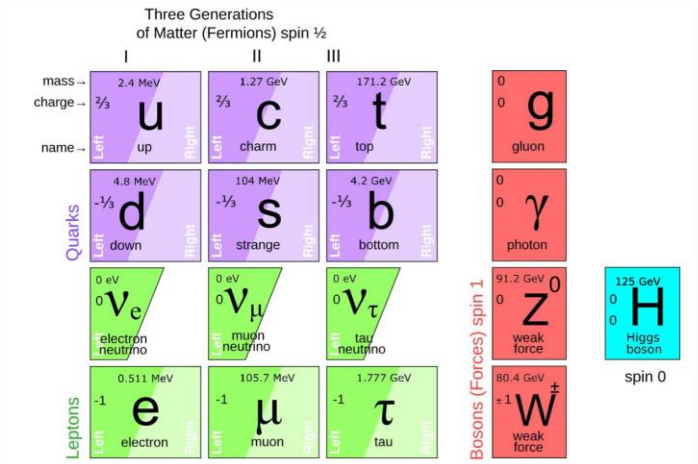
**February 17 2023**

**ECFA WG1-SRCH topical meeting**
***Heavy Neutral Lepton search potential of future HET factories***

FCC

# Heavy Neutral Leptons (HNL)

- Heavy RH neutrinos predicted by many extensions of the SM (left-right-symmetry, SO(10) GUT, …),




- Heavy RH neutrinos are a type of heavy neutral lepton (HNL), and are sterile neutrinos wrt SM interactions

- HNLs represent one of the renormalisable "portals" to a BSM sector (e.g. "dark sector")

- Can address various shortcomings of the SM: e.g. Abdullahi et al 2203.08039, MaD 1303.6912
  - Neutrino masses: seesaw mechanism
  - Baryogenesis via leptogenesis
  - Dark matter
  - Oscillation anomalies
  - …

- Low scale seesaw models exist… …and are testable at colliders… …in particular FCC-ee

Asaka/Shaposhnikov 0505013 Argawal et al 2102.12143
Deppisch et al 1502.06541, Cai et al 1711.02180
Alimena et al 2203.08039 Antusch/Fischer 1612.02728

# HNL SM Weak Interactions

**Common phenomenological description: "Single HNL Model"**

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

- One flavour of HNLs $N$
- Couples to SM only through mixing $\theta_a$ with SM neutrinos, where a = e, μ, τ
- Model with five parameters : $M$, $\theta_e$, $\theta_\mu$, $\theta_\tau$, 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 describe some phenomenological aspects of realistic models with suitable choices of** : $M$, $\theta_e$, $\theta_\mu$, $\theta_\tau$, $R_{ll}$.

# Overview

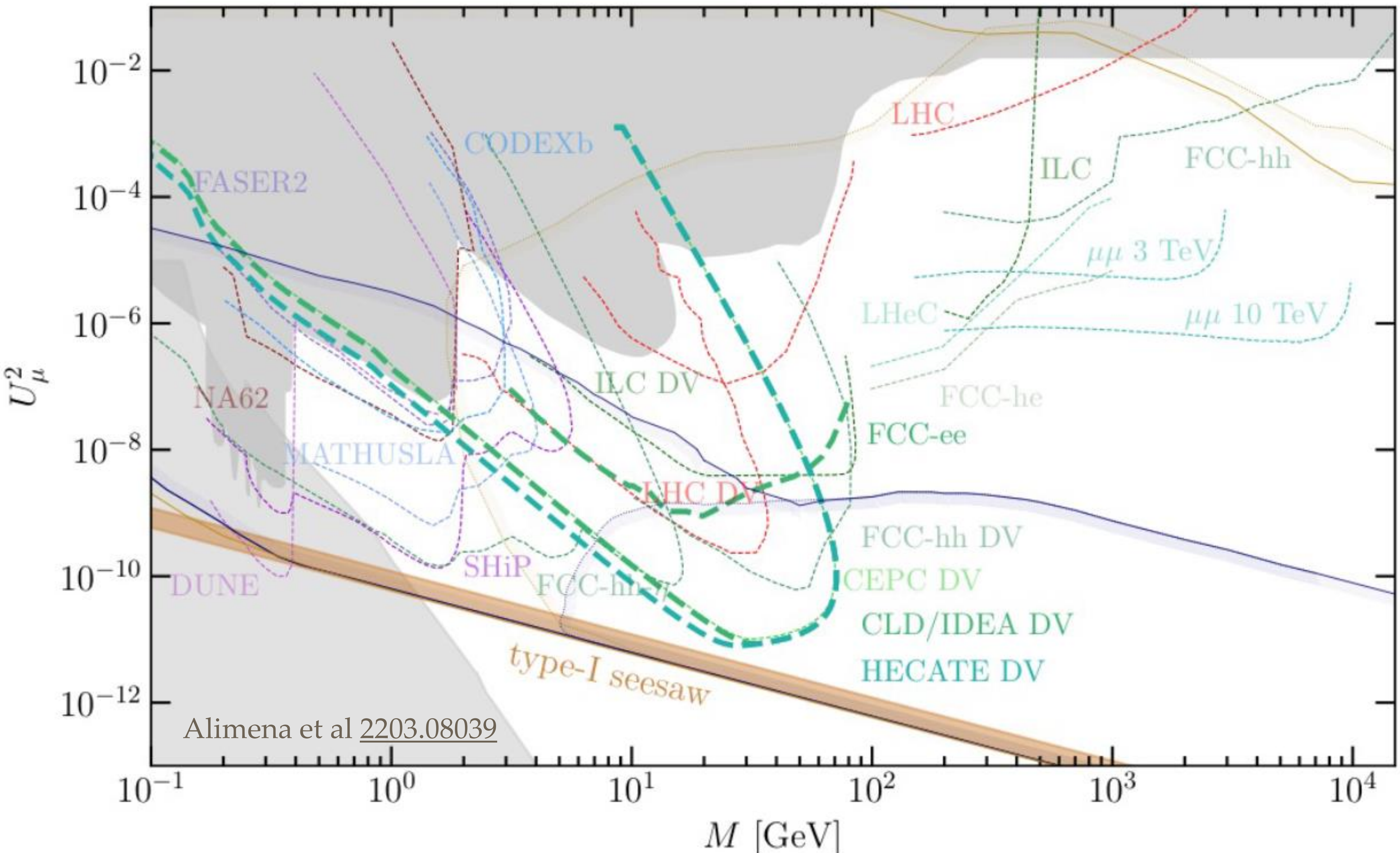
Part I: What can FCC-ee measure?

- HNL discovery potential
- Flavour mixing pattern
- Lepton number violation

Part II: Summary of (some) recent activities

- HNL discovery potential
- Lepton number violation

# HNL Search Summary




Alimena et al 2203.08039

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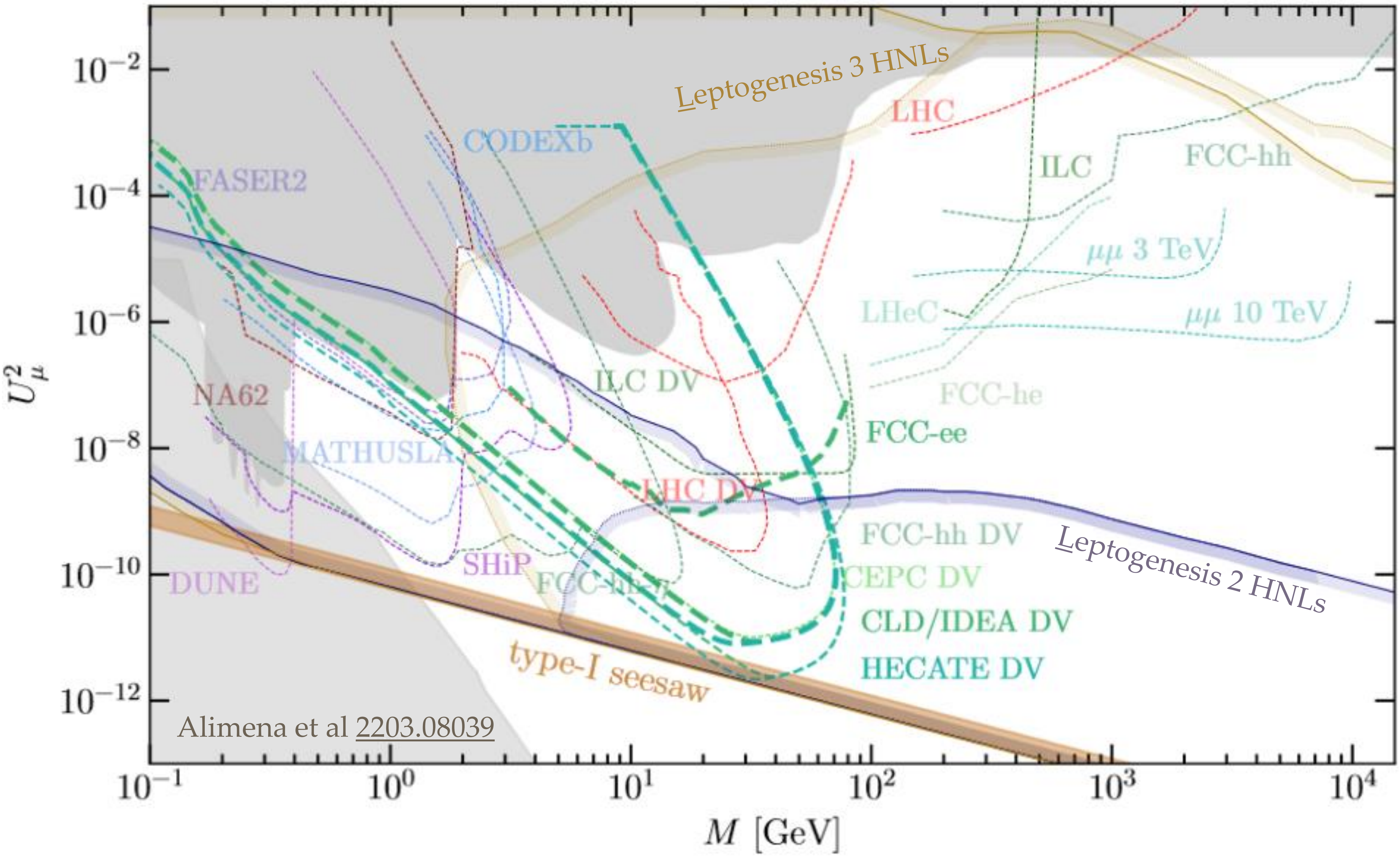
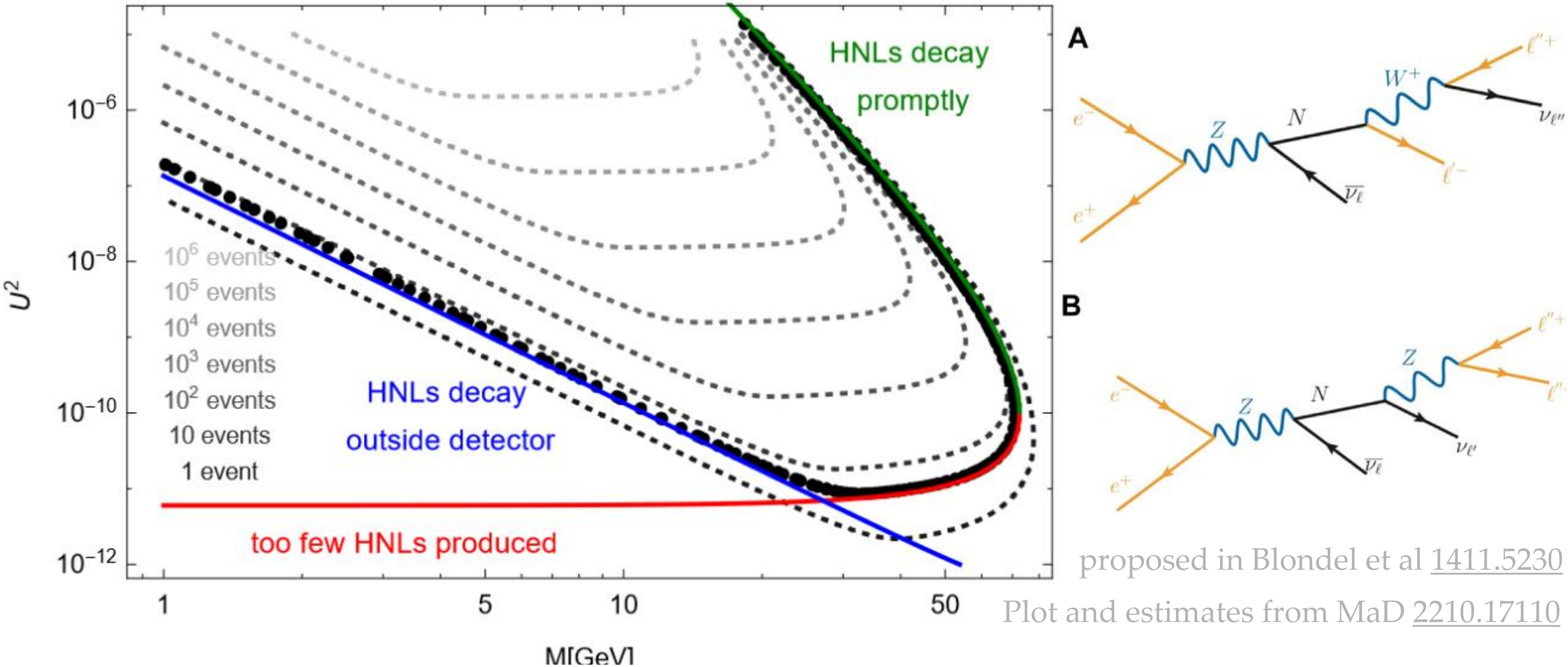


# DV Vertex Searches during Z-pole Run




proposed in Blondel et al 1411.5230

Plot and estimates from MaD 2210.17110

$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}} \left(\frac{M}{\rm GeV}\right)^{-6} \left(1 - (M/m_Z)^2\right) \, {\rm cm}.$$

$c_{\rm dec} = 1$ ($c_{\rm dec} = 1/2$) for Majorana (Dirac) HNL

(note that “Dirac” vs “Majorana” dichotomy is insufficient to describe realistic HNLs, see talk by Jan Hajer)

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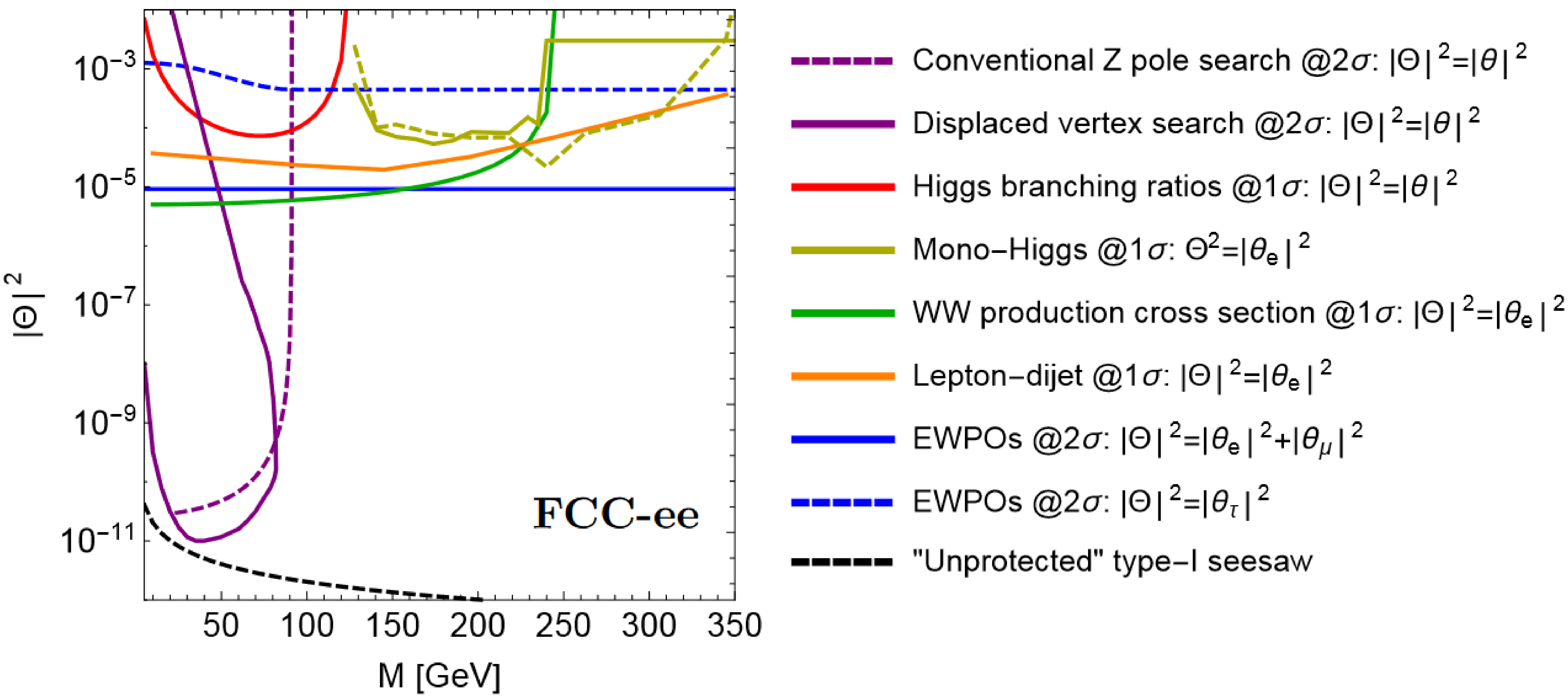
≤
≤

# Other Searches




Antusch/Fischer 1612.02728

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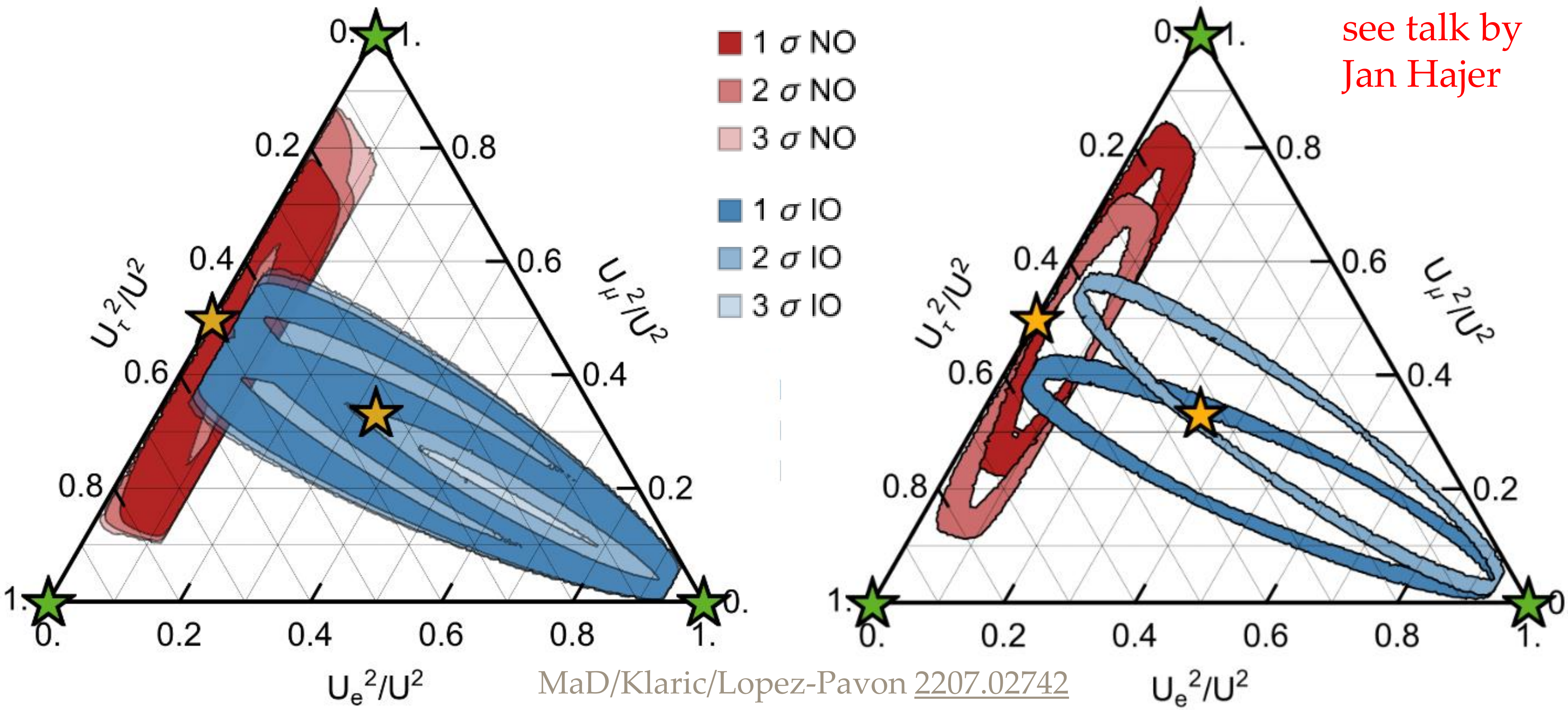
# Testing the Seesaw Mechanism

- Neutrino oscillation data strongly constrains properties of heavy neutrinos
- Restricts decay branching ratios into individual SM flavours in νMSM-like model




see talk by Jan Hajer

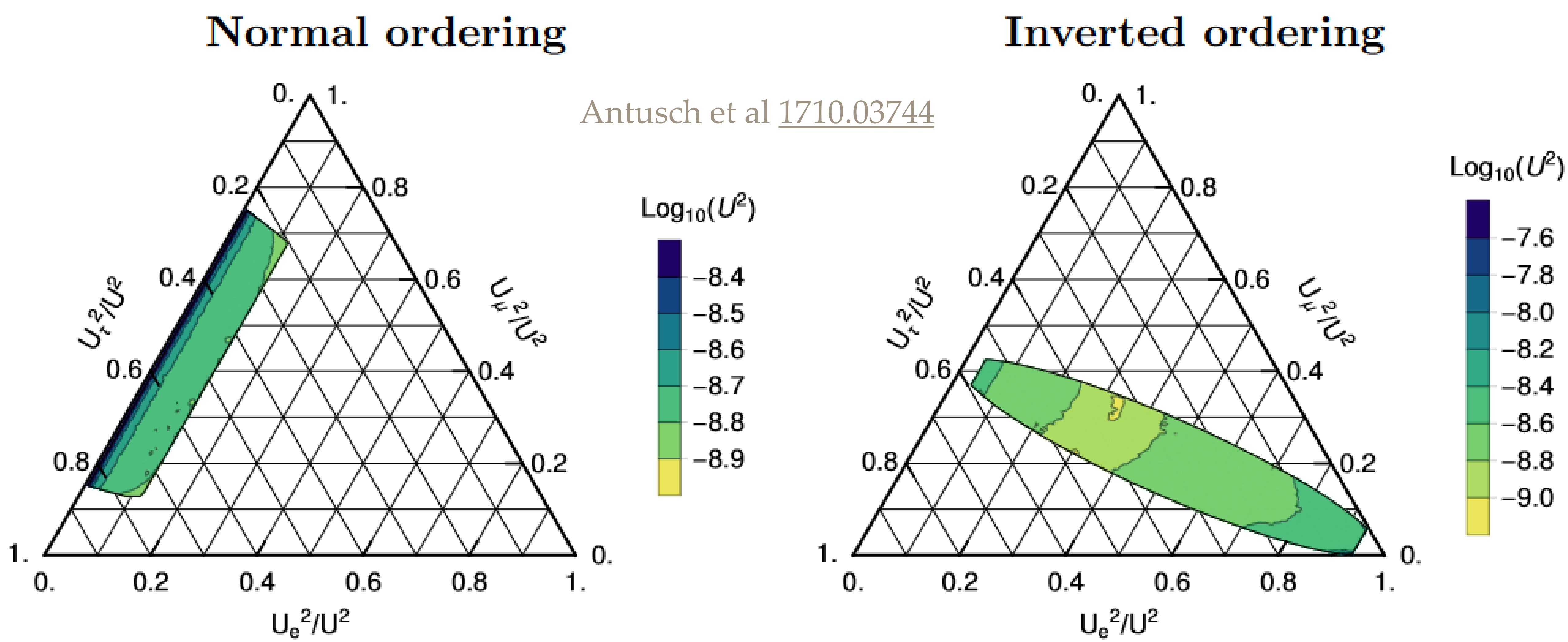
MaD/Klaric/Lopez-Pavon 2207.02742

Current constraints

DUNE projection

- **Can potentially be measured at percent level with FCC-ee** Antusch et al 1710.03744

# Predictions from Leptogenesis




Antusch et al [1710.03744](https://arxiv.org/abs/1710.03744)

- Requirement for leptogenesis imposes additional constraints on branching ratios Antusch et al 1710.03744
- Recently confirmed and refined in Hernandez et al 2207.01651

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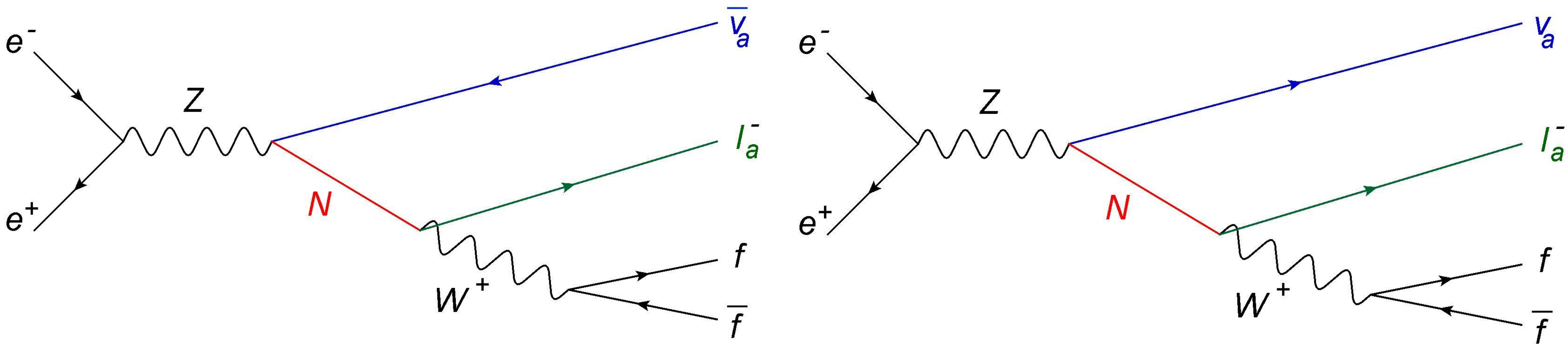
# LNV at Lepton Colliders



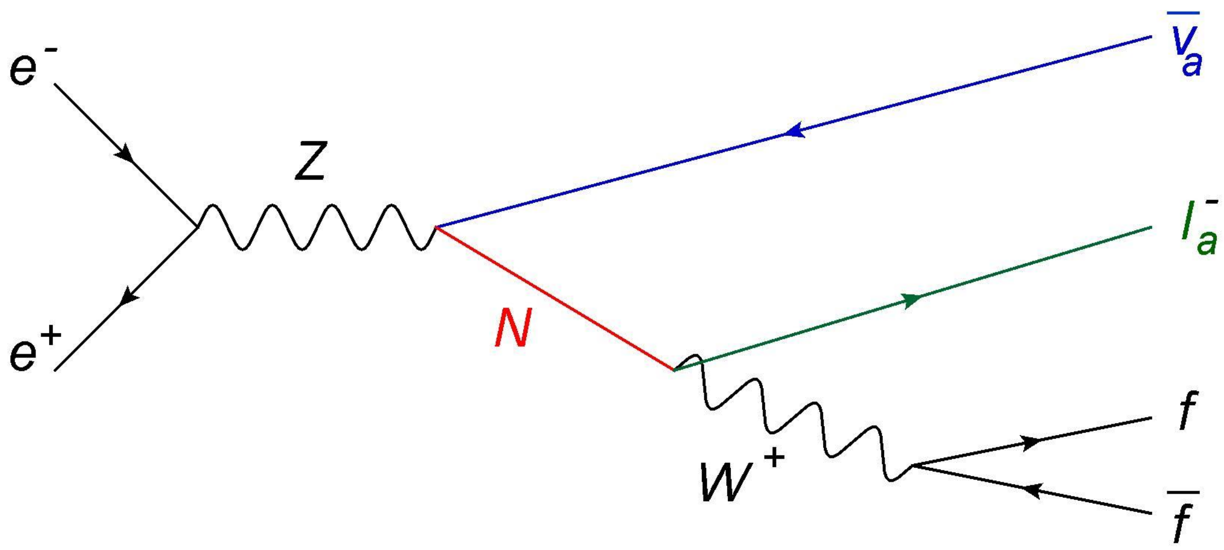

**How to practically distinguish Dirac from Majorana *N*?**

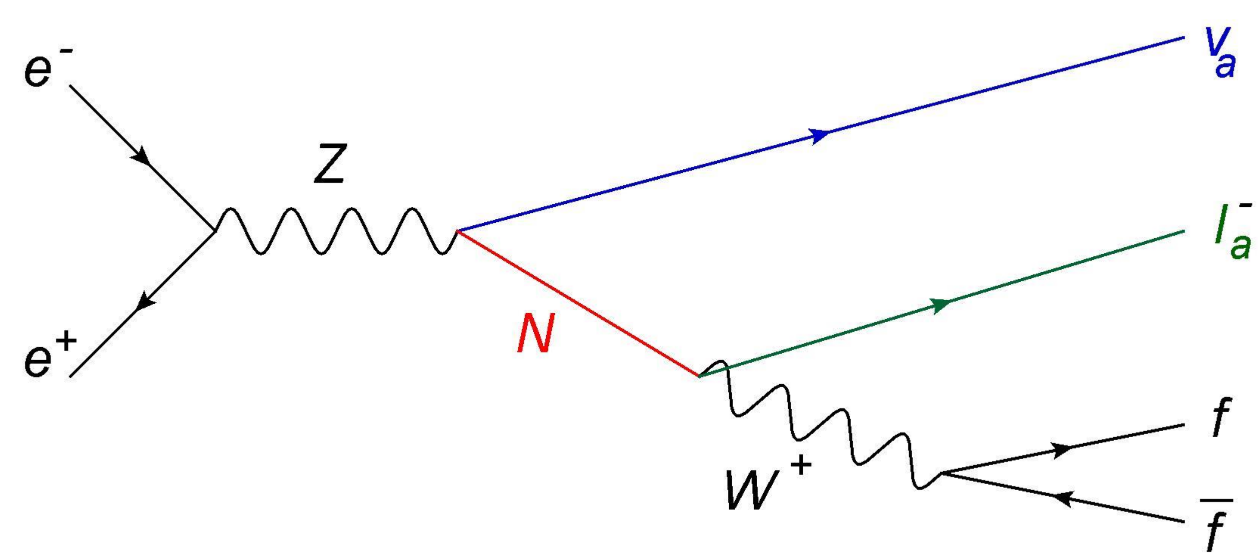
1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N

- Largest event numbers: displaced vertices in *Z*-pole run
- Neutrino in final state unobservable
- Rely on indirect methods 2) – 4)
- 4-momentum of *N* can still be fully reconstructed

Blondel et al 1411.5230

# 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

# 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 length differs:
  Dirac: : $c_{dec} = 1$
  Majorana: $c_{dec} = 2$

$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}}\left(\frac{M}{\rm GeV}\right)^{-6}\left(1 - (M/m_Z)^2\right)\,\mathrm{cm}.$$

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

➢ **Extract $U_a^2$ from total # decays ,**
**$c_{dec}$ from # decays between displacement $l_0$, $l_1$**

$$N_{\rm obs} \simeq u_\beta^2 N_{{\rm HNL}\alpha}\left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right]$$

$$l_1 = \frac{1}{2}(3/2)^{1/3} d_{\rm cyl}^{2/3} l_{\rm cyl}^{1/3}$$

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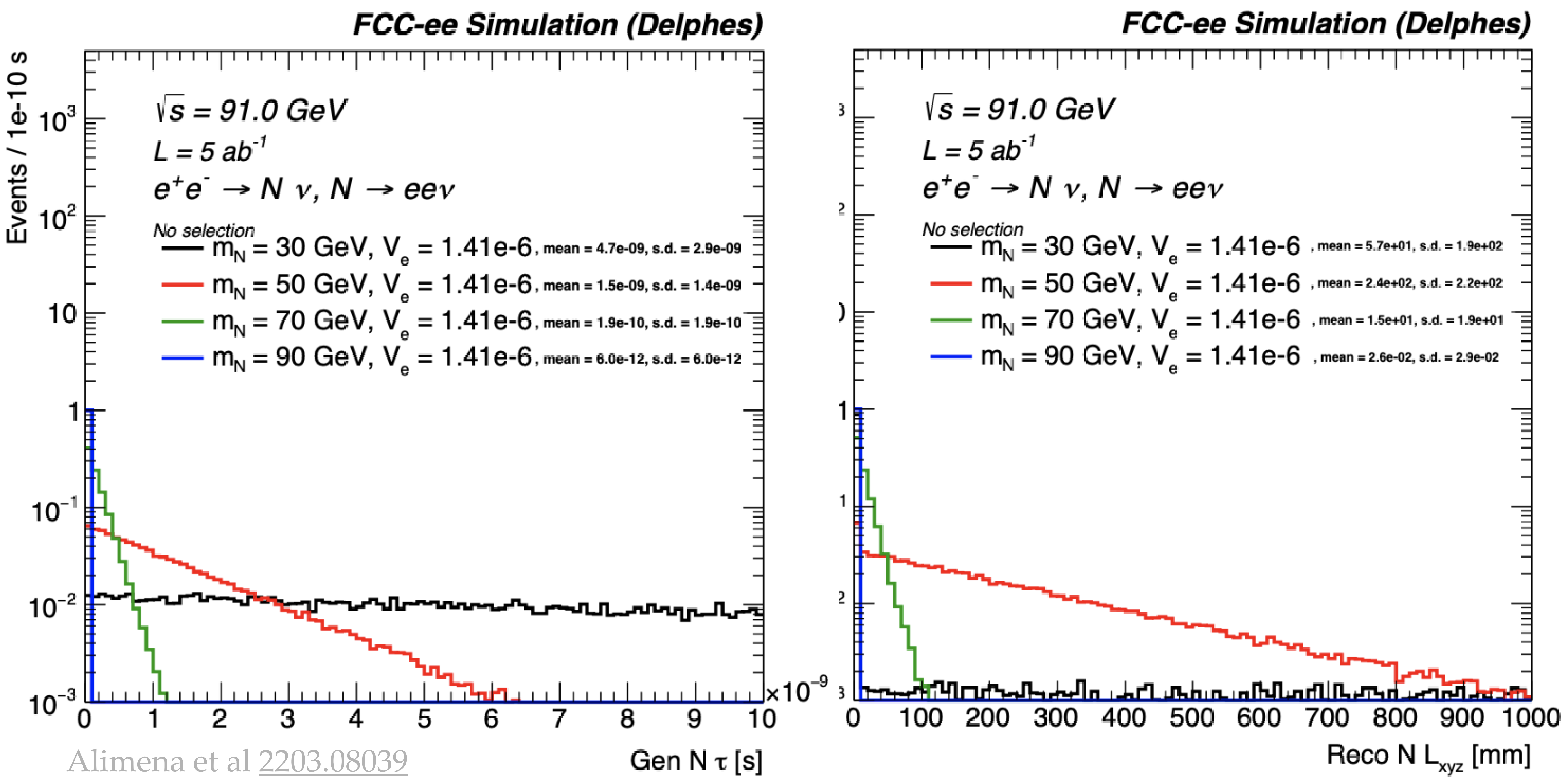
# Some Recent Activites

- Informal working group (chaired by Juliette Alimena)
- Development of FCC-specific tools [see talk by G. Ganis in January]
- Current studies go beyond "naïve theorist estimates"
  - Simulations under way with Madgraph5 v3.2.0 + Pythia8 + Delphes
  - Special thanks to master students Sissel Bay Nielsen, Dimitri Moulin, Lovisa Rygaard, Rohini Sengupta, Tanishq Sharma
- Independent studies in many groups all over the world

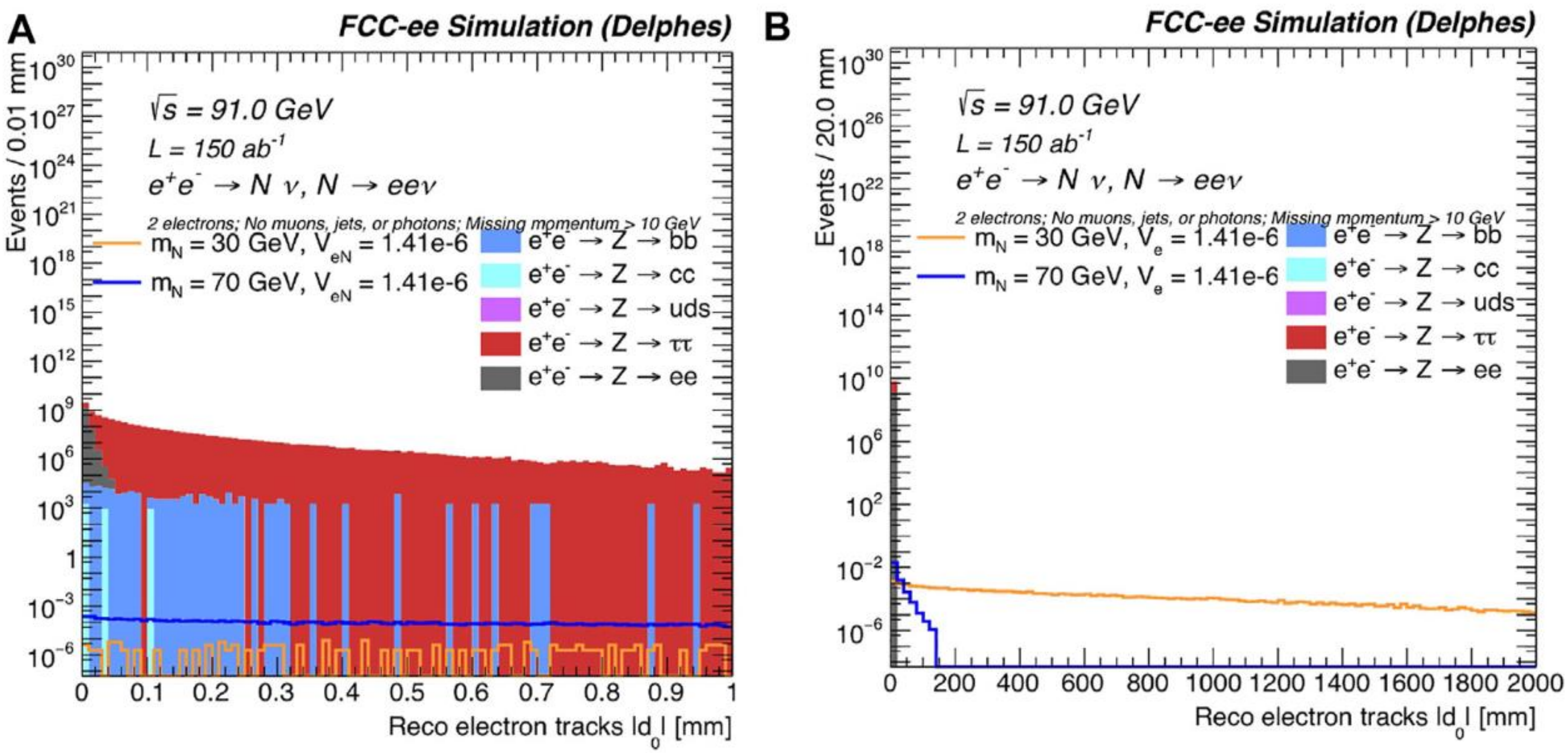
# Signal Simulation




Alimena et al 2203.08039

generator level | reconstruction level

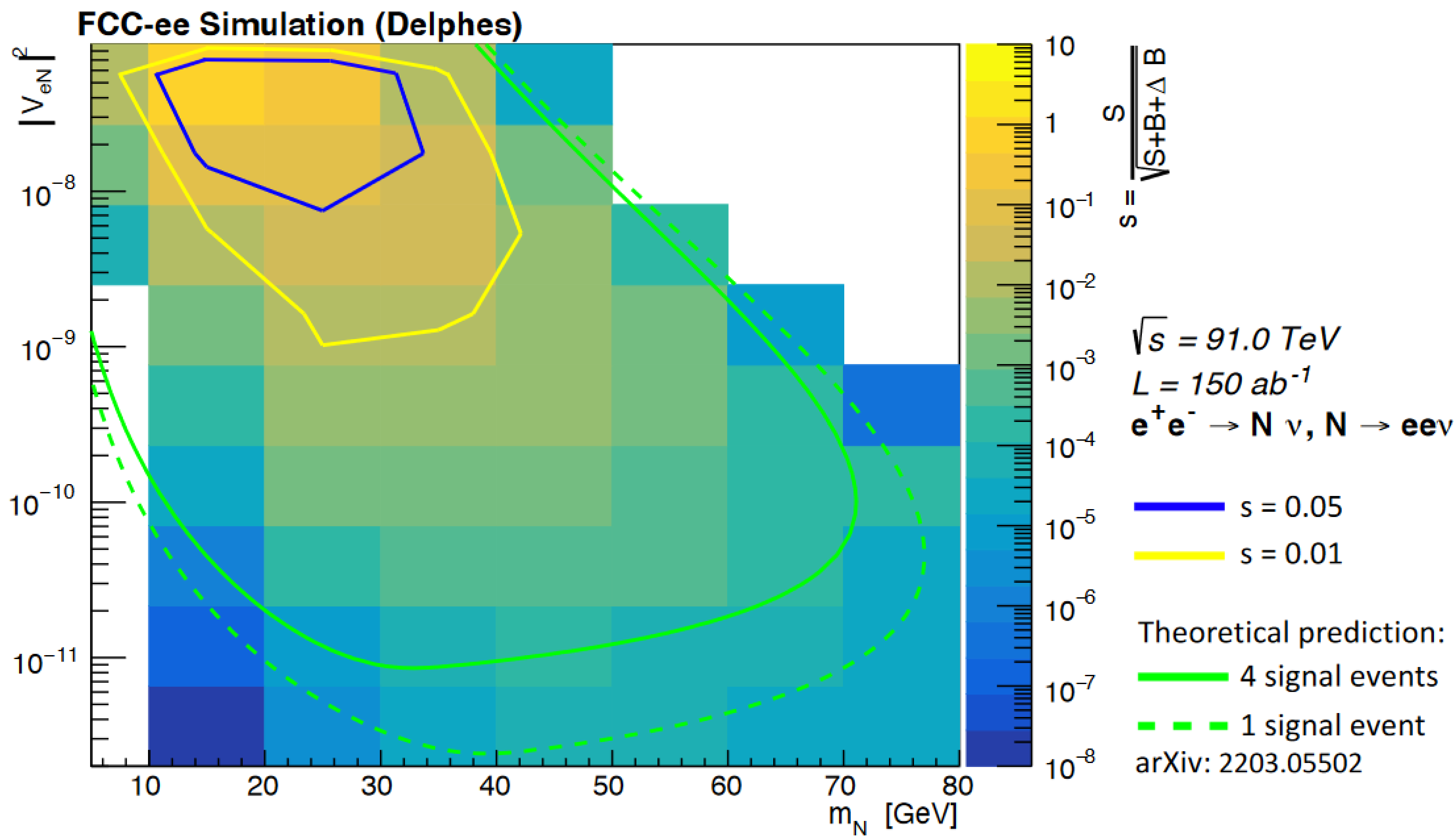
# Background Simulation




Alimena et al
2203.08039

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

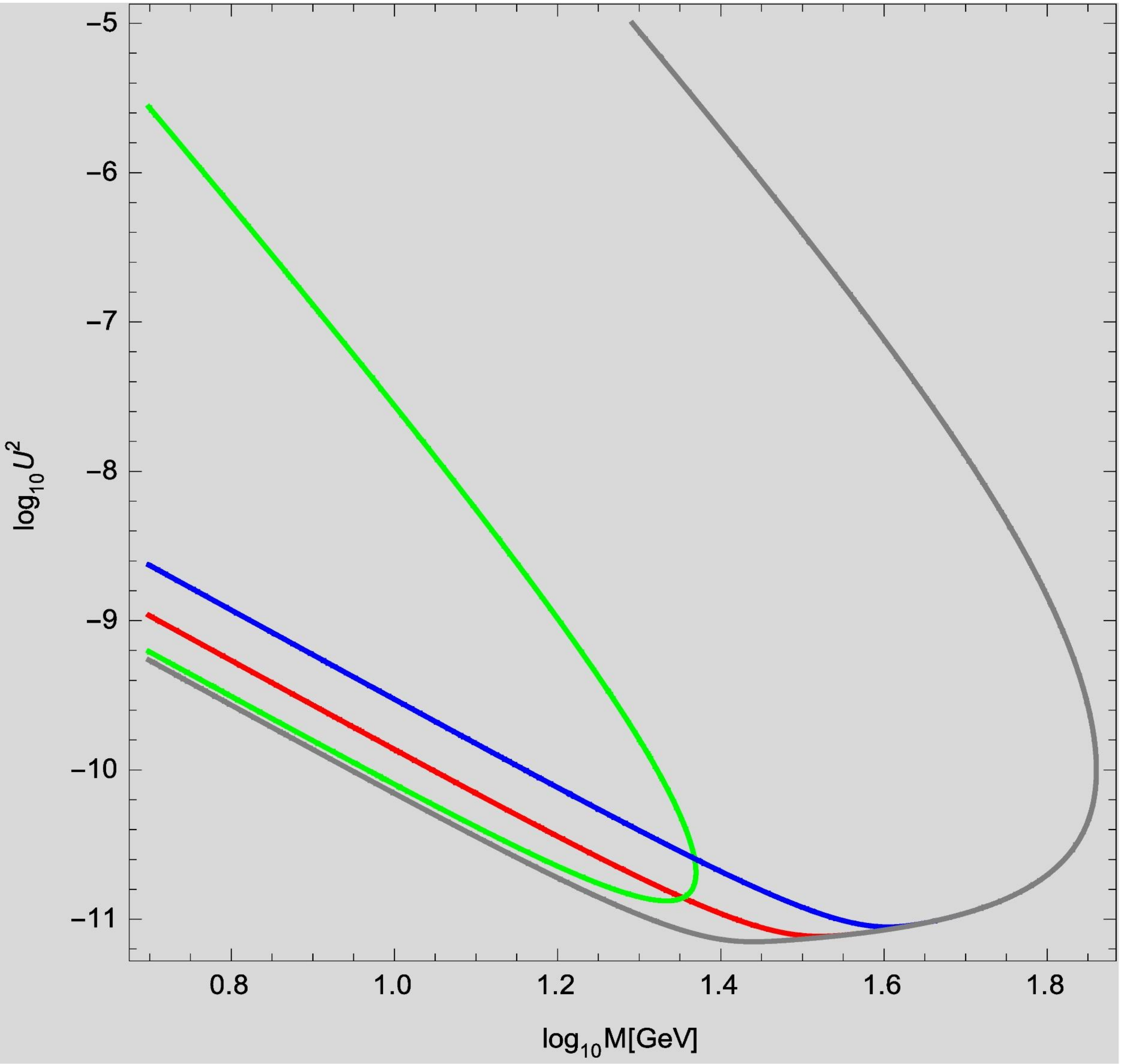
# Sensitivity Region




- First estimates using official machinery
- First time includes background simulations, limited by background statistic

Lovisa Rygaard master thesis

# Optimising the Cavern Size




Tracker only

Complete detector
(including calorimeter)

HECATE-like extension

HECATE + complete
detector

- Used analytic estimates from MaD 2210.17110
- See also talk by G. Polesello

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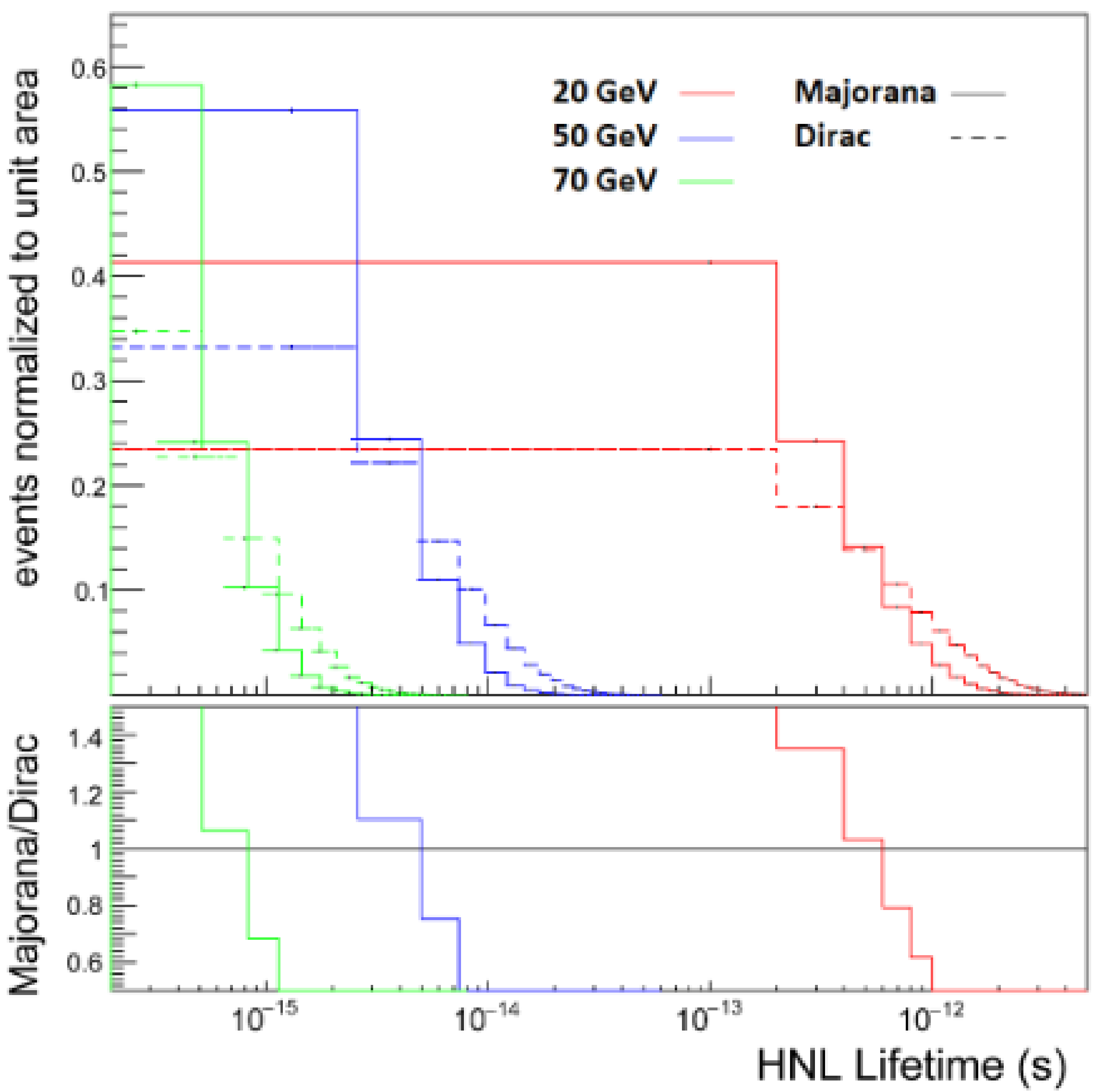
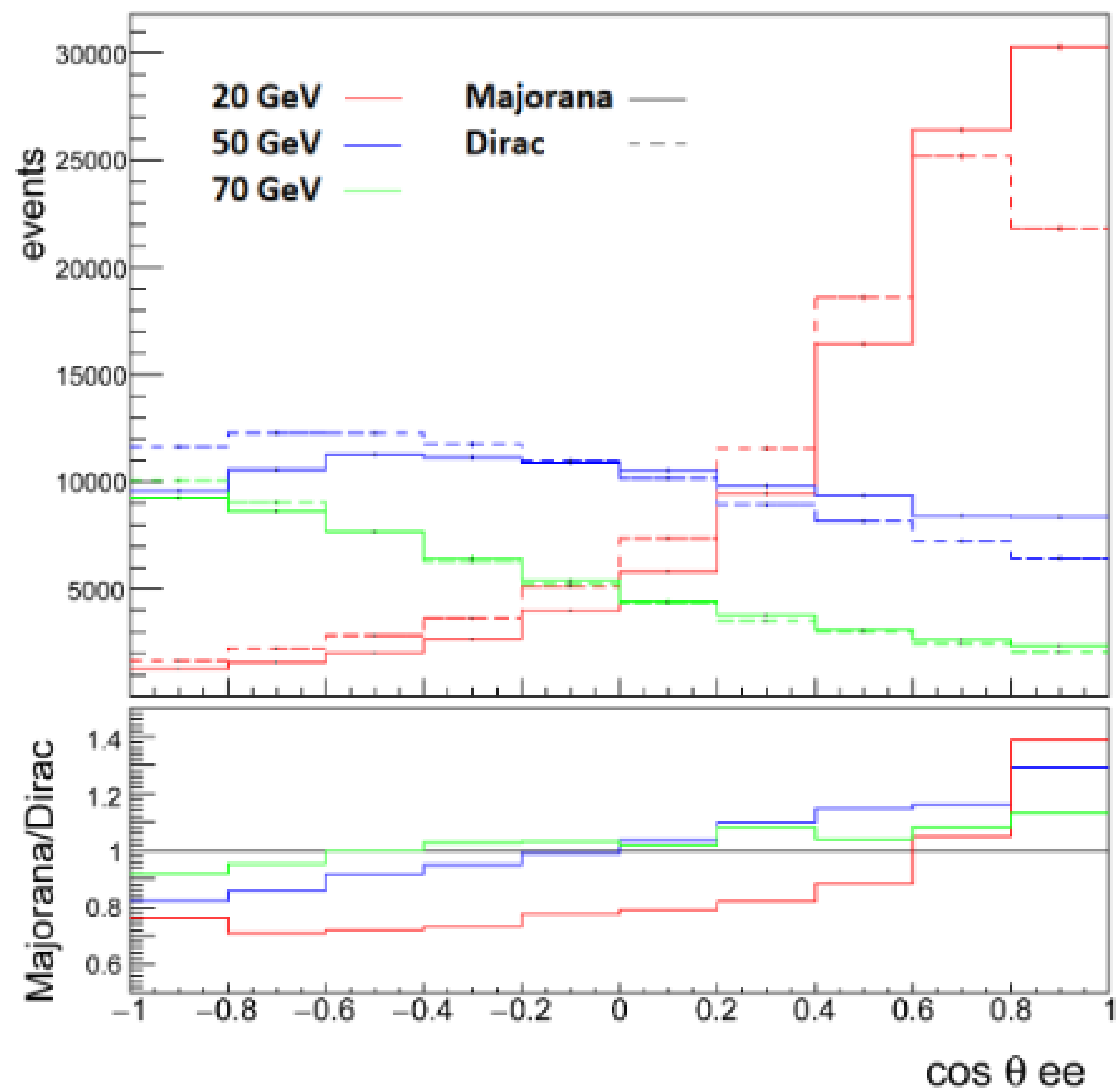
# Lepton Number Violation




(a)

HNL lifetime



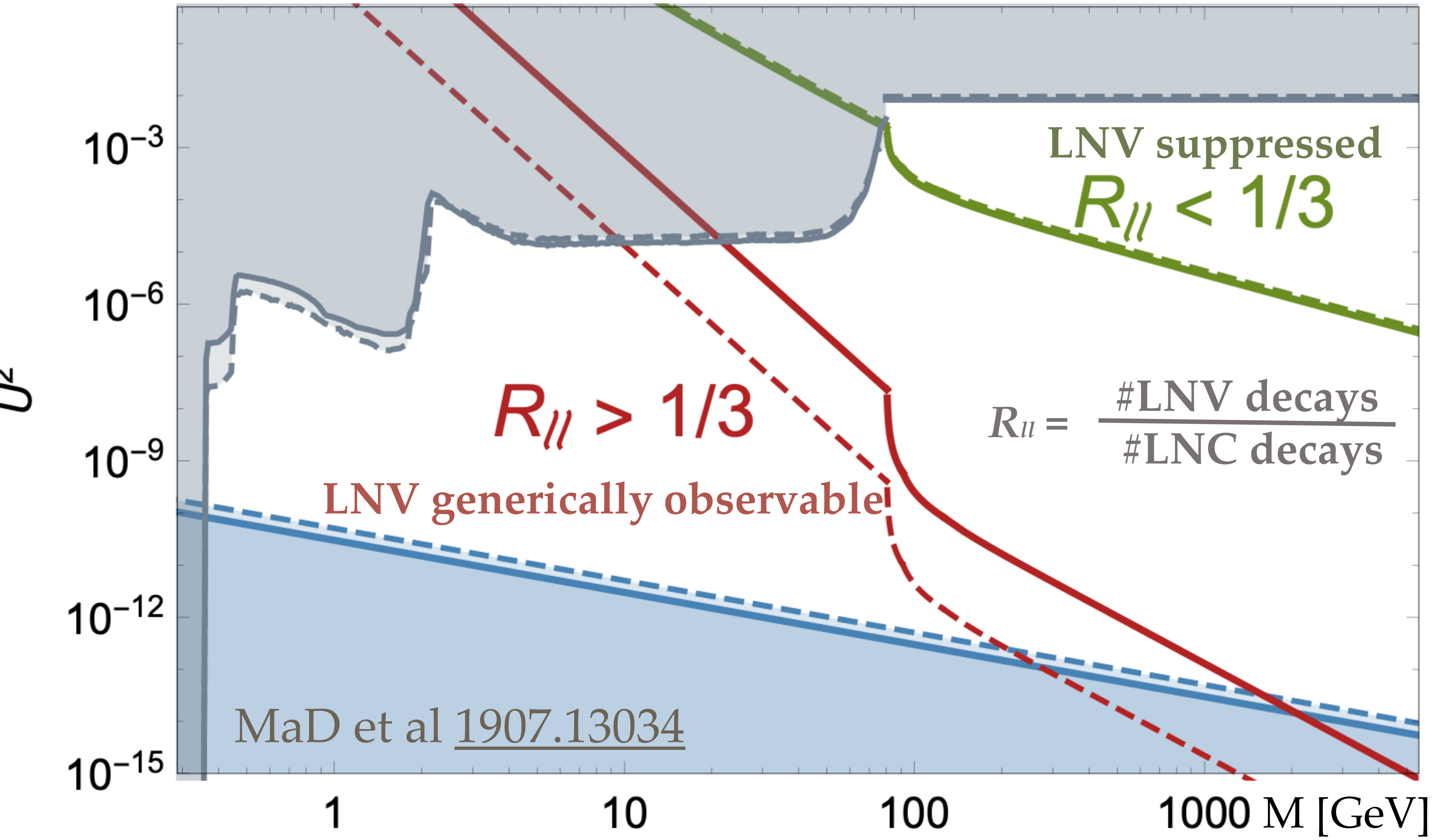

(b)

Angular distribution
of decay products

Alimena et al 2203.08039

# Majorana nature of HNLs: Can LNV decay be observed?

- Same mixing angle controls collider protection cross section and light neutrino masses
- Collider-testable mixing angles require B-L symmetry to protect neutrino masses
- HNLs in such models tend to be "pseudo-Dirac" Kersten/Smirnov et al 0705.3221




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

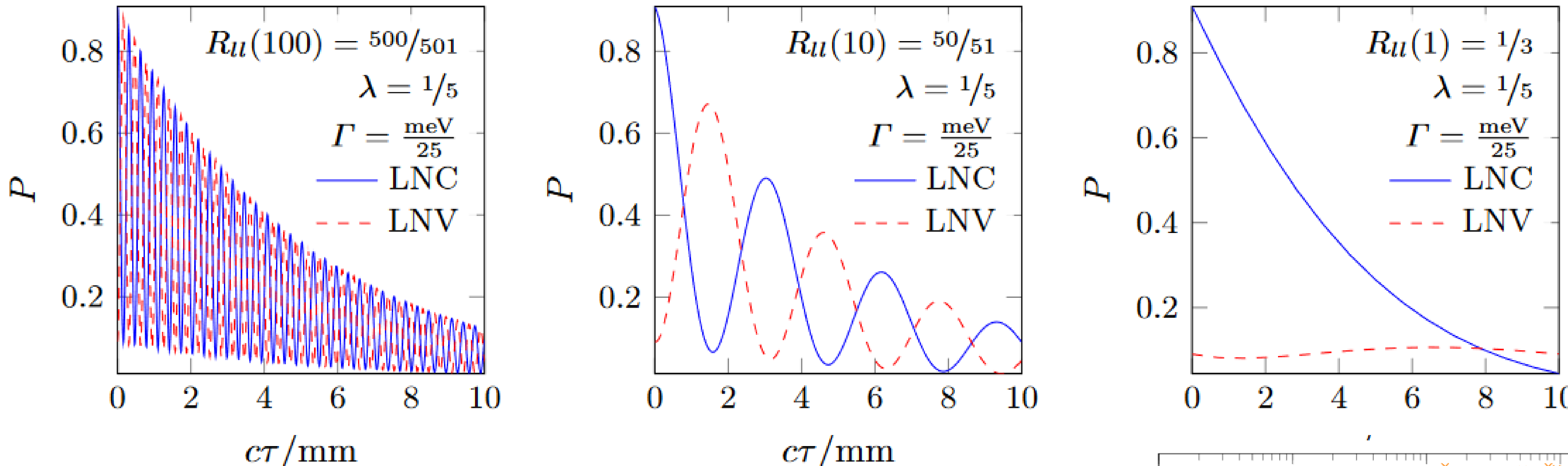
e.g. Anamiati et al 1607.05641

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

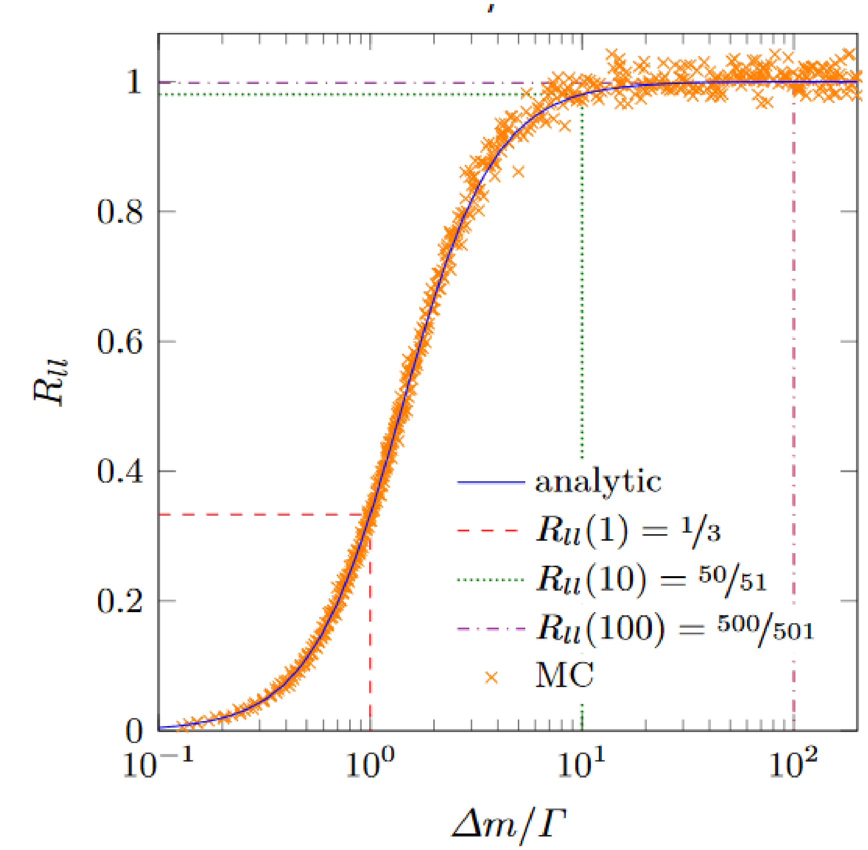
see talk by Jan Hajer

| mass spectrum | $c_{\rm prod}$ | $c_{\rm dec}$ | $R_{ll}$ | appearance |
|---|---|---|---|---|
| $\Delta M > \delta M_{\rm exp} \gg \Gamma_N$ | 1 | 1 | 1 | two Majorana HNLs with mixing $U^2$ each |
| $\delta M_{\rm exp} > \Delta M \gg \Gamma_N$ | 2 | 1 | 1 | one HNL, mixing $2U^2$, lifetime as Dirac, $R_{ll}$ as Majorana |
| $\delta M_{\rm exp} > \Gamma_N \gg \Delta M$ | 2 | 1 | 0 | one Dirac HNL with mixing $2U^2$ |

# Simulating Heavy Neutrino Oscillations




- Oscillations of pseudo-Dirac HNLs in the detector may be observed by studying $R_{ll}$ as function of displacement
- Current framework of [MadGraph] and [HeavyN FeynRules] only allows to simulate single "Dirac" or "Majorana" HNL
- MadGraph patch to simulate oscillations has been published in Antusch/Hajer/Rosskopp 2210.10738



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# Conclusions

- Heavy neutrinos appear in many a well-motivated extensions of the SM, can be a portal to a "hidden sector", …
- Can explain neutrino masses and cosmological problems (leptogenesis, DM,…)

- FCC-ee is an excellent machine to discover heavy neutrinos, especially during Z-pole run
- FCC-ee can study HNL properties and test connection to neutrino masses and leptogenesis

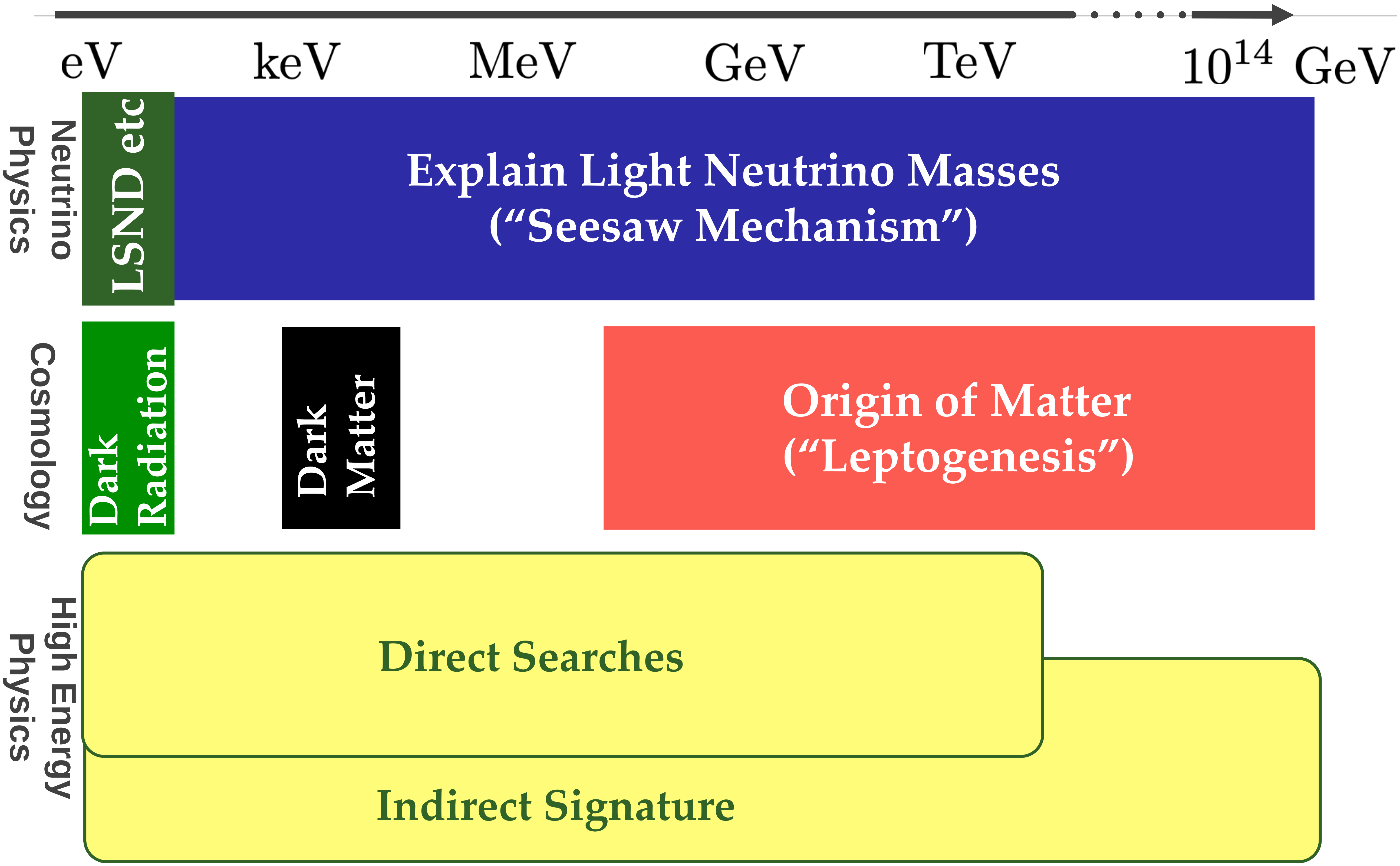
- Tools are under development, studied now go beyond "naïve theorist estimates"
- Oscillations in detector can be simulated

- So far mostly leptonic final states have been studied, other final states need study
- Reconstruction / object definitions for detections in outer detector layers need study
- Collimated objects when M is low need study
- Define benchmarks to capture pheno of realistic neutrino mass models

**Anyone who wants to join is welcome!**

# Backup Slides

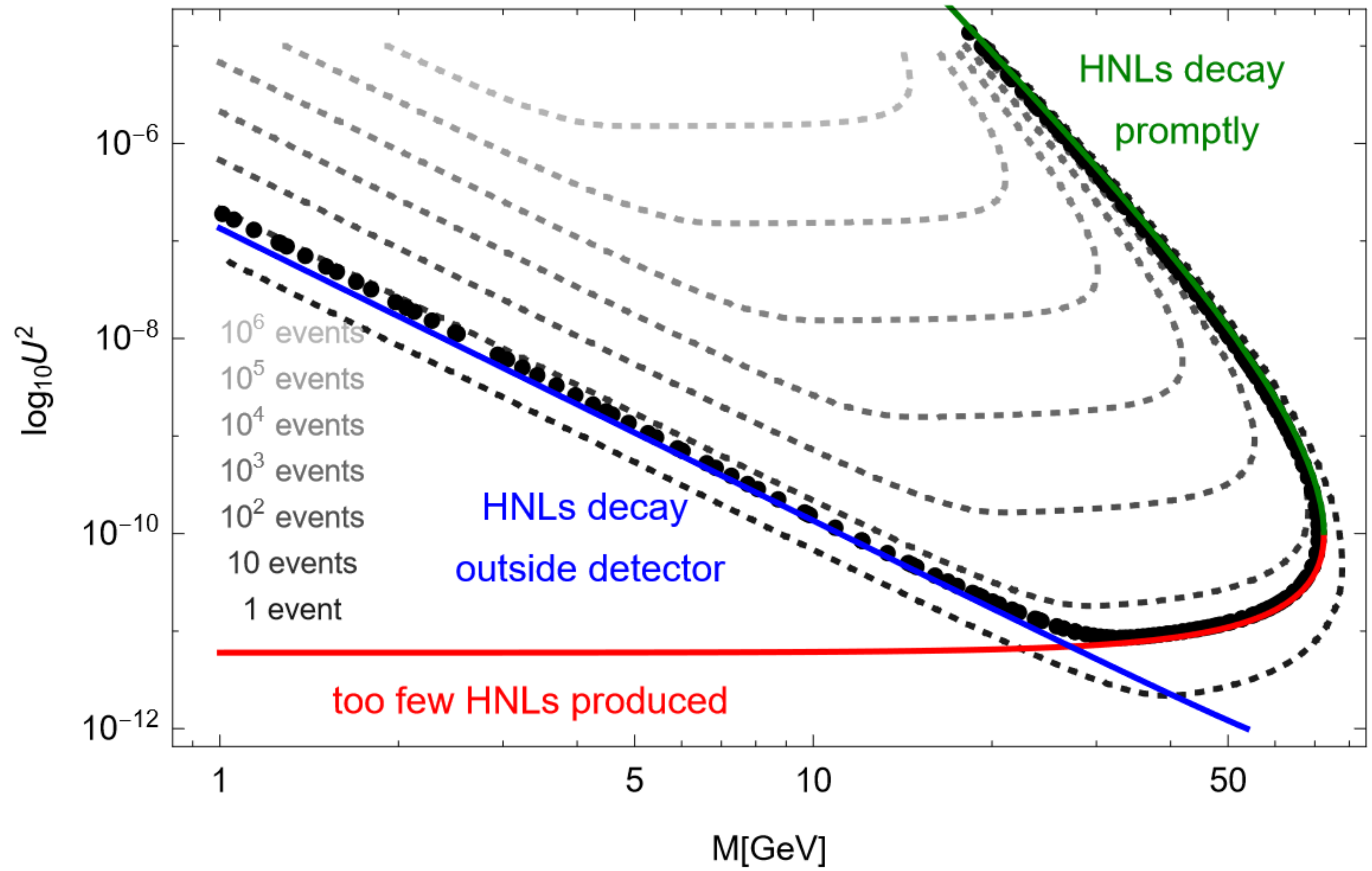
# Heavy Neutrino Mass Scale



# Sensitivity Region

$$U^2_{\rm max} = \frac{W_{-1}(XY)}{X} \simeq \frac{\log(XY)}{X}$$

$$U^2_{\rm min} = \frac{W_0(XY)}{X} \simeq Y$$



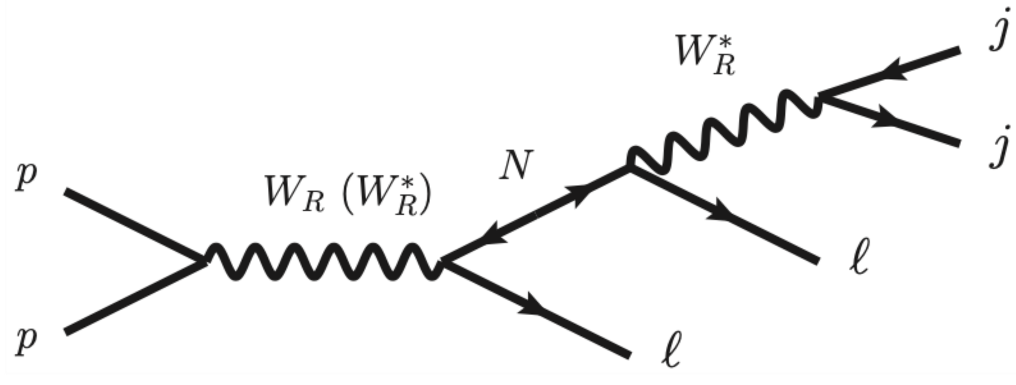

$$U^2_{\rm min} = \frac{2^{1/6}3^{1/3}8\pi^{3/2}(\mathrm{p}_N Y)^{1/2}}{(ac_{\rm dec})^{1/2}G_F M^3 d_{\rm cyl}^{1/3} l_{\rm cyl}^{1/6}} \simeq \sqrt{\frac{N_{\rm obs}}{\mathrm{u}_\alpha^2\mathrm{u}_\beta^2}}\frac{57}{G_F M^3}\sqrt{\mathrm{p}_N}d_{\rm cyl}^{-1/3}l_{\rm cyl}^{-1/6}\left(\epsilon_{\alpha\beta}N_Z N_{\rm IP}ac_{\rm dec}c_{\rm prod}\Pi\right)^{-1/2}$$

$$Y = \frac{U^2 N_{\rm obs}/\mathrm{u}_\beta^2}{\epsilon_{\alpha\beta}N_{\rm HNL\alpha}} = \frac{N_{\rm obs}/(\mathrm{u}_\alpha^2\mathrm{u}_\beta^2)}{2\epsilon_{\alpha\beta}\mathrm{B}_\alpha c_{\rm prod}N_{\rm IP}\Pi N_Z} \qquad X = \frac{l_0}{U_\beta^2\lambda_N} = -\frac{aG_F^2 l_0 M^6 c_{\rm dec}}{96\mathrm{p}_N\pi^3}$$

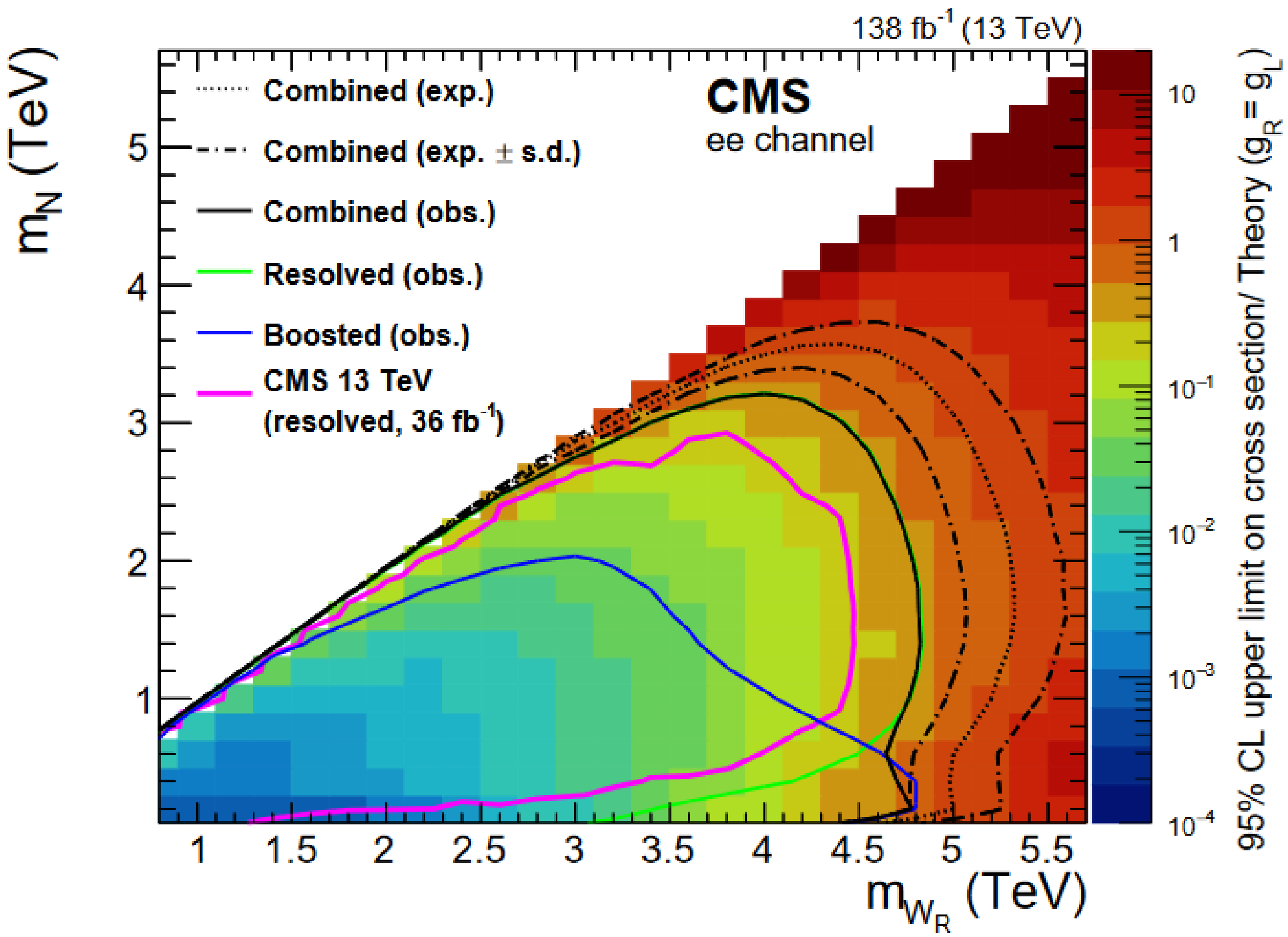
MaD 2210.17110

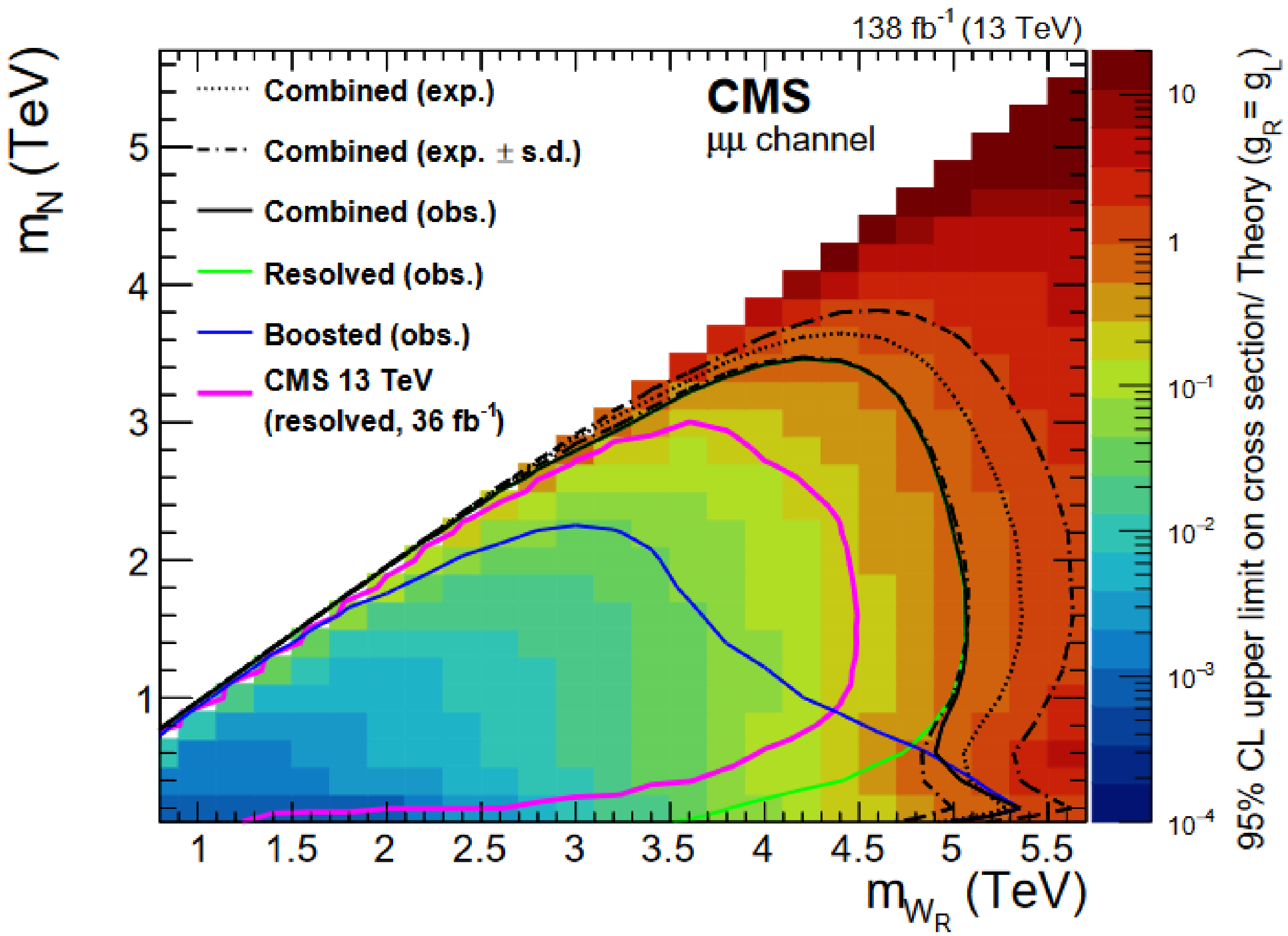
# $W_R$ interactions in LRSM

- New gauge interactions facilitate collider searches…
- …but current LHC bounds are strong
- $W_R$ mass bound > 4 TeV makes detection at FCC-ee difficult



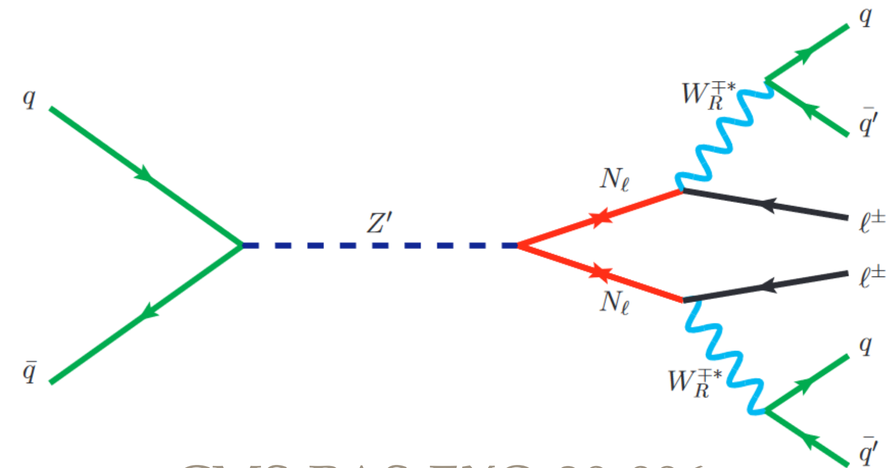
CMS 2112.03949



# Z’ interactions in LRSM

- New gauge interactions facilitate collider searches…
- …but current LHC bounds are strong
- $Z'$ mass bound > 4 TeV makes detection at FCC-ee difficult

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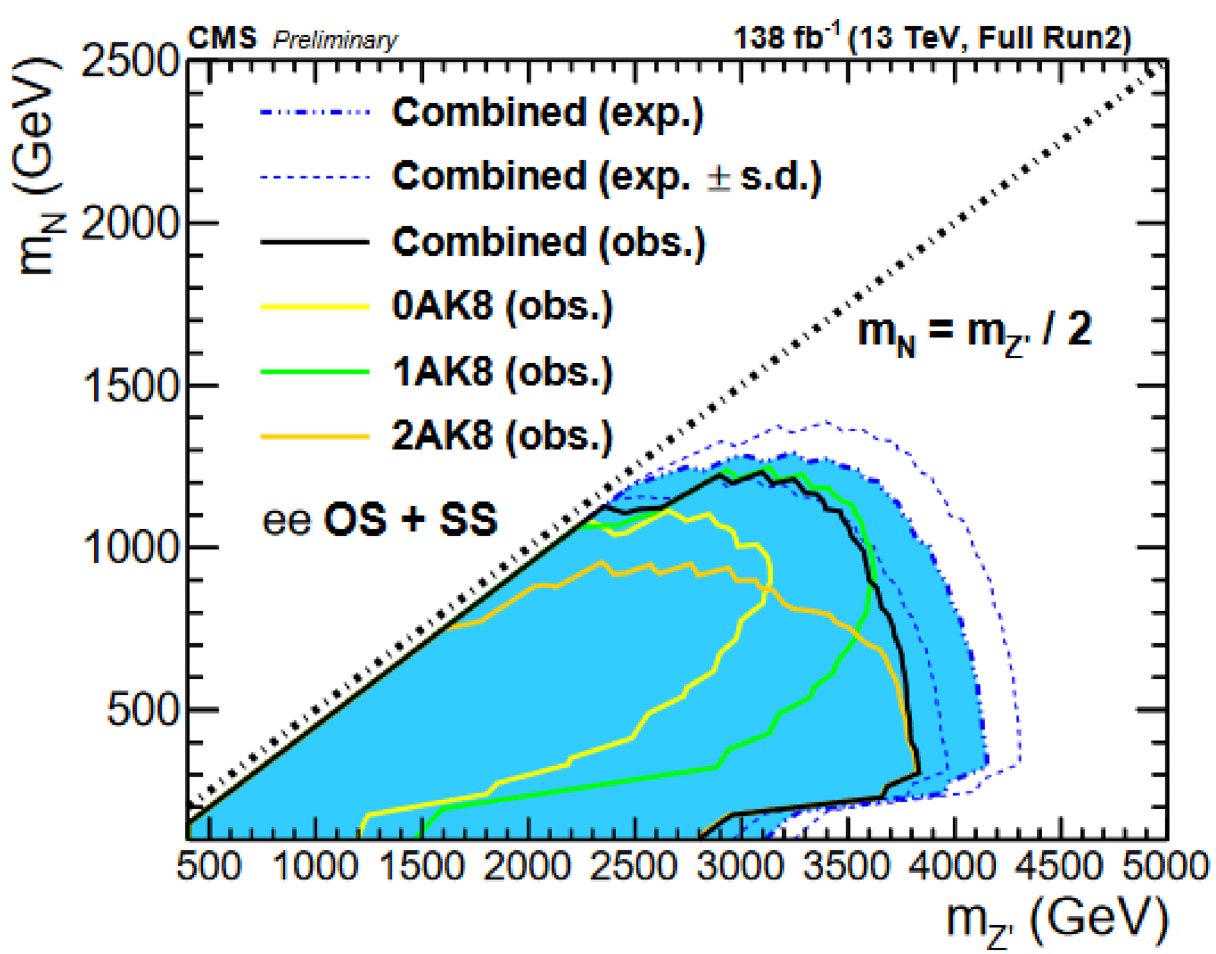
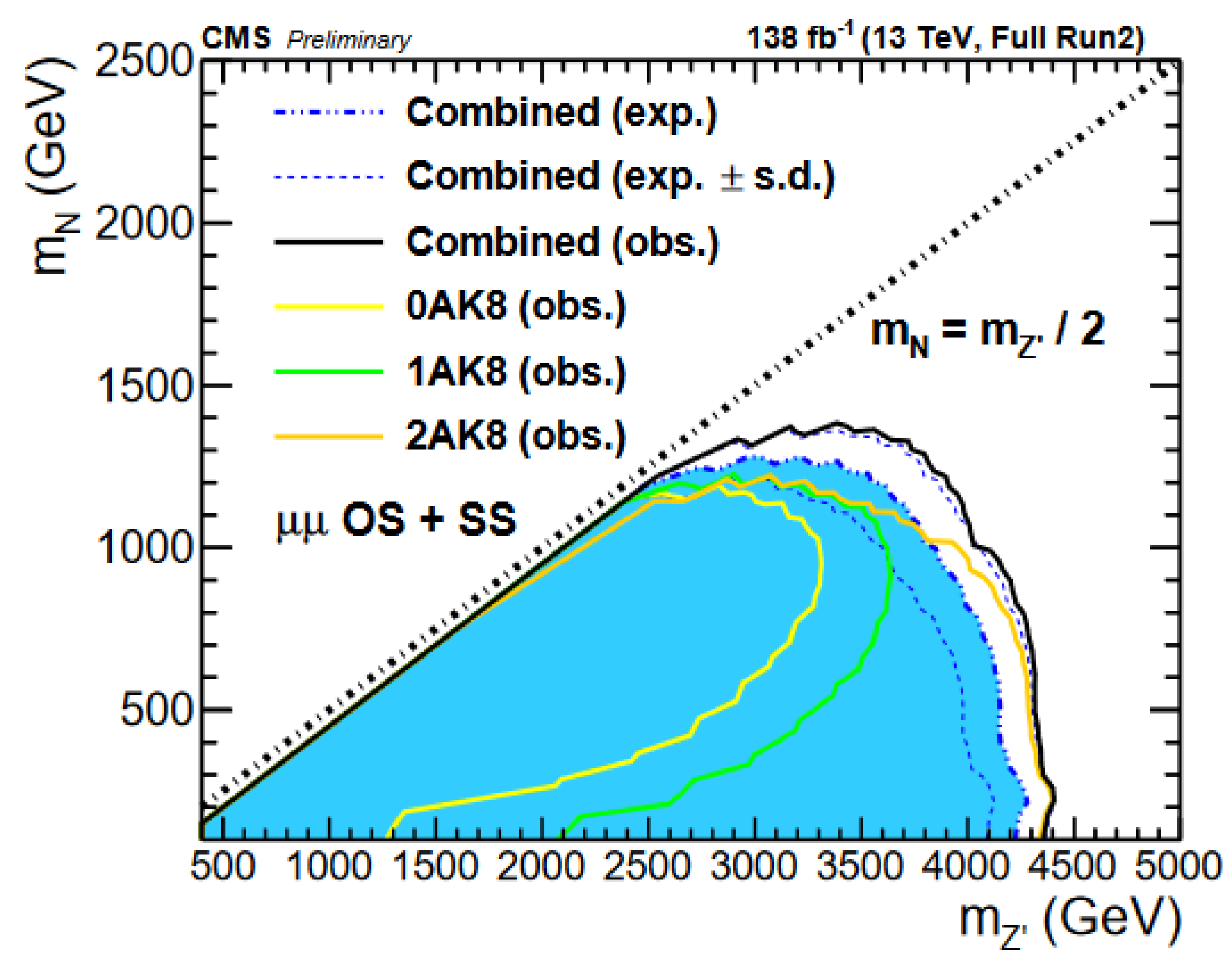
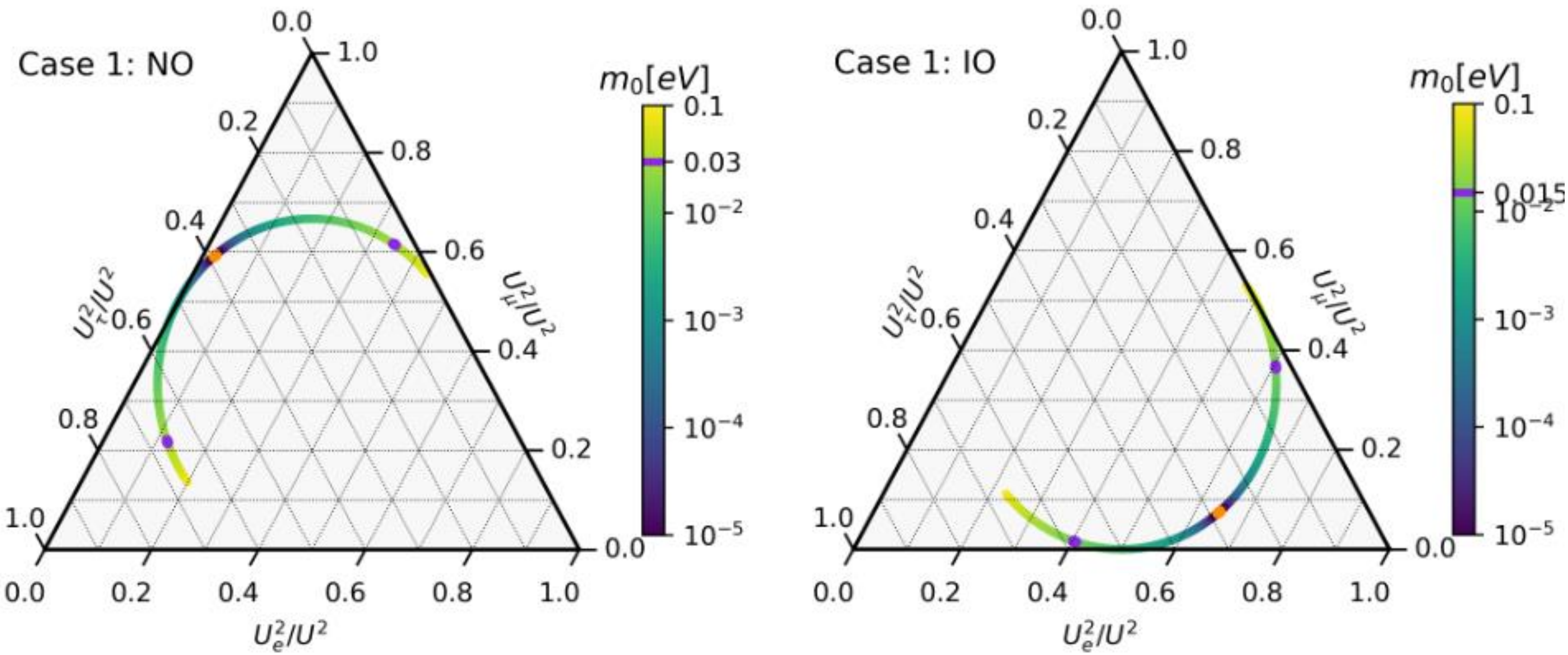


# Testing Flavour Symmetries




MaD/Georis/Hagedorn/Klarix 22xx.xxxxx (cf. 2203.08538)

- Consider model with three HNLs and discrete flavour symmetries
- Branching ratios very predictive