INFN FUTURE CIRCULAR COLLIDER

BSM physics at the FCC-ee : Heavy Neutral Leptons

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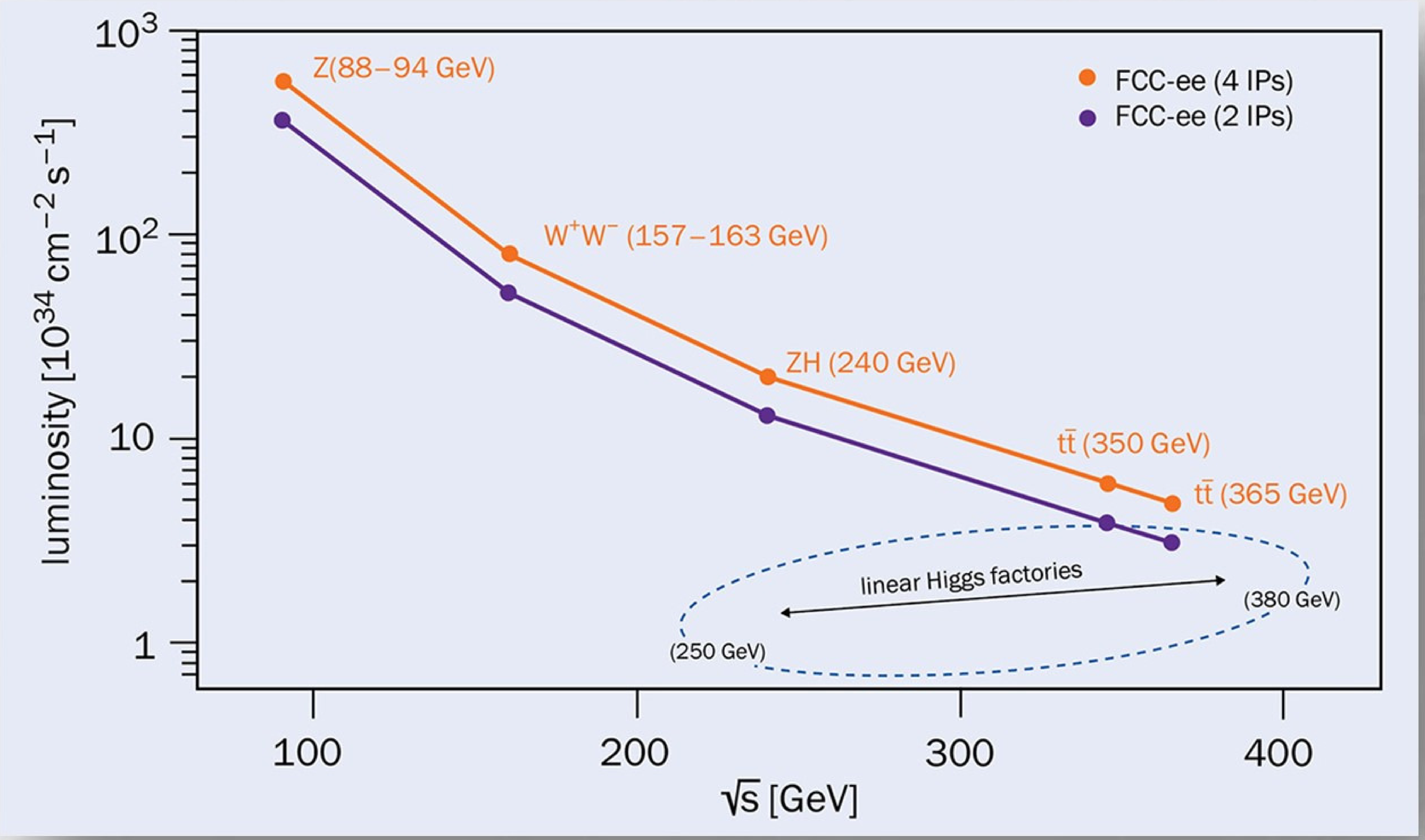
BSM at FCC-ee

A Higgs, top, EW and flavour factory, for tests of the Standard Model at an unprecedented level

Designed to operate at c.m. energies from 90 to 365 GeV

Key words: **clean environment** and **high statistics**

https://cerncourier.com



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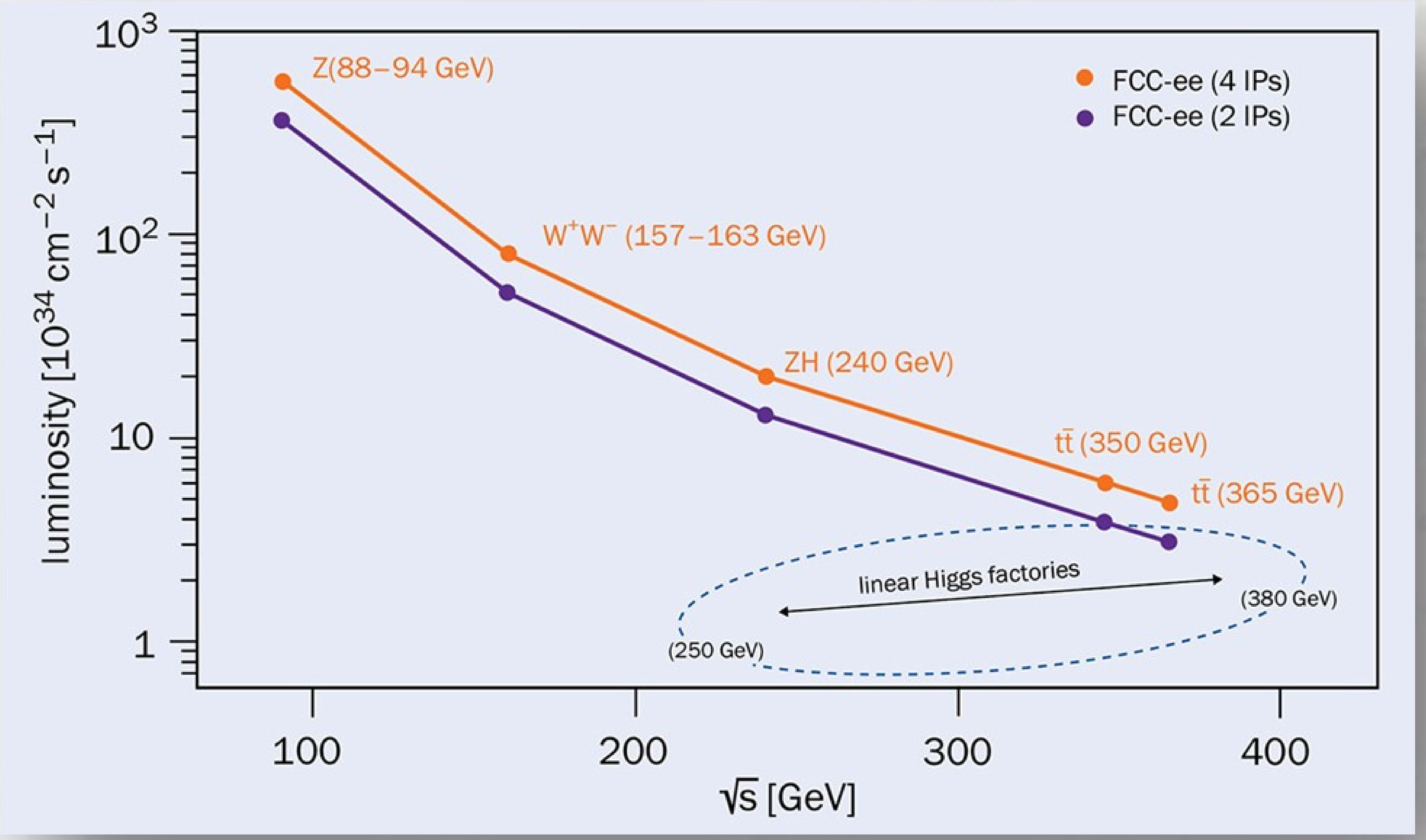

Possibility to direct search for BSM physics

Tera-Z run (5 orders of magnitude more than LEP)

- Huge gain in **sensitivity for feebly-coupled new particles** with mass in ~ 1 - 91 GeV
- Broad search program, mostly model-independent

Feebly interacting BSM particles

Heavy Neutral Leptons
Dark photons
Axion Like Particles
Exotic Higgs decays

Detector requirements

Large decay volume
High segmentation (tracker, calorimetry, muon)
Impact parameter resolution for large displacement
Timing
No limitations related to triggering

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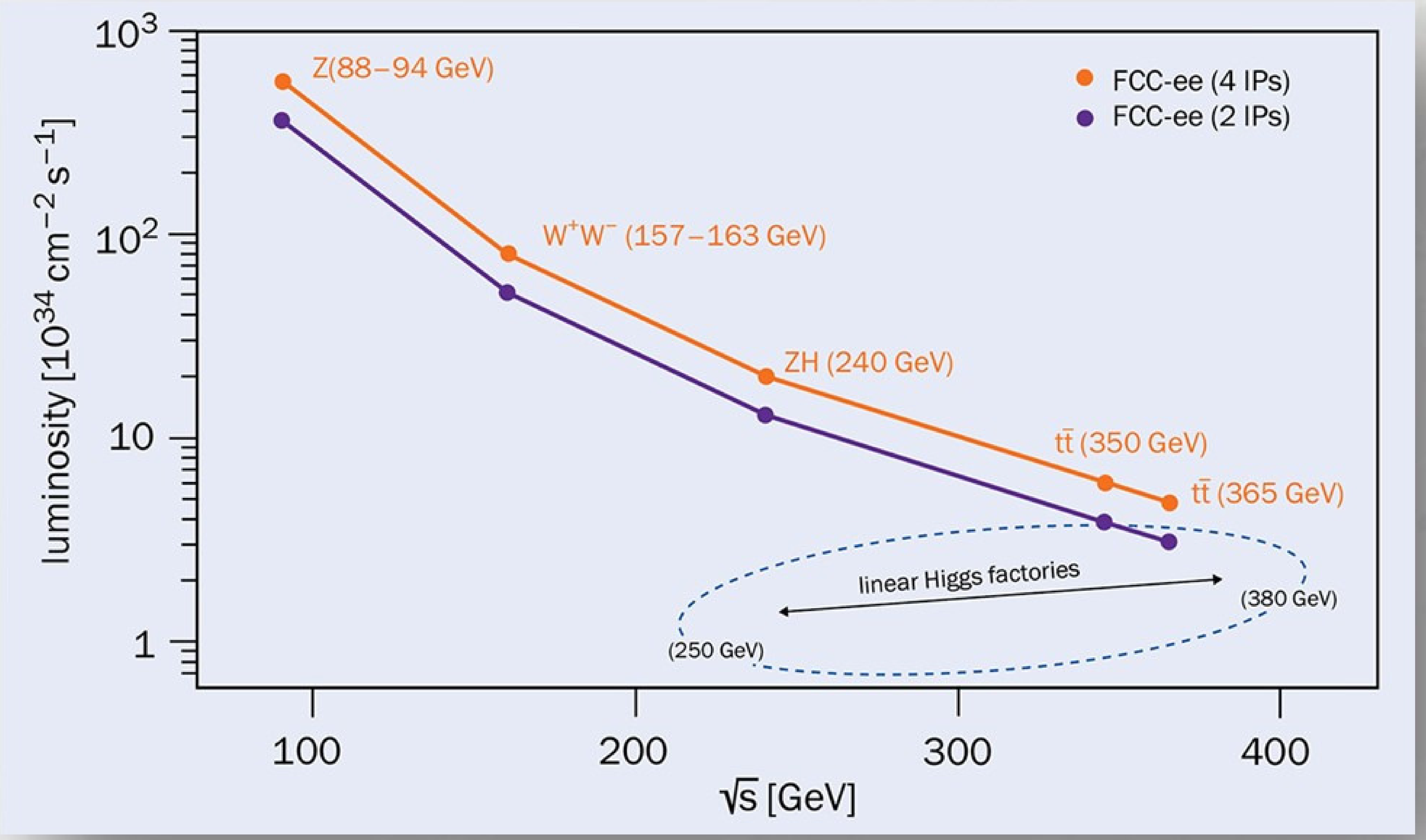

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This talk will focus on HNLs, but...
Intense activity on all the mentioned channels within the FCC-PED community

HNLs, a promising new physics channel

Open **key questions** on SM neutrinos (mass ordering, mass mechanism, Dirac/Majorana nature...)

- HNLs can explain small ***ν* masses**, e.g. through seesaw mechanism
- HNLs as potential candidates for **dark matter**
- HNLs CP-violating decays in early universe may explain **baryon asymmetry**

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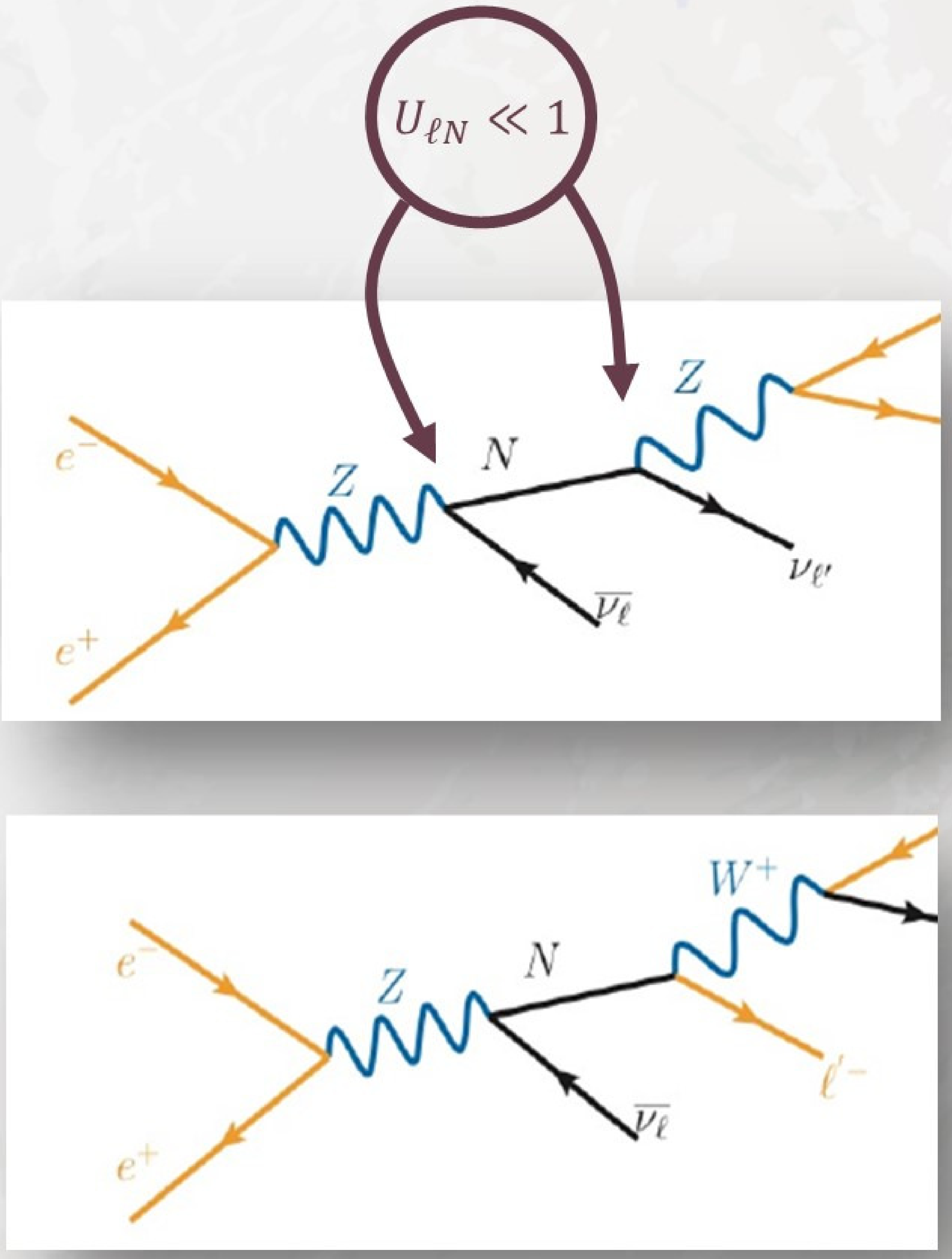


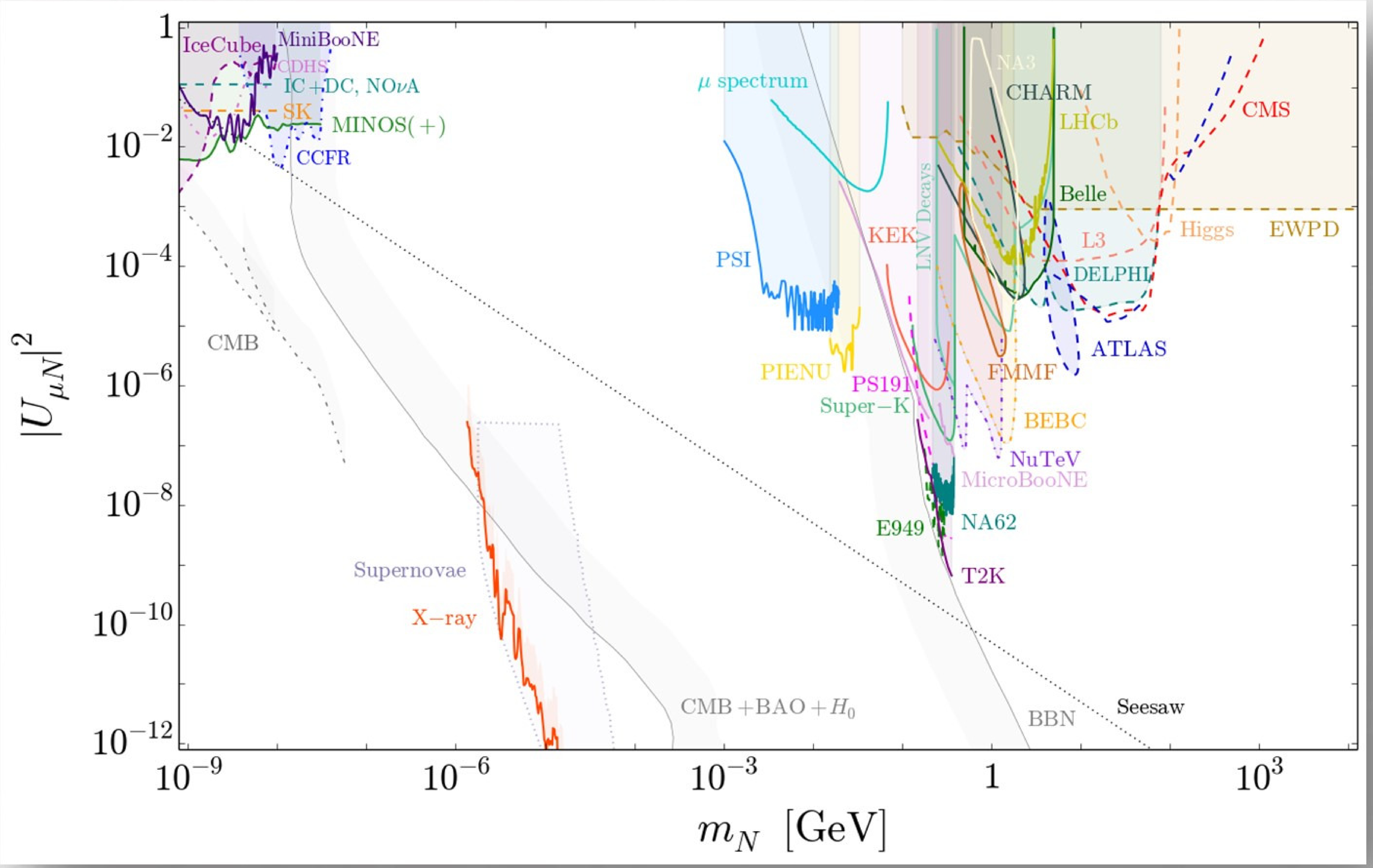
Experimental point of view: **a heavy fermion with suppressed interactions**

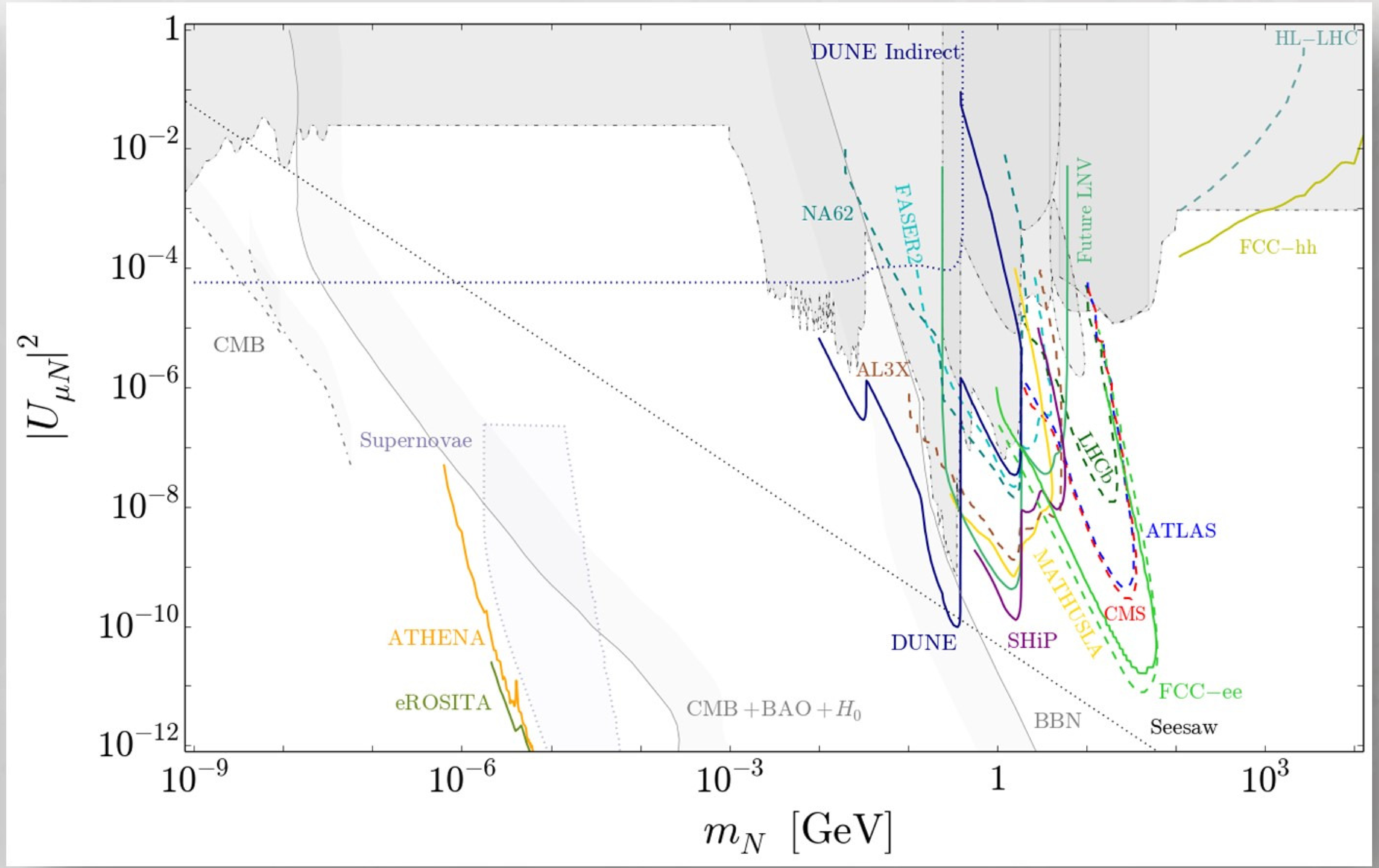
Minimal scenario, production and decay are controlled by two model parameters

$$(\boldsymbol{m_N}, \boldsymbol{U_{\ell N}})$$

Small mixing $U_{\ell N}$ with SM leptons → **suppressed production**, and **long decay path**

Existing limits and projections





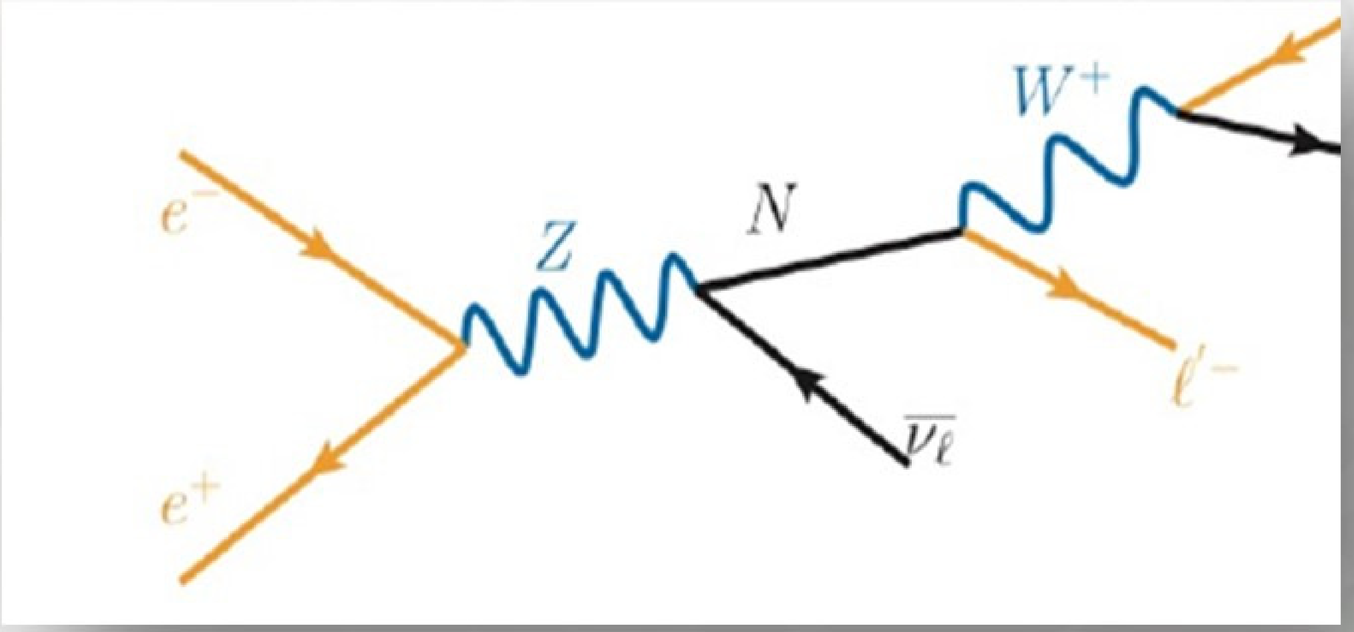
arXiv:1912.03058

N→μjj as benchmark channel

Production of **HNL in Z decay** through mixing with light neutrinos
One HNL flavour assumed → two parameters, $(\boldsymbol{m_N}, \boldsymbol{U})$

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

$$\Gamma_N \simeq c_{dec}\frac{a}{96\pi^3}\,G_F^2\,\boldsymbol{U^2 m_N^5} \quad (m_N < 80\text{ GeV})$$



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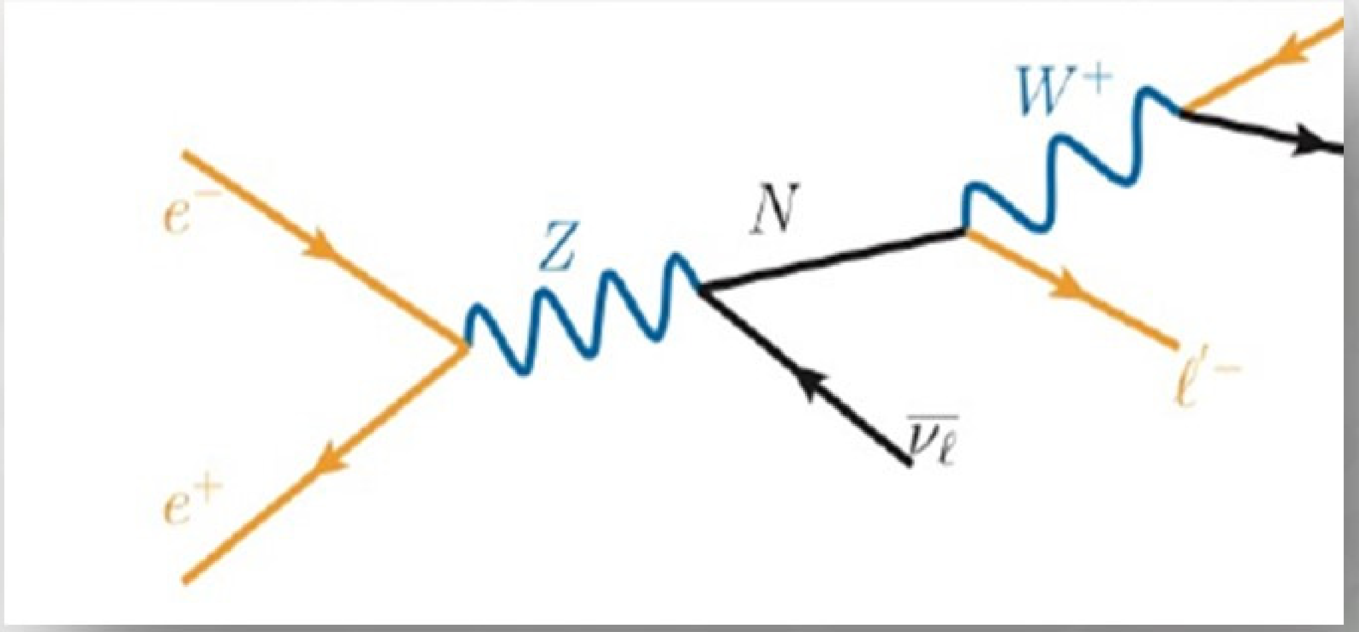

$$\boldsymbol{N \to \mu jj}$$

- High production rate
- Visible final state allowing for full reconstruction of the kinematics

Displaced and **prompt** signatures are both accessible at the FCC: severe **requirements** on the performance of the detector

The simulation

The workflow

- Model (UFO)
- Samples generation
  - ◊ MG5aMC@NLO
  - ◊ PYTHIA8
- IDEA parametrisation
  - ◊ DELPHES
- Analysis tools

The simulation

The workflow

Model (UFO)

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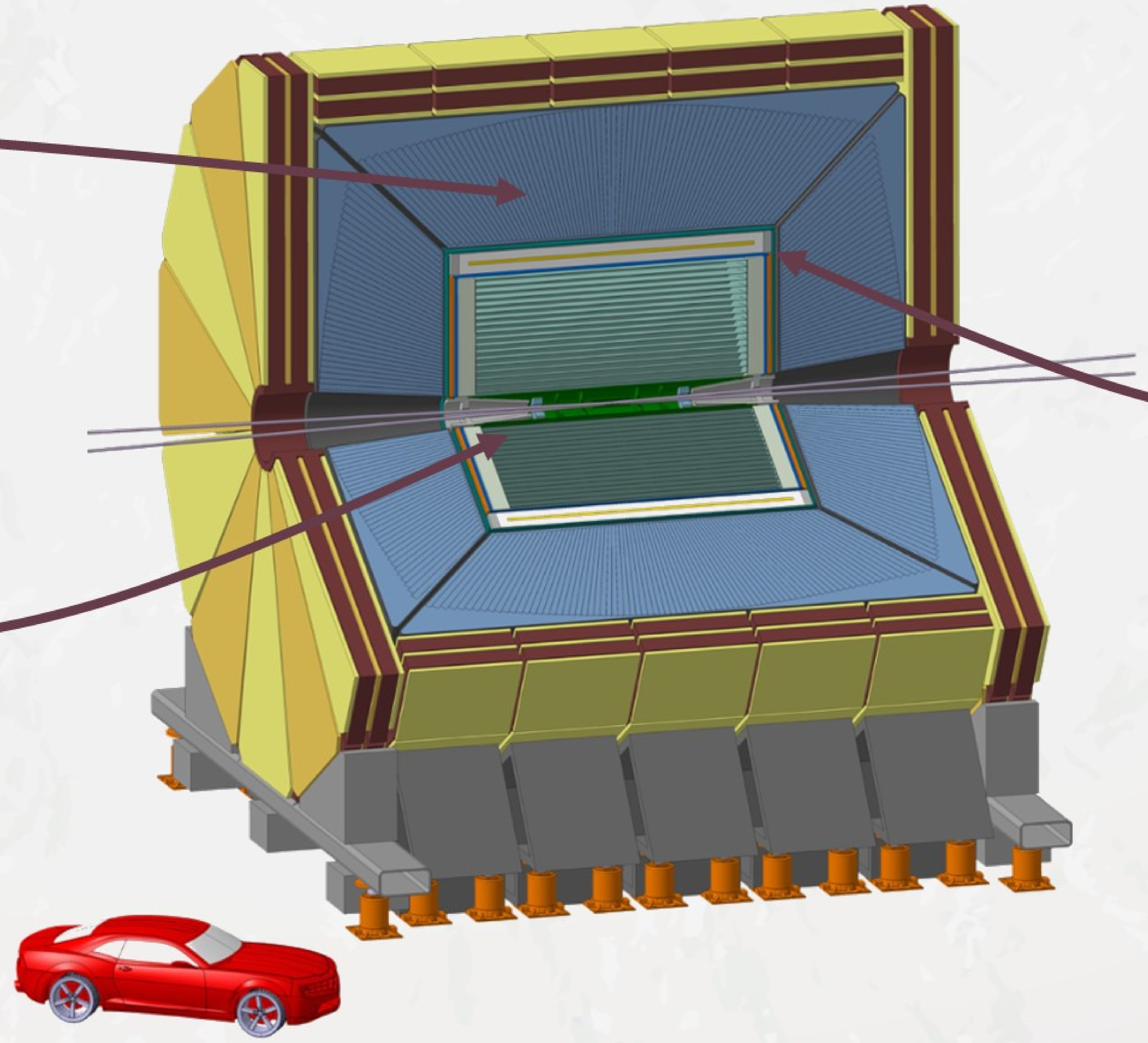
◊ DELPHES

Analysis tools

IDEA layout

Calorimetry: High resolution, segmented, dual-readout fiber calorimeter



Tracker: MAPS sensors + drift chambers

DELPHES:
- Advanced simulation of the full geometry + efficient tracking and vertexing code
- [1.2-31 cm]: 5 cylindrical layers (down to 3 µm resolution) + 6 endcap disks (7 µm resolution)
- [34-200 cm]: 112 4m-long coaxial layers modelling the drift chambers

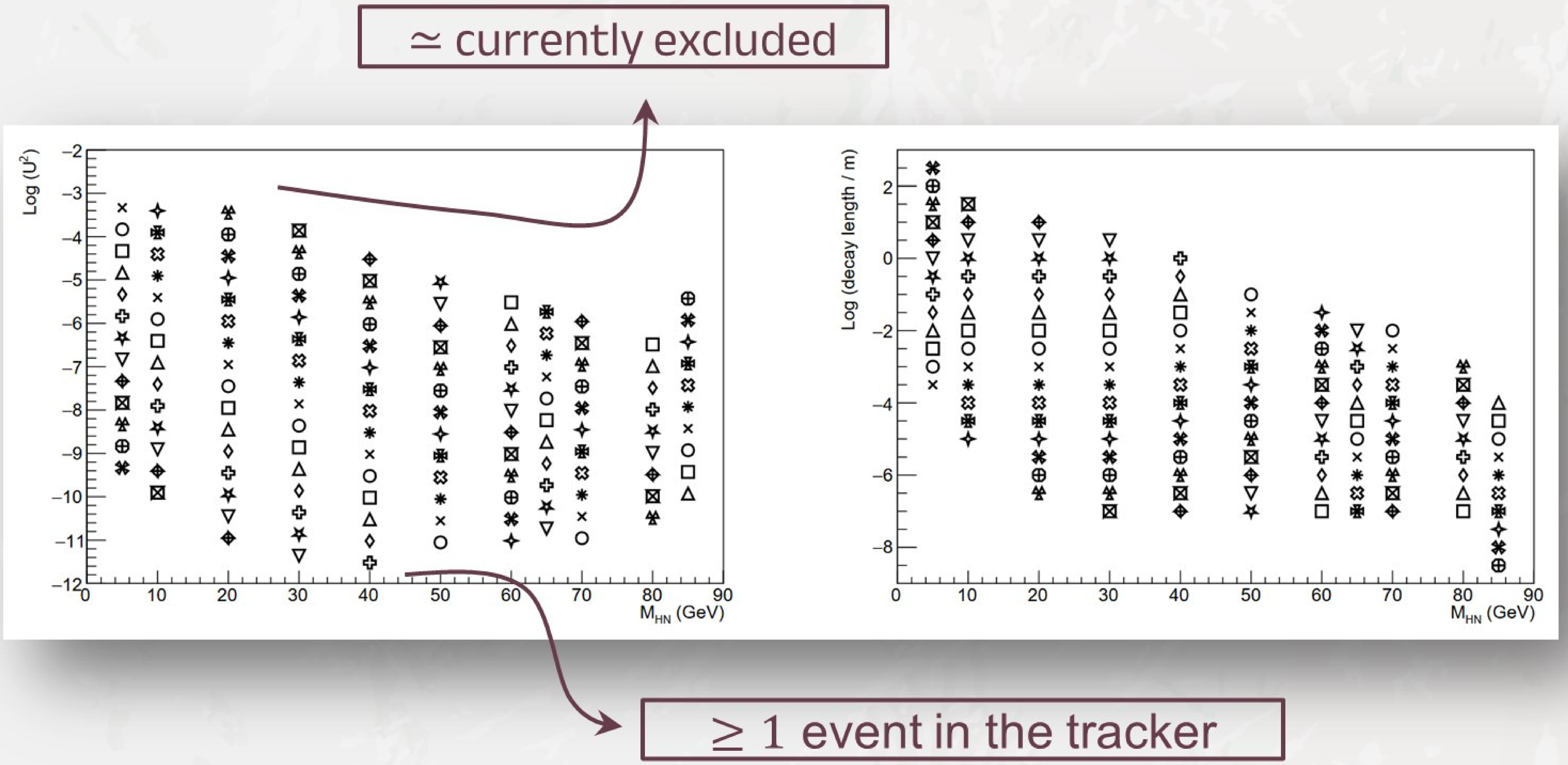
Timing layer

- Assumed to be 2 m from the interaction point
- TOF precision within few tens of ps

The analysis

Sensitivity limits extracted over a **wide range** of parameter space

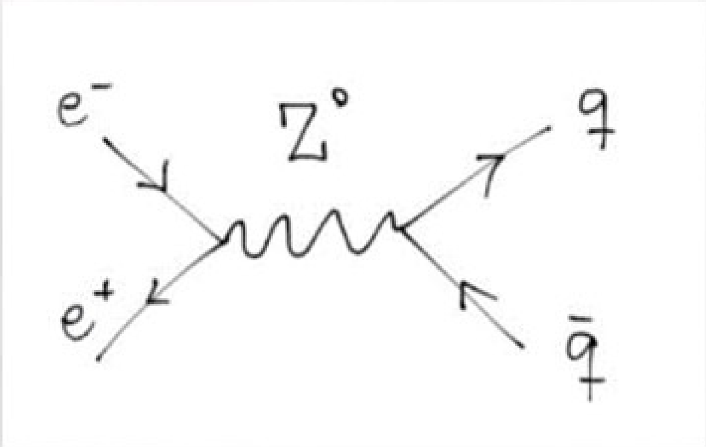
Working with the Z-pole run statistics: L_{int} **= 240 ab^{-1}**



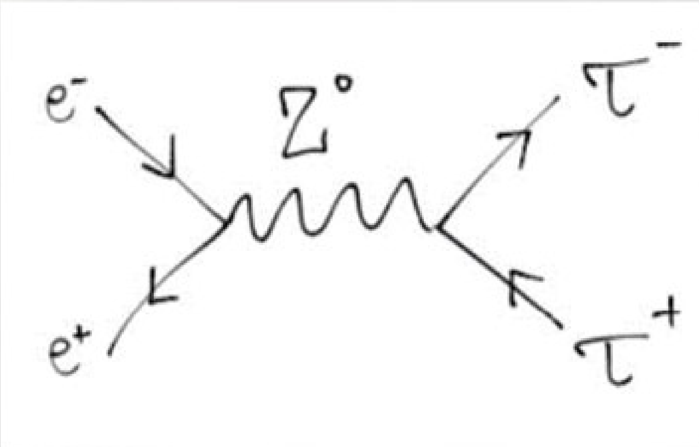
Crucial role of both **energy resolution** and **vertexing capabilities,** to maximize signal yield over background

Prompt vs **long-lived** separation
[radial vertex position ≲ 0.5 mm]
so to have **no backgound** in the long-lived regime

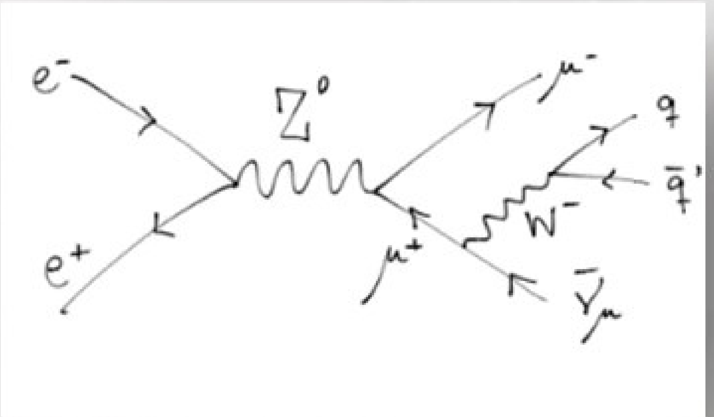
Background



$Z \to bb/cc/uds$ especially relevant at high mass

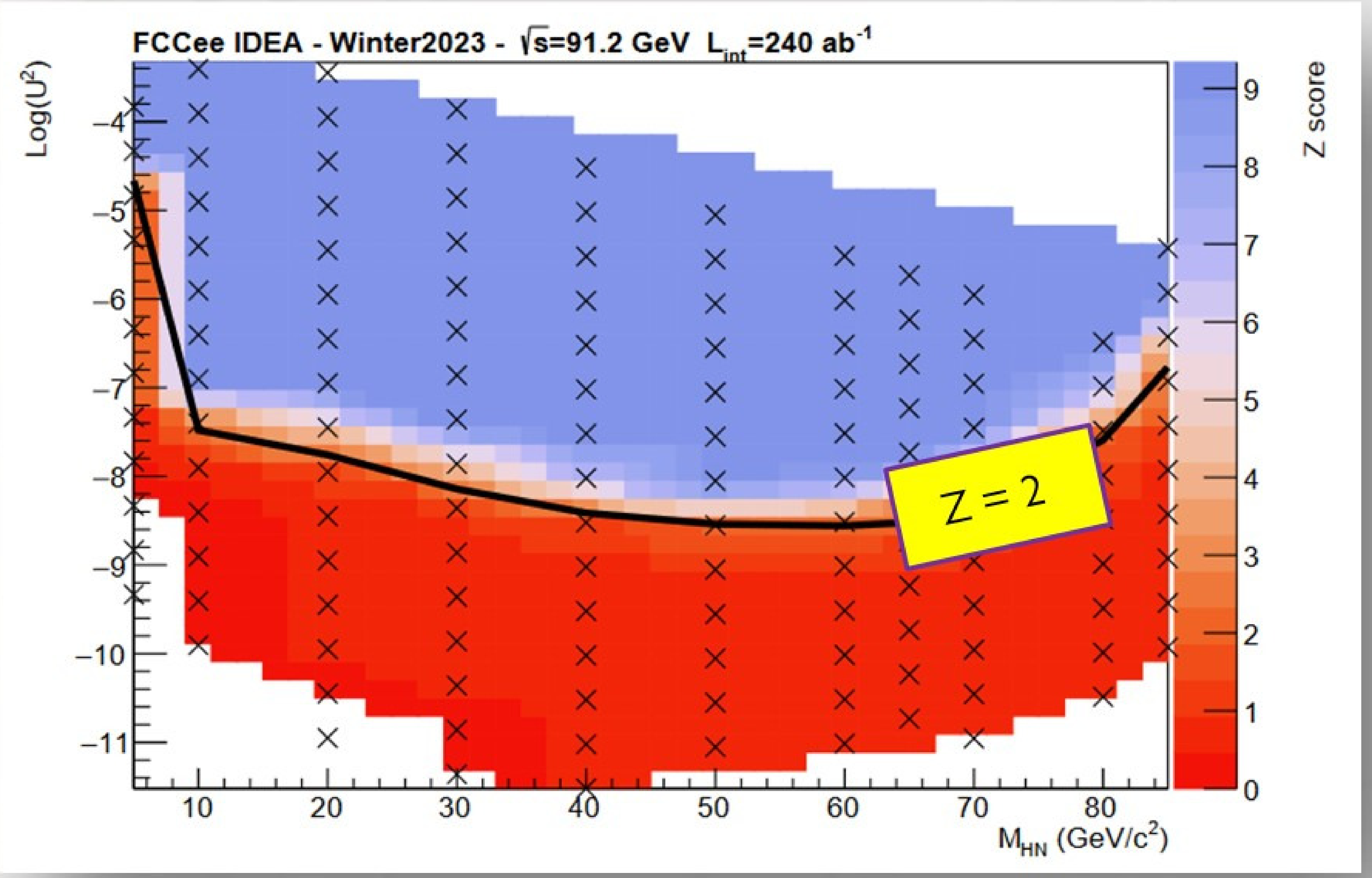


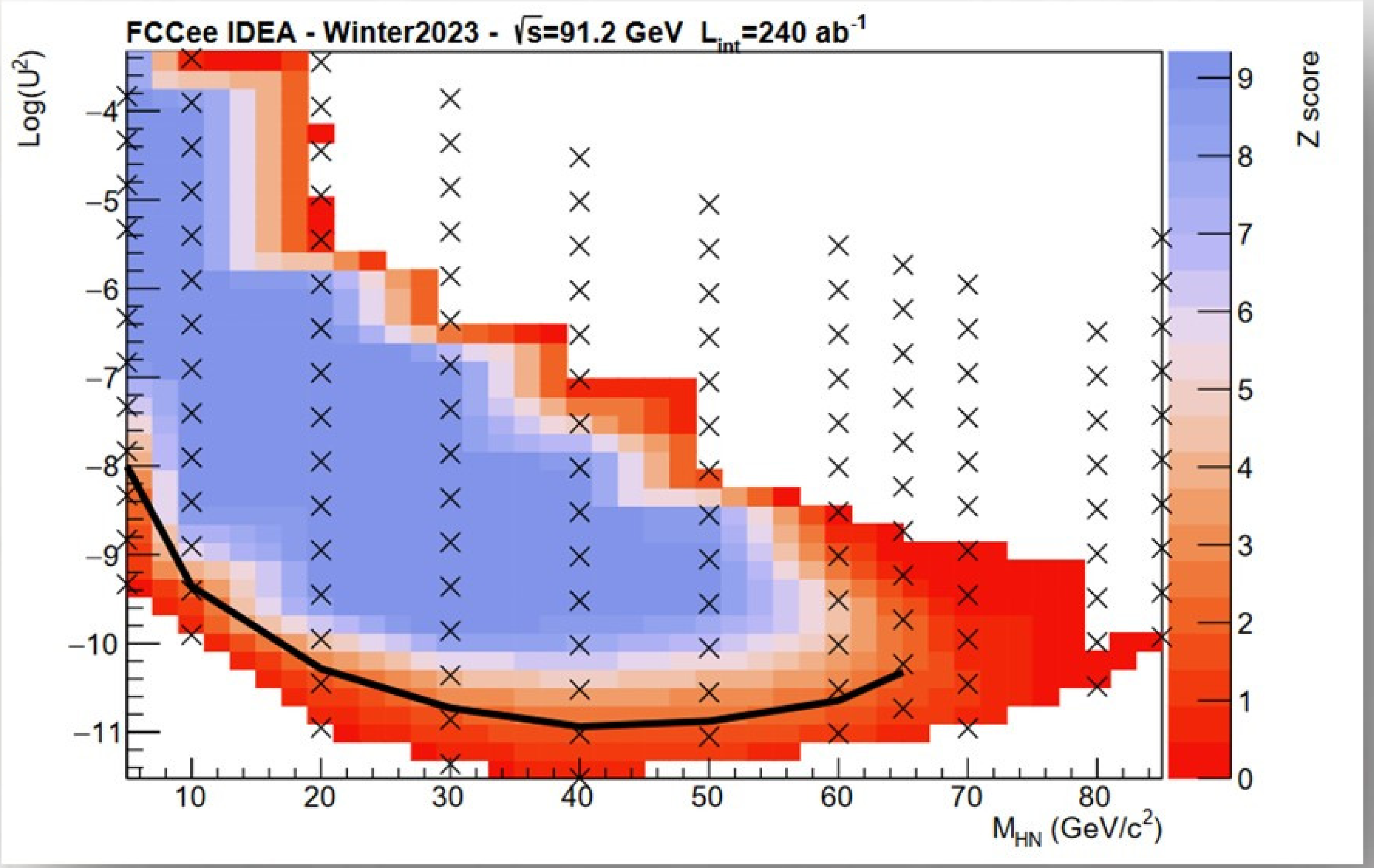
$Z \to \mu\mu, Z \to \tau\tau$, more easily suppressed



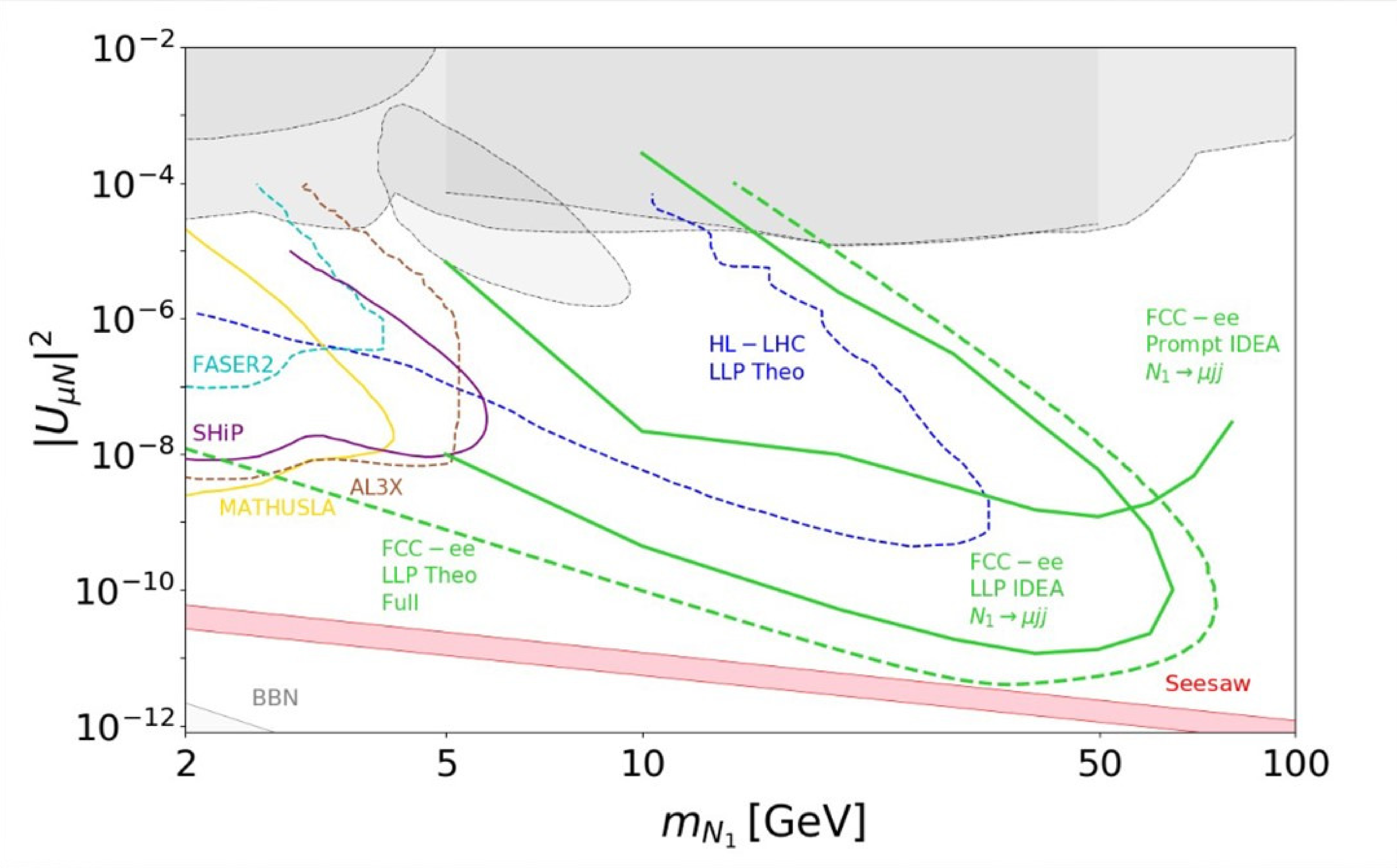
Four-fermion process: irreducible but purely prompt

The results





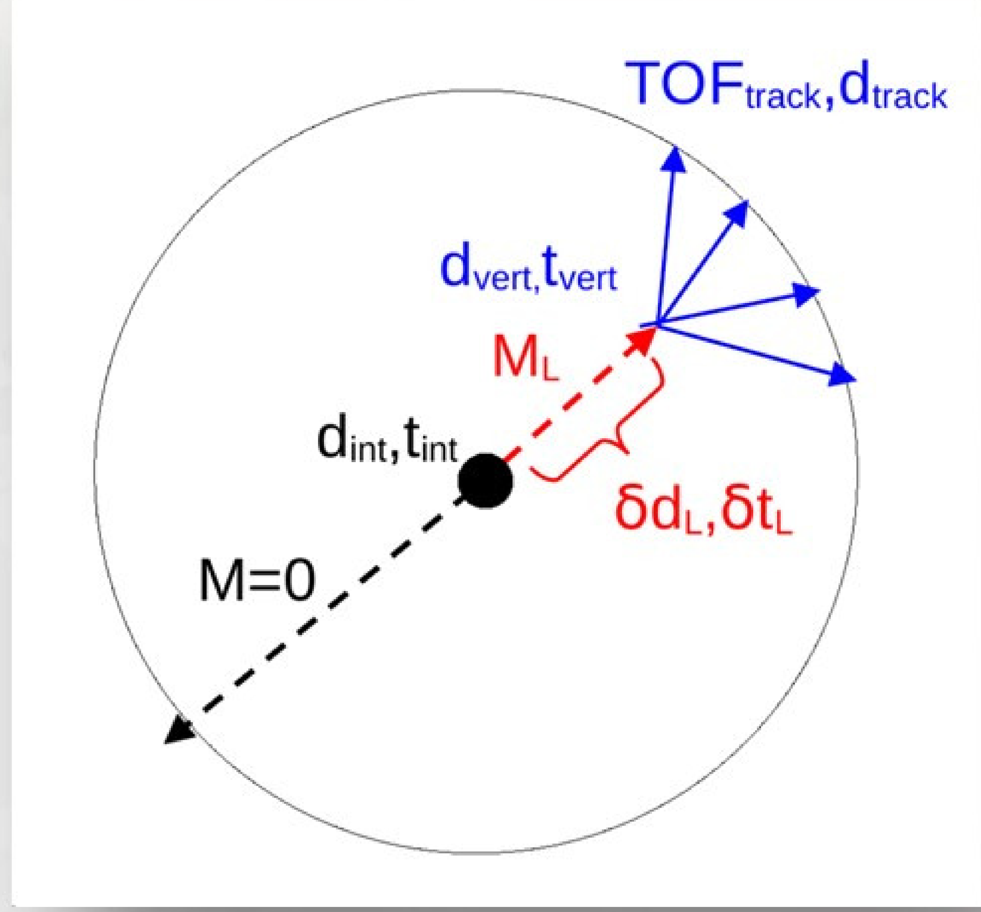
Sensitivity limit: U^2 value producing 95% CL excess of events



arXiv:1912.03058

More on the mass measurement

$$m_N = E_{cm}\sqrt{\frac{1-\beta_N}{1+\beta_N}} = E_{cm}\,F(\beta_N) \qquad \sigma(m_N) \sim E_{cm}F'(\beta_N)\,\sigma(\beta_N) \qquad \beta_N = \frac{\delta d_N}{\delta t_N}$$



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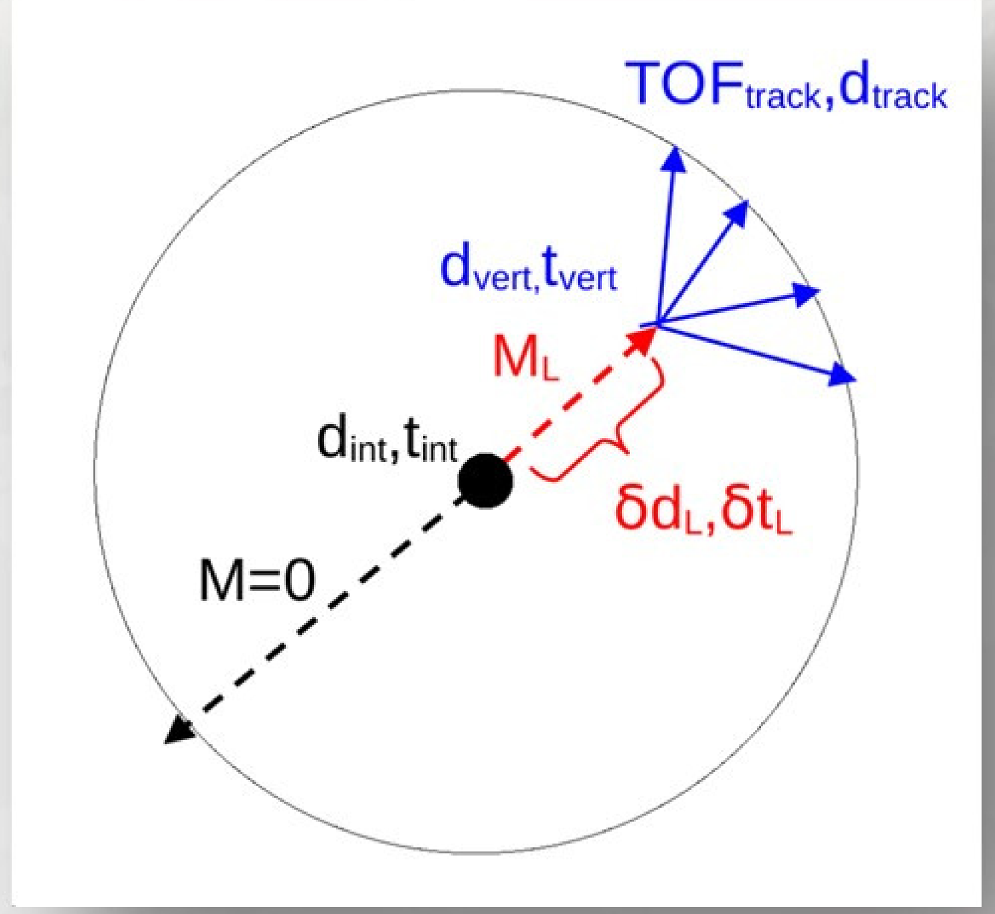

The **HNL mass** can be constrained by measuring its decay **timing and path**

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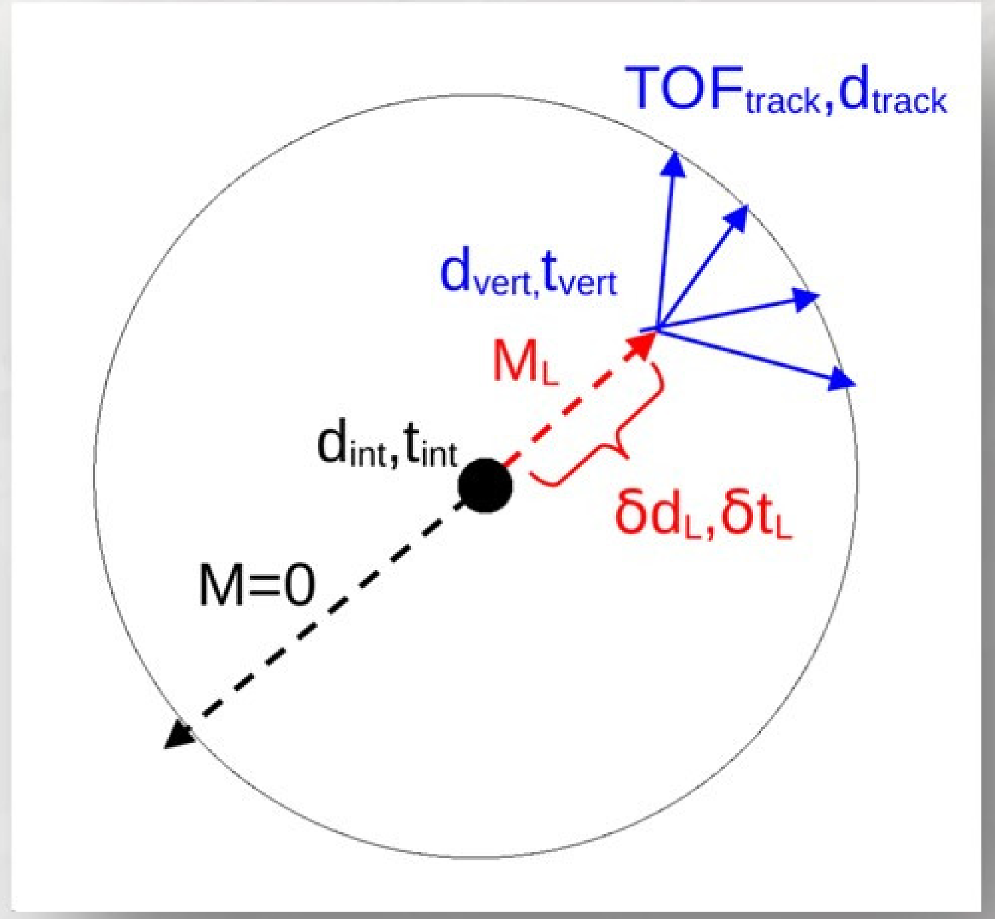
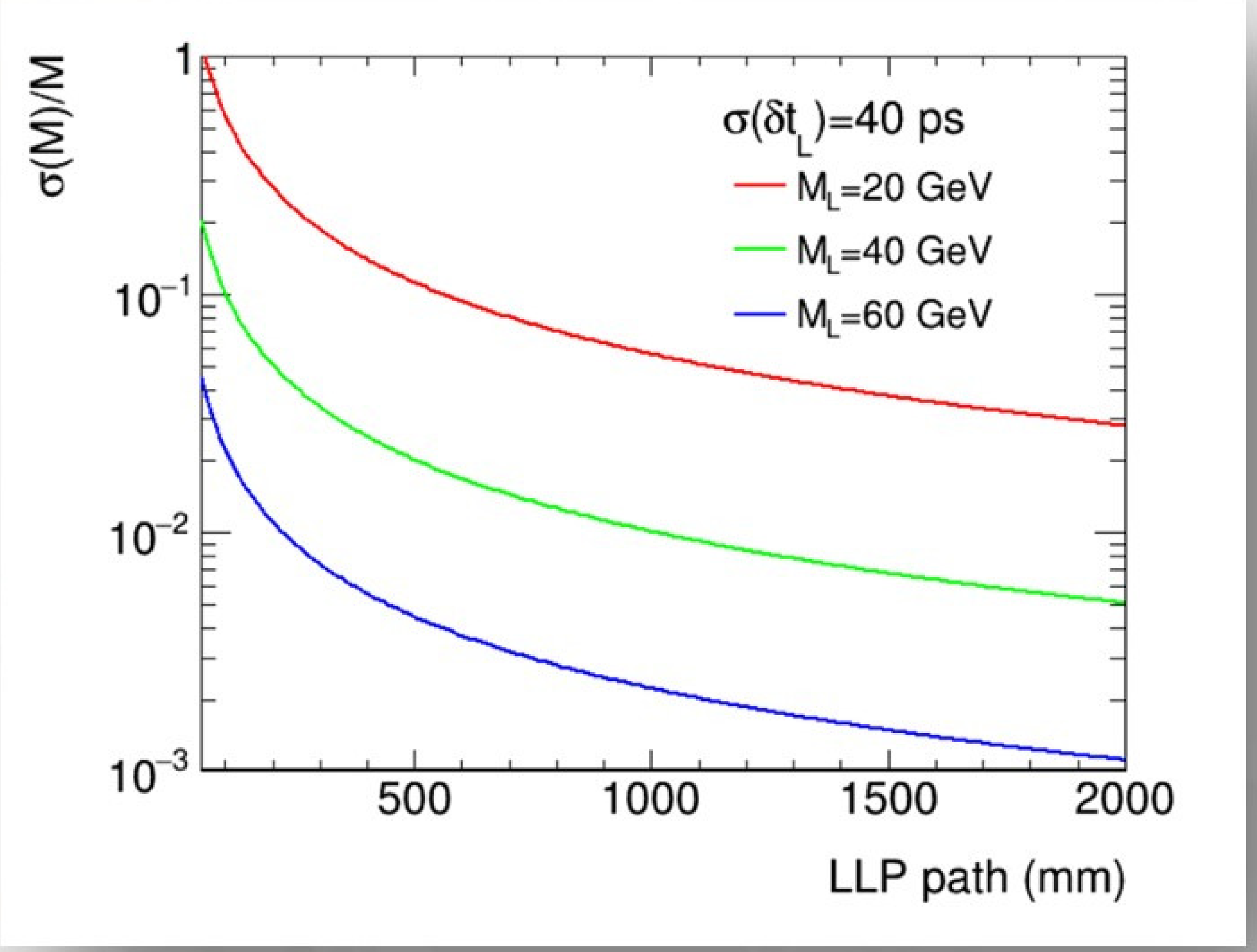


The **HNL mass** can be constrained by measuring its decay **timing and path**

Resolution controlled by the uncertainty on HNL decay time and on the **undetected interaction point** *

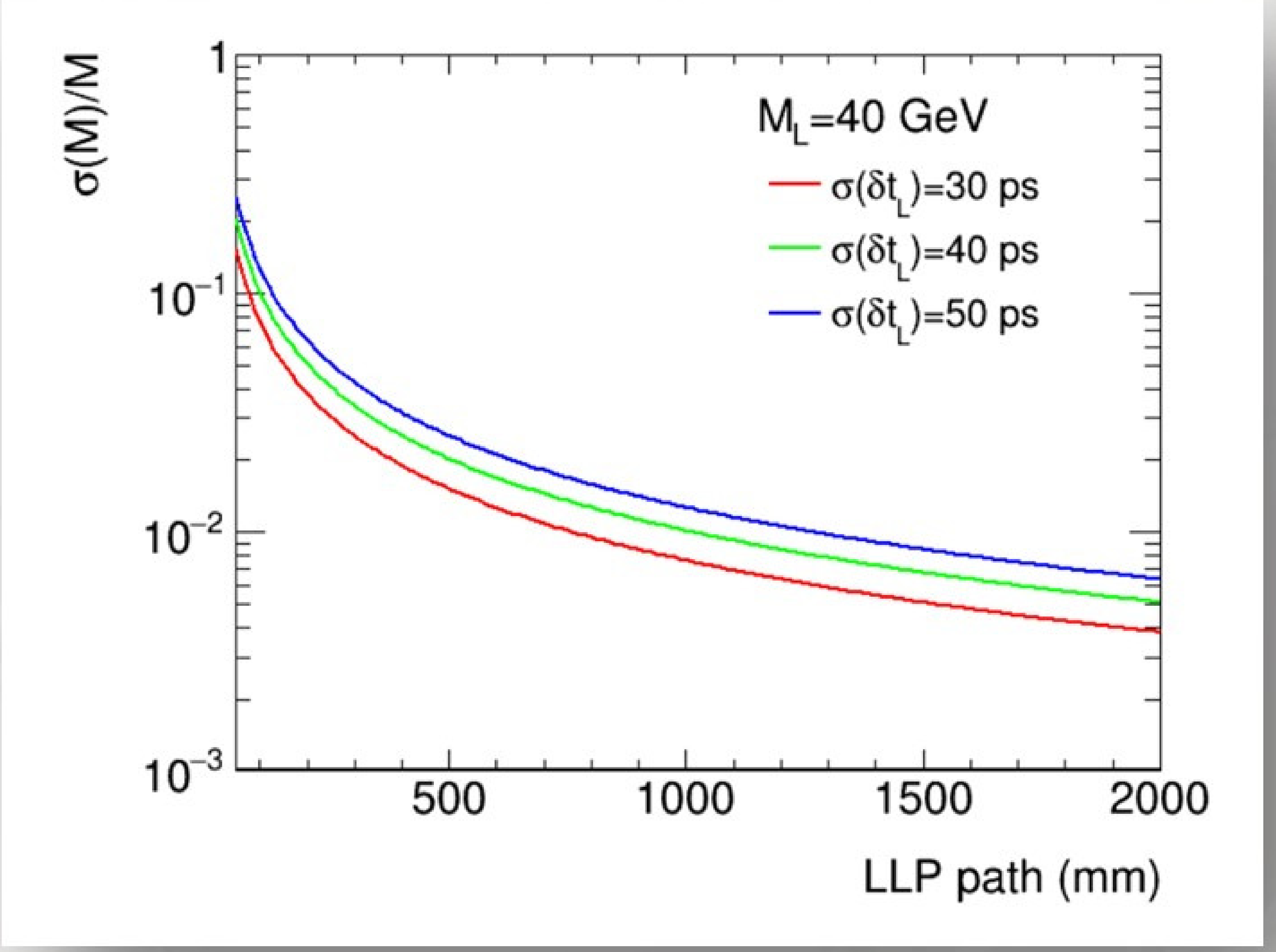
* σ_x = 5.96 μm, σ_y = 23.8 nm, σ_z = 0.397 mm, σ_z = 36.3 ps



Measurement below the percent level is possible with plausible detector performance,

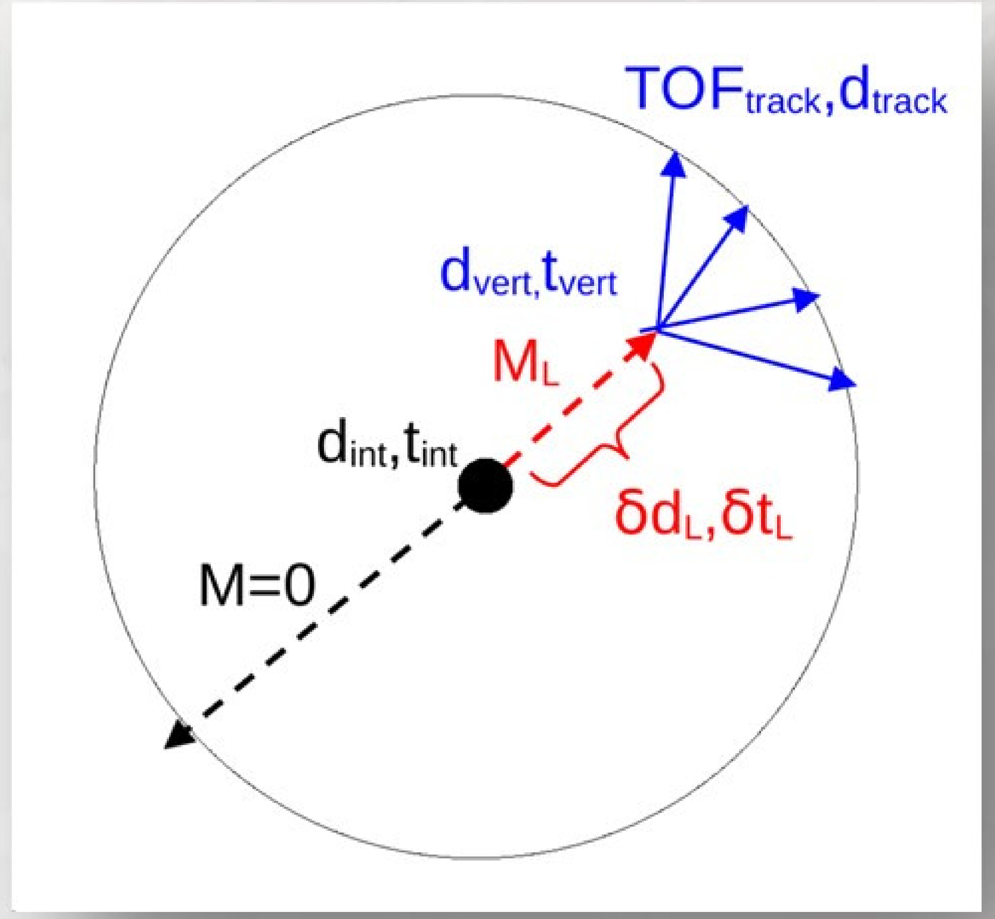
for sufficiently high masses

and long lifetimes



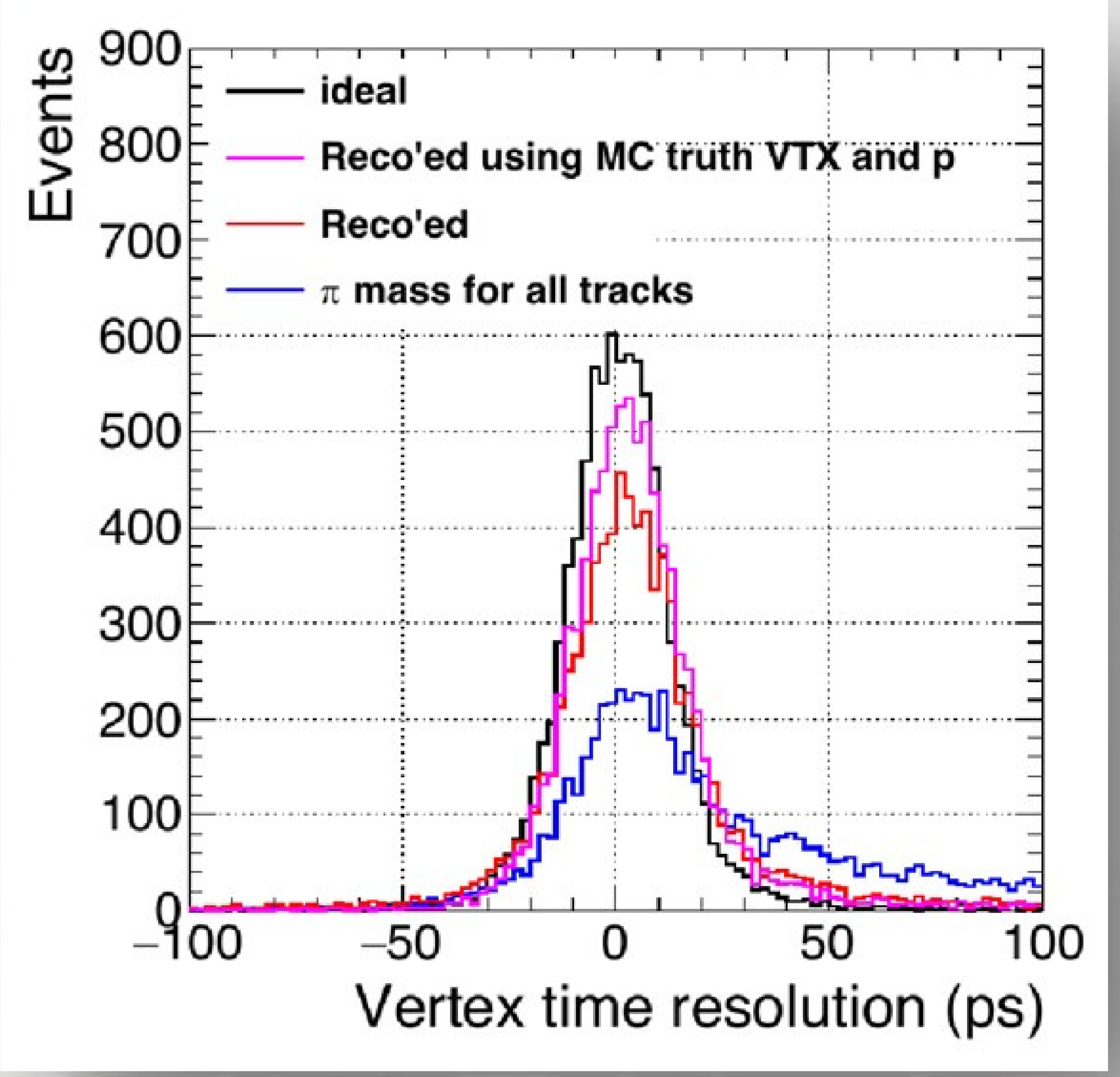
More on the mass measurement

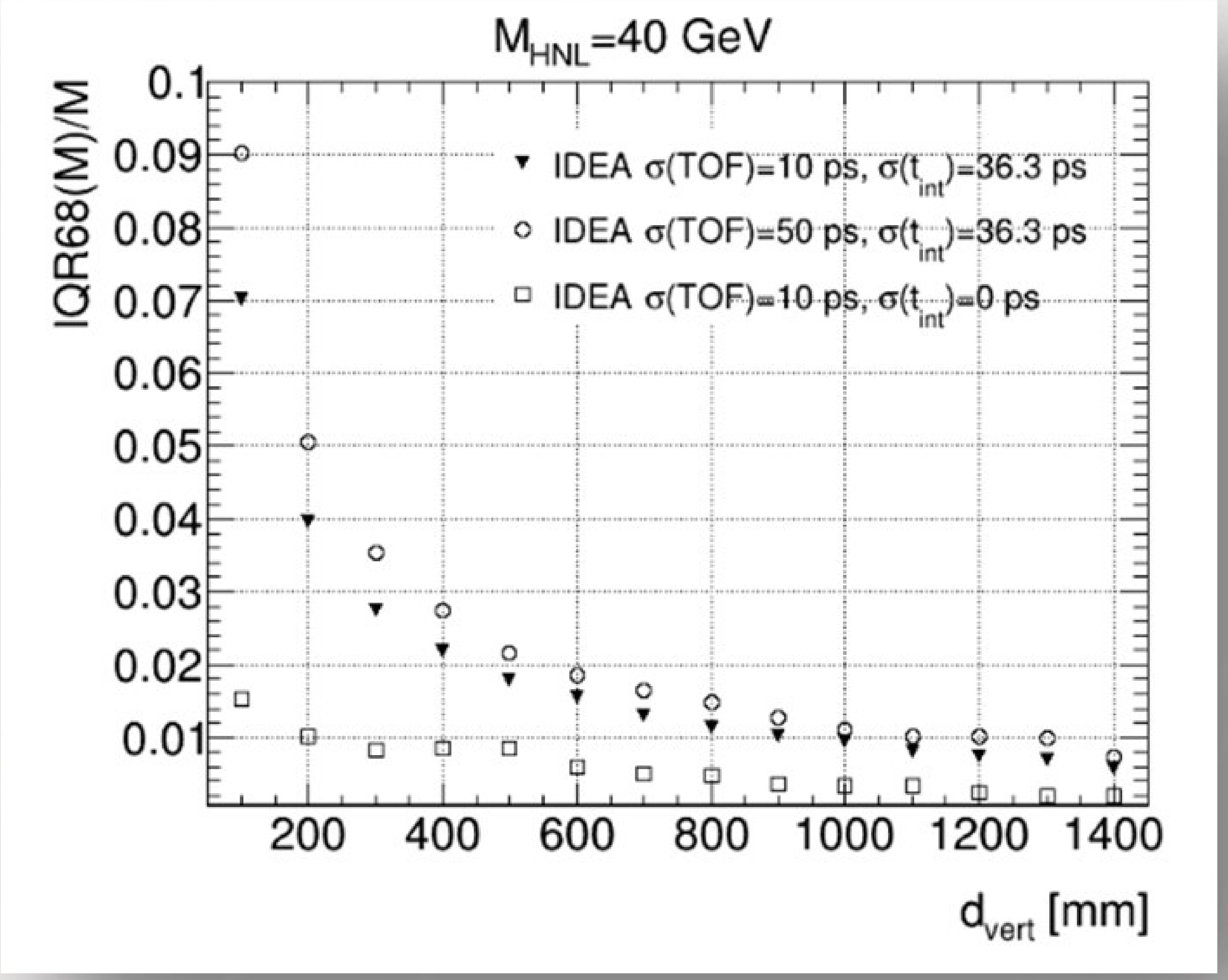
arXiv:2406.05102

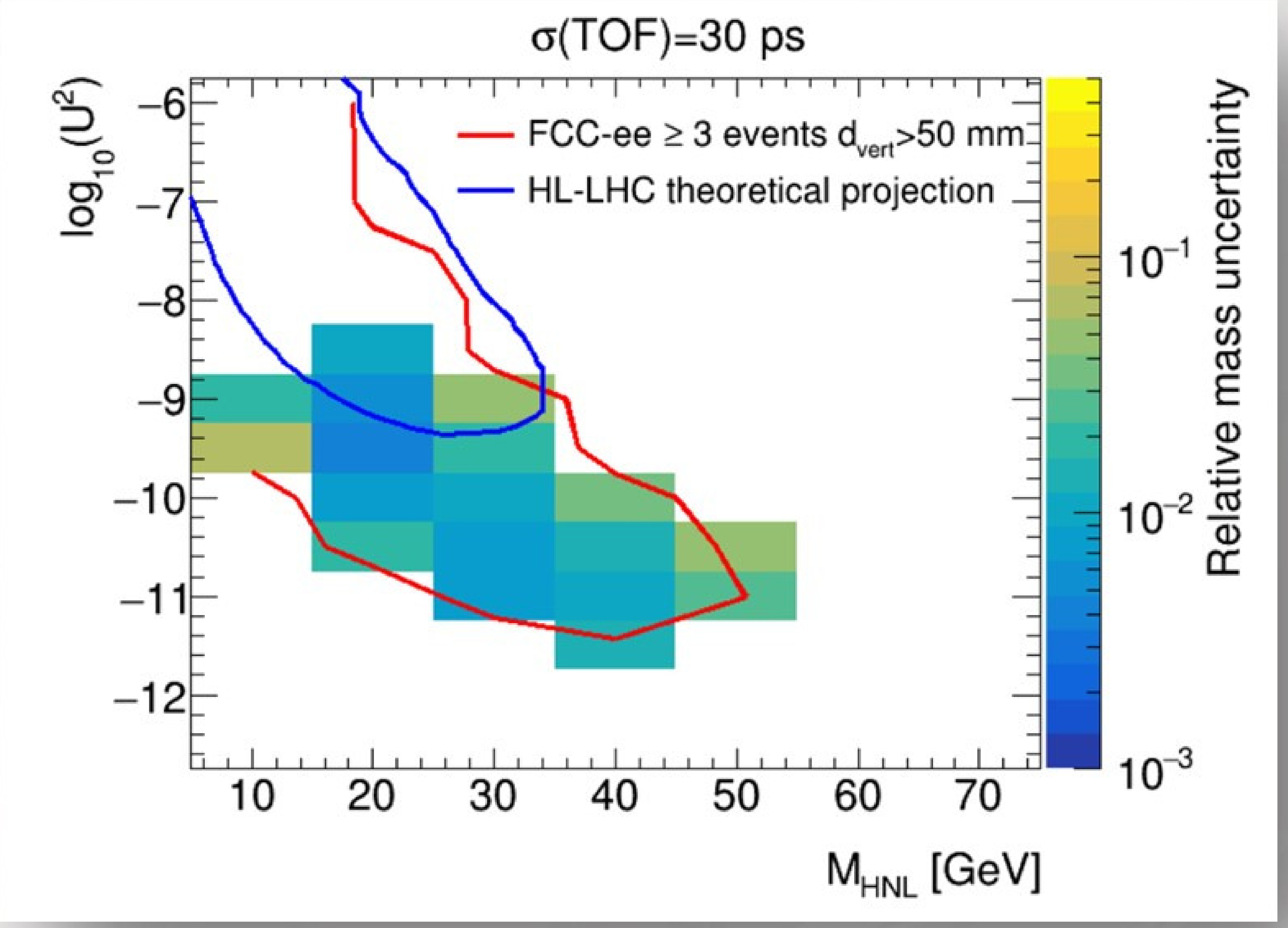


Realistic conditions simulated in IDEA, using the $N \to \mu jj$ channel

- $\sigma(\mathrm{TOF})$ determined only by detector technology
- The HNL vertex is known and its flight distance is computed
- Iterative procedure set up to optimize the mass hypotheses, possibly spoiled by the long HNL flight distance
- Timing resolution roughly scaling with sqrt of number of tracks
- $200\mu m \simeq \sigma(d_{vert})$ dominated by the uncertainty on the interaction point
- Dependence on HNL yield vs (m_N, U): evaluated with MC for the expected Z-pole run luminosity

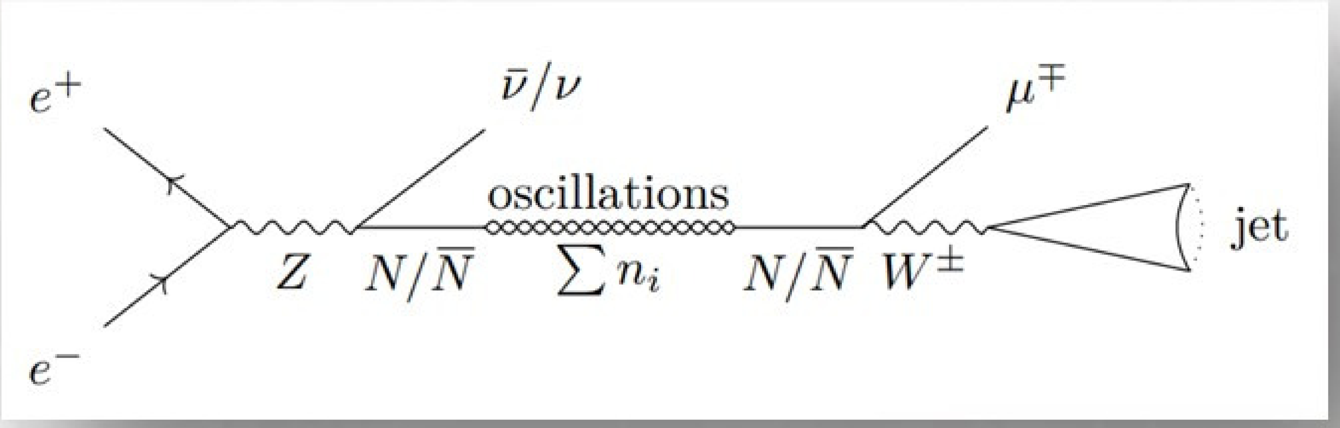




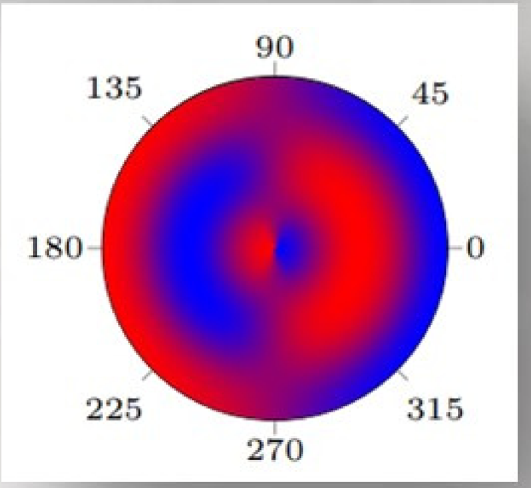


Expanding the phenomenology

See model in arXiv:2210.10738, arXiv:2308.07297



J. Haier et al



Sterile pseudo-Dirac neutrinos, almost mass-degenerate

Same mixing to SM, generating **superposition of $N, \overline{N}$** during Z decay

Oscillation between lepton-number conserving (**LNC**) and lepton-number violating (**LNV**) processes

In which parameter space **can we detect oscillations** at FCC-ee ?

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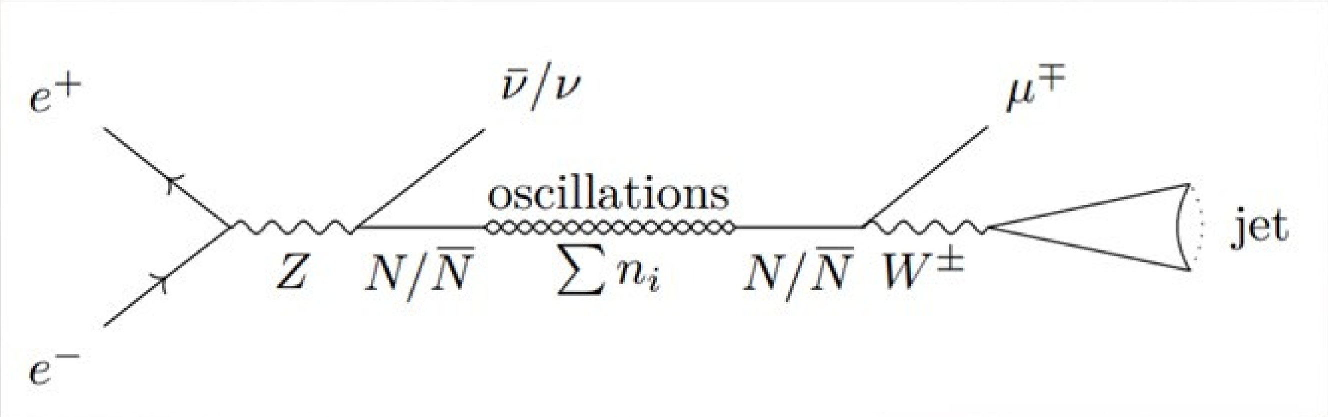

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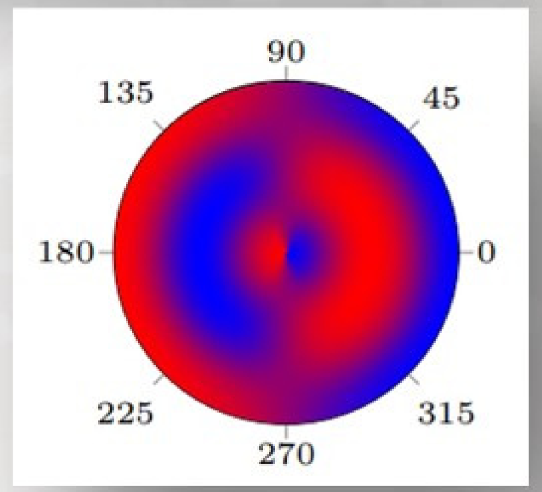

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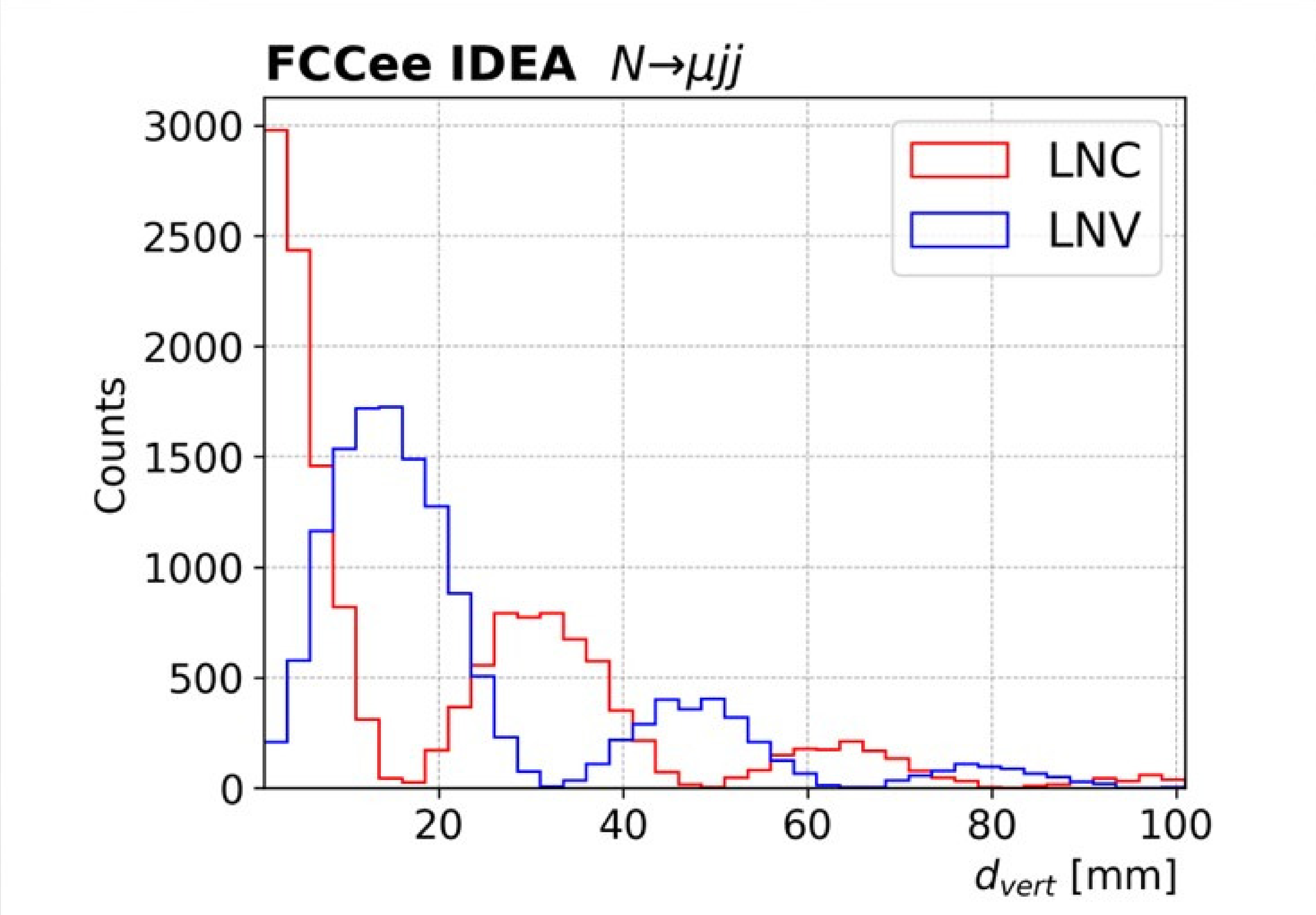
One cannot detect whether N recoils against ν or $\bar{\nu}$ → use **angular asymmetry from Z polarization**

$$P_{osc}^{LNC^{(+)},LNV^{(-)}}(d) = \frac{1 \pm \cos(\Delta m\, d)}{2}$$

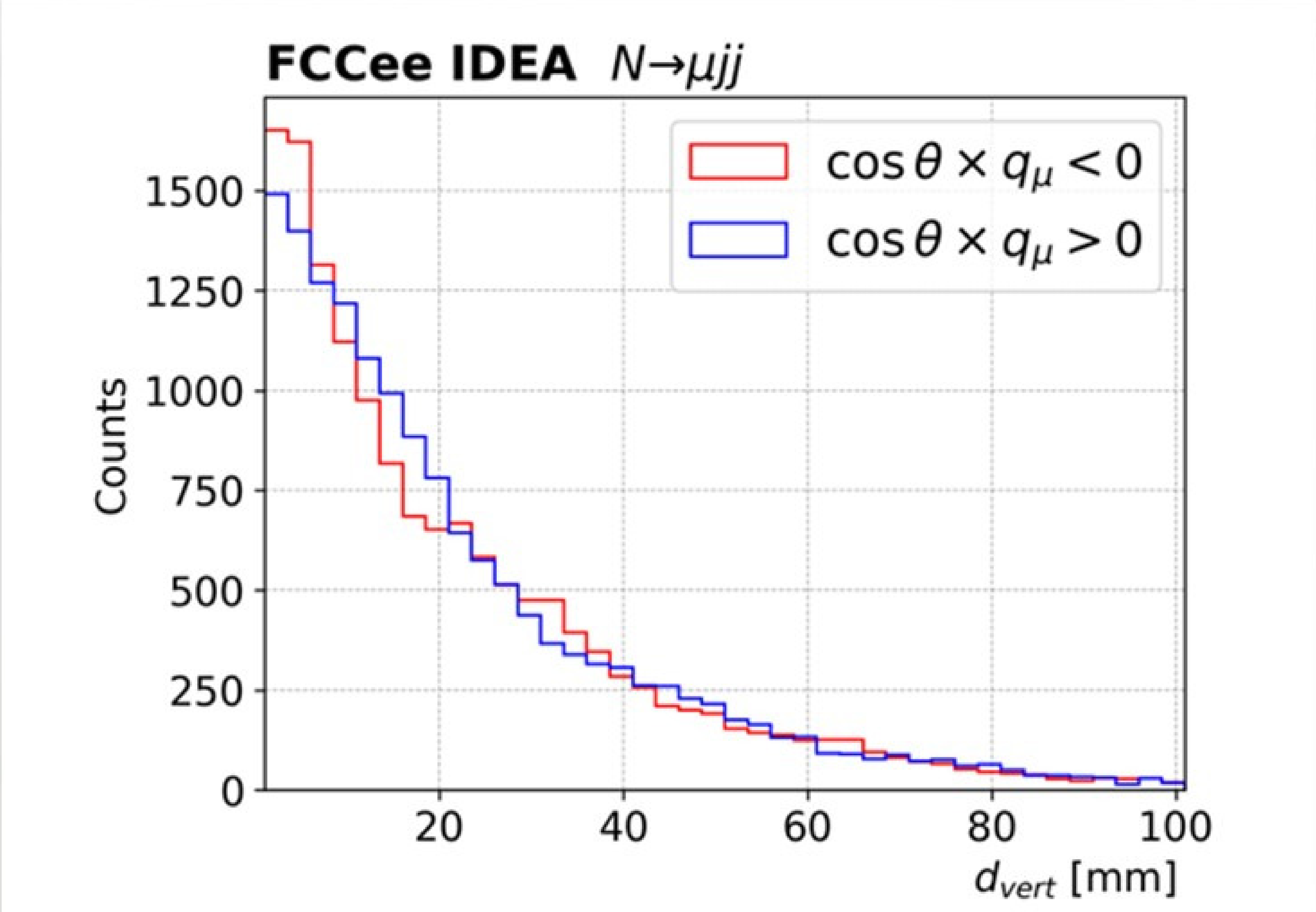
$$A_{\ell^\mp}^{FB} = \frac{P_{\ell^\mp}^{[\pi/2,0]} - P_{\ell^\mp}^{[\pi,\pi/2]}}{P_{\ell^\mp}^{[\pi/2,0]} + P_{\ell^\mp}^{[\pi,\pi/2]}} = A_{N,\bar{N}}^{FB}\, \Delta P_{osc}$$

ν detected (MC truth)



$c\tau_{dec} = 10$ mm; $c\tau_{osc} = 15$ mm

Matching angular distribution with lepton charge



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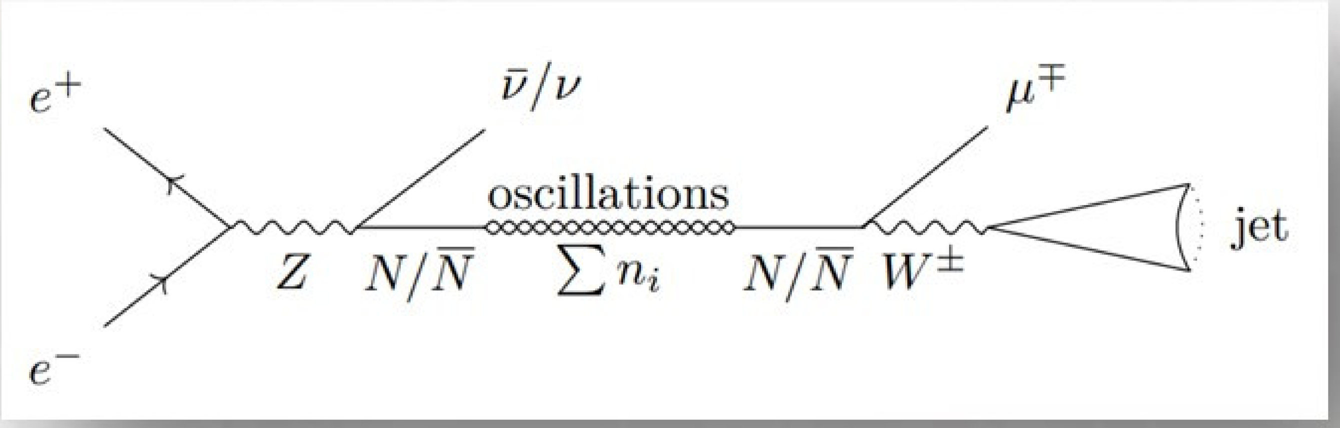

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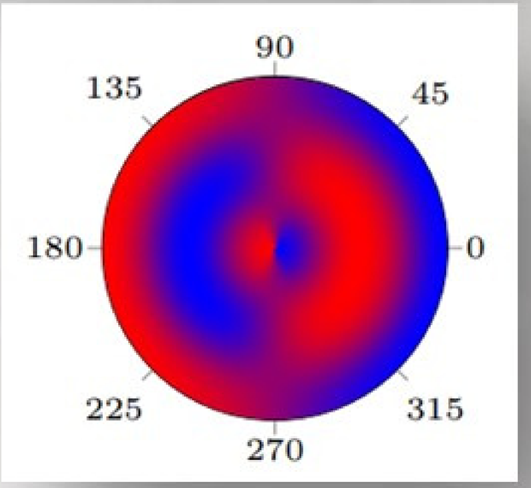
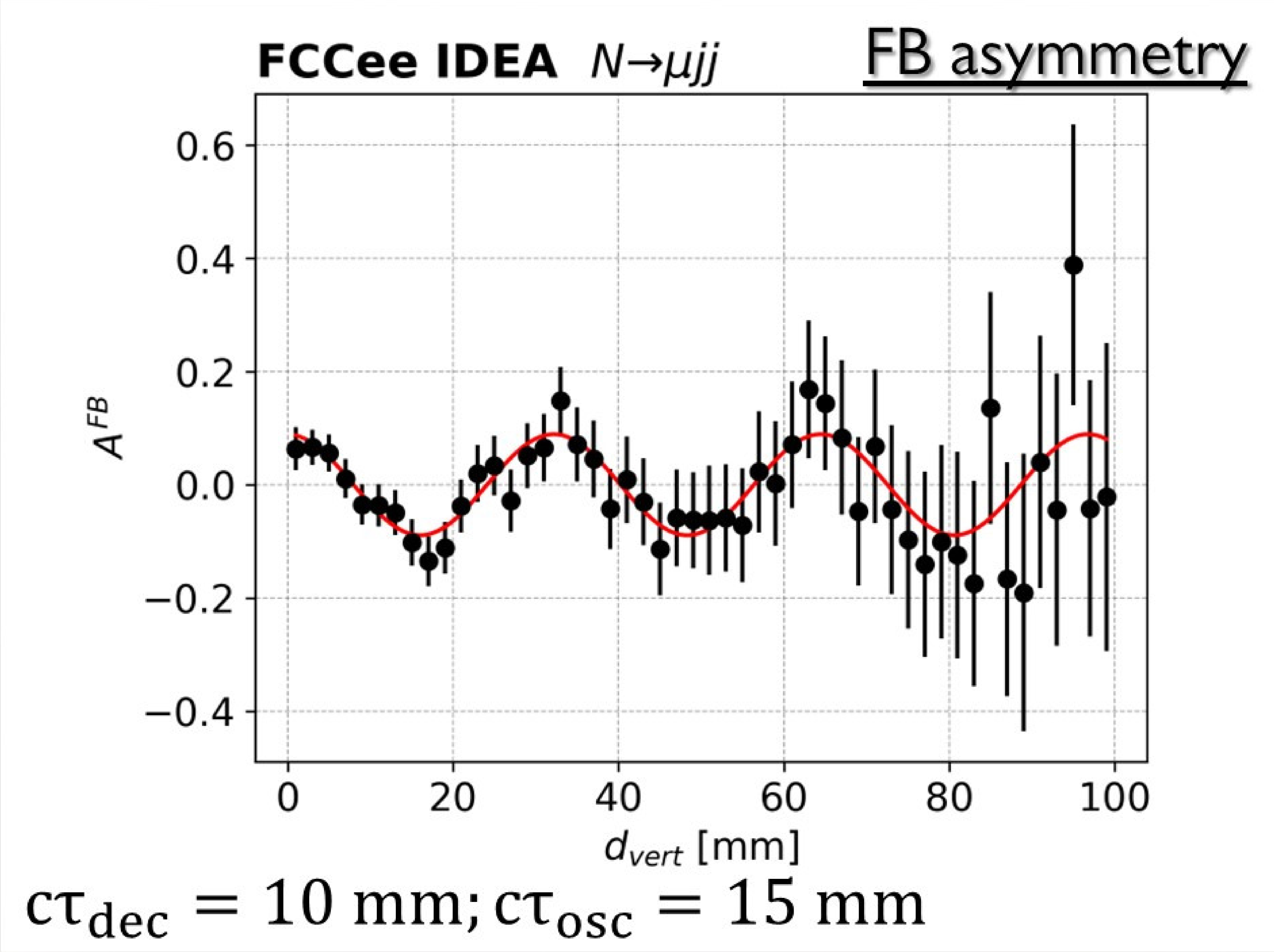


In which parameter space **can we detect oscillations** at FCC-ee ?

The signal has been passed through the **full analysis workflow**

$c\tau_{oscillation}$ simulated **between 1.5 and 150 mm**
Event selection based on displaced vertices → **zero SM background**



- ✓ Good oscillation detection capability in the detector
- ✓ **Oscillation period** seems **measurable**, if $c\tau_{osc} \lesssim c\tau_{dec}$

Summary and outlook

... this talk: not representative of the **many FCC BSM analyses** under study!
Multiple groups working on various benchmark channels at FCC-ee

Excellent potential for direct searches of BSM signatures both in **prompt** and **long-lived** channels

HNL: electron, neutrino decay channels
Multiple heavy neutrino states
Dirac/Majorana discrimitation

Exotic Higgs decays
Axion-like particles and light scalars
....

Full exploitation of this potential poses severe **requirements on detector** performance

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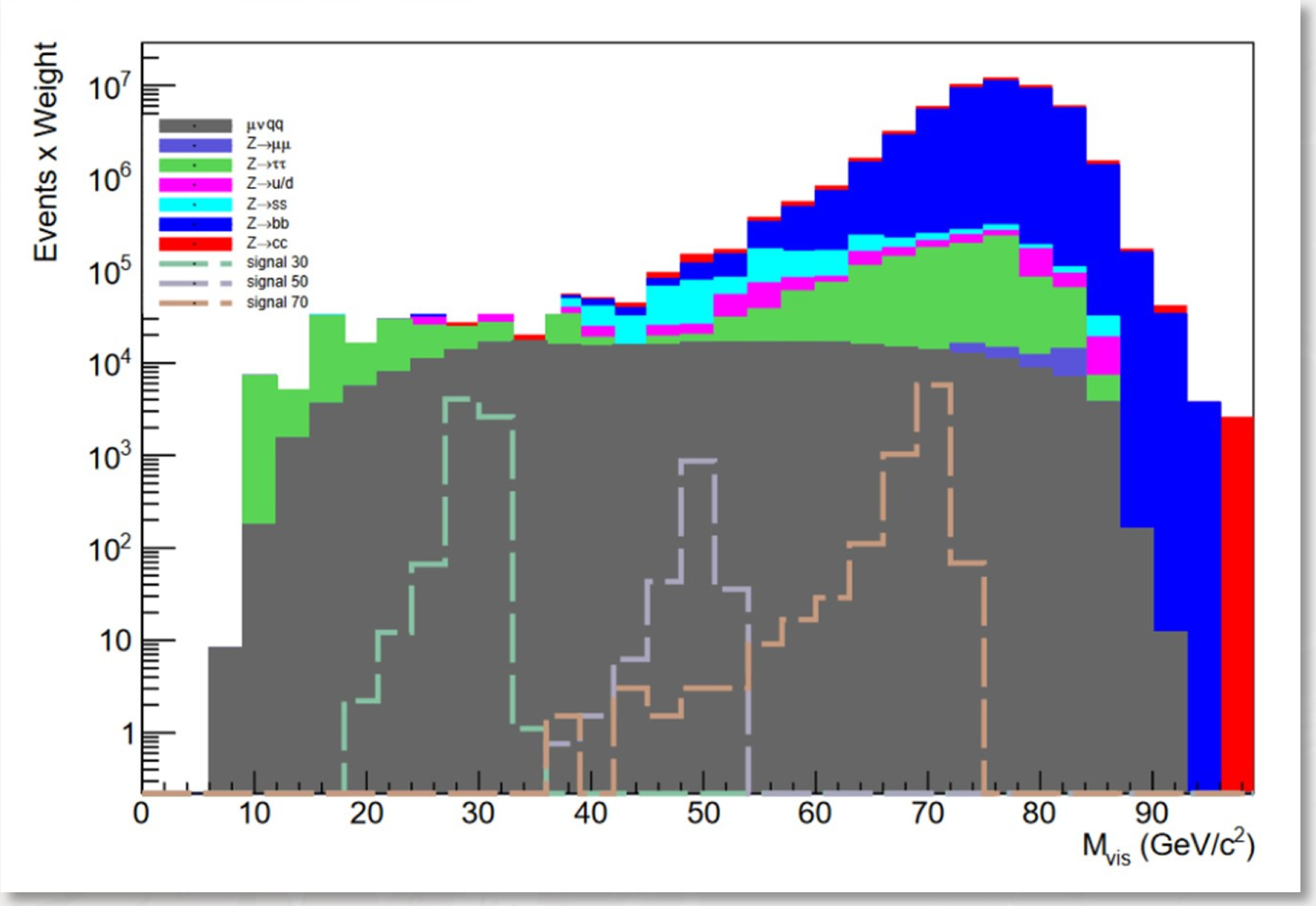
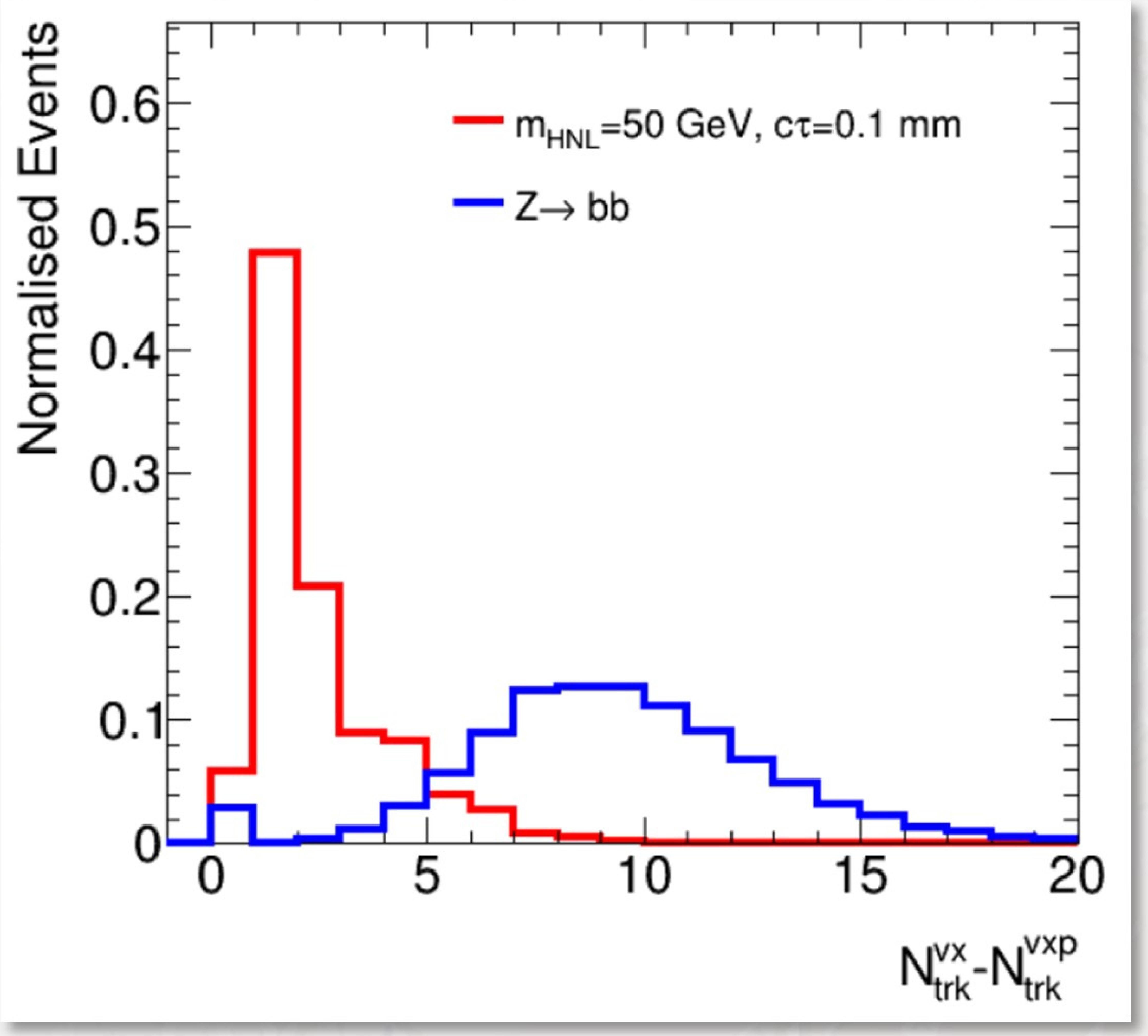
HNL production is a key BSM search for FCC-ee
Analyses prove sensitivity down to small mixing angles

Vigorous activity on benchmark model parameters is ongoing, at the moment based on parametrised performance of detectors

Extra plots


Events x Weight
μνqq
Z→μμ
Z→ττ
Z→u/d
Z→ss
Z→bb
Z→cc
signal 30
signal 50
signal 70
M_{vis} (GeV/c^2)


Normalised Events
m_{HNL}=50 GeV, cτ=0.1 mm
Z→ bb
N_{trk}^{vx}-N_{trk}^{vxp}

Dependence on hadronic resolution

1. Window for baseline study from DELPHES
2. Assume signal efficiency unchanged after enlarging mass window according to resolution
3. Calculate number of background events for enlarged window and calculate significance

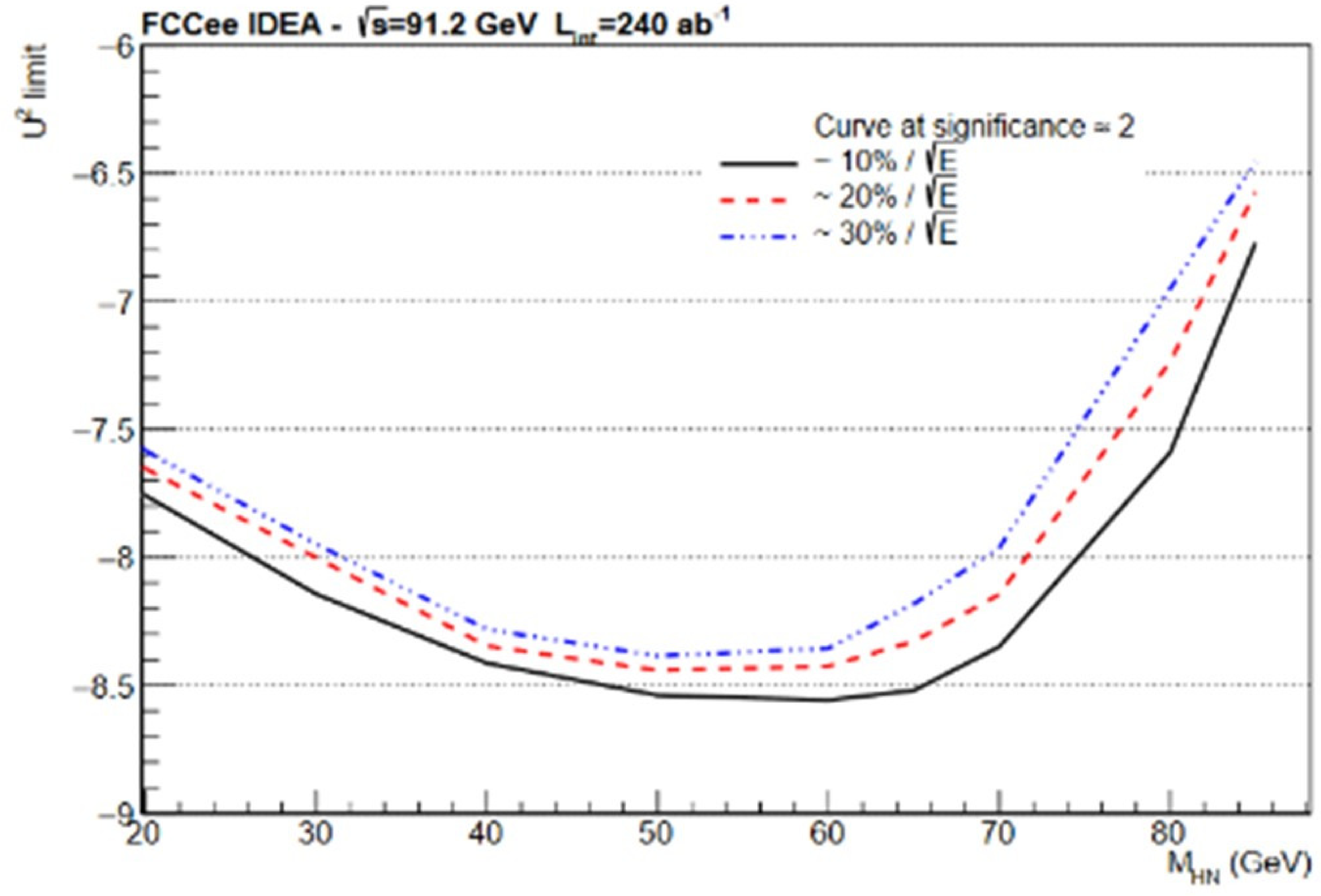


Fig. 24 Curves at Significance = 2 for different values of the assumed hadronic resolution. Each line is a linear interpolation of Z vs. $\log(U)$ at the value $Z = 2$.

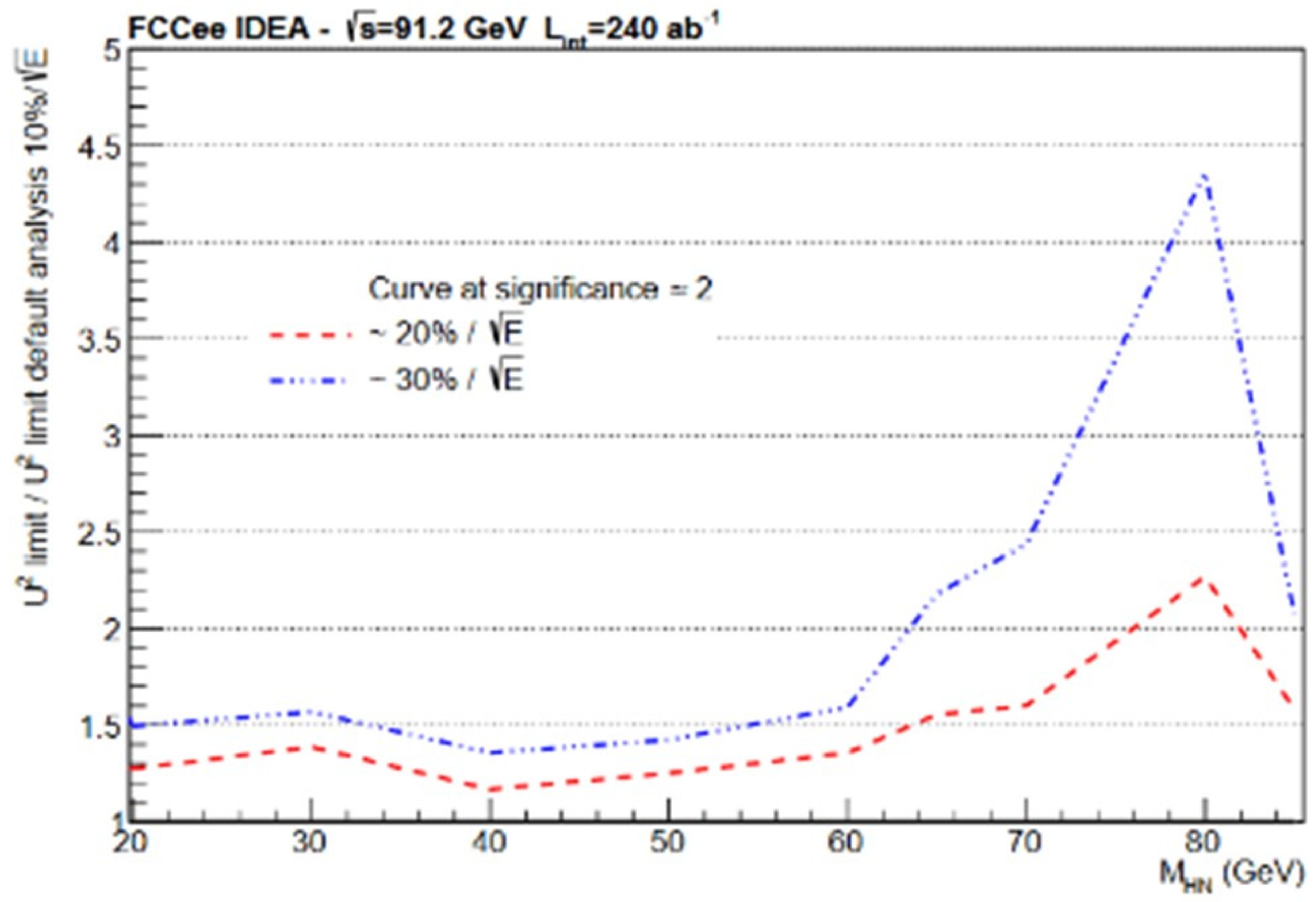
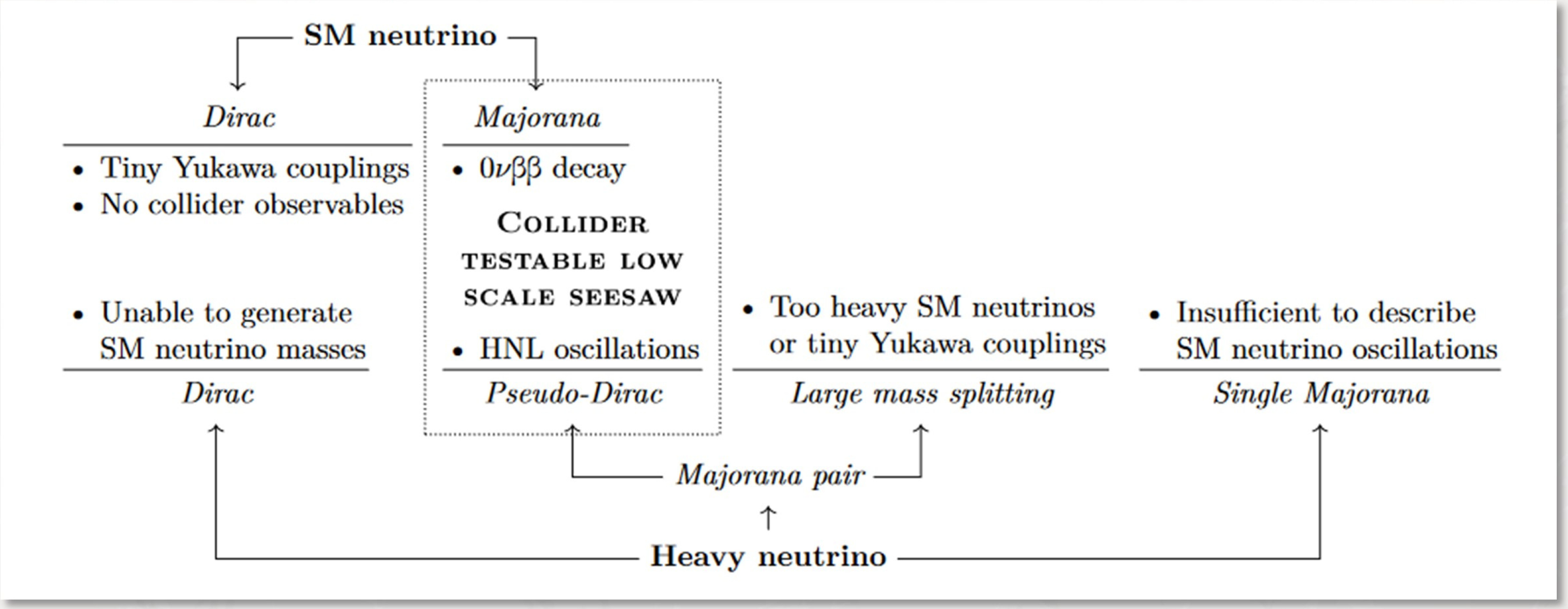


Fig. 25 Ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{N_1}.



https://arxiv.org/pdf/2210.10738