Searches for HNLs at FCC-ee in the final state N1->μjj

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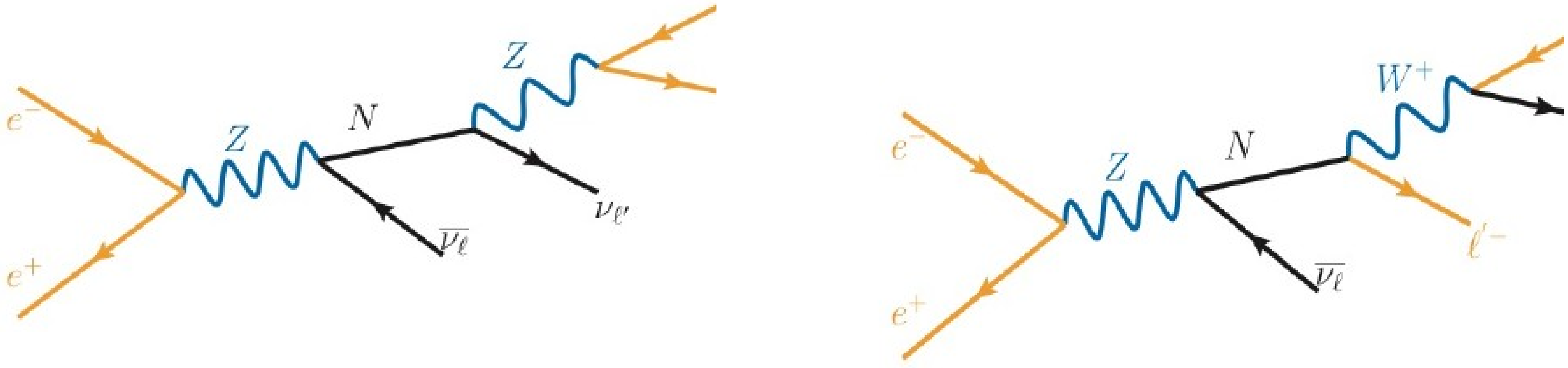
Introduction

Production of HNL in Z decay through mixing with light neutrinos



If only 1 HNL flavour assumed, model defined in terms of two parameters: m_N and U, mixing parameter

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

$$|U_N|^2 \equiv \sum_{\ell=e,\mu,\tau} |U_{\ell N}|^2$$

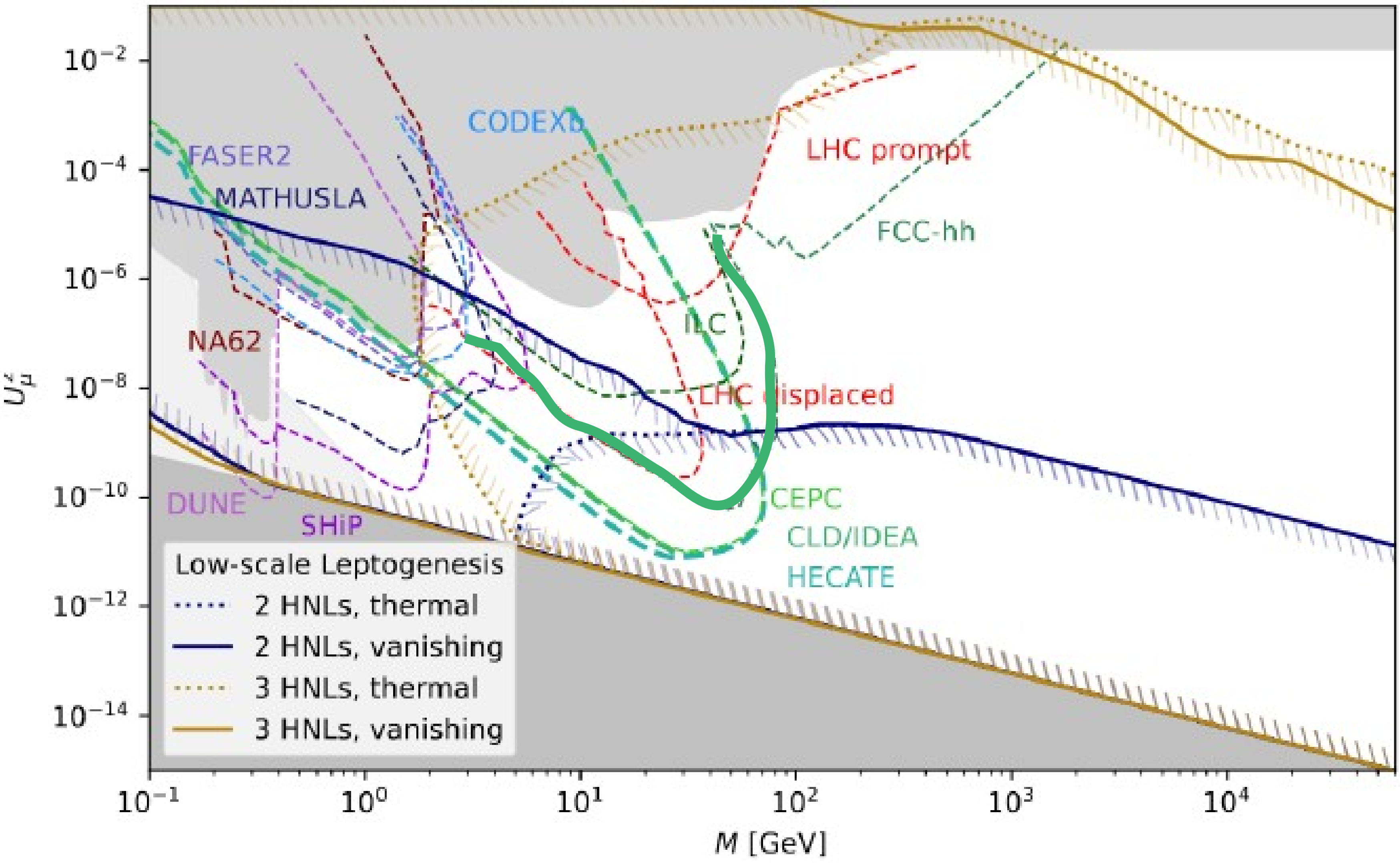
Decay width:
(m_{HN}<80 GeV)

$$\Gamma_N \simeq c_{\mathrm{dec}} \frac{a}{96\pi^3} U^2 M^5 G_F^2$$

a~12
M.Drewes arXiv:2210.17110

Expectations

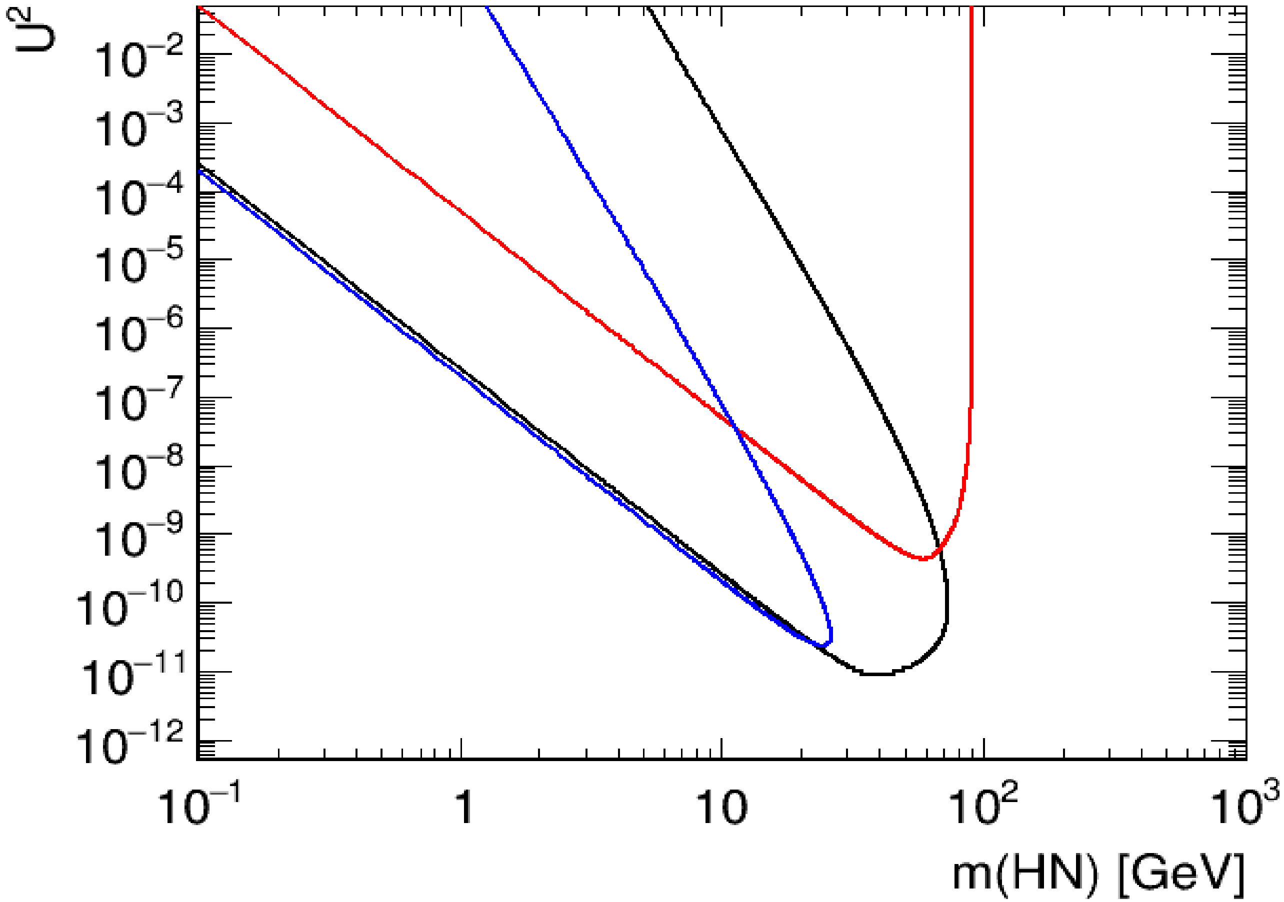
ArXiv:2203.05502



Assume for FCC-ee $5x10^{12}$ Z produced

Thick green line: approximate CEPC reach

Focus on production rates at FCC-ee 91 GeV

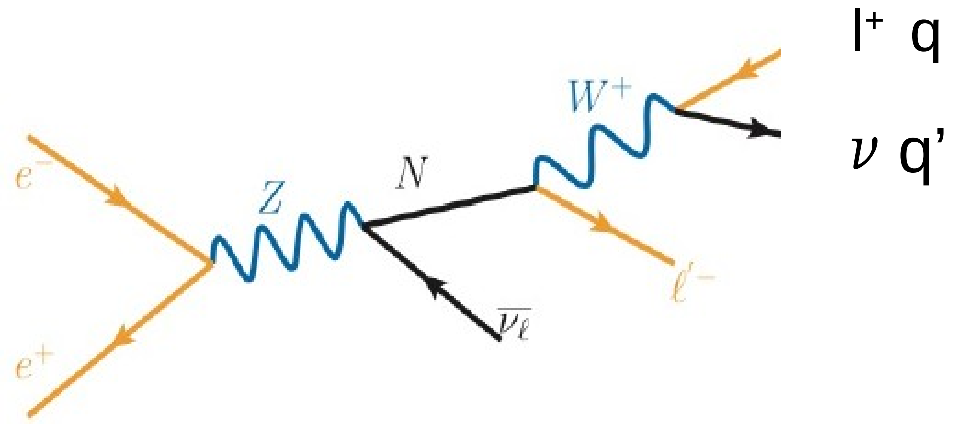


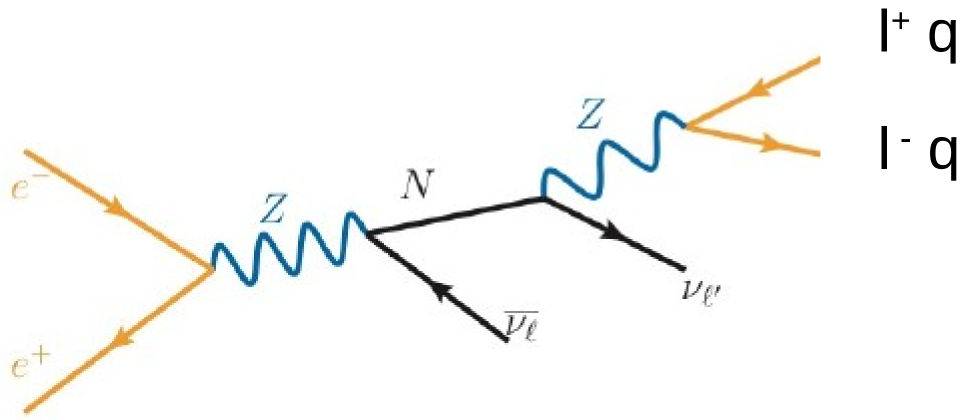
Assume 1 flavour active
$5x10^{12}$Z at Z peak
Require 100 events for prompt decay and
4 events for long-lived

Red: Prompt:
0< λ < 1mm
Black:ID decay
0.04<λ< 150 cm
Blue: Calo decay
200<λ< 450 cm

Curves based on the formulas of M. Drewes
arXiv:2210.17110

Decay signatures





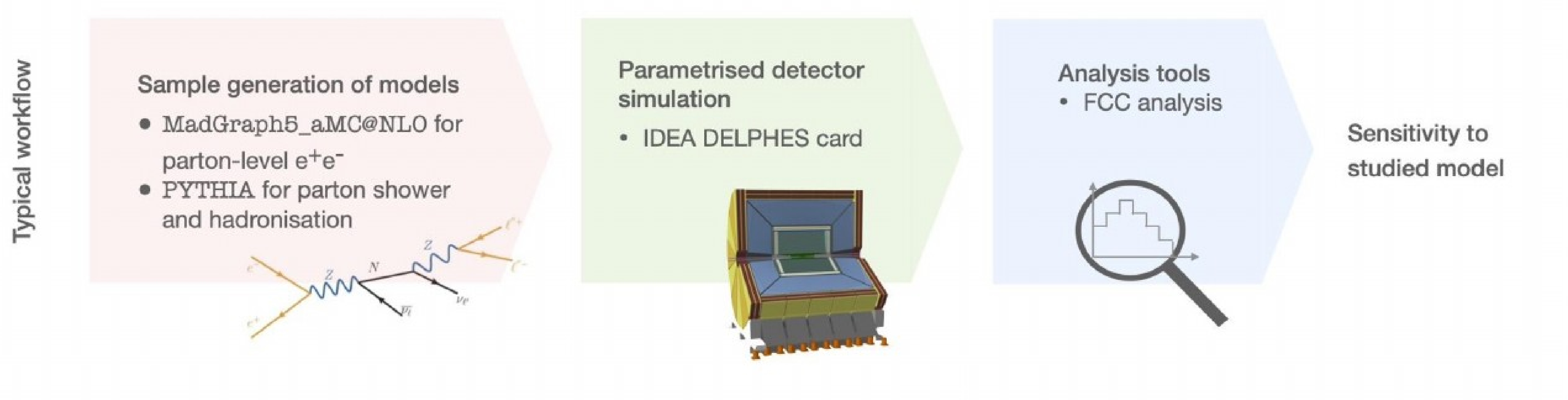
Analysis matrix: for HNL

- Decay final state (l=e,μ):
  - j j l ~50%
  - j j nu ~20%
  - l l nu ~5%
  - l l’ nu ~9%
  - l τ nu ~9%

  (BRs for m_{HN}<80 GeV)
- Decay lengths
  - Prompt
  - LL decay In ID
  - LL decay in Calo

Focus for this analysis in jjμ

Workflow

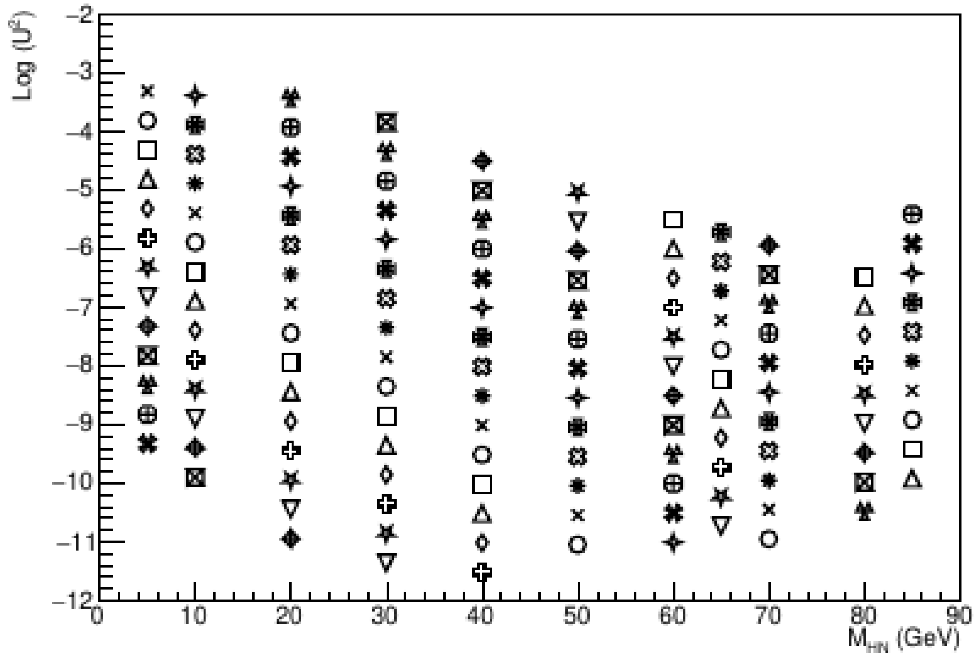


- Background files produced centrally based on FCC software.
- Signal and irreducible backgrounds produced locally
- DELPHES output stored in EDM4HEP format
- Use FCCsoftware to produce ntuples for analysis based on FCCanalysis package
  Use winter2023 production
    - Main limitation: statistics at peak

Signal and Background samples

Large signal grid generated in M_{HNL}-U^2 plane:

10k events per sample



Z Decay backgrounds: Official Winter23 production

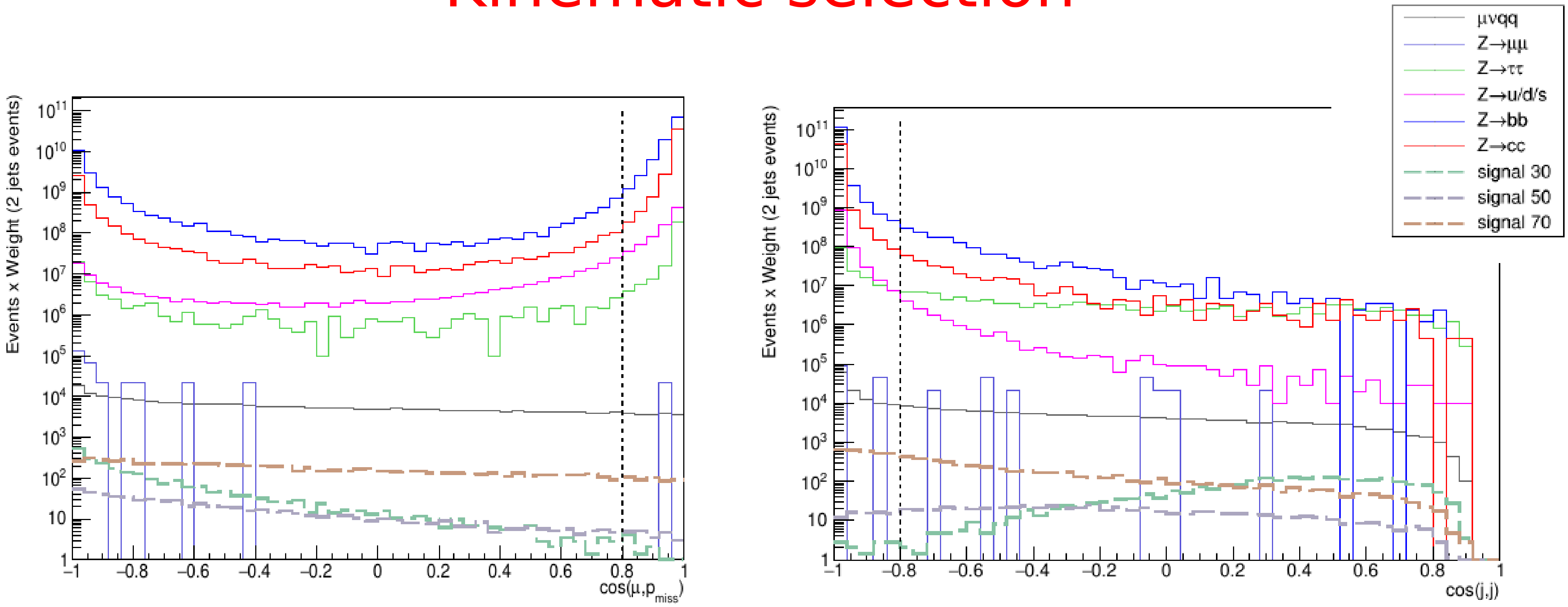
Irreducible μνjj generated with MG5 and passed through the full chain, with statistics corresponding to 240 ab^{-1}

Analysis Flow

1. Event Filter	2. Event Selection	3. Vertex selection
1 muon ≥ 3 tracks $E_\mu \geq 3$ GeV $E_{miss} \geq 5$ GeV	1 lepton (muon) Cuts on p_{miss}, jets, μ and visible mass	$N_{tracks} - N_{tracks}^{primary} < 5$ $\chi^2_{vtx,primary} < 10$

4. Mass-dependent kin. selection	5a. Displacement: prompt	5b. Displacement: LL
M_{vis} within $2 \times 10\%\sqrt{M}$ E_{miss} within $2 \times 10\%\sqrt{p_\nu}$	$r_{vert}^{primary} > 0.5$ mm $D_{0,\mu} < 8\sigma$ if $M_{N_1} > 70$	$r_{vert}^{primary} < 0.5$ mm

Kinematic selection



Two different signal regions depending on number of jets

2 jets: Dominant at masses>50 GeV where two jets from HNL decay well separated

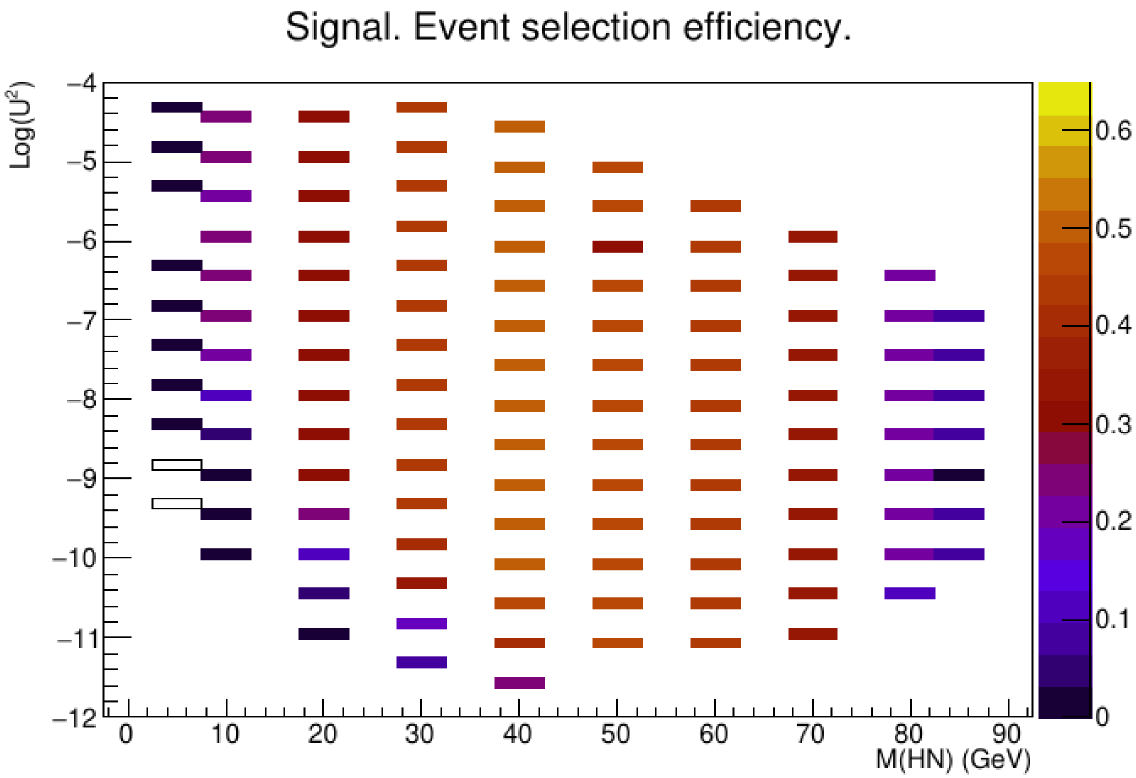
1jet: Dominant at lower masses where two jets are collimated

For each region look at variables providing separaration wrt SM backgrounds

Kinematic selection

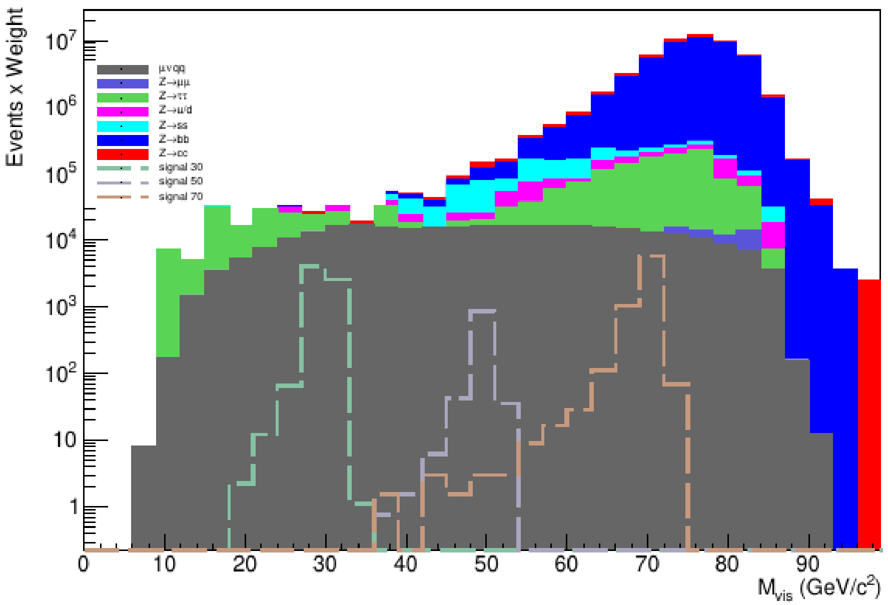
Variable	N_{jet}	$\cos(p_{miss})$	$\cos(p_{miss}, \mu)$	E_j, M_j	$\cos(j, \mu)$	$\cos(j, \mu)$	M_{tot}
Cut	$= 1$	< 0.94	< 0.50	$> 3\,\text{GeV}$ $> 0.2\,\text{GeV}$	< 0.96	> -0.5	> 80

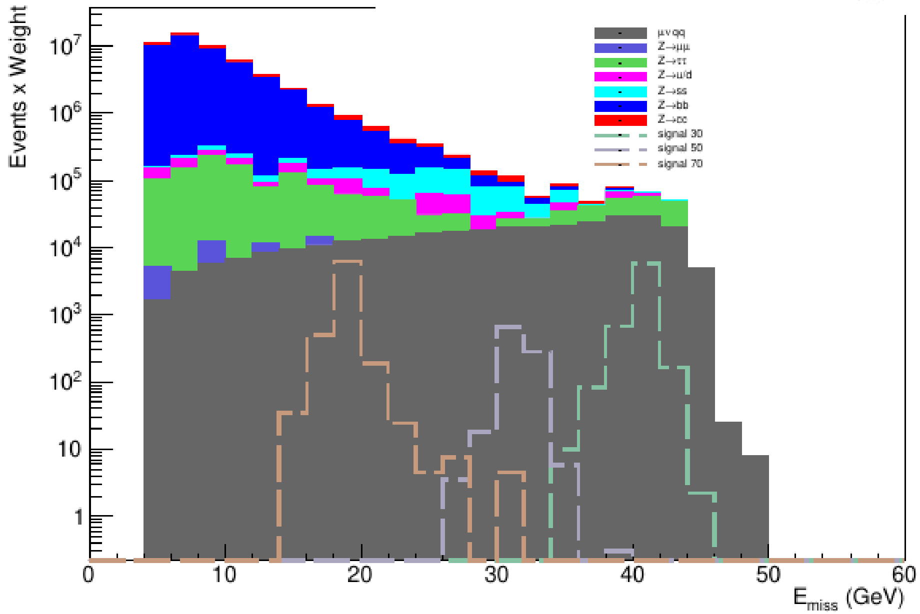
Variable	N_{jet}	$\cos(p_{miss})$	$\cos(p_{miss}, \mu)$	E_j, M_j	$\cos(j, j)$	$\cos(j, \mu)$	$\cos(j, \mu)$	M_{tot}
Cut	$= 2$	< 0.94	< 0.80	$> 3\,\text{GeV}$ $> 0.2\,\text{GeV}$	> -0.80	< 0.80	> -0.98	> 80

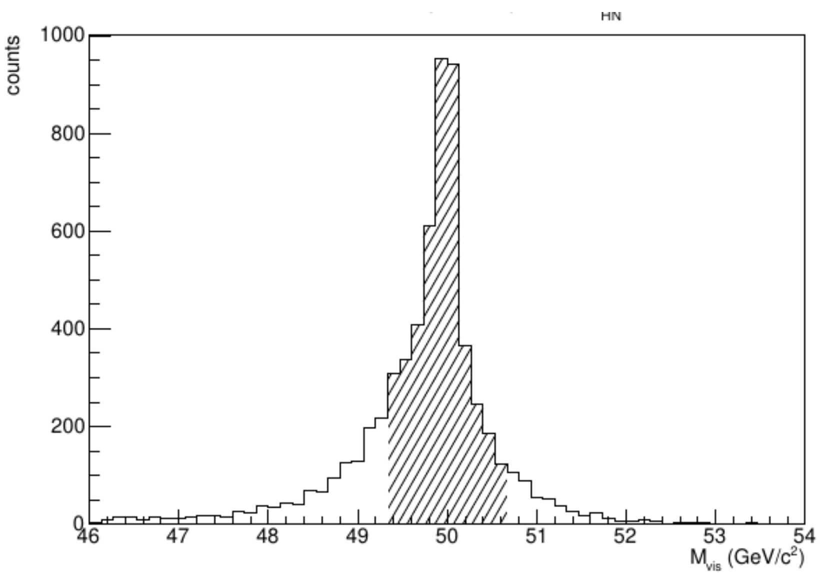


Mass-dependent selection

$$\hat{p}_\nu(M_{N_1}) = \frac{M_Z^2 - M_{N_1}^2}{2\,M_Z}$$







Non gaussian shape of signal because of PFA, very optimistic resolution because of neglect of confusion term

90% of signal in window

$$M_{vis} \in M_{N_1} \pm 2 \times 10\% \times \sqrt{M_{N_1}/\,\mathrm{GeV}}$$

Apply also cut on Emiss:

$$E_{miss} \in \hat{p}_\nu(M_{N_1}) \pm 2 \times 10\% \sqrt{\hat{p}_\nu/\,\mathrm{GeV}/c}$$

Vertex-based selection

$$N_{tracks} - N^{primary}_{tracks} < 5$$
$$\chi^2_{vtx,primary} < 10$$

Require primary vertex well
reconstructed and most of the
Tracks used for primary vertex
Large rejection for heavy flavours

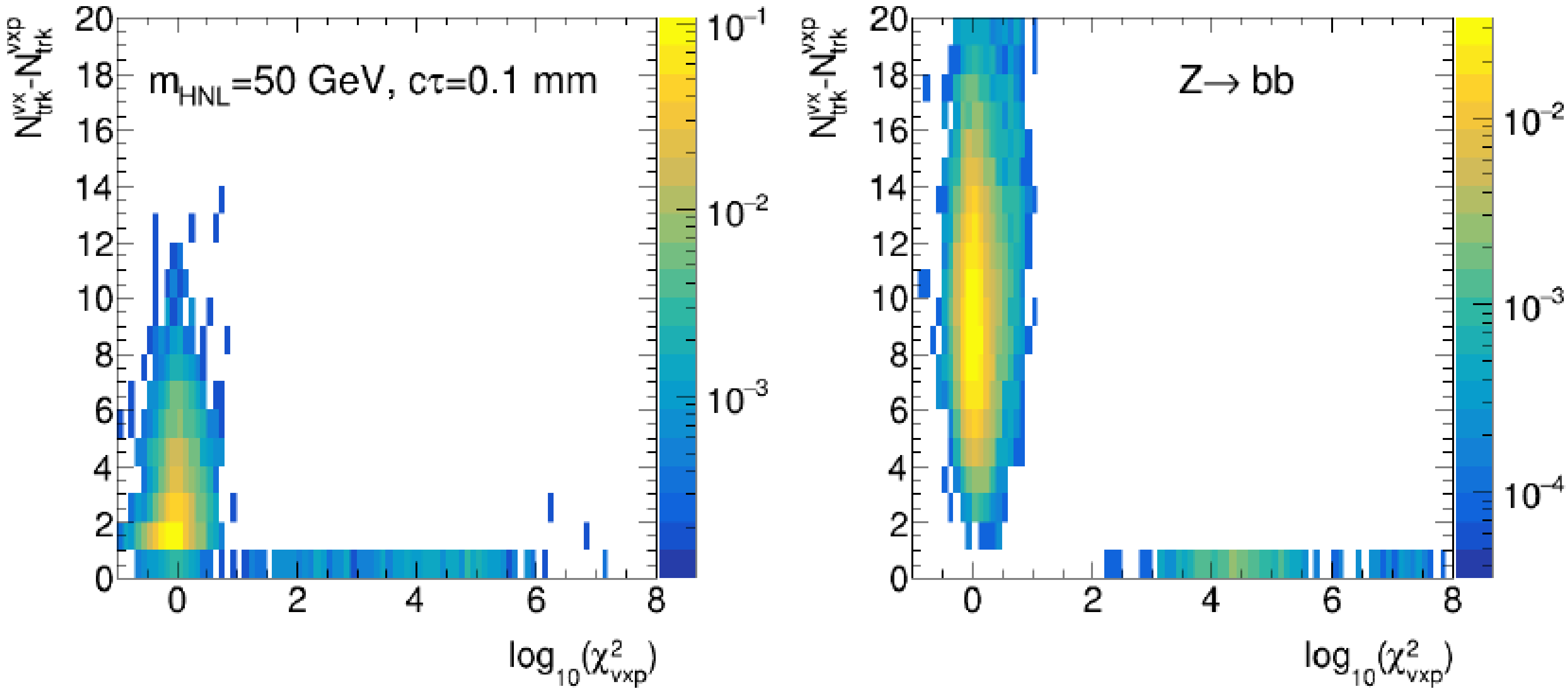
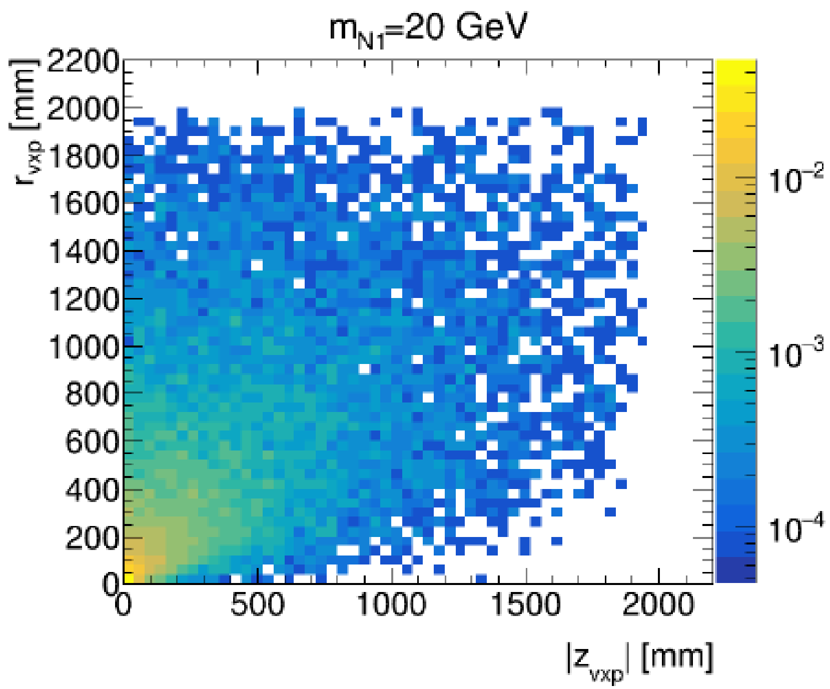
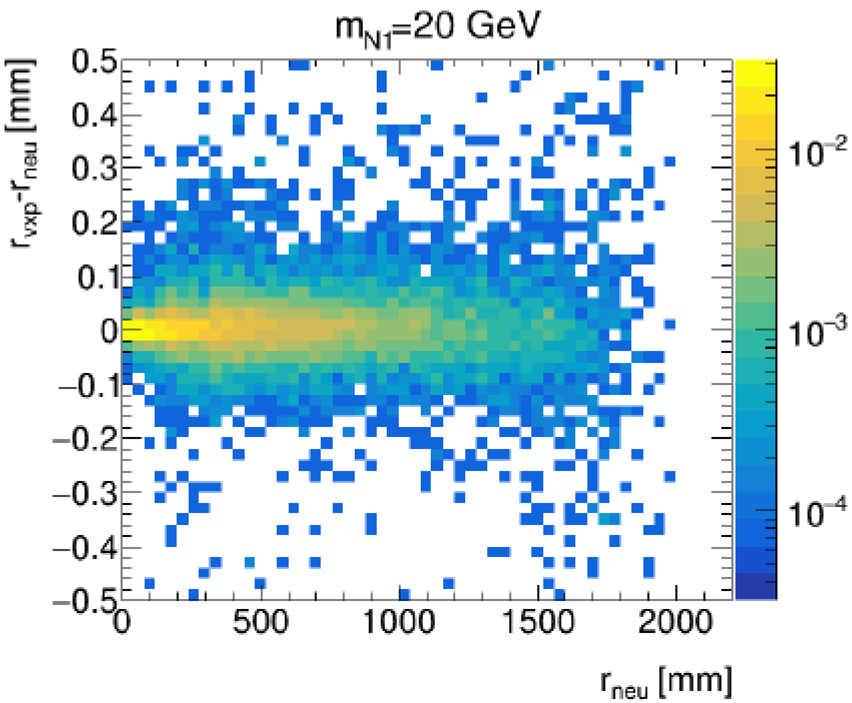


Fig. 13 Correlation of the difference between the total number of reconstructed tracks in the event and the tracks attached to the primary vertex with the value of $log_{10}(\chi^2_{vx})$ for an example 50 GeV signal (Left) and $Z \to bb$ (Right) after the selection cuts.

Prompt vs Long Lived selection





Primary vertex well reconstructed in the volume of the detector

Very good resolution in position of HNL reconstructed vertex

Separation between Prompt and Long Lived to some extent arbitrary, choose transverse position of primary vertex such that backgrounds become zero:

r_{vxp}=0.5 mm

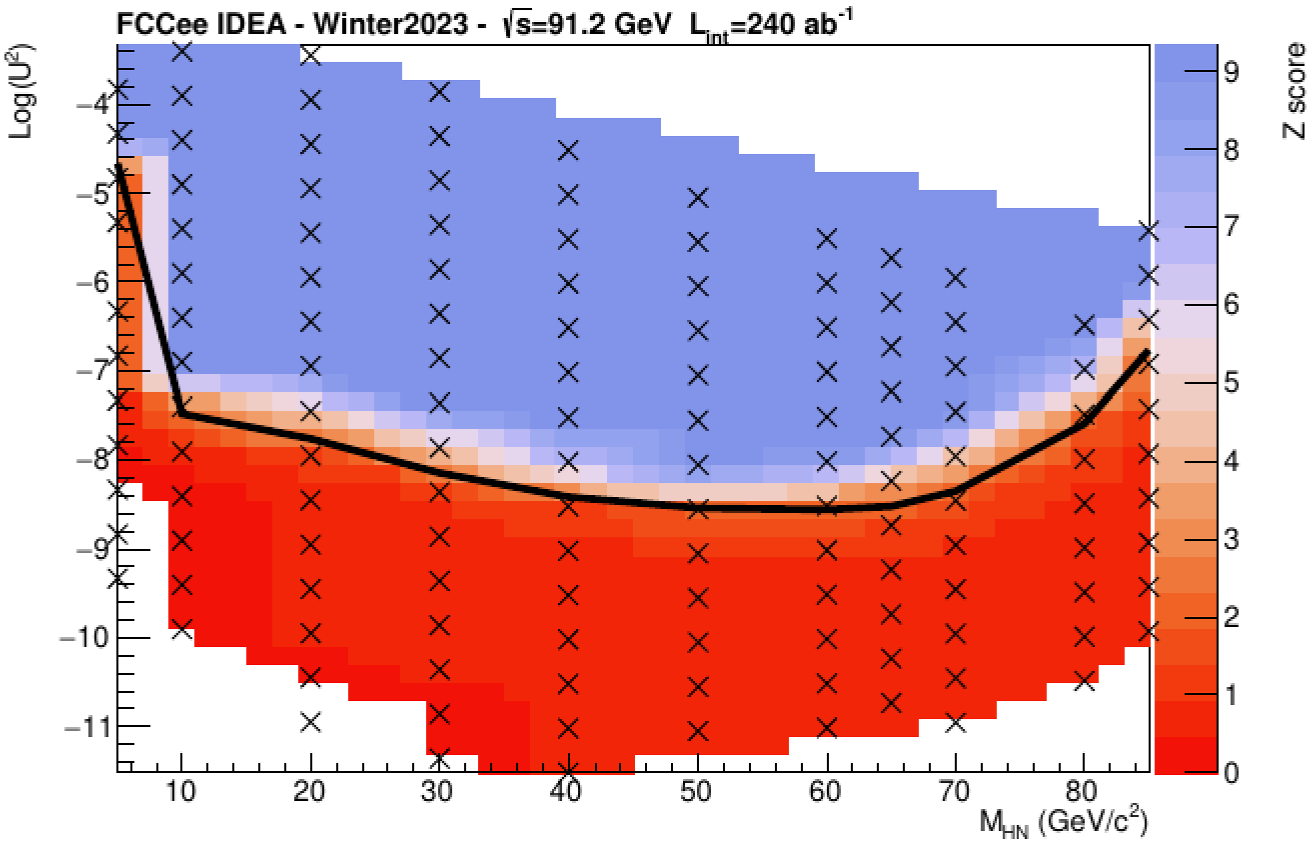
About five times values r_{vxp} for extreme tails of backgrounds

Prompt results

- Baseline: Integrated Lumi = $\mathbf{240\ ab^{-1}} \leftrightarrow 8 \times 10^{12}$ Z boson events
- Looking for U^2 producing 95% CL excess of events

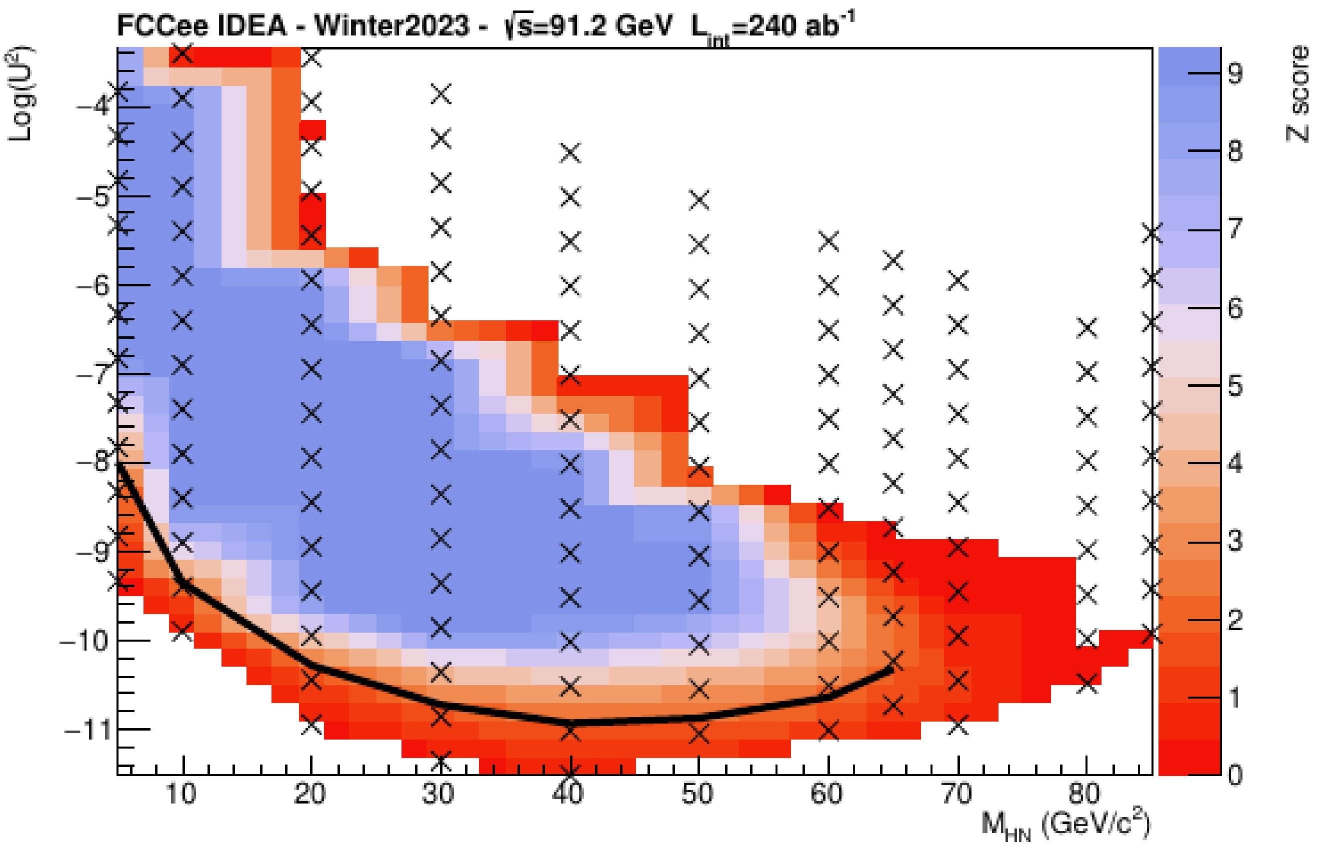
$$\text{For each HNL mass } M\text{:}\quad P[n < b \mid HNL(M, U^2)] = 1 - \text{CL}$$

b = #background events

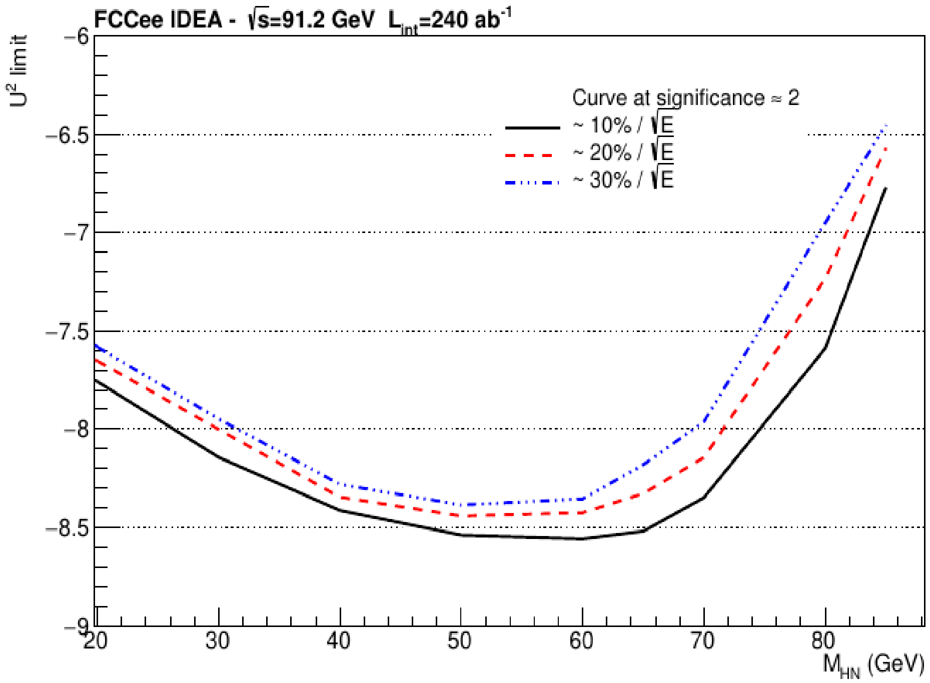


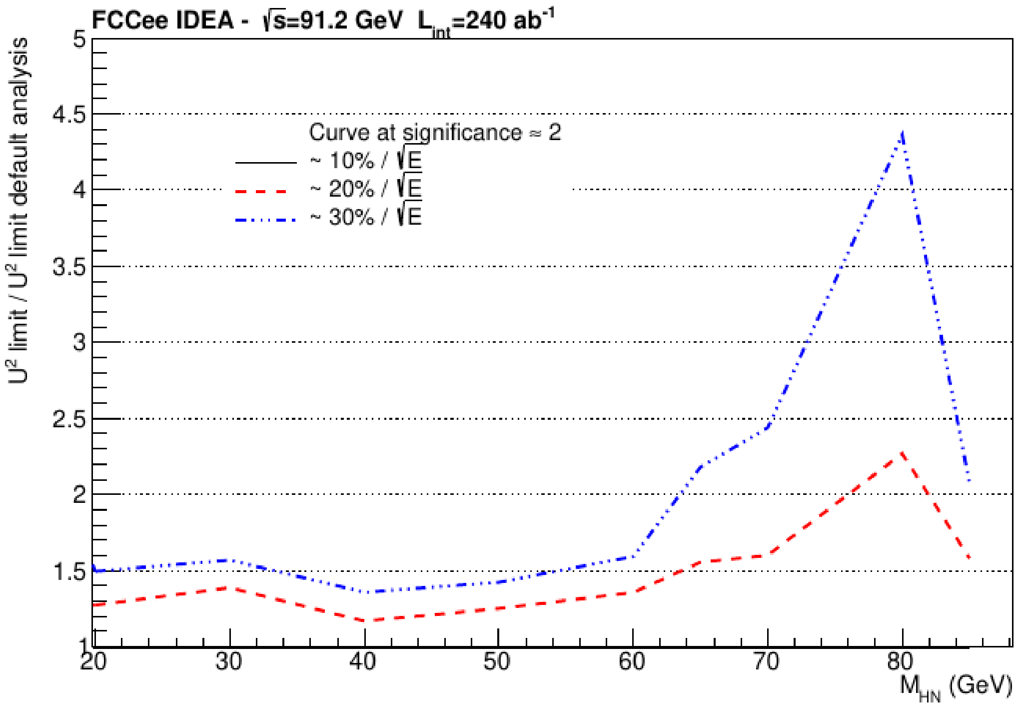
LLP results

Backgrounds=0: sensitivity curve defined as points in parameter space where 3 events are expected after cuts



Dependence on hadronic resolution





Window for baseline study from DELPHES

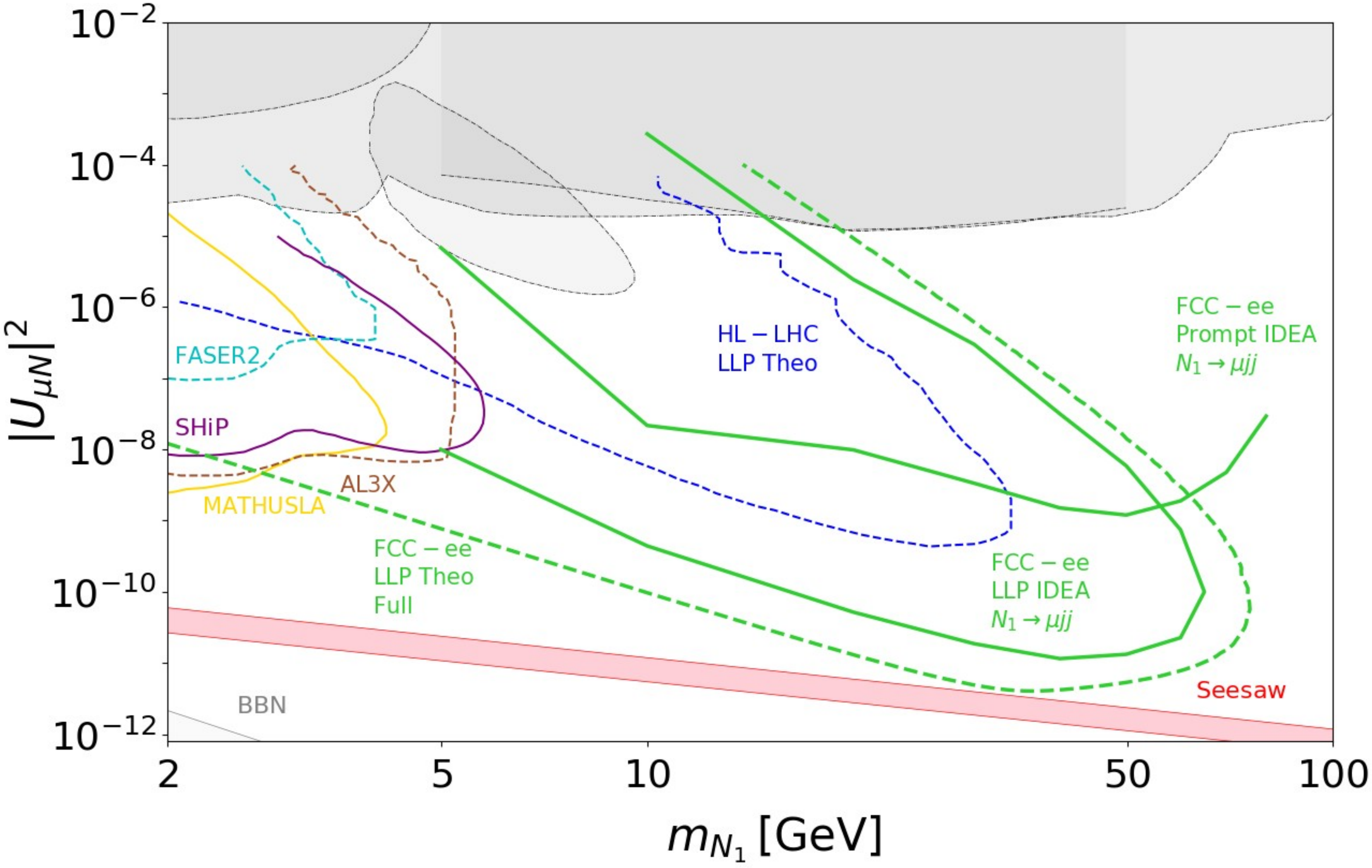
$$M_{N_1} \pm 2 \times 10\% \times \sqrt{M_{N_1} / \,\mathrm{GeV}}$$

Assume that for different resolutions enlarge the window accordingly.

Assume signal efficiency always the same

Calculate number of background events for enlarged window, and calculate significance

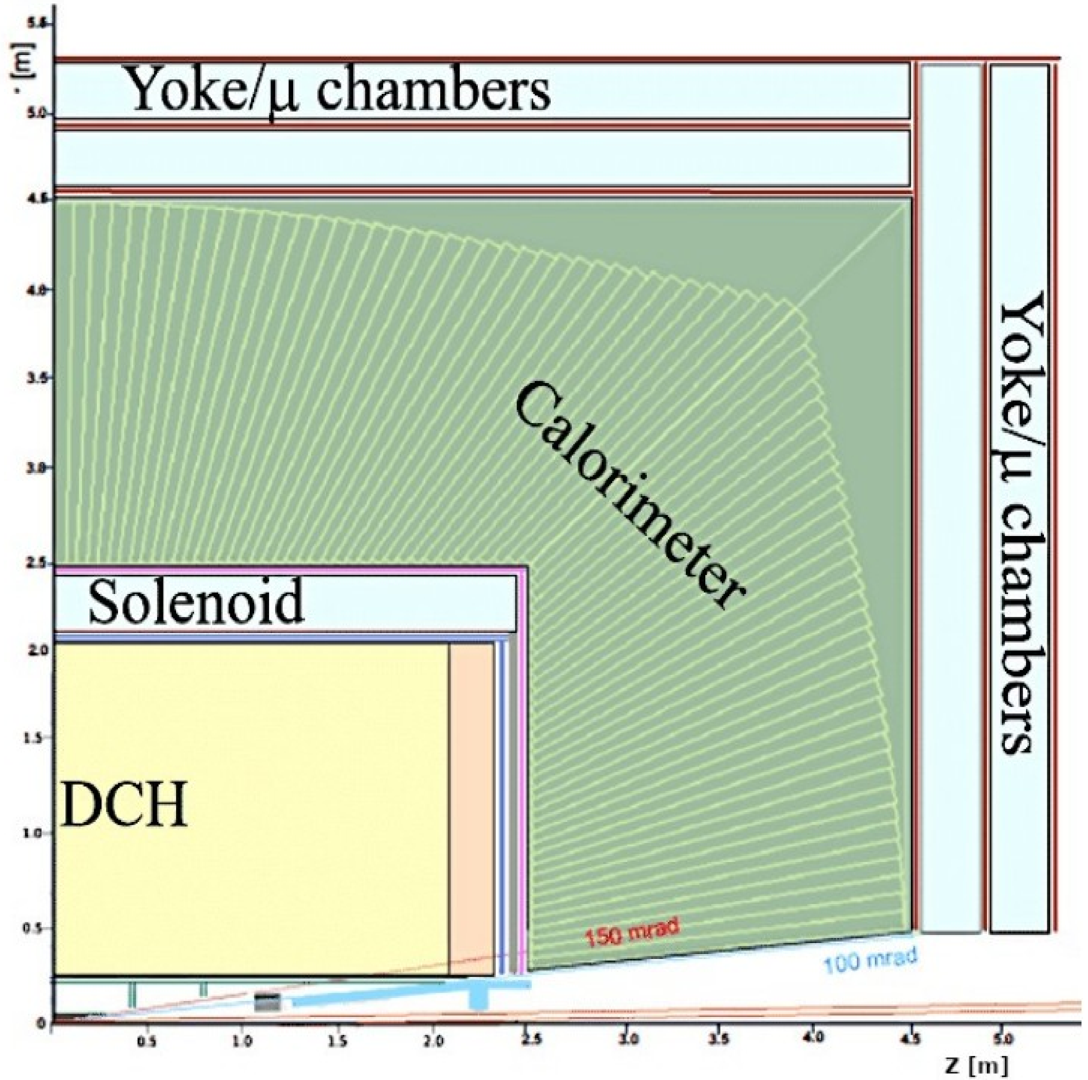
Final result



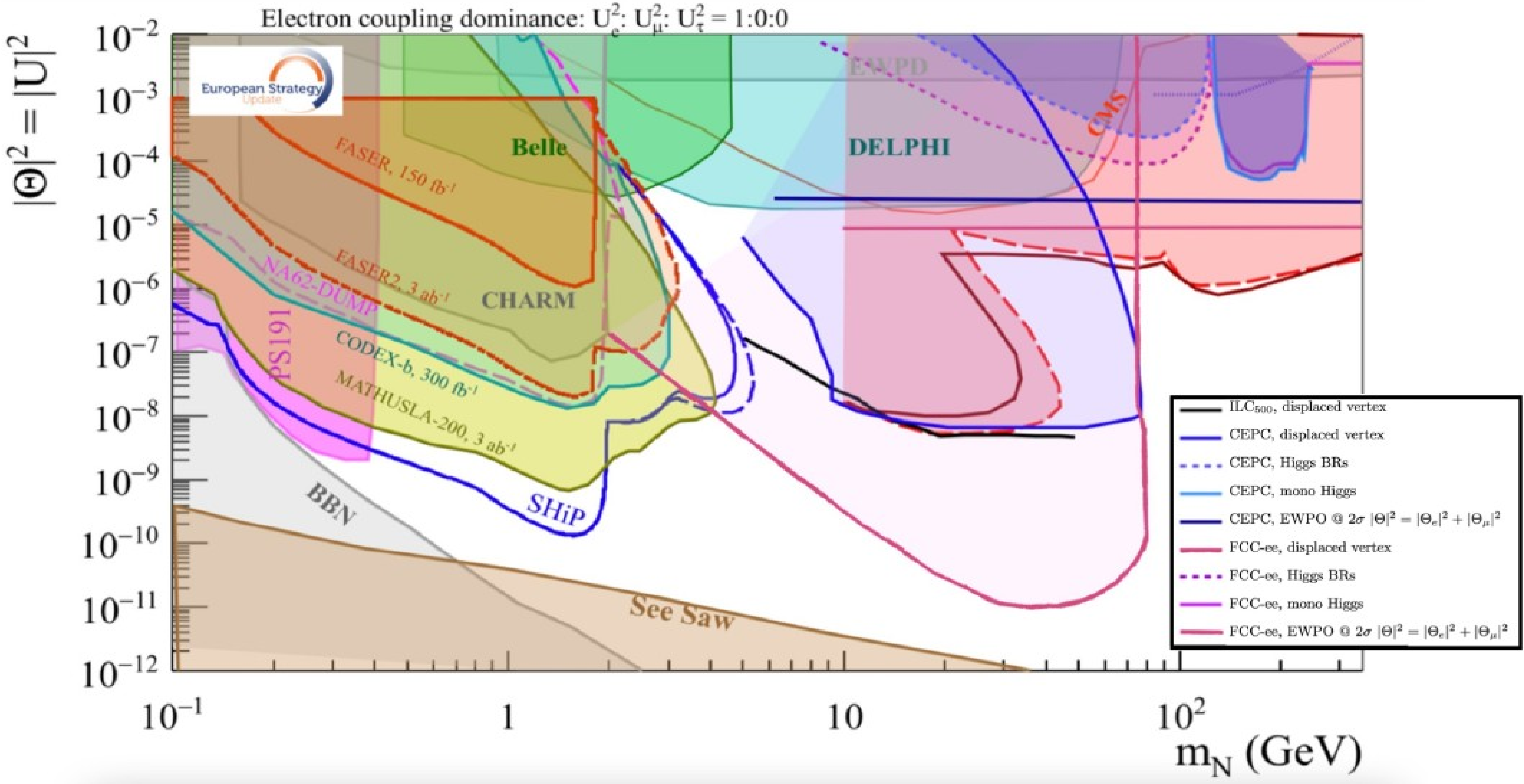
Backup

IDEA concept

- Muon chambers
  - µRwell in the return yoke
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - Preshower µRwell
- Thin superconducting solenoid
  - 2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°
- Transparency for tracking
  - Si pixel vertex detector
  - Drift Chamber
  - Si wrappers (strips)
- Beam Pipe: R ~ 1.5 cm



Slide by R.Ferrari



Electron coupling dominance: U_e^2: U_μ^2: U_τ^2 = 1:0:0
$|\Theta|^2 = |U|^2$
European Strategy Update
EWPD
Belle
DELPHI
CMS
FASER, 150 fb^{-1}
FASER2, 3 ab^{-1}
CHARM
NA62-DUMP
PS191
CODEX-b, 300 fb^{-1}
MATHUSLA-200, 3 ab^{-1}
SHiP
BBN
See Saw
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
1
10
10^2
m_N (GeV)
ILC$_{500}$, displaced vertex
CEPC, displaced vertex
CEPC, Higgs BRs
CEPC, mono Higgs
CEPC, EWPO @ 2σ $|\Theta|^2 = |\Theta_e|^2 + |\Theta_\mu|^2$
FCC-ee, displaced vertex
FCC-ee, Higgs BRs
FCC-ee, mono Higgs
FCC-ee, EWPO @ 2σ $|\Theta|^2 = |\Theta_e|^2 + |\Theta_\mu|^2$