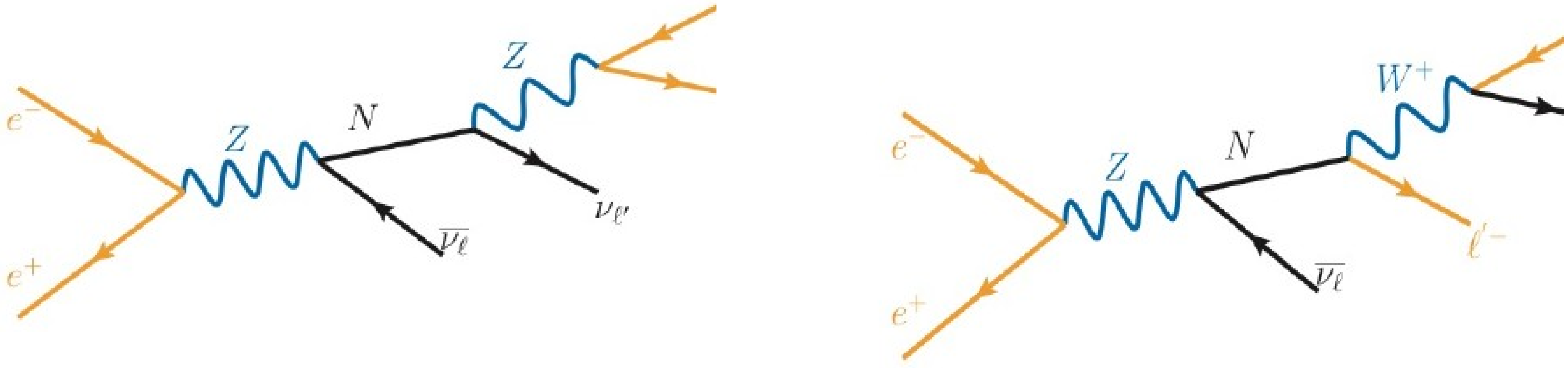
Searches for prompt decays of HNLs at FCC-ee

G.Polesello

INFN Sezione di Pavia

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)

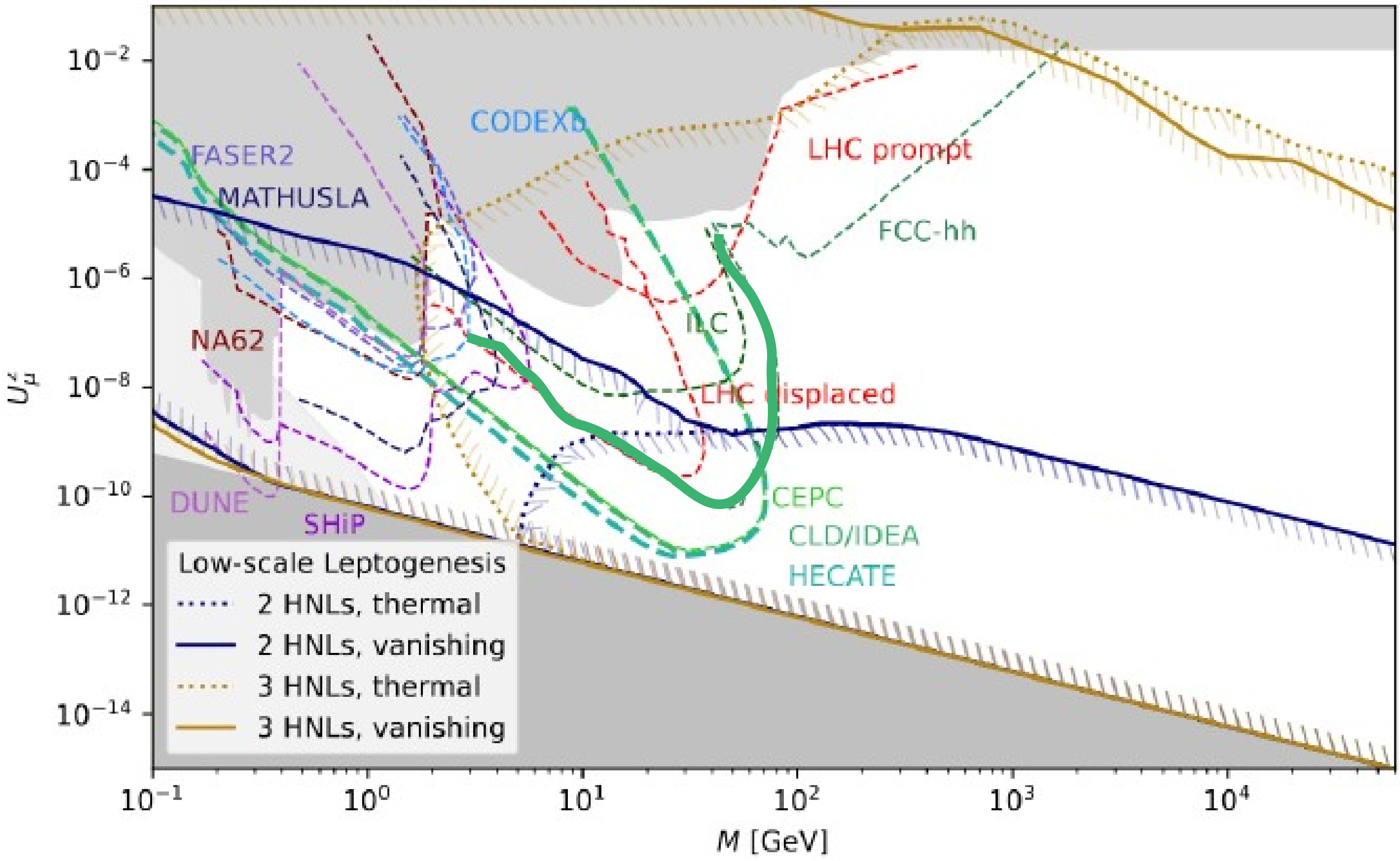
$$\Gamma_N \simeq c_{\mathrm{dec}} \frac{a}{96\pi^3} U^2 M^5 G_F^2$$

a~12

M.Drewes arXiv:2210.17110

Expectations

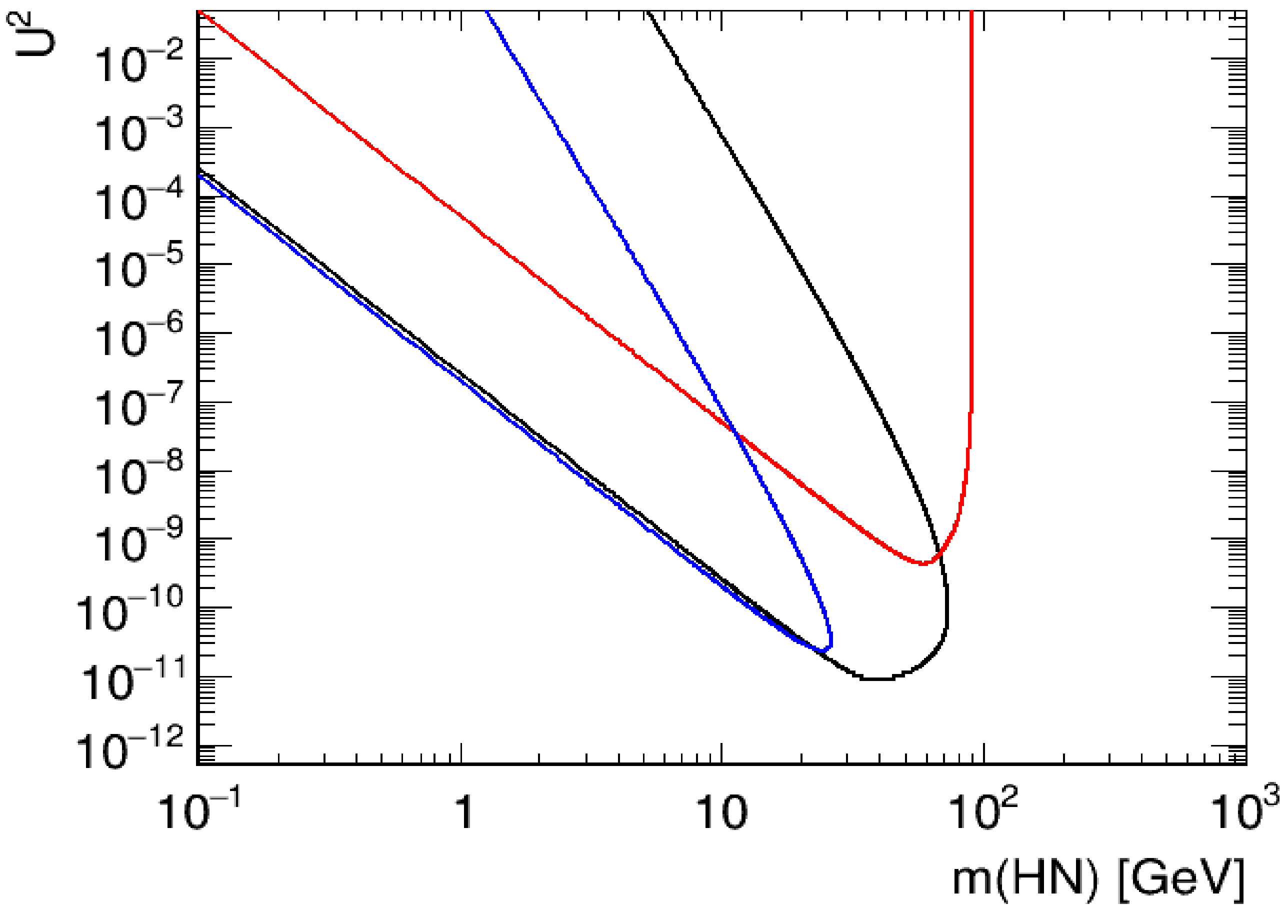
ArXiv:2203.05502



Assume for FCC-ee $5\text{x}10^{12}$ Z produced

Thick green line: approximate CEPC reach

Focus on production rates at FCC-ee 91 GeV

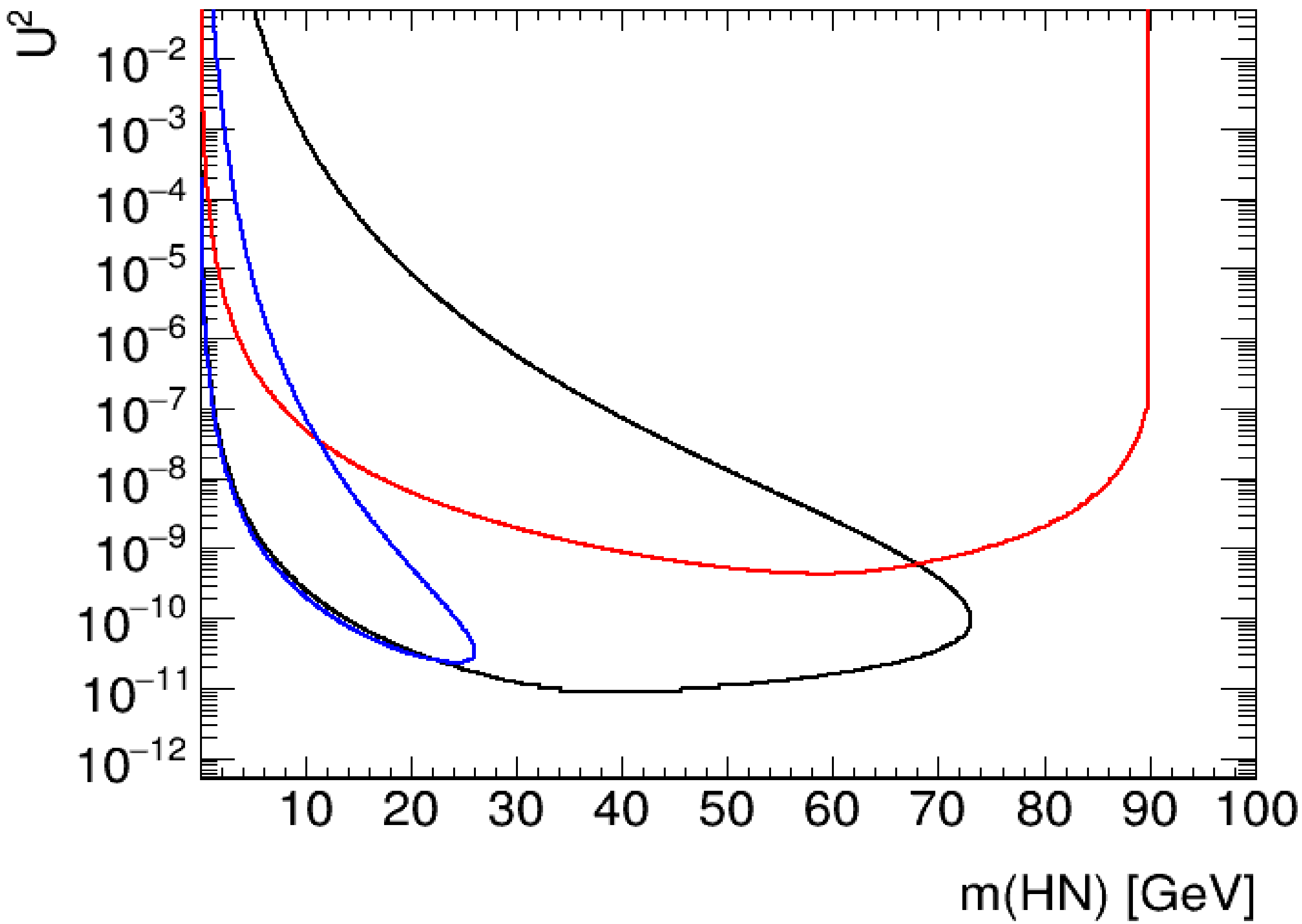


Assume 1 flavour active
$5x10^{12}$Z at Z peak
Require 100 events for prompt decay and
4 events for long-lived

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

Linear scale



Assume 1 flavour active

5×10^{12} Z at Z peak

Require 100 events for prompt decay and 4 events for long-lived

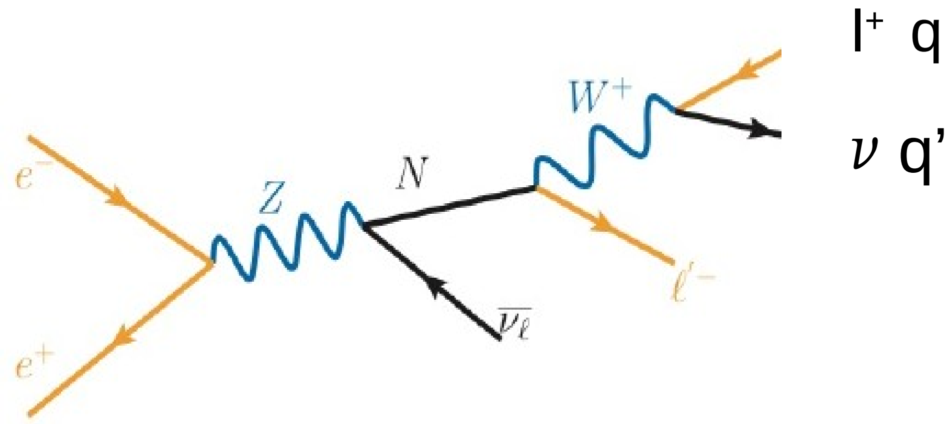
Red: Prompt: $0 < \lambda < 1$ mm

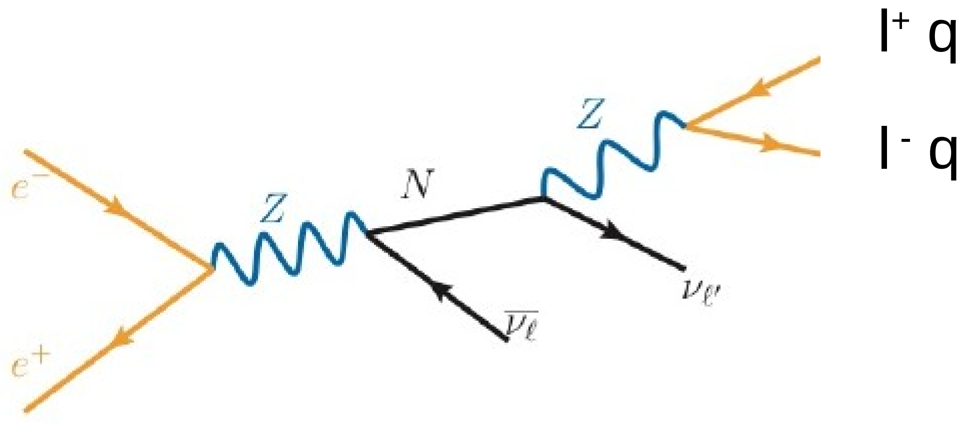
Black: ID decay $0.04 < \lambda < 150$ cm

Blue: Calo decay $200 < \lambda < 450$ cm

Prompt decays dominate for $m_{HNL} > 70$ GeV

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

Previous experimatal FCC/CEPC studies

FCC: Master thesis by Sissel Bay Nielsen(Copenhagen 2017)

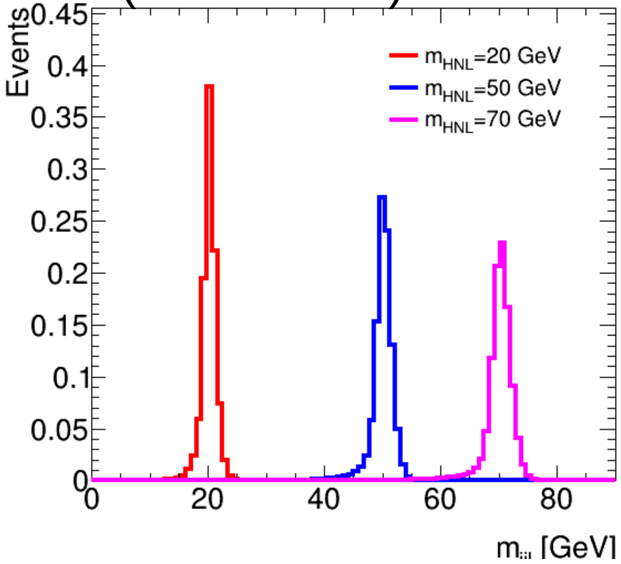
Two CEPC papers

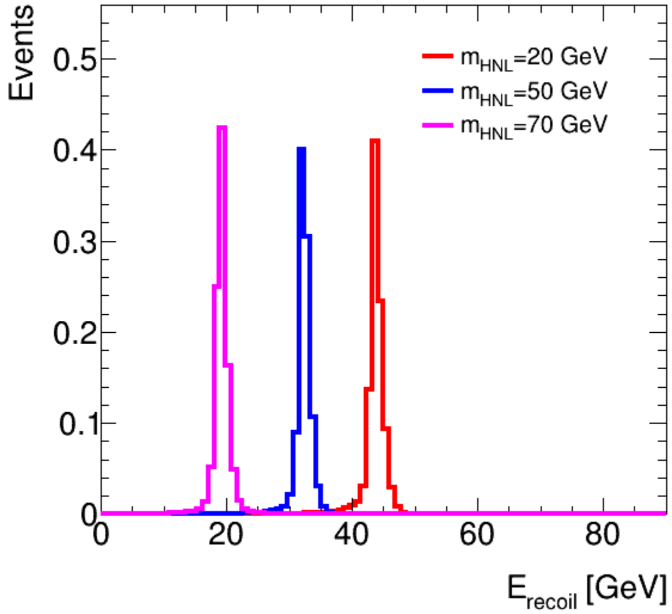
- arXiv:1903.02570:2jet+lep
  m_{HNL}:10-90 GeV
- arXiv:2201.05831 Monojet+lep
  m_{HNL}: 3-15 GeV

Concentrate on lepton+jj decays:

- Highest BR
- Full reconstruction of HNL mass
- Full reconstruction of recoil neutrino

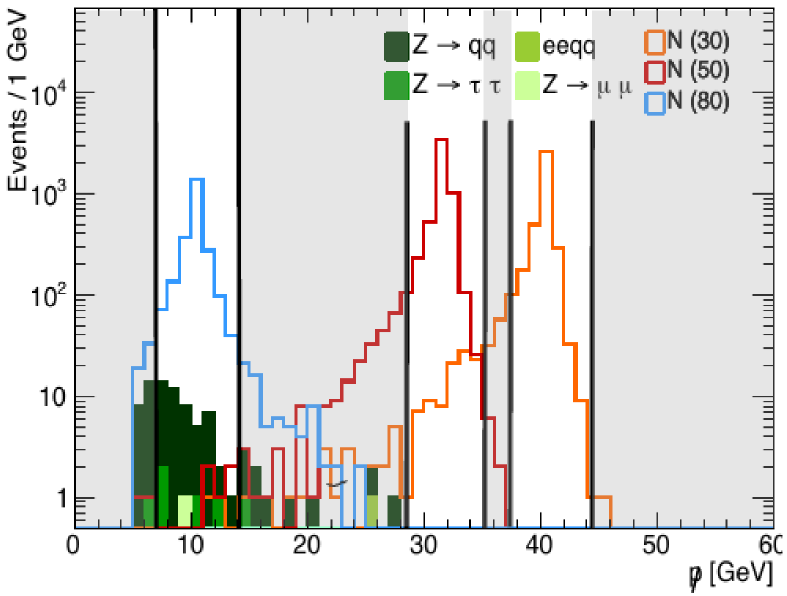
IDEA DELPHES card (GP+N.Valle)

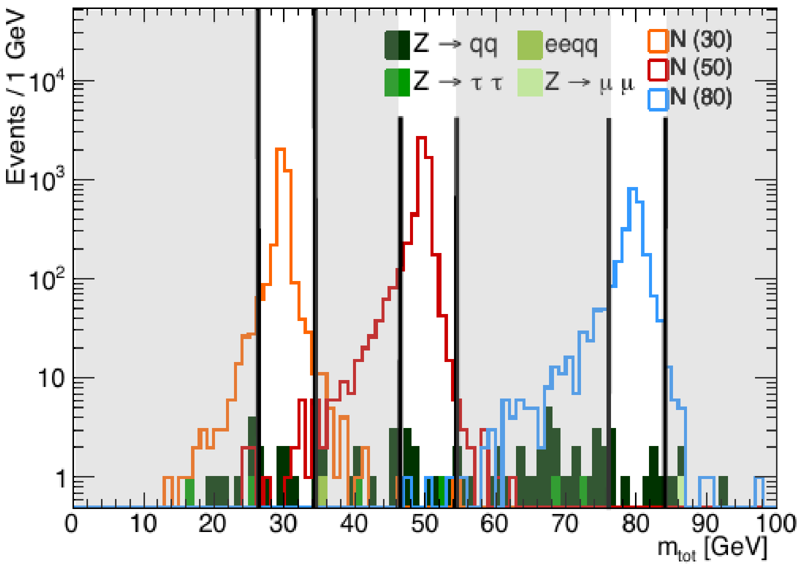


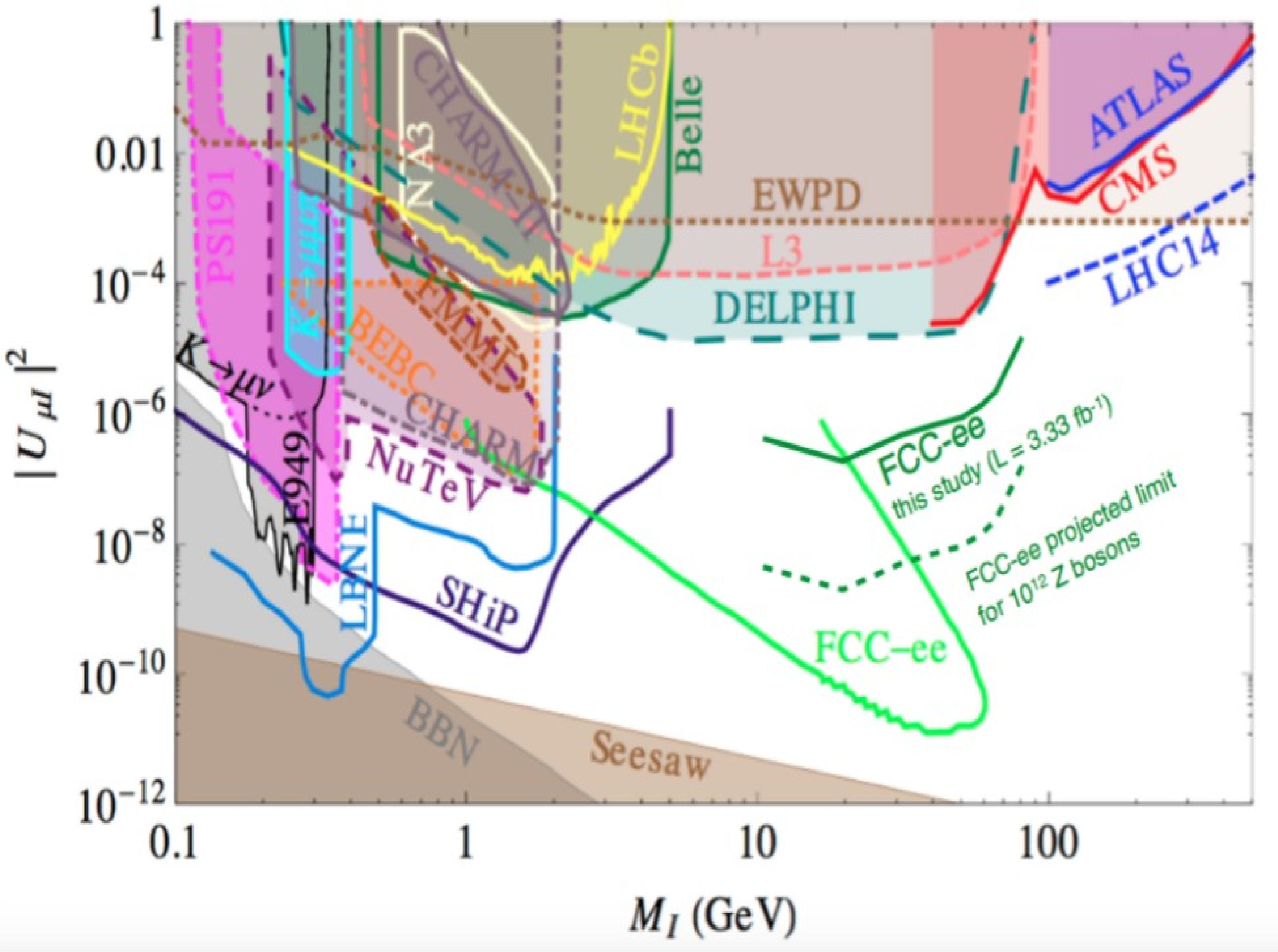


Results (FCC)

Sissel Bay Nielsen's Master thesis







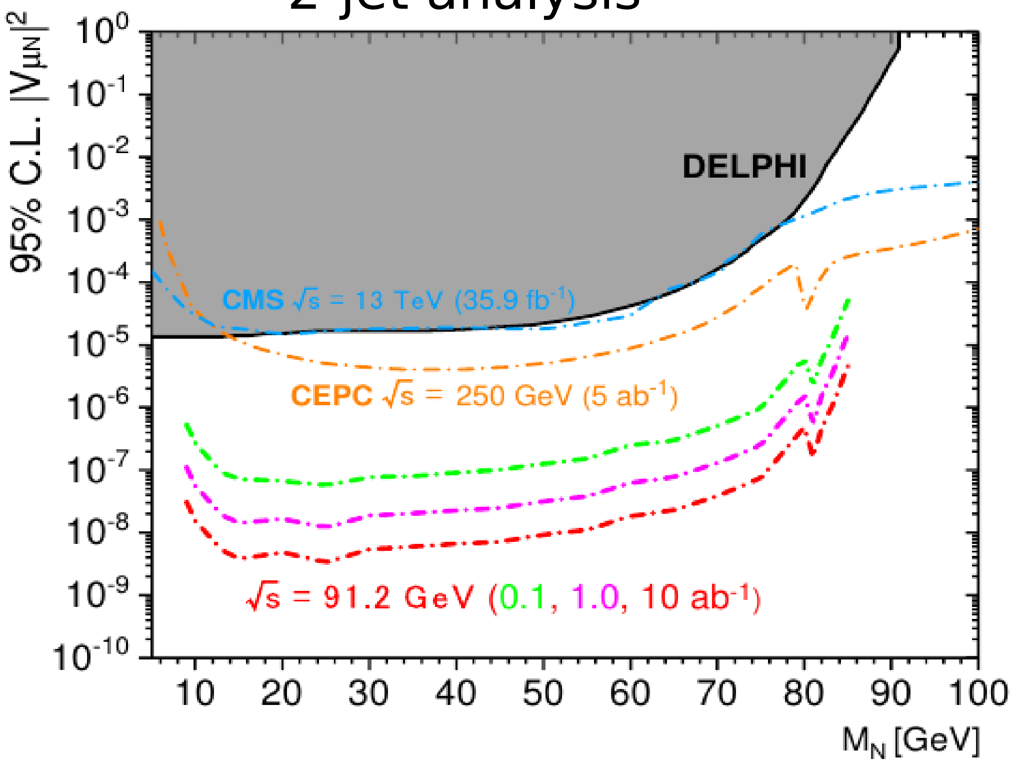
DELPHES for CLIC detector, μjj channel

Study performed for 3.3 fb^{-1} (10^8Z)

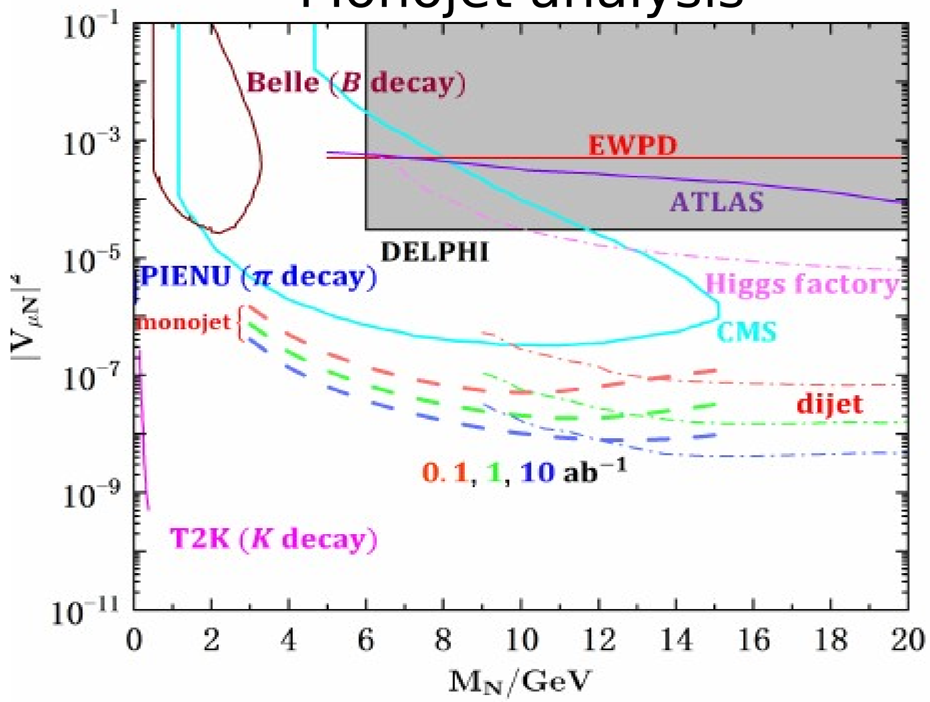
Difficult to extrapolate to 5×10^{12} Z because of MC statistics

Results (CEPC)

2-jet analysis



Monojet analysis



Results both for ejj and μ jj final state.

All Z decays and 4-fermion backgrounds considered

Main background for monojet analysis $Z \to \tau\tau$

Coverage extended down to 3 GeV

Ongoing work

Framework: FCC PED BSM group (conveners R. Gonzalez Suarez, GP)

Aim: Evalute coverage of parameter space based on all relevant signatures in FCC conditions based on:

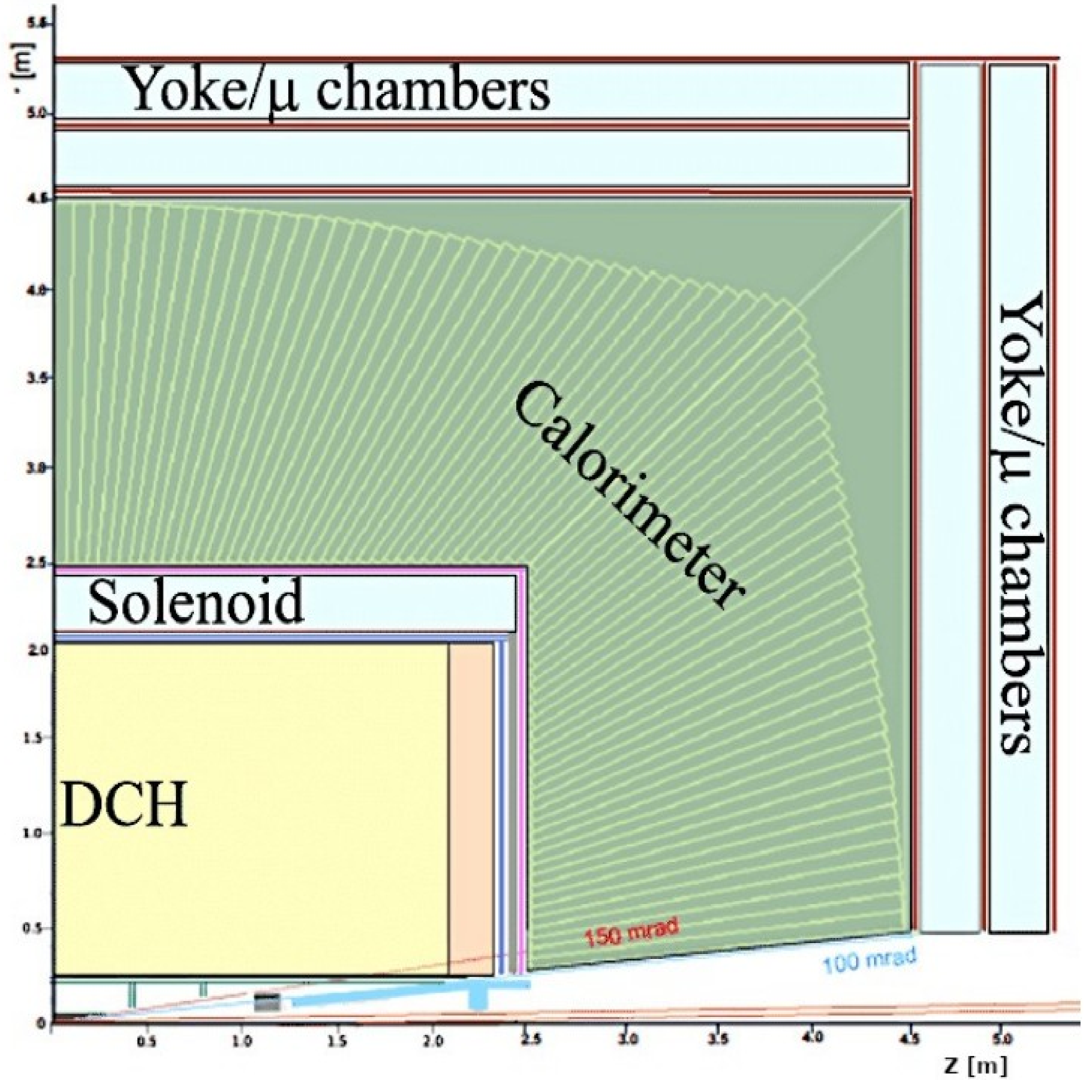
Tools: Official FCC analysis software suite

- Common officially generated background samples
- Signal samples generated with MG5+PY8
- DELPHES parametrised simulation of IDEA Detector
- DELPHES output stored in EDM4HEP format and analysed based on FCC analysis software

For LLP signatures see talk by M. Drewes today and the nice review talk by S. Kulkarni at last FCC physics week in Krakow.

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

FCC-ee / CepC general requirements

- $\Delta(1/p_T)$
  - high precision measurement at the end of tracker
- $\sigma_{r\Phi}$
  - finely segmented vertex detector
- Challenging requirements for detector materials

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

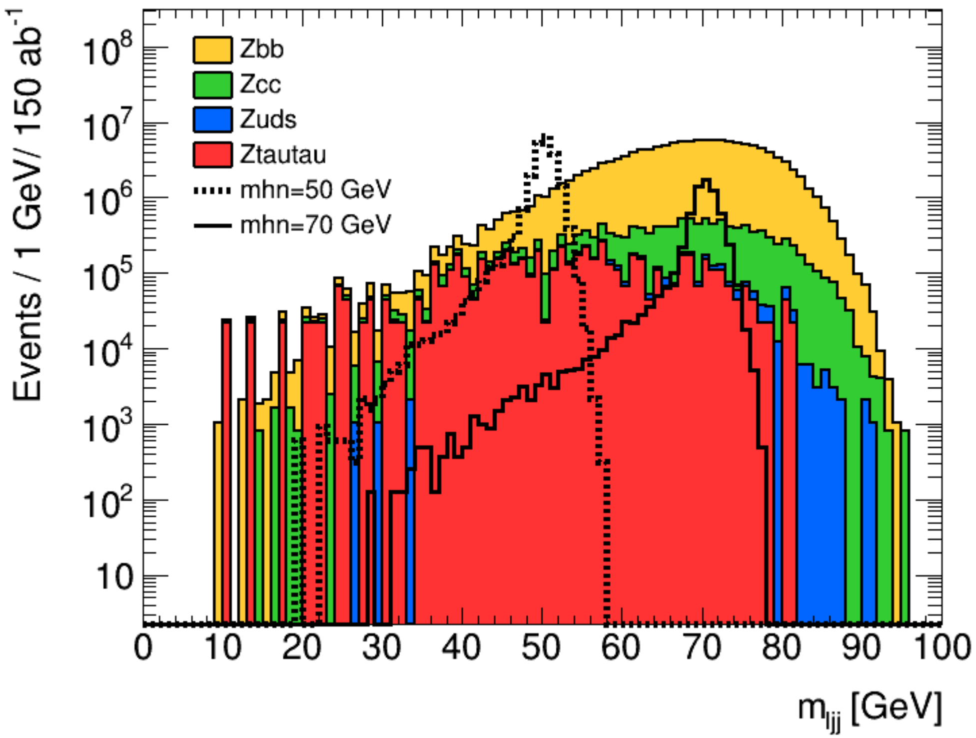
Slide by R.Ferrari

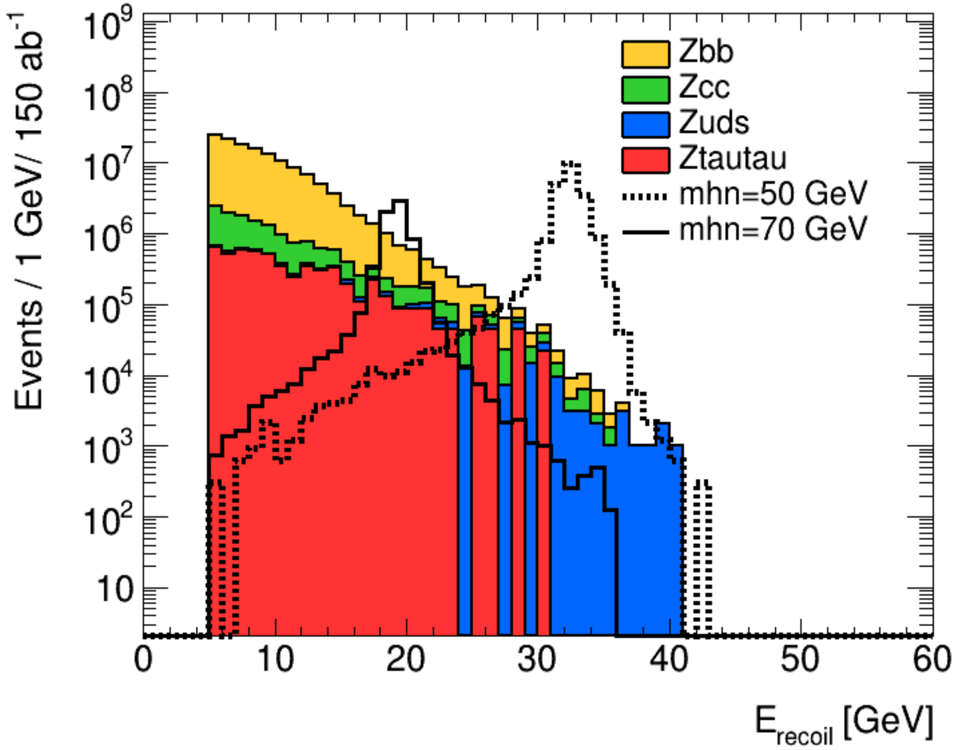
DELPHES setup for Spring 2021:

- Detailed parametrisation of IDEA tracker, including covariance matrices
- Calo resolution: EM 11%/sqrt(E), HAD: 30%/sqrt(E), 1% constant term
- Particle flow approach to jet reconstruction

HN→μjj: preliminary distributions

N. Valle, GP





Comparison of distributions of m_{jjl} and E_{recoil} for signal (U2=1e^{-4}) and all Z decay backgrounds from official Spring 2011 production, after angular selections inspired by the existing FCC study except cut on impact on mass window

(Z→ tau tau includes also Z→ muons)

HN→μjj: the role of vertex detector

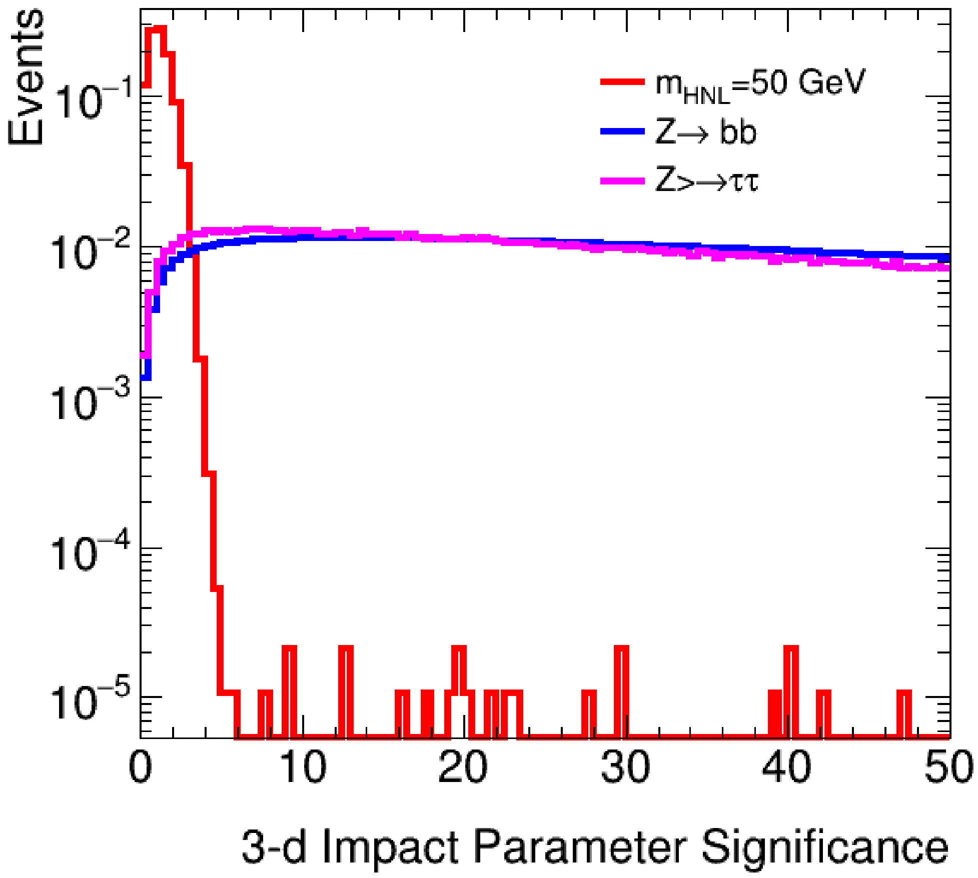
N. Valle, GP

Very detailed parametrisation of tracking performance of IDEA Implemented in DELPHES - FCC

Heavily used for LLP studies

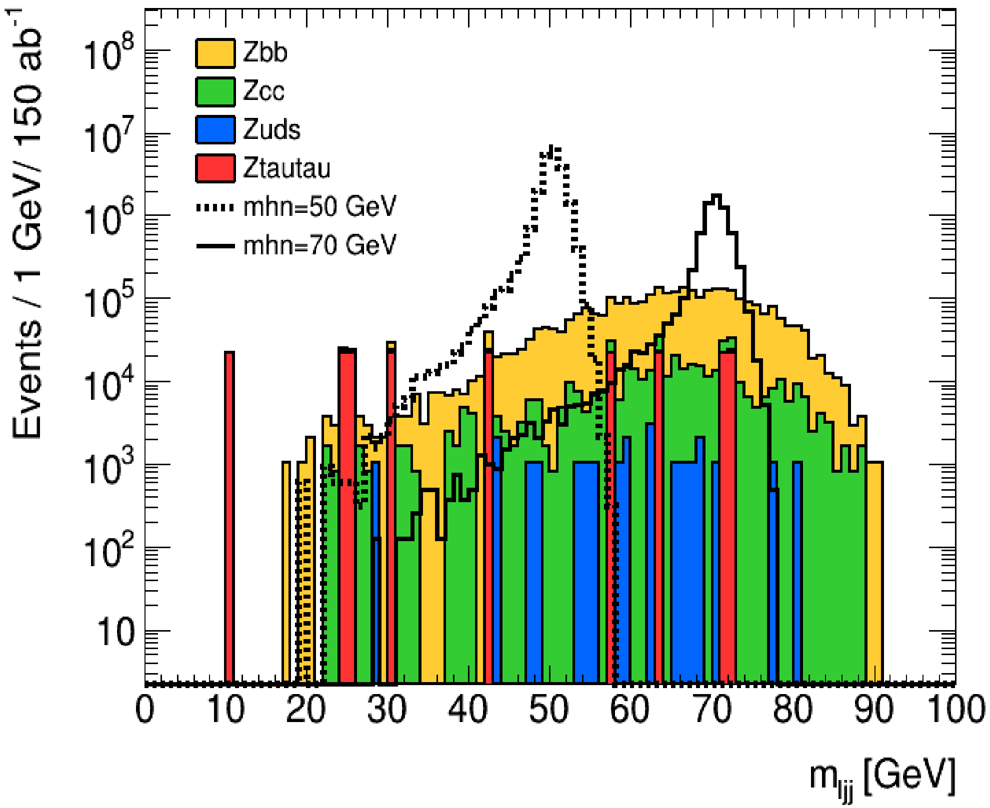
For prompt studies, strong rejection of backgrounds from $Z \rightarrow jj$ and $Z \rightarrow \tau\tau$ based on cut on impact parameter of muon.

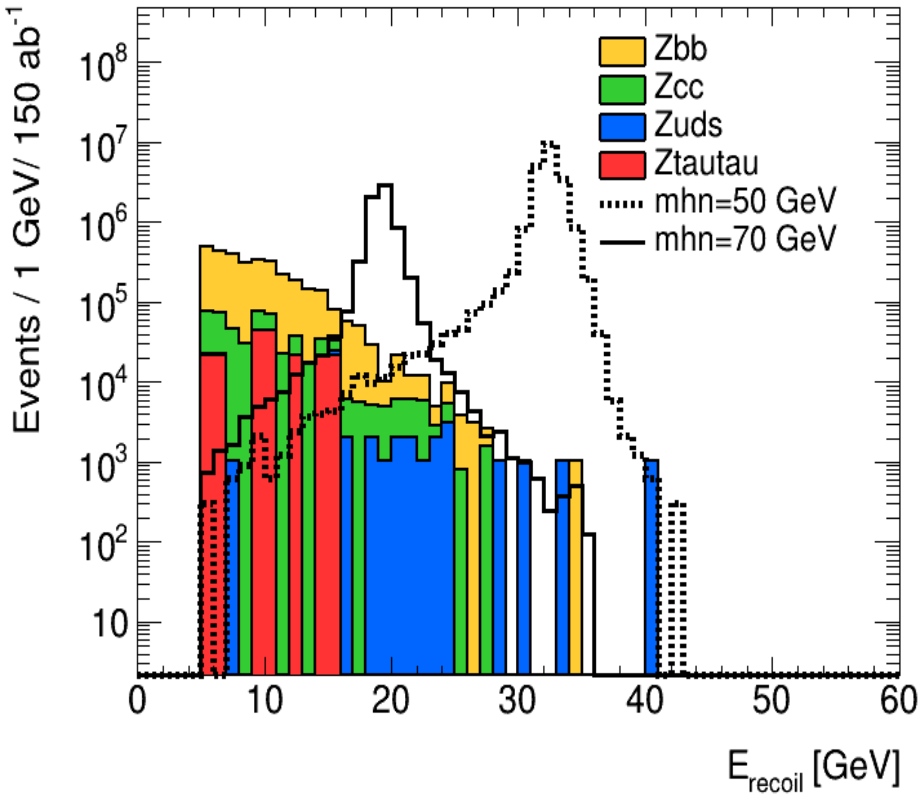
Expect even better rejection when New ML-based b-tagging algorithms in ntuples



After cut on muon impact parameter

N. Valle, GP



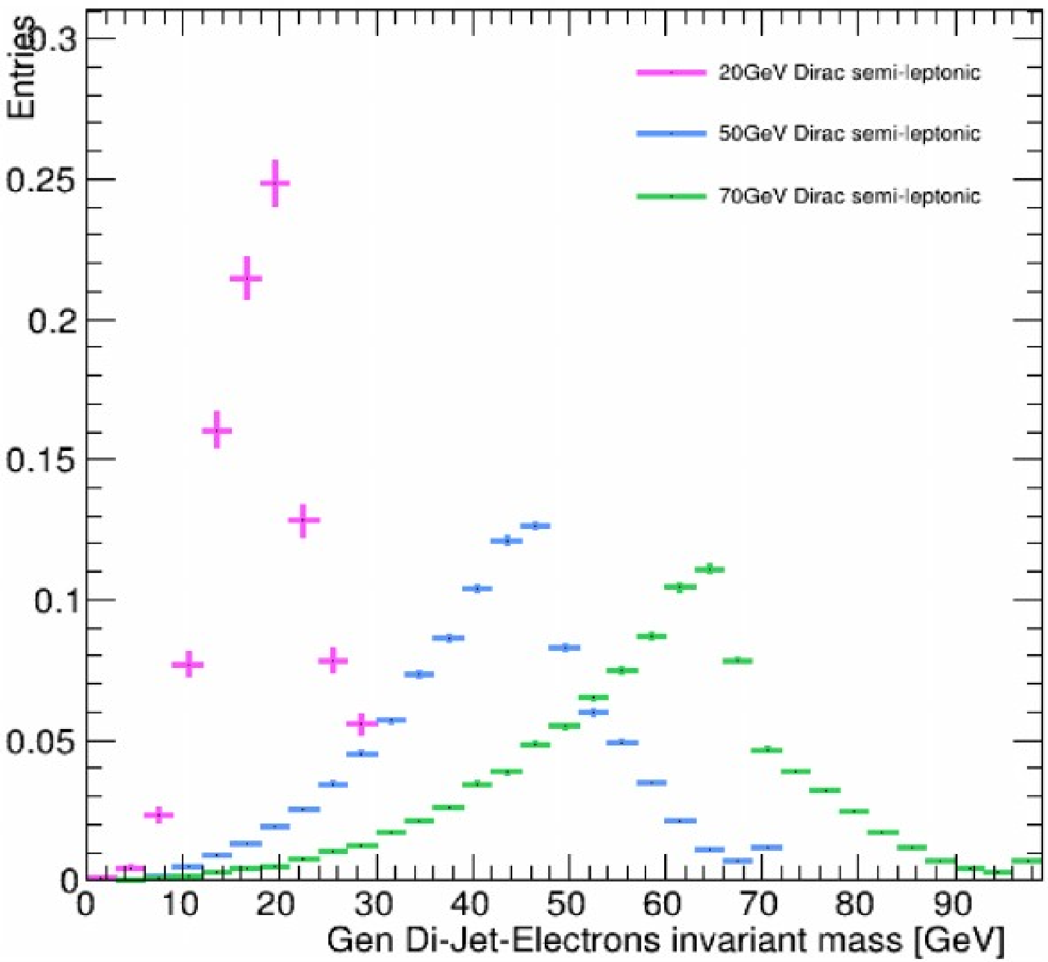


Work in progress to understand the impact of $e^+e^- \rightarrow 4$ fermions, in particular irreducible $e^+e^- \rightarrow \mu\ \nu$ qq

HN→ejj: first look at generator level

A. Sfyrla,
D. Moulin,
P. Kontaxakis

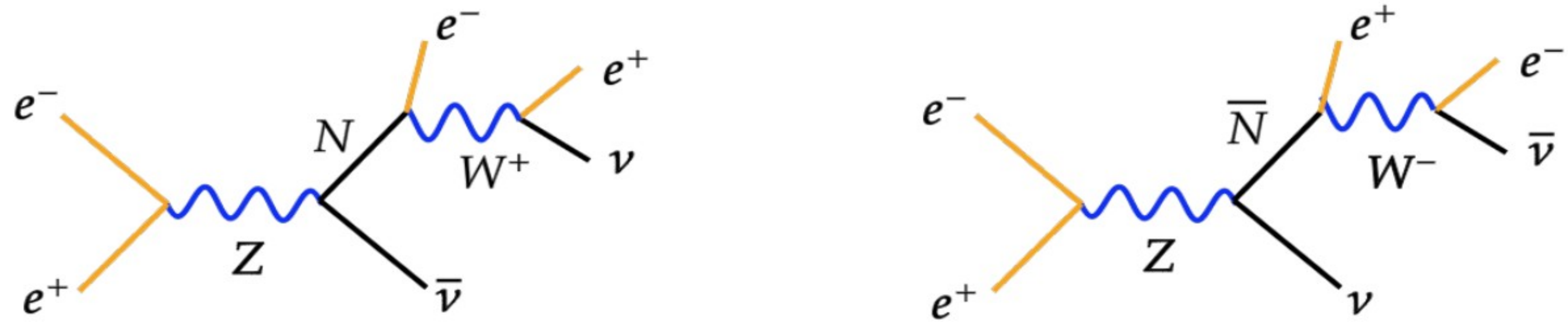
GEN Level



Dirac versus Majorana

Blondel et al
arXiv:2105.06576

No same-sign lepton signature as for W→ l HNL, rely on final state kinematics



- Dirac neutrinos $(e^+e^- \to Z \to \nu\bar{N};\ e^+e^- \to Z \to \bar{\nu}N)$

$$\frac{1}{\sigma_{N,\bar{N}}}\frac{d\sigma_{N,\bar{N}}}{d\cos\theta} \propto \left(g_R^2\,(1 \mp \cos\theta)^2 + g_L^2\,(1 \pm \cos\theta)^2 + \frac{M_N^2}{m_Z^2}\,(g_L^2 + g_R^2)\ \sin^2\theta \right)$$

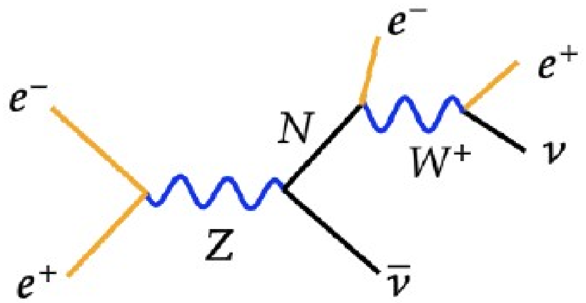
- Majorana neutrinos $(e^+e^- \to Z \to \nu N)$

$$\frac{1}{\sigma_N}\frac{d\sigma_N}{d\cos\theta} \propto \left(1 + \cos^2\theta + \frac{M_N^2}{m_Z^2}\sin^2\theta \right)$$

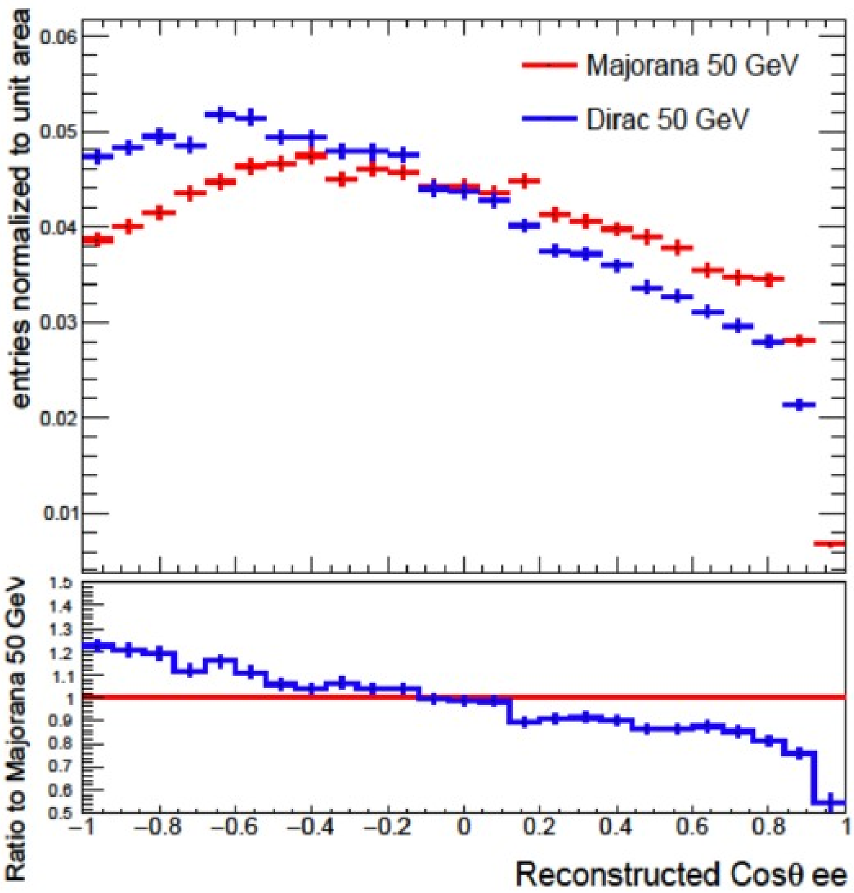
Relevant both for prompt and LLP, LLP has additional handle in lifetime

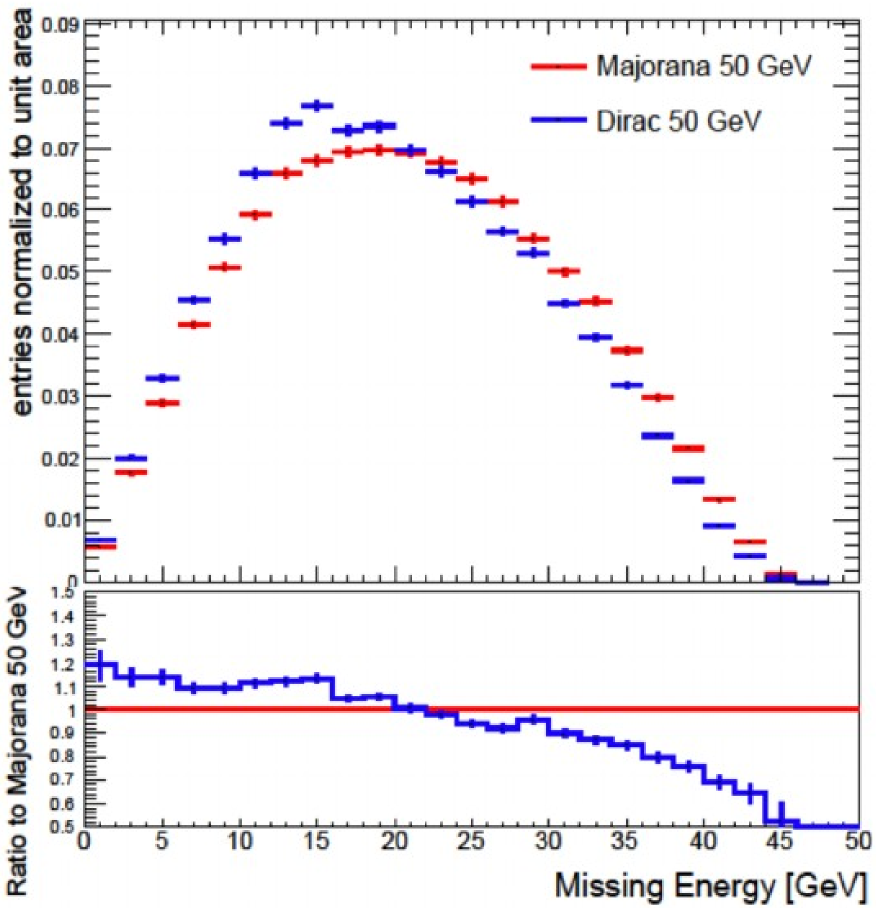
Master thesis
Tanishq Sharma

Dirac versus Majorana: HNL→ $e^+e^-\nu$



Define final state variables for which difference Dirac-Majorana can be observed.



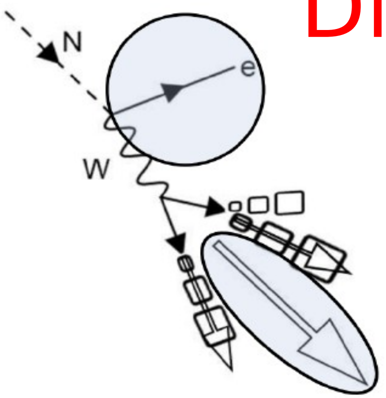


17/02/23

Missing energy and angle between electrons seem promising

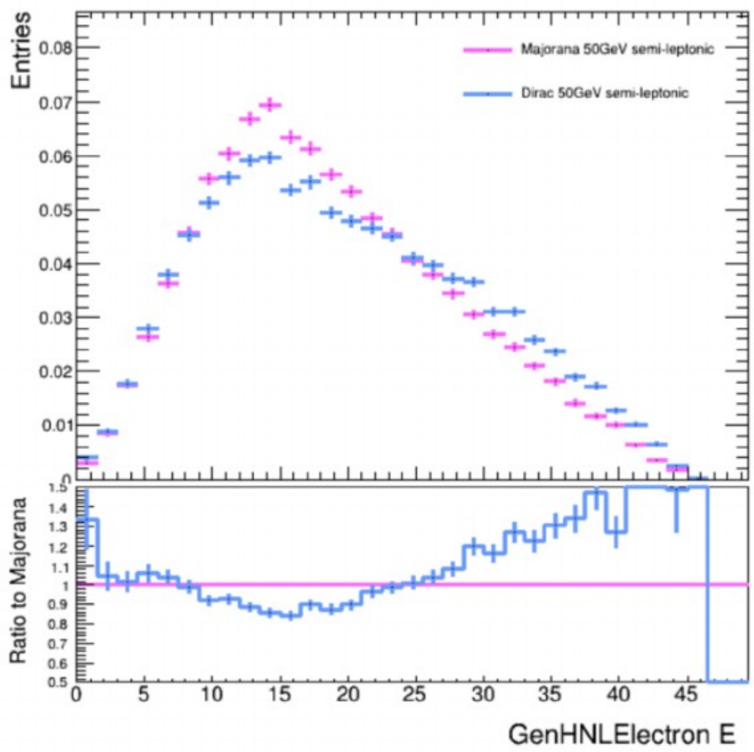
Dirac versus Majorana: HNL→ ejj

A. Sfyrla,
D. Moulin,
P. Kontaxakis

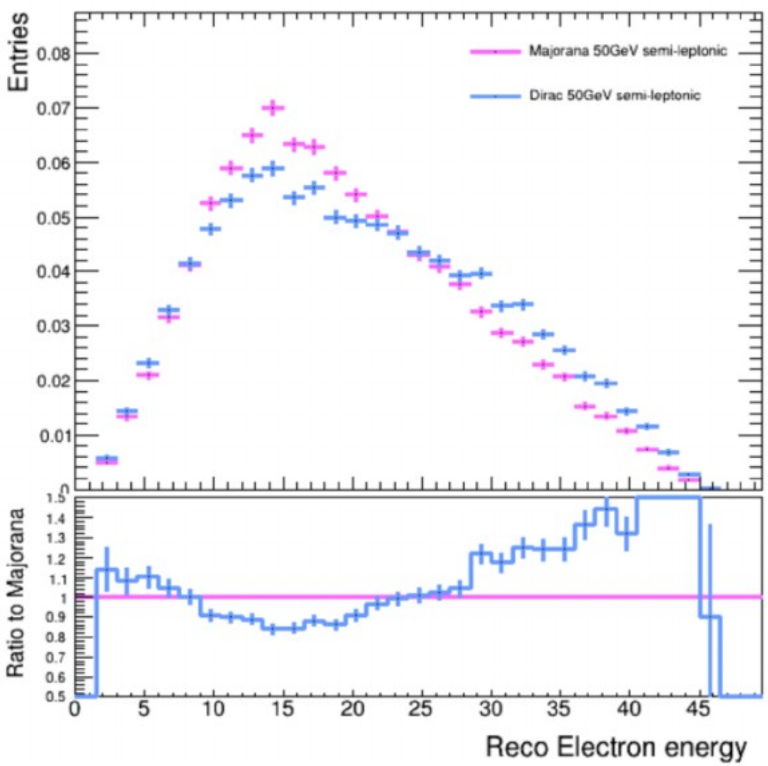


Ongoing study: define variables at generator level,
verify that discrimination power remains at reco level (DELPHES)

GEN Level



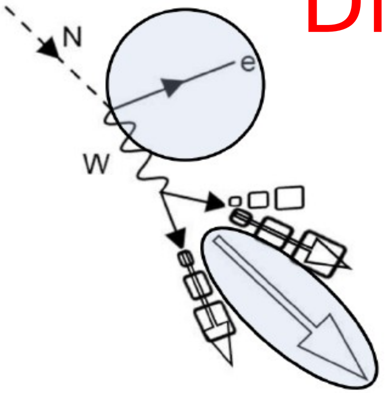
RECO Level



Electron energy promising both at generator and reco level

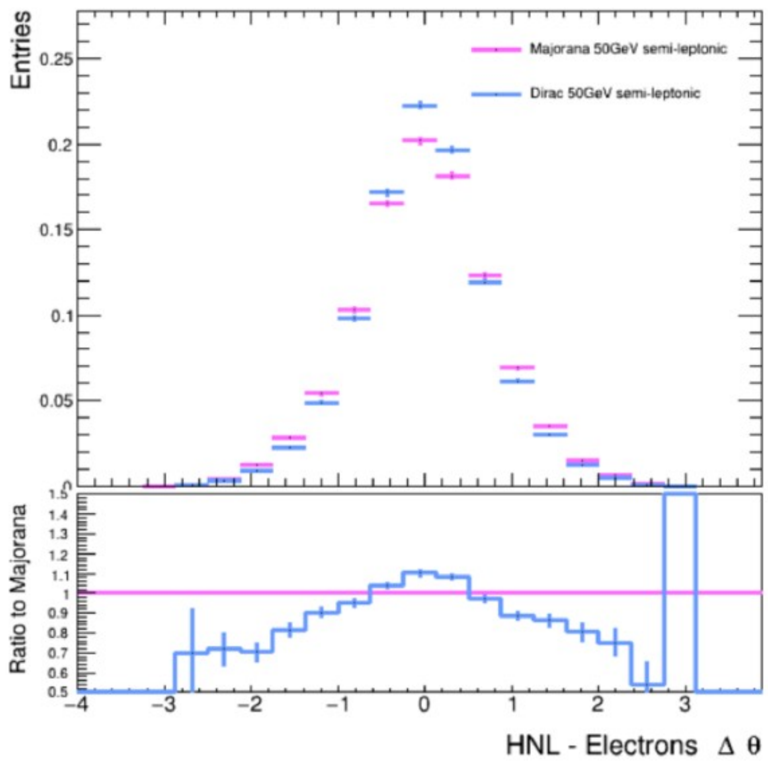
Dirac versus Majorana: HNL→ ejj

A. Sfyrla,
D. Moulin,
P. Kontaxakis

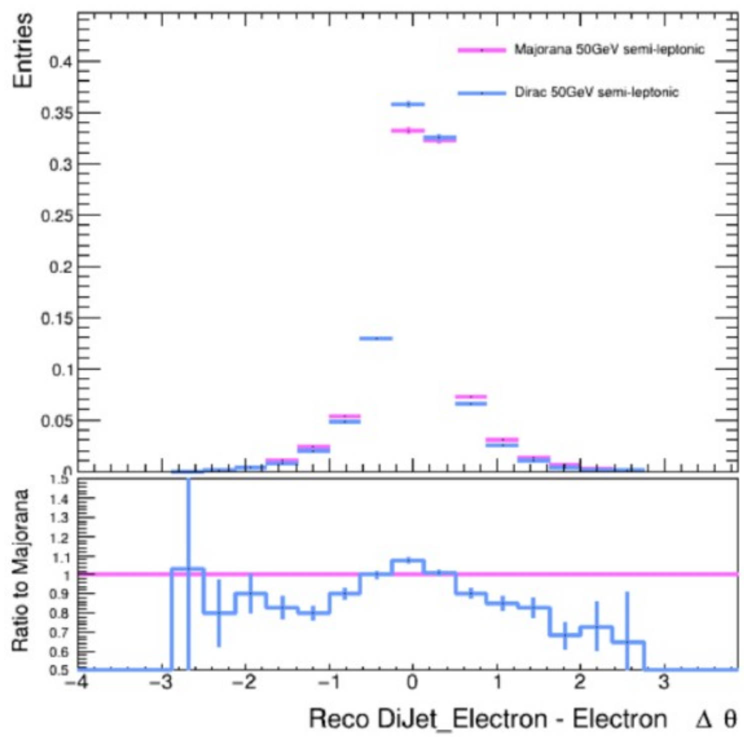


Ongoing study: define variables at generator level,
verify that discrimination power remains at reco level (DELPHES)

GEN Level



RECO Level



Other variable: angle between electron and HN

Conclusions

- HNL production is a flagship BSM physics channel for FCC-ee
- Coverage of very small mixing angles allowed by high statistics at the Z pole
- Complementary role of prompt and LLP signatures in covering relevant parameter space
- Lively activity in PED FCC BSM group to explore the most sensitive signatures both for prompt and LLP
- Promising studies ongoing for discrimination of Dirac and Majorana HNLs

Backup

Group organisation

Exp Conveners:

Rebeca Gonzalez-Suarez, GP

MC contact: Sarah Williams

Indico category:

https://indico.cern.ch/category/5664/

Very active LLP group chaired by Juliette Alimena (~10-15 people) with bi-weekly working meetings

Working on developing critical mass for prompt signatures

BSM physics

Enter your s

January 2023

- Jan 19 Searches for Long-Lived particles - planning

December 2022

- Dec 15 Searches for Long-Lived particles - planning
- Dec 08 Searches for Long-Lived particles - planning
- Dec 01 Searches for Long-Lived particles - planning

November 2022

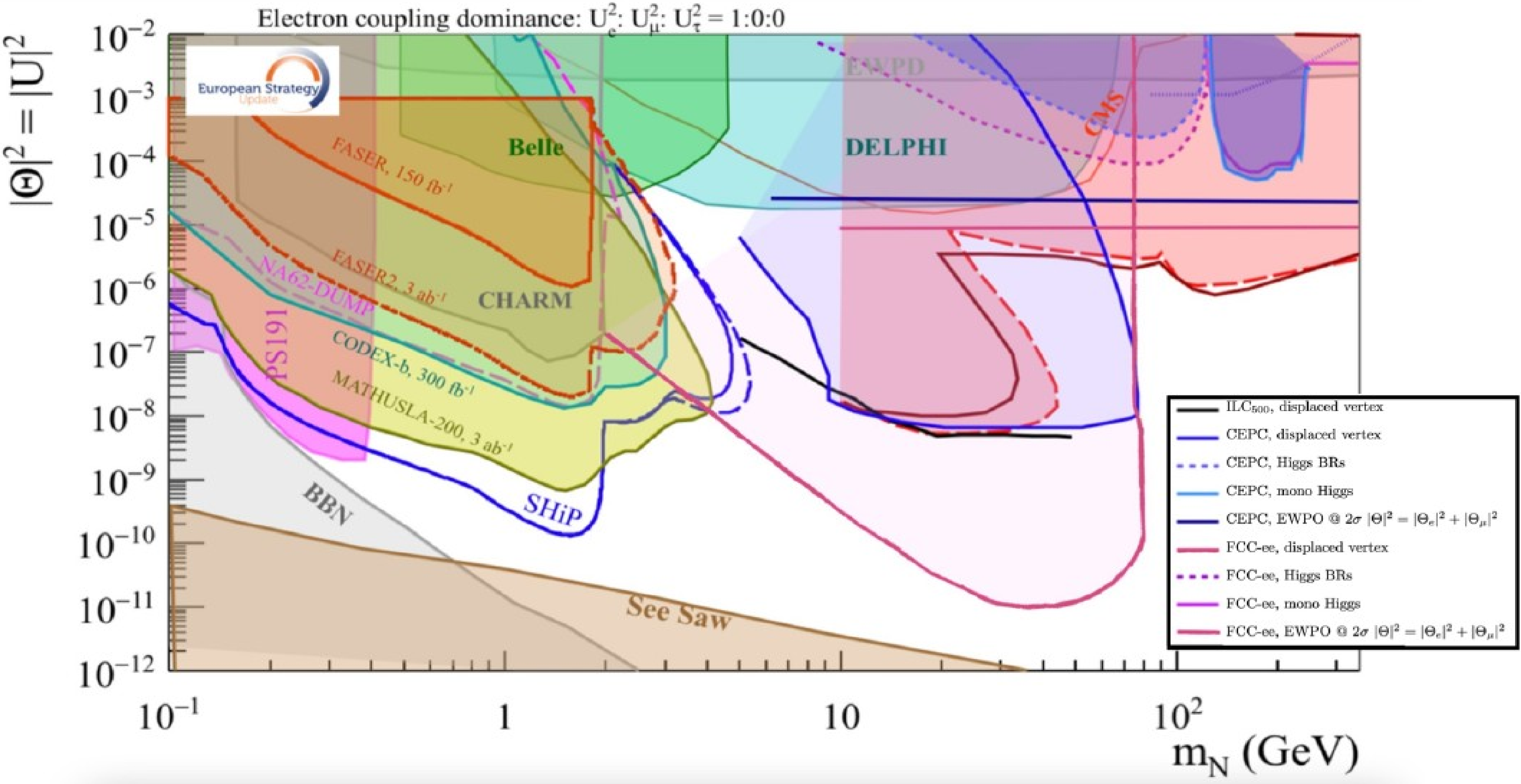
- Nov 17 Searches for Long-Lived particles - planning
- Nov 10 Searches for Long-Lived particles - planning

October 2022

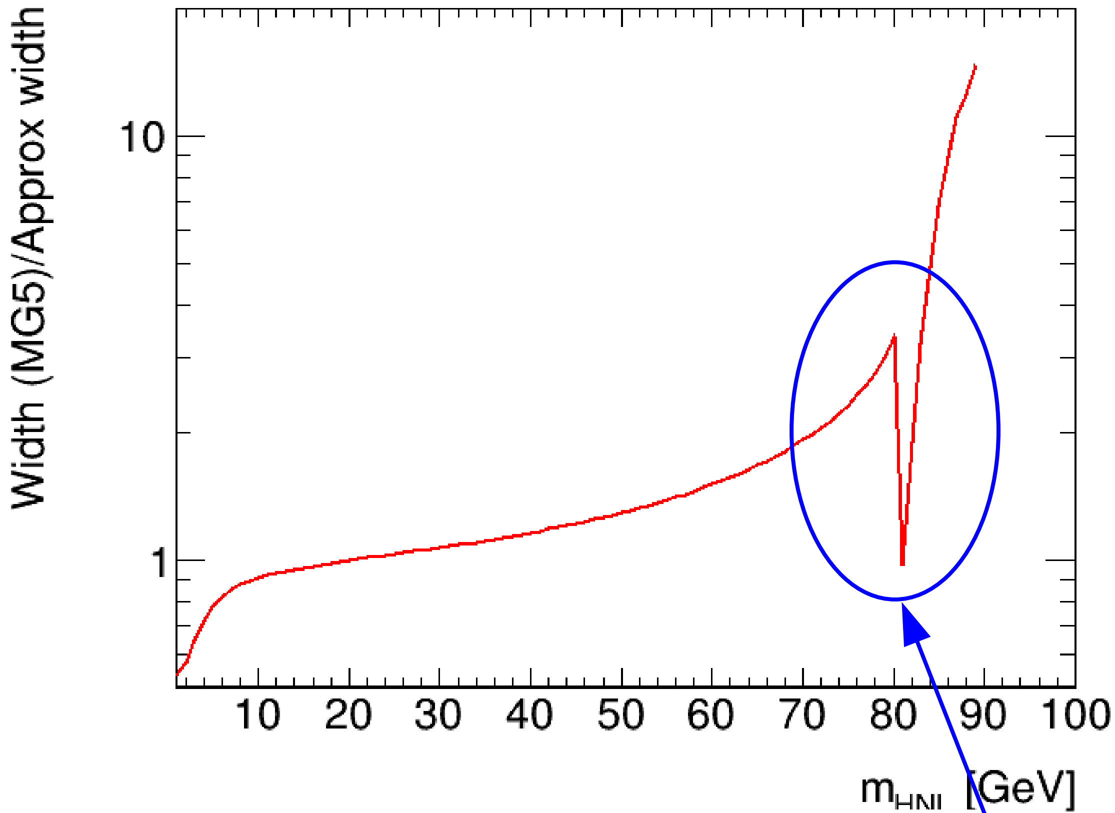
- Oct 27 Searches for Long-Lived particles - planning
- Oct 13 Searches for Long-Lived particles

September 2022

- Sep 29 Searches for Long-Lived particles
- Sep 19 Searches for Long-Lived particles - planning
- Sep 15 - Sep 16 FCC BSM Physics Programme Workshop



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}
NA62-DUMP
CHARM
PS191
CODEX-b, 300 fb^{-1}
MATHUSLA-200, 3 ab^{-1}
SHiP
BBN
See Saw
m_N (GeV)
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
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 $|\Theta|^2 = |\Theta_e|^2 + |\Theta_\mu|^2$

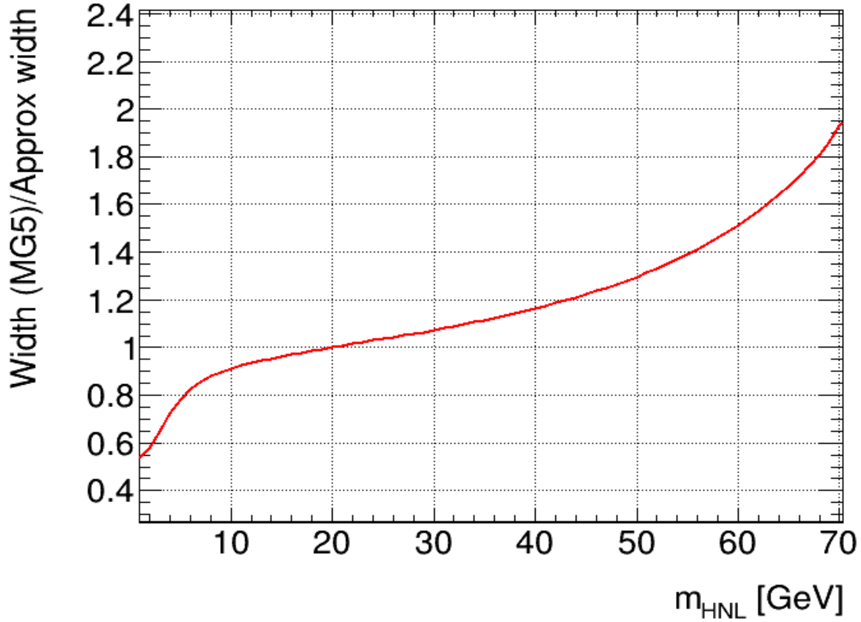


Limitation of approx formula

HNL width in arXiV:2210.1711 calculated as

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

with a~12 for m<m(Z)



Performed width calculation with MG5

Difficulty in negotiating the switch from 3-body to 2-body HNL → Wl

Perfect agreement for MHN=20 GeV

Disagreement ~factor 2 for MHN=70 GeV

No big difference on log-log plot

HNL→μjj prompt analysis: preliminary cuts

Preselection:

- >=1μ, e>3 GeV
- >=3 tracks
- Emiss>5 GeV

Selections

- 2 jets with energy>3 GeV and mass>0.2 GeV
- $-0.94<\cos(\theta_{miss})<0.94$
- $\cos(\theta_{lm})<0.8$
- $-0.8<\cos(\theta_{jj})<0.98$
- $\max(\cos(\theta_{j1l}),\cos(\theta_{j2l}))<0.8$