Sensitivity of the FCC-ee to decay of an HNL into a muon and two jets

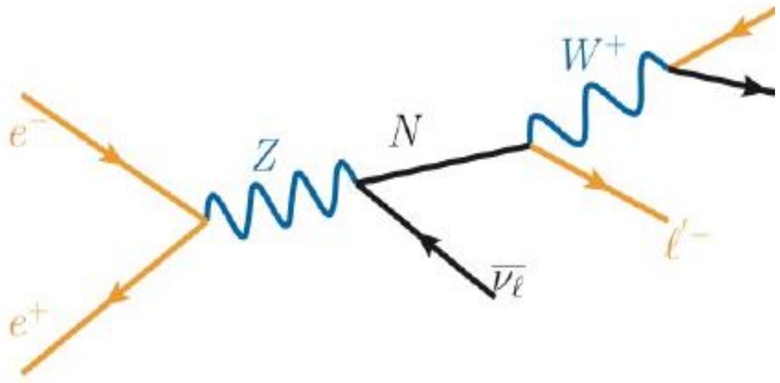
G. Polesello, N. Valle
INFN, Pavia

22 May 2023 - Physics Performance Meeting

Framework

- Heavy Neutral Leptons (HNLs) as one of the most promising new physics channels for FCC-ee at the Z pole

- In this presentation: production from Z decay through mixing with light ν, decay: HNL→ $\mu q \bar{q}'$
  - High branching fraction ~50%
  - Good background rejection through constraints on HNL mass and missing energy



Framework

- One flavor assumed
- Model defined in terms of HNL mass and coupling U with active neutrino. HNL lifetime $\sim 1/U^2$
  - This analysis:
    - scan over the HNL mass, from 5 to 85 GeV
    - scan over U^2 according to existing excluded limits and a proper decay length (see next slide)
- Prompt analysis at high ($>\sim$ 50 GeV/c^2) HNL mass; Long-lived analysis at low HNL mass.

Based on *arXiv:2210.17110,*

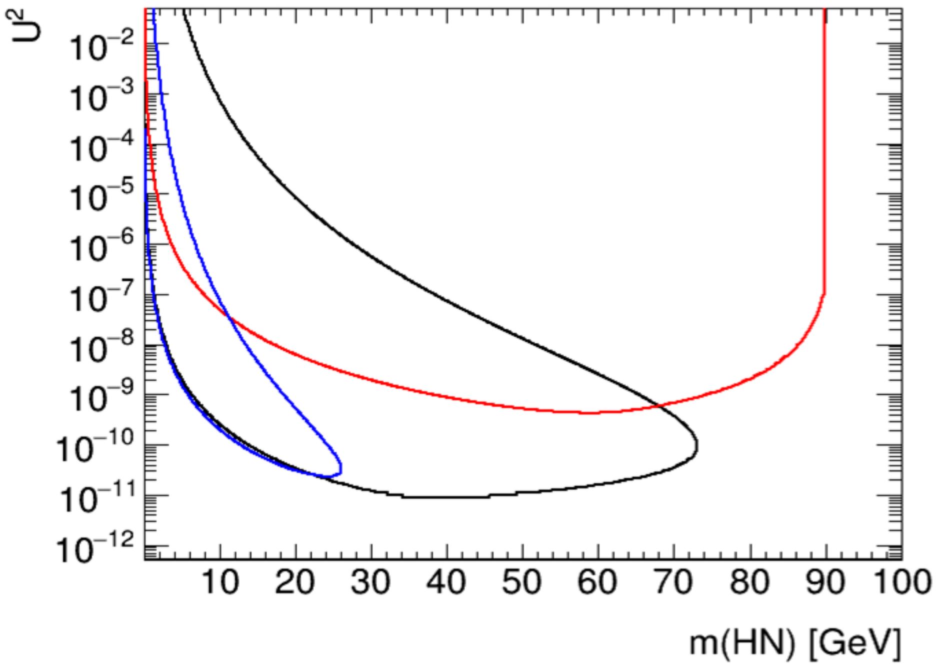
5×10^{12} Z events at Z peak

Requiring

100 evts for prompt decay (red)

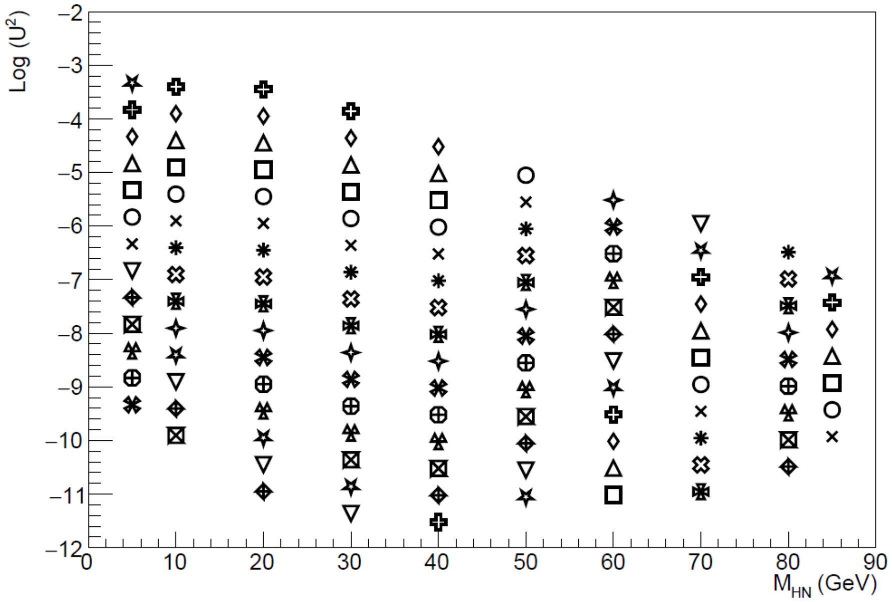
and

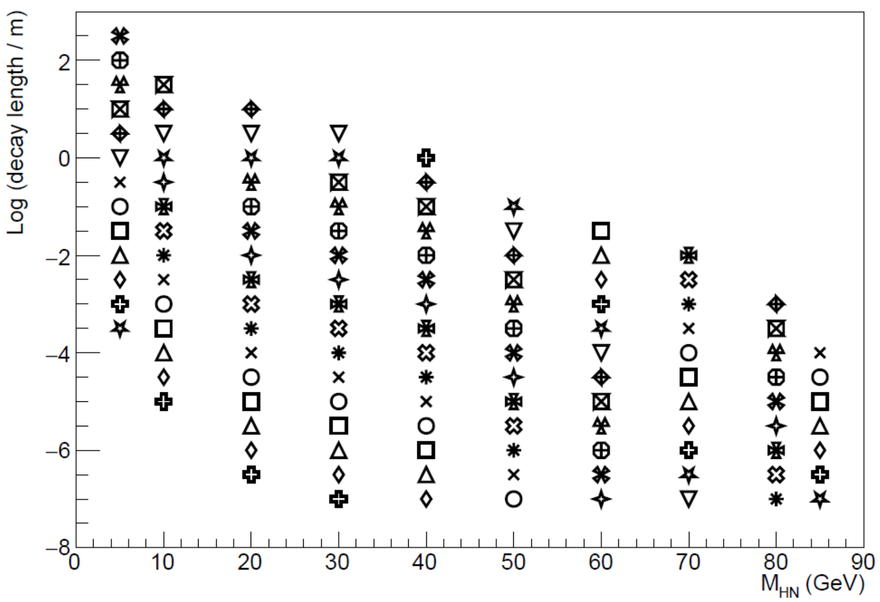
4 events for long-lived (black: decay $0.04 < \lambda < 150$ cm)



Samples

- Signal: 10k events for each point in (U^2, m_{HNL}) plane: MG5, Model SM_HeavyN_CKM_AllMasses_LO model, setting N_2, N_3 with $\sim \infty$ mass and no mixing.
- 91.2 GeV center-of-mass energy
- Pythia8 for hadronization and DELPHES for IDEA Detector fast simulation: official Spring2021 cards

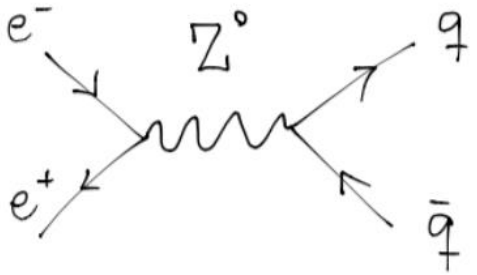


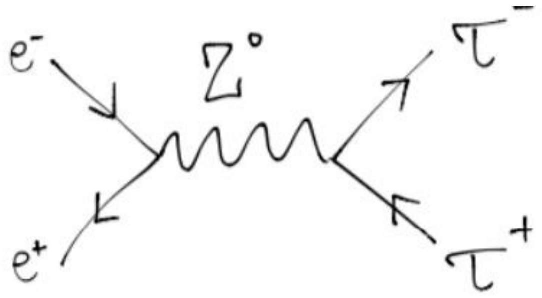


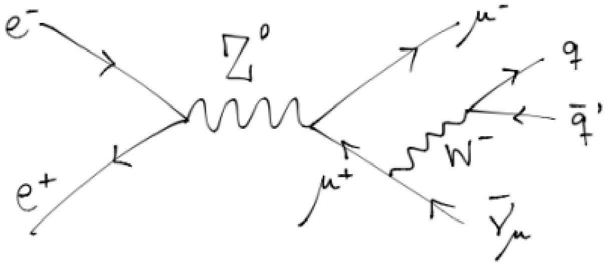
Samples

- Background:
  A. Z boson hadronic decay: muon in the final state from decay of a meson in one jet ("$Z \rightarrow bb,\ Z \rightarrow cc, Z \rightarrow u/d/s$")
  B. Z boson leptonic decays "$Z \rightarrow \mu\mu,\ Z \rightarrow \tau\tau$" : muon and jets in the final state
  C. four-fermion process $e^+e^- \rightarrow \mu\nu qq'$, which is an irreducible background

- A. and B. from official [Spring2021 production]
- C. 500k events with MG5 , requiring only $|\eta| < 5$ and $M_{jets} > 5$ GeV. Pythia8 for hadronization and DELPHES for IDEA Detector fast simulation, using official Spring2021 cards







Samples

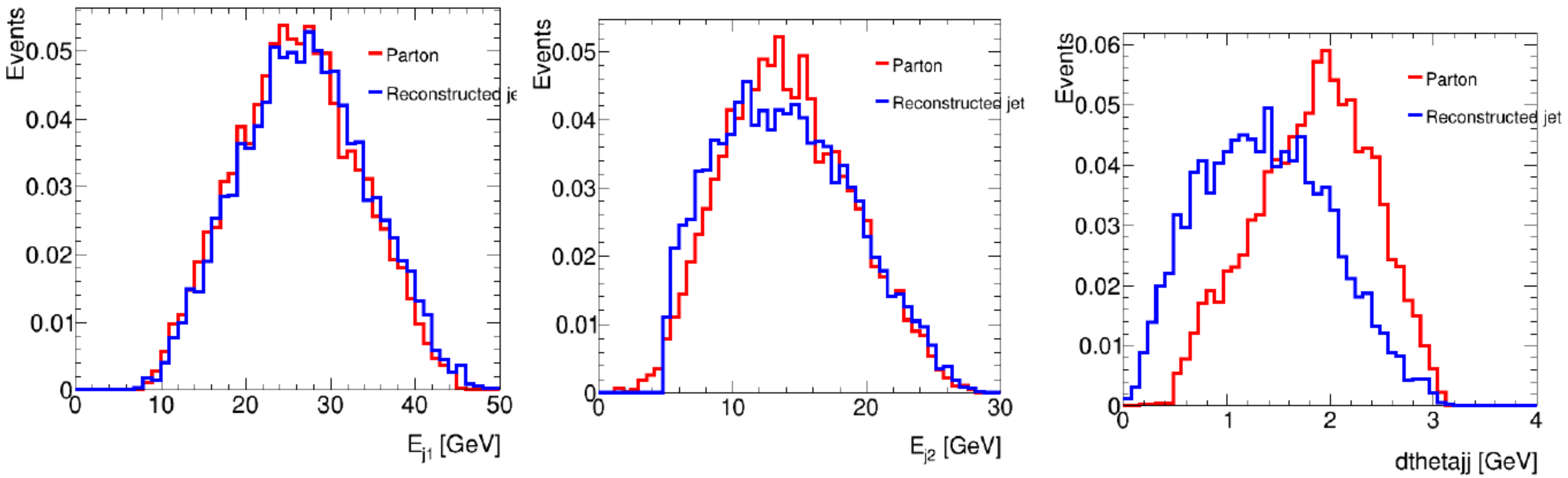
- Target lumi: 150 ab^{-1}, 5×10^{12} Z bosons

$$Weight = \frac{1}{N_{gen}} \sigma \times L_{int}$$

Sample	N_{gen}	Weight
Signal		
10 GeV	10.0k	5498
20 GeV	10.0k	5096
30 GeV	10.0k	4568
40 GeV	10.0k	3897
50 GeV	10.0k	3091
60 GeV	10.0k	2182
70 GeV	10.0k	1254
80 GeV	10.0k	471
Background		
$Z \to bb$	980.0M	1017
$Z \to cc$	990.0M	790
$Z \to u/d/s$	1.0B	2792
$Z \to \mu\mu$	10.0M	21931
$Z \to \tau\tau$	10.0M	22148
$\mu\nu qq$	500.0k	1

Analysis outline

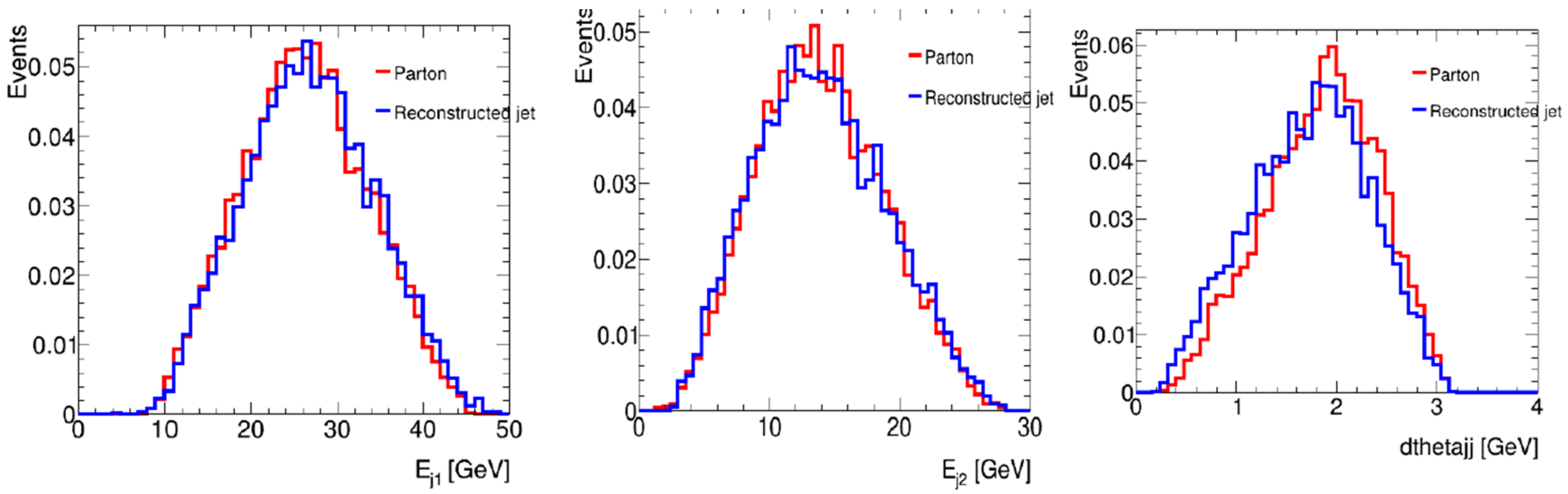
- Events filter with official FCCSW tools:
  - ≥ 3 tracks; $E_{miss} > 5$ GeV ; at least one muon with $p > 3$ GeV$/c$
- Truth of stable particles + reco particle-flow objects + vertices written on output n-tuples
- Jet reconstruction:
  - Detailed study on different algorithms offered by FASTJET (see June 2022 meeting). Comparison with 4-momenta of partons
  - ➢ Durham k_T alogorithm, forcing #jets = 2 if more than 2 jets are found



Truth
vs
anti-k_T clustering

Analysis outline

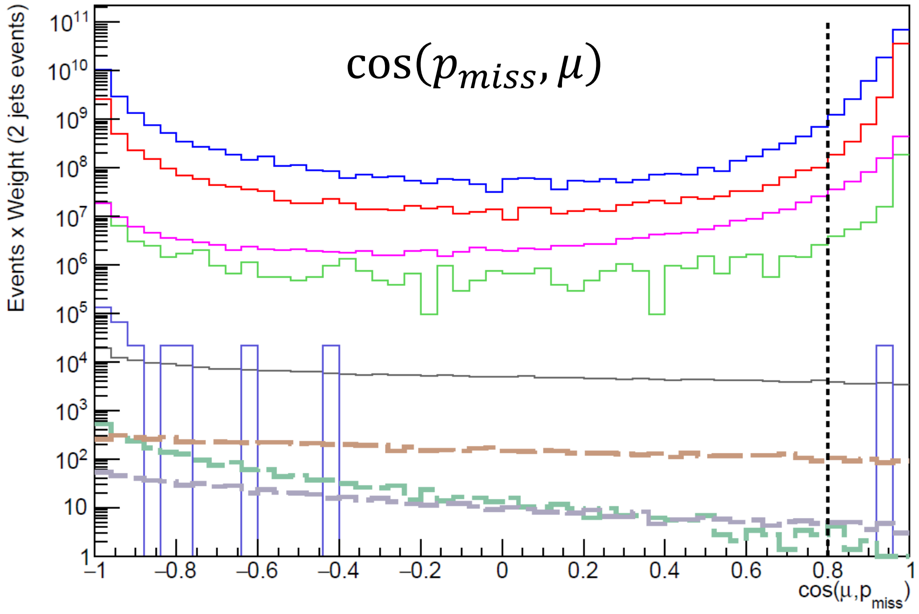
- Events filter with official FCCSW tools:
  - ≥ 3 tracks; $E_{miss} > 5$ GeV ; at least one muon with $p > 3$ GeV$/c$
- Truth of stable particles + reco particle-flow objects + vertices written on output n-tuples
- Jet reconstruction:
  - Detailed study on different algorithms offered by FASTJET (see June 2022 meeting). Comparison with 4-momenta of partons.
  - ➢ Durham k_T alogorithm, forcing #jets = 2 if more than 2 jets are found

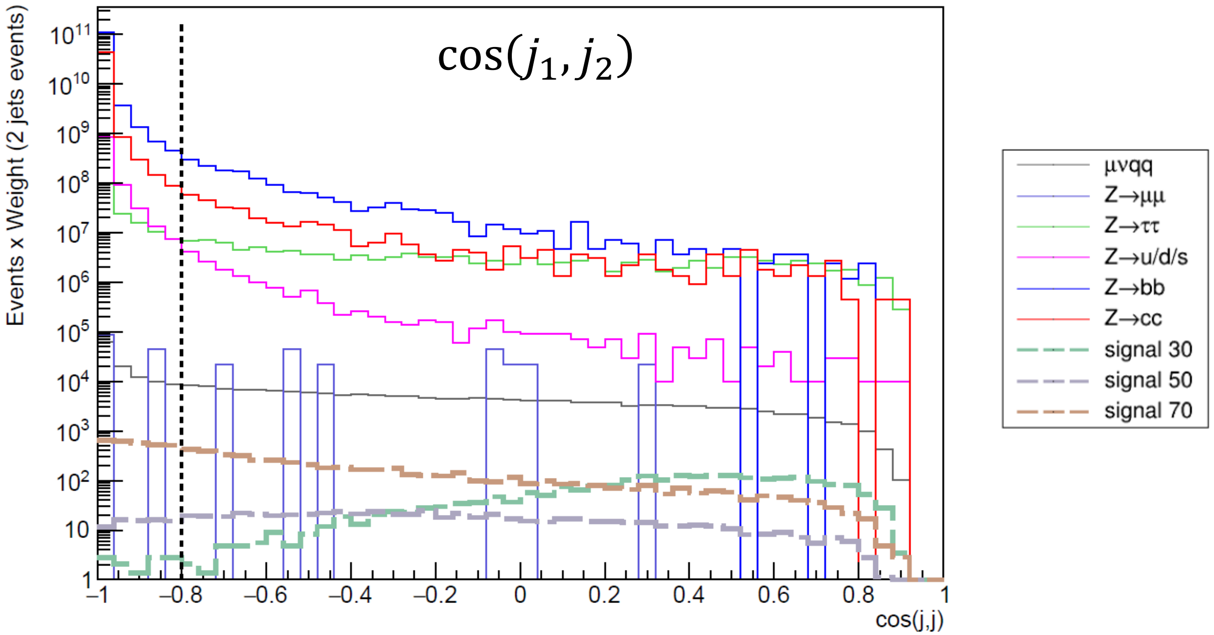


Truth
vs
Durham k_T clustering ✓

Analysis outline

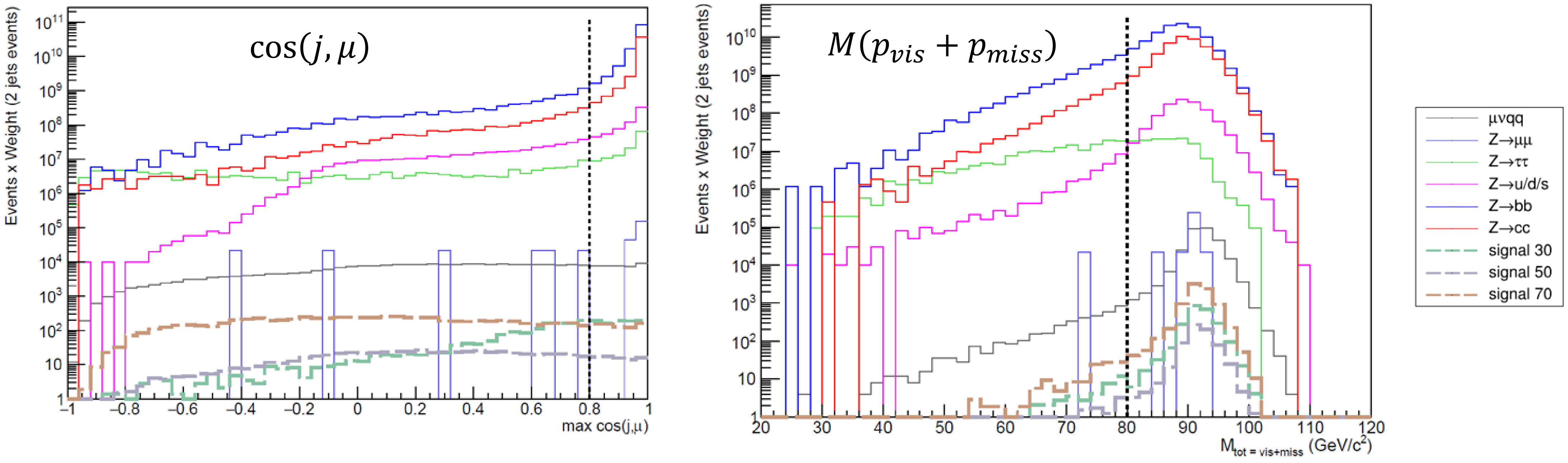
- Sum of visible 4-momenta to select HNL mass and ν recoil energy: independent from jet algorithm
- Further background rejection by cutting on jets and muon angular distributions
- Event selecton dependent on #jets + mass-dependent M_{vis} and E_{miss} cuts
- Discriminating variables:





Analysis outline

- Sum of visible 4-momenta to select HNL mass and ν recoil energy: independent from jet algorithm
- Further background rejection by cutting on jets and muon angular distributions
- Event selecton dependent on #jets + mass-dependent M_{vis} and E_{miss} cuts
- Discriminating variables:



- + technical cuts on missing momentum θ, and jet mass

Analysis outline

- Efficiency of each selection on background: (% events passing the cut)

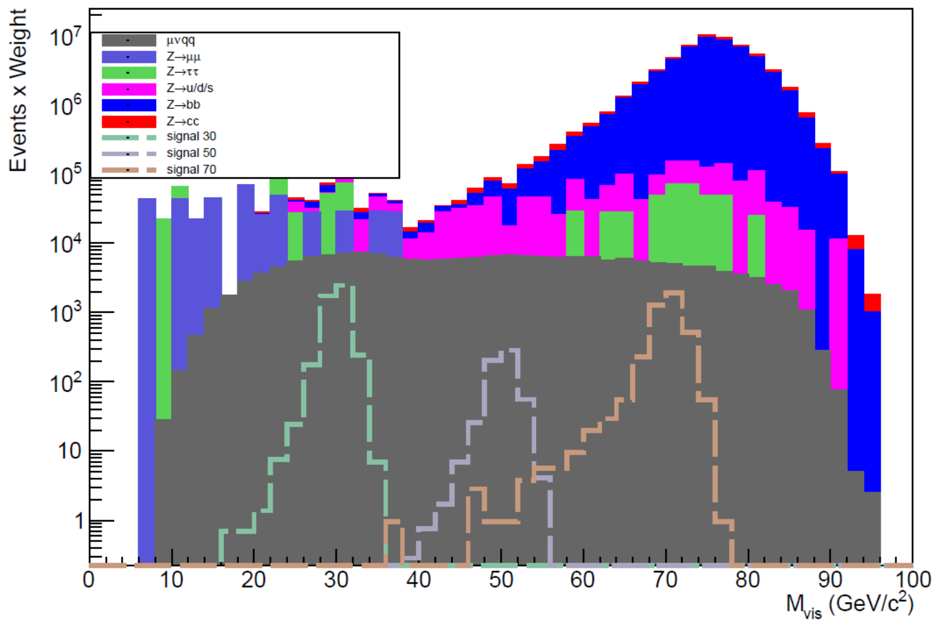
Variable	N_{jet}	$\cos(p_{miss})$	$\cos(p_{miss},\mu)$	E_j, M_j	$\cos(j,j)$	$\cos(j,\mu)$	$\cos(j,\mu)$	M_{tot}	
Cut	$=2$	<0.94	<0.80	>3 GeV >0.2 GeV	>-0.80	<0.80	>-0.98	>80	Combined
Background									
$Z\to bb$	*(100)*	91	18	100	1	7	33	89	0
$Z\to cc$	*(100)*	91	10	100	1	5	16	95	0
$Z\to u/d/s$	*(100)*	86	22	100	2	37	70	98	0
$Z\to\mu\mu$	*(6)*	40	93	27	60	40	80	93	0
$Z\to\tau\tau$	*(3)*	93	24	13	46	58	52	44	0
$\mu\nu qq$	*(73)*	94	94	99	61	86	96	99	44

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 GeV >0.2 GeV	<0.96	>-0.5	>80	Combined
Background								
$Z\to bb$	*(0)*	–	–	–	–	–	–	–
$Z\to cc$	*(0)*	–	–	–	–	–	–	–
$Z\to u/d/s$	*(0)*	–	–	–	–	–	–	–
$Z\to\mu\mu$	*(94)*	30	99	64	88	57	96	5
$Z\to\tau\tau$	*(97)*	93	8	100	100	0	35	0
$\mu\nu qq$	*(27)*	93	94	100	98	63	99	56

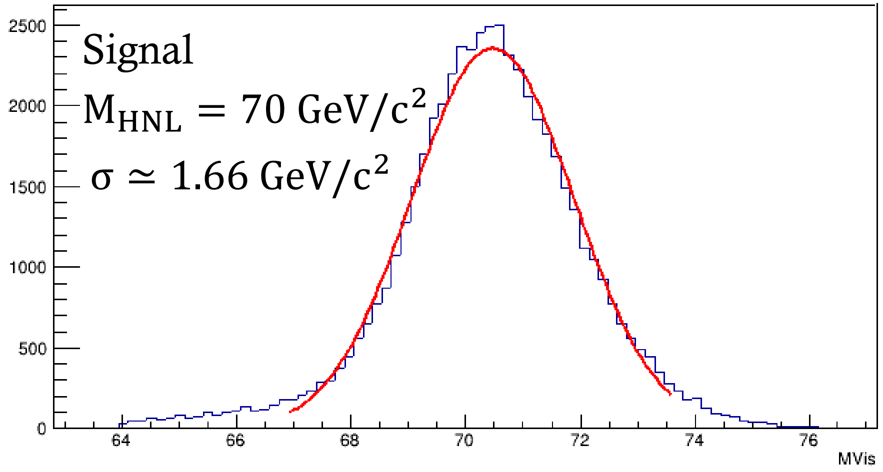
- Signal efficiency from ~80 % (M=20 GeV) to ~50 % (M=70 GeV). ~30 % at M=80GeV

Analysis outline

- Sum of visible 4-momenta to select HNL mass and ν recoil energy



$\sigma \simeq 18\% \sqrt{M}$

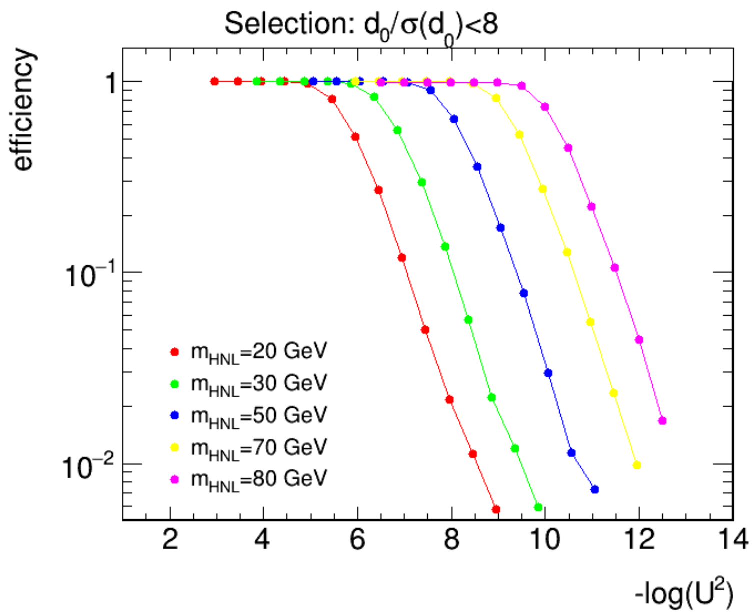


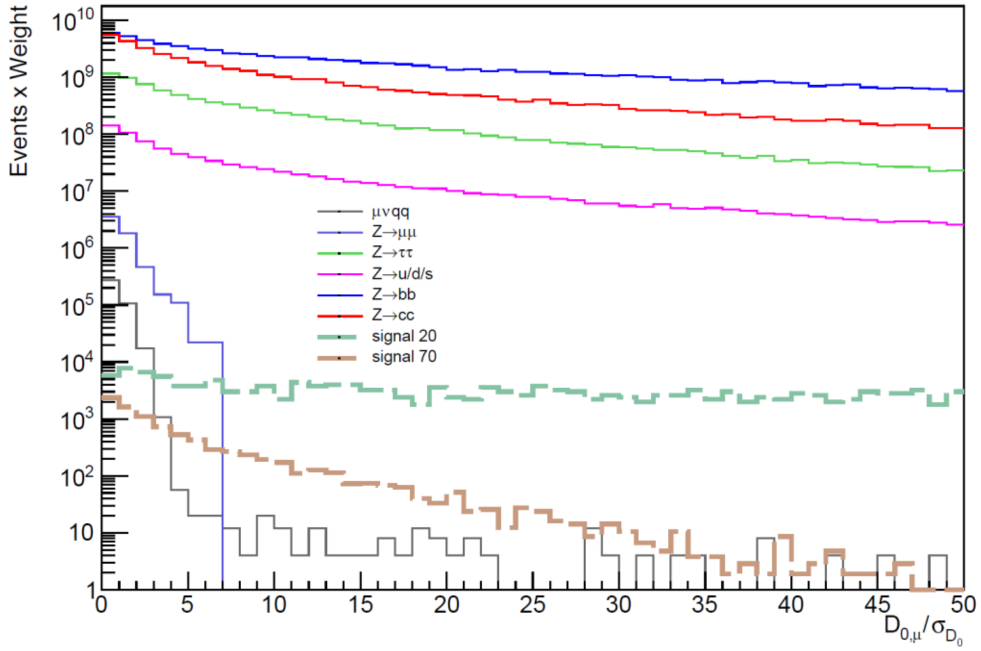
- Requiring $M_{vis} \in M_{HNL} \pm \Sigma$ and $E_{miss} \in p_{\nu,nominal} \pm \Sigma$
- With $\Sigma = 2 \times 20\% \times \sqrt{M_{HNL}}$
  - 20 GeV $\rightarrow \Sigma = 1.9$ GeV … 70 GeV $\rightarrow \Sigma = 3.3$ GeV
  - Fixed mass window and different width factors also studied

Vertex displacement

- Residual background mainly from hadronic ($b\bar{b}$) Z decay at higher mass and 4-fermion channel at low mass
- Hadronic channel suppressed by requiring muon coming to Interaction Point
- Irreducible background purely prompt: suppressed by looking for long-lived HNL events
  - Prompt analysis at high mass: muon impact parameter $D_{0,\mu} < 8\ \sigma$
  - Long-lived analysis at low mass: $D_{0,\mu} > 1$ mm
  - $\sigma = O(5\ \mu m)$ → far from a critical region for jet reconstruction
  - Importance of tracker pointing resolution

❖ Working to implement selection based on results of vertex fitter



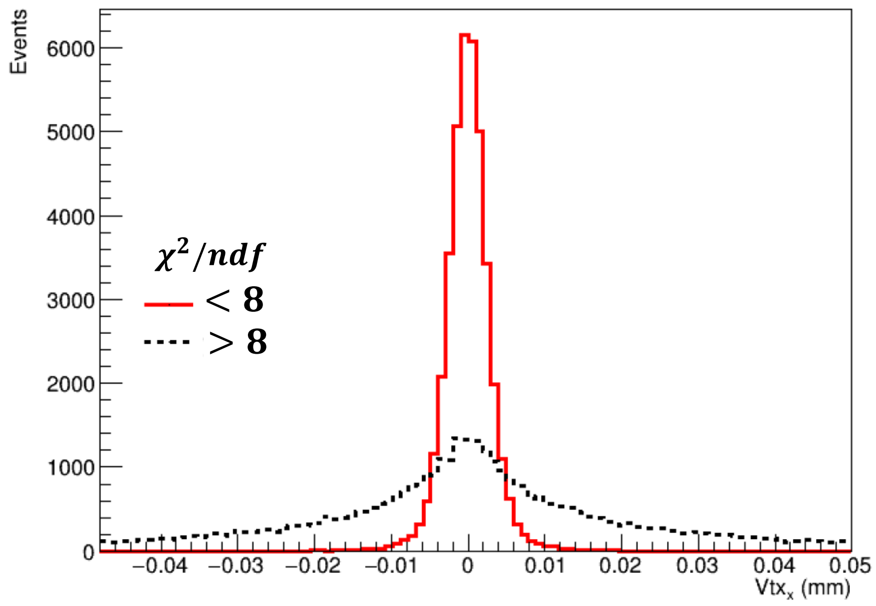


Vertex displacement

- Residual background mainly from hadronic ($b\bar{b}$) Z decay at higher mass and 4-fermion channel at low mass
- Hadronic channel suppressed by requiring muon coming to Interaction Point
- Irreducible background purely prompt: suppressed by looking for long-lived HNL events
  - Prompt analysis at high mass: muon impact parameter $D_{0,\mu} < 8\ \sigma$
  - Long-lived analysis at low mass: $D_{0,\mu} > 1$ mm
  - $\sigma = O(5\ \mu m) \rightarrow$ far from a critical region for jet reconstruction
  - Importance of tracker pointing resolution

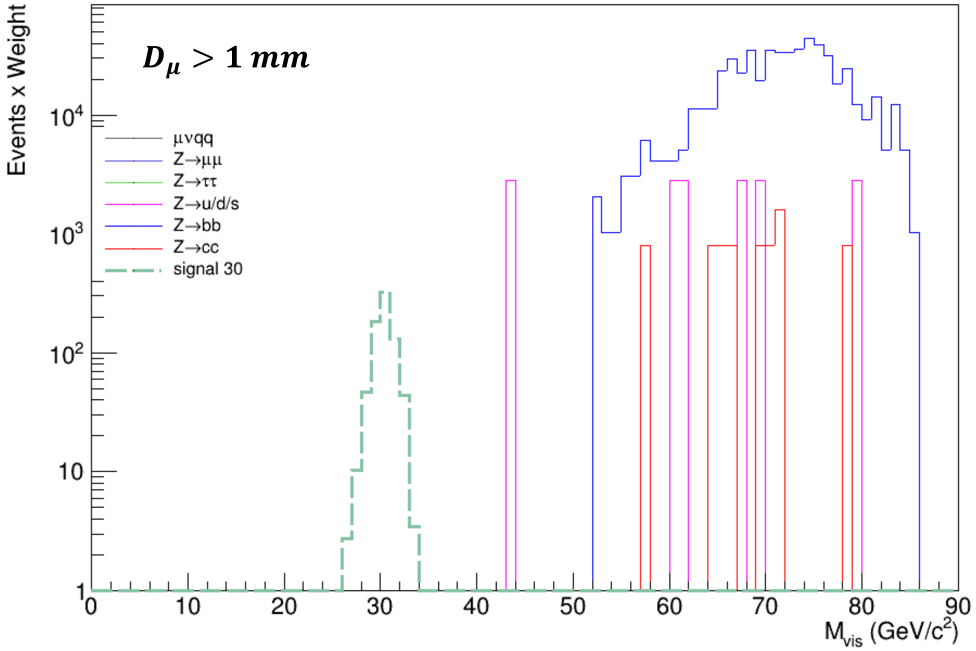
❖ Working to implement selection based on results of vertex fitter

- Beam spread in Spring2021:
  - ~ 300 μm along z
  - ~ 4.5 μm along y
  - Implemented as Vertex Spread in Pythia8 also in our MG samples
- Looking into Winter2023



LL analysis with no background

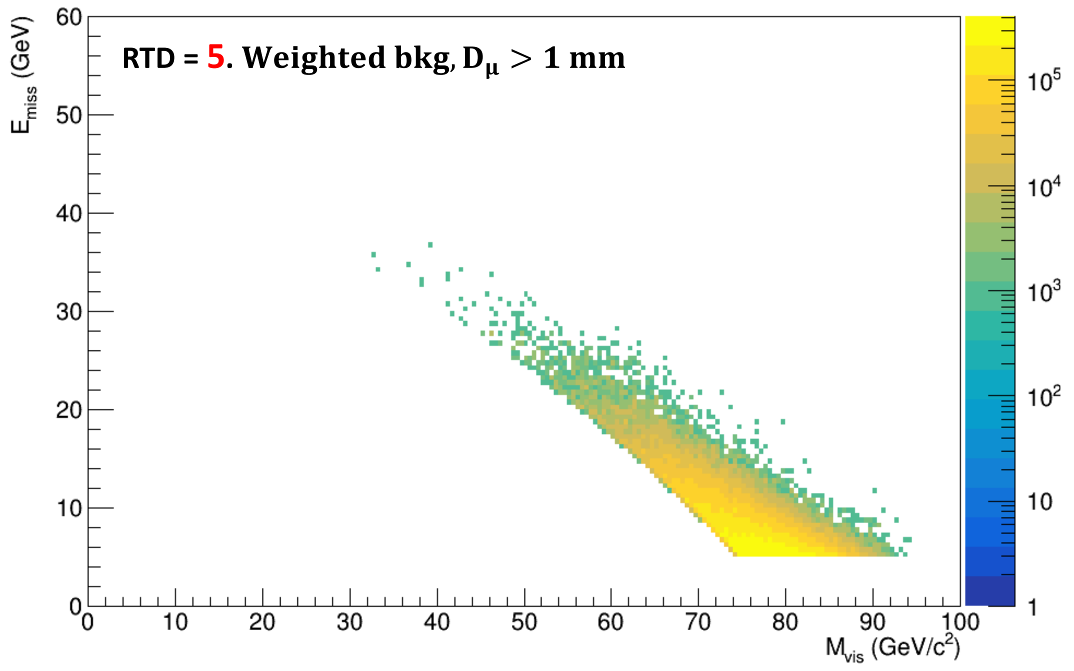
- Very few events left by $D_{0,\mu} > 1$ mm at low mass → high sensitivity to statistical fluctuation

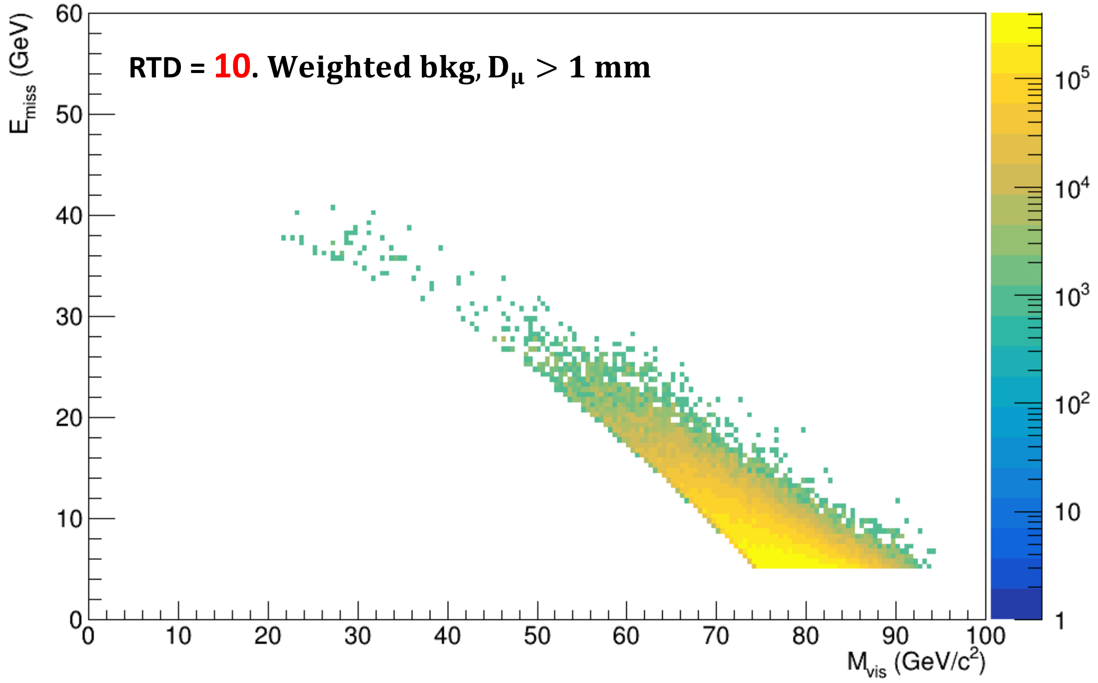


- Systematics to be properly evaluated given the high MC weights, and given the senstivity to some analysis parameters (e.g. next slide)

LL analysis with no background - parenthesis

- Systematics to be properly evaluated given the high MC weights, and given the senstivity to some analysis parameters
- E.g.: jet merging scale = 5^2 GeV^2 vs 10^2 GeV^2



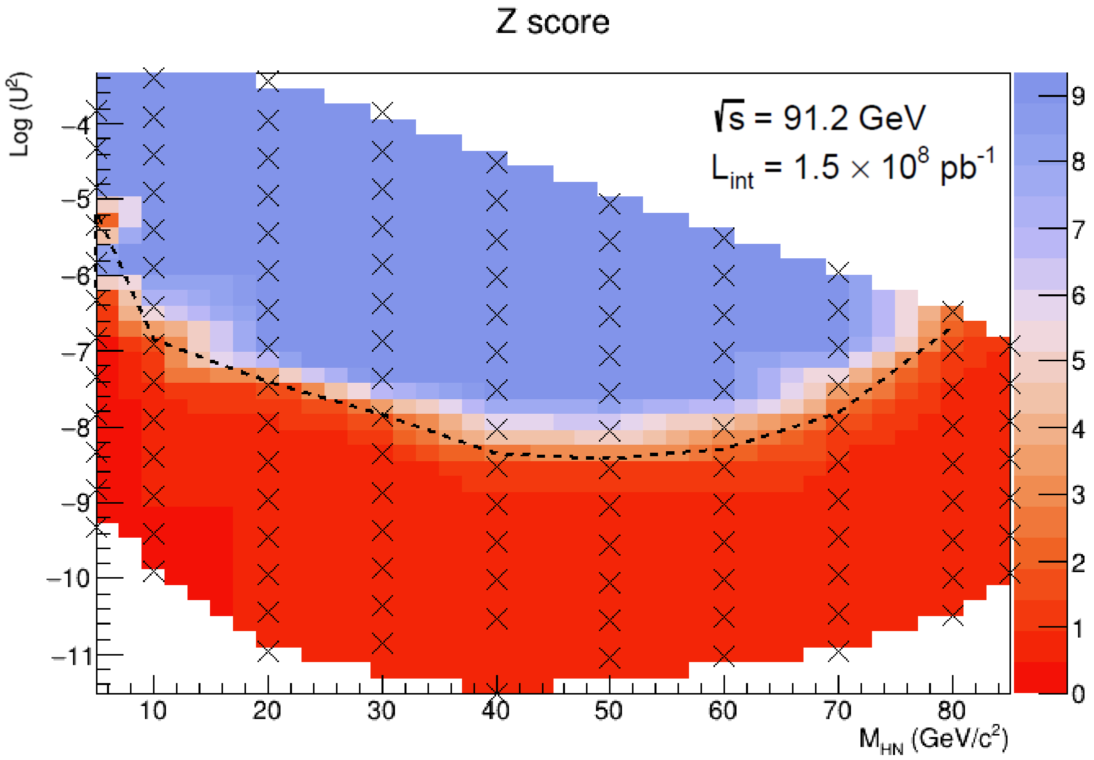


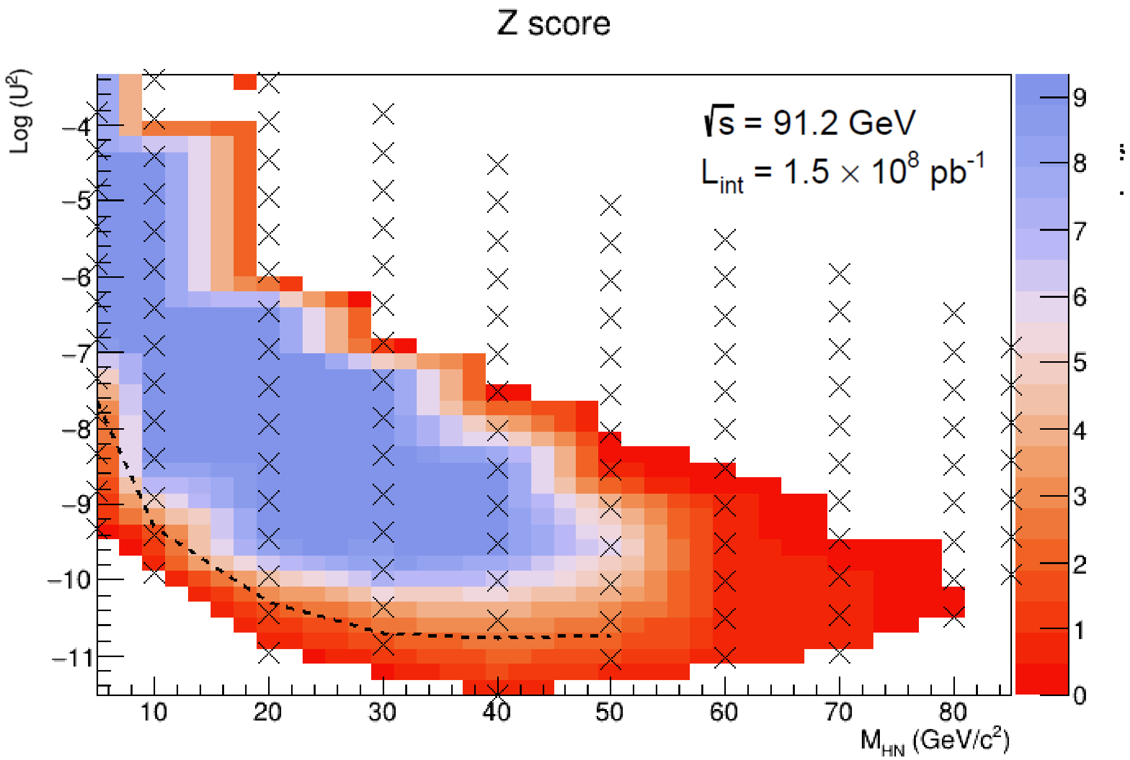
- Currently looking into signatures in any of the residual bacgkround contributions

(Preliminary) results

- Looking for U^2 producing 95% CL excess of events

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





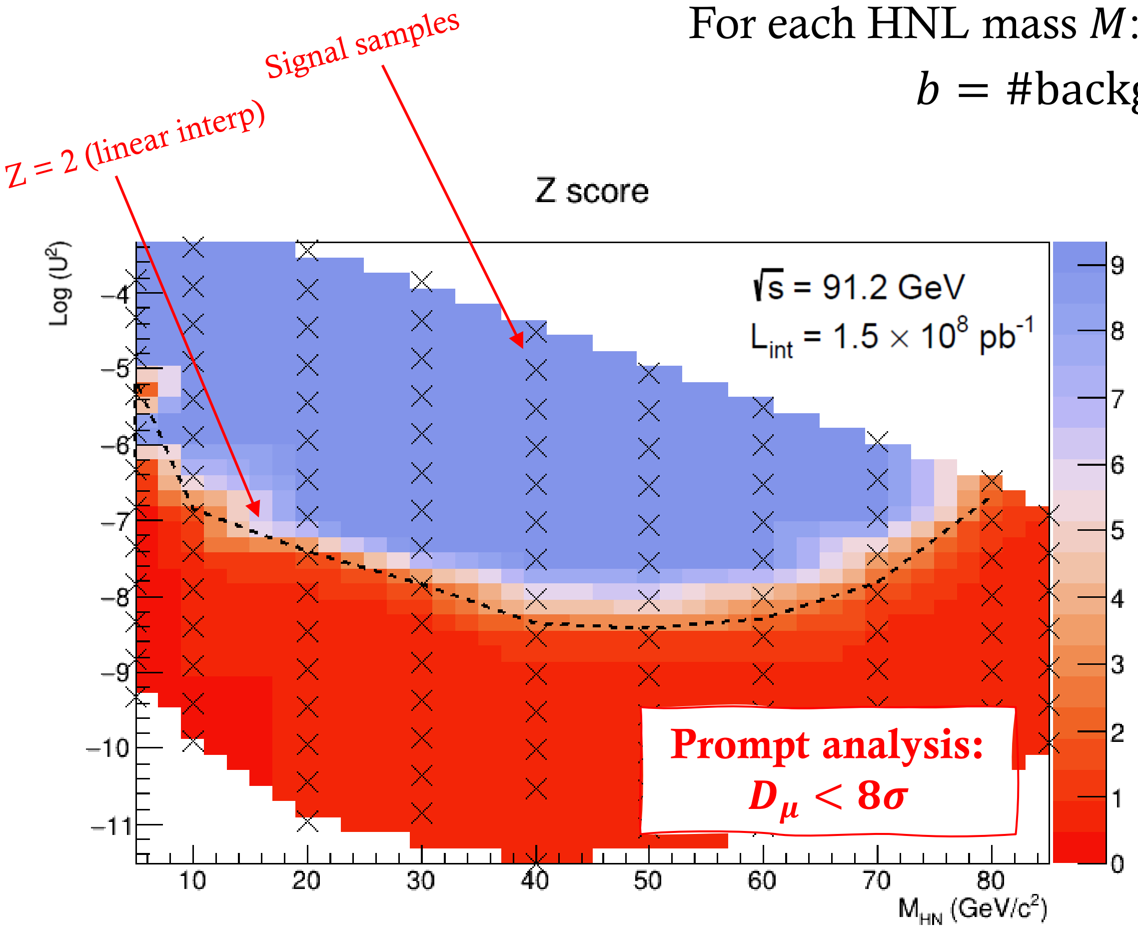
- Delaunay triangles interpolation in the *M-Log(U)* plane

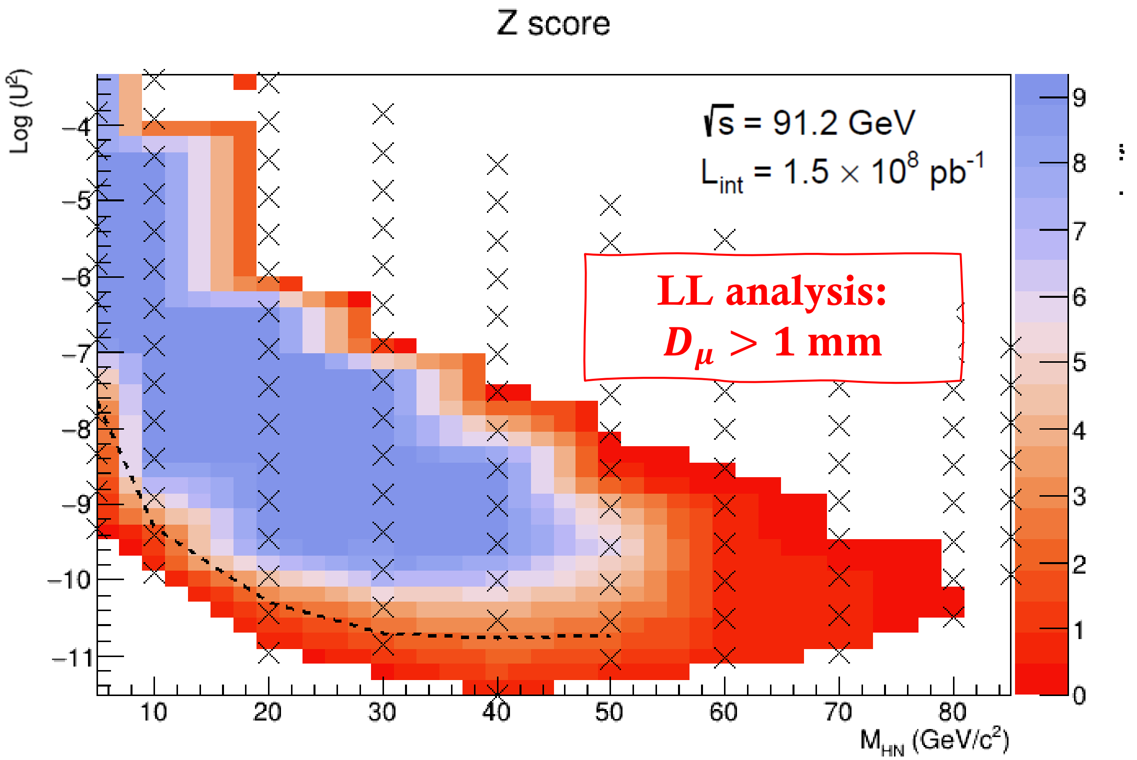
(Preliminary) results

- Looking for U^2 producing 95% CL excess of events

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

$b =$ #background events





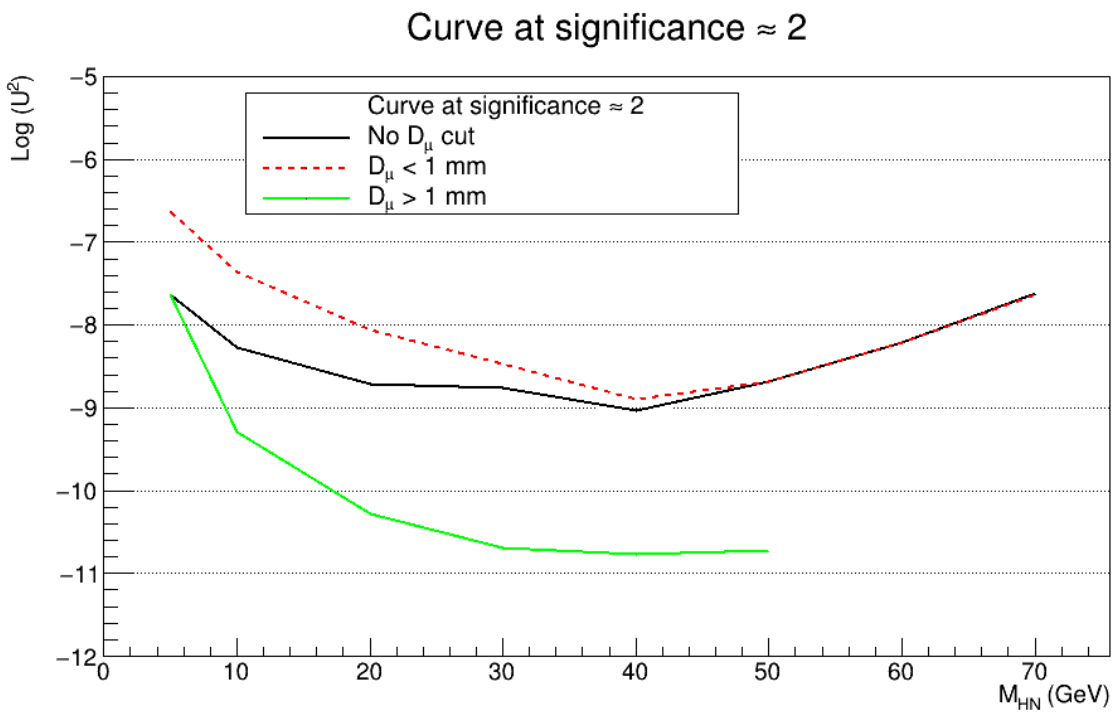
- Delaunay triangles interpolation in the *M-Log(U)* plane

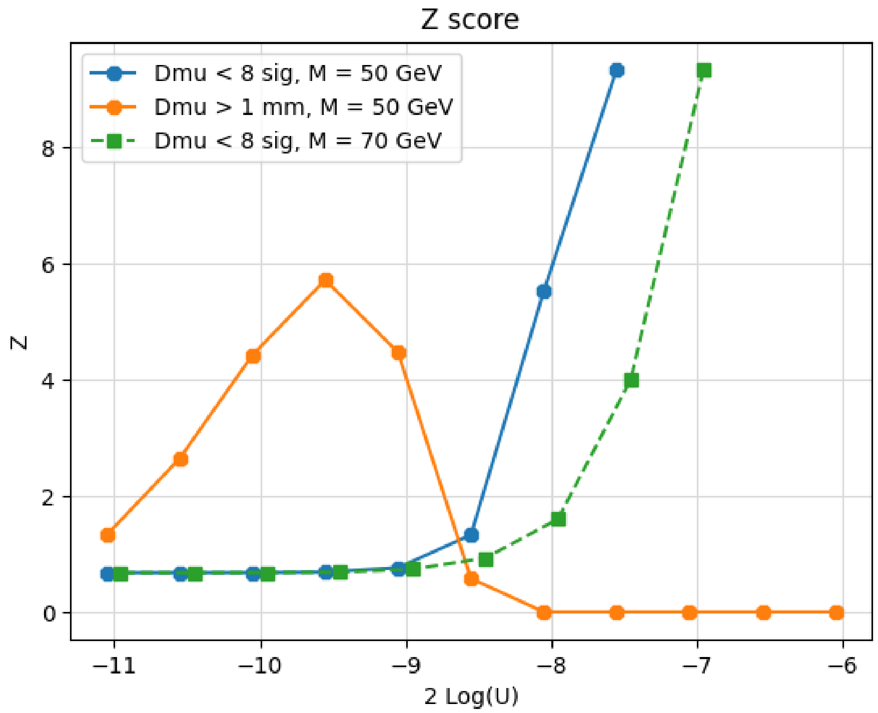
(Preliminary) results

- Looking for U^2 producing 95% CL excess of events

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

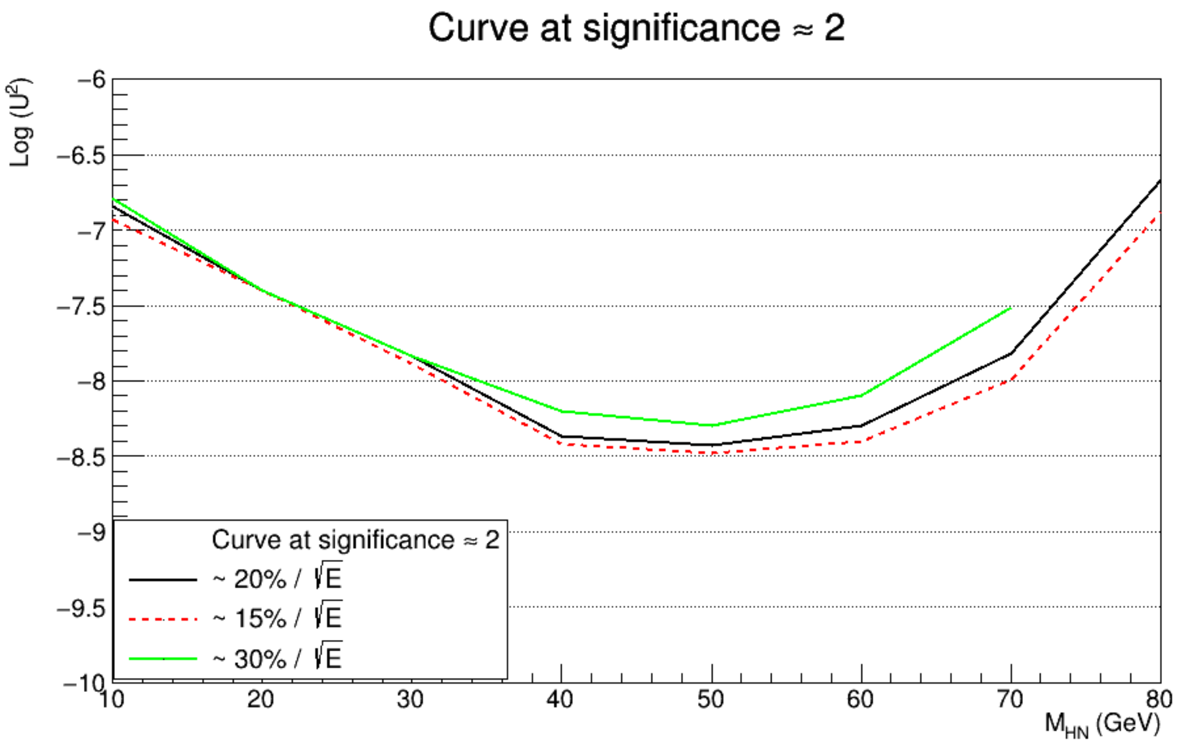
$$b = \#\text{background events}$$





(Very preliminary) view on detector resolution

- Fast simulation with parametric energy resolution based on particles
- Impact of resolution could be assessed ''home-made'' by smearing jets built from stable particles
- A faster approach: enlarge or narrow the mass window to simulate a larger/narrower signal peak



Summary

- Sensitivity to HNL → $\mu j j'$ studied in the mass range 5 – 80 GeV
- The study completes and extended Snowmass reports results focused on long-lived signatures
- The long-lived decays dominate at smaller ($< 50\ \mathrm{GeV/c^2}$) HNL mass and the foreseen background can be (fully) rejected by the presented event selections
- Analysis presented here based muon impact parameter cut, effective variable especially for prompt signals. Other possiblities are under study

Next steps

- Open work lines on:
  - Closer look at the origin of some remaining background events
  - Study of reconstructed vertices, by exploiting the latest software functionalities
  - Jet energy smearing and its impact on the sensitivity of the analysis
- Systematics will be included
- Analysis note draft v1.0 exists... preparing the next version (some corrections already presented here)
  - Thanks for the valuable suggestions already received.. working on them.