Measuring mass of long-lived particles with inner detector timing

R. Aleksan, E. Perez, G. Polesello, N.Valle

Introduction

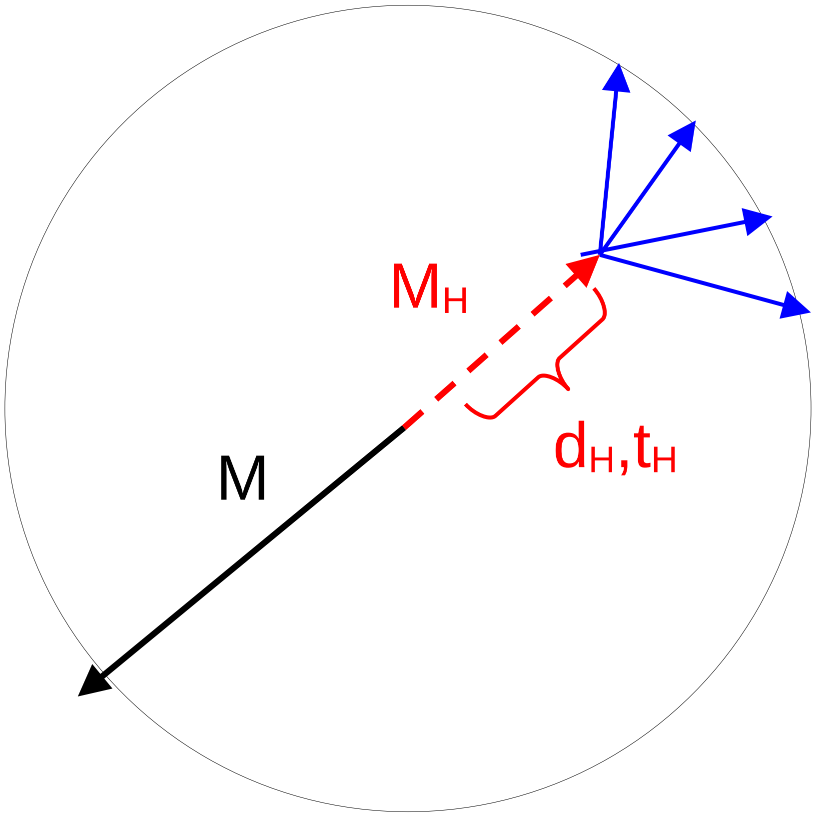
In e+e- collider with CMS energy E_{CM} produce long-lived neutral H recoiling against particle of known mass M

H decays at distance d_H from the interaction point, with a delay from the time of the interaction t_H .

$$p_H = \frac{\sqrt{(E_{CM}^2 - (M_H + M)^2)(E_{CM}^2 - (M_H - M)^2)}}{2E_{CM}}$$

$$p_H = M_H \gamma \beta$$

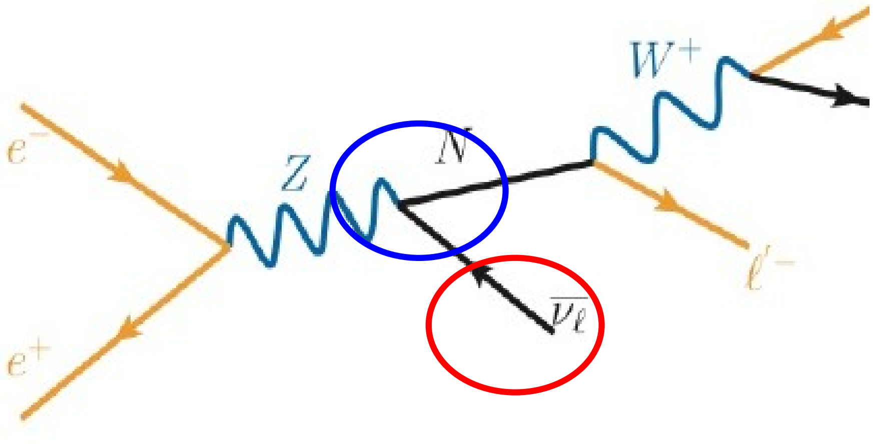
$$\beta = d_H / t_H / c,$$



Solve for M_H, $\rightarrow$ $M_H = f(E_{CM}, M, \beta)$, all known or measurable quantities.

What precision on M_H in plausible BSM model for realistic FCC-ee detector?

Example: HNL decay in IDEA



Mass of recoiling particle=0 → no uncertainty

Interaction point undetected → uncertainty on time and position of interaction

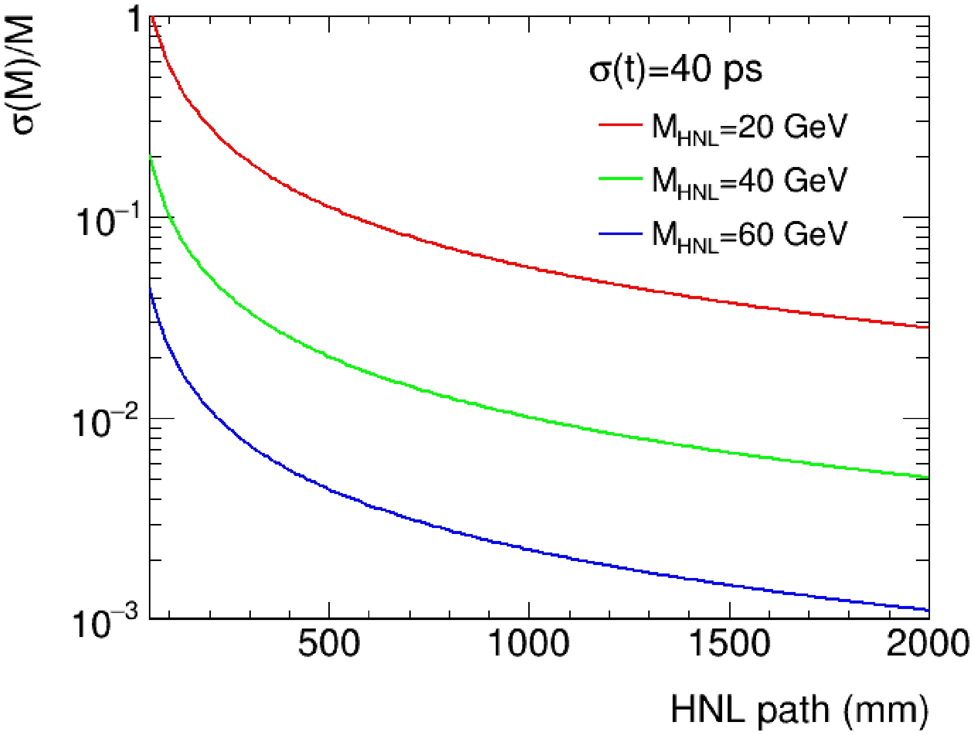
$$m_H = E_{CM}\sqrt{\frac{1-\beta}{1+\beta}} \equiv E_{CM}F(\beta)$$

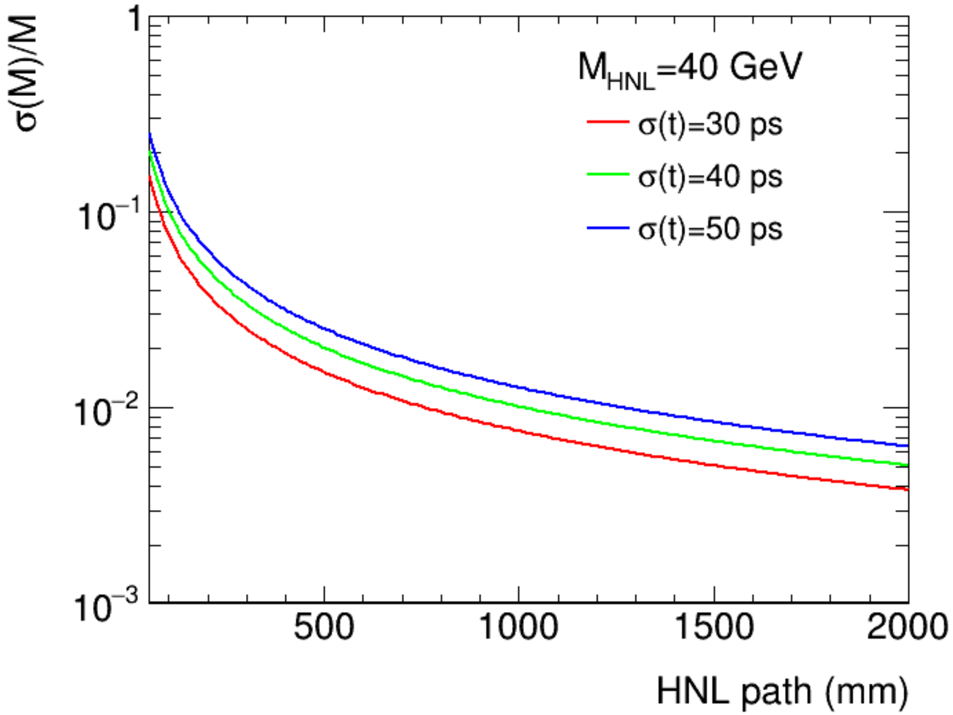
$$\sigma(M_H) = E_{CM}\frac{1}{\sqrt{\frac{1-\beta}{1+\beta}}(1+\beta)^2}\sigma(\beta) \equiv E_{CM}F'(\beta)\sigma(\beta)$$

Analytic formulas

Assuming σ(t) dominant

$$\sigma(M_H) = \frac{E_{CM}\beta^2 F'(\beta) c\sigma(t)}{d_H}$$

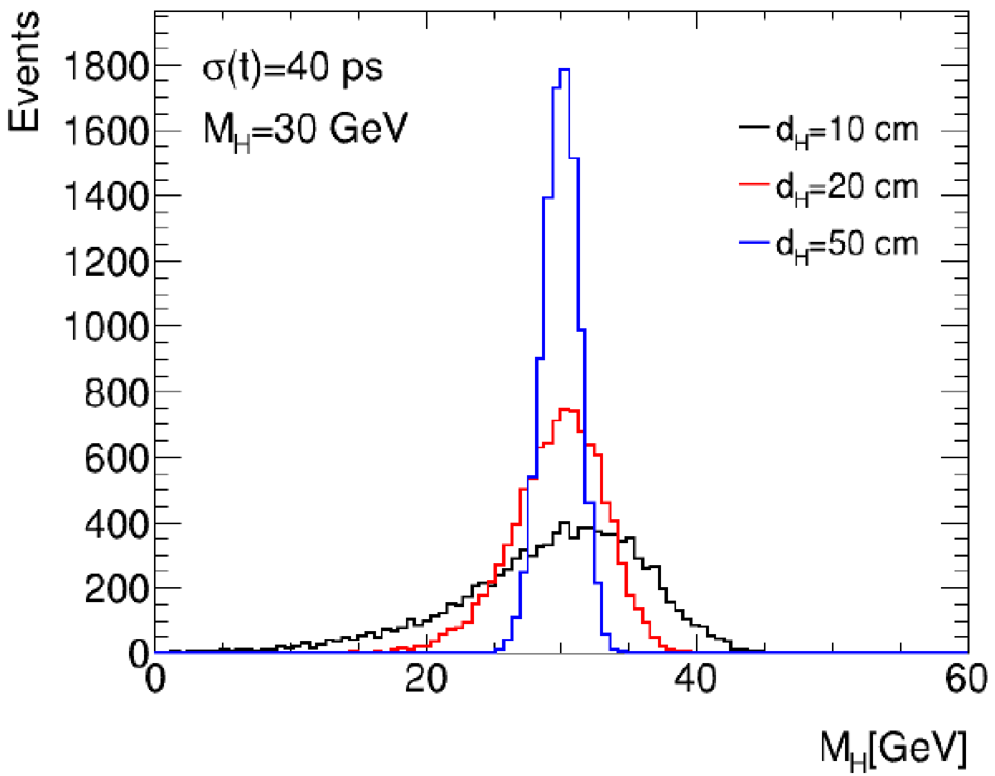


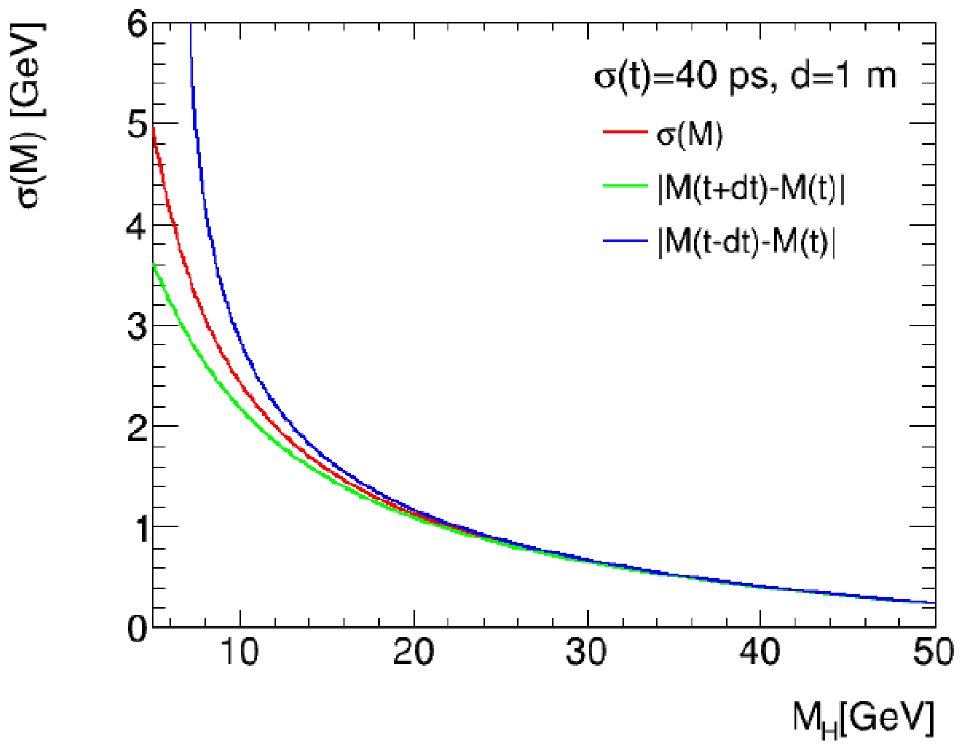


Strong dependence on mass
For high masses one can get below percent level

M=40 Gev:
Few tens of ps timing resolution: mass resolution below 1% for a path between 50 cm and 1 m

Shape of mass resolution



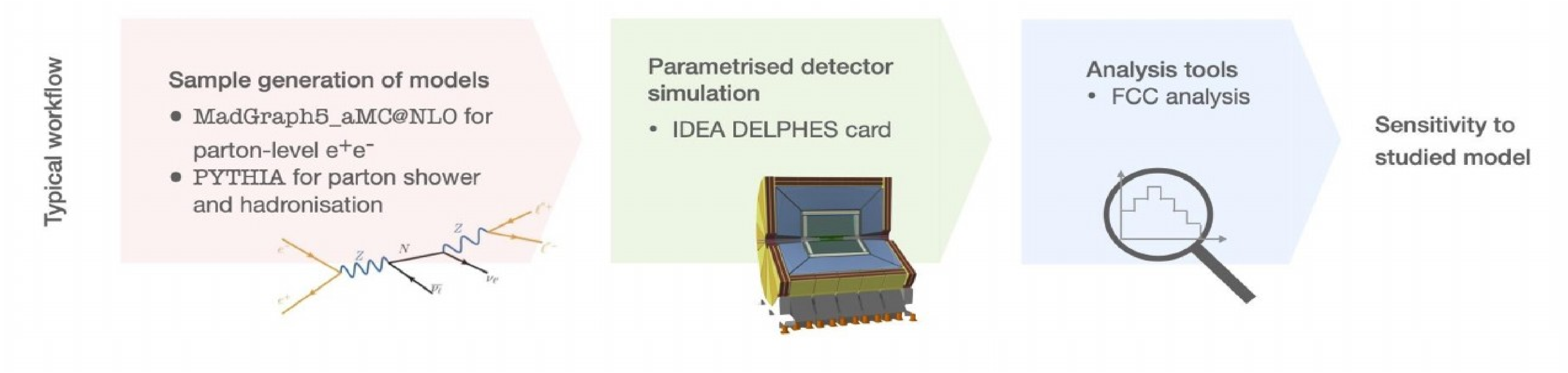


For short decay path
large low mass tail

For low masses β approaches 1
and low part tail of resolution explodes

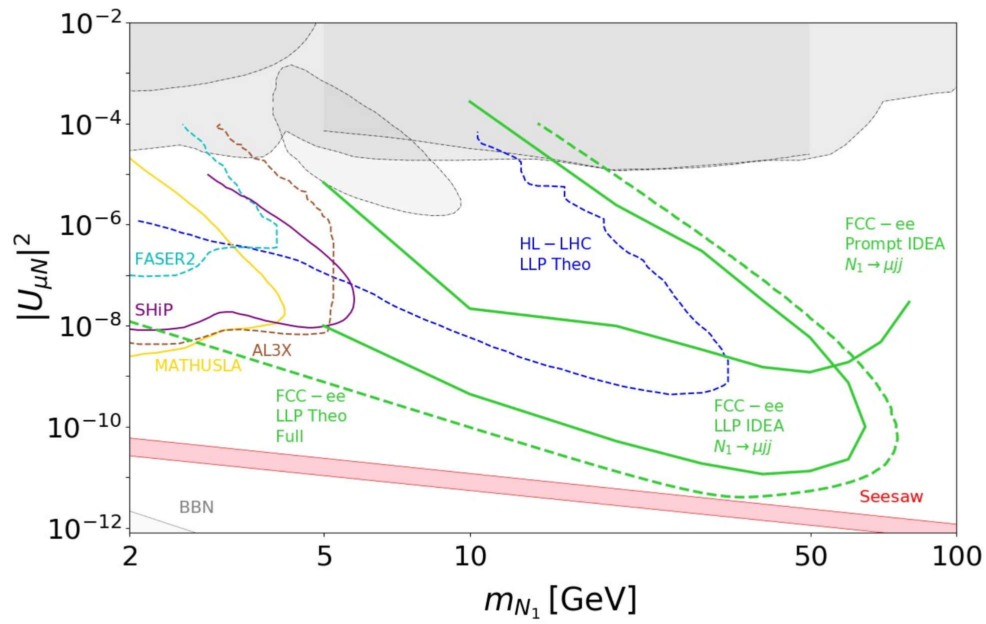
Promising results → go for detailed analysis on simulated samples

Realistic exercise



Samples used for study of reach of HNL→ μ jj search at the Z pole (see talk by N. Valle)

- Generate grid in (U,m) space with MG5aMC@NLO
- DELPHES with IDEA card
- Detailed parametrisation of IDEA tracking performance and well developed vertexing code used for the analysis



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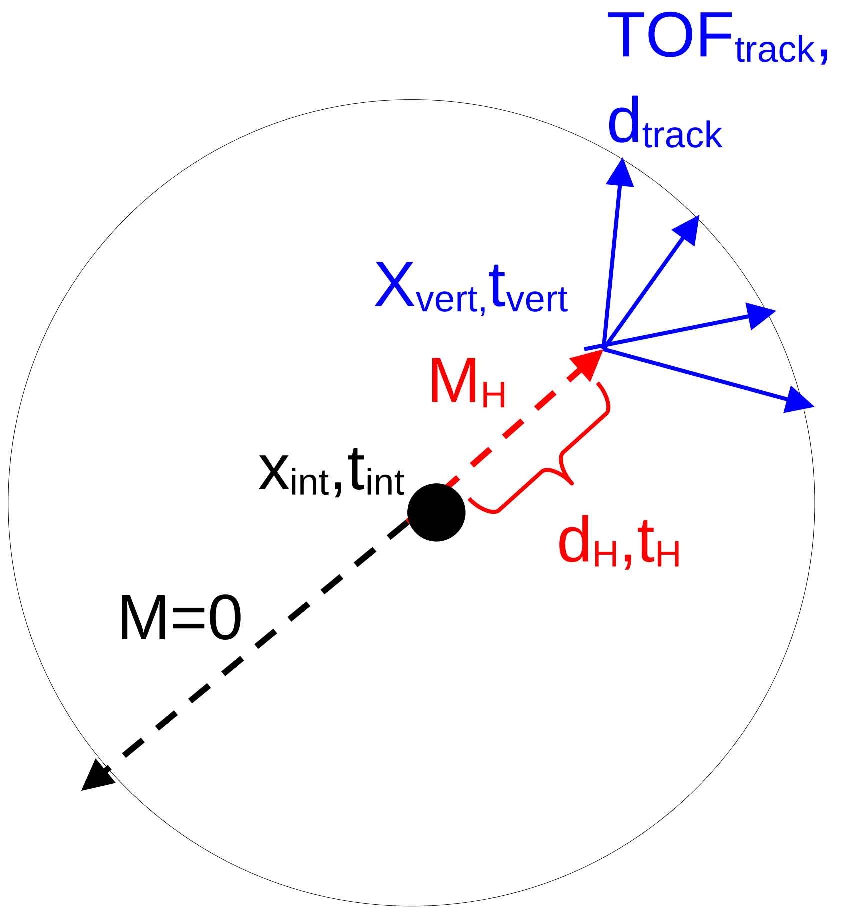
Measurement of t_H



Assume timing layer just outside of tracker (Radius=2m)

Two invisible particles in primary interaction: time and position of interaction (x_{int},t_{int}) unknown

Distribution known from beam parameters

Ebeam (GeV)	45.6
σ_x (μm)	8.4
σ_y (nm)	33.7
σ_z (mm)	15.4
Vertex σ_x (μm)	5.96
Vertex σ_y (nm)	23.8
Vertex σ_z (mm)	0.397
Vertex σ_t (ps)	36.3

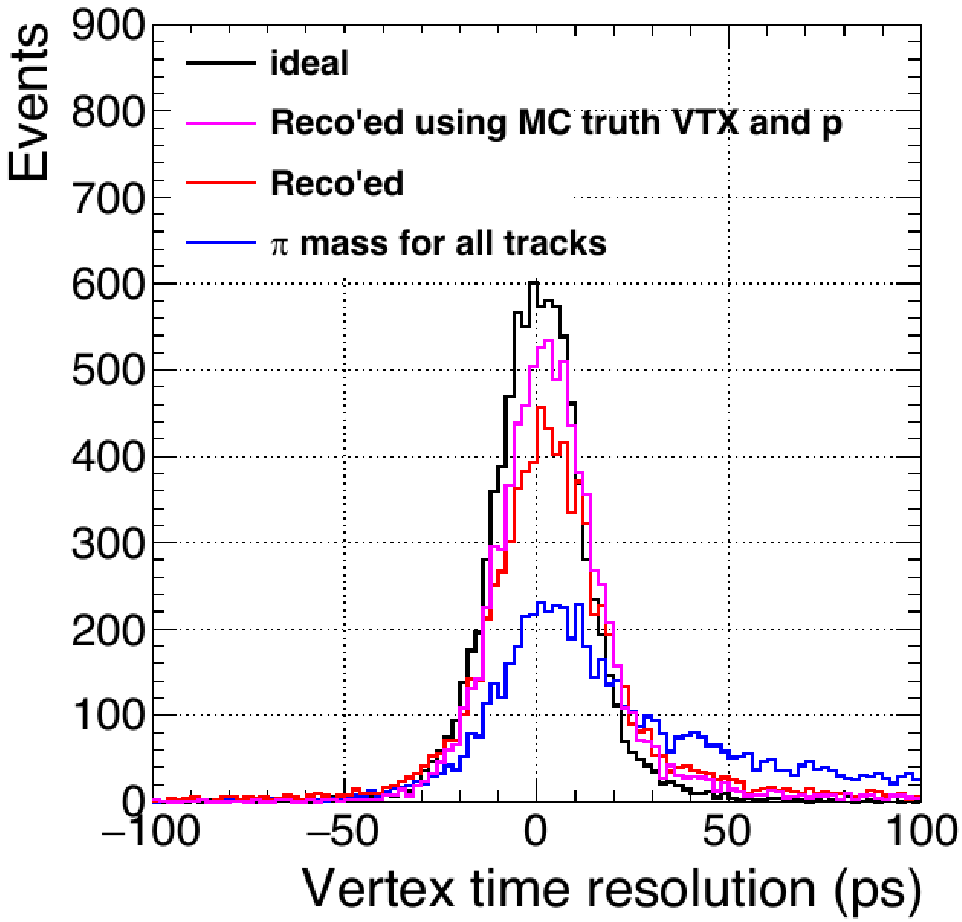
Dec 22 numbers used for winter23 prod

Time of decay vertex:

- Measure TOF wrt nominal interaction time for each decay track
- For each track, momentum and distance between decay vertex and timing layer measured
- If mass of particle known t_{vert} can be measured

Timing resolution on vertex

40 Gev HNL with cτ= 1m
Resolution timing layer 30 ps
Prim. vtx algo in FCCsw. Require $chi2_{vert}!=0$ & $chi2_{vert}<10$



To calculate t_{vert} for each track need mass of particle. In principle gain of of factor 1/sqrt(N) on resolution, with N=number tracks from vtx

Two possibilities:

- One of the tracks is a muon: use muon, mass fixed, but only one track
- Apply iterative algorithm on all non-muon tracks starting from pion hypothesis, and modifying id hypothesis for track with worst compatibility with average

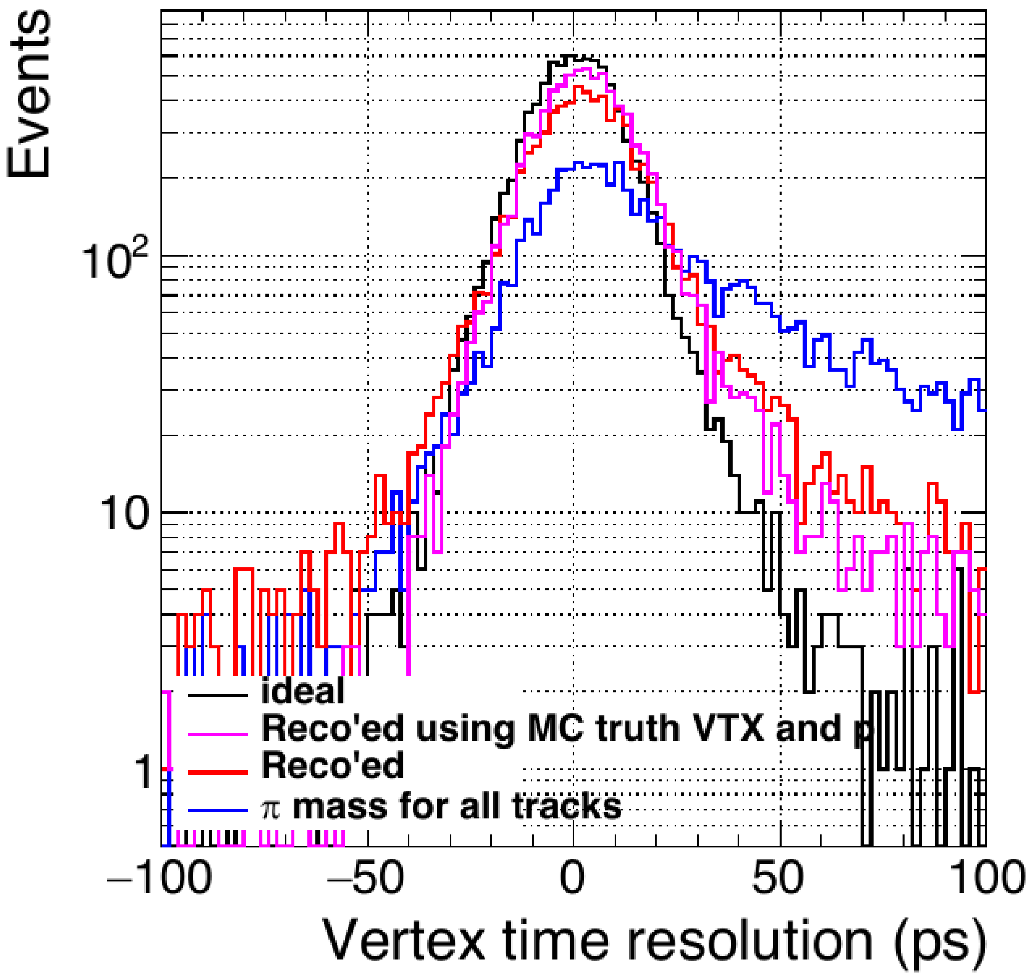
Ideal case gaussian with σ(t)~30 ps/sqrt(N)

If all tracks assumed π, large tails

Iterative algo yields reasonable result

Peak narrower if truth momentum and vtx position assumed

Timing resolution on vertex



Timing layer resolution 30 ps.
Distributions not fully gaussian, evaluate resolution as minimum interval including 68% of events

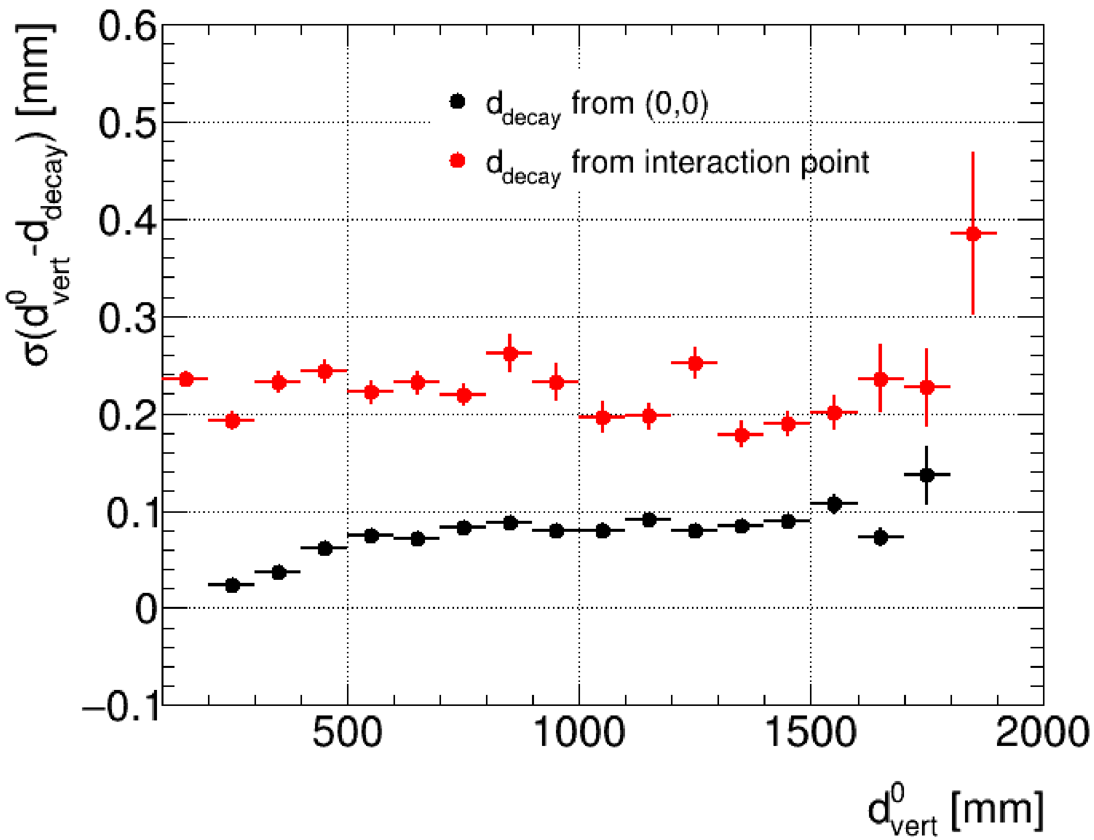
Ideal	12.6 ps
Pion masses	106 ps
Reco’ed	22.8 ps
Reco’ed with MC vtx & p	15 ps

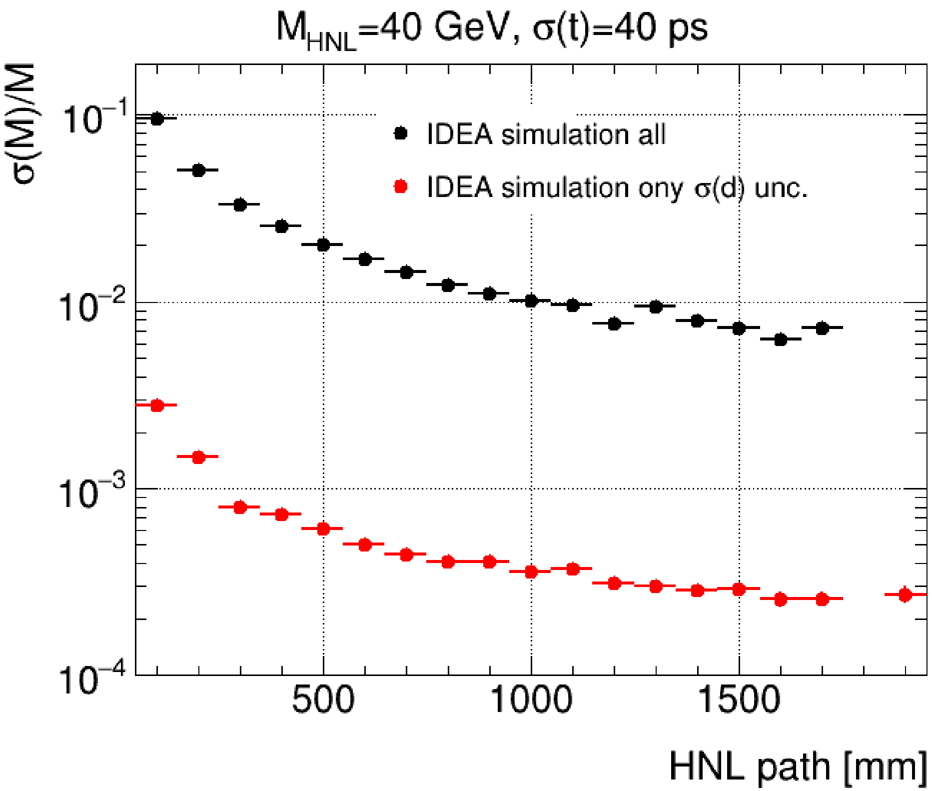
Impact of position uncertainty of decay vertex

Two components

- Unknown position of interaction vertex
- Uncertainty on vertex reconstruction

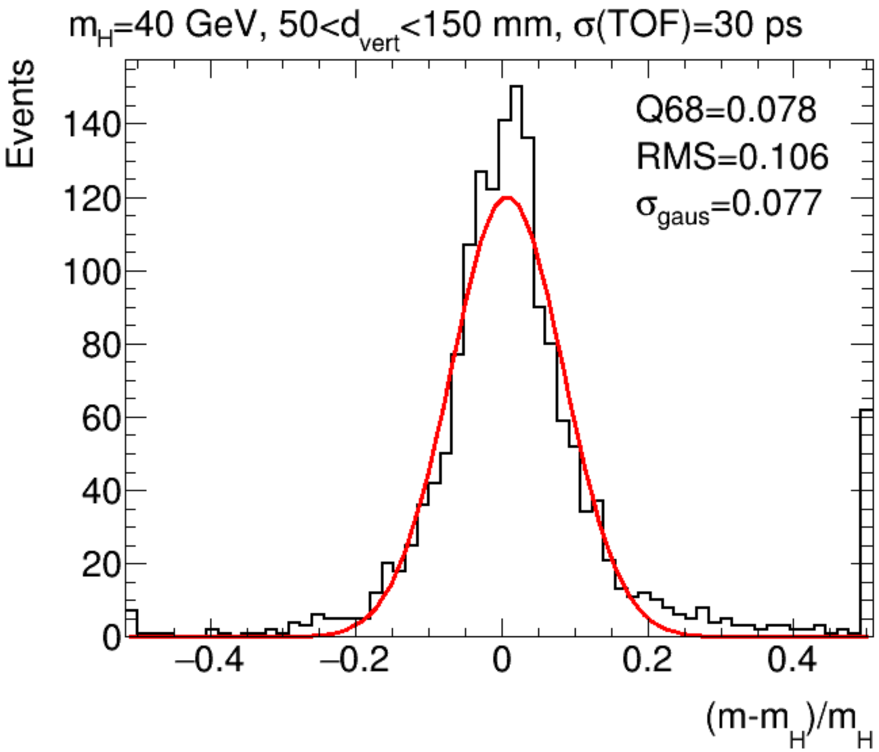
$$\beta = d_H / t_H / c,$$

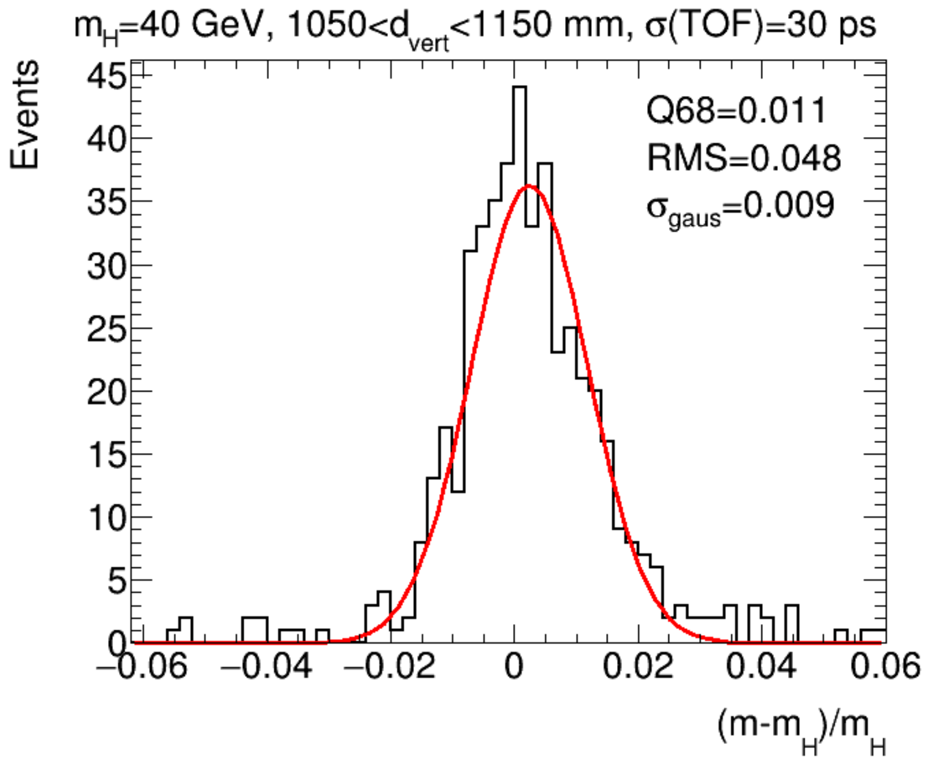




Mass resolution dominated by uncertainty on vertex timing

Measured mass distributions





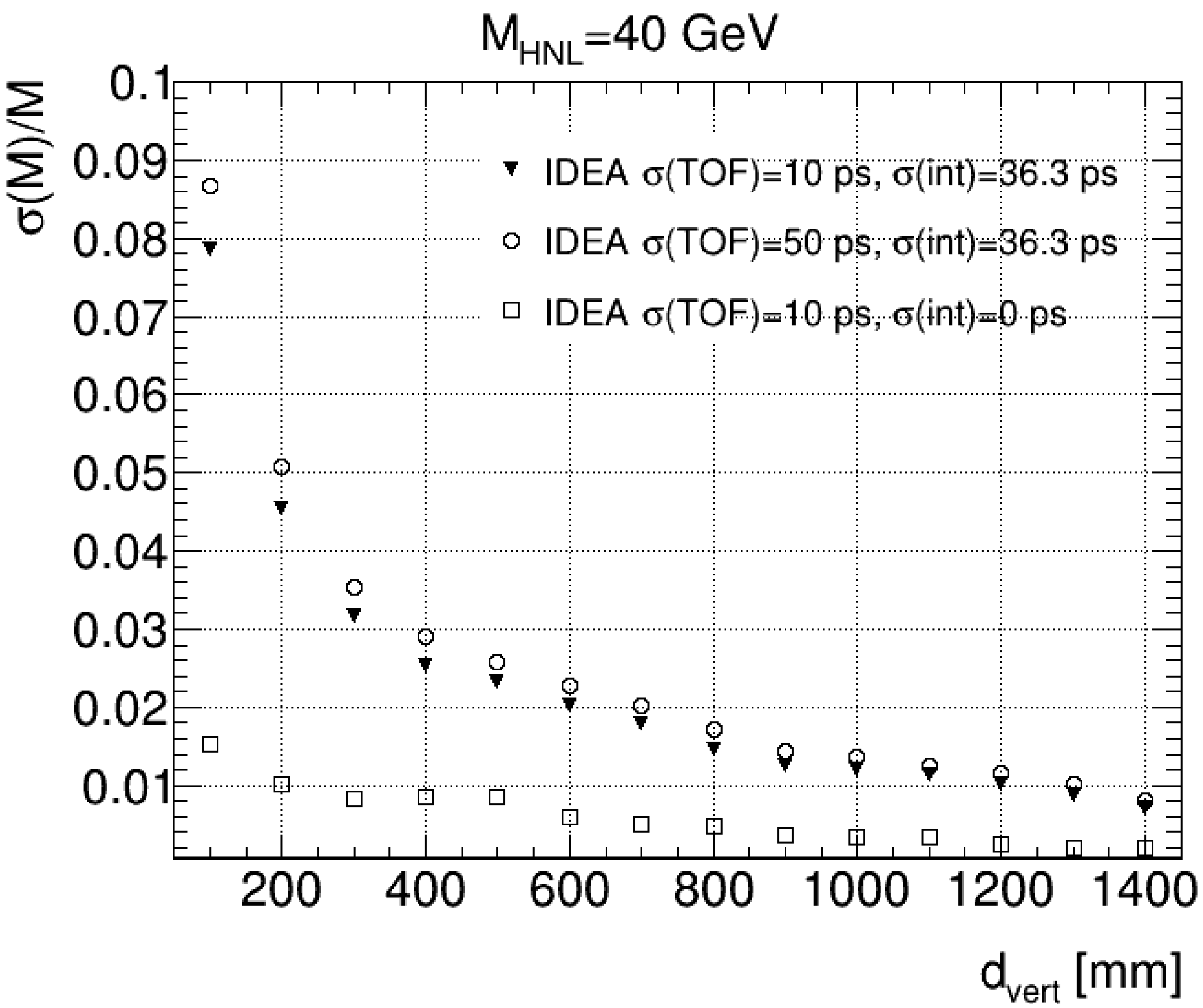
Based on algorithm for t_{vert}, measure mass event-by-event for M_H=40 GeV

Show result for two bins in measured vertex position

Distributions mediocrely fitted by gaussian, with tails on both sides

Use as resolution value: Q68=(Quantile(0.84)-Quantile(0.16))/2

Path dependence of mass resolution



Mild dependence on TOF resolution because of large uncertainty on time of primary interaction

Use Q68 as estimator of resolution

with σ(TOF)=50 ps obtain resolution of order 5% for d_{vert}>15 cm

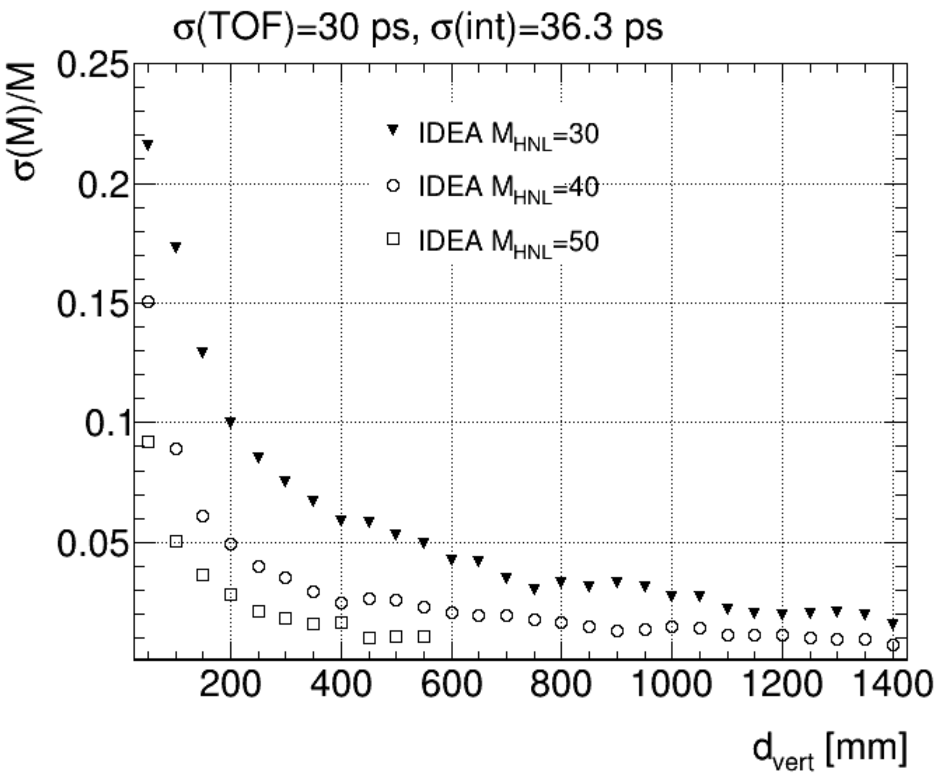
comparable to expected PFA measurement from cristal+DR calo

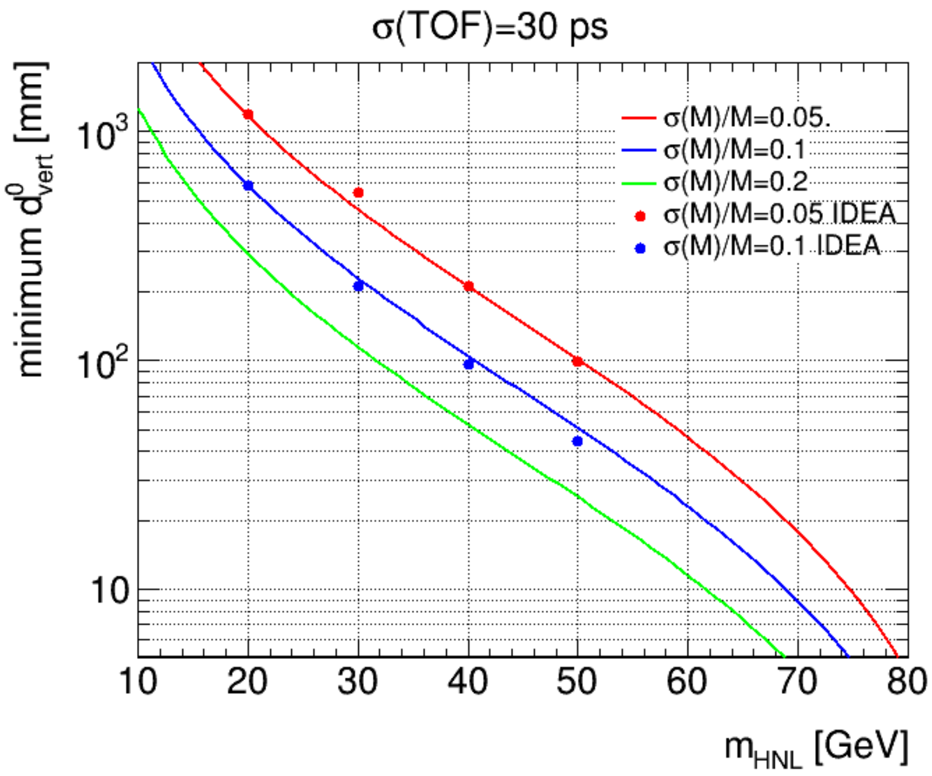
JINST 17 (2022) 06, P06008

Minimum decay length yielding fixed σ(M)/M

$$\sigma(M_H) = \frac{E_{CM}\beta^2 F'(\beta) c\sigma(t)}{d_H}$$

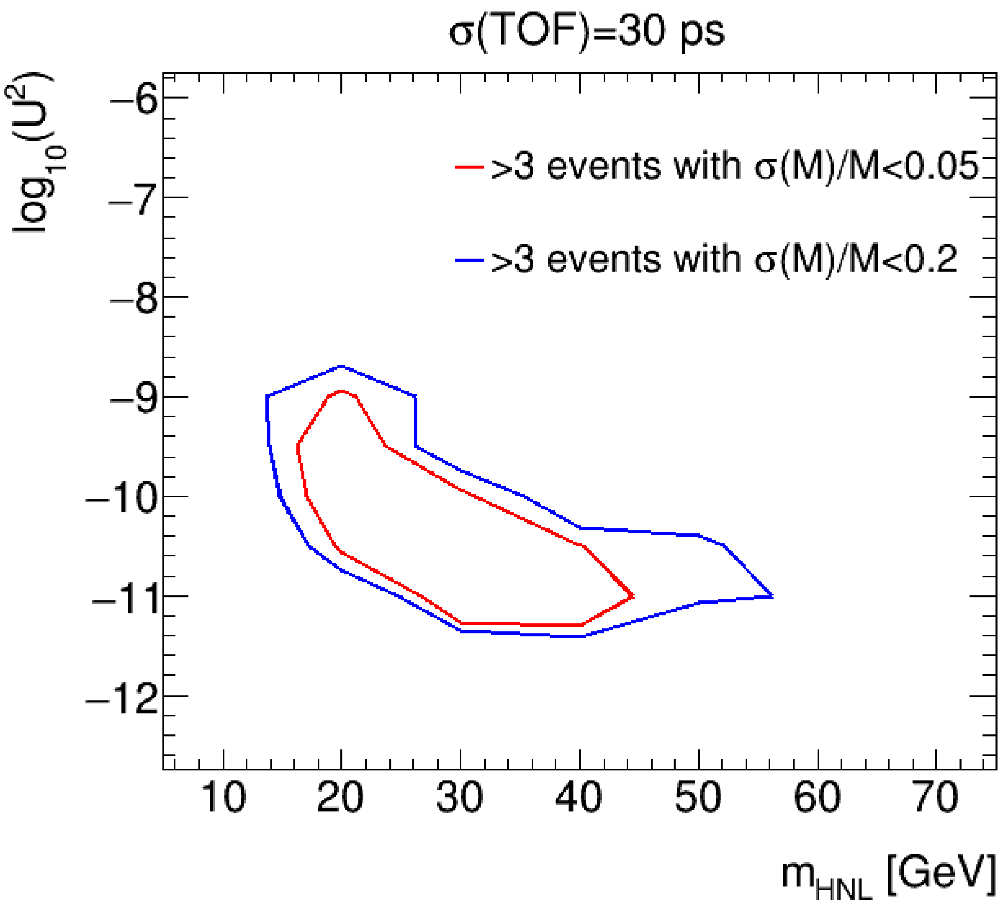
Can be inverted to evaluate the minimum path yielding a desired mass resolution





Use these values to apply lower limit on position of primary vertex to estimate number of well-measured surviving events

Parameter space coverage



Require: chi2 of primary vertex<10,
at least 4 tracks in event.
Zero background events for d_{vert}>50 mm.
Some mild kinematic cuts for masses
for which minimum d_{vert}<50 mm

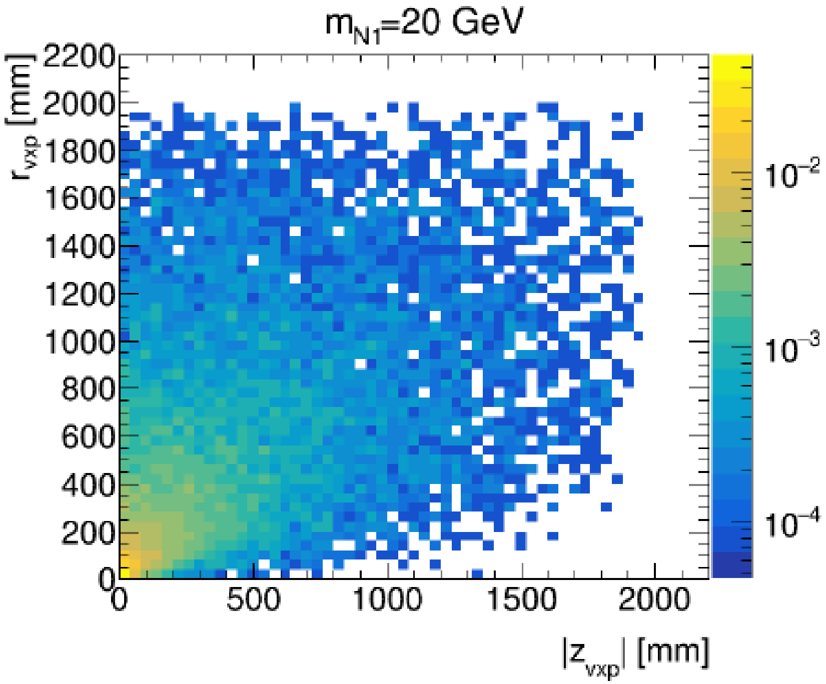
In significant fraction of parameter space
obtain useful mass measurement
from timing

Conclusions

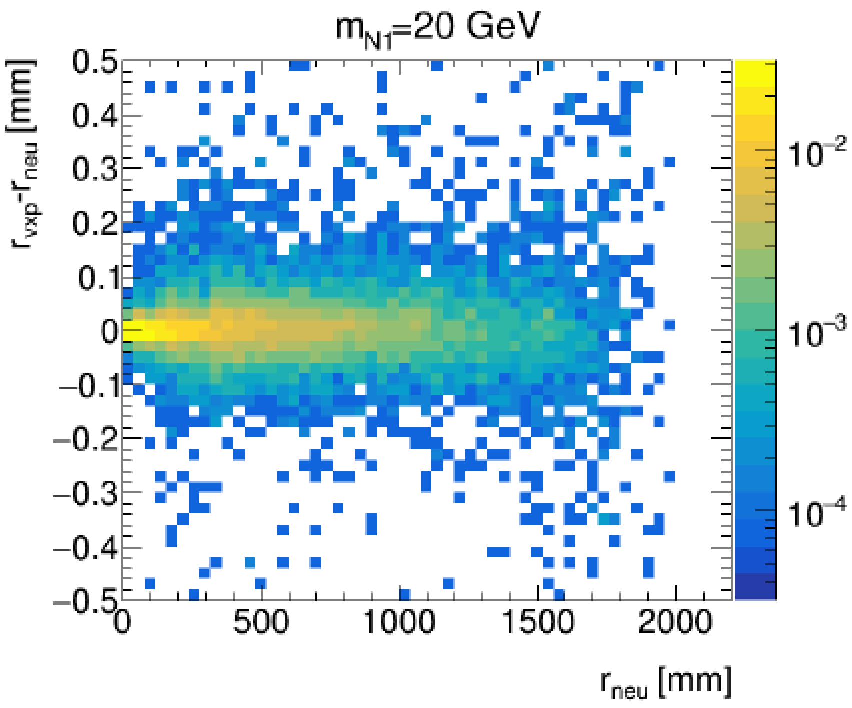
- Detection of decay products of long-lived particles (LLP) may allow measurement of LLP mass based on recoil formula and accurate measurement of position and timing of decay vertex
- Benchmarked on HNL production with HNL→ μjj
- For a timing layer with σ(t) a few tens of ps, mass resolution at percent level for long enough path and high enough mass
- Timing resolution dominated by unknown time of primary vertex
- Developed algorithm to precisely measure timing of decay vertex based on parametrised simulation of IDEA tracker
- Useful measurement of HNL mass from timing over large part of accessible HNL parameter space

Backup

Prompt vs Long Lived selection



Primary vertex well reconstructed in the volume of the detector



Very good resolution in position of HNL reconstructed vertex

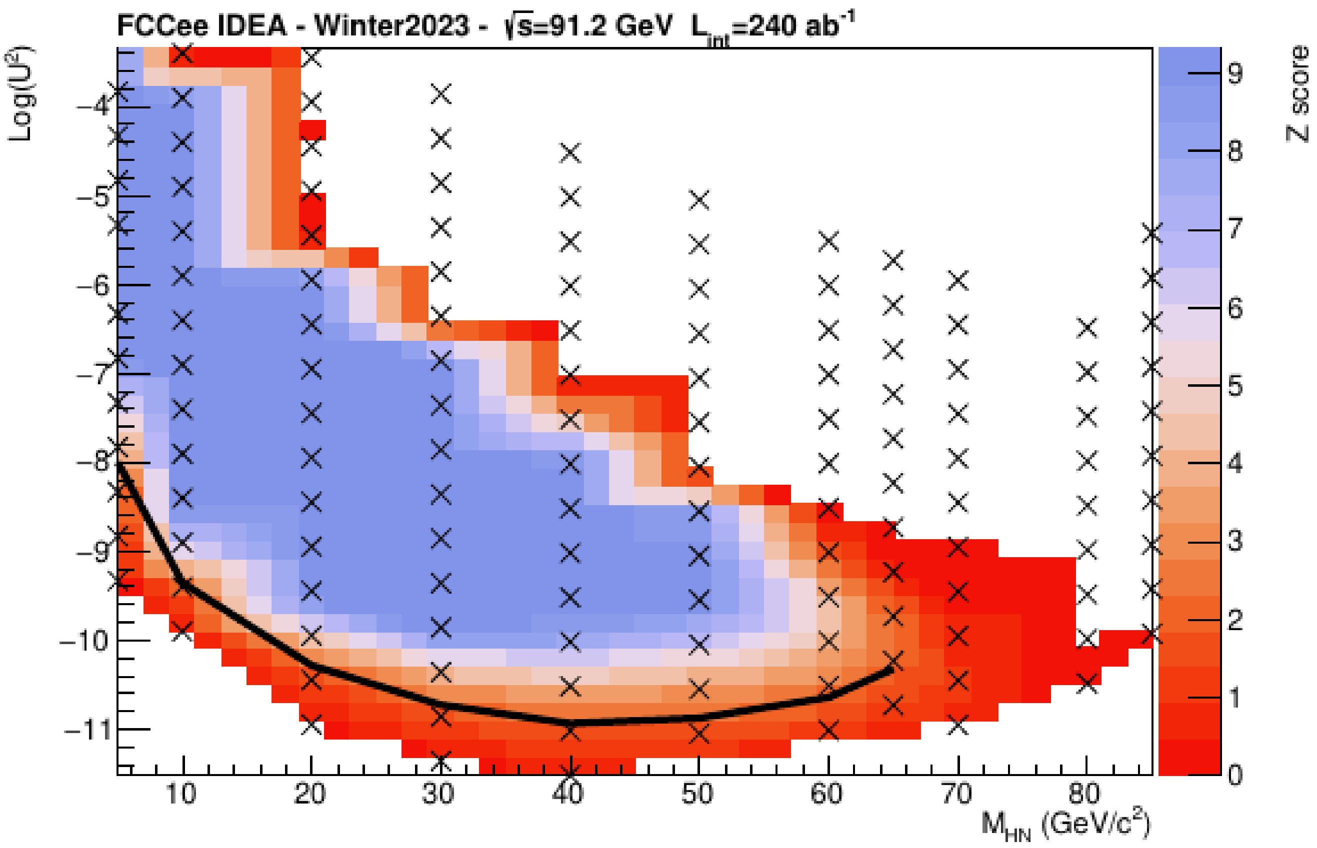
Separation between Prompt and Long Lived to some extent arbitrary, choose transverse position of primary vertex such that backgrounds become zero:

r_{vxp}=0.5 mm

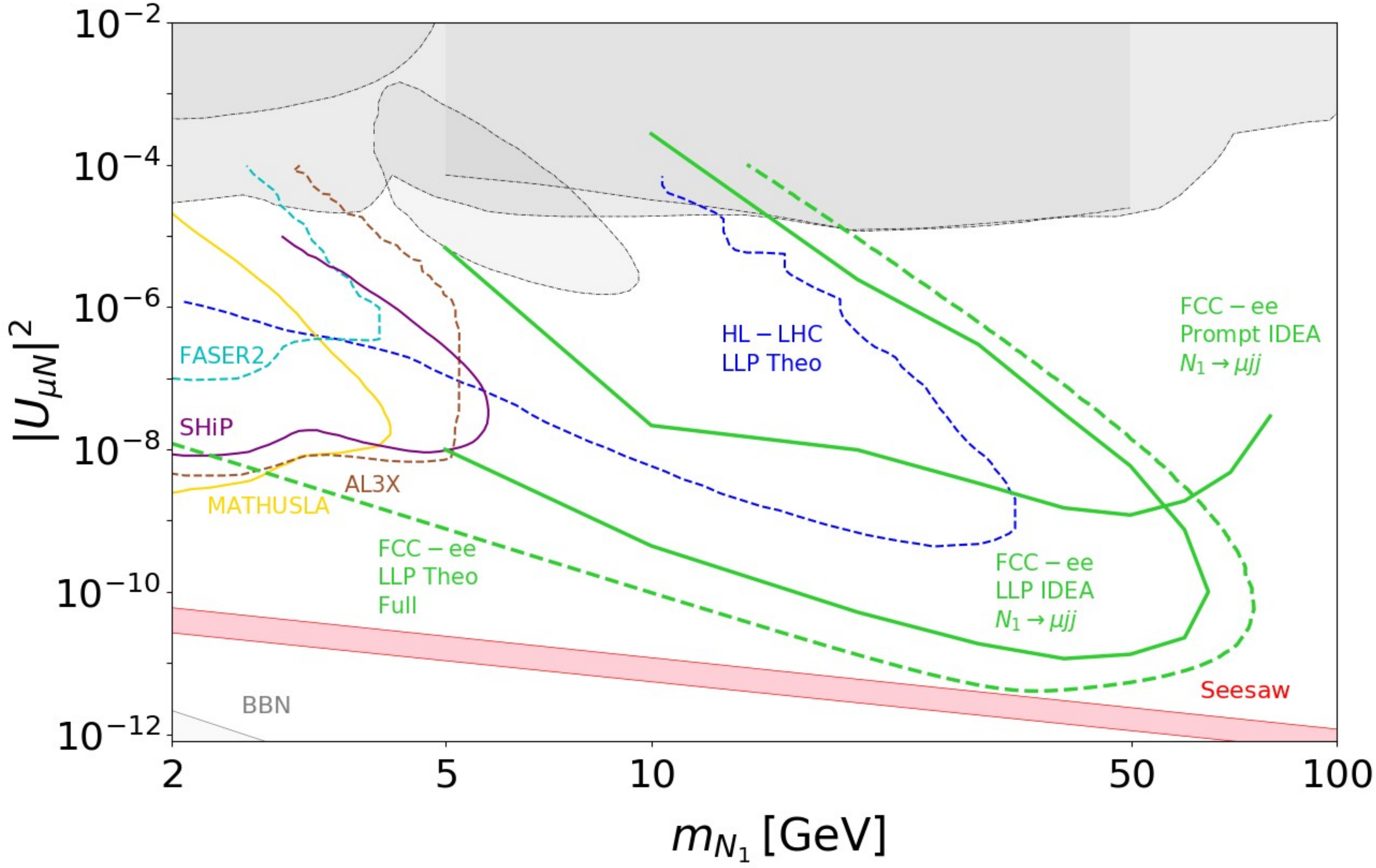
About five times values r_{vxp} for extreme tails of backgrounds

LLP results

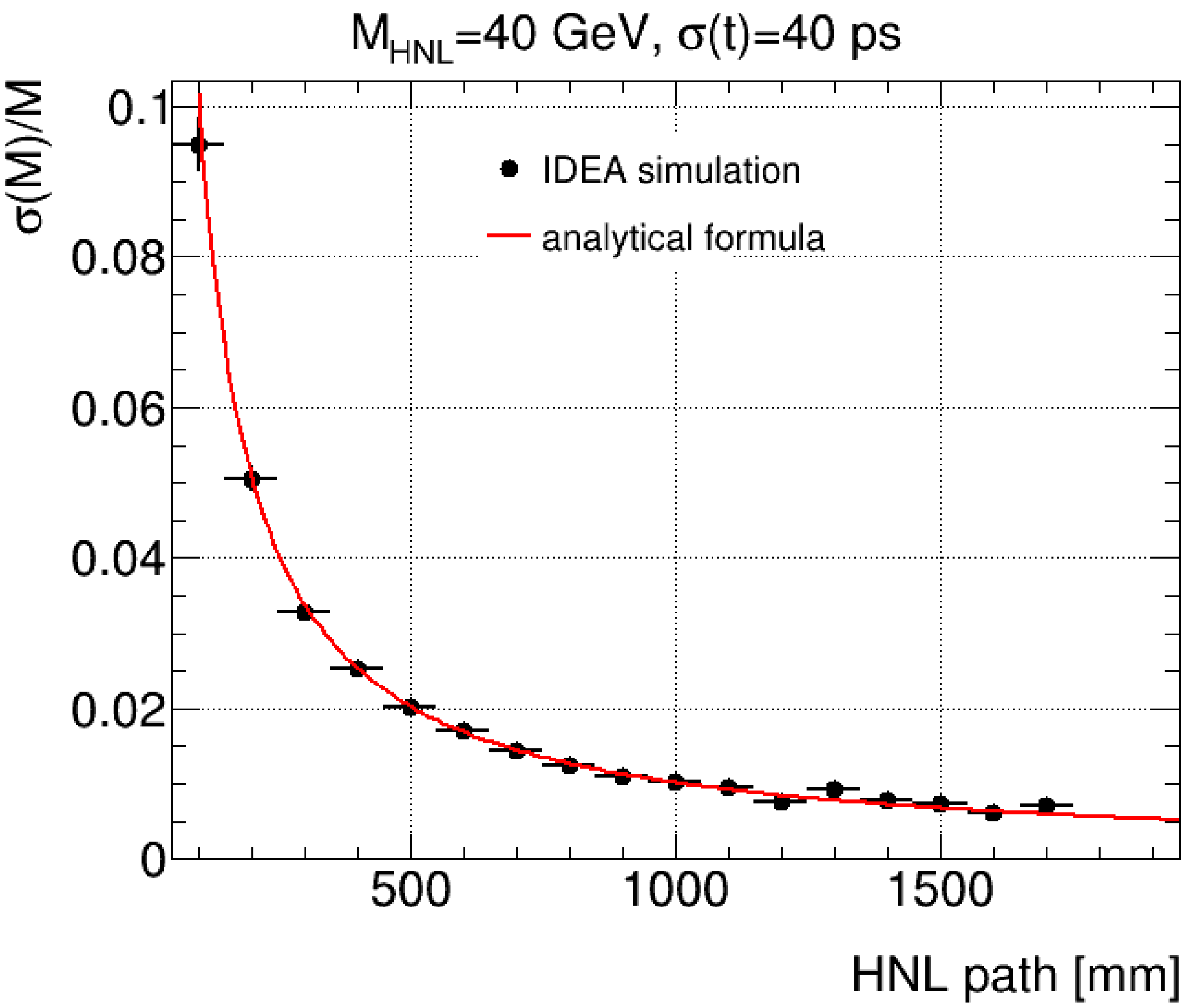
Backgrounds=0: sensitivity curve defined as points in parameter space where 3 events are expected after cuts



Final result



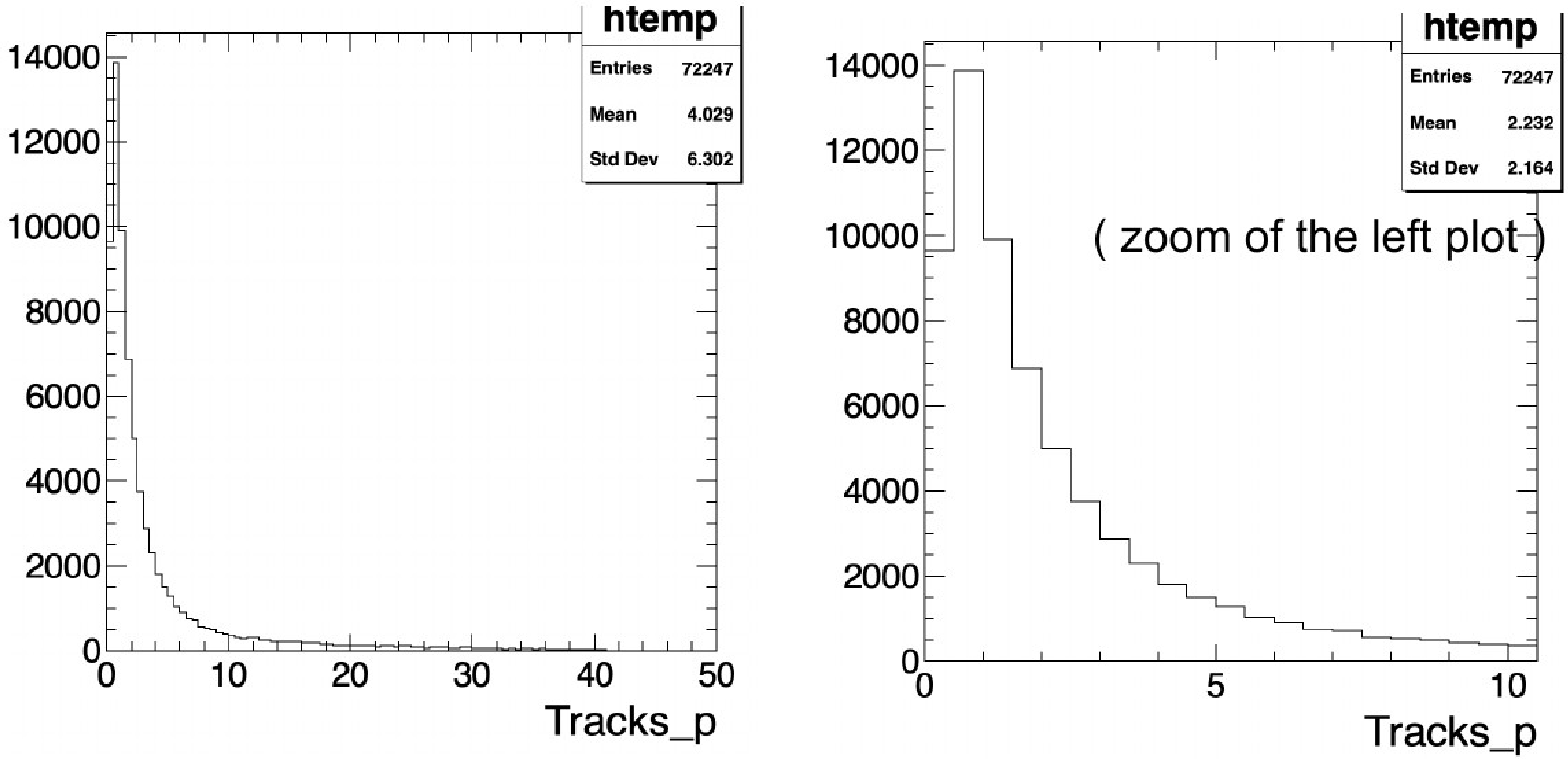
Analytic formulas vs. simulation



Consider decay
HNL → μjj

Compare analytic formulas to DELPHES simulation of IDEA detector with detailed parametrisation of the performance of the tracker

Possible gain from dE/dx PID



Momentum of the tracks: peak at ~ 1 GeV where dN/dx is blind.
But average ~ 4 GeV, so some improvement expected although the resolution is expected to be ~ √2 worse than for prompt tracks.