Validation of the IDEA Tracking Reconstruction for Prompt and Displaced Muon Signatures at FCC-ee

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Motivation: Why displaced tracking?

Question: Can the current IDEA Tracking Reconstruction chain find and fit prompt and displaced charged-particle tracks.

- The study is performed on a fully simulated detector response.
- The goal is to identify possible reconstruction blind spots or failure regions.
- Physics interpretation depends on efficiency, resolution, and systematic effects.

Physics Benchmarks

For prompt tracks

$$e^+e^- \to Z \to \mu^+\mu^-,$$

For Displaced tracks

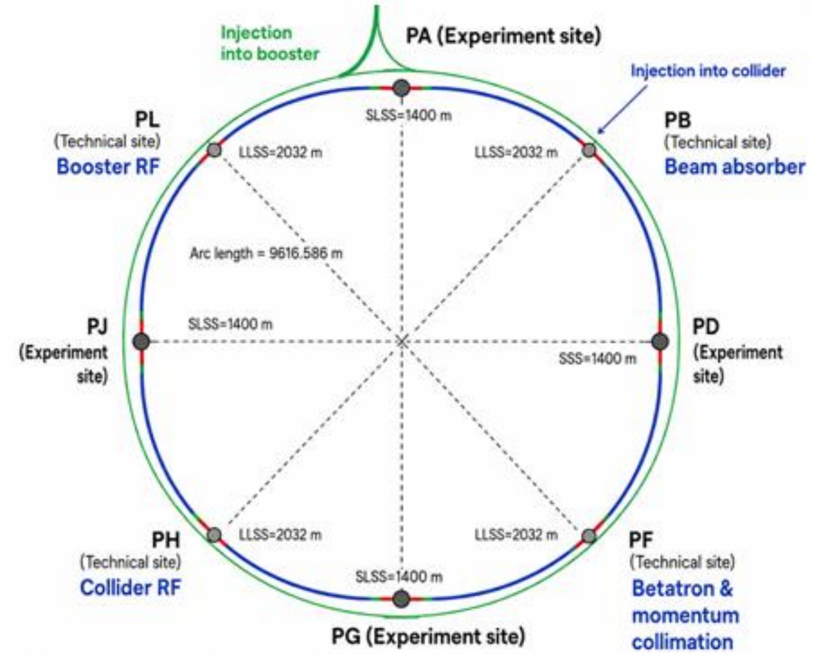
$$e^+e^- \to Z \to N_\mu \nu_\mu, \qquad N_\mu \to \mu^+\mu^-\nu_\mu.$$

Heavy Neutral Lepton with muon mixing

The Future Circular Collider(FCC-ee)

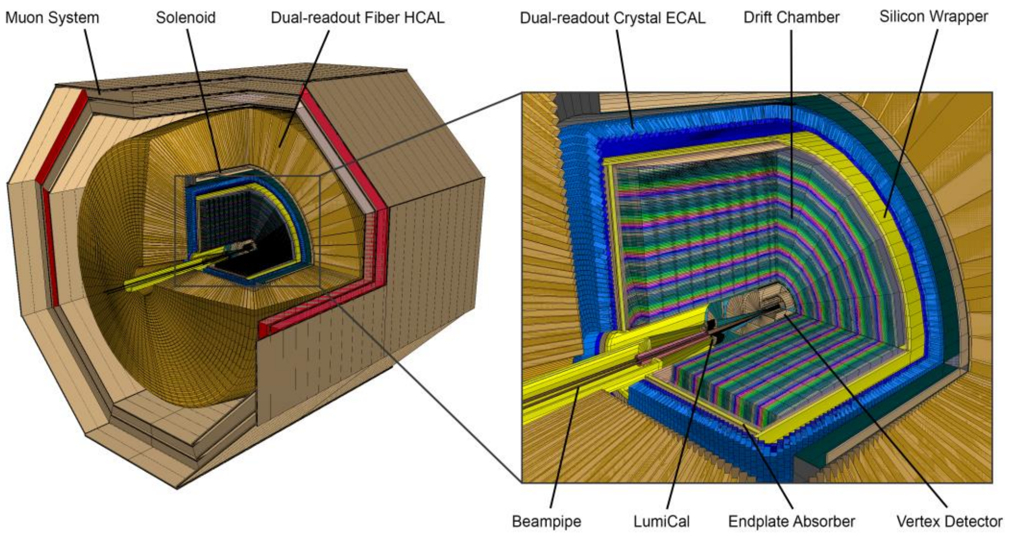
- FCC-ee is a proposed circular collider based at CERN
- FCC-ee circumference around 90 km
- ~2028 Project Approval by CERN Council

- Expected large number of Z bosons
- Clean environment (precisely known initial state)
- high luminosity



Working point	Z pole	WW threshold	ZH	$t\bar{t}$	
$\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340–350	365
Lumi/IP [10^{34} cm^{-2}s^{-1}]	140	20	7.5	1.8	1.4
Lumi/year [ab^{-1}]	68	9.6	3.6	0.83	0.67
Run time [years]	4	2	3	1	4
Integrated luminosity [ab^{-1}]	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH $+65$k $WW\to H$	2×10^{6} $t\bar{t}$ $+370$k ZH $+92$k $WW\to H$	

The IDEA Detector Concept - Tracker



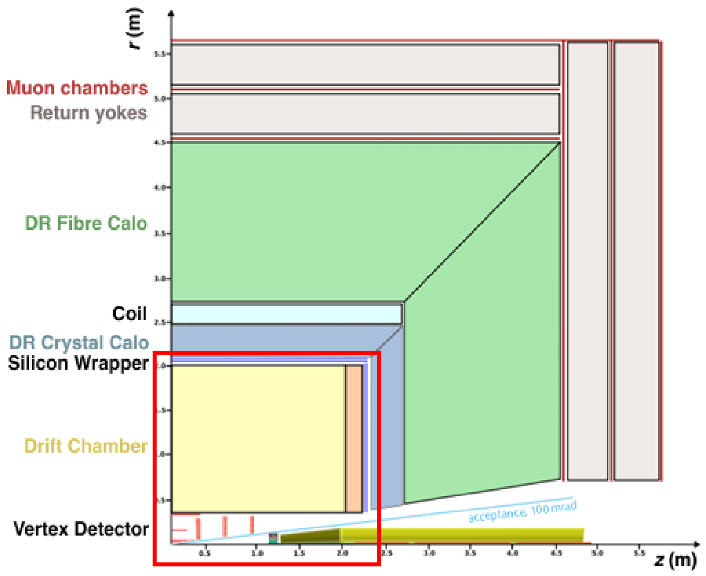


Figure 3: Overview of the IDEA detector layout.

VTX — Silicon vertex detector

- $R \approx 14–36\ mm$ inner layers
- outer VTX: $R \approx 130–315\ mm$
- Precise vertex and impact-parameter measurements

DCH — Drift chamber

- $R \approx 0.35–2.0\ m, |\ z\ | < 2.0\ m$
- 112 measurement layers, $B \simeq 2\ T$
- Gas mixture: 90% He and 10% iC_4H_{10} (isobutane)
- Main tracking lever arm

SiWr — Silicon wrapper

- $R \approx 2.04–2.08\ m$
- Precise outer constraint on the fitted trajectory

→ The large tracking volume also gives sensitivity to tracks produced away from the interaction point.

Reconstruction framework

MadGraph5 or particle gun → **Simulation** *DD4hep + Geant4* → **Digitization** *Silicon and DCH digis* → **Track finding** GGTF;*ONNX Model* → **Track fitting** *Genfit2*

Source: FCC-config

Track Finder

- digitized tracker hits are encoded as graph / geometric features
- a pre-trained GNN model exported in ONNX → maps hits to an embedding space
- clustering in this space defines track candidates in Pre-fitTracks

Track Fitter

- fits candidate hits with a deterministic annealing filter
- provides track parameters and covariance matrices
- may reject candidates with no usable state or invalid fit quality

Validation strategy: Sample

1. Single-muon guns

Controlled single-track tests

- Prompt and displaced production points
- Fixed momentum and polar-angle scans

→ Isolates detector and kinematic effects

2. $Z \rightarrow \mu^+\mu^-$

Prompt two-track physics topology

- **MadGraph5_aMC@NLO** + **Pythia8** at $\sqrt{s} = 91.188\mathrm{GeV}$
- events = 918320

→ Tests pair reconstruction and candidate ambiguity

3. Heavy Neutral Leptons (HNLs)

Displaced two-track physics topology

$$Z \rightarrow N_\mu \nu_\mu \qquad N_\mu \rightarrow \mu^+\mu^- \nu_\mu$$

- **MadGraph5_aMC@NLO** + **Pythia8** at $\sqrt{s} = 91.188\mathrm{GeV}$
- events = 921k
- $\mathrm{M_N} = 40\mathrm{GeV} \qquad \mathrm{U}_{\mu\mathrm{N}} = 2 \times 10^{-6}$

→ Tests reconstruction away from the interaction point

Validation strategy: truth matching and efficiencies

Reconstructable truth muons:

- $|PDG| = 13$ and stable final state.
- At least four truth-linked tracker sim hits.
- $|\cos\theta| \leq 0.99$.

Candidate match:

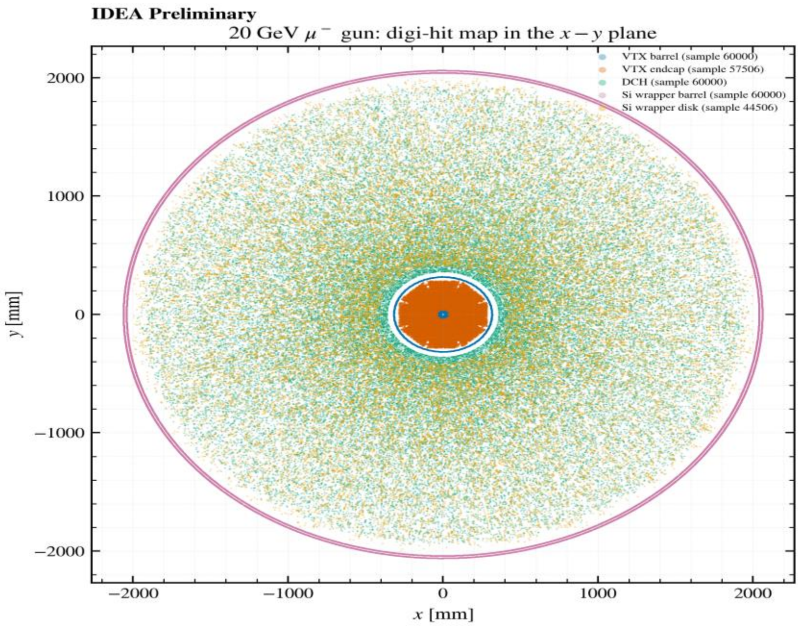
$$P(t, c) = \frac{Nhits(c \leftarrow t)}{Nhits(c)}$$

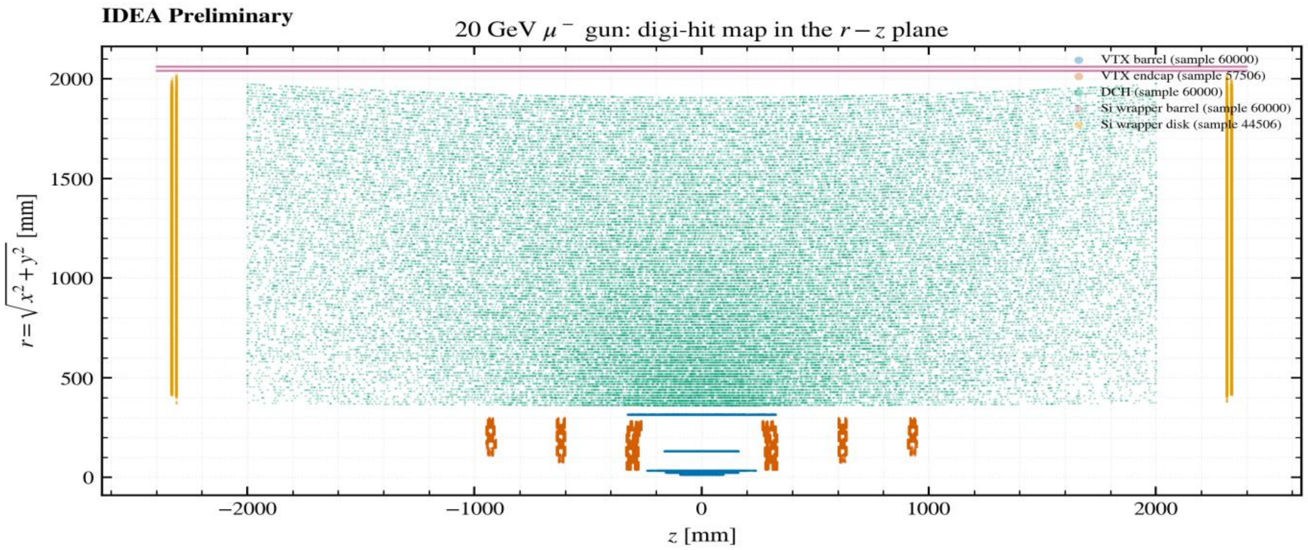
A candidate passes for truth muon t when $P \geq 0.75$ and it contains at least four reconstructed hits.

Reconstruction efficiencies

- **Finder efficiency:** $$\epsilon_{finder} = \frac{N(\text{truth muons matched to finder})}{N(\text{reconstructable truth muons})}$$
- **Fitted-track efficiency:** $$\epsilon_{fit} = \frac{N(\text{truth muons matched to fitted tracks})}{N(\text{reconstructable truth muons})}$$
- **Fit retention:** $$\epsilon_{\mathrm{ret}} = \frac{N(\text{finder-matched muons retained after fitting})}{N(\text{finder-matched muons})}$$
- **Two-track efficiency:** $$\epsilon_{\mu\mu} = \frac{N(\text{events with both muons fitted})}{N(\text{events with reconstructable pair})}$$

Detector response: 20 GeV muon gun





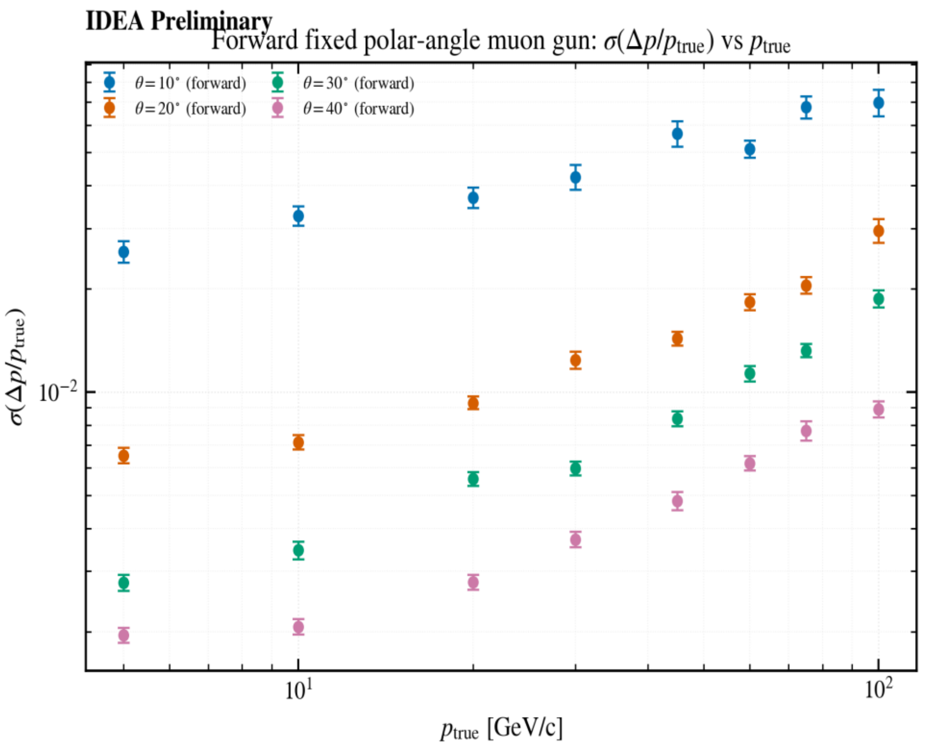
Sample

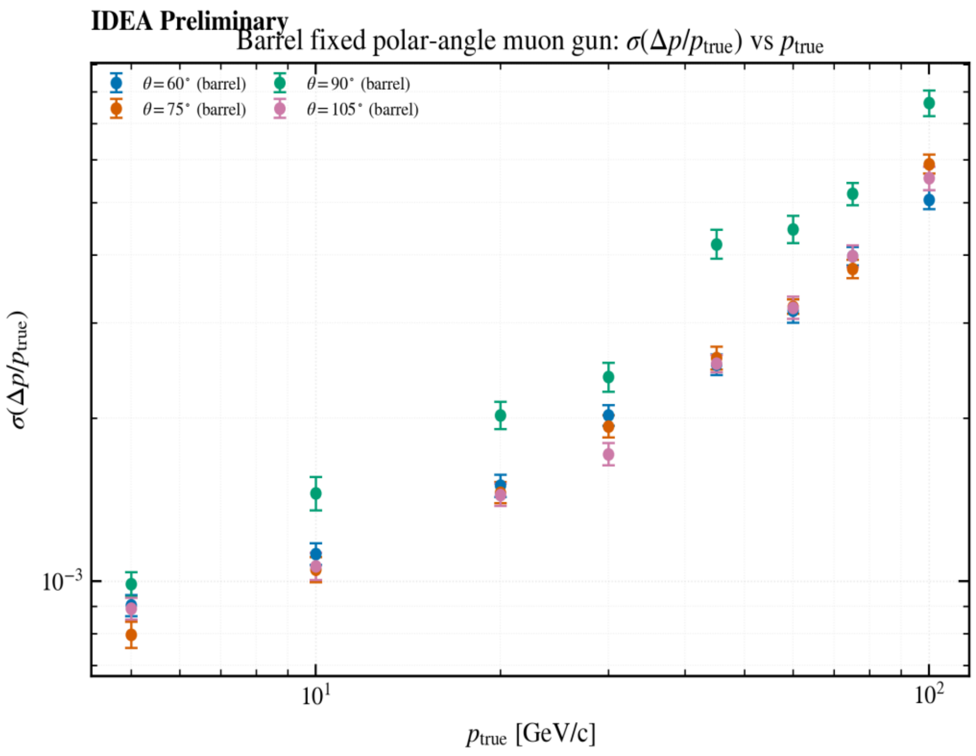
- $50{,}000\ \mu$ −events
- $10^\circ < \theta < 170^\circ$.
- $p = 20\ GeV$.
- Uniform azimuth.

Checks:

- **VTX**, **DCH**, and **silicon-wrapper** structures are populated.
- All truth muons have at least four linked tracker sim hits.
- This establishes detector coverage and acceptance.

Controlled prompt-muon performance

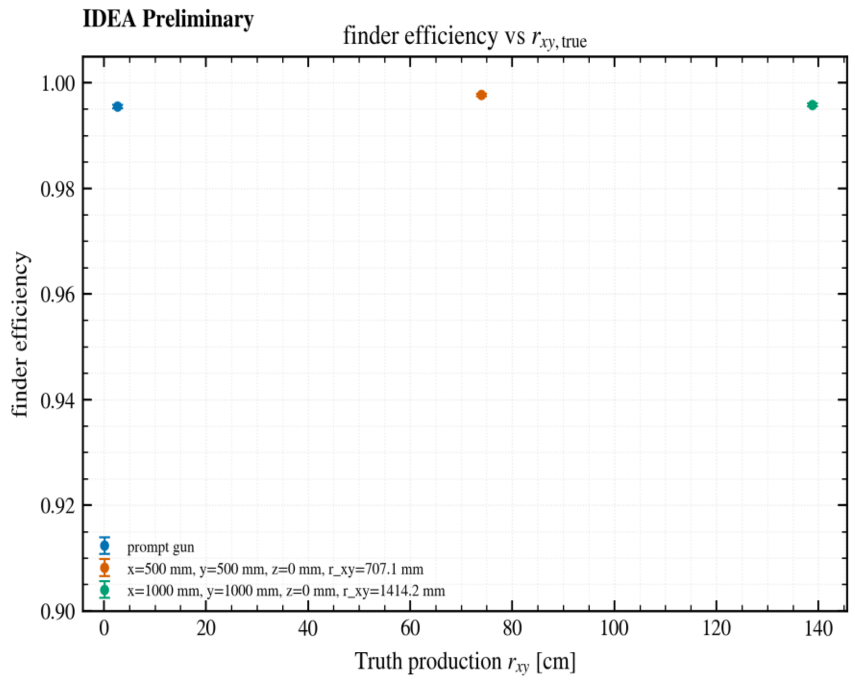




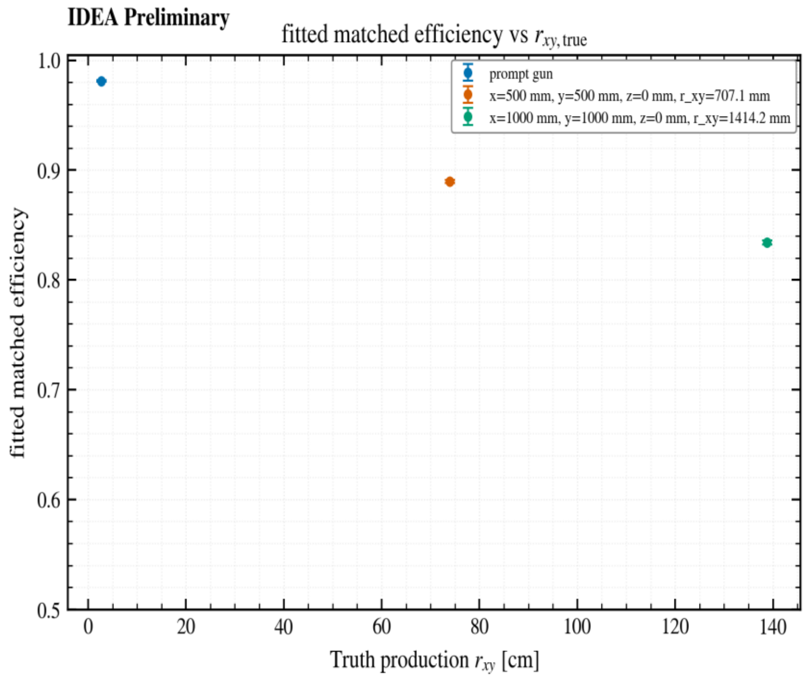
Region	Polar angle	p = 10GeV	p = 100GeV
forward	$10^{o} - 40^{o}$	0.21-3.26%	0.89-6.98%
barrel	$60^{o} - 105^{o}$	0.105-0.145%	0.506-0.764%

- **Angle:** Forward tracks → shorter transverse lever arm → poorer resolution.
- **Momentum :** Higher p → smaller curvature → poorer resolution.

Prompt and displaced single-muon



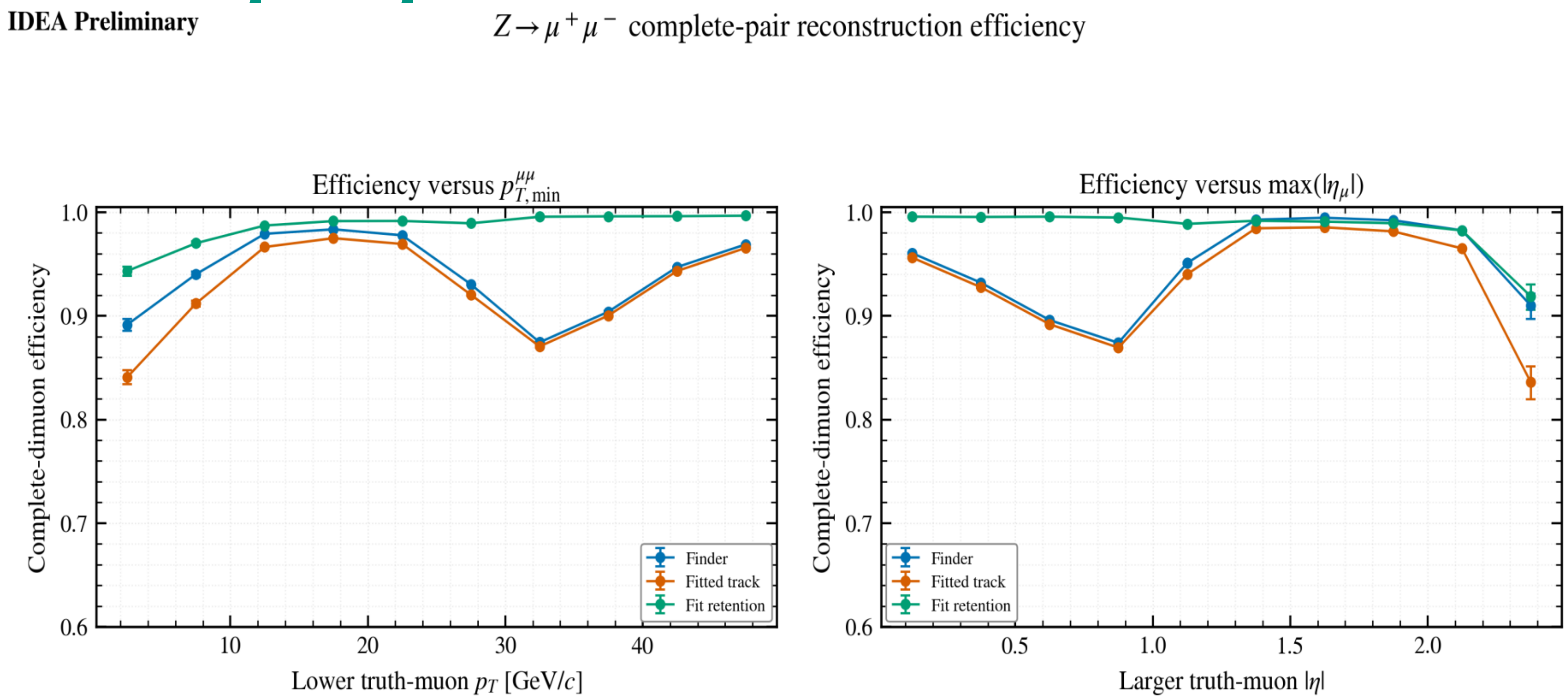
- $R\_xy = 0$ mm
- $R\_xy = 707$ mm
- $R\_xy = 1414$ mm
- Keeping $z = 0$



R_{xy} [mm]	finder [%]	fitted [%]	fit retention [%]
0	$99.549^{+0.030}_{-0.032}$	$98.104^{+0.062}_{-0.064}$	$98.549^{+0.054}_{-0.056}$
707	$99.768^{+0.021}_{-0.023}$	$88.970^{+0.144}_{-0.145}$	$89.177^{+0.143}_{-0.144}$
1414	$99.583^{+0.029}_{-0.031}$	$83.409^{+0.171}_{-0.172}$	$83.758^{+0.170}_{-0.171}$

- **Finder >99.5%:** displaced muons still leave enough hits to form candidates..
- **Fitted efficiency drops with radius:** fewer inner hits and a shorter lever arm make fitting harder..
- **Main loss:** occurs during fitting, not candidate finding.

Results: $Z \to \mu + \mu -$

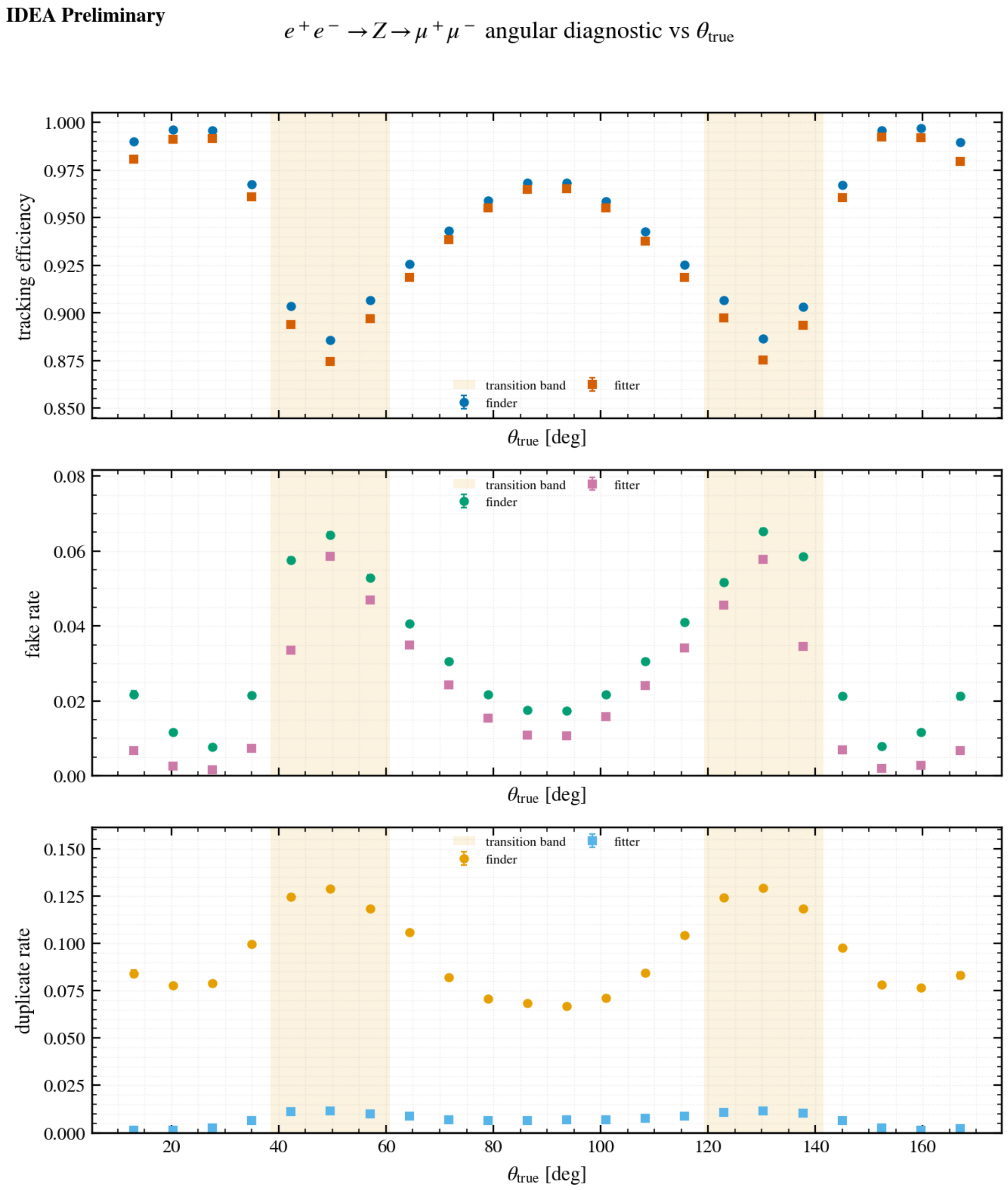


- Once both prompt muons are found, the fitter retains more than 99.3% of the pairs
- The dominant event-level loss is therefore associated with finding rather than fitting.
- The loss is strongly localized “transition” detector region

Inclusive performance

Quantity	Efficiency
Both muons found	$93.596^{+0.026}_{-0.026}\,\%$
Both muons fitted	$92.981^{+0.027}_{-0.027}\,\%$
Fit retention	$99.344^{+0.009}_{-0.009}\,\%$

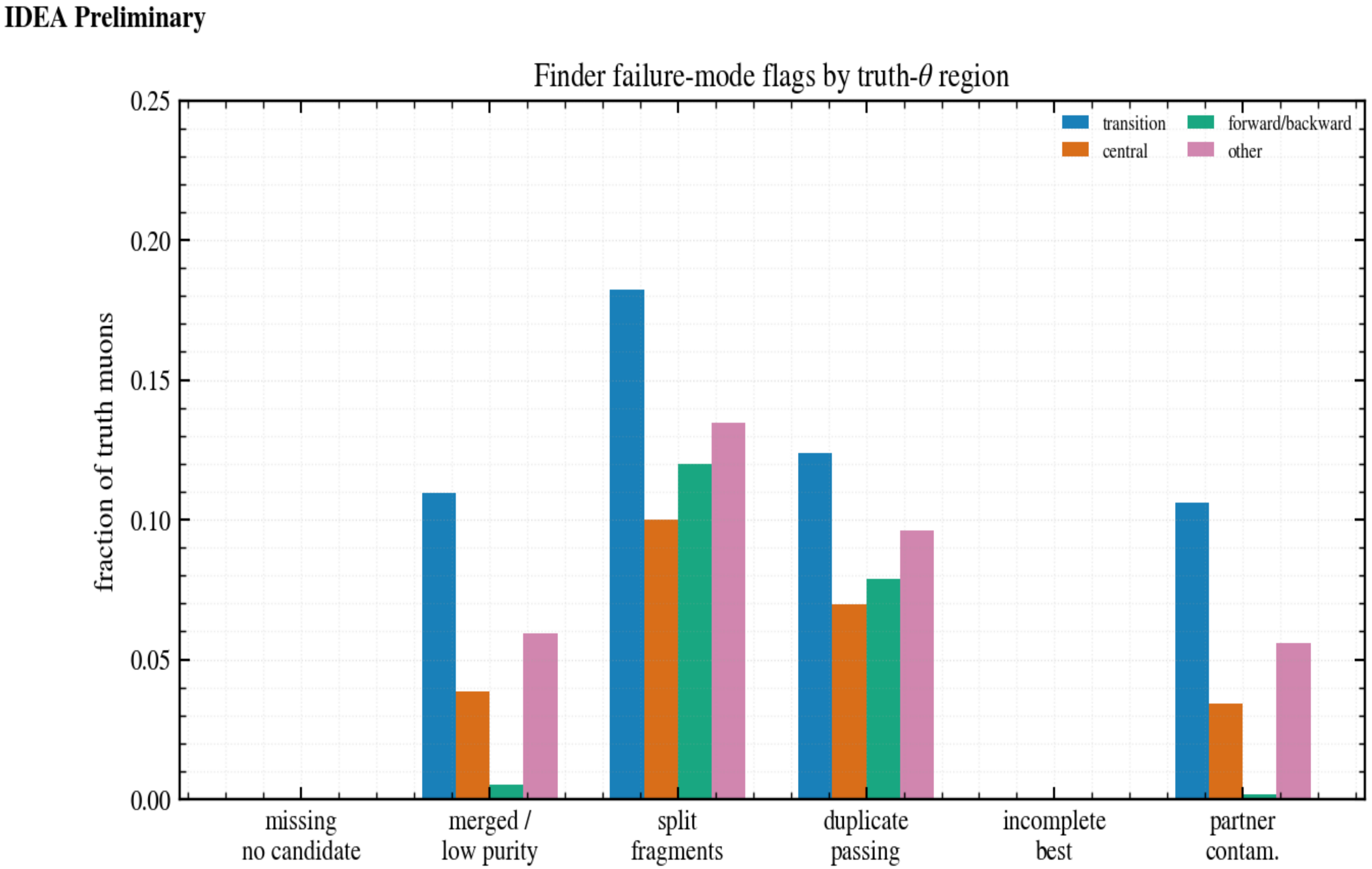
The angular dips are a finder-stage feature



- The mirrored low-efficiency bins coincide with enhanced fake & duplicate rates
- Local efficiency reductions occur near the barrel–forward transition bands.
- Finder and fitted-track efficiencies follow the same structure.
- The pair fit-retention remains high once both tracks are found.

→ The angular inefficiency originates mainly during track finding, not fitting.

Why? Candidate ambiguity in the "transition regions"



Transition region

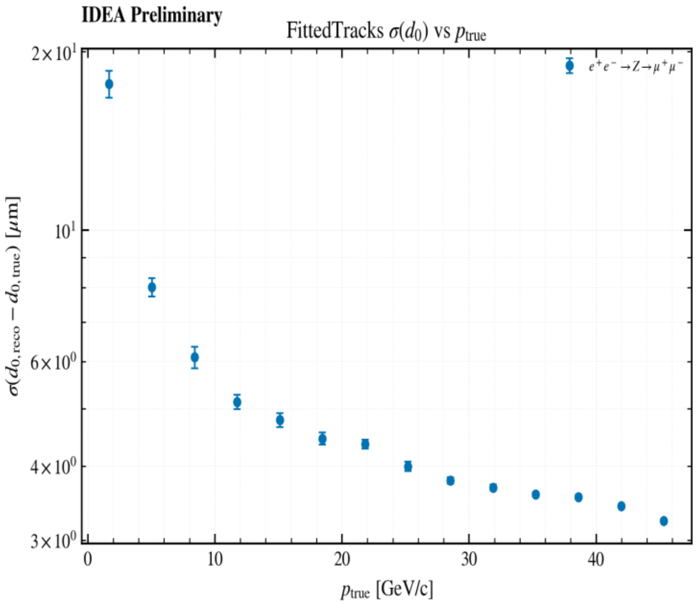
Duplicate passing:	**12.38%**
Partner hits in best candidate:	10.62%
Low-purity best candidate:	10.97%

- **Low-purity / merged candidates increase strongly** in the transition region.
- Duplicate candidates and partner-muon contamination also increase.
- The problem is therefore **hit assignment during pattern recognition**, not simply missing detector hits.

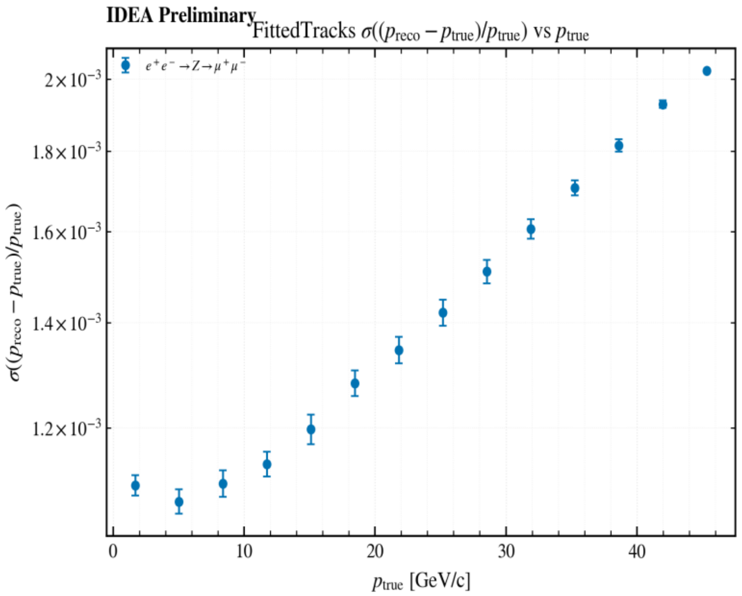
→ Localized GNN pattern-recognition limitation - not a detector-acceptance loss.

Fitted-parameter precision on the prompt sample

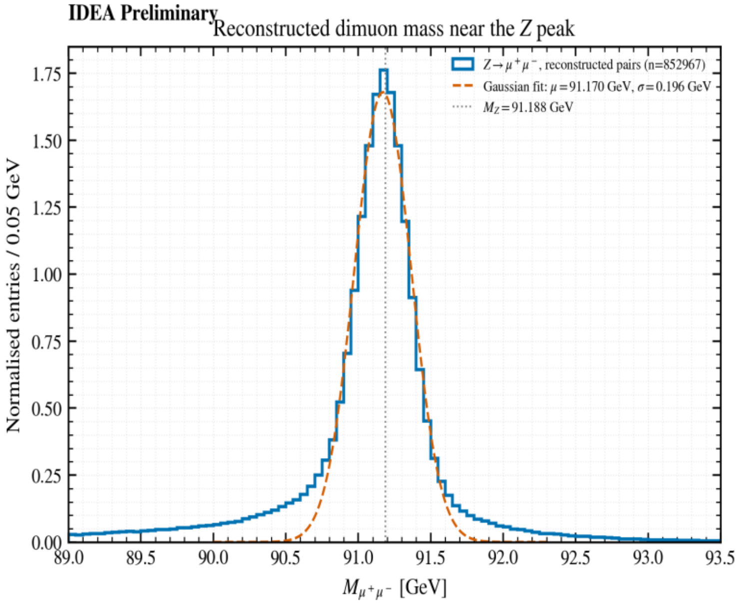
Impact parameter resolution



Relative Momentum



Dimuon peak



- **Track origin:** d_0 resolution reaches a few μm at high momentum.
- **Momentum:** relative momentum resolution is at the 10^{-3} level and worsens with momentum.
- **Event check:** the fitted tracks reconstruct the Z peak at $91.170\ GeV$,close to the expected value $91.188 GeV$.

HNLs as a displaced-track benchmark

What is an HNL?

- A hypothetical heavy neutral fermion that mixes weakly with SM neutrinos.
- Small mixing can give a long lifetime.
- The HNL can therefore travel a measurable distance before decaying, producing displaced charged tracks.

Process:

$$e^+e^- \rightarrow Z \rightarrow \quad N_\mu \nu_\mu$$

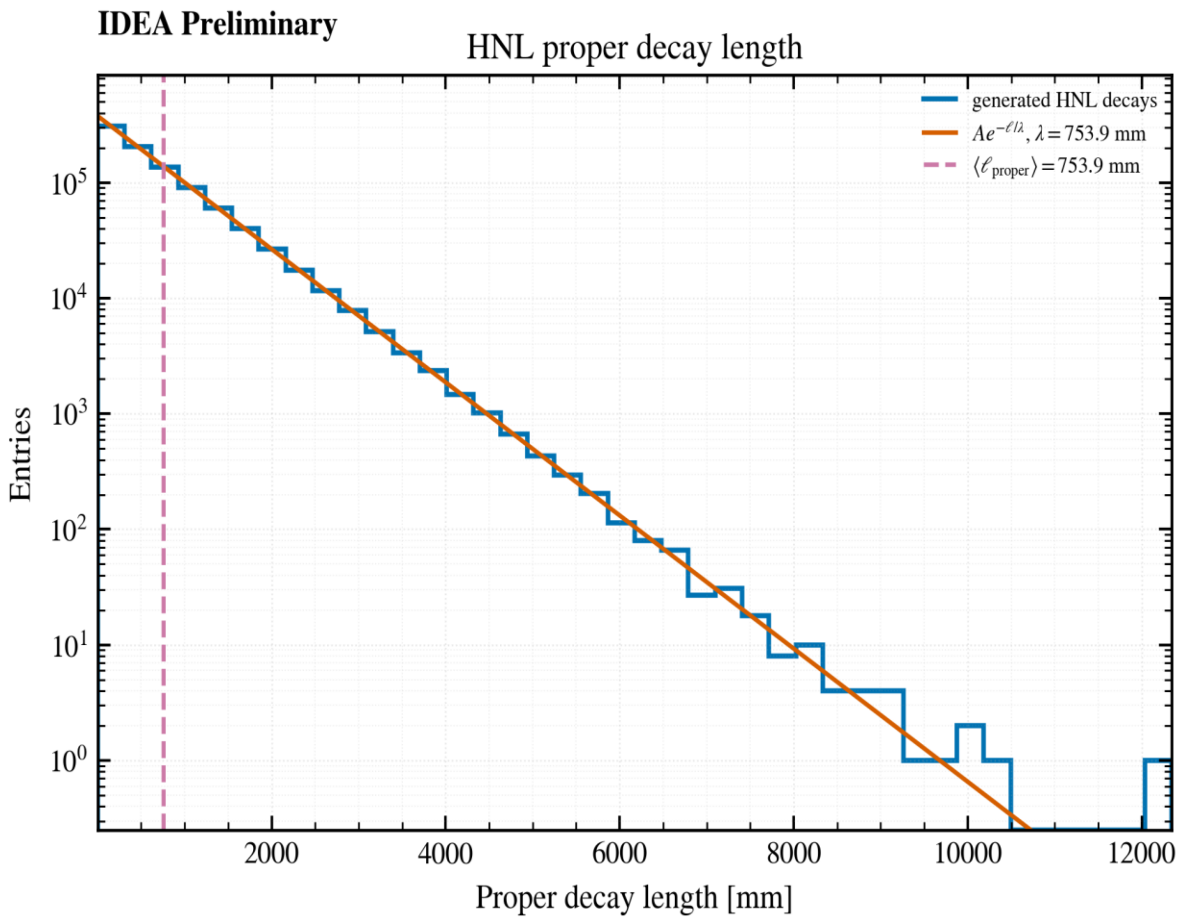
$$N_\mu \rightarrow \mu^+\mu^- \nu_\mu$$

Benchmark:

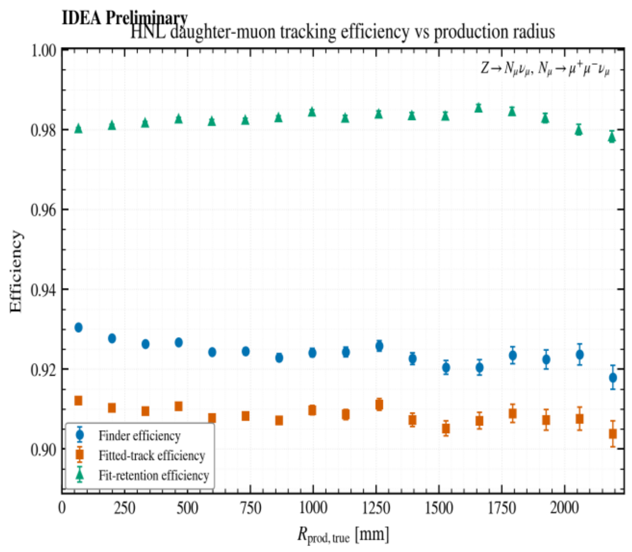
$$M_N = 40GeV \qquad U_{\mu N} = 2\ x\ 10^{-6}$$

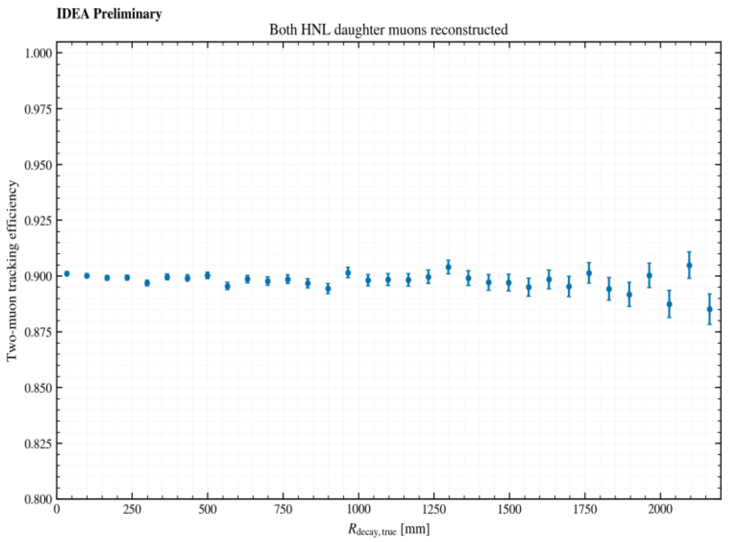
nominal $c\tau = 754.6\text{mm}$

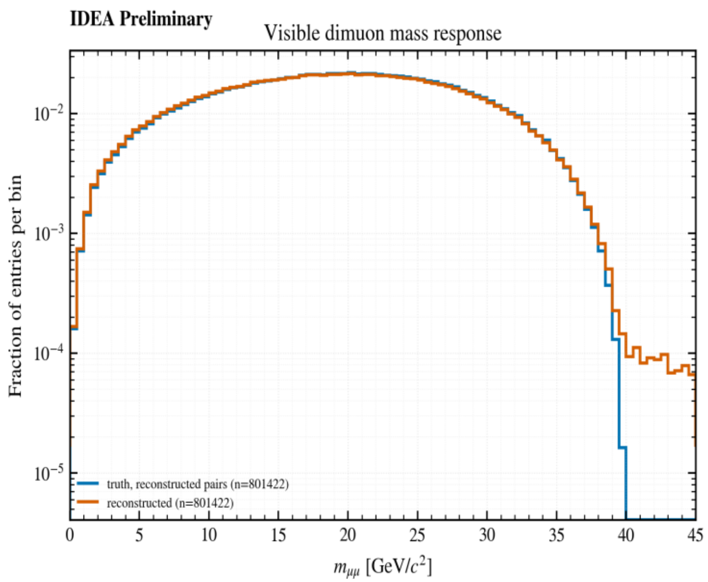
generated mean $= 753.9mm$



Visible HNL decay: event-level reconstruction





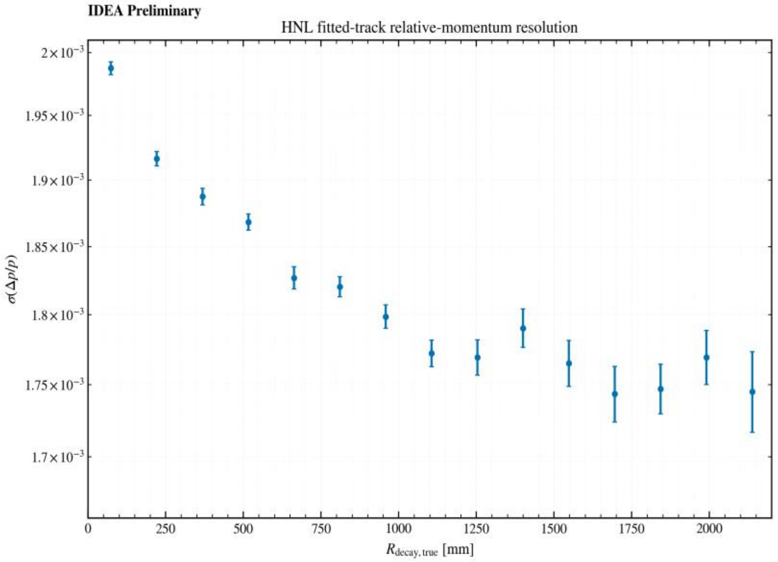


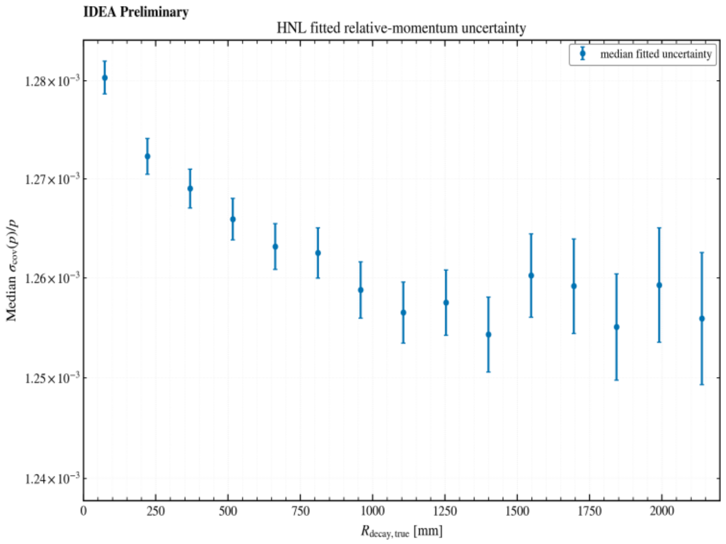
- **Fit retention:** 98.19% of finder-matched muons remain matched after fitting.
- **Pair efficiency:** 89.89% of reconstructable HNL pairs have both fitted tracks.
- **Radius dependence:** diagnostic only

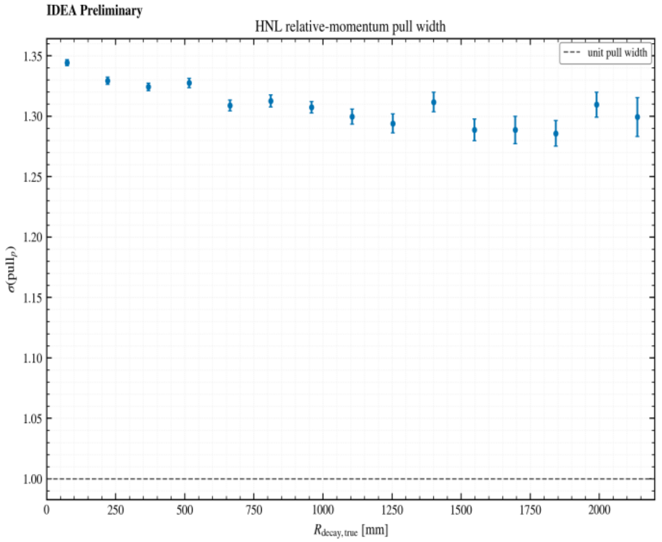
Efficiency definition	Efficiency [%]
Finder, per reconstructable muon	$92.6703^{+0.0193}_{-0.0194}$
Fitted track, per reconstructable muon	$90.9885^{+0.0212}_{-0.0213}$
Fit retention	$98.1852^{+0.0103}_{-0.0103}$
Both fitted tracks, per reconstructable pair	$89.8930^{+0.0319}_{-0.0320}$

- **Visible mass:** no 40 GeV peak because the neutrino is not reconstructed.

Track-parameter performance: residuals versus covariance







- Momentum resolution is broadly stable with decay radius.
- Residual widths describe the selected successfully fitted population
- The pull width is 1.27–1.35, above the ideal value of 1; the fitted uncertainties require an approximate scale factor of 1.3.

Summary and Outlook

Candidate finding

- The finder performs efficiently for isolated prompt and displaced muon guns
- In $Z \to \mu + \mu -$events, angular losses are associated with candidate ambiguity and mixed truth-hit content.
- The fitted-track angular dependence largely inherits the finder response.

Track fitting

- Fit retention is high for the prompt dimuon sample.
- Additional post-finder losses become important for tracks produced far from the interaction point.
- Pull widths above unity show that the fitted covariance underestimates the measured core spread in the studied samples.

→ The finder model and reconstruction configuration were evaluated as produced; no model retraining or parameter optimization was performed

→ The $Z \to \mu + \mu -$ “transition-region” deficit correlates with mixed candidates, but the available evidence does not establish a unique detector-geometry cause.

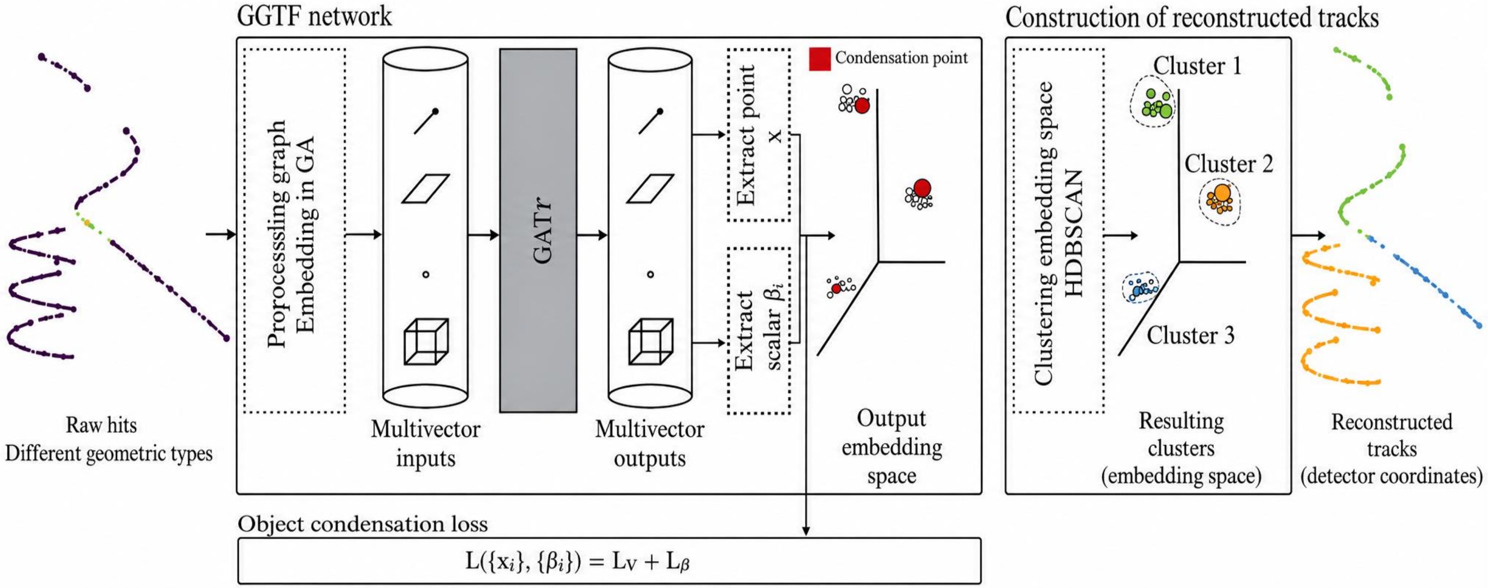
→ The HNL result is a tracking study. A displaced-vertex fit and a complete HNL event selection are outside its scope.

Outlook:

- A dedicated study on model retraining and parameter optimization is needed

BACKUP

GGTF



- Silicon and drift-chamber hits are encoded as geometric-algebra multivectors and processed together by GATr.
- For each hit i, the network predicts a three-dimensional learned embedding $xi$and a condensation score βi.
- The highest-score unassigned hit with $\beta i > T\beta$ seeds a candidate. Unassigned hits satisfying $\|xj - xi\| < Td$ are attached to it; the procedure is repeated to form the finder output.

Configured post-inference thresholds

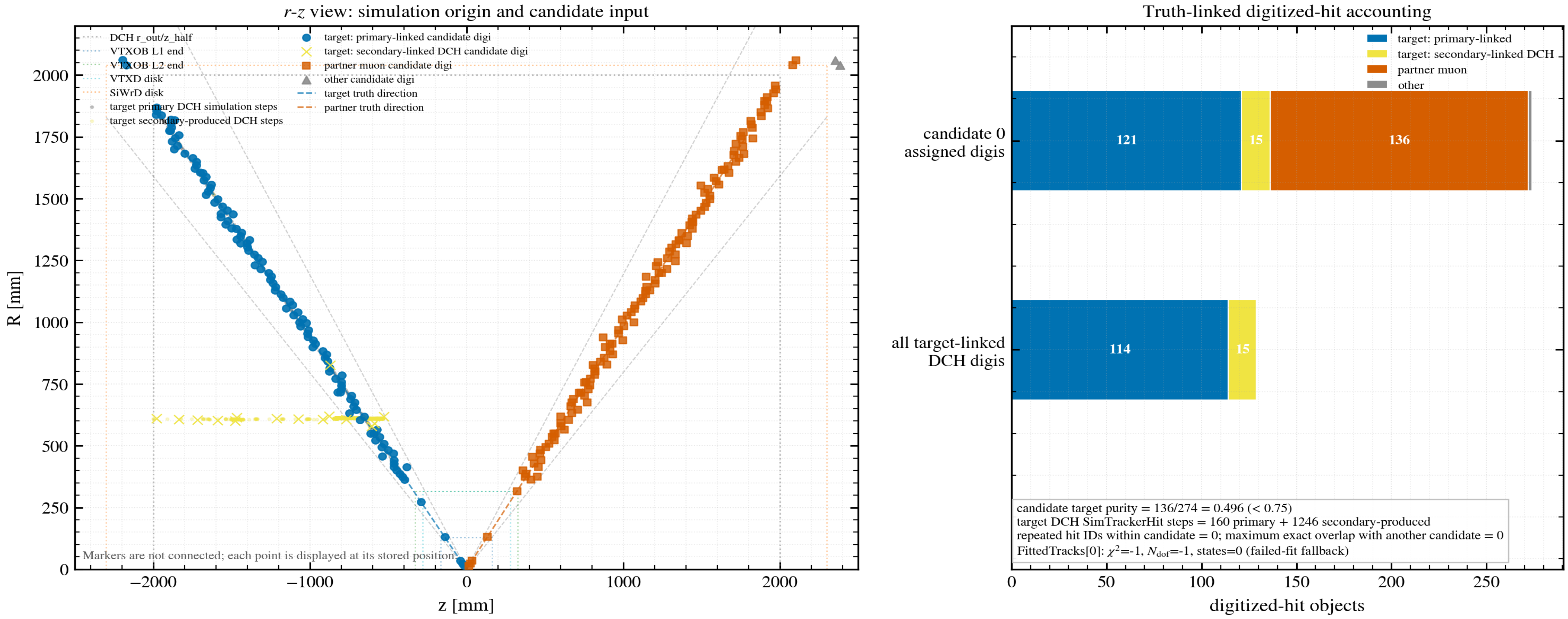
- Model was trained on $Z -> qq$ no background
- $T\beta = 0.6 \quad Td = 0.3$ (learned embedding space).
- Raising $T\beta$ accepts fewer seeds: fake or duplicate candidates may decrease, but genuine tracks can be lost. Lowering it has the opposite tradeoff.
- Decreasing Td makes hit association tighter and can omit hits or split a trajectory. Increasing it recovers a broader neighborhood but can mix or merge nearby trajectories.

→ No retraining or parameter optimization was done!!!

Event Display

IDEA Preliminary

$Z \to \mu^+\mu^-$ event 148413: secondary DCH activity and finder-candidate accounting



Simulation-step counts are energy-deposition records, not counts of independent detector measurements or particles.

BACKUP

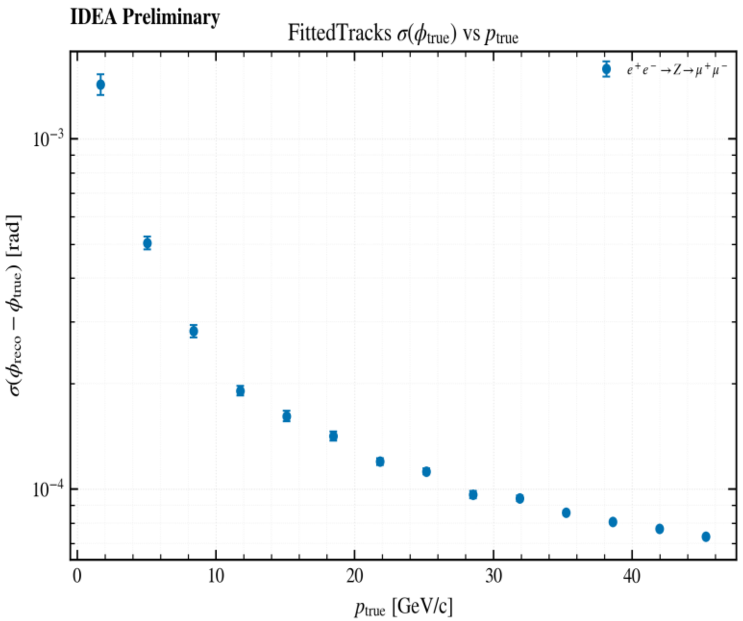
region	finder efficiency	fake rate	duplicate rate
transition bands	0.899	0.058	0.124
central control	0.964	0.020	0.069
forward/backward control	0.995	0.011	0.079

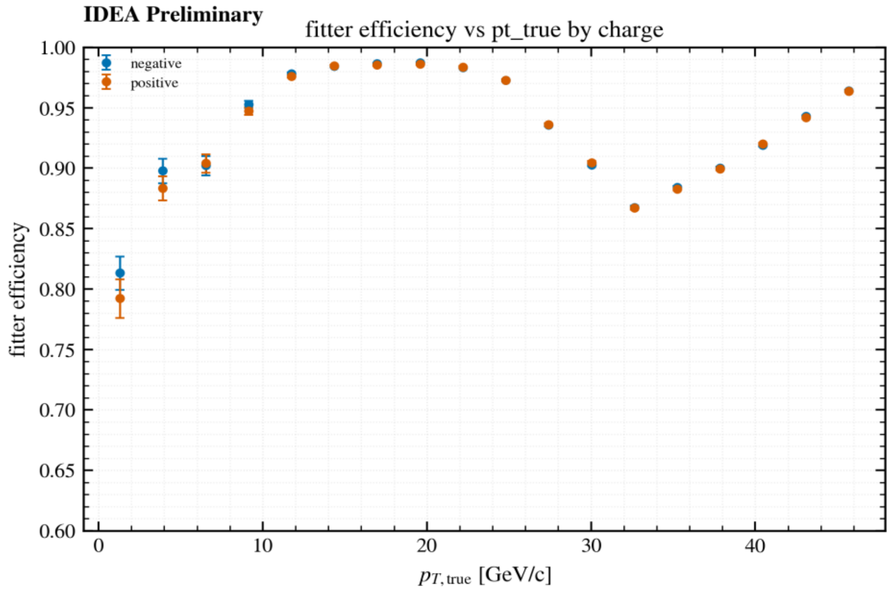
Transition: $38.5^\circ < \theta < 60.7^\circ$ *and* $119.3^\circ < \theta < 141.5^\circ$

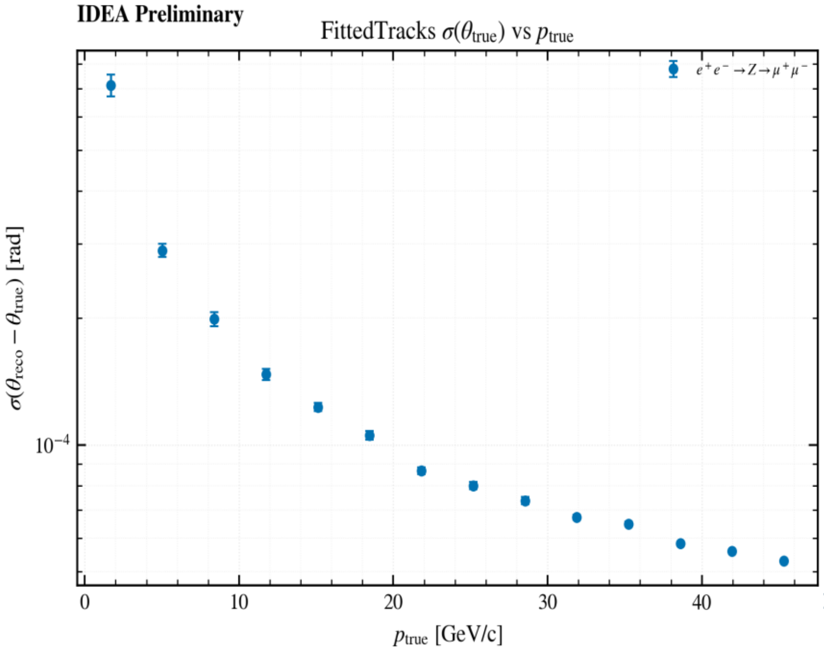
Central control: $75^\circ < \theta < 105^\circ$

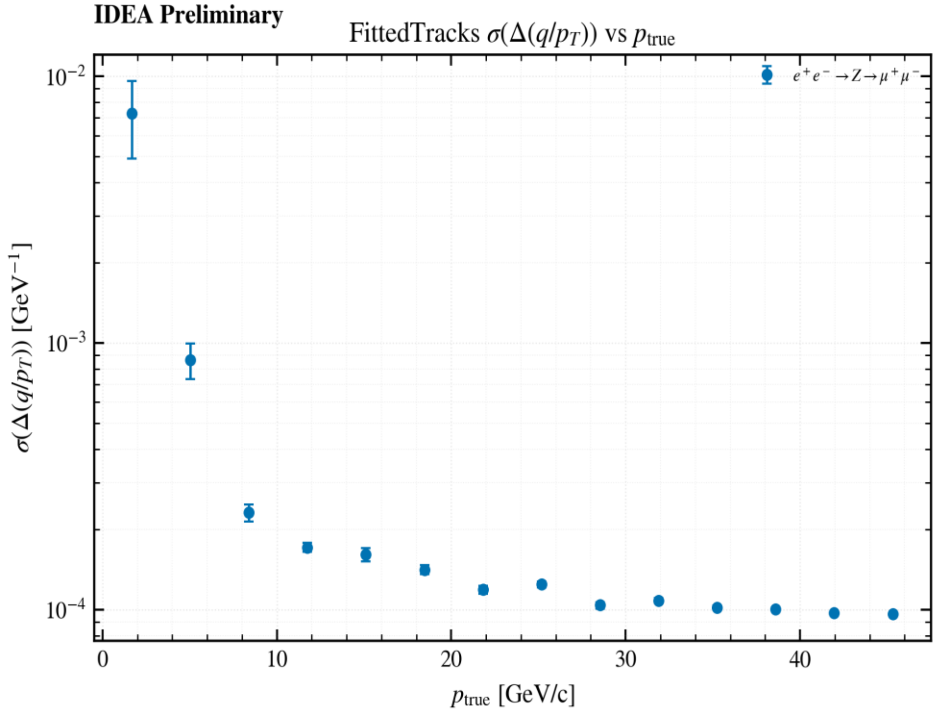
Fwd/bwd: $9^\circ < \theta < 31.5^\circ$ *and* $148.5^\circ < \theta < 171^\circ$

Track parameters Z Sample

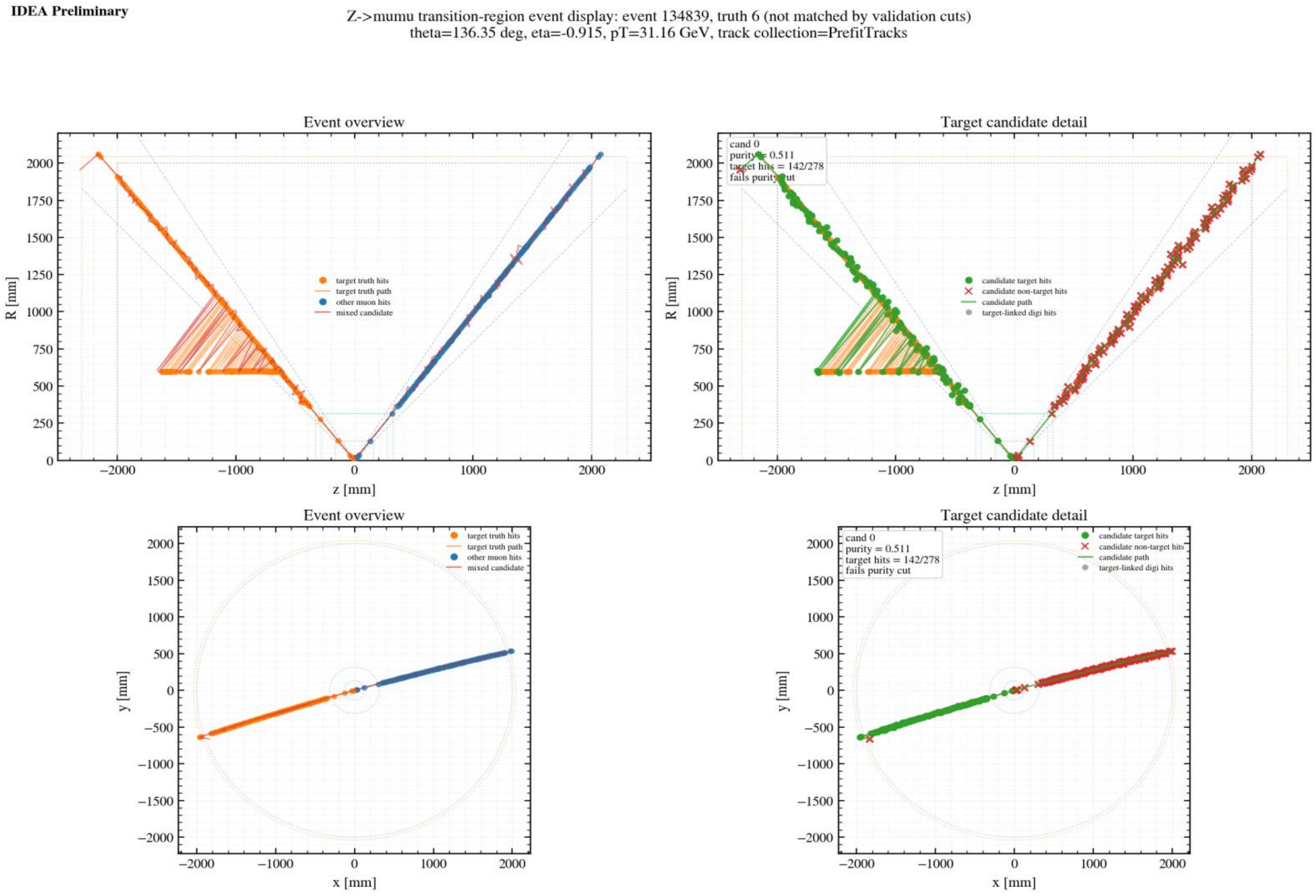








One event makes the mechanism visible

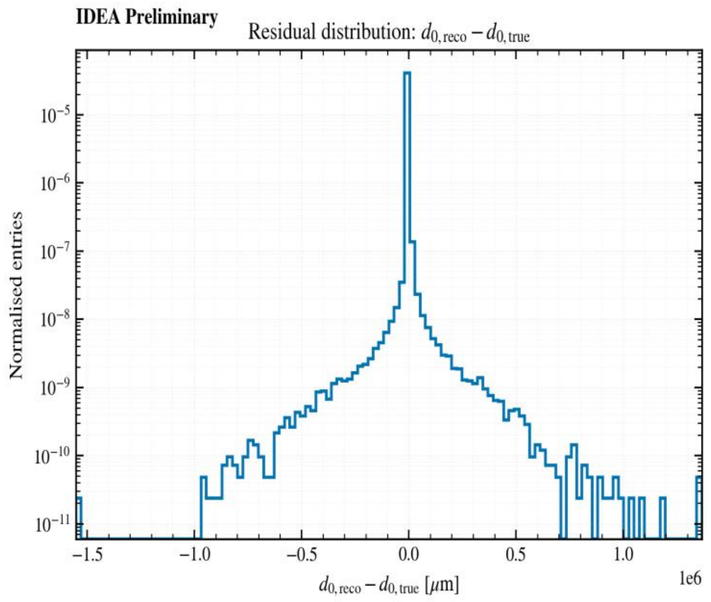


Event 134839
For the selected transition-region truth muon, candidate 0 contains:

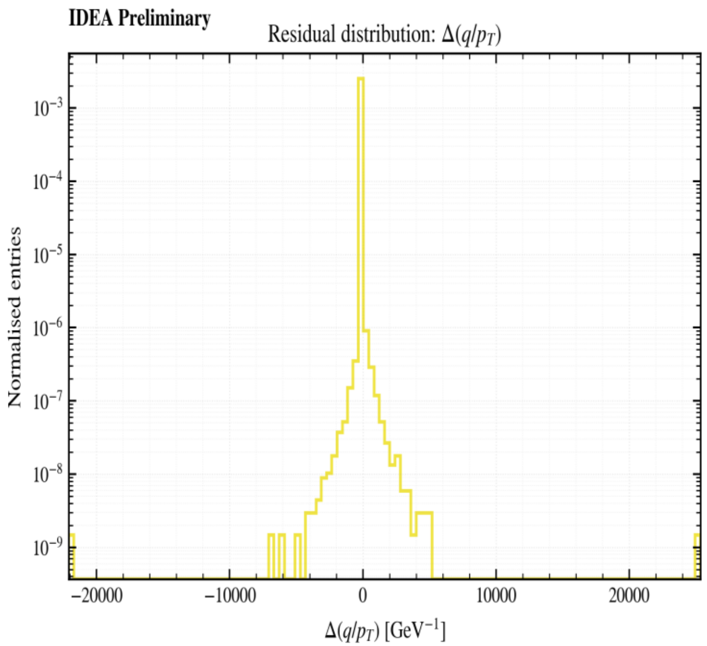
- 142 $hits$ from the target muon;
- 135 $hits$ from the partner muon;
- 278 $assigned\ hits$ in total; target $purity\ =\ 0.511$.

The finder has combined two truth contributions. The strict per-muon match therefore rejects this candidate.

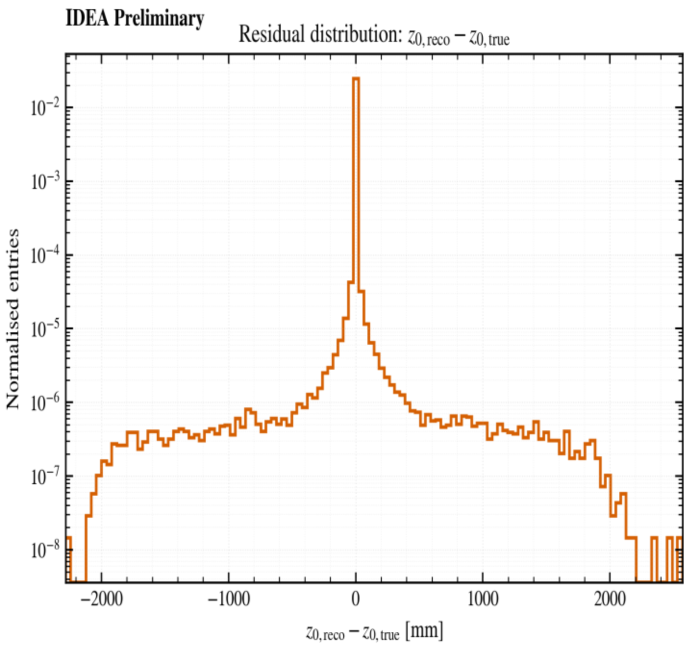
Residuals



IDEA Preliminary
Residual distribution: $d_{0,\mathrm{reco}} - d_{0,\mathrm{true}}$
Normalised entries
$d_{0,\mathrm{reco}} - d_{0,\mathrm{true}}$ [μm]
1e6

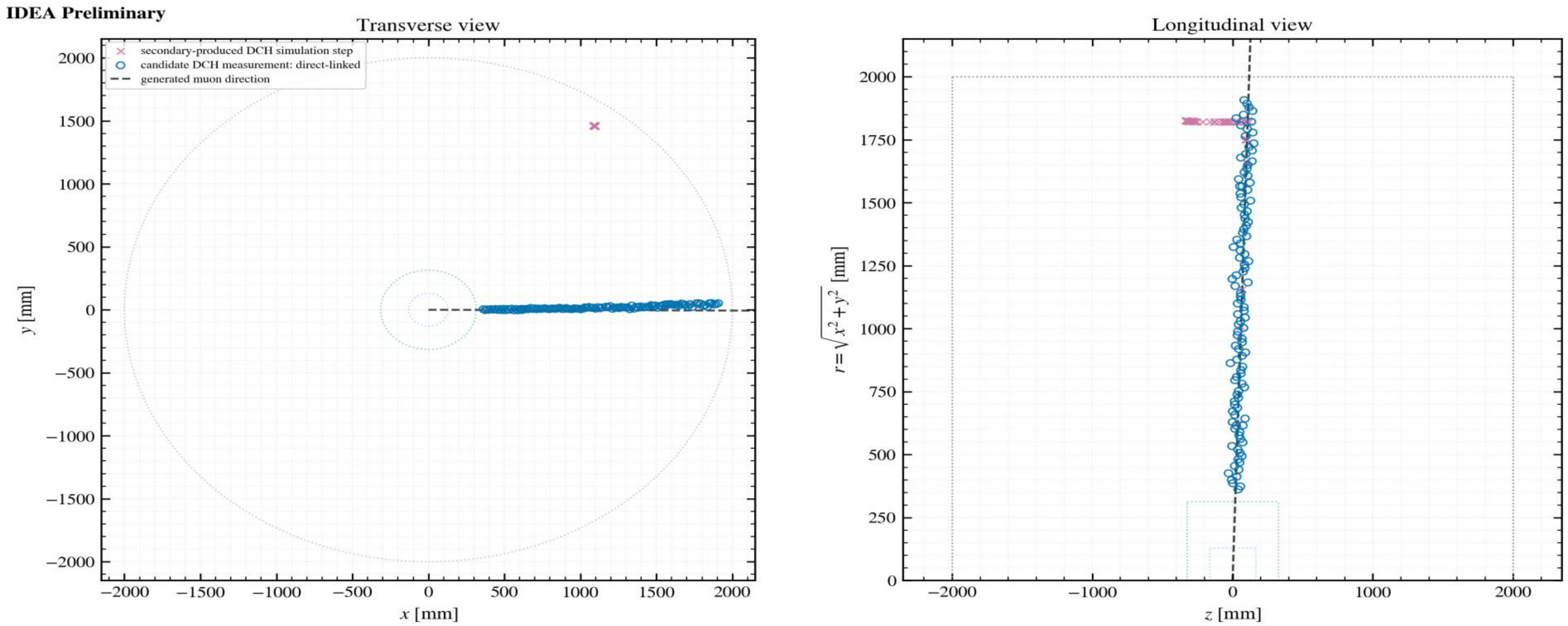


IDEA Preliminary
Residual distribution: $\Delta(q/p_T)$
Normalised entries
$\Delta(q/p_T)$ [GeV^{-1}]



IDEA Preliminary
Residual distribution: $z_{0,\mathrm{reco}} - z_{0,\mathrm{true}}$
Normalised entries
$z_{0,\mathrm{reco}} - z_{0,\mathrm{true}}$ [mm]

Secondary activity



Event contains at least one	Events	Fraction [%]
Secondary-produced DCH simulation step	48 425	$96.850^{+0.077}_{-0.079}$
Secondary-linked digitized DCH measurement	39 551	$79.102^{+0.181}_{-0.182}$
Finder candidate containing a secondary-linked DCH measurement	39 551	$79.102^{+0.181}_{-0.182}$