Photon Angular Reconstruction and π^0 Kinematic Reconstruction with a High-Granularity Timing Calorimeter

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May 20, 2026

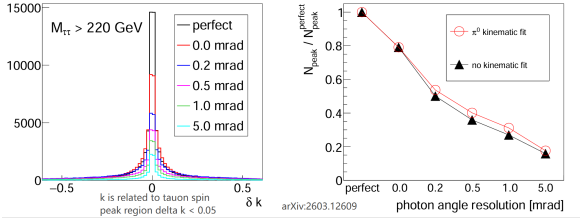
ILD Analysis/Software Meeting

Motivation

- Neutral pions are reconstructed through $\pi^0 \to \gamma\gamma$.
- The reconstructed π^0 direction and energy depend directly on the two photon directions.
- In a π^0 kinematic fit,

$$m^2_{\pi^0} = 2E_{\gamma_1}E_{\gamma_2}\left(1 - \cos\theta_{12}\right)$$

- Better photon position reconstruction $\Rightarrow$ better π^0 direction reconstruction.



Photon-direction implications in tau spin analysis.

- Precision timing calorimetry opens new opportunities
  - E.g., Combining the starting hit with the shower barycenter; see Henri's report.

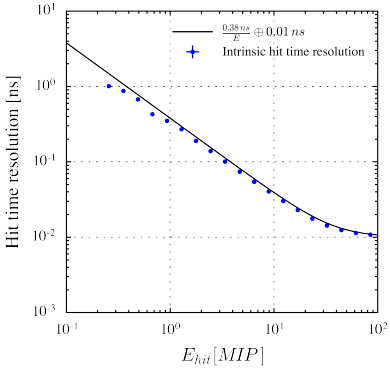
Detector Setup and Timing Model

- ILD detector concept with highly granular Si-W ECAL.
- ECAL cell size: $5.5 \times 5.5\,\mathrm{mm}^2$.
- Photons generated within $|\cos\theta| < 0.95$.
- Hit timing resolution

$$\sigma_t = \frac{A}{E} \oplus C$$

$$A = 380\,\mathrm{ps} \cdot \mathrm{MIP}, \quad C = 10\,\mathrm{ps}$$

- Photon reconstruction uses 4D-Arbor (Henri's approach).



Ref. arXiv:2209.02932

Reconstruction Strategy

1. Find the shower starting hit.
2. Select high-quality hits with geometric and timing-based selections.
3. Parameterize the hit-angle resoluttion.
4. Reconstruct the photon agnular position with an hit angle resolution-based weighted average.
5. Optimize the hyperparameters for each method (see backup).

Starting Hit Finding

- Philosophy: tolerant to timing errors.

1. Find the starting-hit candidates using timing information:

$$t_{\text{cand}} < t_{\text{hit}} + n_\sigma \sqrt{\sigma^2_{t,\text{cand}} + \sigma^2_{t,\text{hit}}}$$

2. Select the starting hit using spatial information.

- The starting hit is chosen as the candidate closest to the interaction point.

Property:

- For timing resolution $= 0$, it reduces to choosing the earliest hit.
- For timing resolution $\to \infty$, it reduces to the spatial-only choice.

Hit Selection

- Longitudinal window:
  $-25\,\mathrm{mm} < l < 200\,\mathrm{mm}$
- Cone cut:
  $$d \leq k_c(l - l_0)$$
- Select a fraction f_{earliest} of the earliest hits using t, which preferentially keeps hits closer to the shower start.

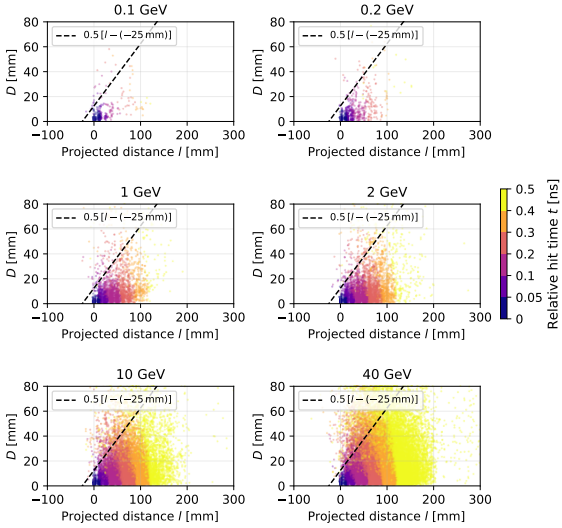
Definitions

$$l = (\boldsymbol{r} - \boldsymbol{r}_{\mathrm{start}}) \cdot \hat{\boldsymbol{r}}_{\mathrm{start}}$$

D = distance of hit to momentum ray

d = distance of hit to IP-seed ray

$$t = t_{\mathrm{obs}} - t_{\mathrm{start}}$$



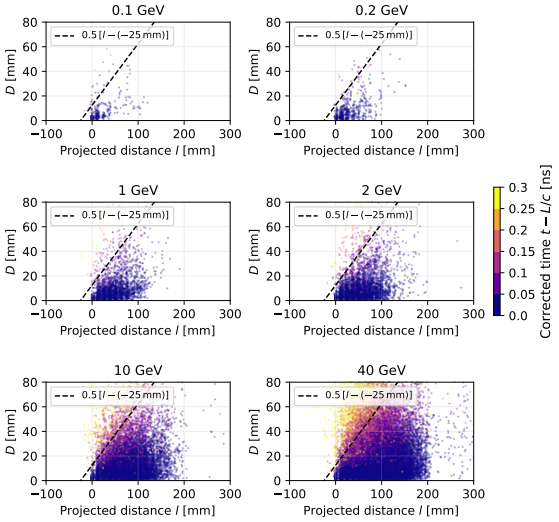
Hit Selection: Continued

- Select a fraction f_{fast} of fast hits using t_c.
- These hits are preferentially closer to the photon axis.

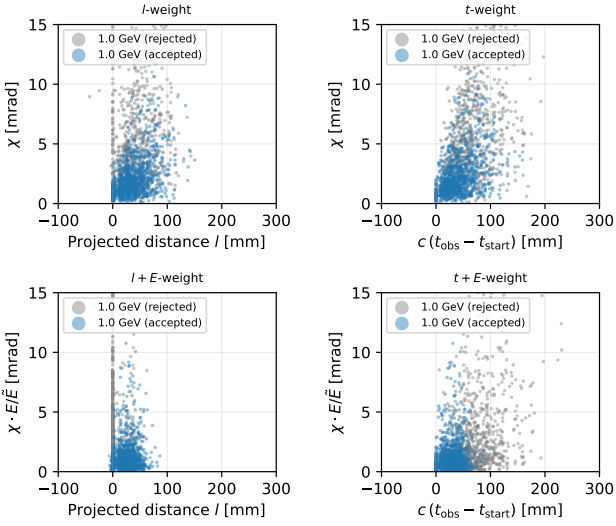
Definition

$$t_c = t_{\text{obs}} - L/c$$

- t_{obs}: observed hit time.
- L: distance from the interaction point to the hit.



Hit Distribution



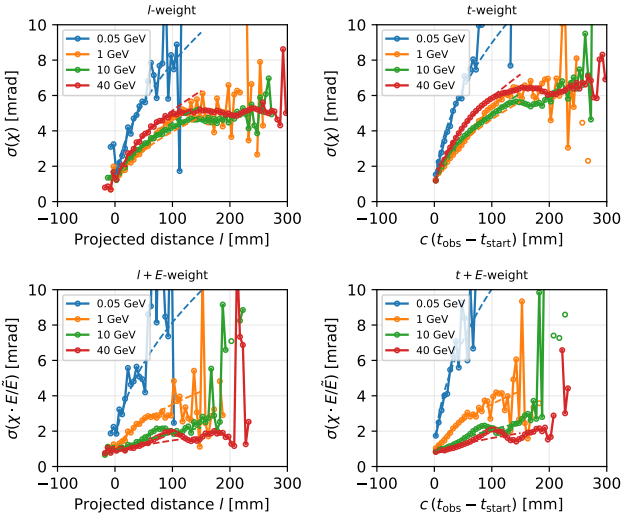
Variables

δ_i or χ	hit-by-hit angle to $\hat{\boldsymbol{p}}_{\text{truth}}$
E_i	hit energy
$\tilde{E}$	quadratic-mean hit energy
l	longitudinal distance
t	relative hit time

10 ps Optimized Selections

Parameter	l, l+E	t, t+E
n_σ	1.2	0
f_{earliest}	1.00	1.00
f_{fast}	0.5	0.5
k_c	0.6	∞

RMS Parameterization

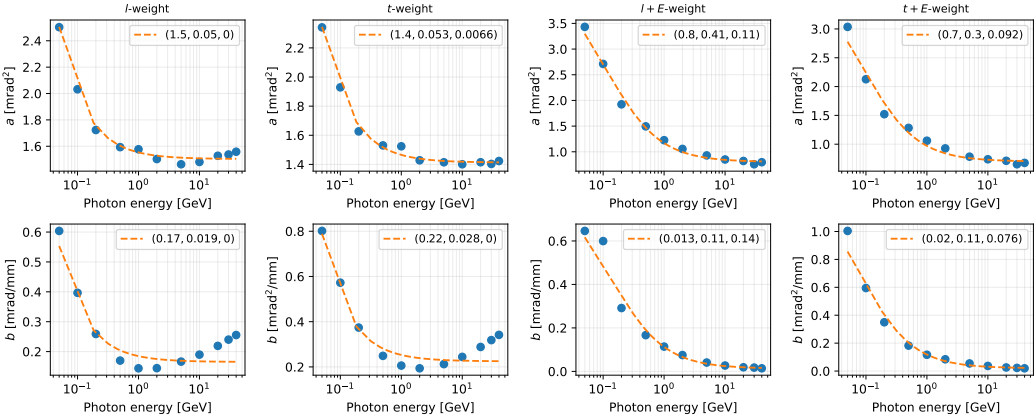


- Parameterize the hit-level RMS of δ_i or $(E\delta_i)$ to build hit weights, $w_i = 1/\sigma_i^2(\delta)$.

$$\sigma(\delta) = \sqrt{a + b\,x}$$

- Use the same form, where $x = l$ or $x = t$.
- a and b are fit parameters.

a and b Parameterization

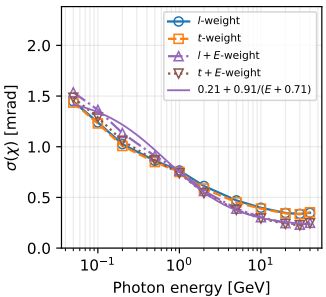


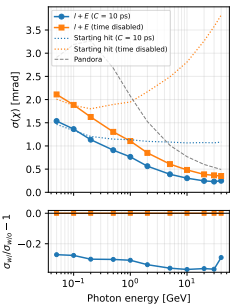
$$a \text{ or } b = a' + \frac{b'}{c' + E}, \qquad c' > 0$$

Photon Position Resolution vs Energy

$E + a', b', c' \implies a, b; \quad a, b + (l \text{ or } t) \implies \sigma_i(\delta)$

- We use either $\sigma_i^{-2}(\delta)$ or $E_i\,\sigma_i^{-2}(\delta)$ as the weight for hit i.
- The final photon angular resolution is denoted by $\sigma(\chi)$.

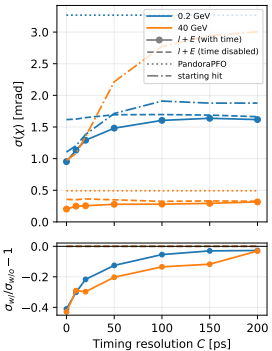




- Resolution improves monotonically with photon energy.
- Full weighting beats seed-only at higher energy; Pandora is worse, especially at low energy.

Dependence on Timing Resolution

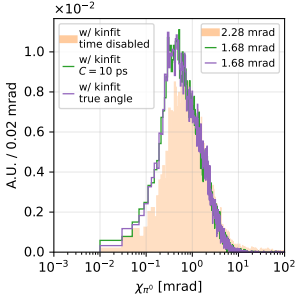
- We scale the constant and stochastic terms with the same factor.
- The hyperparameters are optimized for each timing resolution.

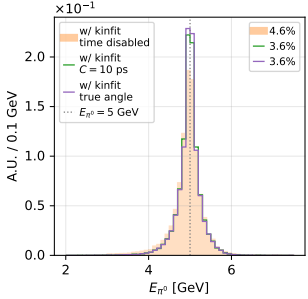


Performance degrades as the timing resolution worsens, and the gain from timing is largest at low photon energy. Timing becomes especially useful below about 25 ps.

Impact on π^0 Kinematic Reconstruction

- $5\,\mathrm{GeV}$ π^0 sample at 10 ps.
- Event preselection: two photons reaching the calorimeter; at least one reconstructed cluster per photon; leading cluster for each photon kept.
- Kinematic fit with free parameters E_1' and E_2', constrained by the nominal π^0 mass.

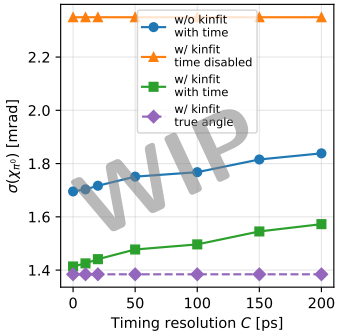


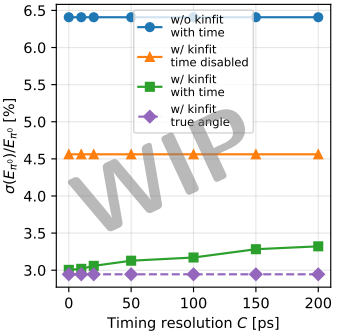


Timing remains more useful at $200\,\mathrm{ps}$ for photons from π^0 decays than for single photons; changes in purity and efficiency may explain this behavior.

Preliminary: Impact on π^0 Kinematic Reconstruction

- 5 GeV π^0 sample using clusters from PandoraPFA, with event preselection and a kinematic fit.
- Hyperparameters are optimized for both single-photon samples and photons from π^0 decays.





Summary

- A multi-hit weighted reconstruction outperforms a seed-only or barycenter only approach.
- Precision calorimeter timing improves photon angular position bellow a few tens of picoseconds.

Outlook

- Improve the use of hit energy, e.g. by incorporating it directly in the $\sigma(\delta)$ parameterization.
- Study further the performance in π^0 reconstruction and jet environments.
- Study scenarios where timing is only partially supported in the ECAL.

Thank you.

Optimized Reconstruction Parameters