T-CALO

Photon Position Reconstruction and π^0 Reconstruction with a High-Granularity ***Timing*** Calorimeter

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July 2, 2026

for the

17th Workshop of the

FCPPN/L

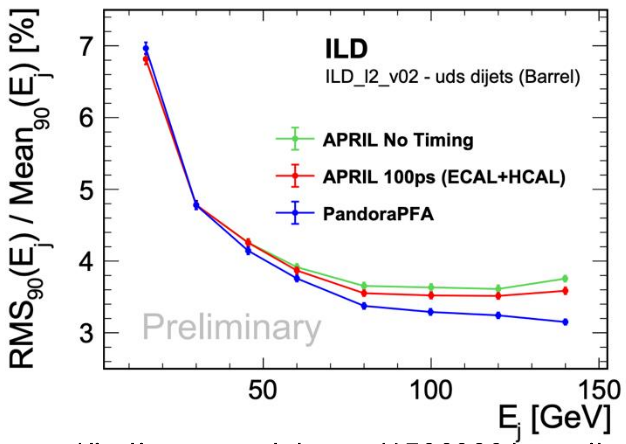
France-China Particle Physics Network and Laboratory

Current status of timing calorimeter analyses in CALO5D and TCALO

- Progress from Tanguy et. al with Arbor
    - **An advantage from timing is observed at higher center-of-mass energies** with Arbor. However, this still needs to be validated after improving the re-clustering.
- Jet energy resolution with timing calorimeter using BDT-based cluster tree building by Hao: no advantage from timing has been observed yet.
- Total event energy regression with timing calorimeter using a graph neural network by Bohdan et. al: **a small advantage from timing is observed.**
- A Study of PFA with graph neutral network using condensation approach by Uli Einhaus et. al. is still in progress.
- Particle energy regression with timing calorimeter using a CNN-based neural network by Xin et. al: no advantage from timing has been observed yet.

All are in progress

I will focus on the photon position reconstruction with timing calorimeter in this presentation



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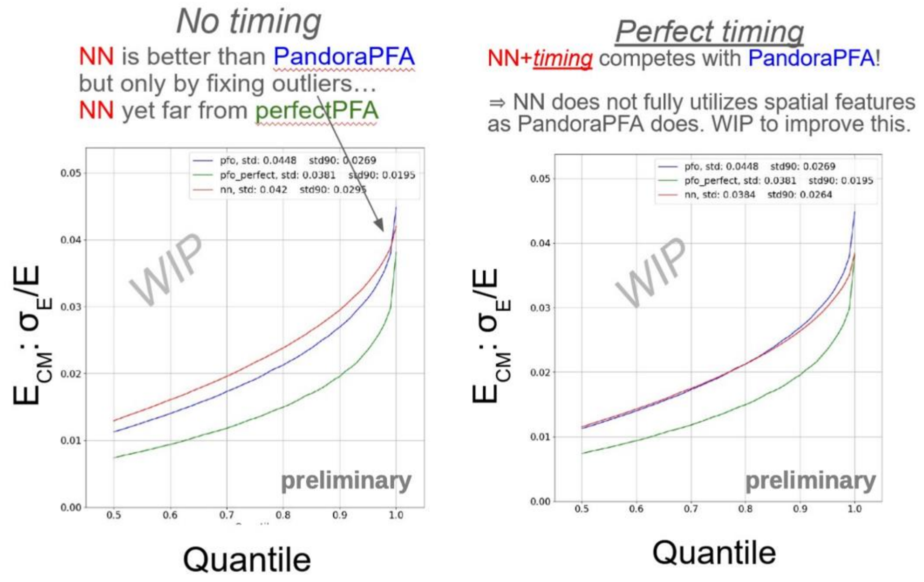

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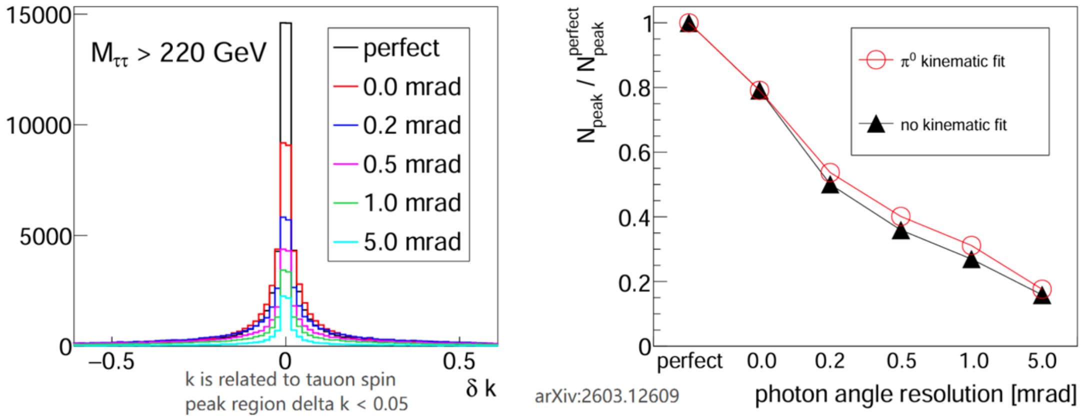
Outline

- Motivation
- Simulation setup and timing Model
- Photon position reconstruction strategy
- Impact on π^0 kinematic reconstruction
- Conclusion

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.
- Kinematic fit improved via better photon angle
  - $m_{\pi^0}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{12})$
- π^0 direction sensitive to photon momentum direction

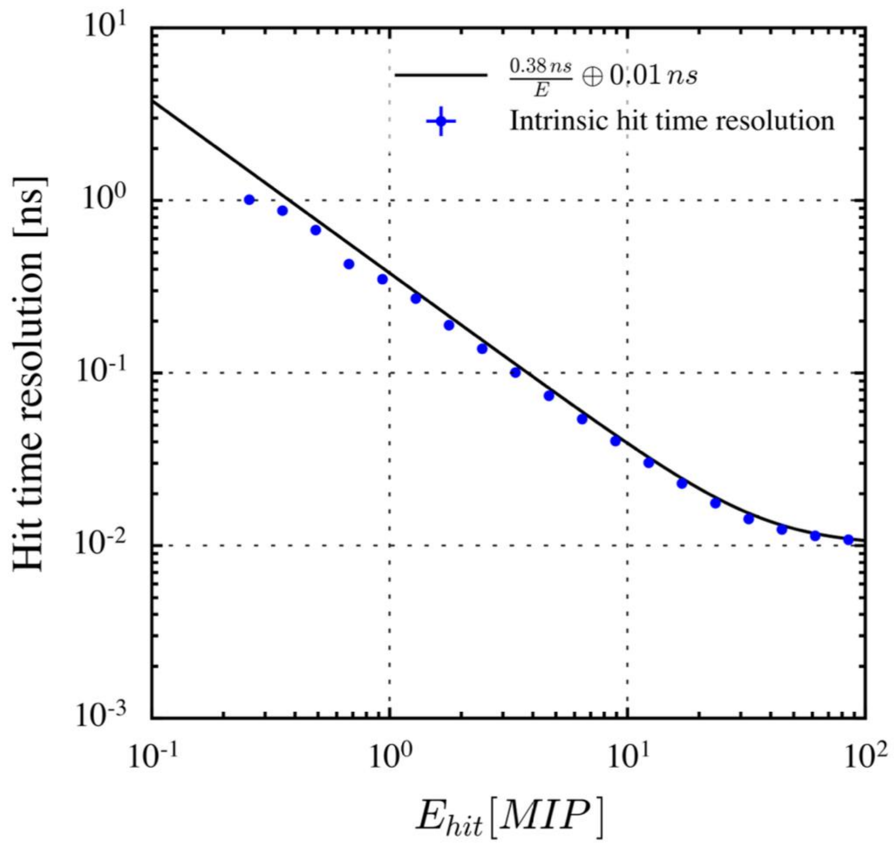


Photon-direction implications in tau spin analysis.

- Precision timing calorimetry opens new opportunities
  - E.g., Combining the starting hit with the shower barycenter; see H. Videau, *Possible uses of time in calorimeter objects reconstruction*, Detector Concepts Meeting, CERN, 2026.
  - https://indico.cern.ch/event/1664040/contributions/7013190/attachments/3268134/5837394/4D_approach.pdf

Simulation setup and timing model

- ILD detector concept with high granular Si-W ECAL
  - ECAL cell size: 5.5 ×5.5 mm2
- Photon
  - within $|\cos\theta| < 0.95$
- Hit timing resolution σ_t
  - $\sigma_t = \frac{A}{E} \oplus C$
  - A=380 ps·MIP, C=10ps Where E is the energy of hit
- Reconstruction
  - Single photon is reconstructed with **4D-Arbor** approach (see Henri's slides)



Ref. arXiv:2209.02932
CMS HGCAL intrinsic timing resolution

Photon position reconstruction strategy

1. Find the starting hit
2. Select high-quality hits with geometric and timing-based selections.
3. Parameterization of hit position dispersion
4. Reconstruct the photon position using the hit position dispersion
5. Optimize the all the hyperparameters (see backup)

1 Starting hit finding

- Philosophy: be tolerant to timing errors
- **A)** Find the candidates for starting-hit.
  - For candidate, the following is hold for all the other hits

$$t_{cand} < t_{other\ hit} + n_\sigma \sqrt{\sigma_{t,cand}\hat{}2 + \sigma_{t,hit}\hat{}2}$$

If a hit is a candidate as starting-hit, then **no** other hits can be **definitely** earlier than the candidate

  - To be clear, ≥ 2 candidates is possible
- **B)** select starting hit using spatial information
  - The starting hit is chosen as the candidate which is closest to the IP
- Property
  - For timing resolution = 0, it reduces to choosing the earliest hit.
  - For timing resolution →∞, it reduces to the spatial-only choice.

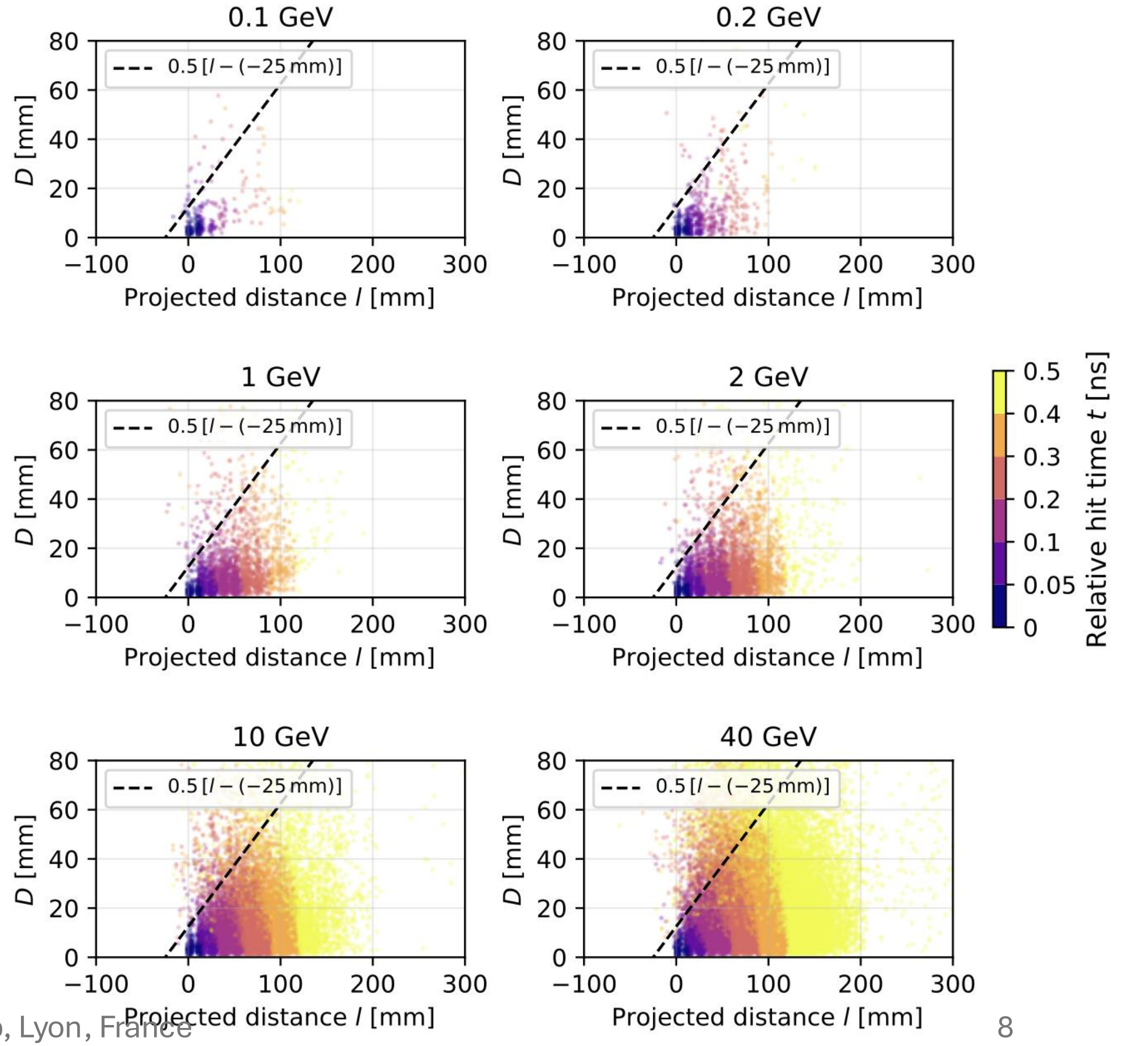
2 Select high-quality hits

- A) Longitudinal window
  - -25mm < l < 200 mm
  - l: longitudinal distance using starting hit reference

$$l = (\boldsymbol{r}_{hit} - \boldsymbol{r}_{start}) \cdot \boldsymbol{r}_{start}/r_{start}$$

- B) Cone window
  - $d < k_c(l - l_0)$
  - d distance of hit to IP-starting-hit axis
  - k_c: tangent of the cone half-angle
  - $l_0 = -25mm$
- C) Select a fraction, f_{early}, of earliest hits using the
  - $t_R = t_{abs} - t_{abs,start}$
  - Keeping the hits closer the shower start

D: hit to true photon momentum-axis
The dash showing an example of cone, but using D



2 Select high-quality hits

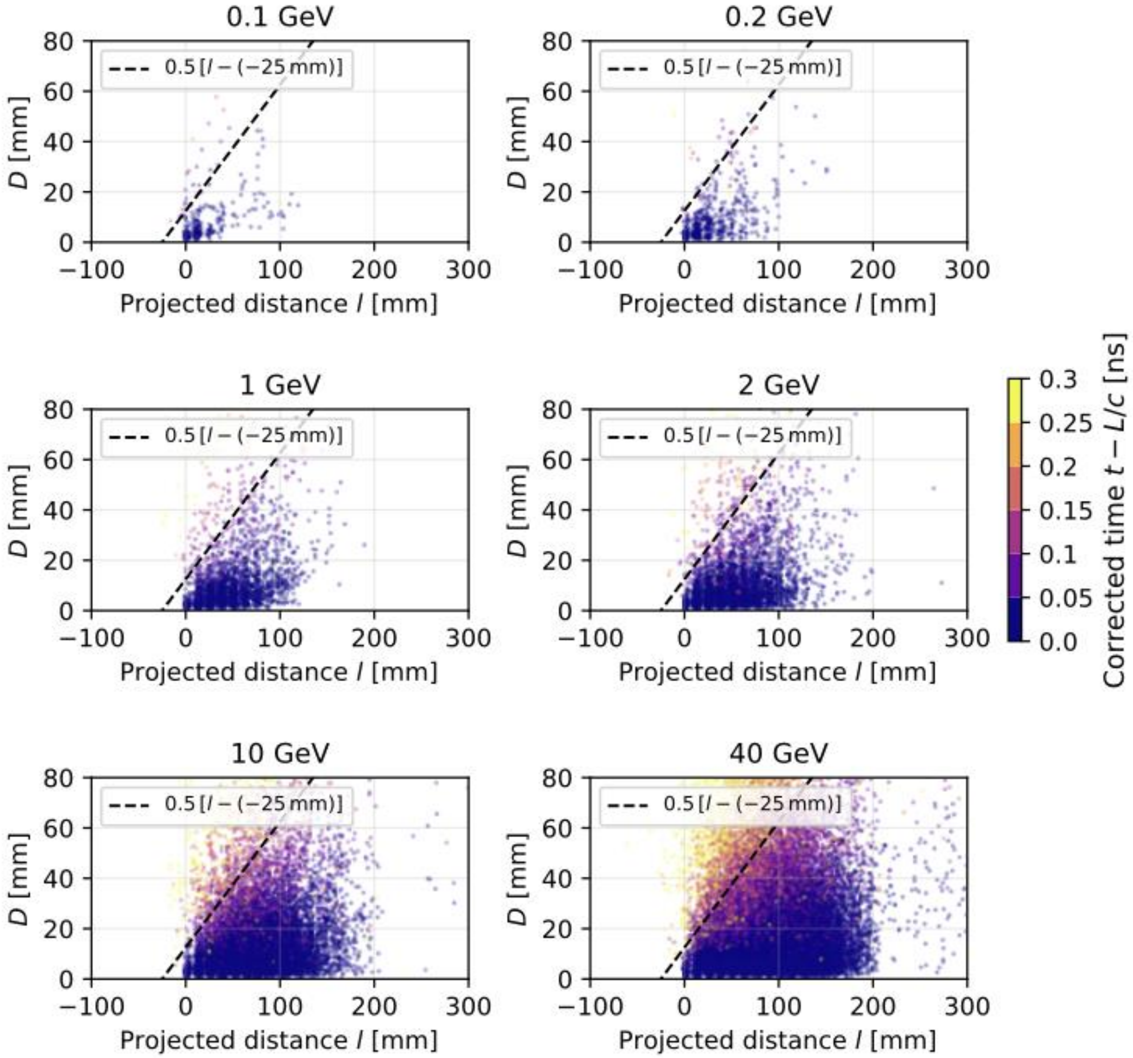
- D) Select the fastest fraction, f_{fast}, of hits using t_c.

$$t_c = t_{abs} - L/c$$

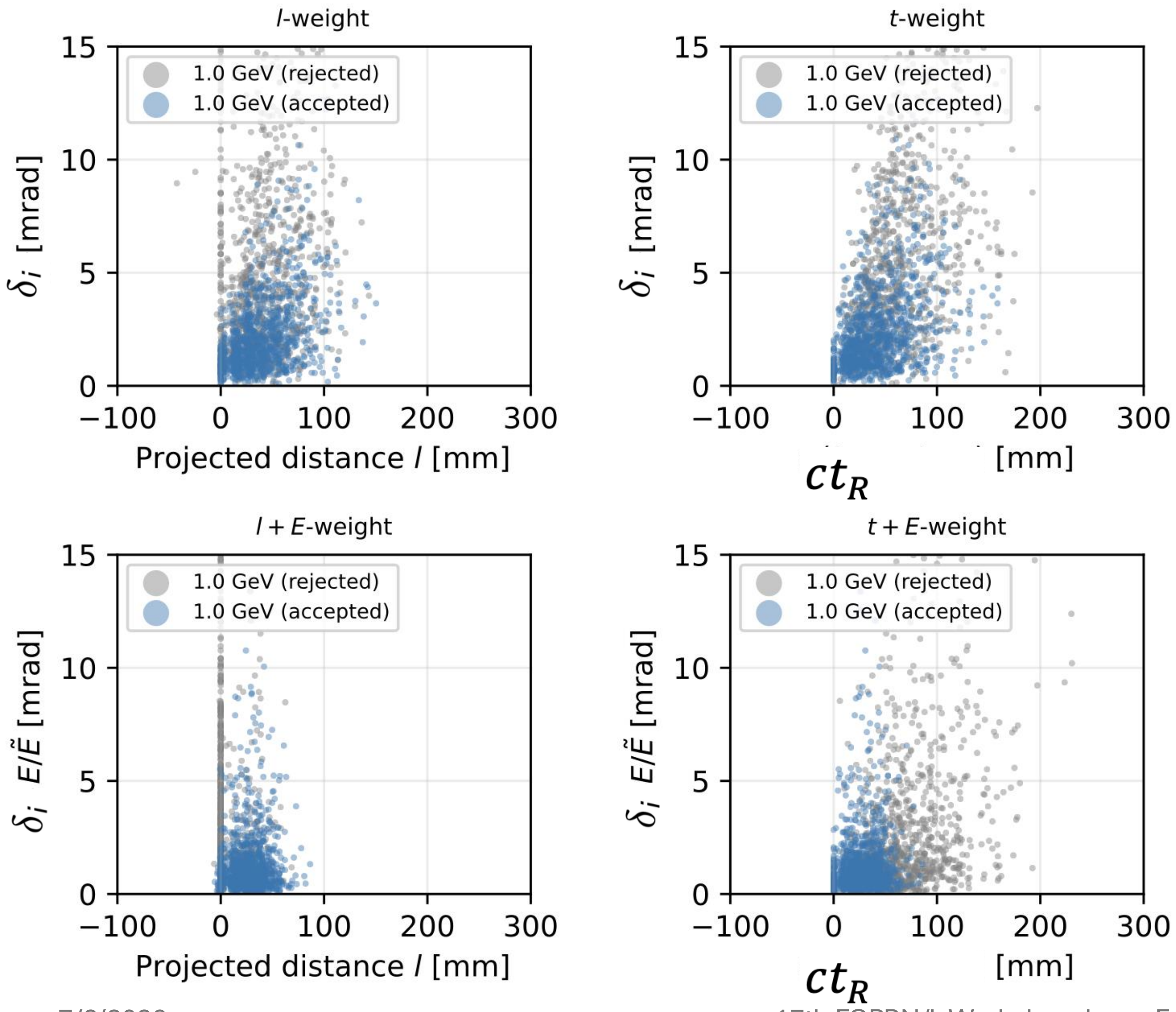
$$t_{\mathrm{abs}}: \textit{the absolute hit time}$$

$$L: \textit{distance of hit to the IP}$$

D: hit to true photon momentum-axis
The dash showing an example of cone, but using D



3 Parameterization of hit position dispersion



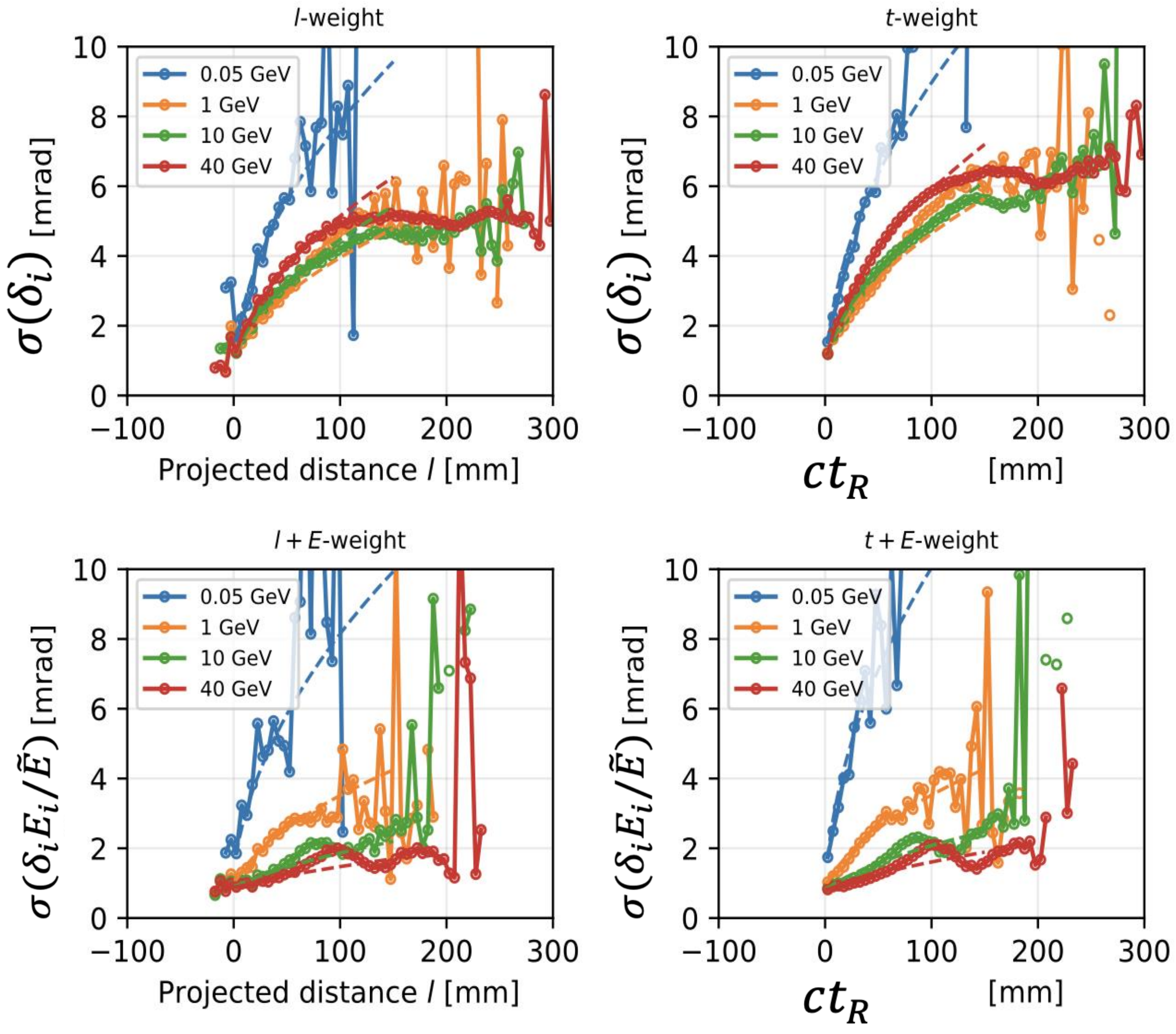
Variable Definitions

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

10 ps Optimized Selections

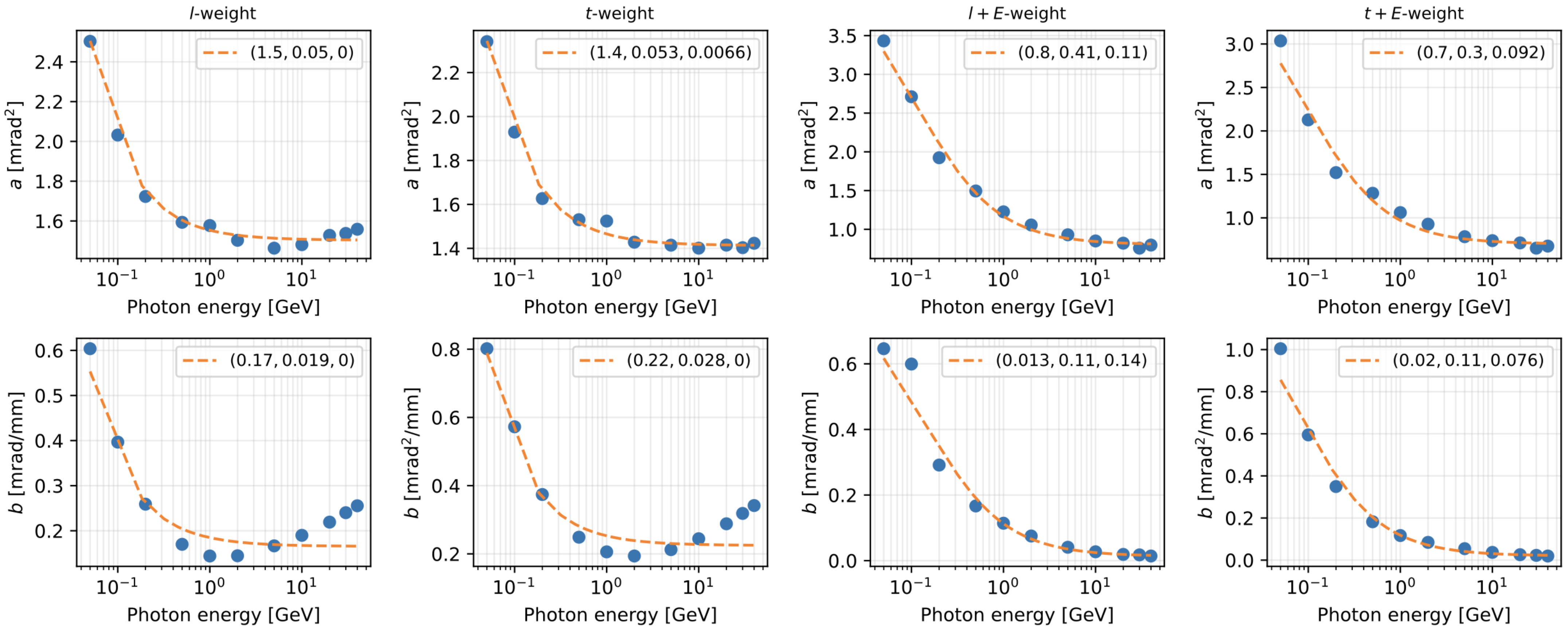
Parameter	l, l+E	t, t+E
n_σ	1.2	0
f_{earliest}	1.00	1.00
f_{fast}	0.5	0.5
k_c	0.6	∞

3 Parameterization of hit position dispersion



- Why: Hit angle dispersion $\sigma(\delta_i)$ or $\sigma(\delta_i E_i/\tilde{E})$ will used as weight later $w_i = 1/\sigma\hat{}2$
- Formula
  - $\sigma = \sqrt{a + b\ x}$
  - x is either l or ct_R
  - a and b are fit parameters

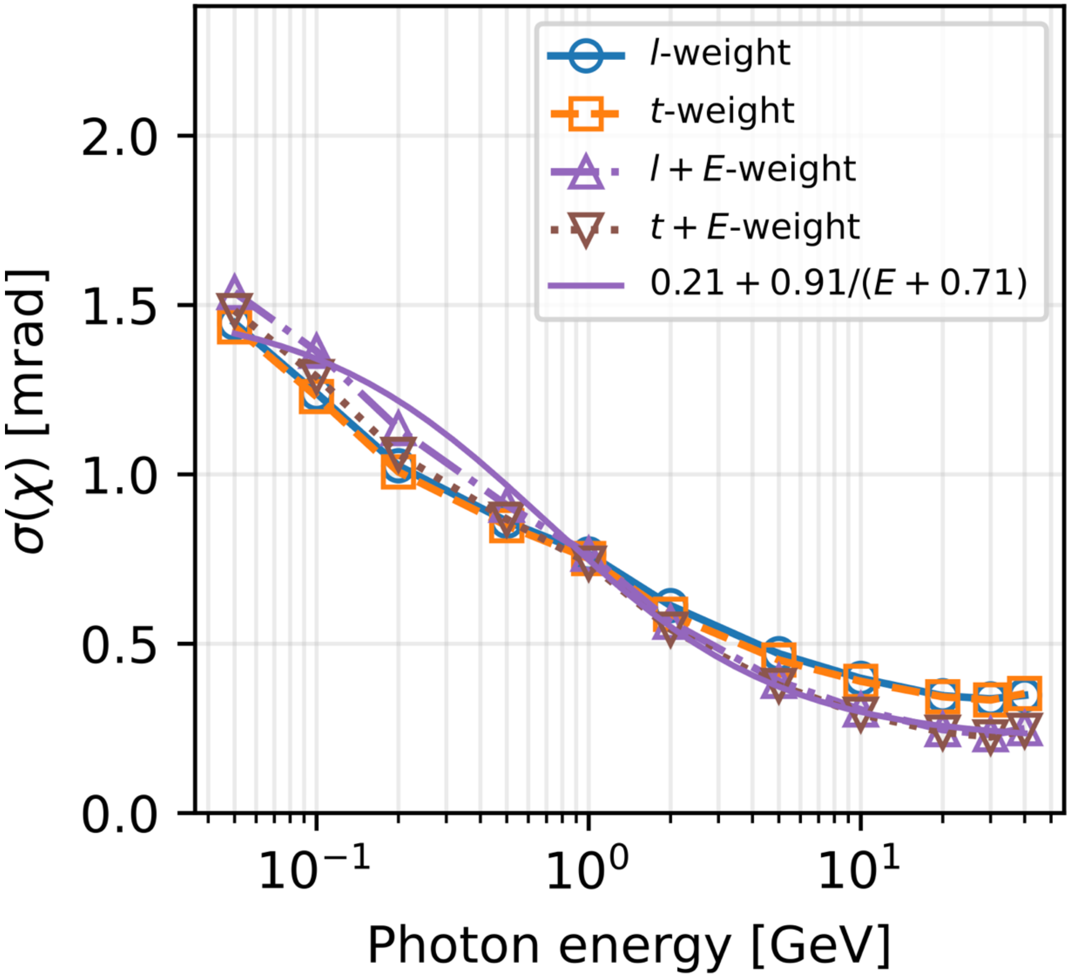
3 Parameterization of hit position dispersion



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

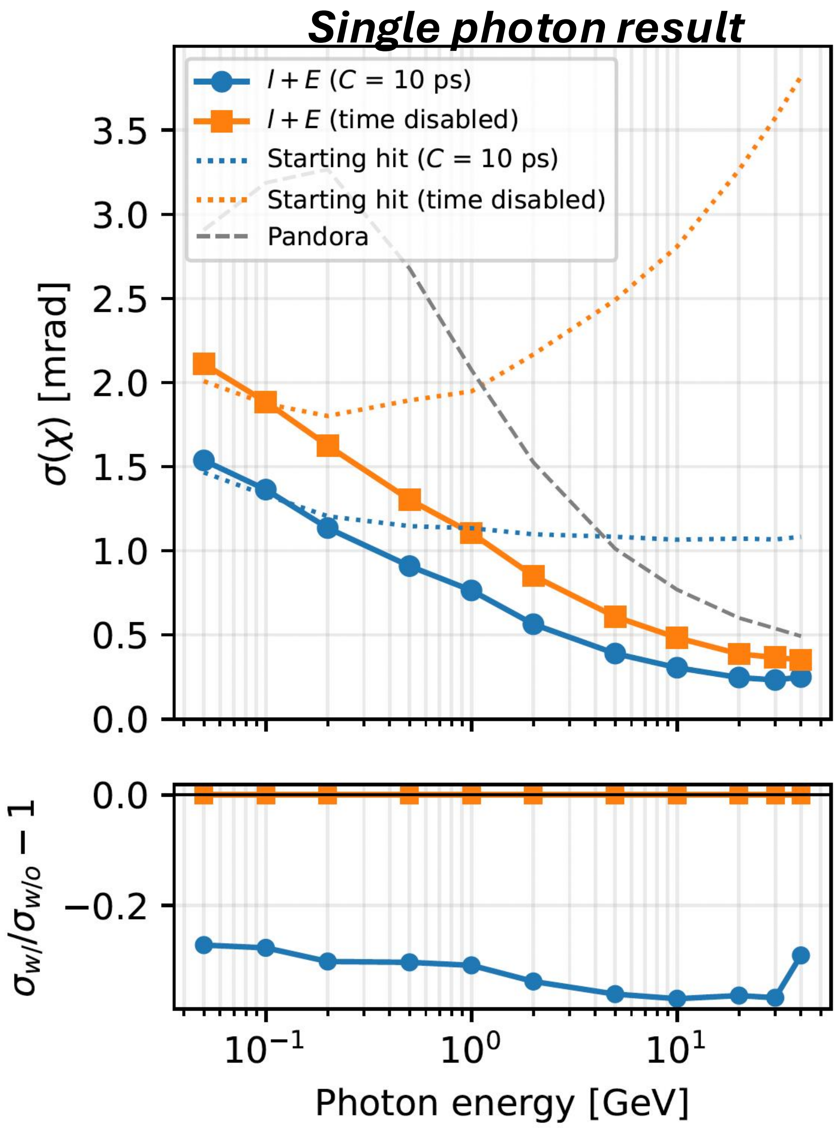
4 Photon position reconstruction

- E_{photon} + $a', b', c' \Rightarrow a, b$
  $a, b + (l\ or\ t_R) \Rightarrow hit\ dispertion$
- Photon angular position obtained by averaging the hit position using $w_i = 1/\sigma\hat{}2$ as weight
- The resolution of photon angular position is obtained and denoted by σ(χ).



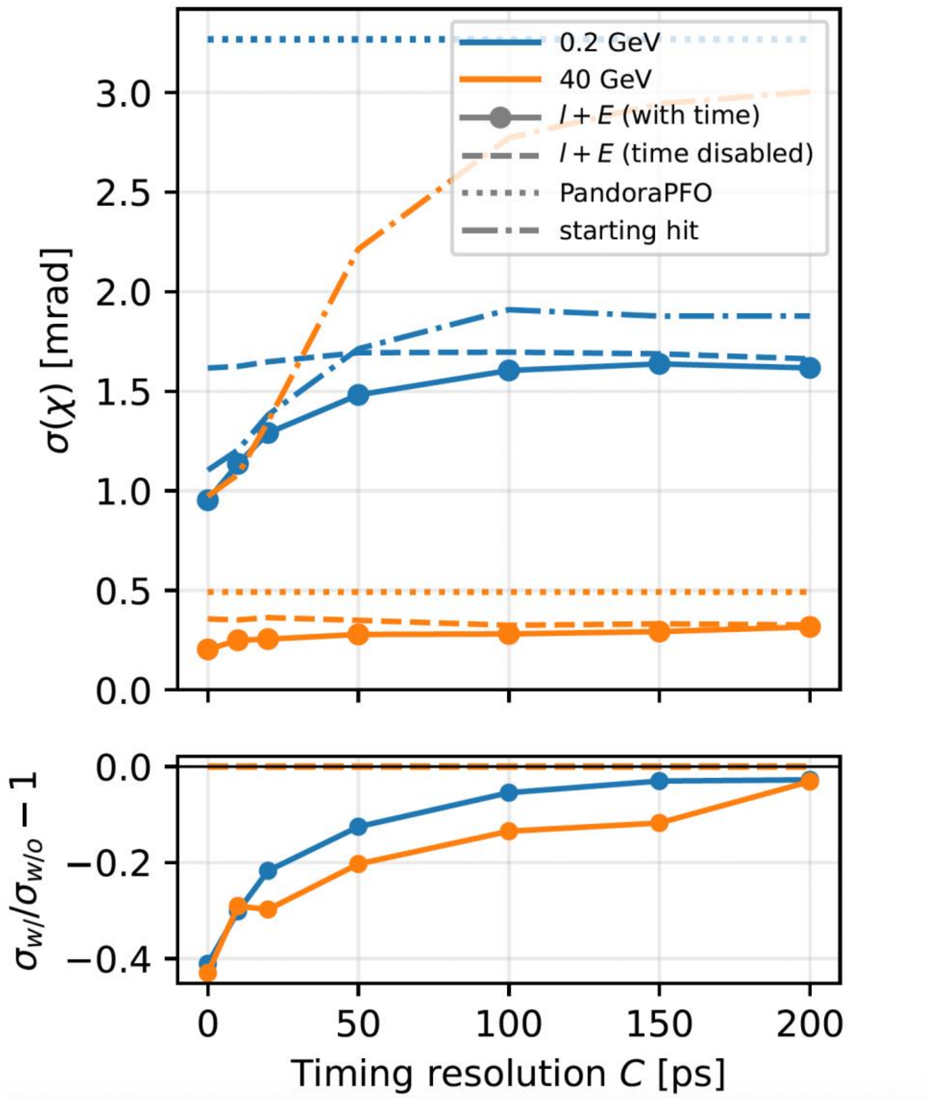
4 Photon position reconstruction

- L+E (time disabled)
  - We can disable time by removing time in hits selection and avoiding t(+E) methods
- Starting hit method:
  - Determine the photon position using the starting-hit solely
- Pandora:
  - This represents barycenter method
- Observations:
  - Barycenter method is better at higher energy than starting hit method, but worse at lower energy
  - Our methods converge to the starting hit method at low energy
  - Our methods still have a advantage compared to the barycenter method
- Conclusion
  - With time, we can gain about 30% improvement in the photon position



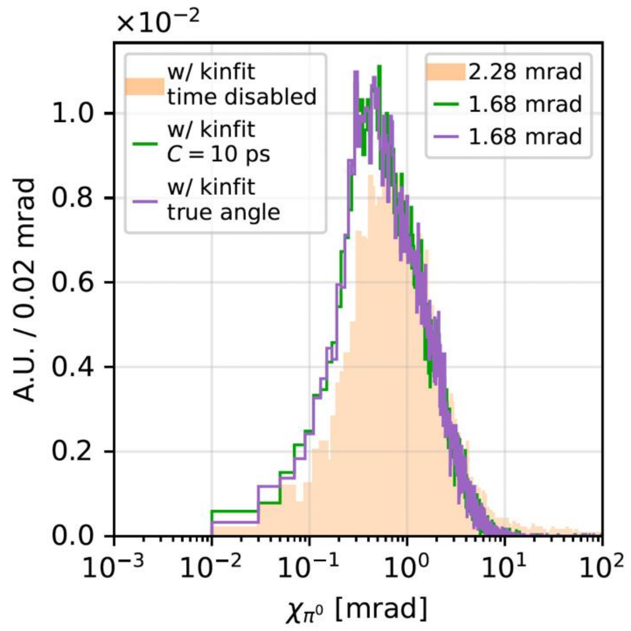
4 Photon position reconstruction

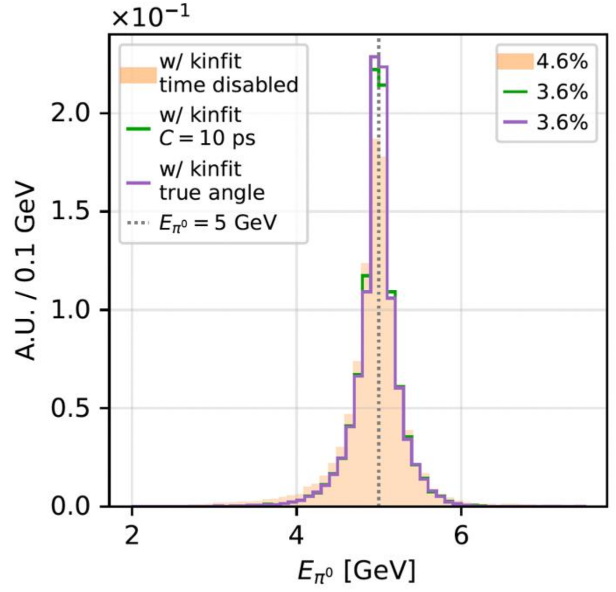
- We scale the constant and stochastic terms with the same factor.
- The hyperparameters are optimized for each timing resolution. (backup)
- Observation:
  - The resolution improve significantly at around 25 ps for both low and high energy photon



Impact on π^0 kinematic reconstruction

- Simulation:
  - 5 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



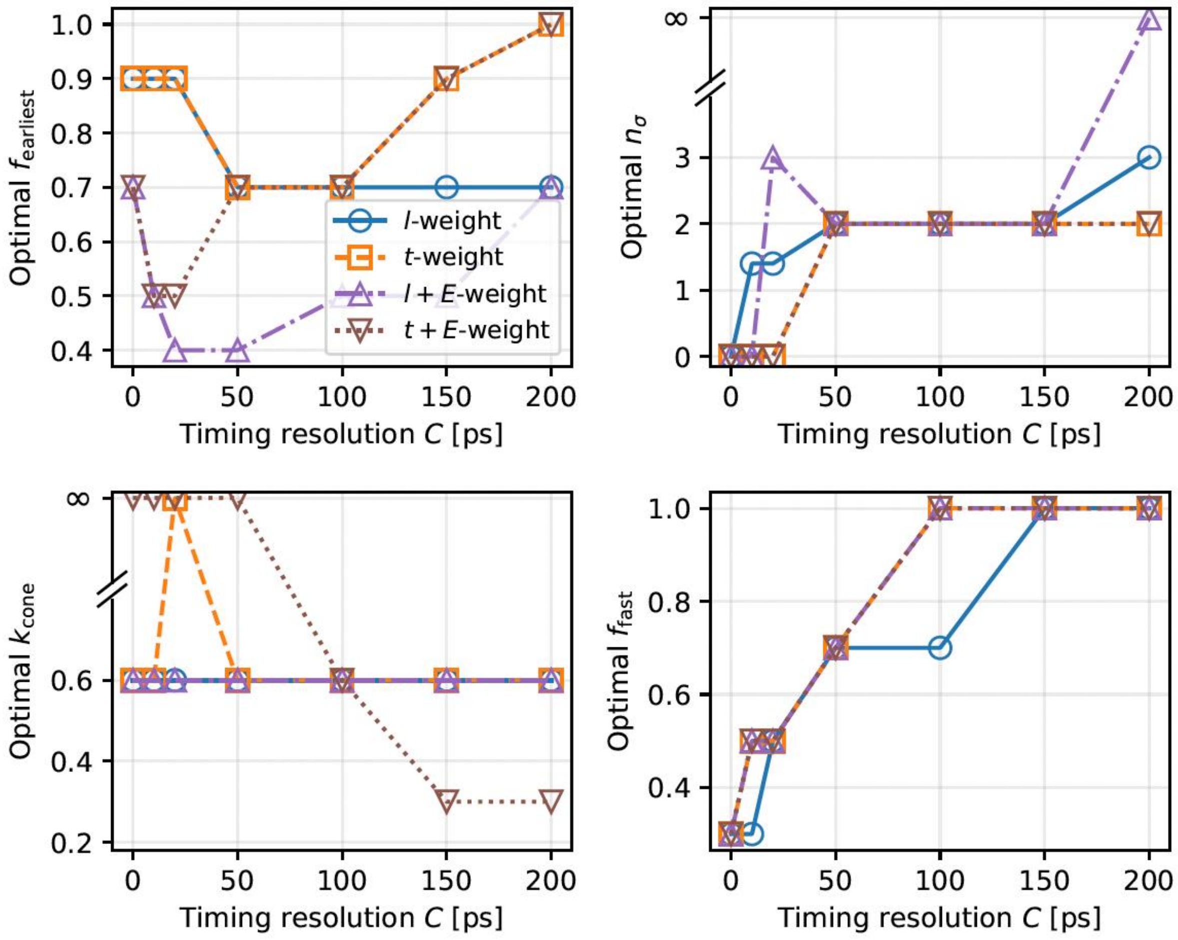


Conclusion

- Conclusion:
  - A multi-hit weighted reconstruction algorithm was developed for single photons.
    - outperforms a starting hit or barycenter only approaches (or their combination not shown here)
  - Precision calorimeter timing improves photon position bellow a few tens of picoseconds
  - Significant benefits to the neutral pion reconstruction
- Limitations:
  - The vertex of photon are assumed to be known
- Outlook
  - Improve the use of hit energy, e.g. by incorporating it directly in the $\sigma(\delta)$ parameterization
  - Study further the performance in $\pi 0$ reconstruction and in jet environments
  - Machine learning (AI) approach
  - Study scenarios where timing information is only partially supported in the ECAL

Thanks

Optimized Reconstruction Parameters



Preliminary: Impact on π^0 Kinematic Reconstruction

- $5\,\mathrm{GeV}$ 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.