中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Cluster Time Measurement with CEPC Calorimeter

Che, Y., Boudry, V., Videau, H. et al. Cluster time measurement with CEPC calorimeter. Eur. Phys. J. C 83, 93 (2023).

Yuzhi Che, Manqi Ruan

Institute of High Energy Physics, Chinese Academy of Sciences

CEPC味物理–新物理和相关探测技术研讨会

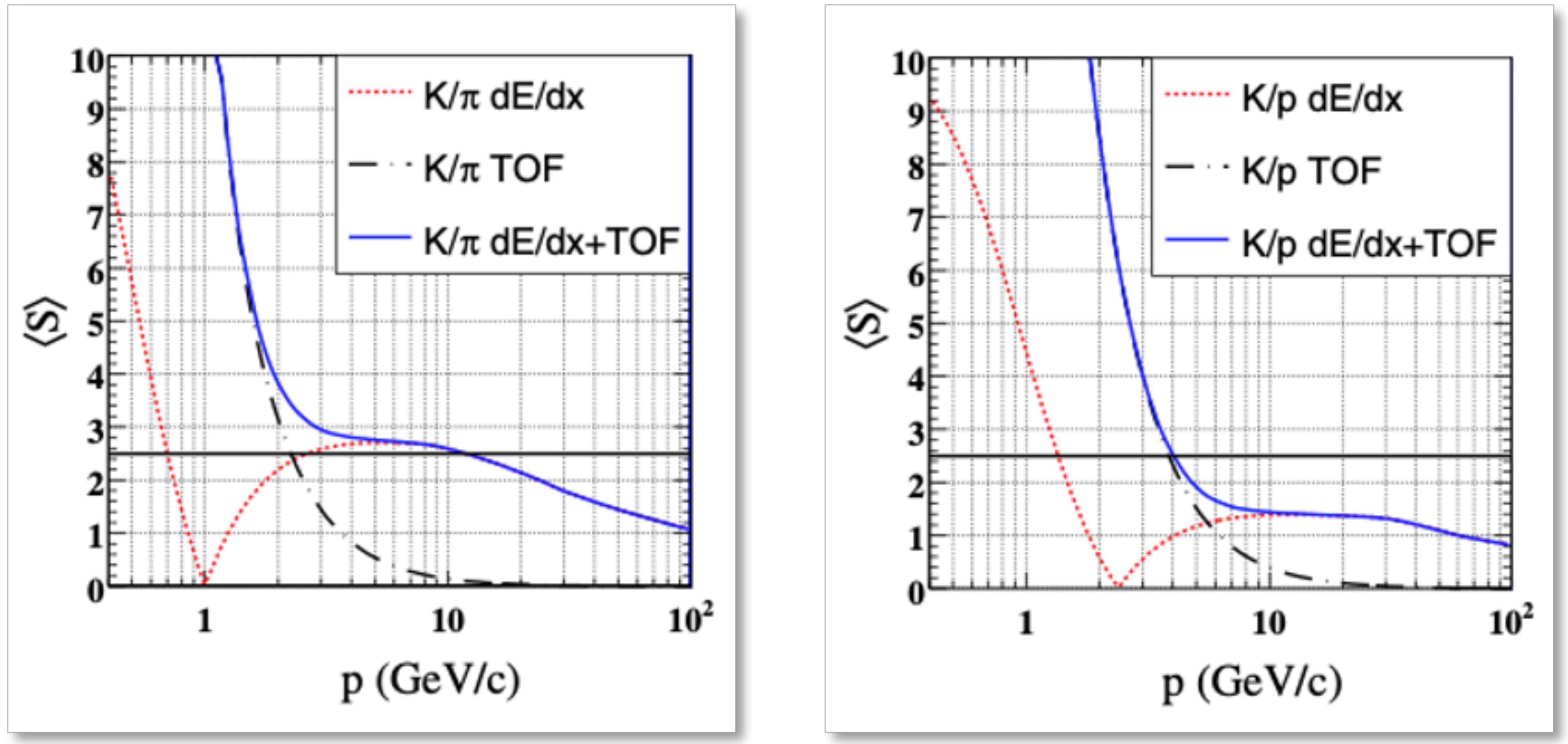
Aug. 15, 2023

1. Motivation

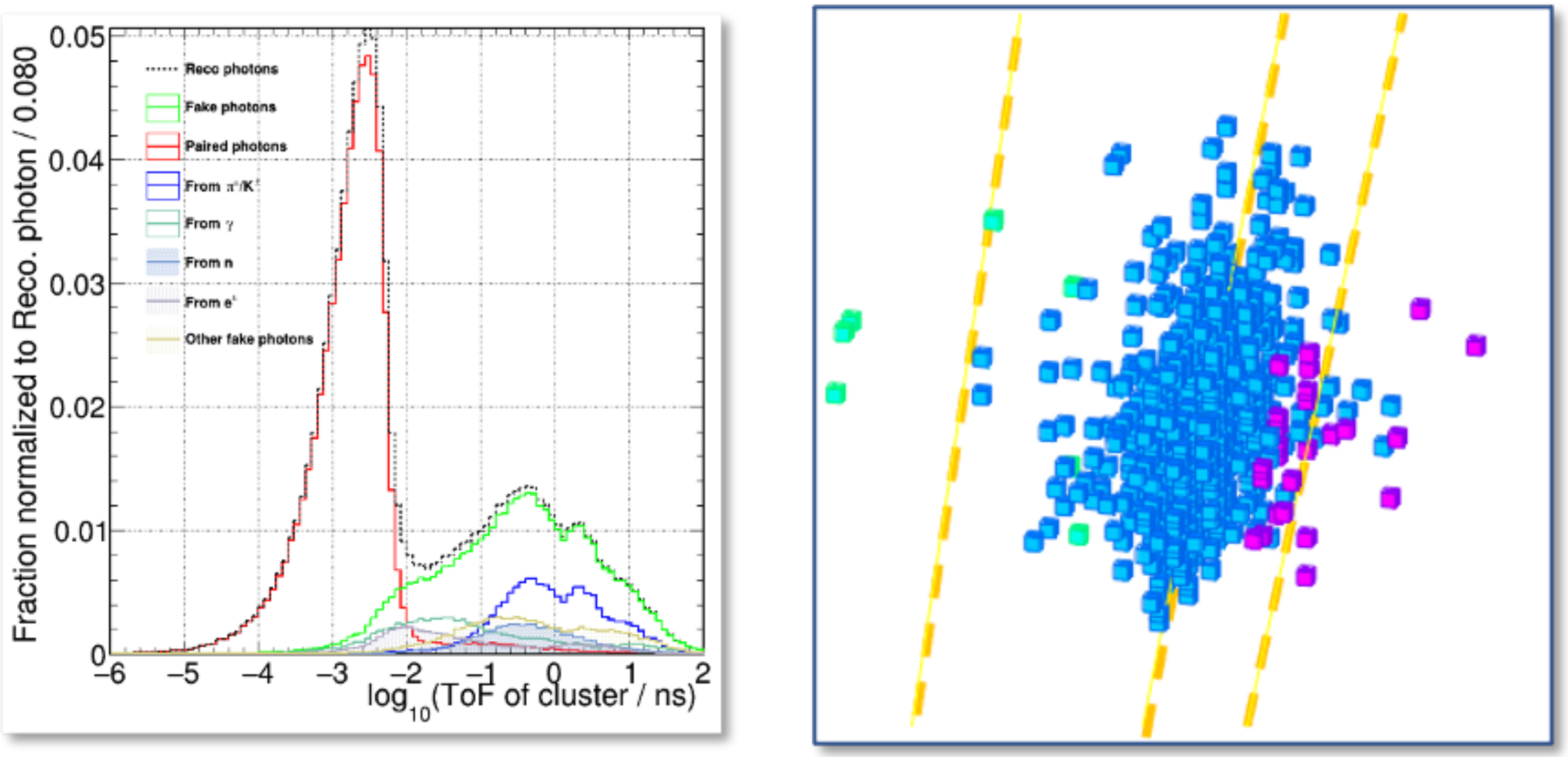
- **@LH–LHC**: mitigate pileup effect

- **An effective $K^{\pm}/\pi^{\pm}/p^{\pm}$ identification:** dE/dx information has not enough separation for charged particles ($K^{\pm}/\pi^{\pm}/p^{\pm}$) in specific momentum region. **TOF information** could be a valuable compensation for it.

- **Better PFO clustering** (cluster fragments identification) can be achieved with the **cluster TOF** information.



Separation power of cluster TOF with resolution of 50 ps.[1]



Truth cluster TOF distribution of real photon and fake photon clusters.

F. An, S. Prell, C. Chen, J. Cochran, X. Lou, and M. Ruan, Monte Carlo Study of Particle Identification at the CEPC Using TPC dE / Dx Information, Eur. Phys. J. C **78**, 6 (2018).

Cluster ↔ Hit

How to ...?
How accurate ...?
How scale ...?

2.1. Basic configurations

The baseline electromagnetic calorimeter (ECAL) optimized for the CEPC:

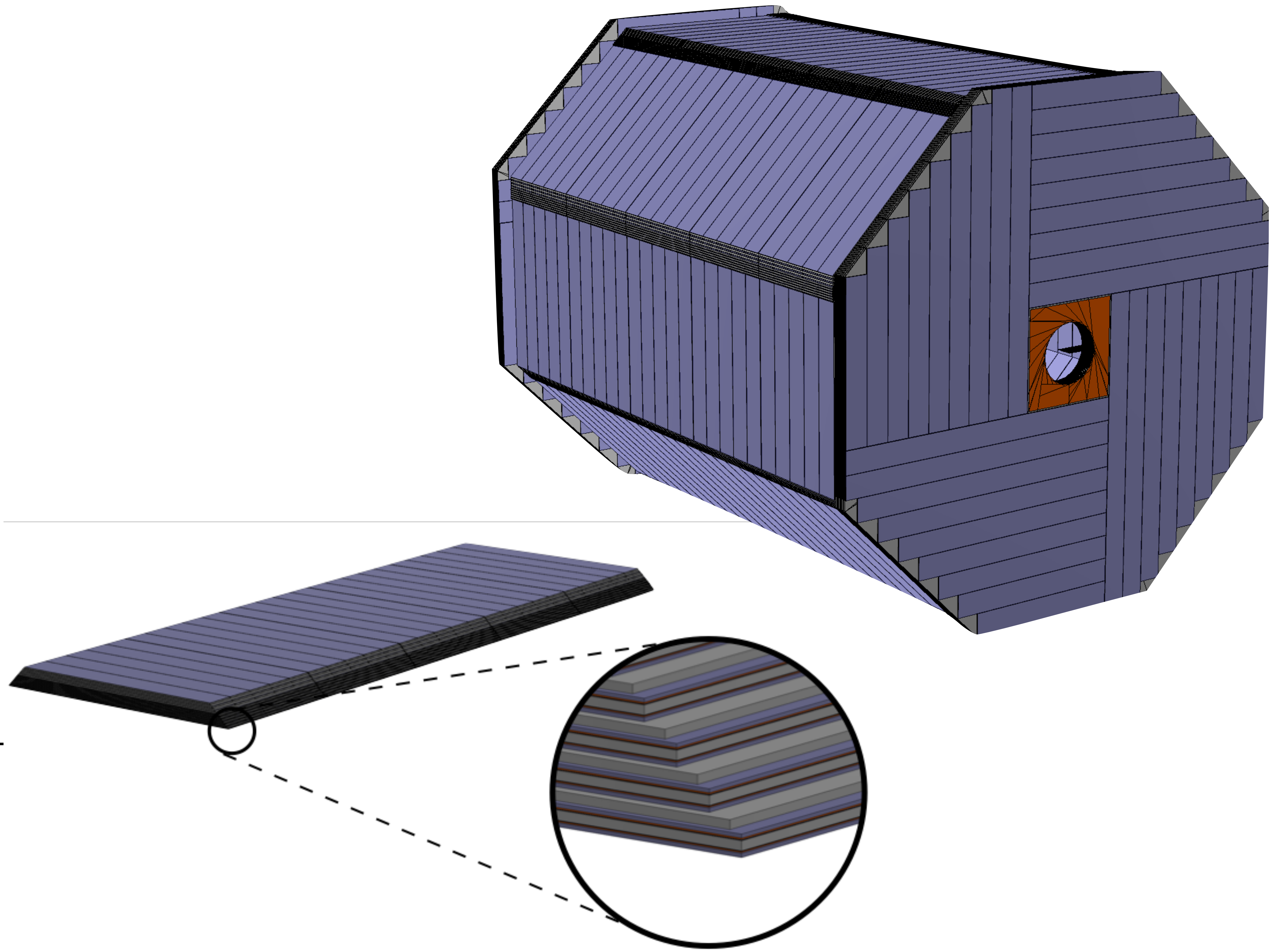
longitudinal direction: 30 (= 20 + 10) Layers

- First section: **20 layers**
    - tungsten plate $(2.1\,mm)$ + silicon sensor $(0.5\,mm \times (10 \times 10)\,mm^2)$
- Second section: **10 layers**
    - tungsten plate $(4.2\,mm)$ + silicon sensor $(0.5\,mm \times (10 \times 10)\,mm^2)$

ECAL inner radius: 1847 mm

B Field: 3 T (set to 0 in this research)

Sample: Single particle with momentum 0 ~ 30 GeV and direction (x,y,z) = (0, 1, 0).



The CEPC Study Group, CEPC Conceptual Design Report: Volume 2-Physics & Detector, ArXiv Preprint ArXiv:1811.10545 **2**, (2018).

2.2. Assumption: Intrinsic hit time resolution

The time resolution of single silicon diode can be parameterized as $\sigma_T = \frac{A}{\sqrt{2}S_{eff}} \oplus C$, where:

A: noise term, C: constant term, S: effective signal strength (by MIP) $S_{eff} = S_1 S_2 / \sqrt{S_1^2 + S_2^2}$,

$\sqrt{2}$: factor accounts for the two independent sensors.

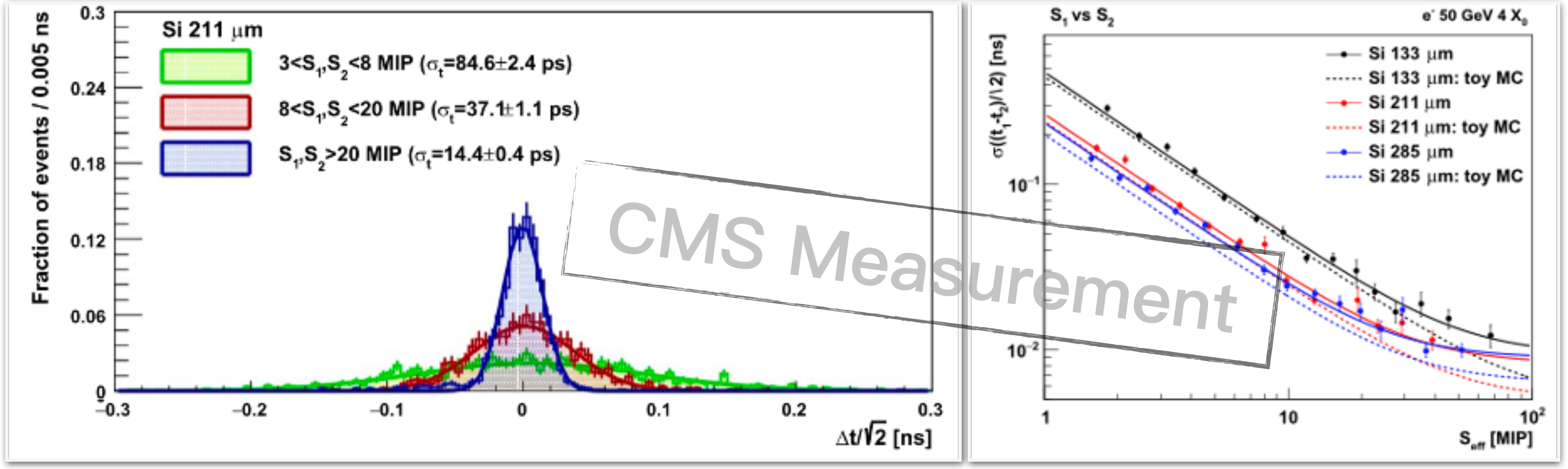
Hit time digitization in simulation:

- Record the truth level ECAL hits time.
- Smear the hits time with a Gaussian distribution,

$$T_{hit}^{digitized} = Gaus\left(T_{hit}^{truth}, \sigma_{T_{hit}}\right),$$

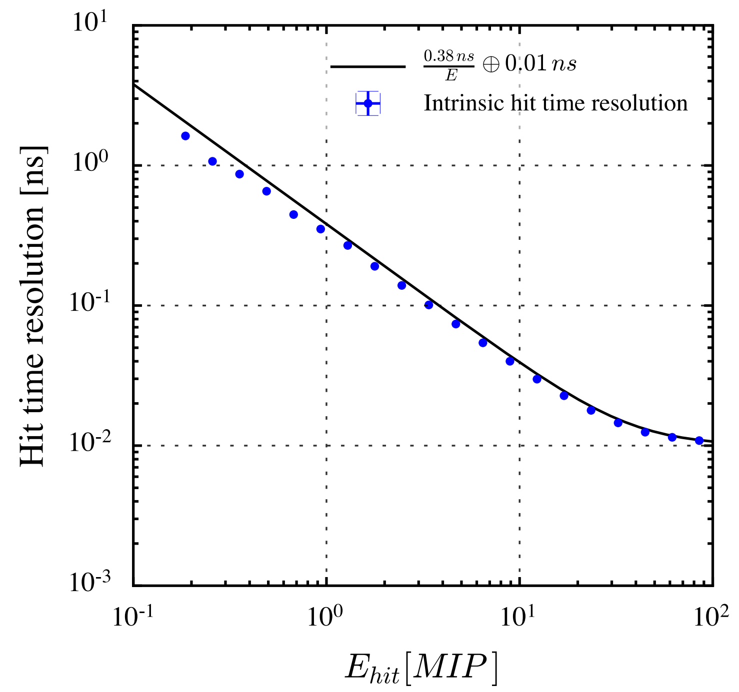
$$\sigma_{T_{hit}} = \sqrt{\left(\frac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}.$$

where E_{hit} is hit energy before digitization by unit of MIP.



Det 1	Det 2	Fit Function	A [ns×ADC]	C [ns]
Measurement I				
S_1(133-μm)	S_2(133-μm)	$\frac{\sigma(t_1-t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2}S_{eff}} \oplus C$	0.69 ± 0.01	0.010 ± 0.001
S_1(211-μm)	S_2(211-μm)		0.38 ± 0.01	0.009 ± 0.001
S_1(285-μm)	S_2(285-μm)		0.34 ± 0.01	0.010 ± 0.001

The current technology level: time resolution of single silicon sensor.



Mimic detector response in Simulation:

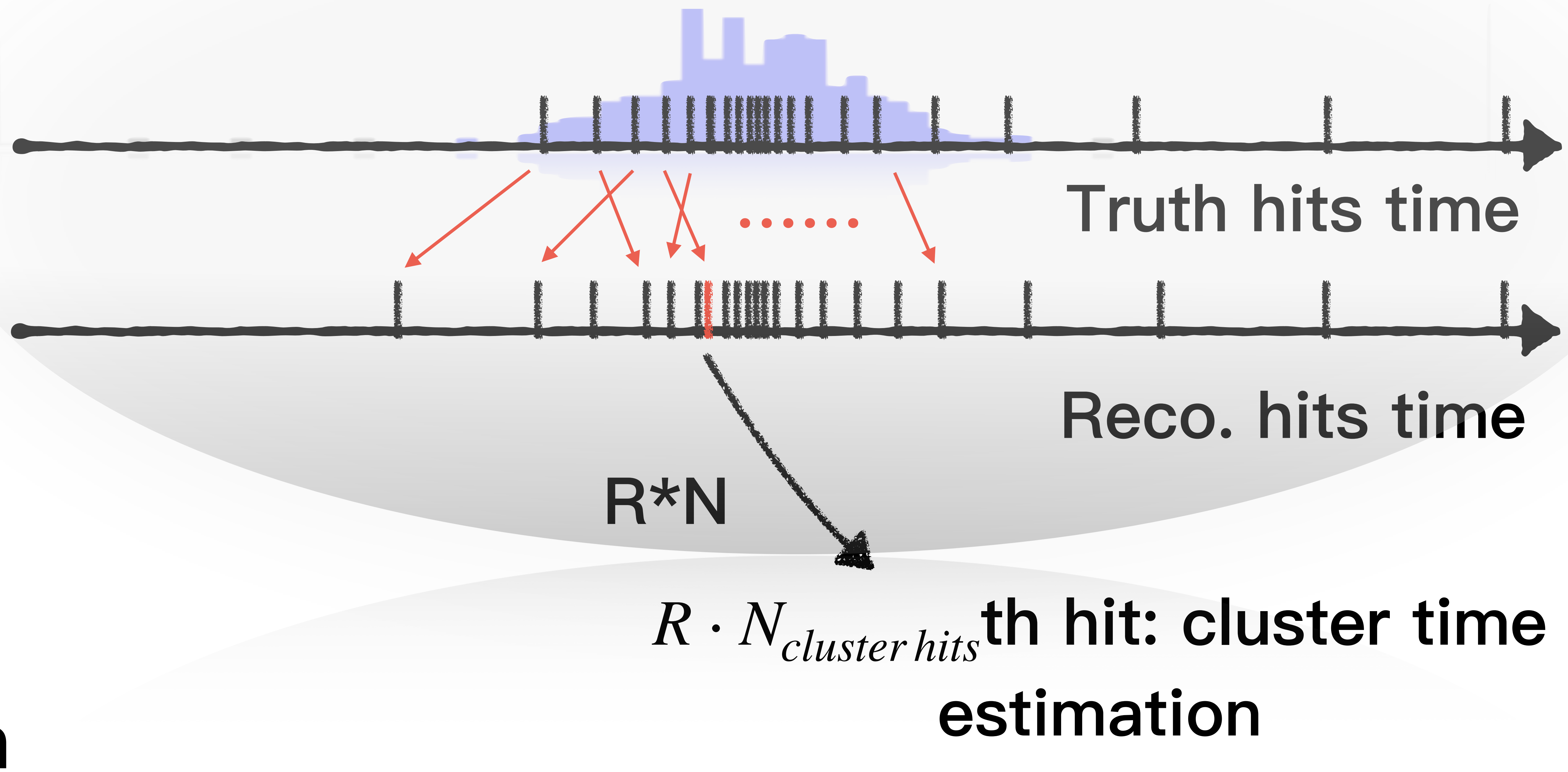
Hit time digitization result. Smeared the truth hits time with a gaussian parameterized by the CMS measurement.

N. Akchurin, etc, *On the Timing Performance of Thin Planar Silicon Sensors*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 859, 31 (2017).

3.1. Algorithm

A brief cluster TOF estimator:

1. Record the digitized ECAL hits
2. Sort the hits according to $T = t - L_{IP \to hit}/c$
3. Define a fraction: **R**
4. Select the fastest $(R \cdot N_{cluster\,hits})$th hit, and take its time as the cluster TOF evaluation value.

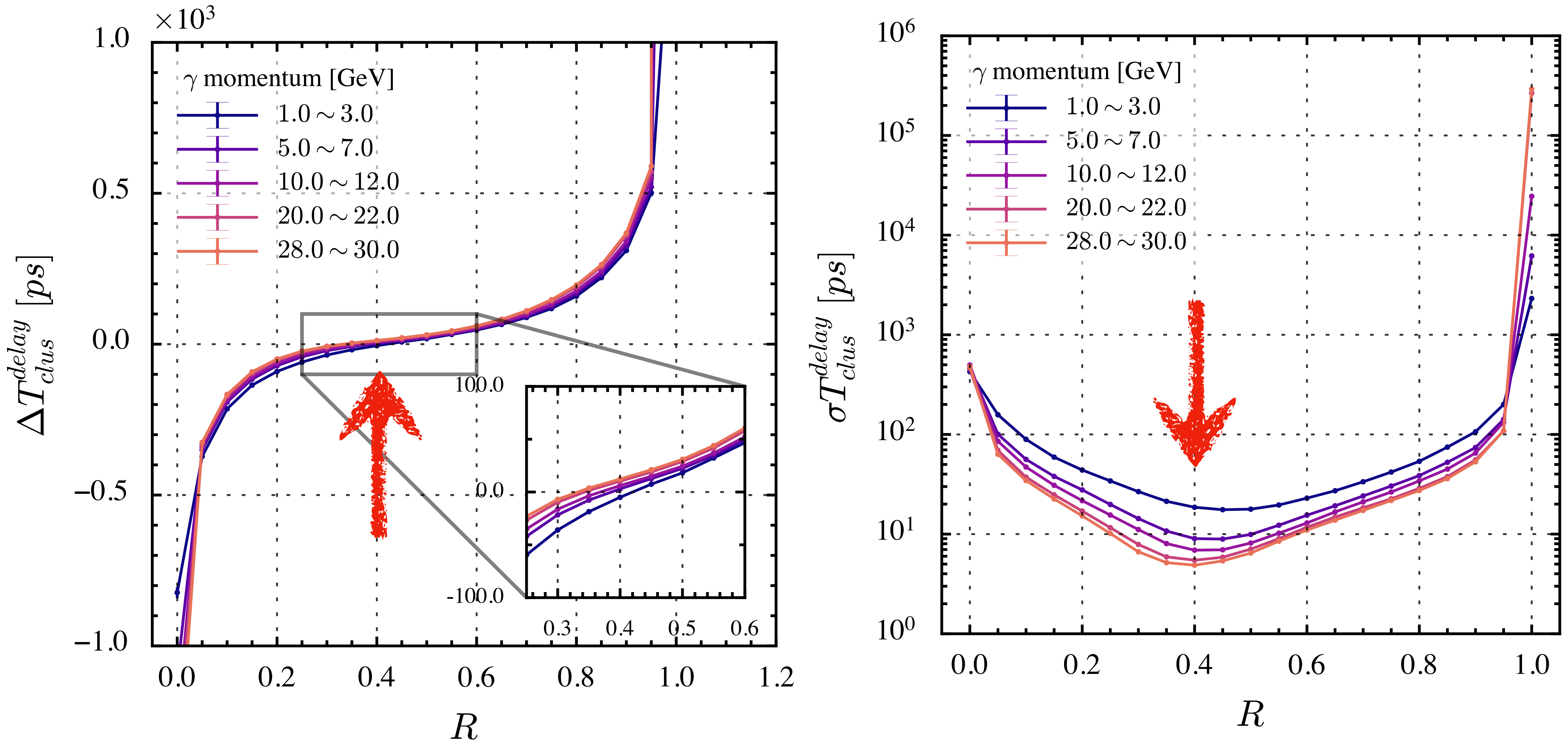


3.2. Algorithm & performance: Performance vs. fraction R

Take the result of photon and pion samples,

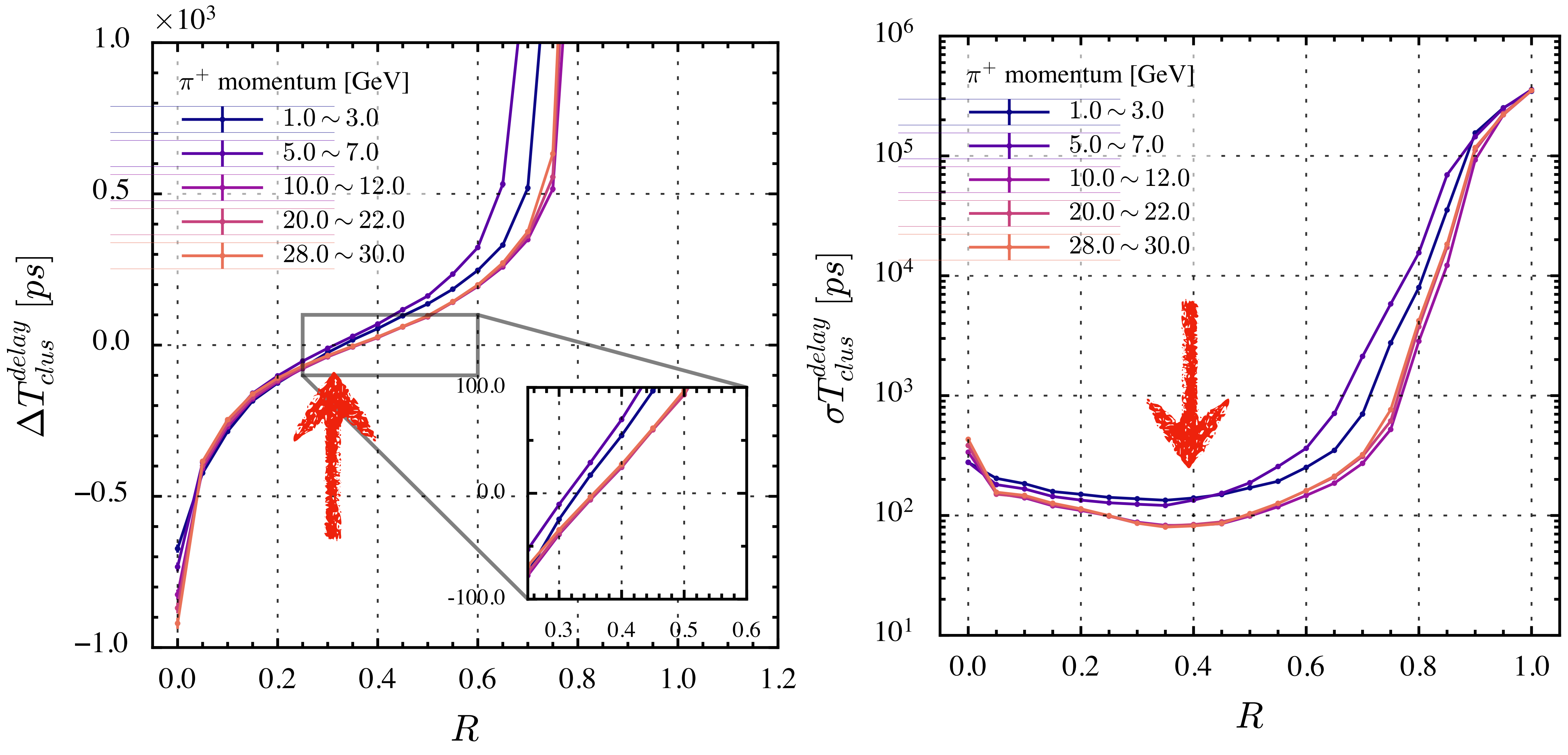
The none-bias R and minimum resolution R are close to each other but not exactly equal.

Photon



The estimation (left) bias and (right) resolution versus fraction R for perfect photon clusters.

Pion

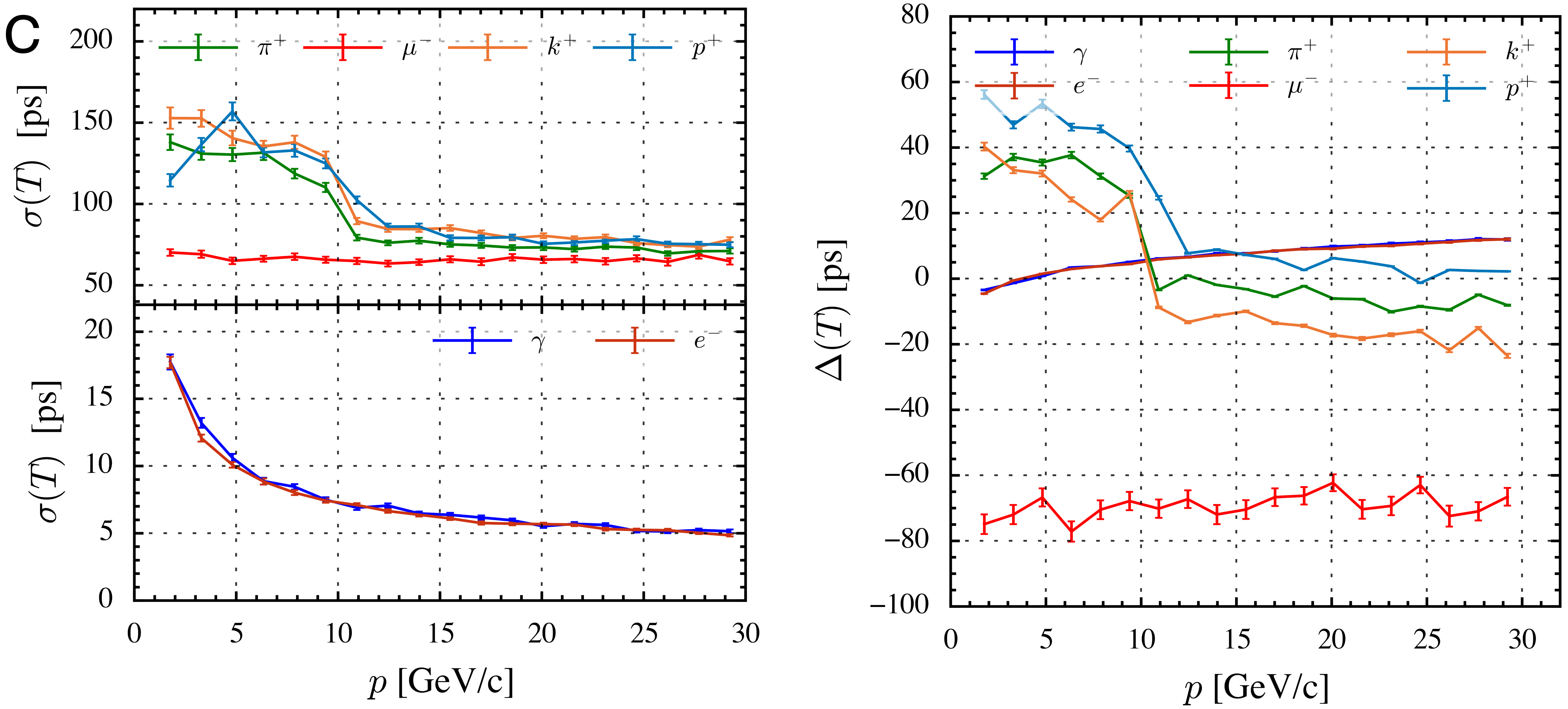


The estimation (left) bias and (right) resolution versus fraction R for perfect pion clusters.

3.3. Performance vs. incident momentum

- Optimize the hits number fraction R = 0.4 for a minimum **time resolution,**
  - time resolution for perfect hadronic clusters: **80–160 ps**
  - for perfect EM clusters: **5–20 ps.**
- The time reconstruction is accompanied by a **certain bias,**
  - Calibration.
  - Close for $K^{\pm}/\pi^{\pm}/p^{\pm}$.

Resolution **Bias**



The (left) resolution and (right) bias of perfect $\gamma/e^-/\mu^-/\pi^+/K^+/p^+$ clusters versus the MC truth incident momentum.

Physics list: QGSP_BERT_HP

Section 4.
Further exploration:

What’s the cluster time resolution with:

Q: realistic clustering?

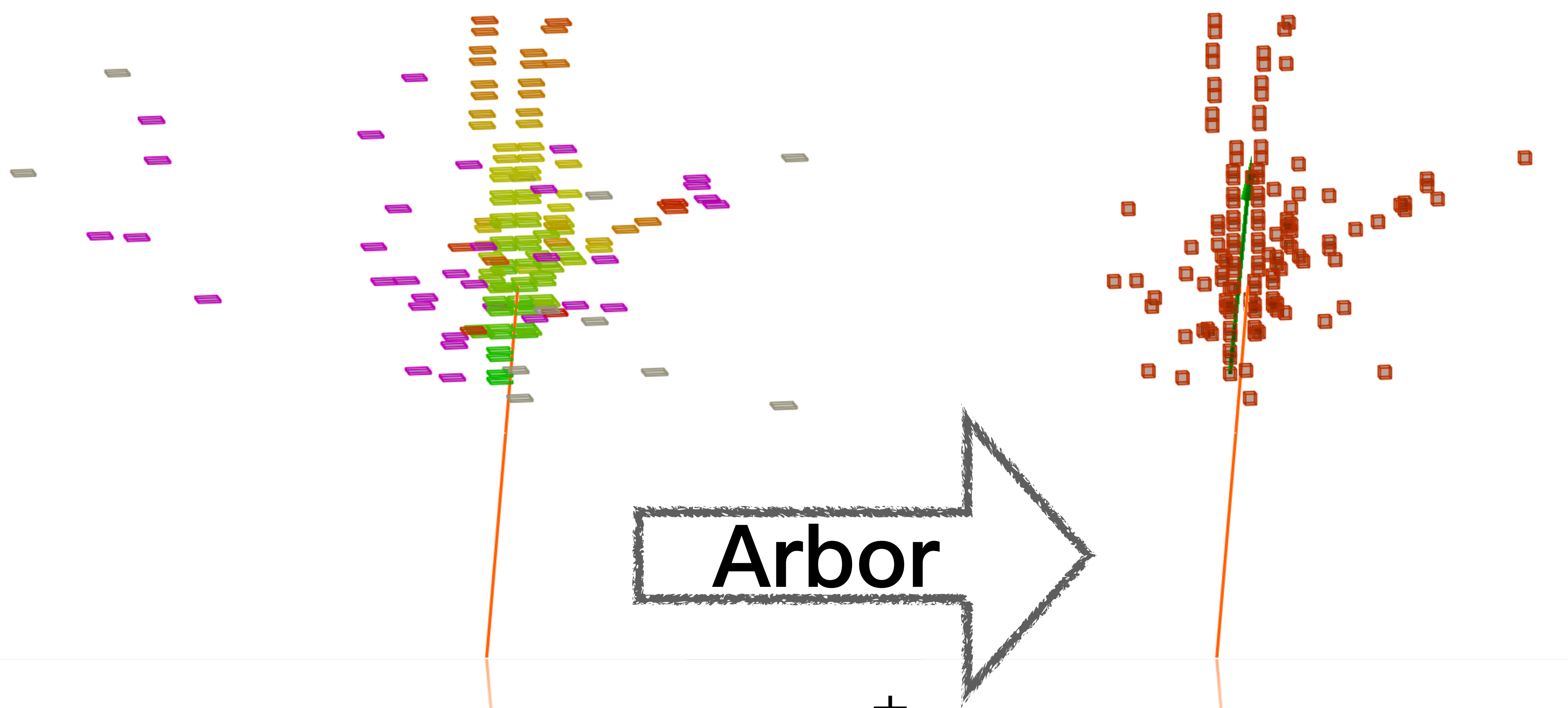
for example: Arbor?

Q: different hit time resolution

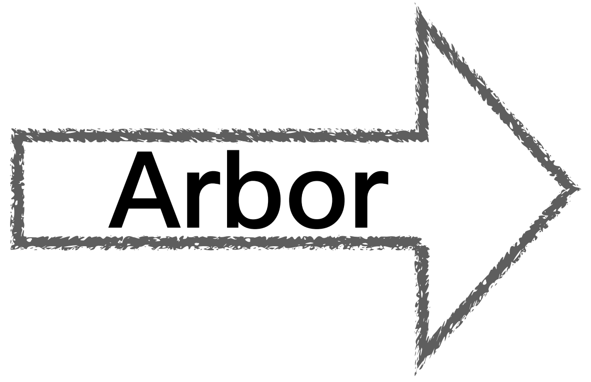
Q: different #timing layers

4.1. Influence of the Arbor clustering

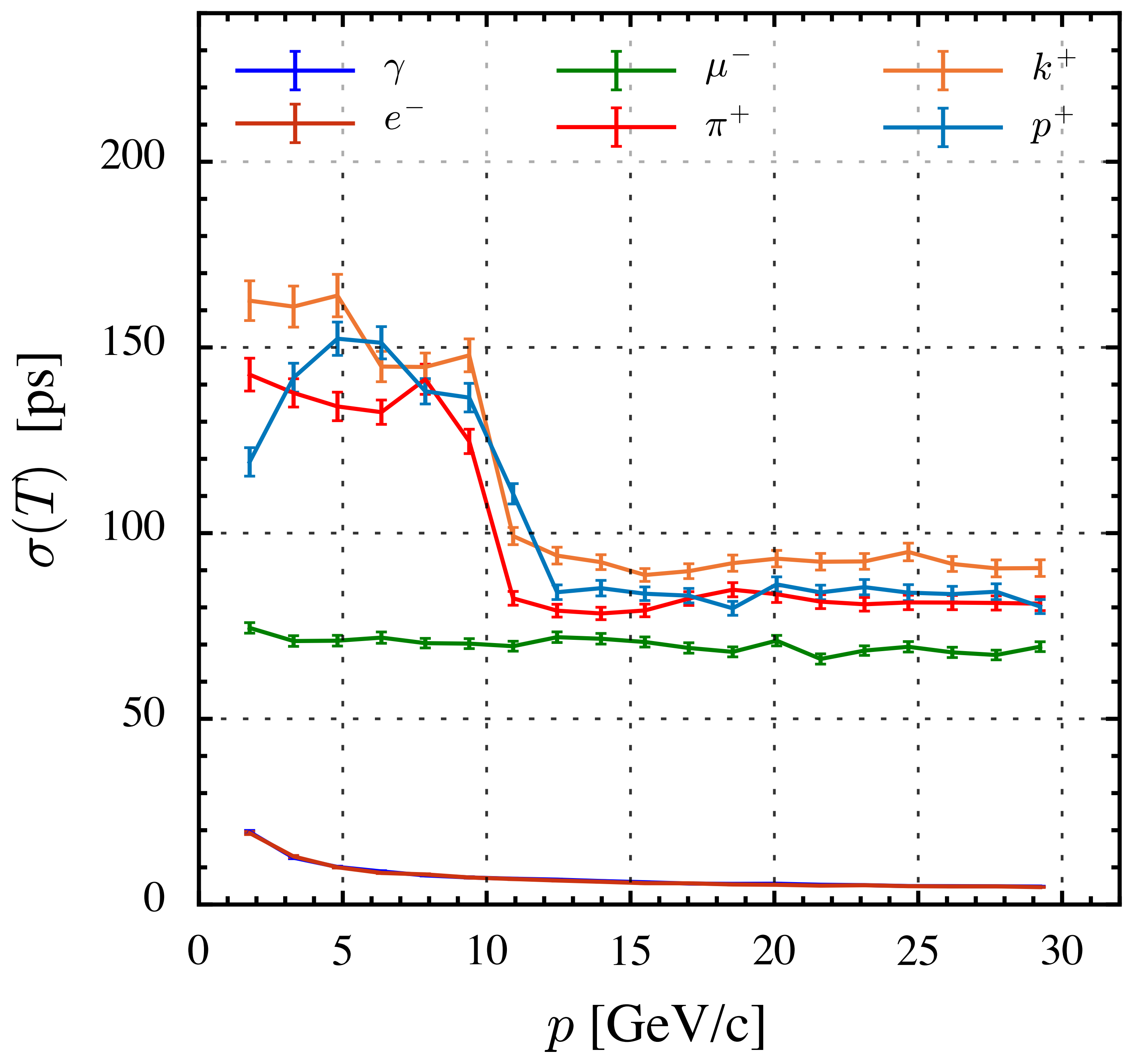
- **Arbor clustering module** with parameters optimized for the CEPC improve the time resolution of hadronic clusters by 50%~80%.



Event display of a 10 GeV $\pi^{\pm}$ shower in ECAL, (left) without clustering and (right) after clustering by Arbor. The color of the hits in the left figure represents the true time.

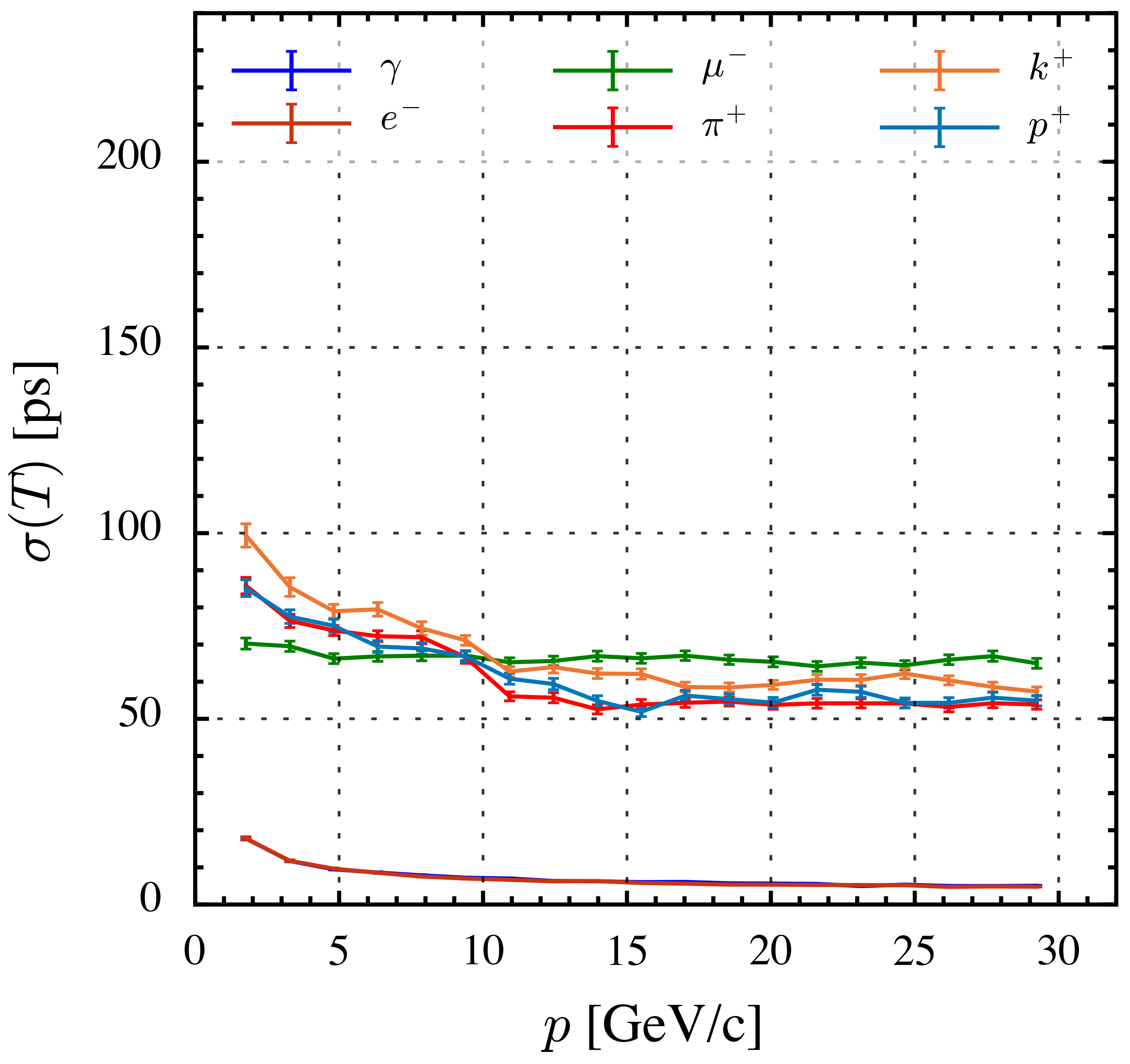


Perfect clustering



Time resolution for perfect clusters, including all hits of a shower.

Arbor clustering



Time resolution for Arbor clusters

Section 4.
Further exploration:

What’s the cluster time resolution with:

A: Impact of realistic clustering

Arbor improves time resolution by ~50% for hadronic cluster.

Q: different hit time resolution

Q: different #timing layers

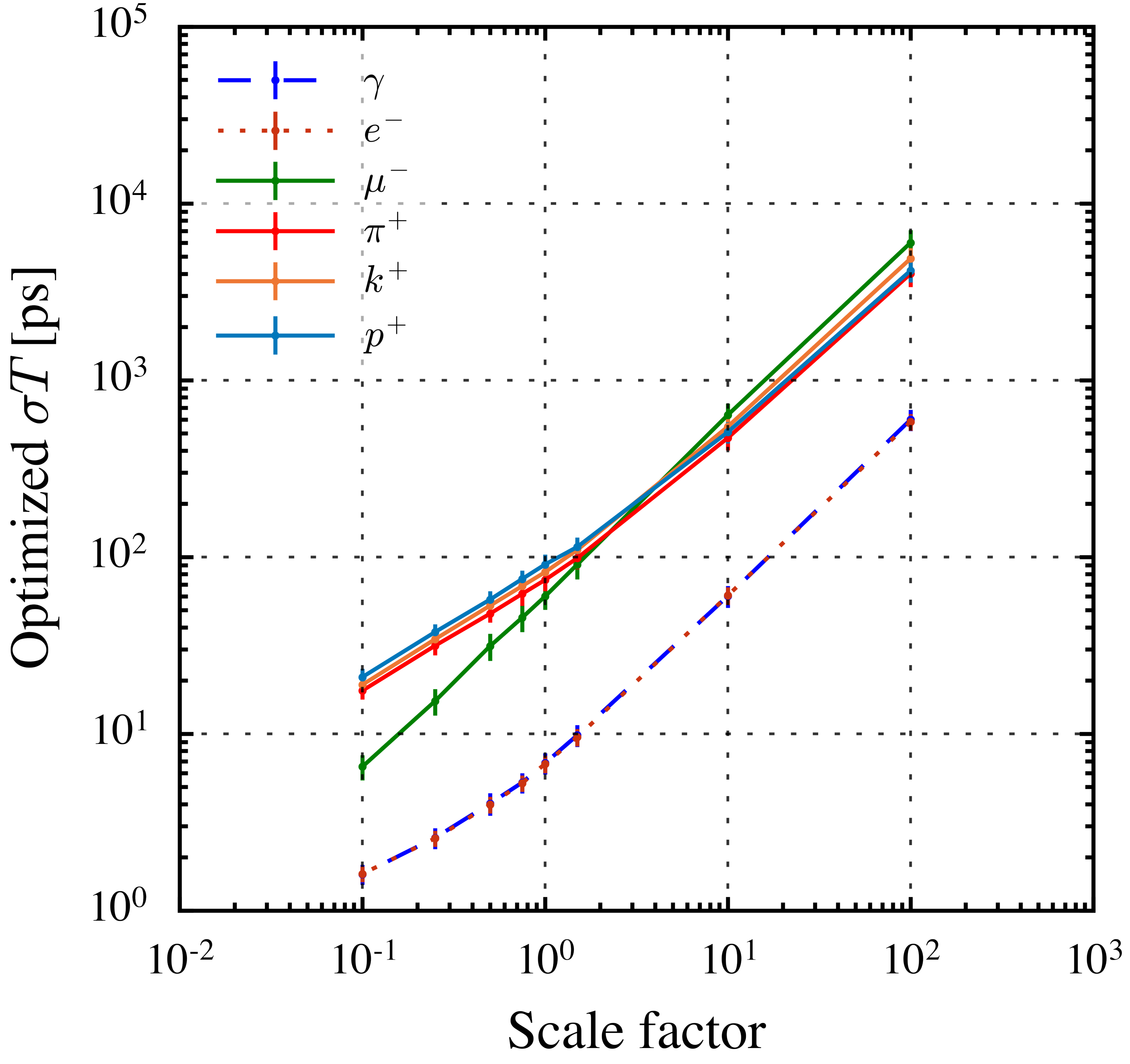
4.2. Intrinsic hit resolution

- Scale the intrinsic hit resolution:

$$\sigma_{T_{hit}} = factor \cdot \sqrt{\left(\frac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}$$

, and optimize the hit number fraction R.

- The dependence of the cluster time resolution on the intrinsic hit resolution is approximately **linear**. The improvement of the timing performance is appreciated.



The scaling behavior of the shower time resolution for 10–15 GeV particles versus the intrinsic hit time resolution

Section 4.
Further exploration:

What's the cluster time resolution with:

A: Impact of realistic clustering

Arbor improves time resolution by ~20%/ 40% for EM/hadronic cluster.

A: different hit time resolution

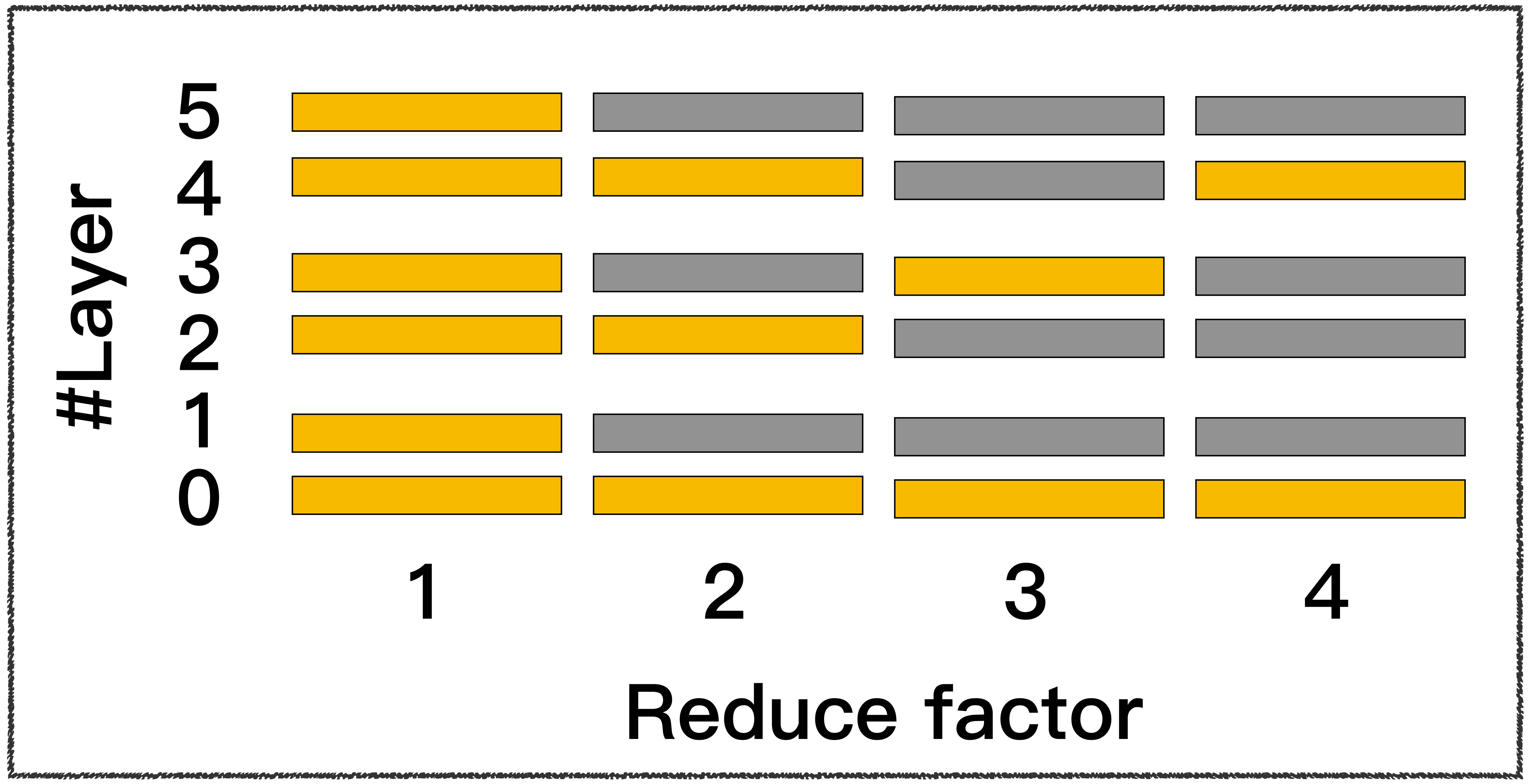
linear!

Q: different #timing layers

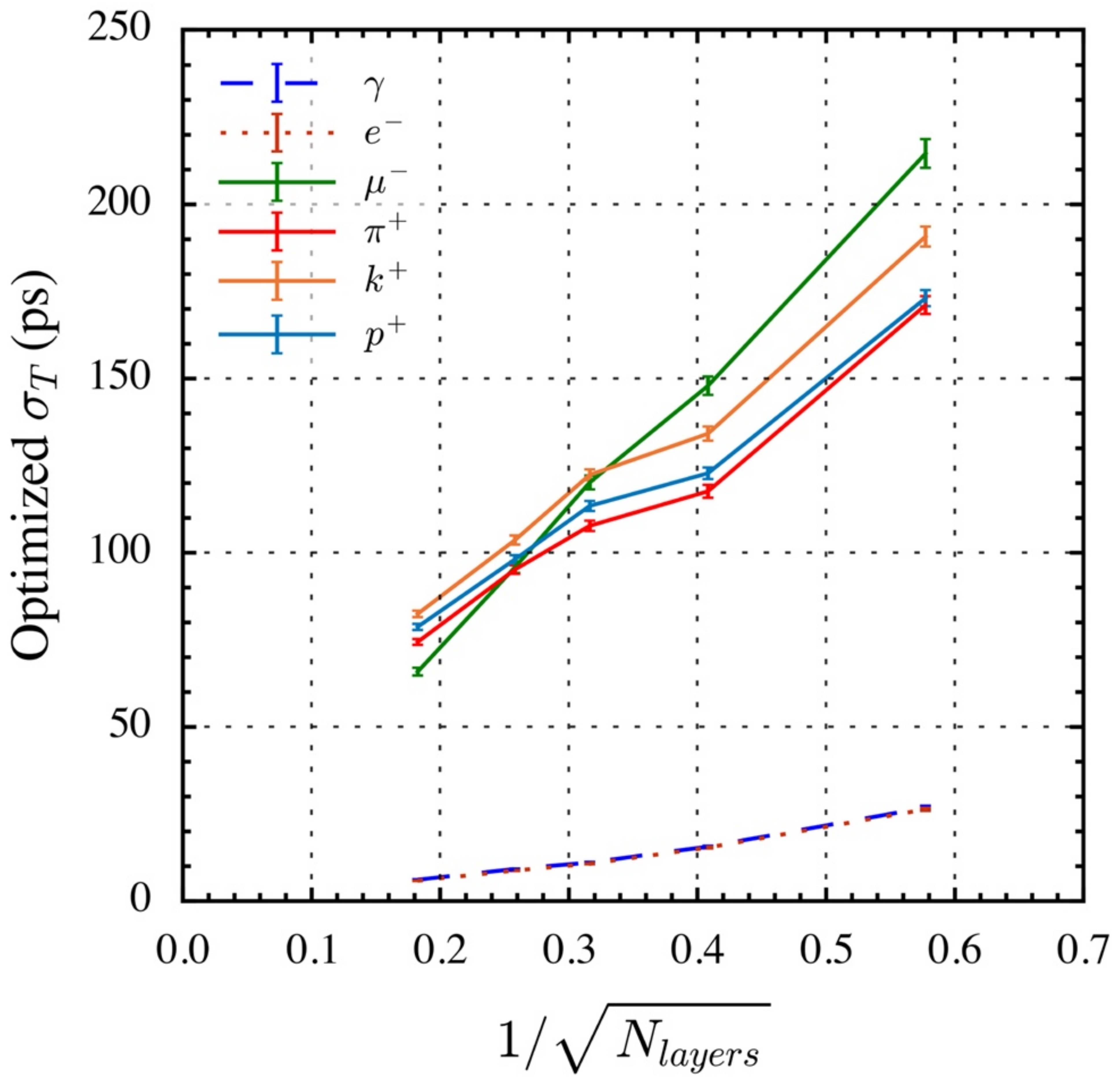
4.3. Number of the timing layers

- In fact, maybe only a part of the ECAL layers are equipped with the timing electronic.

- Reducing the timing layers number by factor 2, 3, 5, 10, the cluster time resolution varies in a form of $\propto 1/\sqrt{N_{layer}}$

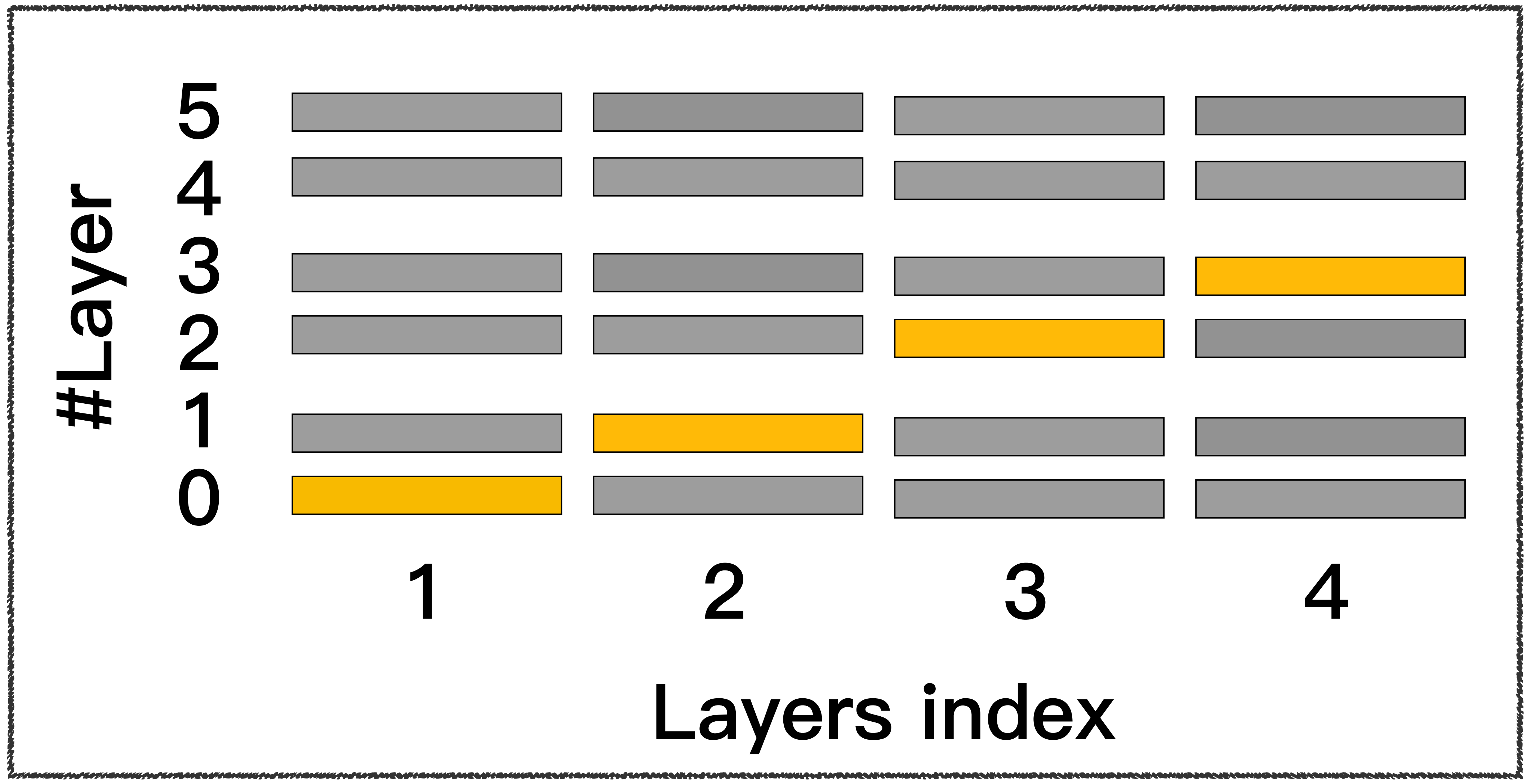


A schematic diagram of timing layer isometric sampling. Only the **layers** whose number can be divided exactly by the reduce factor are served to record hit time information.

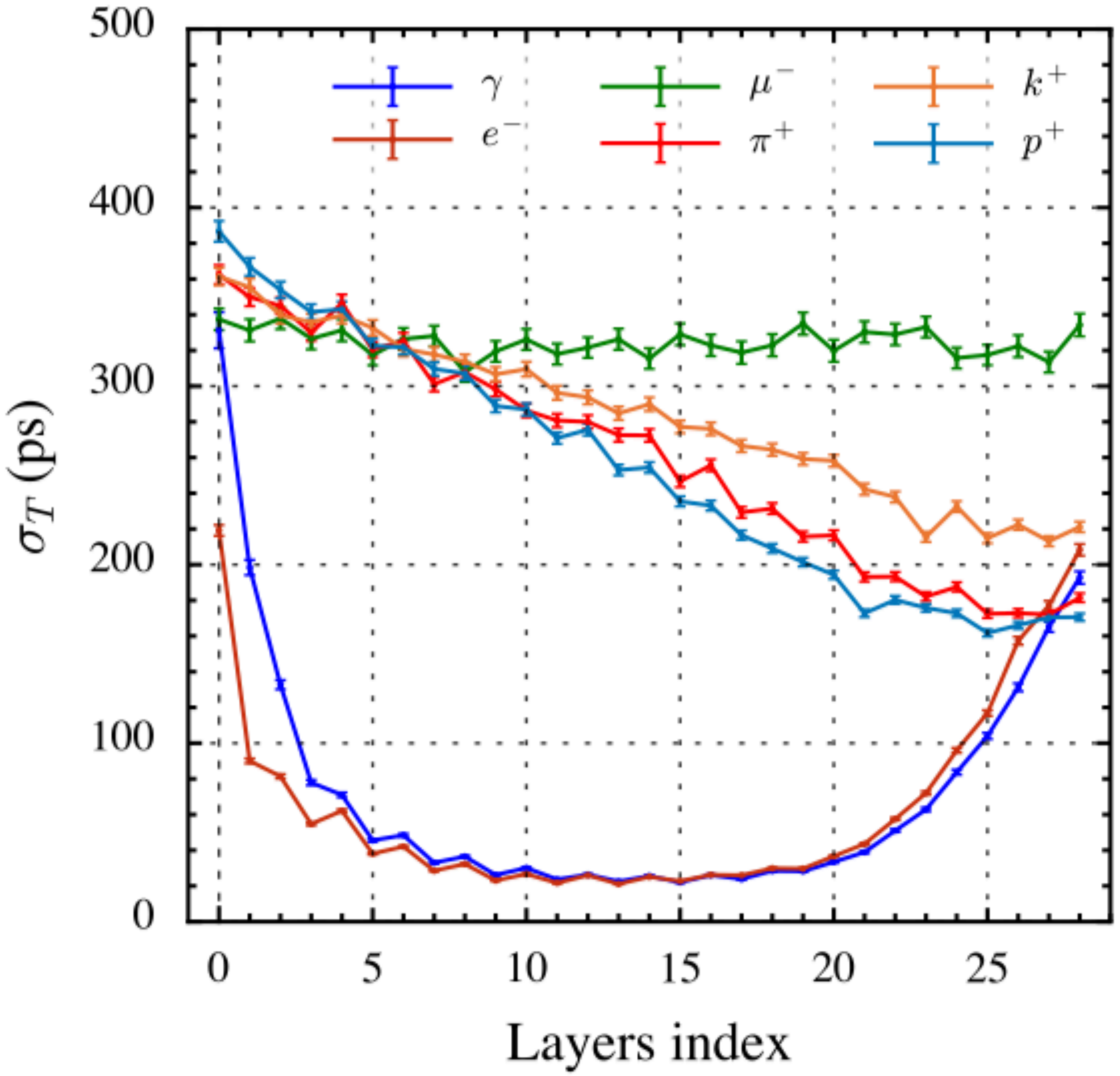


Cluster time resolution versus (left) layers number and (right) its square root for perfect (top) pion (bottom) photon clusters..

- **Better choice**: Arranging timing layers closer to the shower maximum position.



A schematic diagram of timing layer sampling. Only the one **layer** is used to record hit time information.



The time resolution from a single layer for 25–30 GeV particles as a function of the layer index

Section 4.
Further exploration:

What's the cluster time resolution with:

A: Impact of realistic clustering

Arbor improves time resolution by ~20%/40% for EM/hadronic cluster.

A: different hit time resolution

linear!

A: different #timing layers

$$\sigma(T_{clus}) \propto 1/\sqrt{N_{layer}}$$

Conclusion

- A brief cluster TOF reconstruction algorithm are implemented.
- **Cluster Time:** Under current CMS silicon sensor timing technology, CEPC ECAL can provide the **time resolution**:
  - for perfect EM clusters with 0 to 30 GeV energy can reach 5 ~ 20 ps,
  - for perfect hadronic cluster, can reach 80 ~ 160 ps.
- **Influencing factors:**
  - **Arbor clustering module** improves the hadronic cluster time resolution by a factor of ~1.5
  - The cluster time resolution is proportional to the **intrinsic time resolution**.
  - Cluster time resolution is inversely proportional to the $\sqrt{N_{layer}}$.

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Thanks for your attention

Yuzhi Che, Manqi Ruan

2023年8月15日

中国科学院高能物理研究所

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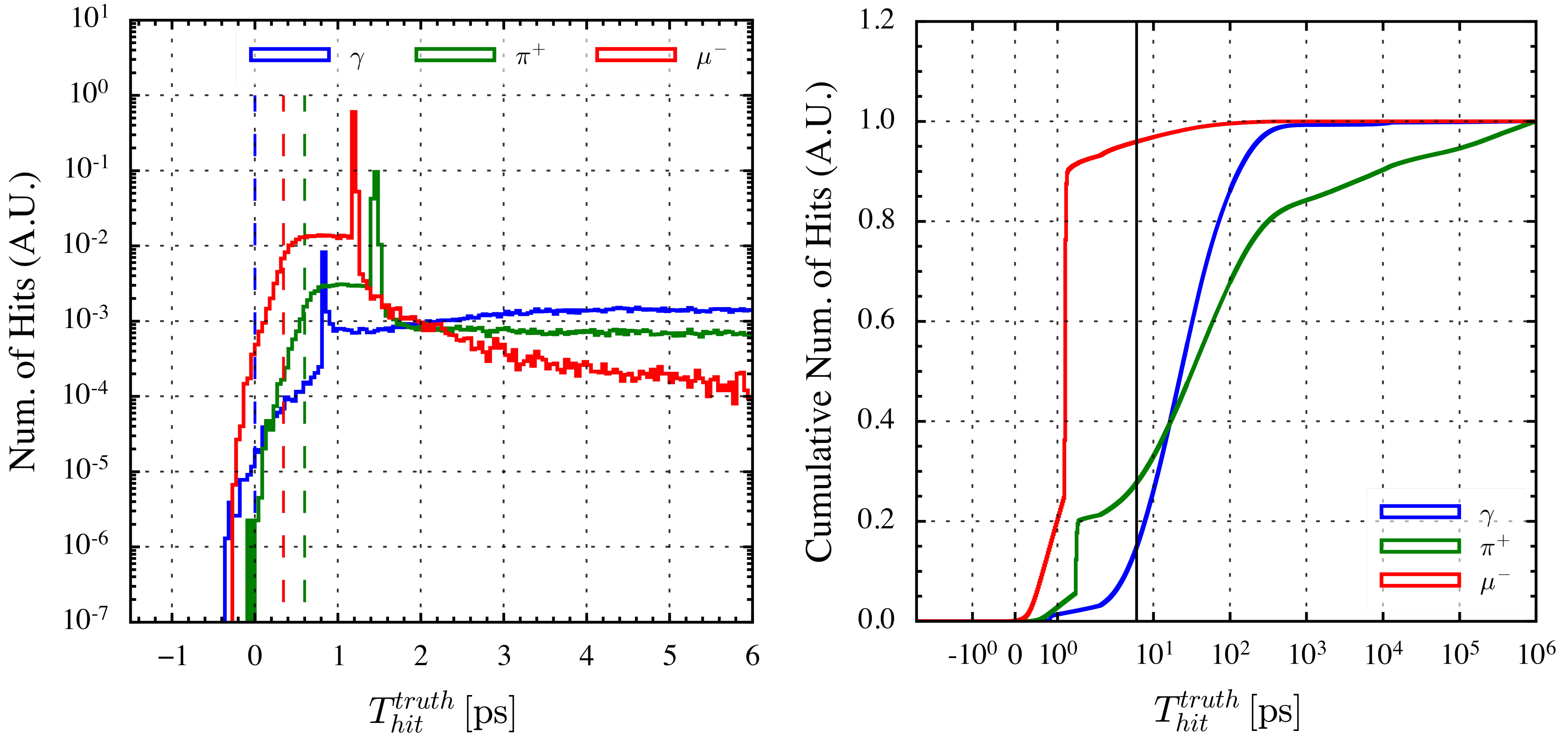
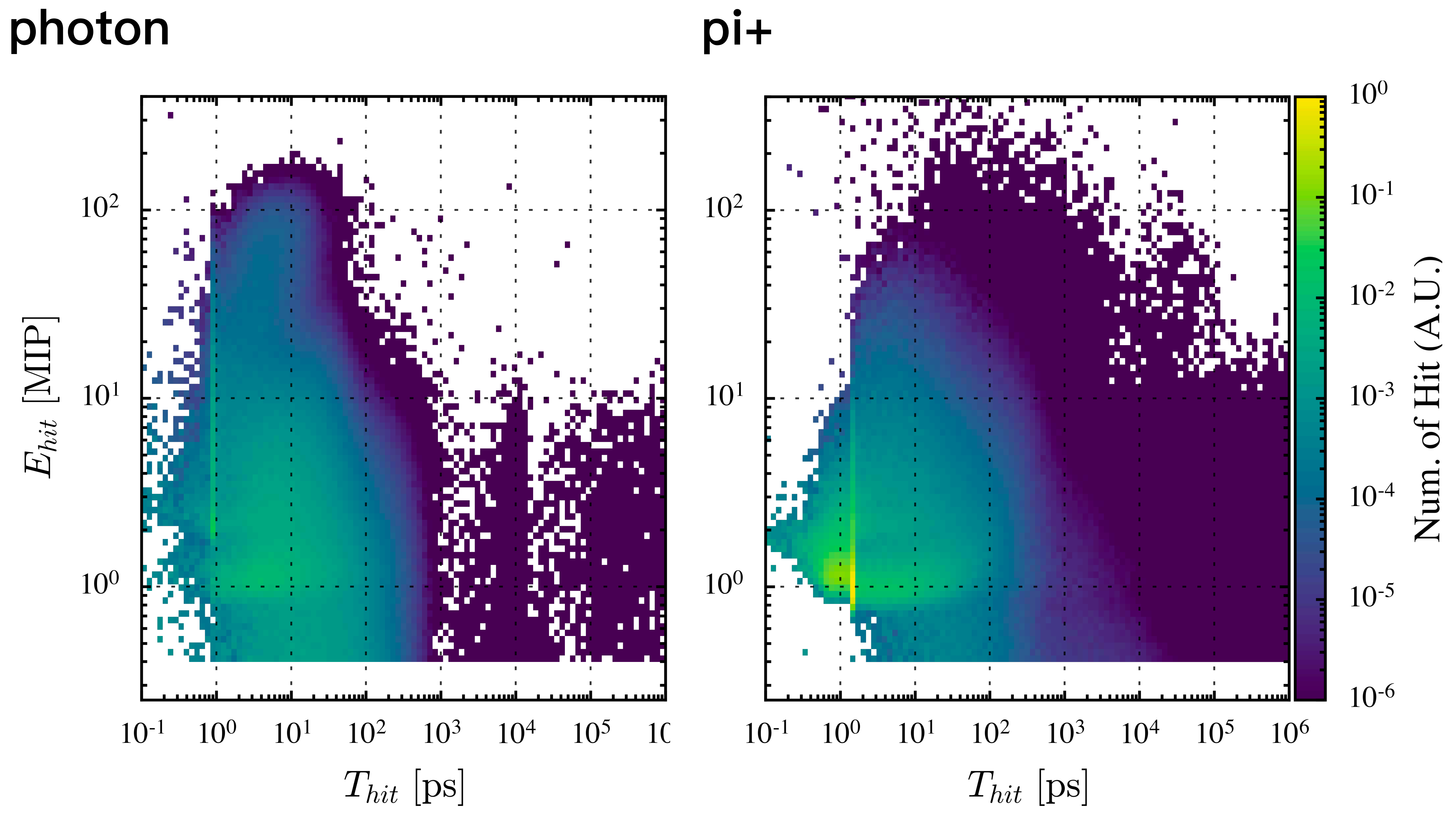
Back Up

Shifted time: $T = t - L_{IP\to hit}/c$,

$L_{IP\to hit}$: distance from IP to the center of the hit.



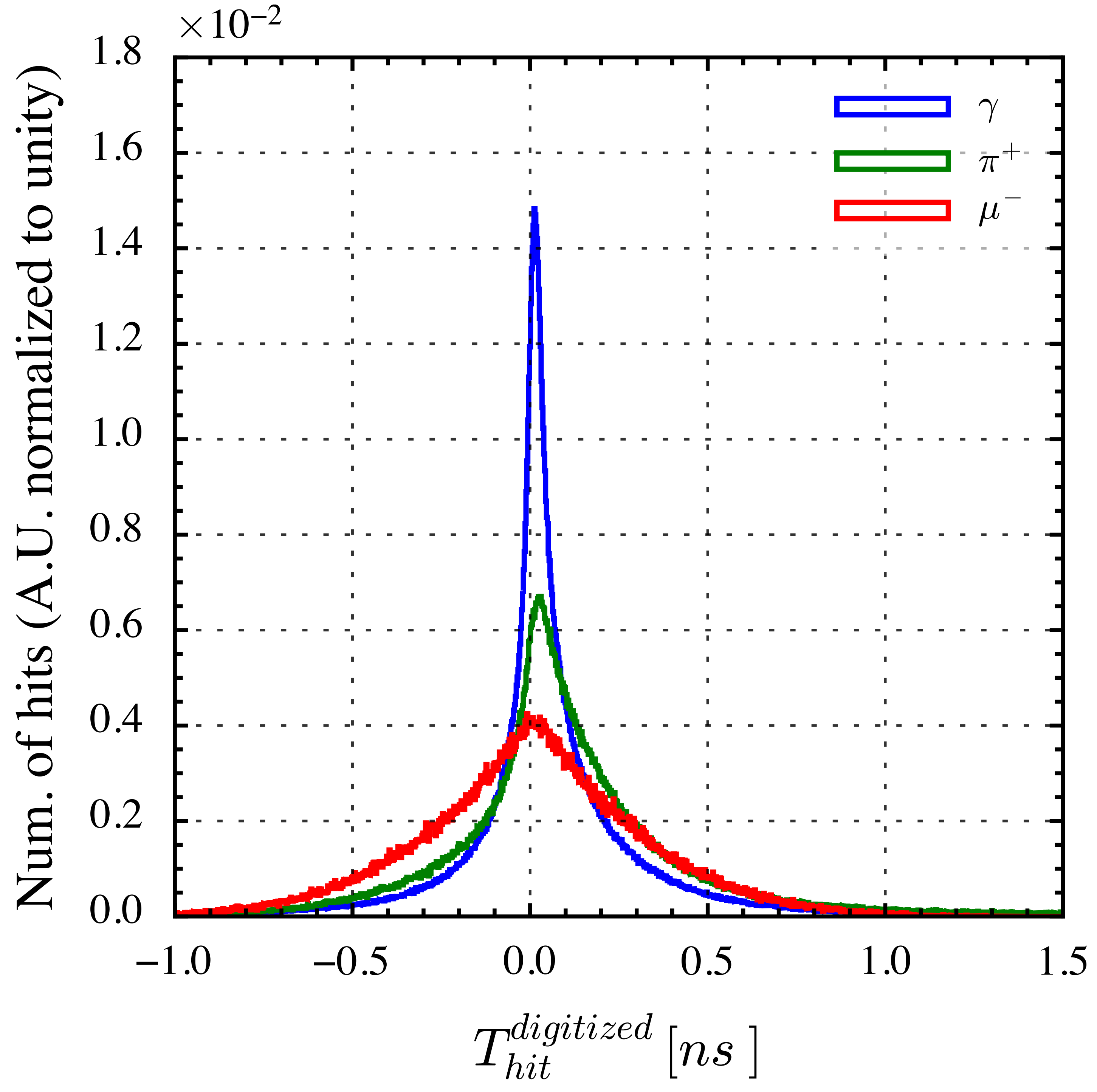
The shower truth time spectrum of 10 GeV $\gamma/\pi^+/\mu^-$ showers, all normalized to the total number of hits before 1000 ns. The dashed lines donate the expected ToF of the corresponding particles.



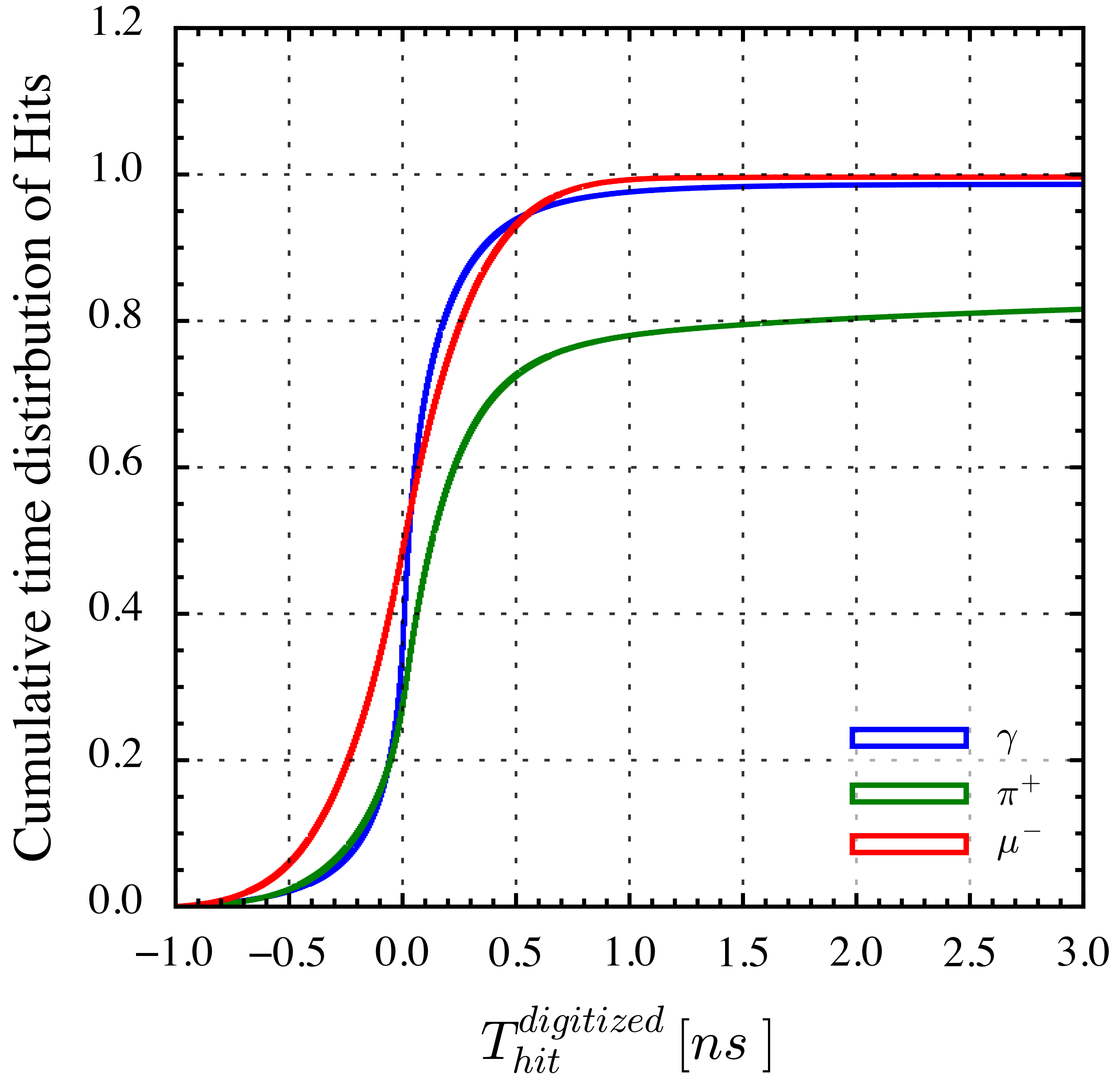
Time vs. energy distribution of ECAL hits in (left) 10 GeV photon and (right) 10 GeV π^+ hits sample, where the hit time is normalized as, $T_{delay} = T_{hit} - L_{IP\to hit}/c$

3.2. Shower time spectrum after digitization

Because the intrinsic time resolution is correlated with hit energy, the shower time spectrum shows highly none-gaussian, including a narrow peak and a long tail.

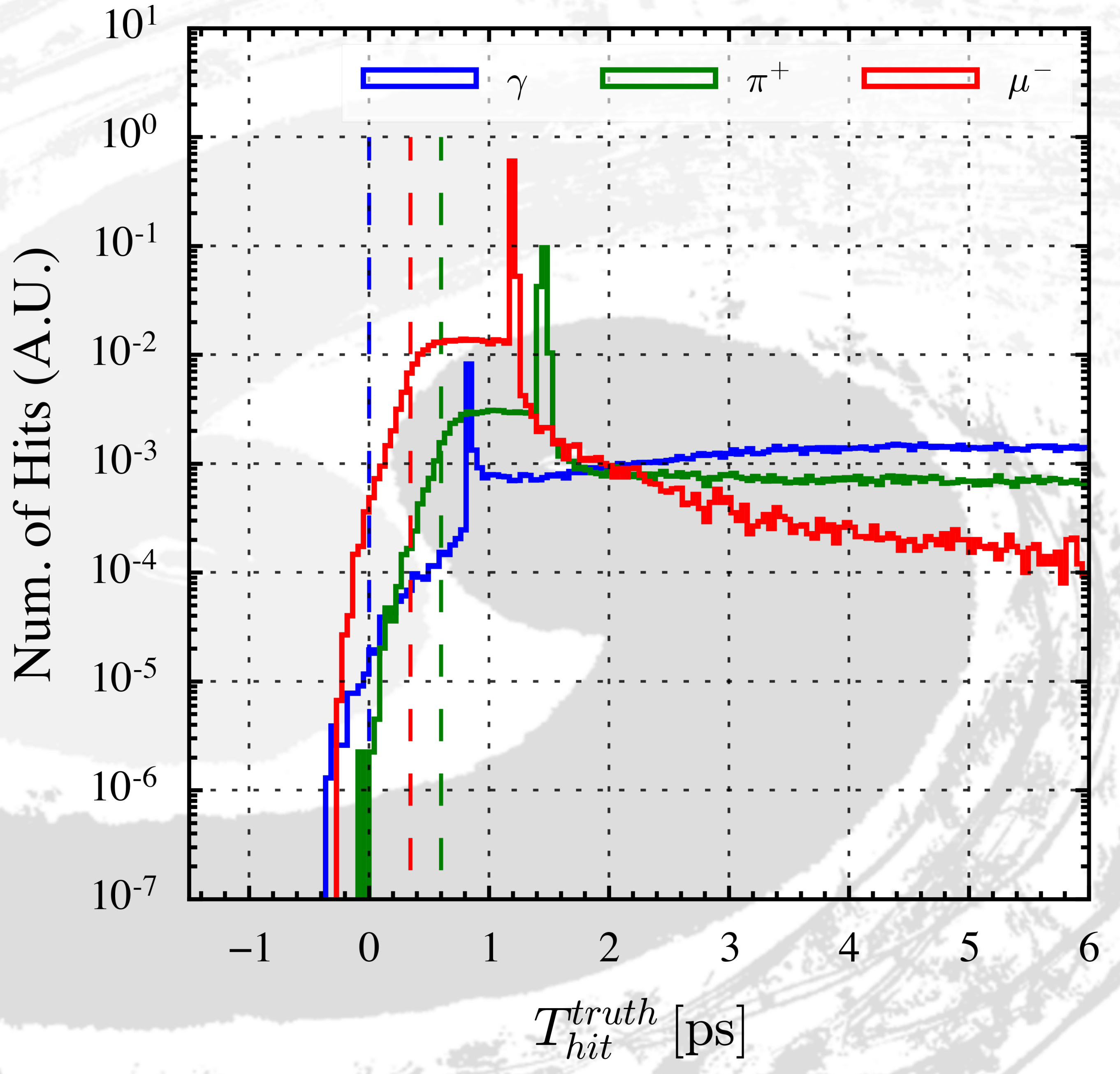


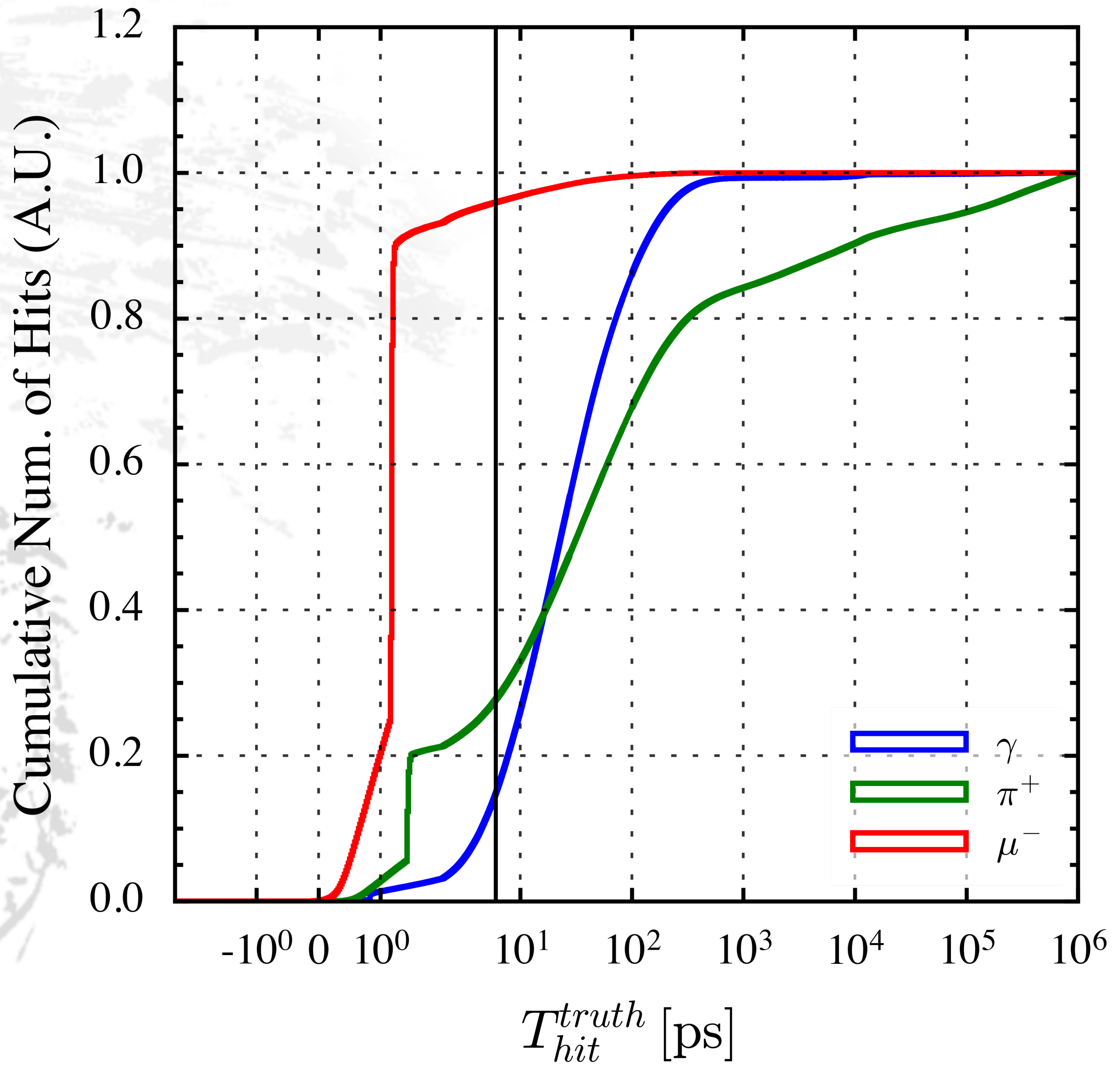
Time distribution of shower hits after digitization



Cumulative distribution of hit time in showers after digitization.

The time definition of cell hits





The shower truth time spectrum of 10 GeV $\gamma/\pi^+/\mu^-$ showers, all normalized to the total number of hits before 1000 ns. The dashed lines donate the expected ToF of the corresponding particles.

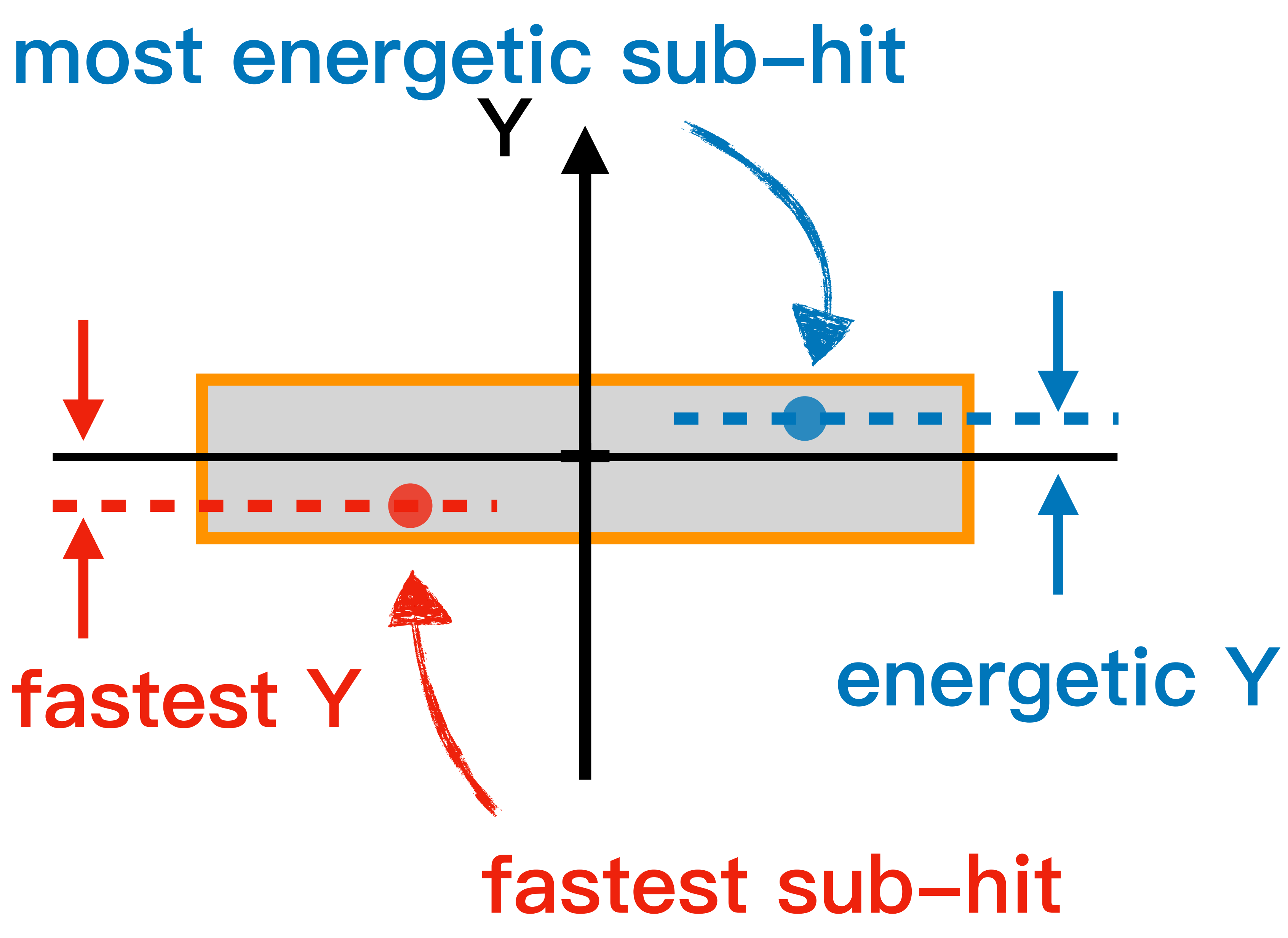
Sub-hit distribution inside cell

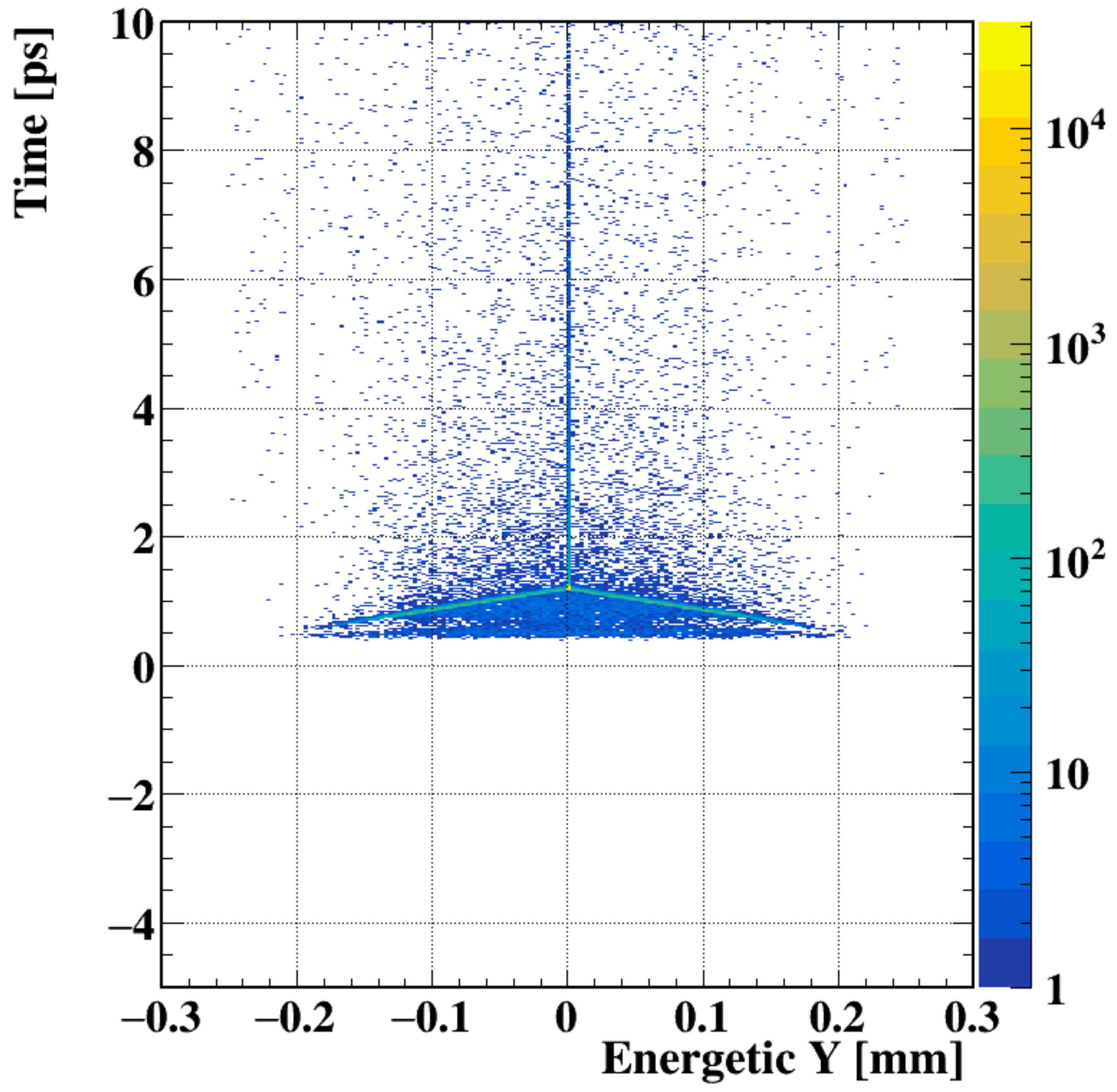
Conventions:

- Hit time (t_{hit}): time of the most energetic sub-hit in the cell

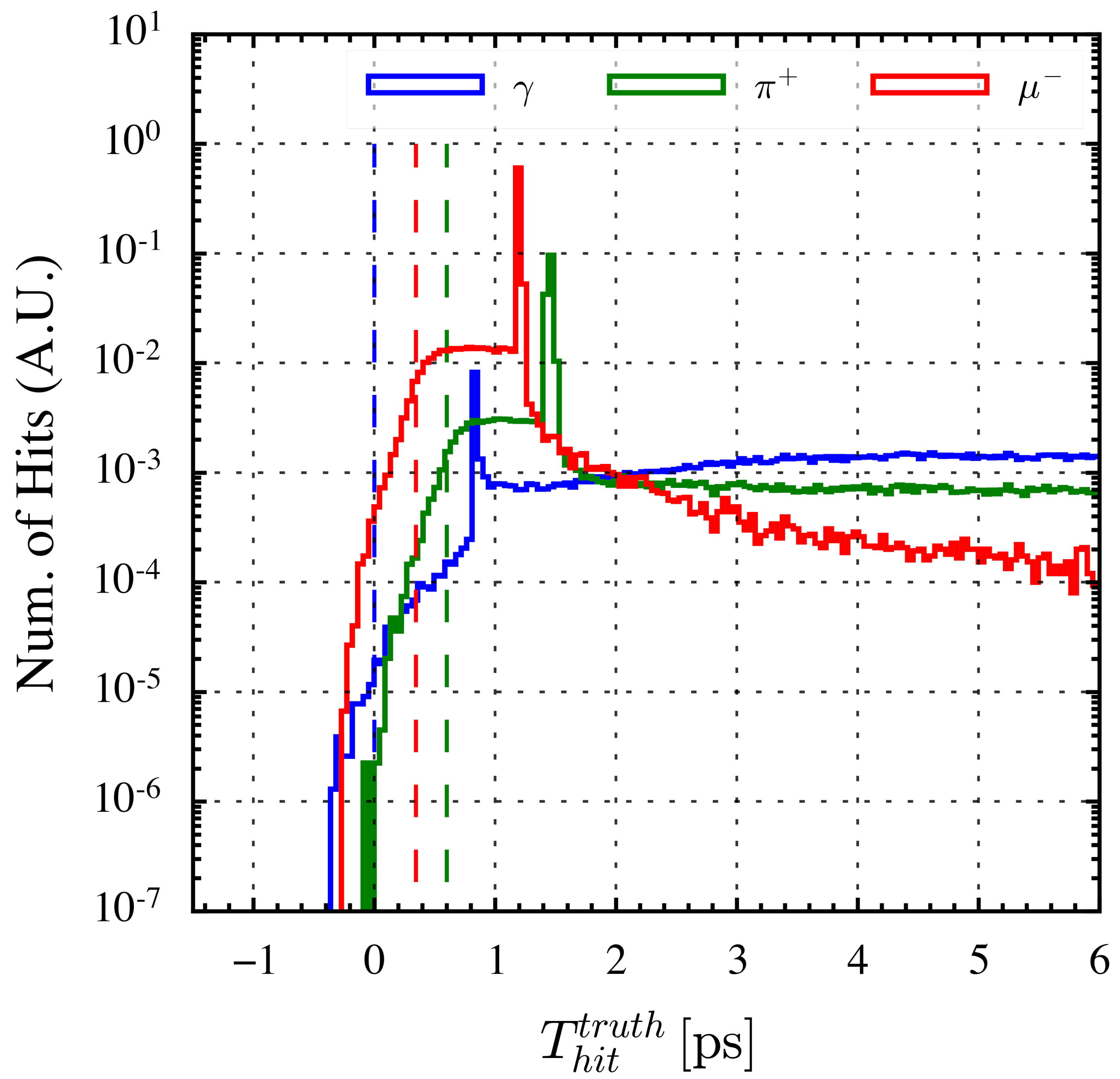
- Hit position: center of the cell

- Shifted time: $T_{shift} = t_{hit} - L_{IP \to hit}/c$
  $L_{IP \to hit}$: distance from the IP to hit position.

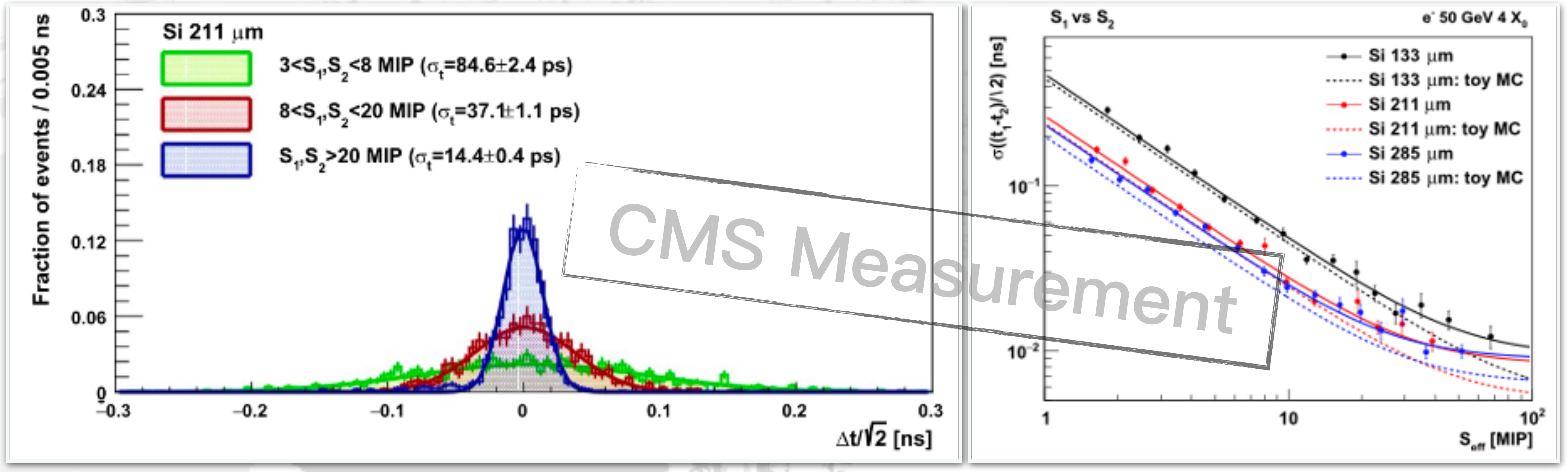




The most energetic sub-hit



Intrinsic hit time resolution



Det 1	Det 2	Fit Function	A [ns×ADC]	C [ns]
Measurement I				
S_1(133-μm)	S_2(133-μm)	$\frac{\sigma(t_1-t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2}S_{\text{eff}}} \oplus C$	0.69 ± 0.01	0.010 ± 0.001
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The current technology level: time resolution of single silicon sensor.

BackUp. time resolution of CMS silicon sensor

Nuclear Instruments and Methods in Physics Research A 859 (2017) 31–36

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

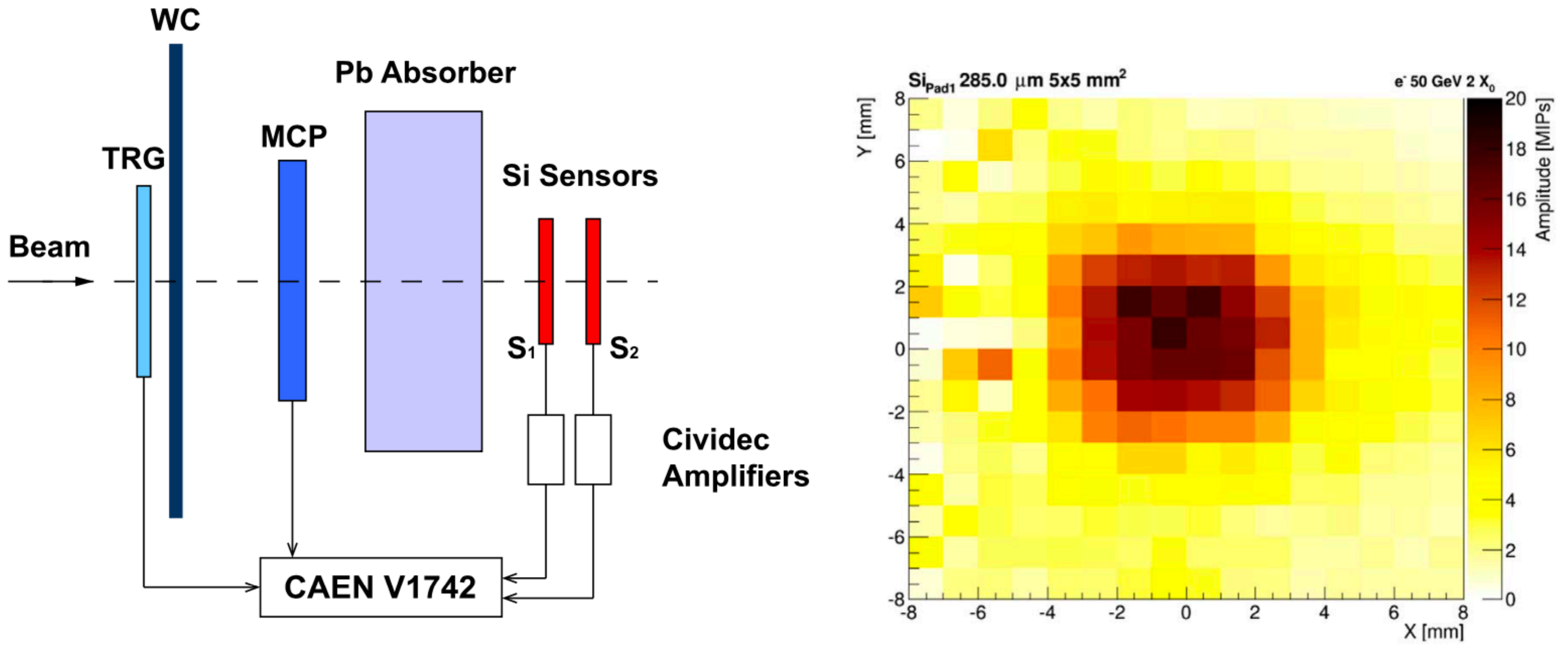


Fig. 1. The schematic of the layout displays the main components and the readout scheme on the left. Downstream of the trigger counter (TRG) and wire chambers (WC), a micro-channel plate (MCP) photomultiplier tube was positioned to provide a timing reference in front of the silicon sensors. Various lead plates were placed in between the MCP and the sensors to evaluate their response to multi-MIPs. A typical response pattern of a 285-μm thick silicon sensor (5×5 mm^2) to 50 GeV electrons when normalized to the MIP signal is displayed on the right. Note that the sensors were placed behind $2X_0$ of lead absorber in this case.

Measurement I: Fig. 8 presents the timing resolution as a function of the effective signal amplitude in units of MIPs and the effective signal-to-noise ratio. We defined the effective signal strength as $S_{eff} = S_1 S_2 / \sqrt{S_1^2 + S_2^2}$. It can be seen that the timing performance improves with increasing signal strength (Fig. 8-left), but that for equal S_{eff}/N the timing performance of the three sensor types is similar (Fig. 8-right). The solid lines in Fig. 8 represent the fits to a form

$$\frac{\sigma(t_1 - t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2} S_{eff}} \oplus C$$

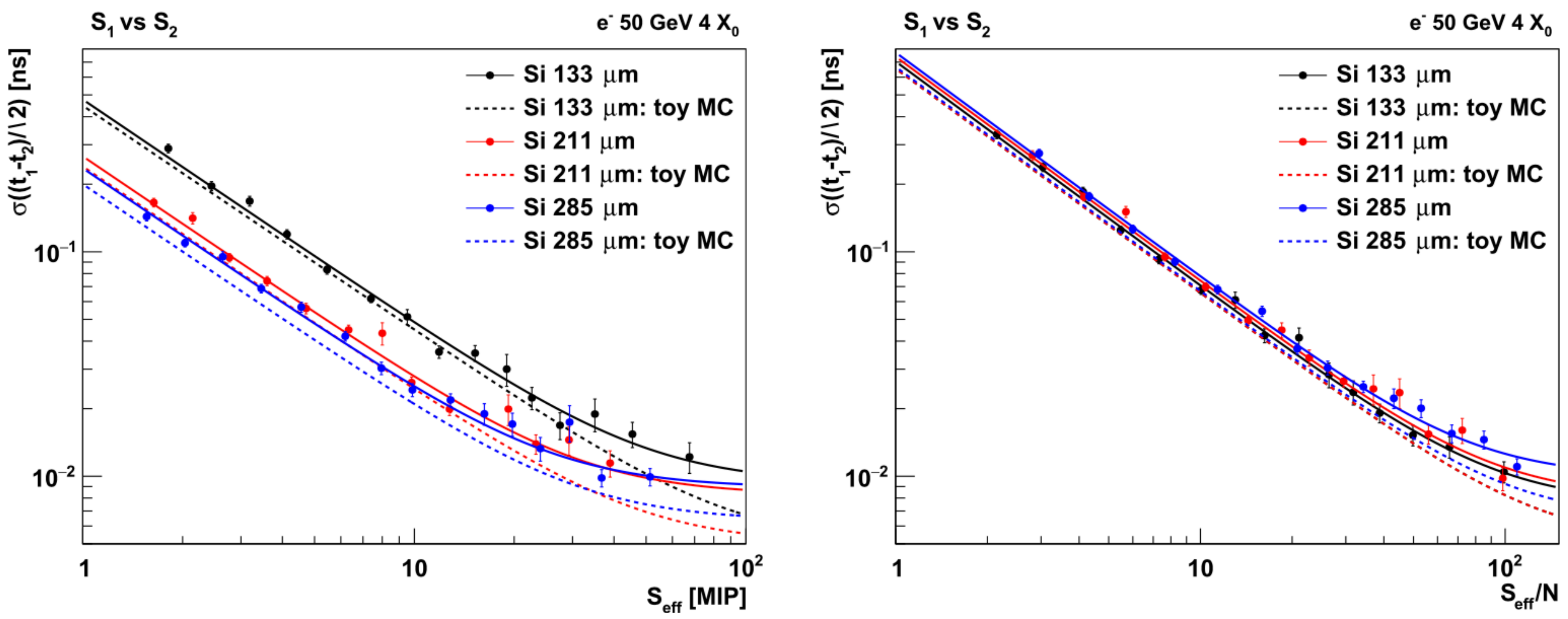
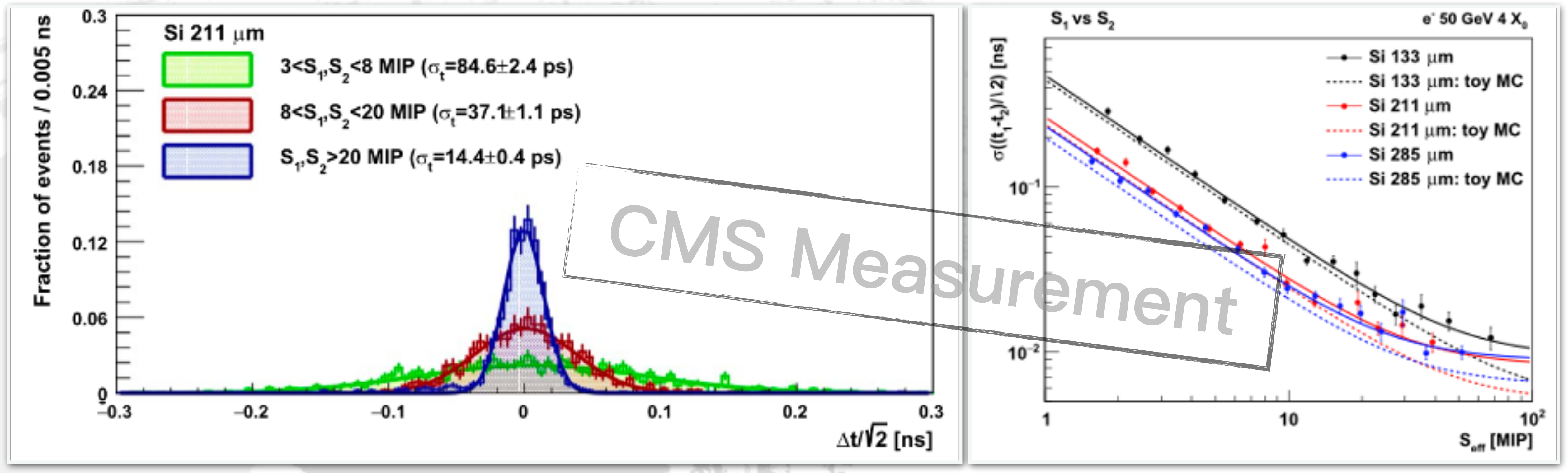


Fig. 8. The timing resolution based on two silicon sensors as a function of the effective signal strength in units of MIPs (left) and as a function of the signal-to-noise ratio (right). The fitted resolution functions with a noise (*A*) and a constant term (*C*) are also shown as solid lines. The dashed lines represent toy simulation results (see text for details).

N. Akchurin, etc, *On the Timing Performance of Thin Planar Silicon Sensors*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **859**, 31 (2017).

Definition of perfect cluster



Det 1	Det 2	Fit Function	A [ns×ADC]	C [ns]
Measurement I				
S_1(133-µm)	S_2(133-µm)	$\frac{\sigma(t_1-t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2}S_{\mathrm{eff}}} \oplus C$	0.69 ± 0.01	0.010 ± 0.001
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S_1(285-µm)	S_2(285-µm)		0.34 ± 0.01	0.010 ± 0.001

The current technology level: time resolution of single silicon sensor.

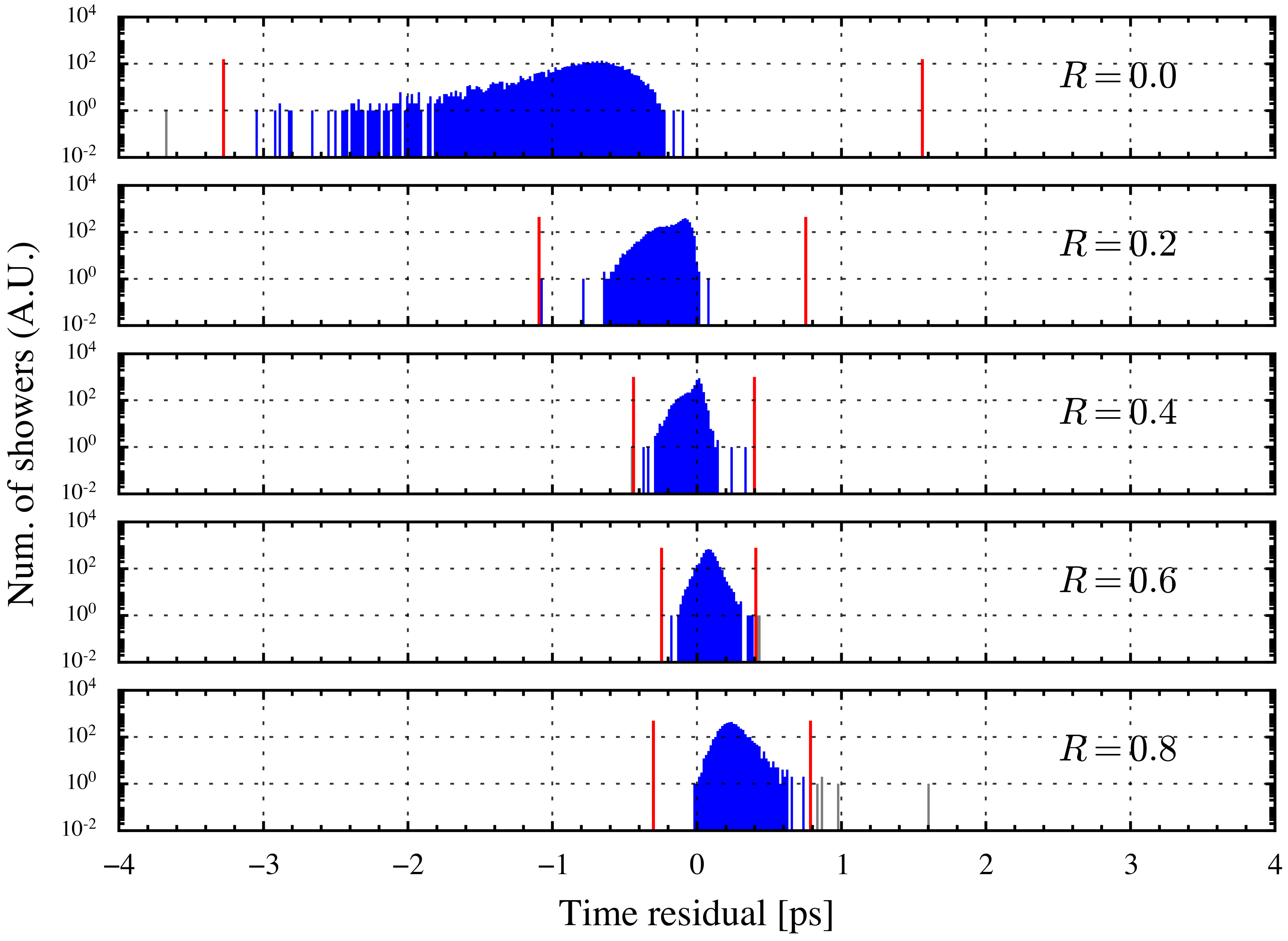
4.1. Algorithm & performance: Definition of bias & resolution

Selected the **single particle events** where the primary particle reached ECAL and at least 1 cluster is reconstructed.

Perfect cluster: include **all of hits** in the event.

Define the following concept to evaluate the timing performance for **perfect clusters**:

- **Truth** cluster TOF: fastest hit time in the shower
- Estimation **bias**: $\Delta T = mean\{T_{reco} - T_{exp}(p)\}$
- Estimation **resolution**: $\sigma_T = StdDev\{T_{reco} - T_{expect}(p)\}$



The distribution of the difference between reconstructed shower time and the true time in the 10 GeV π^{+} sample. To remove the outliers, a time residual window (red lines) is defined as $[Q_2 - 5(Q_3 - Q_1), Q_2 + 5(Q_3 - Q_1)]$, where Q_1, Q_2 and Q_3 are the three quartiles of the distribution.

Set a $\pm 5\sigma_{total}$ window around the mean value, to remove the extremely abnormal events.

Section 5.
Further exploration:

What's the cluster time resolution with:

A: Impact of realistic clustering

Arbor improves time resolution by ~20%/40% for EM/hadronic cluster.

A: different hit time resolution

linear!

A: different #timing layers

$$\sigma(T_{clus}) \propto 1/\sqrt{N_{layer}}$$

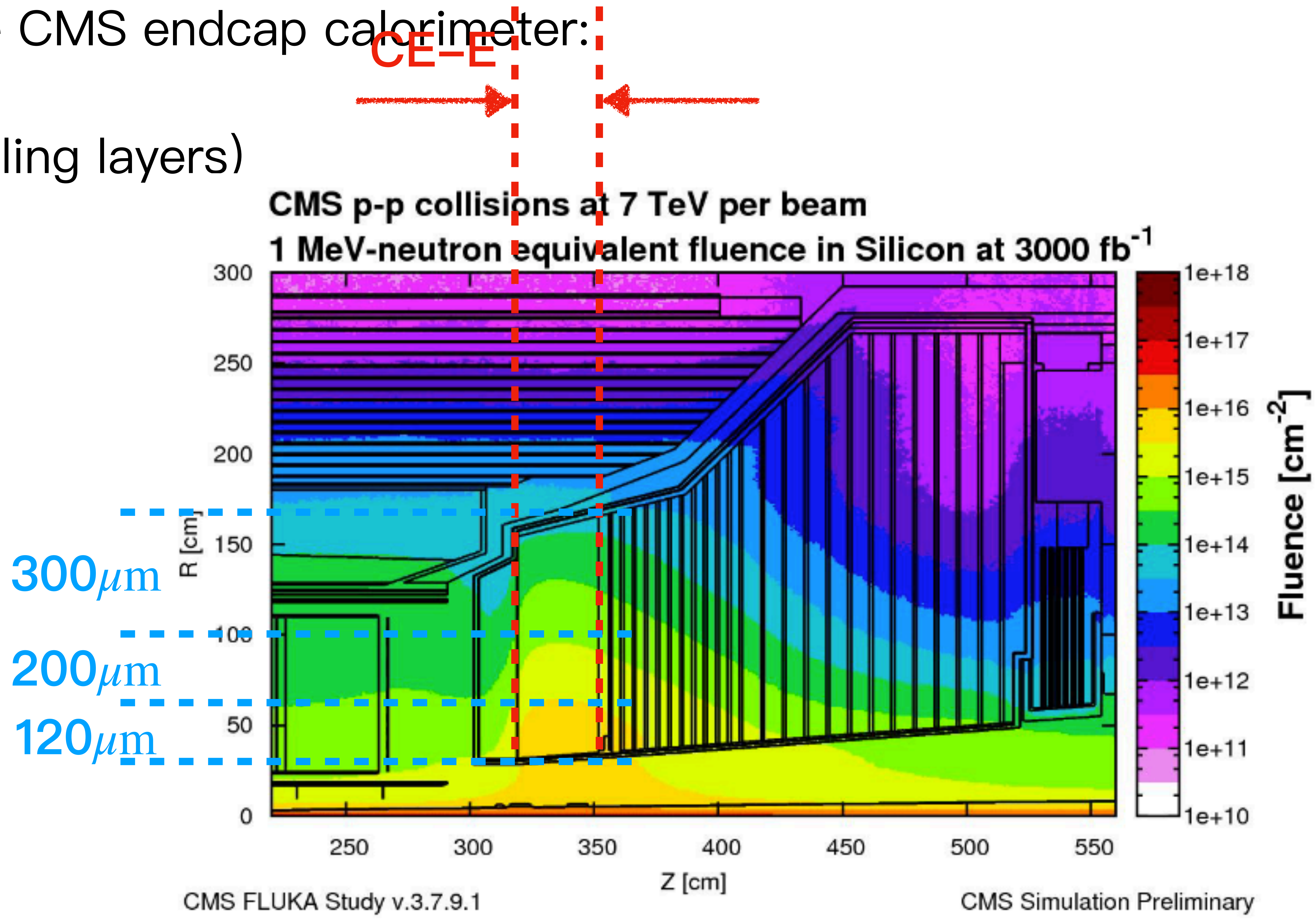
Q: CMS HGCAL

CMS HGCAL

The electromagnetic compartment of the CMS endcap calorimeter:

WCu absorber + Silicon sensor (28 sampling layers)

Depth: $26\ X_0\ (1.7\lambda)$



Active thickness (μm)	**300**	**200**	**120**
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	≈180	≈100	≈70
Smallest inner radius (cm)	≈100	≈70	≈35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

Silicon sensors in CE-E and CE-H layers having only silicon sensors, showing thickness of active silicon, cell size, and S/N for a MIP before and after an integrated luminosity of 3000 fb−1.

The Phase-2 Upgrade of the CMS Endcap Calorimeter. in CERN Document Server (2017).

5.4. Alternative estimator

Time resolution of photons with traverse momentum of 5 GeV.

Radius range (cm)	30-70	70-100	100-180
p (pt = 5 GeV)	23.4 - 53.5 GeV	16.7 - 23.4 GeV	10.2 - 16.7 GeV
Reference shower time resolution (ps)	< 5 ps	6 - 6 ps	6 - 7 ps
Active thickness (μm)	120	200	300
Noise term A (ns * MIP) [1]	0.69	0.38	0.34
Constant term C (ns)	0.010	0.009	0.010
Thickness correction from intrinsic hit time resolution	1.8	1	0.9
Cell size correction	~ 1	< 1	< 1
Shower timing resolution on CMS (ps)	< 9 ps	5 - 6 ps	5.4 - 6.3 ps

[1] The noise term and constant term are from: N. Akchurin, etc, On the Timing Performance of Thin Planar Silicon Sensors, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 859, 31 (2017).

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linear!

A: different #timing layers

$$\sigma(T_{clus}) \propto 1/\sqrt{N_{layer}}$$

A: CMS HGCAL

$\sigma(T_{cluster}) : 5 \sim 9$ ps for photon with $p_T = 5GeV$