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

Shower Time Spectrum in Calorimeter

Yuzhi Che, Manqi Ruan

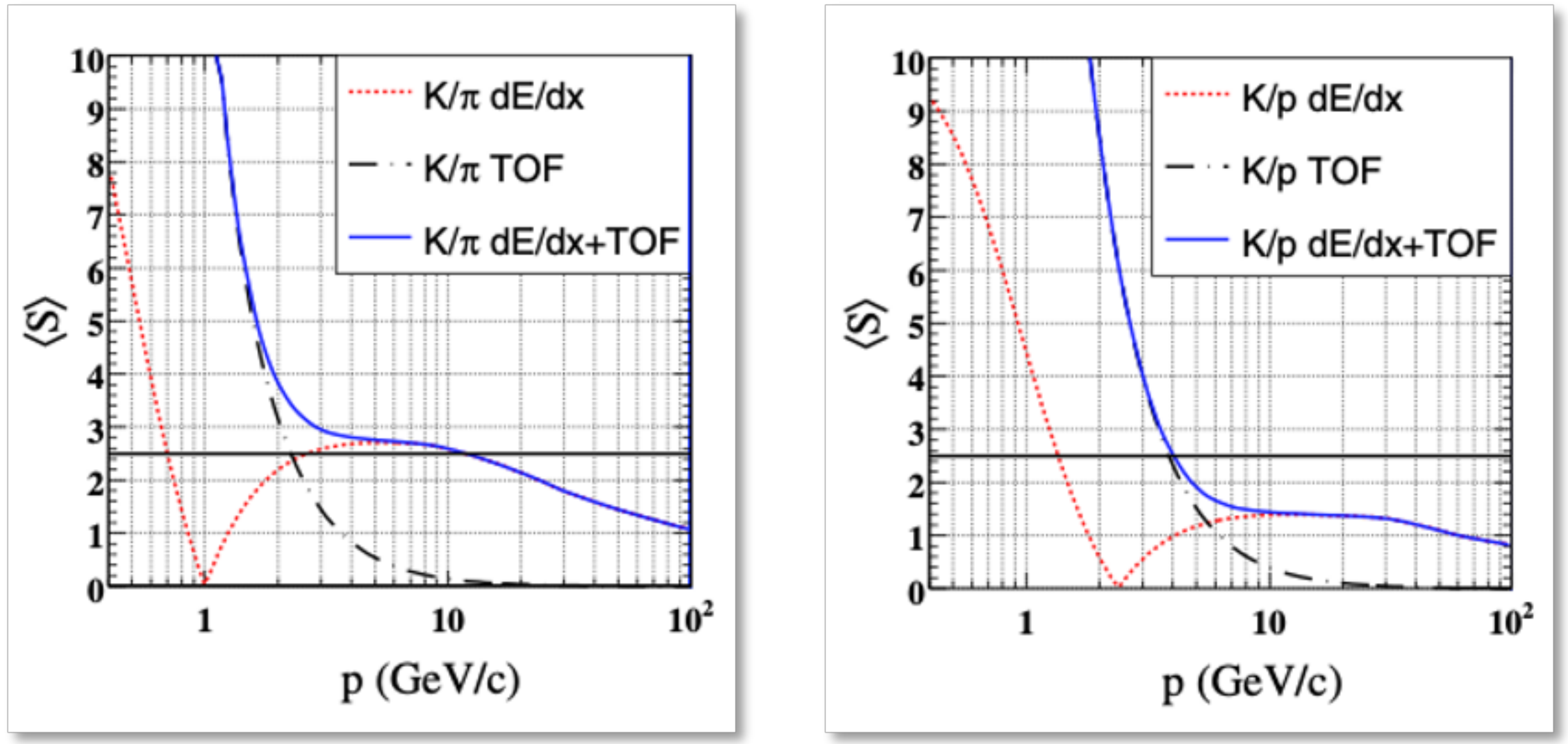
Institute of High Energy Physics, Chinese Academy of Sciences

The 2022 International Workshop on the High Energy Circular Electron Positron Collider
Oct 24, 2022

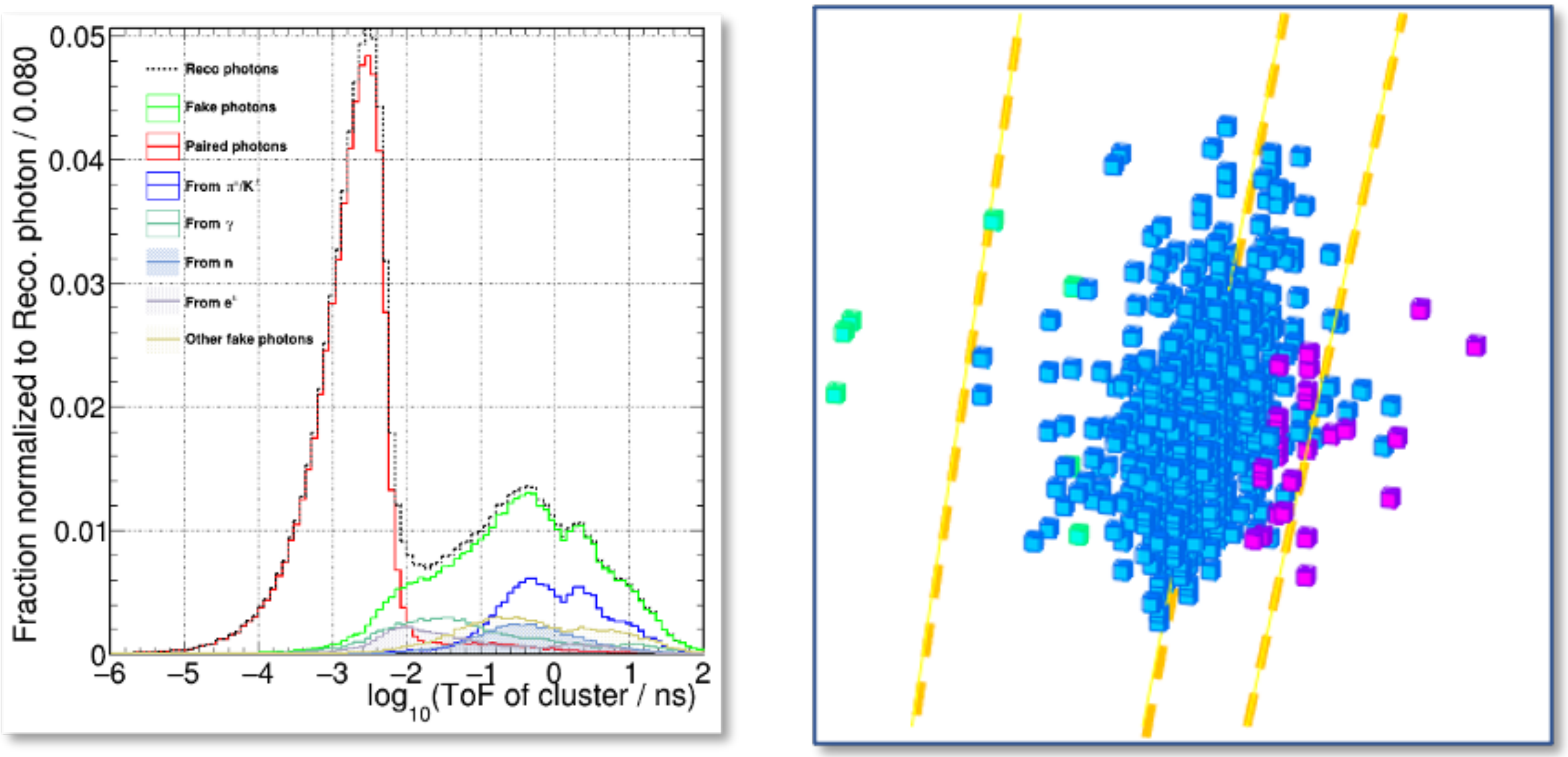
1. Motivation

- **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]



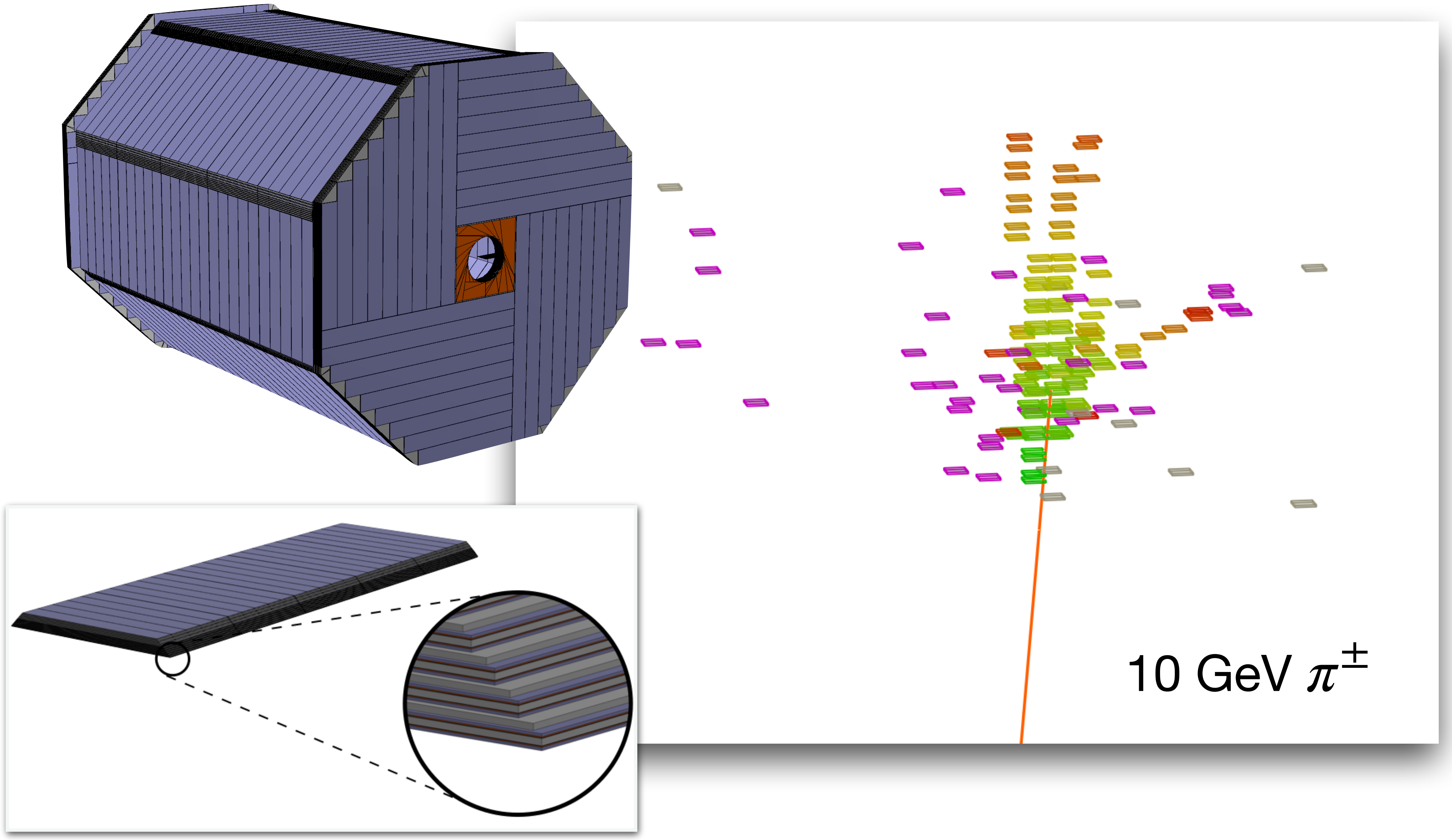
Truth cluster TOF distribution of real photon and fake photon clusters.

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).

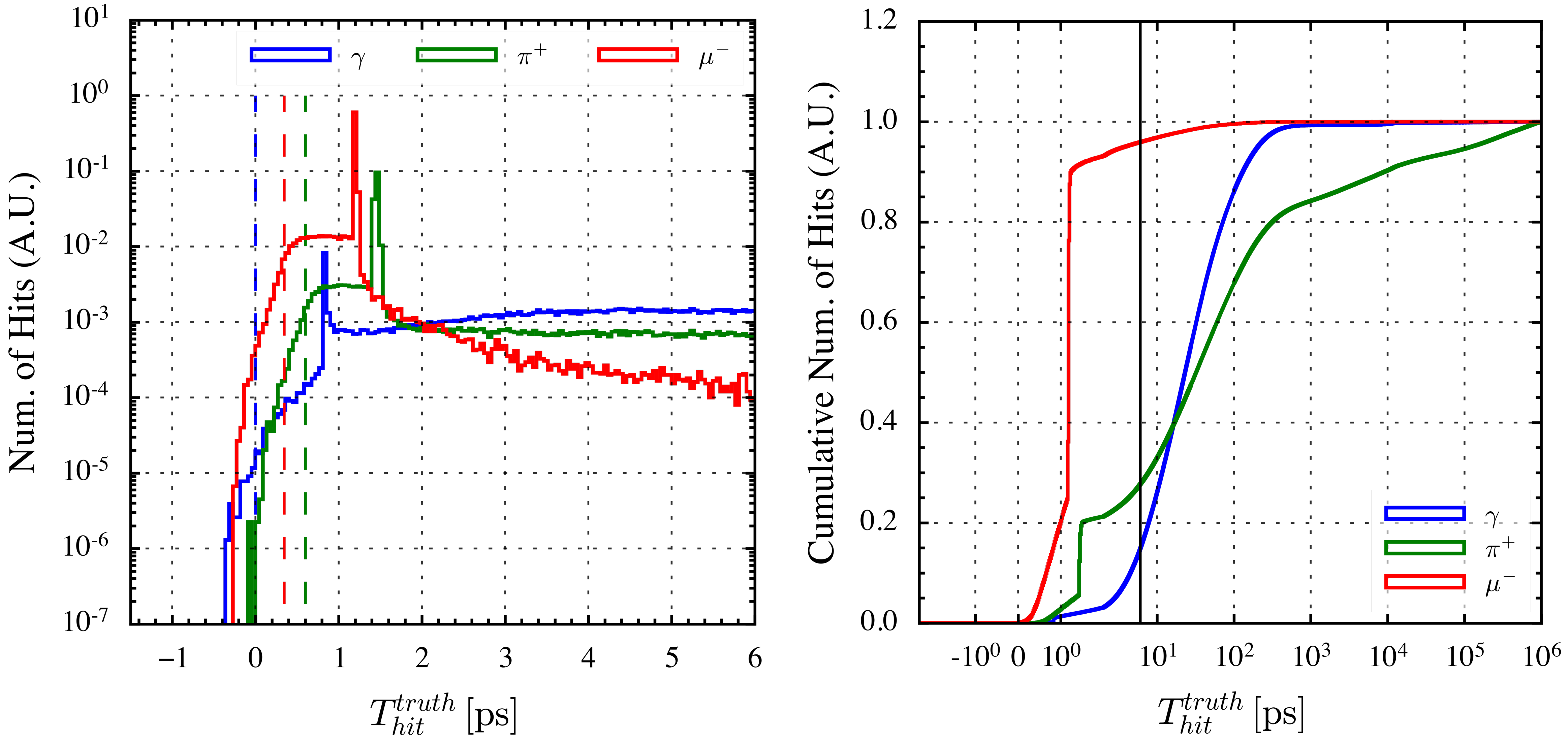
Content

Calorimeter response: Truth level

- **CEPC baseline Si–W ECAL**
- **B Field** = 0
- **Sample:** Single particle with momentum 0 ~ 30 GeV and direction (x,y,z) = (0, 1, 0).



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

Calorimeter response: 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:

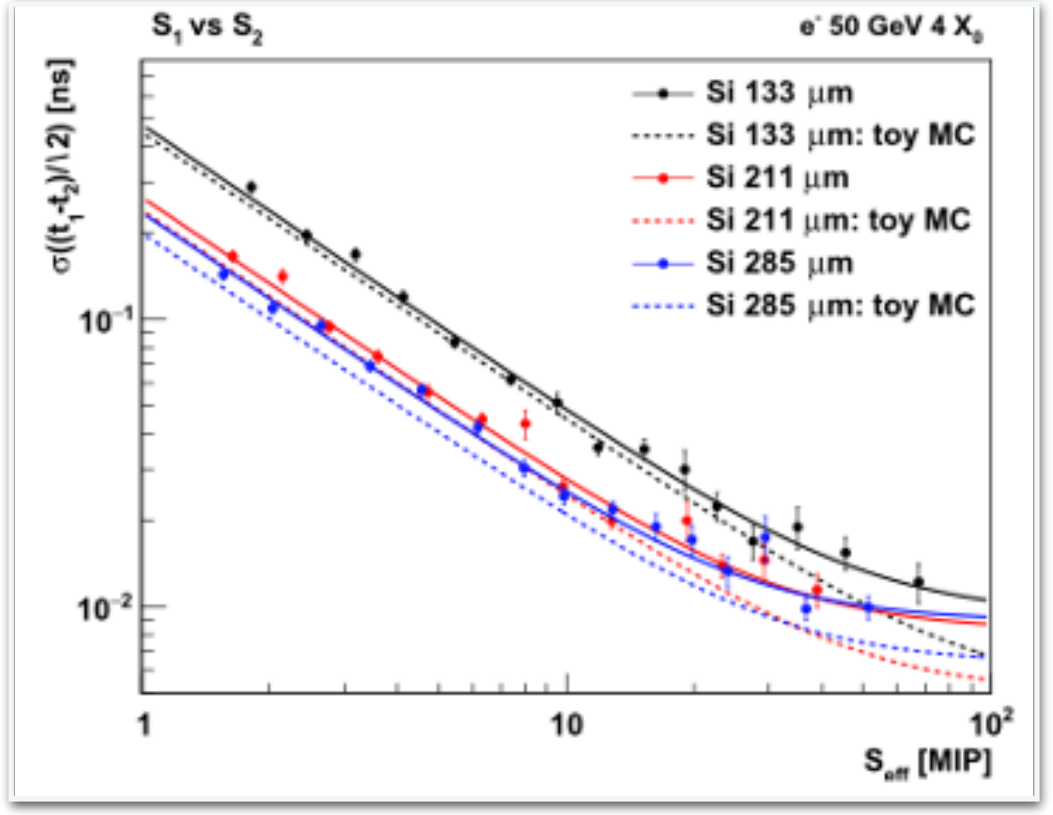
A: noise term, C: constant term, S: effective signal strength (by MIP) $S_{eff} = S_1S_2/\sqrt{S_1^2 + S_2^2}$,

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

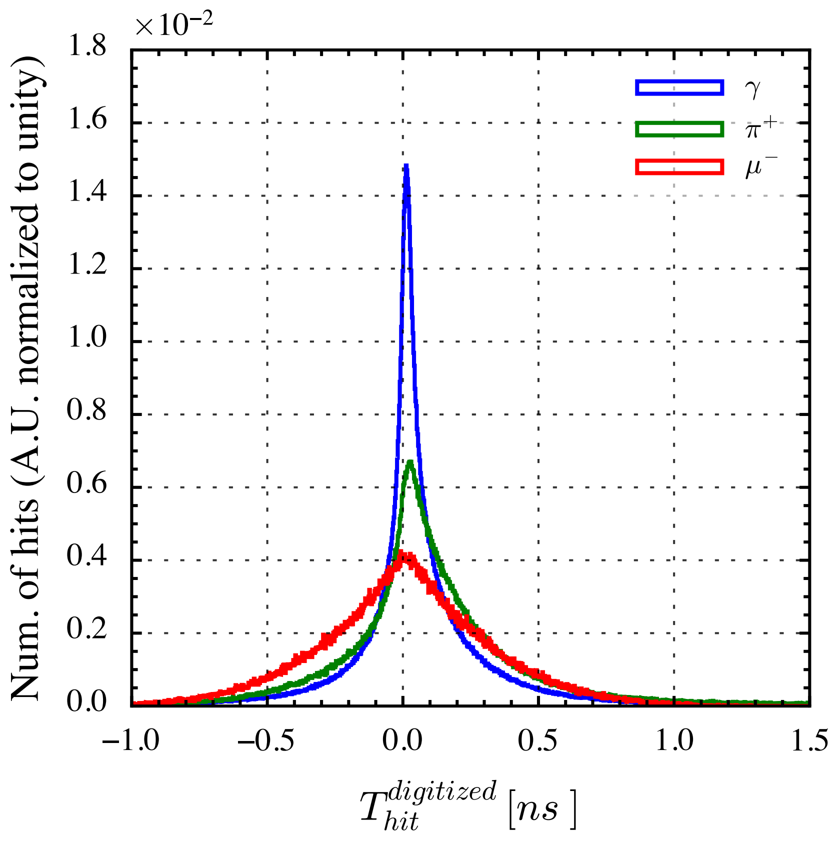
Det 1	Det 2	Fit Function	A [ns×ADC]	C [ns]
Measurement I				
S_1(133-µm)	S_2(133-µm)	$\frac{\sigma(t_1 - t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2}S_{eff}} \oplus C$	0.69 ± 0.01	0.010 ± 0.001
S_1(211-µm)	S_2(211-µm)		0.38 ± 0.01	0.009 ± 0.001
S_1(285-µm)	S_2(285-µm)		0.34 ± 0.01	0.010 ± 0.001

Hit time digitization in simulation:

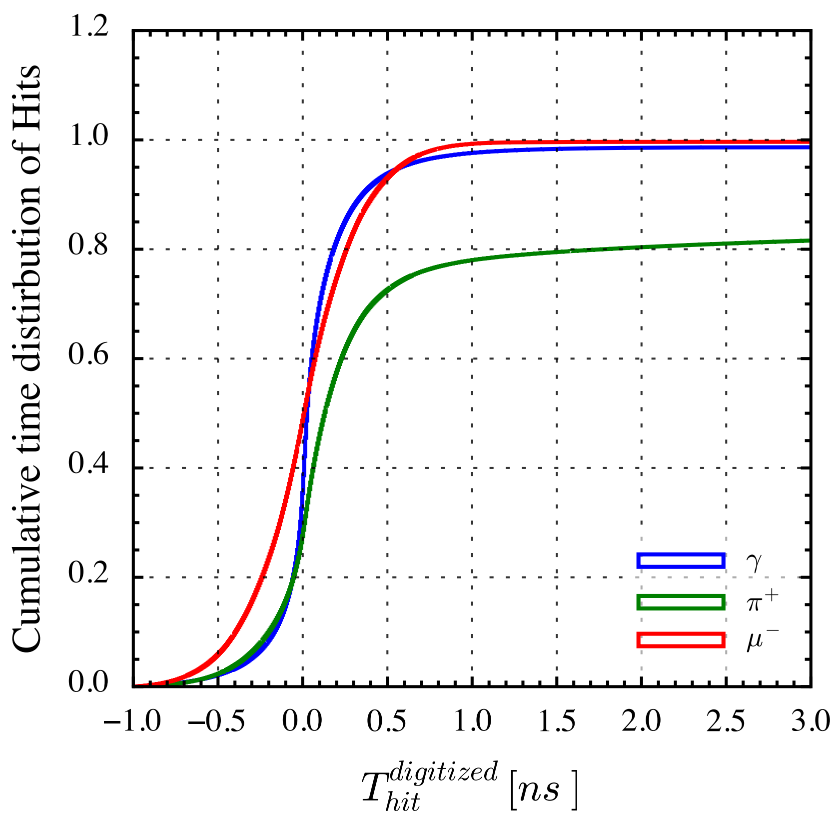
- Record the truth level ECAL hits time.
- Smear the hits time with a Gaussian distribution,
  $T_{hit}^{digitized} = Gaus\left(T_{hit}^{truth}, \sigma_{T_{hit}}\right)$,
  $$\sigma_{T_{hit}} = \sqrt{\left(\frac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}.$$
  where E_{hit} is hit energy before digitization by unit of MIP.



Experimental measurement of timing resolution of the CMS silicon diode.



Time distribution of shower hits after digitization



Cumulative distribution of hit time in showers after digitization.

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).

Section 2.
ToF reconstruction:

Assuming:

- All of the hits give a time (t) and a resolution (σ_t).

Question:

- How to combine the hit time information,
  - to evaluate the cluster time,
  - as accurate as possible?

Discussion:

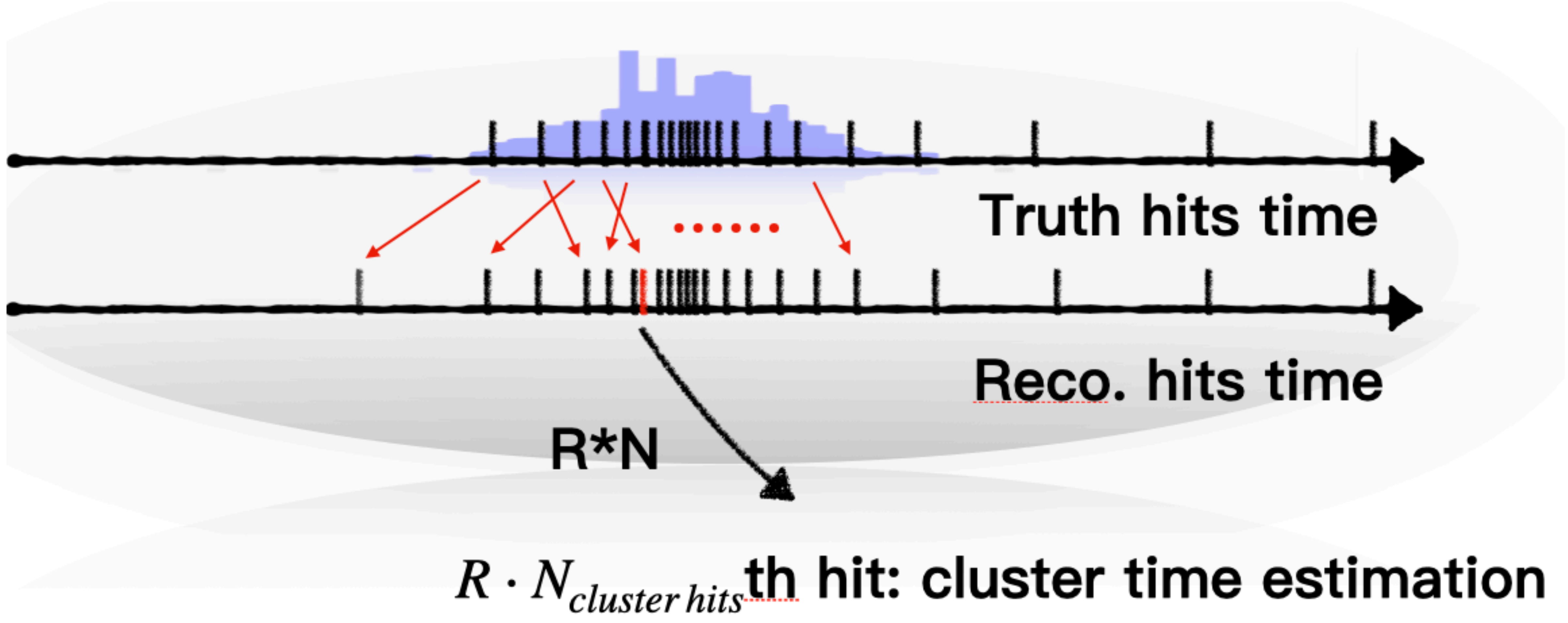
- Scaling behavior?

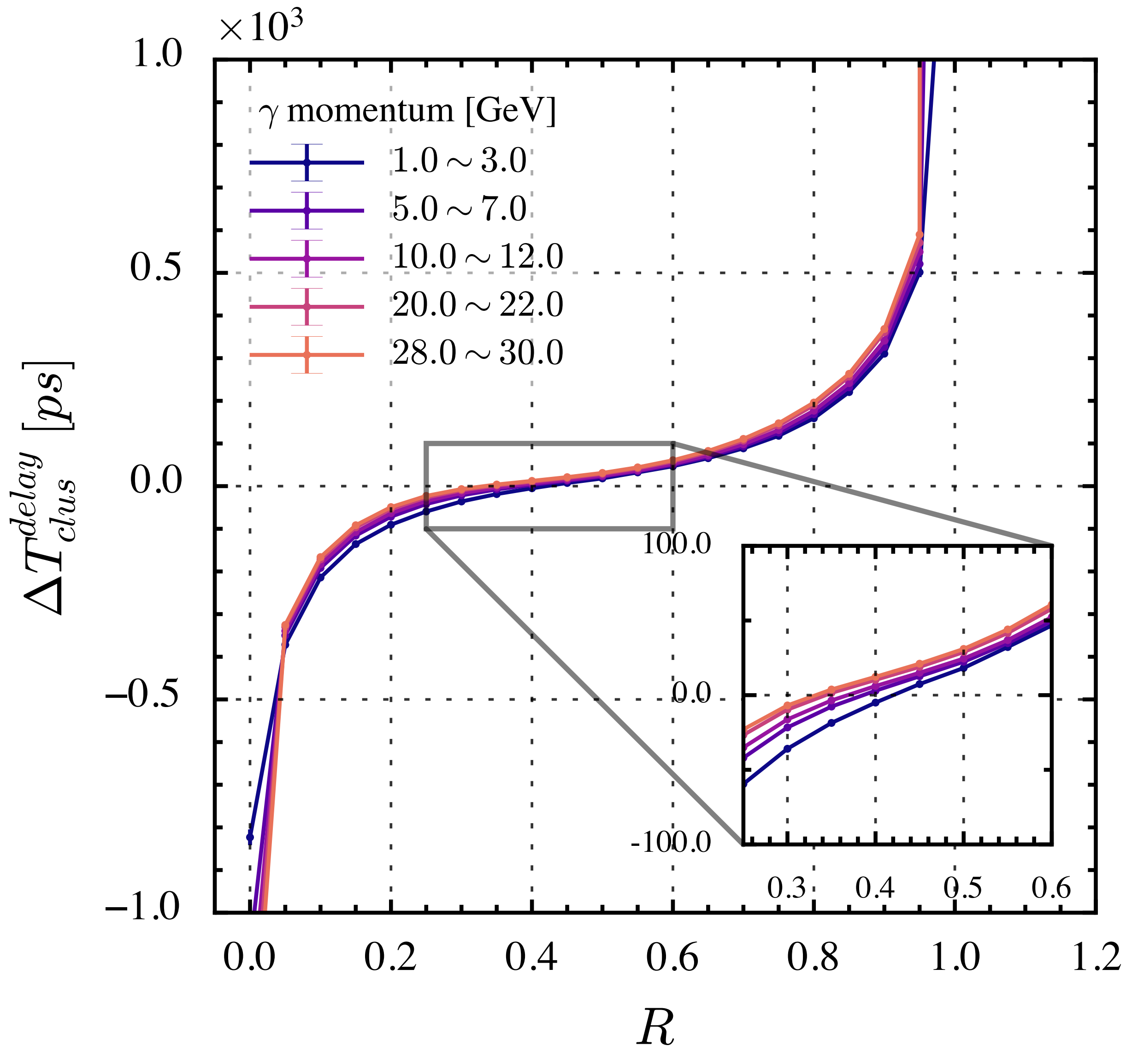
A brief cluster TOF estimator:

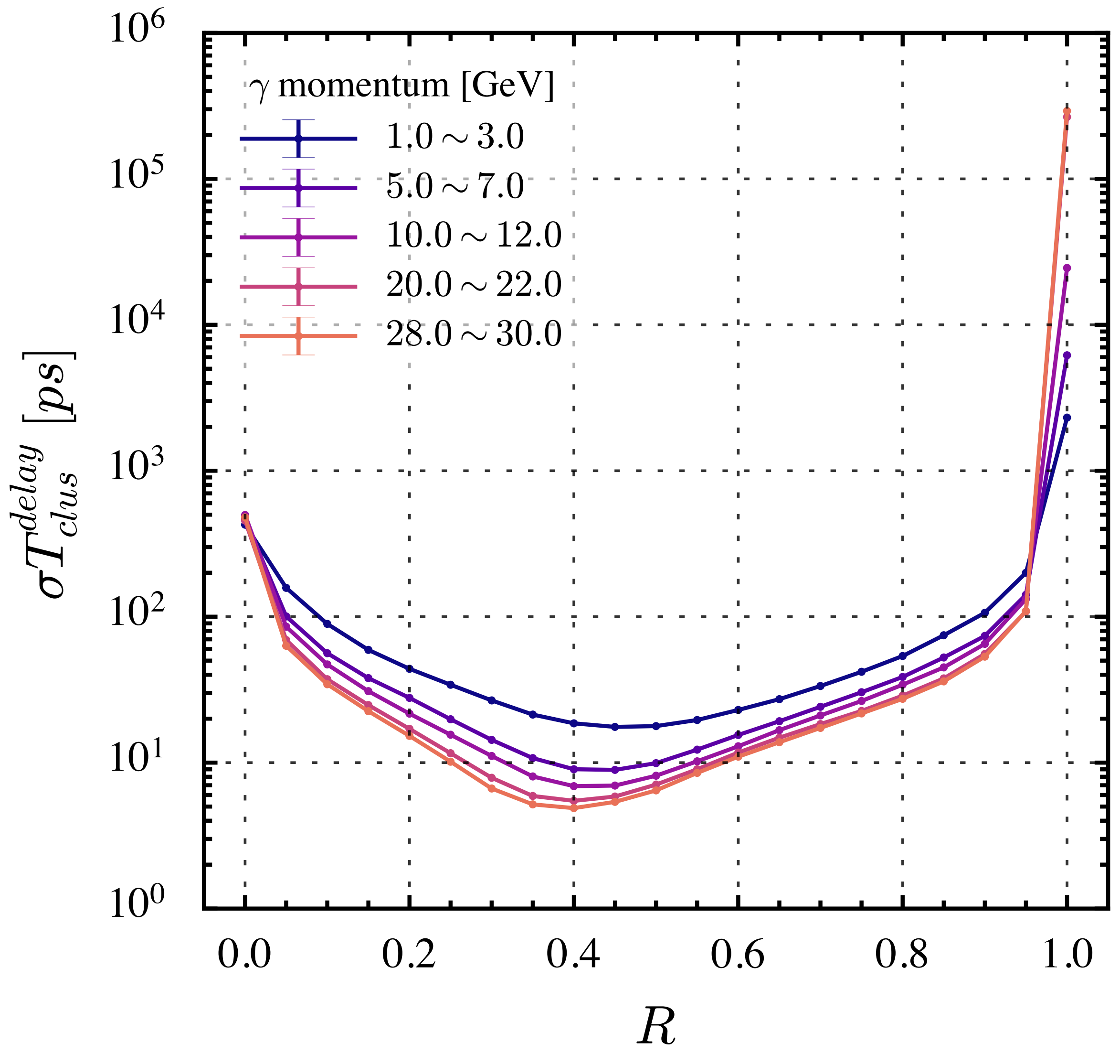
1. Record the digitized ECAL hits
2. Sort the hits according to the digitized time
3. Define a fraction: **R**
4. Select the fastest $(R \cdot N_{cluster\,hits})$th hit, and take its time as the cluster TOF evaluation value.

Optimize R:

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



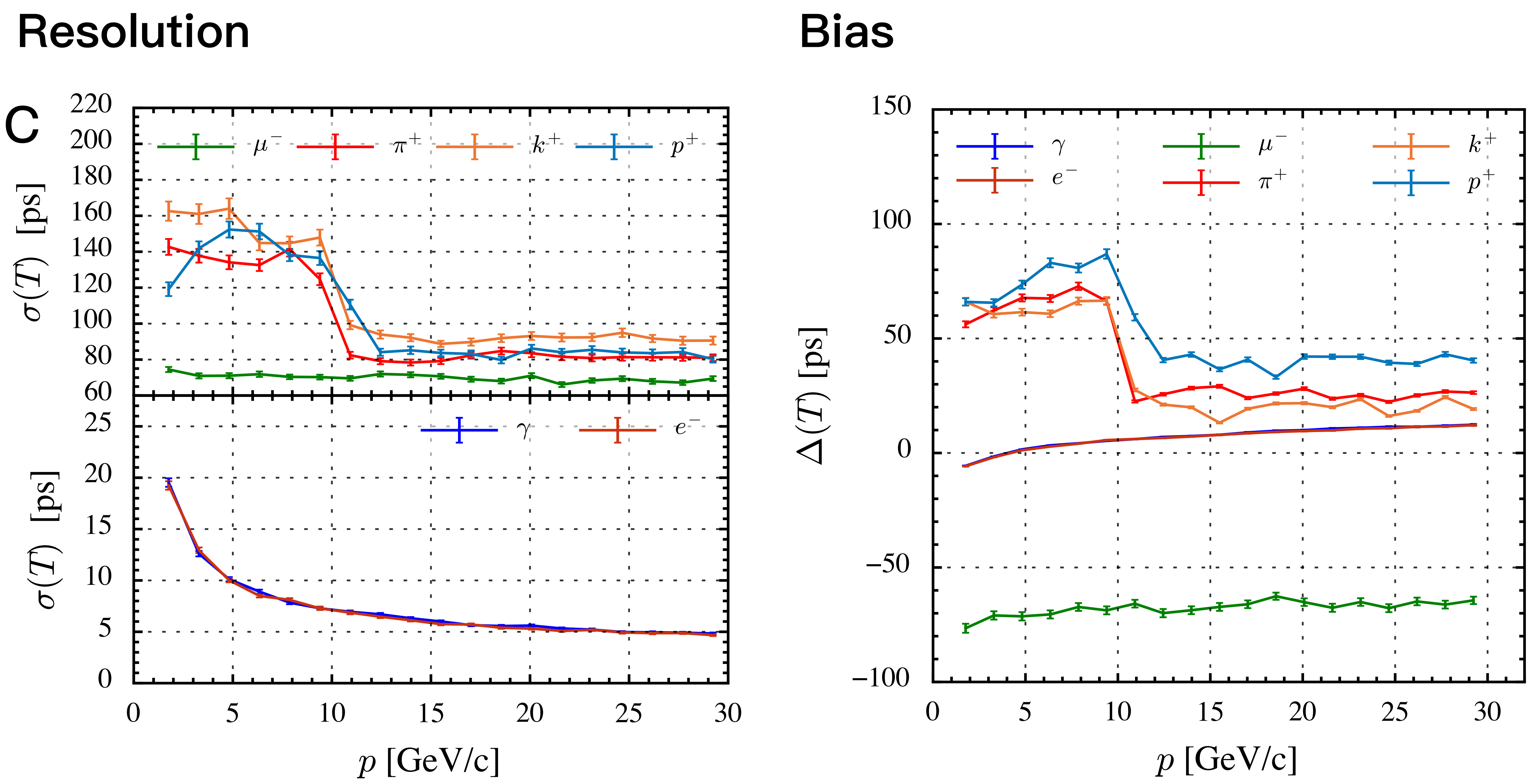




The estimation (left) bias and (right) resolution versus fraction R for perfect photon clusters.

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 $K^{\pm}/\pi^{\pm}/p^{\pm}$.

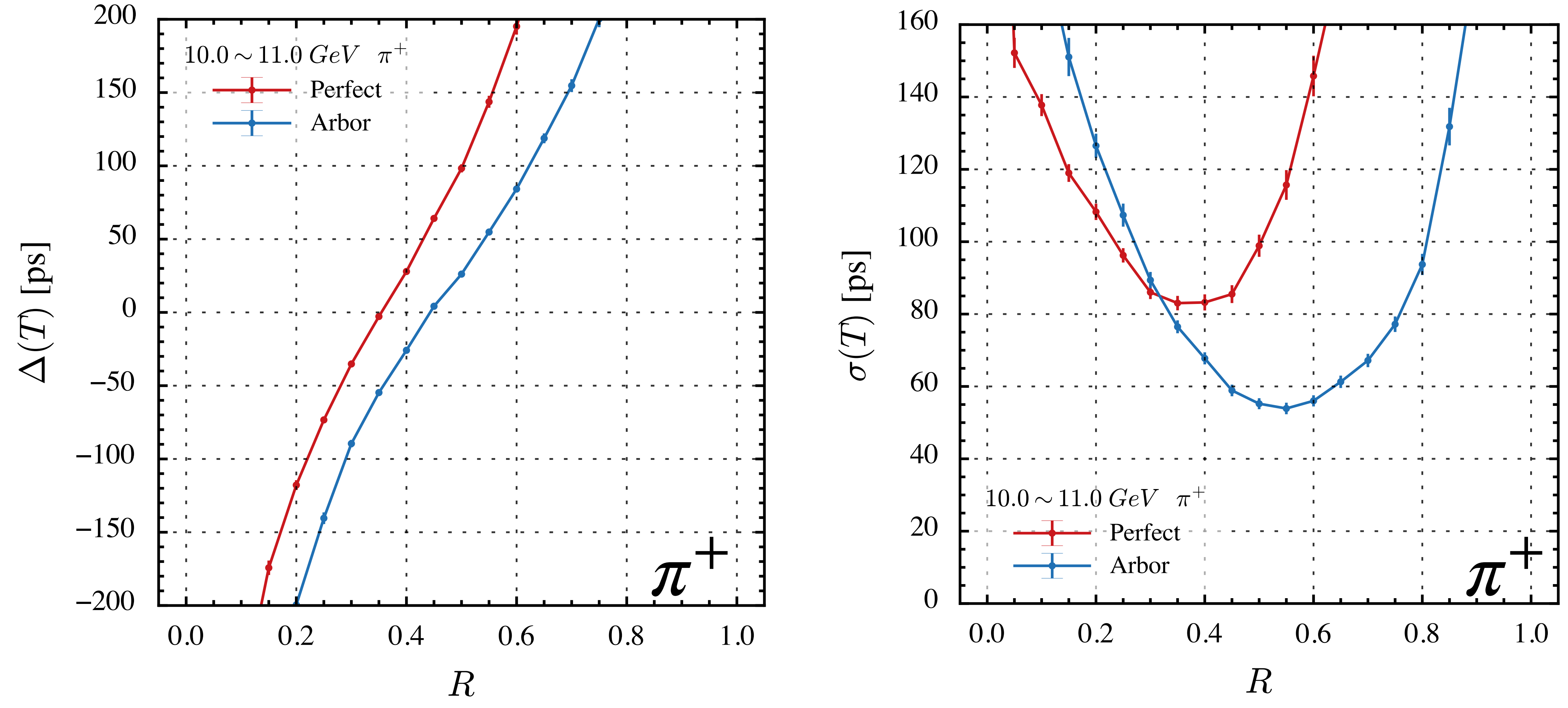


The (left) bias and (right) resolution of perfect $\gamma/e^{-}/\mu^{-}/\pi^{+}/K^{+}/p^{+}$ clusters versus the MC truth incident momentum.

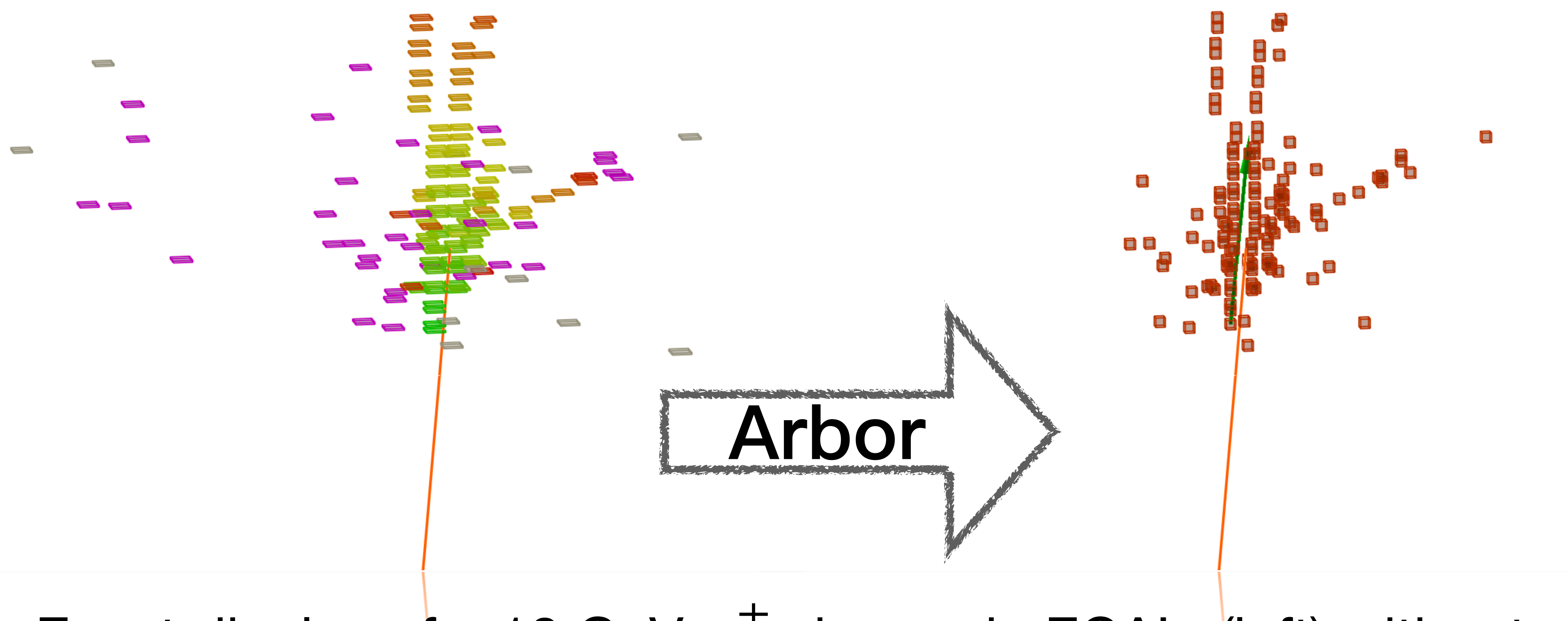
Physics list: QGSP_BERT_HP

Influence of the Arbor clustering

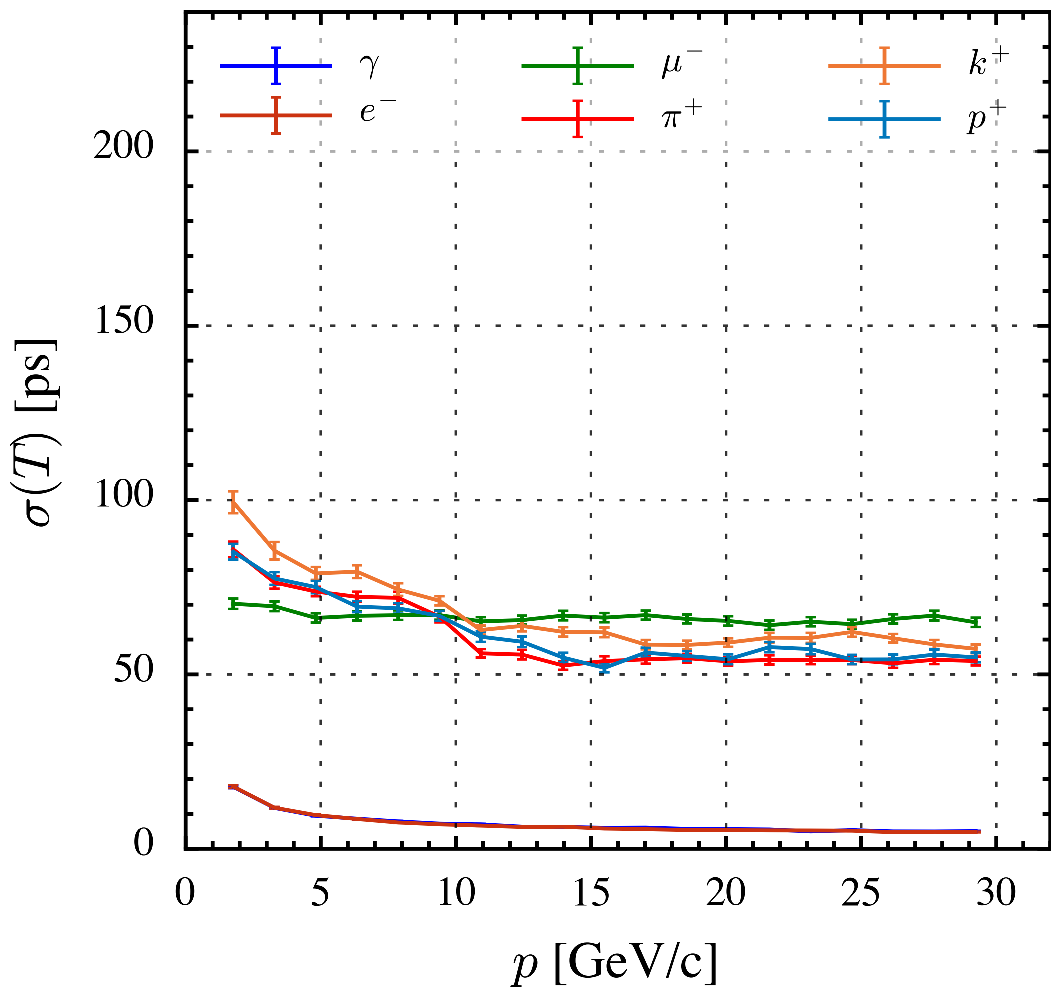
- **Arbor clustering** module partly removes the slow component of clusters, and improves the hadronic cluster time resolution by a factor ~ 1.5



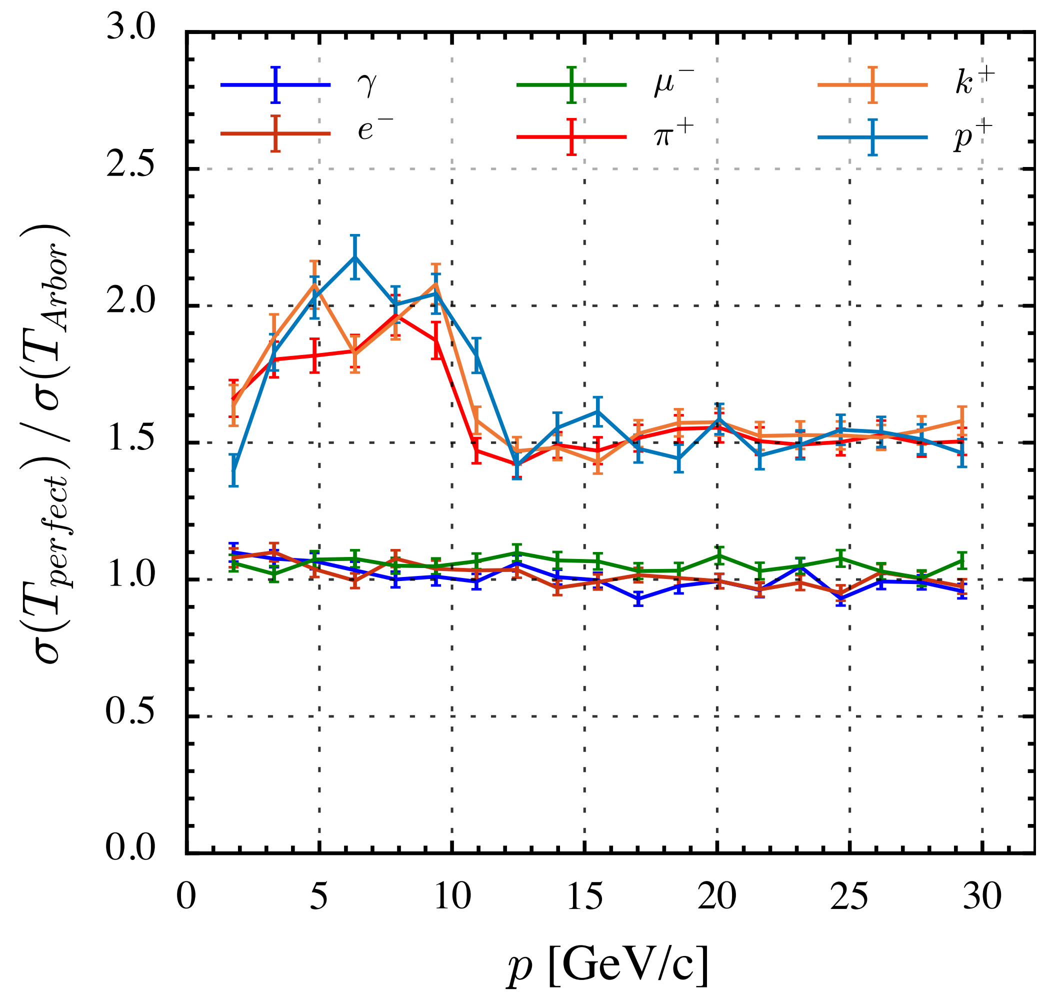
Estimator (left) bias and (right) resolution comparison between Arbor and perfect pion clusters.



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.



Time resolution for Arbor clusters



The time resolution ratio of perfect clusters over Arbor clusters.

Intrinsic hit resolution

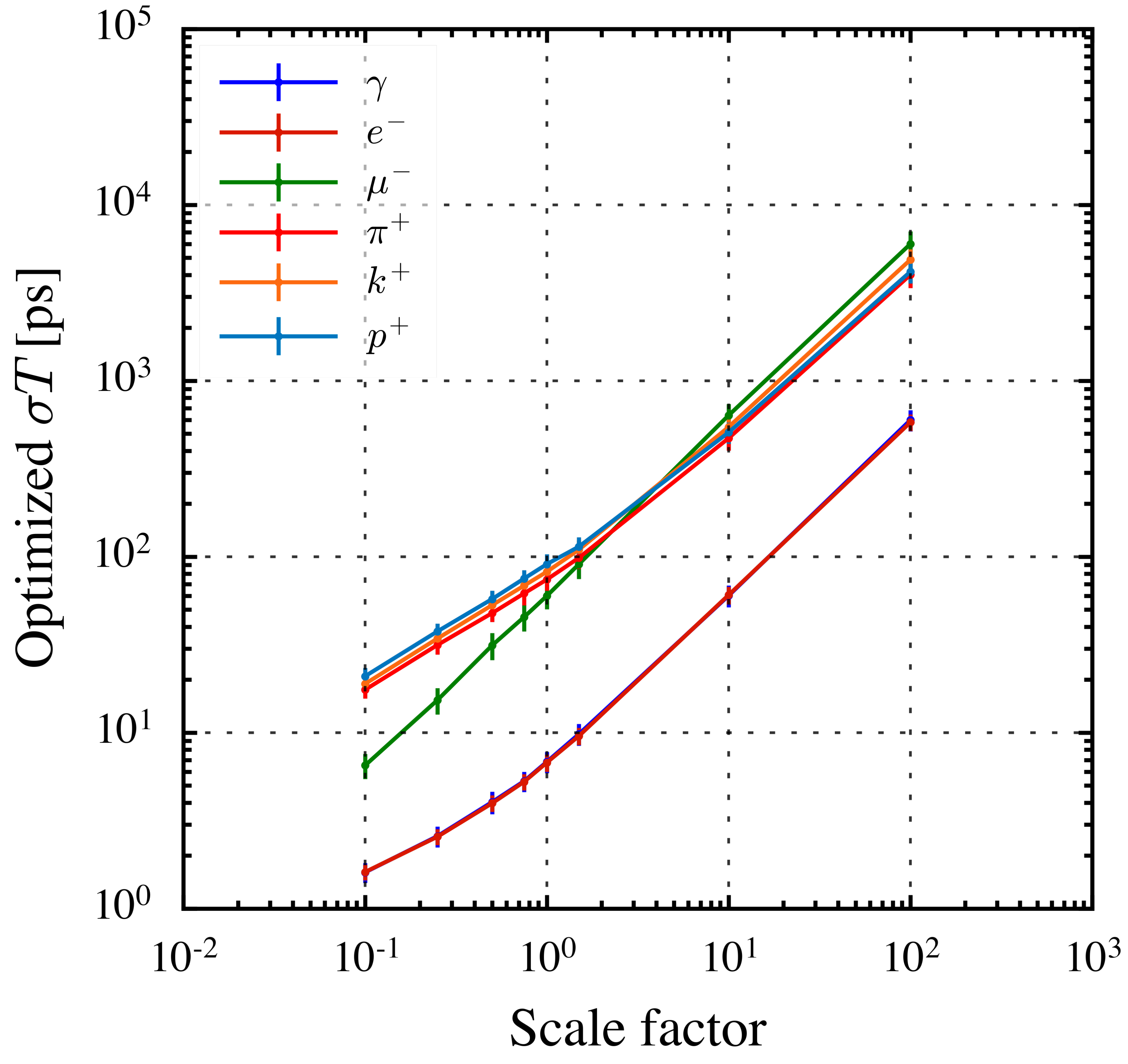
- Scale the intrinsic hit resolution:

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

, 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.

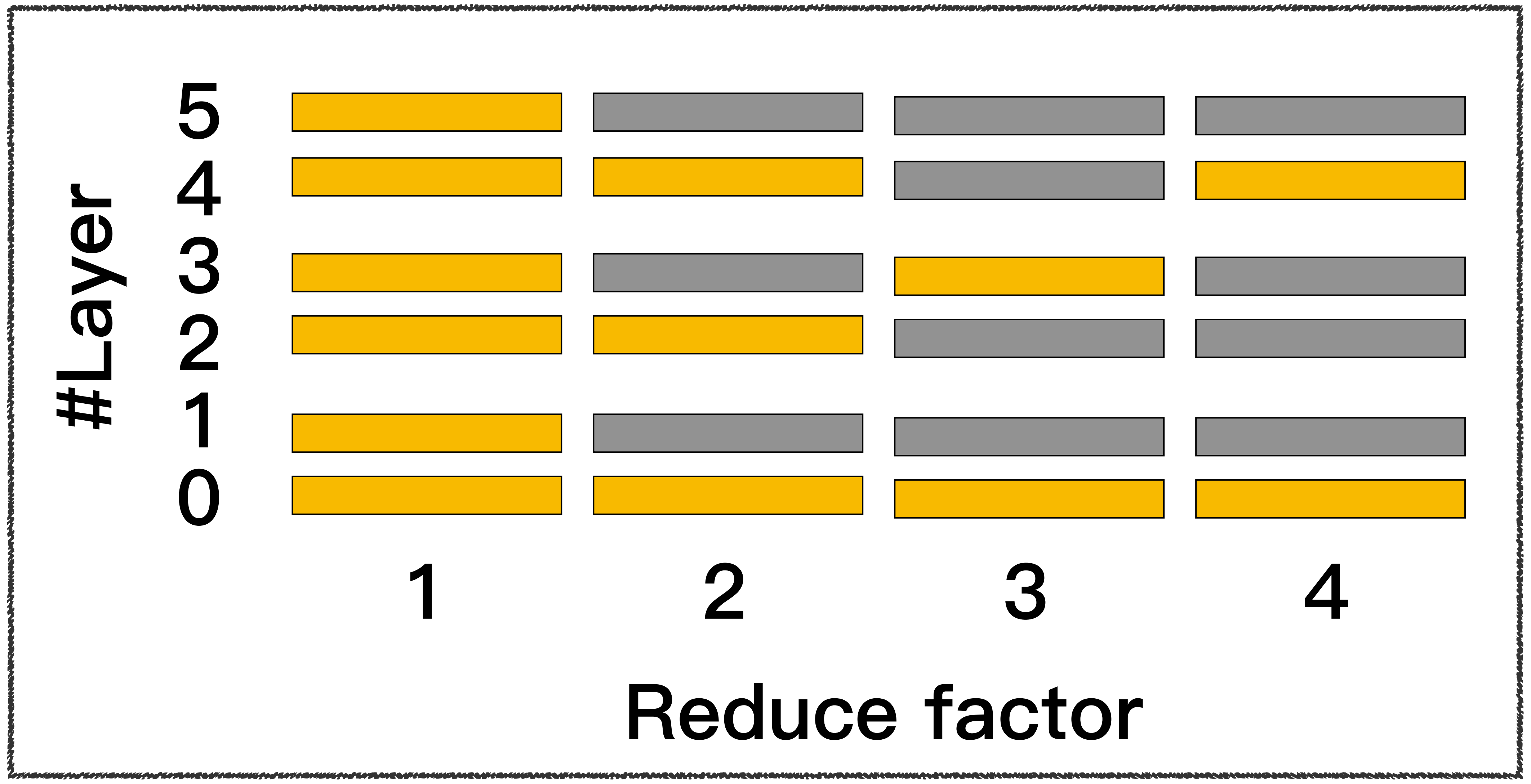
$\sigma(T_{Cluster})$ ←~ linear→ $\sigma(t_{hit})$



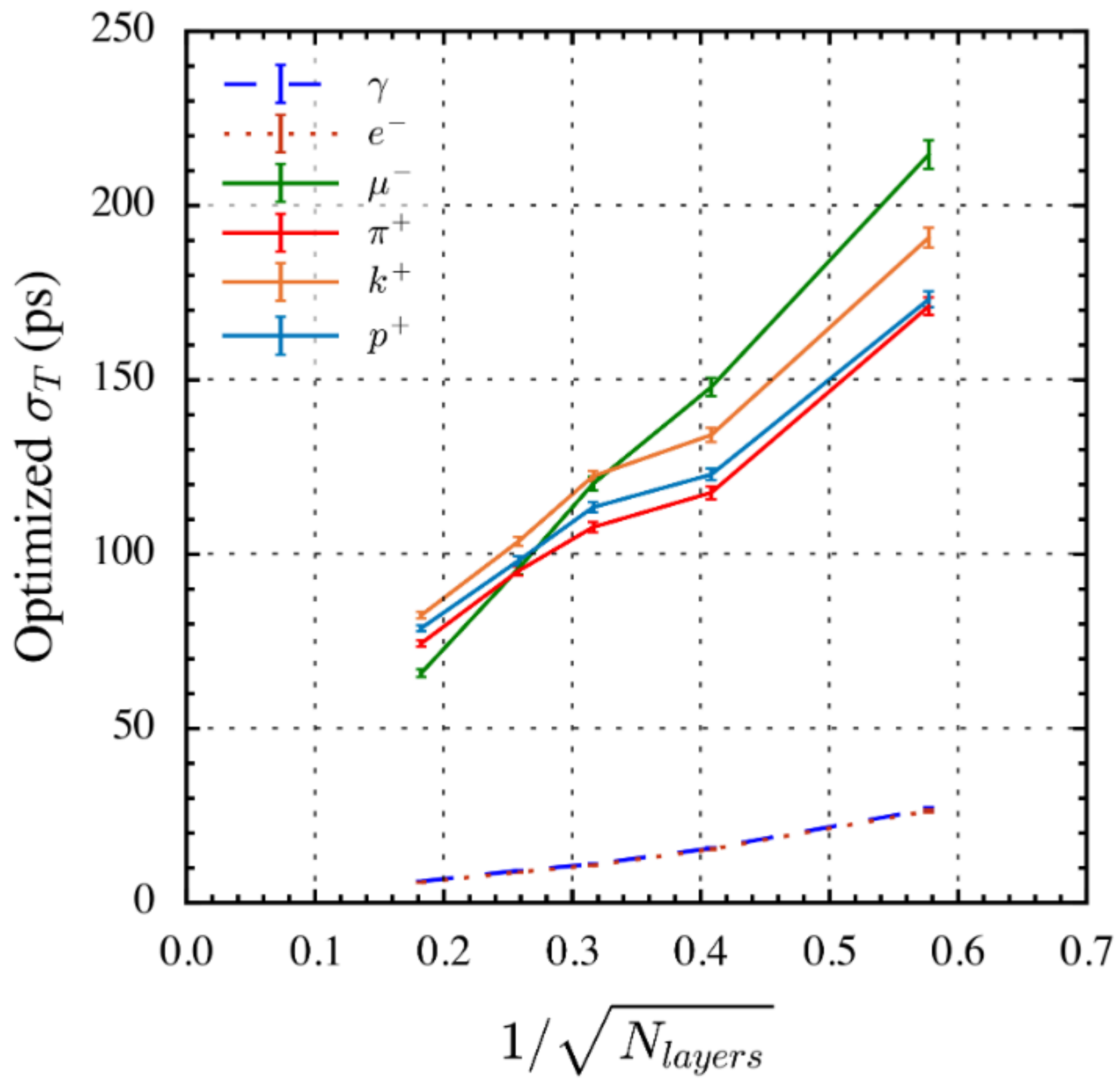
Number of the timing layers

- 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 $\propto 1/\sqrt{N_{layer}}$

$\sigma(T_{Cluster}) \longleftrightarrow N_{layer}$ ~ statistical



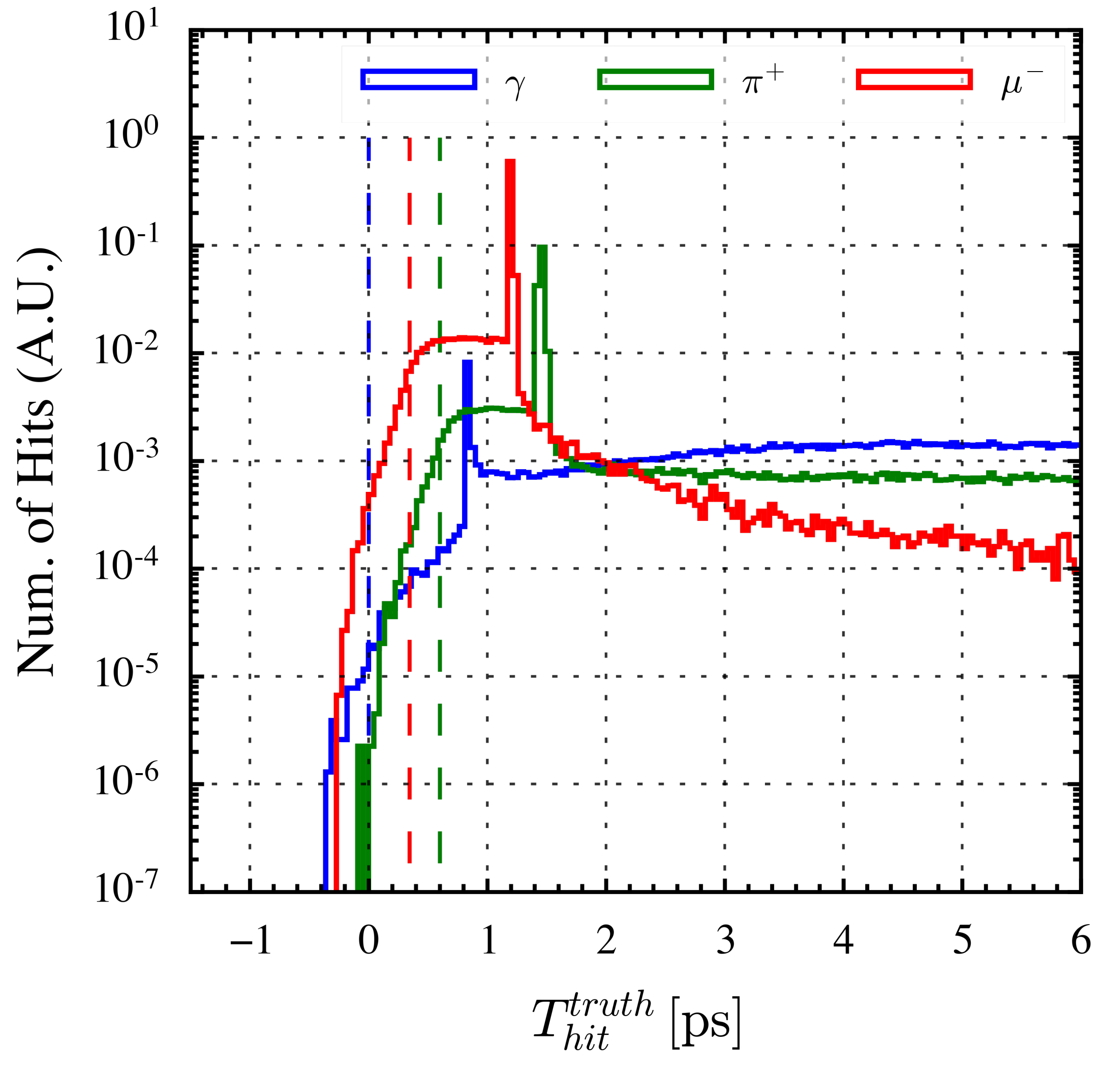
A schematic diagram of timing layer isometric sampling. Only the **layers** whose number can be divided exactly by the reduce factor are served to record hit time information.

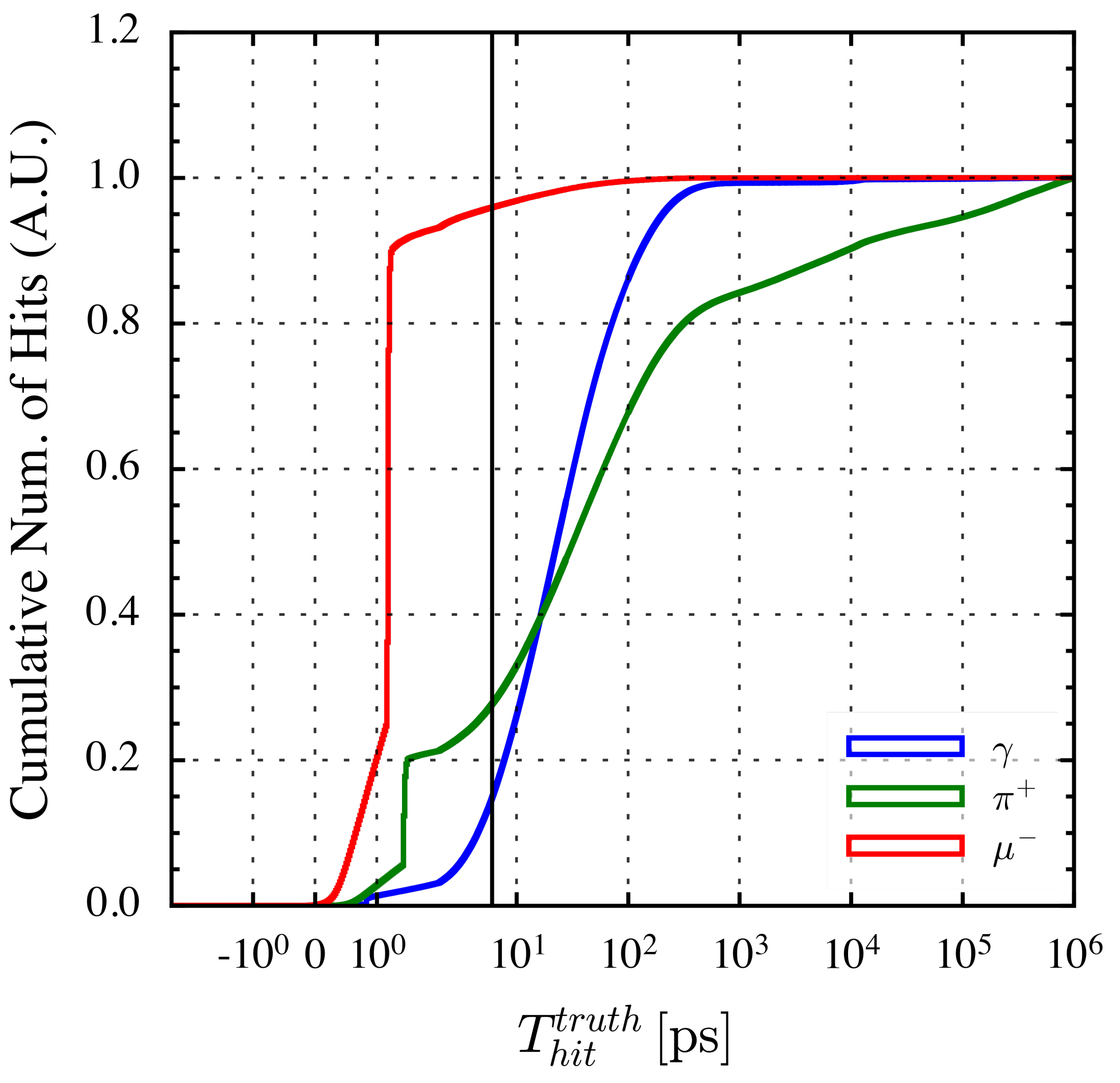


Cluster time resolution versus (left) layers number and (right) its square root for perfect (top) pion (bottom) photon clusters..

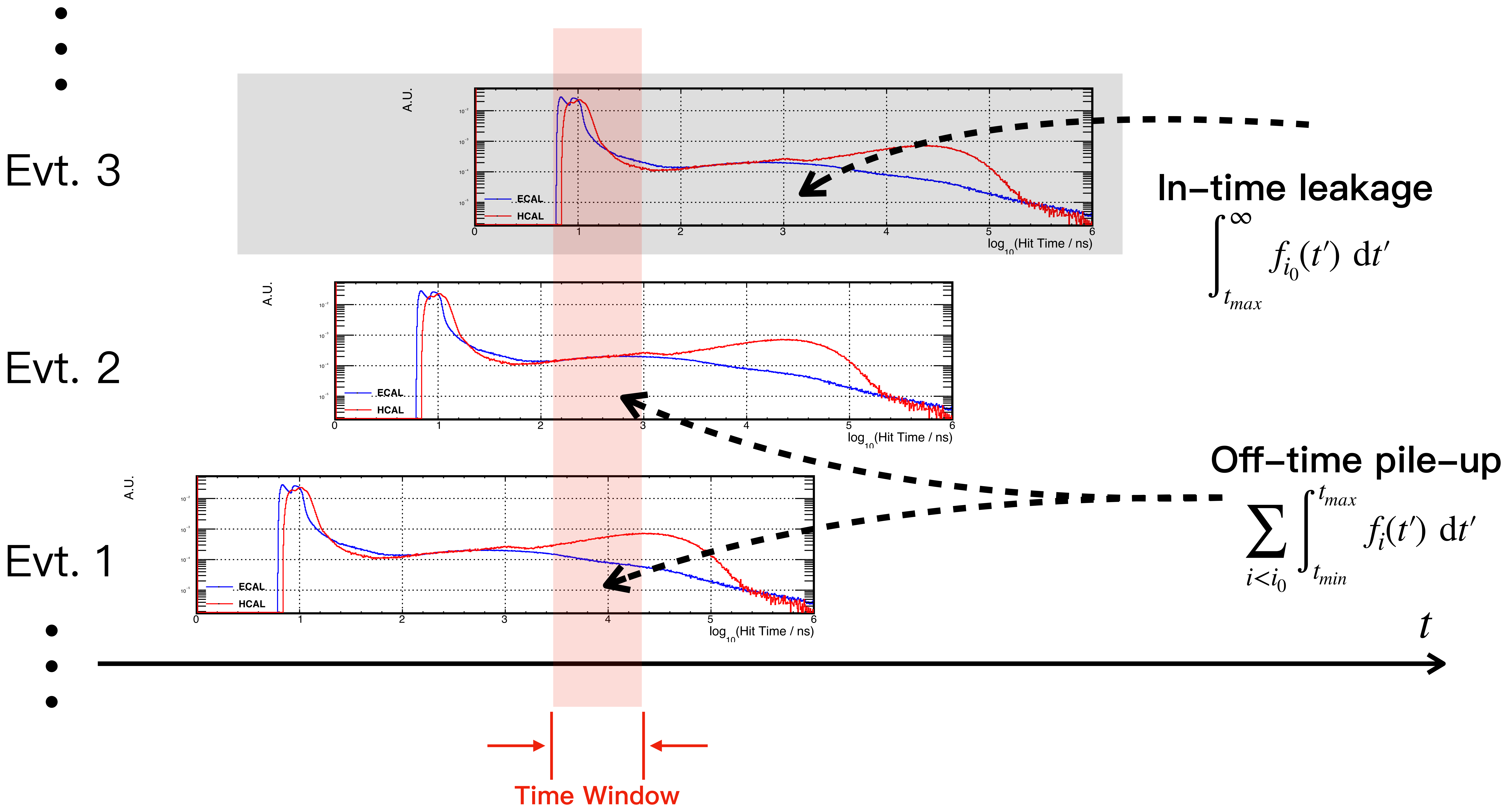
Section 3.
Leakage and Pile-up

- Slow components of hadronic showers may induce signal off-time pile-up and in-time leakage





Leakage & Off-time Pile-up in $Z \to q\bar{q}$



Off–time pile–up: Z–qq events

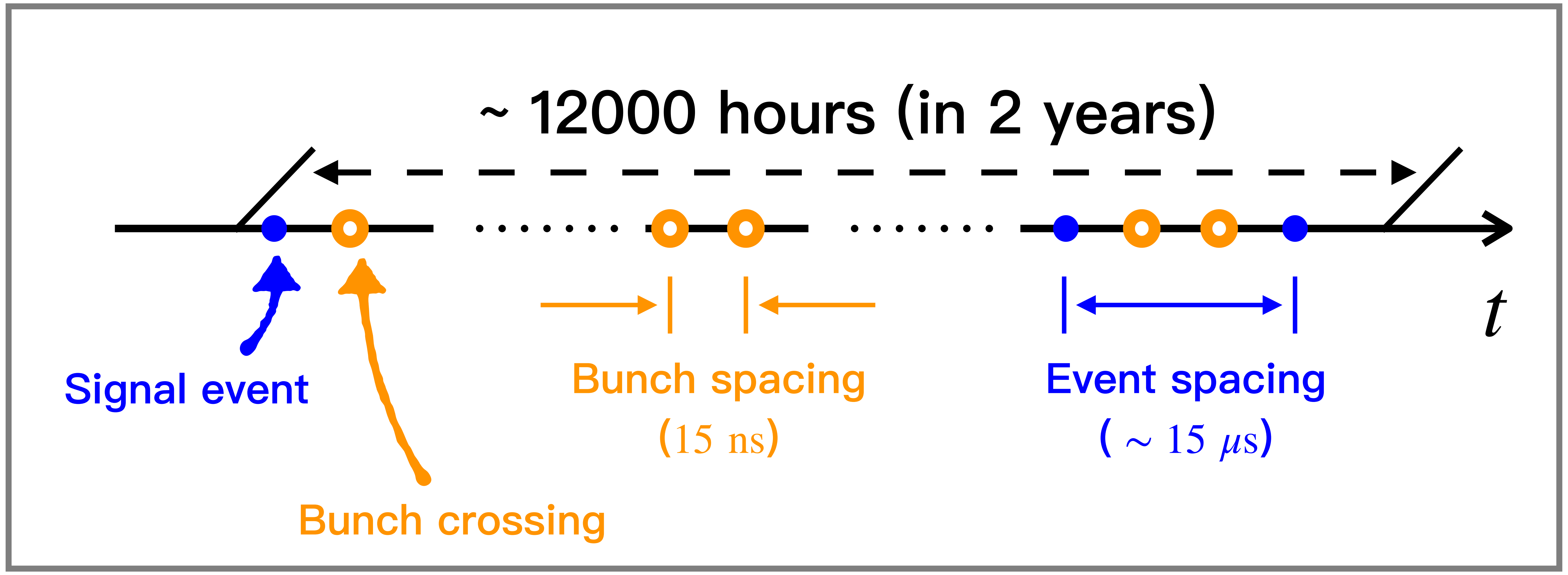
- Z boson yield: $N = 3 \times 10^{12}$

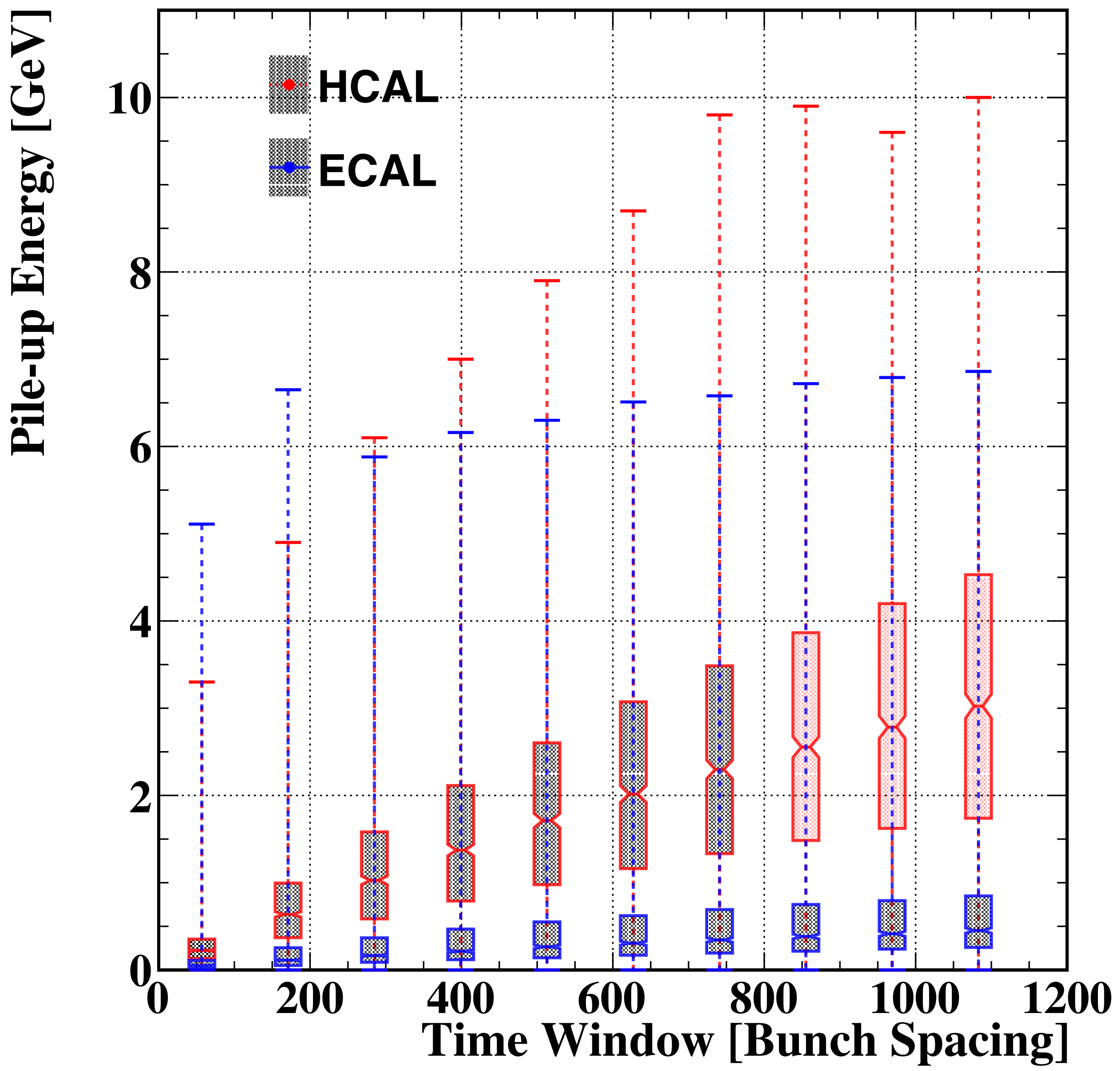
- The average time spacing between two $Z \to q\bar{q}$ events:
  $\sim 1.6 \times 10^4$ ns (1 100 Bunch Spacing)

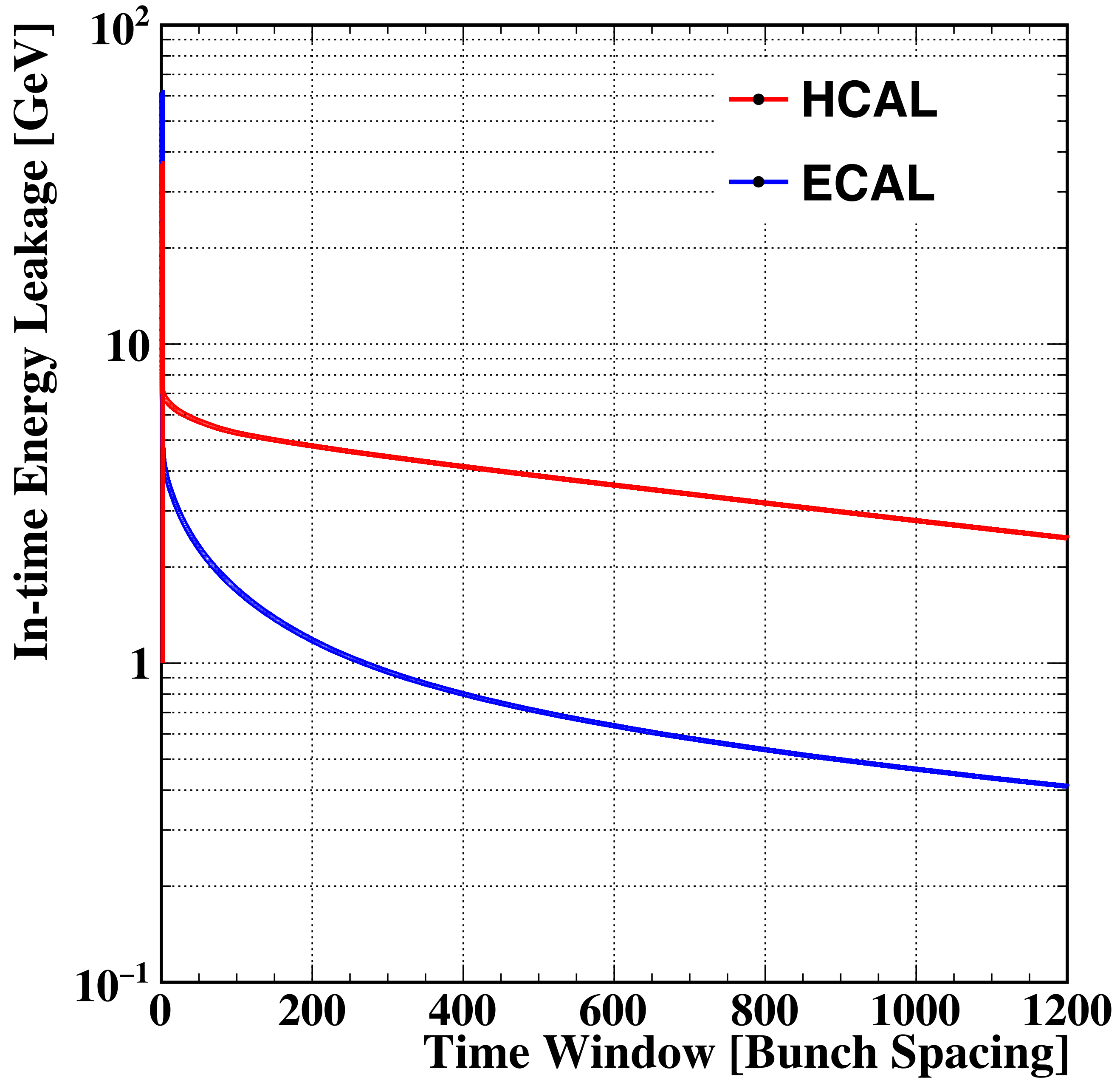
Toy MC:

- Random event time t_i, $i = 0,1,2,\ldots,N$:
  - Uniformly distributed in run time $T_{\text{run}} = 12\,000\ h$
  - $t \bmod (\text{Bunch spacing}) = 0$
- Event spacing Δt: time difference between two nearby events

CEPC Z pole scheme







@ Muchen He, Fanjie Meng

6. 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 $\sqrt{N_{layer}}$.
- **Off–time pile–up and in–time leakage:**
  - During Z pole operation, depending on the setup of time window, a event faces to:
    - 0 ~ 0.5 GeV energy pile–up in ECAL and 0 ~ 3 GeV in HCAL,
    - 0.4 ~ 4 GeV energy leakage in ECAL and 2 ~ 7 GeV in HCAL.

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

Thanks for your attention

Yuzhi Che, Manqi Ruan

Oct. 24, 2022

Back Up

2. Basic configurations

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

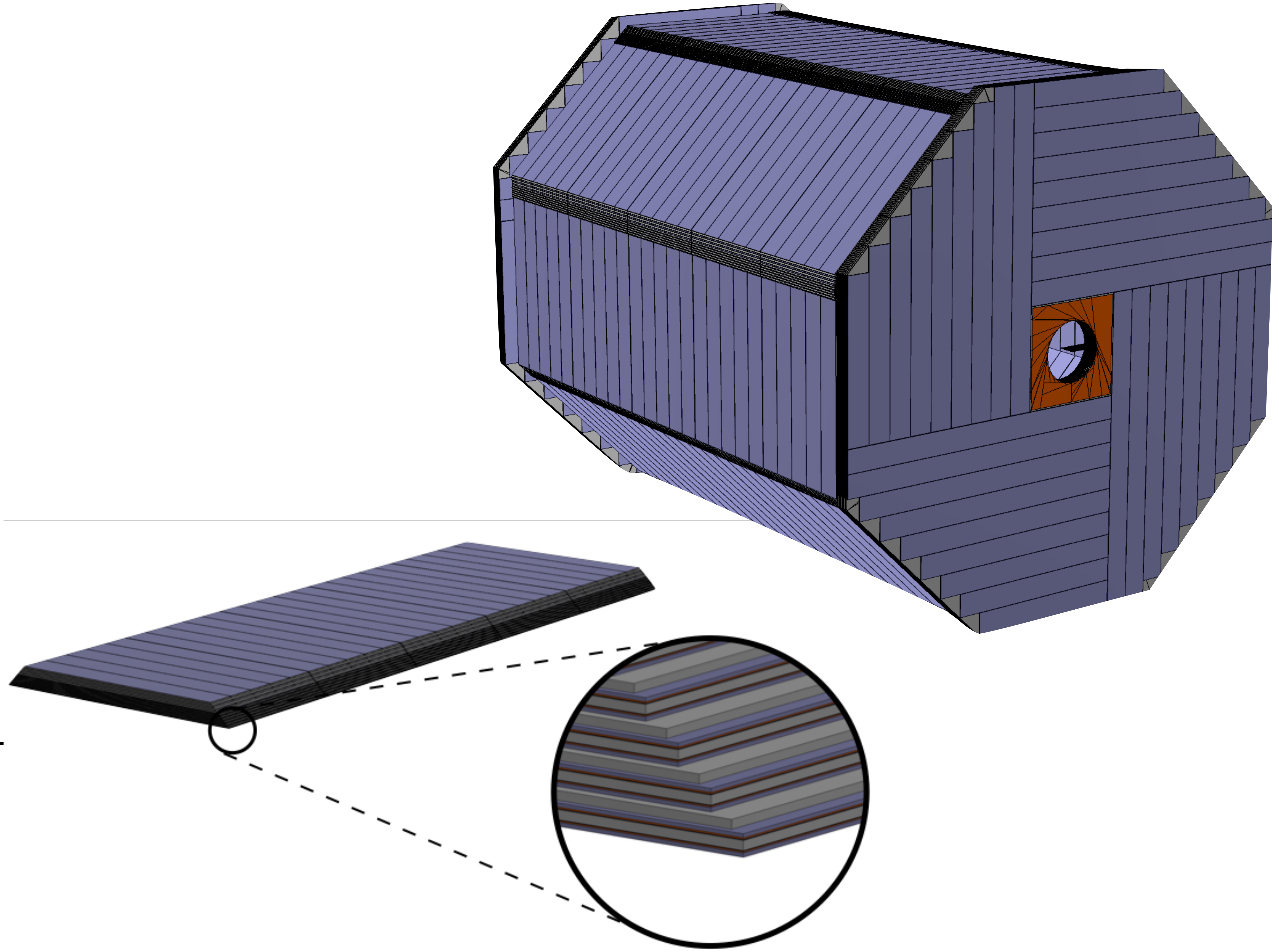
longitudinal direction: 30 (= 20 + 10) Layers

- 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

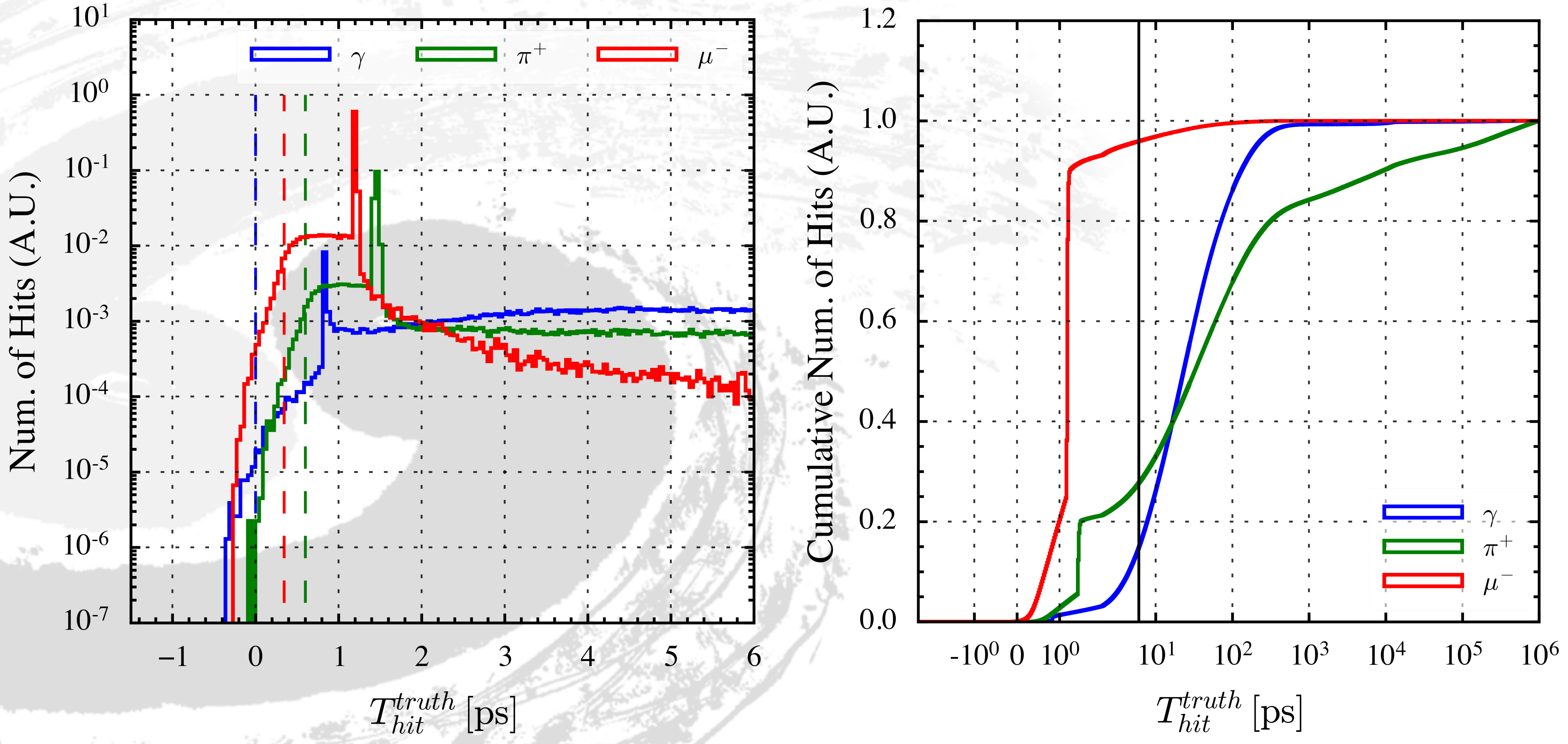
B Field: 3 T (set to 0 in this research)

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).

The time definition of cell hits

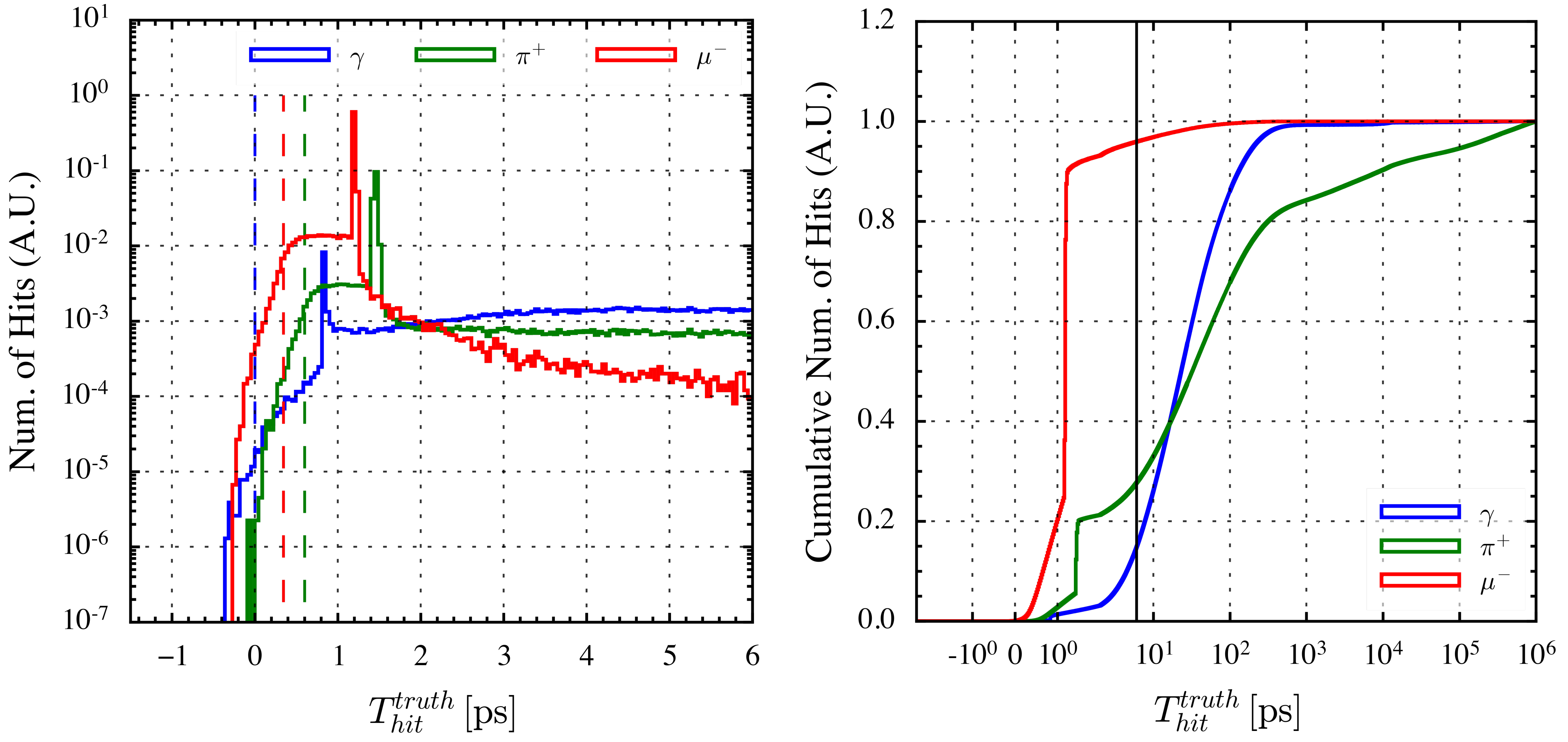


The shower truth time spectrum of 10 GeV $\gamma/\pi^+/\mu^-$ showers, all normalized to the total number of hits before 1000 ns. The dashed lines donate the expected ToF of the corresponding particles.

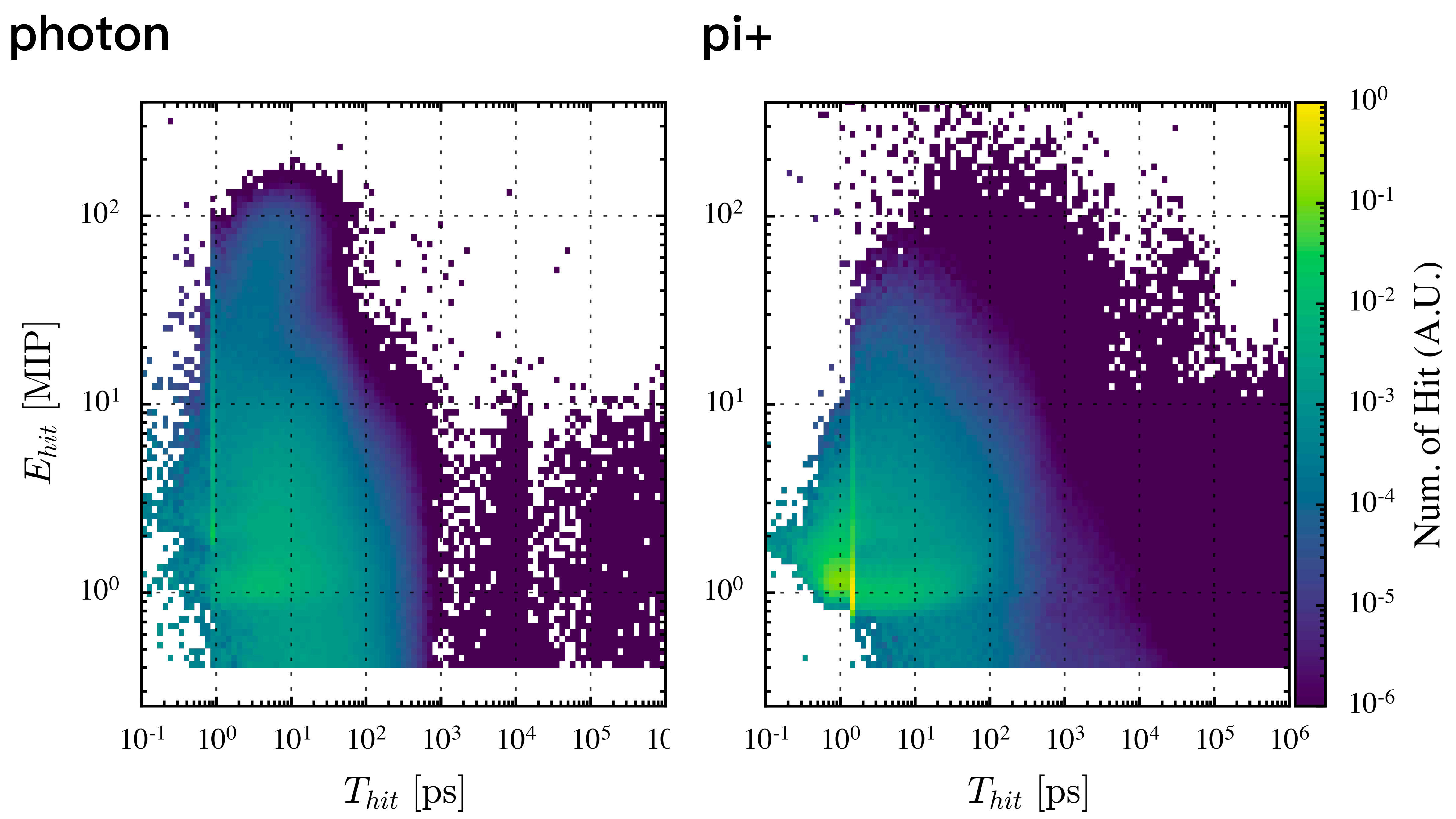
3.1. Calorimeter response: Truth level

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

$L_{IP\rightarrow hit}$: 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, $T_{delay} = T_{hit} - L_{IP\rightarrow hit}/c$

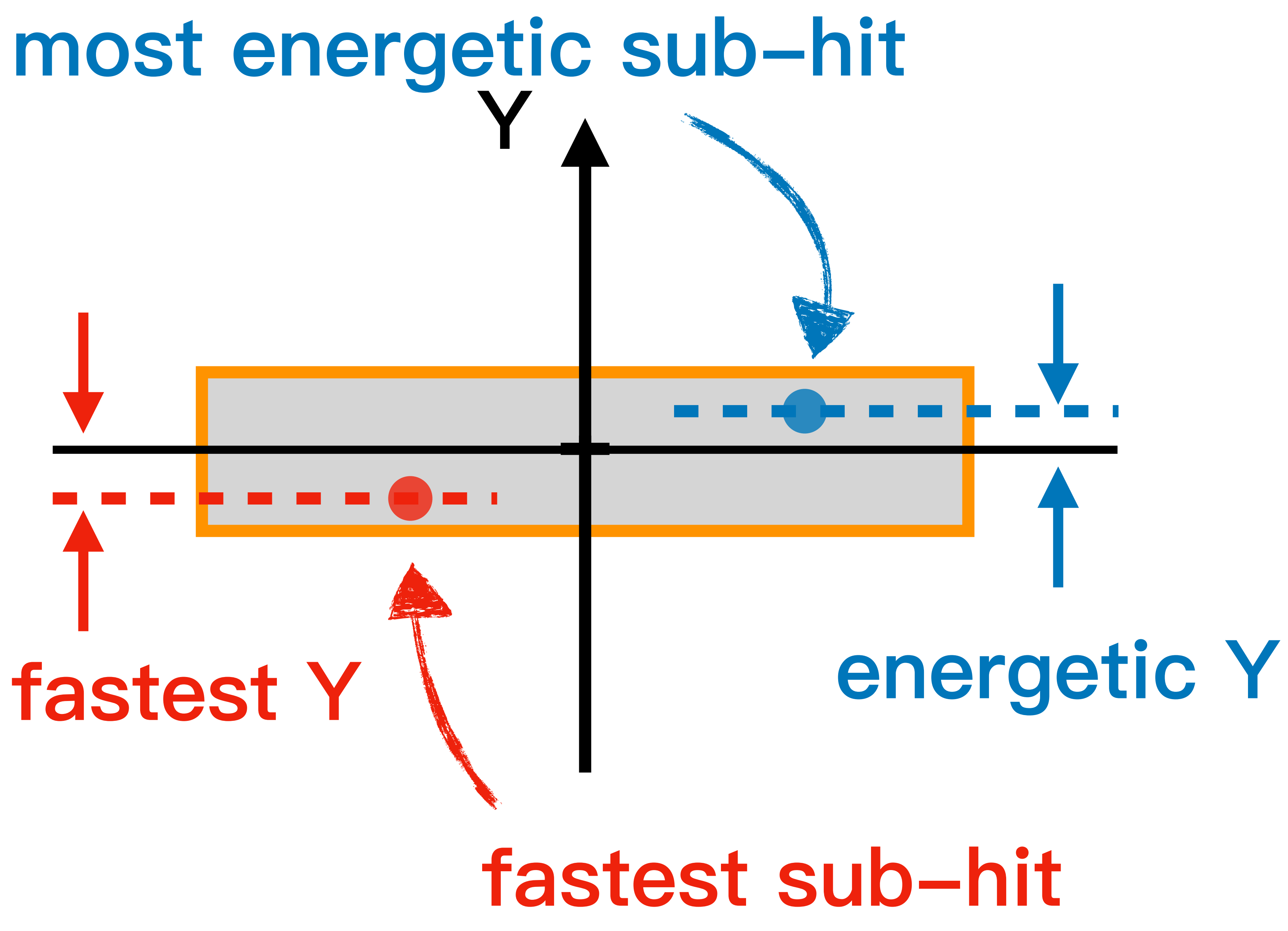
Sub–hit distribution inside cell

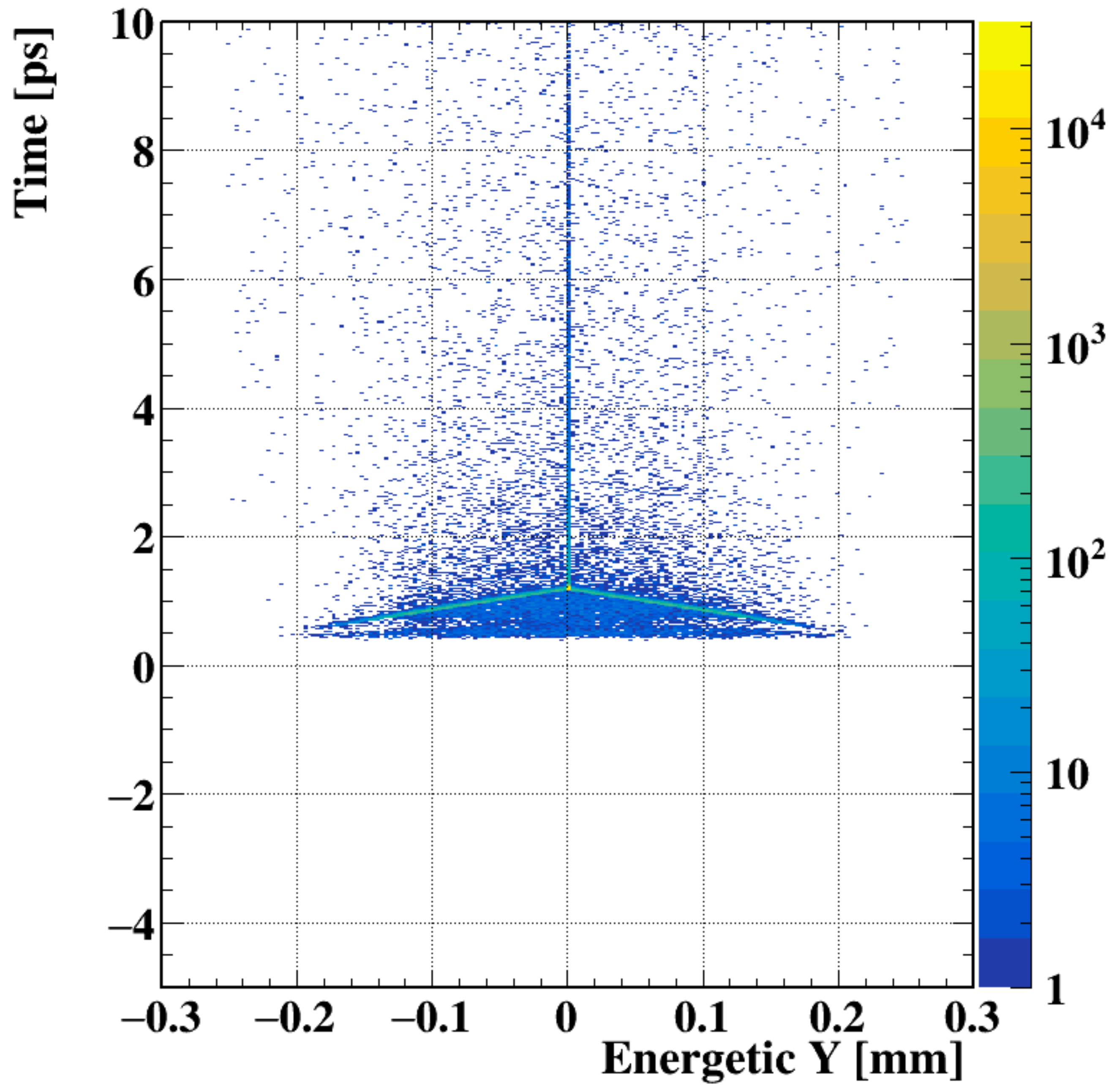
Conventions:

- Hit position: center of the cell

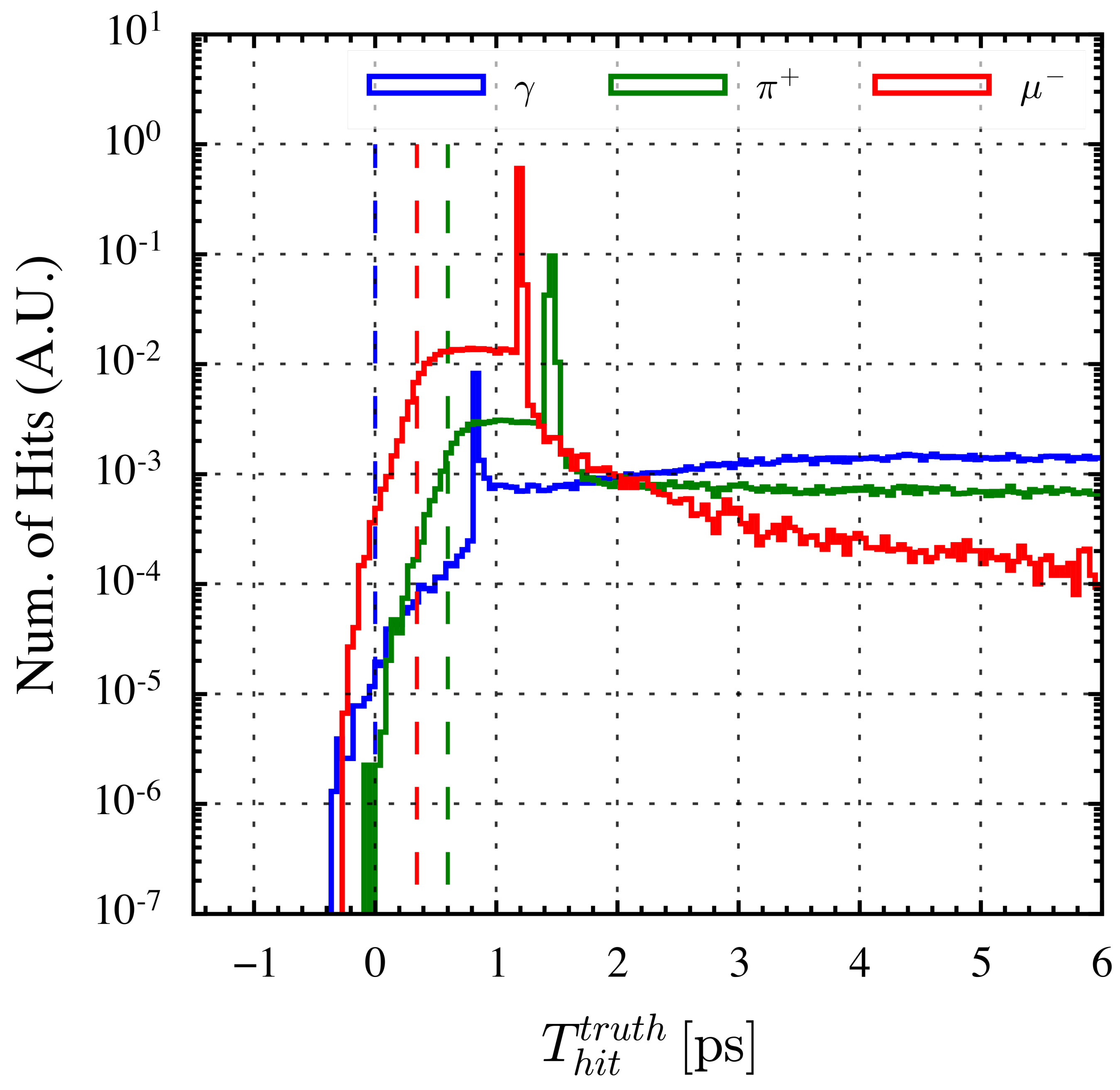
- Shifted time: $T_{\mathrm{shift}} = t_{\mathrm{hit}} - L_{\mathrm{IP}\to\mathrm{hit}}/c$
  $L_{\mathrm{IP}\to\mathrm{hit}}$: distance from the IP to hit position.

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

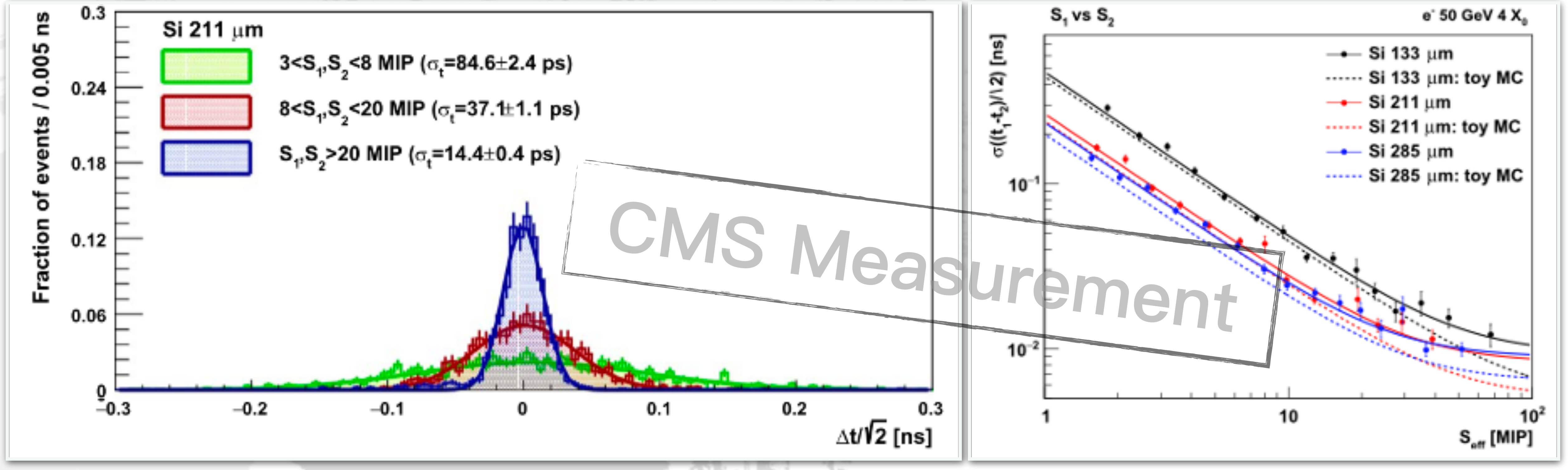




The most energetic sub-hit



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
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.

3.2. Calorimeter response: Intrinsic hit time resolution

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

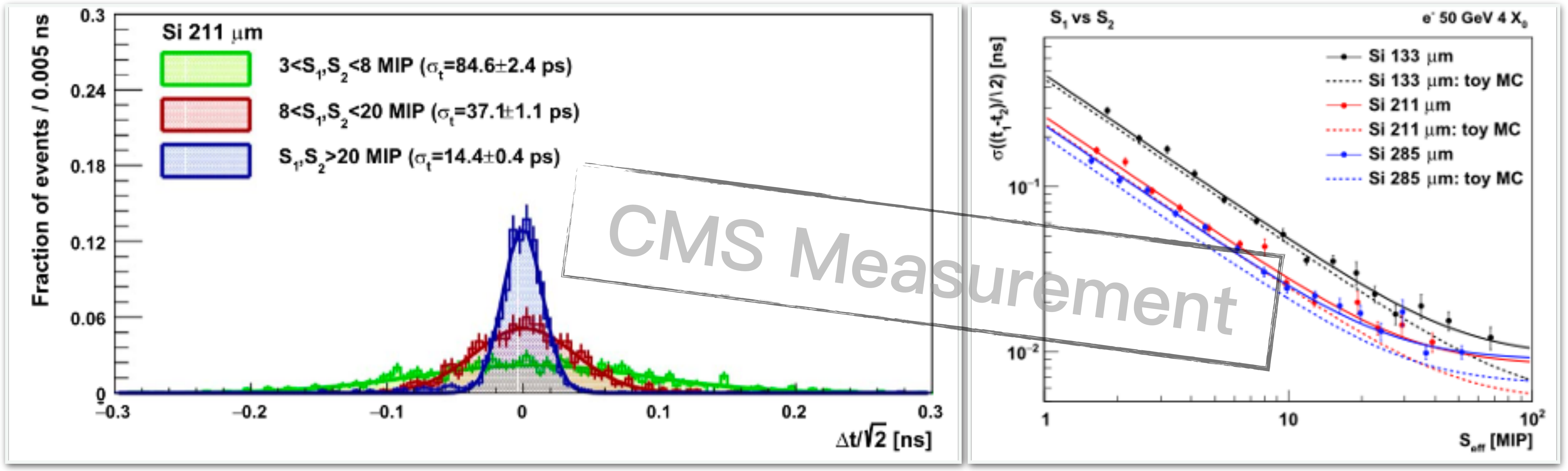
Hit time digitization in simulation:

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

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

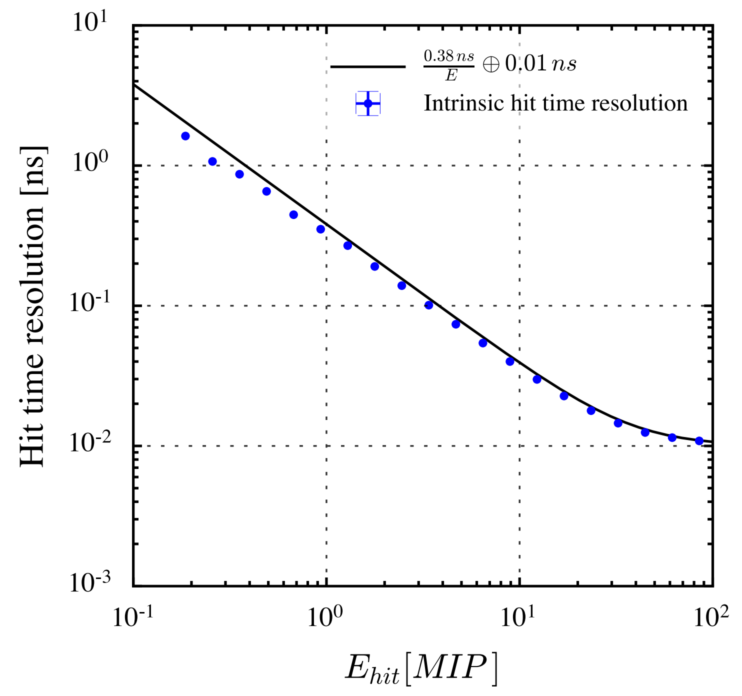
  $\sigma_{T_{hit}} = \sqrt{\left(\dfrac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}$.

  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).

BackUp. time resolution of CMS silicon sensor

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

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

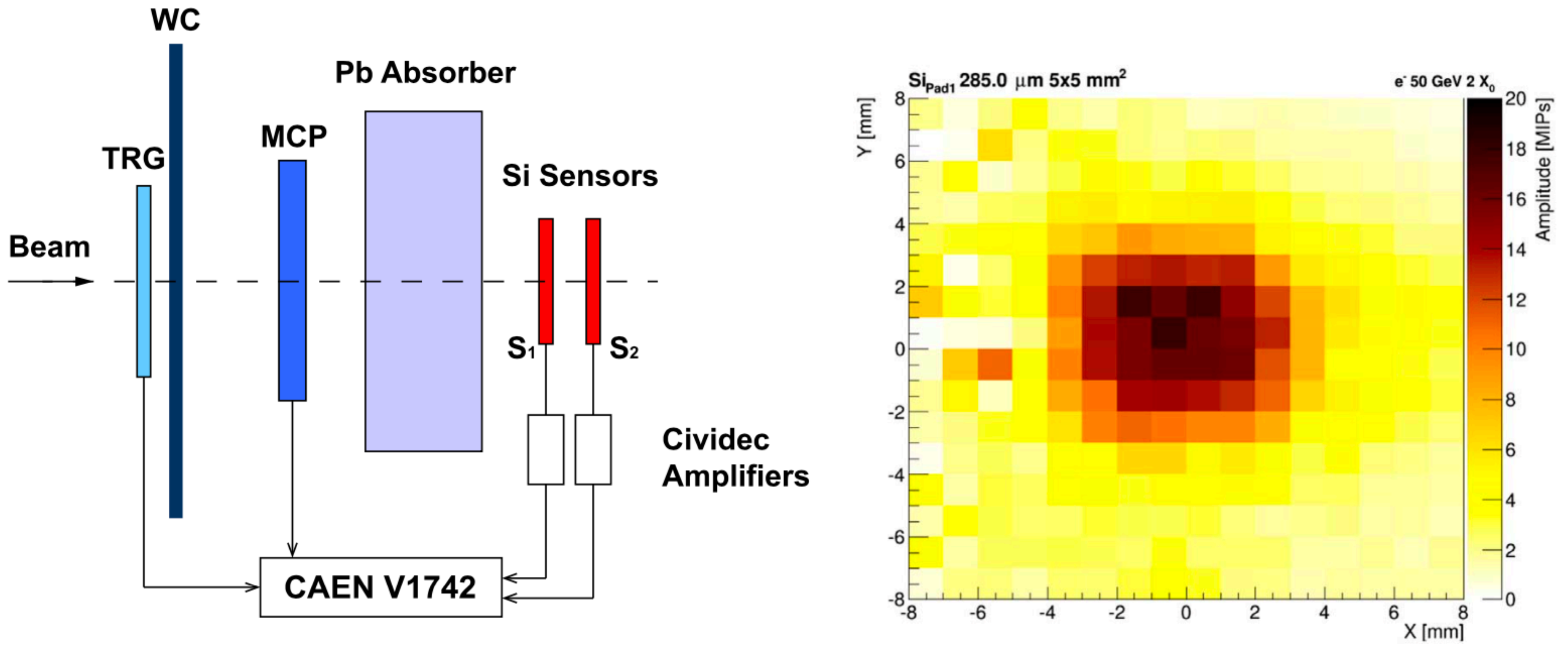


Fig. 1. The schematic of the layout displays the main components and the readout scheme on the left. Downstream of the trigger counter (TRG) and wire chambers (WC), a micro-channel plate (MCP) photomultiplier tube was positioned to provide a timing reference in front of the silicon sensors. Various lead 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

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

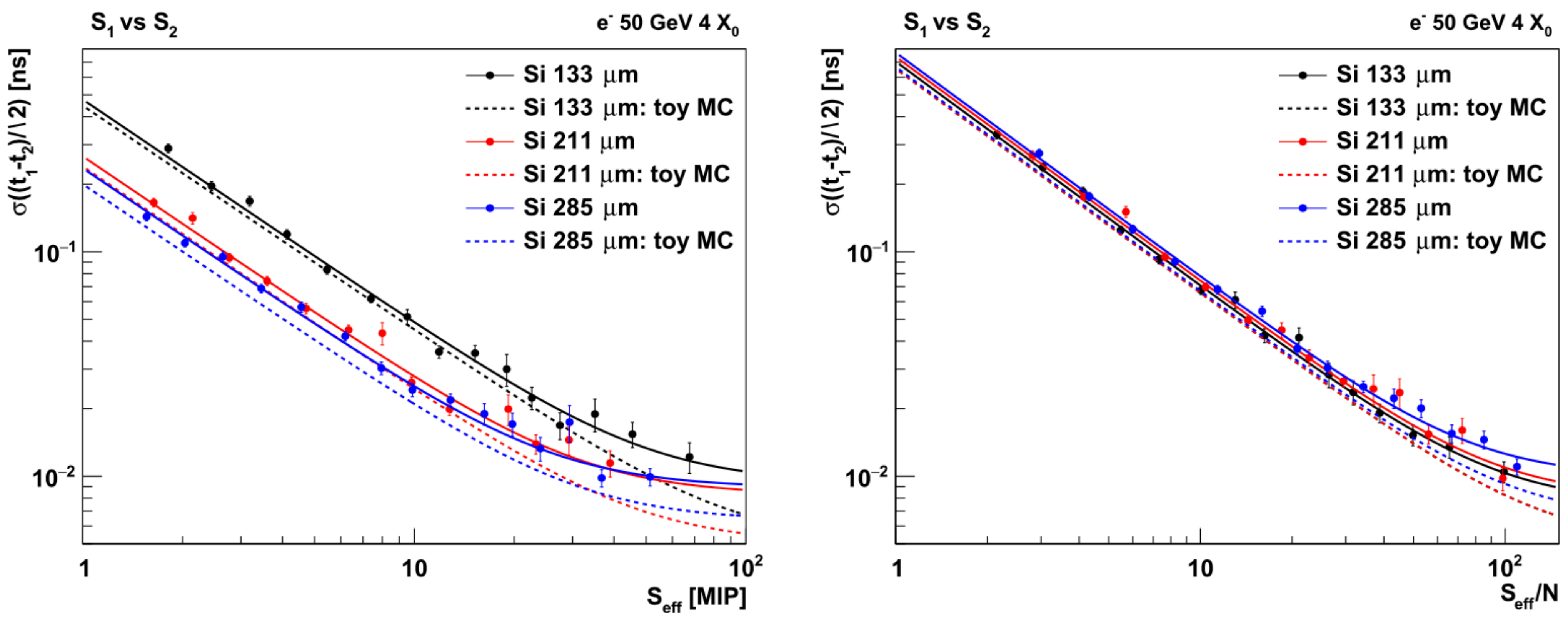
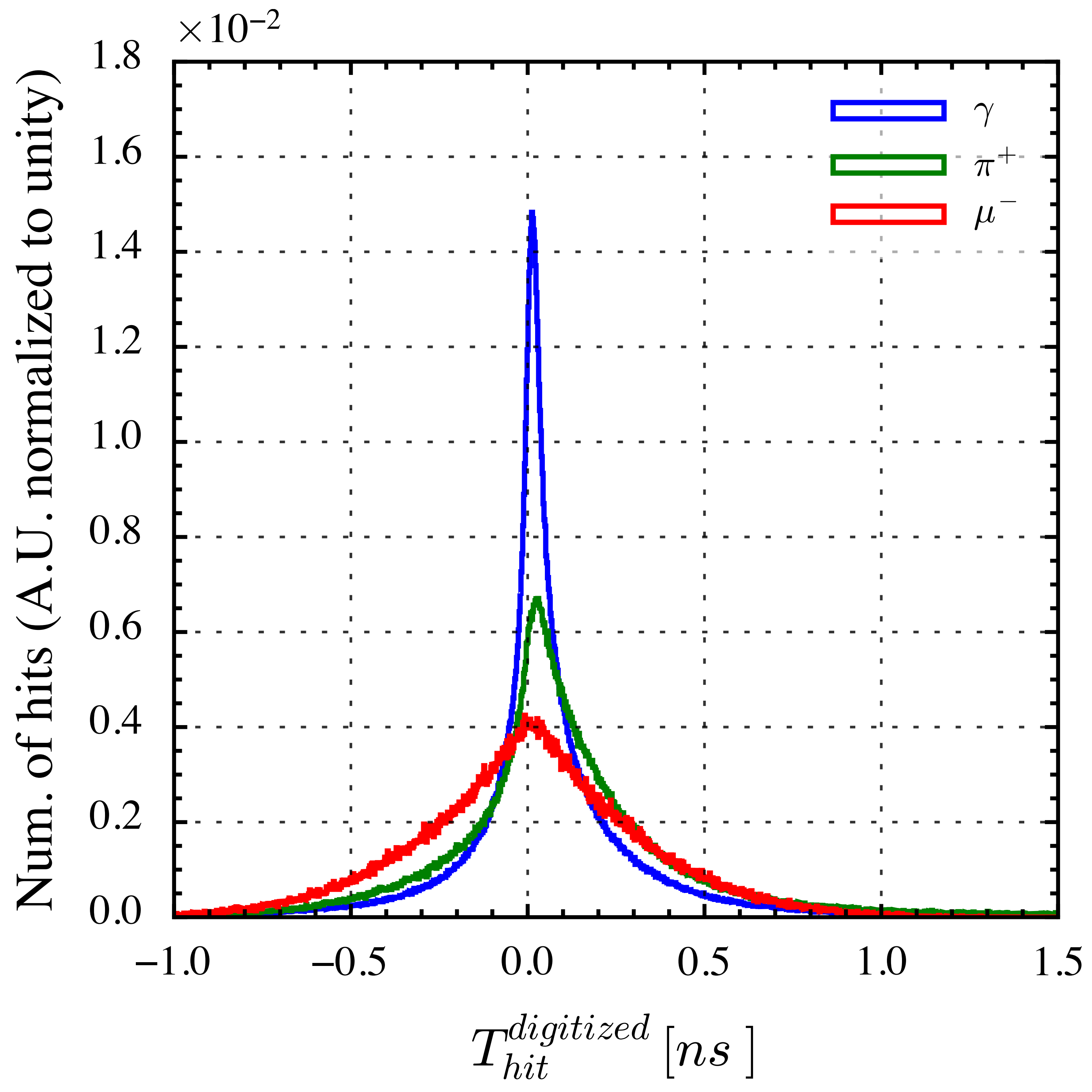


Fig. 8. The timing resolution based on two silicon sensors as a function of the effective signal strength in units of MIPs (left) and as a function of the signal-to-noise ratio (right). The fitted resolution functions with a noise (*A*) and a constant term (*C*) are also shown as solid lines. The dashed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

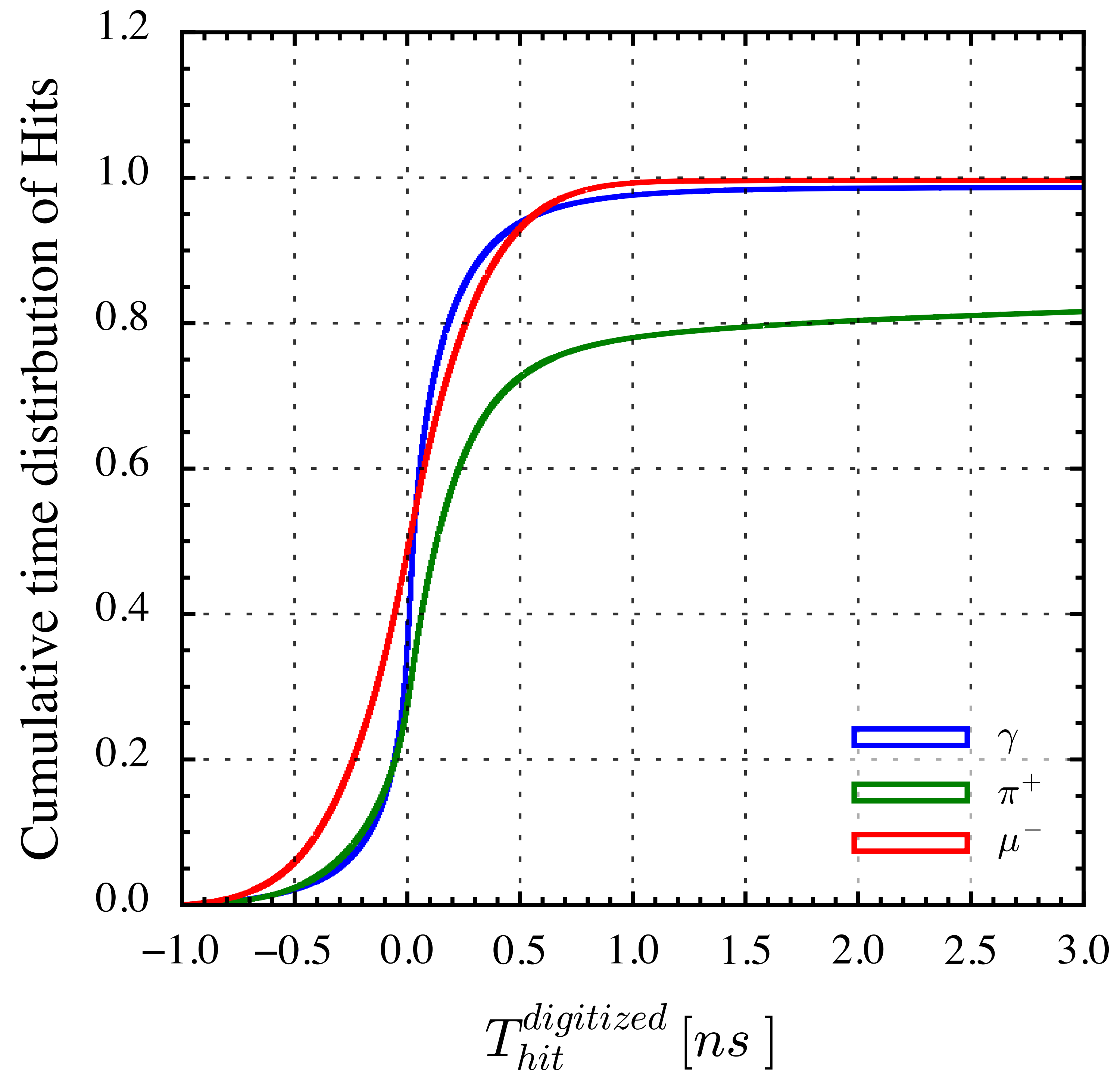
N. Akchurin, etc, *On the Timing Performance of Thin Planar Silicon Sensors*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **859**, 31 (2017).

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.

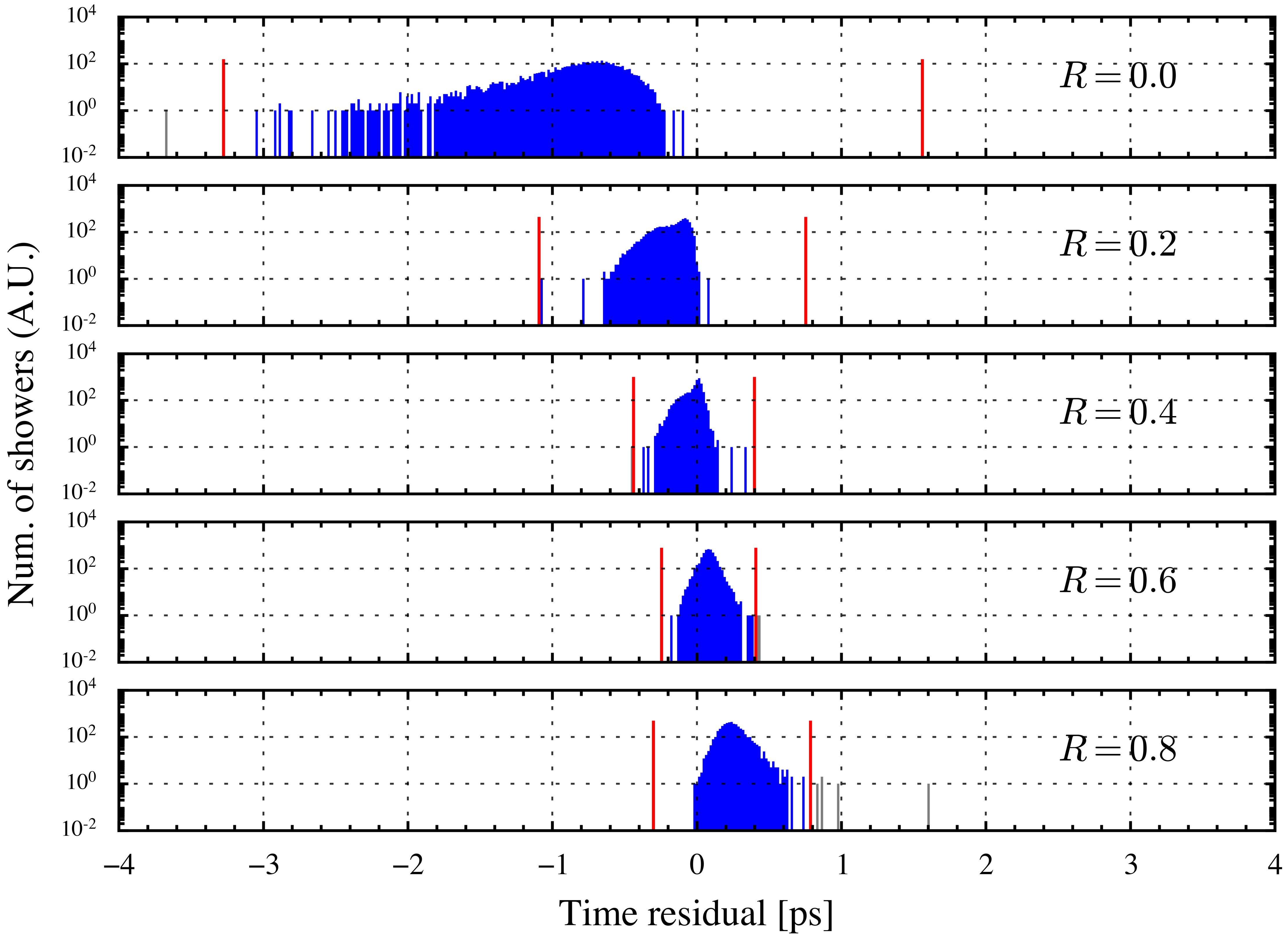
4.1. Algorithm & performance: Definition of bias & resolution

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: $\sigma_T = StdDev\{T_{reco} - T_{expect}(p)\}$



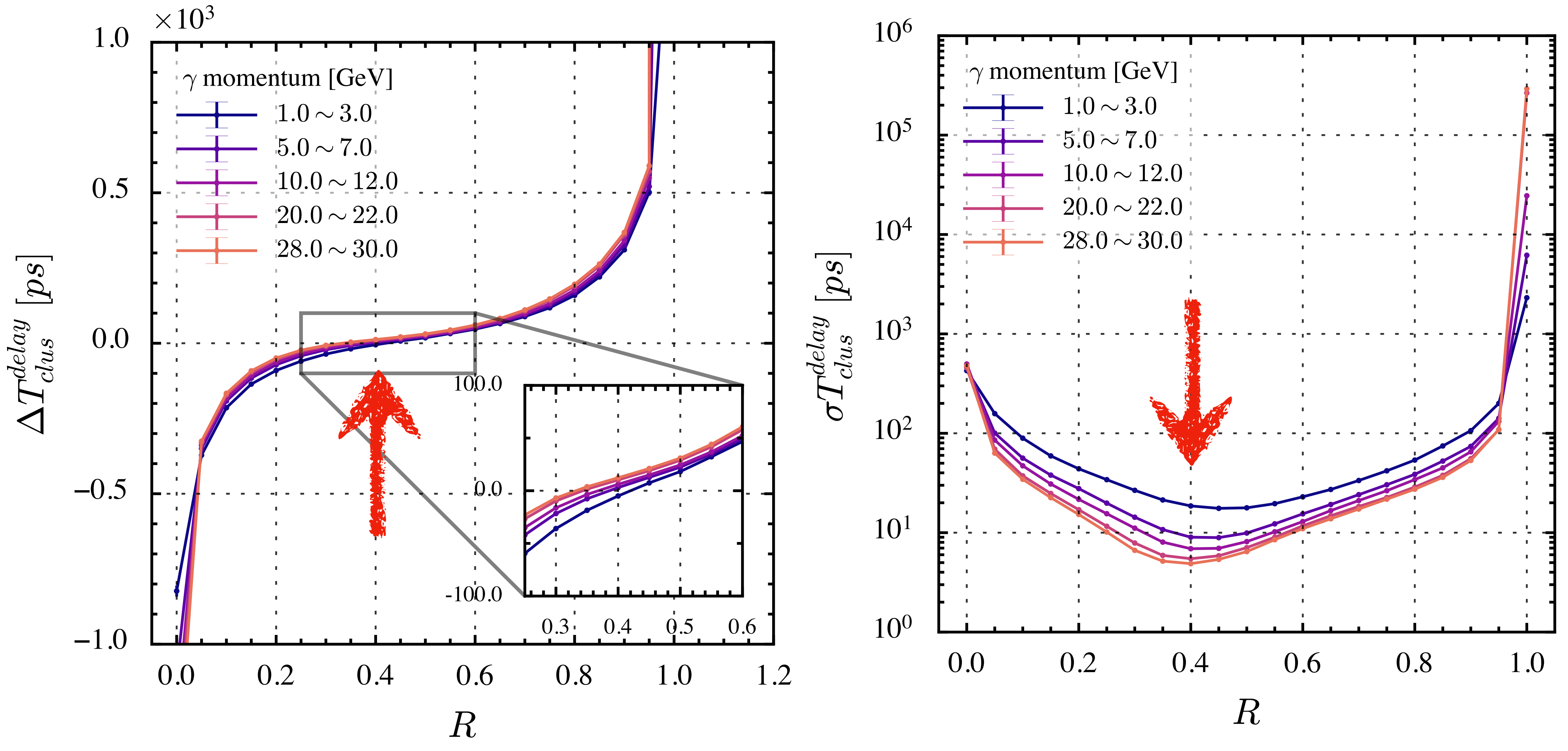
The distribution of the difference between reconstructed shower time and the true time in the 10 GeV π^{+} sample. To remove the outliers, a time residual window (red lines) is defined as $[Q_2 - 5(Q_3 - Q_1), Q_2 + 5(Q_3 - Q_1)]$, where Q_1, Q_2 and Q_3 are the three quartiles of the distribution.

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

Take the result of photon and pion samples,

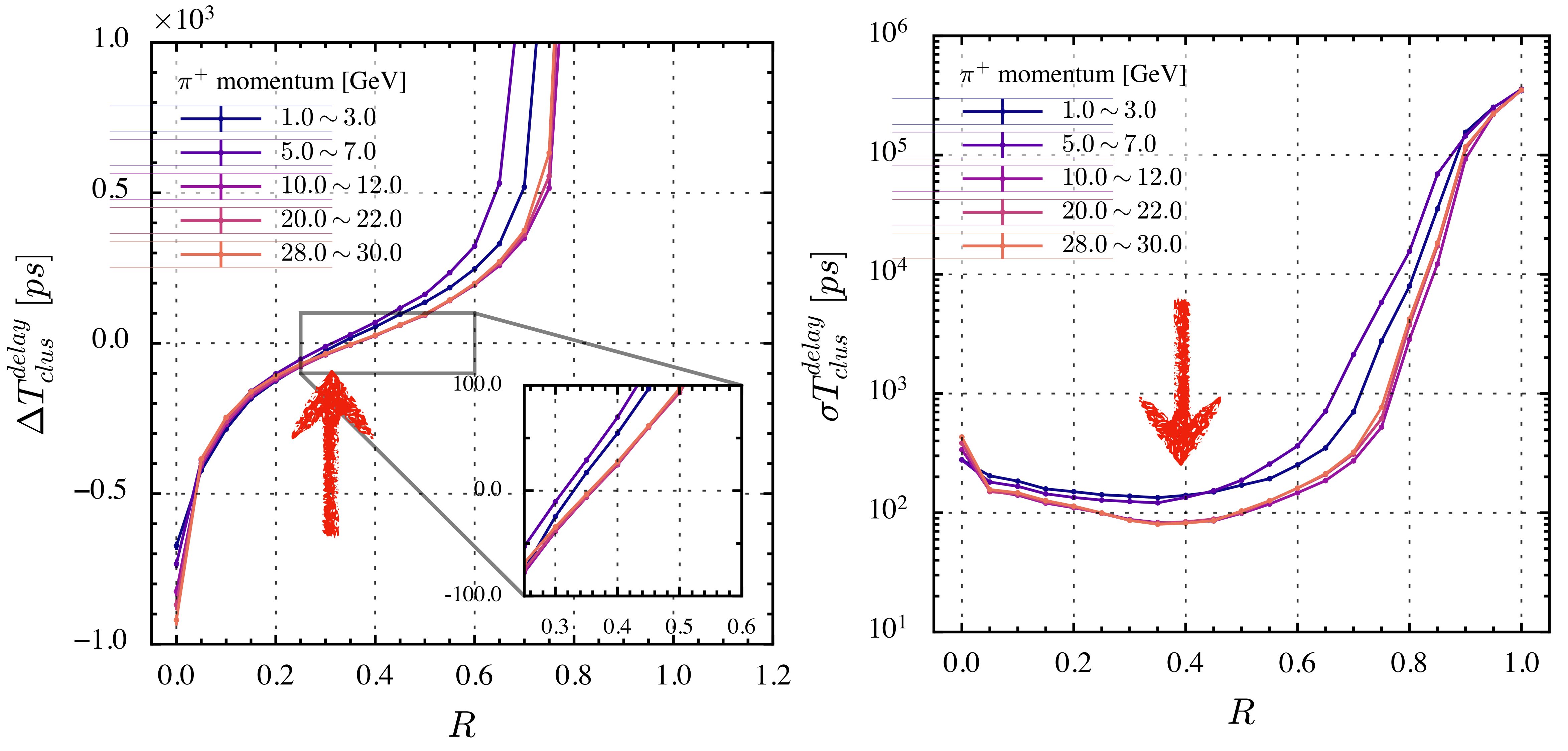
The none-bias R and minimum resolution R are close to each other but not exactly equal.

Photon



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

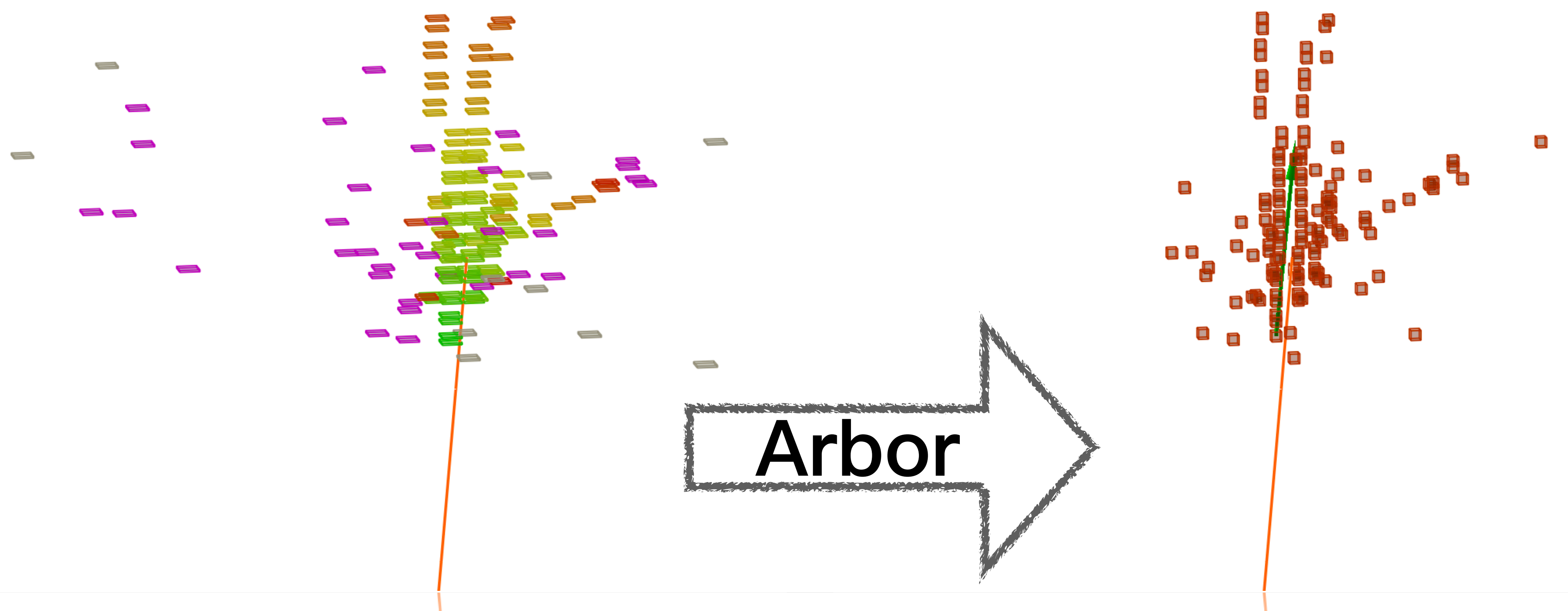
Pion



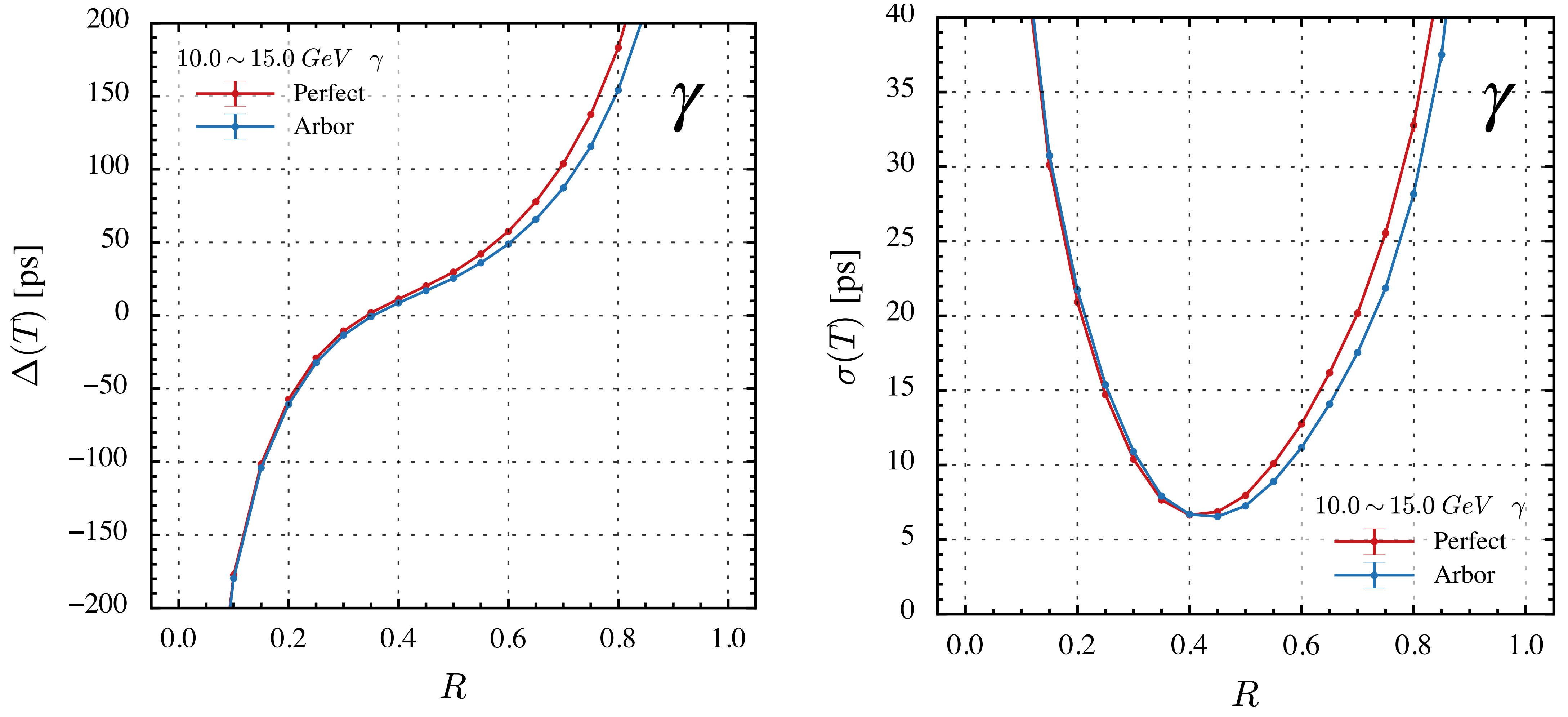
The estimation (left) bias and (right) resolution versus fraction R for perfect pion clusters.

5.1. Influence of the Arbor clustering

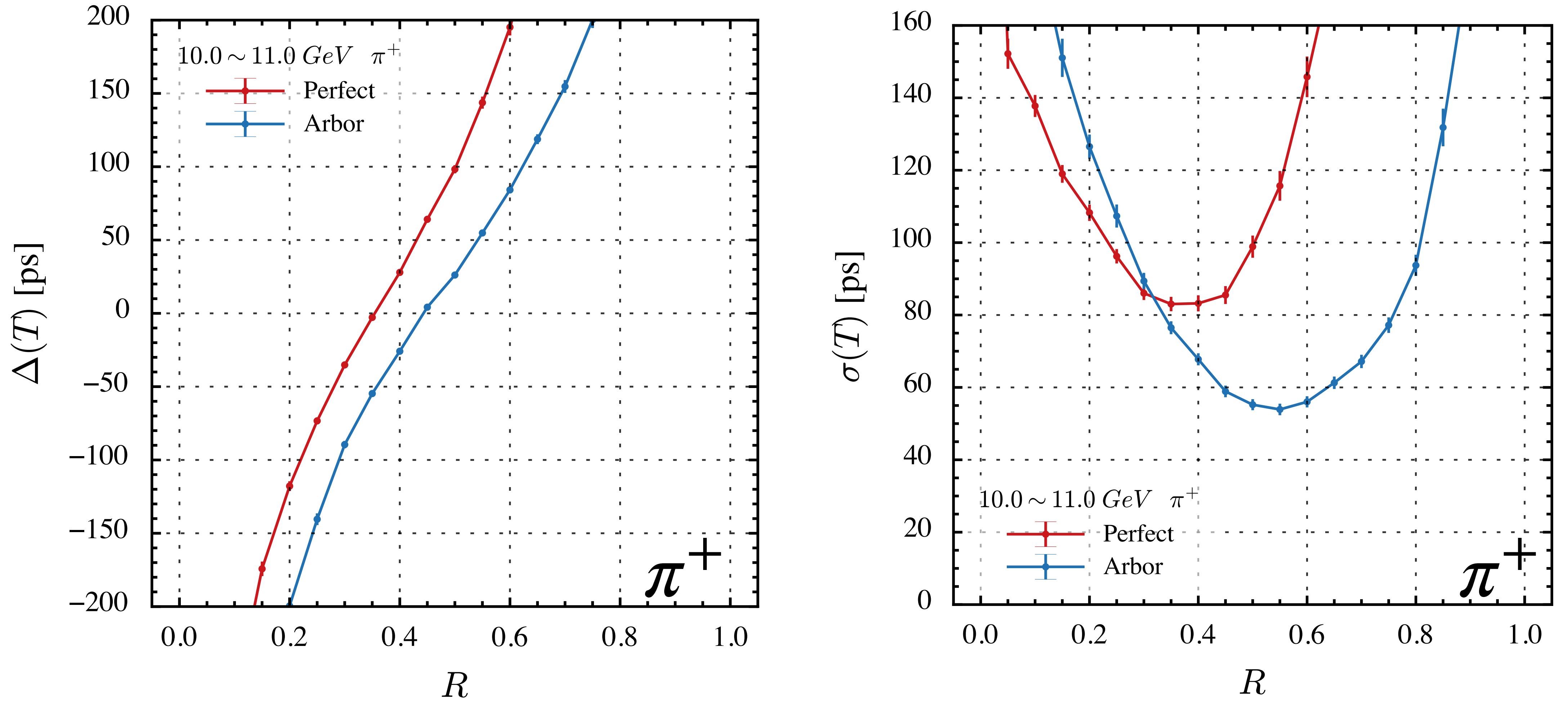
- **Arbor clustering** module partly removes the slow component of clusters, and improves the hadronic cluster time resolution by a factor ~ 1.5 (85ps/55ps)



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.



Estimator (left) bias and (right) resolution comparison between Arbor and perfect photon clusters.

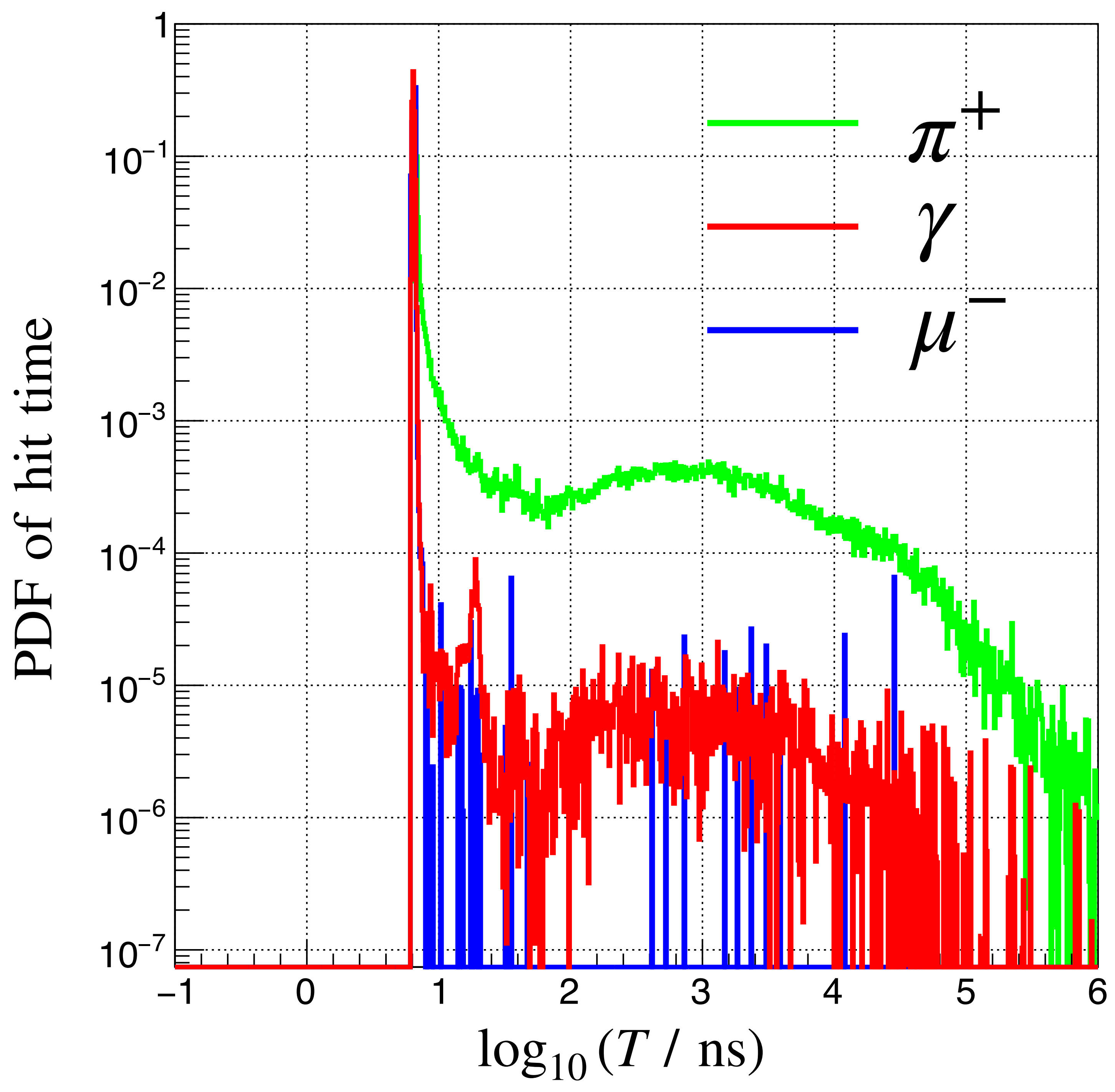


Estimator (left) bias and (right) resolution comparison between Arbor and perfect pion clusters.

In–time Leakage

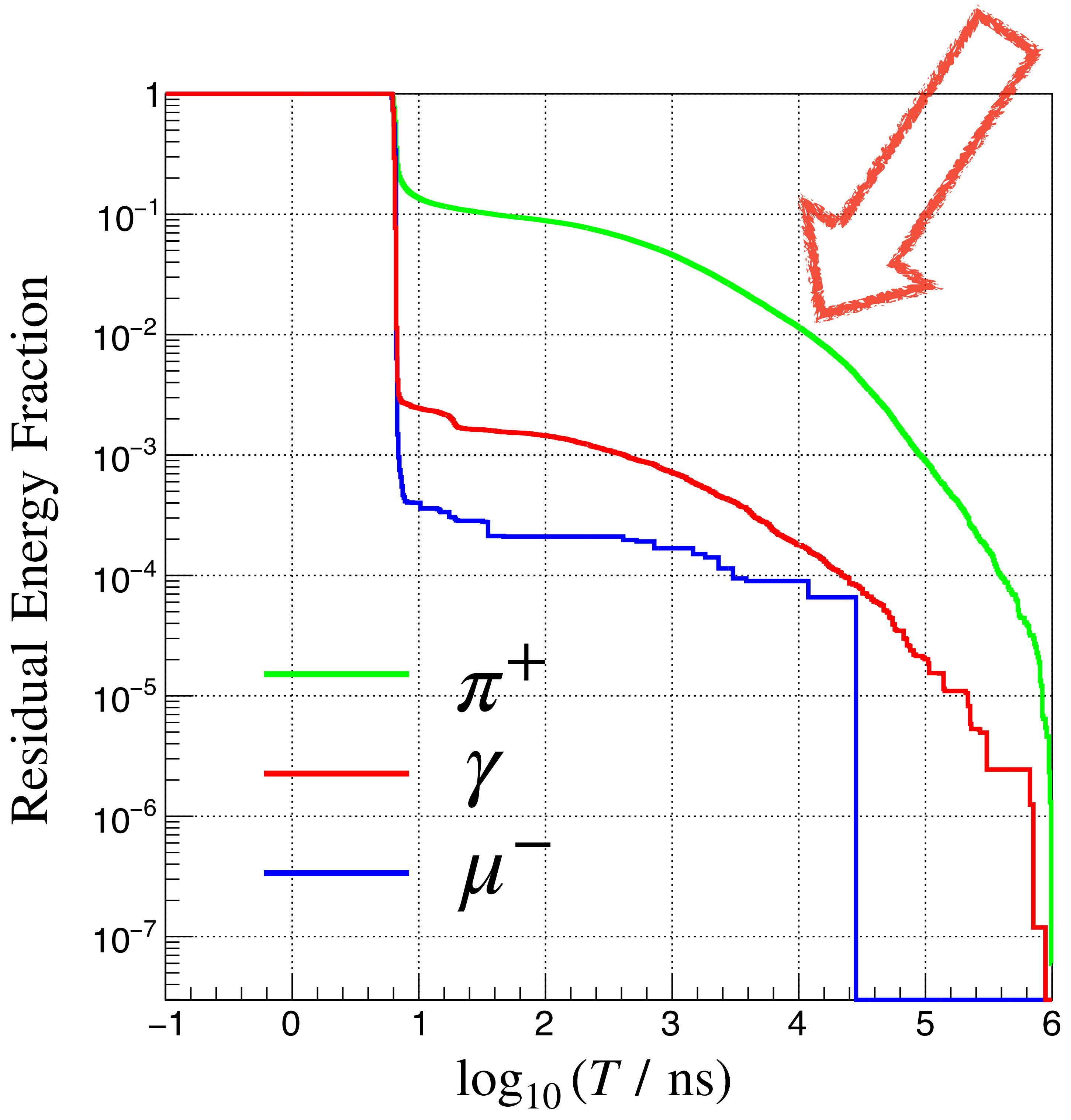
Probability **D**ensity **F**unction: $f(t)$

Cumulative **D**ensity **F**unction: $F(t) = \int_0^t f(t')\,\mathrm{d}t'$



Energy in–time leakage:

$$R(t) = 1 - F(t) = \int_t^\infty f(t')\,\mathrm{d}t'$$



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

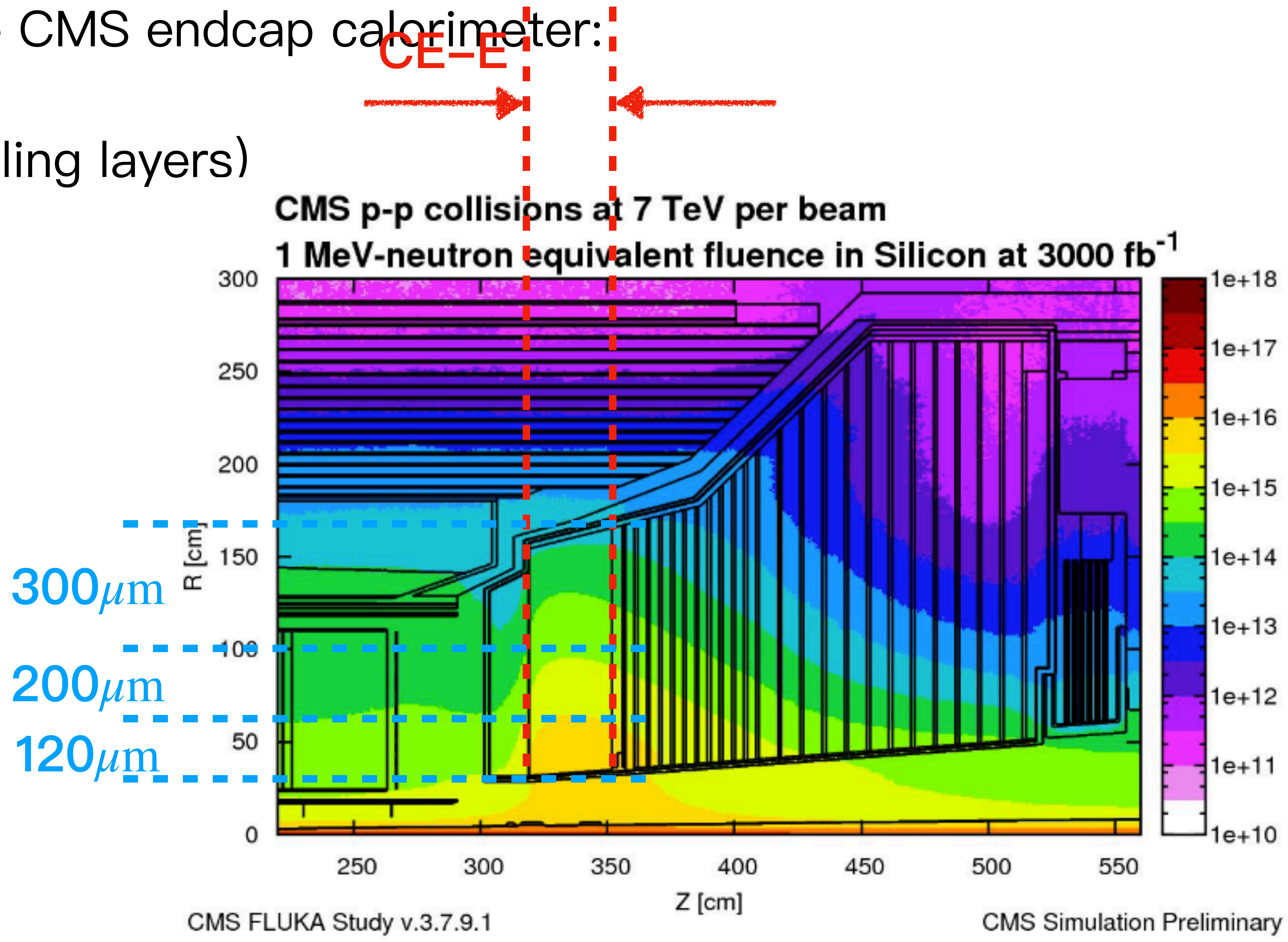
The electromagnetic compartment of the CMS endcap calorimeter:

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)	$\approx$180	$\approx$100	$\approx$70
Smallest inner radius (cm)	$\approx$100	$\approx$70	$\approx$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).

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

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

A: CMS HGCAL

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