Time reconstruction at Calorimeter Cluster

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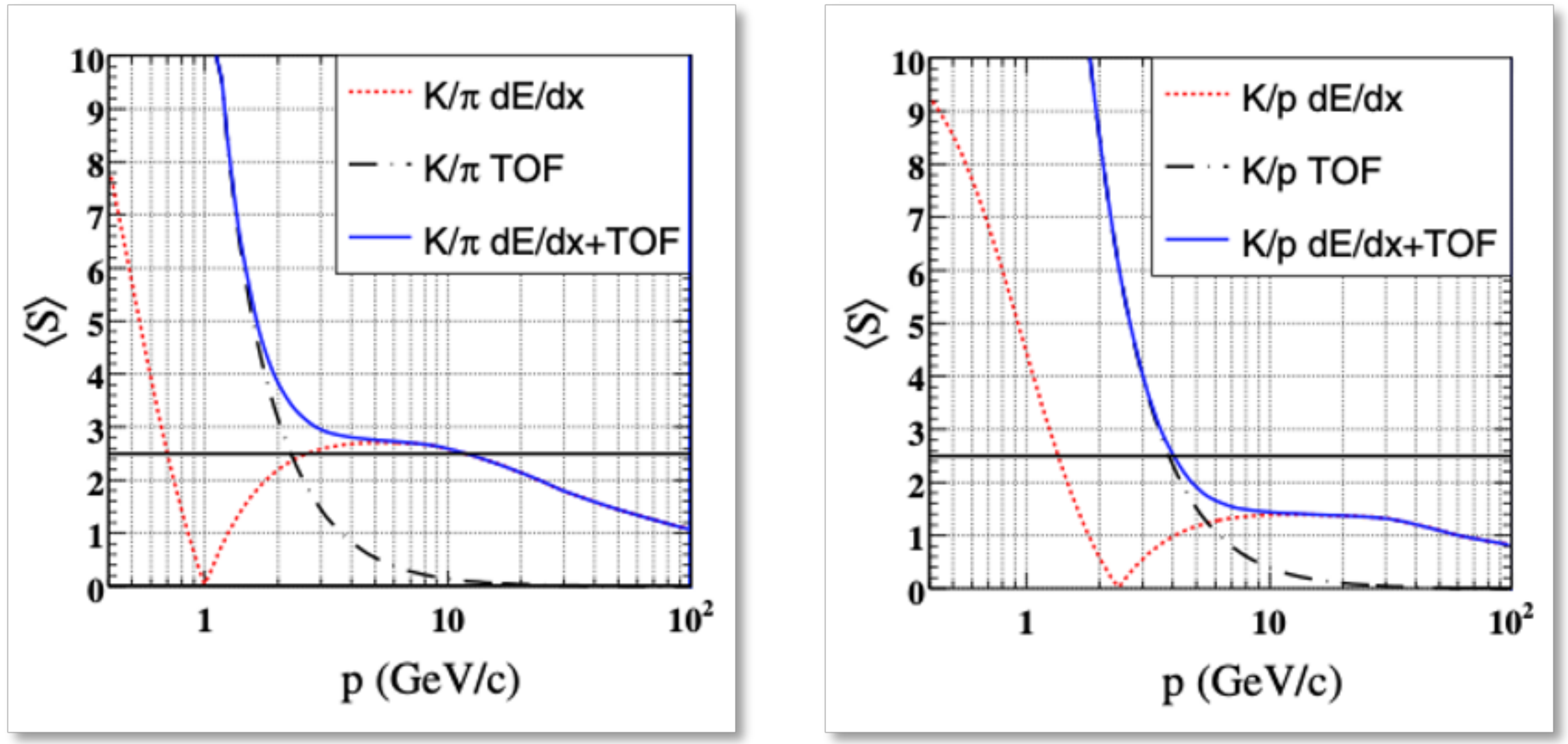
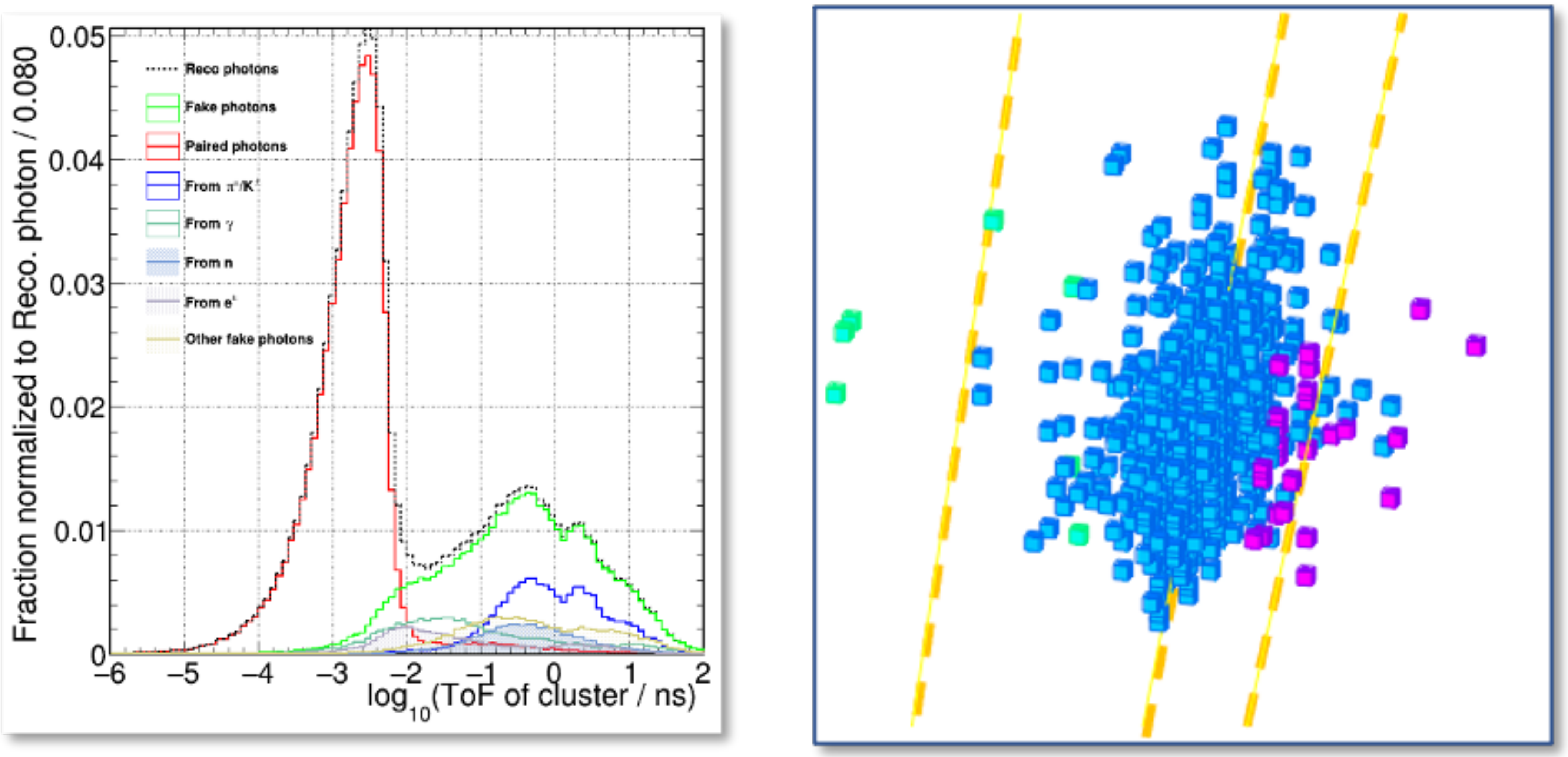
- **An effective $K^{\pm}/\pi^{\pm}/p^{\pm}$ identification:** dE/dx information has not enough separation for charged particles ($K^{\pm}/\pi^{\pm}/p^{\pm}$) in specific momentum region. **TOF information** could be a valuable compensation for it.

- **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).

Sample

CEPC baseline electromagnetic calorimeter (ECAL):

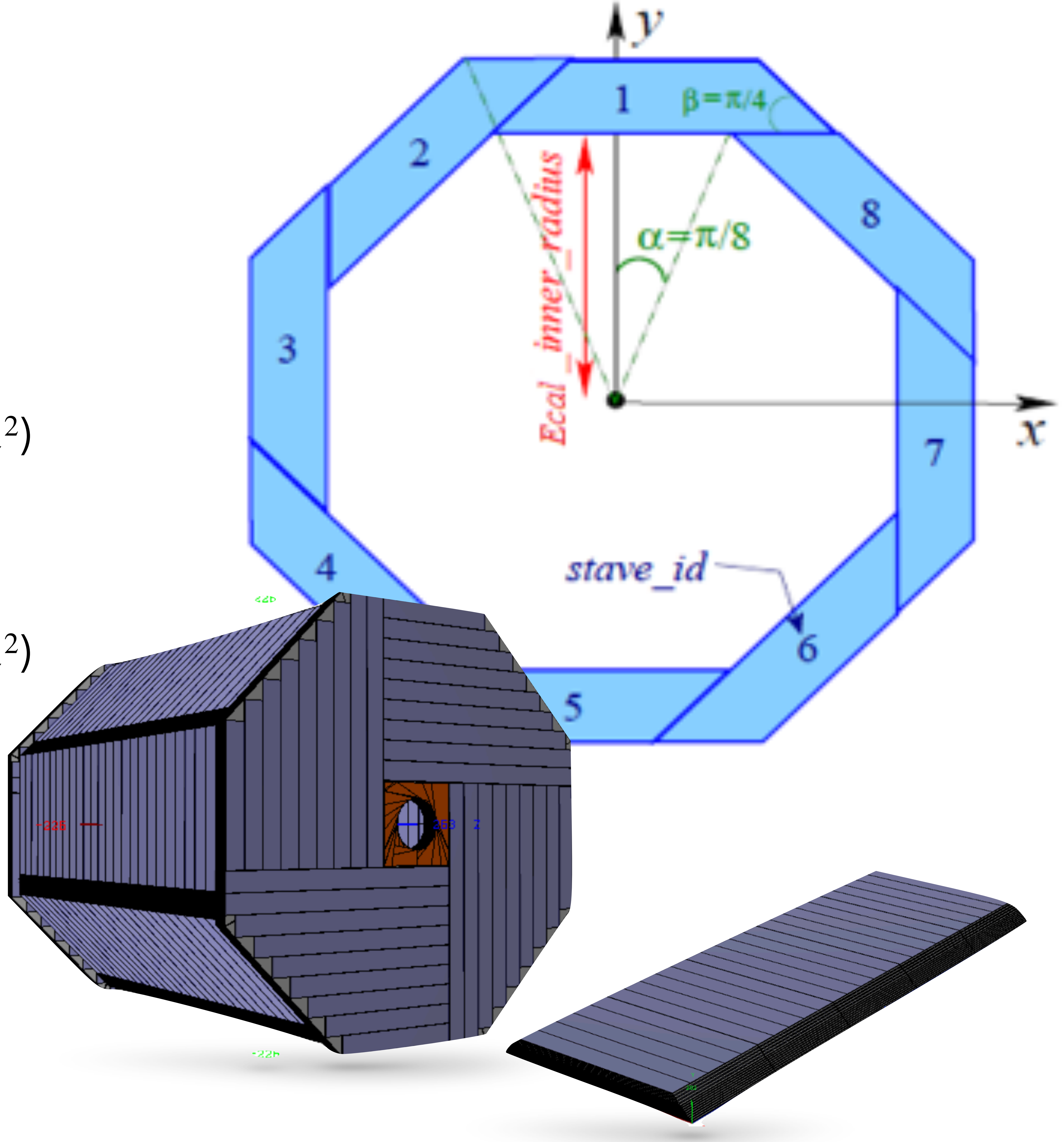
longitudinal direction: 30 (= 20 + 10) Layers

- 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, 0.1).



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

Hit Time Digitization

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.

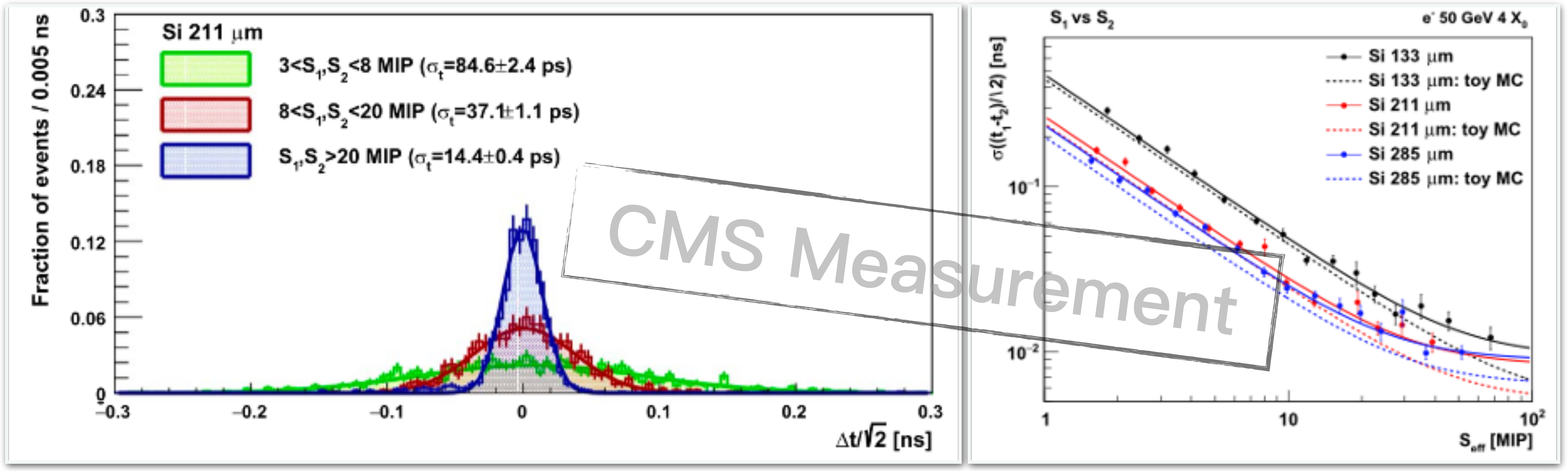
Hit time digitization in simulation:

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

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

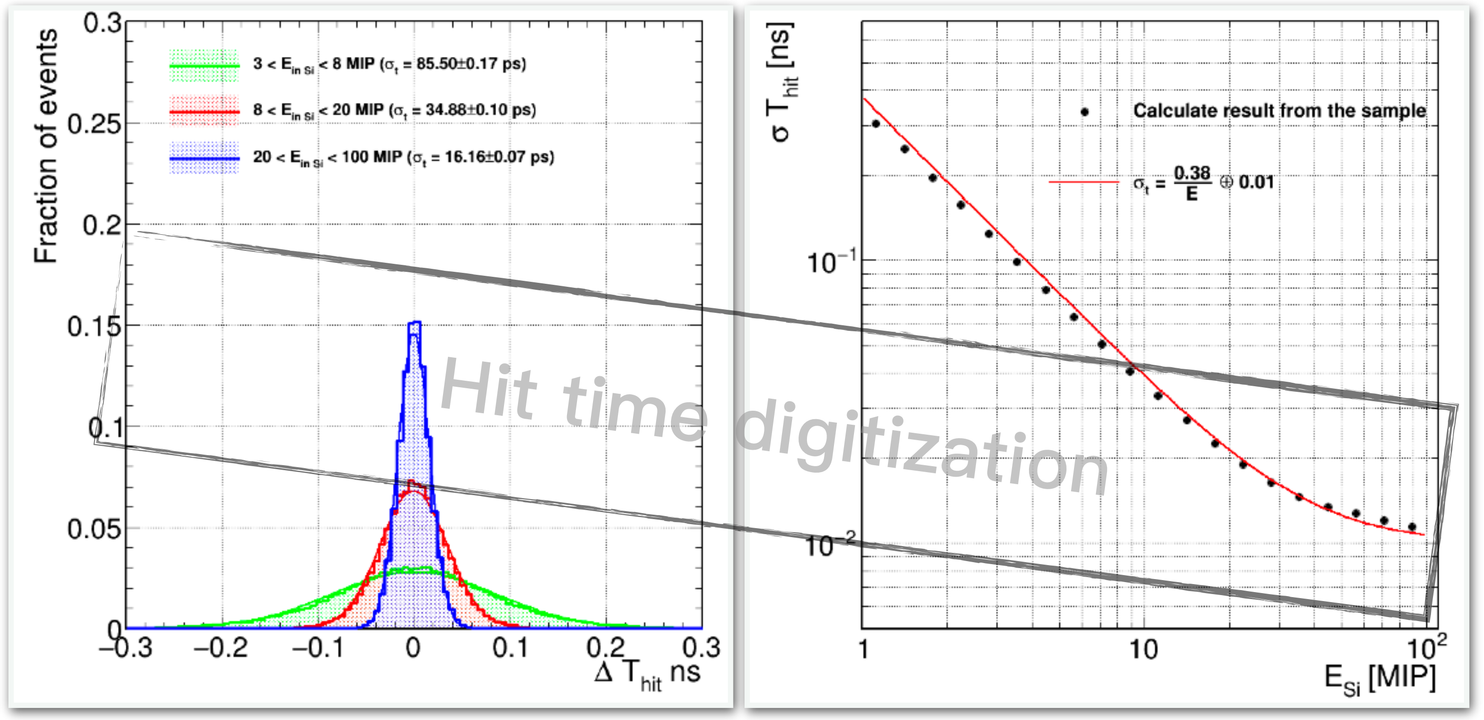
  $\sigma_{T_{hit}} = \sqrt{\left(\frac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}$.

  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.



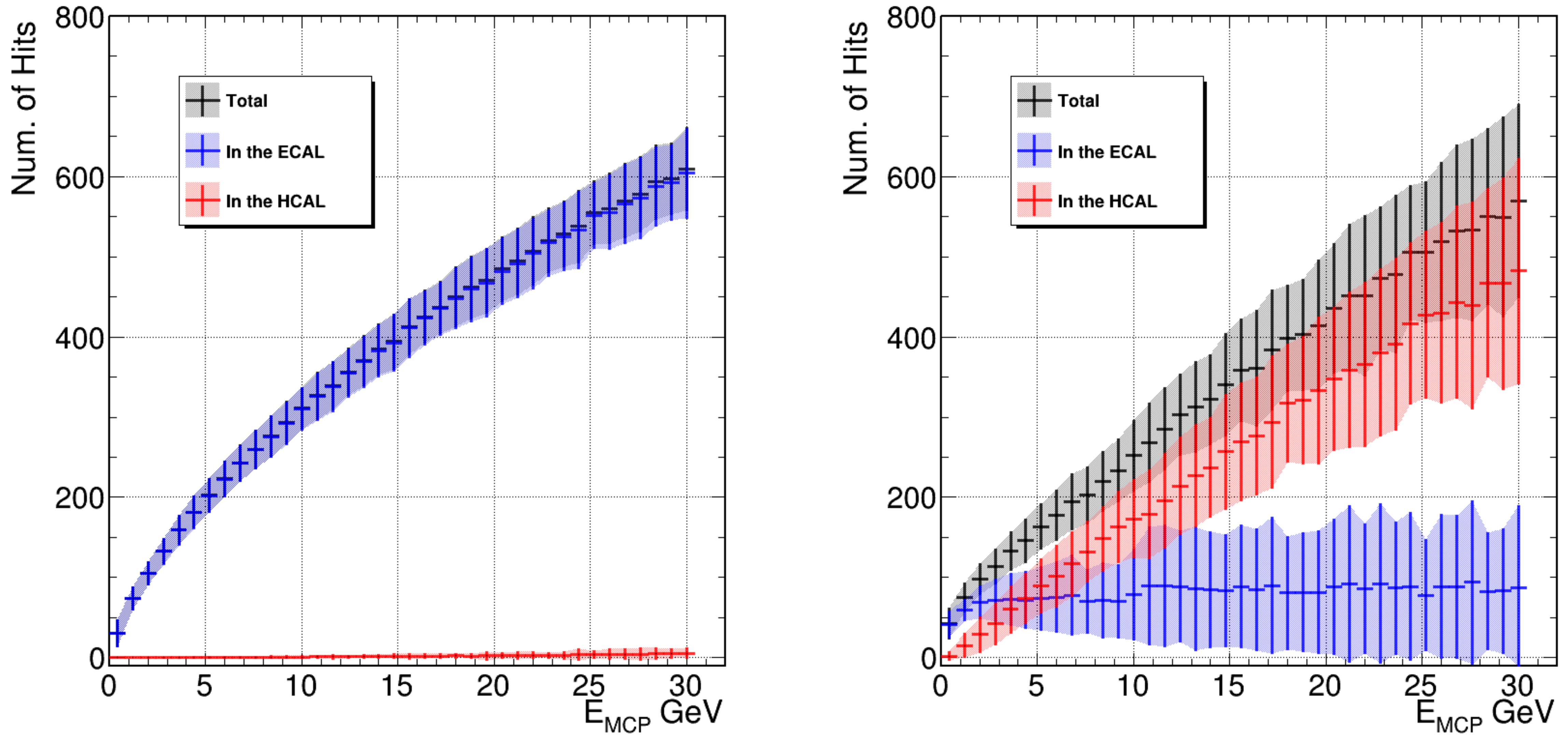
Hit time digitization result. Smeared the truth level hits with gaussian parameterized by the CMS measurement.

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).

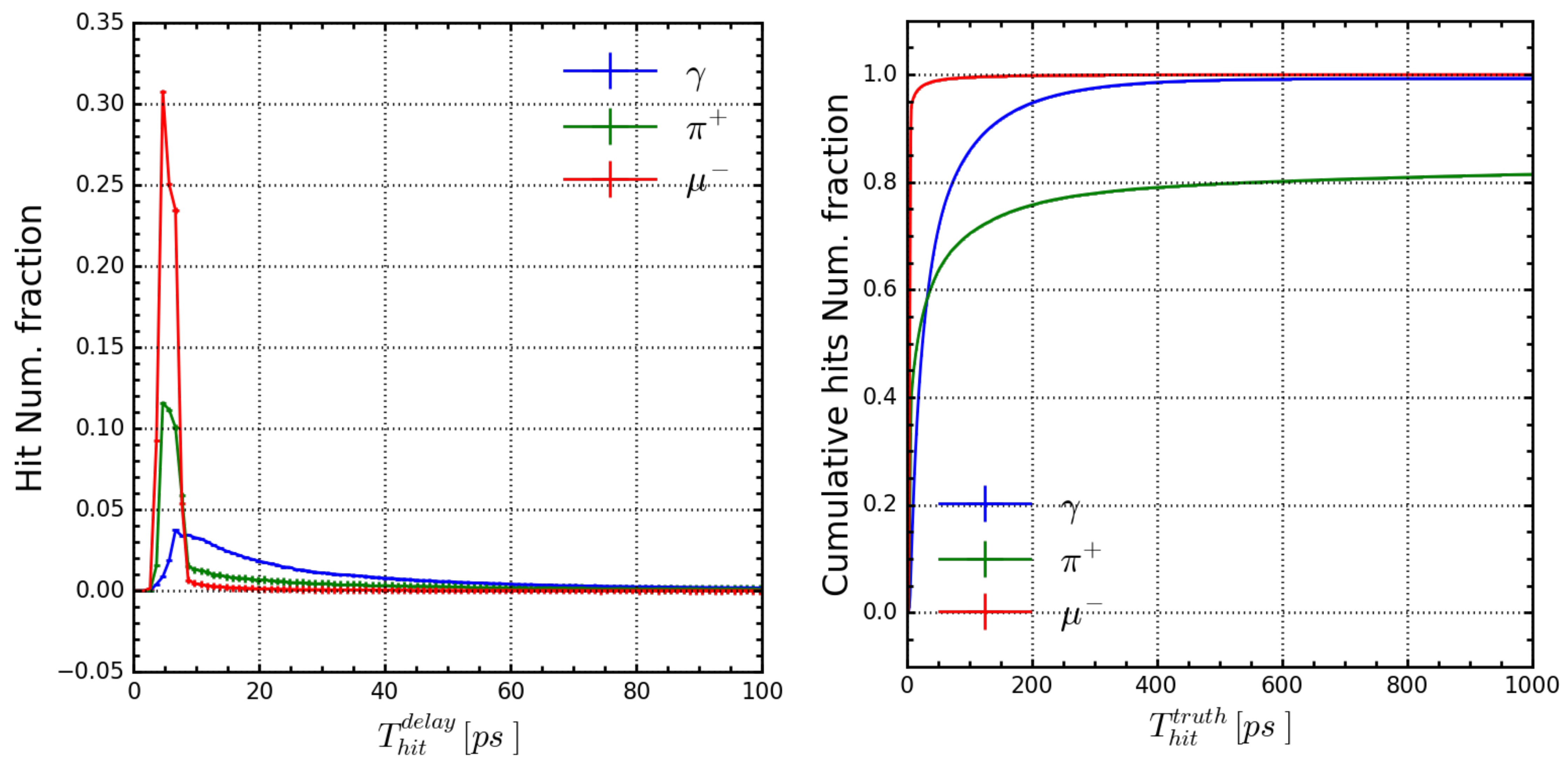
Shower Hits

Compared to EM shower, hadronic shower

- leads less ECAL hits.
- contains a more compact **fast component** and lower energy distribution, and longer **tail** with later shower hits.



Number of (left) photon; (right) π^+ hits in ECAL/HCAL versus MC truth particle energy. The error bar represents the standard deviation of the hit num.

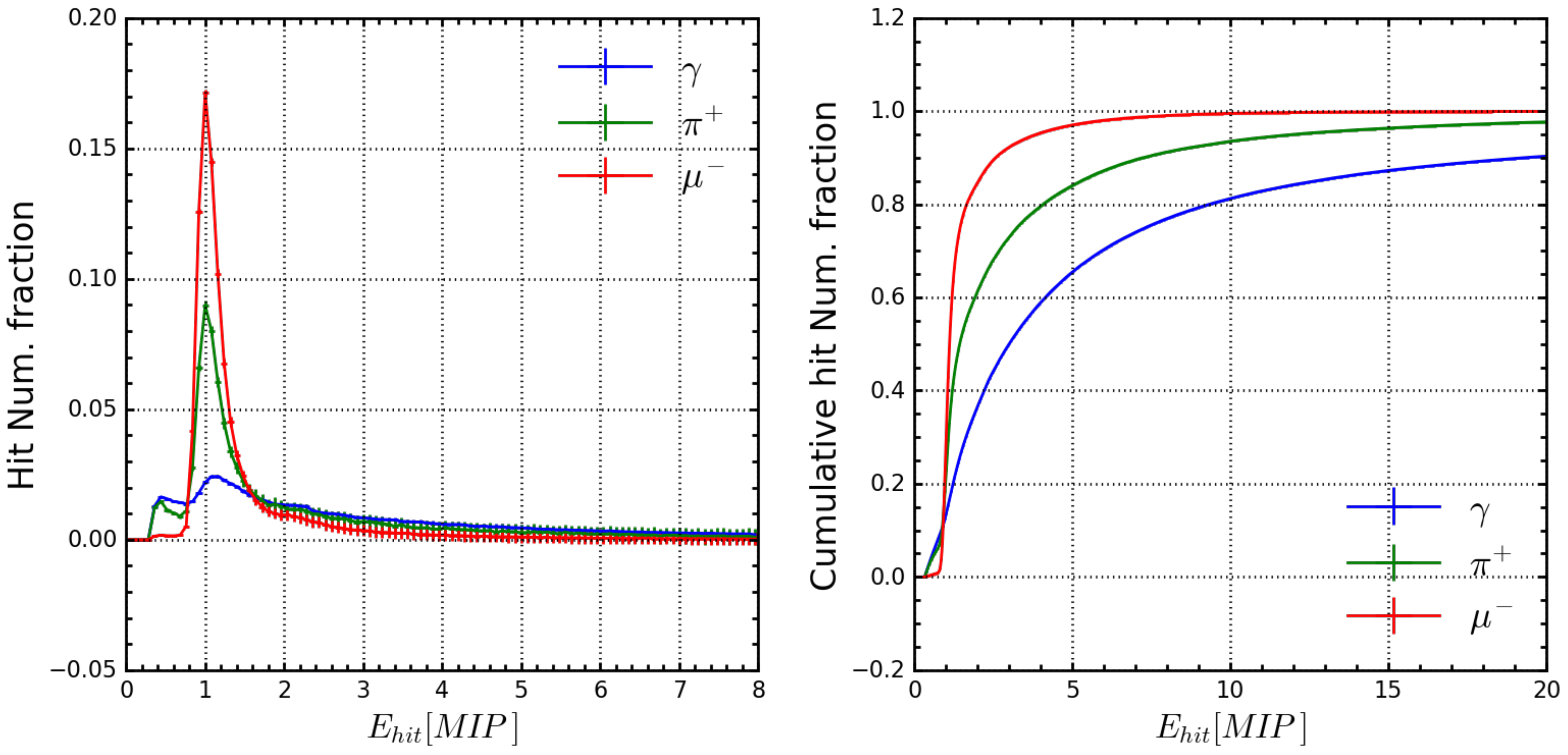


Shower hit truth time (left) distribution and (right) cumulative distribution in range of 0~100 ps and 0~1 ns, respectivly.

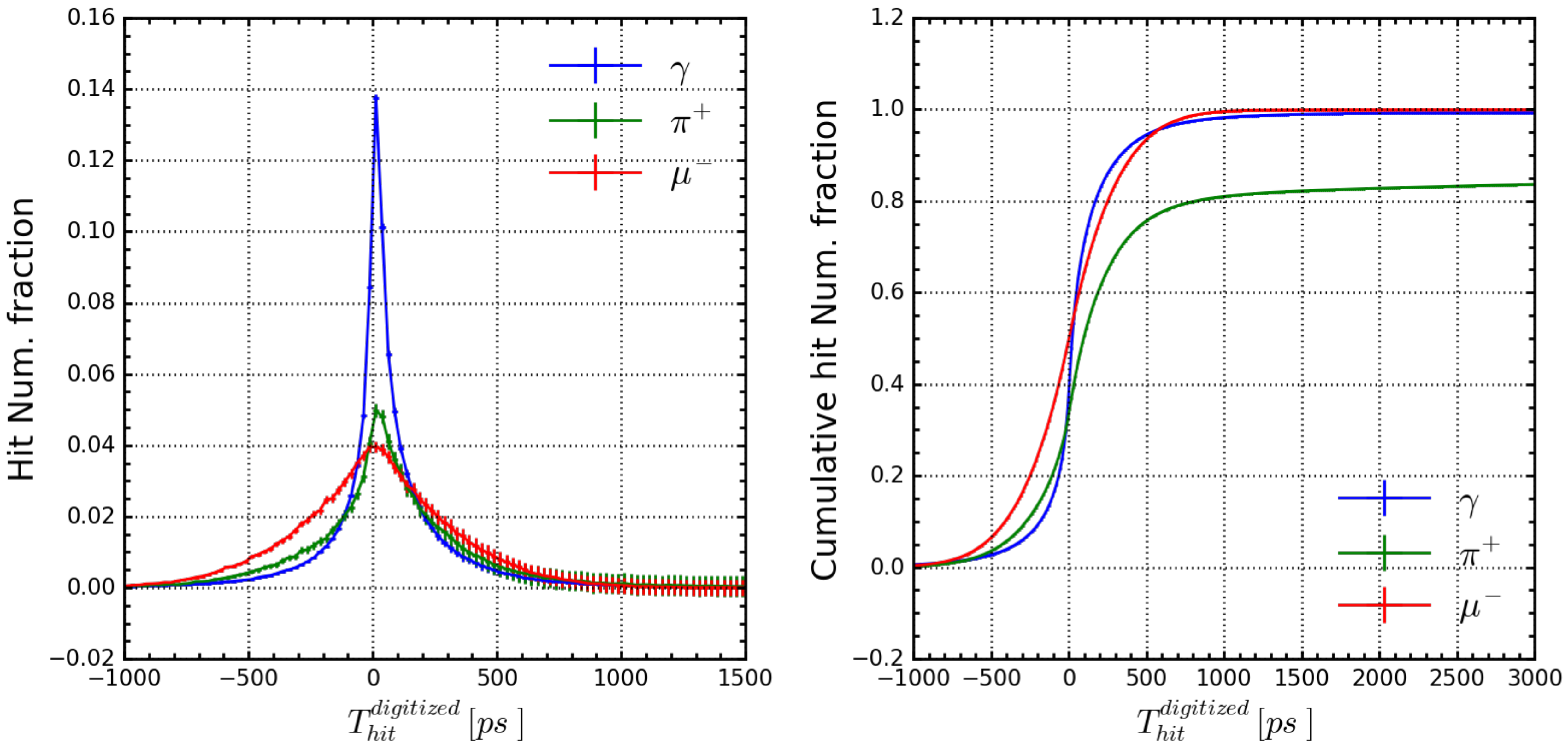
Shower Hits

Since the intrinsic timing capability of the single sensors depends on the hit energy, the digitized hit time shows distribution with a narrow peak, especially for EM showers.

The tails with later shower hits should be removed before cluster time estimation.



Hit energy distribution normalized to a MIP of ~10 GeV γ, π^+, μ^-.



Digitized hit time distribution of ~10 GeV γ, π^+, μ^-.

Time Reconstruction Algorithm

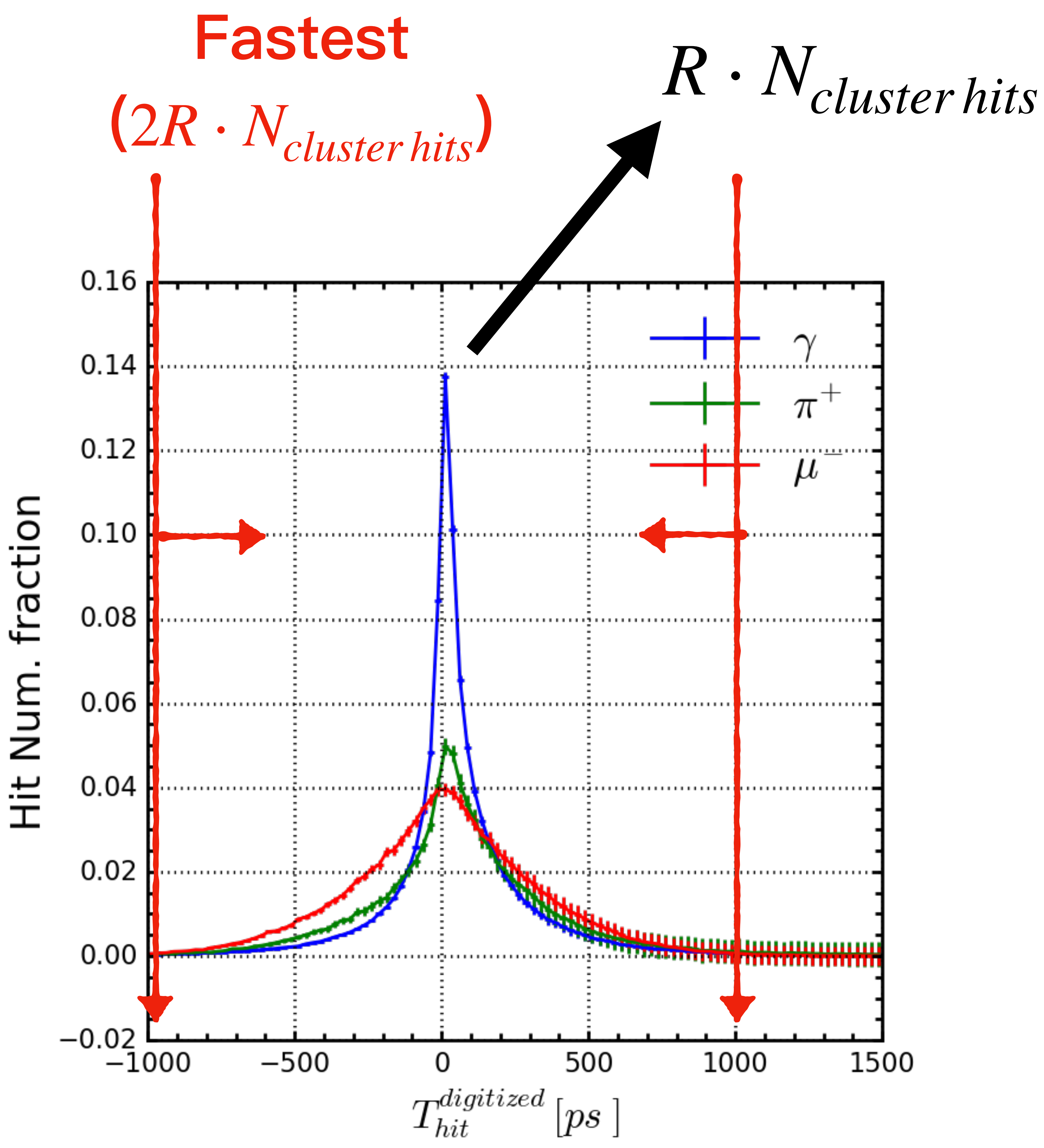
A fraction mean cluster TOF estimator:

1. Record the digitized ECAL hits

2. Sort the hits according to the digitized hit time

3. Define a fraction: **R**

4. Take the fastest $(R \cdot N_{cluster\,hits})$th hit time as the cluster ToF estimation.
   (P.S. When $R < 0.5$, it is equivalent to take the **median** time of the fastest $(2R \cdot N_{cluster\,hits})$ hits as cluster ToF estimation.)

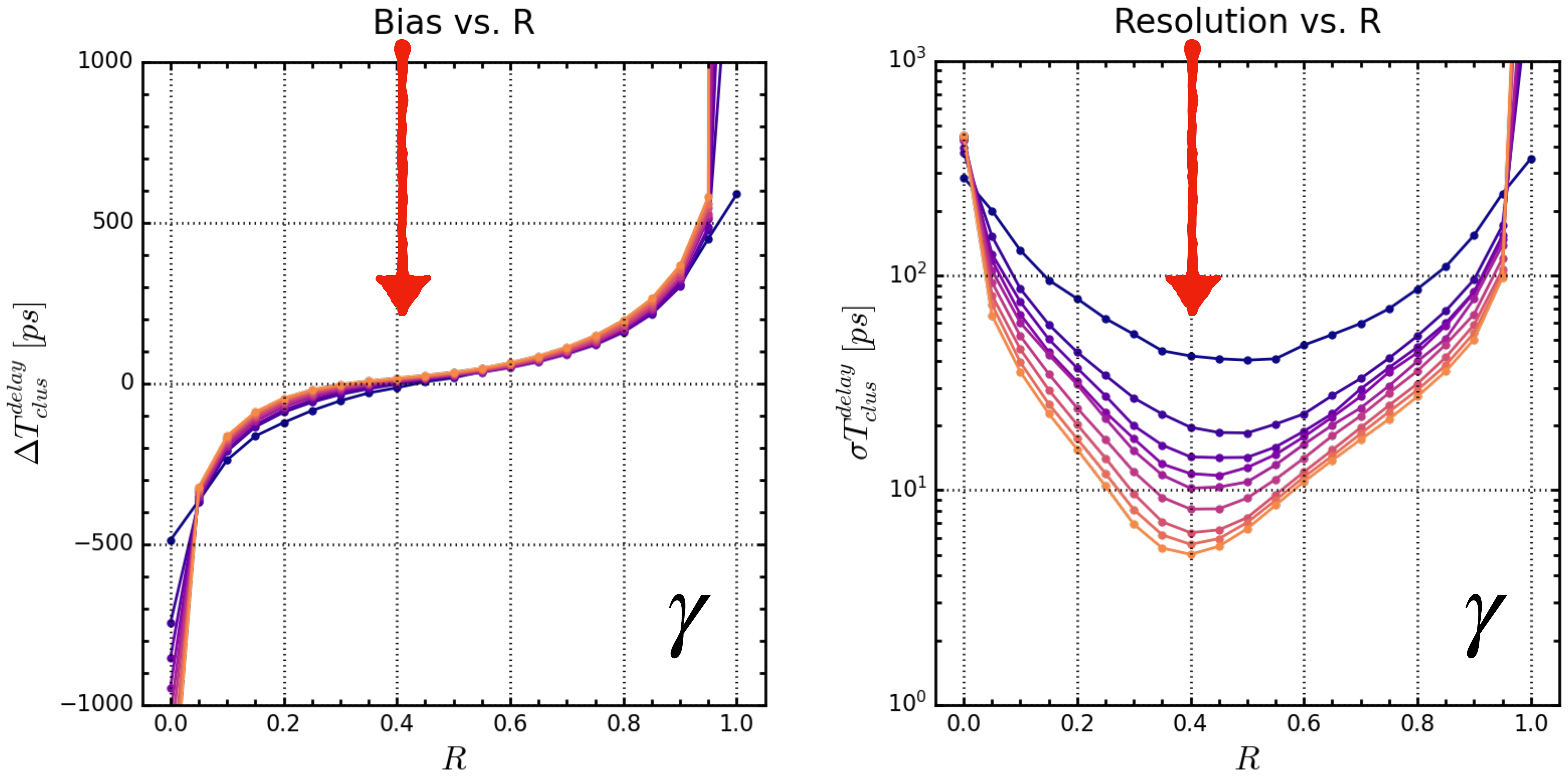


Digitized hit time

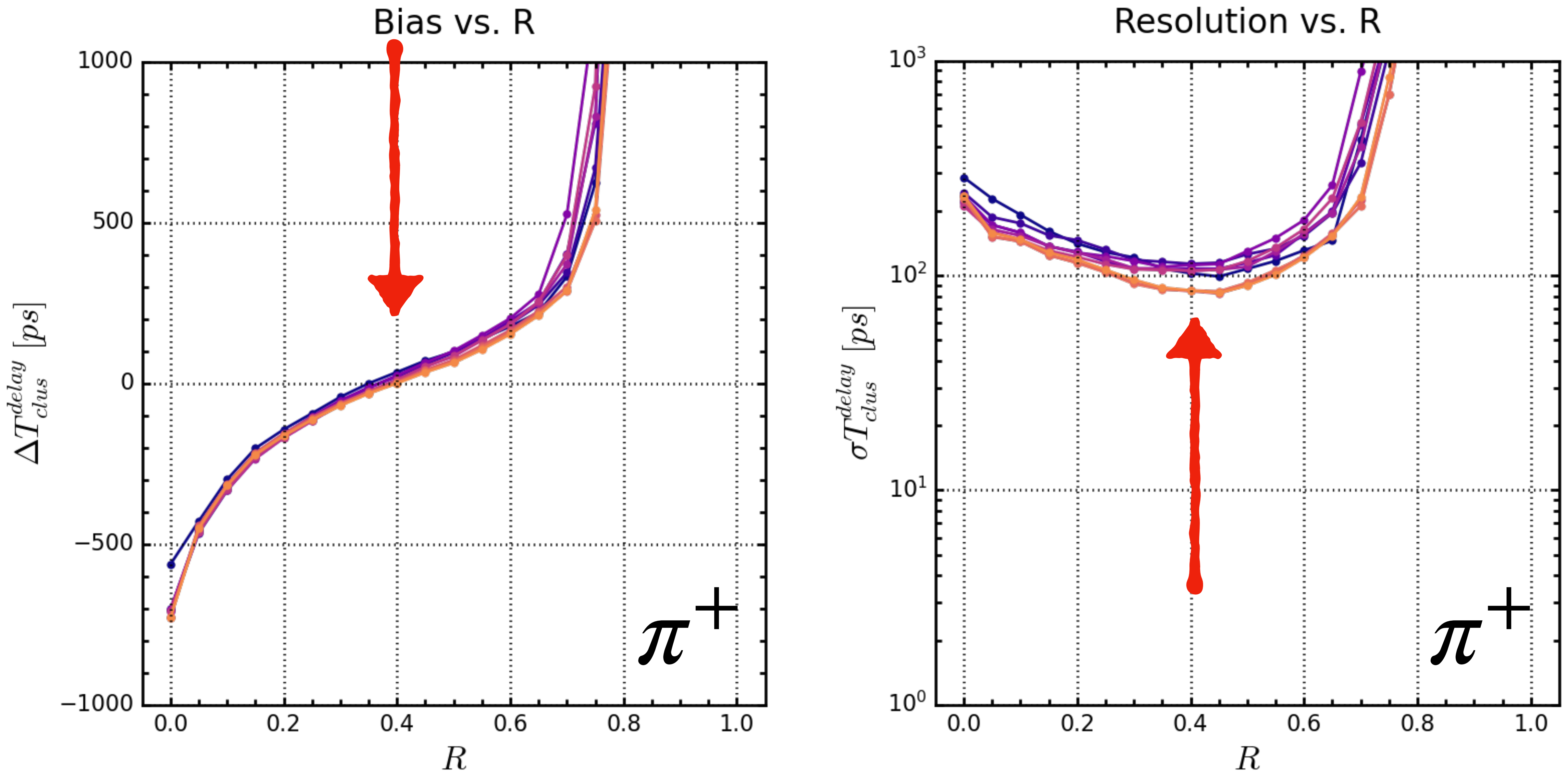
Timing Performance vs. fraction R

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.



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



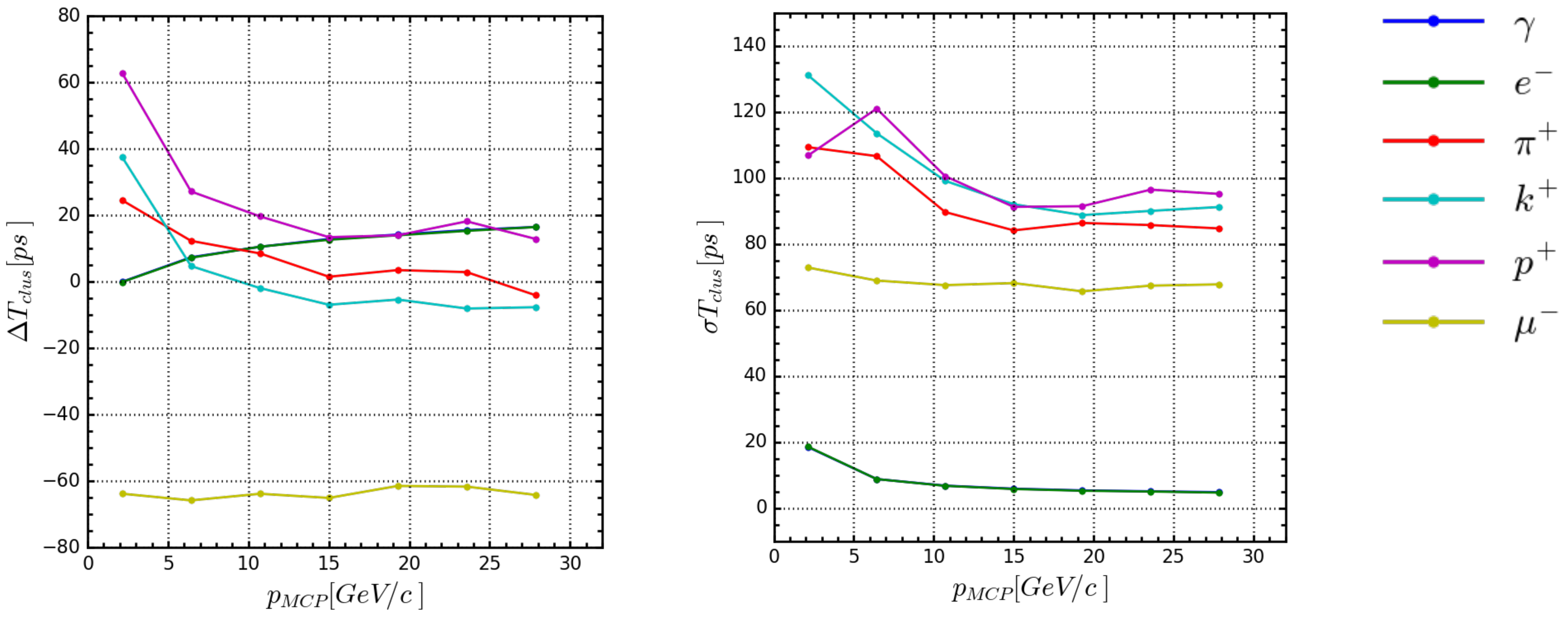
The estimation (left) bias and (right) resolution versus fraction R for perfect pion clusters.

Performance vs. incident momentum

Optimize the hits number fraction R = 0.4 for a minimum **time resolution,**

time resolution for perfect hadronic clusters: **80–140 ps**

for perfect EM clusters: **5~20 ps.**

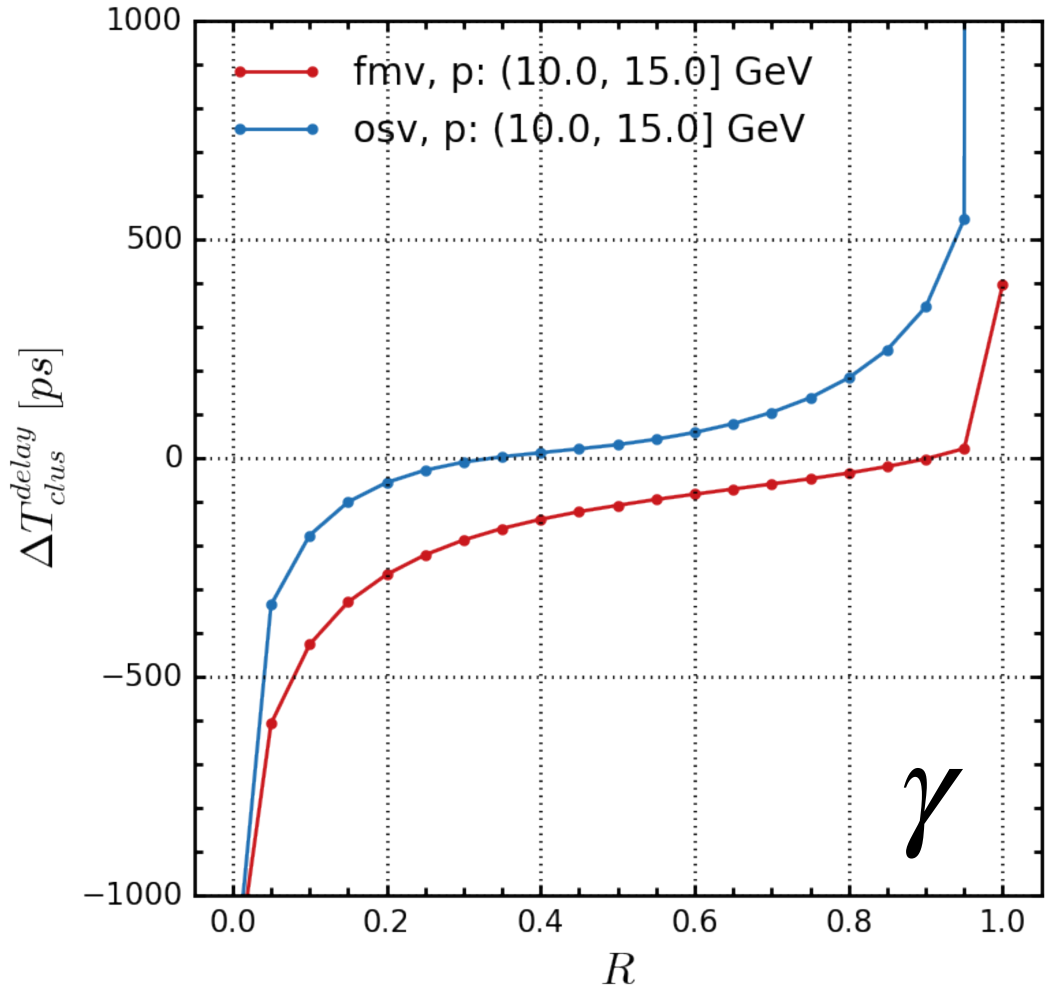


The (left) bias and (right) resolution of perfect $\gamma/e^-/\mu^-/\pi^+/K^+/p^+$ clusters versus the MC truth incident momentum.

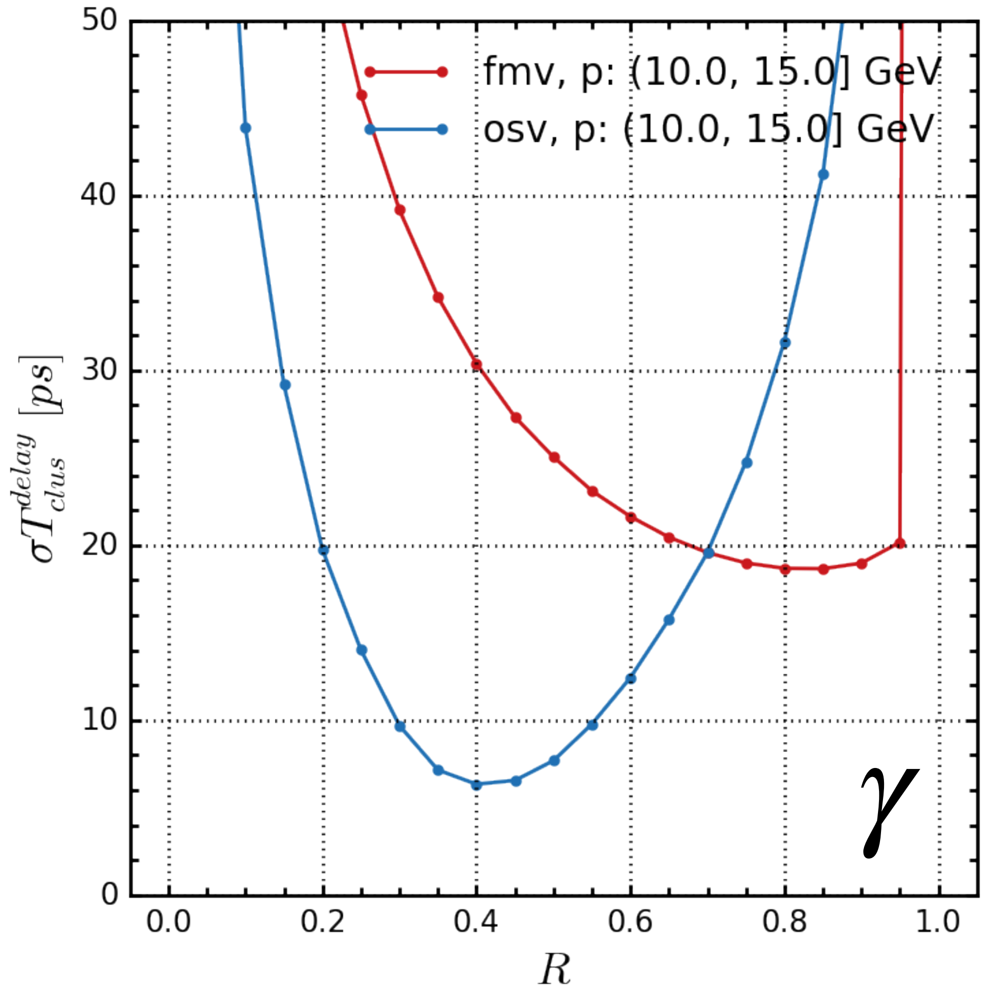
Median or Average ?

- Alternative strategy: evaluate the expectation of the fast component by average:
  - Record and sort the hit time.
  - take the **average** of the fastest $(R \cdot N_{cluster\,hits})$ hit time as the estimation.
- **Average (alternative strategy):** The average time of the fastest R*N hits.
- **Median (mentioned previously):** The single time value of the fastest R*N'th hit.

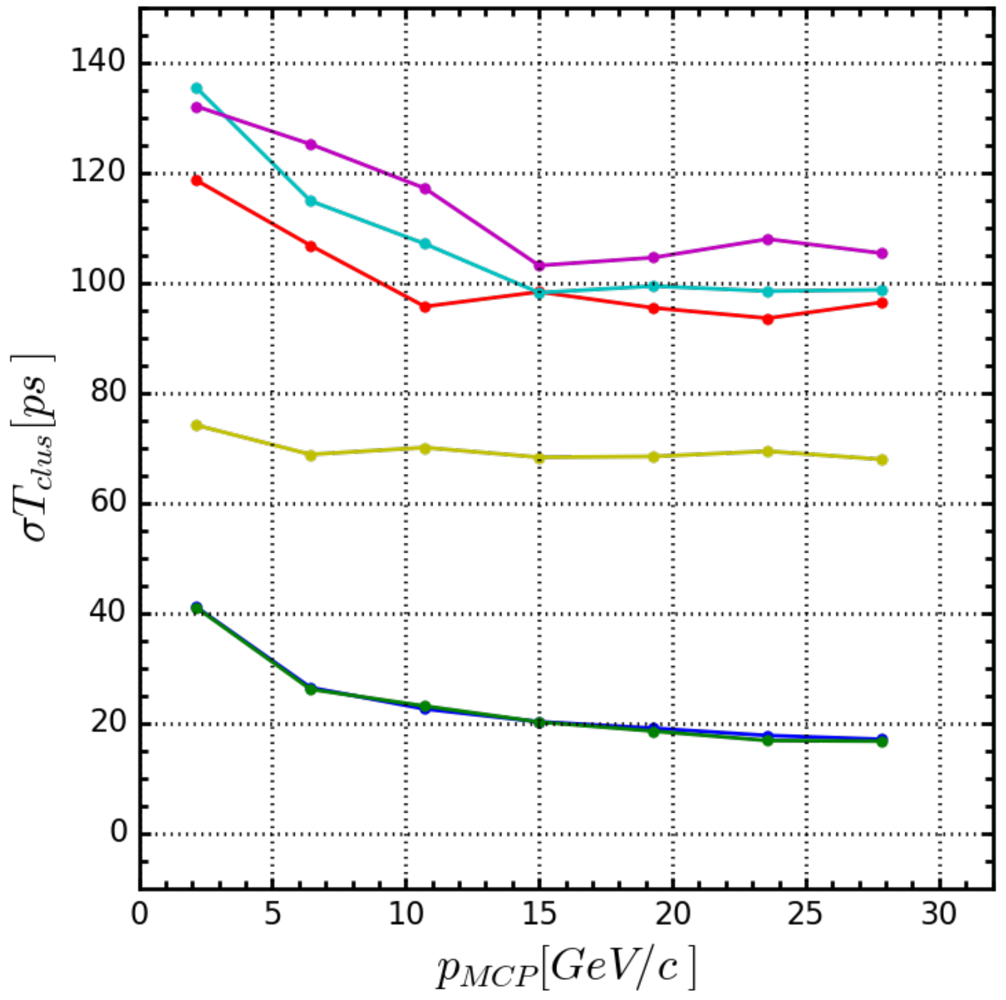
The median based estimator provide time resolution improvement by a factor of ~1.1 and **2~3.5** for hadronic and EM showers, respectively.



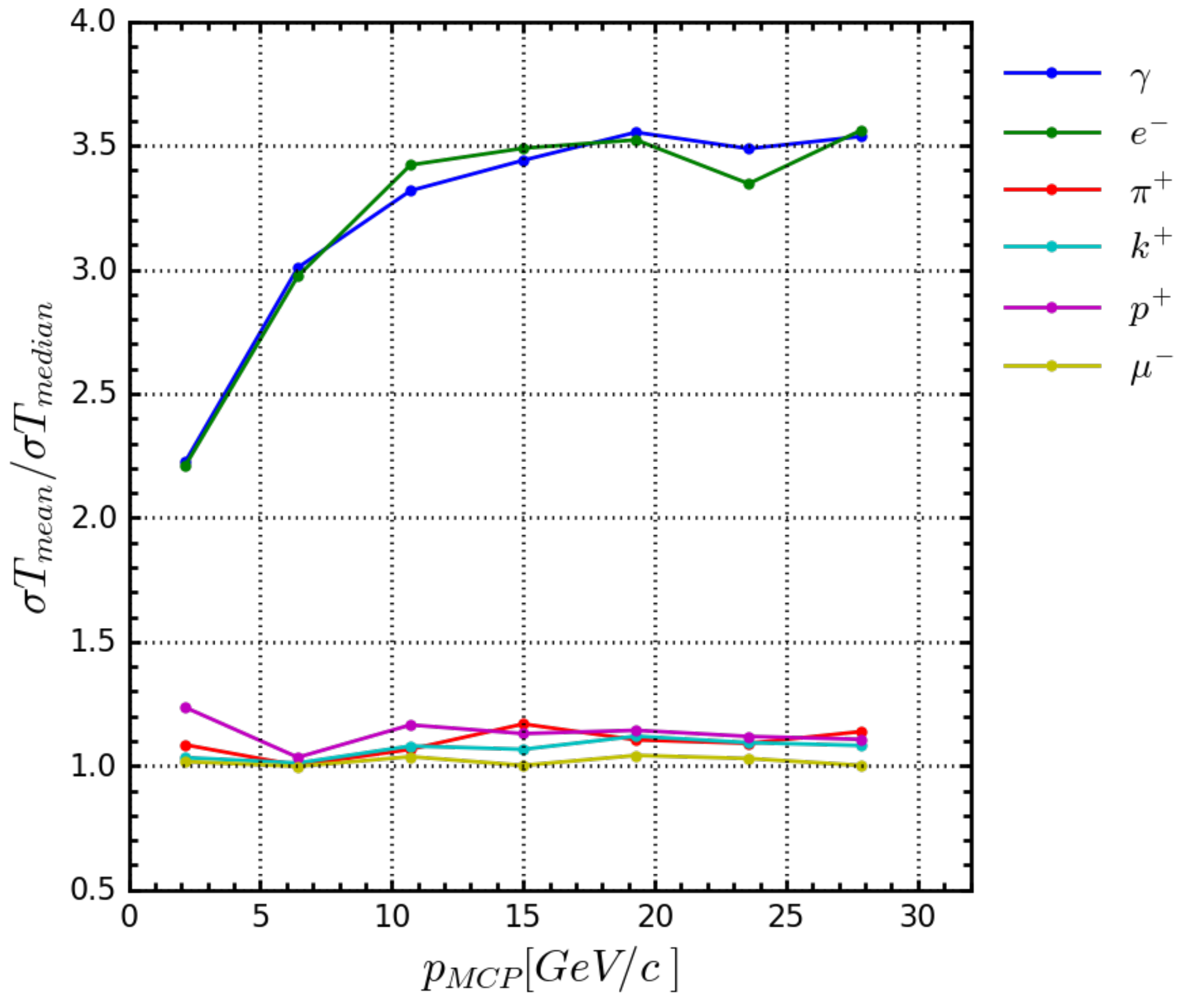
Estimator bias comparison



Estimator resolution comparison



Time resolution with average based estimator



Time resolution ratio of average and median based estimator

Further exploration:

What’s the cluster time resolution with:

Q: realistic clustering?

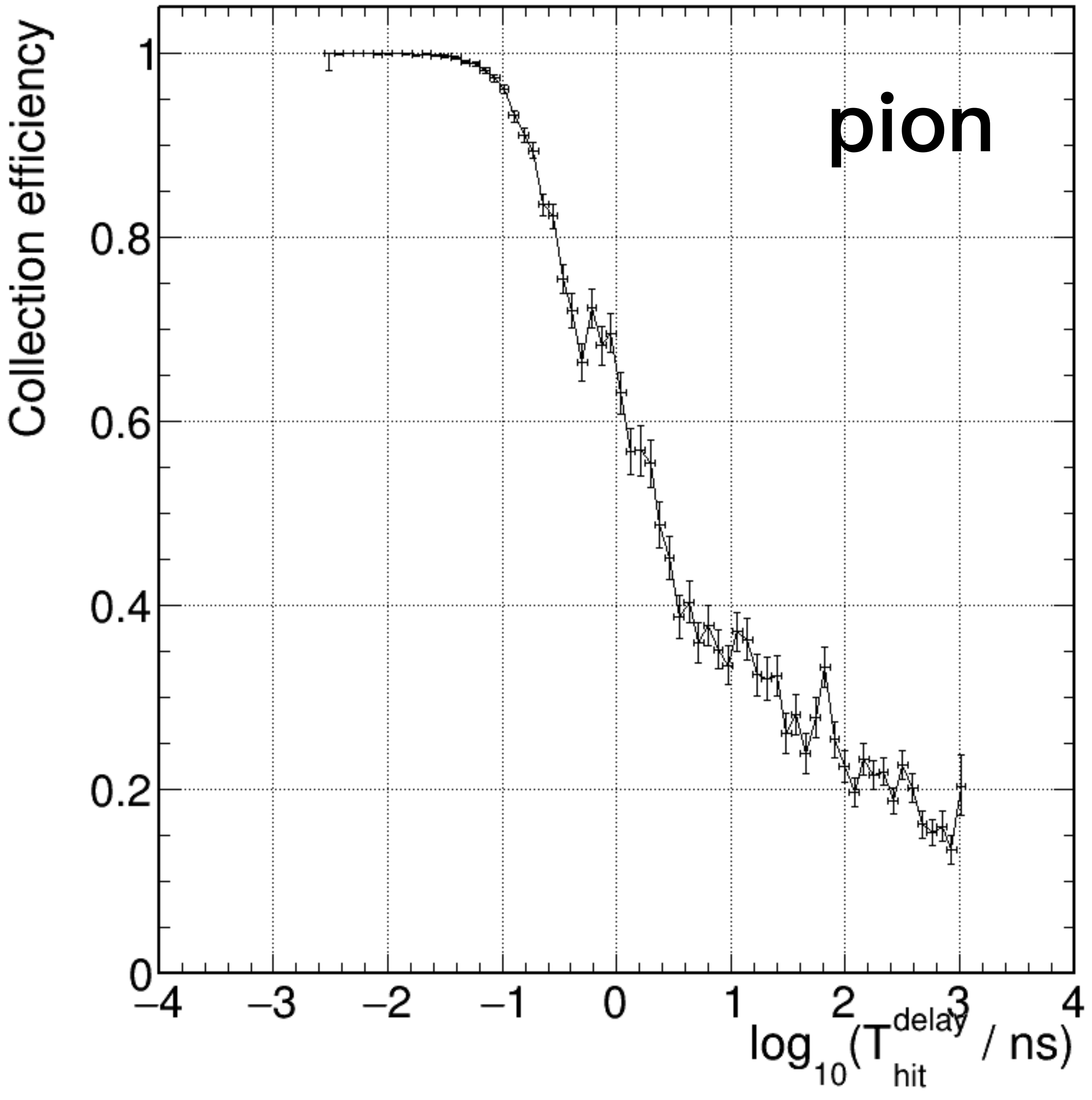
for example: Arbor?

Q: different hit time resolution

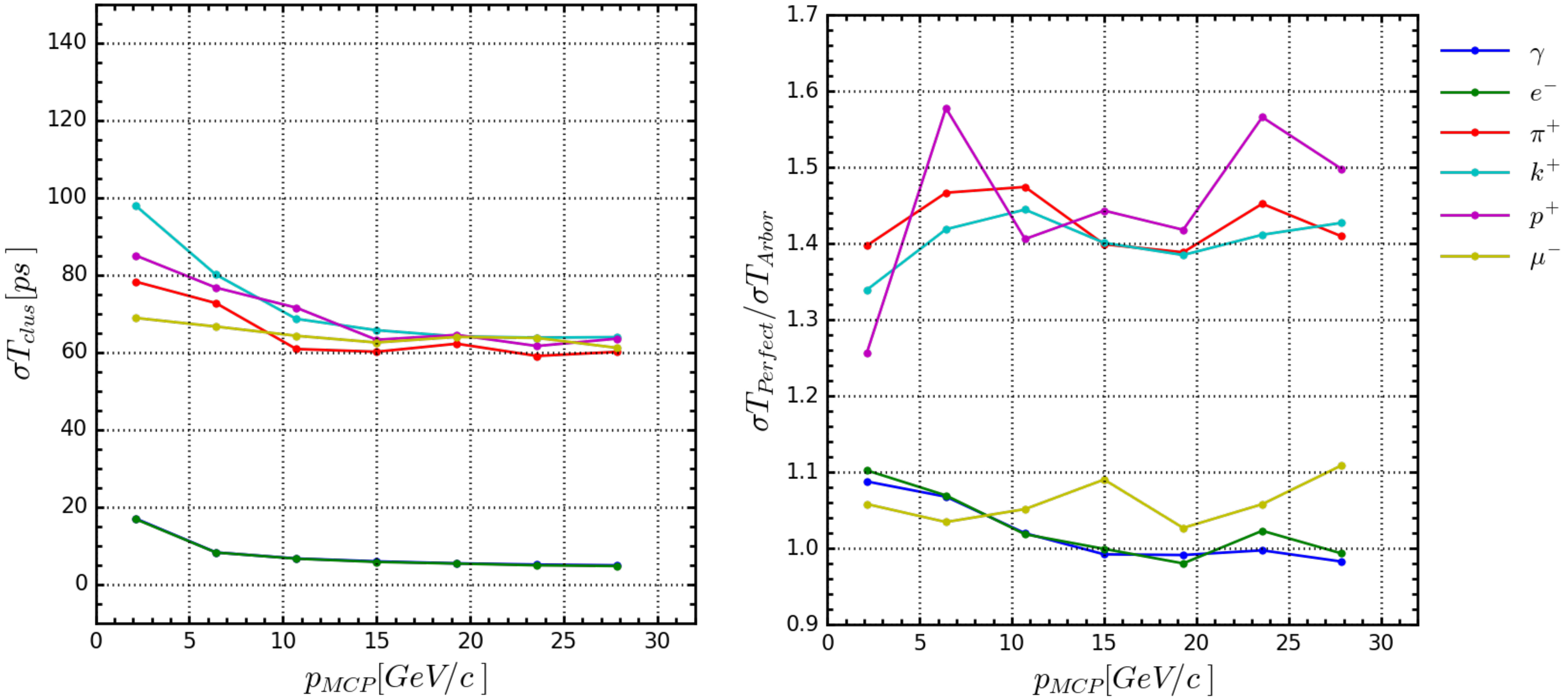
Discussion A : Impact of Realistic Clustering

Arbor clustering module removes isolated hits, which correspond later hit time.

Arbor with parameters optimized for the CEPC improves the time resolution of EM and hadronic clusters by 0~10% and 40%, respectively.



Hit collection efficiency of Arbor for π^+ ECAL hits.



The time estimation resolution for (left) perfect, (middle) Arbor clusters and (right) their ratio as a function of MC truth momentum.

Further exploration:

What's the cluster time resolution with:

A: **Impact of realistic clustering**

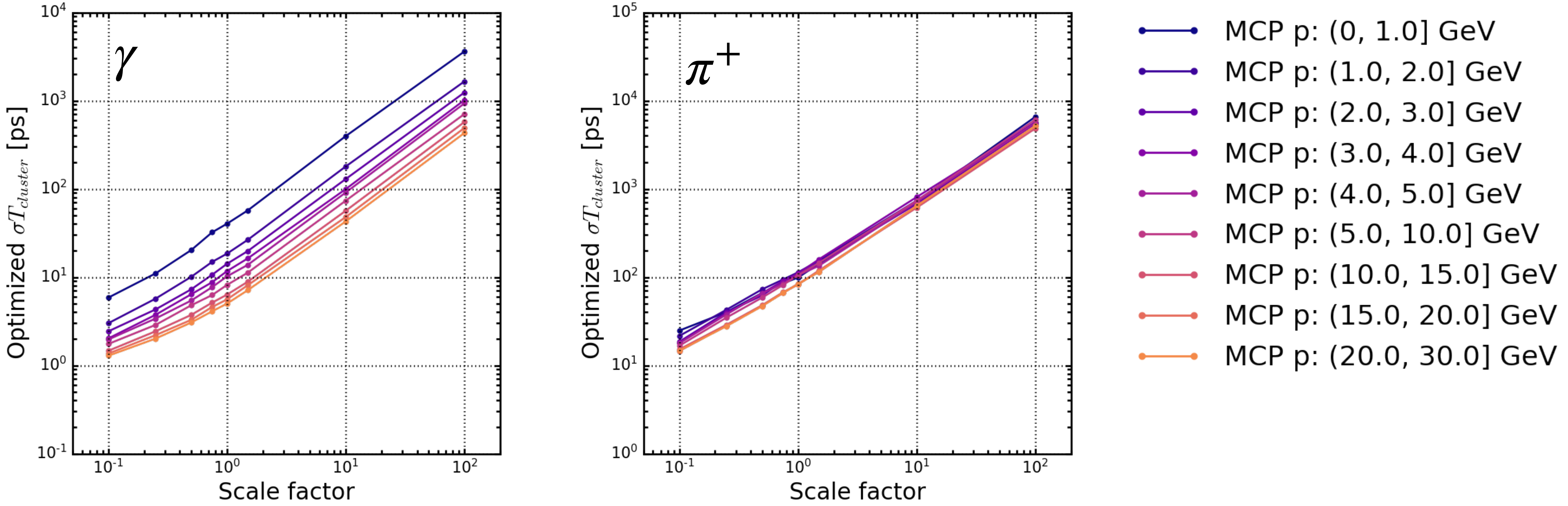
Arbor improves time resolution by 0~10%/40% for EM/hadronic cluster.

Q: **different hit time resolution**

Discussion B : Scaling with Intrinsic Hit Time 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 cluster time resolution versus the intrinsic hit time resolution in (left) photon and (right) pion samples.

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!

Conclusion

- A brief cluster TOF reconstruction algorithm based on median hit time are implemented.
- **Cluster Time:** Under CEPC baseline setup and current silicon sensor timing technology, 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 ~ 140 ps.
- **Median based** time estimator could improve the EM cluster TOF resolution by a factor of ~3 from the **average based** one.
- **Arbor clustering module** improves the EM (hadronic) cluster time resolution by a factor of ~1.1 (1.4)
- The cluster time resolution is linear to the **intrinsic hit time resolution**.

Thanks for your attention

Back Up

BackUp. time resolution of CMS silicon sensor

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

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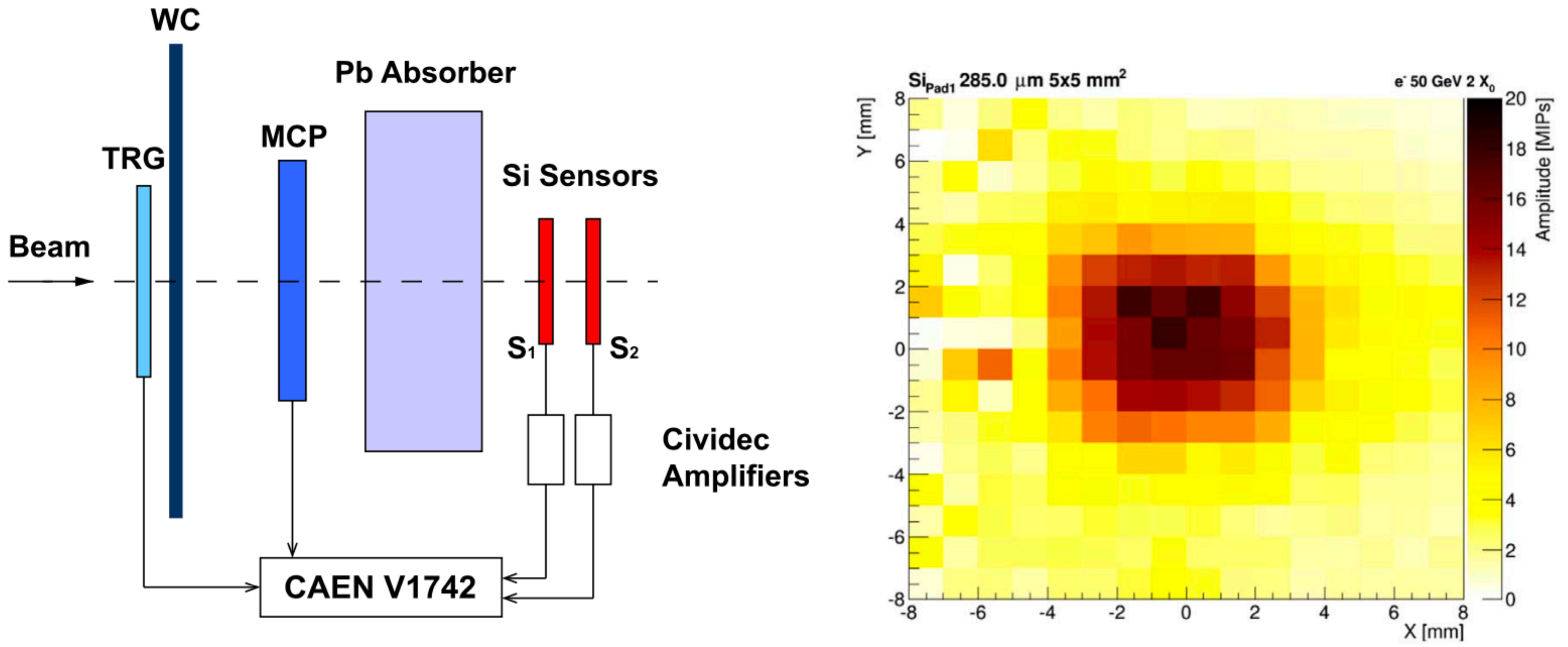


Fig. 1. The schematic of the layout displays the main components and the readout scheme on the left. Downstream of the trigger counter (TRG) and wire chambers (WC), a micro-channel plate (MCP) photomultiplier tube was positioned to provide a timing reference in front of the silicon sensors. Various lead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

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

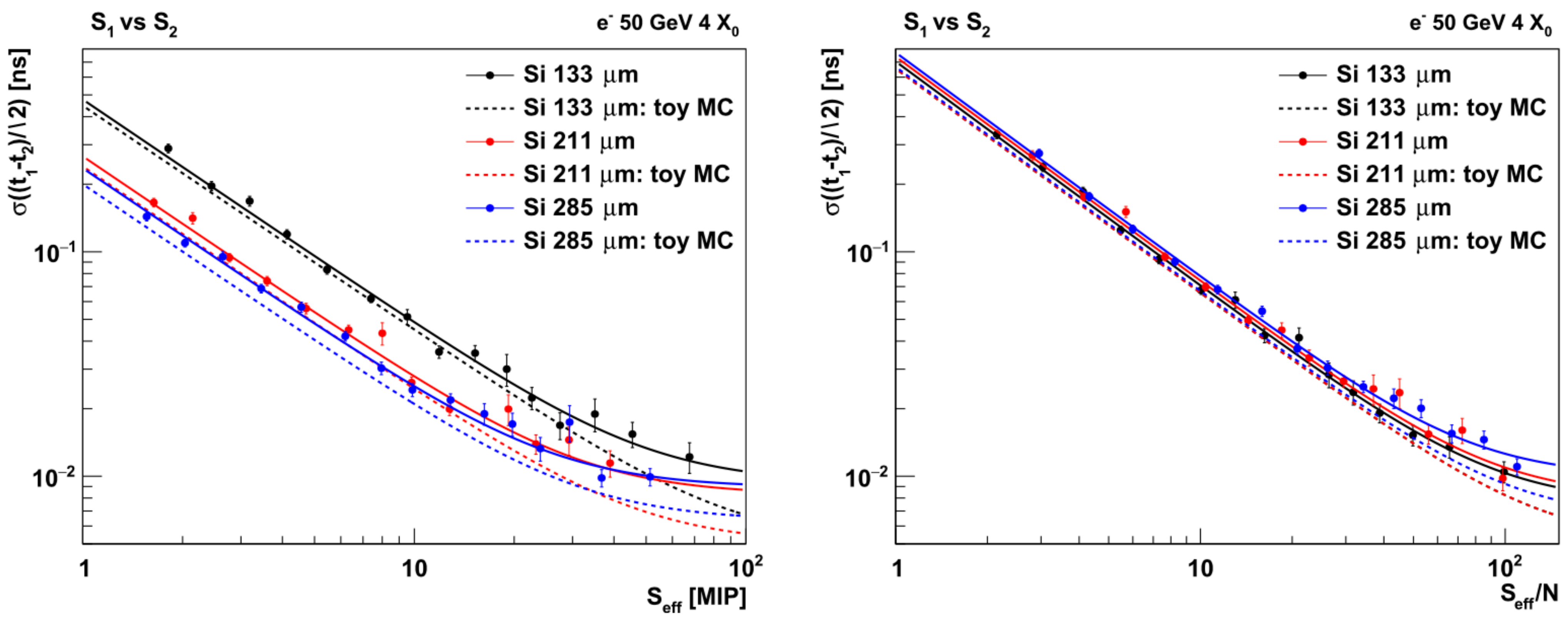


Fig. 8. The timing resolution based on two silicon sensors as a function of the effective signal strength in units of MIPs (left) and as a function of the signal-to-noise ratio (right). The fitted resolution functions with a noise (A) and a constant term (C) are also shown as solid lines. The dashed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

BackUp. Detail of expected truth cluster TOF

The B Field is turned off, and the momentum of the particles is fixed along y axis, so the flight distance L ~ 1847 mm (inner radius of ECAL)

- **Expected** cluster TOF:

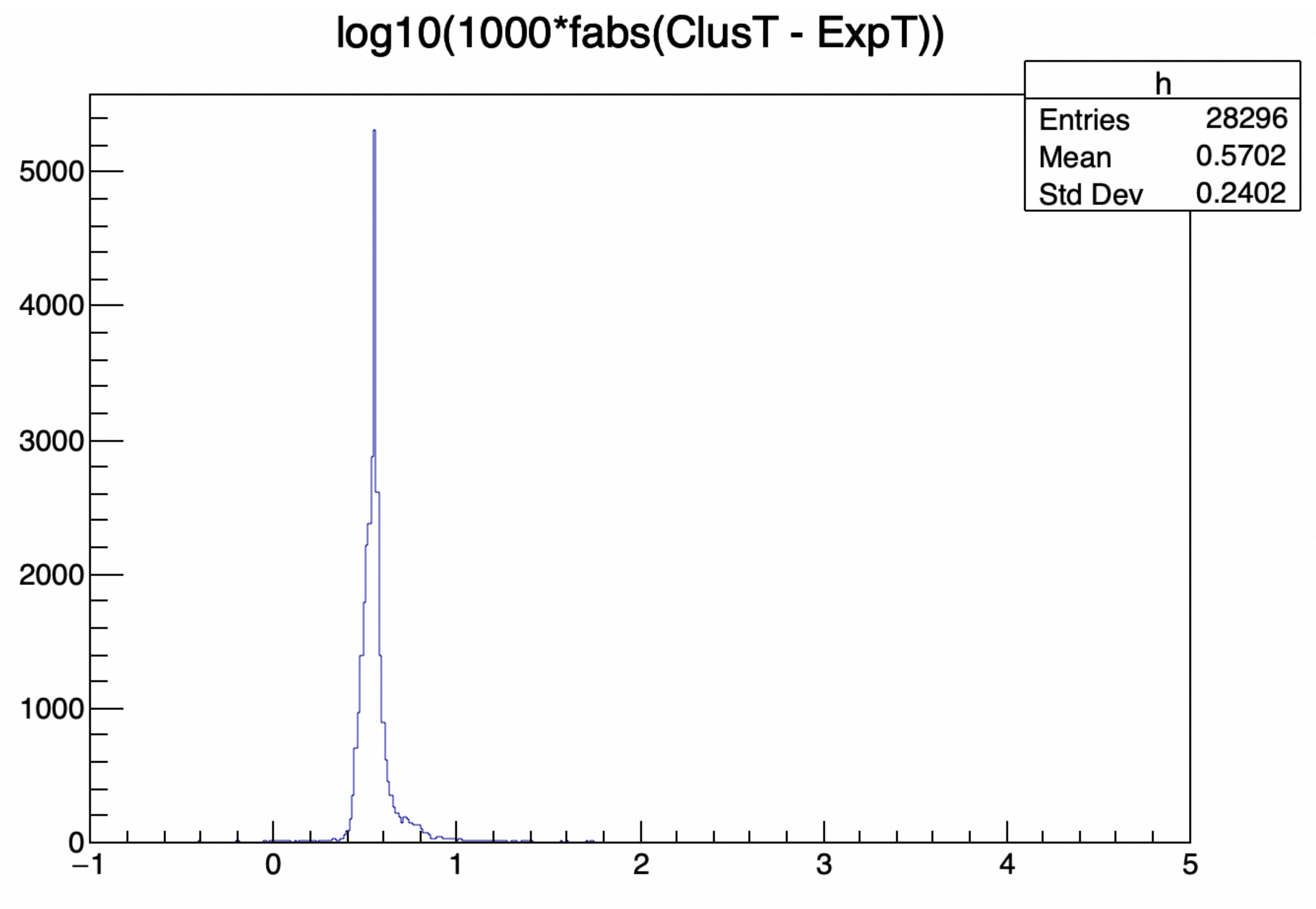
$$T_{expect}(p) = L/c \cdot (\frac{\sqrt{p^2 + m^2}}{p} - 1)\,.$$

- The **fastest truth hit time** in the cluster:

$$T_0 = min\{T_{hit_i}^{delay}\}, i = 1,2,...,N_{hit}$$

The difference:

$$|T_0 - T_{exp}| \sim 0.6\,ps$$



The difference between expected cluster TOF and fastest truth hit time (by pico second), in pion sample.

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

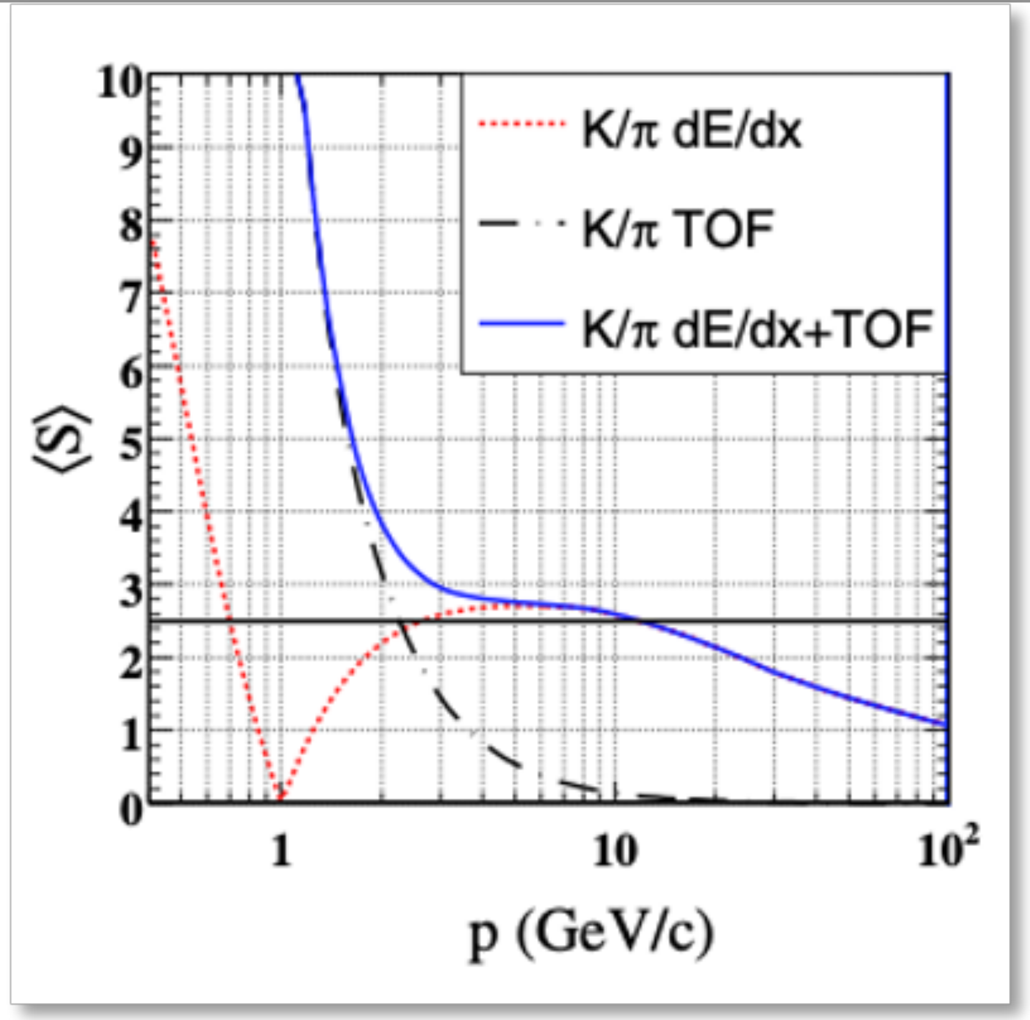
- The separation power of particle A and B:

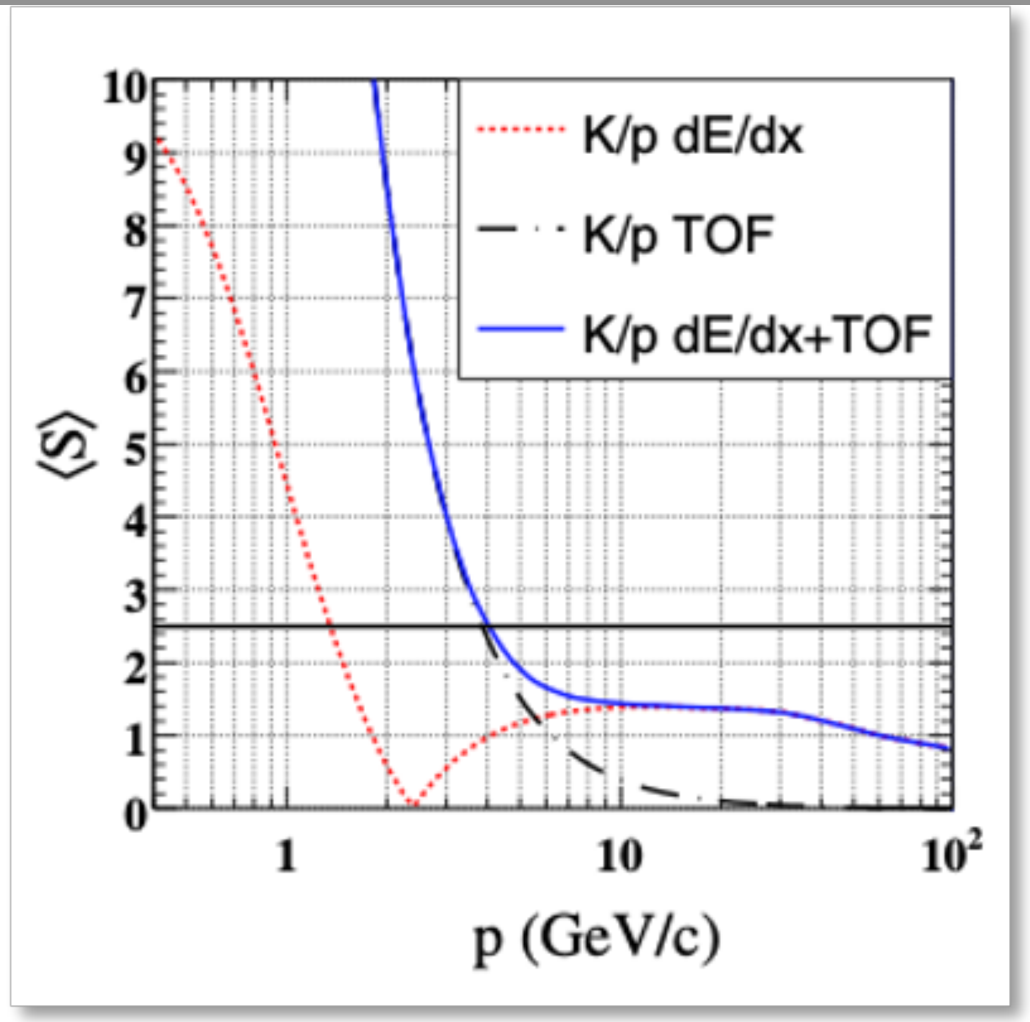
$$S_{A,B}|_{p\in bin_i} = \frac{\left| < T_{bias,A} >_{bin_i} + T_{expect,A} - < T_{bias,B} >_{bin_i} - T_{expect,B} \right|}{\sqrt{\sigma^2_{T_A} + \sigma^2_{T_B}}}$$

With the flight distance of **shortest straight line distance** from IP to the ECAL front face:

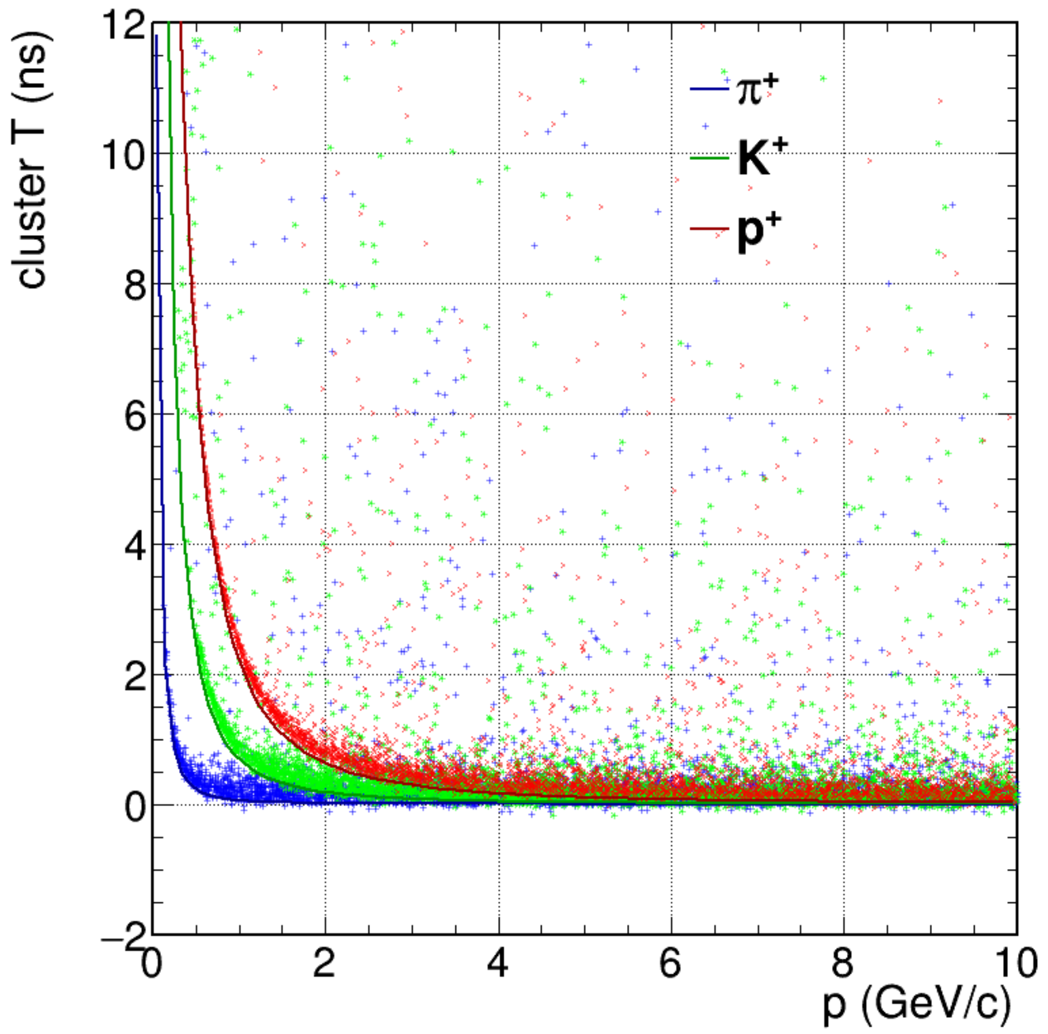
- The current estimator can provide separation power higher than 2.5σ for K^+/π^+ (K^+/p^+) with momentum up to 1.3 (2.2) GeV.

- Cluster TOF can make up for the lack of dE/dx information in the momentum around 1 (2) GeV.

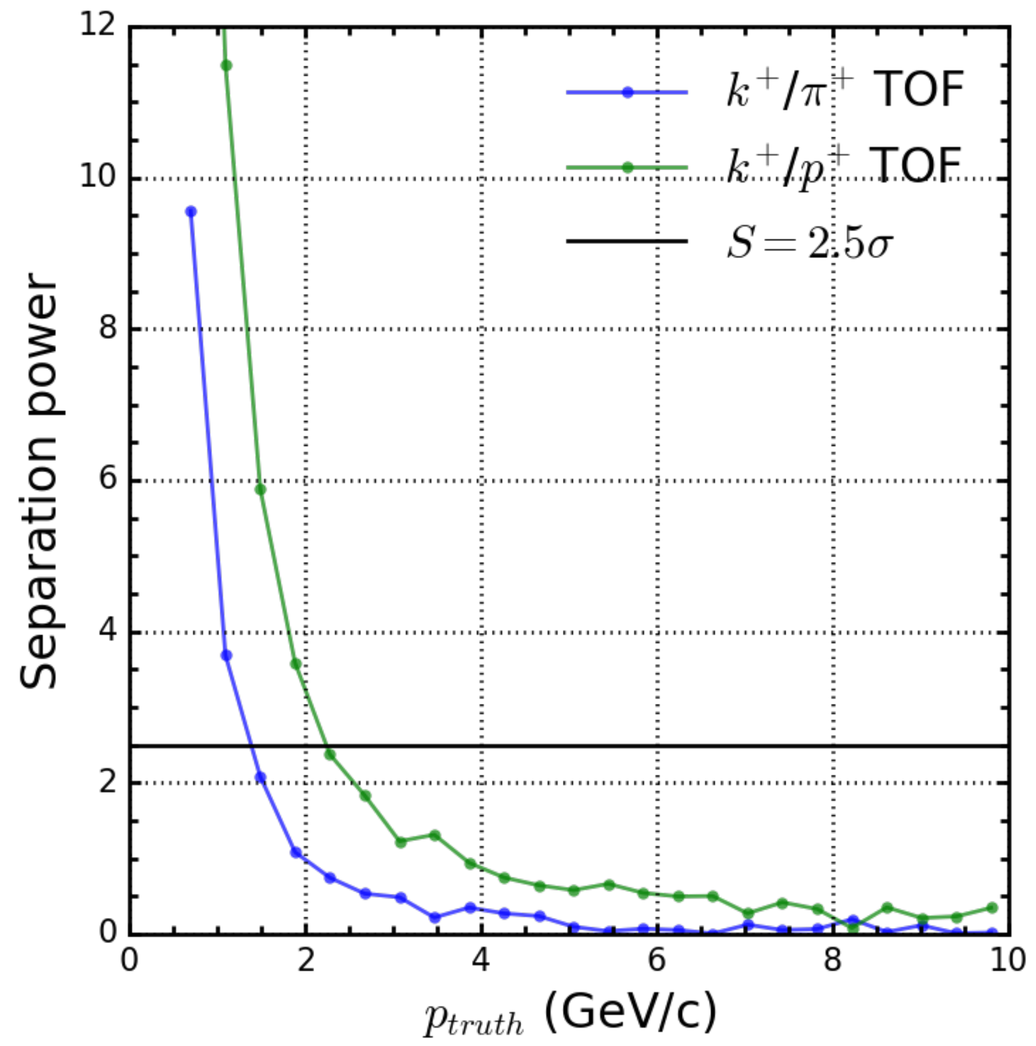




Separation power of cluster TOF with resolution of 50 ps.[1]



The scatter of reconstructed time for $K^+/\pi^+/p^+$ versus incident momentum.



K^+/π^+ and K^+/p^+ separation.

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).

4.1. Algorithm & performance: Estimation bias & resolution

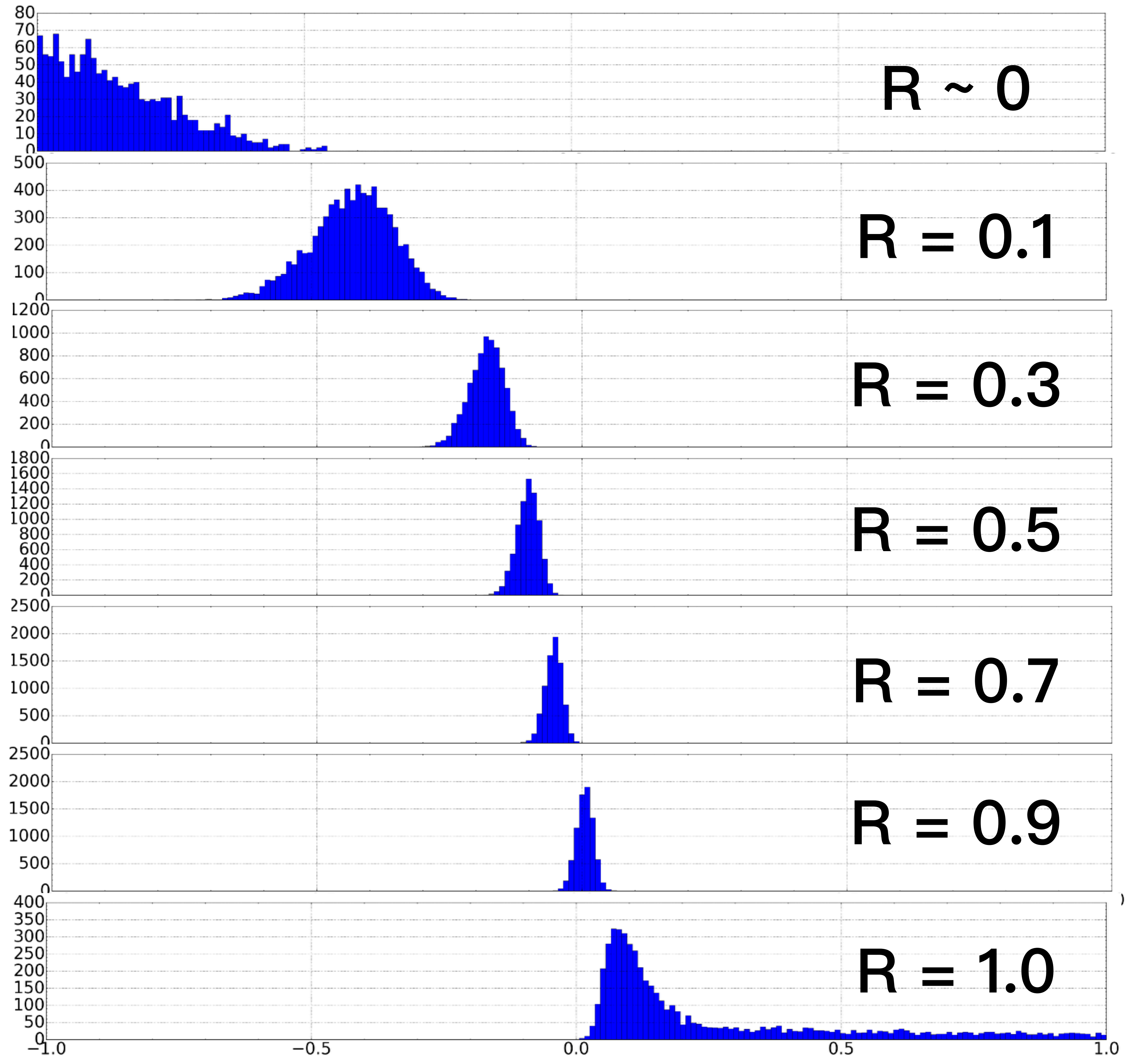
Selected the **single particle events** where the primary particle reached ECAL and at least 1 cluster is reconstructed.

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

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

- Truth cluster TOF: $T_{expect}(p) = L/c \cdot (\frac{\sqrt{p^2+m^2}}{p} - 1)$.
- Estimation bias: $\Delta T = mean\{T_{reco} - T_{exp}(p)\}$
- Estimation resolution: $\sigma_T = StdDev\{T_{reco} - T_{expect}(p)\}$

20 ~ 30 GeV photon



The reconstructed perfect pion cluster time residual distribution under different R values.

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.

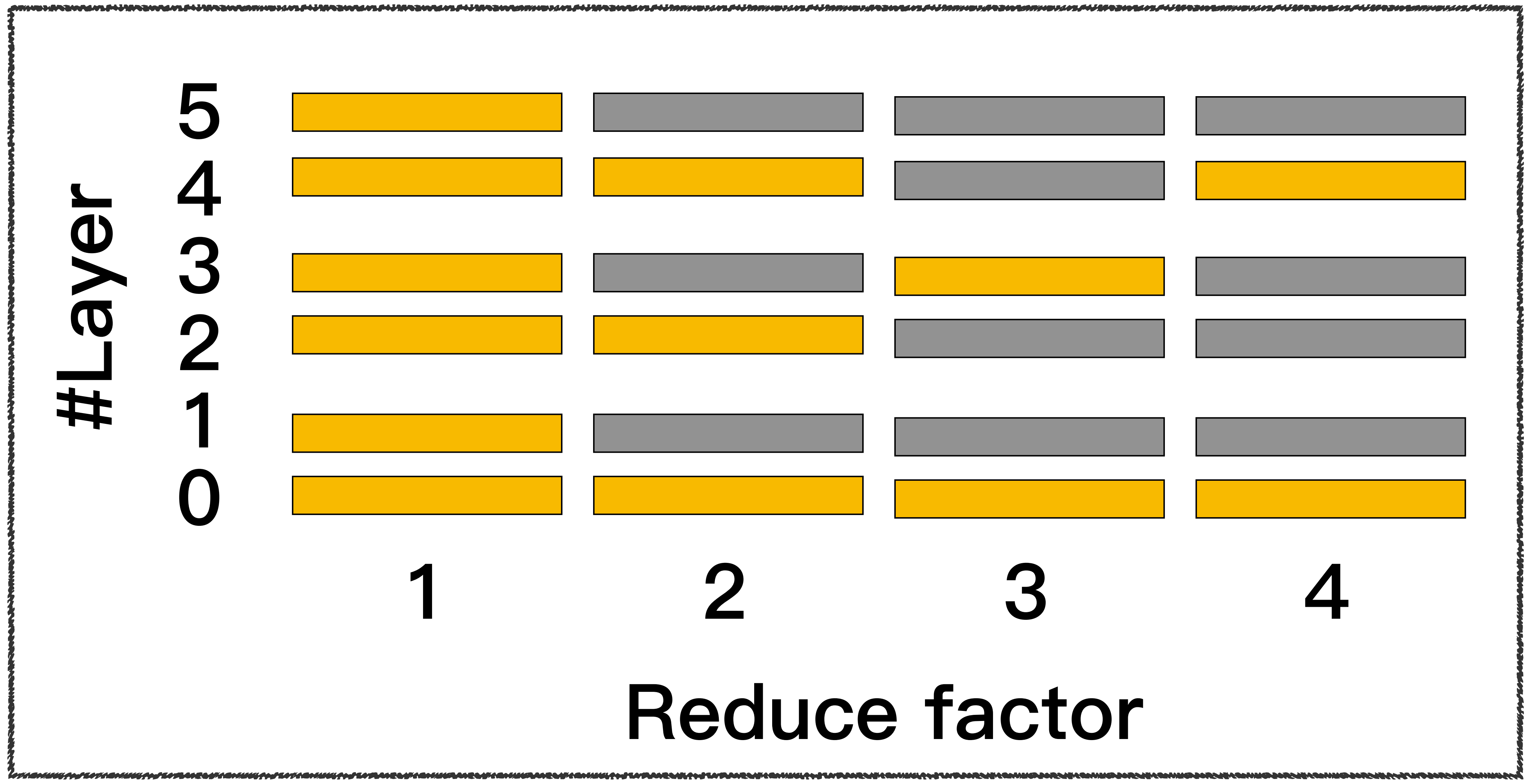
A: **different hit time resolution**

linear!

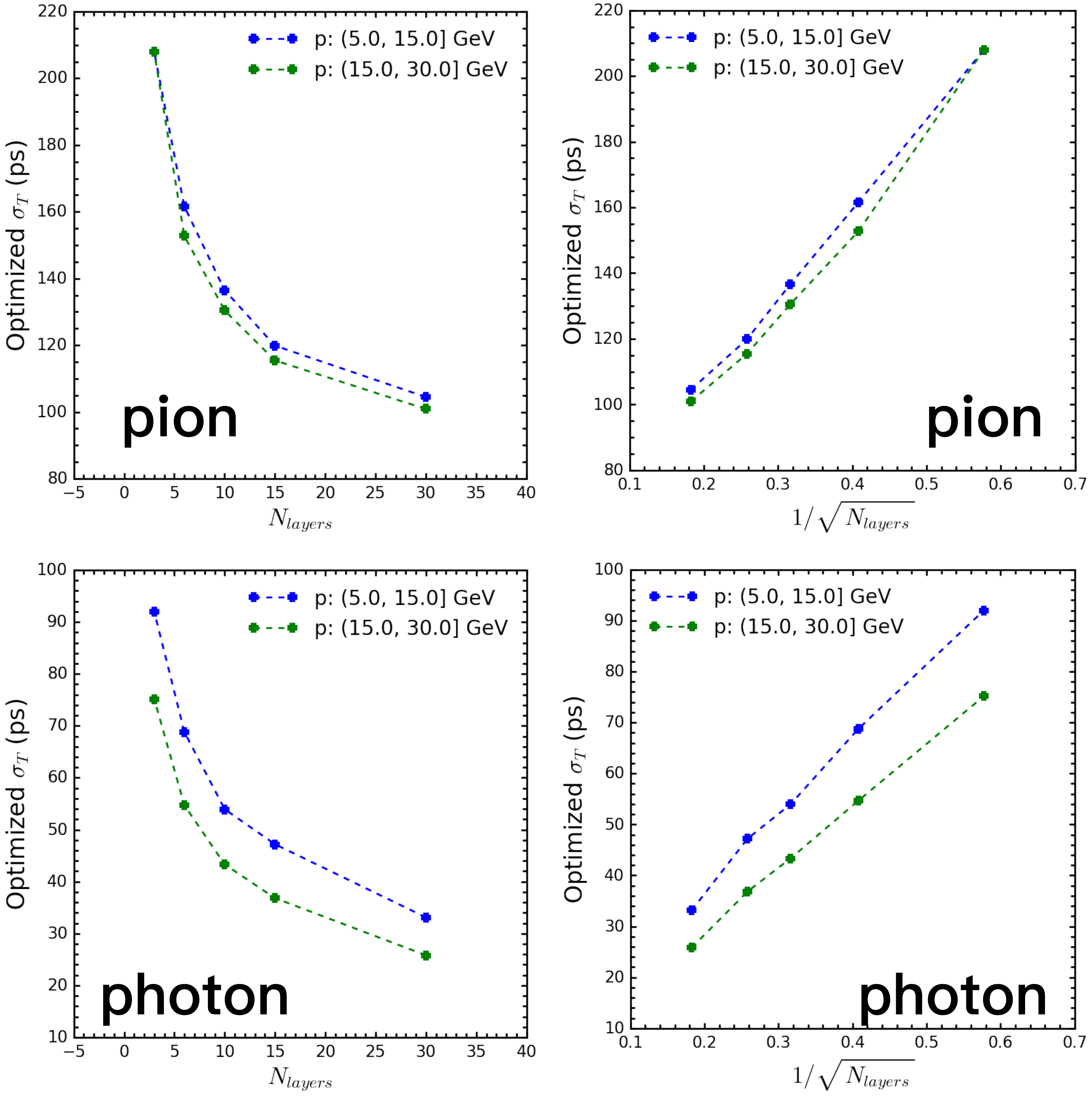
Q: **different #timing layers**

Q: **Better time estimator?**

- 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..