# Time reconstruction at Calorimeter Cluster

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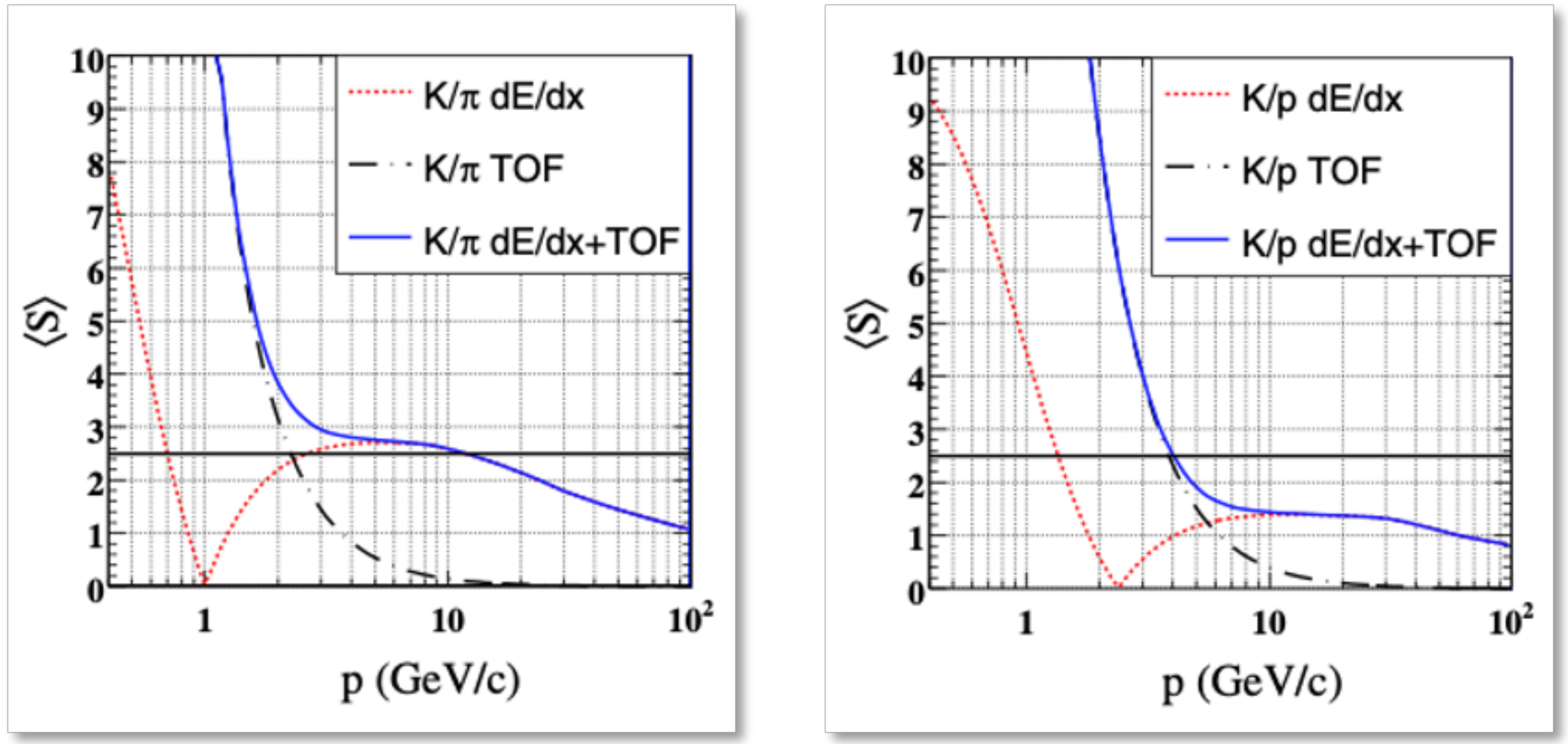
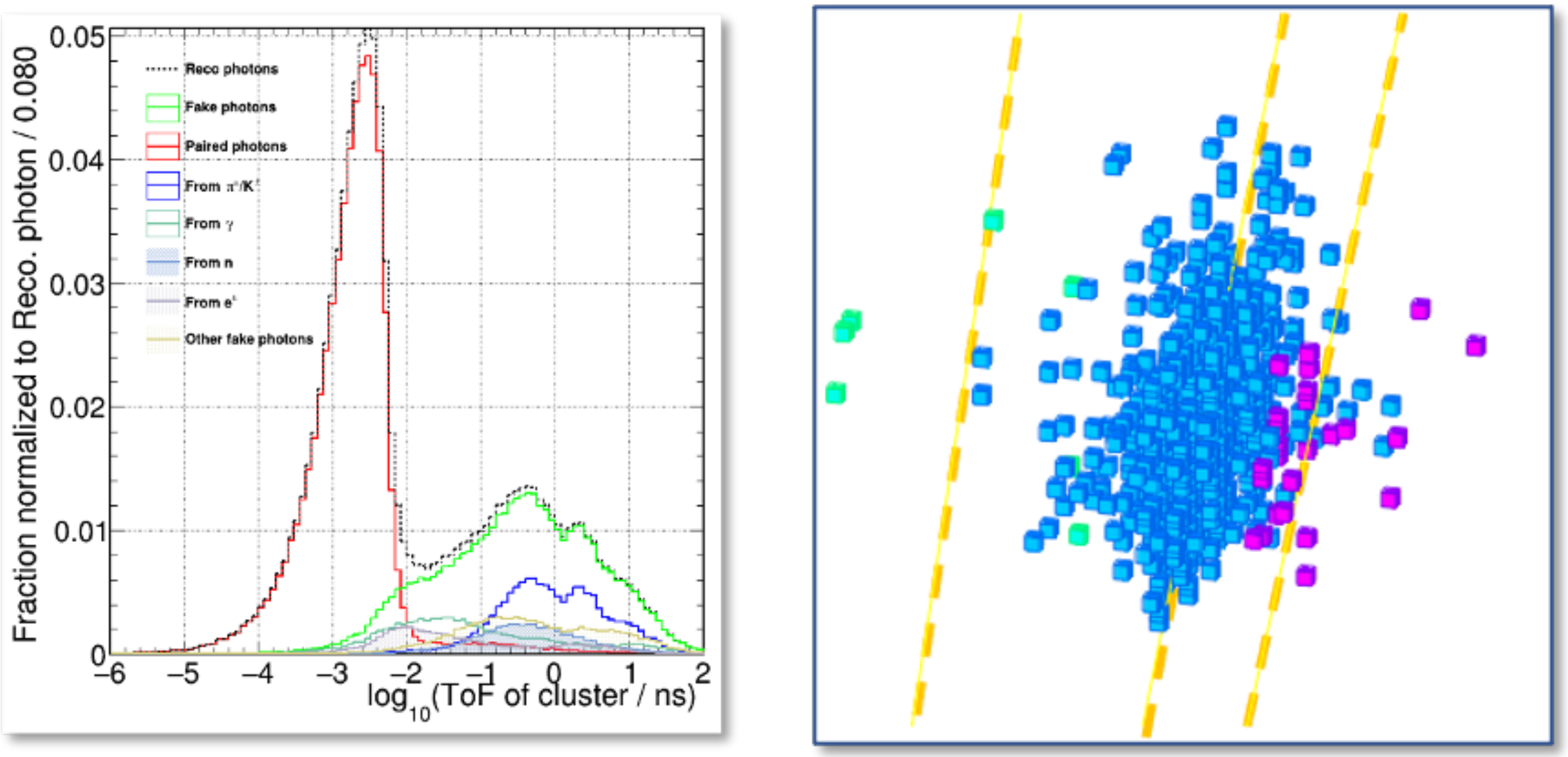
# Content

- **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).

# 2. Basic configuration: CEPC baseline setup

**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

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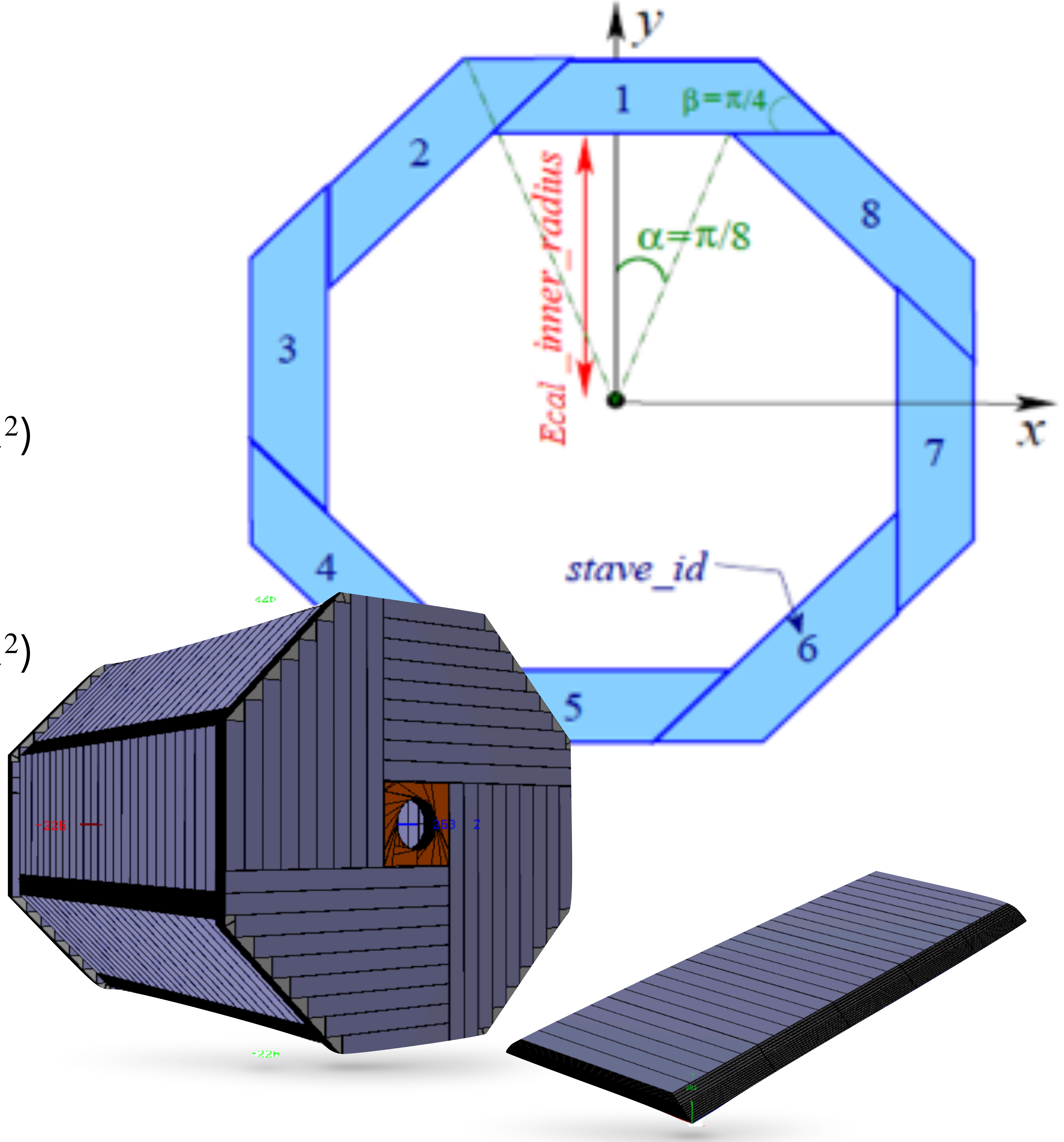
**B Field:** 3 T ( set to 0 in this research )

**Sample:** Single particle with momentum 0 ~ 30 GeV and direction (x,y,z) = (0, 1, 0.1).

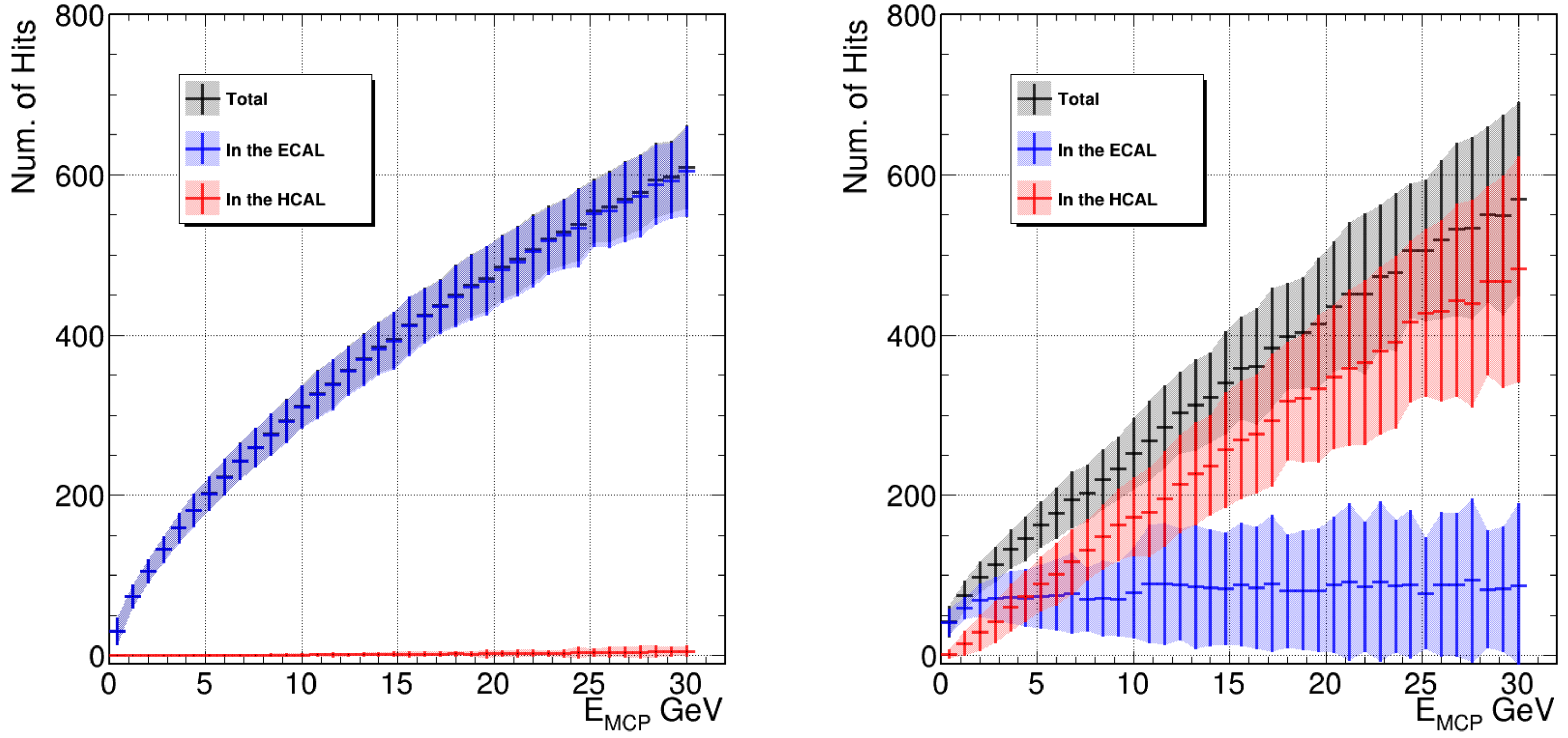



The CEPC Study Group, CEPC Conceptual Design Report: Volume 2-Physics & Detector, ArXiv Preprint ArXiv:1811.10545 **2**, (2018).

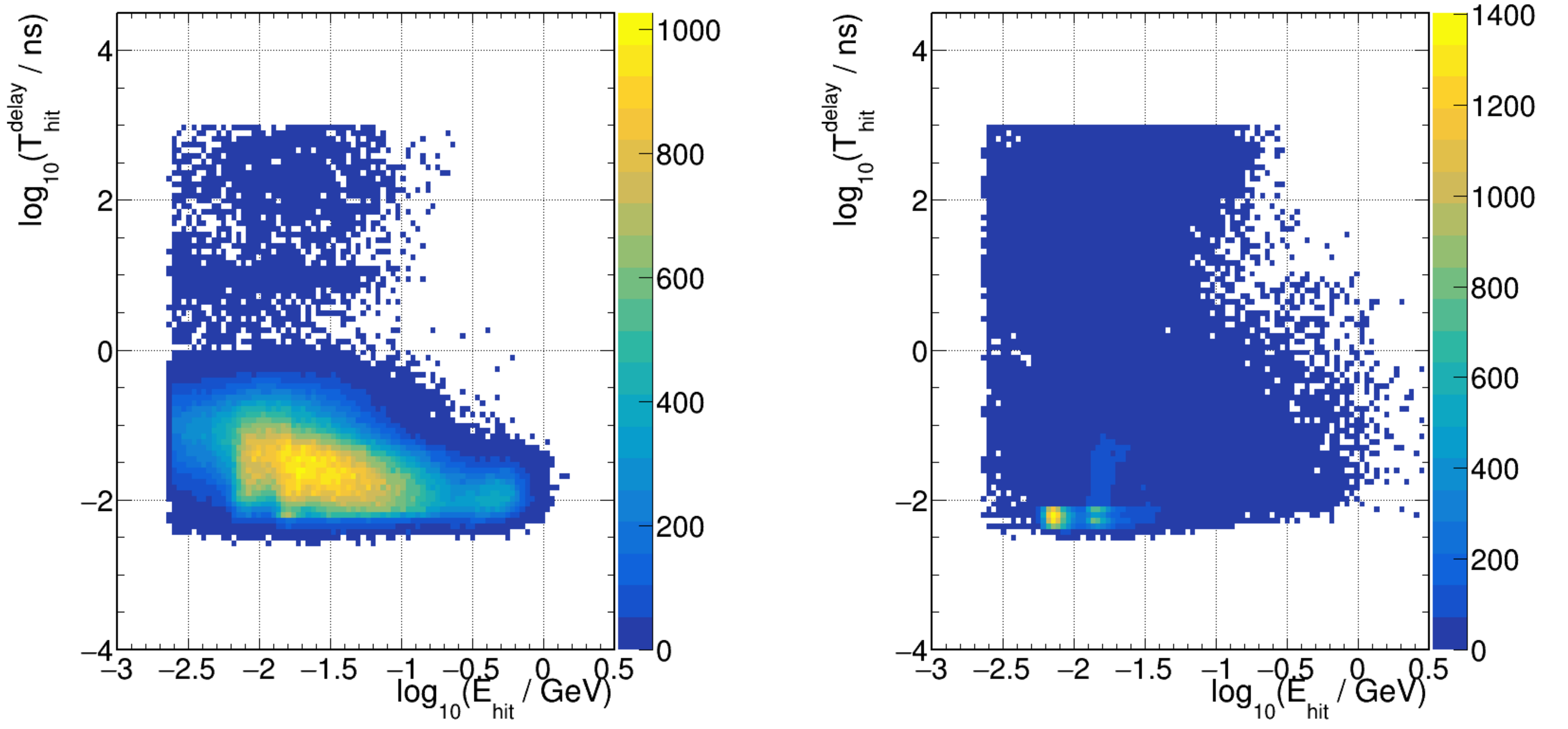
# 3.1. Calorimeter response: Truth level

Compared to EM shower, hadronic shower

- leads less ECAL hits.
- contains a more compact fast component and lower energy distribution.




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




Time vs. energy distribution of ECAL hits in (left) 10 GeV photon and (right) 10 GeV $\pi^+$ hits sample, where the y axis,

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

# 3.2. 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) $S_{eff} = S_1 S_2 / \sqrt{S_1^2 + S_2^2}$,

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

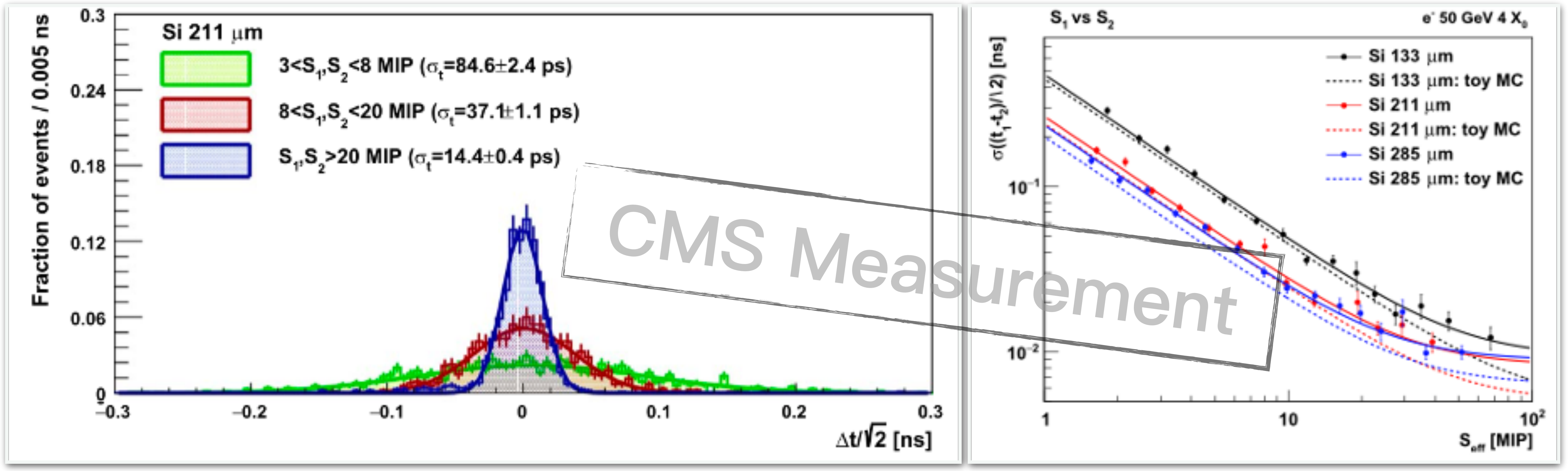
**Hit time digitization** in simulation:

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

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

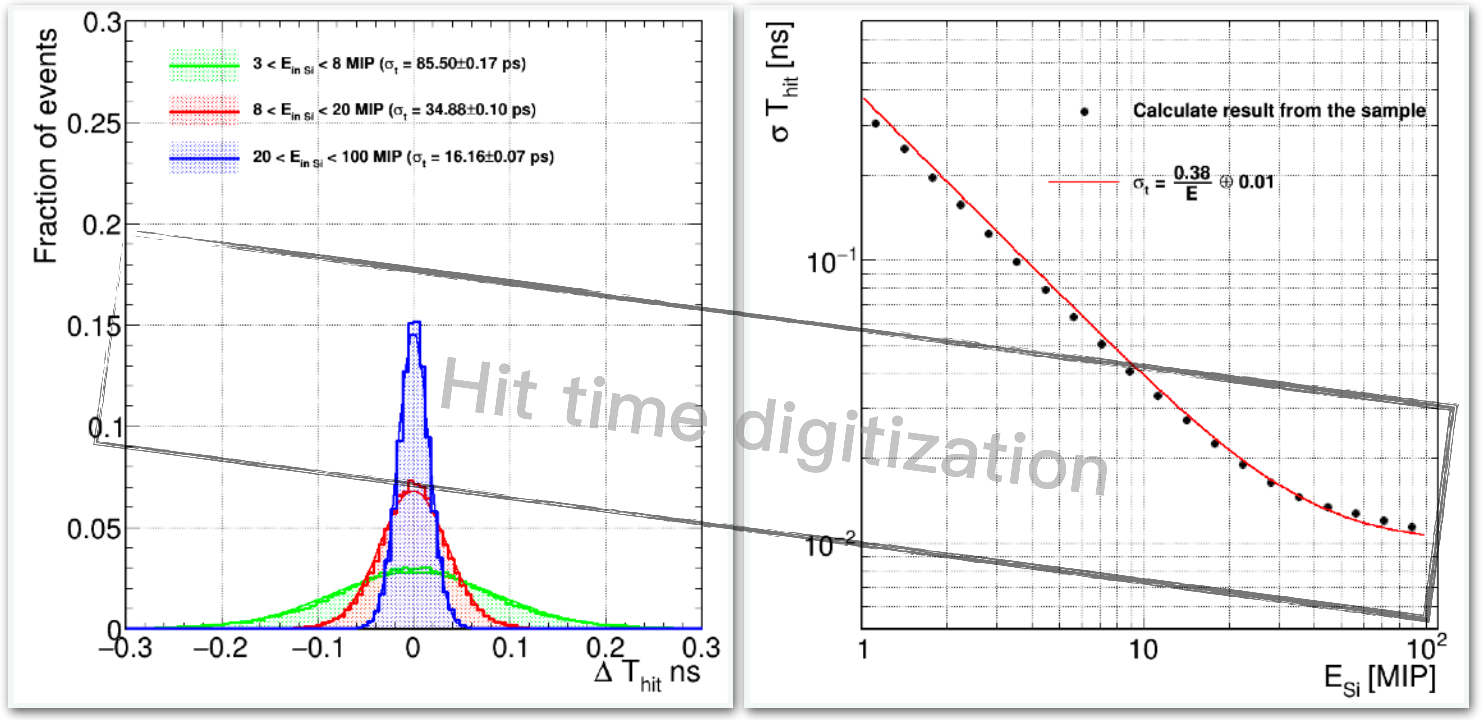
  $$\sigma_{T_{hit}} = \sqrt{\left(\frac{0.38\ ns}{E_{hit}}\right)^2 + (0.01\ ns)^2}.$$

  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.



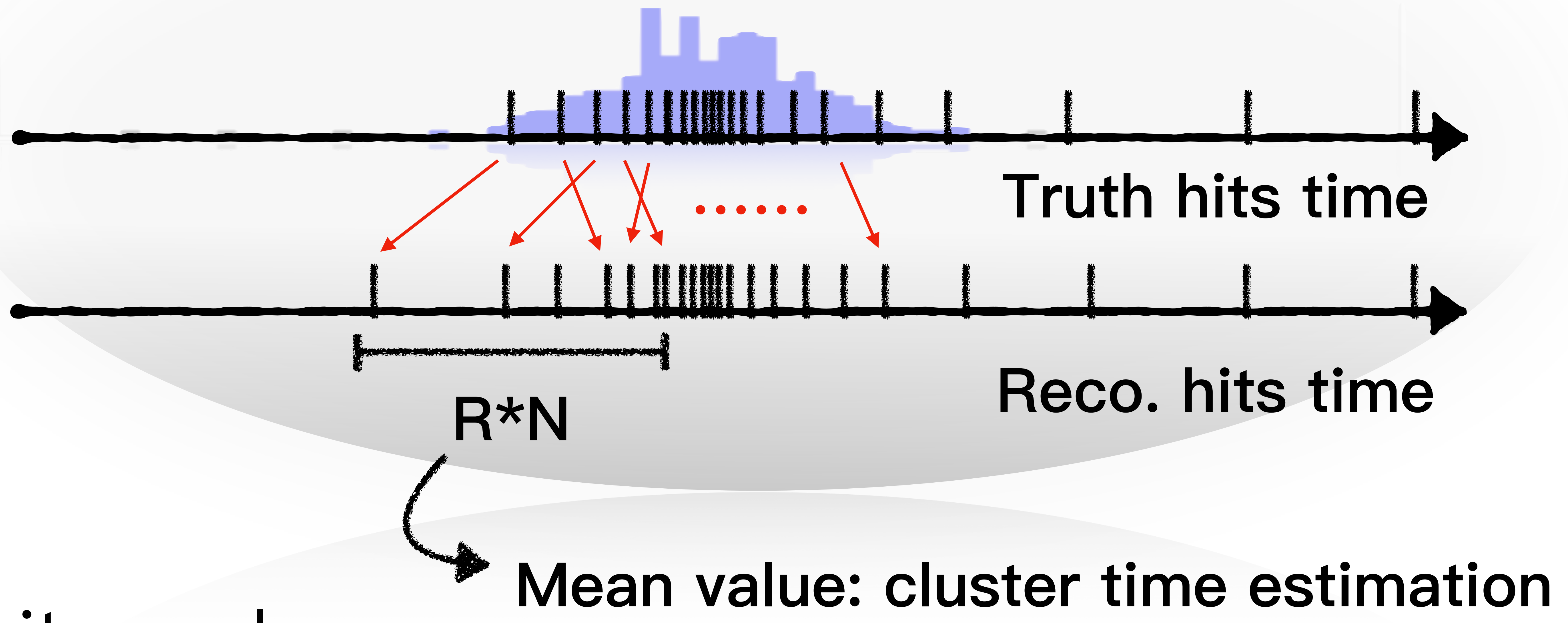

Hit time digitization result. Smeared the truth level hits with gaussian parameterized by the CMS measurement.

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).

# 4. Algorithm & performance

A fraction mean cluster TOF estimator:

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



# 4.1. Algorithm & performance: Estimation bias & resolution

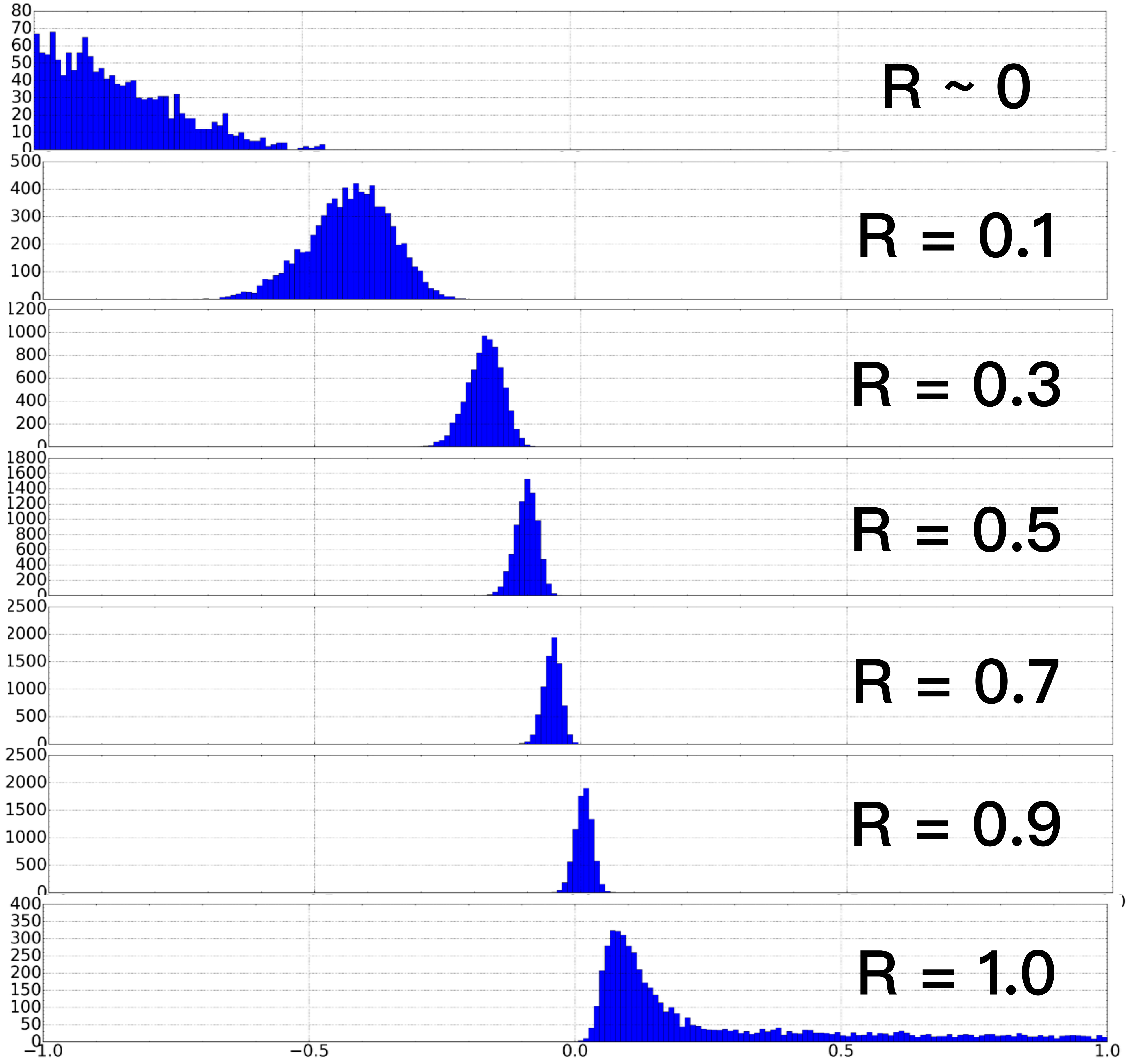
Selected the **single particle events** where the primary particle reached ECAL and at least 1 cluster is reconstructed.

**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

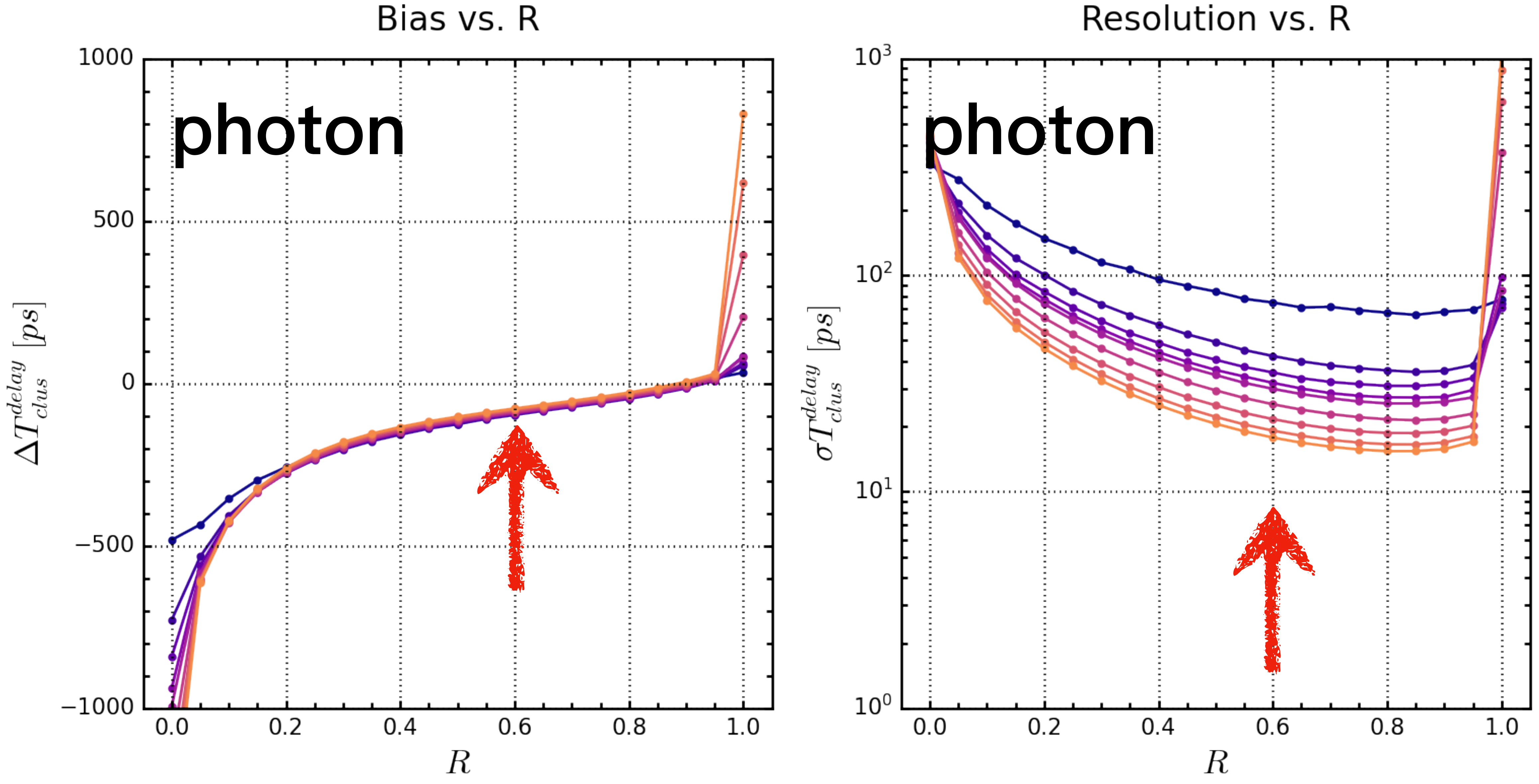



The reconstructed perfect pion cluster time residual distribution under different R values.

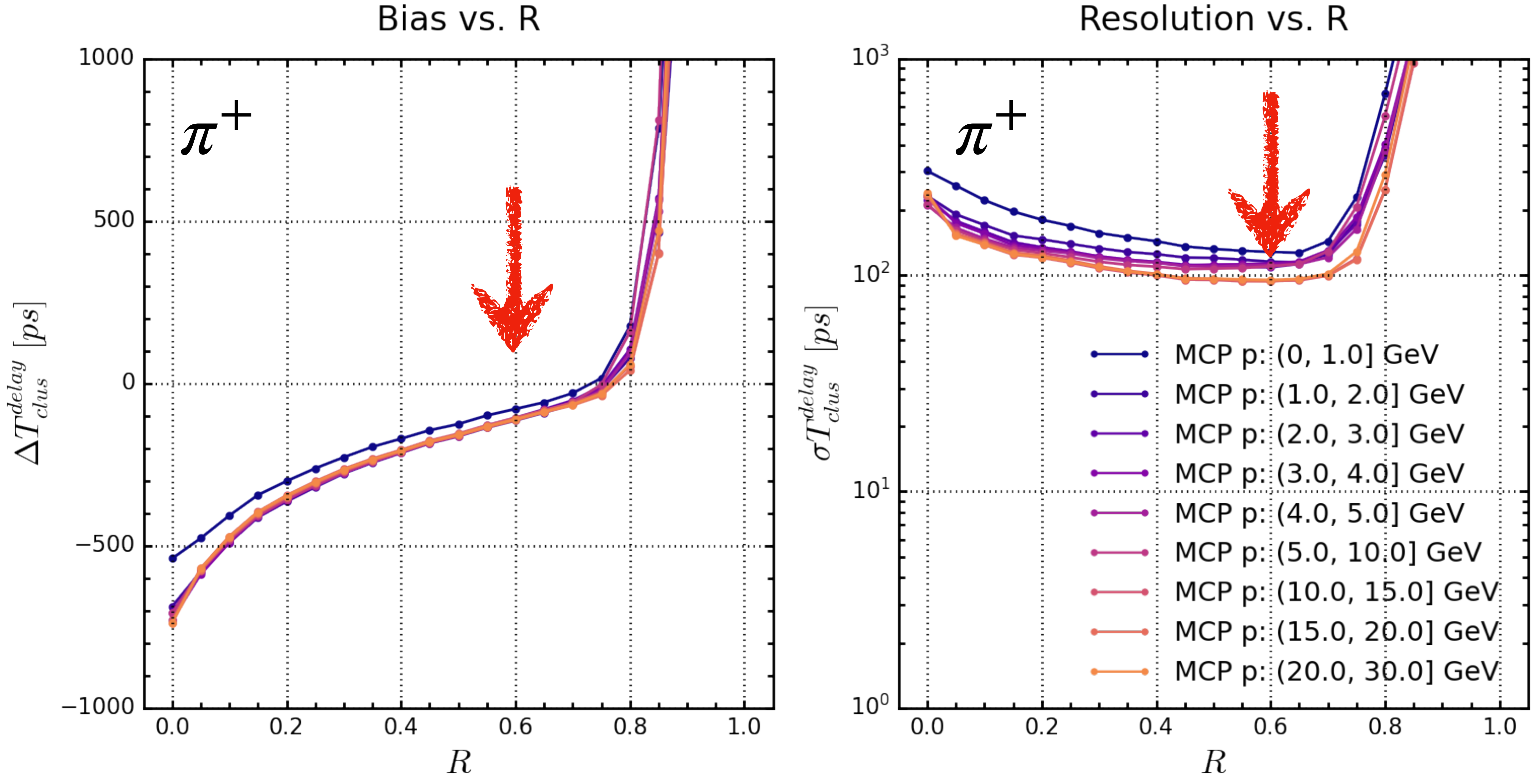
Set a $\pm 5\sigma_{total}$ window around the mean value, to remove the extremely abnormal events.

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.



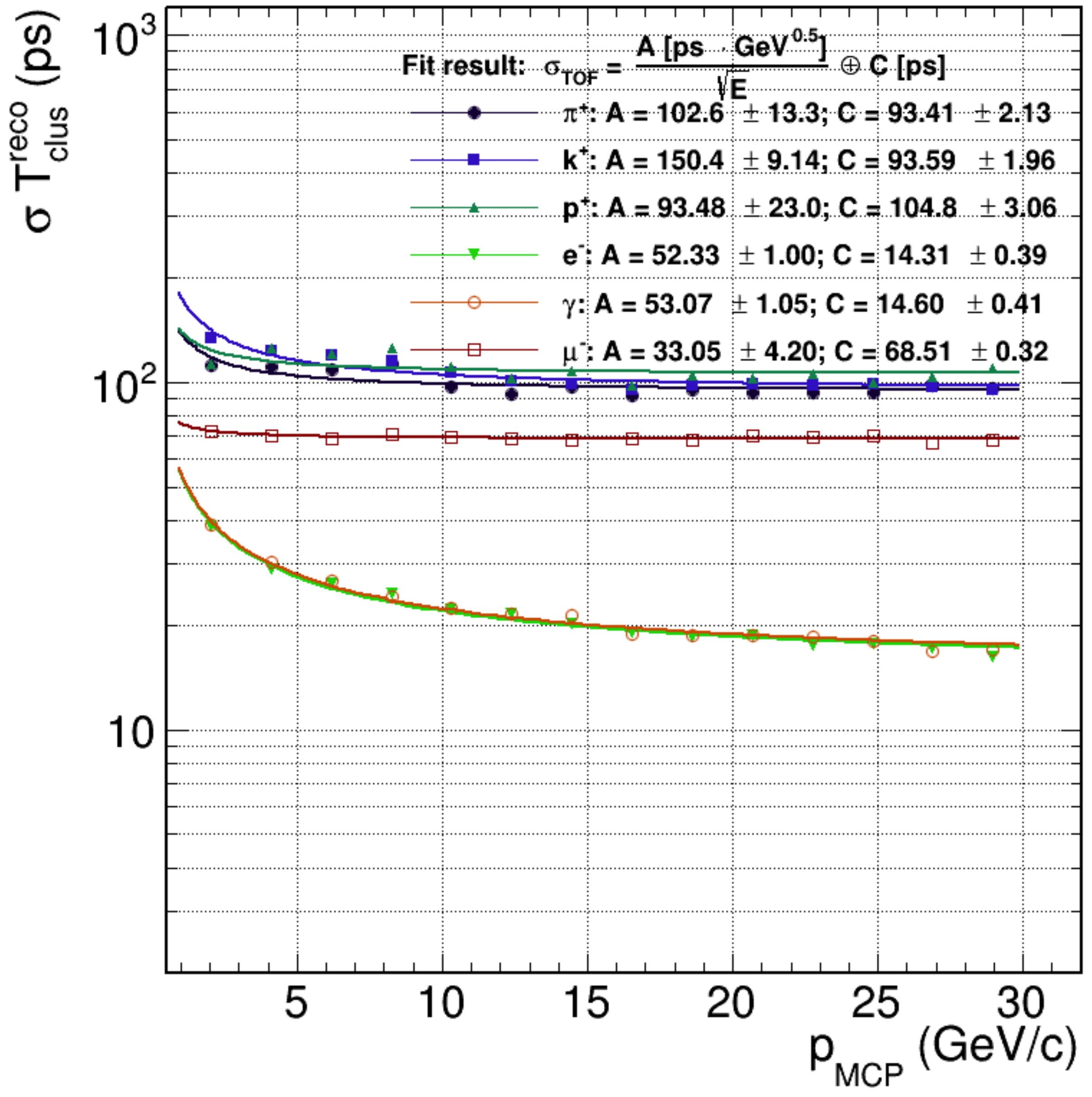

The estimation (left) bias and (right) resolution versus fraction R for perfect photon clusters.



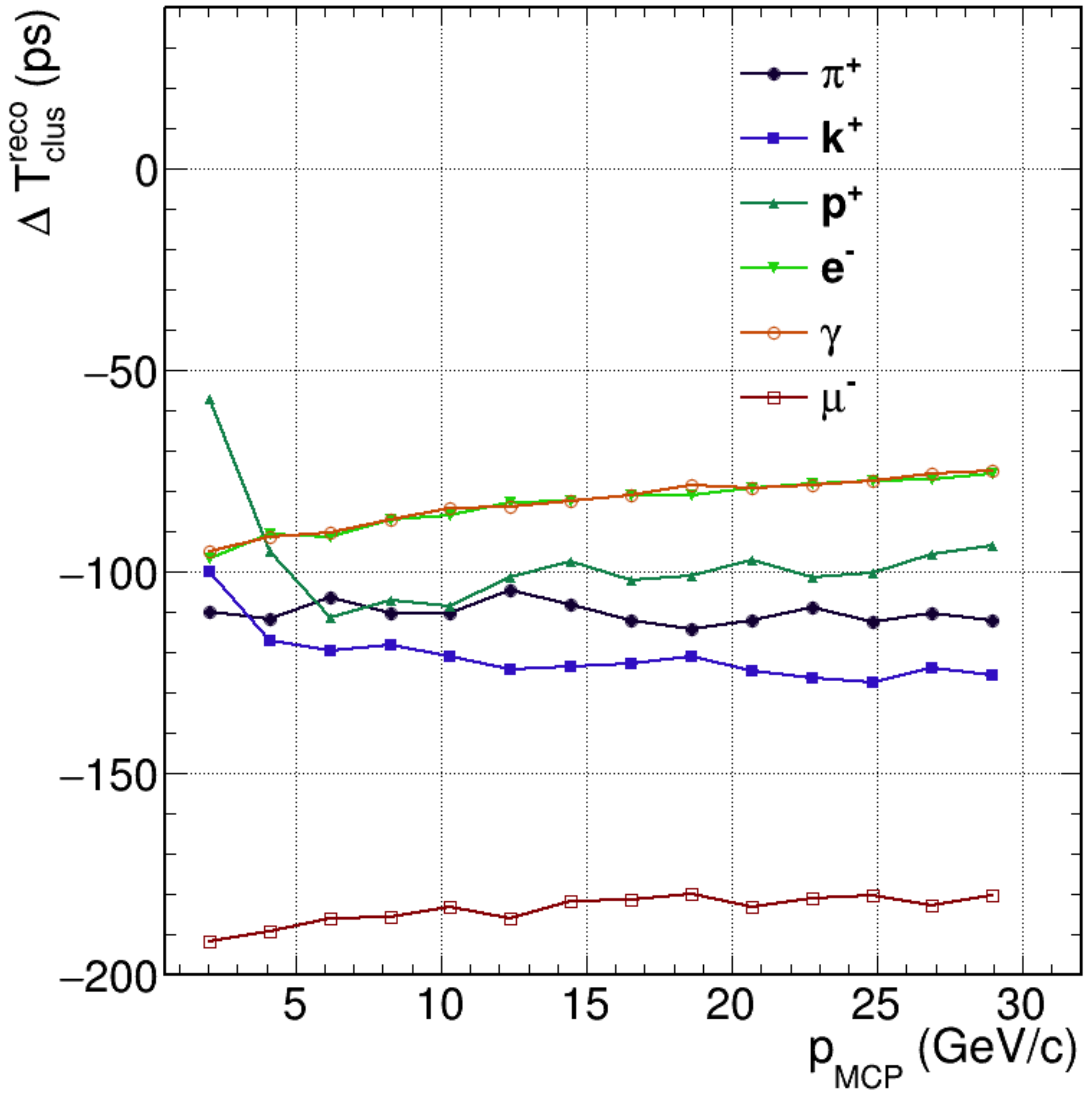

The estimation (left) bias and (right) resolution versus fraction R for perfect pion clusters.

- Optimize the hits number fraction R = 0.6 for a minimum **time resolution,**
  - time resolution for perfect hadronic clusters: 90–150 ps
  - for perfect EM clusters: 10–50 ps.
- The time reconstruction is accompanied by a **certain bias,**
  - –70 ps for hadronic clusters
  - –50 ps for EM clusters.

**Resolution**




**Bias**




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

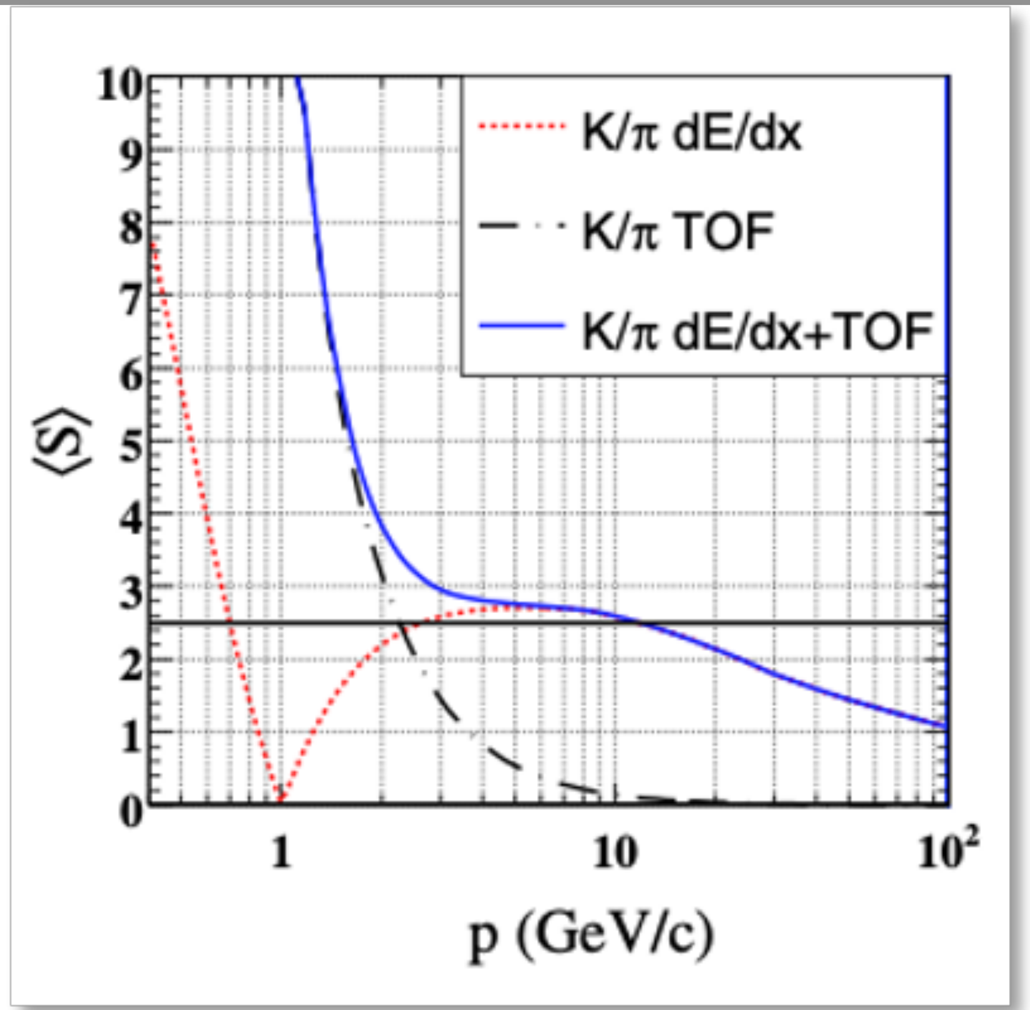
# 4.2. Algorithm & performance: $K^{\pm}/\pi^{\pm}/p^{\pm}$ separation

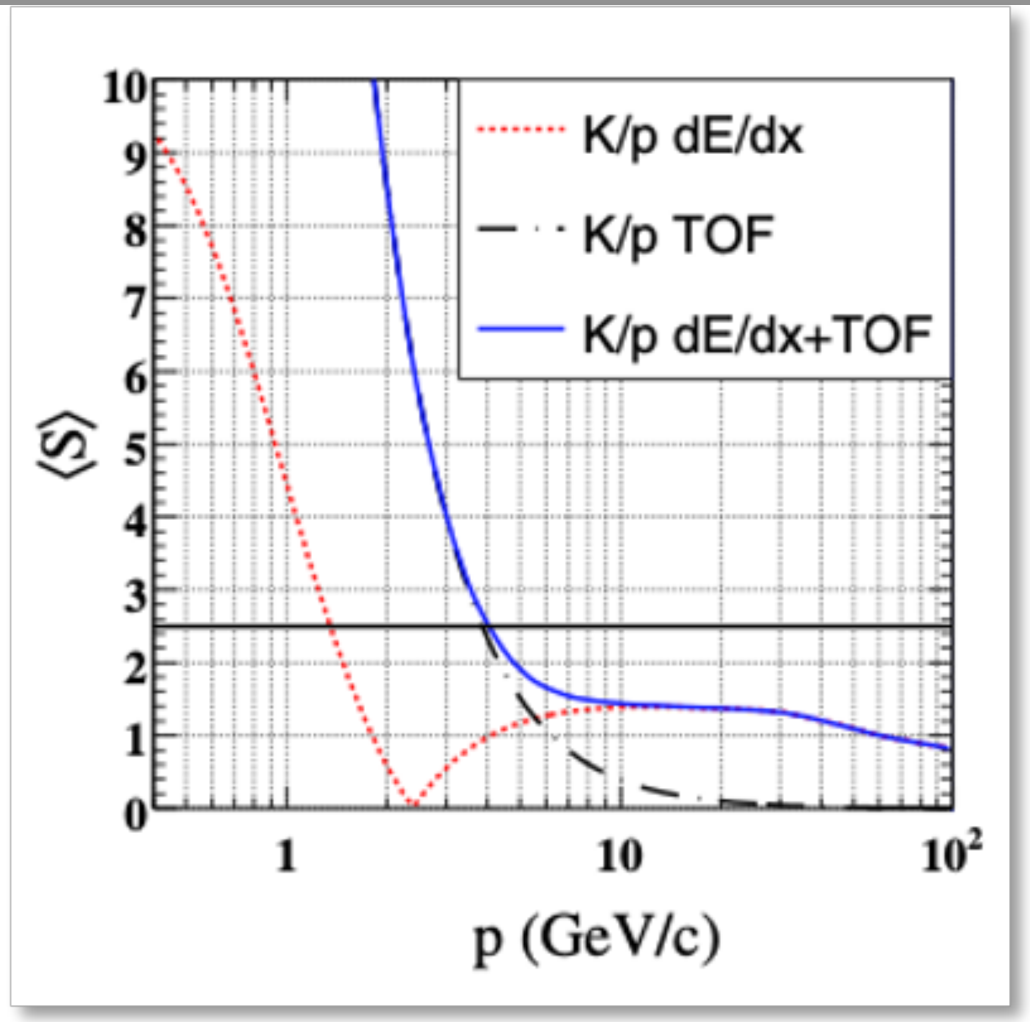
- The separation power of particle A and B:

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

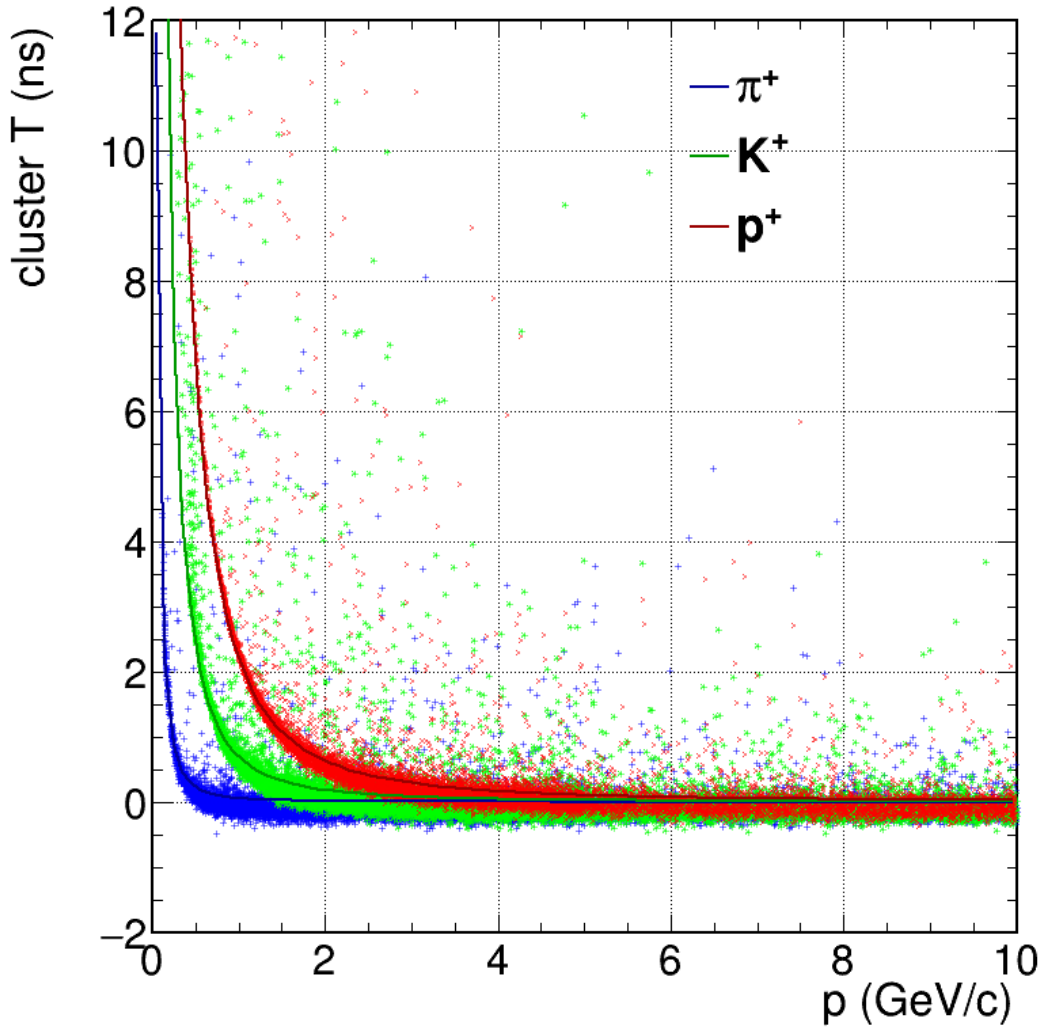
- The current estimator can provide separation power higher than $2.5\sigma$ for $K^+/\pi^+$ ($K^+/p^+$) with momentum up to 1.3 (2.2) GeV.

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

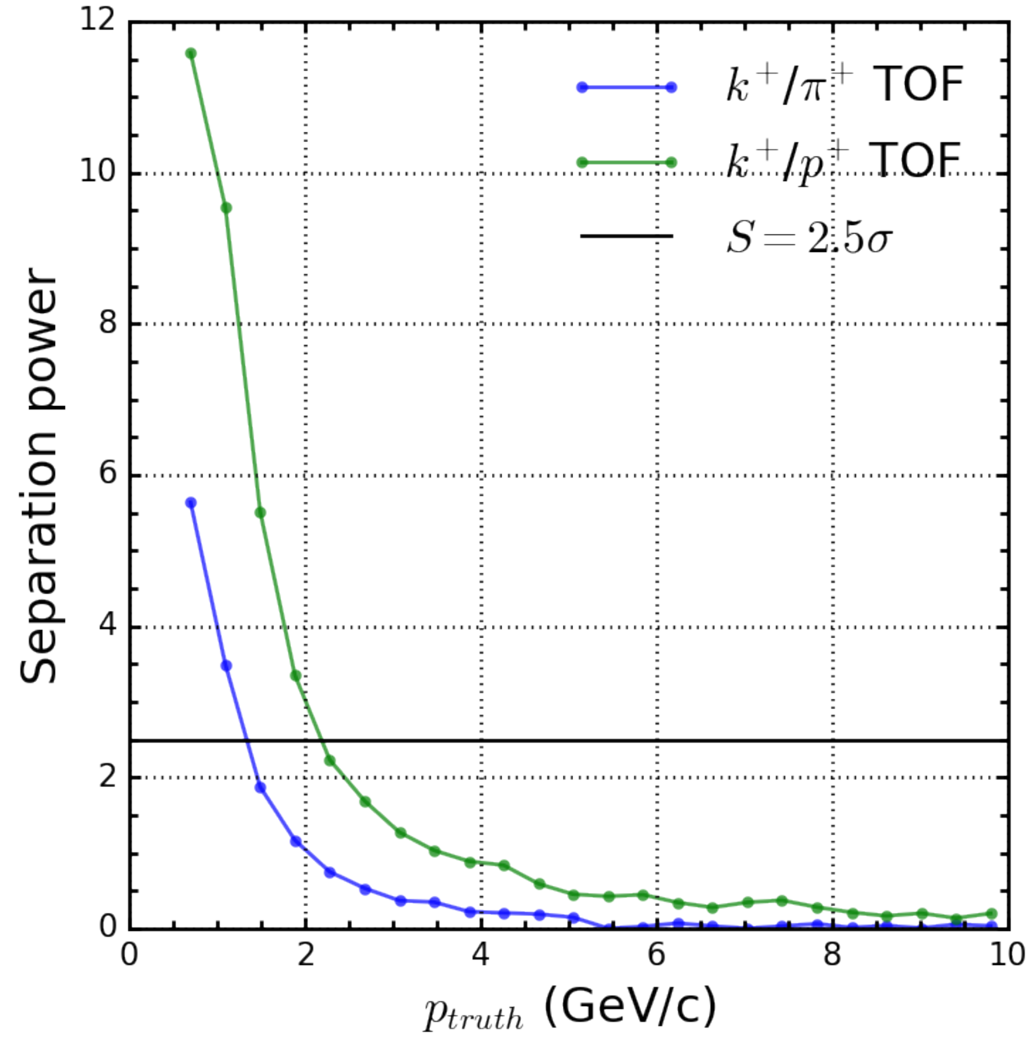



Separation power of cluster TOF with resolution of 50 ps.[1]




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




$K^+/\pi^+$ 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).

# 4.3. Section Summary

- Under the current CMS technology, the time resolution:
  - for perfect EM clusters with 0 to 30 GeV energy can reach 10 ~ 50 ps,
  - for perfect hadronic cluster can reach 90 ~ 150 ps.
- **PID performance:** The mentioned timing reconstruction can provide $K^+/\pi^+$ ($K^+/p^+$) **separation** higher than $2.5\sigma$ for momentum up to 1.3(2.2) GeV, and make up for the gap of the dE/dx separation power in momentum range around 1 GeV and 2 GeV.
- *The fake photons from fragment clusters are hopeful to be vetoed by the cluster time information (waiting for further research).*

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:

Q: realistic clustering?

for example: Arbor?

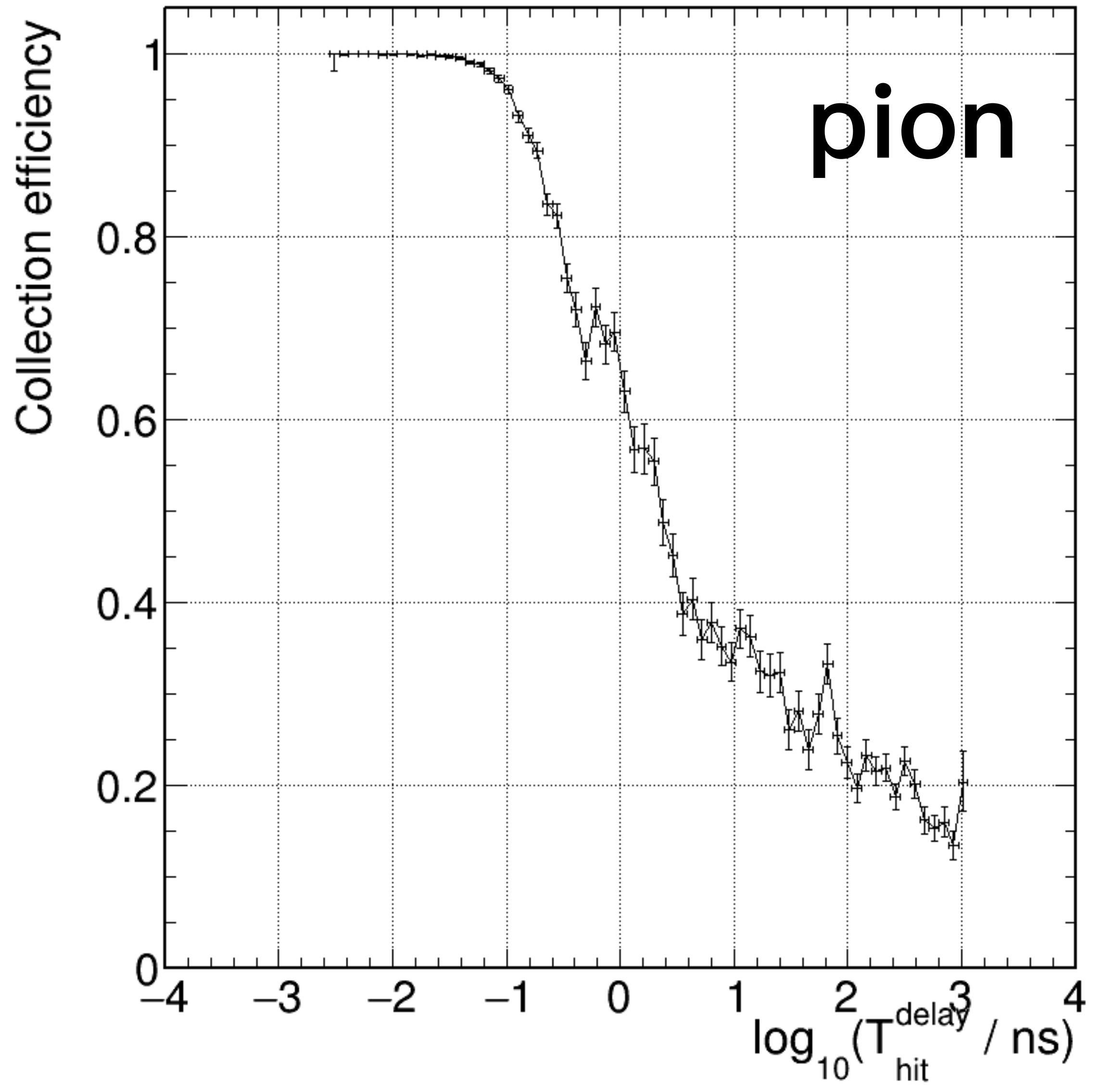
Q: different hit time resolution

Q: different #timing layers

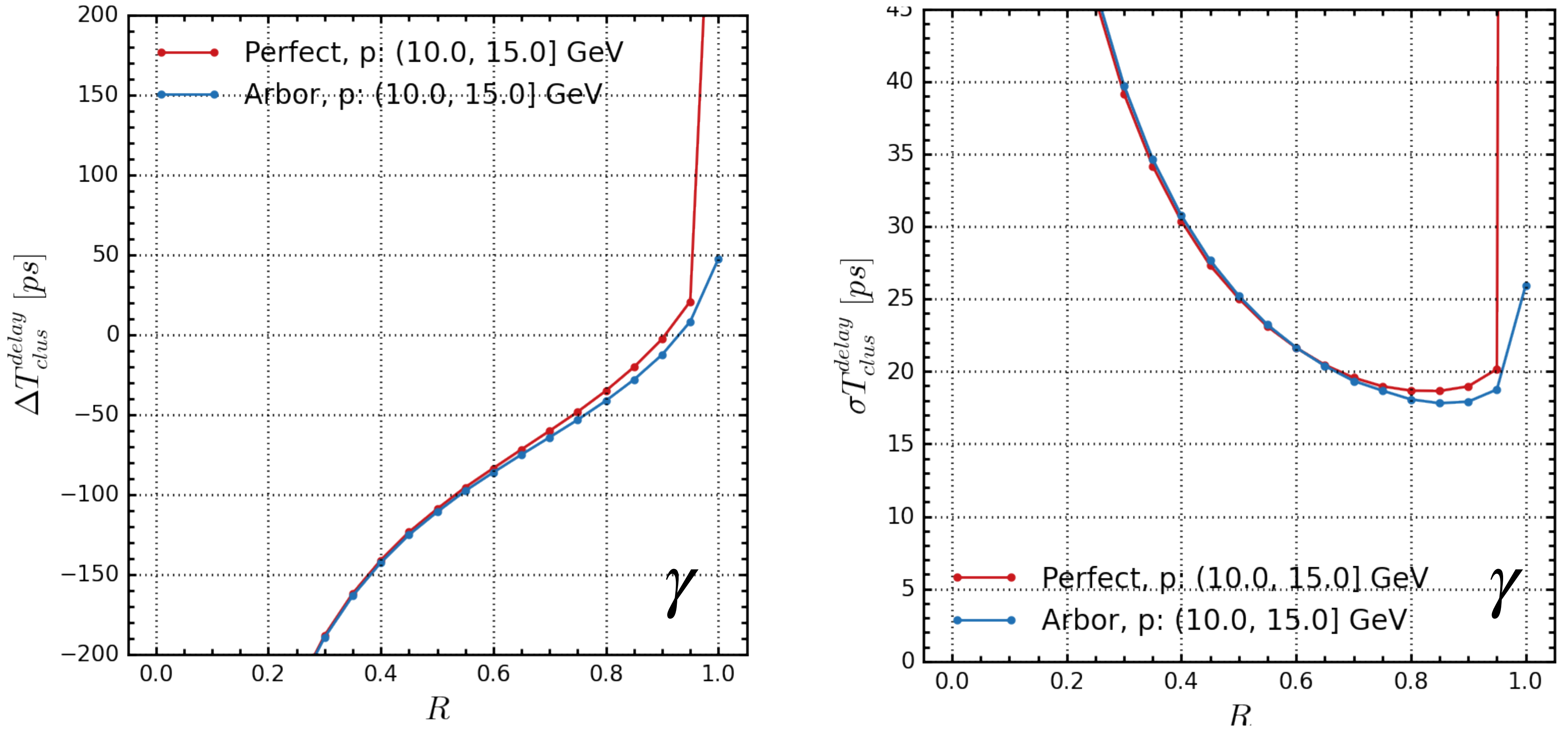
Q: Better time estimator?

# 5.1. Influence of the Arbor clustering

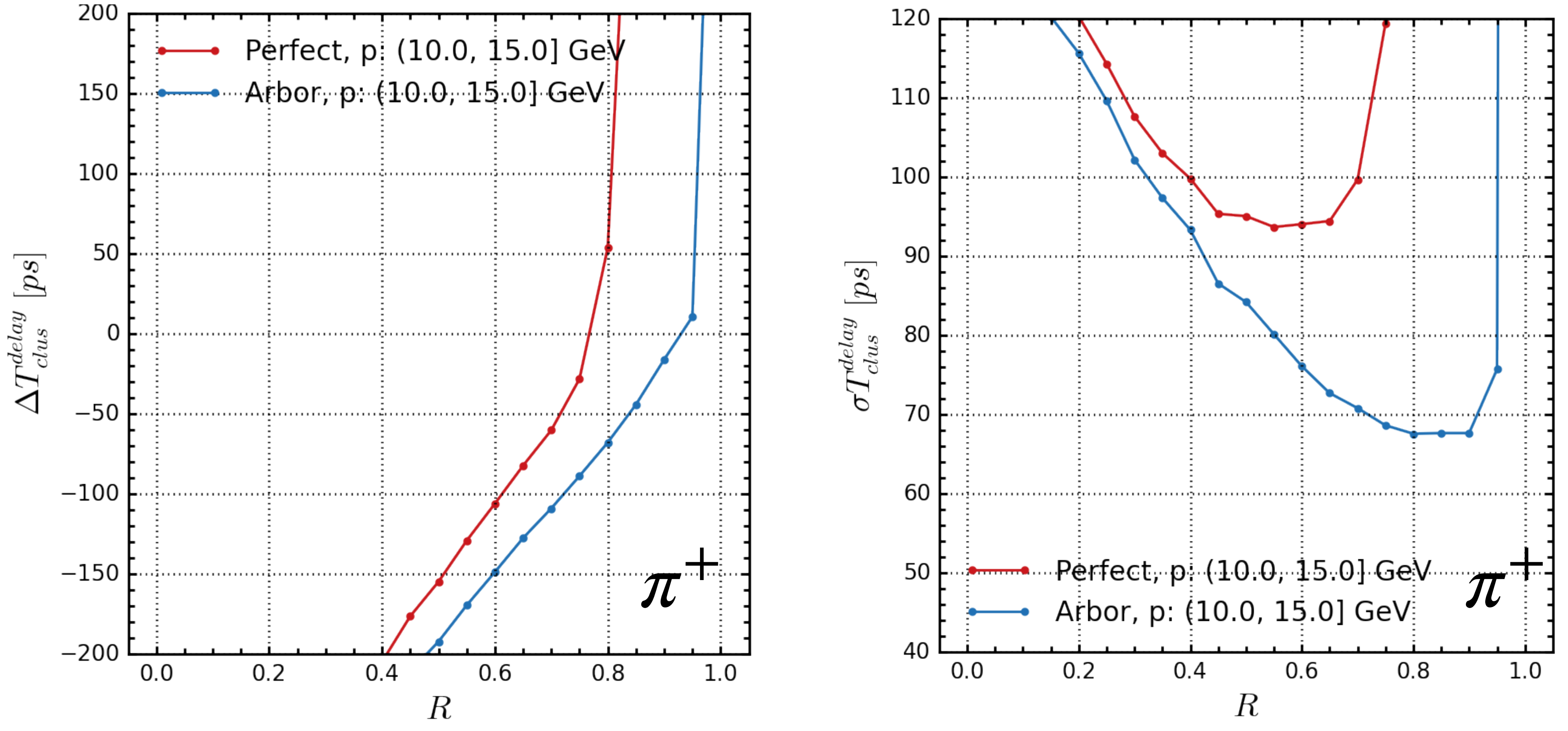
- **Arbor clustering** module partly removes the slow component of clusters, and improves the hadronic cluster time resolution by a factor ~ 1.4 (70ps/50ps)




Hit collection efficiency of Arbor for $\pi^+$ ECAL hits.



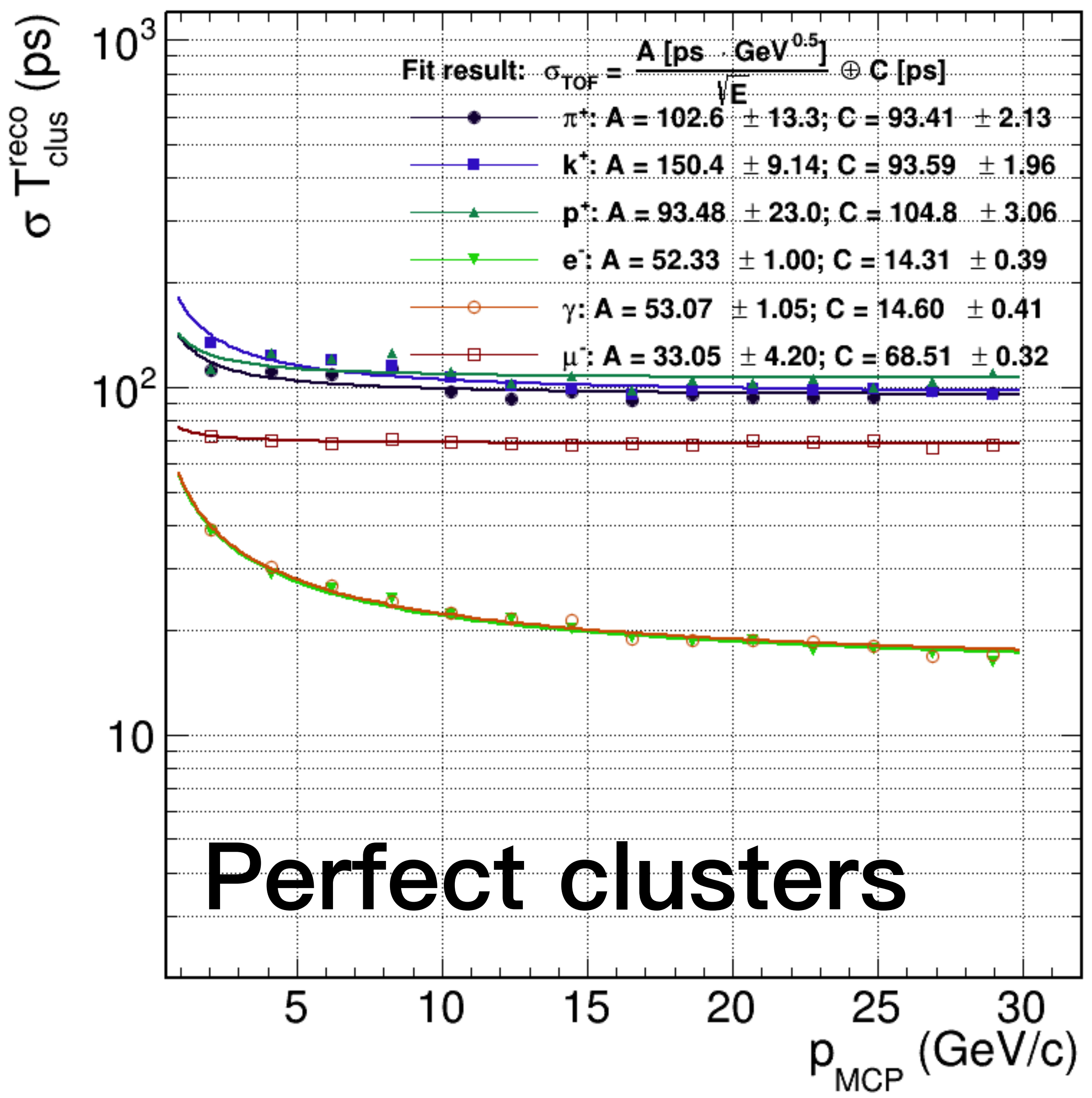

Estimator (left) bias and (right) resolution comparison between Arbor and perfect photon clusters.



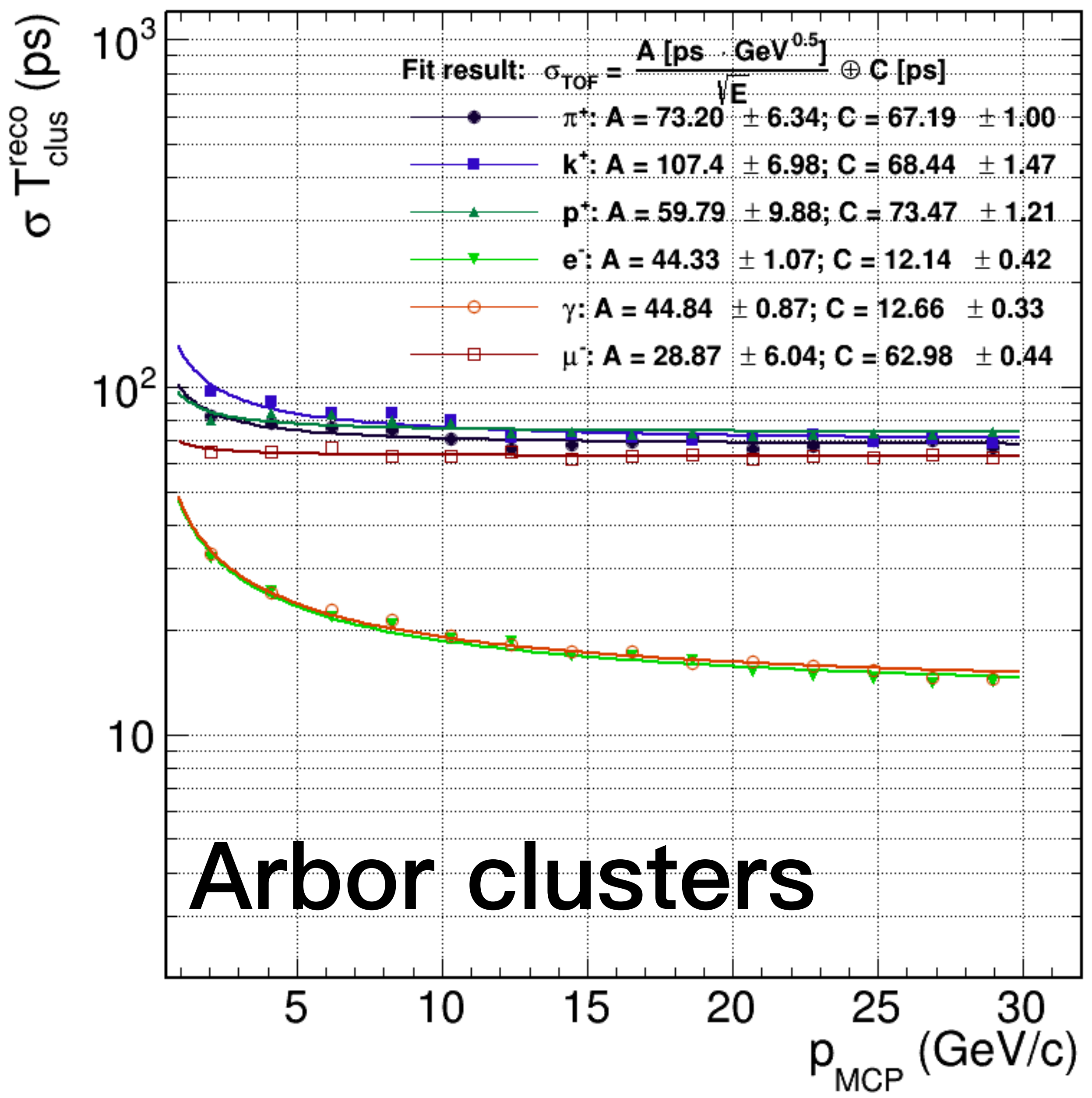

Estimator (left) bias and (right) resolution comparison between Arbor and perfect photon clusters.

# 5.1. Influence of the Arbor clustering

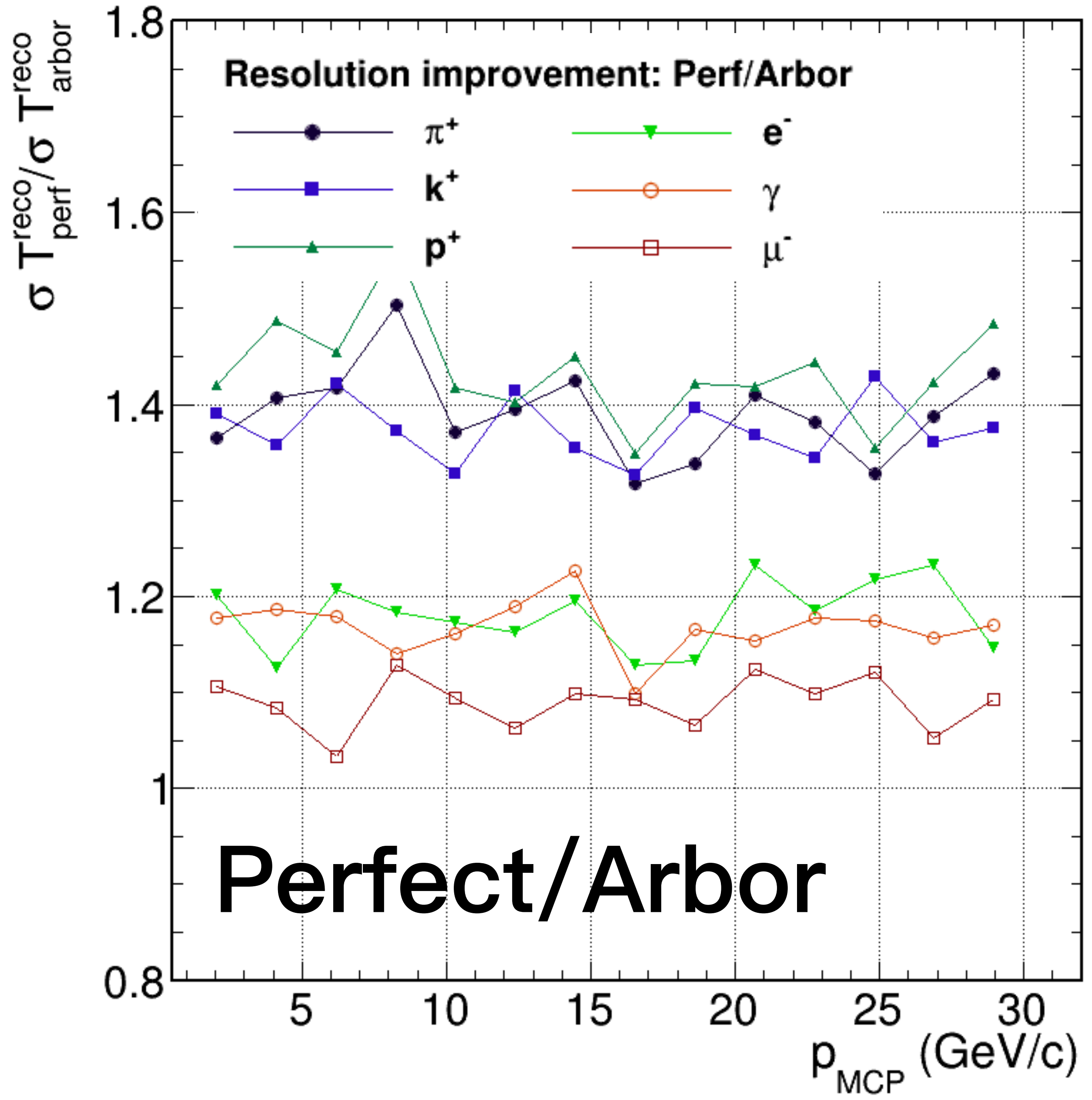
Arbor clustering module with parameters optimized for the CEPC improve the time resolution of EM and hadronic clusters by 20% and 40%, respectively.




Time resolution for perfect clusters




Time resolution for Arbor clusters




The time resolution ratio of perfect clusters over Arbor clusters.

## 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.

Q: **different hit time resolution**

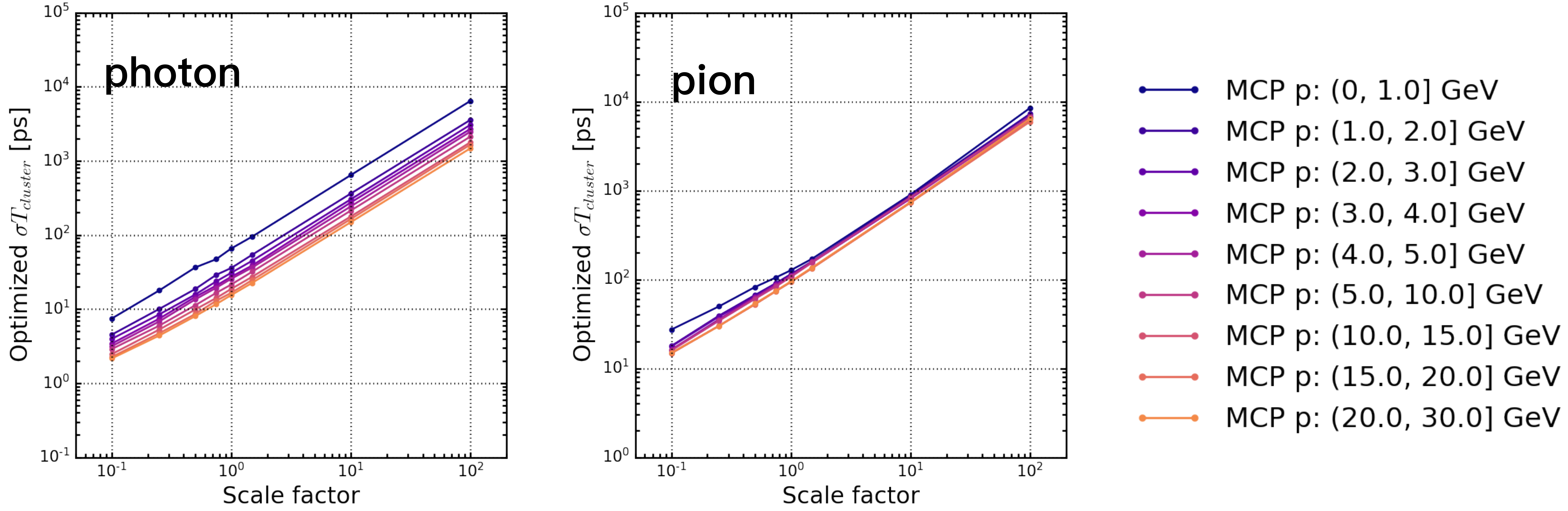
Q: **different #timing layers**

Q: **Better time estimator?**

# 5.2. 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.



## 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

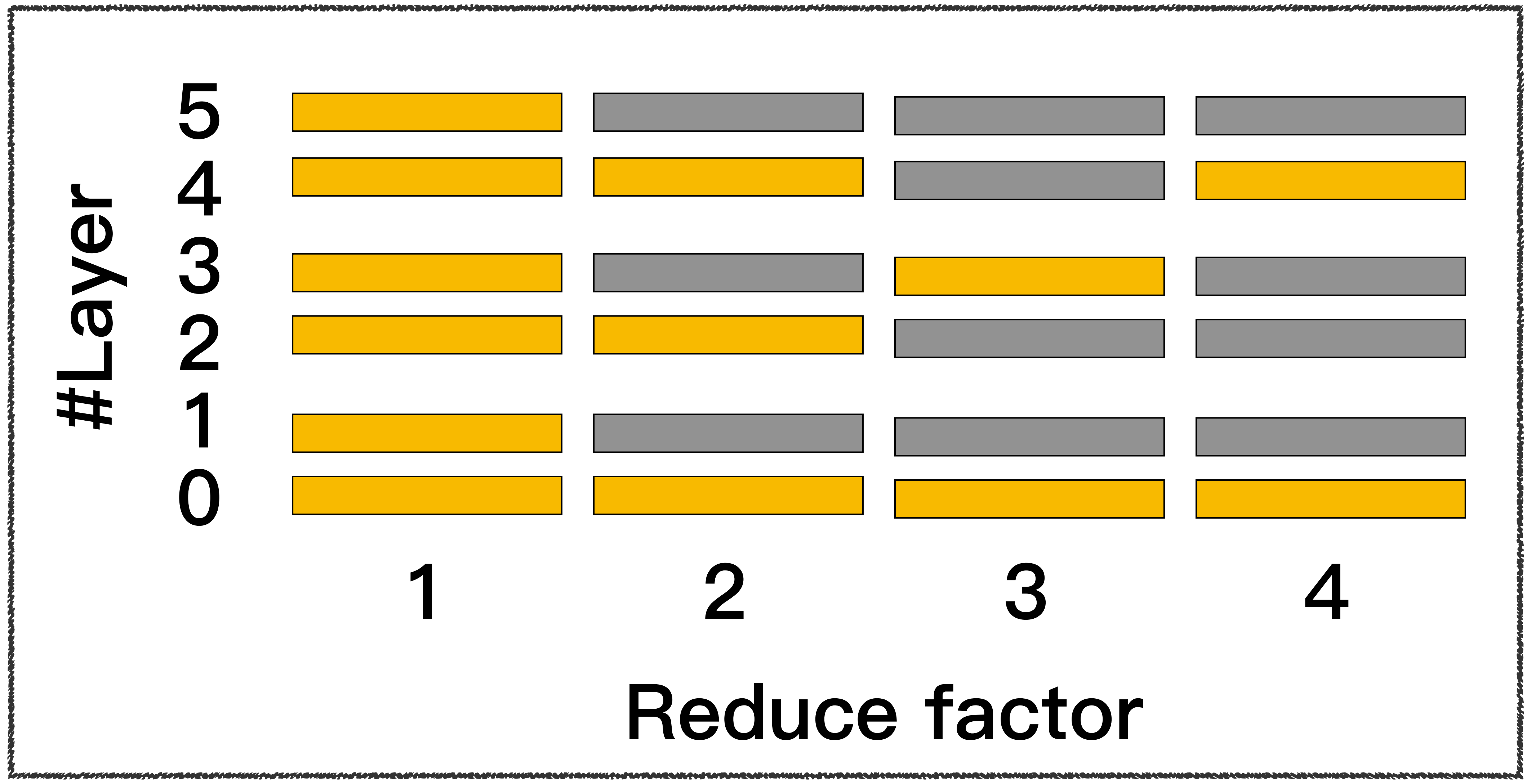
linear!

**Q:** different #timing layers

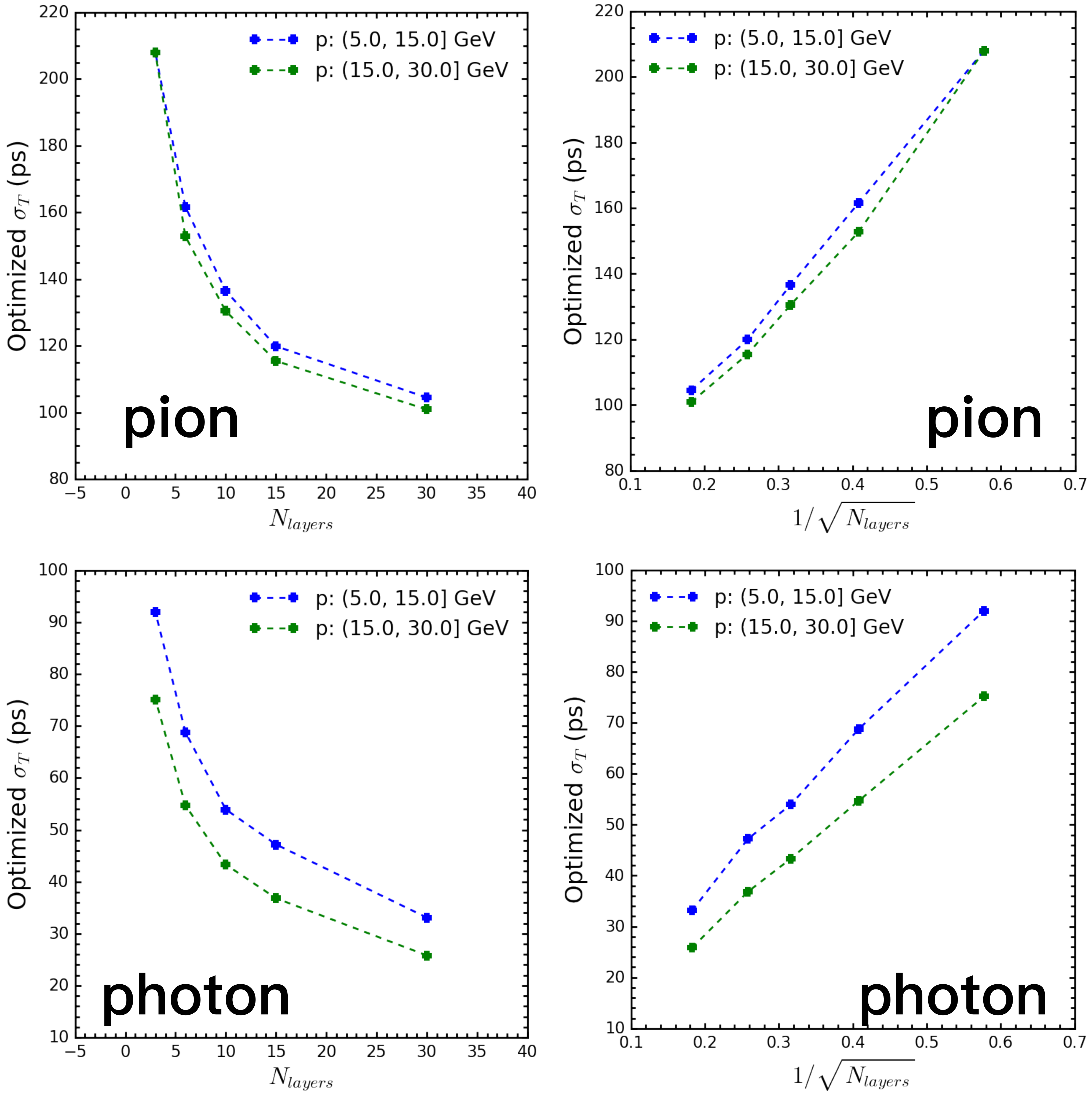
**Q:** Better time estimator?

# 5.3. 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..

## 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

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

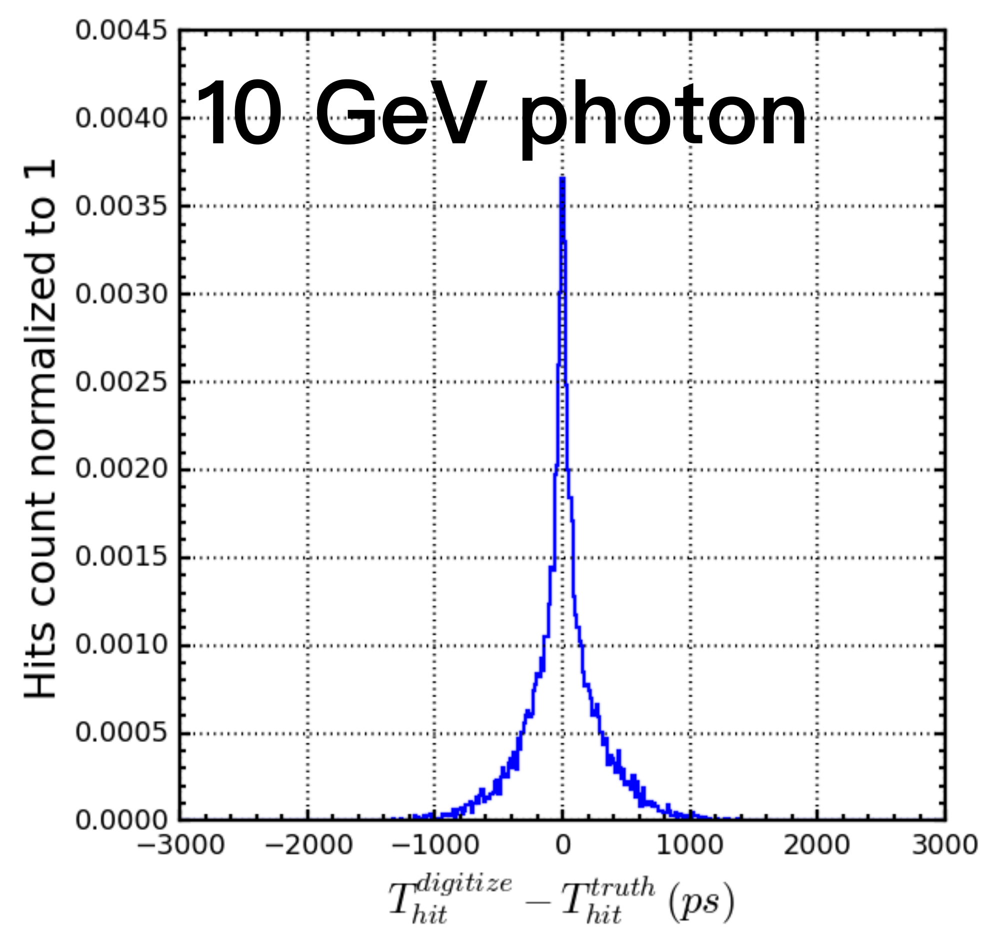
**Q:** better time estimator?

# 5.4. Alternative estimator

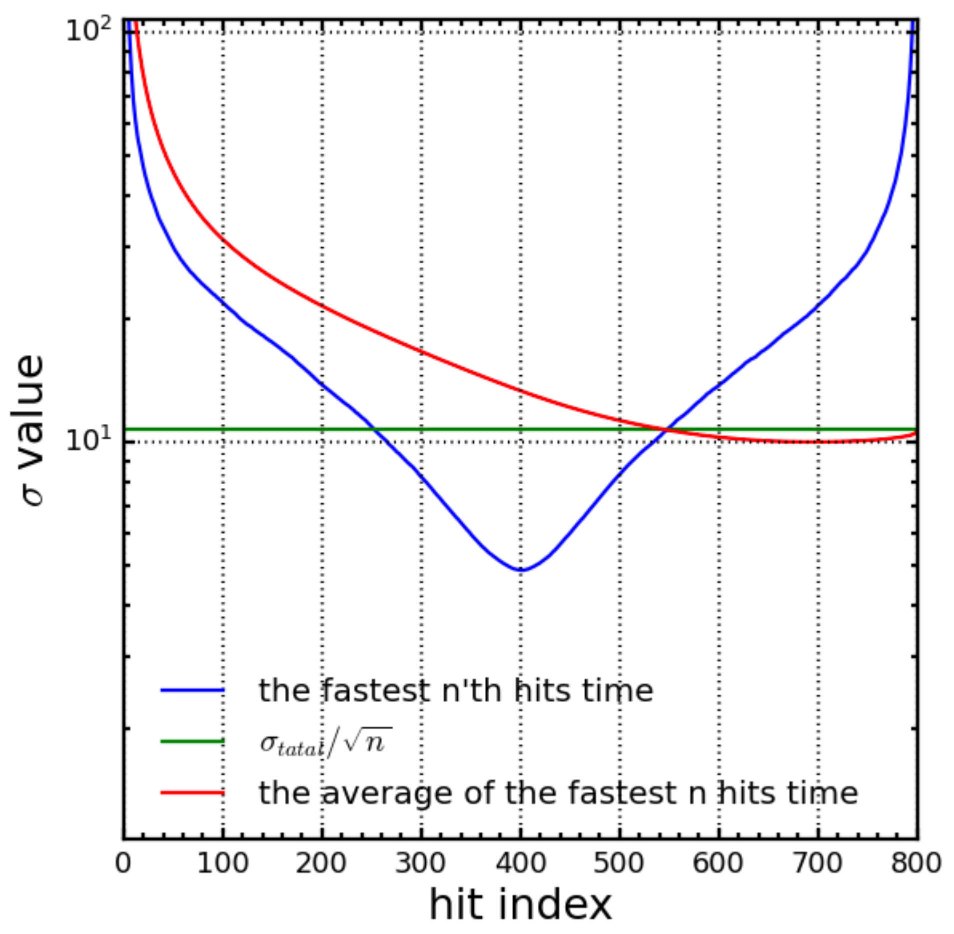
- Despite the time development of cluster hits time at the truth level, the distribution of the digitized hit time residual is highly none–gaussian, in which **order statistic (median) provides more accurate estimation of expectation than average value.**

- **Fraction Mean Value Estimator (FMV, current):**
  The average time of the fastest R*N hits.

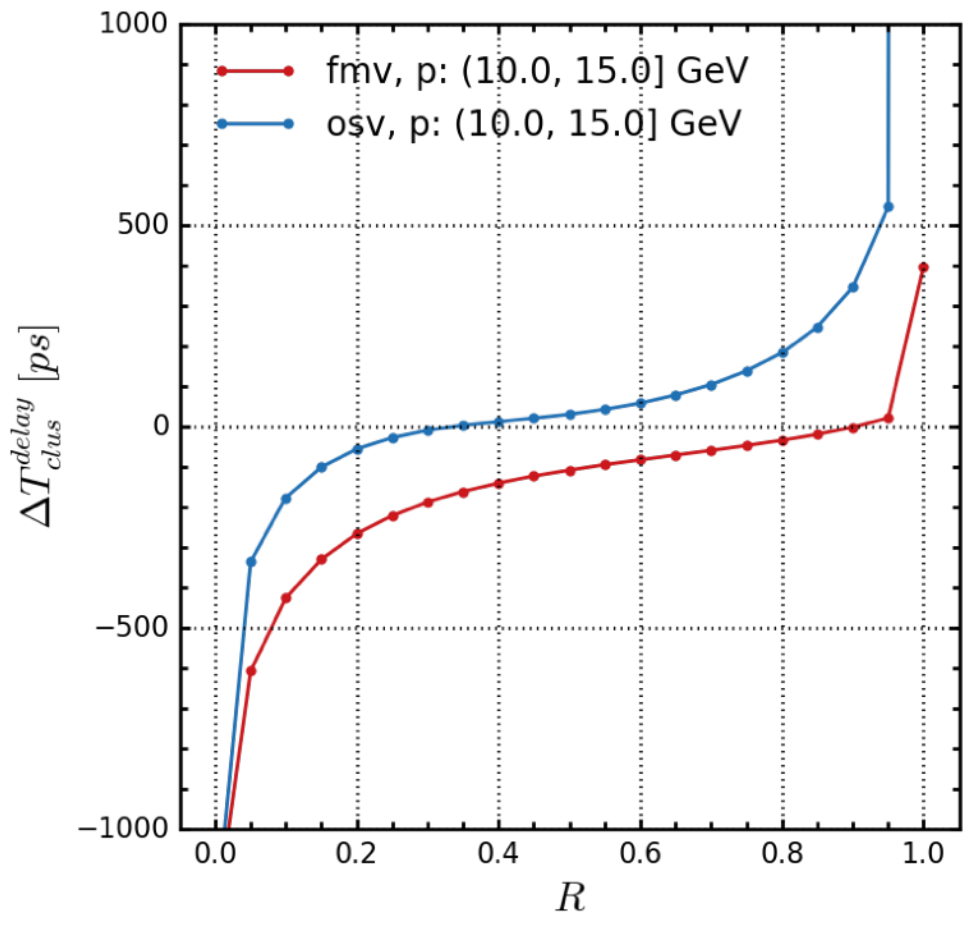
- **Order Statistic Value Estimator (OSV, alternative):**
  The single time value of the fastest R*N'th hit.



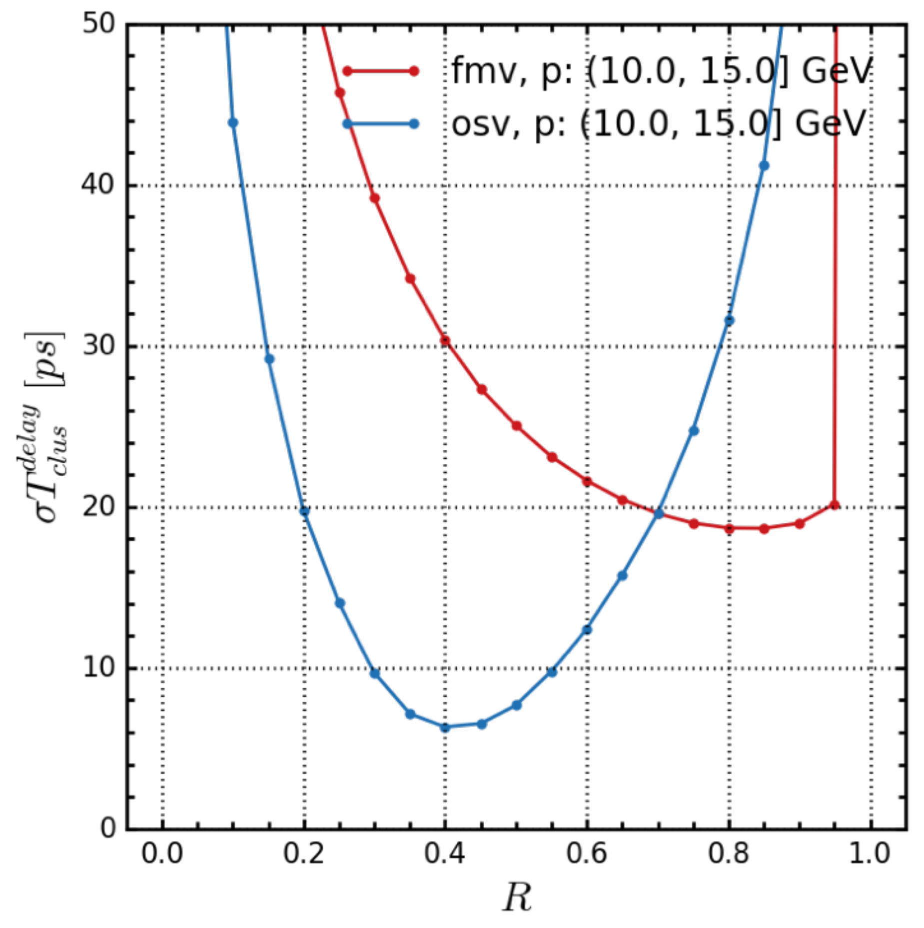
Hit digitization residual



Toy MC of the left distribution. 1w toy clusters with 800 hits.



Estimator bias comparison

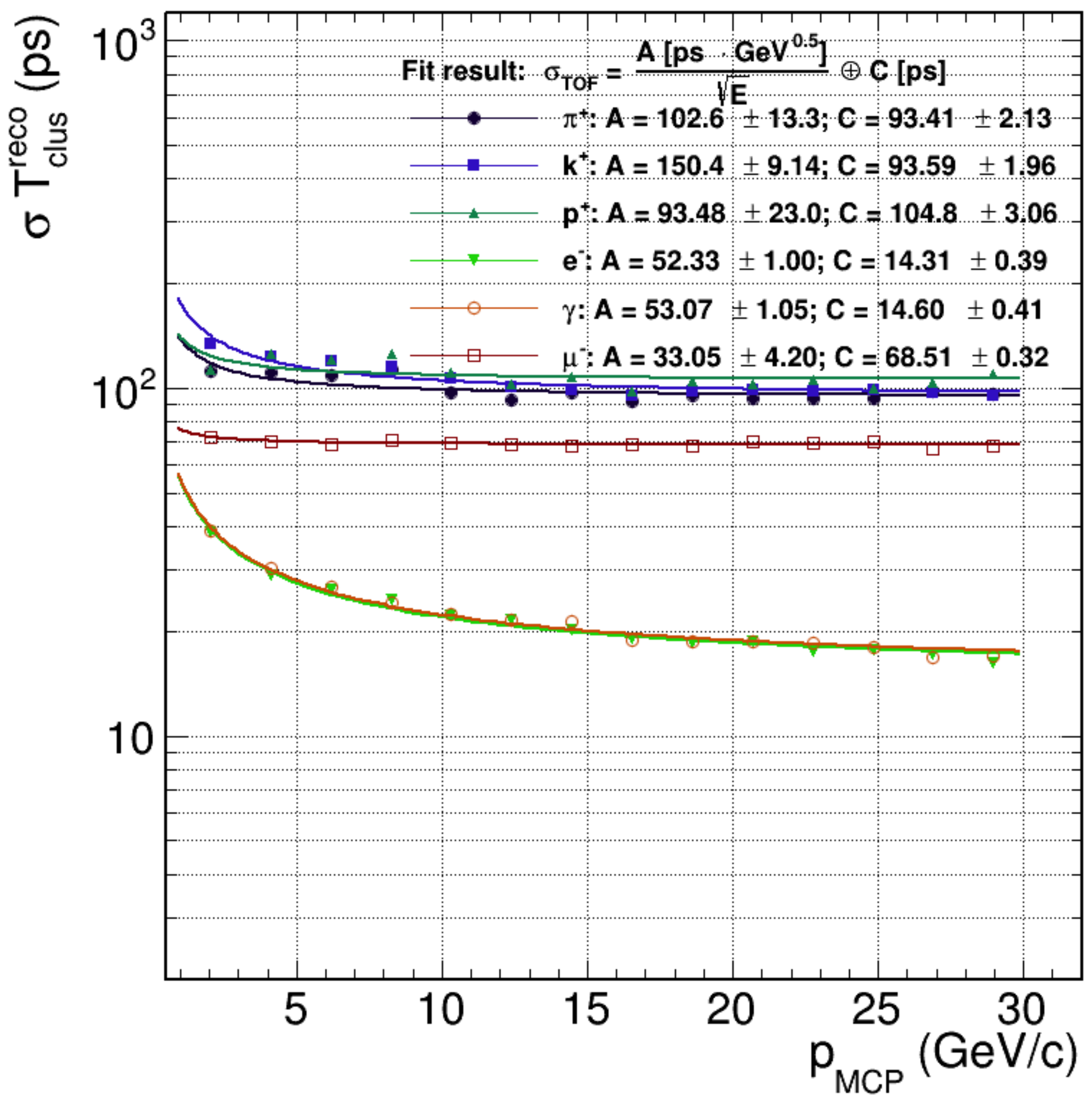


Estimator resolution comparison

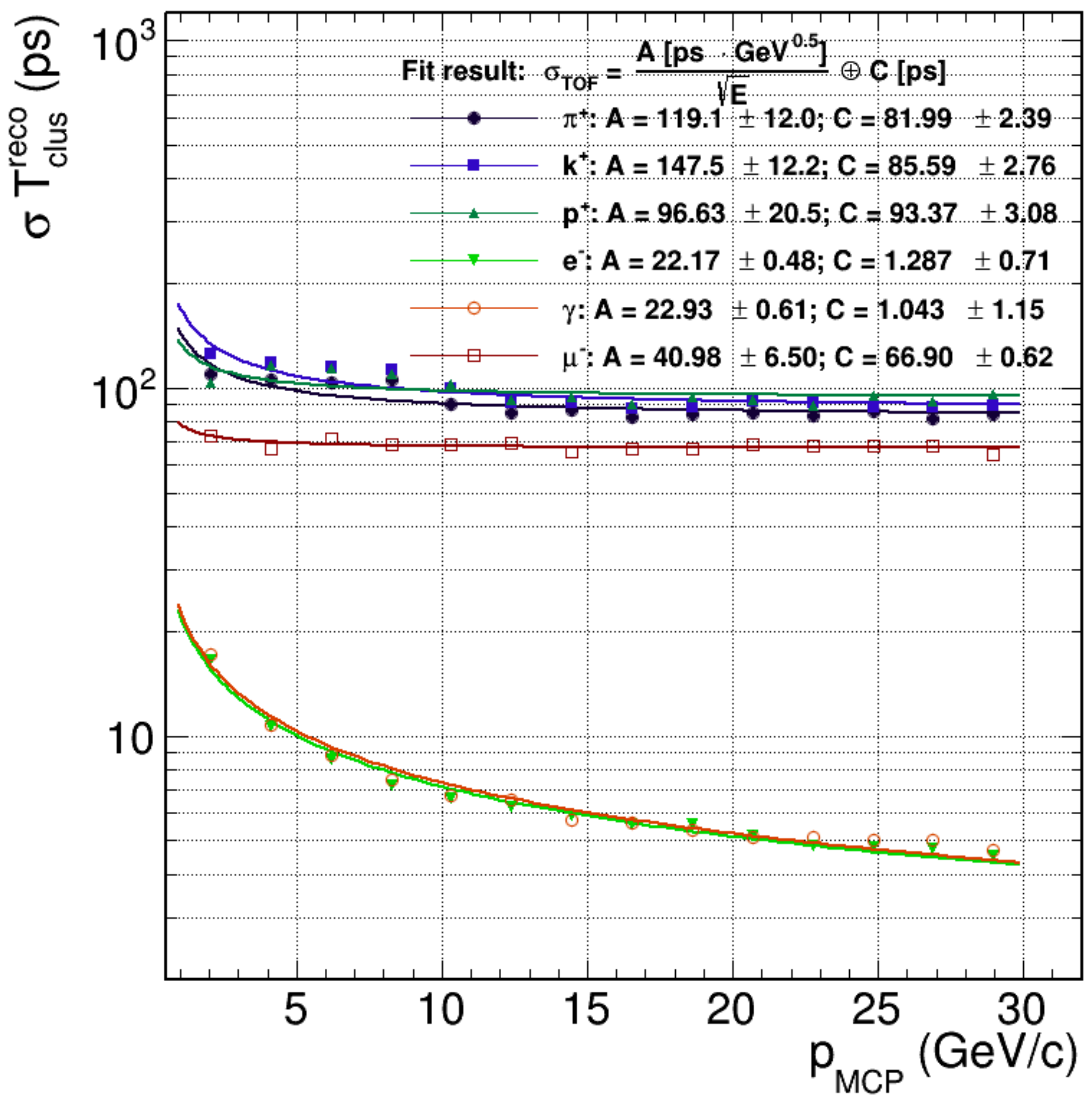
# 5.4. Alternative estimator

With the optimized the R value for FMV (R = 0.6) and OSV (R = 0.4) for minimum resolution respectively,  the OSV estimator could improve,

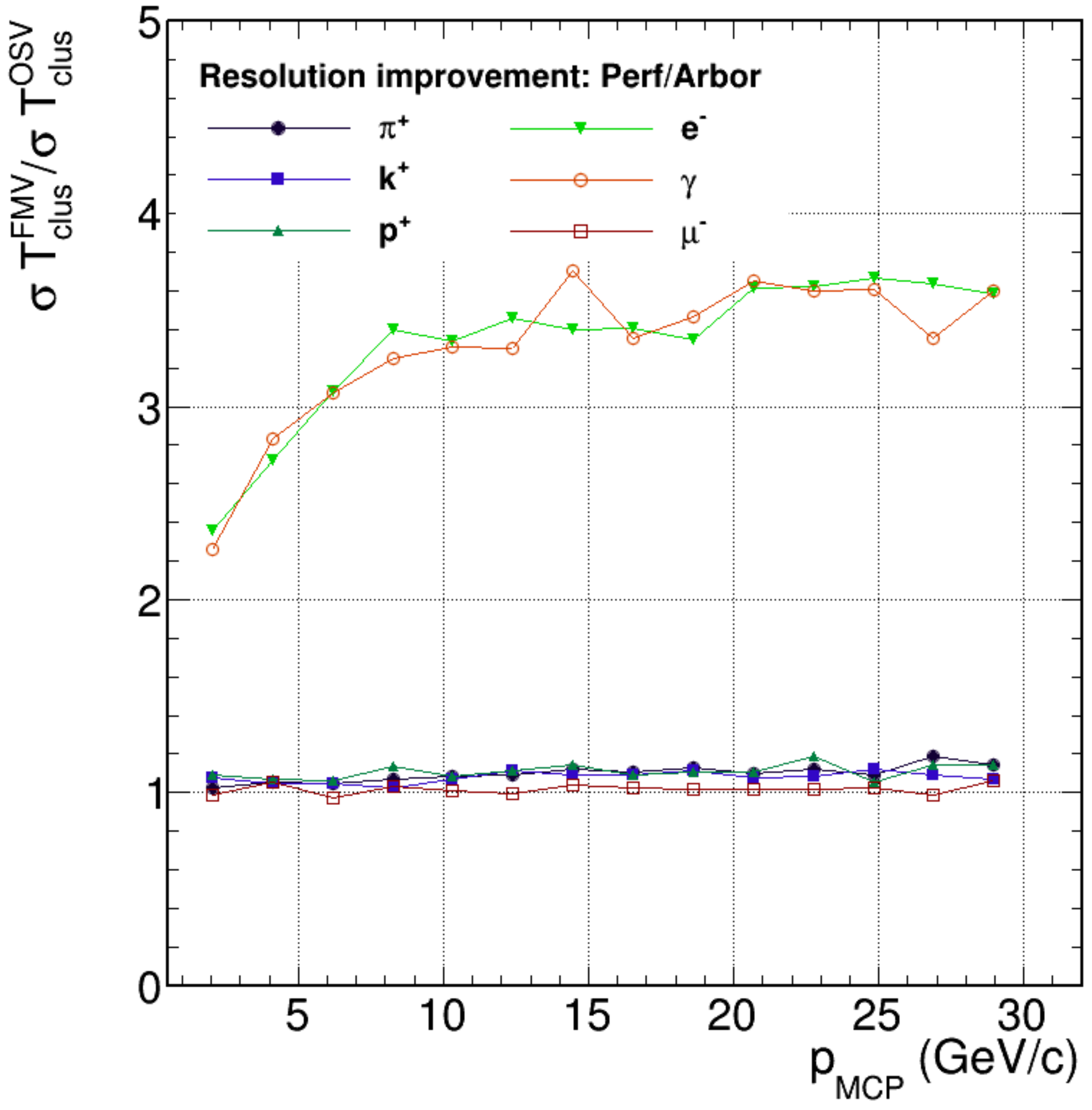
- the time resolution for perfect **hadronic clusters** by a factor of ~1
- the time resolution for perfect **EM clusters** by a factor of ~3




Time resolution of FMV estimator




Time resolution of OSV estimator




Time resolution ratio of FMV over OSV.

## 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:** **better time estimator?**

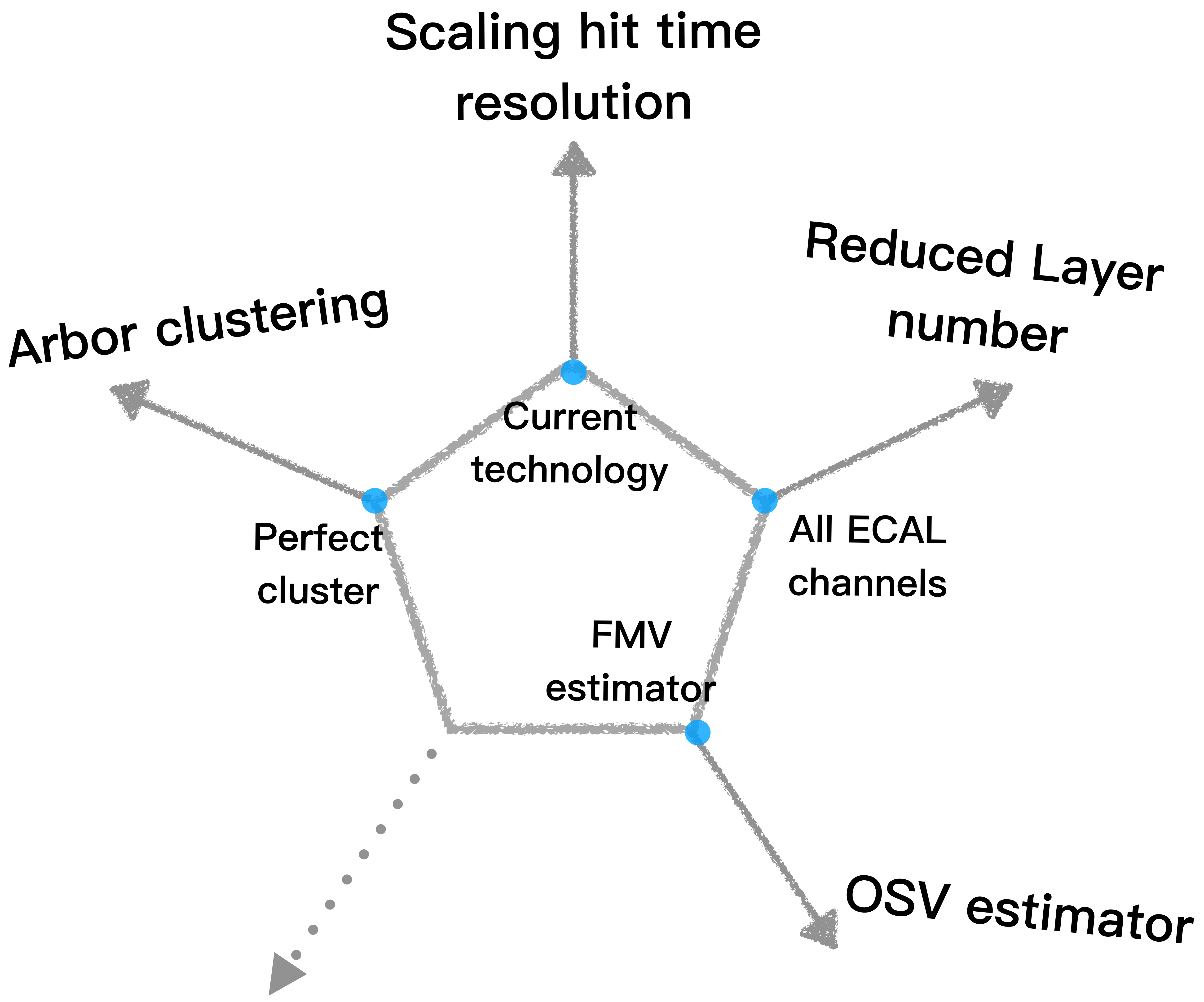
… Order based algorithm improves time resolution up to 3 times, compared to base algorithm(mean value…)…

# 6. Conclusion

- A brief cluster TOF reconstruction algorithm 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 10 ~ 50 ps,
  - for perfect hadronic cluster, can reach 90 ~ 150 ps.
- **PID performance:** The mentioned timing reconstruction can provide $K^+/\pi^+$ ($K^+/p^+$) **separation** higher than $2.5\sigma$ for momentum up to 1.3(2.2) GeV, and make up for the gap of the dE/dx separation power in momentum range around 1 GeV and 2 GeV.

# 6. Conclusion

- **Arbor clustering module** improves the EM (hadronic) cluster time resolution by a factor of ~1.2 (1.4)
- The cluster time resolution is proportional to the **intrinsic time resolution**.
- Cluster time resolution is inversely proportional to the $\sqrt{N_{layer}}$.
- **Alternative strategy**: OSV estimator could improve the EM cluster TOF resolution by a factor of ~3.



# Thanks for your attention

January 19, 2021

# Back Up

# 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

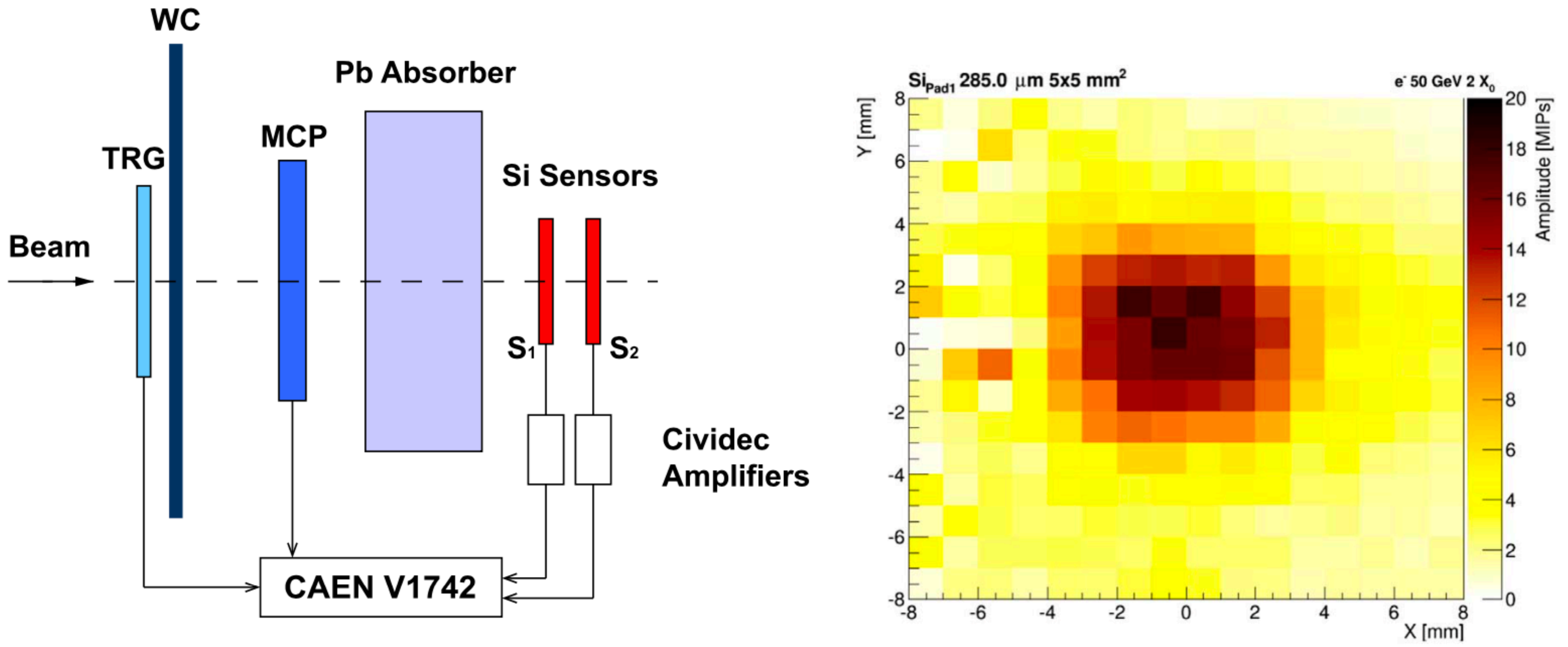



**Fig. 1.** The schematic of the layout displays the main components and the readout scheme on the left. Downstream of the trigger counter (TRG) and wire chambers (WC), a micro-channel plate (MCP) photomultiplier tube was positioned to provide a timing reference in front of the silicon sensors. Various 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 mm²) to 50 GeV electrons when normalized to the MIP signal is displayed on the right. Note that the sensors were placed behind $2X_o$ 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

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

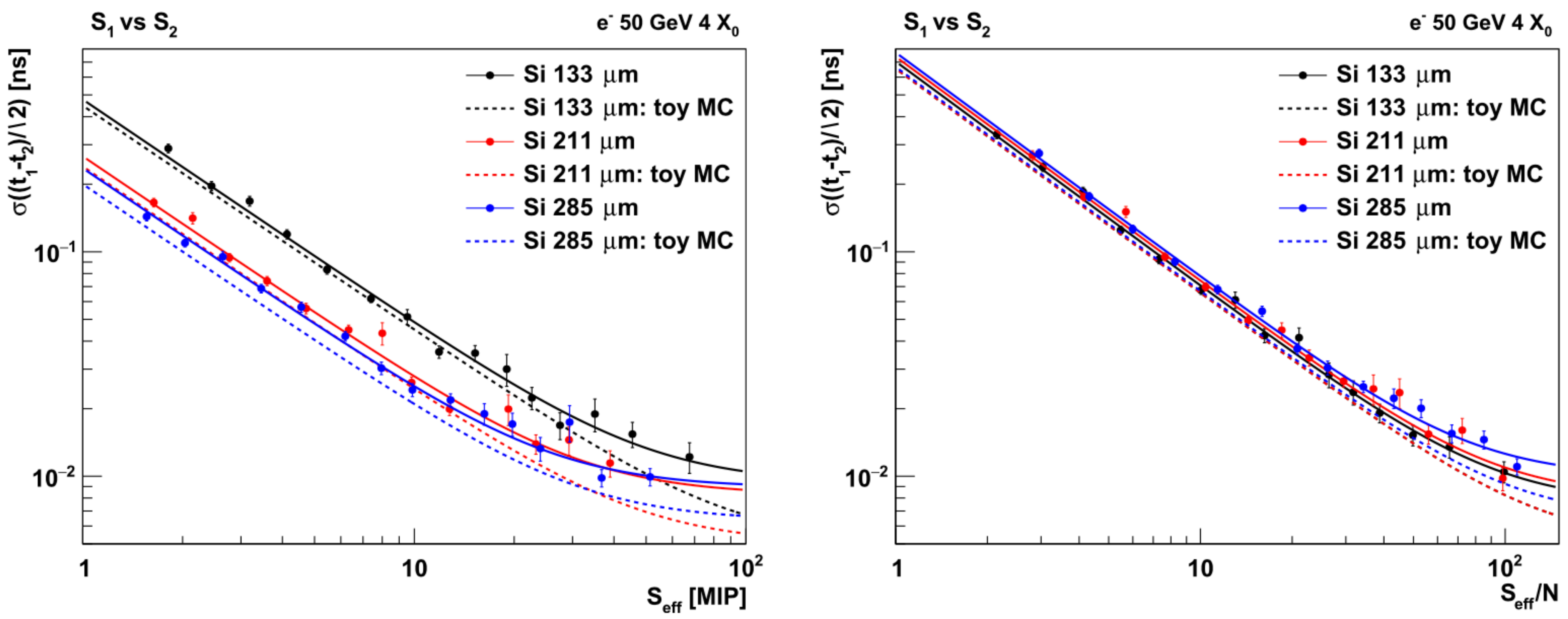



**Fig. 8.** The timing resolution based on two silicon sensors as a function of the effective signal strength in units of MIPs (left) and as a function of the signal-to-noise ratio (right). The fitted resolution functions with a noise (*A*) and a constant term (*C*) are also shown as solid lines. The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

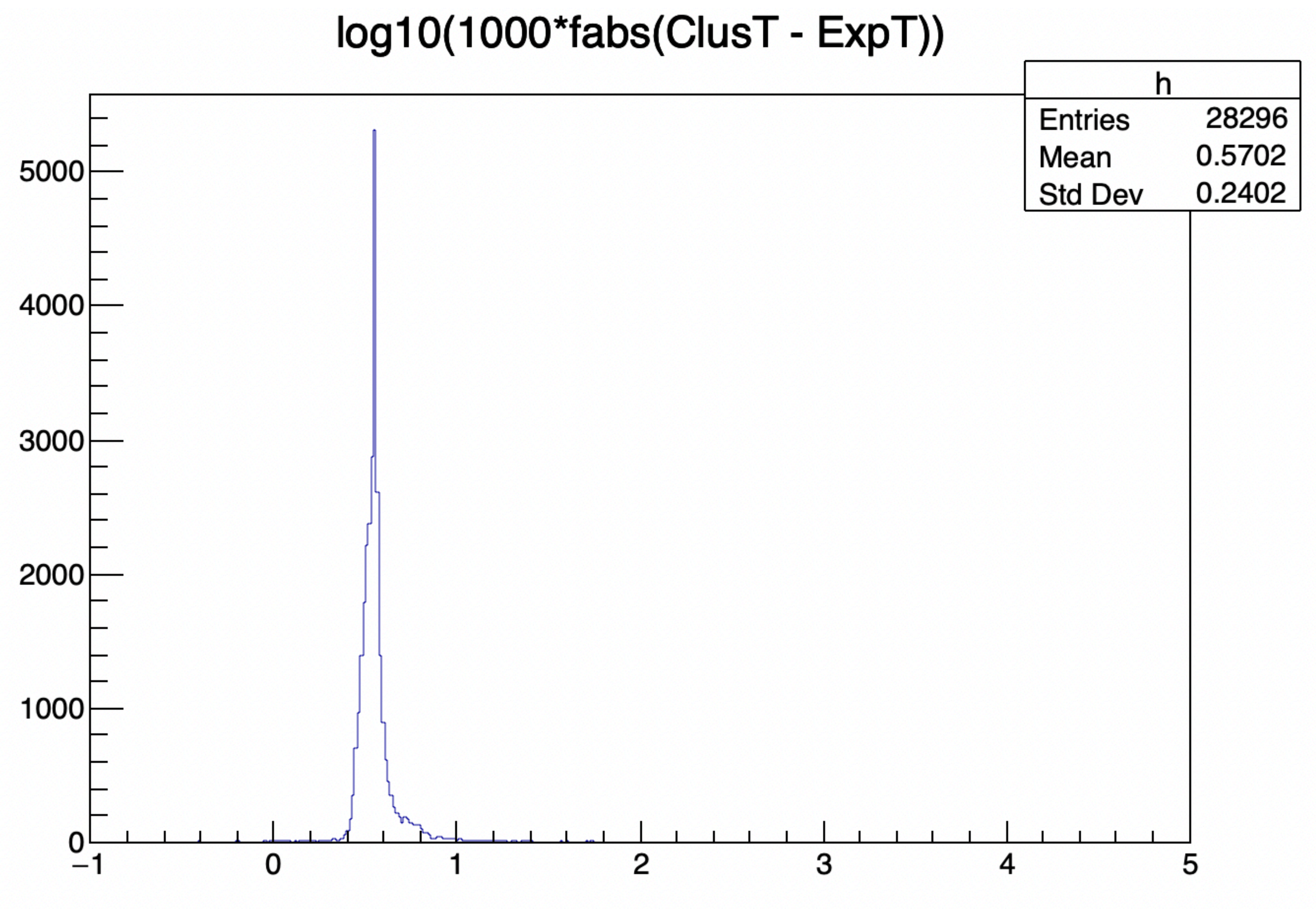
$$T_{expect}(p) = L/c \cdot (\frac{\sqrt{p^2 + m^2}}{p} - 1)\,.$$

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

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

The difference:

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

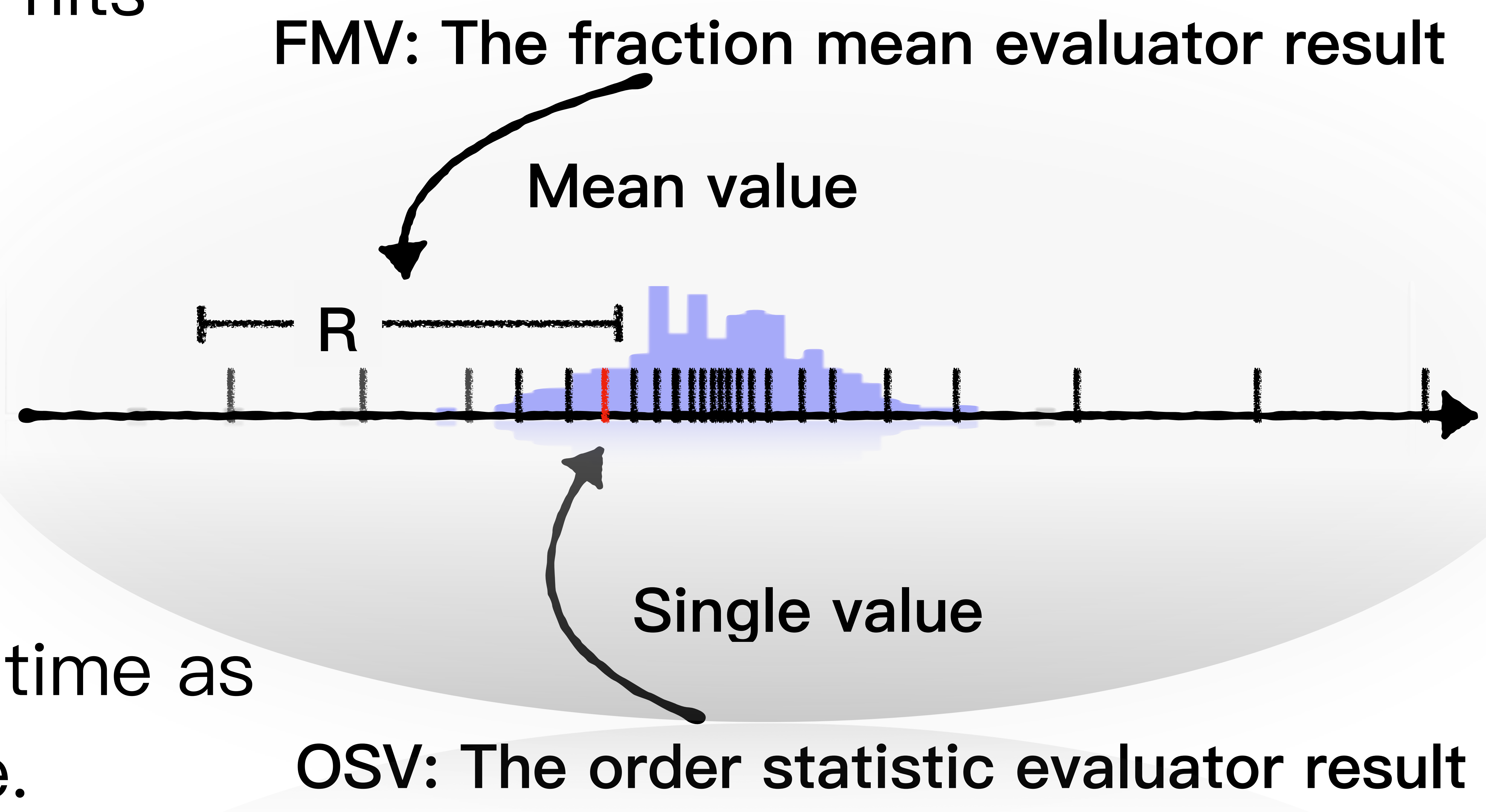



The difference between expected cluster TOF and fastest truth hit time (by pico second), in pion sample.

# Update 8: Evaluator of Order Statistic

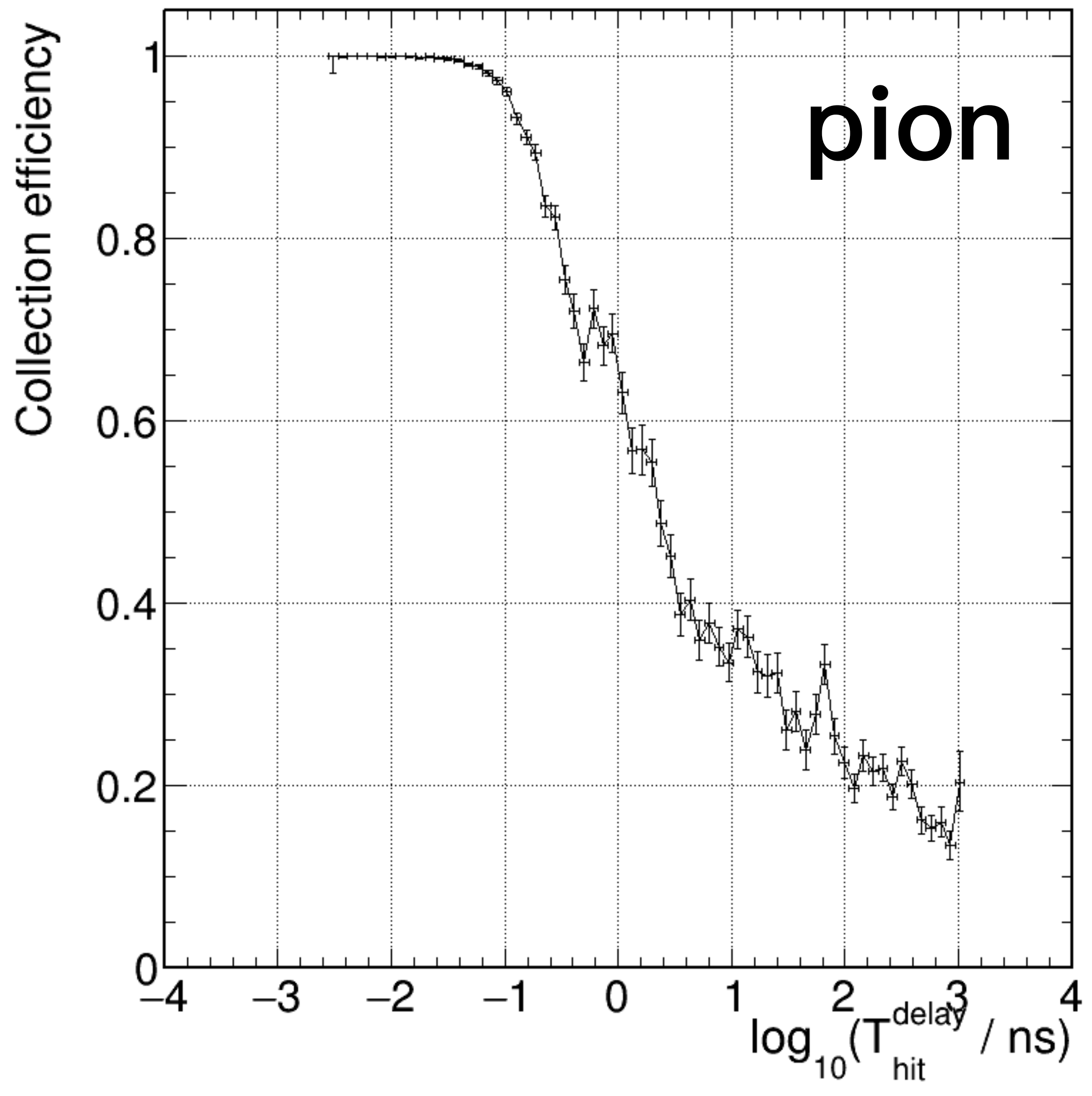
A New cluster TOF evaluator:

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

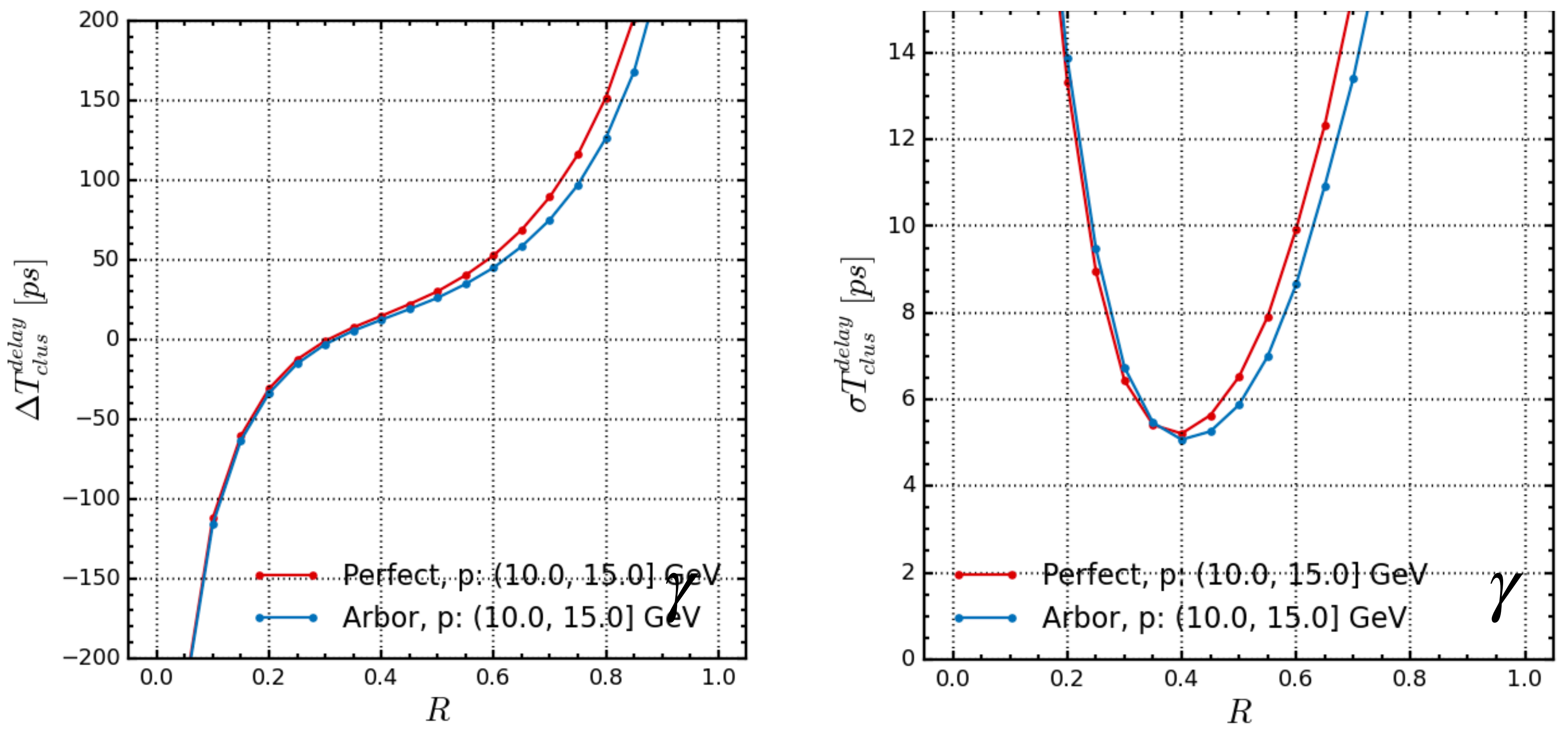


# BackUp. Influence of the Arbor clustering to OSV

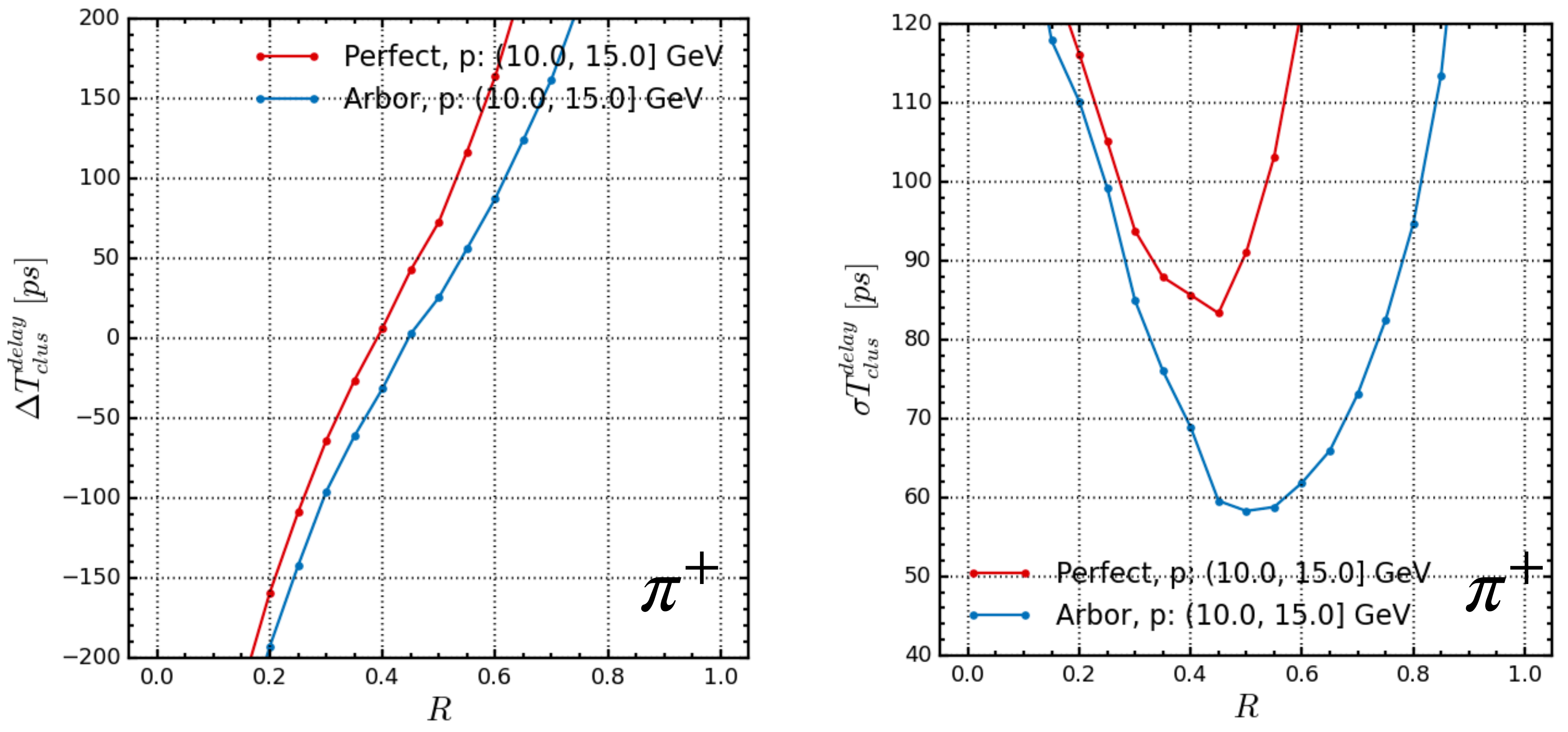
- **Arbor clustering** module partly removes the slow component of clusters, and improves the hadronic cluster time resolution by a factor ~ 1.4 (81ps/59ps)




Hit collection efficiency of Arbor for $\pi^+$ ECAL hits.




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

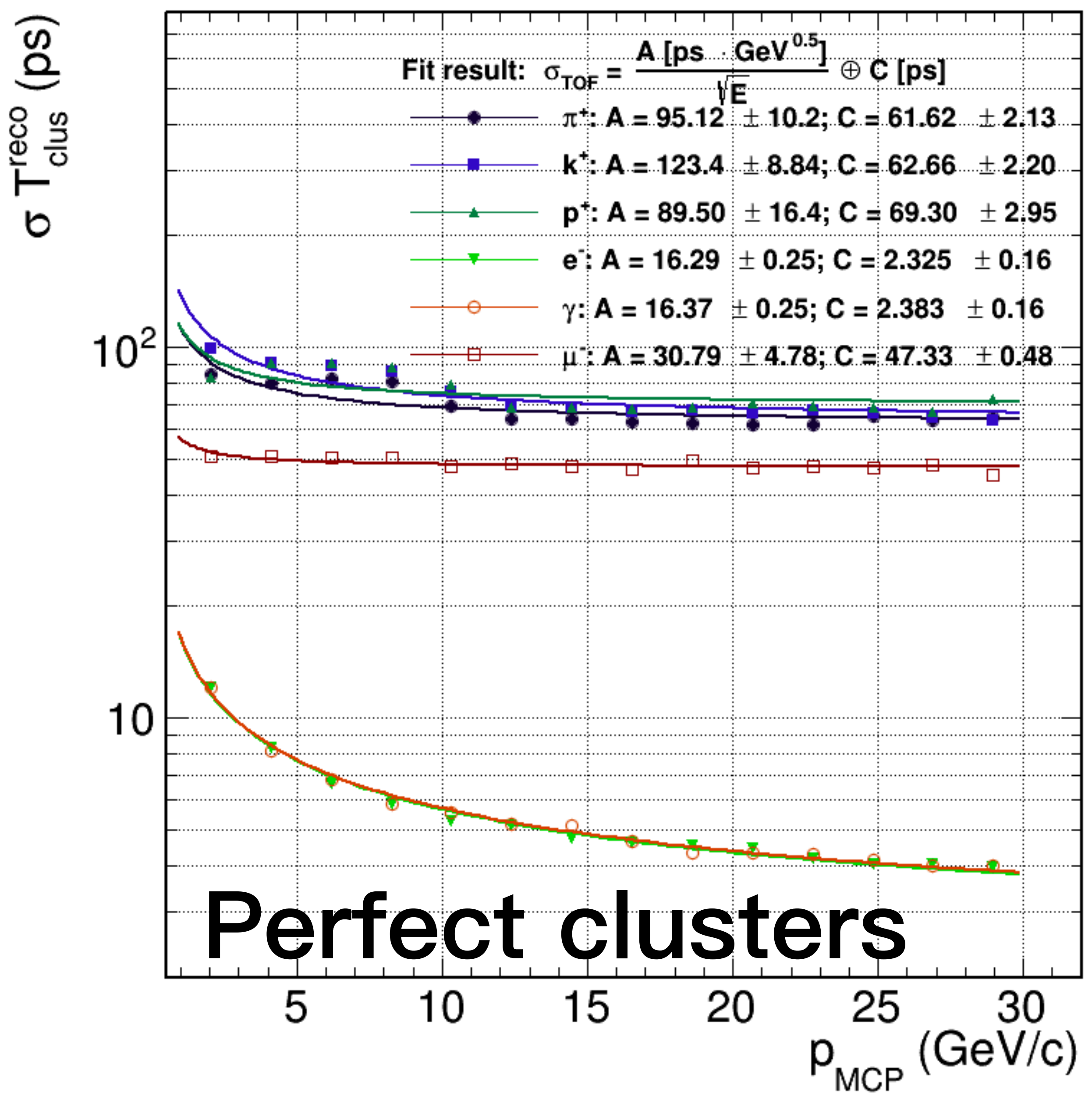



Estimator (left) bias and (right) resolution comparison between Arbor and perfect photon clusters.

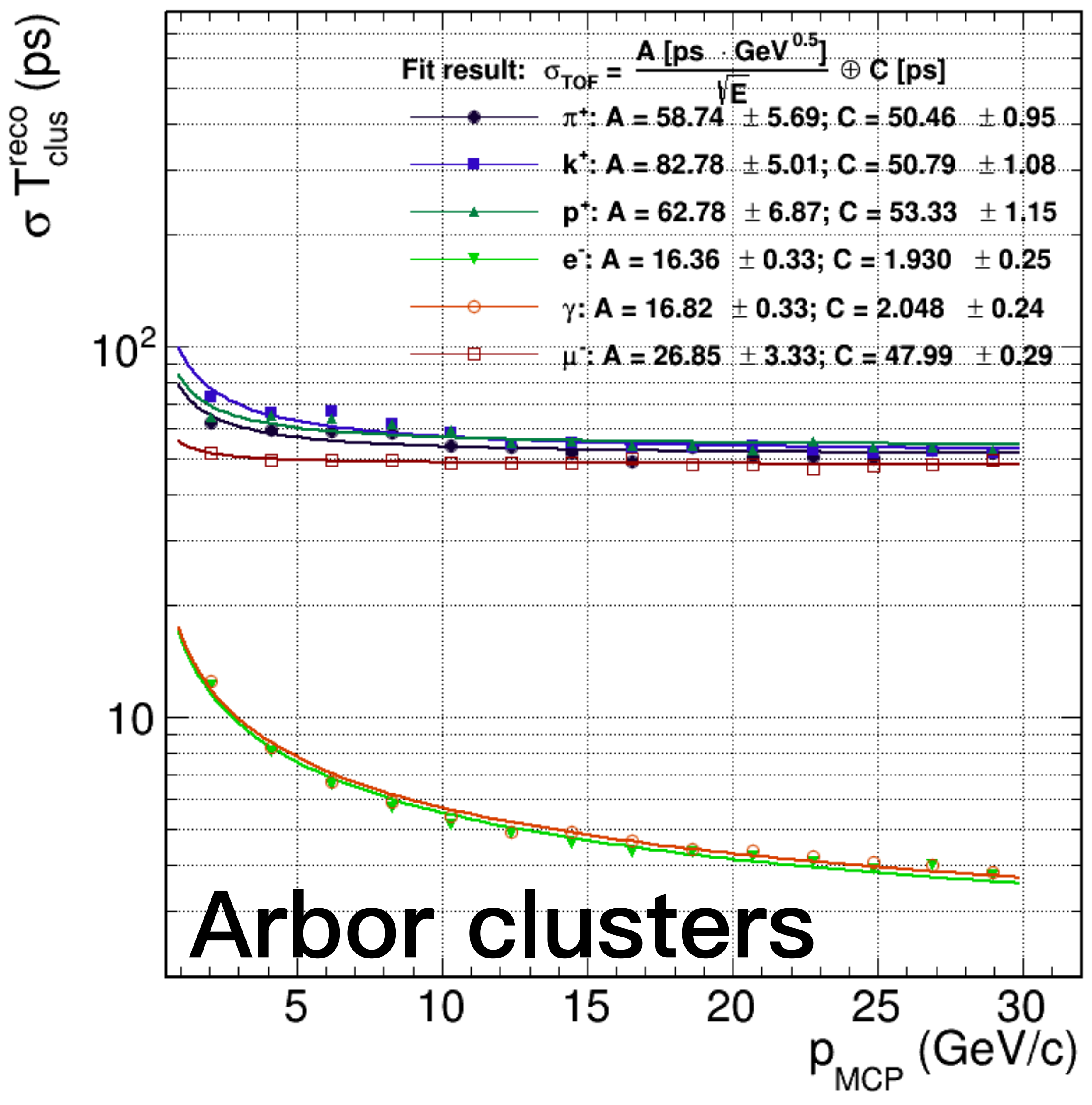
# BackUp. Influence of the Arbor clustering to OSV

Using OSV estimator, and set the R = 0.4

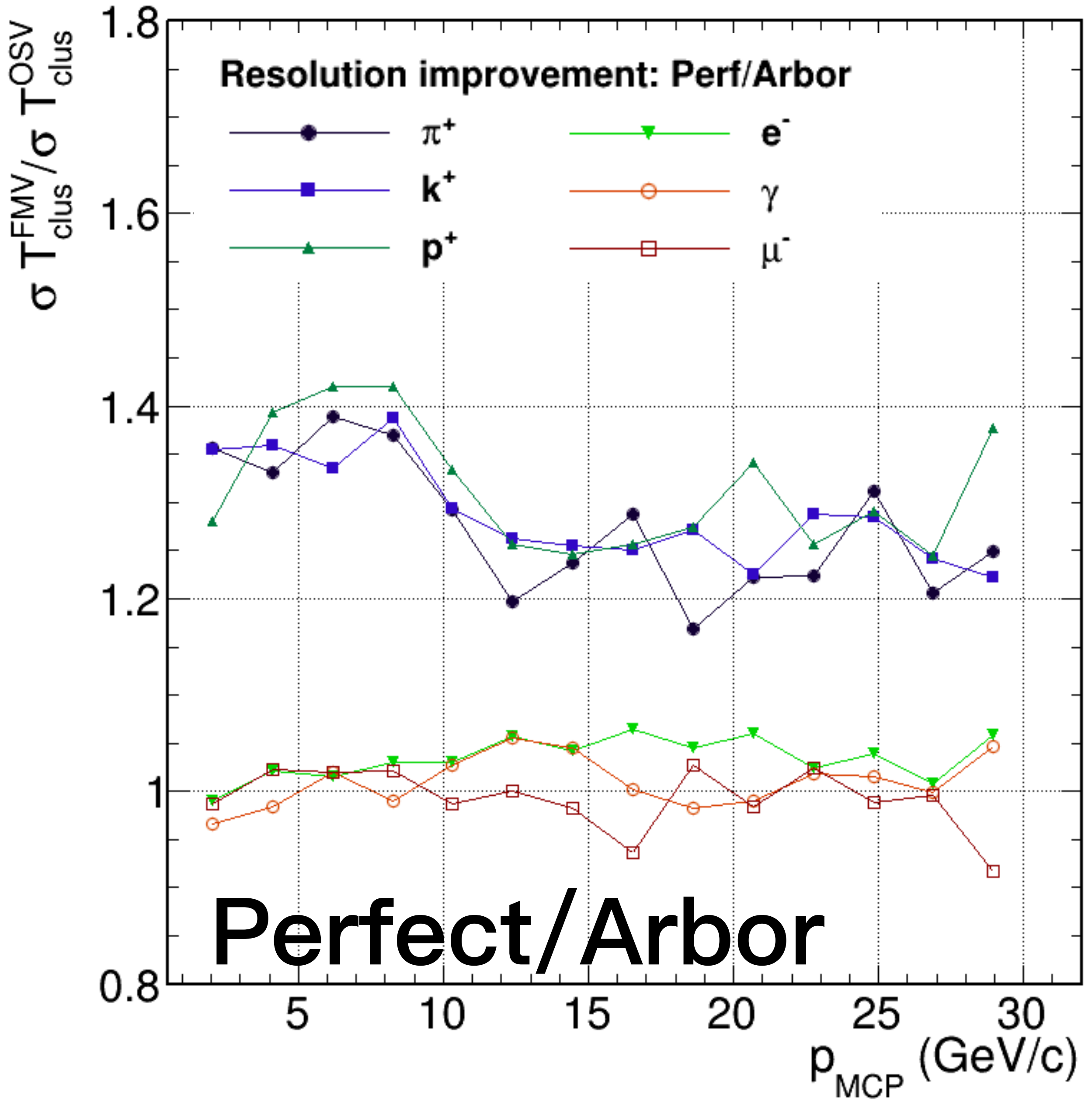
Arbor clustering module with parameters optimized for the CEPC improve the time resolution of EM and hadronic clusters by a factor of ~1 and ~1.3, respectively.




Time resolution for perfect clusters




Time resolution for Arbor clusters




The time resolution ratio of perfect clusters over Arbor clusters.