

Shower Time Spectrum in Calorimeter

Yuzhi Che, Manqi Ruan

Institute of High Energy Physics, Chinese Academy of Sciences

中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会 2022年8月11日

Content



Basic configuration

Calorimeter response

4

5

6

2

3

Algorithm & performance

Further exploration

Off-time pile-up



1. Motivation

• **@LH_LHC**: mitigate pileup effect

- An effective K[±]/π[±]/p[±] identification: dE/dx information has not enough separation for charged particles (K[±]/π[±]/p[±]) 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.

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).



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



Truth cluster TOF distribution of real photon and fake entification at the CEPC Using TPC dE / photon clusters.





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 $0 \sim 30$ 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).







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



5



Num. of Hit

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, $T_{hit}^{digitized} = Gaus\left(T_{hit}^{truth}, \sigma_{T_{hit}}\right),$ $\left| \left(\frac{0.38 \ ns}{E_{hit}} \right)^2 + (0.01 \ ns)^2 \right|.$ $\sigma_{T_{hit}} = 1$

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

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).





Mimic detector response in Simulation:

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





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







4. Algorithm & performance

A brief cluster TOF estimator:

- Record the digitized ECAL hits 1.
- 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.





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





4.3. 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

 ^[3]
 (1)
 ^[3]
 ^[3]
 - for perfect EM clusters: 5-20 ps.
- The time reconstruction is accompanied by a certain bias,
 - Calibration.
 - Close for $K^{\pm}/\pi^{\pm}/p^{\pm}$.

Physics list: QGSP_BERT_HP



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





Section 5. Further exploration:

What's the cluster time resolution with:





realistic clustering?

for example: Arbor?

different hit time resolution

different #timing layers



• 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 π^{\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.

5.1. Influence of the Arbor clustering



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.



5.1. Influence of the Arbor clustering

time resolution of hadronic clusters by 50%~80%.



Time resolution for perfect clusters

Time resolution for Arbor clusters

Arbor clustering module with parameters optimized for the CEPC improve the

The time resolution ratio of perfect clusters over Arbor clusters.



Section 5. Further exploration:

What's the cluster time resolution with:



Impact of realistic clustering

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

different hit time resolution

Q:

A:

different #timing layers



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.

different hit time resolution

linear!

different #timing layers



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.

different hit time resolution

linear!

different #timing layers

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



Section 6. Off-time pile-up



1

 Slow components of hadronic showers may induce signal pile-up with the next event.



Off-time pile-up: Time spectrum in larger region

Probability Density Function: f(t)

Cumulative Density Function: $F(t) = \int_0^t f(t') dt'$



Residual Energy Fraction:

 $R(t) = 1 - F(t) = \int_{t}^{\infty} f(t') dt'$

10 Residual Energy Fraction 10⁻² 10^{-3} 10- π^+ 10^{-5} 10^{-6} μ 10-2 3 5 $\log_{10}(T / \text{ns})$



Off-time pile-up: Z-qq events

- **Z** boson yield: $N = 3 \times 10^{12}$
- The average time spacing between two $Z \rightarrow q\bar{q}$ events: $\sim 3 \times 10^4$ ns (2000 Bunch Spacing)

Toy MC:

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

@ Muchen He, Fanjie Meng

Probabiliy Density of Event Spacing

5

з

0

CEPC Z pole scheme



Off-time pile-up



@ Muchen He & Fanjie Meng

 $Z \rightarrow qq$ events.



Distribution of the pile-up energy fraction



6. Conclusion

- A brief cluster TOF reconstruction algorithm are implemented.
- - 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:

• Cluster Time: Under current CMS silicon sensor timing technology, CEPC ECAL can provide the time resolution:

• During Z pole operation, there will be percent level energy in ECAL & HCAL that pile-up with the next event.











Thanks for your attention

Yuzhi Che, Manqi Ruan





Back Up



The time definition of cell hits





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

The most energetic sub-hit





Intrinsic hit time resolution



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

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 $S_{\rm eff} = S_1 S_2 / \sqrt{S_1^2 + S_2^2}$. It can be seen that the timing performance improves with increasing signal strength (Fig. 8-left), but that for equal $S_{\rm eff}/N$ 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

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

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).



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 microchannel 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- μ m 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 $2X_0$ of lead absorber in this case.









Definition of perfect cluster



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

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



The distribution of the difference between reconstructed shower time and the true time in the 10 GeV \$\pi^{+}\$ 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.





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.

different hit time resolution

linear!

different #timing layers

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





CMS HGCAL

The electromagnetic compartment of the CMS endcap calorimeter:

WCu absorber + Silicon sensor (28 sampling layers)

Depth: 26 X_0 (1.7 λ)

Active thickness (μ m)	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

300µm [—] **200**µm **120**µm

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.

different hit time resolution

linear!

different #timing layers

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

CMS HGCAL

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

