

Timing calibration using single pion events

2023, October 26

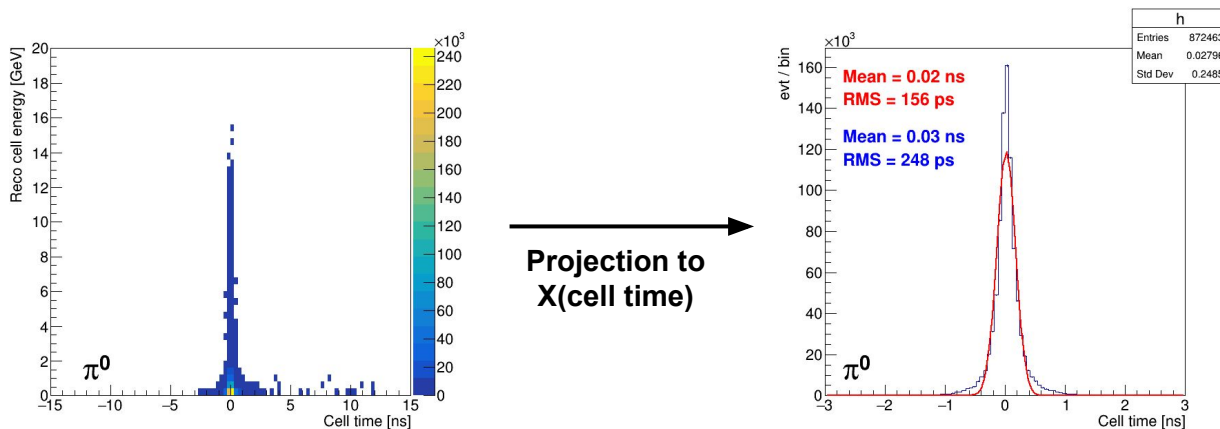
<https://indico.slac.stanford.edu/event/8516/>

Sanha Cheong
Valentina Cairo
Zahra Farazpay
Ariel Schwartzman
Lorenzo Santi
Kim Doyeong 김도영

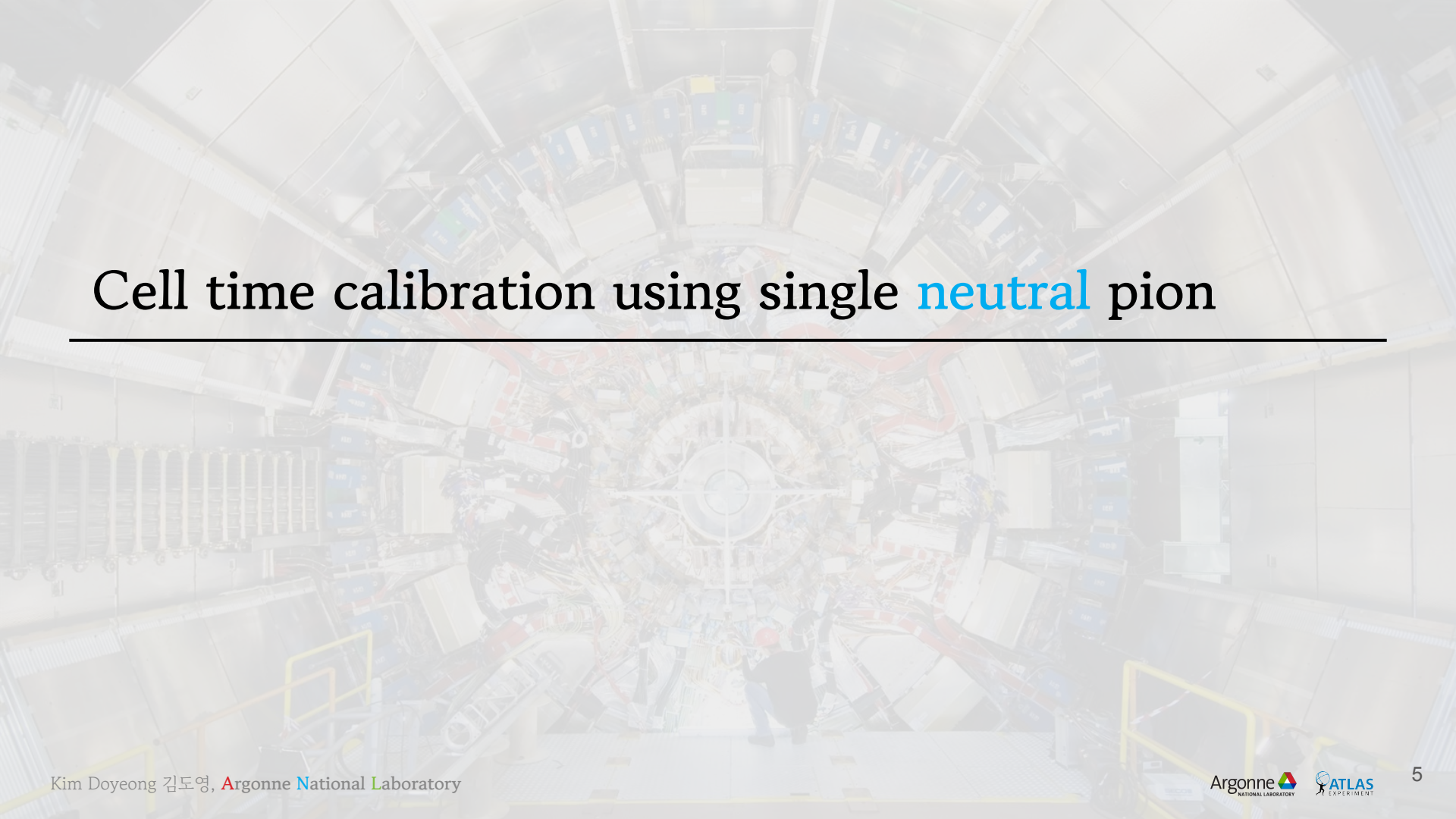


- Cell time information has huge potential to enhance our understanding of jets at HL-LHC and beyond
- Many physics program at (HL-)LHC can benefit from 5D calorimeter information synergizing with other sub-detectors (HGTD, ITk)
 - LLP searches, Higgs & Di-Higgs, precision SM measurements, and other BSM searches
 - Improve PU suppression
- ATLAS calorimeter systems measure time as well as energy, however, cell time information is rarely utilized
 - So far, people use cuts on cell time to reject out-of-time PU but rigorous calibration hasn't been done yet
- Our goals:
 - **Understanding cell timing using single pion** (charged, netral, w/wo PU) Scope of today's slides
 - Understanding cell timing **using jets**
 - Improve jet calibration (- study with slow neutrons, probably take this off?)
 - Study of jet's time of arrival and vertex t0 reconstruction using calorimeters cell time

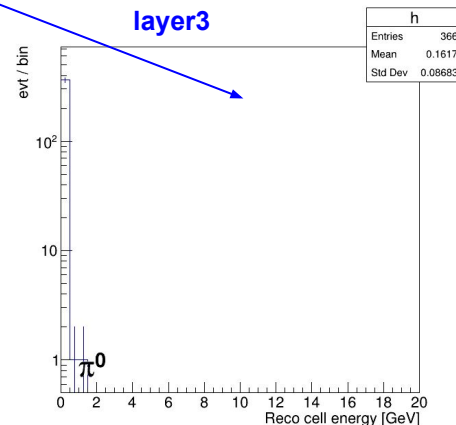
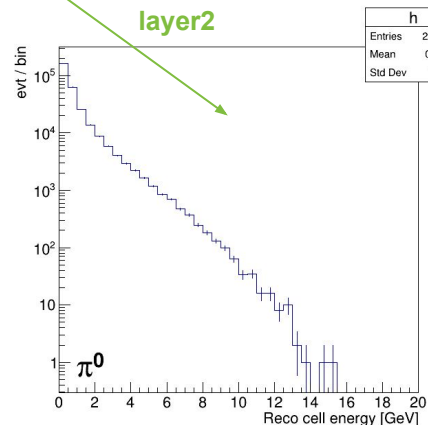
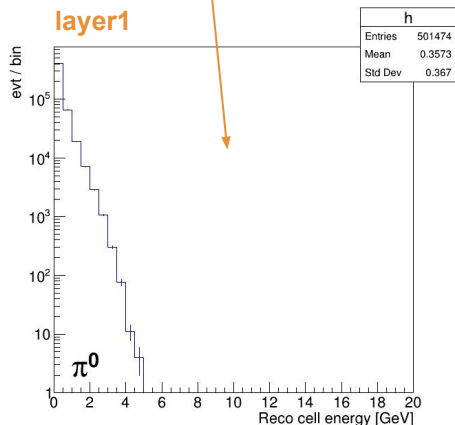
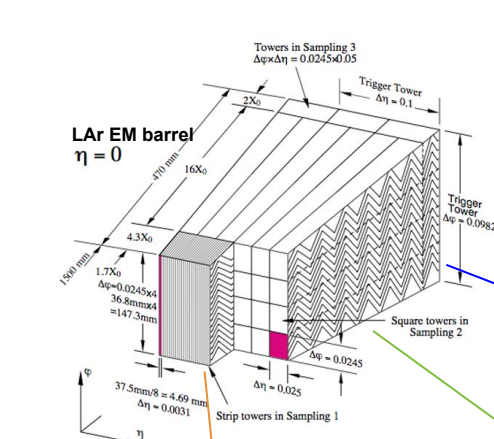
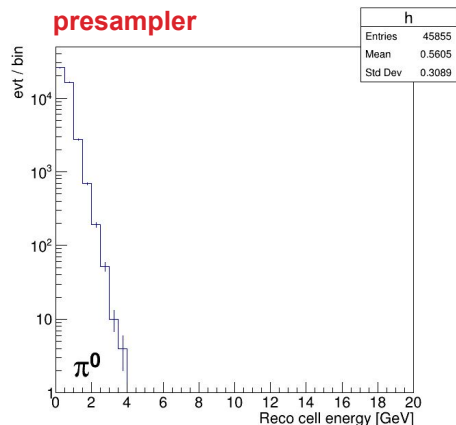
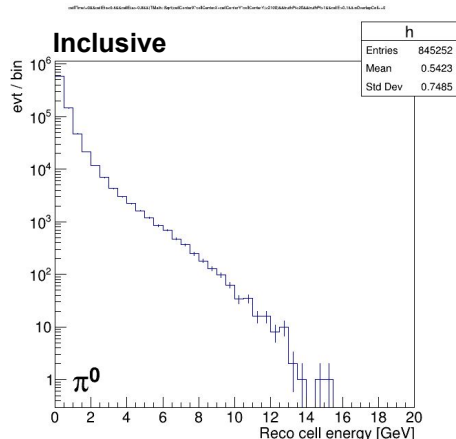
- For our purpose, the pions of interest has low p_T (1 ~ 20 GeV)
 - JER is decent at high p_T with calorimeter, but not at low p_T regions
 - We focus on pions with p_T 1~20 GeV, which can be included in jets with relatively poor JER
 - Challenges here is that low p_T pions are dominant by cells with E below 2 GeV, where timing resolution blow up quickly
 - In addition, timing resolution and also systematic offset of mean values depend on layer by layer
- We can find fit functions to calibrate the pions as functions of cell E and layer



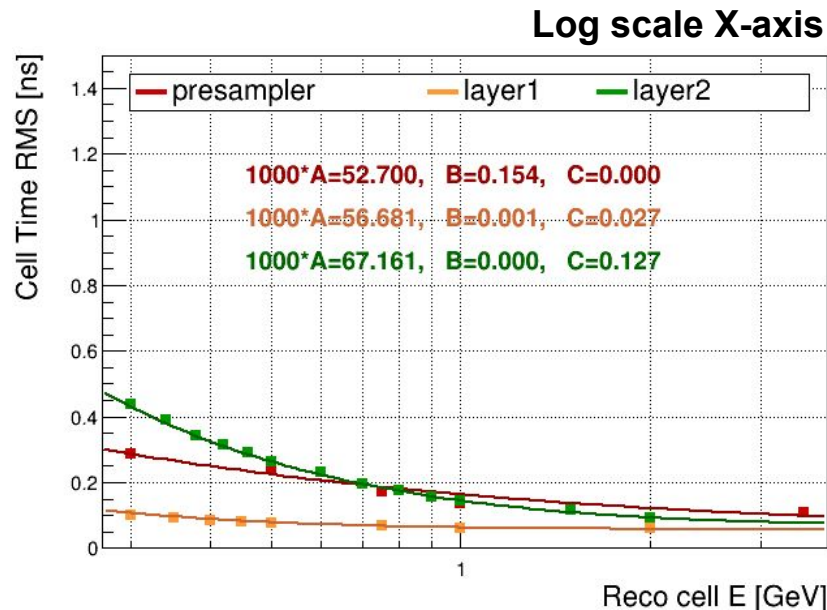
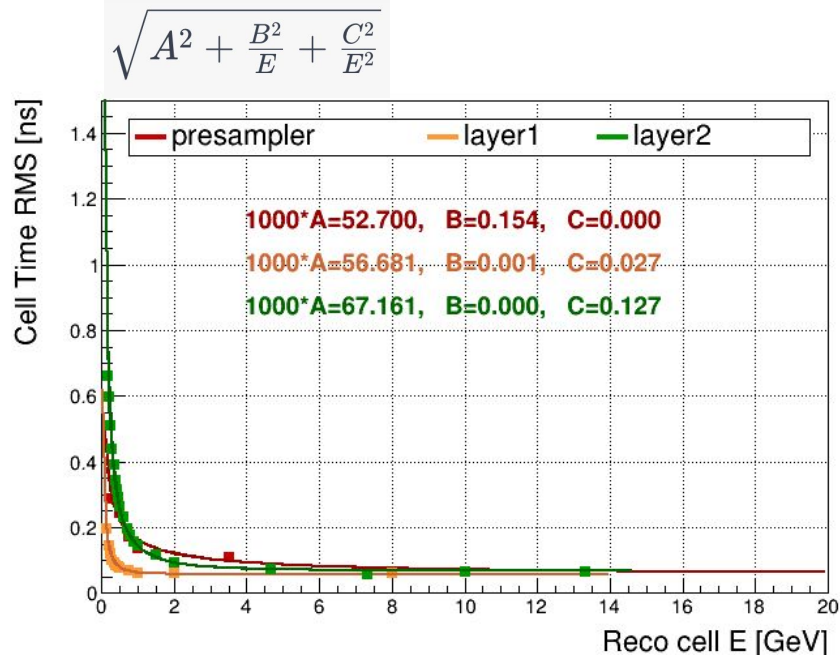
- We can find fit functions to calibrate the pions as functions of cell E and layer
 - Current focus is pions in the central region ($|\eta| < 0.8$)
 - Pile-up is not considered for this study (yet)
 - Set of fit functions are found for charged and neutral pions independently (Their hadronization are different)
 - The fit functions are used to calculate weighted average of the timing resolution of pions



Cell time calibration using single **neutral** pion

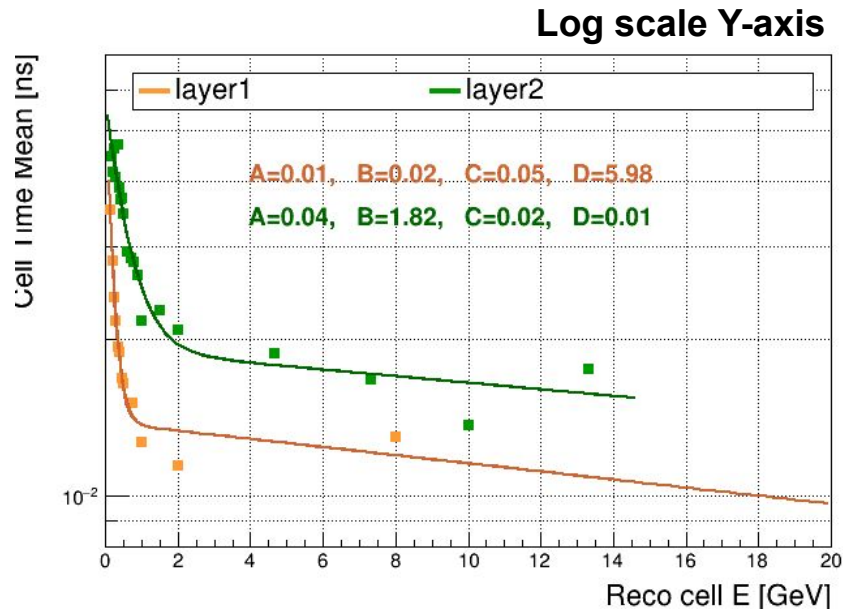
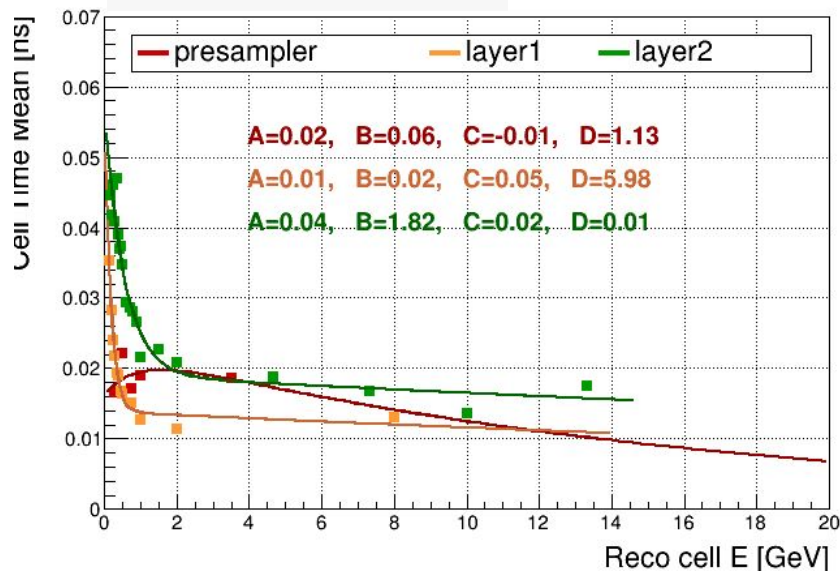


- Check reco cell E range within the region of our interest
- There is no cell which has more than 16 GeV
- Most of the energy deposited in **layer 2**



- Cell time resolution is parametrized by reco cell E and layer
- The constant term (i.e. A) depends on **layer** (range from 52.7 ~ 67.1 ps)
- Layer 3 is excluded in this study as $\pi^0 \rightarrow \gamma\gamma$ deposited most of its energy before layer 3 and we are statistically limited

$$A \cdot e^{-B \cdot E} + C \cdot e^{-D \cdot E}$$



- Cell time resolution is parametrized by reco cell E and layer
- The constant term (i.e. A) depends on **layer** (range from 52.7 ~ 67.1 ps)
- Layer 3 is excluded in this study as $\pi^0 \rightarrow \gamma\gamma$ deposited most of its energy before layer 3 and we are statistically limited

To have a same set of pions for comparison, the following selections are applied

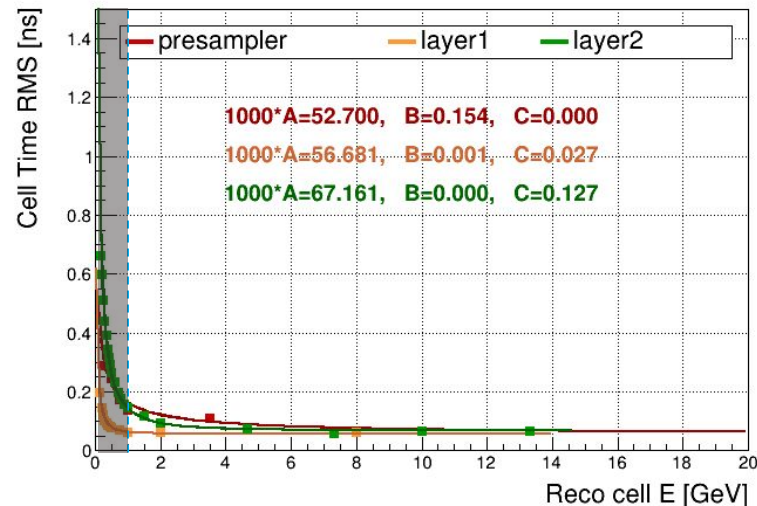
- $1 \text{ GeV} < \text{Truth pion } pT < 20 \text{ GeV}$
 - Only non-zero cell time cells
 - LAr EM Barrel ($|\eta| < 0.8$)
 - Layer 1 and 2 only
 - Reco cell $E > 0.1 \text{ GeV}$
- Baseline selection

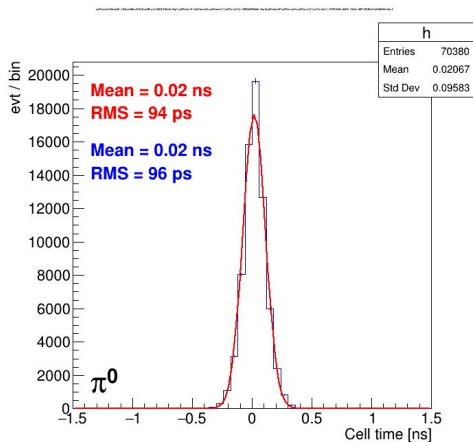
Up to this selection, 88504 pions (= Total #pion)

- At least one cell in a pion has reco cell $E > 1 \text{ GeV}$

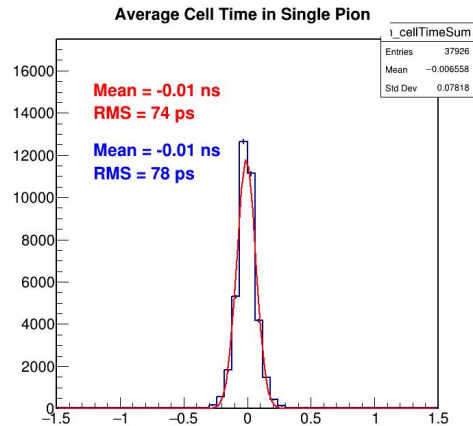
To pick up same set of events after additional cut on reco cell E

→ **37926 pions** ($37926/88504 = 42.9\%$)
(= #pion with 1GeV cell)





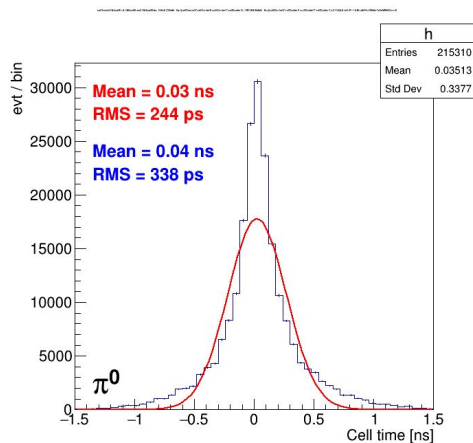
cell time per cell
(Not averaged)



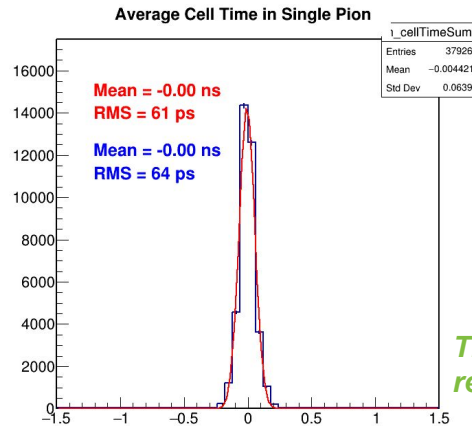
Averaged cell time per pion
1/RMS² weighted

- Cells passed all event selection
- Additional selection: reco cell E > 1 GeV
- Right plot is weighted average with calibration, where $w_i = (1/\text{RMS}^2)$
- Calibration is done using fits functions for mean values $t_0(\text{cell E, layer})$ then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

$$\frac{\sum_i (w_i \cdot (t_i - t_0))}{\sum_i w_i}$$



cell time per cell
(Not averaged)

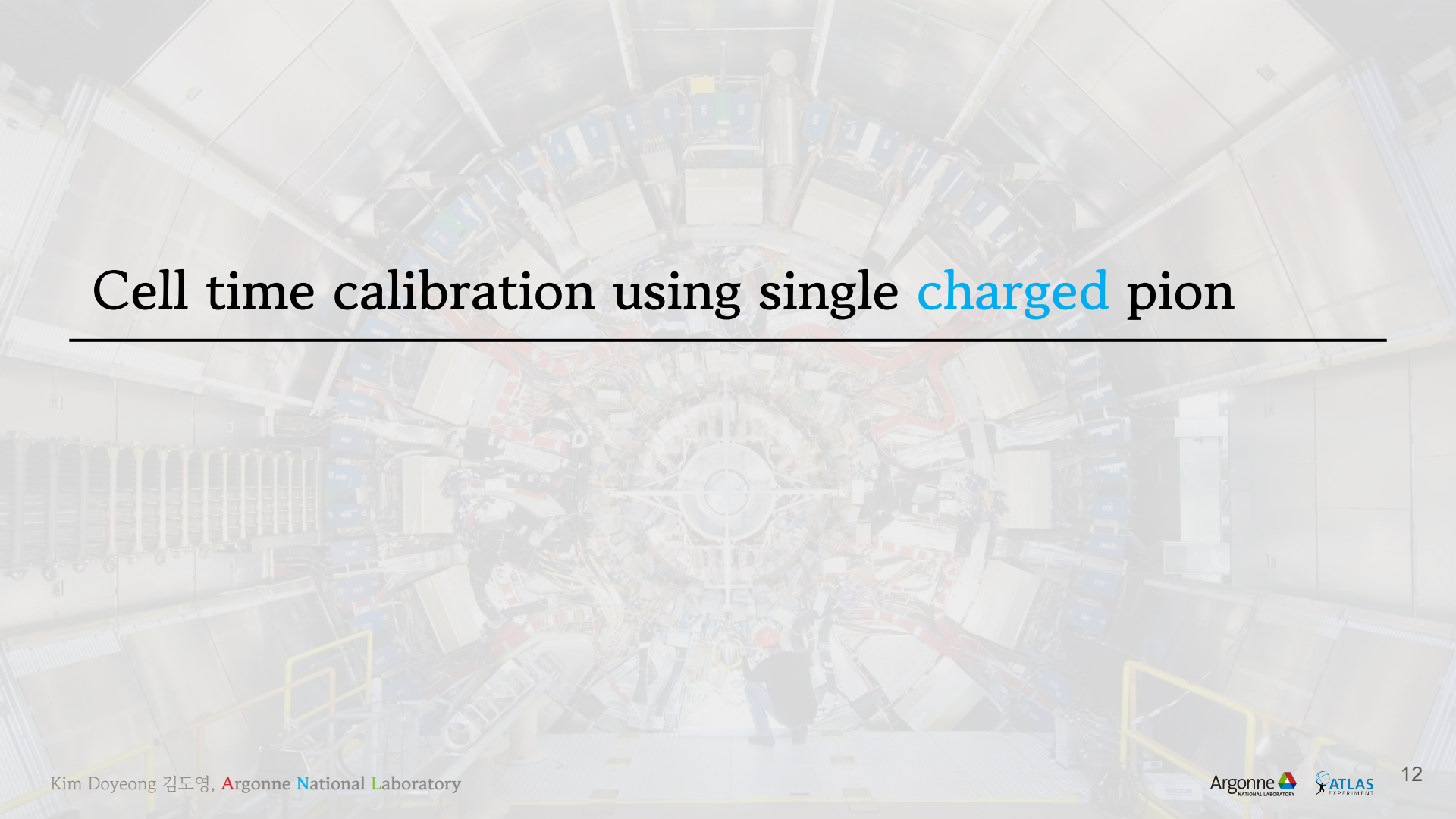


Averaged cell time per pion
1/RMS² weighted

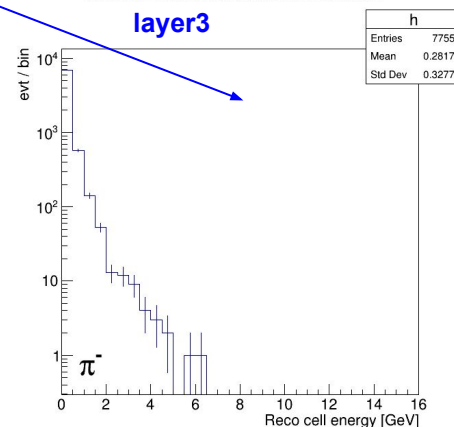
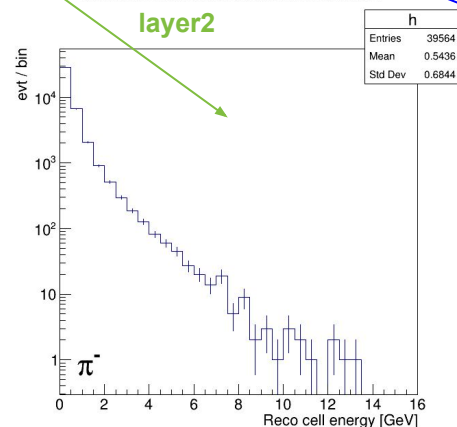
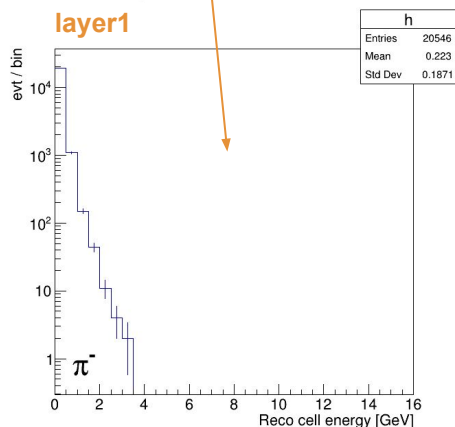
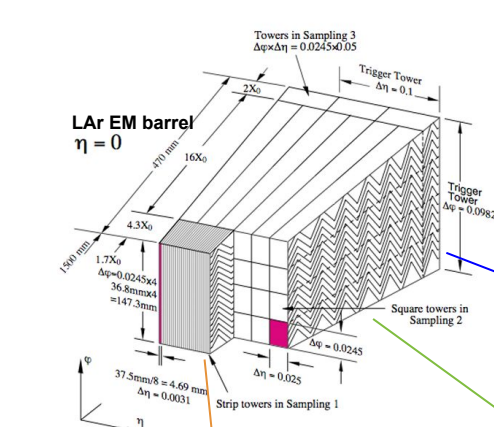
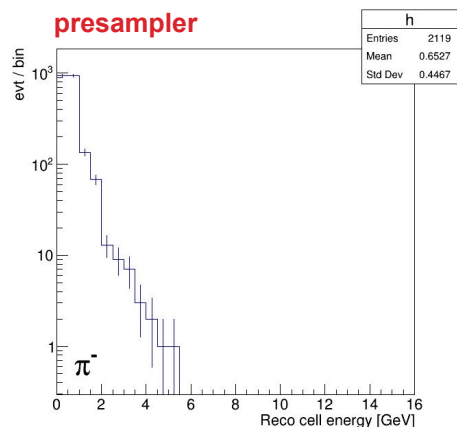
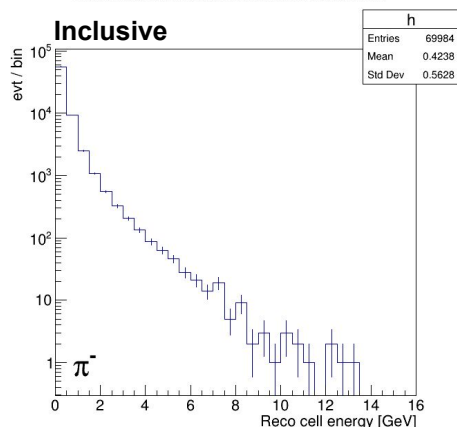
*The best cell time
resolution achieved*

- Cells passed all event selection
- Additional selection: reco cell E > 0.1 GeV**
(still, at least one cell in each pion has cell E > 1 GeV)
- Right plot is weighted average with calibration**, where $w_i = (1/\text{RMS}^2)$
- Calibration is done using fits functions for mean values t_0 (cell E, layer) then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

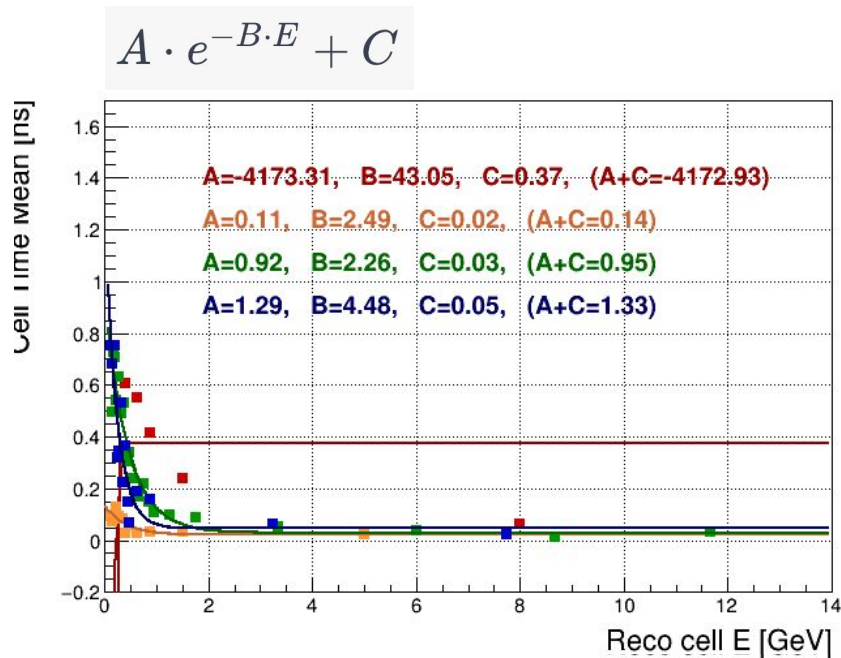
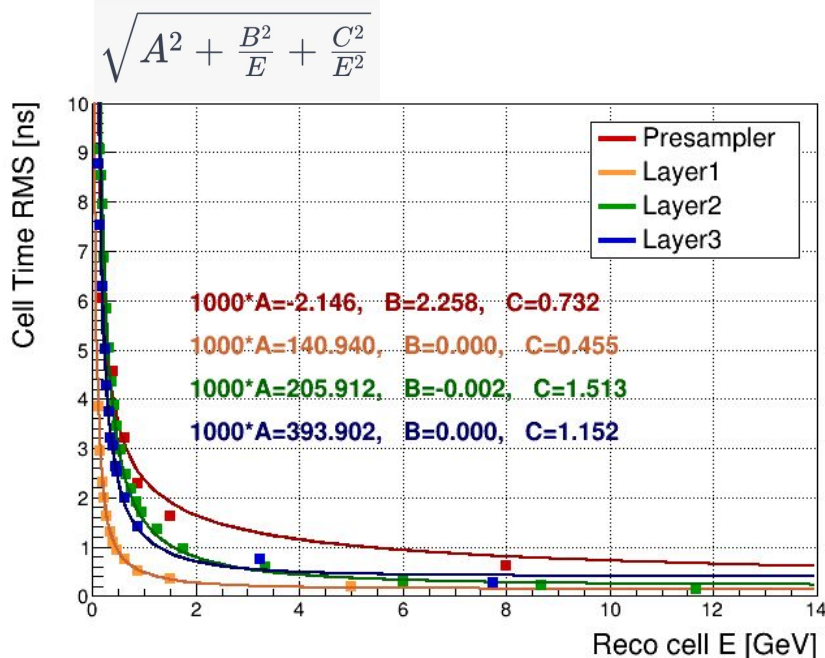
$$\frac{\sum_i (w_i \cdot (t_i - t_0))}{\sum_i w_i}$$



Cell time calibration using single charged pion



- Check reco cell E range within the region of our interest
- There is no cell which has more than 14 GeV



- Timing resolution and mean are parametrized by cell E (E)
- The constant term (i.e. A) depends on **layer**
- RMS differences between layers are ~50ps at cell E of 5 GeV

Can remove presampler...

To have a same set of pions for comparison, the following selections are applied

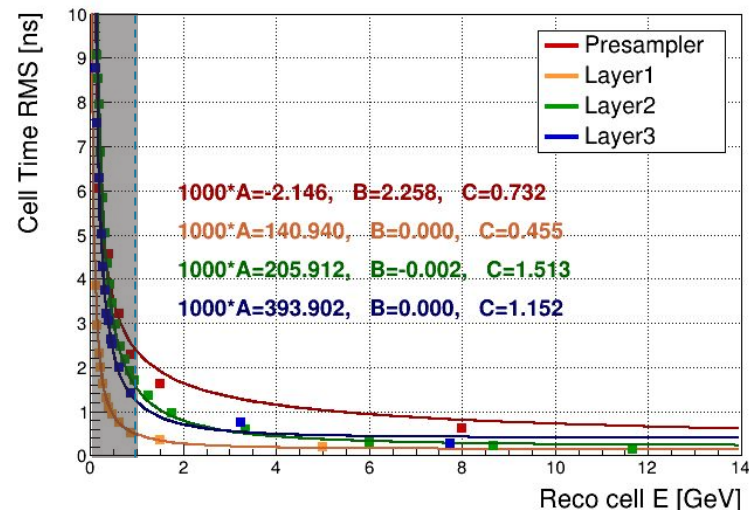
- $1 \text{ GeV} < \text{Truth pion } p_T < 20 \text{ GeV}$
 - Only non-zero cell time cells
 - LAr EM Barrel ($|\eta| < 0.8$)
 - Layer 1, 2 and 3 only
 - Reco cell E $> 0.1 \text{ GeV}$
- Baseline selection

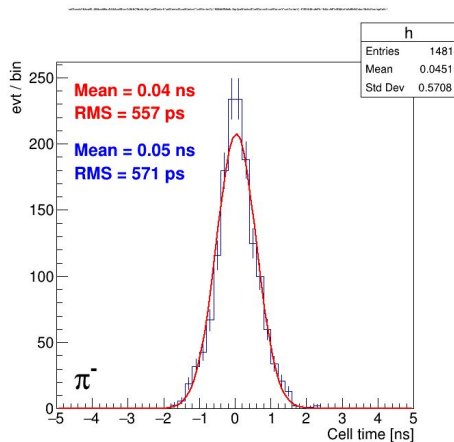
Up to this selection, 13111 pions (= Total #pion)

- At least one cell in a pion has reco cell E $> 2 \text{ GeV}$

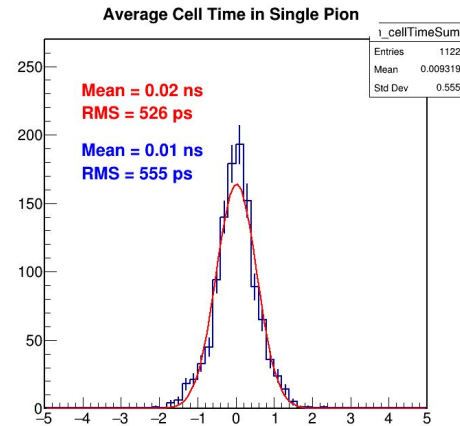
To pick up same set of events after additional cut on reco cell E

→ **1122 pions** ($1122/13111 = 8.65\%$)
(= #pion with 1GeV cell)

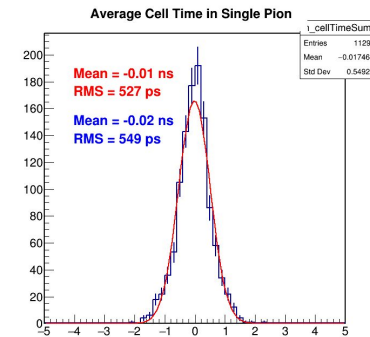




cell time per cell
(Not averaged)



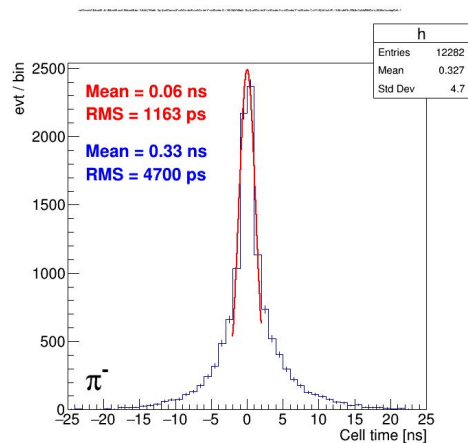
Averaged cell time per pion
1/RMS² weighted



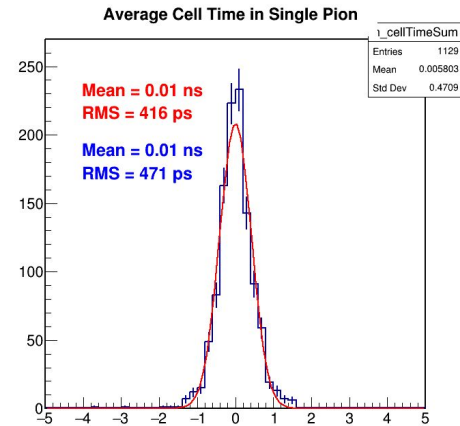
With tile
(just for now, will remove)

- Cells passed all event selection
- Additional selection: reco cell $E > 2$ GeV
- Right plot is weighted average with calibration, where $w_i = (1/\text{RMS}^2)$
- Calibration is done using fits functions for mean values $t_0(\text{cell } E, \text{layer})$ then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

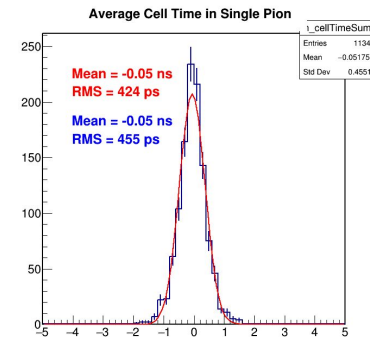
$$\frac{\sum_i (w_i \cdot (t_i - t_0))}{\sum_i w_i}$$



cell time per cell
(Not averaged)



Averaged cell time per pion
1/RMS² weighted



With tile
(just for now, will remove)

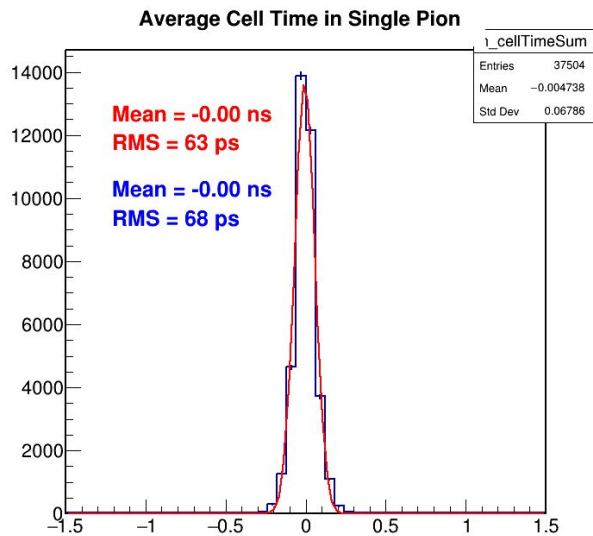
- Cells passed all event selection
- Additional selection: reco cell $E > 0.1$ GeV
- Right plot is weighted average with calibration, where $w_i = (1/\text{RMS}^2)$
- Calibration is done using fits functions for mean values $t_0(\text{cell } E, \text{layer})$ then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

$$\frac{\sum_i (w_i \cdot (t_i - t_0))}{\sum_i w_i}$$

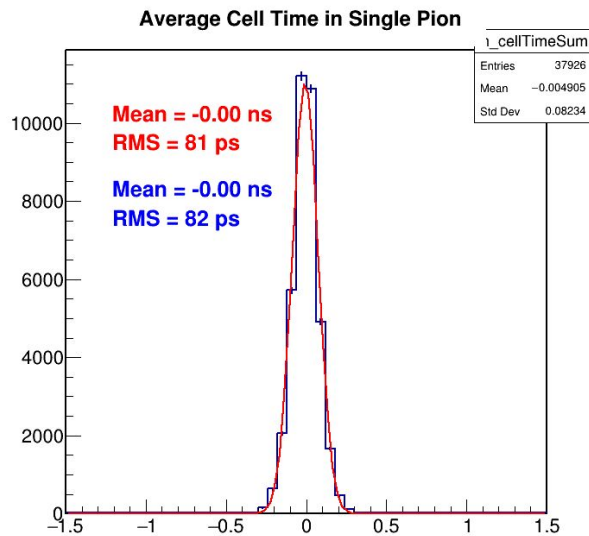
Summary

- **Using neutral pions with at least one energetic cell ($>1\text{GeV}$),**
 - we can achieve a very decent timing resolution (~ 60 ps) at central region
 - 1GeV cut on reco cell E still kept 42.9% of pions among all pion that passed baseline selection
- **Using neutral pions with at least one energetic cell ($>2\text{GeV}$),**
 - we can achieve a timing resolution of ~ 450 ps at central region
 - 2GeV cut on reco cell E still kept 8.65% of pions among all pion that passed baseline selection
- The results shows huge potential that 5D calorimeter can complement the timing information obtained from the precision timing detector
(improve t_0 vertexing with extended eta coverage)
- This implies new idea for PFlow i.e. using neutral pion vetoing tracks
- **Room for improvement & plan**
 - Cell significance may give us better cut than 1GeV cut on cell E
 - Extending the study to pion with PU and jets ultimately

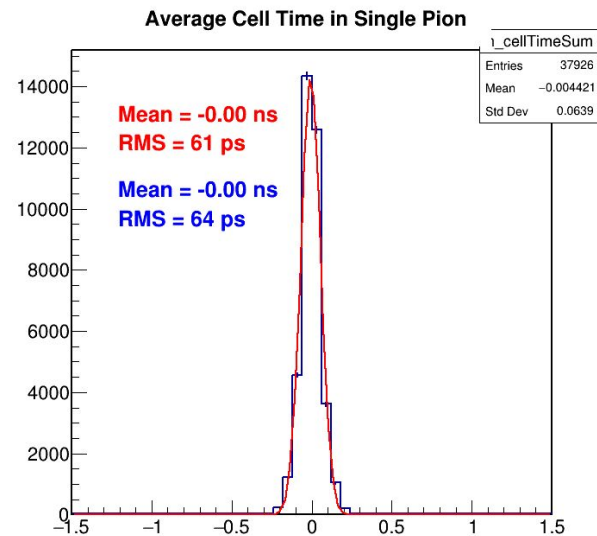
Backup



Layer 1 only



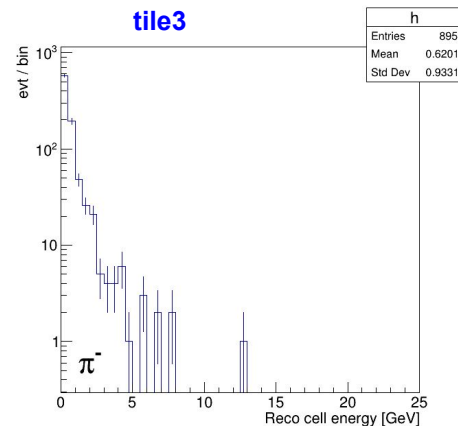
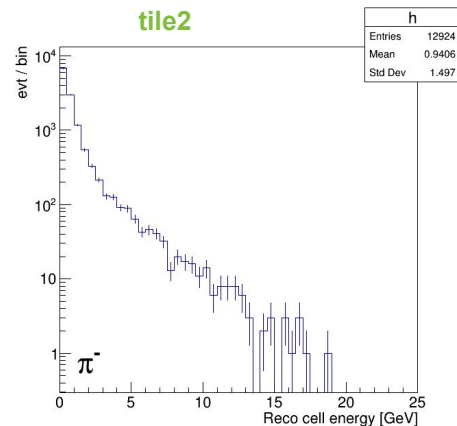
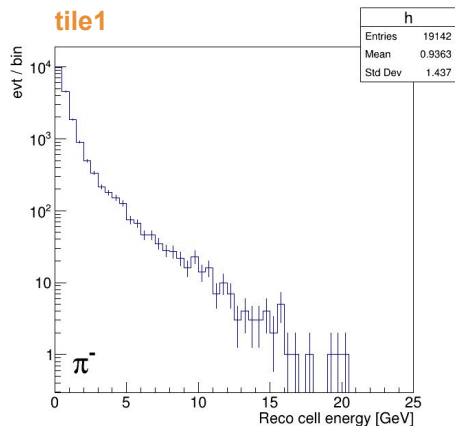
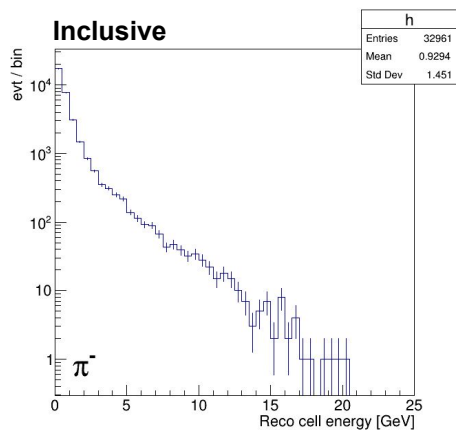
Layer 2 only

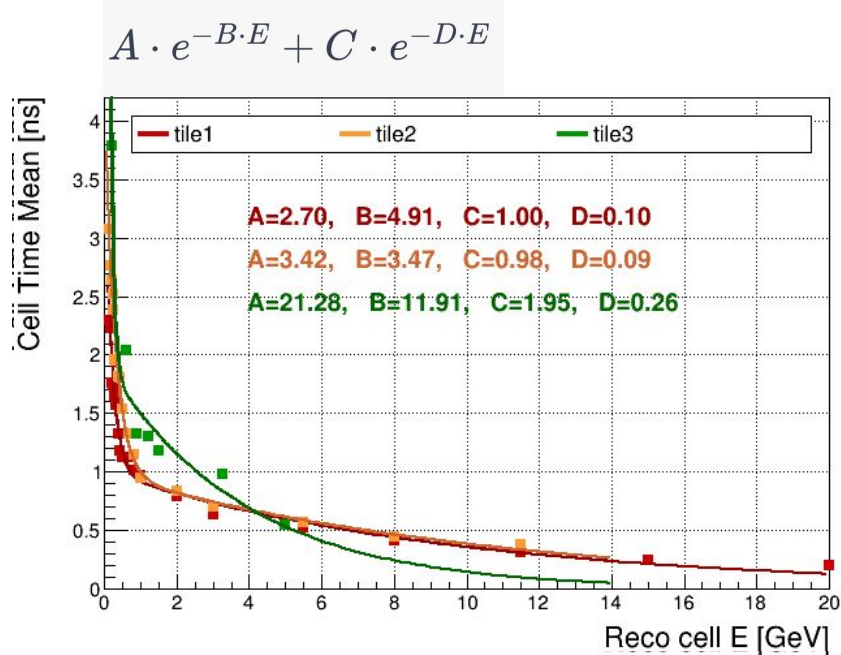
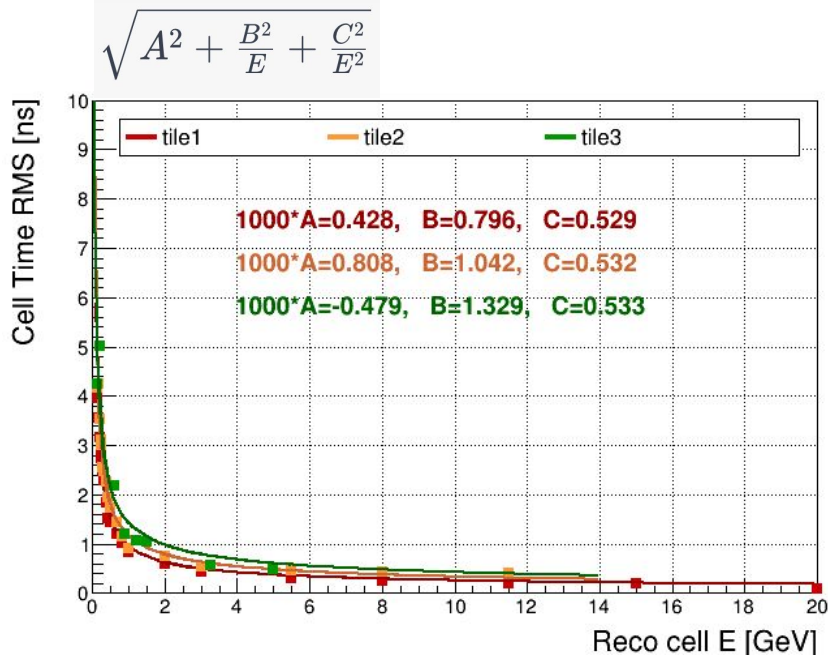


Layer 1+2

- All plots are weighted average with calibration, where $w_i = (1/\text{RMS}^2)$
- **Calibration** is well done and distributions are centered at 0 in each layer and inclusively Calibration is done using fits functions for mean values $t_0(\text{cell E, layer})$ then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

$$\frac{\sum_i (w_i \cdot (t_i - t_0))}{\sum_i w_i}$$

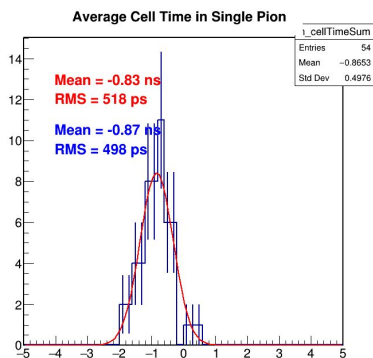




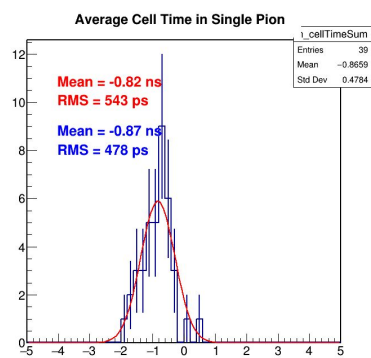
- Timing resolution and mean are parametrized by cell E (E)
- The constant term (i.e. A) depends on **layer**
- RMS differences between layers are ~50ps at cell E of 5 GeV

Can remove presampeler...

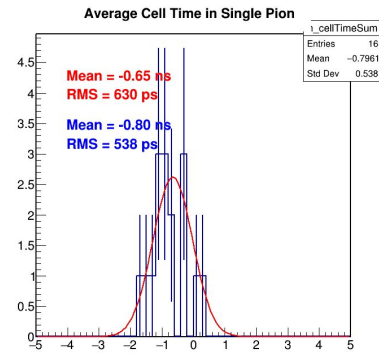
Inclusive



tile1



tile2



tile3

- Cells passed all event selection
- Additional selection: reco cell E > 2 GeV
- Right plot is weighted average with calibration, where $w_i = (1/\text{RMS}^2)$
- Calibration is done using fits functions for mean values $t_0(\text{cell E, layer})$ then offset is subtracted cell by cell ($t_i - t_0$) before averaging cell time of single pion

Overlapped cells within an event

We coincidentally found that there could be overlapped cells within an event

0	cellE = 1.0374	cellTime =	2.3166
1	cellE = 0.36766	cellTime =	1.9161
2	cellE = 0.3251	cellTime =	-0.24404
3	cellE = 0.25441	cellTime =	-0.64209
4	cellE = 0.22627	cellTime =	3.5027
5	cellE = 0.2012	cellTime =	-3.9121
6	cellE = 0.16394	cellTime =	12.035
7	cellE = 0.16394	cellTime =	12.035
8	cellE = 0.12405	cellTime =	9.5905
9	cellE = 0.10802	cellTime =	-1.4767

- Indeed, there are identical cells in pi0 samples
 - which is reasonable due to poor separation bwt two photons in the $\pi^0 \rightarrow \gamma\gamma$
- However, overlapped cells in an event are always clustered into two different clusters
- One of the examples (event number = 1029943) are shown in the next three slides
 - ROOT interactive mode print out to see overlapped cells in the event
 - Cells with non-zero cell time in the η - φ plane only with cluster #0
 - Cells with non-zero cell time in the η - φ plane only with cluster #1
- Confirmed in the topo-cluster algorithm paper
 - Overlapped cells are allowed within the first and the second energetic clusters and their energy is weighted to calculate the energy of two clusters

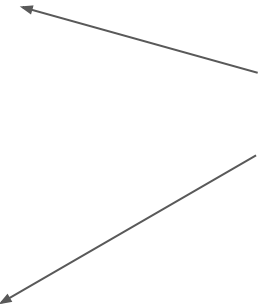
```
root [2] CellTree->Scan("eventNumber:cellTime:cellE:truthPt:nCluster:clusterIndex","eventNumber==1029943&&cellTime!=0")
```

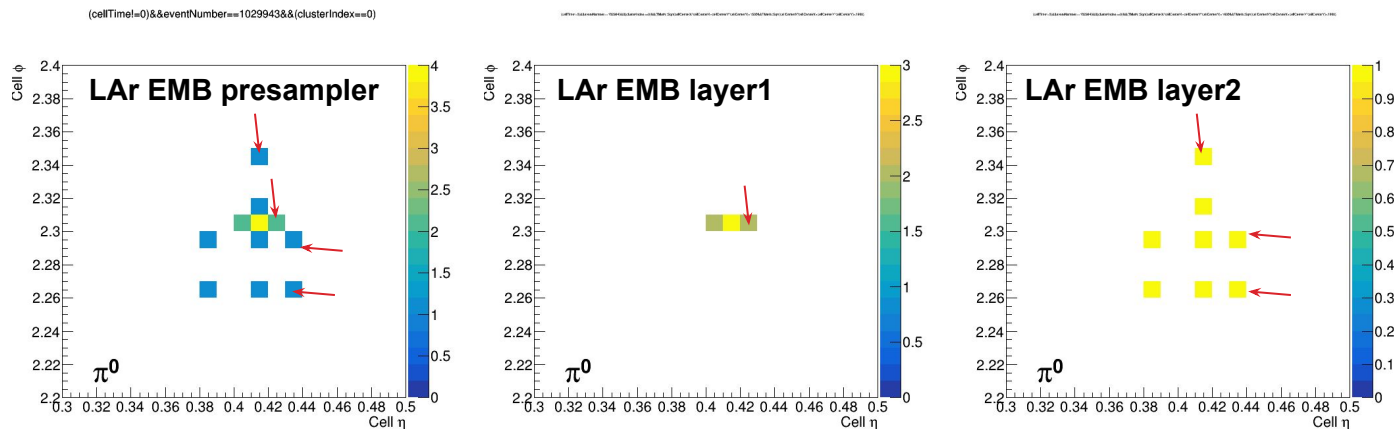
```
*****
*   Row   * eventNumb *   cellTime *   cellE *   truthPt *   nCluster * clusterIn *
*****
* 15444006 * 1029943 * -0.051002 * 4.4773607 * 18.928133 * 2 * 0 *
* 15444007 * 1029943 * 0.1209749 * 1.1254522 * 18.928133 * 2 * 0 *
* 15444008 * 1029943 * 0.3460252 * 0.3676609 * 18.928133 * 2 * 0 *
* 15444009 * 1029943 * 0.0330029 * 0.2203069 * 18.928133 * 2 * 0 *
* 15444010 * 1029943 * 0.1290044 * 0.1841076 * 18.928133 * 2 * 0 *
* 15444013 * 1029943 * -0.191986 * 0.1002538 * 18.928133 * 2 * 0 *
* 15444014 * 1029943 * 0.1199941 * 0.2232729 * 18.928133 * 2 * 0 *
* 15444015 * 1029943 * 0.0620064 * 0.6248078 * 18.928133 * 2 * 0 *
* 15444016 * 1029943 * 0.0089996 * 2.1793856 * 18.928133 * 2 * 0 *
* 15444017 * 1029943 * -0.004999 * 0.7265049 * 18.928133 * 2 * 0 *
* 15444018 * 1029943 * -0.017003 * 0.3989754 * 18.928133 * 2 * 0 *
* 15444044 * 1029943 * -0.083012 * 1.1080262 * 18.928133 * 2 * 0 *
* 15444045 * 1029943 * 0.2029828 * 1.0263322 * 18.928133 * 2 * 0 *
* 15444046 * 1029943 * -0.021996 * 0.7027812 * 18.928133 * 2 * 0 *
* 15444048 * 1029943 * -0.215992 * 0.3212919 * 18.928133 * 2 * 0 *
* 15444049 * 1029943 * 0.0599943 * 0.1893969 * 18.928133 * 2 * 0 *
* 15444054 * 1029943 * 0.0129976 * 1.6982902 * 18.928133 * 2 * 1 *
* 15444056 * 1029943 * -0.020000 * 1.0290801 * 18.928133 * 2 * 1 *
* 15444060 * 1029943 * 0.1030200 * 0.3845300 * 18.928133 * 2 * 1 *
* 15444061 * 1029943 * -0.148977 * 0.2721398 * 18.928133 * 2 * 1 *
* 15444062 * 1029943 * 0.0370025 * 0.4063319 * 18.928133 * 2 * 1 *
* 15444065 * 1029943 * 0.0019996 * 0.2039948 * 18.928133 * 2 * 1 *
* 15444066 * 1029943 * -0.153974 * 0.1379622 * 18.928133 * 2 * 1 *
* 15444086 * 1029943 * -0.083012 * 1.1080262 * 18.928133 * 2 * 1 *
* 15444087 * 1029943 * 0.2029828 * 1.0263322 * 18.928133 * 2 * 1 *
Type <CR> to continue or q to quit ==>
* 15444088 * 1029943 * -0.021996 * 0.7027812 * 18.928133 * 2 * 1 *
* 15444090 * 1029943 * -0.215992 * 0.3212919 * 18.928133 * 2 * 1 *
* 15444091 * 1029943 * 0.0599943 * 0.1893969 * 18.928133 * 2 * 1 *
```

```
==> 28 selected entries
```

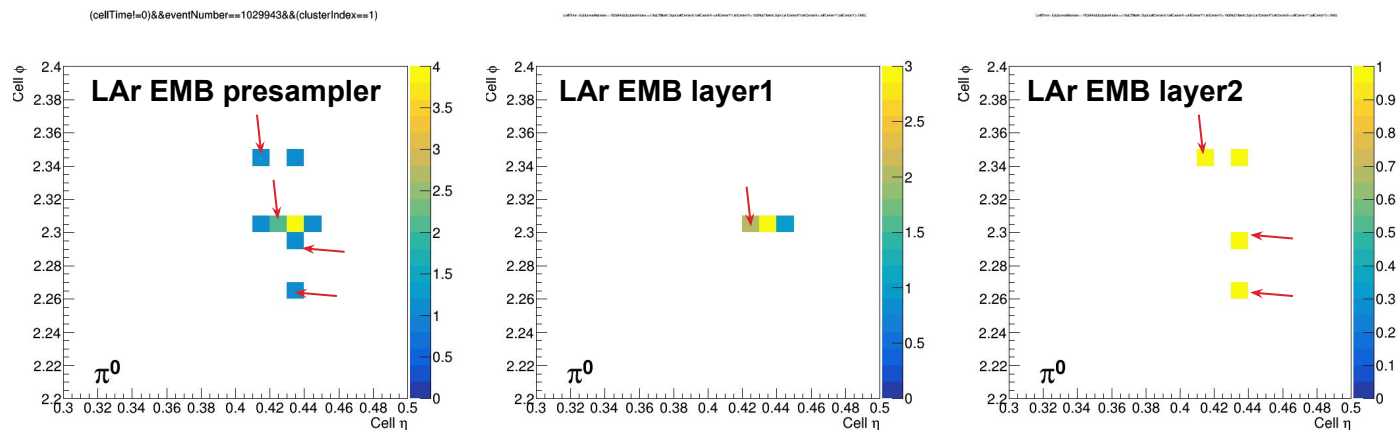
```
(long long) 28
```

The same cells clustered in
two different clusters





- Cells with non-zero cell time in the η - ϕ plane only with cluster #0
- No other selections are applied
- Red arrows indicate the overlapped cells



- Cells with non-zero cell time in the η - ϕ plane only with cluster #1
- No other selections are applied
- Red arrows indicate the overlapped cells

The cluster splitting algorithm can find cells which are neighbours to two or more signal maxima. In this case, the cell is assigned to the two highest-energy clusters after splitting of the original topo-cluster it is associated with. This means that each cell is only shared once at most, and, even then, is never shared between more than two clusters.

The sharing of its signal between the two clusters with respective energies $E_{\text{clus},1}^{\text{EM}}$ and $E_{\text{clus},2}^{\text{EM}}$ is expressed in terms of two geometrical weights $w_{\text{cell},1}^{\text{geo}}$ and $w_{\text{cell},2}^{\text{geo}}$. These weights are calculated from the distances of the cell to the centre of gravity of the two clusters (d_1, d_2), measured in units of a typical electromagnetic shower size scale in the ATLAS calorimeters,⁶ and the cluster energies,

$$w_{\text{cell},1}^{\text{geo}} = \frac{E_{\text{clus},1}^{\text{EM}}}{E_{\text{clus},1}^{\text{EM}} + r E_{\text{clus},2}^{\text{EM}}} , \quad (6)$$

$$w_{\text{cell},2}^{\text{geo}} = 1 - w_{\text{cell},1}^{\text{geo}} , \quad (7)$$

$$r = \exp(d_1 - d_2) . \quad (8)$$

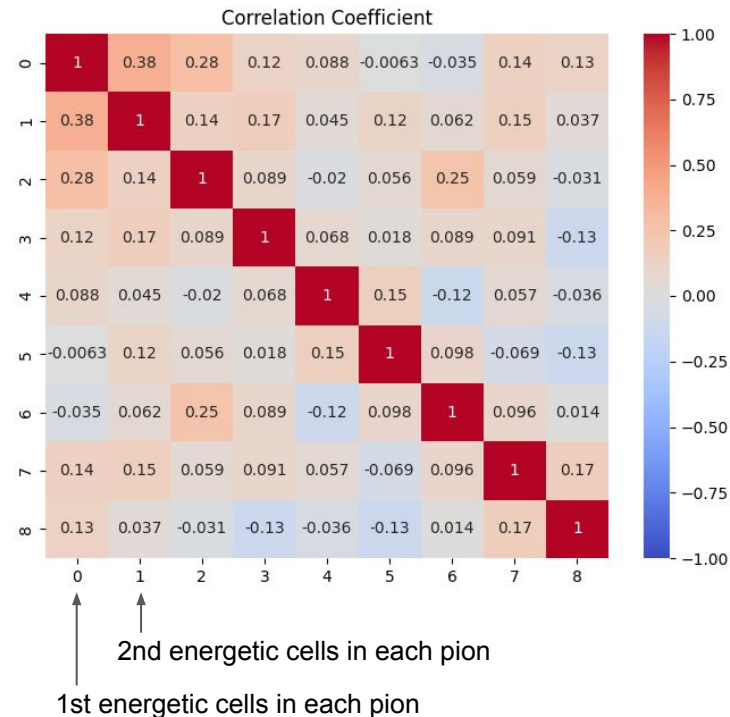
<https://arxiv.org/pdf/1603.02934.pdf>
page.18

Correlation btw cell time in a single pion

Baseline selection

- $1 \text{ GeV} < \text{Truth pion } p_T < 20 \text{ GeV}$
- Only non-zero cell time cells
- LAr EM Barrel ($|\eta| < 0.8$)
- Only layer2(where most of the energy is deposited) is considered
- After the above selection #cell in the first cluster(cluster 0) of a pion ≥ 9
- At least one cell in a pion has reco cell E $> 1 \text{ GeV}$

The correlation coefficients btw 1st to 9th energetic cells in each pion are plotted
 Three are a weak correlation btw a few energetic cells



- Overlapped cells in LAr Berrel region = 3.2%
Before baseline selection

