The Testbeam results of sPHENIX INTT

Cheng-Wei Shih

daniel30915shih@gmail.com

Department of Physics, National Central University, Chungli, Taiwan

March 4, 2022

Abstract

The sPHENIX is an upgrade project of RHIC's (Relativistic Heavy-Ion collider) former PHENIX experiment. The sPHENIX aims to study the strongly interacting quark-gluon plasma by measuring jets, jet correlations and Upsilons (Υ_s) precisely. The INTermediate Tracker (INTT) is one of the most important sub-detectors of the tracking system of the sPHENIX. The INTT consists of 56 silicon ladders to form two layers of silicon tracker. It bridges the tracks of the MVTX and TPC, and aims to improve the momentum resolution for charged particles with high transverse momentum, aids the pattern recognition, and the event synchronization. As a tracker, the detection efficiency of the INTT should be close to 100%. By doing so, all of the track-candidate hits can be kept. A testbeam experiment was performed at the end of 2021, at ELPH, Japan. It provides us a chance to understand the performance of the INTT more complete. The testbeam results achieved by Cheng-Wei will be presented in this docuement.

1. Introduction

The INTT is a tracker with 78 μm strip width, and the material budget of a single ladder is around 1.08%. In the testbeam experiment, 4 ladders were installed and 3 of them were functional. See the figure 1. The
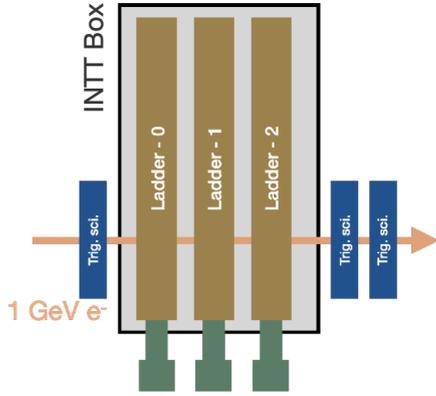

Figure 1: *The schematic of INTT Testbeam configuration*

electron beam with energy around 1 GeV was used. Due to the low material budget of the INTT and the zero magnetic field testbeam environment, the hit track is expected to be a straight line. Based on these concepts, the tracks can be identified by checking the reduced χ^2 of the linear polynomial fitting. Click the link to check the detailed introduction of tracking algorithm. In the algorithm, a key information, event profile, indicates the condition of each event. The example of the event profile is shown in the figure 2.

- In the top-left plot, each ladder has a cluster and the reduced χ^2 is small, the event profile is 111.
- In the top-right plot, each ladder has a cluster. Though it is not a horizontal track but as long as

the reduced χ^2 is small enough, the event profile is still 111.
- In the bottom-left plot, though there are 3 clusters in total, the position of the layer-2 cluster is far away from the rest clusters, the event profile is 110.
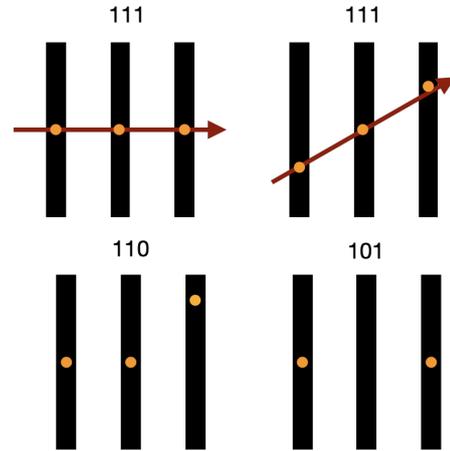- In the bottom-right plot, there are only 2 clusters in total, the event profile is 101.

Figure 2: *The example of the event profile*

The topics covered by this document are listed below :

- Alignment study
- Detection efficiency
  - The window size study
  - The study of efficiency affected by the longitudinal misalignment
  - Ladder detection efficiency
- The dependency study of the efficiency and the event process time

- Coulomb scattering study
- Energy deposit DAC scan

2. Alignment study

This chapter describes the alignment study on the ladder tranverse axis, for the study on the longitudinal axis, please check the chapter 3.2. In order to obtain the true effciency result, the ladder alignment is an important topic to be studied first. In the real experiment, we don't really know whether the position of the ladders are all aligned well. One of the methods for this purpose is to study the alignment with the testbeam data. The idea is that the trajectories of the charged particles are assumed to be straight lines. If the ladders are assumed to be aligned well but they aren't in practice, the cluster positions of the ladders will not be able to form a straight line. The reduced χ^2 of a straight line fitting to those clusters will be larger. The peaks of the residual distributions will not be at zero as well. The figure 3 gives a concept of the alignment method.
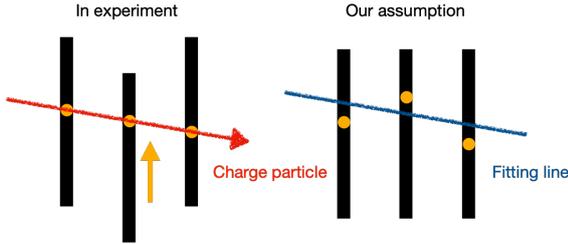

Figure 3: *The schematic of the alignment method with data*

Take run 89 as an example, the residual distributions before the alignment correction is shown in figure 4. As you can see that the peaks of the distributions are not at zero. The figure 5 shows that a -0.2846 mm
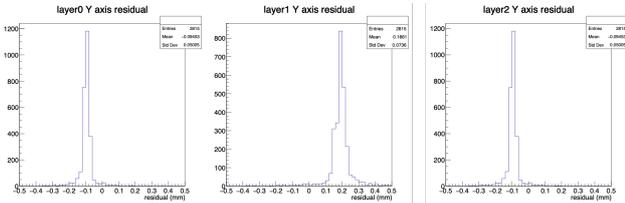

Figure 4: *The residual distributions before alignment correction*

correction at layer-1 is reuqired for alignment.

After the position correction, the peaks of the residual distributions are now at zero, shown in figure 6.

3. Detection efficiency

The main proposal of the Testbeam2021 is to study the ladder detection efficiency. The reason is that in the Testbeam2019, the efficiency could only approach to
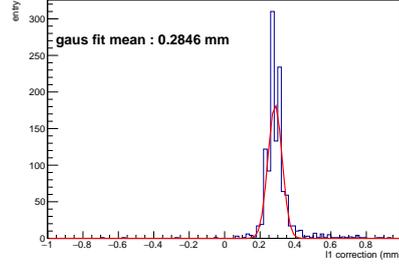

Figure 5: *The amount of the required position correction at layer-1 for run 89*
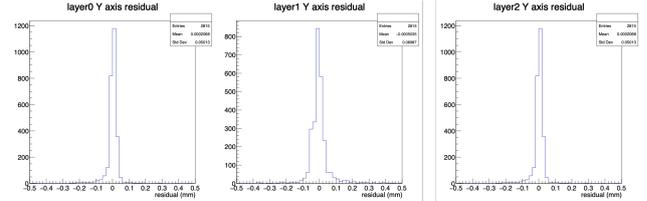

Figure 6: *The residual distributions after alignment correction*

96%. It is not good enough for a tracker, especially a intermediate tracker. The efficiency is expected to be near 100% to make sure no track candidates are missed. In the efficiency study macro, only the first BCO group is considered. The efficiency is calculated by the equation 1, here takes the layer-0 as example :

$$\frac{number\ of\ 111\ event}{number\ of\ 111\ event\ +\ number\ of\ 011\ event} \quad (1)$$

3.1. The window size study

Before obtain the final detection efficiency results, the window size should be determined first. The window size is a key parameter for the detection efficiency. It is the tolerance of the residual of the fitting line and cluster position. It is expected that the detection efficiency should increase as window size becomes larger. The run 89 is used for this study. The window size range is scanned from 10 μm to 0.5 mm, the result is shown in figure 7.

For the case of layer-0 and layer-1, the results show that the efficiency does incease as the window size increase, and reach to the plateau easily. But for the layer-2 case, it is another story. The efficiency increases in the beginning, but decreases slightly when the window size starts to be larger than 0.1 mm. The reason can be explained by the figure 8. In the left-hand schematic of figure 8, layer-2 doesn't have a qaulified hit. And because of the larger window size, the position difference of the layer-0 cluster and the layer-1 cluster is within in the tolerance. So the event profile becomes "110", and it then contributes to the denominator of the layer-2 efficiency calculation. But for the right-hand schematic of figure 8, with a smaller window size, the
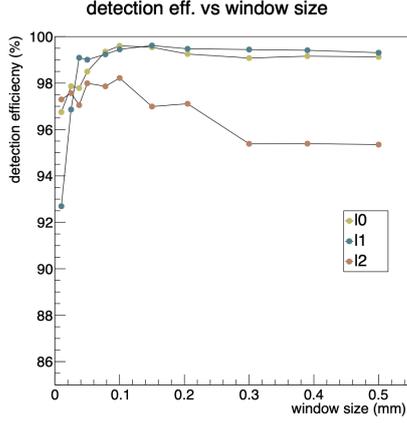
Figure 7: *The detection efficiency as function of window size*
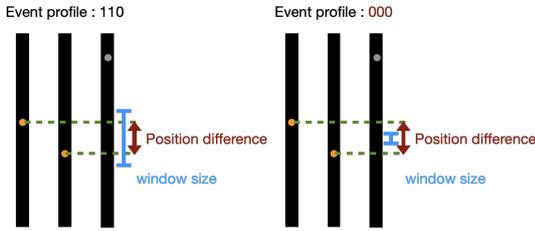

Figure 8: *The figure to explain why the efficiency of layer-2 decreases as window size goes larger*

position difference is now larger than the tolerance. The event profile beomces "000" that doesn't contribute to the efficiency calculation of any layer. This special phenomenon can happen on any of the layers. However in the Testbeam2021, such phenomenon happened on layer-2 more often. The final windows size is choosen to be 0.21 mm which is 3σ of the layer-1 residual distribution of figure 6.

3.2. The study of efficiency affected by the longitudinal misalignment

The INTT is a strip tracker, whose channel size is 78 $\mu m \times 16$ (20) mm for type A (B). The resolution on the longitudinal axis is too poor to study the misalignment. But there are some interesting events found in data, prove that the ladders are not aligned well on longitudinal axis. The example is shown in the figure 9 . There

Figure 9: *The evidence of misalignment on longitudinal axis*

are 4 hits in this event. 1 hit is from layer-0 (module = 1), 1 hit is from layer-1 (module = 6) and 2 hits are from layer-2 (module = 5). The channel ID (chan_id) of these 4 hits are close to each other which indicates

that they may be from same trajectory and able to be fit well by a straight line fitting. But the chip ID (chip_id) of layer-2 hits are different with the rest 2 hits. One of the possible reason is shown in figure 10. The layer-2 ladder is not aligned well on the longitudinal axis, the particle goes through chip 10 instead of chip 11. One algorithm so called "LoE_removal" (Longitudinal
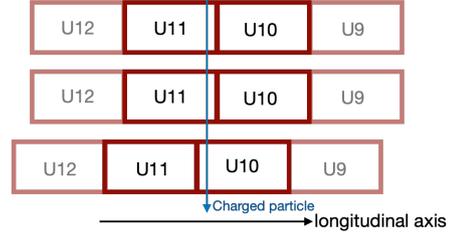

Figure 10: *The longitudinal misalignment can describe this kind of events well*

Offset Effect) is added in the current tracking macro. It helps to pick up this kind of events, and make sure the events will not contribute to the efficiency calculation. Click here for more detailed description of LoE. The efficiency with and without the LoE_removal is shown in figure 11. The LoE_removal improves the efficiency
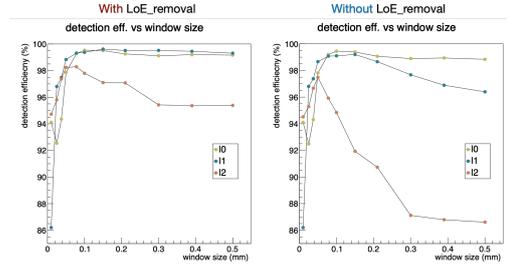

Figure 11: *The efficiency with and without the LoE_removal*

of layer-1 and layer-2 by an amount of 2.56% and 8.57 %.

3.3. Ladder detection efficiency

Now the studies of the alignment and window size are done, it is time to check the ladder detection efficiency. The data of the production runs are checked, the efficiency of each runs is listed in table 1.

The detection efficiency can be up to 99.6 % which fits the reuqirement. The layer-0 efficiency of run 58 is lower than the average. The further study on run 58 is performed. The event code distribution is shown in figure 12.

And the description of the event code is shown in table 2.

Run ID	effi. l0 (%)	effi. l1 (%)	effi. l2 (%)
52	$99.647^{+0.109}_{-0.149}$	$99.402^{+0.143}_{-0.182}$	$98.640^{+0.215}_{-0.252}$
53	$99.511^{+0.117}_{-0.149}$	$99.282^{+0.142}_{-0.173}$	$98.240^{+0.221}_{-0.250}$
54	$99.632^{+0.100}_{-0.132}$	$99.491^{+0.118}_{-0.149}$	$98.793^{+0.182}_{-0.211}$
55	$99.567^{+0.110}_{-0.142}$	$99.510^{+0.117}_{-0.149}$	$98.376^{+0.213}_{-0.242}$
57	$99.349^{+0.134}_{-0.165}$	$99.320^{+0.137}_{-0.168}$	$98.291^{+0.216}_{-0.245}$
58	$94.464^{+0.382}_{-0.408}$	$99.472^{+0.122}_{-0.155}$	$98.692^{+0.193}_{-0.223}$
88	$98.709^{+0.284}_{-0.354}$	$99.544^{+0.167}_{-0.244}$	$96.529^{+0.460}_{-0.523}$
89	$99.251^{+0.165}_{-0.206}$	$99.475^{+0.138}_{-0.180}$	$97.108^{+0.320}_{-0.357}$

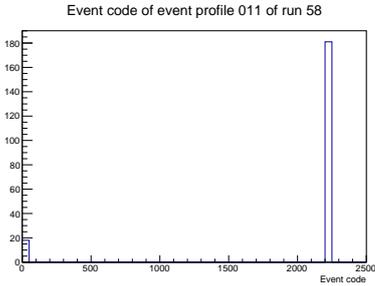**Table 1:** *The detection efficiency results of production runs*

Figure 12: *The event code distribution of 011 event of run 58*

The figure 12 shows that for most of the 011 events, there are only 2 qaulified hits.

4. THE DEPENDENCY STUDY OF THE EFFICIENCY AND THE EVENT PROCESS TIME

One of the possible reason to explain the detection efficiency can be only up to 96 % in Testbeam2019 is that the beam clock and the INTT clock are not synchronized. Some of the events may not have enough process time to save the data. In our hypothesis, if the event doesn't have enough time to process the hits, maybe some of the hits will be missed. Because of the missed hits, it may lead to only 2 quantified hits saved in the event, and result in event profile to be 011 / 101 / 110. Based on this concept, the relation of the detection efficiency and the event process time should have some tendency, the schematic of the expected tendency is shown in figure 13. The event process time is so called the BCO phase. The interval of INTT clock is ~ 106 ns, so the maximal event process time (BCO phase) is 106 ns.

A new feature is installed in the Testbeam2021, we are able to measure the event process time by using an external CAMAC TDC module. The data of the production runs is used except the run 58 becuase of the relatively bad performance of layer-0. The plots of the detection efficiency of different layers as function of

Event code	Description
< 100	has 3 quantified hits in same chip
~ 2200	has 2 quantified hits in same chip
~ 33000	LoE events

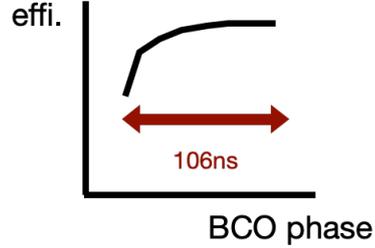**Table 2:** *The description of event code*

Figure 13: *The hypothesis of the relation between efficiency and event process time*

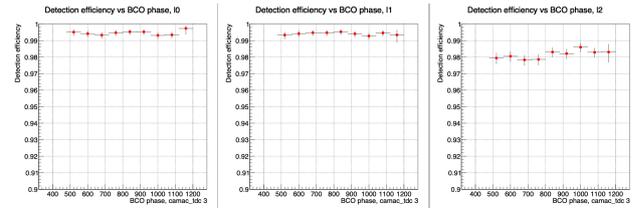BCO phase are shown in the figure 14. The tendency

Figure 14: *The detection efficiency of 3 layers as function of BCO phase*

is not evident, the detection efficiency seems to be independent to the BCO phase.

Another approach is to use the data of run 58. As mentioned before, the layer-0 efficiency of run 58 is $\sim 94\%$. The bad layer-0 efficiency of run 58 is due to only 2 quantified hits in same chip for most of the 011 event. In our hypothesis, those 011 events are lack of the enough process time. Their BCO phase distribution is expected to be a narrow width distribution, it should not be a flat distribution. The schematic of expected distribution is shown in the figure 15, and the result is shown in the figure 16.

The result turns out to be a flat distribution, it seems to be no tendency. Our hypothesis may be incorrect.

5. COULOMB SCATTERING STUDY

A good understanding of multiple coulomb scattering of relativistic particles in the INTT is important for tracking system and calorimeter. The scattering angular distribution is not just a Gaussian distribution, it has a long tail for both sides. From the paper [1], for a target with low material budget , the scattering angular
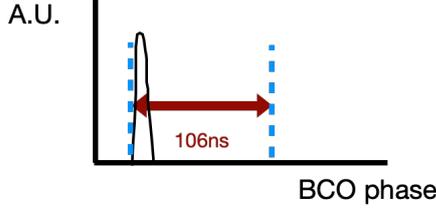
Figure 15: *The expected BCO phase distribution of 011 event of run 58*
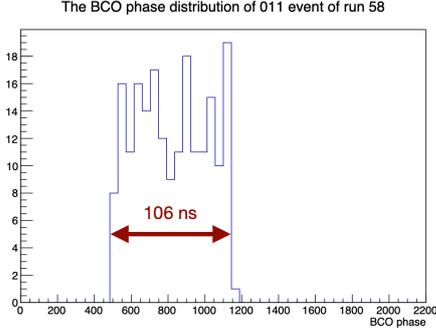

Figure 16: *The result of BCO phase distribution of 011 event of run 58*

distribution can be fit by the equation 2.

$$
f(\theta) = N \cdot \left((1-a) \cdot \frac{1}{\sigma_G \sqrt{2\pi}} e^{-\frac{(\theta-\mu)^2}{2\sigma_G^2}} + a \cdot \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma\Gamma(\frac{\nu}{2})} \left(1 + \frac{(\theta-\mu)^2}{\nu\sigma^2}\right)^{-\frac{\nu+1}{2}} \right) \tag{2}
$$

The former is the Gaussian distribution, and the latter is the Student's t distribution. The equation has six free parameters, the normalization term N, relative fraction a of the Student's t distribution, the mean value μ shares to both distributions, the width of the Gaussian σ_G, the width σ of Student's t and the parameter ν to describe the tail. The parameter ν is of importance in this study. For $\nu \to \infty$, the Student's t distribution turns into a Gaussian, whereas for $\nu \to 1$, the tails get more pronounced.

Since there are 3 layers of INTT ladders in the testbeam, the scattering at layer-1 can be checked. The scattering at layer-1 is calculated by slope-3 - slope-2, the figure 17 is the demonstration. In order to make the statistic as big as possible, all the BCO groups are included in the study. The result is shown in figure 18.
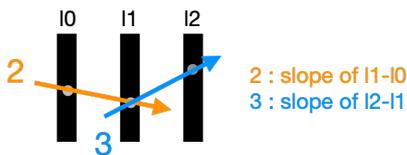

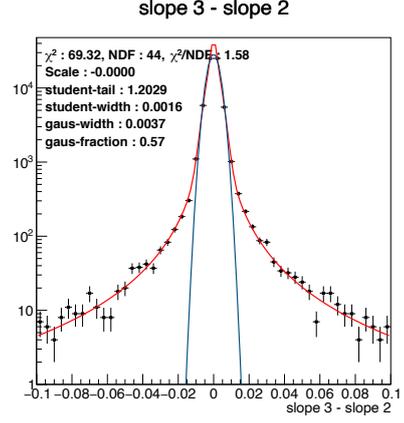**Figure 17:** *The method to calculate the scattering at layer-1*

Figure 18: *The result of angular scattering at layer-1, where the "student-tail" is ν parameter*

From the fitting, the ν parameter is 1.203. The next step is to compare the ν obtained from the MC.

6. ENERGY DEPOSIT DAC SCAN

The energy deposit is another important topic. It helps us to determine the threshold value with best S/N ratio of the INTT. The 3-bits readout chips are used by INTT which means only 8 bins to describe the signal. To cover the whole range of the energy deposit distribution and with a good resolution, the DAC scan is performed. Several runs are performed, and there are 3 bins with same adc setting (overlapping bins) between the adjacent run. The 1st and 2nd overlapping bins are the scaling bins, and the 3rd overlapping bin is the overflow bin that is negelected in the study. In the Testbeam2021, the whole energy deposit distribution is separated into 8 runs, the adc setting is shown in the table 3.

adc setting	run1	run2	run3	run4	run5	run6	run7	run8
adc0	8	28	48	68	88	108	128	148
adc1	12	32	52	72	92	112	132	152
adc2	16	36	56	76	96	116	136	156
adc3	20	40	60	80	100	120	140	160
adc4	24	44	64	84	104	124	144	164
adc5	28	48	68	88	108	128	148	168
adc6	32	52	72	92	112	132	152	172
adc7	36	56	76	96	116	136	156	176

Table 3: *The adc setting of the runs for DAC scan*

Only the event with event profile 111, and with only single hit in each layer is selected. The figure 19 shows the energy deposit distributions respective to each run.

The distributions of adjacent runs are then weighted by the 1st and 2nd overlapping bins, the result is shown in figure 20.

Because only the true events are considered, the background becomes very small. The distribution can be well described by the Landau Gaussian convolution, shown in figure 21.
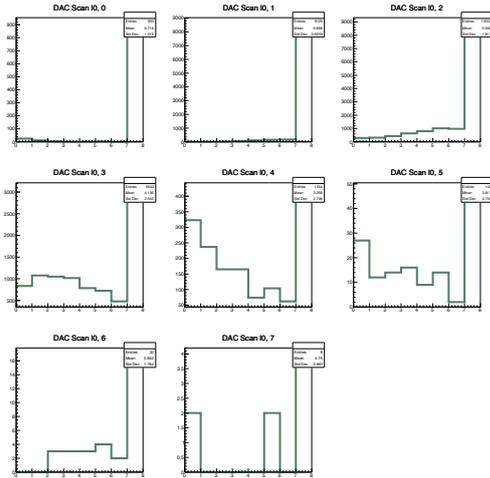
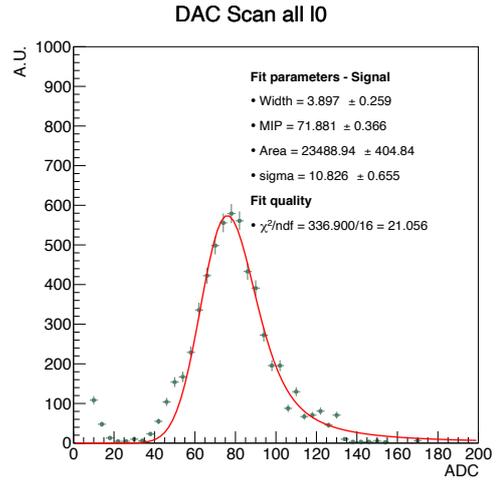**Figure 19:** *The energy deposit distributions of layer-0 respective to each run*

Figure 21: *The energy deposit distributions of INTT, layer-0*

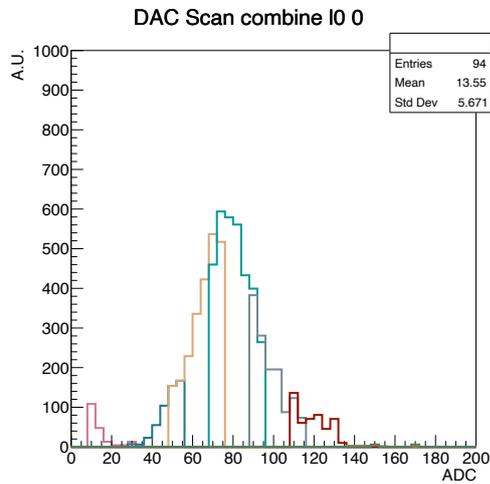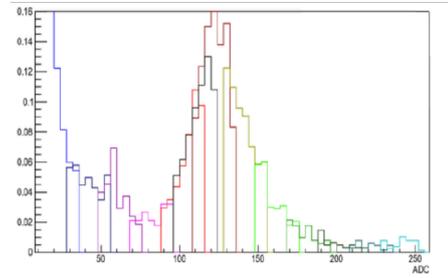**Figure 20:** *The energy deposit distributions of INTT, layer-0*

Figure 22: *The energy deposit distributions with the data of Testbeam2019*

as well, the scattering distribution at layer-1 can be well described by the superposition of Gaussian distribution and Student's t distribution. The peak of the INTT energy deposit is ~ 71.9 and the distribution is fit well with the Landau Gaussian convolution function.

References

[1] Multiple Coulomb Scattering in Thin Silicon, arXiv: 1405.2759v1 [physics.ins-det] 12 May 2014.

The peak is ~ 71.9 adc, and 20 seems to be a good value for threshold. However, the bais voltage 50 V is used in the Testbeam2021, the sensor is not fully depleted. In Testbeam2019 the supplied bias voltage was 100 V, that is enough for full depletion. The result of the data with Testbeam2019 data is shown in figure 22. The peak of the distribution with Testbeam2021 data is smaller than the one with Testbeam2019 data. For a rough confirmation, one thing we can do is to take the cosmic ray data with INTT applied by 50 V.

7.   Conclusion

The data analysis of the Testbeam2021 is performed. With the aids of the pre-studies on window size, alignment and longitudinal misalignment, the final efficiency can be up to 99.6 %. But the efficiency seems to be independent to the BCO phase, our hypothesis may be incorrect. The multiple coulomb scattering is performed