RECONSTRUCTION OF HADRONIC SHOWERS IN THE SND@LHC EXPERIMENT

Alma Mater Studiorum - Università di Bologna

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Master Degree in Physics

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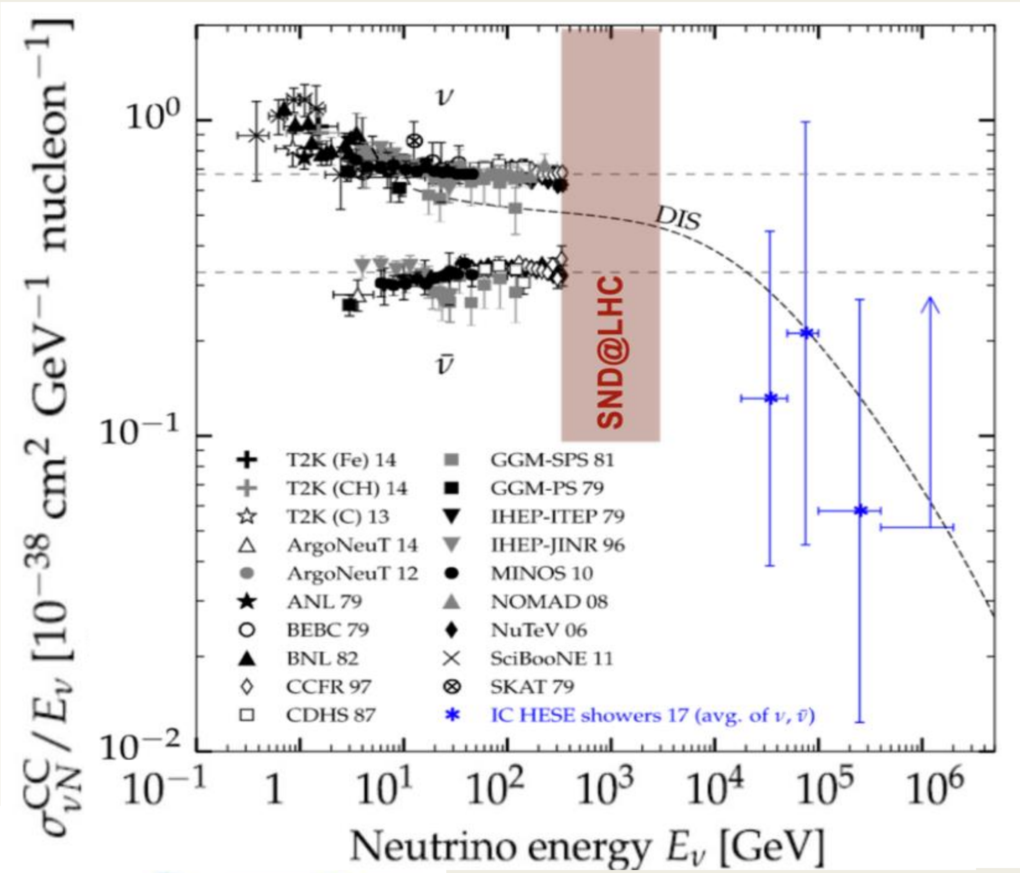
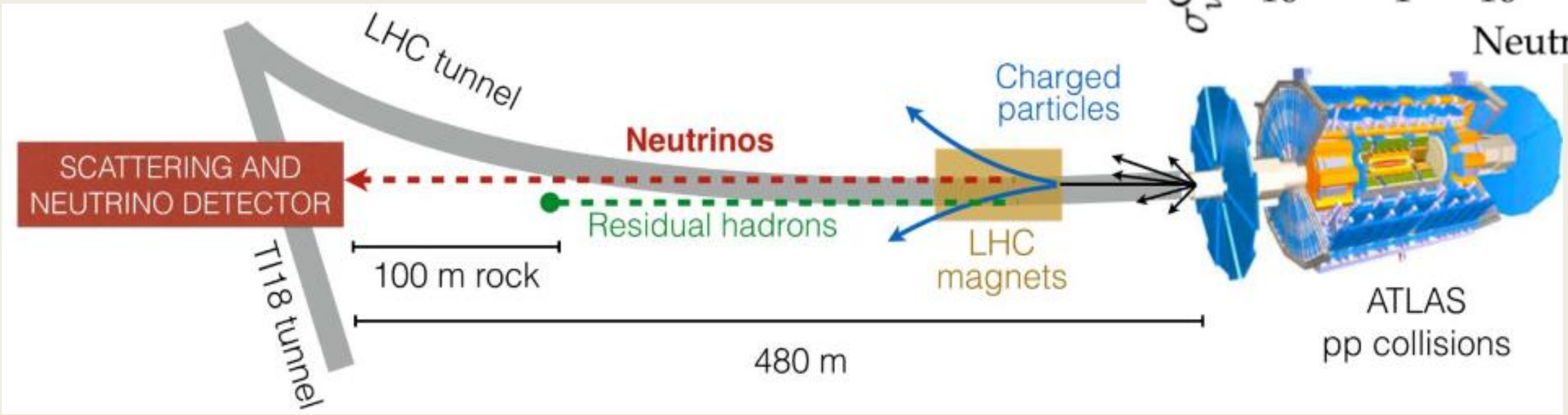
Scattering and Neutrino Detector

- SND@LHC observes all three neutrino flavors in pp collisions ($\mathrm{pp} \rightarrow \boldsymbol{\nu X}$) at LHC in energy range unexplored, from 100 GeV up to few TeV.
- Installed in 2021 in TI18 tunnel, 480 m downstream the ATLAS interaction point, shielded by 100 m of rock.
- It began collecting data in April 2022.
- In July 2023, the experiment reported the direct observation of 8 muonic neutrinos [1].
  A few thousand of $\boldsymbol{\nu}_{\mu}$ are expected by the end of Run 3.



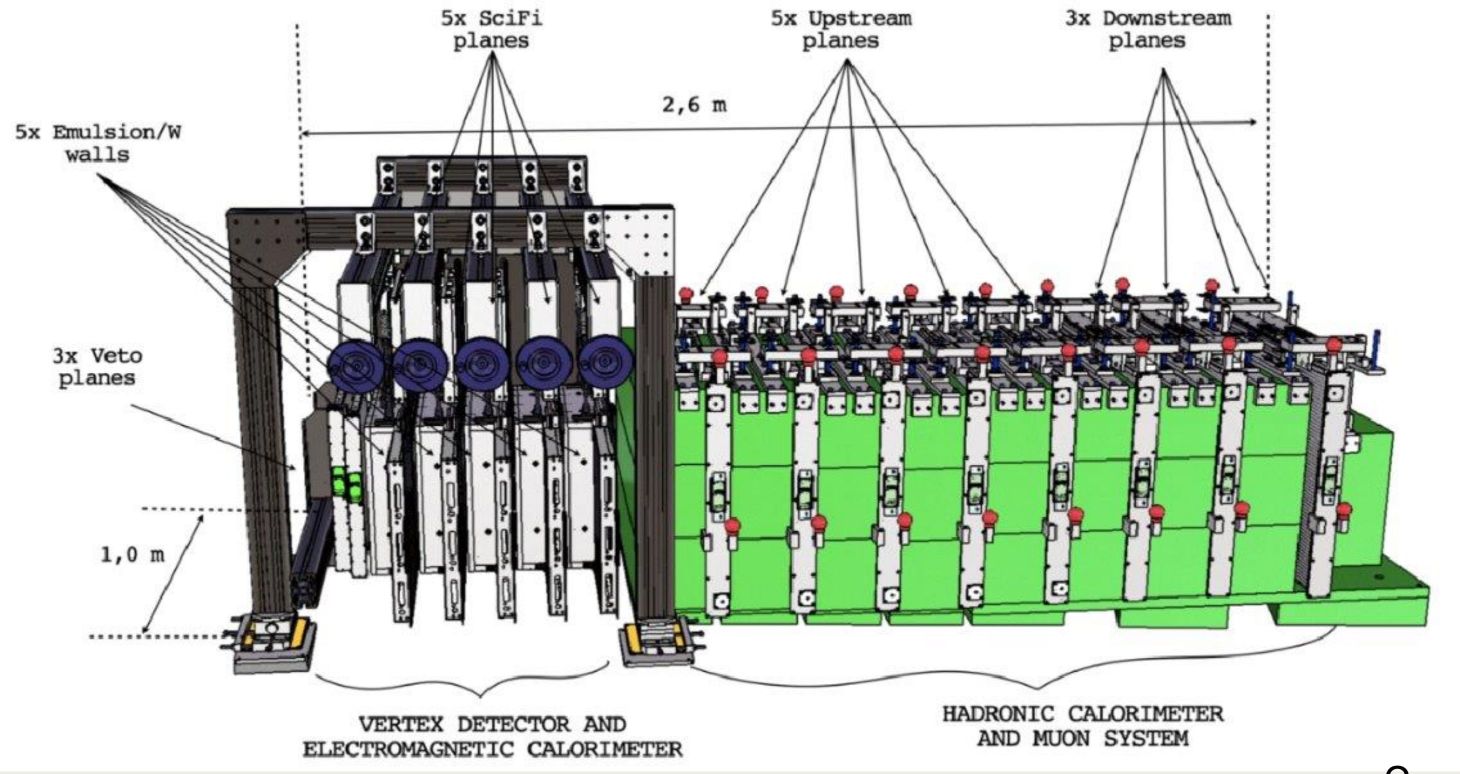


[1] SND@LHC collaboration, Observation of Collider Muon Neutrinos with the SND@LHC Experiment. In: Phys. Rev. Lett. 131.3 (2023), p. 031802. doi: 10.1103/PhysRevLett.131.031802. arXiv: 2305.09383 [hep-ex]

Detector configuration [2]

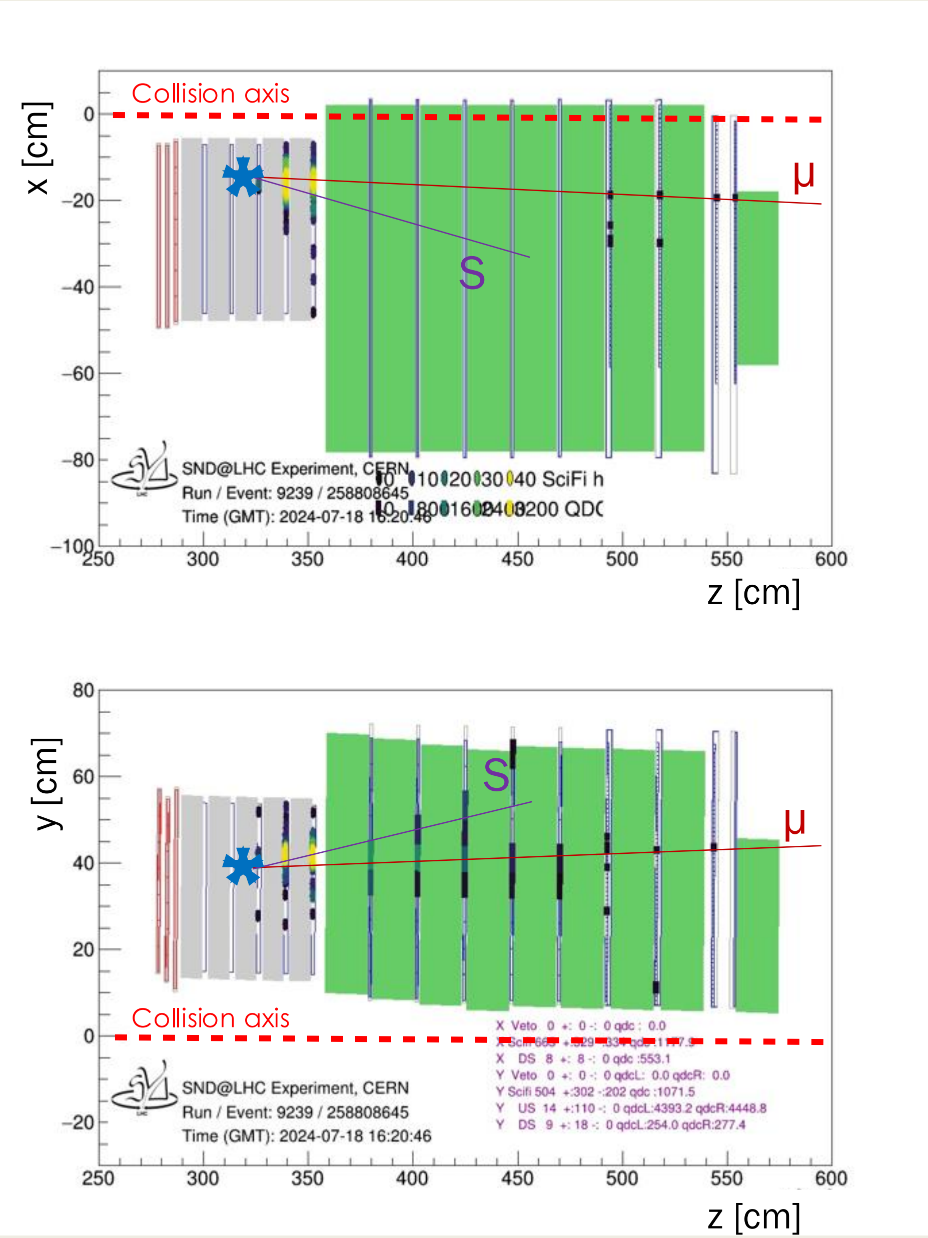
- Veto system: 3 planes of scintillator
- Target with vertex identification and electromagnetic calorimeter is made of alternating:
  - Emulsion layers interleaved with tungsten arranged in walls
  - Scintillating fibers (**SciFi**)
- Hadronic calorimeter, made of iron, and muon tagger:
  - 5 (UpStream, **US**) scintillator planes
  - 3 (DownStream, **DS**) scintillator planes

SciFi, US and DS planes are read by SiPMs, the light collected is converted in digitized charge.



[2] SND@LHC collaboration, SND@LHC: The Scattering and Neutrino Detector at the LHC. 2023. arXiv: 2210.02784 [hep-ex]

Thesis project



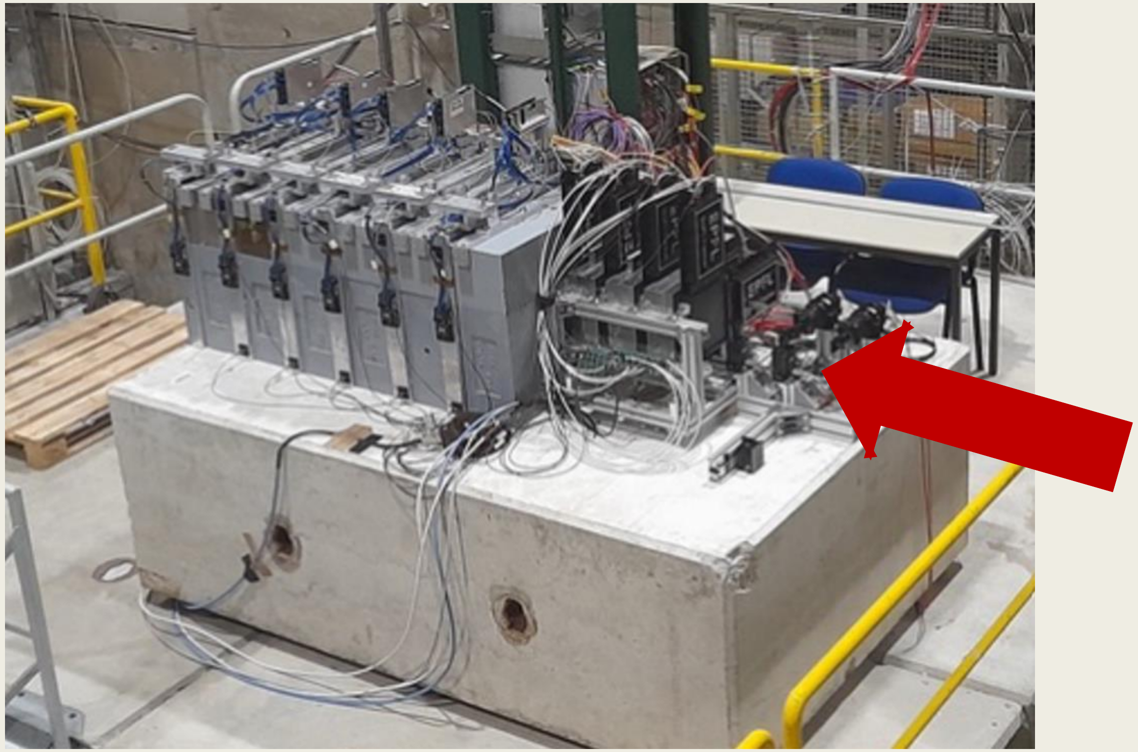
- To determine neutrino energy is necessary to know both the direction and the energy of the hadronic shower and the muon direction.

- The momentum of the muon is determined through the following relation:

$$E_{sh}\theta_{sh} + P_{\mu}\theta_{\mu} = 0$$

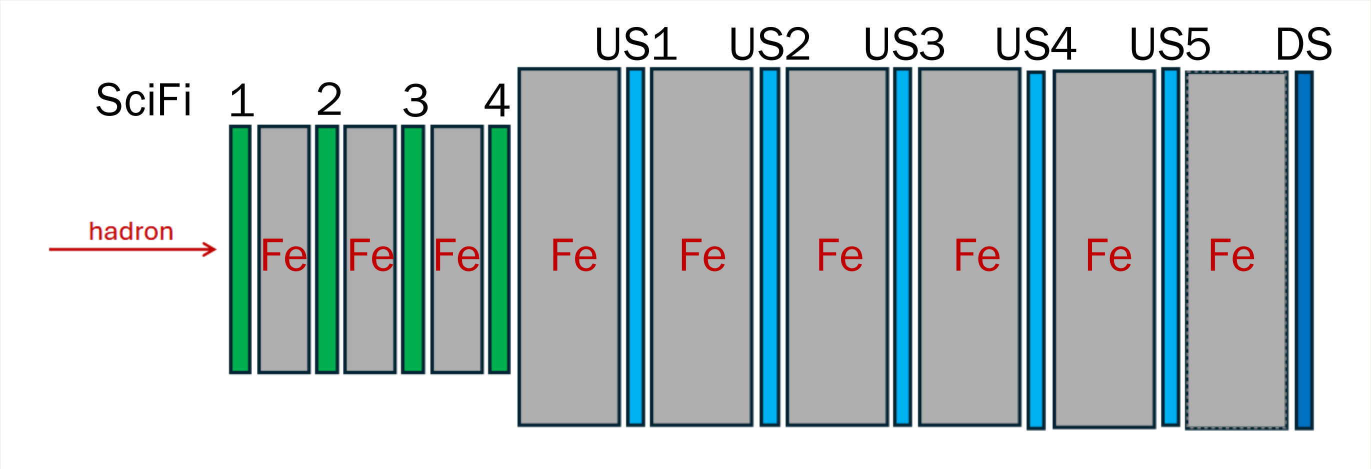
- A test beam detector was built to reproduce SND@LHC for calibrating the calorimeter and estimating uncertainties.

Test beam



In August 2023, the detector was exposed to hadron beams with energies ranging from 100 to 300 GeV with known direction.

Incoming beam



Hadronic shower centroid

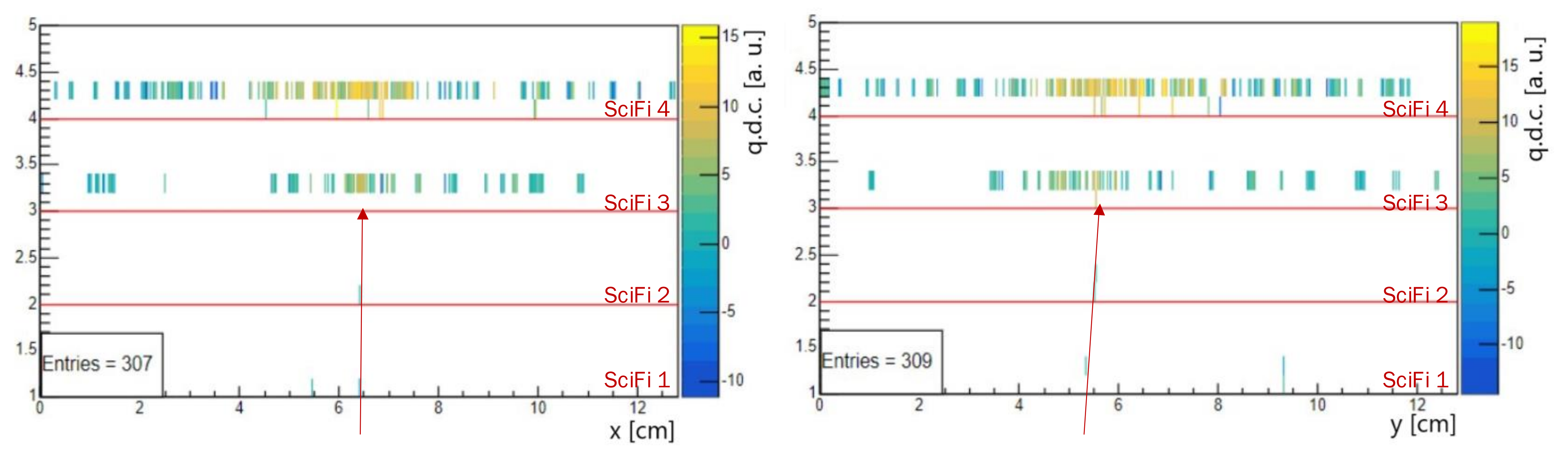
Each hit has:

- a position
- a digitized charge (QDC), related to the energy released in the detector.

It is possible to define the **centroid** for each layer of SciFi (and US).

Average position of the shower in that layer. Computed as the weighted average of hit positions with the QDC.

Shower visualization: 240 GeV pion

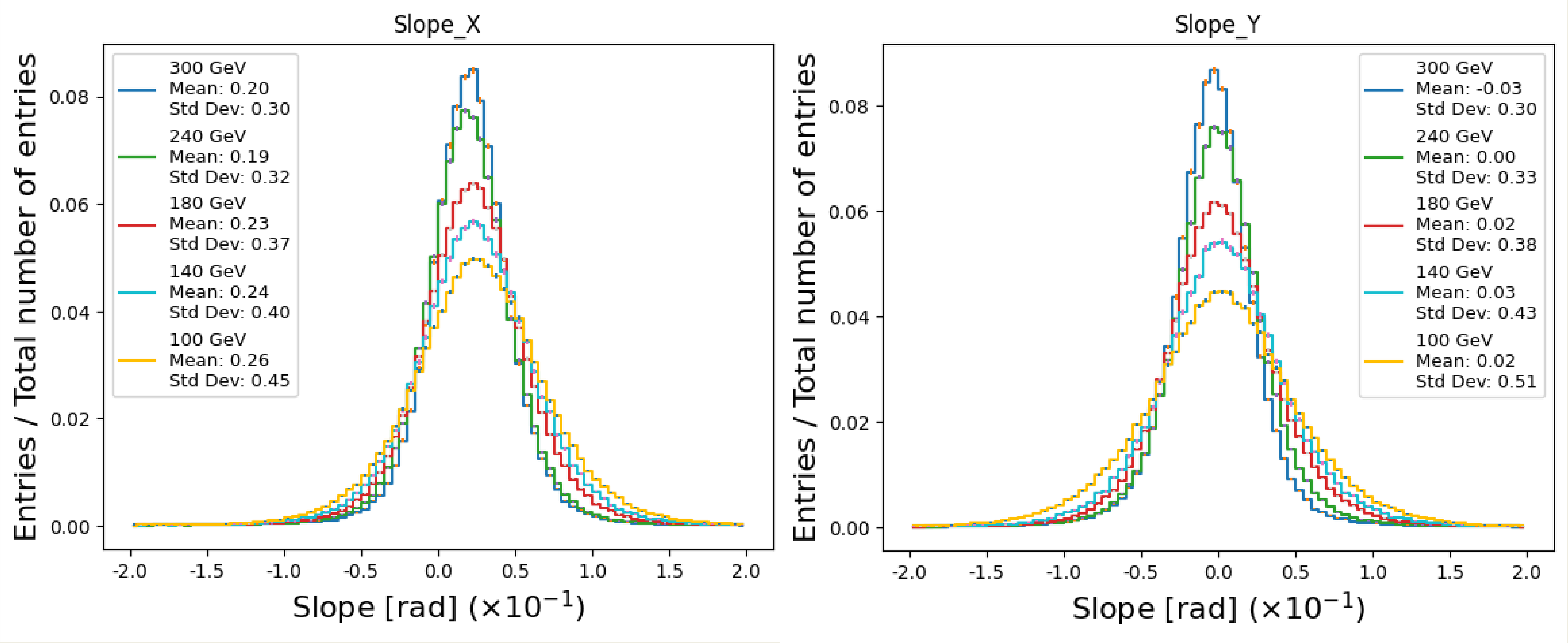


Focus on Shower Start = 2

Shower that starts to be visible from the second SciFi layer.

Shower Direction Determination

The direction of the shower is determined by performing a linear fit based on the depths of the different SciFi layers in the detector.



Shower Direction Determination

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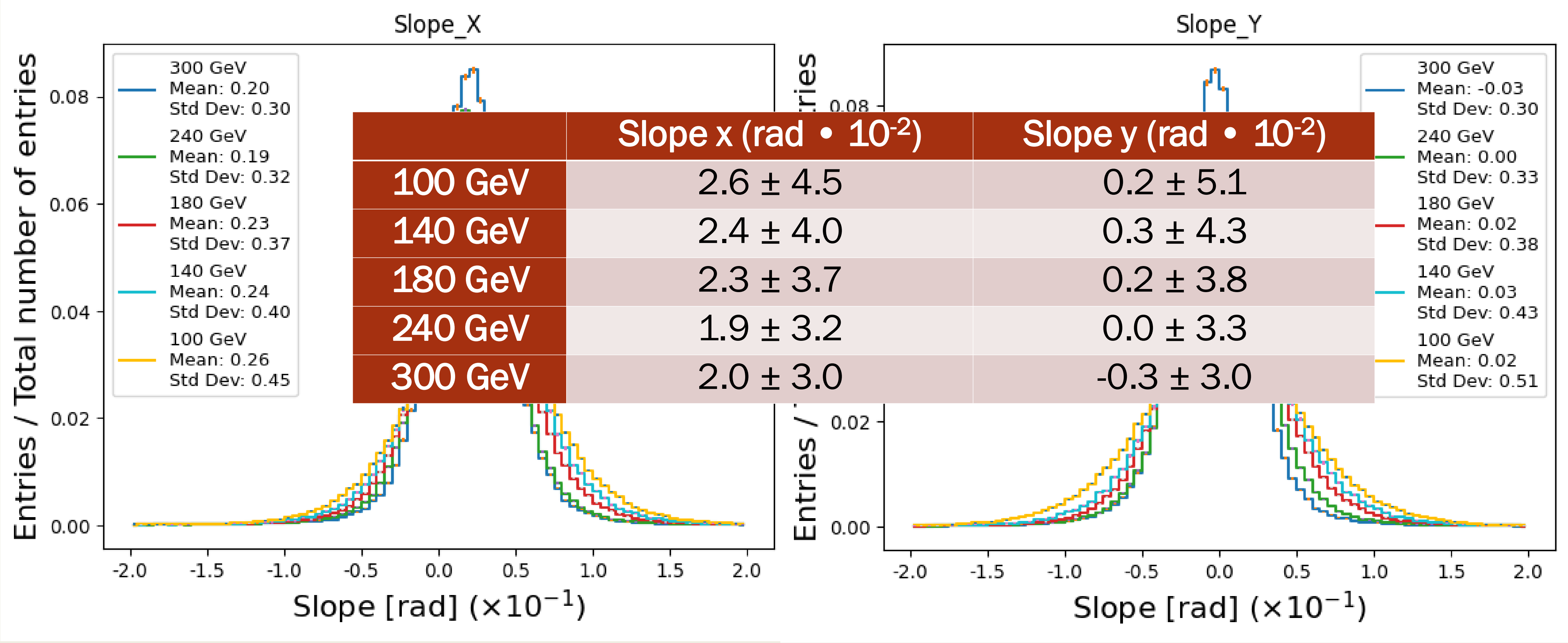
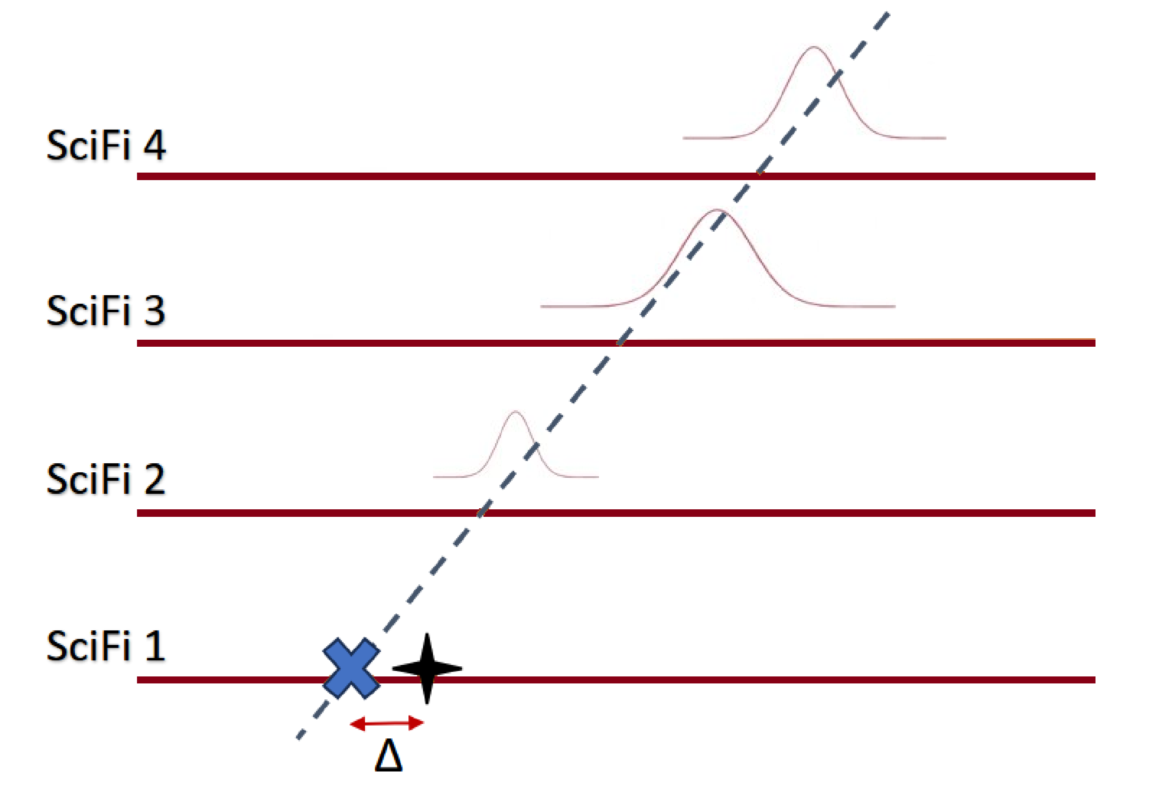


	Slope x (rad • 10^{-2})	Slope y (rad • 10^{-2})
100 GeV	2.6 ± 4.5	0.2 ± 5.1
140 GeV	2.4 ± 4.0	0.3 ± 4.3
180 GeV	2.3 ± 3.7	0.2 ± 3.8
240 GeV	1.9 ± 3.2	0.0 ± 3.3
300 GeV	2.0 ± 3.0	-0.3 ± 3.0

Intercept in SciFi1



To validate the method and calculate the experimental resolution, it is necessary to compare the recorded hit in SciFi1 and the extrapolated intercept in SciFi1.

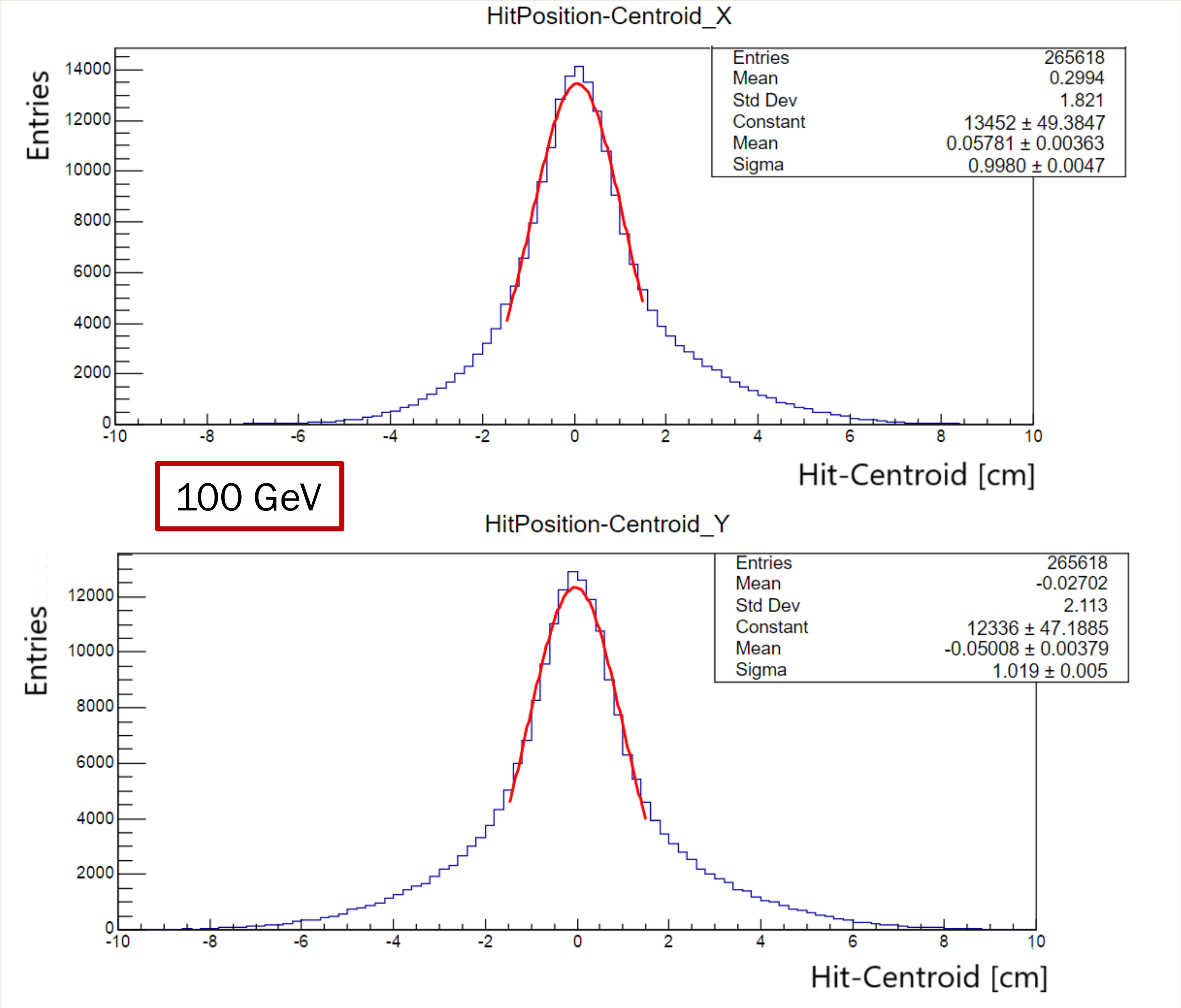
The extrapolated intercept was obtained with:

- $Y = slope_y * z_y + intercept_y$
- $X = slope_x * z_x + intercept_x$

Resolution estimation for Shower Start = 2

Event by event, it was considered the difference between the *"true"* position in SciFi1 and the extrapolated intercept.

"True" position is the mean position of the largest cluster left by the incoming pion.



Resolution estimation for Shower Start = 2

Event by eve
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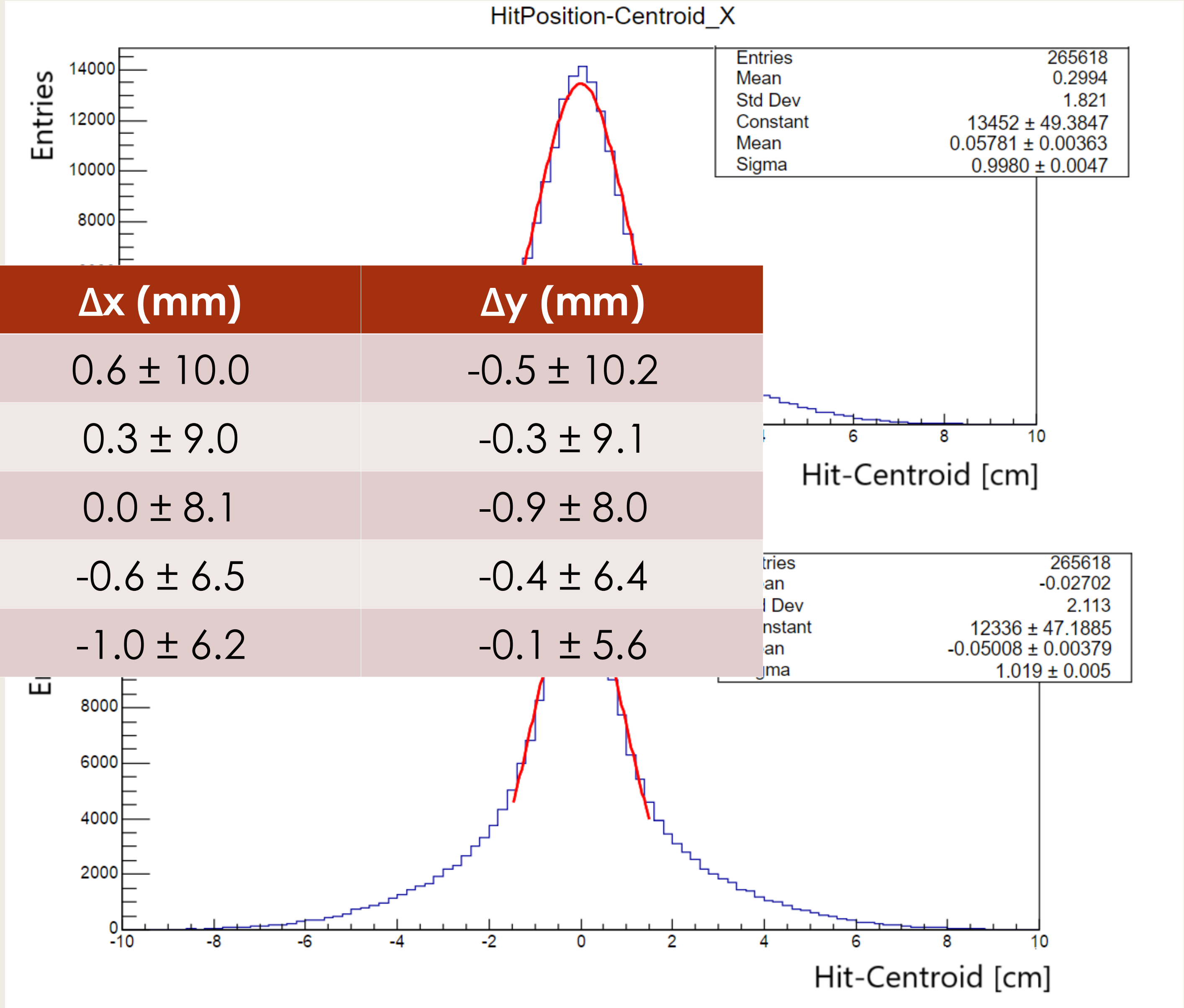
extrapolated

"True" positic
position of the largest cluster left by the incoming pion.

	Δx (mm)	Δy (mm)
100 GeV	0.6 ± 10.0	-0.5 ± 10.2
140 GeV	0.3 ± 9.0	-0.3 ± 9.1
180 GeV	0.0 ± 8.1	-0.9 ± 8.0
240 GeV	-0.6 ± 6.5	-0.4 ± 6.4
300 GeV	-1.0 ± 6.2	-0.1 ± 5.6



Focus on Shower Start = 3

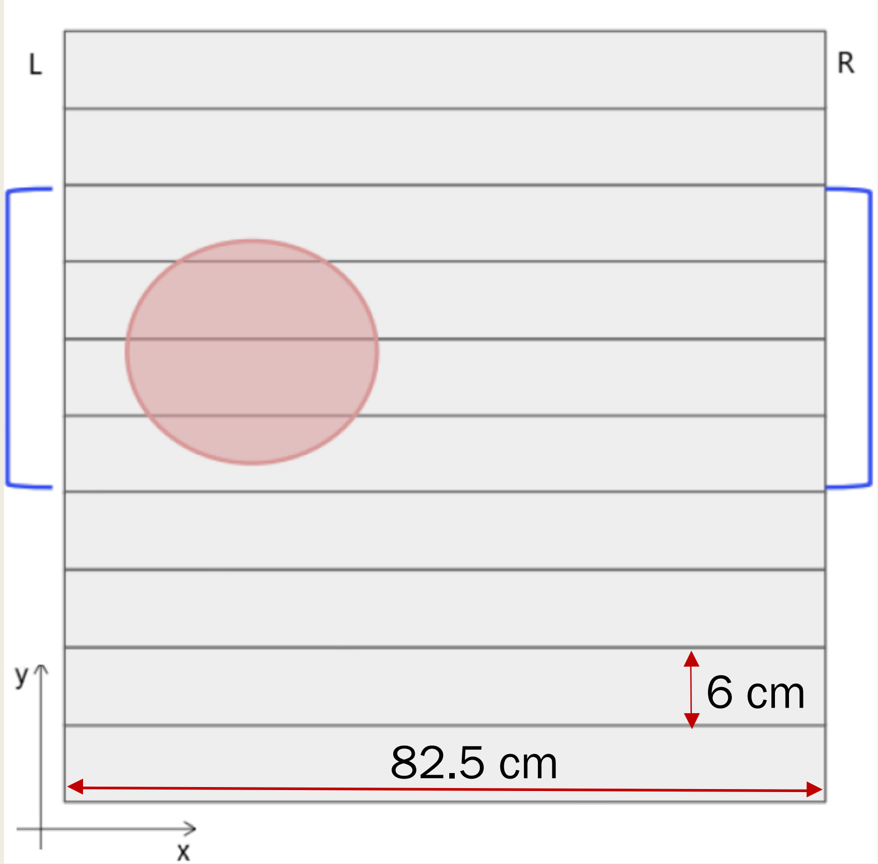
Shower that starts to be visible from the third SciFi layer.

Shower centroid in US

- Each end of US bars is read by 6 SiPMs.
- Centroid calculation also in US bars:

$$y = \sum_{N_{bars}} \frac{y_{bar} \cdot QDC_{bar}}{QDC_{total}}$$

$$x = \frac{QDC_{left} \cdot x_{left} + QDC_{right} \cdot x_{right}}{QDC_{left} + QDC_{right}}$$



- For Shower Start = 2 showers the results obtained are mainly the same as the ones showed before.

Shower direction for Shower Start = 3

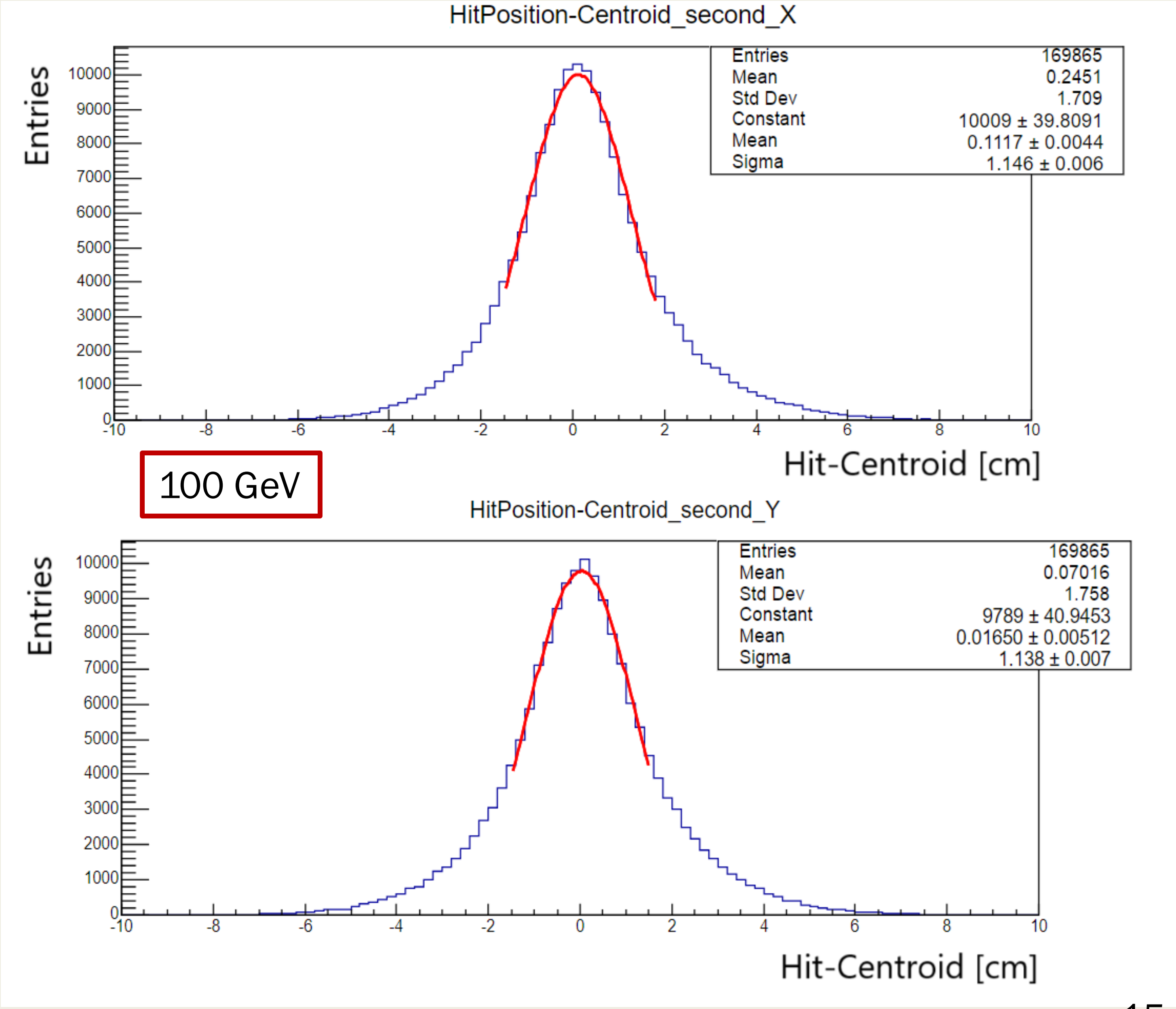
- The introduction of US allowed to study also the performance of the shower reconstruction also for showers tagged as Shower Start = 3.

	Slope x ($rad \cdot 10^{-2}$)	Slope y ($rad \cdot 10^{-2}$)
100 GeV	0.9 ± 4.6	0.5 ± 4.7
140 GeV	1.3 ± 4.7	0.2 ± 4.7
180 GeV	1.9 ± 4.5	-0.1 ± 4.6
240 GeV	2.2 ± 4.2	-0.1 ± 4.0
300 GeV	2.4 ± 4.0	-0.4 ± 4.0

- All consistent with zero.
- Comparable to the Shower Start = 2 case.
- The standard deviation gets slightly worse but consistently. Attributed to the low resolution of US bars.

Resolution estimation for Shower Start = 3

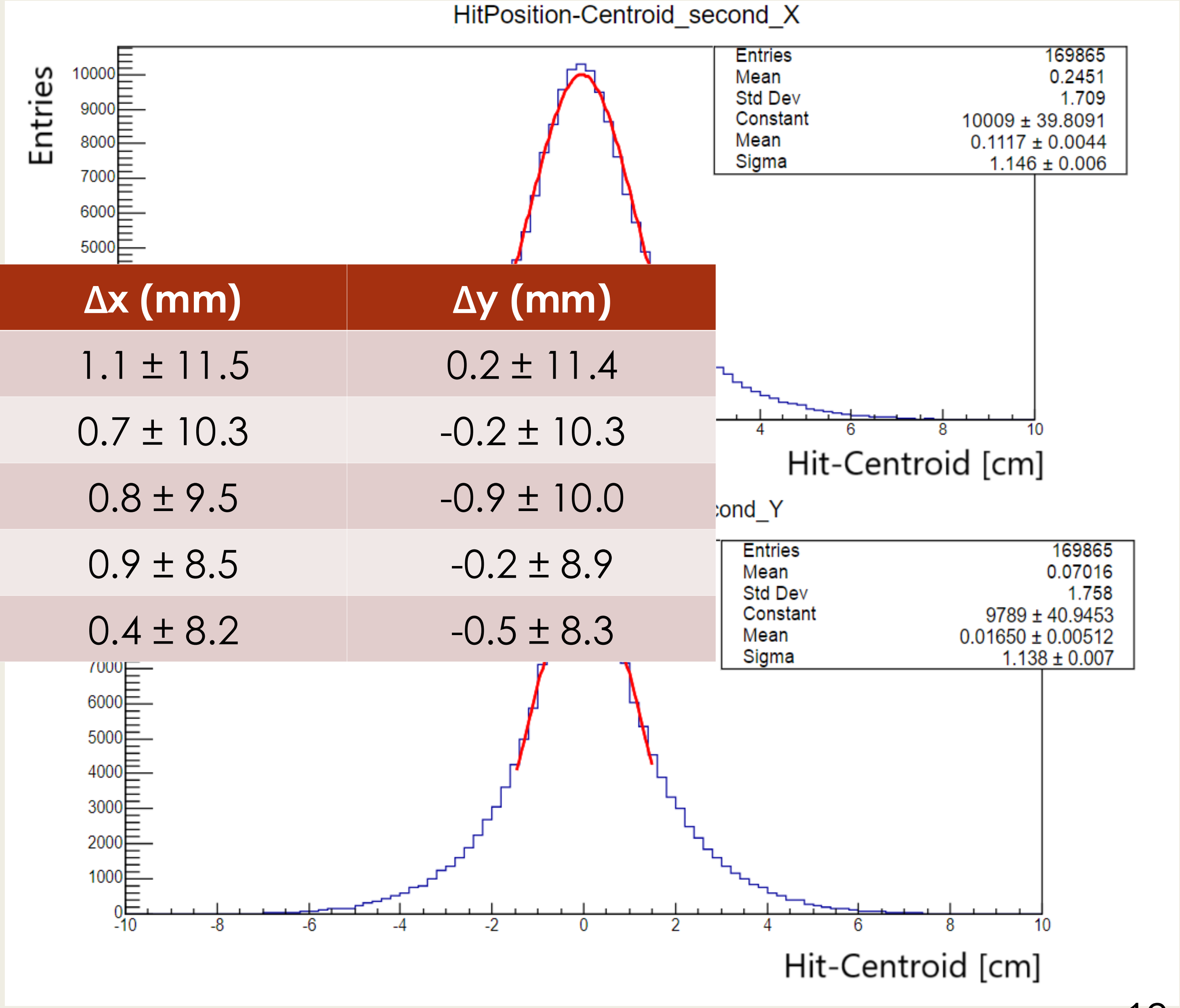
- Only if the *"true"* position in SciFi1 and SciFi2 is lower than 0.5 cm in both x and y direction, the reconstruction is done.
- Difference between the *"true"* position of pion and the extrapolated one through shower direction reconstruction in the SciFi2 plane.



Resolution estimation for Shower Start = 3

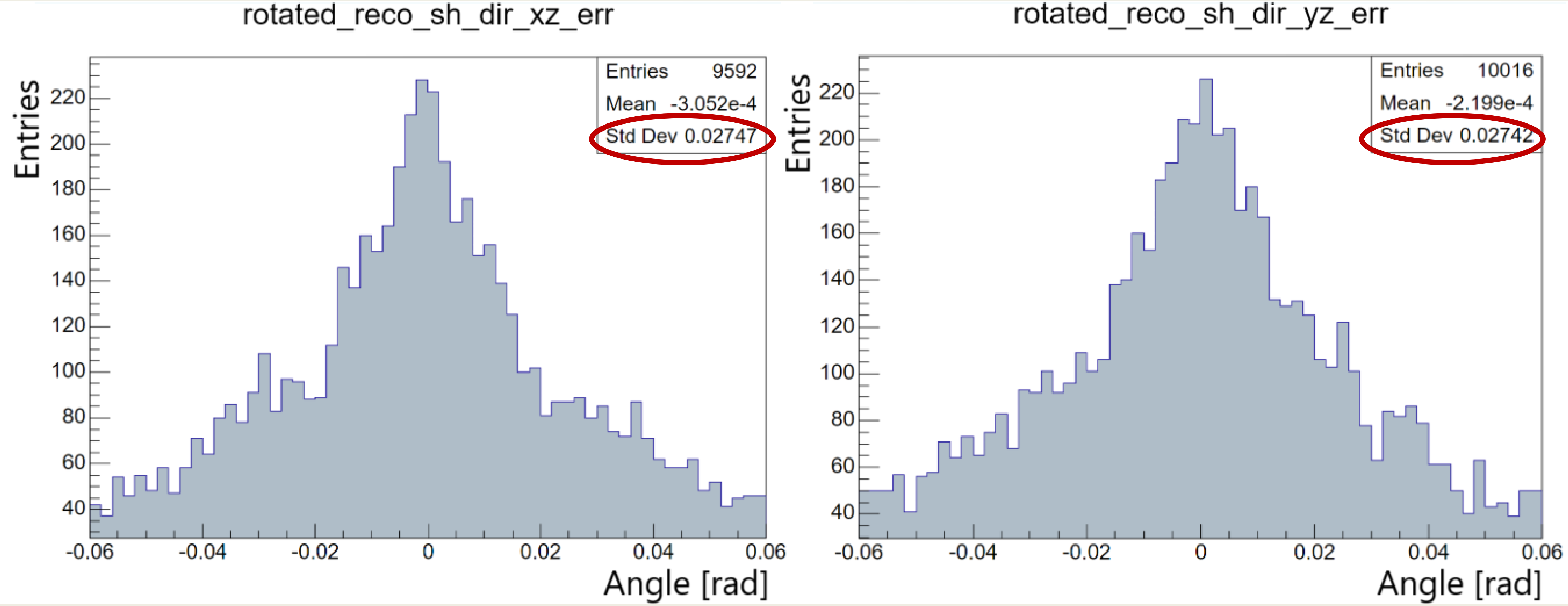
- Only if the *"true"* position in SciFi1 and SciFi2 is lower than (both x and y the reconst done.
- Difference b *"true"* positi and the extrapolated one through shower direction reconstruction in the SciFi2 plane.

	Δx (mm)	Δy (mm)
100 GeV	1.1 ± 11.5	0.2 ± 11.4
140 GeV	0.7 ± 10.3	-0.2 ± 10.3
180 GeV	0.8 ± 9.5	-0.9 ± 10.0
240 GeV	0.9 ± 8.5	-0.2 ± 8.9
300 GeV	0.4 ± 8.2	-0.5 ± 8.3



Resolution and comparison with Monte Carlo

- Positional uncertainty (~10 mm) leads to an estimated slope uncertainty of 30 mrad, derived from the ratio between transverse plane (xy) uncertainty and the detector shower depth, about 30 cm.
- Monte Carlo simulations confirm this uncertainty.



Conclusions

- Neutrino energy reconstruction requires knowledge of the shower direction.
- Test beam data were analyzed to develop a method to reconstruct the direction and estimate the related uncertainties.

- The shower direction was determined by a linear fit of the centroid positions along the different planes.

- The resolution was calculated making the difference between the *"true"* position and the extrapolated one, both for Shower Start = 2 and 3.
  It ranges (5.6 ÷ 11.5) mm implying a slope uncertainty of about 30 mrad.

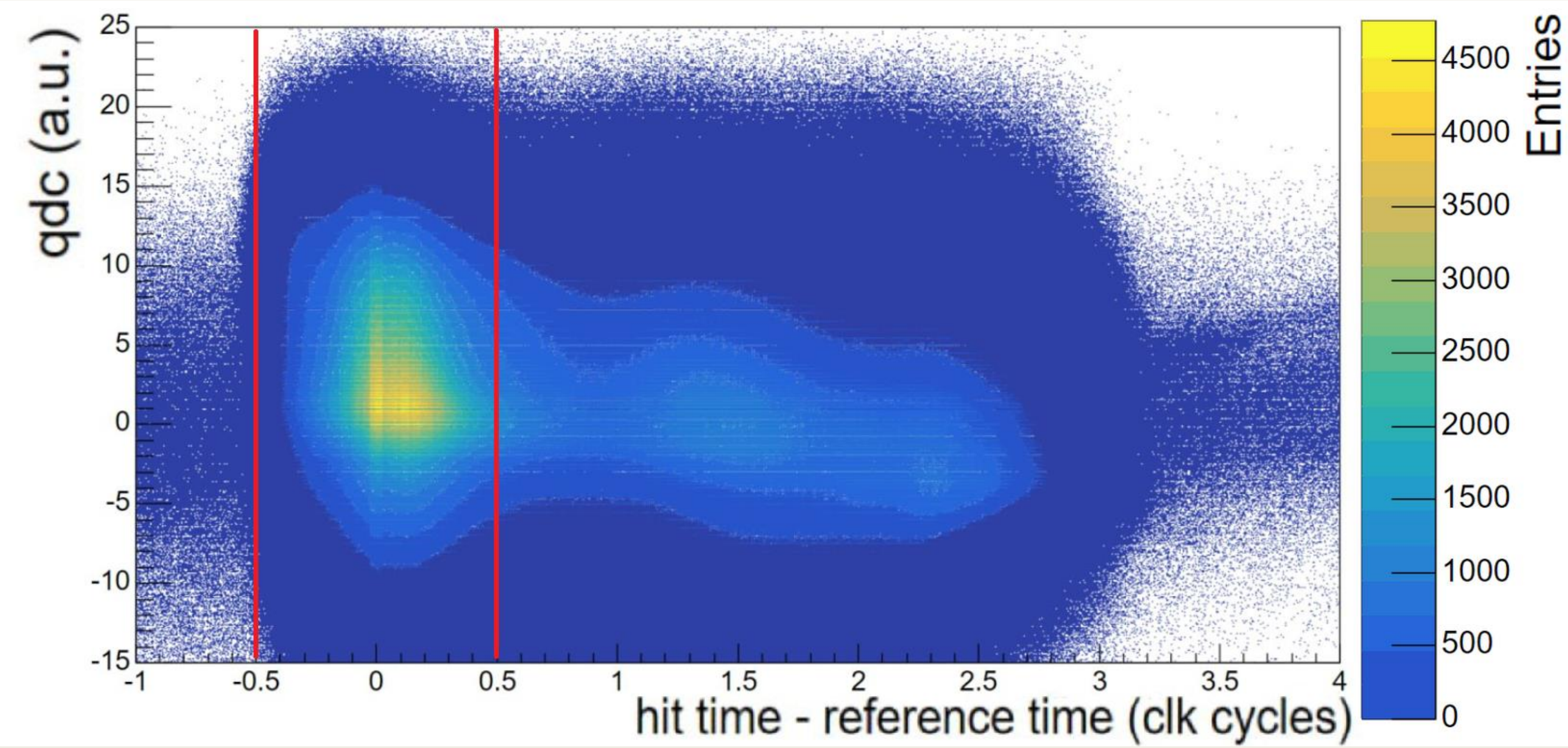
- Improvements:
  - Trim the external parts of the showers

  For US bars:
  - Y direction, using the QDC collected by each SiPM and not the sum, higher granularity
  - X direction, using the arrival times of signals at both the ends of each bar

THANKS FOR YOUR ATTENTION

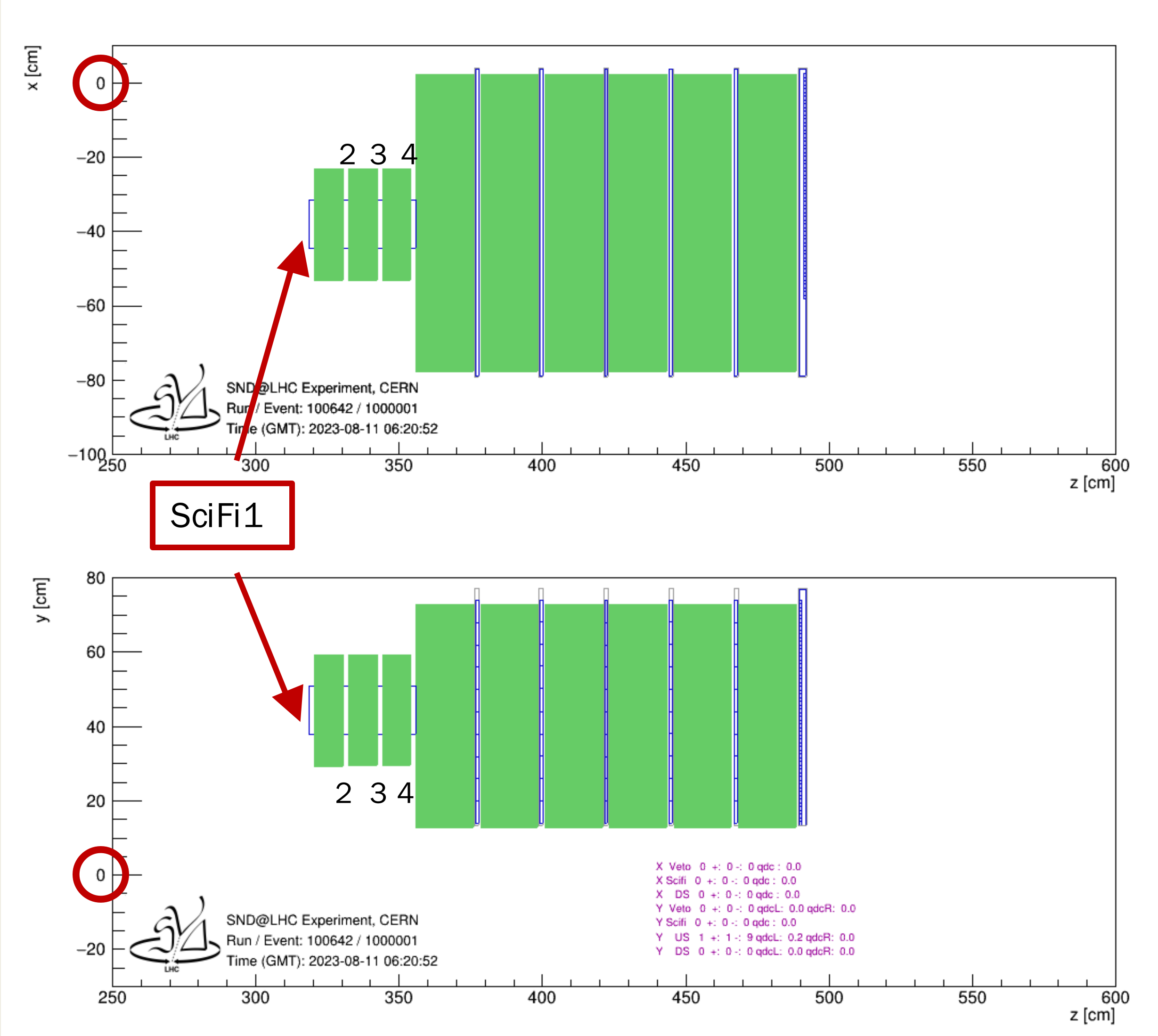
Backup - QDC considerations

Only hits within 0.5 clock cycles from the reference time (most probable time in SciFi) are considered.

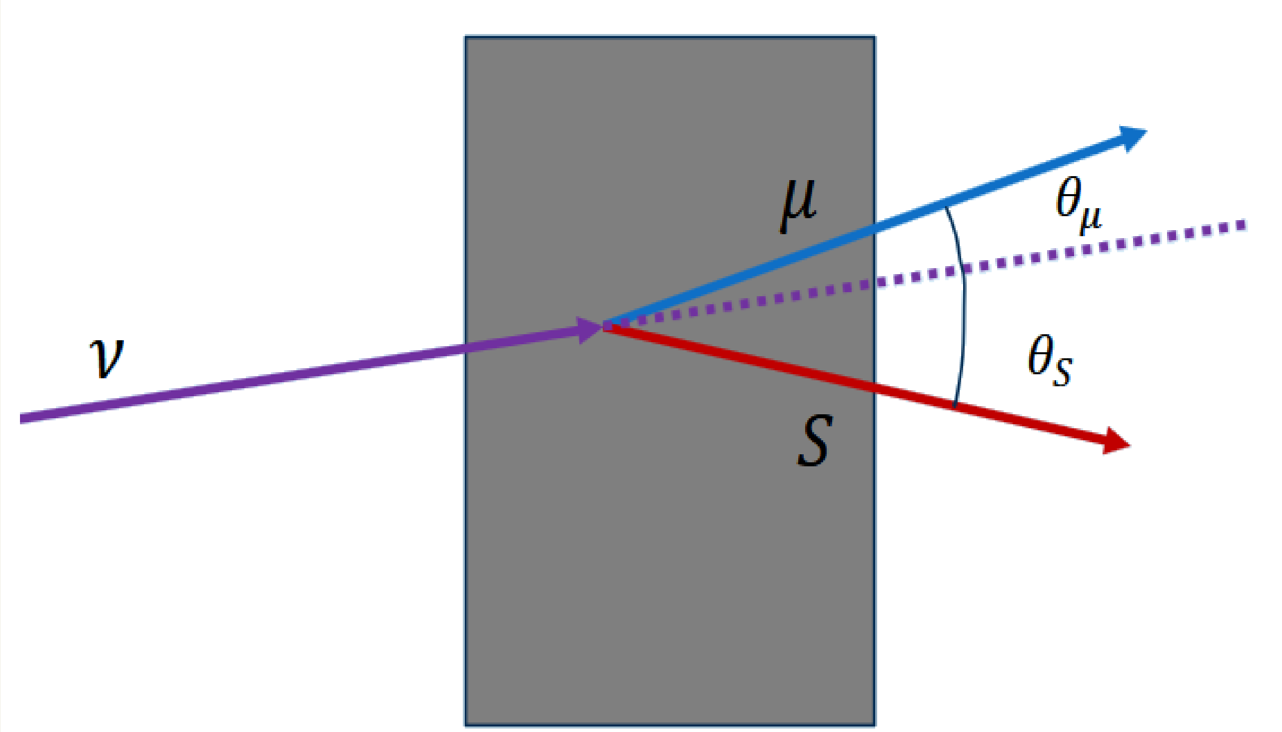


Backup - Test Beam Geometry

Here is reported the geometry of the test beam in its reference frame.



Backup – Neutrino energy resolution



$$E_\nu \simeq E_{shower}\left(1+\frac{\theta_{shower}}{\theta_\mu}\right)$$

$$\delta E_\nu \simeq \frac{E_{shower}}{\theta_\mu}\delta\theta_{shower}$$

Resolution: ~ 55%