中国科学技术大学
University of Science and Technology of China

DAMPE Track Reconstruction: From Kalman Filtering to Convolutional Neural Networks

第五组

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Detector structure

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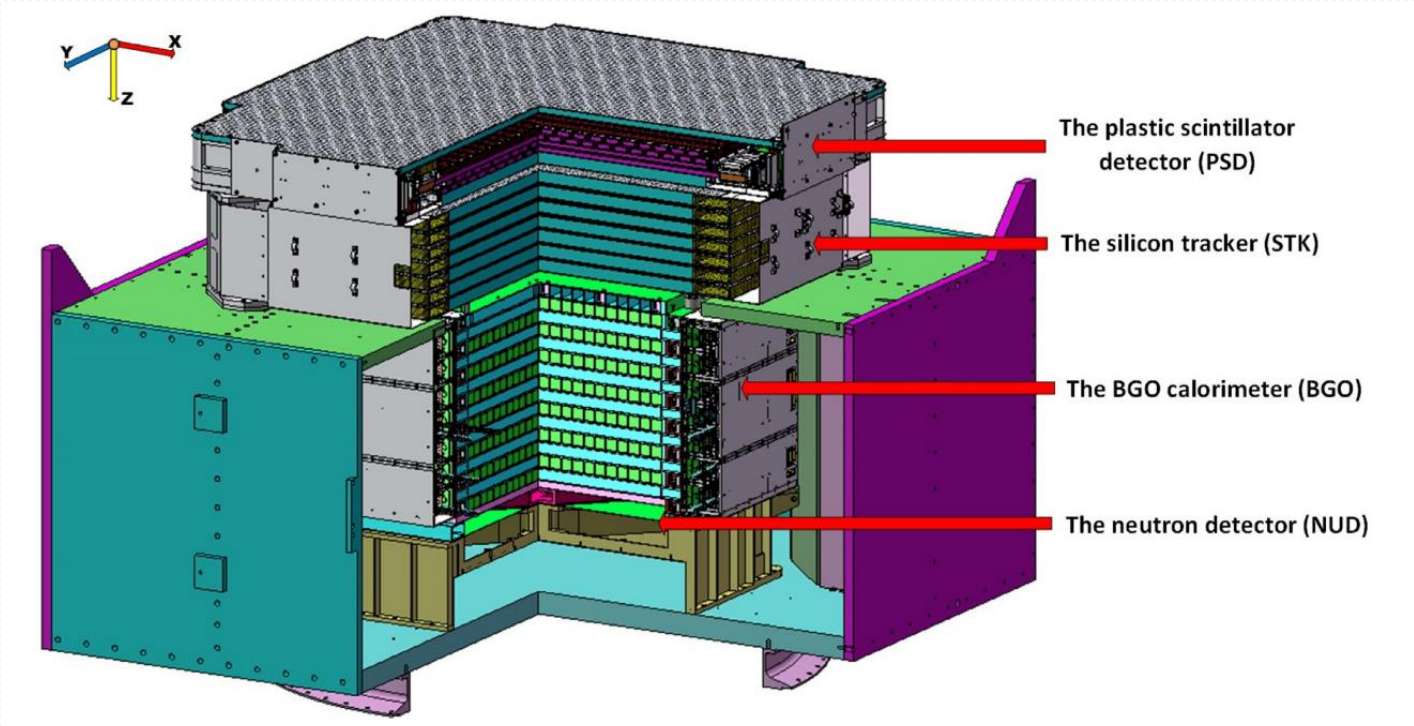
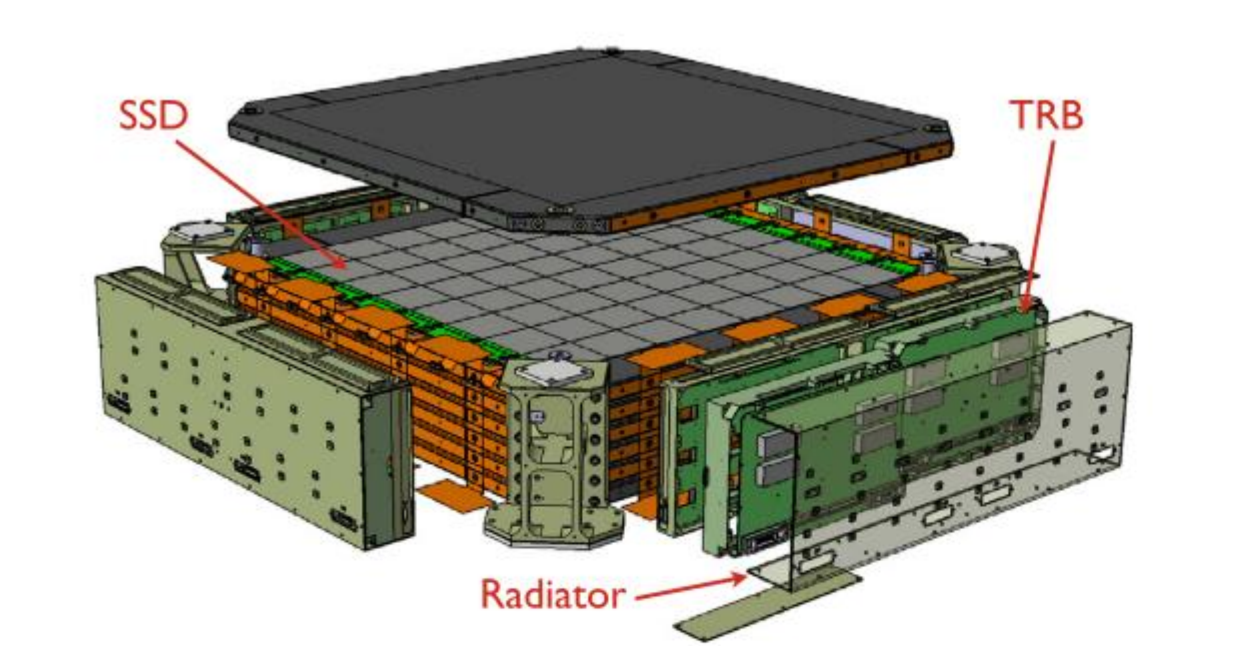
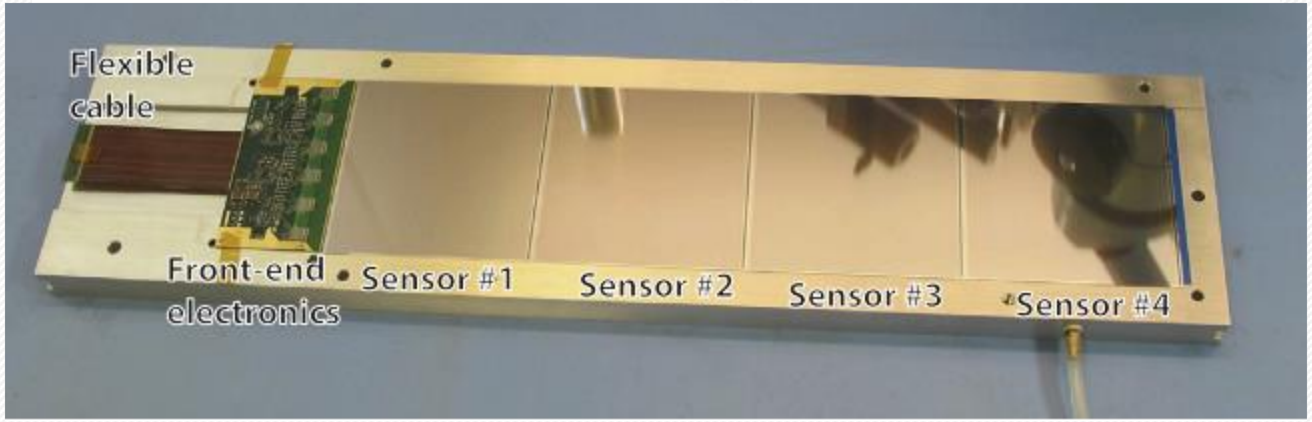


Schematic view of the DAMPE detector

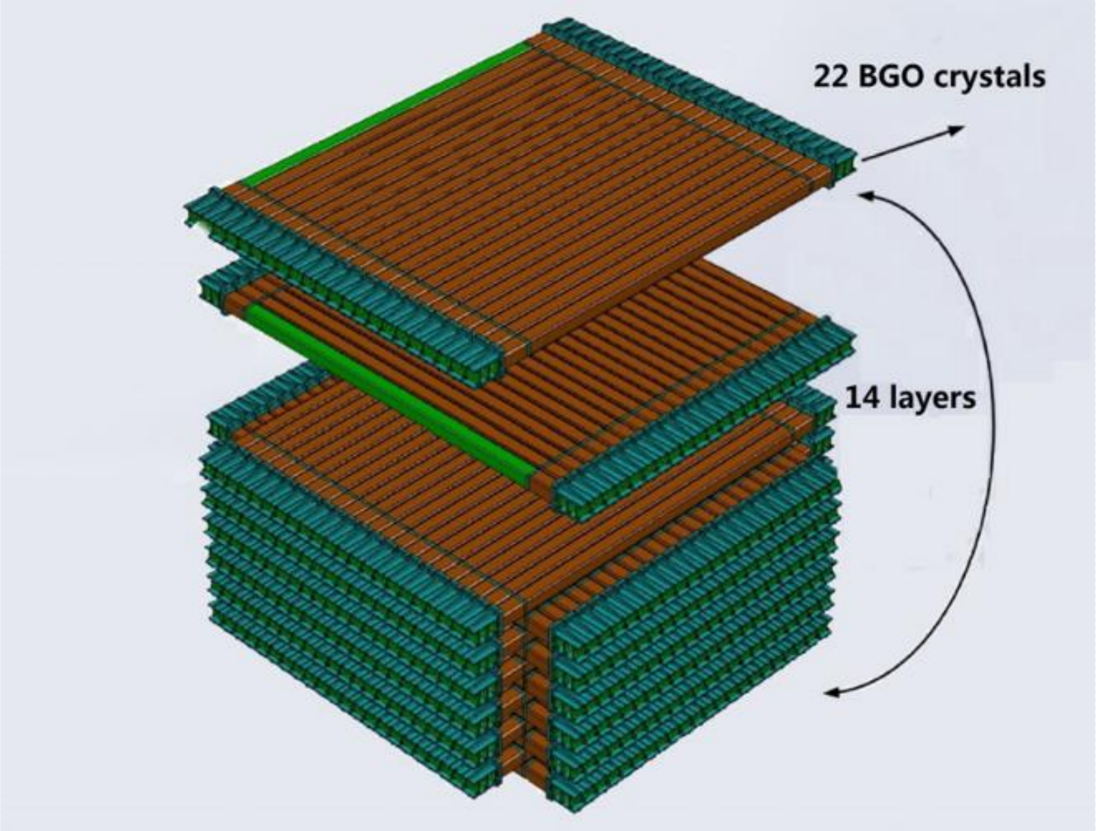
- PSD: Measurement of the absolute charge of incident particles.
- STK: Responsible for track reconstruction and gamma-ray detection.
- BGO: Measure the energy, and record shower propagation direction and profile.
- NUD: Auxiliary detector to improved the discrimination capability between electromagnetic and hadronic showers.

Detector structure



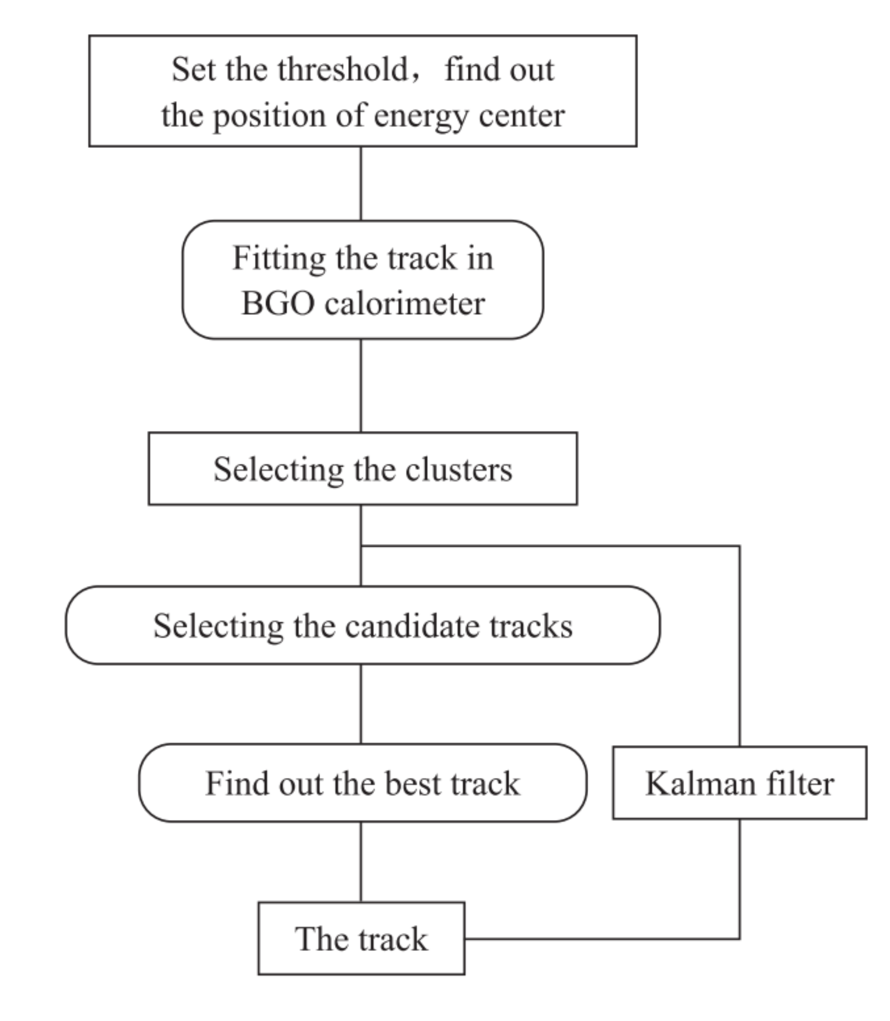


Exploded view of the STK



Schematic view of the DAMPE BGO calorimeter

Track reconstruction process



Flow chart for reconstructing the incident particle trajectory

trajectory reconstruction and particle identification following steps:

- Reconstruction of the shower axis direction in the BGO calorimeter;
- Track reconstruction in the STK using the BGO shower axis direction as a seed;
- Selection of the best STK track from the ensemble of candidate tracks;
- Projection of the STK track onto PSD, calculation of the path length;
- Measurement of the particle absolute charge with PSD using the STK track projection.

Track reconstruction algorithm

Least squares method:

For the known data points, to make the energy weighting $x_i = E_{x_i} x_i$, and fitting with $y = a''x + b''$.

The a'' and b'' as follows:

$$b'' = \frac{\sum_{i=1}^{n} y_i \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i}{n \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

$$a'' = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

E_{xi} express respectively the energy values corresponding to the xi-th and clusters or crystals, a'' and b'' are respectively the slope and intercept of the straight line.

Kalman filter approach:

$$\tilde{q}_{k|k-1} = F \tilde{q}_{k-1}$$

$$\tilde{q}_k = \tilde{q}_{k|k-1} + K_k (m_k - H \tilde{q}_{k|k-1})$$

Use Kalman filtering method, because of its property of minimum unbiased variance, it can remove the random errors in the experiment to obtain the information more close to the reality track.

BGO track reconstruction

BGO track reconstruction follows steps:

1. Only when the energy of a BGO layer exceeds 2% total energy, can this layer be taken as the reference layer to join in the track reconstruction in the BGO calorimeter.

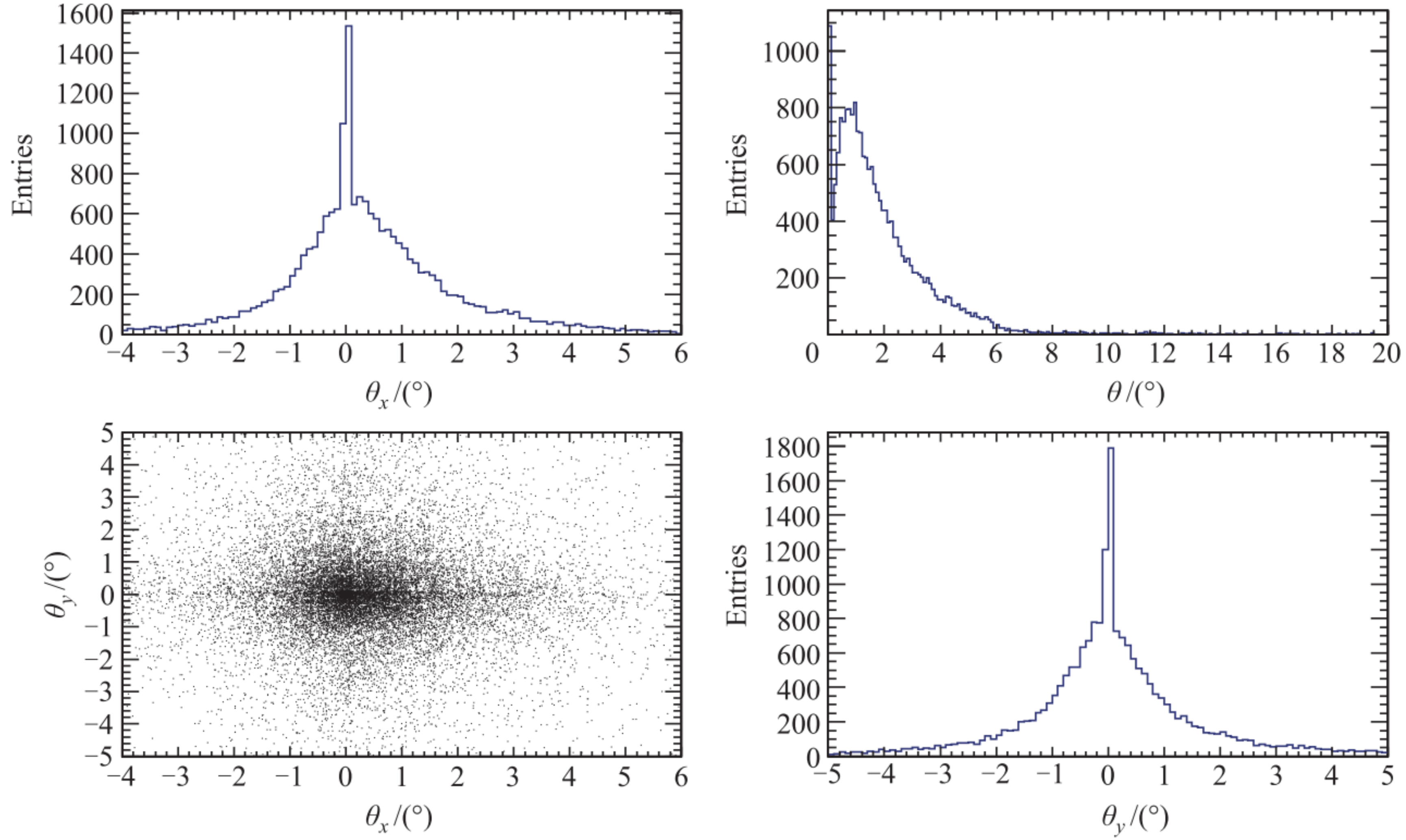
2. select the crystal with the greatest energy deposition and the two crystals in its left and right sides, totally 3 crystals, to calculate the centroid of energy deposition of this layer:

$$\frac{E_{max-1}x_{max-1} + E_{max}x_{max} + E_{max+1}x_{max+1}}{E_{max-1} + E_{max} + E_{max+1}} = x_c$$

x_{max-1}, x_{max+1}, E_{max-1},and E_{max+1} express respectively the positions and energies of the crystals in the left and right of x_{max}.

3. Energy-weighted linear fitting in YZ plane or XZ plane.

BGO track reconstruction



The track reconstruction in the BGO calorimeter

STK track reconstruction

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1.The reconstructed track in the STK from that in the BGO calorimeter shouldbe within ±5◦, and the intercept is taken to be ±25mm.

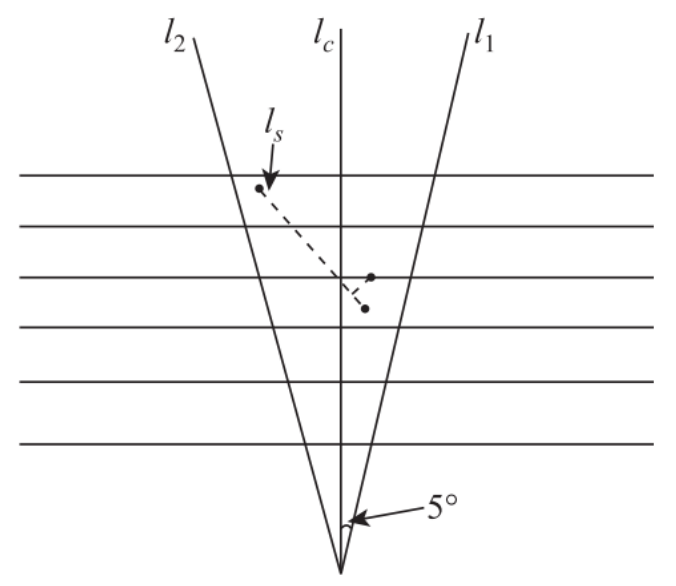
$$l_2 : z = \tan(\arctan a + 5)\, x + 25 + b$$

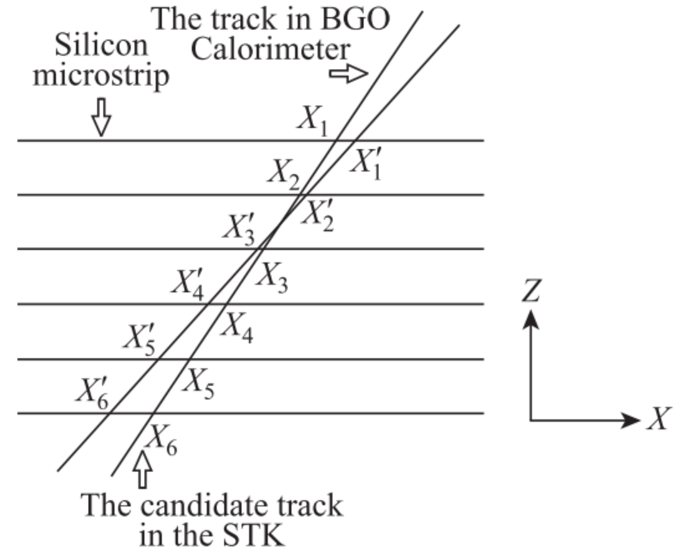
$$l_1 : z = \tan(\arctan a - 5)\, x - 25 + b$$

2. For the STK, two approaches exist for optimal track selection:

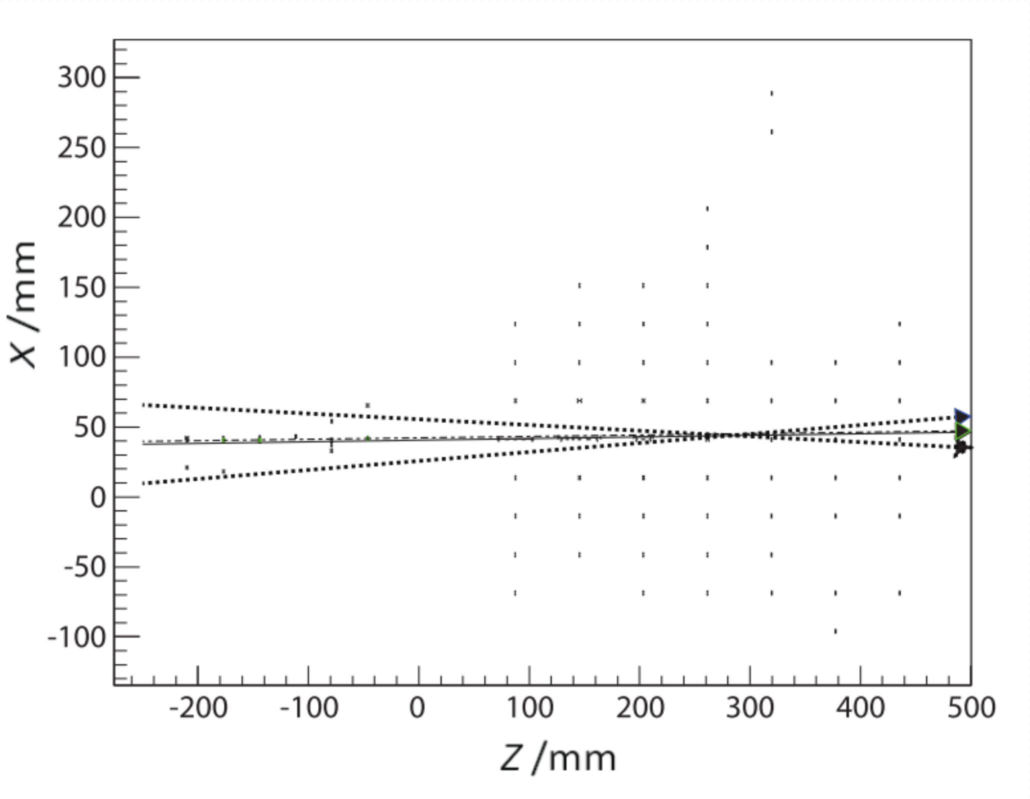
a. Arbitrarily select two points within a defined range to form a straight line, determine whether points on other layers lie close to this line, iteratively refine the selection to identify the line that has the largest number of nearby points and the smallest χ², and finally perform a fit using the points on this line along with those close to it to obtain the reconstructed track.

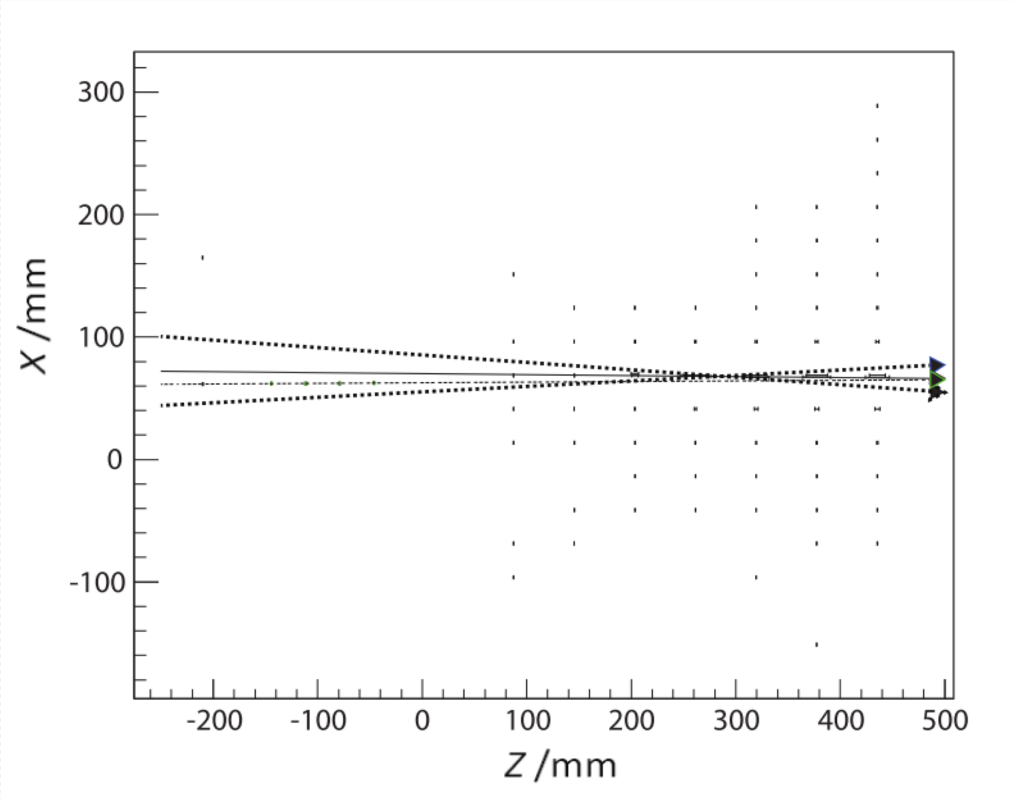
b. Traverse all possible points on the silicon microstrip ($X_1 \dots X_6$), and take the intersection point of the BGO-fitted track with the microstrip ($X_1' \dots X_6'$), and by calculating the minimum value $\sum_{i=1}^{n}(X_i - X_i')^2$, obtain the STK track.





Track reconstruction results

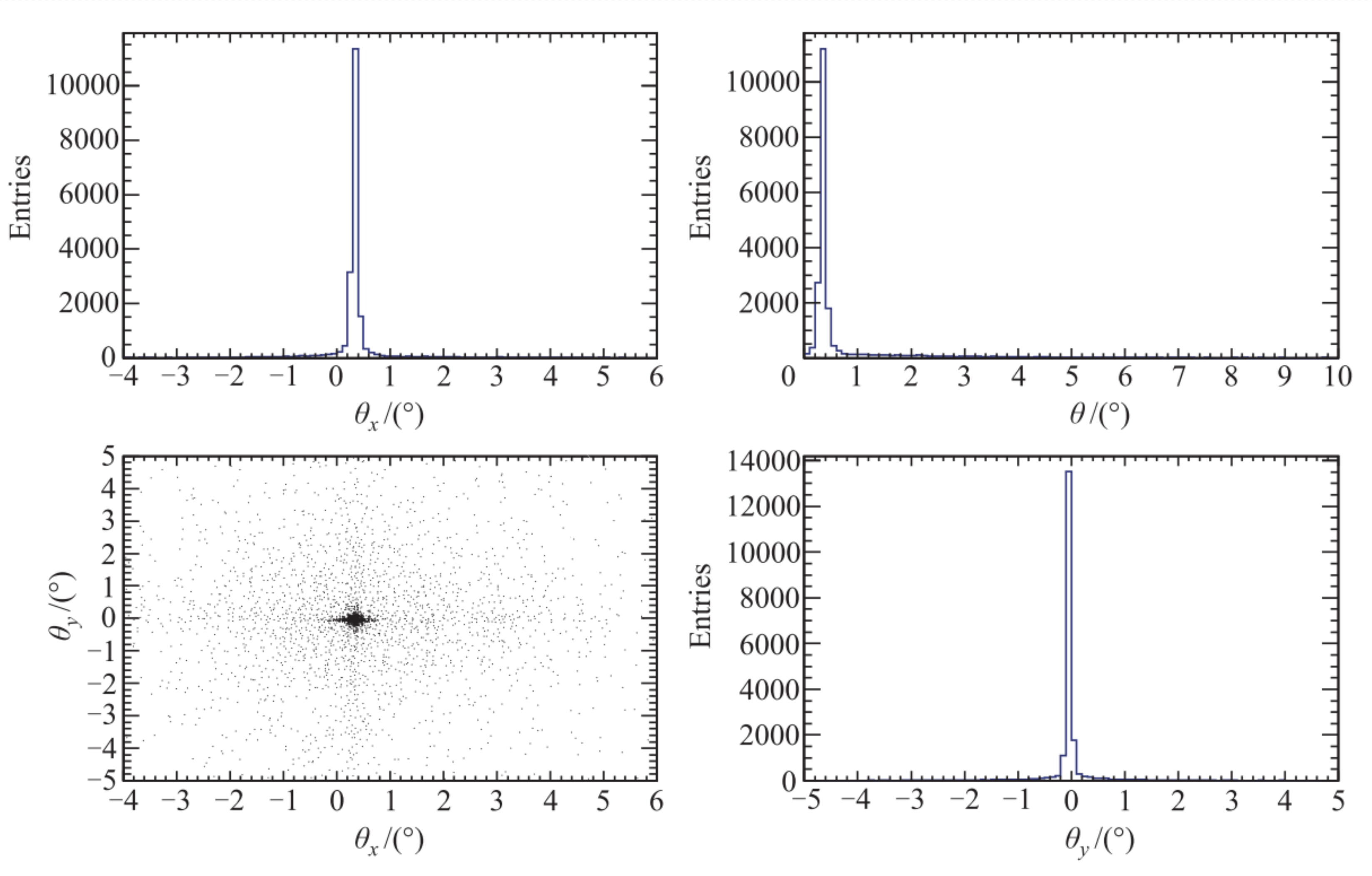




The trajectory of an electron with a momentum of 100GeV and an incident angle of 30° reconstructed by combining the BGO calorimeter and STK.

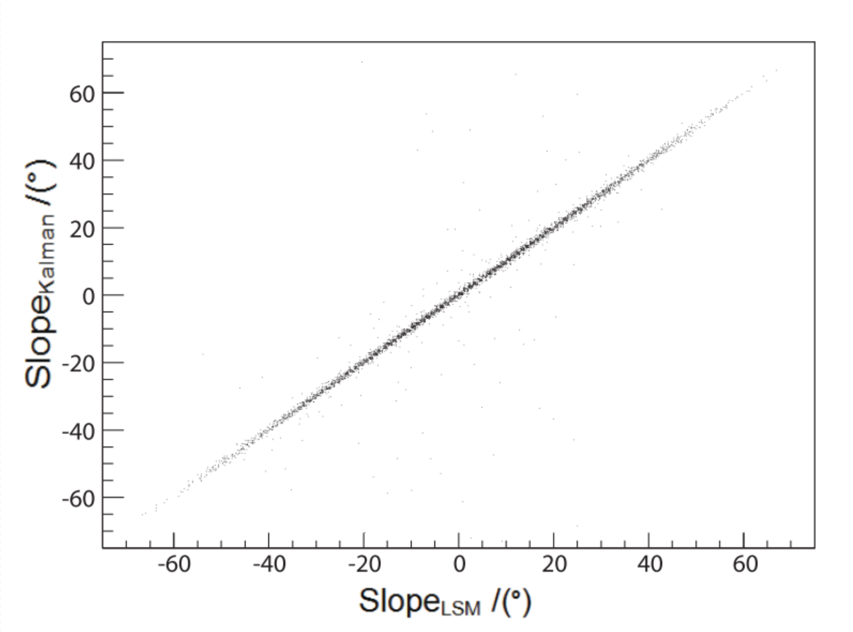
The trajectory of a proton with a momentum of 400GeV and an incident angle of 0° reconstructed by combining the BGO calorimeter and STK.

Track reconstruction results

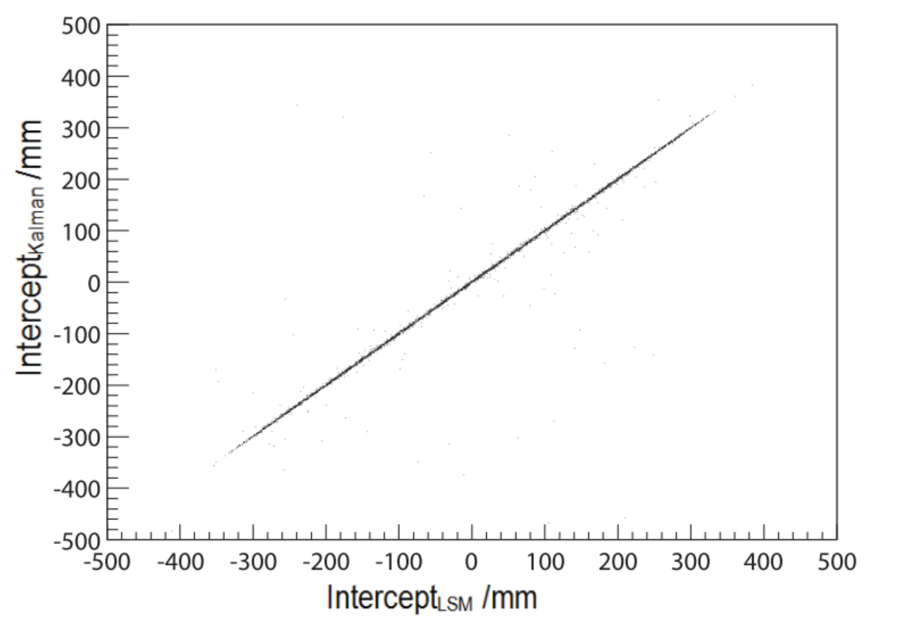


The distribution of track directions in the STK.

Track reconstruction results



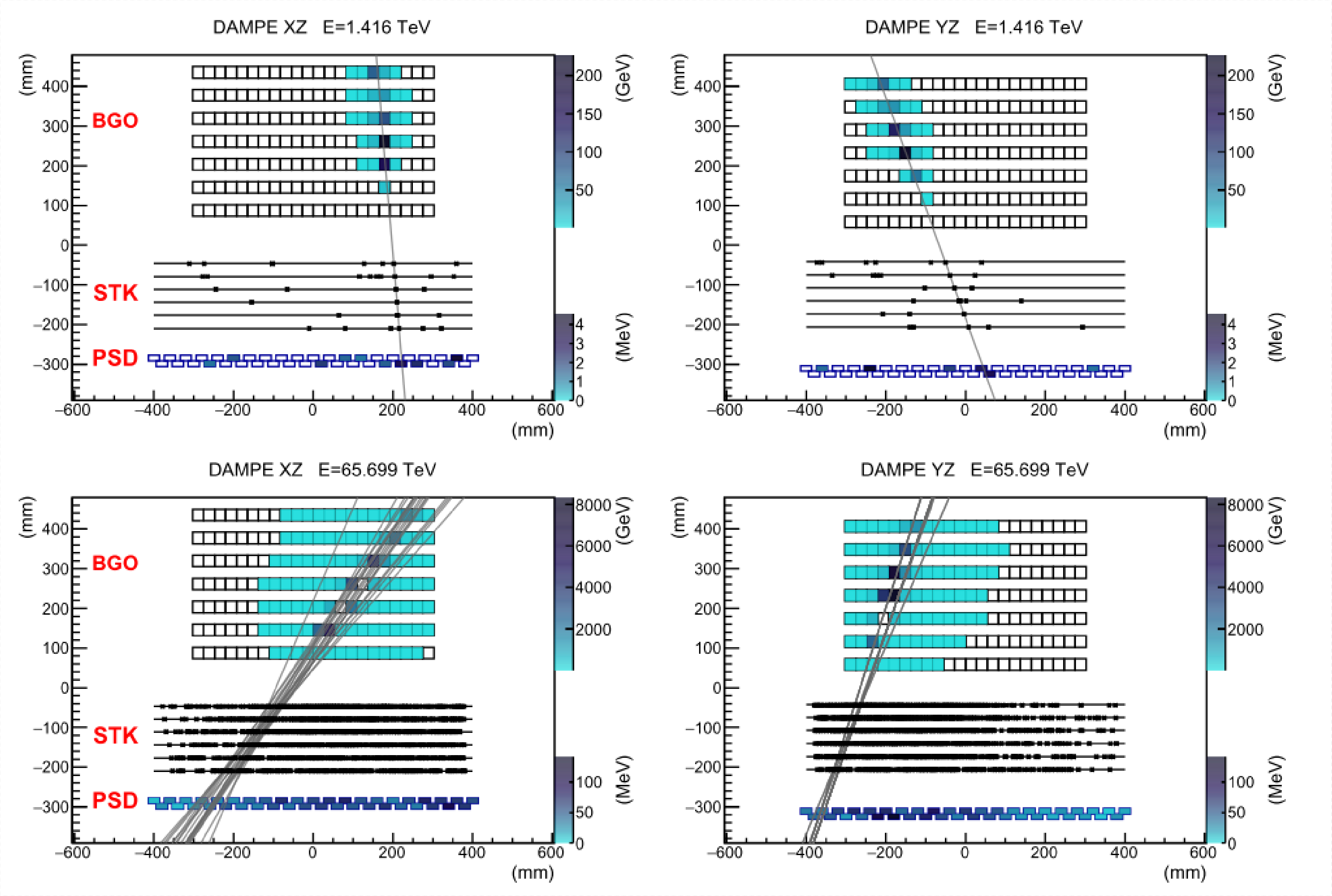
The scatter plot of the slopes (inclinations) fitted with two methods.



The scatter plot of the intercepts fitted with two methods.

Method \ Parameter	100 GeV electron		400 GeV proton	
	Slope	Intercept/mm	Slope	Intercept/mm
Least square method	0.01974	128.336	0.00034237	178.704
Kalman filter	0.01078	129.237	0.0010725	178.759

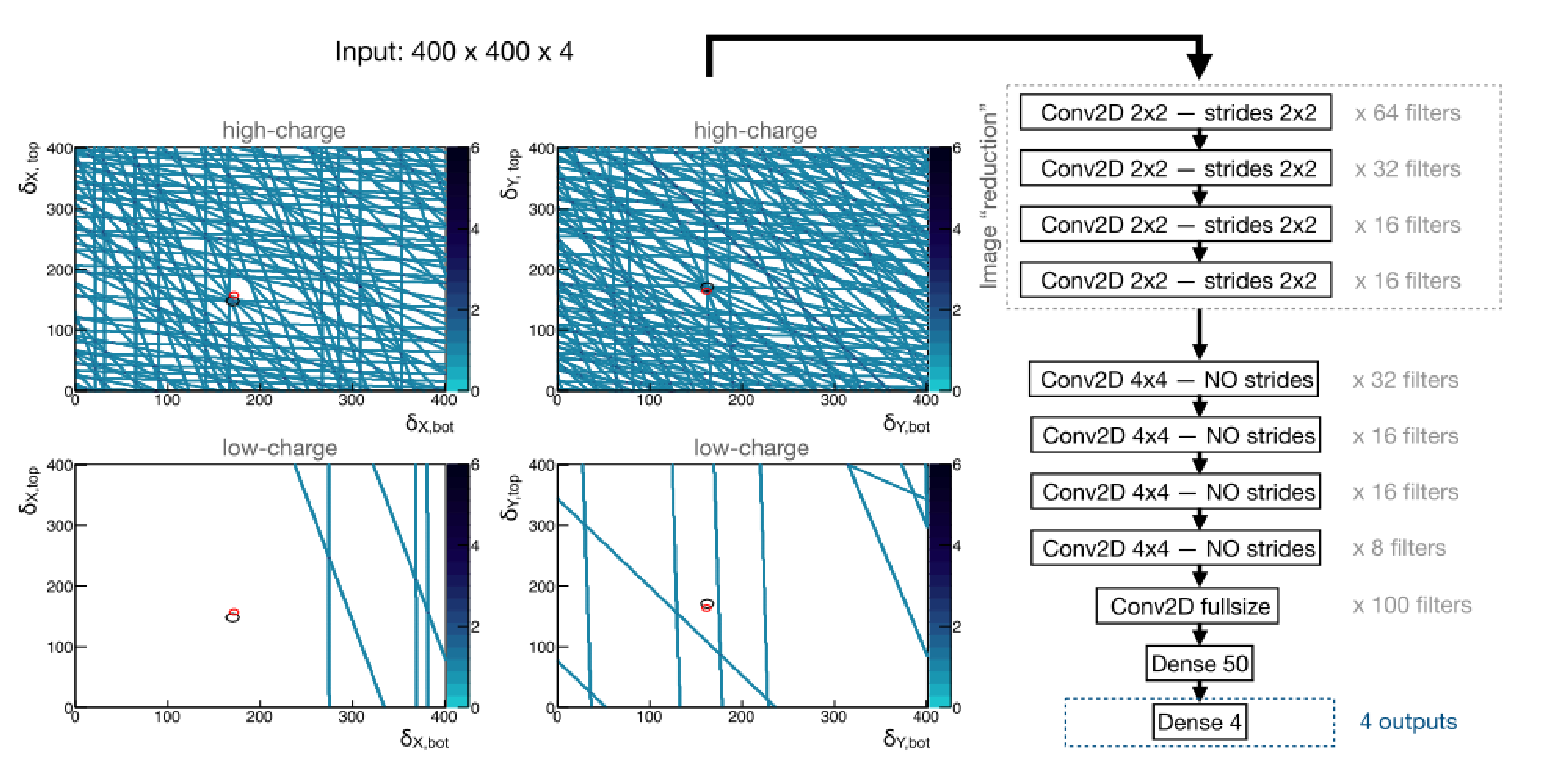
Problems in the high-energy range



In lower energy range, the number of reconstructed track candidates is relatively small.

In the higher energy range, because of pre-shower, there are many hits on the STK that cannot be removed. The number of candidates increases, and the accuracy and efficiency of track reconstruction decrease.

Deep learning method



Hough image of a typical Helium event and the architecture of the tracker CNN. Big (black) and small (red) circles represent the true and the reconstructed trajectory of a primary particle, respectively.

Values on the image axes correspond to the offsets in pixel units from the predicted calorimeter trajectory in the top and bottom layers of the tracker, respectively:

$$\delta_{x,top} \equiv (x_{top} - x_{top}^{BGO\ CNN})/50\mu m + 200$$

Results presentation

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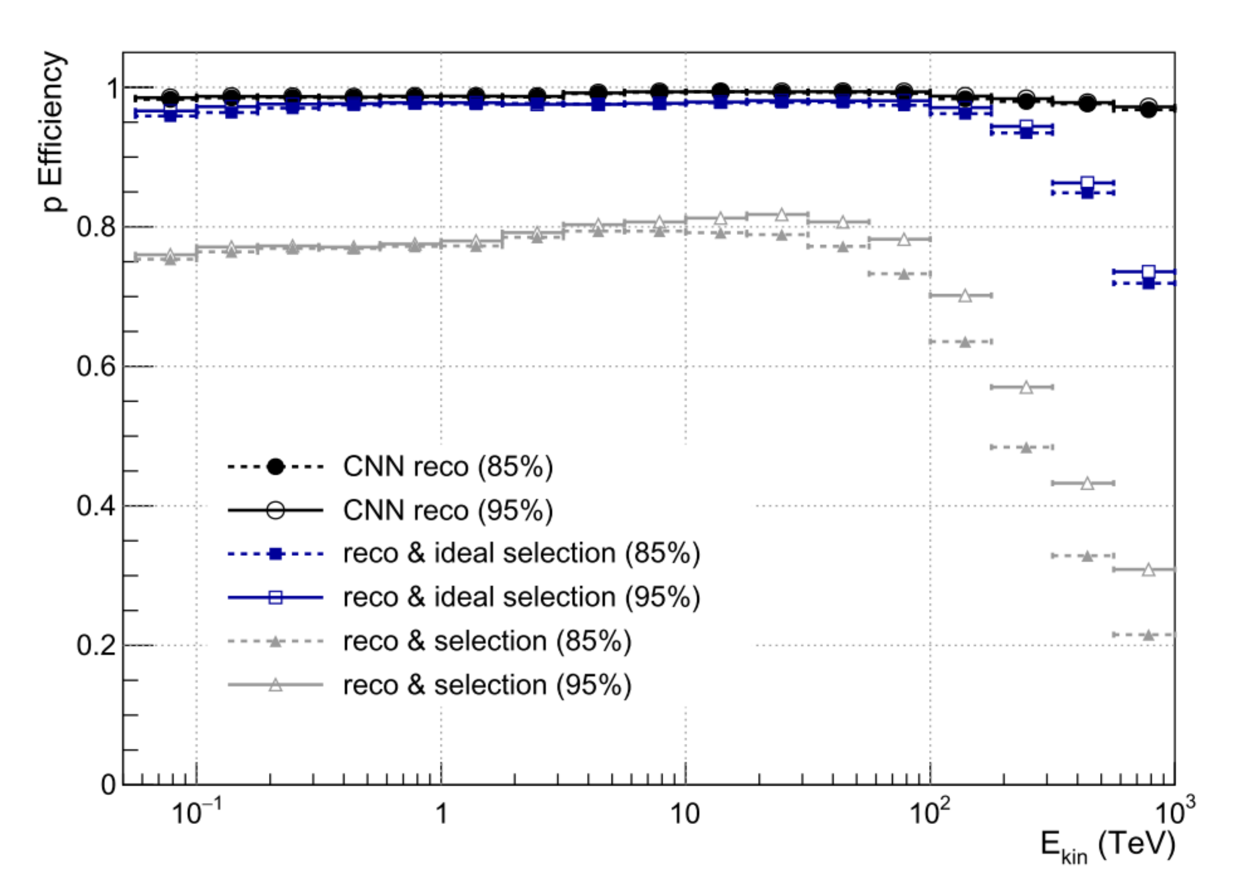

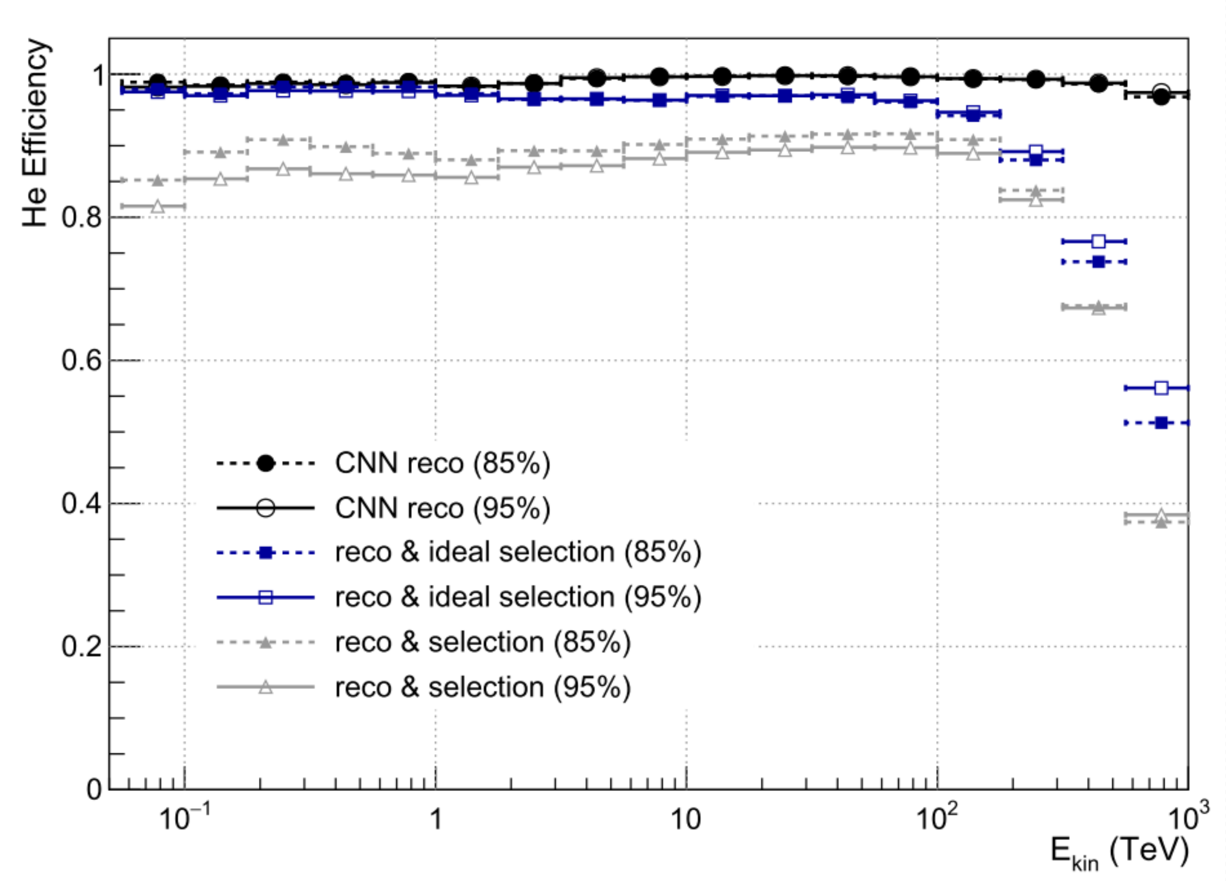

Efficiency of combined track reconstruction and identification derived from MC as a function of the particle kinetic energy: (circles) the developed CNN algorithm; (squares) standard track reconstruction with the ideal identification; (triangles) standard track reconstruction with the standard identification. Proton (top) and helium (bottom) cases are shown.

Summary and outlook

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Summary:

DAMPE track reconstruction proceeds in two stages: BGO track reconstruction and STK track reconstruction. The track reconstruction process in the BGO calorimeter uses the energy centroid method to provide initial constraints.

For the STK, two methods are available: the least squares method and the Kalman filtering method, with the latter being relatively more reliable in the low-energy region.

Building upon traditional methods, the introduction of machine learning significantly improves the accuracy and efficiency of track reconstruction above the PeV energy range.

Outlook:

The track reconstruction and machine learning explorations in DAMPE can be applied to the HERD experiment in the future.

For heavier nuclides, current track reconstruction methods still have shortcomings and require further exploration.

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Thank you for listening!