4D-Based dN/dx Reconstruction in TPC

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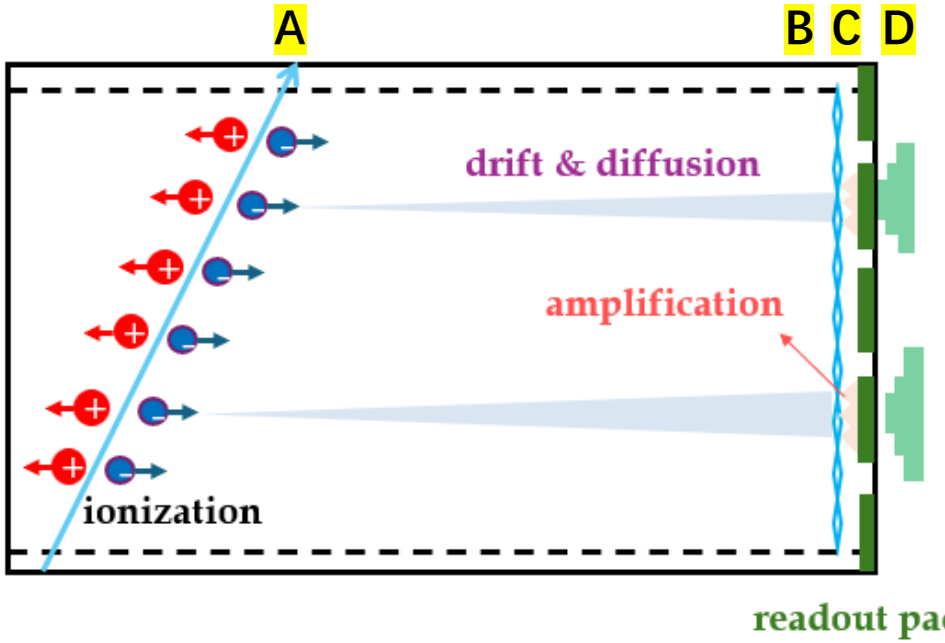
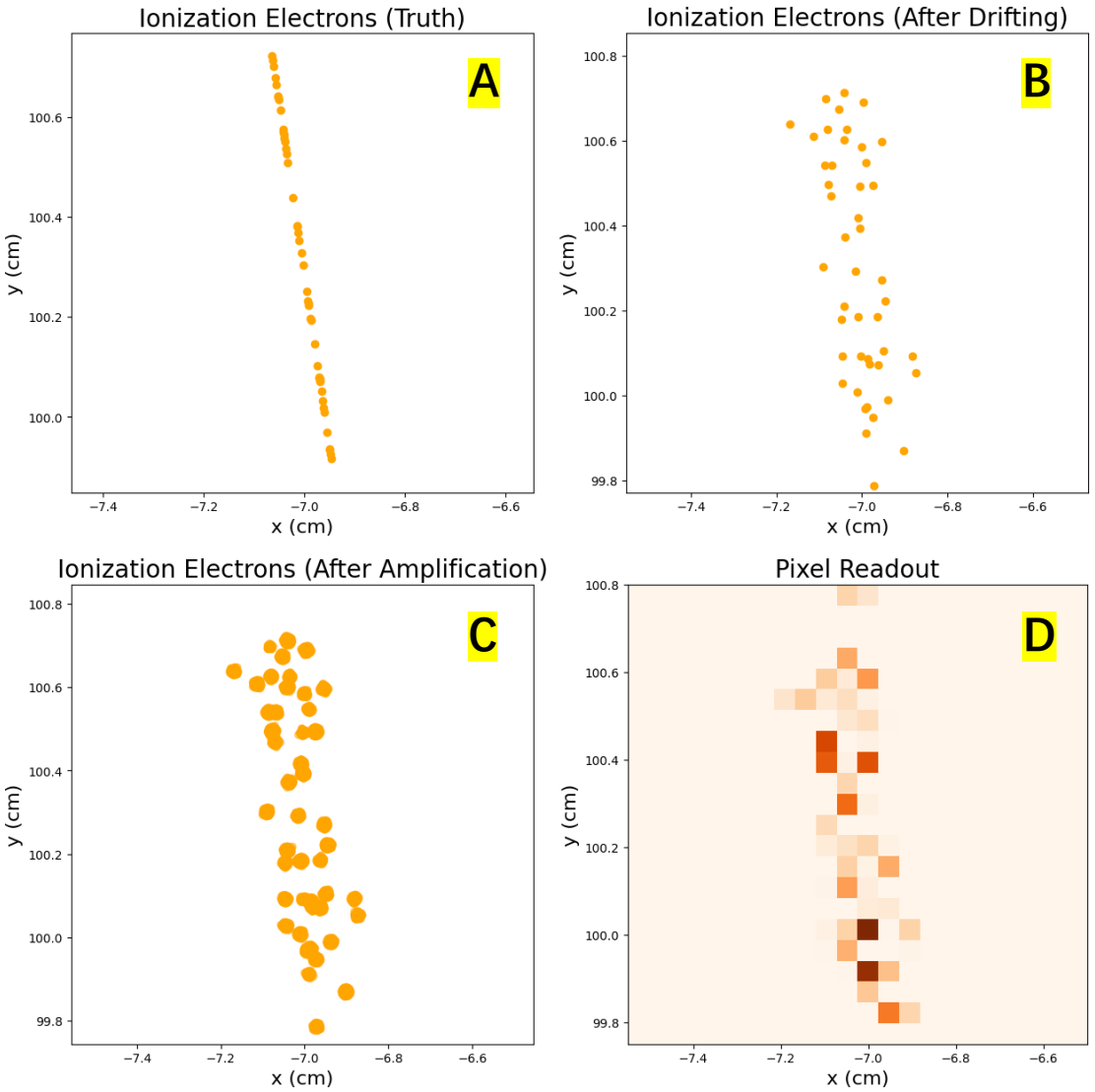
TPC readout



Garfield++-Based Simulation / Digitization Framework

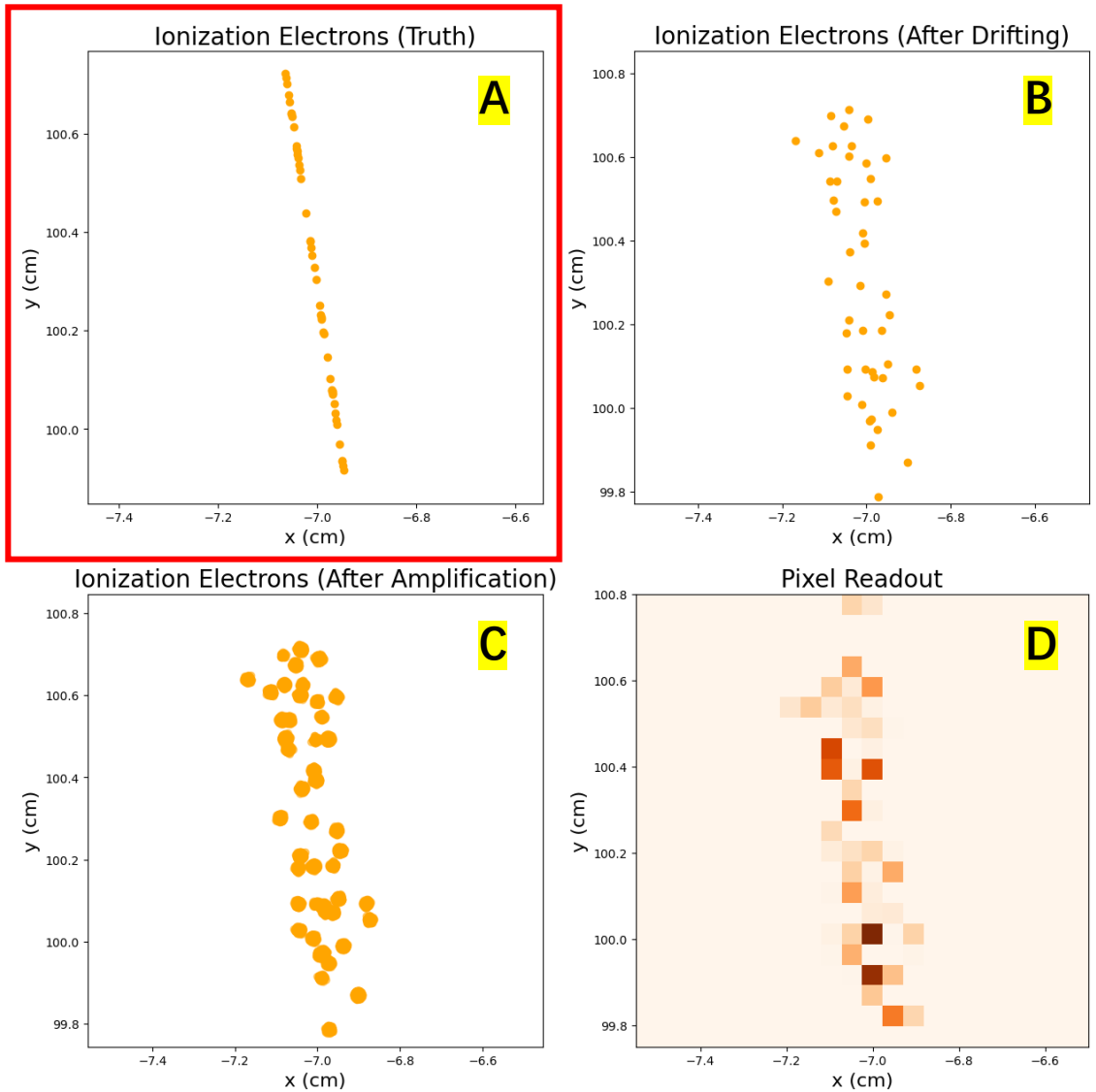
Ionization → Transport → Amplification → Signal Generation



TPC readout

Remarks:

- The ionizations are defined by the gas mixture
- **The current gas mixture is T2K: $Ar/CF_4/iC_4H_{10}$ (95/3/2)**



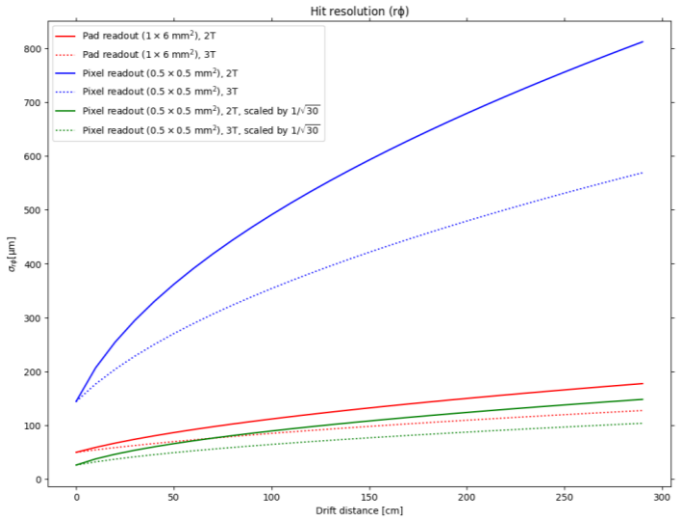
TPC readout

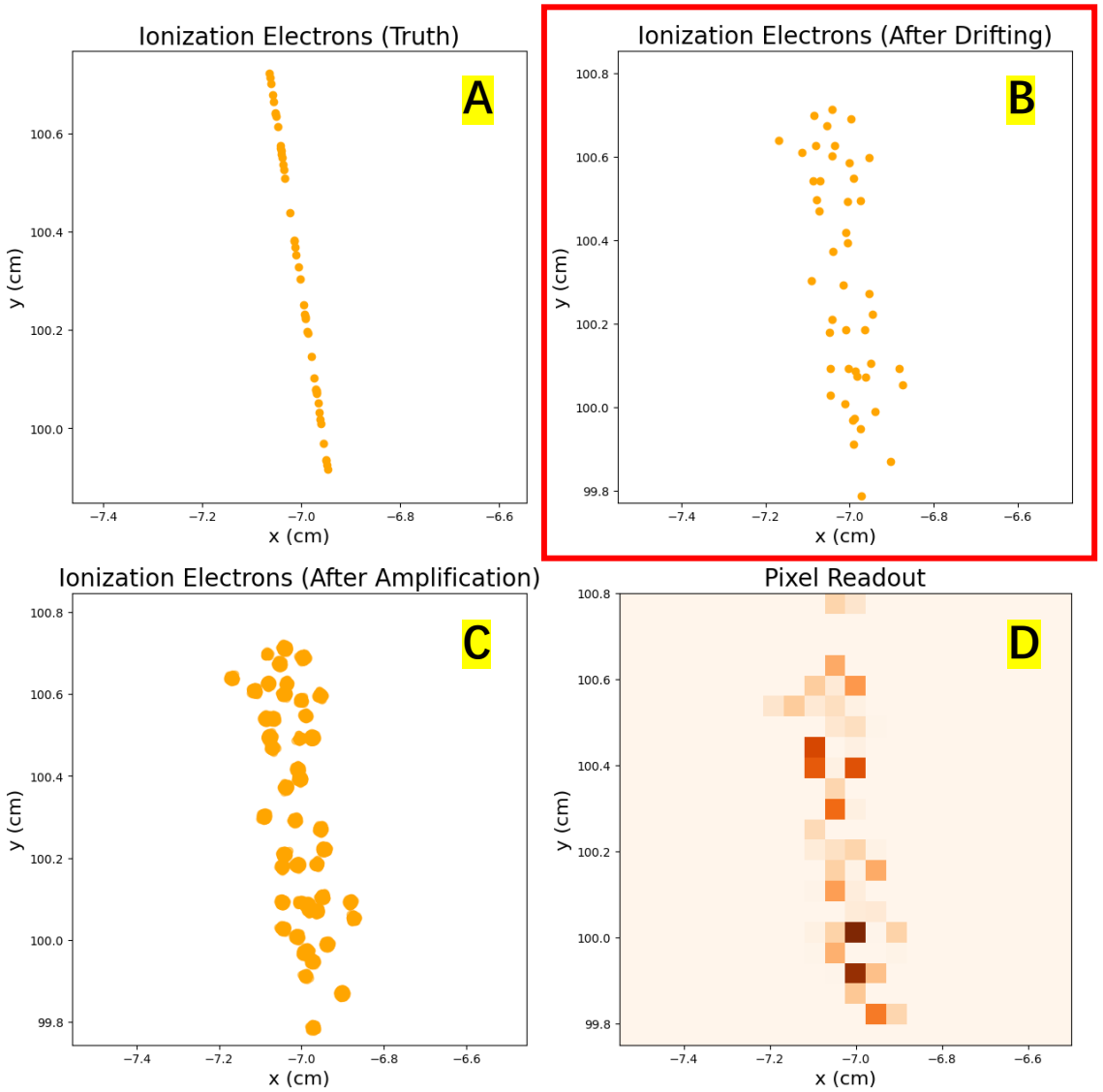
Remarks:

- From A to B, the electron positions are fluctuated by diffusion
- **For 2T field, the fluctuation can up to 800 um**

$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\text{pixel}})^2 + LD_{r\phi}^2 \left(\frac{4.0\ \text{T}}{B}\right)^2}$$

- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144\mu\text{m}$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}),\ 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

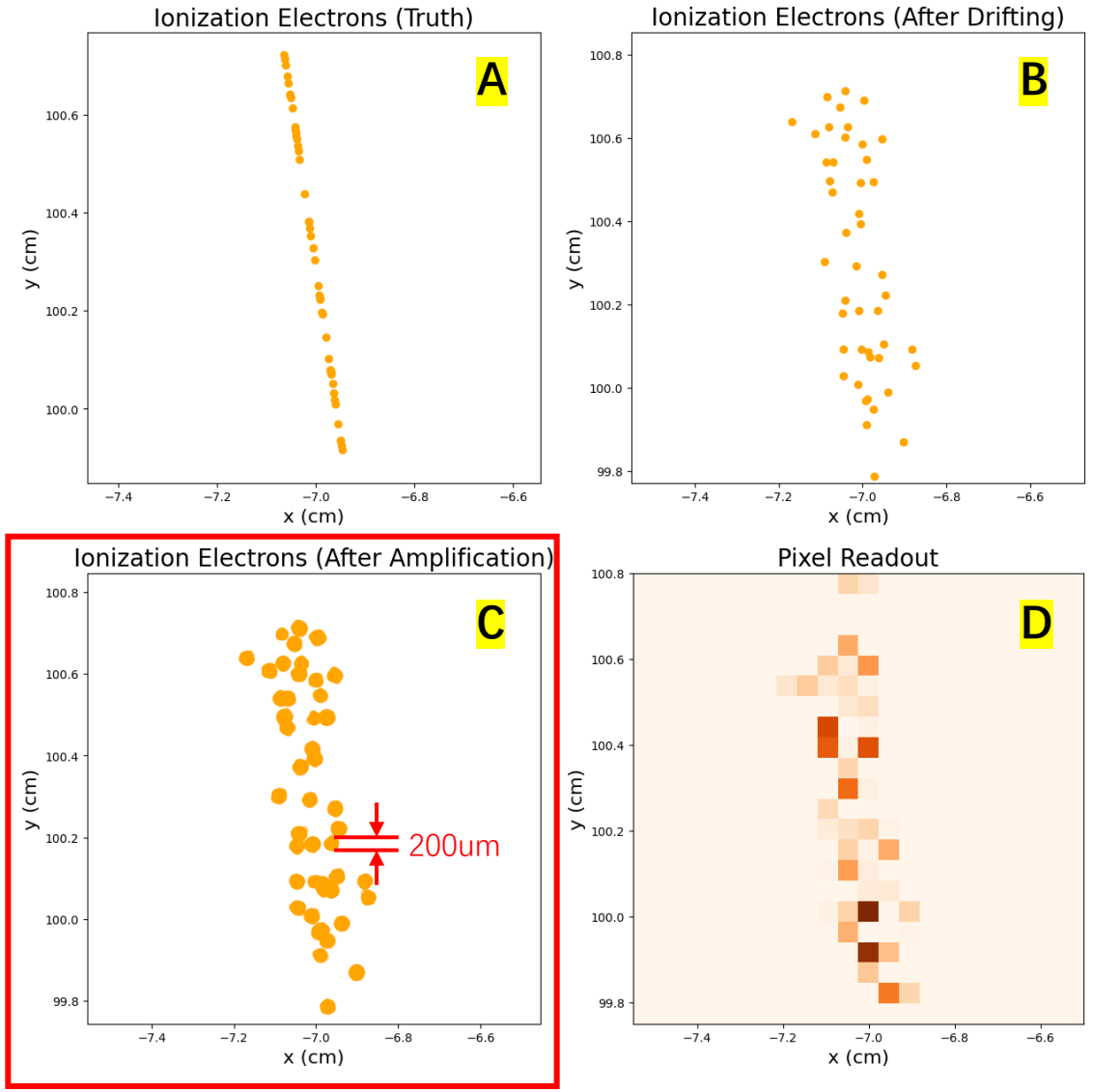




TPC readout

Remarks:

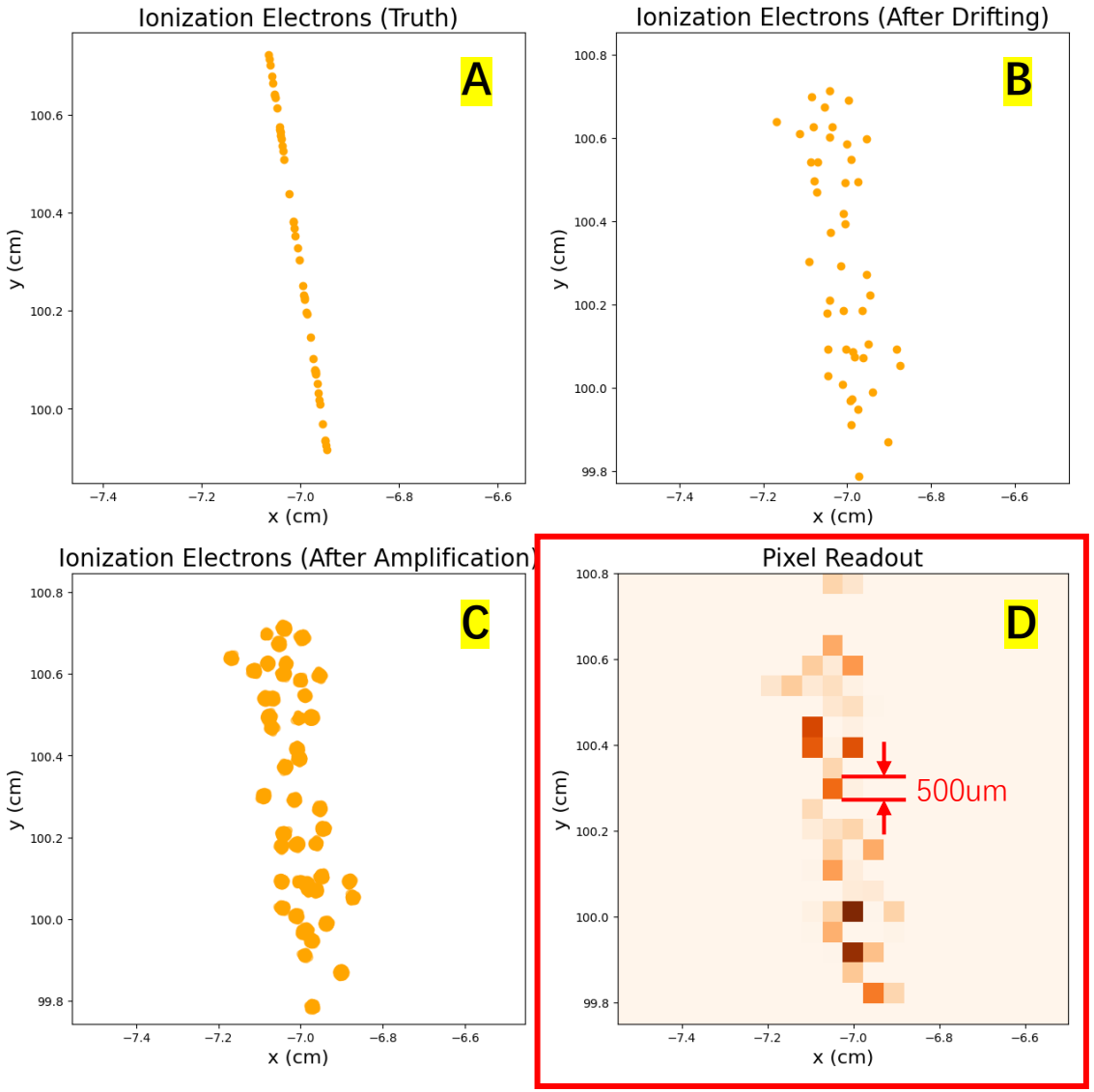
- From B to C, the single electron is amplified, which end up with a **200um spread in space**



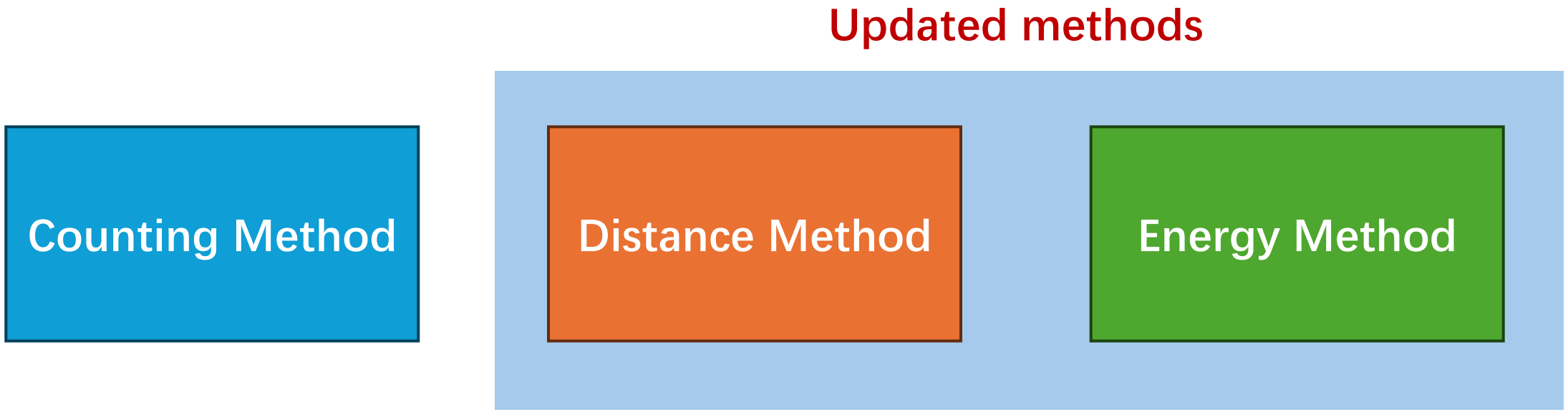
TPC readout

Remarks:

- From C to D, the detector granularity defines the readout pattern
- The current **pixel size is 500x500 um^2**
- **Electronics noise is 100 e$^-$**

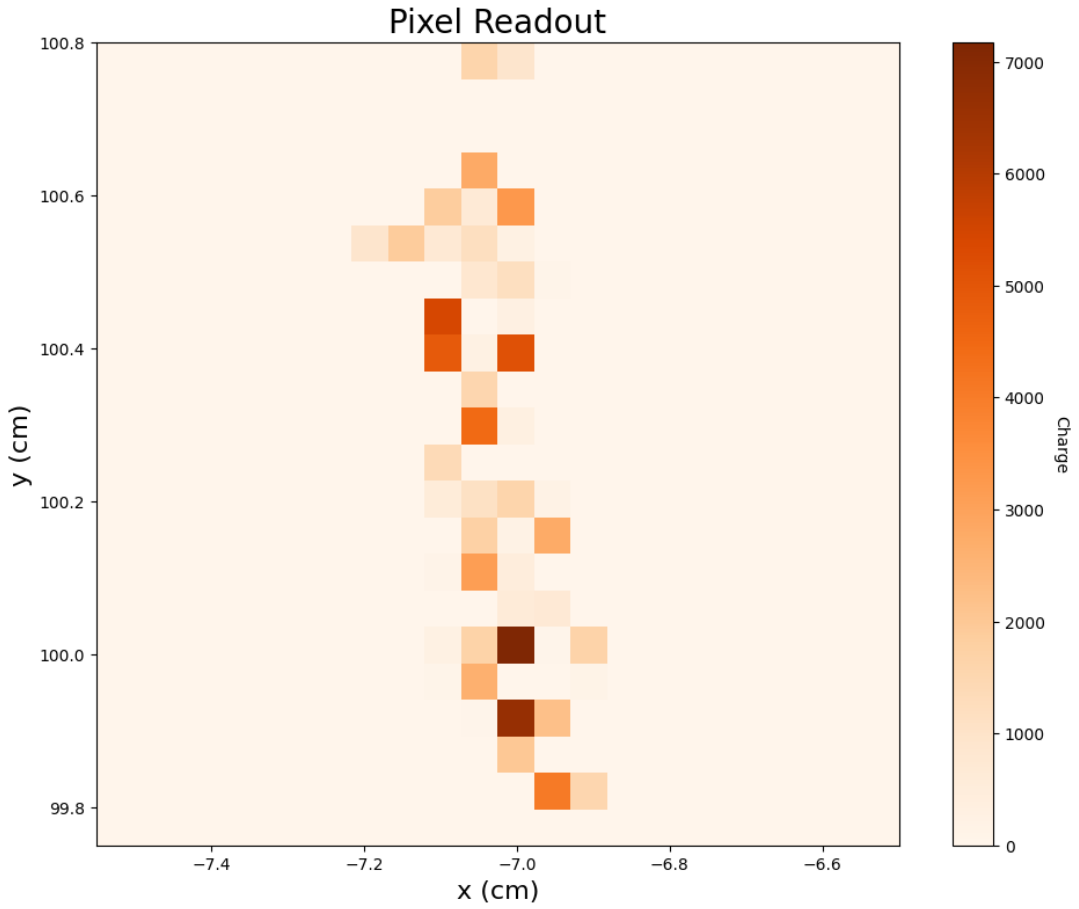


Three ionization measurement methods



- Previously we use the **counting method** for the dN/dx reconstruction
- Two more methods (**distance method** and **energy method**) are being investigated

Counting method



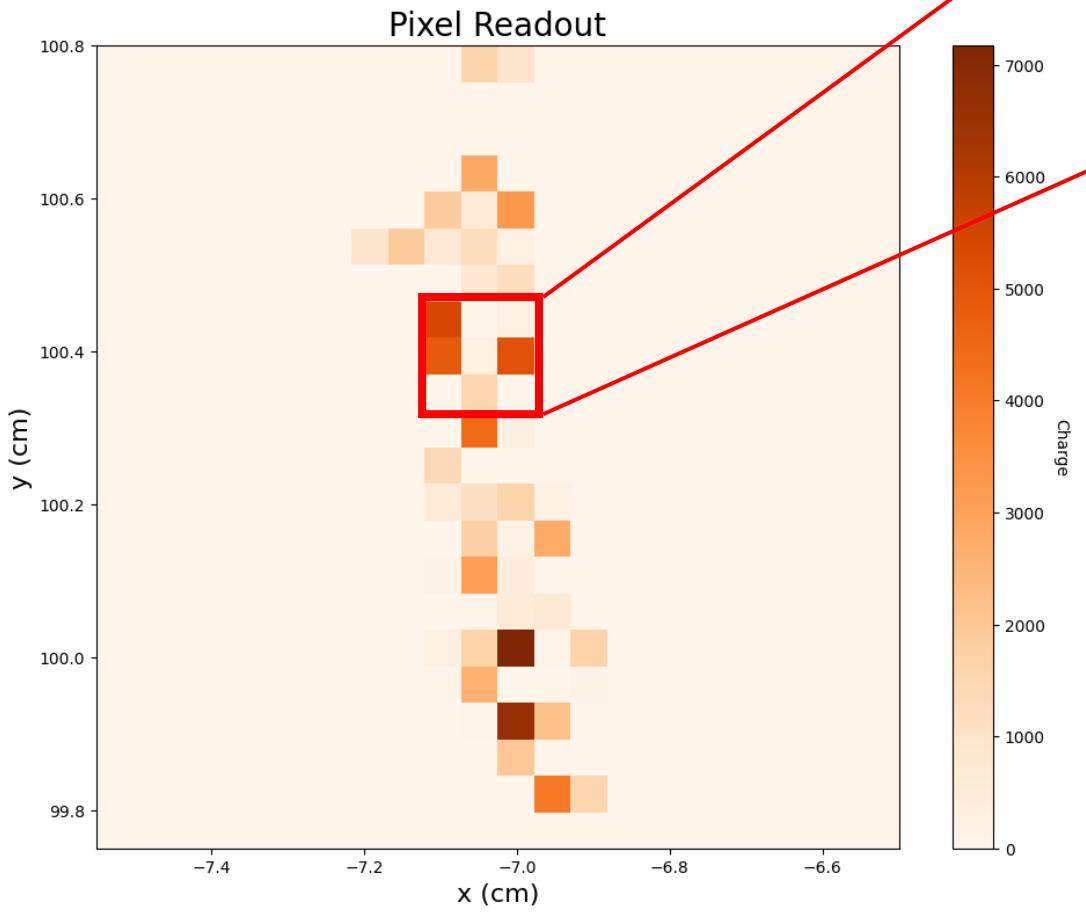
Intuition:

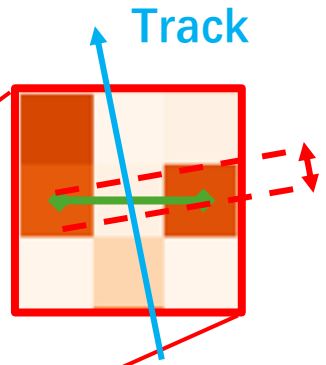
- Ionization is proportional to the number of fired pixels

Algorithm:

- Count the number of hits whose energies are above a threshold

Distance method





d: Projected distance w.r.t. to the track direction

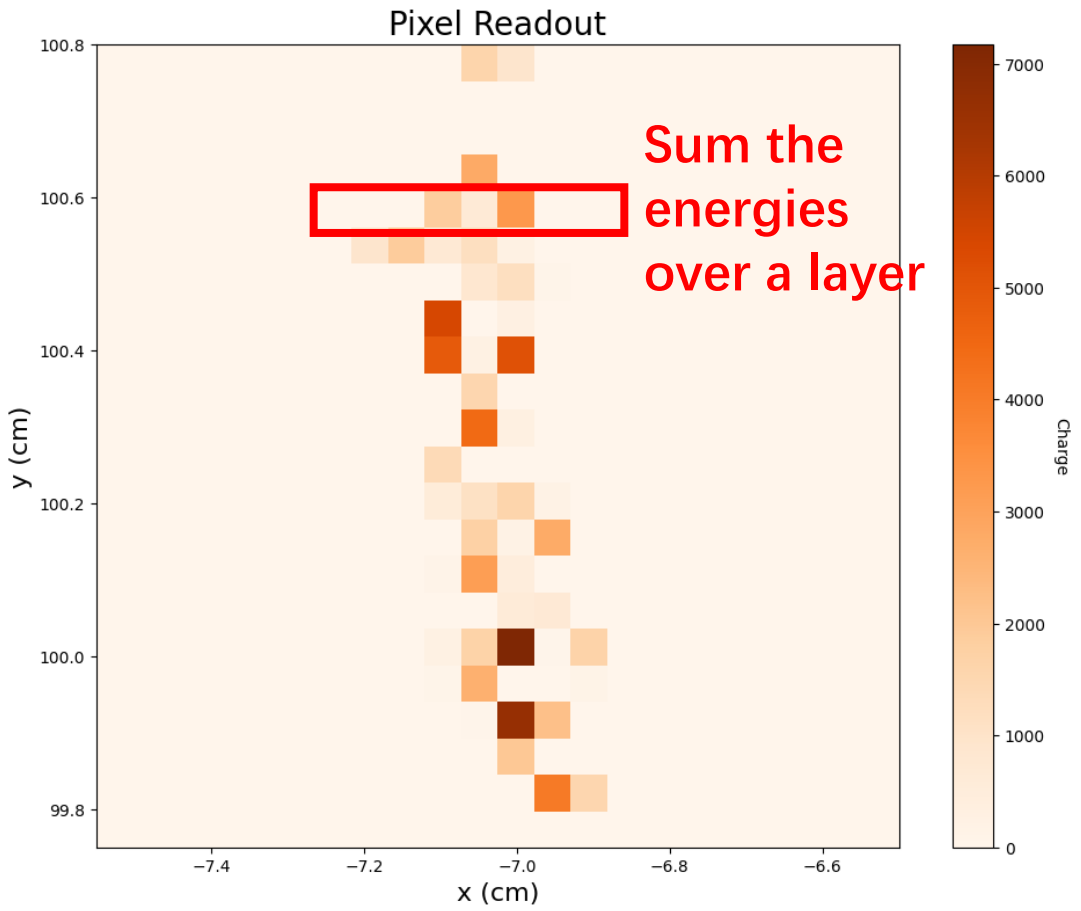
Intuition:

- Ionization is inverse proportional to the average distance between hits

Algorithm:

- Sort the hits along the track direction
- Calculate the projected distances w.r.t. the track direction between adjacent hits
- Average the distances and take the reciprocal

Energy method



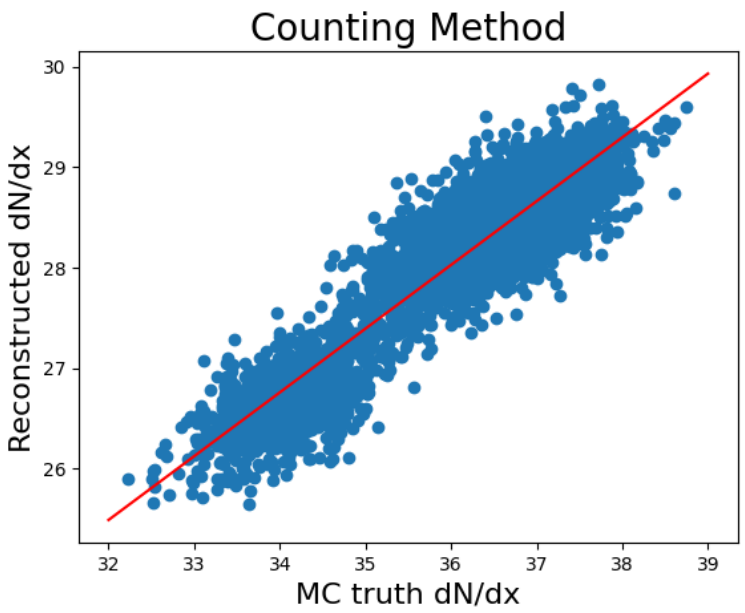
Intuition:

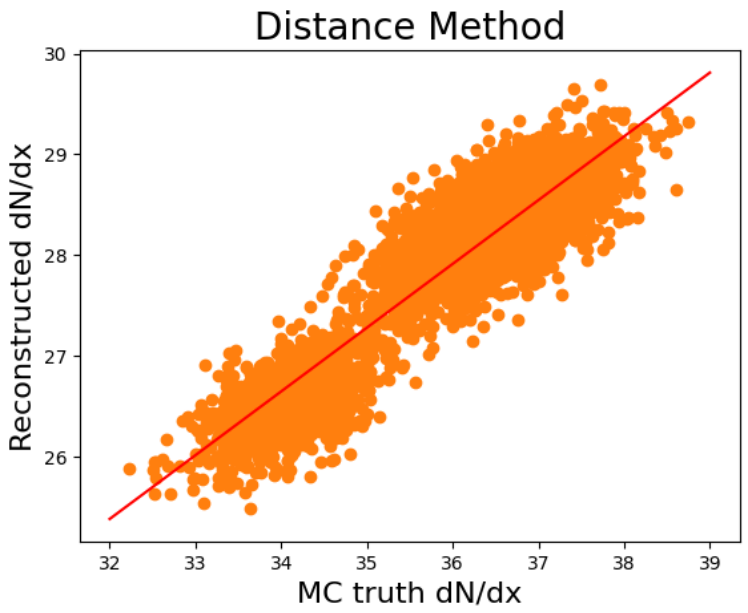
- Ionization is proportional to the energy deposition

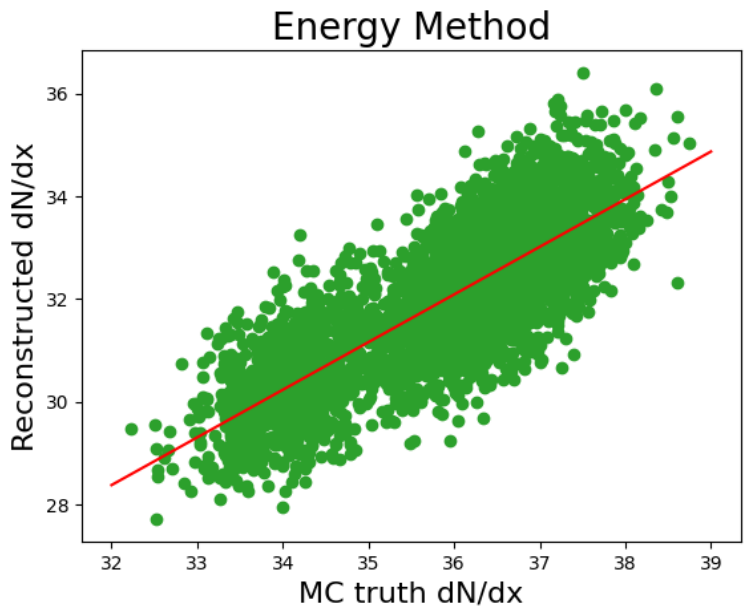
Algorithm:

- Combine hits into layers (row-wise or column wise)
- Calculate the sum of the energy deposition within each layer
- Discard the top 30% of hits with the highest energy and take average

Reconstructed variables vs. MC truth





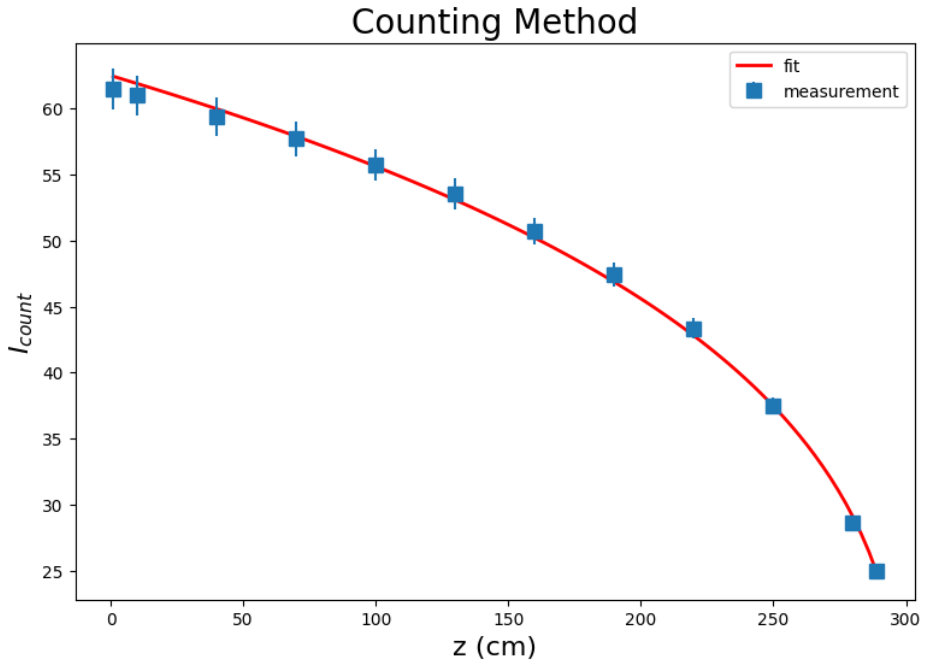


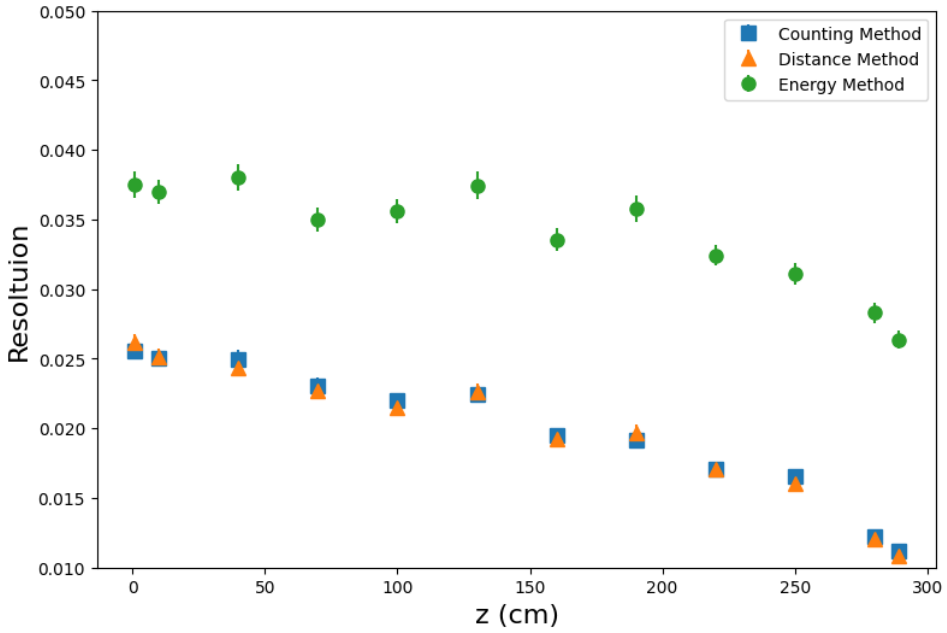
Drift distance = 10 cm

The reconstructed variables have **good linearities** w.r.t. the MC truth, which means they can be used for reconstruction

Measurements are z-dependent

TPC is a large detector. Drift distances can reach up to 2.9 m, the diffusion can not only make the measurement **z-dependent**, but also make the **resolution worse**.

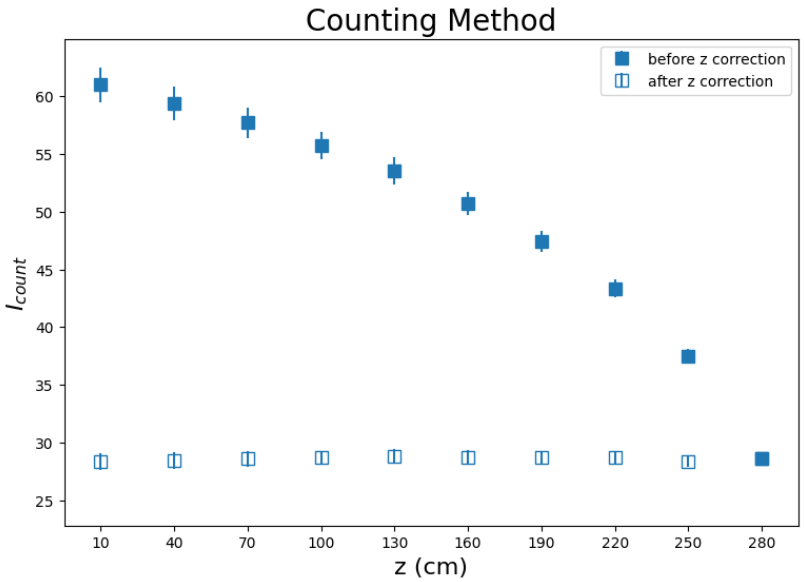


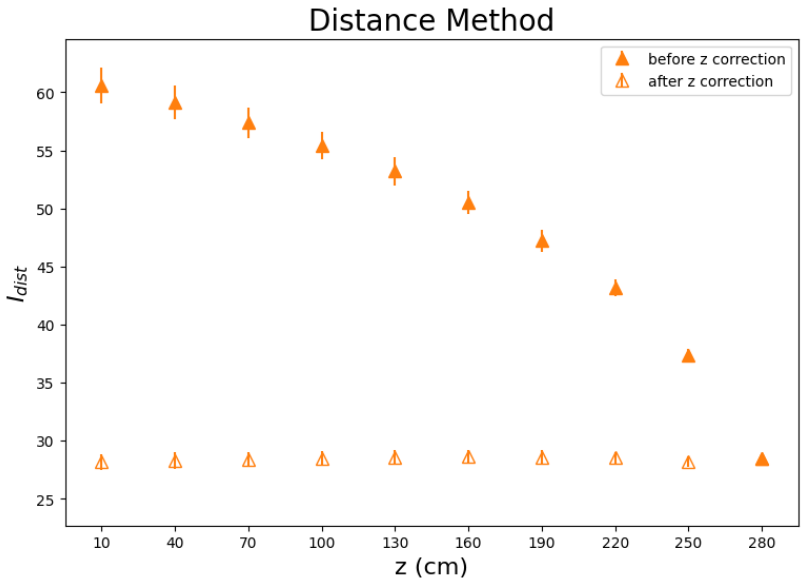


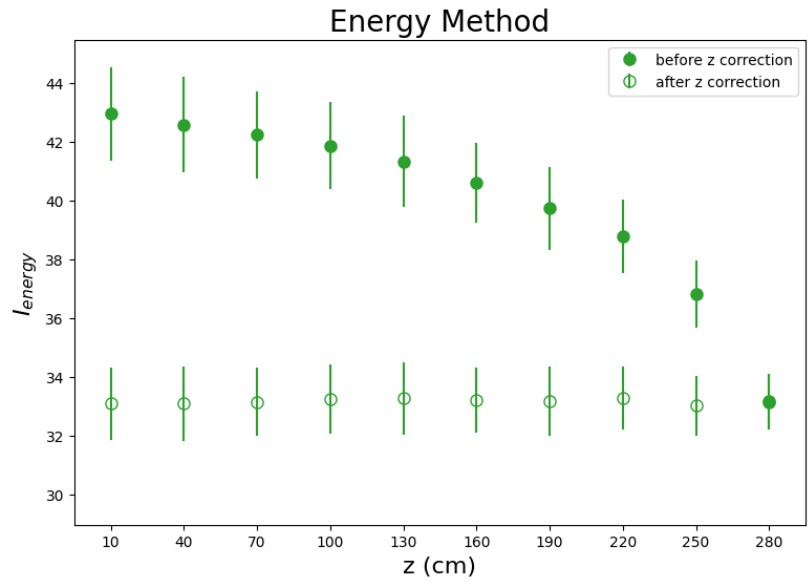
Drift distance correction

Correction function:

$$f(z) = p_0(1 + p_1 z)^{p_2}$$

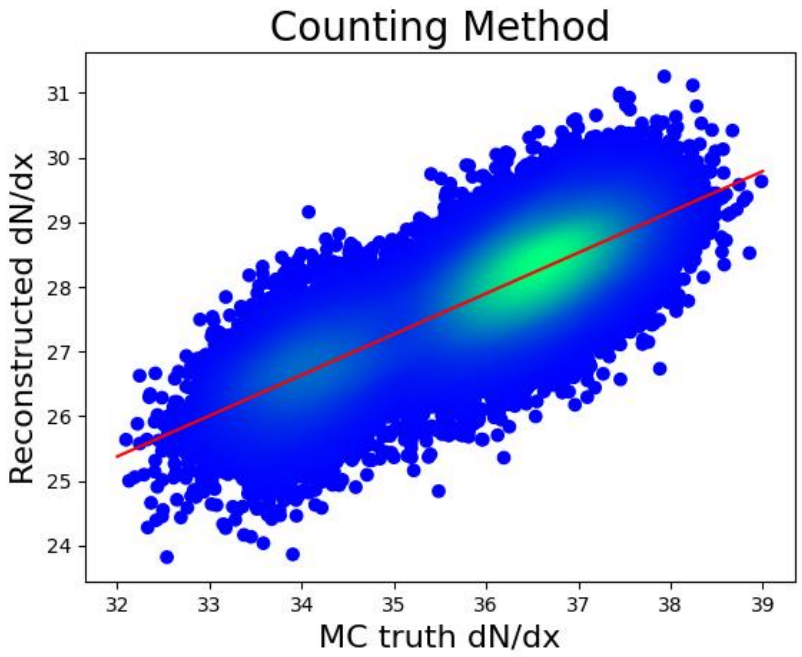


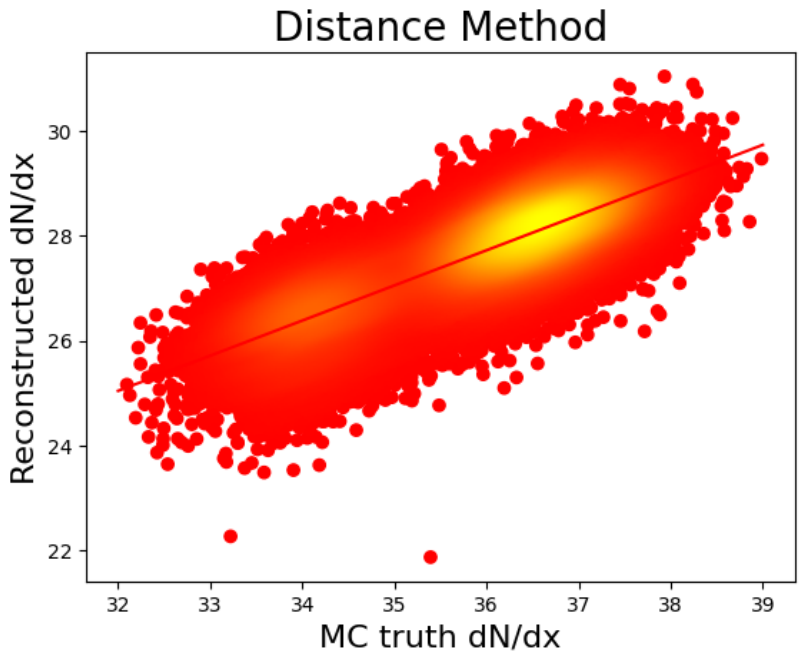


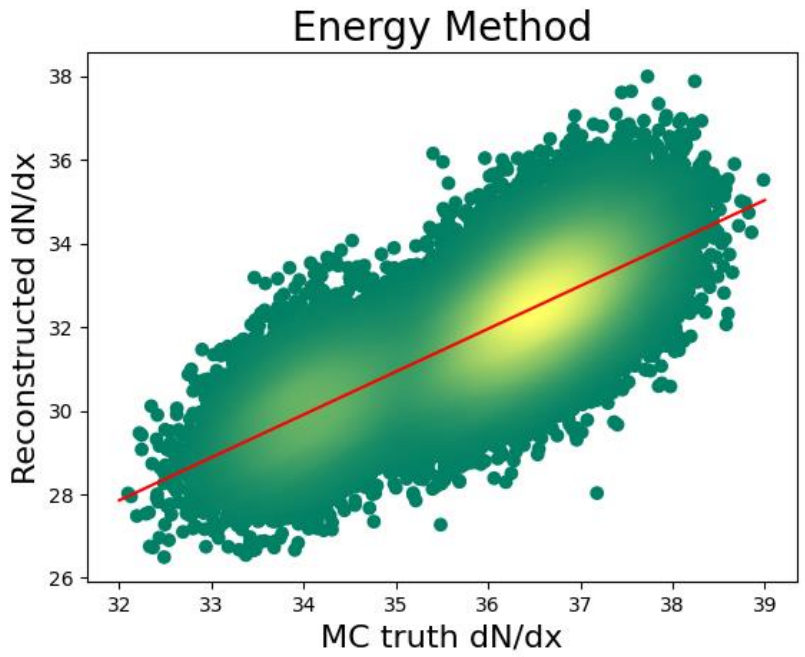


After the z correction, the z-dependent vanish

Calibration to cluster density dN/dx





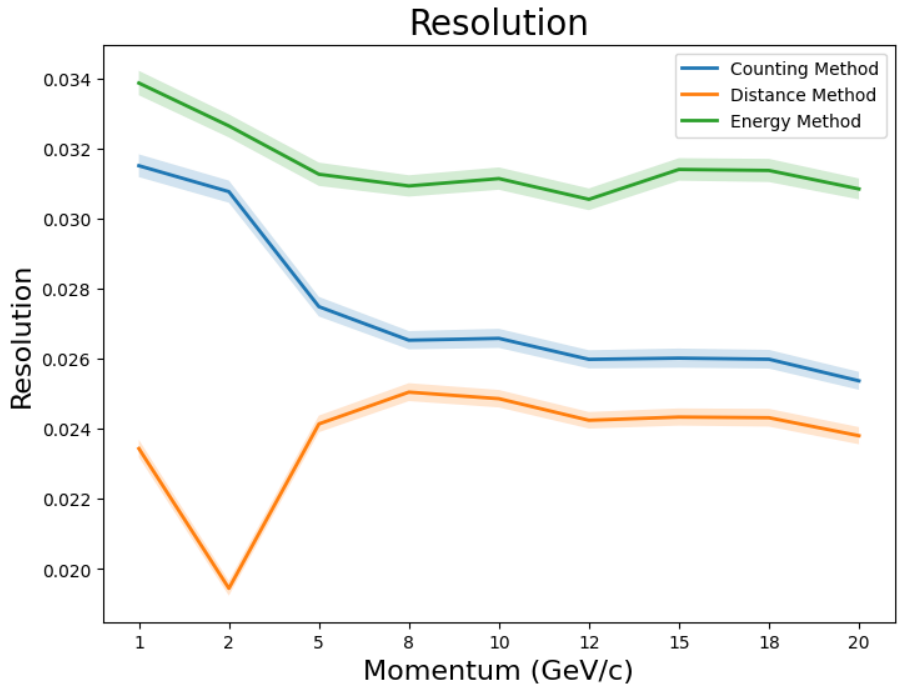


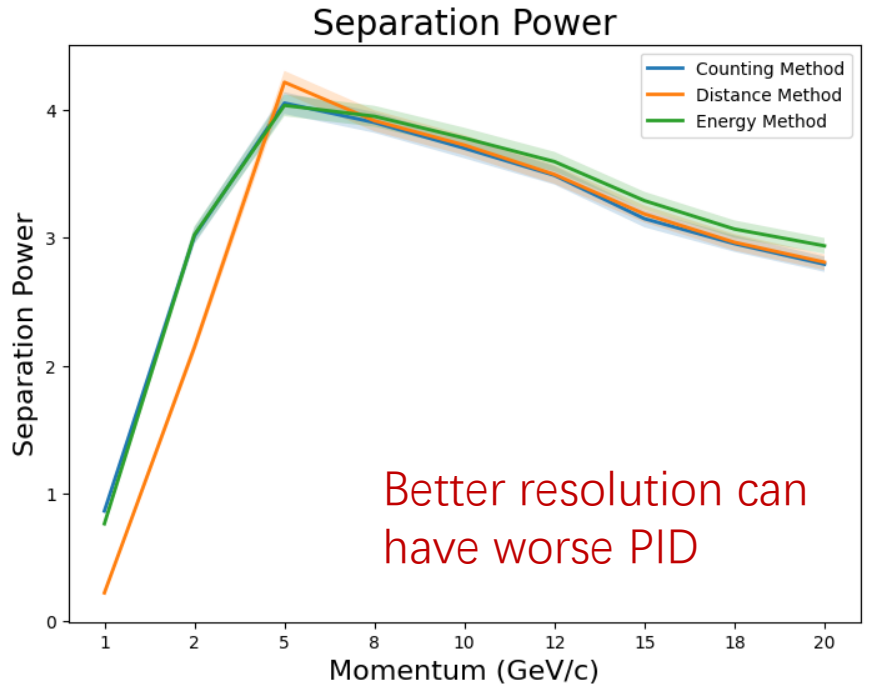
Drift distance: 10~280 cm

Use linear functions to convert the three measurements back to the cluster density: dN/dx

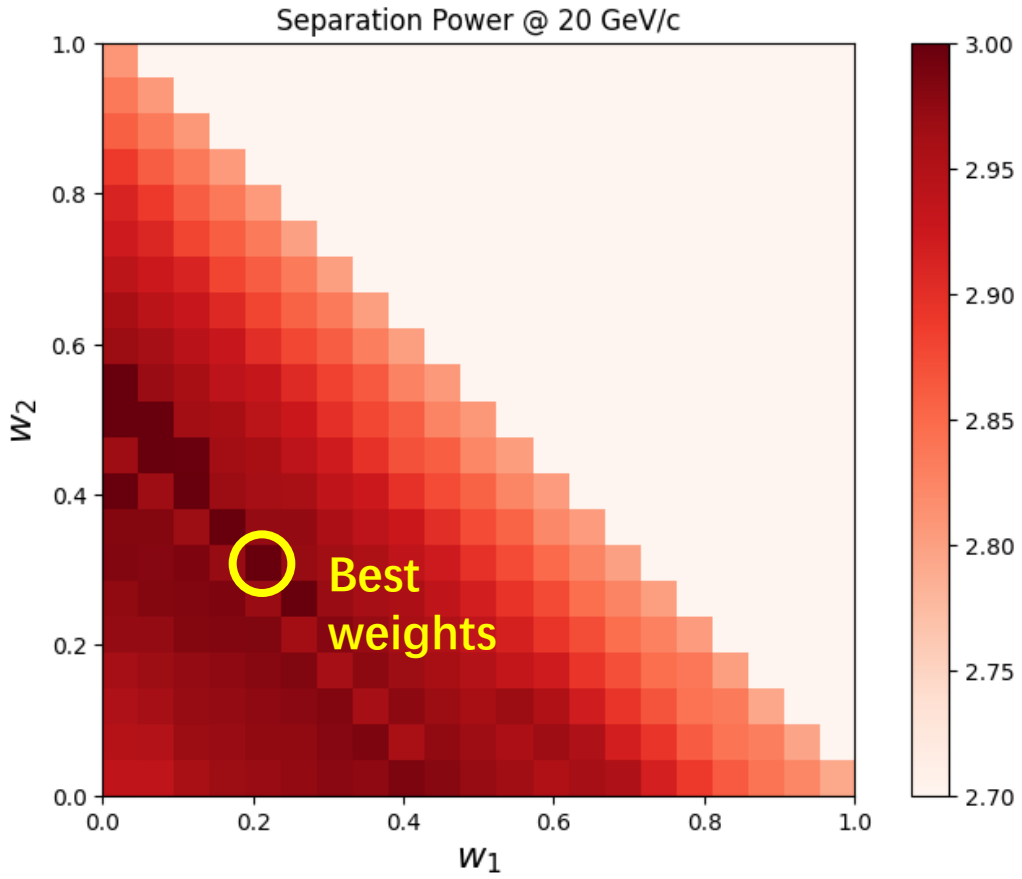
PID evaluation: Particle separation power

- **Important for physics**
  - separation power $= \frac{separation}{resolution} = \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$
  - resolution is NOT important!





Combining the three methods



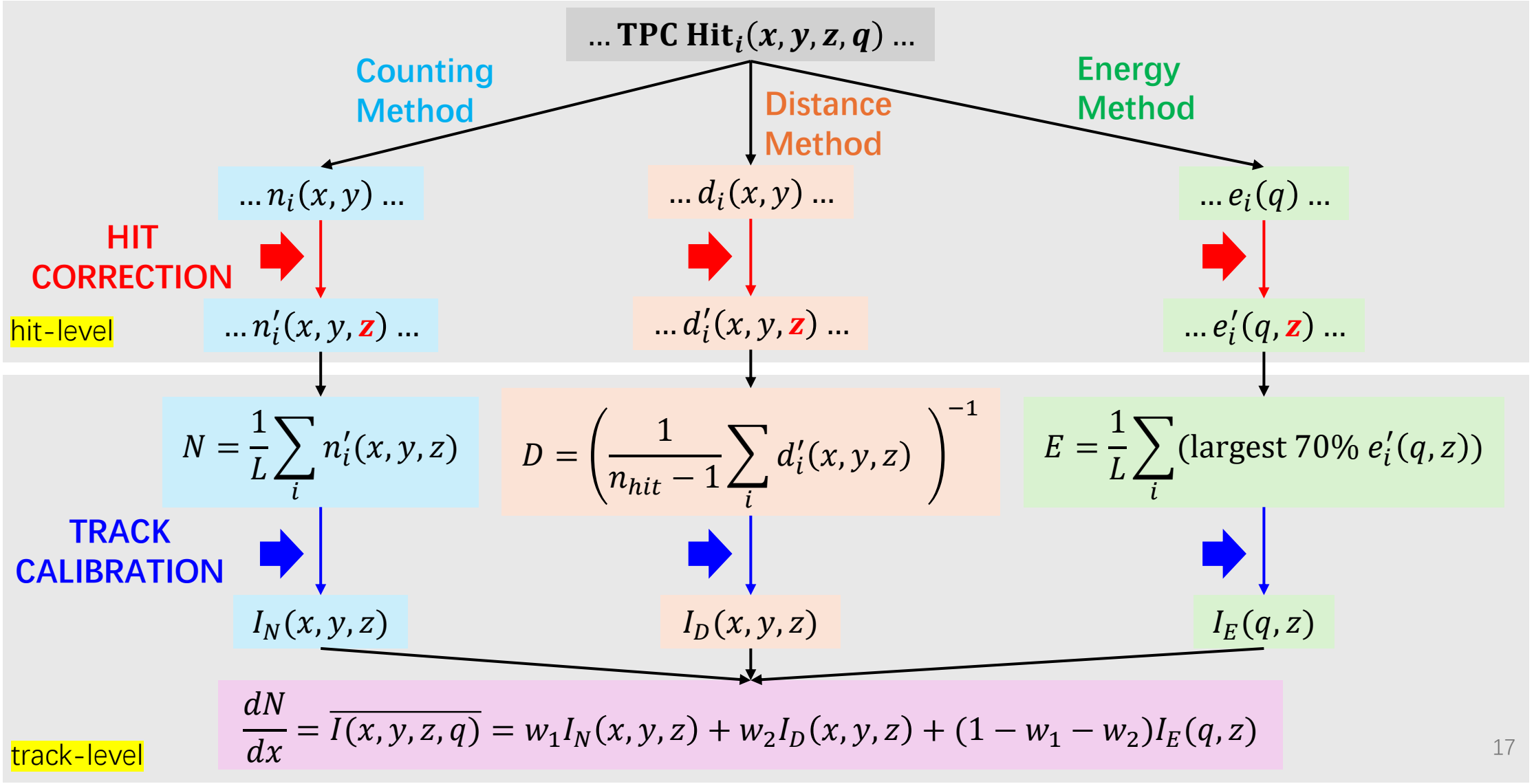
Formula:

- $\frac{dN}{dx} = w_1 I_N + w_2 I_D + (1 - w_1 - w_2) I_E$

Weight optimization:

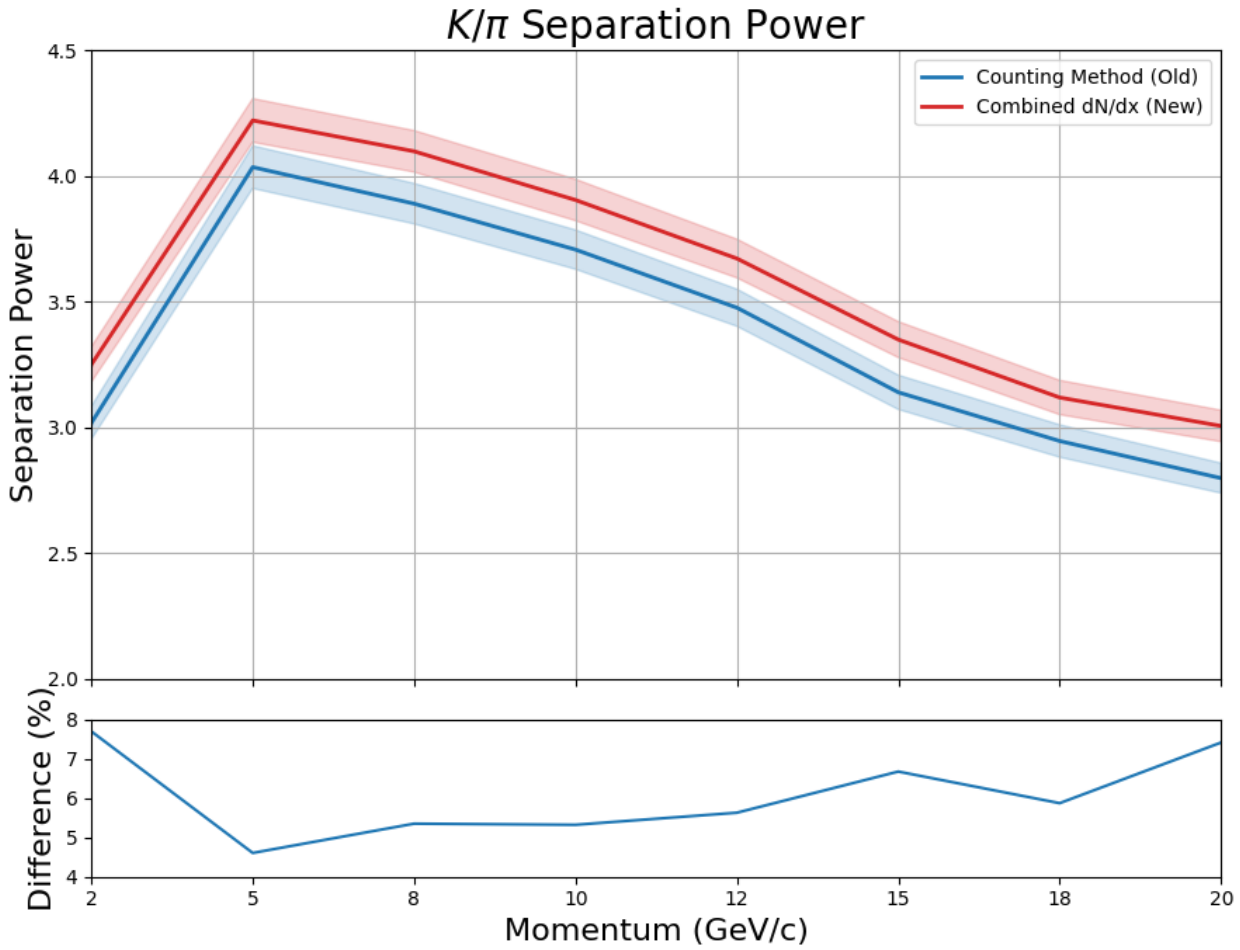
- Figure of merit: K/π separation power @ 20 GeV/c
- Optimized values:
  - $w_1 = 0.2$
  - $w_2 = 0.3$

4D reconstruction flow



$\theta = 60°$, track length ~ 1.4 m

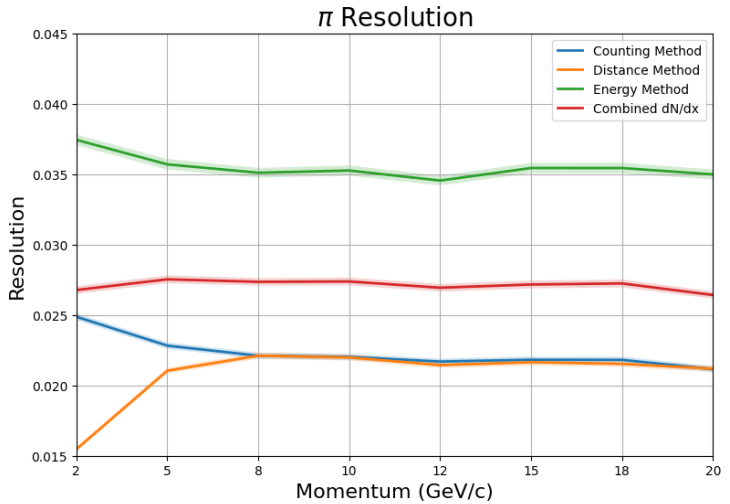
PID performances

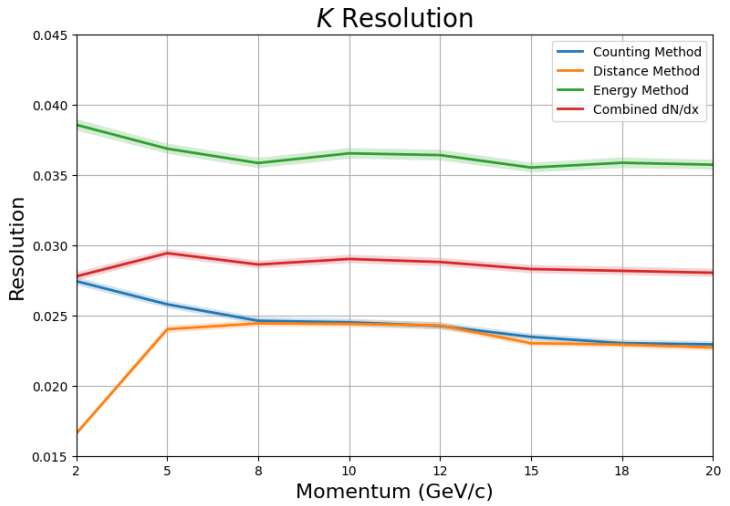


- The new reconstruction algorithm has >5% improvement to the old counting method
- This improvement is NONTRIVIAL. The new algorithm saves a 10% detector radius to reach the same performance

$\theta = 60°$, track length ~ 1.4 m

PID performances (II)

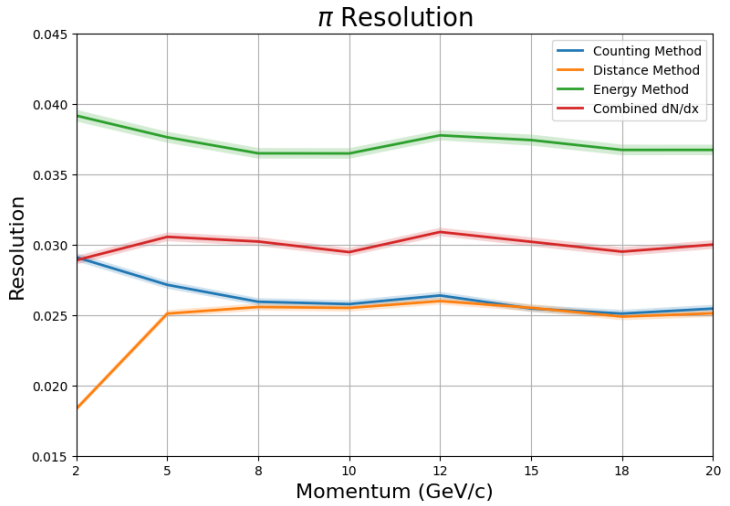


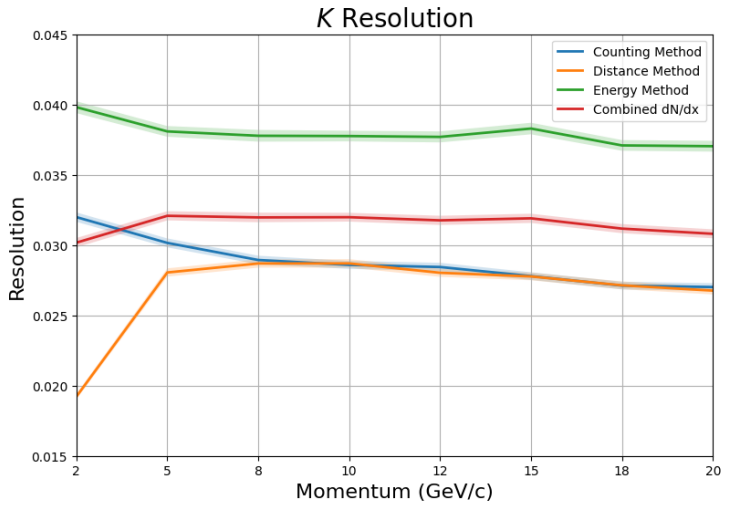


- Combined dN/dx achieves the overall best separation power
- For $\theta = 60°$, p = 20 GeV/c:
  - separation power = 3.0, resolution ~ 2.7%

$\theta = 85°$, track length ~ 1.2 m

PID performances (III)





- Combined dN/dx achieves the overall best separation power
- For $\theta = 85°$, p = 20 GeV/c:
  - separation power = 2.7, resolution ~ 3%

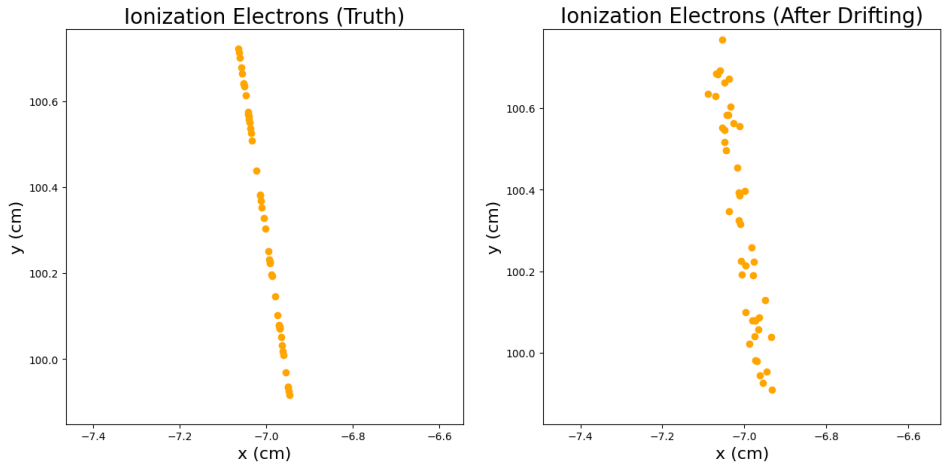
Conclusion

- **A new dN/dx reconstruction with 4D information is developed**
  - Combined counting, distance and energy methods
  - With z-correction at hit level, and calibration at track level
- **The new algorithm achieves >5% improvement w.r.t. the previous algorithm (counting method)**
- **To do:**
  - Optimization of the gas mixture and pixel
  - Implementation in CEPCSW
  - Machine learning

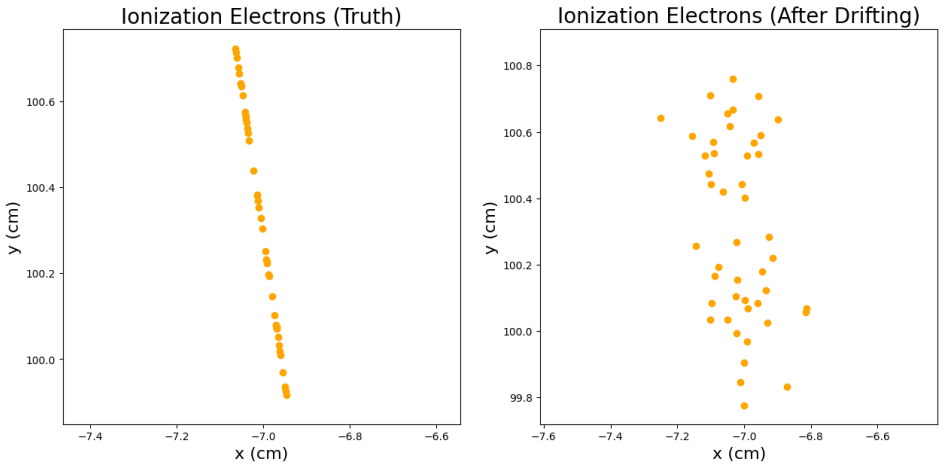
Backups

Readouts in drift distances

Drift distance = 10 cm

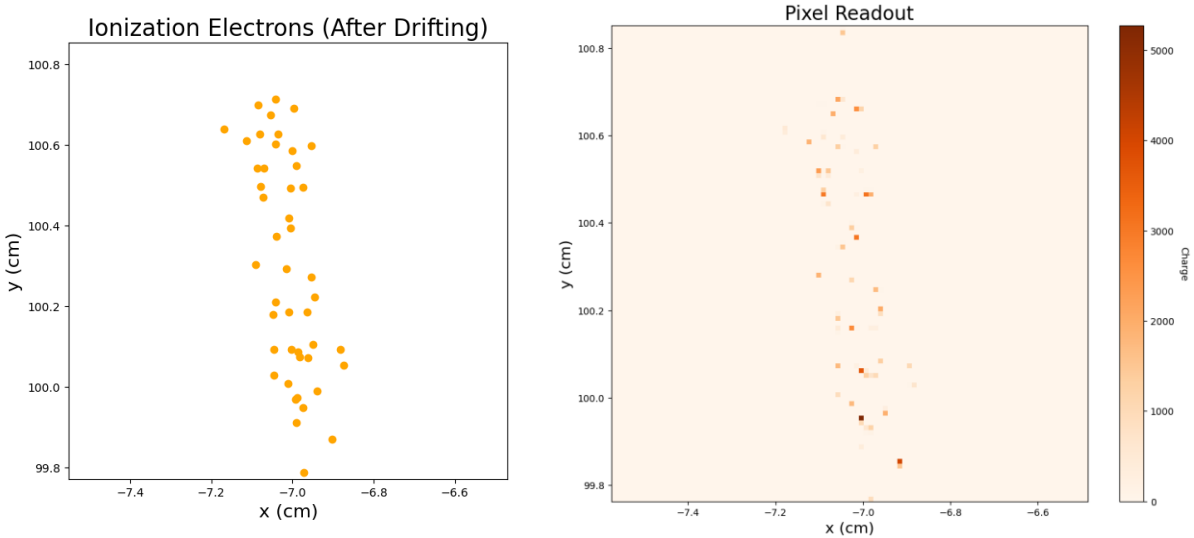


Drift distance = 280 cm

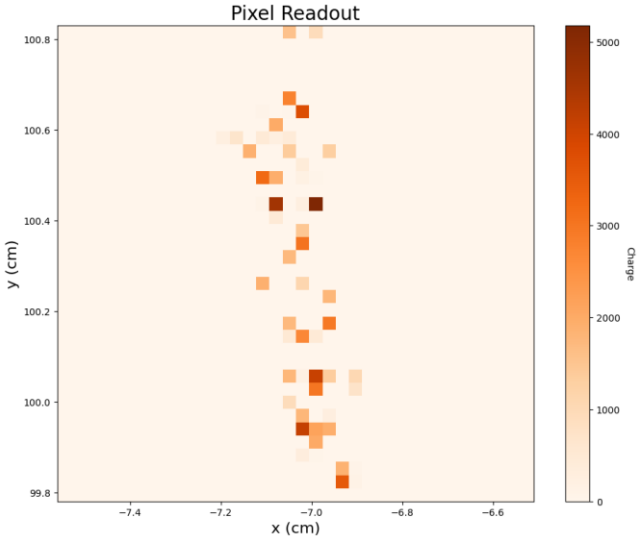


Readouts in pixel sizes

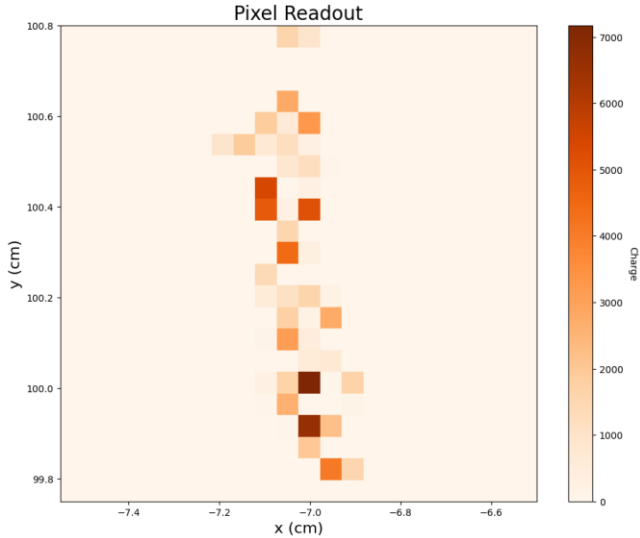
Pixel size = 110 um



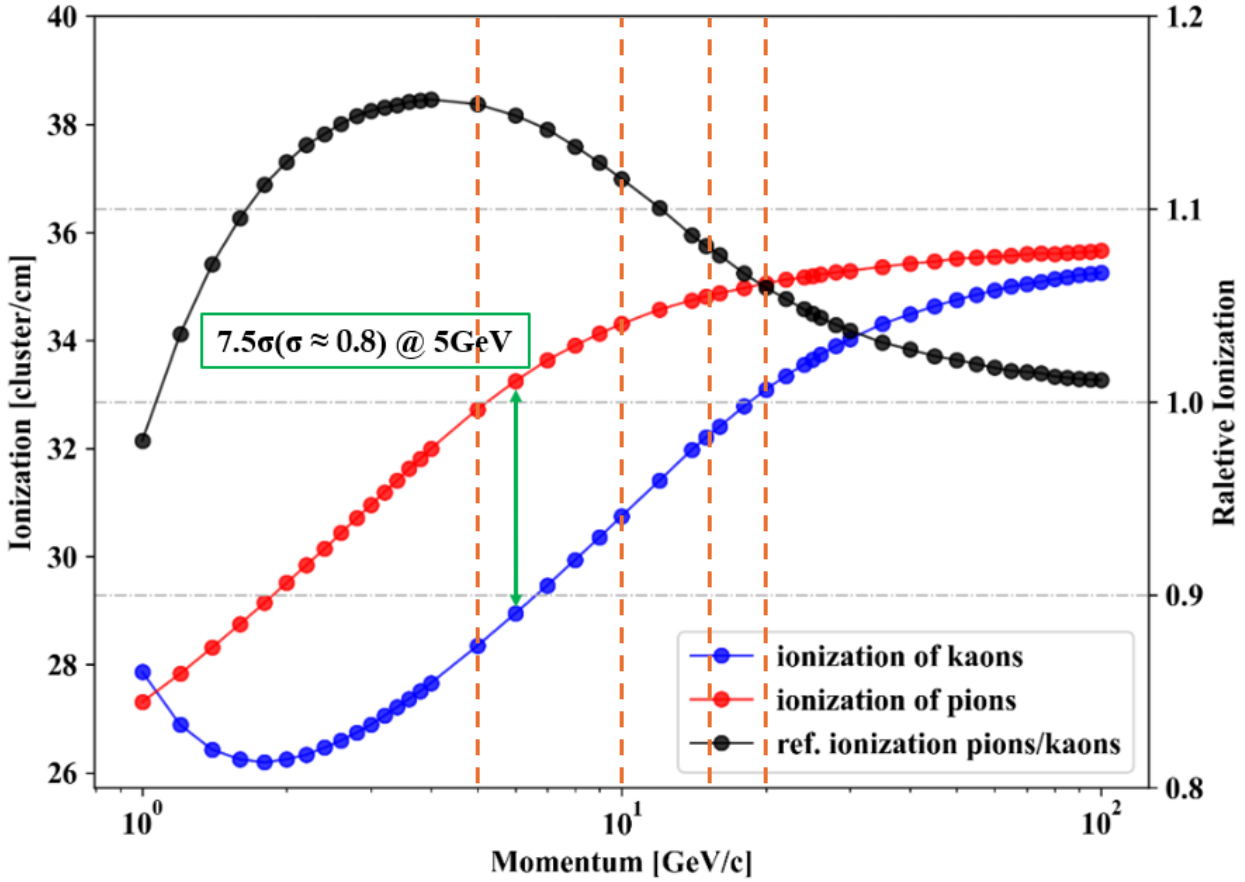
Pixel size = 300 um



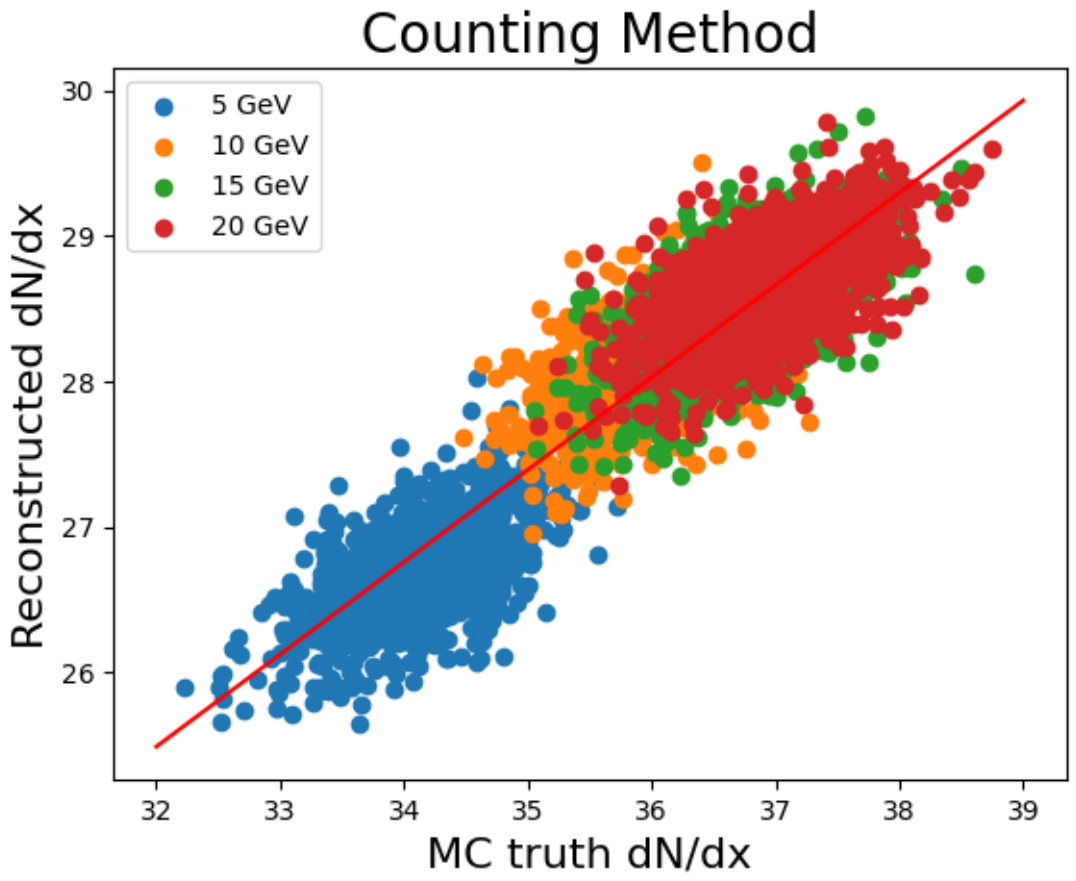
Pixel size = 500 um



Primary ionization from MC truth

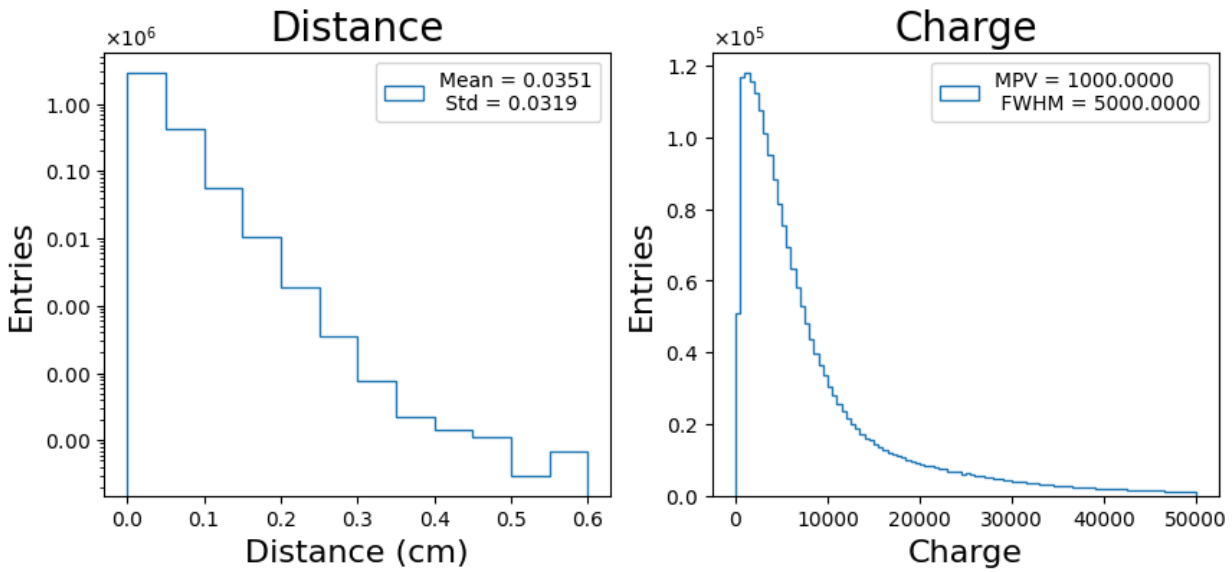


Reconstruction vs. MC truth



Hit level distributions

Drift distance = 10 cm



Drift distance = 280 cm