

# Studies on Particle Identification with $dE/dx$ for the ILD TPC

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES



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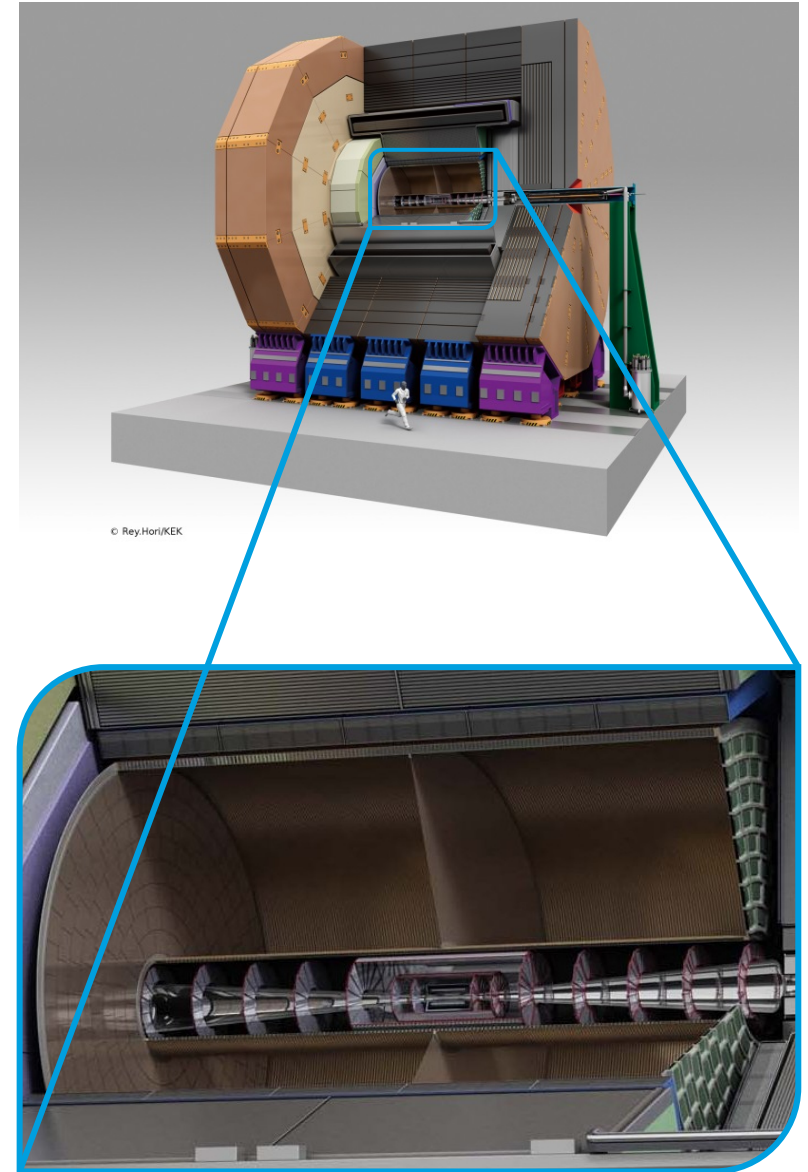
# Measuring $dE/dx$ with a GEM-based TPC Readout Prototype

## Part I

# The International Large Detector

## ILD

- Developed for precision measurements at ILC
- Optimized for particle flow reconstruction
- **TPC with MPGD readout as main tracking detector**
  - ~220 track points → continuous tracking
  - Near 100% tracking efficiency even for low momentum particles
  - Minimal material: 5%  $X_0$  in barrel, 25%  $X_0$  in endcaps
  - 3.5 T solenoid field
  - Momentum resolution required:  $\sigma_{1/p_T} = 10^{-4} \text{ GeV}^{-1}$  (TPC only)  
→ point resolution in transverse direction:  $\sigma_{r\phi} = 100 \text{ }\mu\text{m}$
  - ~5% dE/dx resolution allowing good particle identification



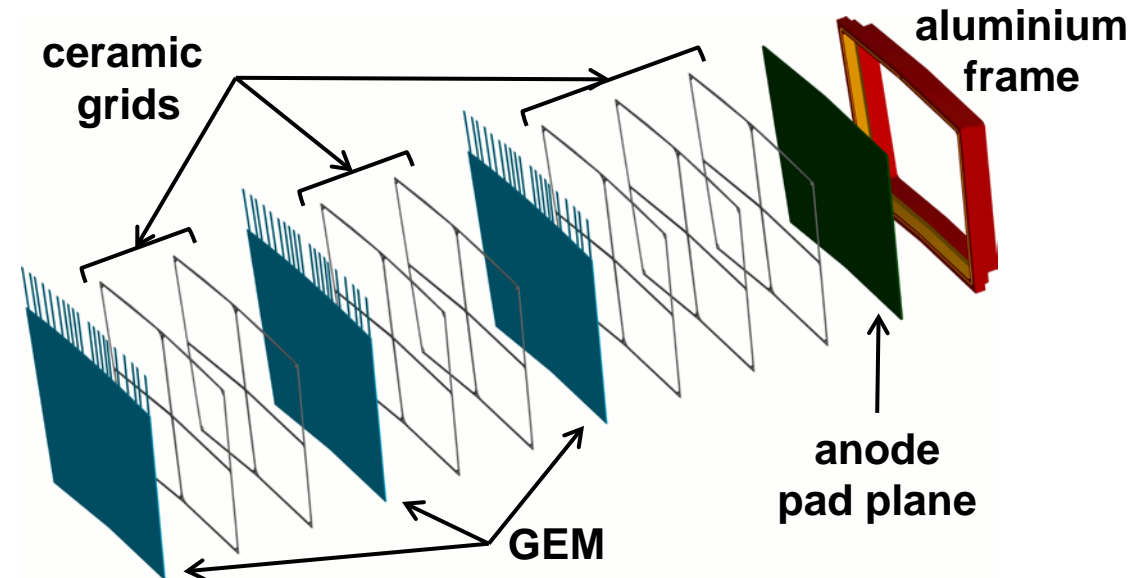
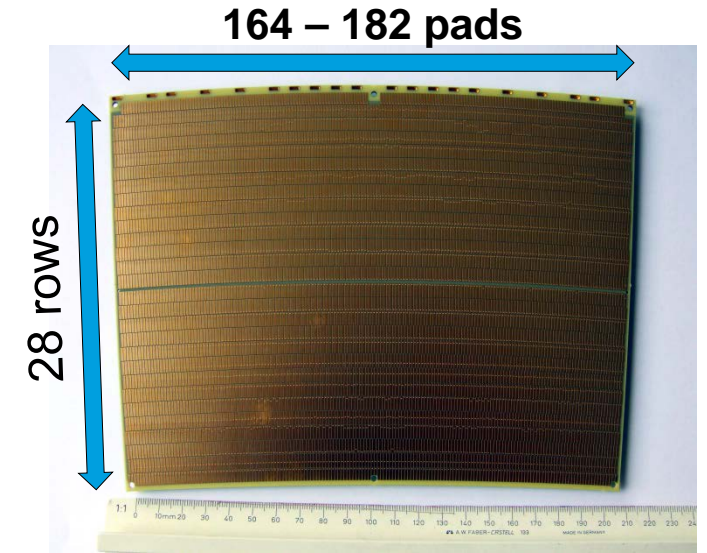
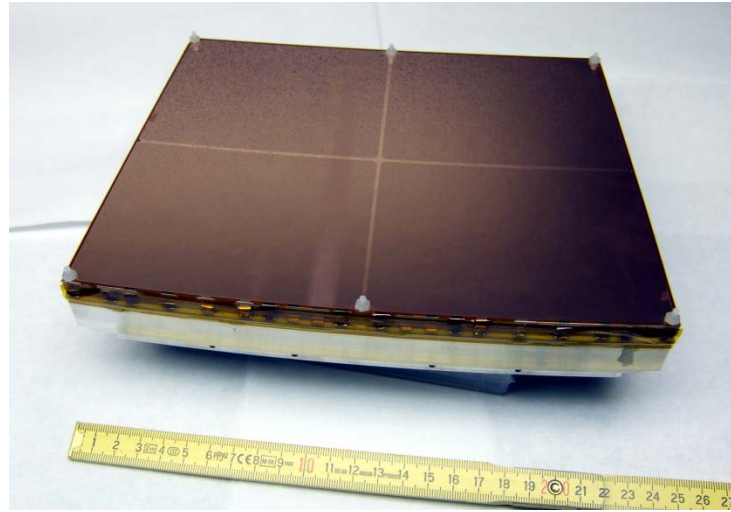
# The DESY GridGEM Module

## Design Goals

- Maximum sensitive area
- Minimal gaps
- Minimal material

## Design Choices

- Integrated, self supporting GEM amplification structure
  - 3 GEM stack supported by thin ceramic grids
- Segmented readout anode:
  - ~5000 pads ( $1.26 \times 5.85 \text{ mm}^2$ ) in 28 rows
  - ~95% sensitive area
- Size and shape as planned for ILD TPC ( $\sim 17 \times 23 \text{ cm}^2$ )
- Custom ALTRO system as readout electronics





# The LCTPC Setup at the DESY II Test Beam Facility

## DESY II

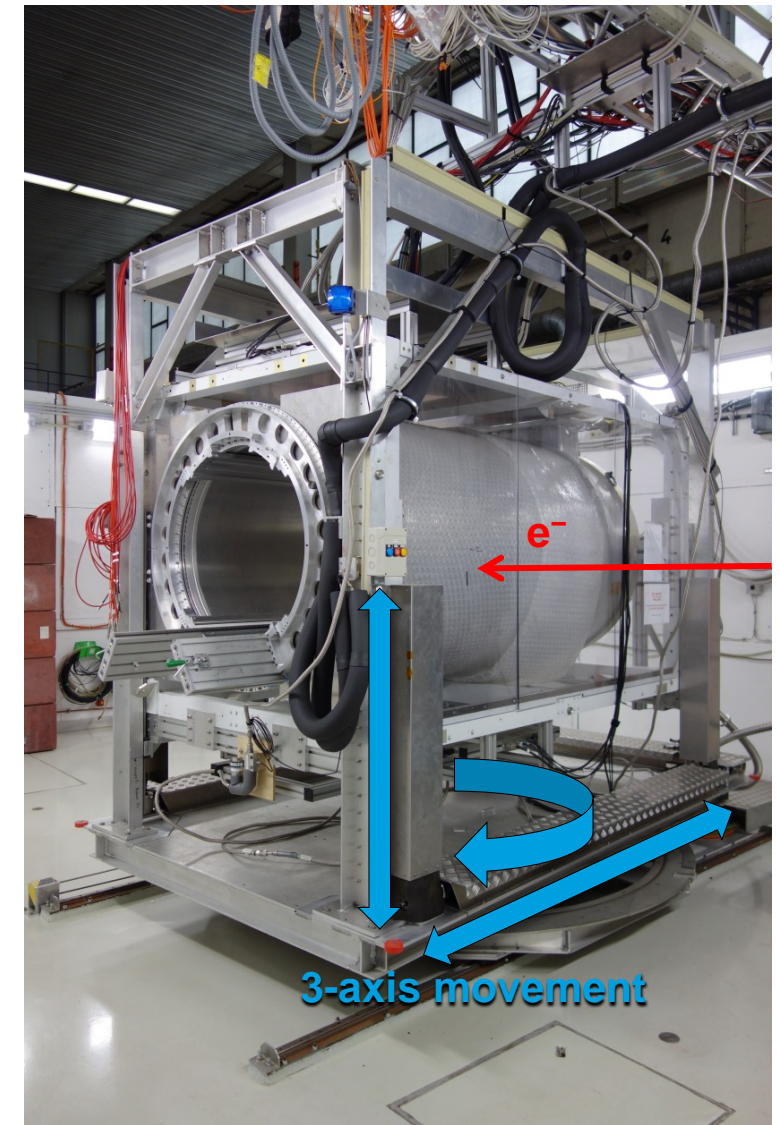
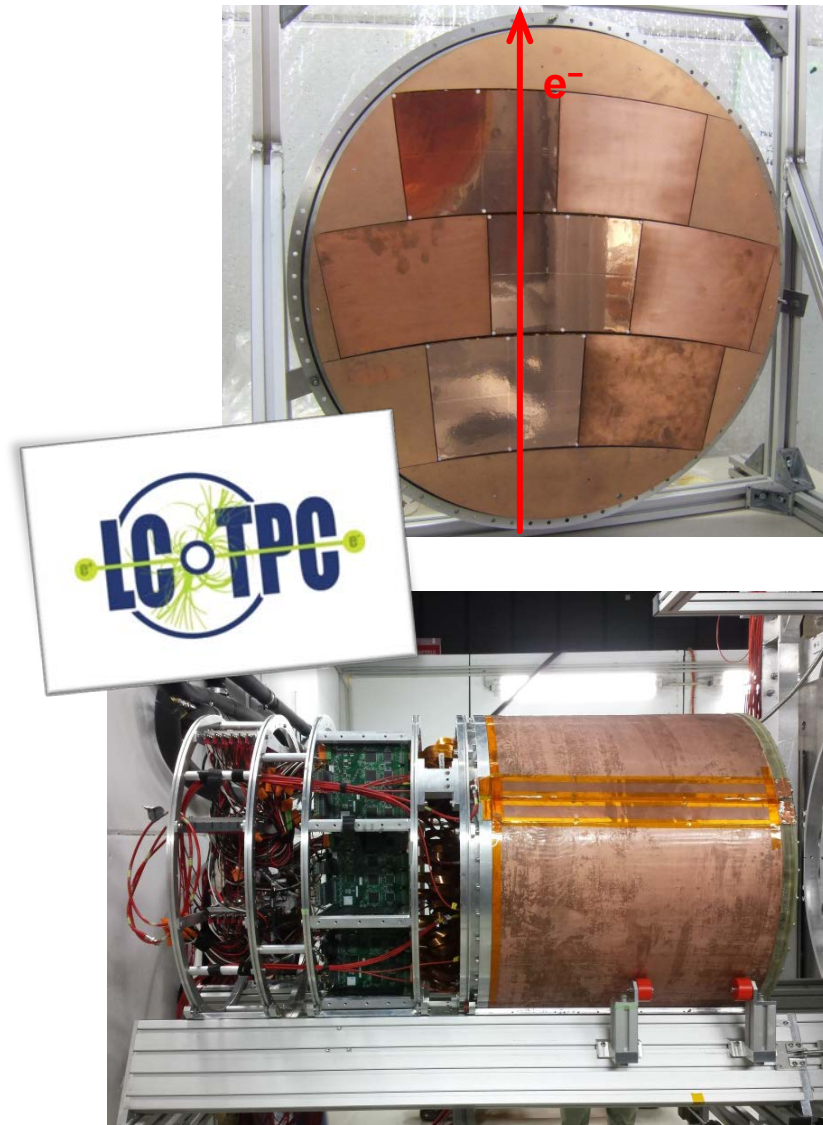
- 1 GeV to 6 GeV electrons

## PCMag

- 1 T superconducting solenoid
- 3-axis moveable stage
- 20%  $X_0$  wall thickness
- 85 cm usable inner diameter

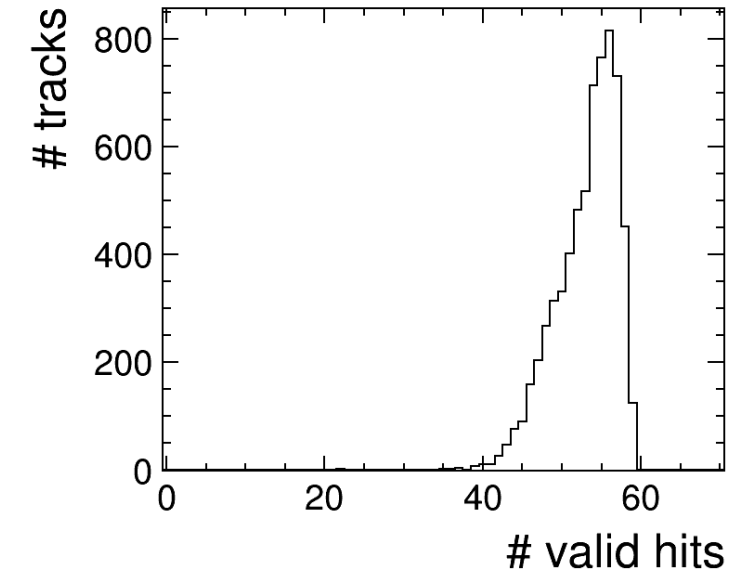
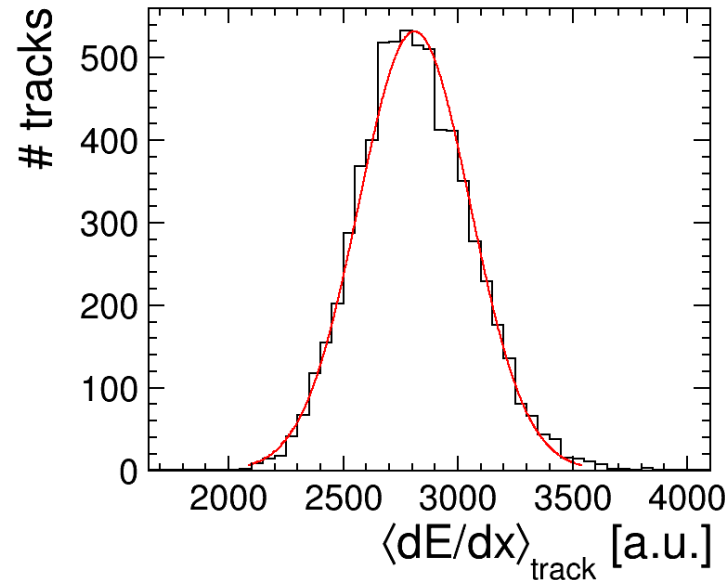
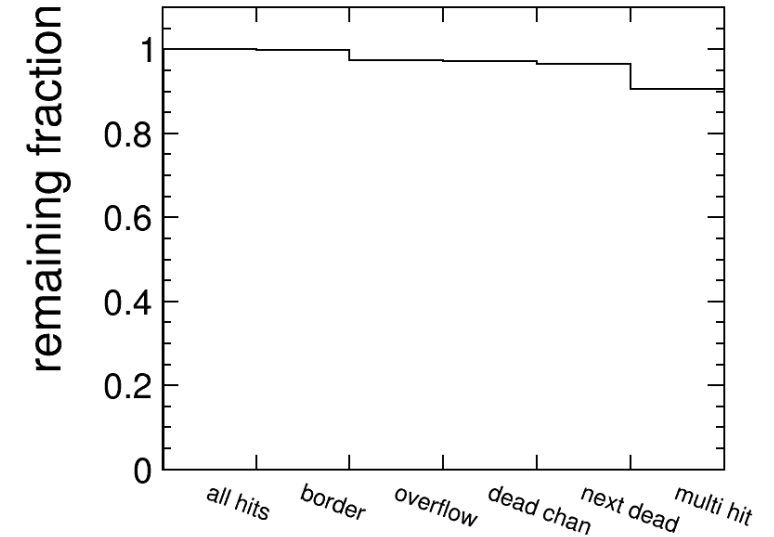
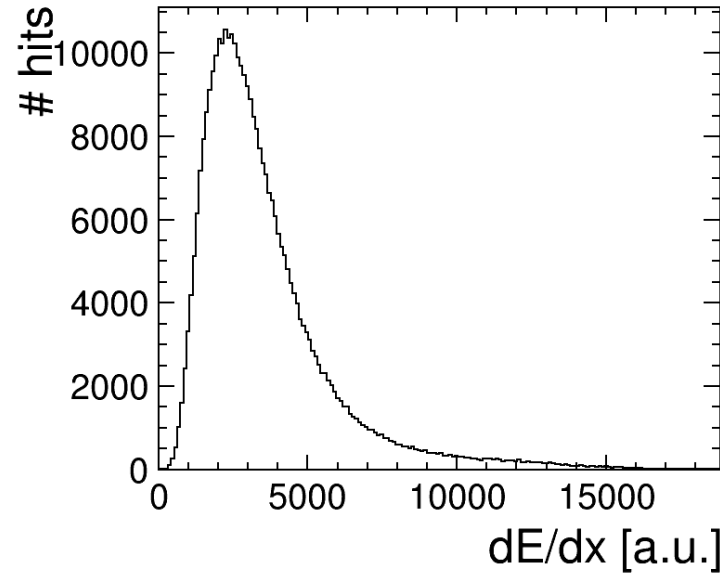
## Large TPC prototype

- 75 cm diameter
- 57 cm maximum drift length
- Endplate with space for 7 modules in 3 rows



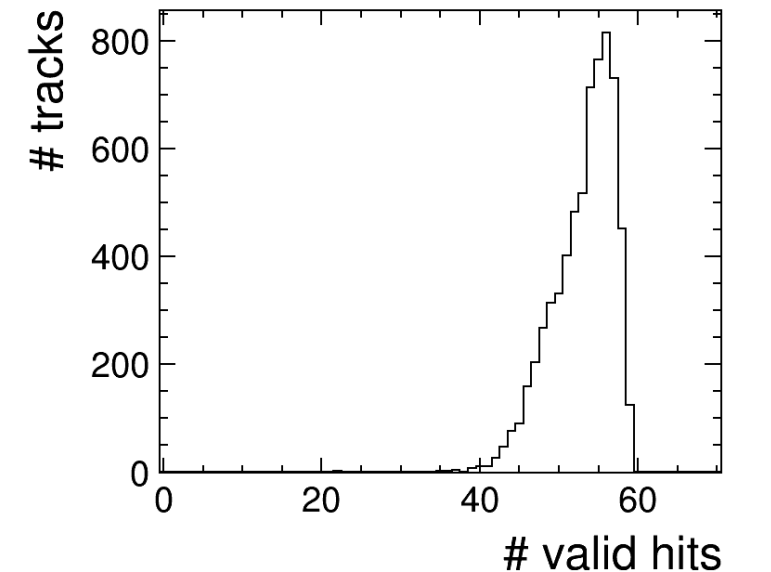
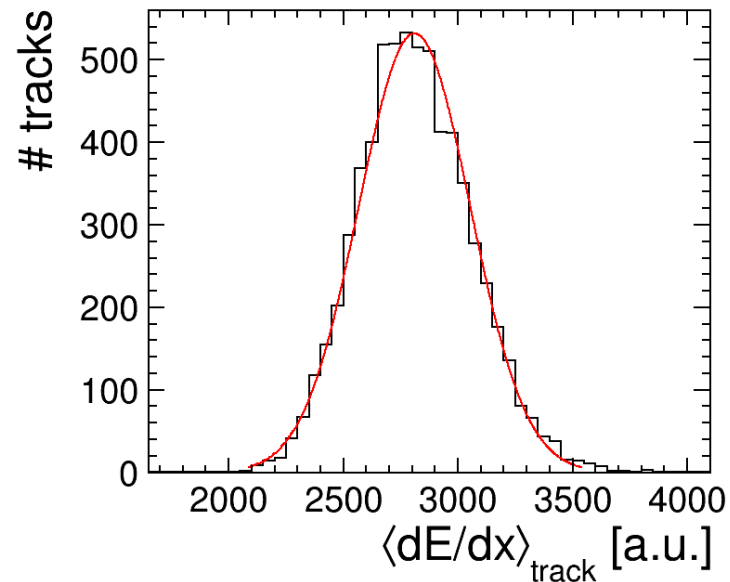
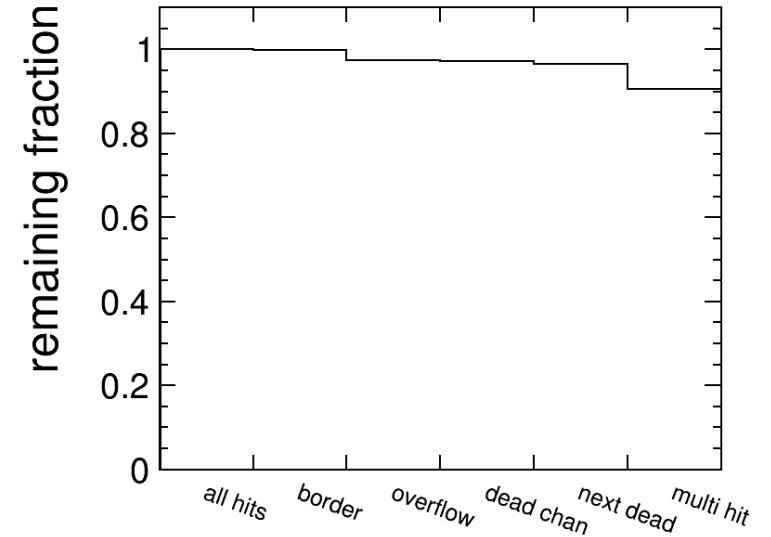
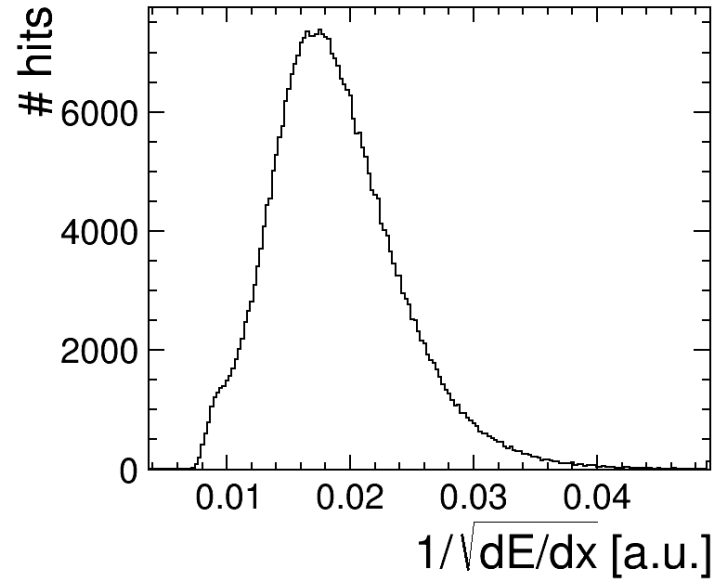
# Measuring dE/dx Resolution

- Row based hit finding → track finding / fitting → hits associated to track used to estimate dE/dx
- Some hit quality cuts are applied:
  - hit not at module edge
  - hit has no channel in overflow
  - no dead channels or next to one
  - no multi hit candidate
- Around 53 valid hits per track
- Track dE/dx calculated from a transformation according to  $est(dE/dx) = 1/\sqrt{dE/dx}$
- dE/dx resolution from RMS/mean in this sample is  $(8.7 \pm 0.1)\%$



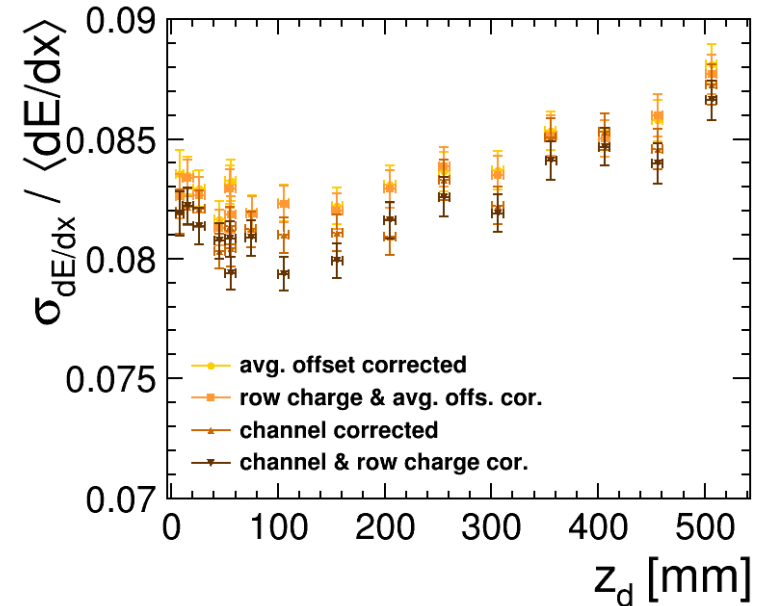
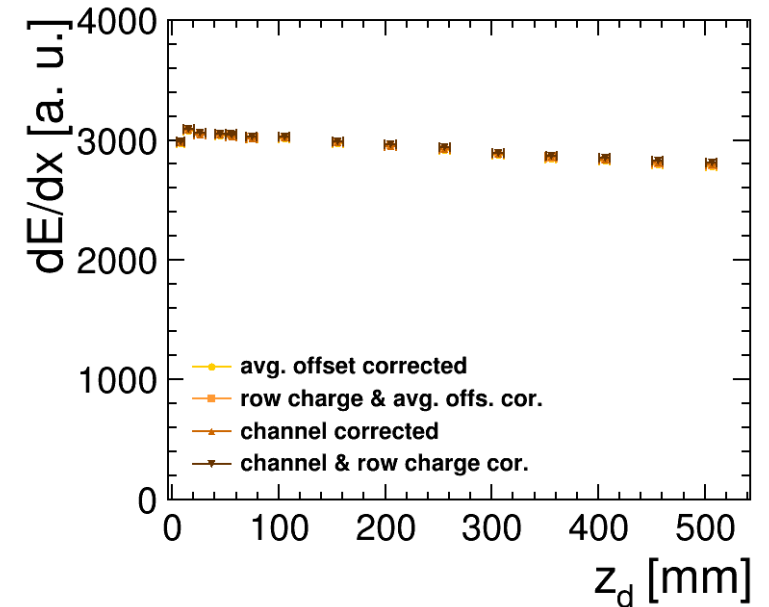
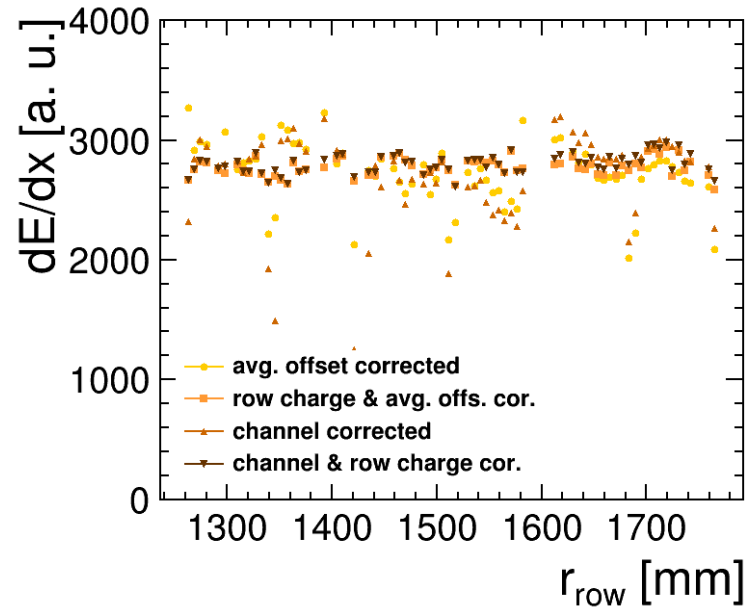
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# Charge Calibration

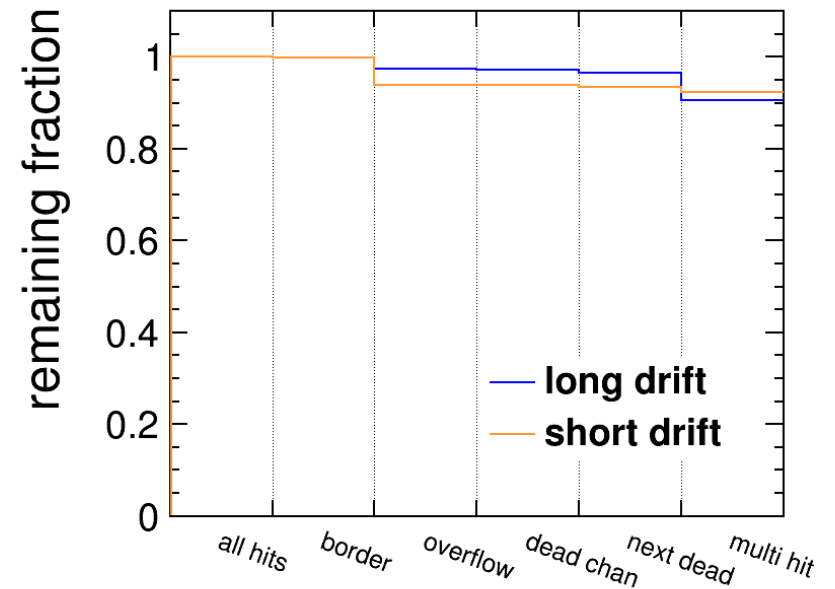
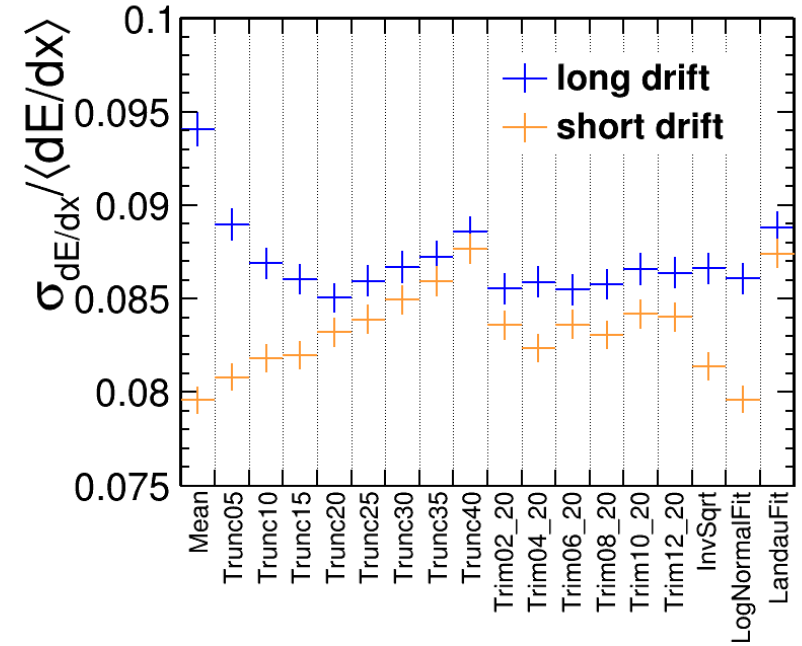
- Channel Correction (CC) was determined by pulsing the lowest GEM, gaining a calibration factor and offset for each channel.
- Readout does not provide self calibration.
- Row Charge Correction (RCC) corrects mean charge on each row to average of all rows.
- Equivalent to a local gain calibration, since all tracks pass over each row at the same location.
- Only minor improvement in  $dE/dx$  resolution by applying CC.
- Resolution dominated by fluctuations of primary ionization.
- RCC has no significant impact on the  $dE/dx$  resolution, since gain was already quite homogeneous.
- All other results make use of both correction methods.





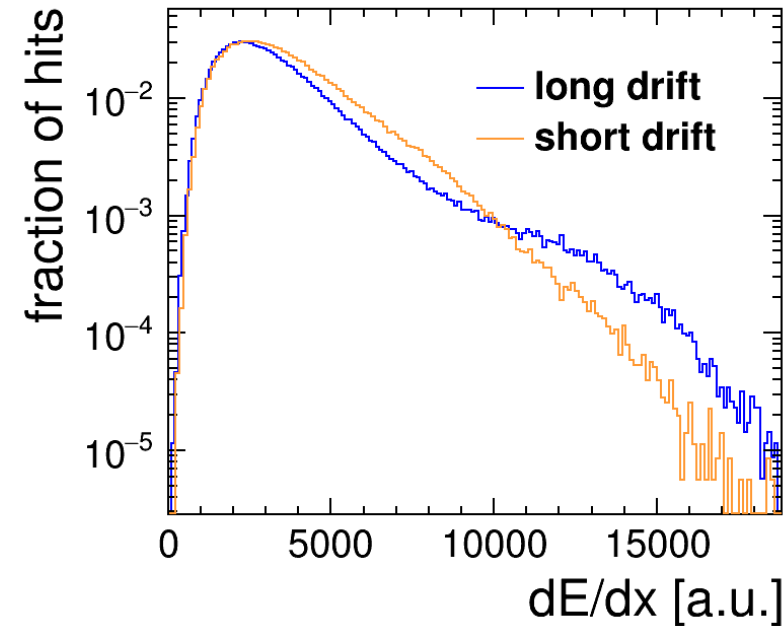
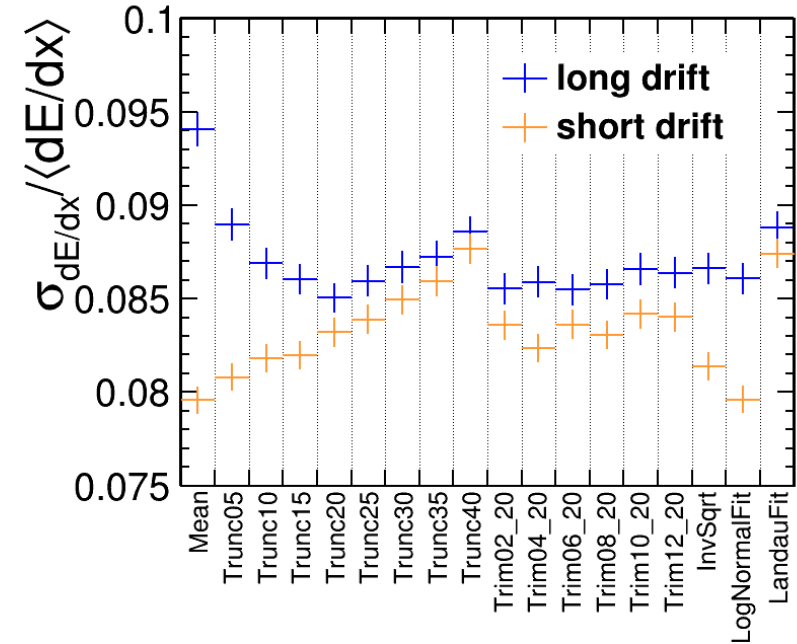
# Comparing Track dE/dx Estimators

- Different methods to calculate track dE/dx were compared:
  - Truncated mean: Cut off fraction of highest charge hits.
  - Trimmed mean: Also cut off some lowest charge hits.
  - Using  $1/\sqrt{dE/dx}$  as an estimator gives a more symmetric distribution.
  - Landau / log-normal binned likelihood fit.
- Changing fraction of hits with channels in overflow at different drift distances
  - drastically influence best truncation fraction and also performance of other methods.
- Long drift suffers from electron attachment during drift, so resolution at short drift is better on average.
- Overflow fraction would be minimized in real detector.
  - Use long drift data to compare estimators.



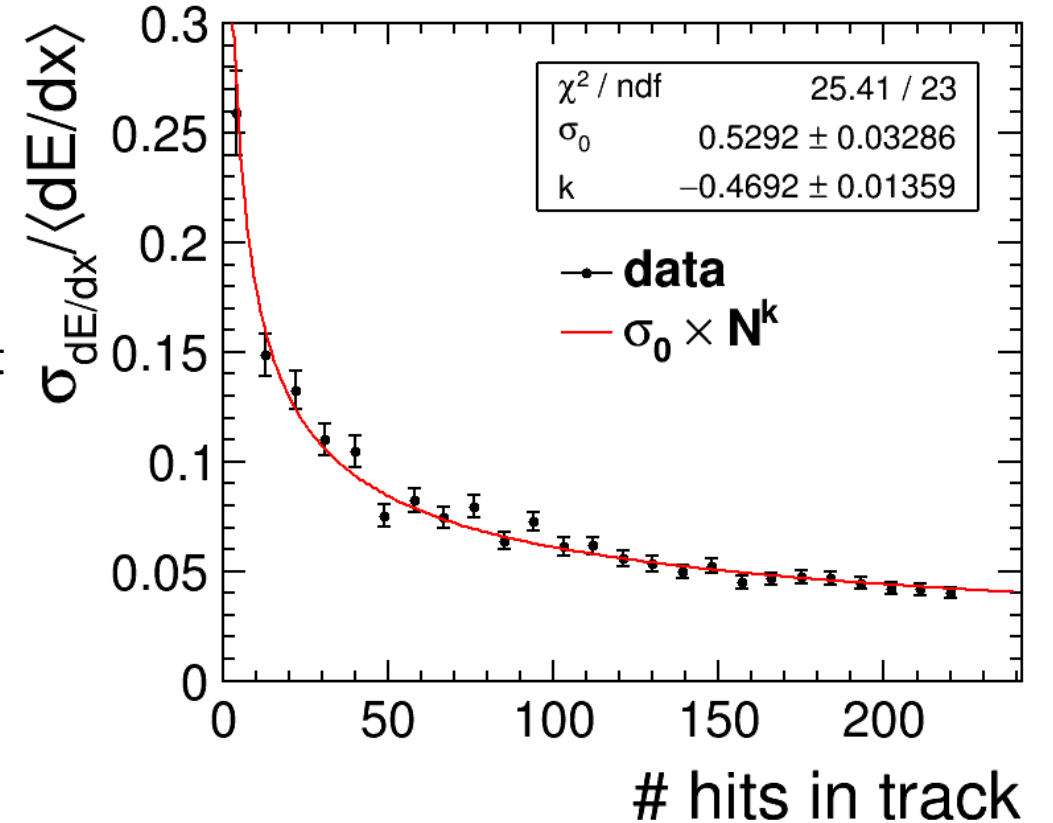
# Comparing Track dE/dx Estimators

- Overflow fraction would be minimized in real detector.  
→ Use long drift data to compare estimators.
- Inverted square-root method performs similarly well as truncation.
- Best truncation fraction is found to be around 20%.
- Trimming does not provide any improvement over truncation.
- Landau distribution does not describe our dE/dx distribution well.  
→ No good resolution expected from fit.
- Log-normal distribution does not describe tail at long drift.



# Extrapolating to ILD TPC

- Randomly combining hits from several real tracks to a pseudo track allows to test arbitrary track lengths.
- Allows extrapolating dE/dx resolution to tracks in the ILD TPC with up to 220 hits (large ILD) or 165 hits (small ILD).
- Expected power law dependency found:  $\sigma(\text{dE/dx}) \propto N^k$
- Fitted exponents k vary between -0.45 and -0.48 for different data taking runs.
- Non-Gaussian shape of hit dE/dx distribution  
→ no  $1/\sqrt{N}$  behavior of ideal Gaussian distribution
- Resolution of ILD TPC can be estimated to be  $(4.2 \pm 0.1)\%$  for tracks with 220 hits (165 hits:  $(4.8 \pm 0.1)\%$ ).
  - This assumes no invalid hits → lower limit on resolution.
  - Assuming 10% invalid hits resolution is increased by ~0.2%.



# **dE/dx with Highly Granular Readouts & Cluster Counting**

## **Part II**

# dE/dx and Granularity

- dE/dx resolution was observed to depend on total sample length L (TPC radius) and number of samples N (number of readout rows):

$$\sigma(\text{dE/dx}) \propto L^{-0.34} \times N^{-0.13}$$

- Derive readout granularity  $G = N/L$  and row height  $H = 1/G = L/N$ :

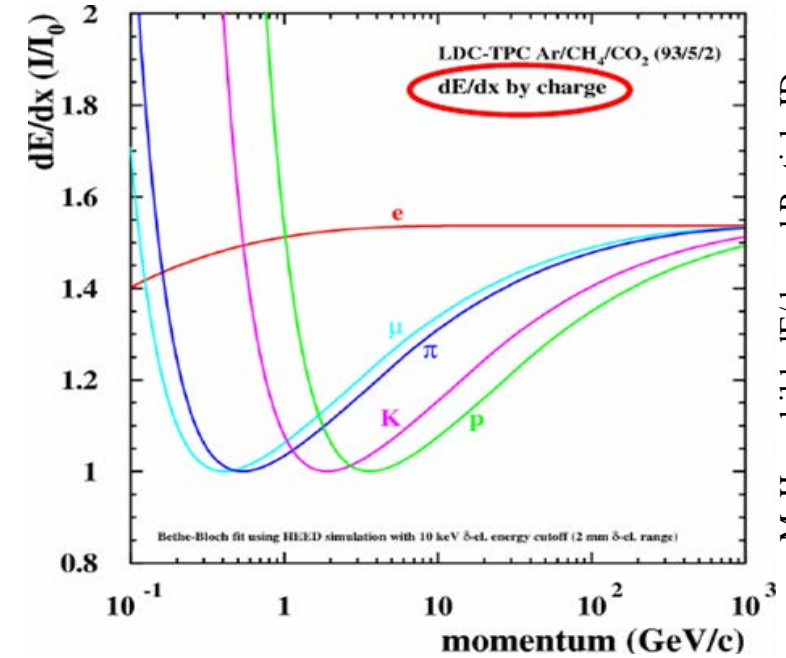
$$\sigma(\text{dE/dx}) \propto L^{-0.47} \times G^{-0.13} = H^{-0.34} \times N^{-0.47}$$

- Usual approach: Keep H constant, vary N (e.g. extrapolating to ILD).
- Here: Keep L constant, vary G.
- This should improve dE/dx resolution with conventional methods for higher granularity.
- Also check new algorithm enabled by very small pads: cluster counting.

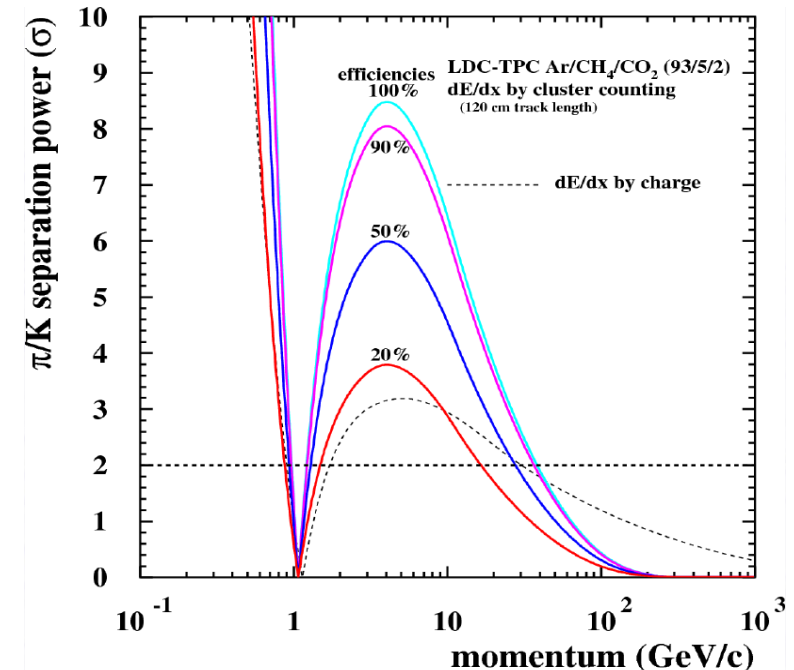


# Cluster Counting

- Charge produced on a certain track distance is Landau distributed.
- The number of ionisation events on this distance is Poisson distributed  
 → smaller RMS → better correlation → better particle identification.
- Counting clusters allows for improved particle separation compared to conventional charge summation.
- Depends on fraction of identified clusters (counting efficiency).  
 → Need sufficient granularity to identify clusters!

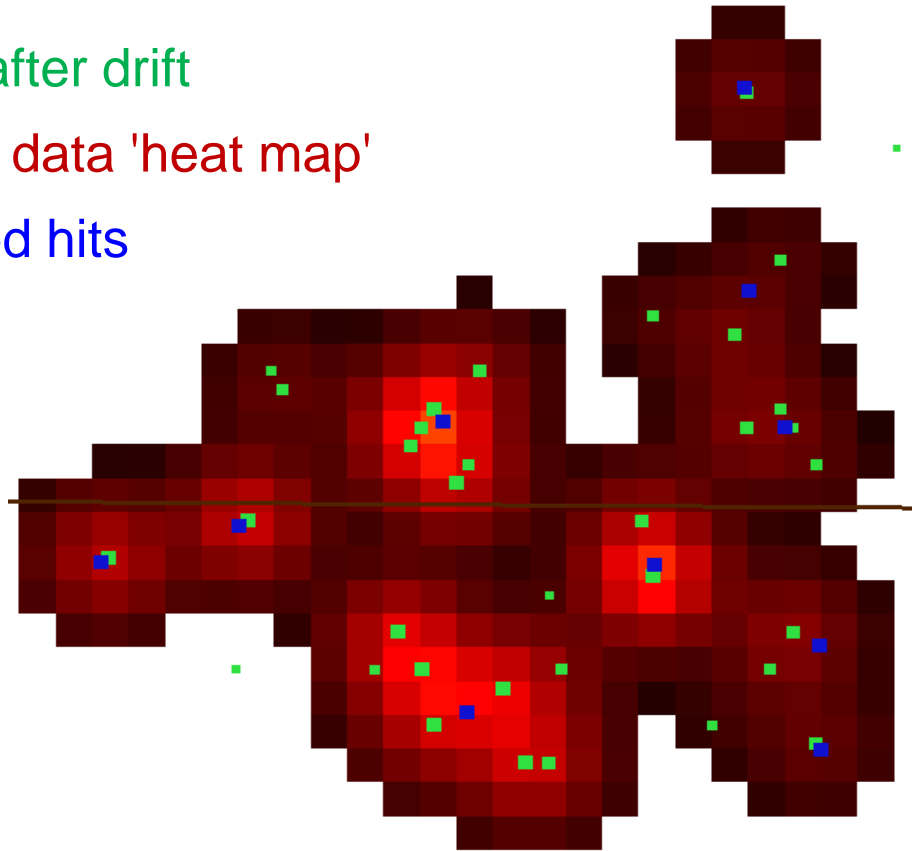


M. Hauschild: dE/dx and Particle ID  
 Performance with Cluster Counting;  
 at ILC Ws. Valencia 2006



# Software

- Cluster identification via external software 'Source Extractor'  
→ returns 'hits' for tracking  
[<http://www.astromatic.net/software/sextractor>]
- Event display:
  - Green: electrons after drift
  - Red: digitised raw data 'heat map'
  - Blue: reconstructed hits
- Identify and count clusters / hits



Generate MCParticles

Primary Ionization

Drift

GEM Amplification

Projection onto Timepix

Timepix Digitization

Simulation

Export to .fits

Source Extractor

Import to .slcio

Tracking: Hough Trafo

Reconstruction

Analysis  
e.g. cluster-hit  
identification

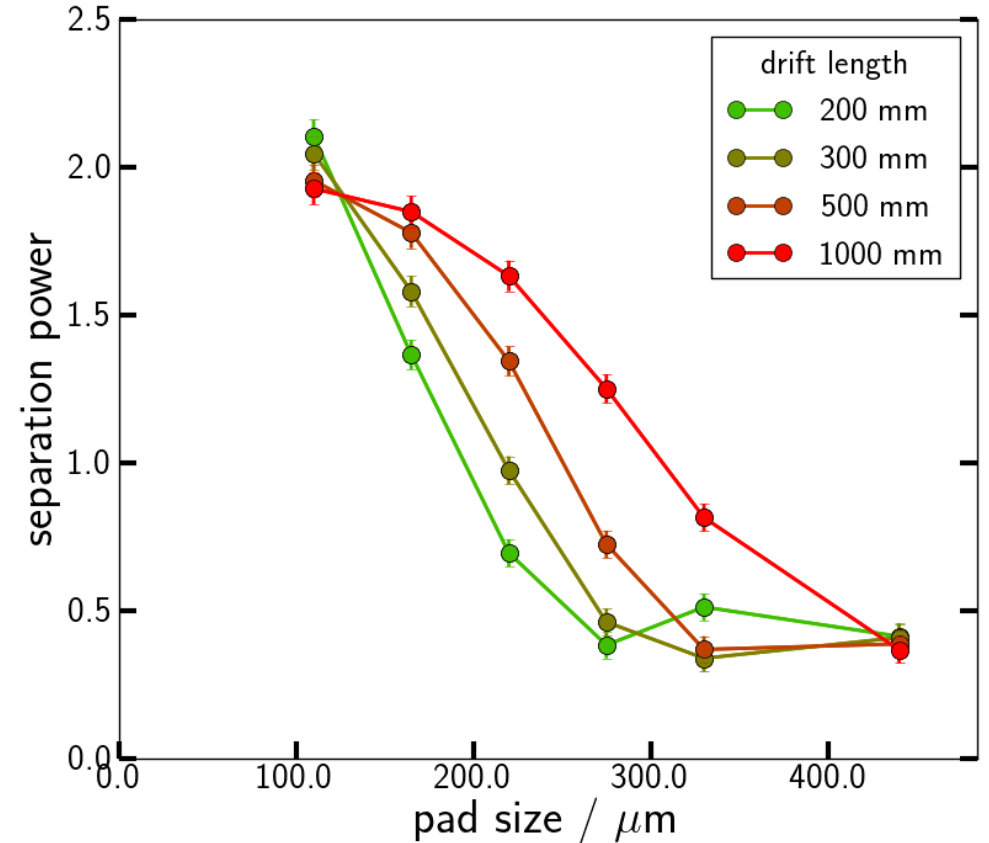
Analysis

# Pion-Kaon Separation Power by Cluster Counting

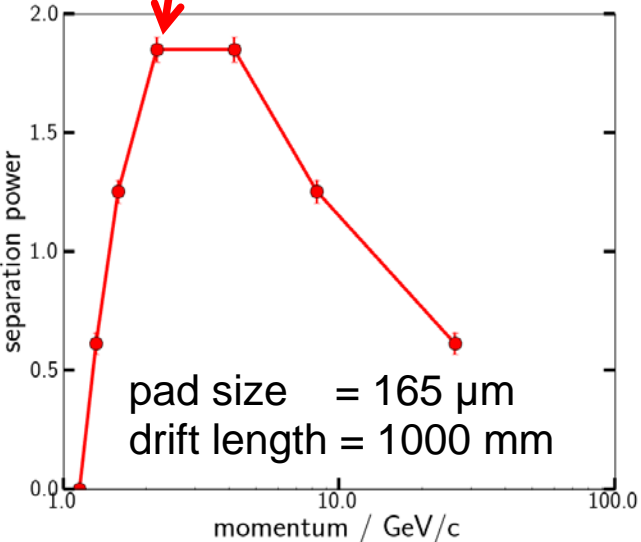
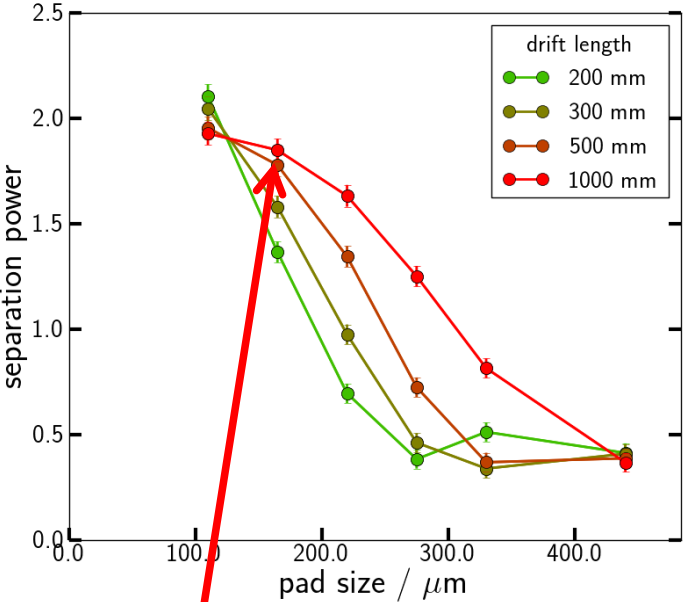
- Separation power defined as:

$$S = \frac{|\mu_{\pi} - \mu_K|}{\sqrt{(\sigma_{\pi}^2 + \sigma_K^2)/2}}$$

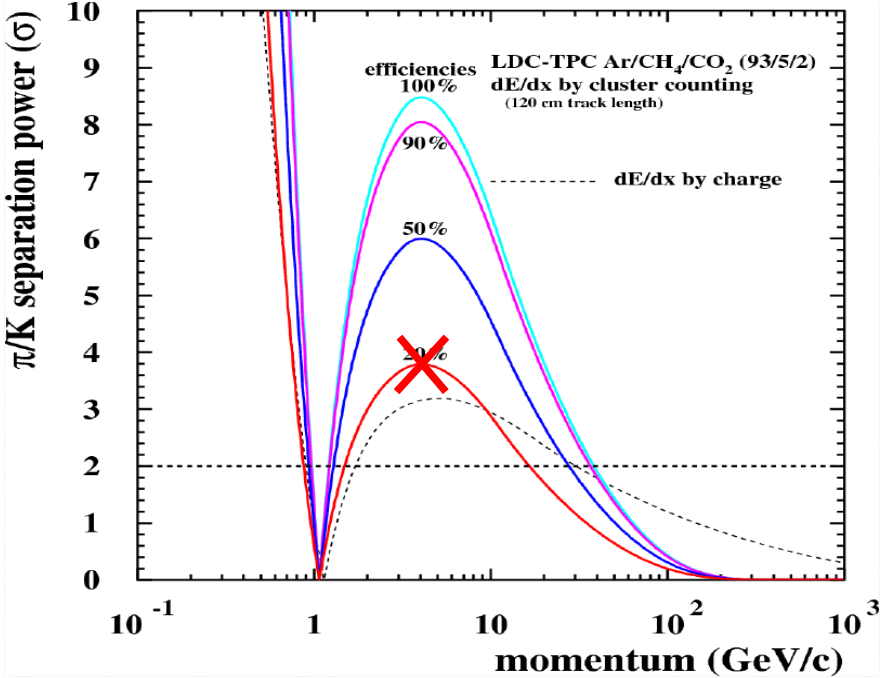
- Track length  $L = 300$  mm
- $B = 1$  T
- separation for maximum ionization difference ( $\sim 15\%$ )



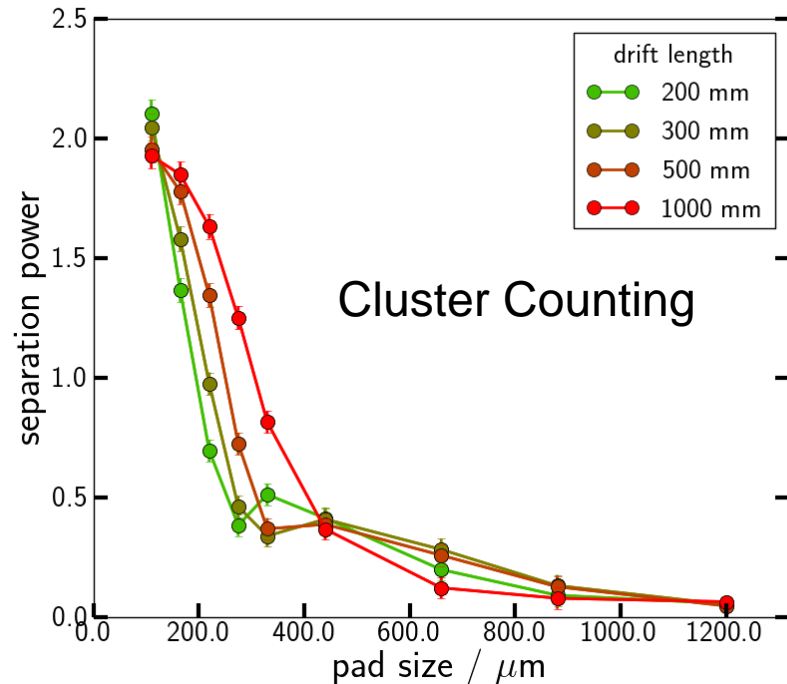
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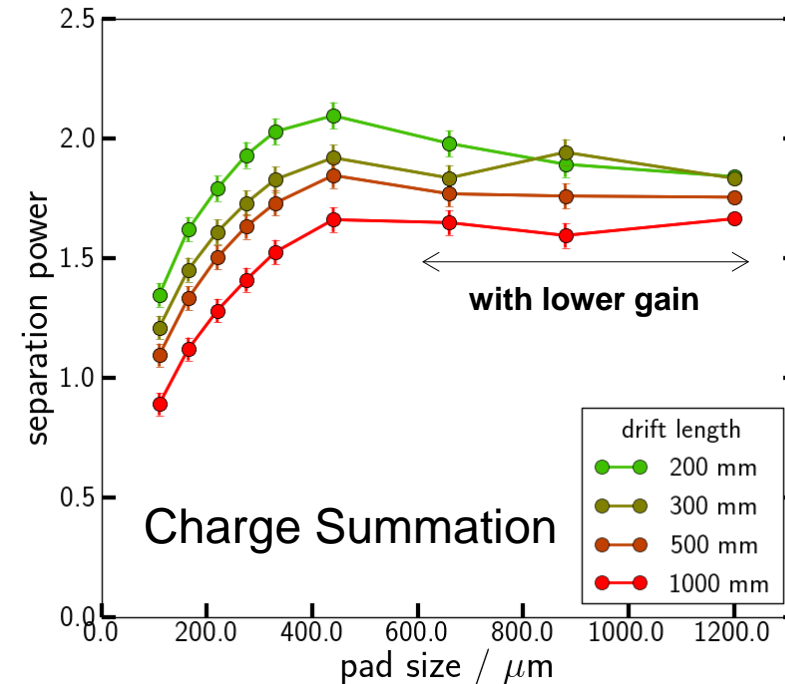
- Extrapolation by  $1/\sqrt{N}$  to ILD with track length  $L = 1.35$  m.
- Gives a separation power of 3.8 with 165  $\mu\text{m}$  pads and 3.4 with 220  $\mu\text{m}$  pads.
- Improvement to conventional charge based measure.



# Pion-Kaon Separation Power – Larger Pads



- Cluster counting breaks down at  $\sim 300 \mu\text{m}$ .
- 'Inverted' order of drift length because of less bunching, thus more single electrons are reconstructed.

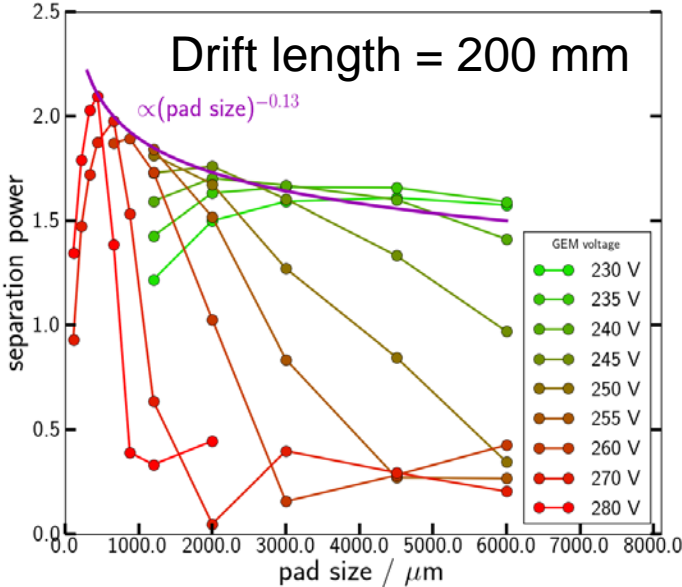
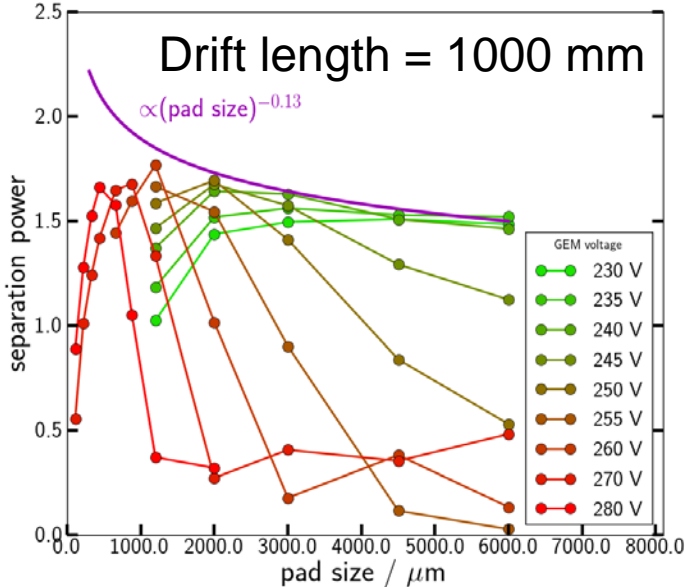


- Curves drop with lower pad size because of pixel charge threshold, given a constant gain.
- Drop to larger pad size is expected:  

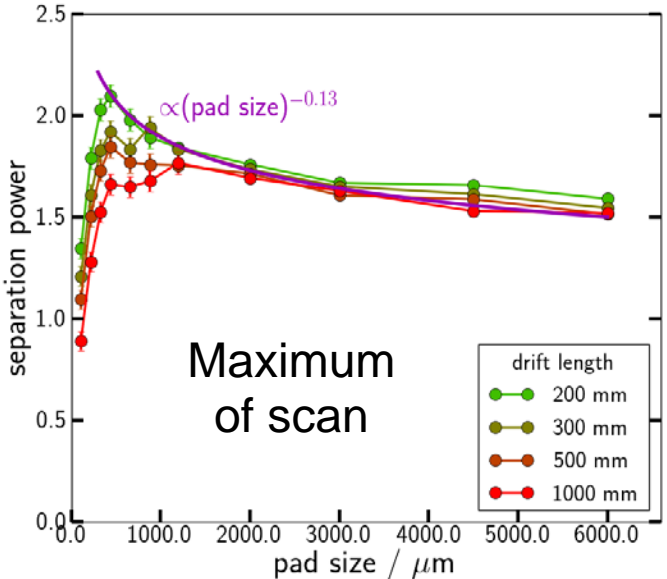
$$\sigma(dE/dx) \propto G^{-0.13}$$



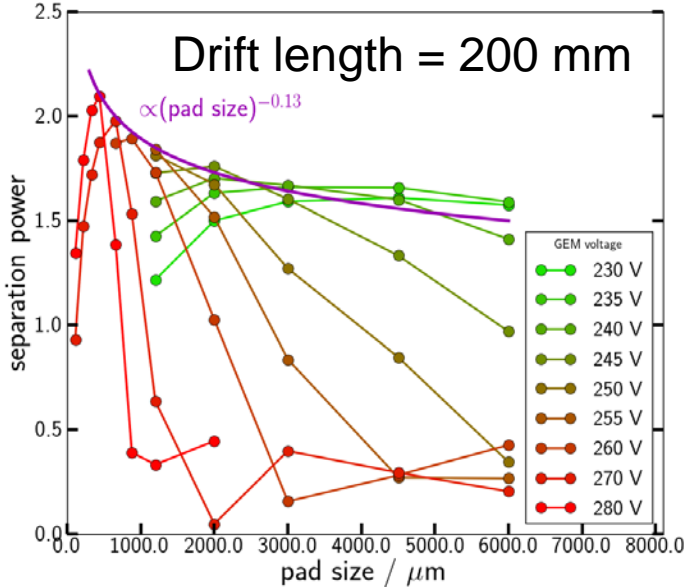
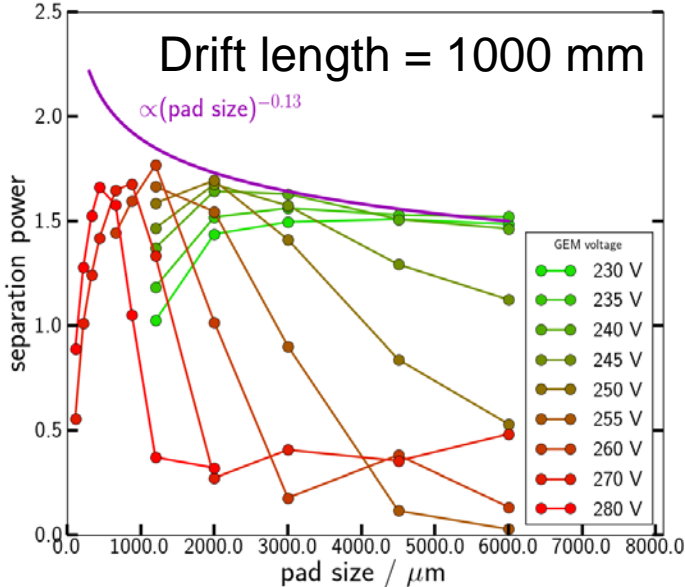
# GEM Gain Dependence of Charge Summation



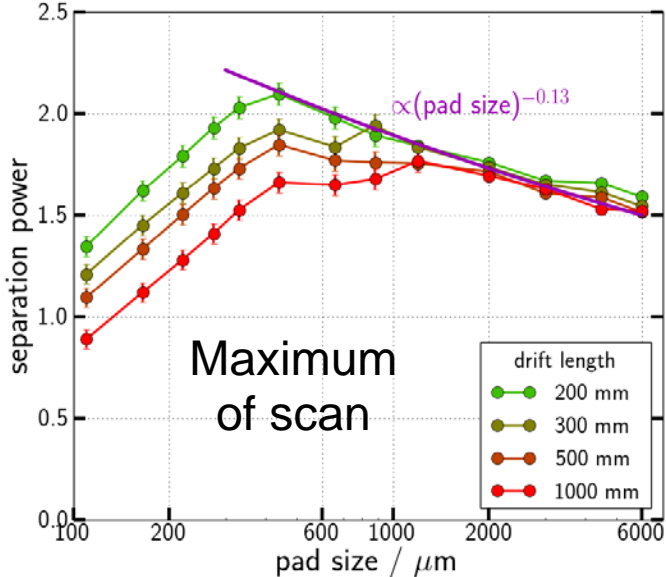
- Too high voltage: overflow
- Too low voltage: threshold effects
- Adjust voltage to pad size, take respective maximum separation power at each point.



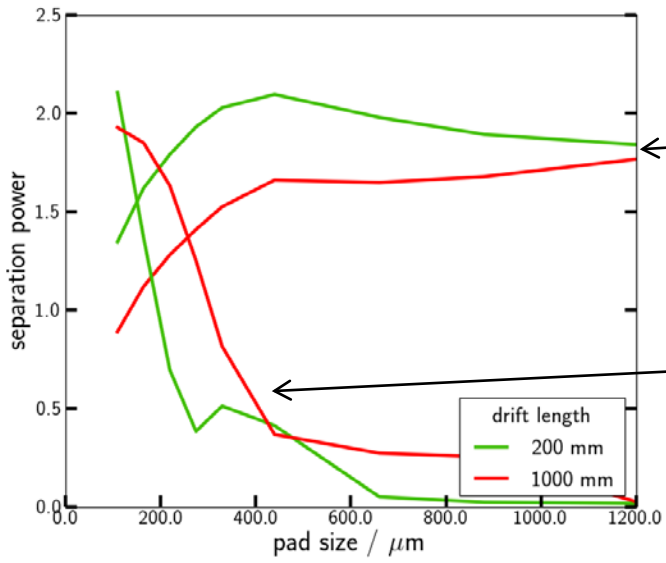
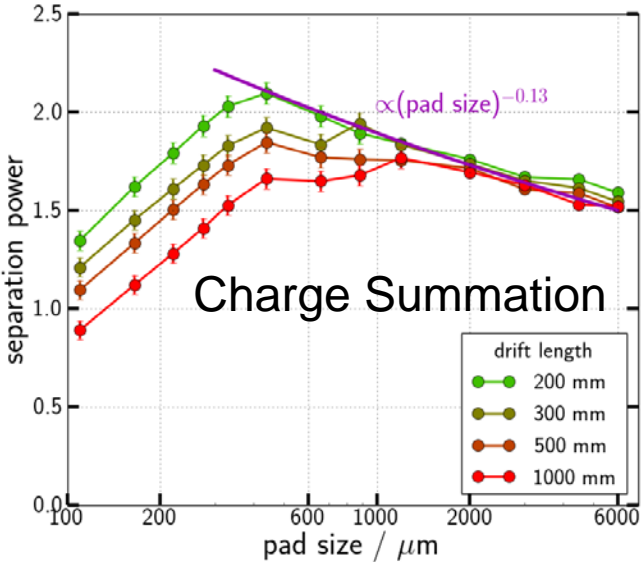
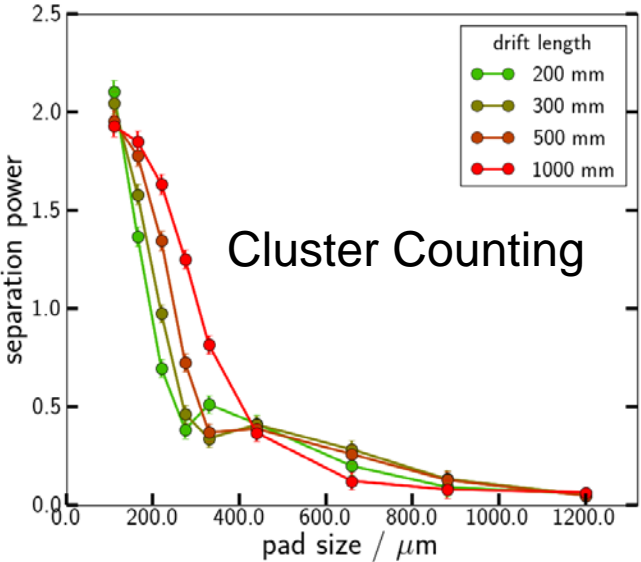
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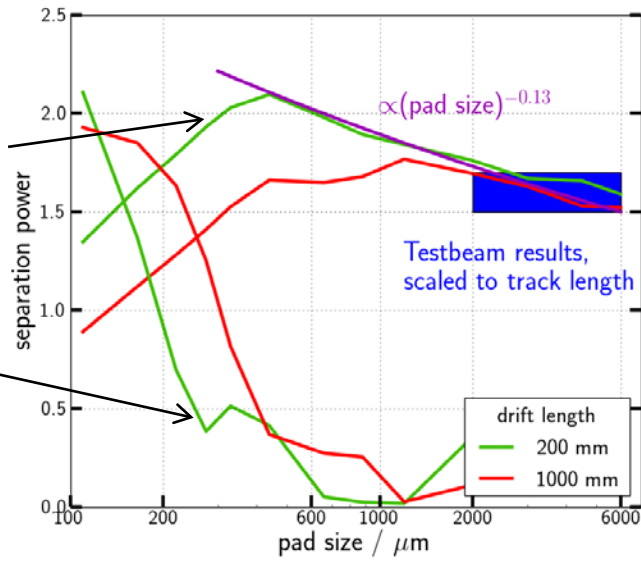


# Combined Pion-Kaon Separation Power



← Charge Summation

← Cluster Counting



# Summary

- Using a large TPC prototype the  $dE/dx$  resolution with the DESY GridGEM module was successfully measured to be  $(8.7 \pm 0.1)\%$  for tracks with  $\sim 53$  valid hits.
- The  $dE/dx$  resolution for the track length of  $\sim 220$  hits expected in the ILD TPC was estimated to be about  $(4.2 \pm 0.1)\%$  (small ILD, 165 hits:  $(4.8 \pm 0.1)\%$ ).  
→ Exceeds ILD design goal of 5%.
- Simulations show expected behaviour of increased separation power (improved  $dE/dx$  resolution) for higher granularity with conventional charge summation.
- Cluster counting only works for very granular readouts with pad sizes below  $300 \mu\text{m}$ .

**Thank you**



# Charge Calibration

- Row Charge Correction (RCC) corrects mean charge on each row to average of all rows.
  - Equivalent to a local gain calibration.
- Channel Correction (CC) was determined by pulsing the lowest GEM, gaining a calibration factor and offset for each channel.
  - Readout does not provide self calibration.
  - CC offset shifts the  $dE/dx$  mean → applying the average offset to uncorrected data allows to judge changes in  $dE/dx$  resolution.
- Only minor improvement in  $dE/dx$  resolution by applying CC.
  - Resolution dominated by fluctuations of primary ionization.
- RCC has no significant impact on the  $dE/dx$  resolution.

