Particle Identification with dE/dx with GEM and a Pad based readout

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LCTPC Collaboration Meeting
DESY, 10.01.2019

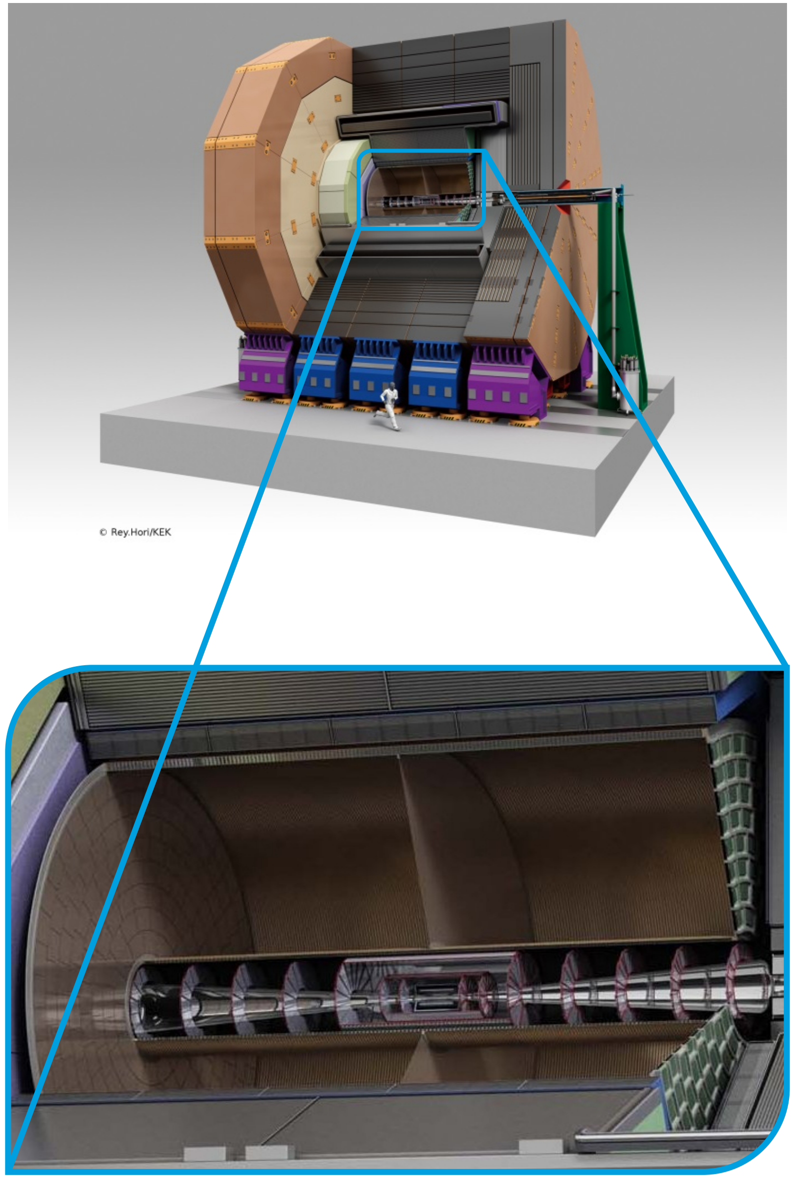
Measuring dE/dx with the DESY GridGEM Modules

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: $\sigma_{1/p_T} = 10^{-4}\ \mathrm{GeV}^{-1}$ (TPC only)
    → point resolution in transverse direction: $\sigma_{r\varphi} = 100\ \mu\mathrm{m}$
  - ~5% dE/dx resolution allowing good particle identification



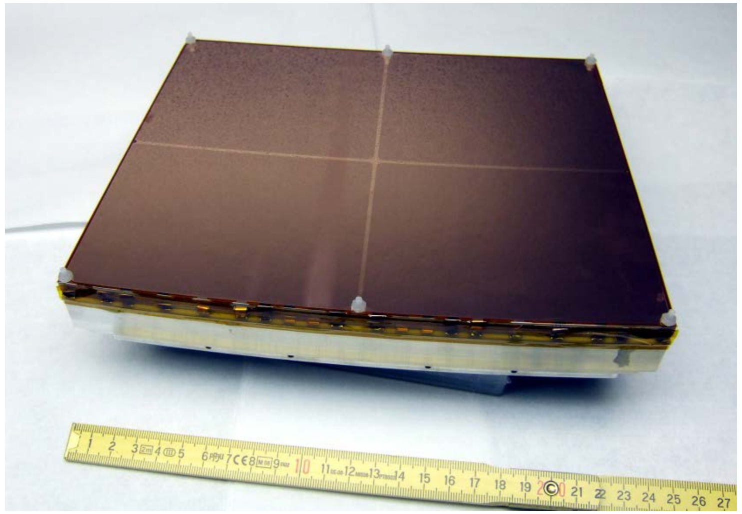
The DESY GridGEM Module

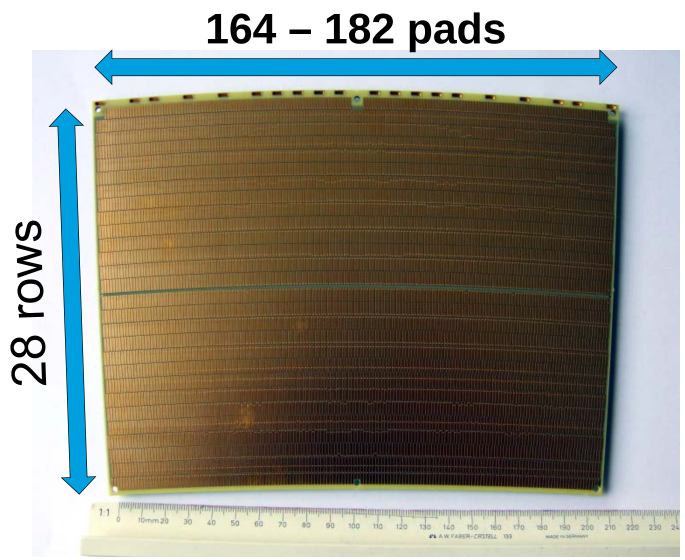
Design Goals

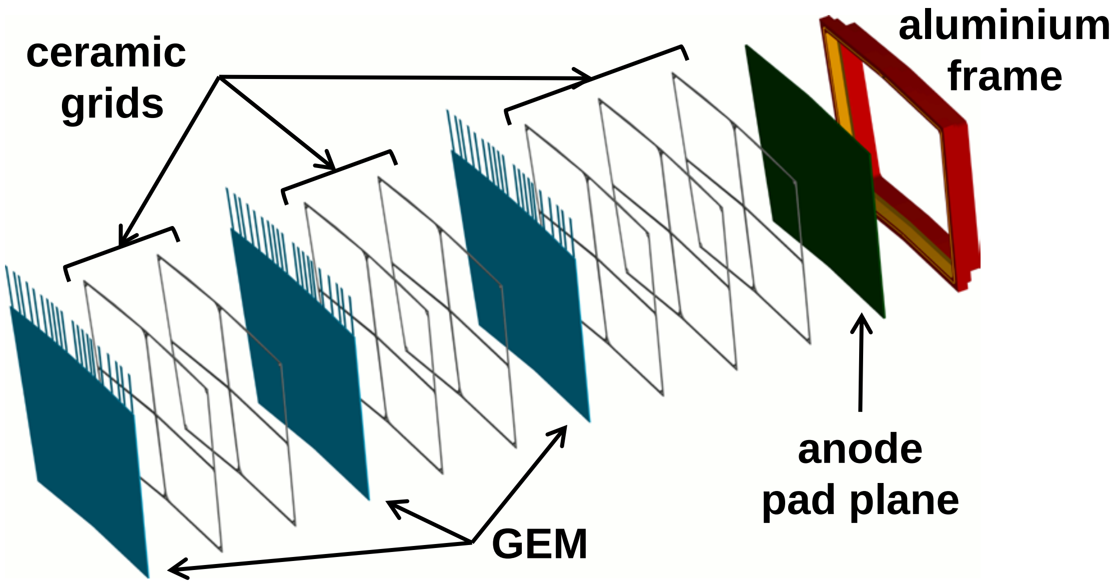
- Maximum sensitive area
- Minimal gaps
- Minimal material

Design Choices

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







The LCTPC Setup at the DESY II Test Beam Facility

DESY II

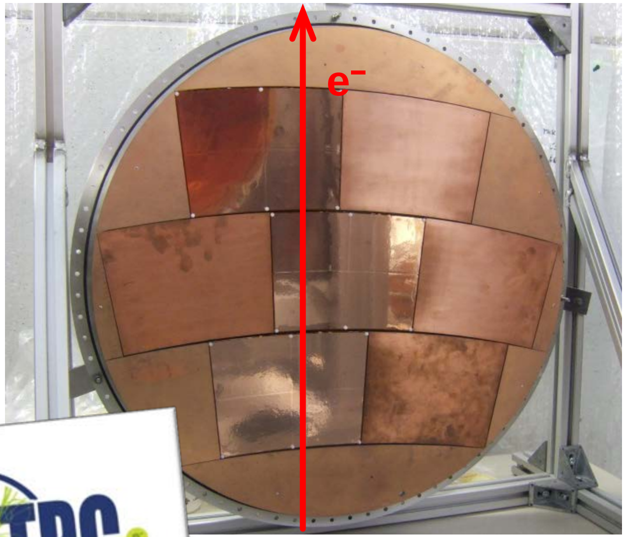
- 1 GeV to 6 GeV electrons

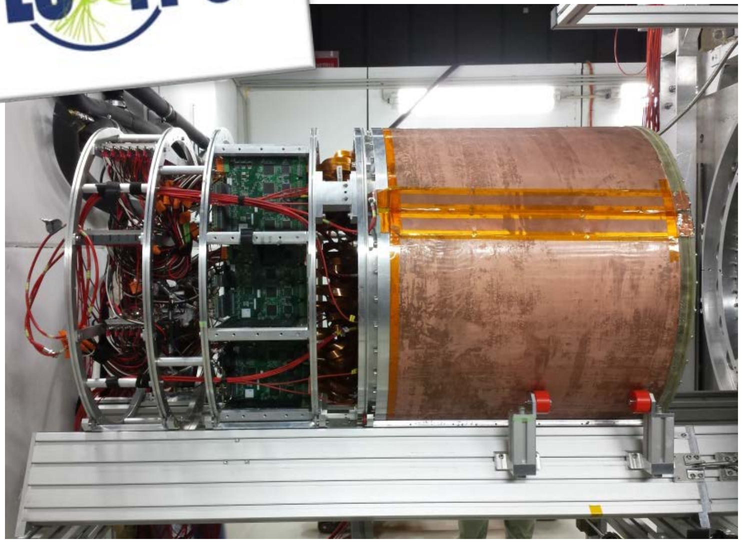
PCMag

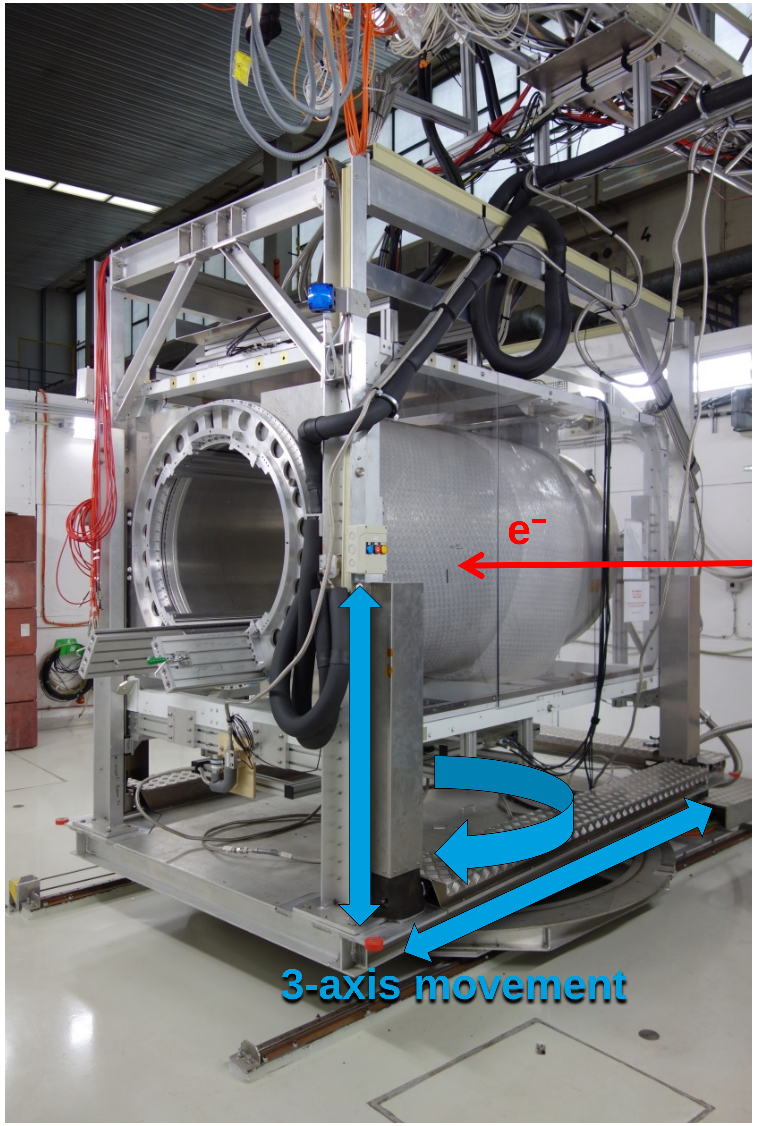
- 1 T superconducting solenoid
- 3-axis moveable stage
- 20% X_0 wall thickness
- 85 cm usable inner diameter

Large TPC prototype

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

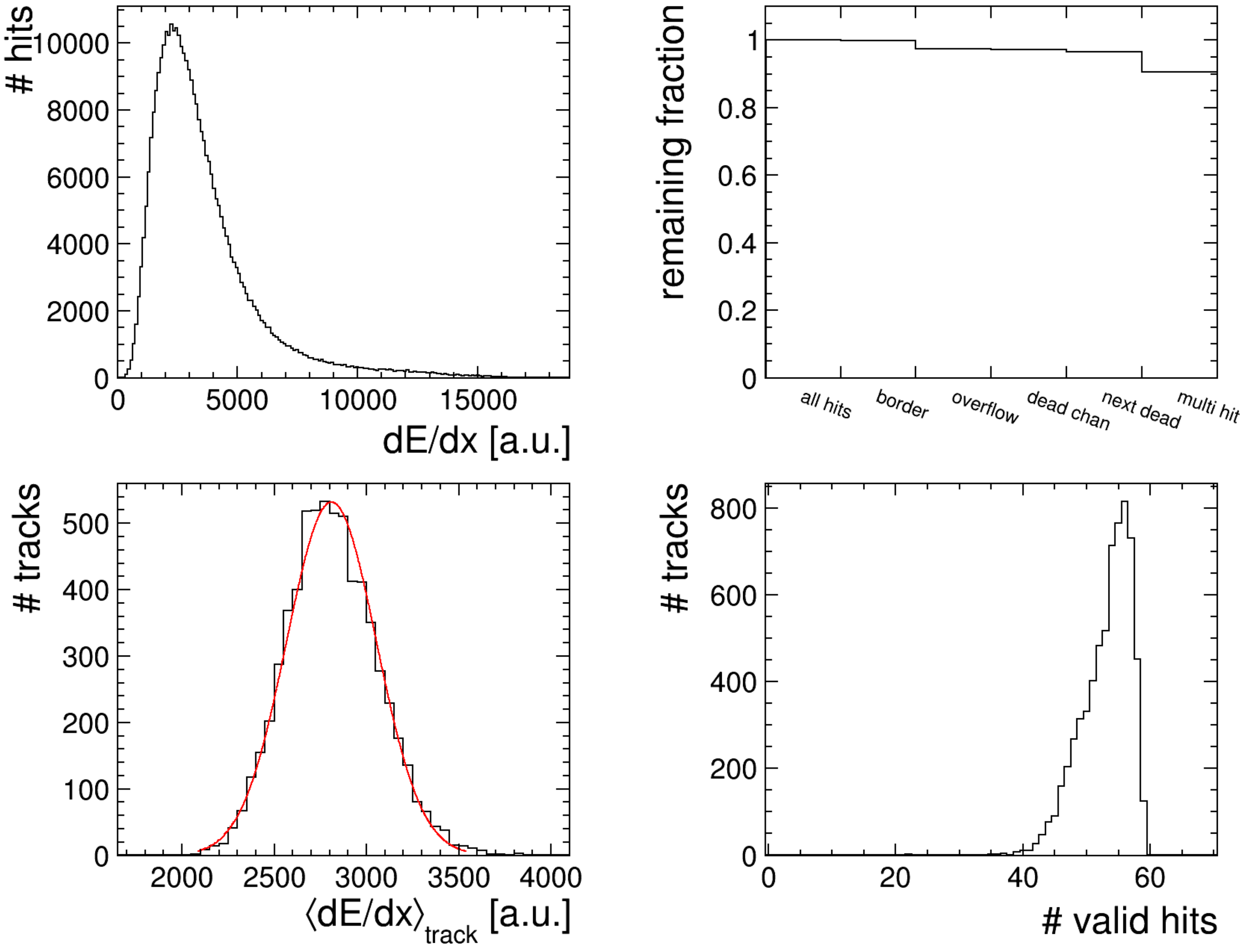






Measuring dE/dx Resolution

- 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 $est(\mathrm{dE/dx}) = 1/\sqrt{\mathrm{dE/dx}}$
- dE/dx resolution from RMS/mean in this sample is $(8.7 \pm 0.1)\%$



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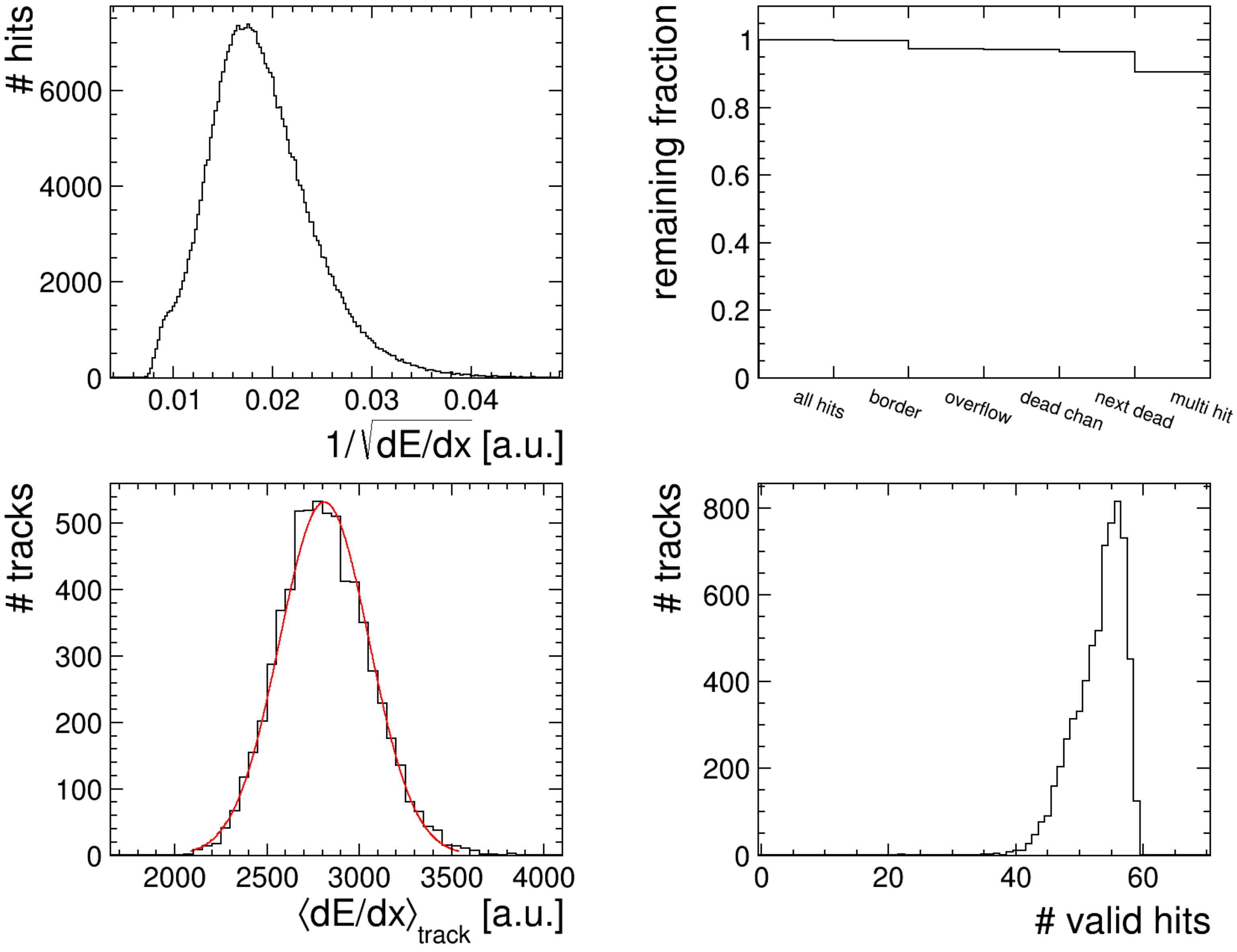
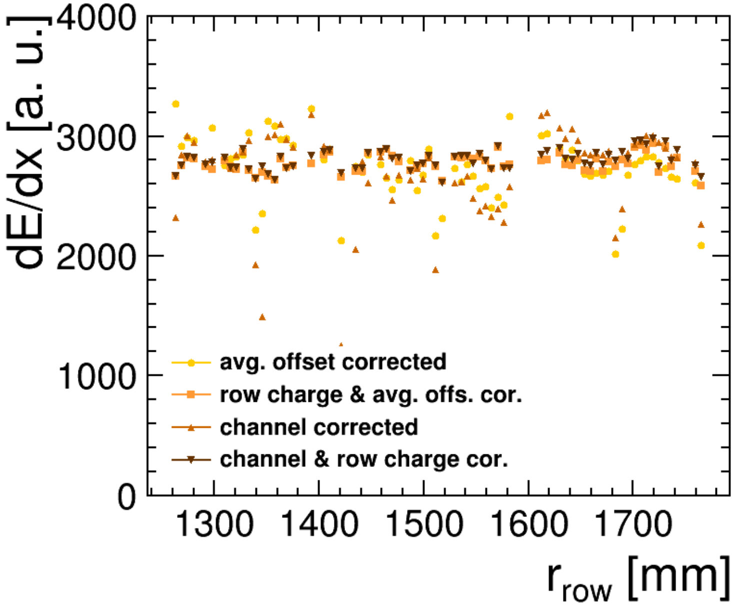
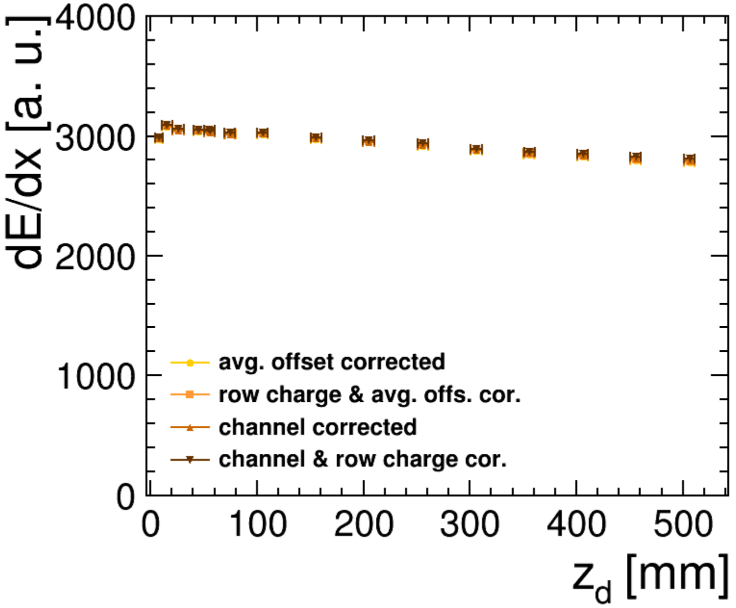
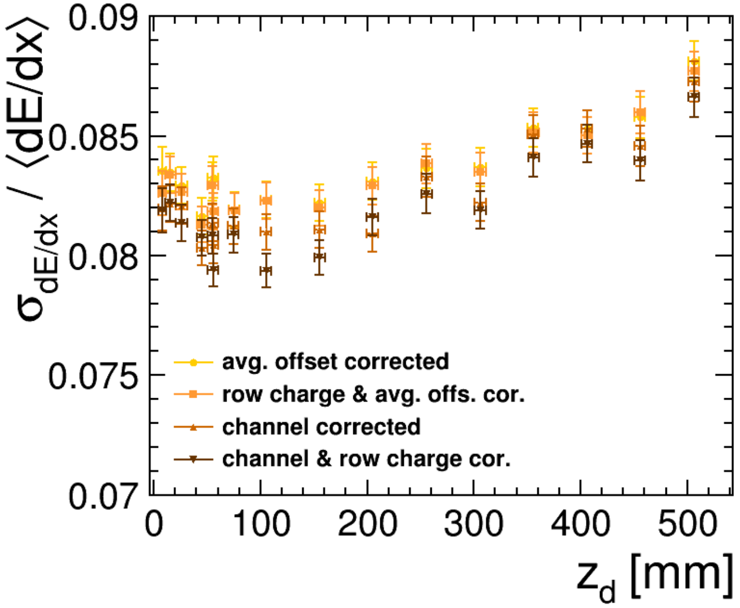


Charge Calibration

- 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.

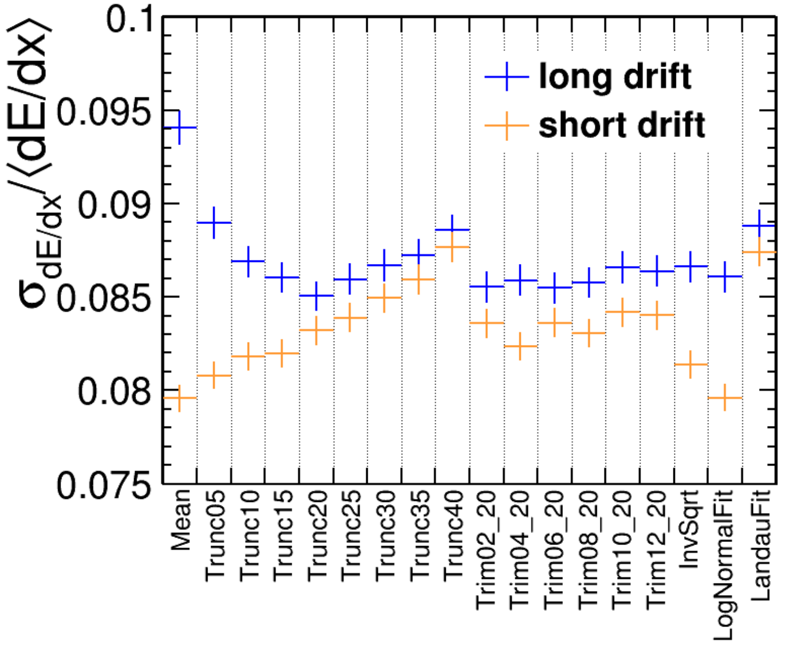


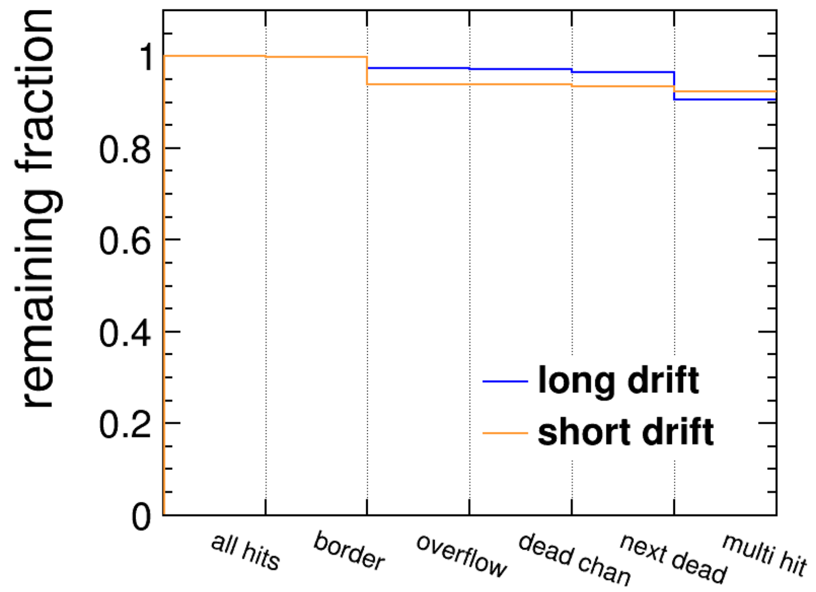




Comparing Track dE/dx Estimators

- 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.
- Overflow fraction is larger for higher ionizing particles.
  → Reduces separation between particle species.
- Overflow fraction would be minimized in real detector.
  → Use long drift data to compare estimators.





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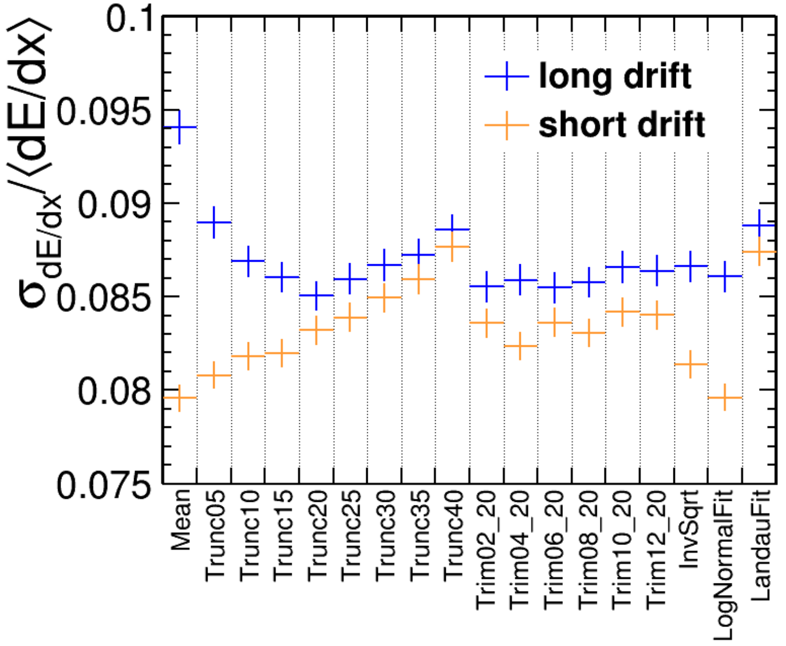
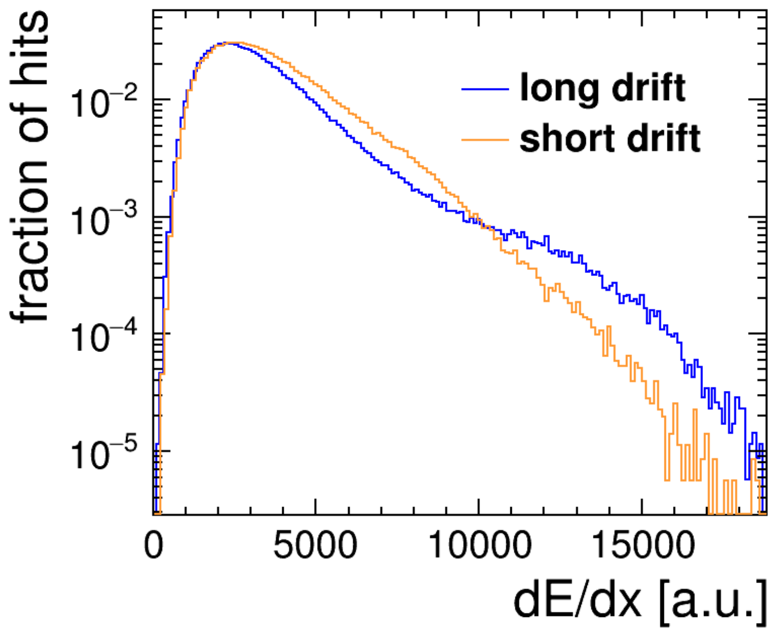
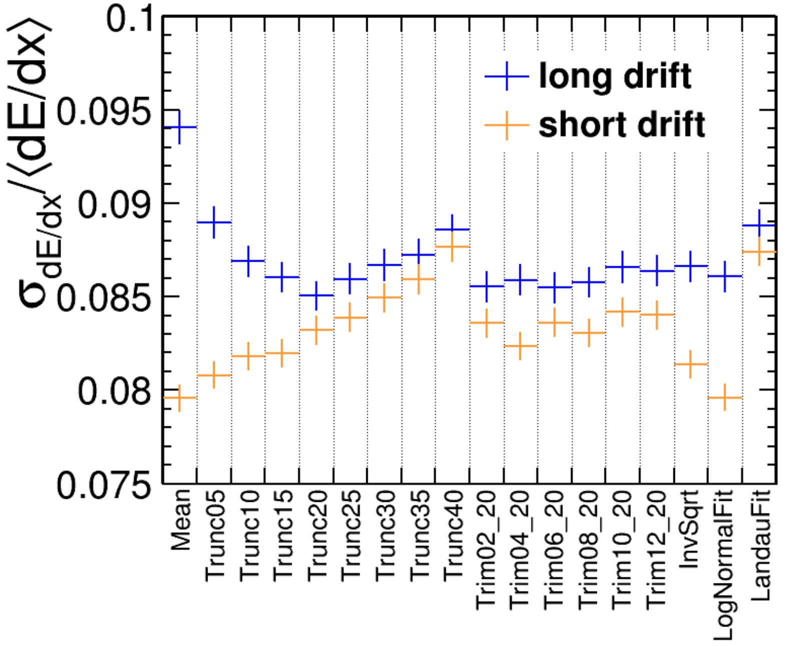
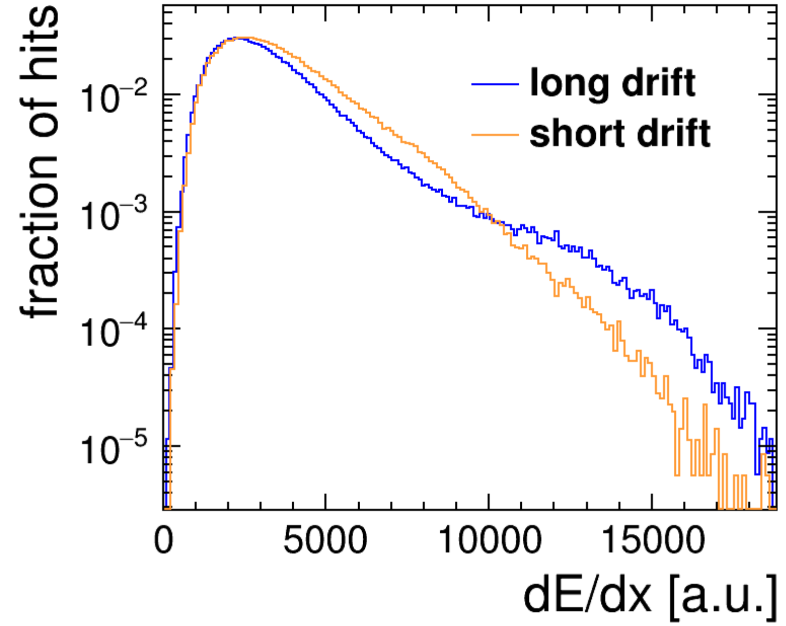




Comparing Track dE/dx Estimators

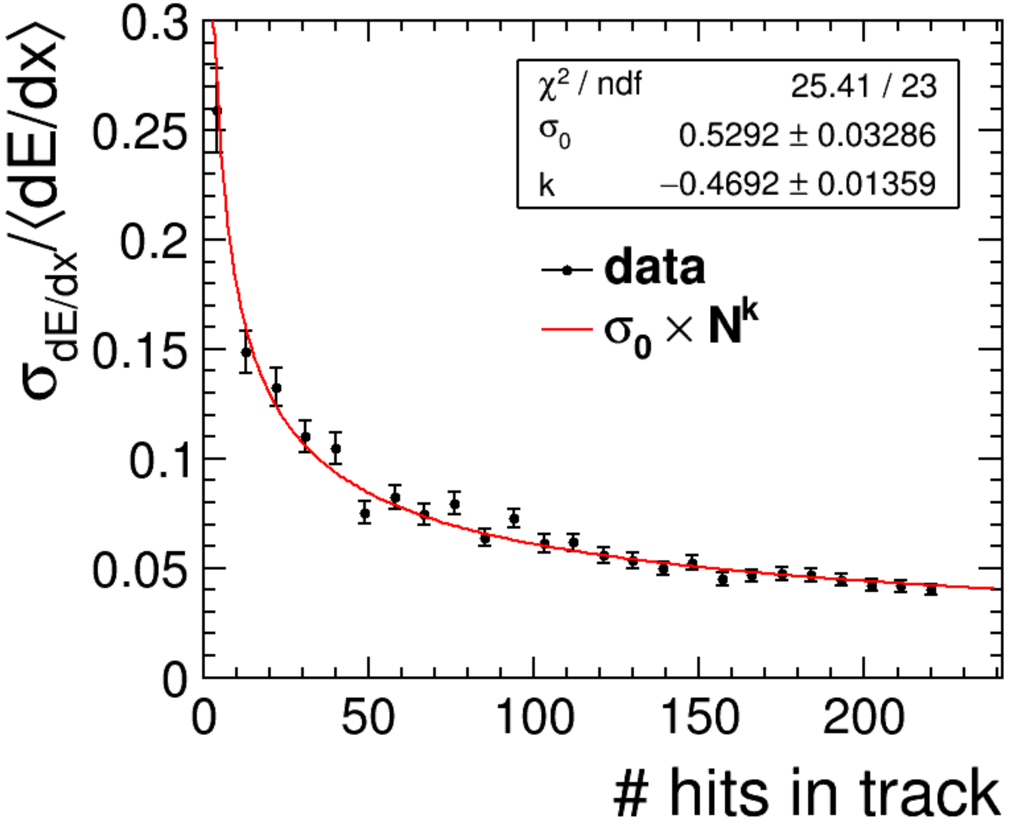
- Overflow fraction would be minimized in real detector.
  → Use long drift data to compare estimators.
- Inverted square-root method performs similarly well as truncation.
- Best truncation fraction is found to be around 20%.
- Trimming does not provide any improvement over truncation.
- Landau distribution does not describe our dE/dx distribution well.
  → No good resolution expected from fit.
- Log-normal distribution does not describe tail at long drift.
- Fitting methods need ~10 times more computing time.





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: $\sigma(\mathrm{dE/dx}) \propto \mathrm{N}^{\mathrm{k}}$
- Fitted exponents k vary between -0.45 and -0.48 for different data taking runs.
- Non-Gaussian shape of hit dE/dx distribution
  → no $1/\sqrt{\mathrm{N}}$ 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) on that length:

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

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

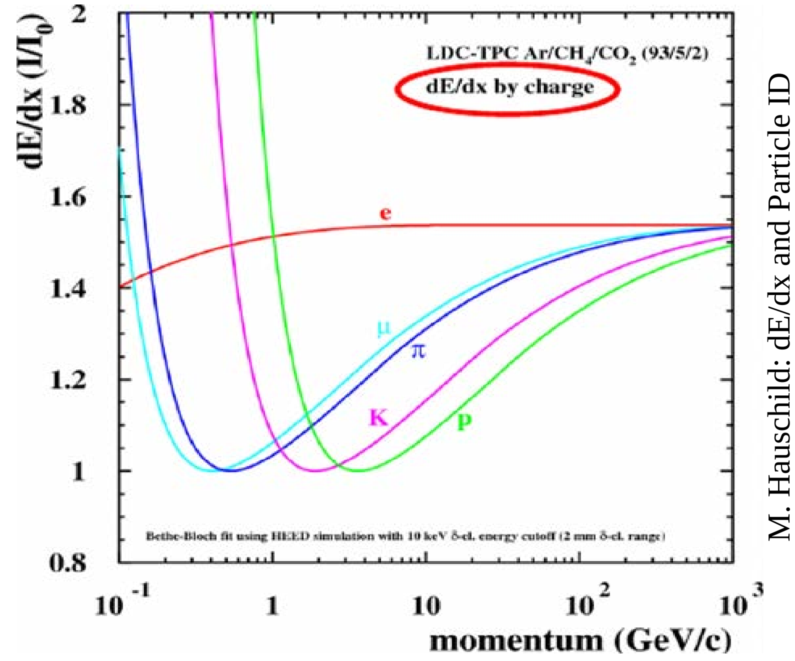
$$\sigma(dE/dx) \propto L^{-0.47} \times G^{-0.13} = H^{-0.34} \times N^{-0.47}$$

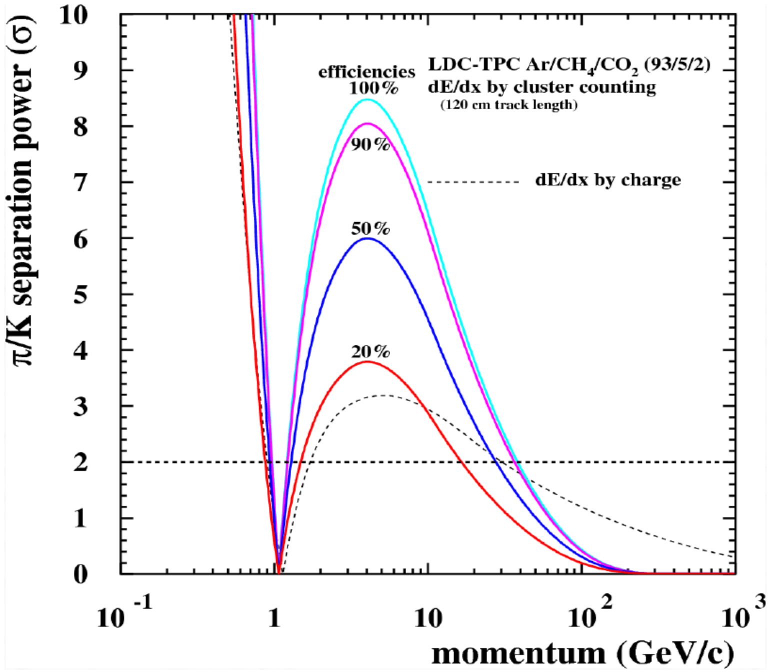
- Usual approach: Keep H constant, vary N (e.g. extrapolating to ILD).
- Here: Keep L constant, vary G.
- This should improve dE/dx resolution with conventional methods for higher granularity.
- Also check new algorithm enabled by very small pads: cluster counting.

* Blum, Riegler, Rolandi: “Particle Detection with Drift Chambers”, 2008

Cluster Counting

- Charge produced on a certain track distance is Landau distributed.
- The number of primary ionisation events on this distance is Poisson distributed
  → smaller variance → 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!

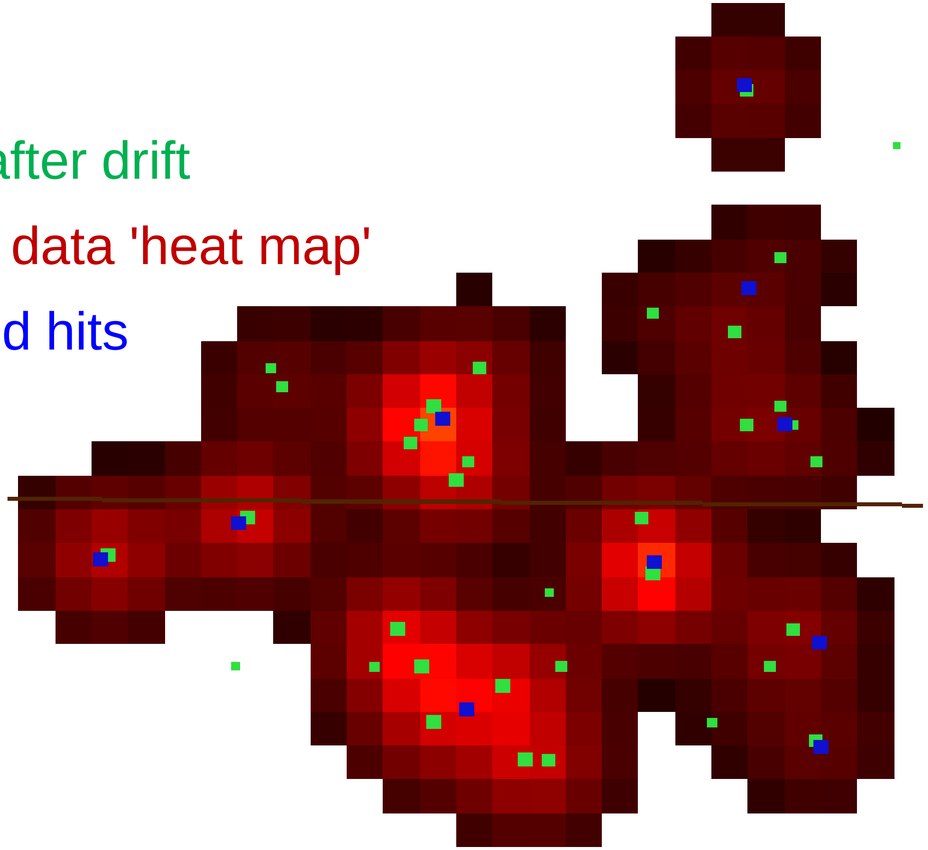




M. Hauschild: dE/dx and Particle ID Performance with Cluster Counting; at ILC Ws. Valencia 2006

Software

- Simulation with MarlinTPC in ILCSoft
- 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



Simulation
- Generate MCParticles
- Primary Ionization
- Drift
- GEM Amplification
- Projection onto Timepix
- Timepix Digitization

Reconstruction
- Export to .fits
- Source Extractor
- Import to .slcio
- Tracking: Hough Trafo

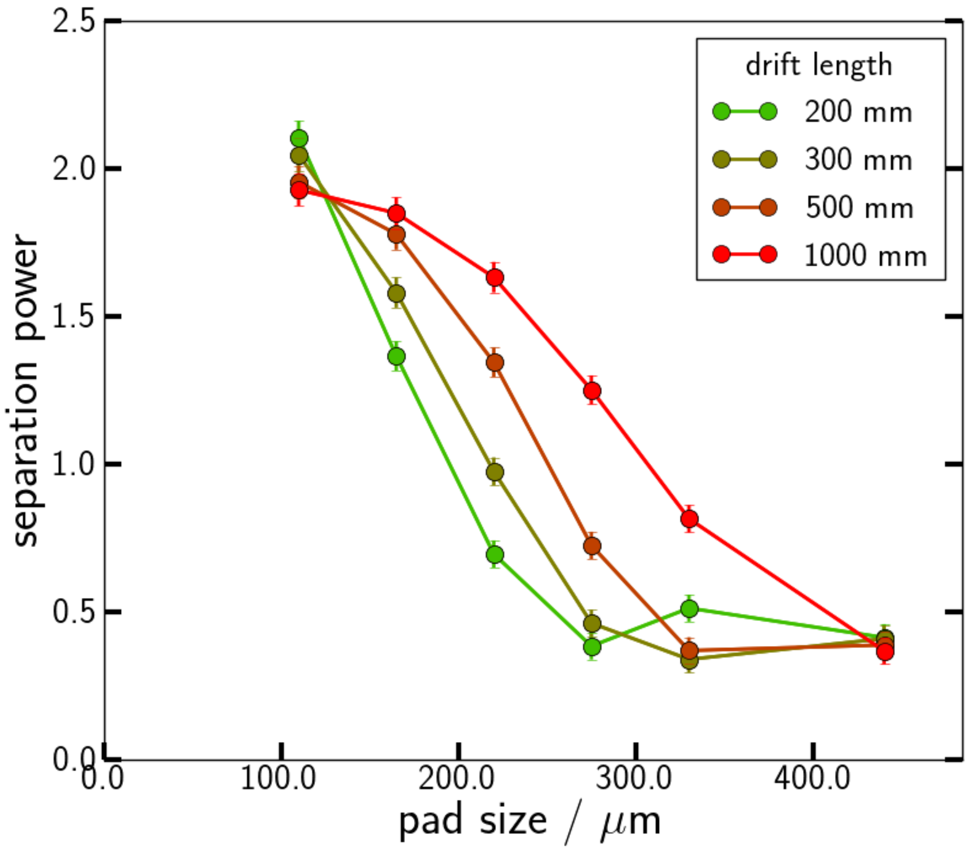
Analysis
- Analysis e.g. cluster-hit identification

Pion-Kaon Separation Power by Cluster Counting

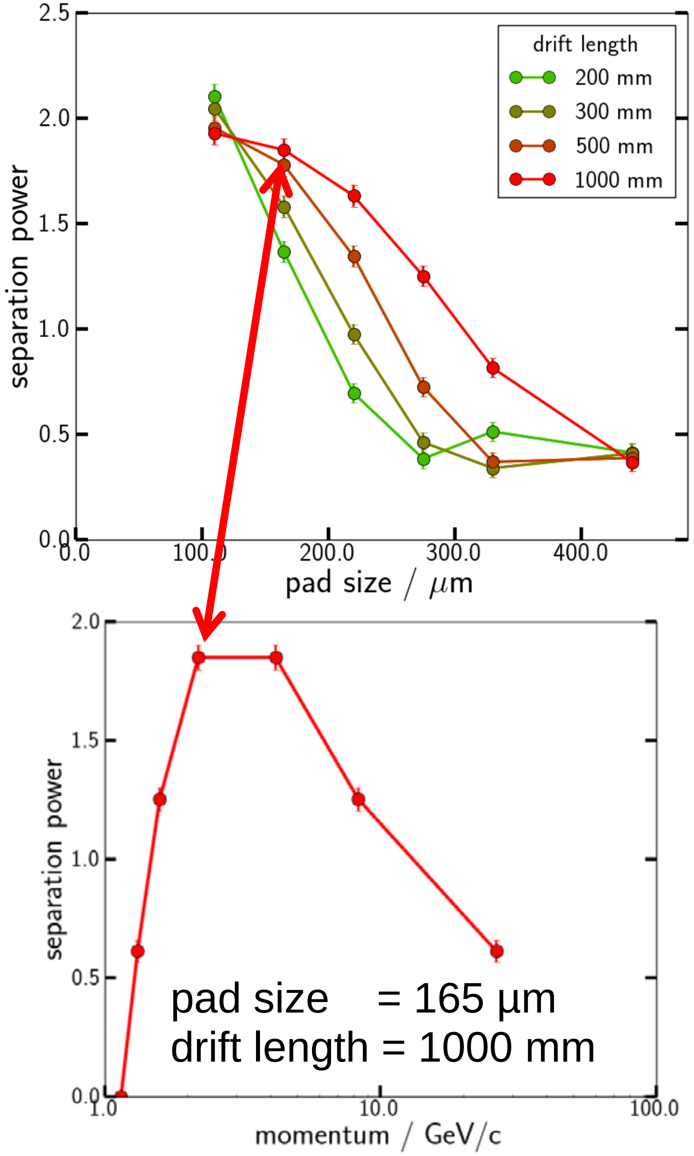
- Separation power defined as:

$$S = \frac{|\mu_\pi - \mu_K|}{\langle\sigma\rangle} = \frac{|\mu_\pi - \mu_K|}{\sqrt{(\sigma_\pi^2 + \sigma_K^2)/_2}}$$

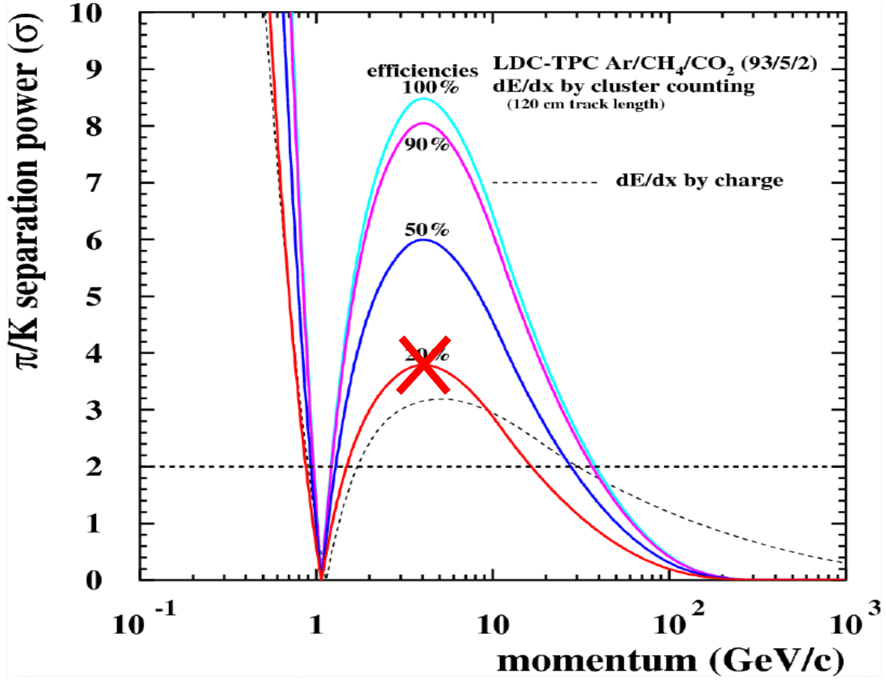
- Track length $L = 300$ mm
- $B = 1$ T
- separation for maximum ionization difference (~15 %)



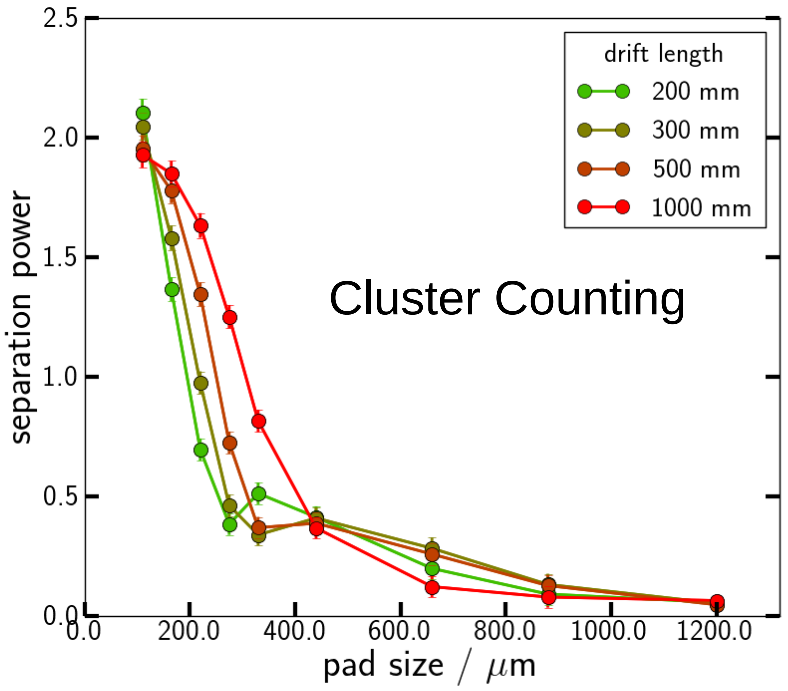
Pion-Kaon Separation Power by Cluster Counting

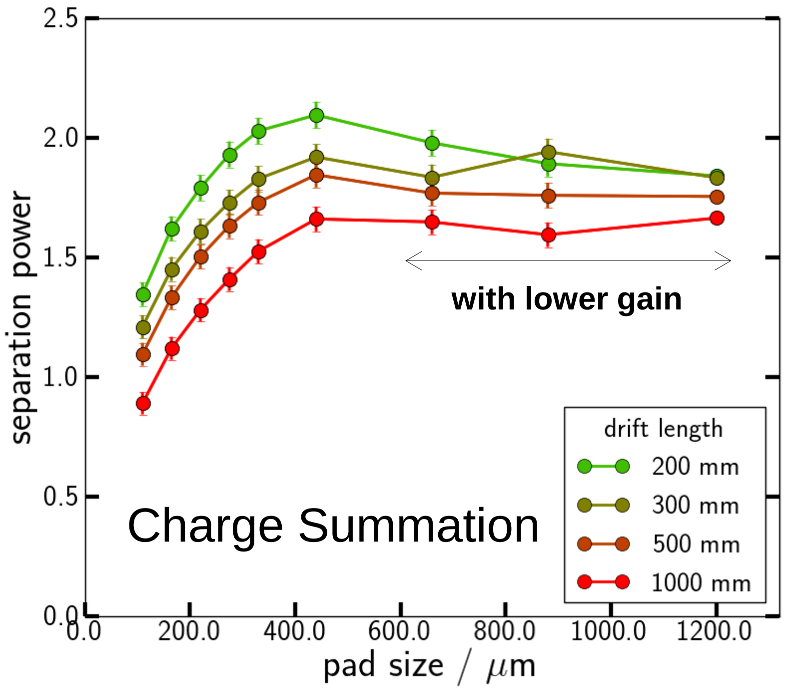


- Extrapolation by $1/\sqrt{N}$ to ILD with track length $L = 1.35$ m.
  - Gives same result as track segment combination.
- Gives a separation power of 3.8 with 165 µm pads and 3.4 with 220 µm pads.
- Improvement to conventional charge based measure.



Pion-Kaon Separation Power – Larger Pads



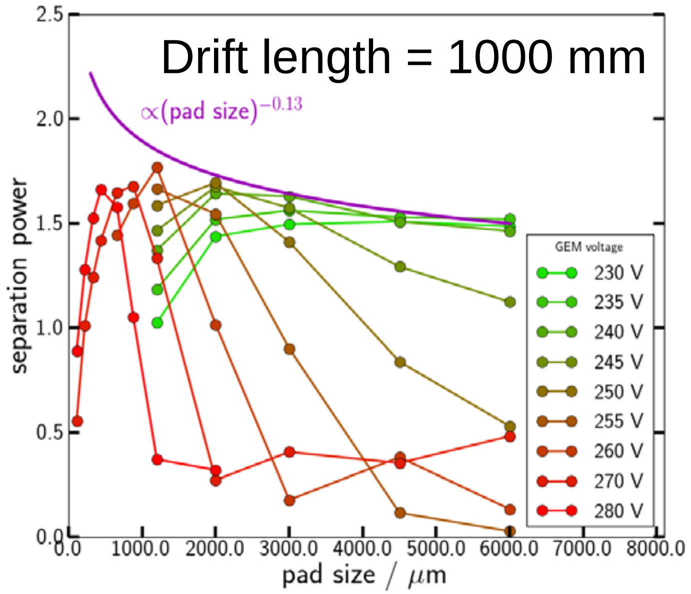


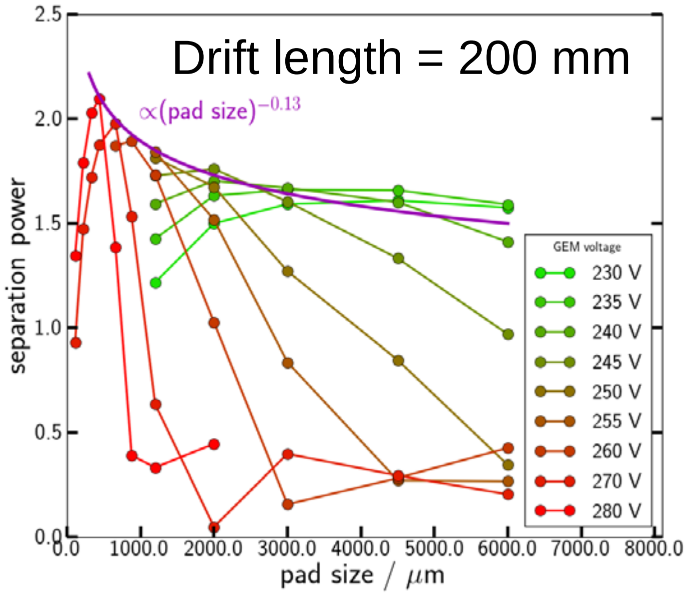
- Cluster counting breaks down at ~300 µm.
- 'Inverted' order of drift length because of less bunching, thus more single electrons are reconstructed.

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

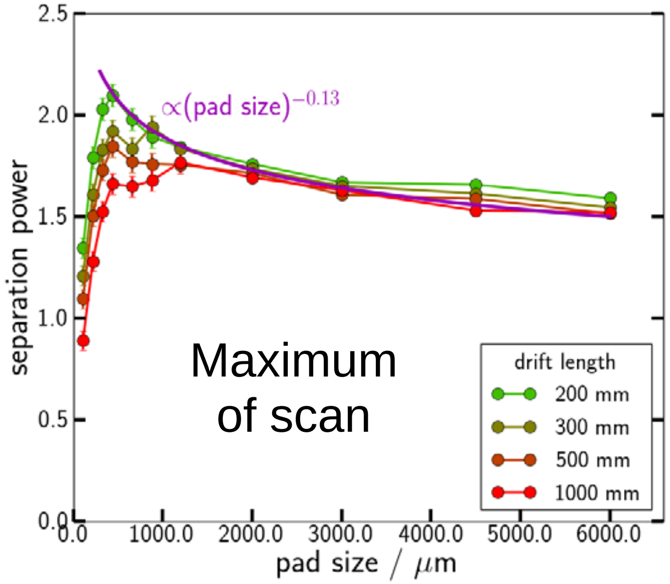
$$\sigma(dE/dx) \propto G^{-0.13}$$

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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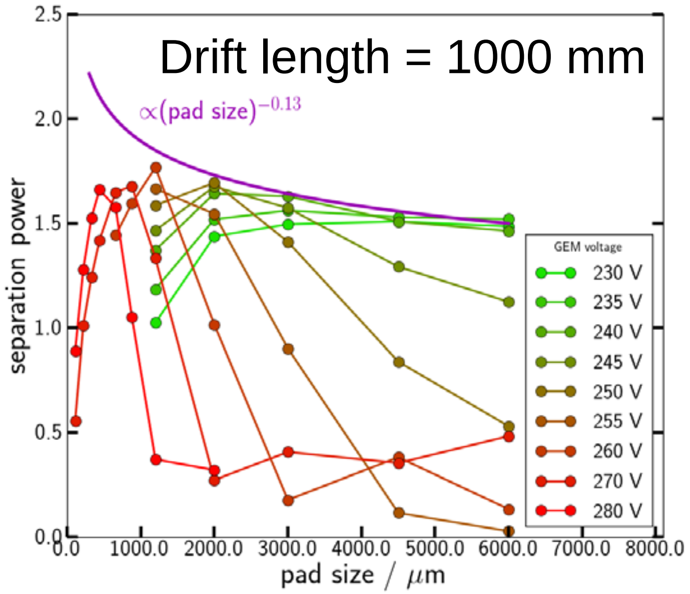

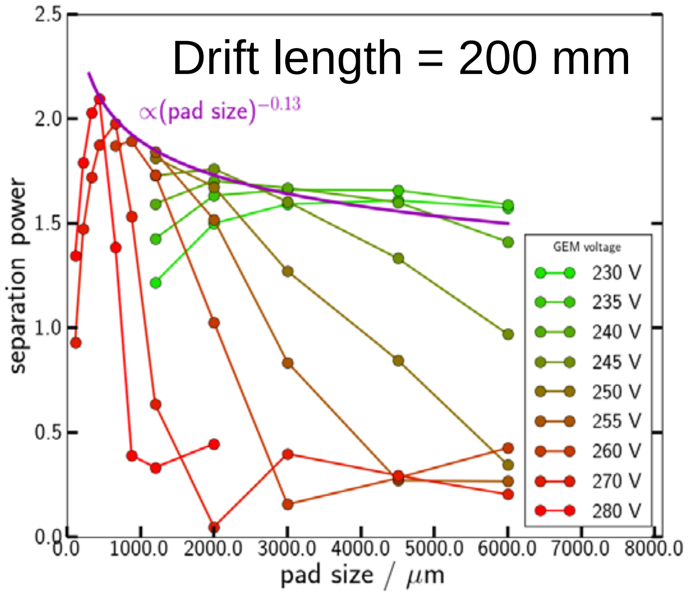

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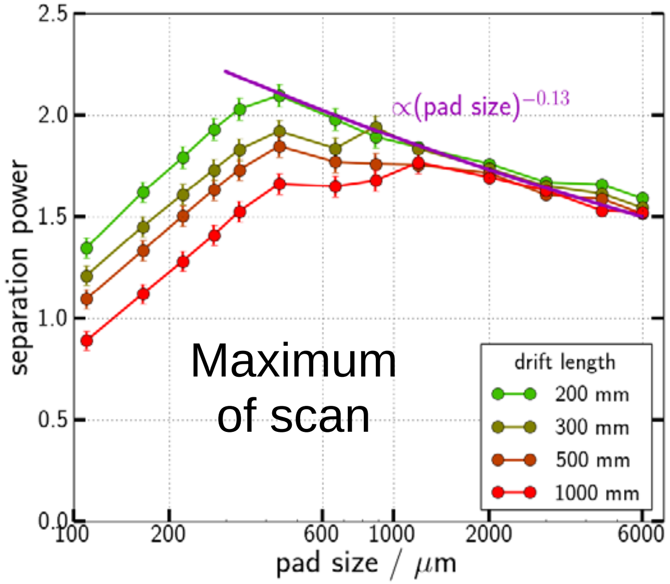
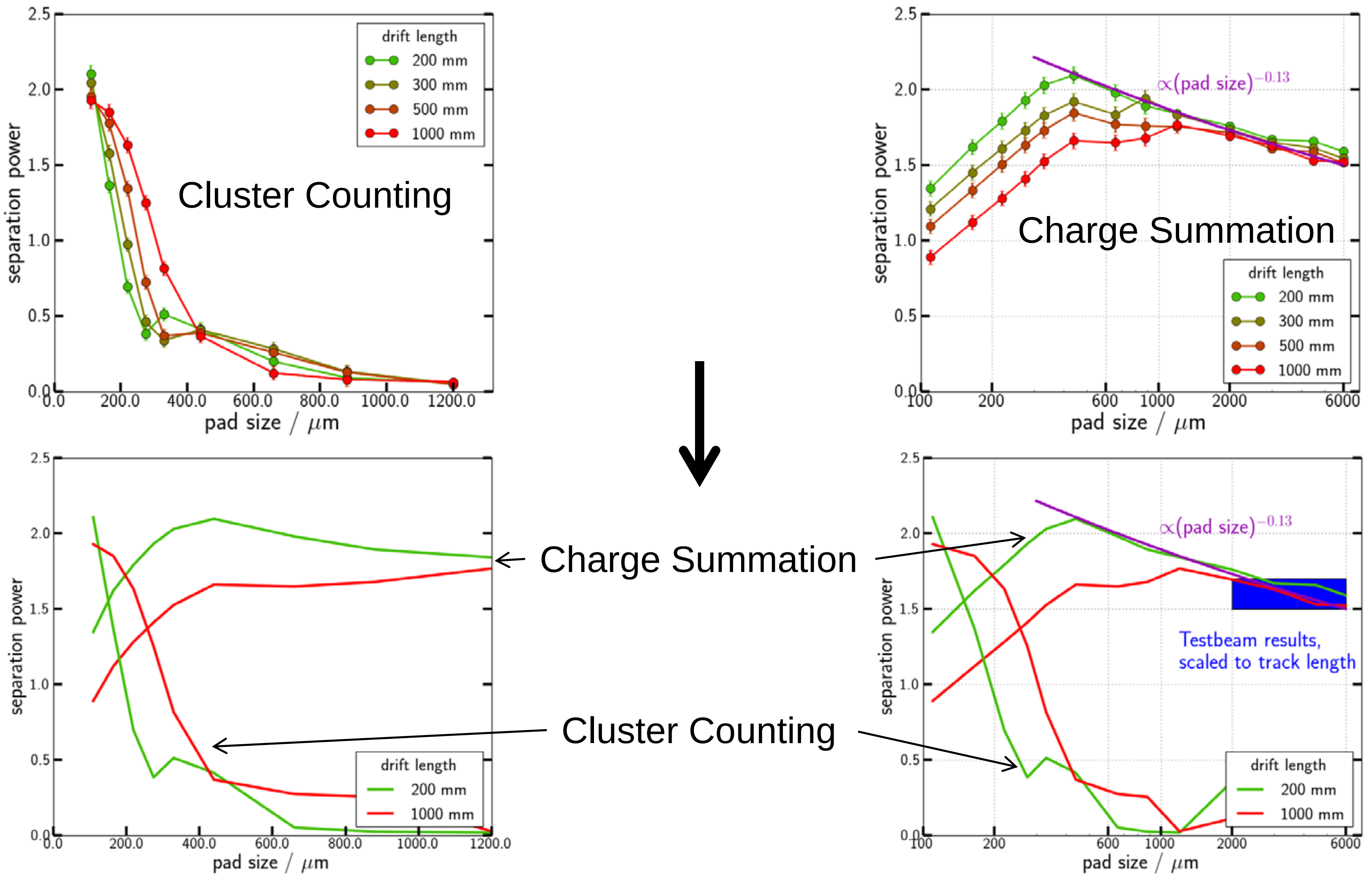


Combined Pion-Kaon Separation Power



Translation to Resolution

- For very small pad sizes, the separation power between Pions and Kaons at maximum ionization difference goes up to $S = 2$ for a track length of 300 mm.
- For a large-ILD sized TPC with 1350 mm depth this results in a separation power of $S = 4.24$, which can be translated into a resolution of 3.5 %
- A separation power of $S = 1.5$ for 300 mm would result in $S = 3.18$ at 1350 mm, which can be translated into a resolution of 4.7 %

On special request:

- Going from large to small ILD, assuming applicability of the formula on slide 14 improvement *with respect to usual small ILD* can be calculated for the cases of:
- Fixed number of rows ($\mathrm{N} = \mathrm{const.}; \mathrm{H} \propto \mathrm{r}$) → resolution improves by a factor 0.963
- Fixed number of channels and pad pitch ($\mathrm{H} \propto \mathrm{A} \propto \mathrm{r}^2$) → improves by a factor 0.955
- Results in an improvement of about 0.2 percentage points over the usual small ILD with fixed granularity.

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 ~53 valid hits.

- The dE/dx resolution for the track length of ~220 hits expected in the ILD TPC was estimated to be about $(\mathbf{4.2} \pm \mathbf{0.1})\%$ (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 µm.

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.