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

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For the International Large Detector (ILD) at the planned International Linear Collider (ILC) a Time Projection Chamber (TPC) is foreseen as the main tracking detector. To achieve the required point resolution, Micro Pattern Gaseous Detectors (MPGD) will be used in the amplification stage. A readout module using a stack of three Gas Electron Multipliers (GEM) for gas amplification was developed at DESY. In a test campaign at the DESY II Test Beam Facility the performance of three of these modules was investigated. In this contribution results were presented on the particle identification capabilities of the system using the specific energy loss ($dE/dx$). The results from the prototype were used to extrapolate to the performance of the full ILD TPC, where a $dE/dx$ resolution of better than 5% could be achieved. In addition, simulation studies were performed to optimise the readout pad size for improved $dE/dx$ separation power. These studies also investigated the possibility to measure the deposited energy by counting the number of ionisation clusters (cluster counting). For small enough pads this approach was found to give similar or better performance compared to the traditional method of measuring the deposited charge.
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## 1 Project Background

This R&D project is part of the design effort for the International Large Detector (ILD, [1]) at the planned International Linear Collider (ILC, [2]). The FLC TPC group at DESY is a member of the LCTPC collaboration [3], which is driving the efforts of developing a Time Projection Chamber (TPC) for the ILD. Different readout and amplification technologies based on micro pattern gaseous detectors (MPGD) are currently studied within the collaboration. FLC TPC is developing a readout module with a gas amplification stage composed of Gas Electron Multipliers (GEM, [4]) mounted on thin ceramic grids.

The feasibility of using GEM mounted on thin ceramic grids in a TPC amplification stage was first demonstrated with 10 cm × 10 cm GEM [5]. In the next step, measurements were performed at the DESY II test beam with a series of larger readout modules. With this data it was shown that the design goals for the ILD TPC regarding spacial resolution could be reached [6, 7]. A new generation of three modules was build for the beam tests described in Section 2, using improved tooling described in [8].
2 Determining $dE/dx$ Resolution from Beam Tests

Beam tests were performed at the DESY II Test Beam Facility with a large TPC prototype inside a 1 T solenoid magnet (Section 2.2). Three readout modules with a GEM gas amplification stage were used (Section 2.1) in the measurements for the determination of the $dE/dx$ resolution (Section 2.3).

2.1 The DESY GEM Module

In Figure 1 the GEM module and its major components are shown. The footprint of a module is a sector of an annulus with an inner radius of 1400 mm and an outer radius of 1600 mm encompassing about 8.4°, similar to the geometry of the readout modules intended for the ILD TPC. The mechanical base of the module is an aluminium back frame, which is used to mount it in the TPC end plate. A printed circuit board carrying the segmented readout anode is glued onto the back frame. The 4832 readout pads are arranged in 28 concentric rows with a pitch of 1.2625 mm along the rows and 5.85 mm row pitch. On top of the pad board, the amplification structure is build up out of three GEMs supported by 1 mm high alumina-ceramic ($\text{Al}_2\text{O}_3$) frames. Additional frames serve as spacers between the GEM foils to define the transfer and induction gaps of 2 mm and 3 mm, respectively, as shown in Figure 1b. Since the frame bars are only 1.4 mm wide and the space needed for the high voltage connections of the GEMs was kept at a minimum, the module has a sensitive area of over 90%. The readout electronics are based on the ALICE TPC ReadOut (ALTRO) analog-to-digital converter (ADC) chip and the PCA16 pre-amplifier [9, 10]. The ALTRO chip provides digitisation with 10 bit resolution at sampling frequencies of 5 MHz, 10 MHz or 20 MHz. At 40 MHz the effective resolution is reduced to about 8.5 bit. For the beam tests it was run at 20 MHz to make use of the full resolution.

(a) A fully assembled GEM module. (b) Explosion view of the module.\(^1\)

Figure 1: The DESY GEM module and its major components.

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2.2 The LCTPC Prototype Setup

For the development of the different technologies the LCTPC collaboration build a common setup at the beam line T24/1 at the DESY II Test Beam Facility. The beam line delivers electrons with energies up to 6 GeV at rates of about 100 Hz and up to several kHz for lower energies [11]. Four scintillator fingers are placed into the beam to provide a coincidence signal as a trigger for the main setup.

The first part of the setup is a large TPC prototype (LPTPC) with about 570 mm maximum drift distance and a diameter of 75 cm. The anode end plate shown in Figure 2a provides slots for seven readout modules arranged in three rows. The measurable track length perpendicular to these rows is about 500 mm. Unused slots can be closed with dummy modules for an uniform termination of the drift field. The field-cage wall constitutes a little more than 1% of a radiation length $X_0$ [12].

A superconducting solenoid magnet generating a 1 T magnetic field, the so-called Persistent Current Magnet (PCMag), is installed in the experimental area of the beam line. As shown in Figure 2b, it is mounted on a movable stage, which can be translated vertically and horizontally perpendicular to the beam axis, as well as rotated around the vertical axis to change the angle of the beam inside the TPC. The usable inner diameter of the magnet measures 85 cm. Due to a lightweight construction without a field return yoke, the magnet walls make up only about 20% of a radiation length [13]. This is especially important as the electron beam has to pass through the magnet wall to reach the TPC inside and any material in front of the TPC deteriorates the beam quality.

![LPTPC anode end-plate.](image1) ![PCMag in area T24/1 at DESY II.](image2)

**Figure 2:** The LCTPC test beam setup. (a) The inside of the anode end plate of the LPTPC with its seven module slots. The three mounted modules are distinguishable by their shinier surface. (b) The PCMag on its movable stage.

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A gas system, described in [14], provides a constant flow rate of the chosen gas, which in this tests is the gas mixture used in the TPCs in the near detector of the T2K experiment [15]. The T2K gas mixture with the three components argon, tetrafluoromethane (CF₄) and 2-methylpropane (isobutane; HC(CH₃)₃) in a ratio of 95 : 3 : 2, was chosen as a candidate for the ILD TPC because of its high drift velocity and low diffusion allowing for good spacial resolution at long drift distances, as well as its high defocussing in the amplification region for improved charge sharing.

The beam test was performed with a nominal beam energy of 5 GeV. The drift field was chosen as 240 V cm⁻¹, close to the maximum of the drift velocity in T2K gas.

2.3 Reconstruction & Analysis

For the reconstruction and analysis of the beam test data packages from the the iLCSof environment are used [16]. The raw data from the readout electronics are converted into the LCIO format [17]. Then the reconstruction and analysis of the data are performed with Marlin [18], using the processors and scripts in the MarlinTPC package [19].

The raw data consist of a stream of digitised charge values for each channel. In the reconstruction each stream is searched for an excess of charge consistent with the arrival of a signal, so-called pulses. Signal like pulses are required to exceed a minimum threshold for a limited amount of samples. The pulses contain the full time information, the only spacial information is the pad position. Hits are created from neighbouring pulses by searching for local maxima inside one pad row and combining pulses around these. An accurate position parallel to the row is calculated as the charge weighted mean position of the contributing pulses. Since most tracks are expected to cross the rows mostly perpendicular, the position within the row pitch is assumed as the centre of the row. The arrival time of the maximum charge pulse and the known drift velocity are used to determine the position in the drift direction. The charge of the hit is set to the sum of the charge of the corresponding pulses. If the hit includes a pulse, in which a second rise was detected, it is flagged as a multi-hit candidate. Finally, a track finder based on a Hough transformation algorithm is applied on the hit level [20], and all found tracks are subsequently fitted using the General Broken Lines method [21].

2.3.1 Determination of dE/dx Resolution

To avoid contamination of the charge values from overlapping tracks, the dE/dx analysis is only performed on events with a single reconstructed track. As some of the beam electrons lose a lot of energy in the magnet wall and the energy loss curve for electrons drops significantly below energies of about 1 GeV, an equivalent cut on the track curvature is applied.

The average energy loss on a track is calculated from the charge of all hits, that were linked to the track by the track finder. To reduce biases from the measured charge values the hits need to fulfil the following quality criteria:

- Not be at the module edge, as charge could not be fully recorded.
(a) Cumulative efficiency of the cuts. (b) Distribution of valid hits per track.

Figure 3: Effect of the cuts on hit quality applied for the determination of the mean $dE/dx$ of a track. Short and long drift are 20 mm and 500 mm, respectively.

(a) The cumulative efficiency of the cuts. The at module edge cut does not include hits on the first and last row of a module, as those are treated separately. (b) The resulting distribution of the number of valid hits on each track.

- Contain no pulses that saturated the range of the digitiser.
- Contain no dead channels or be right next to one.
- No multi-hit candidate as determined by the pulse finder based on the pulse shape.

Figure 3 shows the cumulative efficiency of these cuts for two different drift distances and the resulting distribution of the number of valid hits on each track. As detailed in Section 2.3.3, the rejection of hits with saturated pulses introduces a bias depending on the drift distance. As the charge cloud is spread over more pads due to diffusion, the average charge per pulse is reduced. Since the average hit charge stays the same, this cut removes more hits with lower charge at short drift distances than at long drift distances. To minimise the influence of this cut, the results shown here were taken a large drift distance, were the fraction of saturated pulses is lowest. Regarding the multi-hit cut, at the time of performing this analysis the hit finder algorithm did not identify multi-hit candidates in the readout plane along a pad row. Only tagging in drift direction is done by the pulse finder as mentioned in the introduction of Section 2.3.

The energy loss per track length $dE/dx$ for each hit is calculated by dividing the hit charge $Q_{hit}$ by the length of the reconstructed track segment $\Delta s$ above the pad row corresponding to the hit.

$$ (dE/dx)_{hit} = \frac{Q_{hit}}{\Delta s}. \quad (1) $$

The $dE/dx$ spectrum of all hits remaining after cuts is depicted in Figure 4a. As expected it shows a Landau-like distribution with a long tail towards high charge values,
Figure 4: The \( \frac{dE}{dx} \) distribution of all hits after cuts. (a) The untreated distribution shows the long Landau-like tail to high values. (b) Transforming the \( \frac{dE}{dx} \) values according to Equation (2) compresses the tail and results in a more symmetric distribution.

Figure 5: Distribution of the average \( \frac{dE}{dx} \) of tracks. A Gaussian fit was applied in a 3\( \sigma \)-range around the mean. The \( \chi^2/ndf = 52.36/26 \) of the fit reflects the slight asymmetry visible in the distribution.
which is suppressed by the dynamic range of the readout electronics. To suppress the influence of these hits, adapting the method used in [22] each hit charge is transformed according to

\[
\frac{dE}{dx}_{\text{trans}} = \frac{1}{\sqrt{\left(\frac{dE}{dx}\right)_{\text{hit}}}},
\]

which results in a narrower and more symmetric distribution, shown in Figure 4b. To calculate the average energy loss of the track the mean of the transformed \(dE/dx\) values of the connected hits is taken and the inverse transformation is applied:

\[
\frac{dE}{dx}_{\text{track}} = \left(\frac{\sum_{\text{hits}} \left(\frac{dE}{dx}\right)_{\text{trans}}}{N_{\text{hits}}}\right)^{-2}.
\]

The distribution of the track mean \(dE/dx\) values, shown in Figure 5, is almost Gaussian except for a small residual tail towards higher values, most likely arising from untagged multi hits. For this reason the \(dE/dx\) resolution is not calculated from the fit parameters, but from the RMS of the smallest interval containing 90% of the entries (RMS\(_{90}\)). The relative resolution in this sample after applying the calibrations from Section 2.3.2 was thereby determined to be \((8.7 \pm 0.1)\%\).

2.3.2 Charge Calibration

In an attempt to imitate the calibrations done for the charge measurement in the final detector, two correction methods were devised. Since the electronics do not provide the possibility for a self-calibration of the readout channels, a similar result could be achieved by pulsing the common electrode of the GEM directly above the readout pads. By varying the amplitude of the pulses the charge induced in the pads changes accordingly, and a calibration factor \(s_{cc}\) and offset \(o_{cc}\) for each channel was gained. The pulse charge is then corrected as \(q_{\text{cor}} = \left(\frac{q_{\text{meas}}}{s_{cc}}\right) - o_{cc}\). Due to the difference in permittivity this calibration is not valid for channels close to the ceramic frames. Therefore, all rows next to the frame were ignored in all analyses.

The second correction targets local inhomogeneities of the gas amplification. Since the electron beam is not moved during data taking, most tracks pass over each row in about the same spot. Therefore, a correction factor can be calculated for each row instead of each pad. To avoid biases from the local track angle, the \(dE/dx\) value of the hits is used instead of the raw charge. The correction factor for a row \(f_{\text{row}}\) is then calculated from a subset of the data as the mean on this row \(\langle dE/dx \rangle_{\text{row}}\) divided by the average of all rows:

\[
f_{\text{row}} = \frac{\langle dE/dx \rangle_{\text{row}}}{\sum_{\text{rows}} \langle dE/dx \rangle_{\text{row}} / N_{\text{rows}}}.
\]

The hit charge in the rest of the data is accordingly corrected as \(Q_{\text{cor}}^{\text{hit}} = Q_{\text{hit}} / f_{\text{row}}\).

Figure 6a shows the impact of both corrections on the spread of the mean charge between individual rows. It is clearly visible, that the correction of the average row charge leads to a much more uniform response. Especially the rows at the module
Figure 6: (a) The average $dE/dx$ on each row with different applied corrections.
(b) The resulting resolution at each measured drift distance. The increase towards higher drift distances is caused by the changing fractions of saturated pulses and multi-hits, as well as electron attachment due to oxygen contamination.

2.3.3 Comparison of $dE/dx$ Estimators

Various methods exist to calculate the average $dE/dx$ of a track, that treat the Landau-tail differently. The most commonly used method is the truncated mean, where a specified fraction of the hits with the highest $dE/dx$ is removed from each track for the calculation of the mean. In some cases this can be improved by additionally removing a small fraction of the hits with the lowest $dE/dx$. This method is called trimmed mean. Another method, adapted from [22], relies on the transformation of the hit charges using Equation (2) to suppress the influence of the tail. Increased computing power allows to try and fit the $dE/dx$ spectrum for each track. Here, the challenge is to find the correct description of the distribution. The Landau distribution, which is only valid for very short sample lengths and therefore does not describe the distribution in Figure 4a well, was tested for comparison purposes. A better fit is achieved by a log-normal distribution, but this does not match the tail.

A comparison of all methods for different cut-off fractions for the truncated and
trimmed mean are shown in Figure 7a. The first thing to note is the large disparity between the two drift distances in the performance of the truncated mean at low truncation fractions. As mentioned in Section 2.3.1, this is caused by the cut on saturated pulses rejecting less hits at higher drift distances due to the larger spread of the charge over more pads. In Figure 7b, the effect of this difference on the shape of the hit dE/dx distribution can be seen. For shorter drift distances below about 100 mm, the tail is completely suppressed and the distribution is perfectly log-normal. This leads to a much better resolution from the low truncation fractions, the inverse-root transformation method and of course the log-normal fit. Since this cut depends on the probability to find a saturated pulse in a hit, it also introduces a bias depending on the primary ionisation density and thus the particle species. Therefore, rather than applying this cut, the fraction of saturated pulses should be kept low by reducing the amplification to achieve the best possible separation power.

For the long drift data with less saturated pulses, the best resolution of (8.5 ± 0.1) % is achieved at a truncation cut-off fraction around 20 %. Additional trimming does not improve upon that. From the two fitting functions, as expected, the log-normal performs better giving a resolution of (8.6 ± 0.1) % compared to the Landau fit with (8.9 ± 0.1) %. Looking at the log-normal fit in the short drift data, where the tail is absent, shows what is possible with a function that matches the underlying distribution almost perfectly with a resolution of (8.0 ± 0.1) %. Generally, the fitting still increases the computing time by a factor of 10, which may not be feasible for the scale of the full ILD data. The inverse-
root method with \((8.7 \pm 0.1)\%\) gives a slightly worse resolution than the best truncated mean. Still it was decided to use this method, as it results in a more symmetric and Gaussian like \(dE/dx\) distribution on hit level and therefore should be less biased.

### 2.3.4 Extrapolation to the ILD TPC

To estimate the performance of a full scale ILD TPC, the results from the prototype measurements need to be extrapolated. Since the tail of the underlying energy loss distribution is cut off due to the finite dynamic range of the electronics, a scaling of \(\sigma_{dE/dx} \propto 1/\sqrt{N_{\text{hits}}}\) with the number of hits \(N_{\text{hits}}\) cannot be assumed. Instead, a power law with an exponent \(k < 0.5\) is expected (see also Equation (7)):

\[
\sigma_{dE/dx} \propto (N_{\text{hits}})^{-k}. \tag{5}
\]

Since the number of valid hits in the prototype is limited to 60 and does not vary greatly (see Figure 3b), an extrapolation to the 220 hits of the ILD TPC using only the existing tracks includes large uncertainties. To circumvent this restriction, randomly selected hits from multiple tracks were combined to form pseudo-tracks of arbitrary length. Since Marlin processes events sequentially, this is limited to hits from consecutive events.

Applying this method the results shown in Figure 8 were generated. The power-law fit returns an exponent \(k = 0.47 \pm 0.01\) and an intrinsic fluctuation for single hits \(\sigma_0 = (53 \pm 3)\%\). This leads to an estimate for the resolution at 220 hits of \(\sigma_{dE/dx}(220) = (4.2 \pm 0.1)\%\). For the smaller version of the ILD TPC with only 165 rows the resolution is \(\sigma_{dE/dx}(165) = (4.8 \pm 0.1)\%\). These values assume all hits are valid, i.e. from perfectly isolated and reconstructed tracks. Taking into account about 10\% invalid hits, both results increase by about 0.2 percentage points.

![Figure 8: The \(dE/dx\) resolution achieved with pseudo-tracks of various lengths. The fitted power law has \(\chi^2/ndf = 25.41/23\). The values of the fit parameters are given in the text.](image)

11
3 High Granularity Readout Simulation

In this section, the effect of a higher granularity of readout of a TPC on the $dE/dx$ resolution is investigated in simulation and quantified.

3.1 Motivation

As laid out in [23, chapter 10], previous gaseous detectors have shown empirically that the achievable resolution of the energy loss measurement behaves like

$$\sigma_{dE/dx} \propto L^{-0.34} \cdot N^{-0.13},$$

with $L$ being the total length of a track in the TPC volume, and $N$ being the number hits of that track. In common cases of comparison, e.g. different TPC sizes, both $L$ and $N$ are affected at the same time. Therefore it can be helpful to express the relation using the parameters pad height $H = L/N$ and granularity $G = 1/H = N/L$, leading to

$$\sigma_{dE/dx} \propto L^{-0.47} \cdot G^{-0.13} = H^{-0.34} \cdot N^{-0.47}.$$  \hspace{1cm} (7)

Given a fixed granularity (i.e. pad height for a row-based readout), the dependence has the well know not-quite-square-root behaviour with an exponent of about $-0.47$. This section, however, investigates the situation of a fixed track length $L$ and varying granularity, for which a weaker dependence with an exponent around $-0.13$ is stated. Since this is an empirical observation, comparing different detectors, it is not an exact theoretical value but rather gives the expected order of a dependence on the granularity.

3.1.1 Cluster counting

The energy loss is conventionally determined from the deposited charge by summing all electrons generated from the ionisation by the incident particle. The number of generated electrons in ionising interactions is given by a Landau distribution which has a long tail towards large values. The relatively large width of this distribution worsens the correlation of the measured energy and the momentum of the particle. It is advantageous to instead count the number of ionising interactions of the incident particle. This follows a Poissonian distribution with a significantly smaller width, resulting in a better correlation and particle identification power, as shown in [24]. In Figure 9, the separation power for pion/kaon-separation depending on the cluster counting efficiency is shown compared to the conventional $dE/dx$ by charge summation. In former experiments with prototypes, a cluster counting efficiency of only 20% to 30% was reached. Nevertheless, the resulting separation power is still expected to be better than by using charge summation. Improved algorithms are expected to deliver a higher cluster counting efficiency. However, cluster counting can only work if a sufficient spatial correlation between the position of the electrons of one cluster is preserved during drift.

To achieve the cluster counting capability, a sufficiently high granularity is needed for the TPC readout system. A possible hardware setup to achieve this, but at the same time keep the flexibility and large anode coverage of a pad-based readout is the ROPPERI system [25].
Figure 9: Theoretical expectation for Bethe-Bloch curves and pion/kaon separation power of $dE/dx$ by cluster counting, from [24].

3.2 Software

In this section, MarlinTPC is used to simulate a highly granular readout of the TPC drift volume, while part of the reconstruction is done with the source extractor software described below. This makes it necessary to export the data to a different data format (.fits) and then re-import it to .slcio. The processor chain consists of

1. primary ionisation,
2. drift,
3. amplification with GEMs,
4. digitisation with the Timepix ASIC,
5. export to .fits,
6. running of the source extractor software to reconstruct hits,
7. import to .slcio,
8. analysis ($dE/dx$ measurements, tracking).
3.2.1 Source Extractor

Since the simulation targets a high granularity with pad sizes smaller than the charge clouds generated by the GEM amplification, the resulting 2-dimensional patterns of the readout are similar to astrophysical sky maps. There, often faint light sources in front of background light are investigated. One software to extract these sources from the sky maps is the source extractor software [26]. It was first utilised and integrated into MarlinTPC by [27]. It takes a 2-dimensional image, equivalent to a 2D-histogram, and computes the most likely position and brightness of sources, based on a provided typical shape.

The software uses a multi-staged approach, iteratively separating the image in subsections and adding sources to the fit. The sources are used as hits in the following steps, and are interpreted as clusters, albeit with a finite cluster identification and counting efficiency. An example is shown in Figure 10.

3.3 Results

Different TPC readout set ups were simulated, in particular varying the anode granularity. The number of reconstructed clusters was counted and compared between a pion and a kaon, which have a local ionisation difference maximum of about 15\% at a momentum around 3 GeV. Through saturation effects the number of reconstructed clusters
is not exactly proportional to the amount of ionisation, so we use the separation power $S$ as a quantitative measure, defined as

$$S = \frac{\left| \mu_\pi - \mu_K \right|}{\sqrt{\left( \sigma_\pi^2 + \sigma_K^2 \right)/2}}. \quad (8)$$

For a track length of 300 mm and a magnetic field of 1 T, a separation power of around 2 could be achieved for very small pad sizes of 110 µm as shown in Figure 11a. Conversely, one can look at the separation power depending on the momentum of the pion and kaon, which is directly related to their ionisation difference. The detailed simulation result in Figure 11b with a fixed pad size of 165 µm and at a drift length of 1000 mm reflects the earlier expectations in [24] shown in Figure 9.

The 300 mm tracks can be extrapolated to an ILD-like TPC with a track length of 1.35 m, resulting in a separation power of $s = 3.8$ for 165 µm pads and $S = 3.4$ for 220 µm pads. For this, combining several tracks gave a result compatible with a simple $(1/\sqrt{N})$-extrapolation. This result lies on the 20% cluster-counting-efficiency line in Figure 9b, which is an improvement over the conventional charged based measure. However, to achieve this, a very small pad size is necessary. Extending the simulation parameter space to larger pads in Figure 12a illustrates the drop at 300 µm. Notably, in the transition region a larger drift distance is beneficial for the cluster counting, since at small drift distances a significant overlap between clusters masks many small ones, which can only be observed with very small pads. The result for cluster counting can also be compared to the conventional charge summation, which is also expected to slowly improve for smaller pads with $\sigma_{dE/dx} \propto G^{-0.13}$, see Equation (7). In Figure 12b this dependence of the separation power by charge summation can be observed, as long as the gain is

![Figure 11: Simulation of separation power by cluster counting between pions and kaons (a) at the ionisation maximum of 15% depending on pad size and drift length and (b) depending on energy (and thus ionisation difference), with a pad size of 165 µm and at a drift length of 1000 mm.](image-url)
adjusted to not run into electronics saturation for the larger pad sizes. For a fixed gain with very small pads threshold effects become relevant and limit the separation power, which is partly compensated at smaller drift lengths because the electrons are more concentrated.

For the aforementioned reasons, at different pad sizes different gains were found to be optimal in terms of resulting separation power. This was investigated for various GEM voltages in Figure 13a and lead to the results in Figure 13b, if the optimal GEM voltage is chosen for each pad size. A maximum gain of $64 \times 10^3$ at 280 V was set for the simulation and it defines the cut-off at the smallest pad sizes. Again, smaller drift distances allow for higher separation powers at small pad sizes because of threshold cut-off compensation. In Figure 13b, the empirical dependence on the pad size was added with an arbitrary scale factor and it matches with the simulation results well apart from the drop in the cut-off region.

Both, the separation power for cluster counting and the one for charge summation have been combined into the plots in Figure 14. Only the smallest and largest simulated drift lengths are drawn. To make them comparable to the existing systems, a blue band was inserted in Figure 14b to indicate the region that is covered by the beam test results, after transforming to separation power for 300 mm long tracks, albeit for rectangular pads of $(1 \times 6)$ mm$^2$ to $(3 \times 7)$ mm$^2$. The separation power of the simulated charge summation is compatible with existing beam test results, and shows the expected rise to smaller pads. Only at very small pad sizes below 300 µm the cluster counting becomes effective, and for larger drift lengths above about 500 mm surpasses the maximum of the charge summation.
Figure 13: Simulation of separation power by charge summation between pions and kaons depending on pad size. (a) Scan of the GEM voltage, i.e. amplification gain, to find the optimum for each pad size. (b) The result with optimised GEM voltage.

Figure 14: Simulation of separation power between pions and kaons for cluster counting and charge summation.
4 Summary

Using a large TPC prototype with about 53 valid hits on 50 cm track length in a 5 GeV electron beam, the $dE/dx$ resolution achieved with three GEM modules was measured to be $(8.7 \pm 0.1)\%$. Extrapolating this result to larger track lengths, the resolution in the large (220 rows) and small (165 rows) ILD TPC was estimated to be $(4.2 \pm 0.1)\%$ and $(4.8 \pm 0.1)\%$, respectively, assuming 100\% usable hits. Taking into account 10\% invalid hits, both values become only about 0.2 percentage points worse, staying at or below the stated goal for the ILD TPC of 5\%.

Furthermore, it was shown that better $dE/dx$ resolution values can be achieved with a higher readout granularity. The separation power between pions and kaons was calculated, using conventional charge summation, as well as using cluster counting. Here, the amplification gain for a GEM-based system was optimised for the chosen pad size to compensate saturation and threshold cut-off effects. The separation power peaks at a pad size around $1 \text{ mm} \times 1 \text{ mm}$, limited by the realistically achievable amplification gain. It follows a $(G^{-0.13})$-dependence, which was empirically observed between different existing gaseous detectors. At very small pad sizes below 300\,$\mu$m it becomes feasible to reconstruct GEM charge clouds using the source extractor software. This enables to do cluster counting and has the potential to further increase the separation power for pad sizes below 200\,$\mu$m and larger drift lengths.

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