The (1020)-meson production cross section measured with the ATLAS detector at $s=7$ TeV

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Citation for published version (APA):
de Nooij, L. (2014). The (1020)-meson production cross section measured with the ATLAS detector at $s=7$ TeV.
's-Hertogenbosch: Boxpress

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Chapter 4

Low $p_T$ tracking

Charged particles may emerge from the interaction point, or from a secondary vertex if produced as decay products of long lived particles. In this chapter the reconstruction of low $p_T$ tracks is examined, which is crucial for the $\phi$-meson reconstruction. The $\phi \rightarrow K^+ K^-$ decay results in kaons with momenta of $\lesssim 1$ GeV compared to the multi-GeV particles from hard processes. The different track parameters and their physical interpretation are discussed. Next, energy loss by charged particles is assessed in detail and later used for particle identification. In the last section, the performance of particle identification using $dE/dx$ is discussed.

4.1 Tracks

In the presence of a homogeneous magnetic field, charged particles follow a helical trajectory. The helix is defined by five track parameters [113], as illustrated in figure 4.1. The track parameters are usually expressed at the point of closest approach to the beam axis, the perigee point, as follows:

- The charged-signed inverse momentum, $q/p$, with $q$ the charge in units of elementary charge $e$. The inverse momentum is related to the curvature $\kappa$ or radius $\rho$ of the track in the $x-y$ plane and the magnetic field $B$ by
  \[
  \kappa \equiv \frac{1}{\rho [m]} = \frac{0.3 \cdot B [T]}{p [GeV]}.
  \]  
  The uncertainties of the curvatures of the tracks are Gaussian distributed, whereas using $q \cdot p$ as track parameter would yield a non-Gaussian distribution for the uncertainties, biasing the reconstruction. In the physics analyses often transverse momentum $p_T$, the projection of the momentum onto the $x-y$ plane, is used.

- The polar angle, $\theta$, the angle with respect to the $z$-axis in $R-z$ plane. Most analyses use the pseudorapidity $\eta = -\ln(\tan(\theta/2))$, as track multiplicity is to first order constant in $\eta$.

- The azimuthal angle, $\phi_0$, the angle to the $x$-axis at the perigee in the $x-y$ plane.
Figure 4.1: Schematic view of the five track parameters of a helical track projected onto the $x − y$ (left) and the $R − z$ plane (right). For this track $d_0$ is negative.

- $z_0$ is the $z$-coordinate at the point of closest approach to the $z$-axis and is referred to as the longitudinal impact parameter.
- $d_0$ is the transverse impact parameter, the point of closest approach to the $z$-axis in the $x − y$ plane. The sign of $d_0$ is determined as:

$$\text{sign}(d_0) = \text{sign} \left( (\vec{p} \times \hat{z}) \cdot \vec{d} \right),$$

(4.2)

where $\vec{p}$ is the momentum vector, $\hat{z}$, the unit vector pointing in the direction of $z$-axis and $\vec{d}$ points to the perigee point from the origin.

Using these parameters, the location of any point on the track can be expressed with respect to any point in the detector. The impact parameters get a physical interpretation when expressed with respect to the primary vertex of the collision, as they are then related to the decay length, which is in turn associated to the lifetime of the particle decaying to charged particles.

The track finding and fitting procedure is performed in roughly three steps:

1. **Pattern recognition** aims to resolve tracks using hits from charged particles. Usually three hits in the pixel detector or spacepoints in the SCT are used to form a seed. Track candidates are formed from the seeds by extrapolating a track through the detector and assigning more hits within a defined window. Each seed can become at most one track candidate.

2. **Ambiguity solving** to remove ambiguities arising from track candidates that share hits or are composed from a random combination of hits. If a track from the pattern recognition passes the first selections from the ambiguity solver, the track is fitted. After track
fitting, each track is assigned a weight, based on the number of hits and holes assigned to the track, and tracks may be disregarded according to their weights. A hole is a layer that the track passed through, but did not leave a hit in. Basic requirements are applied, including the requirement that $p_T > 100$ MeV, a maximum transverse impact parameter of 10 mm and a minimum number of five hits in the silicon detectors. These cuts ensure a basic track quality and remove hit combinations that formed a track unlikely to originate from a particle.

Track fitting aims at obtaining the best estimates for the track parameters, taking into account the traversed detector material and uncertainties in hit position. Charged particles are deflected in the magnetic field and may be scattered through Coulomb interactions in the detector material. Energy loss effects arise from nuclear and electromagnetic interactions in the material and are accounted for in the track fitting procedure by reducing the momentum according to the thickness of the transversed material. Energy loss is examined in detail in the next section of this chapter.

The quality of the track description depends on the number of hits correctly assigned to a track and the resolution of those hits. It is limited by the understanding of inhomogeneities in the magnetic field and the amount of material a particle traverses. If a charged particle traverses the detector, it can have a hadronic interaction with a nucleus in the detector where typically many new particles are produced. These new particles may be reconstructed and the hadronic interaction identified, but the original particle is lost. Moreover, multiple Coulomb scattering and the energy loss effects lead to uncertainties in track extrapolation and therefore influence the precision of the description of the trajectory. The fitting procedure used for the analysis presented in this thesis is based on a global least squares approach \[116\], which includes the minimization of a $\chi^2$ function

$$\chi^2 = \sum \frac{r_{\text{meas}}^2}{\sigma_{\text{meas}}^2} + \sum \left( \frac{(\theta_{\text{proj}}^\text{scat})^2}{\sigma_{\text{scat}}^2} + \frac{\sin^2(\theta_{\text{loc}})(\phi_{\text{proj}}^\text{scat})^2}{\sigma_{\text{scat}}^2} \right), \tag{4.3}$$

The first part of this formula describes the sum over the hit residuals $r_{\text{meas}}$ divided by their uncertainties. The second term refers to multiple Coulomb scattering and is a sum over the scattering angles $\theta_{\text{proj}}^\text{scat}$ and $\phi_{\text{proj}}^\text{scat}$ in individual detector components divided by their uncertainties. The track is described in term of its track parameters and the values for the track parameters for which equation 4.3 is minimized are chosen. If the scattering angles are small, they are described by a Gaussian distribution when they are projected on the $x-y$ plane or $R-z$ plane. The width of this Gaussian is given by the Highland scattering formula \[117\]:

$$\sigma_{\text{MS}} = \frac{13.6}{\beta c p} Z \sqrt{s/X_0(1 + 0.038 \ln(s/X_0))}, \tag{4.4}$$

where $\beta c$, $p$ and $Z$ represent the velocity, momentum and charge of the particle traversing a material. $X_0$ is the radiation length, defined as the amount of matter high energy electrons traverse such that they lose $1/e$ of their energy due to bremsstrahlung. $s/X_0$ is the thickness of the material normalized to $X_0$. From equation 4.4 it is clear that the uncertainty on the scattering angles decreases with increasing momentum.
A charged particle flying through ATLAS traverses the active detector materials where it is detected, but also traverses cables, cooling systems and support structures. Because the total amount of material in a large detector like ATLAS is difficult to characterize precisely from drawings, data-driven methods are used to validate the material model in simulations. The $K^0_S$ mass is known to high precision and by using its decay to two charged pions [118], it is inferred that the total amount of material is understood with an uncertainty smaller than 10%.

In figure 4.2 comparisons for the $p_T$, $\eta$ and the number of pixel clusters per track are shown for data and Monte Carlo. Events are selected with the event selection as described in chapter 5. Here tracks are required to be within $|\eta| < 2.0$, with $p_T > 230$ MeV and with track momentum smaller than 800 MeV, please note that the $p < 800$ MeV requirement causes the decreasing behavior as a function of $\eta$. Reasonable agreement is shown, which illustrates good understanding of the detector, the numbers of dead or otherwise lost pixel modules, and track finding and fitting procedures.

The expected number of clusters of pixel hits on track differs for positively and negatively particles in the low momentum regime up to $p_T < 800$ MeV. A negative track may pass between two pixel modules, due to the fan-like geometry of the detector. This is illustrated using the Atlantis event display [119] in figure 4.3 (a) and (b). The average number of pixel hits on track in data and simulation is compared for positive and negative tracks in figure 4.3 (c) and (d) and is $2.96 \pm 0.01$ per positive track and $2.79 \pm 0.01$ per negative track.

4.2 Energy loss

In this section energy loss and its use for particle identification is discussed.

4.2.1 Bethe–Bloch

Charged particles passing through a medium will lose energy due to Coulomb interactions with atomic electrons, leading to ionization or excitation. The amount of energy lost can be estimated in the following rough derivation, which provides insight in the relevant parameters. To do so it is assumed that:

- the mass of the incoming particle, $M$, is much larger than the electron mass $m_e$, so that the incoming particle follows a straight path. This assumption is obviously not valid if the incoming particle is an electron;
- the velocity of the incoming particle, $v_M = \beta c$, is constant and its charge is $ze$;
- the atomic electron is free and at rest during the collision, $v_M \gg v_e$, which is valid because the velocity of the electron in the atomic orbit is $\sim 0.02c$.

The goal is to find the energy transfer from the incoming particle to the atomic electron in the medium. The energy transfer to one free electron that is originally at rest with mass $m_e$ is

$$\Delta E = \frac{\Delta p^2}{2m_e}. \quad (4.5)$$
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The total momentum transfer can be found by integrating the force over time

\[ \Delta \vec{p} = \int_{-\infty}^{\infty} \vec{F}_C \, dt, \quad \vec{F}_C = \frac{1}{4\pi\varepsilon_0} \frac{ze^2}{r^2} \hat{r}, \]

(4.6)

where \( F_C \) is the Coulomb force and \( r \) is the distance between the atomic electron and the incoming particle. See figure 4.4 for illustration of the parameters. From a symmetry argument it is clear that the longitudinal components (x-components) cancel, so that only the transverse component (y-component) of the Coulomb force \( F_{C,y} \) has an effect

\[ |F_{C,y}| = |\vec{F}_C| \frac{b}{|\vec{p}|} = F_C \cos \theta, \]

(4.7)
Figure 4.3: A positive a) and negative b) pion track in the pixel detector as simulated by Atlantis. The negative track may pass between pixel modules, not leaving a hit. The number of clusters of pixel hits per track for c) positive and d) negative tracks.
where $b$ is the impact parameter, the distance of closest approach to the electron, and $\theta$ the angle between $b$ and $\vec{r}$. When taking $r = b / \cos \theta$, the transverse force on the electron becomes

$$|F_{C,t}| = \frac{1}{4\pi\varepsilon_0} \frac{ze^2}{b^2} \cos^3 \theta.$$  \hspace{1cm} (4.8)

And the momentum transfer can then be expressed as

$$\Delta p_t(b) = \int_{-\infty}^{\infty} |F_{C,t}| dt = \int_{-\infty}^{\infty} |F_{C,t}| \frac{dx}{v} = \frac{1}{4\pi\varepsilon_0} \frac{ze^2}{b^2} \int_{-\infty}^{\infty} \cos^3 \theta \frac{dx}{v}, \hspace{1cm} (4.9)$$

with $dx = bd\theta / \cos^2 \theta$:

$$\Delta p_t(b) = \frac{1}{4\pi\varepsilon_0} \frac{ze^2}{bv} \int_{-\pi/2}^{\pi/2} \cos \theta d\theta = \frac{1}{4\pi\varepsilon_0} \frac{2ze^2}{bv}. \hspace{1cm} (4.10)$$

So that the energy transfer becomes

$$\Delta E(b) = \frac{1}{(4\pi\varepsilon_0)^2} \frac{2^2e^4}{m_e^2 \beta^2 b^2}. \hspace{1cm} (4.11)$$

In a material the incoming particle can interact with all atomic electrons. If the electrons are on a cylinder with length $dx$, thickness $db$ at radius $b$ the incoming particle will interact with

$$N_e = 2\pi b \, db \, dx \, N_A \frac{Z}{A} \rho$$  \hspace{1cm} (4.12)

electrons, where $N_A$ is Avogadro’s constant, $Z$ is the atomic number, $A$ the atomic mass and $\rho$ the density of the medium.

Integrating equation 4.11 over the impact parameter $b$ and including $N_e$ as found in equation 4.12 the expected mean energy loss per unit length becomes

$$- \frac{dE(b)}{dx} = \frac{1}{(4\pi\varepsilon_0)^2} \frac{4\pi^2 e^4}{m_e^2 \beta^2} N_A \frac{Z}{A} \rho \ln \frac{b_{\max}}{b_{\min}}. \hspace{1cm} (4.13)$$
To find $b_{\text{min}}$ and $b_{\text{max}}$ the maximum and minimum energy transfer are considered respectively. The maximum energy transfer occurs when $b$ is smallest and thus the collision is head-on. The electron, originally at rest, acquires velocity $2v$ of the incoming particle. The energy transfer equals the energy of the electron after collision: $\Delta E(b_{\text{min}}) = 2m_e\beta^2c^2\gamma^2$. The minimum energy transfer corresponds to $b_{\text{max}}$ and in this case is the electron is only excited, such that the energy transfer equals the average excitation potential of the medium, $I$.

Combining this and equation 4.13 leads to a description for the energy loss per unit length $-dE/dx$:

$$-\frac{dE}{dx} = \frac{1}{4\pi\varepsilon_0^2} \frac{z^2e^4}{m_e c^2} \frac{N_A Z \rho}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e \beta^2 c^2 \gamma^2}{I} \right]$$

(4.14)

in units of MeV/cm.

A fully quantum mechanical derivation leads to the well-known Bethe–Bloch formula [120]:

$$-\frac{dE}{dx} = \frac{1}{4\pi\varepsilon_0^2} \frac{z^2e^4}{m_e c^2} \frac{N_A Z \rho}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e \beta^2 c^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

(4.15)

where $T_{\text{max}}$ is the maximal kinetic energy that can be transferred, the factor $-\beta^2$ accounts for screening of the Coulomb field by the surrounding matter when interactions take place over longer distances, $\delta(\beta)$ is a density correction due to polarization for the medium, which only becomes important if $\beta\gamma > 30$. $T_{\text{max}}$ introduces a small dependence on $M$ at the highest energies.

Equations 4.14 and 4.15 are similar up to $\beta\gamma < 20$ apart from the factor $I^2$ and $-\beta^2$ in the Bethe–Bloch. The deposited energy falls rapidly as the velocity increases explained as above by the particle having less time to transfer momentum through the Coulomb force to the atomic electron. Figure 4.5 a) shows the mean energy loss in silicon as a function of $\beta\gamma$, using the semi-classical derivation and the Bethe–Bloch formula. The energy loss predicted by the Bethe–Bloch is larger predominantly because of the factor $I^2$. The relativistic rise in the semi-classical derivation arises from the implementation of $\Delta E(b_{\text{min}}) = 2m_e \beta^2 c^2 \gamma^2$. At even larger $\beta\gamma$, the polarization effect would suppress the relativistic rise in the Bethe–Bloch, which is not accounted for in the classical derivation.

If the velocity approaches the speed of light, increasing energy leads to slower increase in velocity and thus a smaller decrease in energy loss. For $\beta\gamma \sim 3 - 4$, $dE/dx$ reaches a minimum where the particle is dubbed a minimum ionizing particle (MIP). For example, a muon with $p \sim 600$ MeV is a MIP. Beyond this, $\beta$ tends to unity and the logarithmic factor in the Bethe equation gives the relativistic rise in $-dE/dx$. This is due to Lorentz contraction of the electric field in the material, making interactions with electrons further away from the track more efficient. Figure 4.5 b) shows the energy loss from the classical derivation for pions, kaons and protons with momenta up to 2.5 GeV to illustrate the effect of particles having different masses.

### 4.2.2 Distribution of energy loss

The most probable value for energy loss, $\Delta p$, is lower than the mean of the expected energy loss as described by the Bethe–Bloch formula. This can be explained by the fact that the Bethe–Bloch derivation assumes that the incoming particle interacts with a large number of electrons. In practice this number is limited, unless the traversed material is very thick or dense, in which
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\[ \text{energy loss} = \frac{p}{Mc} \gamma \beta^{-1} \]

\[ \text{Mean energy loss} \]

Bethe Bloch

Classical

\[ \Delta p = \xi(x) \left[ \ln \frac{2mc^2\beta^2\gamma^2}{l} + \ln \frac{\xi(x)}{l} + 0.2 - \beta^2 \right], \quad (4.16) \]

where \( \xi(x) = \left( \frac{4\pi N_A e^2 \rho^2}{m_e c^2} \right) \left( \frac{Z}{A} \right) (x/\beta^2) \text{MeV} \) for a detector with thickness \( x \) in g cm\(^{-2}\). While \( dE/dx \) is independent of thickness, \( \Delta p/x \) scales as \( a\ln x + b \).

The material distribution for the inner detector is expressed in radiation lengths, \( X_0 \), and interaction lengths, \( \lambda \), and is shown in figure 4.7. The design goal was to keep the amount of

Figure 4.5: a) Comparison between the mean energy loss as calculated in a semi classical way (equation 4.14 dashed line) and with a full quantum mechanical calculation (equation 4.15 solid line). b) Mean energy loss in silicon for pions, kaons and protons with momenta up to 2.5 GeV, using equation 4.14.
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Figure 4.6: Energy loss probability density functions for a pion with energy 500 MeV ($p = 480$ MeV) in silicon, normalized to unity at $\Delta p/x$, from [3].

material as limited as possible, with the least material in the central part of the detector. The larger amount of material at $|\eta| \sim 1.5$, the transition region between the barrel and the end-caps, can be explained by the cables and support structures located between the TRT barrel and end-caps. After traversing the inner detector a charged particle has traversed approximately 0.5 $X_0$ at $|\eta| = 0.5$ and 1.5 $X_0$ at $|\eta| = 1.5$.

4.2.3 $dE/dx$ and resulting signal in the pixel detector

In this section the assessment of the most probable energy loss, $\Delta p$, and the resulting signal for charged particles with momenta $0.2 < p \lesssim 1$ GeV in the ATLAS pixel detector is examined in detail. The measured energy loss will be used for particle identification.

So far, the energy loss by a fast particle that interacts with the individual atoms in a material has been examined. When confined in a lattice, silicon atoms are ordered in a face-centered cubic lattice, such that the wavefunctions of their four valence electrons make covalent bonds and fill up the outer electron shell. The discrete energy states of the atomic shell broaden to form bands. The number of bonding states equals the number of electrons, so in the absence of excitation, e.g. if the lattice is at 0 K, all the electrons are in the lower energy valence band and the material is an insulator. With increasing temperature, electrons may cross the energy band into the conduction band until thermal equilibrium is reached. If a charged particle passes a silicon sensor it will lose energy, causing electrons to be excited across the band gap into the conduction band, creating electron-hole pairs. Although the size of the bandgap $E_g$ for silicon
is 1.12 eV \cite{100}, the average energy lost per ionization is \( W = 3.68 \pm 0.02 \) eV/pair \cite{122}. This is because an excitation across the bandgap in silicon also requires a simultaneous transfer of momentum, absorbed as lattice vibrations.

The amplitude of the signal is directly proportional to energy deposited. Because signals have the same shape, the width of the signal is proportional to the amplitude and thus the energy deposition. This width can be expressed as the duration of the signal, the Time over Threshold (ToT), and is measured by subtracting the leading edge timestamp from the trailing edge timestamp \cite{123}. For any hit generated in the pixel detector information on the L1 trigger that accepted the event, pixel row, pixel column and ToT are stored. The ToT is converted to amount of charge through conversion functions derived by calibration scans in which a known charge is injected in a pixel. Each pixel diode is calibrated to measure a ToT count of 30 for a MIP, while the overflow is at 255.

Charge released by a track crossing the pixel detector is rarely contained in just one pixel. Neighboring pixels are joined together if the signal exceeds the threshold to form clusters and the charge of the cluster is calculated as the sum of the charges of all pixels after calibration correction. In order to ensure only good quality clusters are used, a cluster is excluded if:

- The local position of the cluster is at the edge of the module, because the cluster may then extend beyond the sensor, so charge can be lost over the edge and go underestimated;

- \( \cos(\alpha) < 0.16 \), with \( \alpha \) the track spatial incident angle, because the most probable value of expected cluster charge sharply drops for smaller values of \( \cos(\alpha) \);

- The ToT count exceeds the overflow of 225 counts.

Clusters unaffected by these cuts are referred to as good clusters and represent 91% of all clusters. All tracks with two or more good clusters are accepted for analysis, thereby rejecting 3% of the tracks.
LOW PT TRACKING

The specific cluster energy loss, \( dE/dx \) in units of MeV g\(^{-1}\)cm\(^2\), is derived from the charge contained in a cluster, \( Q \), the average energy needed to create an electron-hole pair \( W \), the path length in the silicon \( x = d/\cos \alpha \) and the silicon density \( \rho \):

\[
\frac{dE}{dx} = \frac{QW \cos \alpha}{\rho d}.
\]  

Figure 4.8 shows how the tails at low charge (mostly caused by charge being lost over the edge of the pixel) are effectively reduced using good clusters only and the agreement between data and Monte Carlo for good cluster \( dE/dx \).

Track \( dE/dx \) is defined as an average of the individual cluster \( dE/dx \) measurements (charge collected in the cluster, corrected for the track length in the sensors), for all the good clusters associated to a track. The average is calculated using the truncated mean to reduce the effect of Landau tails for the expected energy loss; the average is evaluated after having removed the cluster(s) with the highest charge: one cluster is removed for tracks with 2, 3 or 4 good clusters and two clusters for tracks with 5 or more good clusters. A track \( dE/dx \) resolution of \( \sim 12\% \) is measured using particles with \( p_T > 3 \) GeV. This is measured as the RMS of a Gaussian fit to the distribution of \( dE/dx \).

For figure 4.9 the energy loss in the clusters on a track is simulated as a set of four random numbers generated from a Landau distribution with most probable value \( MPV = 240 \) and width \( w = 50 \). The choice for the input parameters reflects the expected energy loss and width in eV/\( \mu \)m for a 500 MeV pion in a 250 \( \mu \)m thick sensor, see figure 4.6. From the four generated numbers the average is plotted before (left) and after (right) having removed the highest numbers. The measured \( MPV \) and \( w \) are found by fitting a Landau to the distributions of these (truncated) means. The mean of the resulting distribution is taken as the average of all means. The input \( MPV \) is overestimated by a factor of 1.24 if using the normal means. The input
MPV is estimated within 2% when using the truncated means and the resolution improves from $w = 200$ to $w = 120$.

4.2.4 Very low momentum particles

For kaons and protons in the very low momentum regime, i.e. momenta up to 200 MeV, the energy loss in the active and support materials of the inner tracker is so large the particles are stopped. This is illustrated in figure 4.10. Kaons are not reconstructed in the central $\eta$ regime, where $|p_T| \sim |p|$. In this region of phase space all energy is lost before reaching the SCT.

4.3 Particle identification

4.3.1 Energy loss fit

To use energy loss for particle identification, the most probable value of the specific energy loss, $\Delta p$, and the charged particle $\beta \gamma$ are parametrized with a probability density function (p.d.f.). This p.d.f. can be factorized into:

1. A function that describes how $\Delta p$ depends on $\beta \gamma$ described by a function with five free parameters that are obtained as a result of a fitting procedure to data;

Figure 4.9: A test using simulated data to estimate the resolution improvement of using the truncated mean for the energy loss measurement (see text). The dashed lines show the input p.d.f. with $MPV = 240$, and the solid lines are the fit result of a Landau to the distribution of the (truncated) means.
2. A Crystal Ball \cite{125} function peaked at $\Delta p(\beta \gamma)$ that describes how the measured $dE/dx$ fluctuates around $\Delta p(\beta \gamma)$ for a given charged particle $\beta \gamma$.

The Crystal Ball was chosen because it has a numerical advantage over the more common Landau-Gaussian fit and is therefore quicker in the computations, while the performance is comparable. From a sample of simulated tracks with $\beta \gamma$ ranging between 0.3 and 10, a suitable parametrization is found for $\Delta p(\beta \gamma)$ \cite{124}:

$$\Delta p(\beta \gamma) = \frac{p_1}{\beta p_3 \ln(1 + (|p_2|/\beta \gamma)^p_3)} - p_4,$$

Figure 4.11 shows a two-dimensional distribution of $dE/dx$ as a function of the signed momentum. The pronounced bands resulting from pions, kaons and protons are indicated. Positively and negatively charged tracks each divided in groups of tracks with two, three and four or more clusters are fitted separately in slices of momentum. In figure 4.12 projections on the momentum axis (and thus the $dE/dx$ distribution in bins of momentum) for positively charged tracks having three good clusters in data is shown, as well as the result of the global fit. The value found for $p_3$ is always between 1.8 and 2.2.

The likelihood that the particle is a pion, kaon or proton is calculated with the measured number of good pixel clusters on the track, the momentum of the particle and the energy loss in the pixel detector. To do so, the result of global fit is used, given that the fluctuations of the energy loss are described by the Crystal Ball. The energy resolution is not good enough to distinguish between muons, electrons and pions, the “light particles”. The absolute probability
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Figure 4.11: Two-dimensional distribution of $dE/dx$ and charge signed momentum for data.

A track originates from a proton, kaon or light particle depends on the likelihoods ($L_p$, $L_K$, $L_l$) and is defined as:

$$
P_p = \frac{L_p}{L_p + L_K + L_l}, \quad P_K = \frac{L_K}{L_p + L_K + L_l}, \quad P_l = \frac{L_l}{L_p + L_K + L_l}. \quad (4.19)$$

4.3.2 Particle ID performance

The majority of charged hadrons produced at the interaction point are pions, that are tagged as light particles. Ignoring the contribution of electrons and muons in the set of particles tagged as a light particle, the likelihood probabilities become $P_{\pi \pm}$, $P_K$ and $P_p$. These probabilities are used for identifying pions, kaons and protons with an efficiency, $\epsilon_{\pi \pm}$, $\epsilon_K$, $\epsilon_p$, measured using a Monte Carlo based method by defining

$$
\epsilon_{\text{particle}} = \frac{N_{\text{particle}}}{N_{\text{particle, truth}}}, \quad (4.20)
$$

where $N_{\text{particle}}$ is the number of selected tracks having at least two good clusters associated with a specific particle type at generator level and $N_{\text{particle, truth}}$ is the subset of $N_{\text{particle}}$ passing a given requirement on $P_{\text{particle}}$. This efficiency is shown in figure 4.13 a) for kaons in three slices of momentum and ten slices in the kaon likelihood probability $P_K$. The efficiency is of the order...
of 90% for kaons with momenta up to 600 MeV, this can be understood from figure 4.11, where the separation between the different energy bands is still clearly visible at 600 MeV. The energy bands start to overlap from $\sim 600$ MeV and the expected tagging efficiency is therefore lower in the momentum slice $600 < p < 800$ MeV. The efficiency decreases with more stringent requirements on $P_K$, because kaons will be less likely to pass the requirements.

When selecting kaons through a cut on $P_K$, the sample will be contaminated with other charged particles depending on the requirement on $P_K$. This contamination consists of mostly pions and is estimated using simulation defining the mistag rate for pions:

$$r_{\pi}^{\pm} = \frac{N_{\pi}^{\pm, \text{pass}}}{N_{\pi}^{\pm, \text{truth}}}$$

where $N_{\pi}^{\pm, \text{truth}}$ is the number of truth pions and $N_{\pi}^{\pm, \text{pass}}$ is the subset of truth pions passing the requirement on $P_K$. $r_{\pi}^{\pm}$ is shown in figure 4.13(b) and is about 10% for momenta up to 600 MeV and as large as 56% for pions with $600 < p < 800$ MeV and $P_K > 0.1$. The mistag rate also decreases with more stringent requirements on $P_K$ to less than 2% when requiring $P_K > 0.9$.

In figure 4.14 $\varepsilon_{\text{pion}}$ is shown as a function of the mistag rates for pions and protons. As expected, the tagging efficiency decreases with increasing momentum and increasingly stringent cuts on the probabilities. The mistag rates increase with increasing momentum and are about 1–10%.
4.4 Summary

Track finding and fitting is an important part of the analysis of $pp$ interactions. Energy loss in the pixel detector is used to select kaons with an efficiency of about 90% for momenta up to 600 MeV. The method loses discriminating power for kaons with momenta of $p_K > 800$ MeV, or $\beta\gamma \sim 2$. Kaons with momenta lower than $|p| \sim 200$ MeV lose all their energy before the first SCT barrel and will be excluded from the analysis. A data-driven way to determine the efficiency for kaon identification is explained in chapter 5.

Figure 4.13: The particle identification efficiency a) and mistag rate b) for kaons in three slices of momentum for different requirements on $P_K$. 
Figure 4.14: The pion and proton mistag rates as a function of the tagging efficiency for kaons. The datapoint with the highest efficiency and mistag rate is for $P_{\text{particle}} > 0.1$ and with the lowest efficiency and mistag rate for $P_{\text{particle}} > 0.9$. 

![Diagram showing mistag rates and efficiencies for kaons and protons](image-url)