clearly identified below 1.5 GeV. There are a few apparent kaons below 1 GeV and even some deuterons can be seen. The time resolution of the hodoscope and preshower TOF data is about 300 ps (see figure 29) which using equation (72) leads to a theoretical maximal momentum of about 0.8 GeV for pion/kaon separation. The time of flight information can of course also be used directly to produce a mass spectrum (equation (73)).

The data used for figures (31) and (32) only represent a small subset of HERMES 1995 data (about 69 runs) and are only supposed to illustrate the possibilities. For the 1996 a thorough time of flight analysis is in progress[27].

3 PID Quantities and Cuts

3.1 PID Quantities

3.1.1 Probabilities

Consider two probabilities:

1. $P(A|X)$: Probability that a particle of type A causes the detector response X.
2. $P(X|A)$: Probability that a measured detector response X was caused by a a particle of type A.

They are related in a **non-trivial** way.

First consider the case of a single particle type A and a single particle identification detector. By normalising the response function of the detector to an integral of 1 a probability distribution p(X) is obtained. The probability $P(A|X) = p(X)$ is given by this probability distribution, while $P(X|A) = 1$ as there is only the one particle type.

Now assume there are several particle types A_i. The probability $P(A_i|X)$ is still given by the normalised detector response, but the probability to **observe** that a particle A_i causes the detector response X becomes $P(A_i) \cdot P(A_i|X)$, where $P(A_i)$ is the probability that the observed particle is of type A_i. $P(A_i|X)$ is now called a **conditional probability**, because it is a probability under the condition that the particle is of type A_i. The probability $P(A_i)$ is in particle physics terminology referred to as the flux factor ϕ^i of the particle type A_i.

For several particle types A_i the probability $P(X|A_i)$ is given by Bayes' theorem

$$P(X|A_i) = \frac{P(A_i) \cdot P(A_i|X)}{\sum_j P(A_j) \cdot P(A_j|X)} \tag{74}$$

which takes the flux factors properly into account.

For the 1995 HERMES data two particle types are of interest: hadrons and positrons. In this case the ratio of the two flux factors $\Phi = \phi^h/\phi^e$ is often quoted. The impact of this flux ratio on the probability $P(X|A_i)$ is illustrated in figure 33 using the TRD truncated mean response for hadrons and positrons. Assuming as an example that the measured response is 25 keV, the conditional probability $P(e|25)$ for a positron is clearly much larger than the conditional probability $P(h|25)$ for a hadron to produce this response. However, if the flux ratio is 100, the expression $P(h)\cdot P(h|25)$ (dotted line) becomes larger than $P(e)\cdot P(e|25)$. Using Bayes' theorem (equation (74)) it follows that $P(25|h) > P(25|e)$ although $P(h|25) << P(e|25)$.

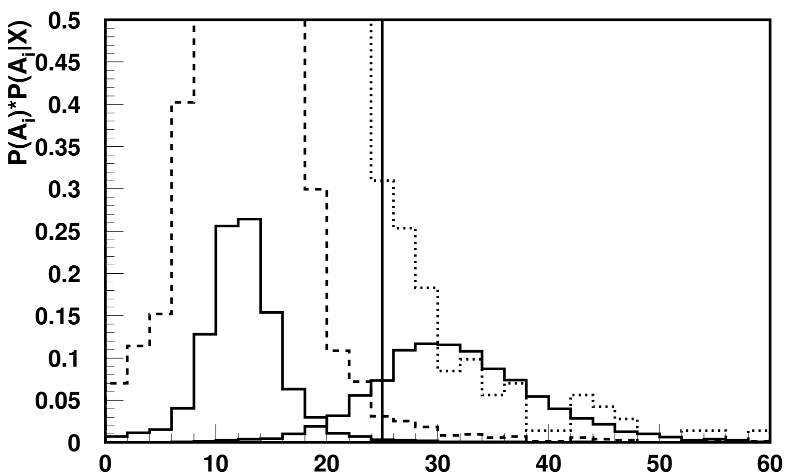

Figure 33: Normalised TRD truncated mean response functions (i.e. conditional probabilities) for hadrons and positrons (solid line) and hadron response function scaled by flux ratios of 10 (dashed) and 100 (dotted).

3.1.2 Definition of PID Quantities

Particle identification (PID) uses the fact that different types of particles cause different detector responses. These responses can be used directly in the data analysis or they can be first converted into probabilities. The first case will be referred to as 'hard cuts'. A cut is a condition that is imposed on a measured quantity to select a specific data sample. If probability based analysis is used, the response of each detector must first be converted into a conditional probability $\mathcal{L}_D^i$ that the response of the detector D was caused by a particle of the type i. This can be done by using distributions generated from test beam data or from clean particle samples obtained with restrictive hard cuts on the other PID detectors in the experiment. These distributions are normalised and either used directly or by fitting with an analytical function. In both cases the conditional probability distributions are referred to as 'parent distributions' $\mathcal{L}_D^i$. The term 'conditional probability' refers to the fact that the parent distributions are normalised to 1.

The conditional probabilities from several detectors D can be combined into an overall conditional probability

$$\mathcal{L}^i = \prod_D \mathcal{L}^i_D \tag{75}$$

The conditional probabilities can be transformed into true probabilities $\mathcal{P}^i$ that a particular particle is of type i, if all particle fluxes, represented by the flux factors ϕ^i, are known. This is a nontrivial problem, since these flux factors are in general functions of momentum and scattering angle

$$\phi^i = \phi^i(p, \theta) \tag{76}$$

or two similar variables. Usually this problem can only be solved by a Monte Carlo simulation of the detectors or by an iterative procedure. In the case that all flux factors are known the probability $\mathcal{P}^i$ is given by Bayes' theorem (74):

$$\mathcal{P}^i = \frac{\phi^i \mathcal{L}^i}{\sum_j \phi^j \mathcal{L}^j} \tag{77}$$

For the simple case of only two particle types, positron and hadron, the positron probability is therefore given as

$$\mathcal{P}^e = \frac{\mathcal{L}^e}{\Phi \mathcal{L}^h + \mathcal{L}^e} \tag{78}$$

where only the conditional probabilities and the flux ratio $\Phi = \phi^h/\phi^e$ have to be known. In this case it is equivalent to create a PID parameter from the ratio of the positron and hadron probabilities by taking the logarithm:

$$PID = \log_{10}\left(\frac{\mathcal{P}^e}{\mathcal{P}^h}\right) = \log_{10}\left(\frac{\mathcal{L}^e}{\Phi \mathcal{L}^h}\right) = \log_{10}\left(\frac{\mathcal{L}^e}{\mathcal{L}^h}\right) - \log_{10}\Phi \tag{79}$$

The advantage of this quantity is that it produces a distribution that intuitively resembles the response of a detector. Furthermore, it is practical that $PID = 0$ is simply the value where a particle is equally likely to be a positron or a hadron and therefore the natural value for a cut. If the flux ratio Φ is neglected, the PID distribution is shifted by $\log_{10}\Phi$. Therefore Φ can be neglected if it is not a strong function of (p, θ). Otherwise a momentum dependent cut can in principle replace the knowledge of Φ. Another way to express PID is by introducing a PID parameter for each detector

$$PID_D = \log_{10}\left(\frac{\mathcal{L}^e_D}{\mathcal{L}^h_D}\right) \tag{80}$$

which results in

$$PID = \sum_D PID_D - \log_{10}\Phi \tag{81}$$

3.1.3 PID2, PID3, PID4

The PID quantity that is used typically for the analysis of 1995 HERMES data is PID3 which combines the calorimeter, preshower and Čerenkov responses and is defined as

$$PID3 = PID_{cal} + PID_{pre} + PID_{cer} \tag{82}$$

$$= \log_{10}\left(\frac{\mathcal{L}^e_{cal}\mathcal{L}^e_{pre}\mathcal{L}^e_{cer}}{\mathcal{L}^h_{cal}\mathcal{L}^h_{pre}\mathcal{L}^h_{cer}}\right) \tag{83}$$

PID3 is not equivalent to the probability $\mathcal{P}^e$, because it does not include the flux ratio. This was done so as not to bias the PID3 parameter with respect to different kinematic cuts, e.g. for DIS and photo production events. It has to be pointed out that a cut on PID3 in this case is not in any way clearly defined. However, PID3 can be used as if it were the response of a single particle identification detector with excellent positron-hadron separation.

The standard particle identification cut for the 1995 inclusive analysis follows the valley between the positron and hadron distributions in the PID3-pulsTRD plane, where pulsTRD is the truncated mean signal of the TRD. A more detailed description can be found in the section 'HERMES PID Cuts' (5.3).

The PID parameters PID2 and PID4 are sometimes used as well. They are defined in an analogous way to PID3. While PID2 uses only the calorimeter and the preshower, PID4 also includes the TRD truncated mean. For 1995 PID4 is constructed using parent distributions for positrons and hadrons generated from pulsTRD spectra. They include no momentum dependence. A full probability analysis of the TRD has been done[28] and will be included in the future as PID5 and PID6. Figure 34 shows PID2, PID3 and PID4 for comparison. The large impact of the TRD is apparent in the difference between PID3 and PID4.

The probability analysis is only as good as the parent distributions that it uses. If they do not resemble the data closely, the produced probability or PID quantity is not correct. Also it should be remembered that the PID quantity as defined in equation (79) is only useful for the case of two particle types. For a larger number of particle types the full probability analysis must be used. As an alternative, the number of parent distributions could be increased. For example for three types of particles (i=positron, pion, kaon) six parent distributions could be used (positron, not-positrons, etc.) for each detector to define three PID parameters.

$$PID^i_D = \log_{10}\left(\frac{\mathcal{L}^i_D}{\mathcal{L}^{\neq i}_D}\right) \tag{84}$$

The disadvantage of this method is the increase in the number of necessary parent distributions, while the distributions may be somewhat easier to interpret.

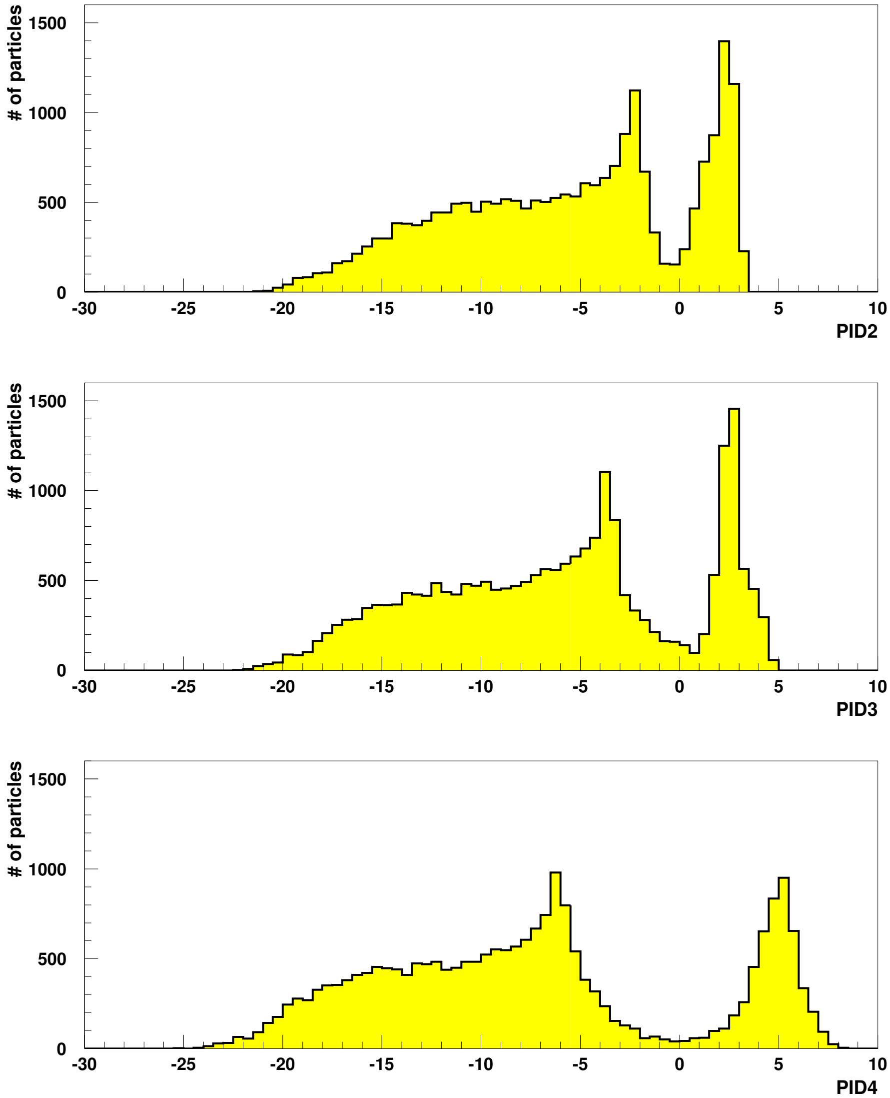

Figure 34: Comparison between the PID parameters PID2, PID3 and PID4. Data from one run (4220). The separation of the hadron (< 0) and positron peaks (> 0) clearly improves from PID2 to PID4.

3.1.4 Parent Distributions

The parent distributions $\mathcal{L}^i_{det}$ for the calorimeter, the preshower and the Čerenkov detector are given as analytical expressions that were fitted to test beam or HERMES data. The TRD parent distributions were obtained originally from a Monte Carlo simulation that was tuned to CERN test beam results. They were later replaced by distributions generated from the 1995 HERMES data, mostly due to an observed difference in the positron distributions with respect to the test beam data related to the use of different radiators. The next sections give a detailed definition of the parent distributions for each detector.

3.1.5 Calorimeter

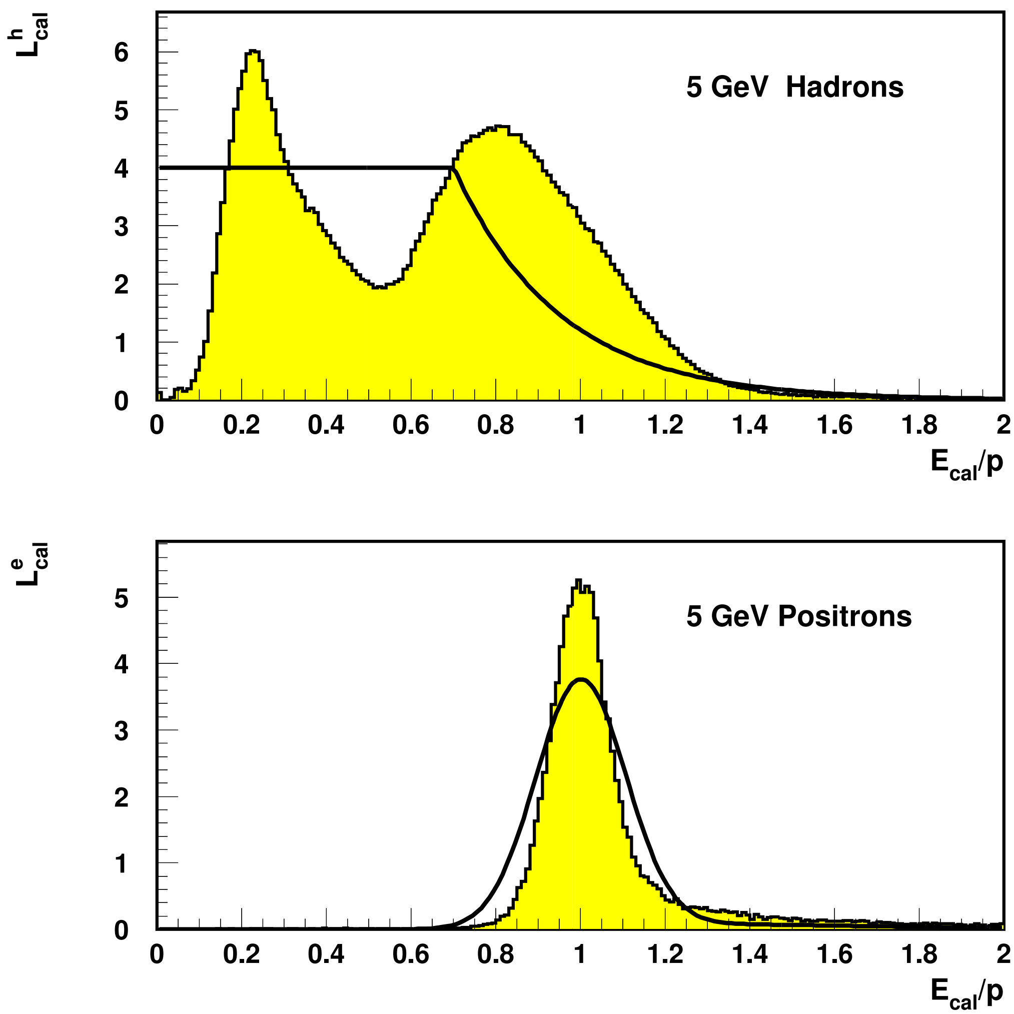

Figure 35: Calorimeter parent distributions for 5 GeV hadrons and positrons (line) in comparison to data (histogram)

The measured calorimeter energy E_{cal} and the ratio $R_{cal} = E_{cal}/p$ of calorimeter energy and momentum are the parameters used for the calorimeter parent distributions. The calorimeter is calibrated so that

$$\langle R_{cal} \rangle = 1 \tag{85}$$

The electron spectrum is modeled as a Gaussian distribution with an additional high energy tail:

$$\mathcal{L}^e_{cal} = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{(R_{cal}-1)^2}{2\sigma^2}} & \text{for } R_{cal} \leq 1 \\ \frac{1}{\sqrt{2\pi}\sigma} \left[e^{-\frac{(R_{cal}-1)^2}{2\sigma^2}} + C_{e1}(R_{cal}-1)e^{-C_{e2}(R_{cal}-1)} \right] & \text{for } R_{cal} > 1 \end{cases} \tag{86}$$

with constants C_{e1}, C_{e2}. The energy resolution of the calorimeter ΔE_{cal} as well as the spectrometer resolution Δp determine σ:

$$\sigma = \sqrt{\Delta E_{cal}^2 + \Delta p^2} \qquad \text{with} \qquad \Delta E_{cal} = a + \frac{b}{\sqrt{p}} \tag{87}$$

where a and b are fit parameters. The hadron parent distribution is set to a constant (C_π) for hadron energies below the trigger threshold E_{thr}. Above the threshold it is described by an exponential decline:

$$\mathcal{L}^h_{cal} = \begin{cases} C_\pi & \text{for } E_{cal} \leq E_{thr} \\ C_\pi e^{-C_\pi(R_{cal} - \frac{E_{thr}}{p})} & \text{for } E_{cal} > E_{thr} \end{cases} \tag{88}$$

The calorimeter parent distributions for 5 GeV hadrons and positrons can be seen in comparison to data in figure (35). Here the data have been normalised to the same integral as the parent distribution. It is apparent that the data are not adequately described by the model. The positron distribution is in principle correct, but uses the wrong resolution. The hadron distribution is wrong because it does not take the influence of the trigger into account. The exponential decline describes the hadron spectrum in E_{cal}/p in principle well. However, the trigger threshold at 3.5 GeV has a drastic effect on the shape of the spectrum, by suppressing the low energy part. This is depicted in figure (36), which also can be understood as a slice of the lower plot in figure (5).

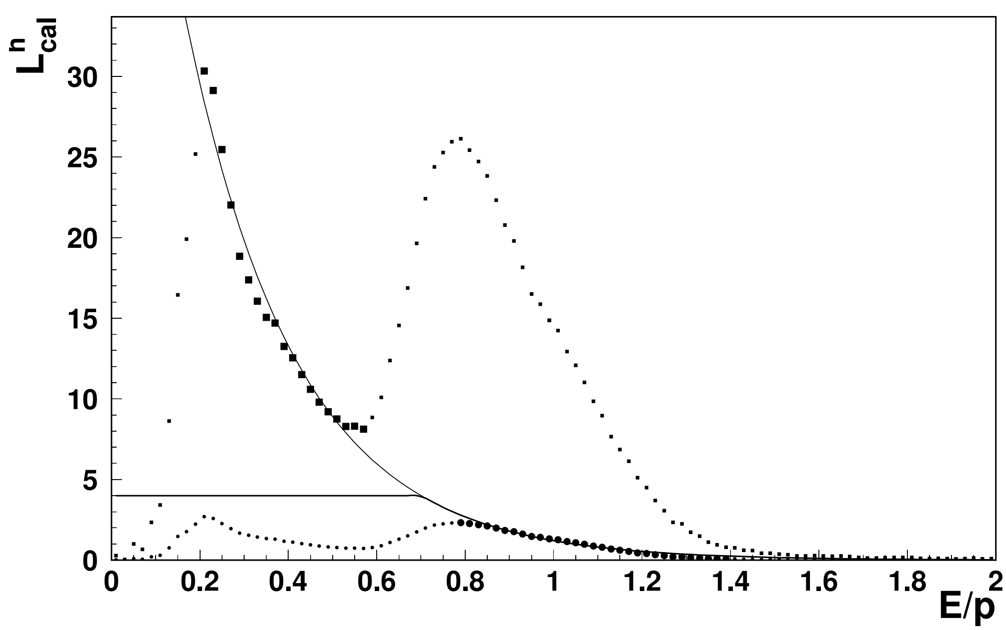

Figure 36: 5 GeV hadrons scaled so that the lower part (squares) or the higher part (circles) of the data fits the exponential function used as parent distribution. This illustrates the effect of the trigger on the calorimeter (E/p) hadron distributions.