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Measurement of the interaction length for pions and protons in TileCal Module 0

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Abstract

The ratio of the interaction lengths for pions and protons in ATLAS iron-scintillator tile hadron calorimeter was measured.
Measured value $\lambda_\pi/\lambda_p = 1.25 \pm 0.01_{stat}{}^{+0.04}_{-0.01 syst}$
is in a good agreement with the calculated value of 1.22.
The results are based on the data from the test beam in June-98, exactly 50, 80, 100 GeV pion data from η-scan.

1 Introduction

In the following text we concentrated on the measurement of the ratio of the pion and proton interaction lengths in Tile Calorimeter Module 0. [1]

The nuclear interaction length λ characterises the interactions in calorimeter; exactly it is the mean free path of particle between two inelastic interactions. This variable is different for various particles. It depends on the inelastic nuclear cross section σ like:

$$\lambda = \frac{A}{N_A \cdot \sigma \cdot \rho} \quad (1)$$

where A, ρ are the atomic weight and density of the target, N_A is the Avogadro number.

The interaction length for pions and protons in TileCal was calculated in [2]:

pions:	λ_π=251 mm
protons:	λ_p=206 mm
	λ_π/λ_p=1.22

2 Reconstruction of the ratio of the pion and proton interaction lengths

The ratio of the pion and proton interaction lengths in TileCal Module 0 was reconstructed using the test beam data from July-1998.

2.1 Cuts

1. The single particles events were chosen using the response of the scintillating counters *s1cou, s2cou, s3cou.*

2. Muons was excluded from analysis using the cut on the energy deposited in Module 0.

3. Protons and pions were separated using the response of the Cherenkov counter *cher1.*

2.2 Method

Module 0 is divided into read-out cells (see figure 1).

To reconstruct the ratio of the interaction lengths the following variables were measured (see figure 2) separately for pions and protons :

N_o - number of all incoming particles
After applying cuts the total number N_o of incoming particles of one type was read.

N - number of non-interacting particles in the first sampling:
For its estimation the spectrum of the energy, deposited in the cell which was irradiated, was used. Example of this energy spectrum is shown in figure 3.

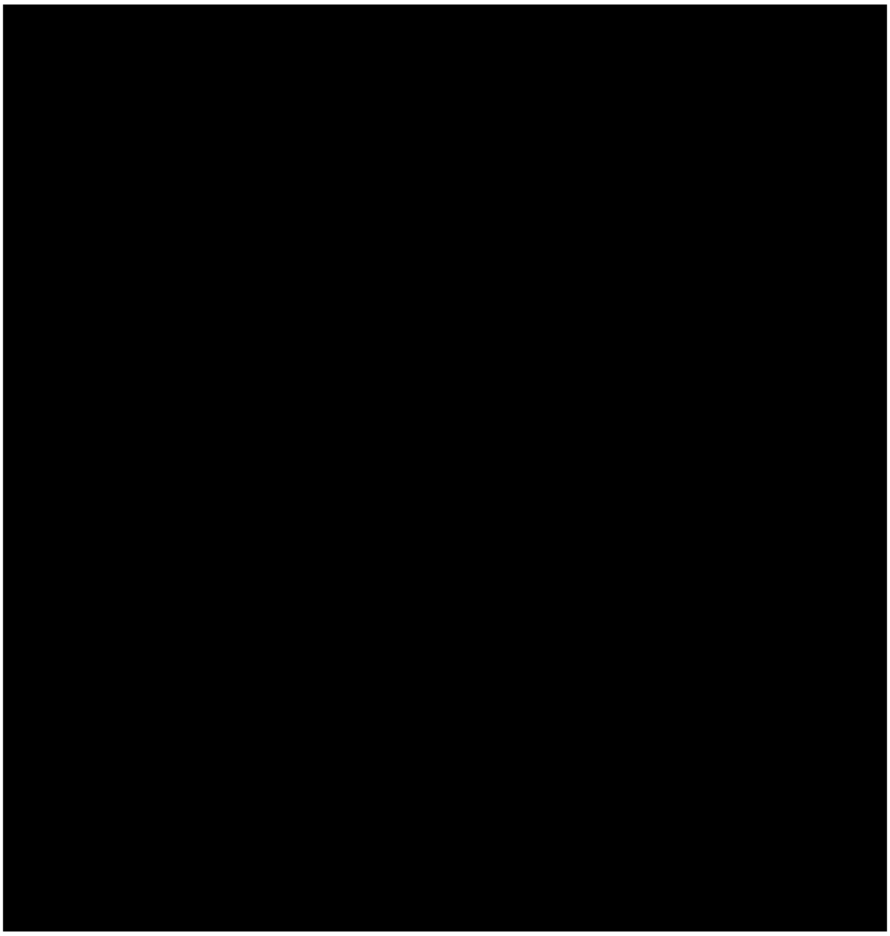

Figure 1: Read-out cells of Module 0

The peak at low energies corresponds to particles which didn't interact inside the first sampling. The higher energies correspond to events when incoming particle began the shower inside the first sampling.

$x(\lambda)$ - thickness of the first sampling:
From measured N, N_o the thickness of the first sampling (expressed in interaction length) was calculated using the equation:

$$N = N_o \cdot \exp\left(-x(\lambda)\right) \Rightarrow x(\lambda) = \ln\left(\frac{N_o}{N}\right)$$

From the thicknesses of the first sampling the ratio λ_π/λ_p of the pion and proton interaction lengths can be calculated using the equation (2)

$$\frac{\lambda_\pi}{\lambda_p} = \frac{x(\lambda_p)}{x(\lambda_\pi)} \tag{2}$$

where
$x(\lambda_p)$ is the thickness of the first sampling expressed in the interaction lengths

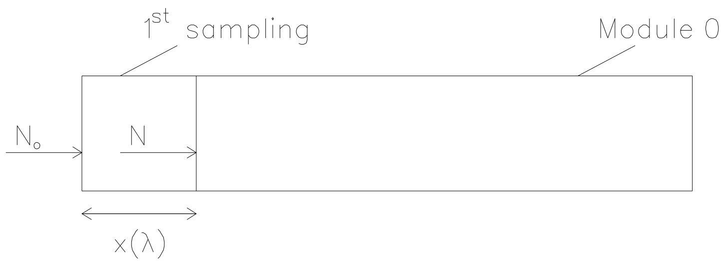

Figure 2: Method of the measurement of the interaction length

of protons,
$x(\lambda_\pi)$ is the thickness of the first sampling expressed in the interaction lengths of pions.

3 Results

Module 0 was irradiated at various pseudorapidities:

$$\eta = \text{-0.15, -0.25, -0.35, -0.45, -0.55, -0.65, -0.75}$$
$$+ \text{ fine } \eta\text{-scan (-0.34, -0.37, -0.40, -0.43, -0.46, -0.49, -0.53)}$$

Energies of particles were: 50, 80, 100 GeV

The results of thickness of the first sampling $x(\lambda, \eta)$ expressed in the interaction length for various eta are shown in figure 4.

The function (3)(described in appendix A) expresses the dependence of the thickness of the first sampling on the pseudorapidity. Using this function the thickness of the first sampling for η=0 was calculated.

$$x(\lambda, \eta = 0) = x(\lambda, \eta) \cdot \sin(2 \cdot \arctan(\exp(-\eta))) \quad (3)$$

The results of the thickness $x(\lambda, \eta = 0)$ of the first sampling are shown in figure 5 and in table 1. The ratio of the interaction length λ_π/λ_p was calculated using the equation (2).

	cut 1	cut 2
$x(\lambda_p, \eta=0)$	$1.407 \pm 0.008_{stat}$	$1.456 \pm 0.009_{stat}$
$x(\lambda_\pi, \eta=0)$	$1.128 \pm 0.007_{stat}$	$1.166 \pm 0.008_{stat}$
λ_π/λ_p	$1.247 \pm 0.008_{stat}$	$1.249 \pm 0.009_{stat}$

Table 1: Results of the thickness of the first sampling for pions and protons in Module 0 (cut 1 : $em0 > E_{min}$, cut 2 : $\langle em0 \rangle - 2 \cdot \sigma < em0 < \langle em0 \rangle + 2 \cdot \sigma$)

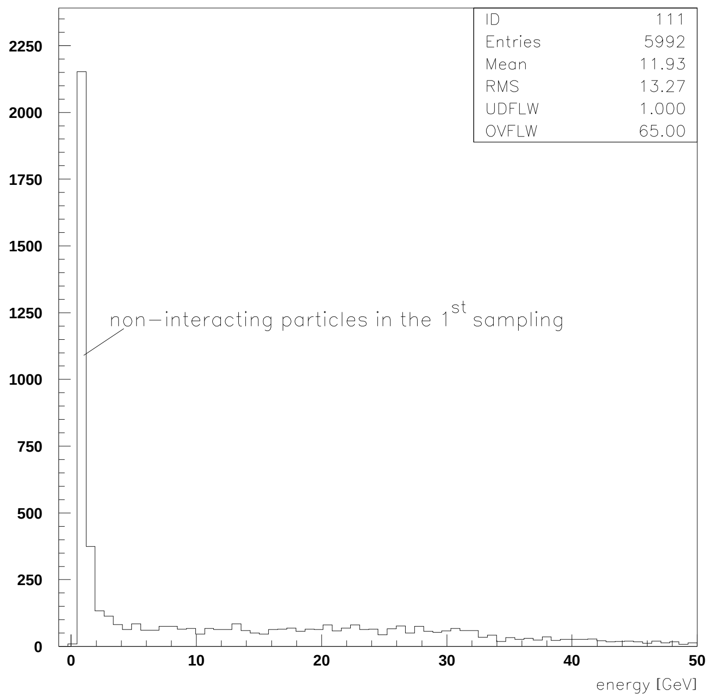

Figure 3: The energy deposited by hadrons in the first calorimeter sampling

4 Influences on the results of the measurement of the thickness of the first sampling

4.1 The efficiency of the Cherenkov counter

We separated pions from protons using the response of the Cherenkov counter, which was set to the π/p threshold.

We tried to estimate the inefficiency of the Cherenkov counter to pions using the response of muons in this counter. For estimation of the number of pions with no signal in Cherenkov we used the following equation:

$$N_{\pi n} = N_{\pi s} \cdot \frac{N_{\mu n}}{N_{\mu s}}$$

where
$N_{\pi s}$,$N_{\mu s}$ is the number of pions, muons causing the signal in Cherenkov counter
$N_{\pi n}$,$N_{\mu n}$ is the number of pions, muons after which passing through was no signal in Cherenkov counter.

We calculated $N_{\pi n}$ for each ntuple and corrected the measured value of the thickness of the first sampling expressed in λ_p using the equation (4) (described in appendix C):

$$x'(\lambda_p) - x(\lambda_p) = -\ln(\varepsilon_\pi \cdot e^{-(x(\lambda_\pi)-x(\lambda_p))} + 1 - \varepsilon_\pi) \qquad (4)$$

where $x'(\lambda_p)$ are the corrected values of the measurement of the thickness of the first sampling; ε_π expresses the amount of the admixture-pions in protons.

In table 1 there are shown already corrected values $x(\lambda_p)$.

4.2 Kaons

The hadronic part of the beam is the mixture of protons, pions and kaons. Using the Cherenkov counters it was not possible to identify kaons in the beam. However we were able to estimate if kaons produced light in Cherenkov counter (described in appendix D).

From *cher*1 settings one can conclude that kaons produced light only in ntuples from fine η-scan.

We calculated the corrections to results of the measurement of the thickness of the first sampling with the assumption that about 5% of hadrons are kaons (the amount of pions is approximately same as the amount of protons). The interaction length for kaons in Module 0 was estimated to be 315 mm (appendix B).

These corrections (systematic errors) are shown in table 1.

4.3 Cut on the energy

We calculated the thickness of the first sampling for two different cuts on the energy *em0* deposited in Module 0.

cut 1 : $em0 > E_{min}$
$E_{min} = 10$ GeV for 50 GeV
$E_{min} = 20$ GeV for 80, 100 GeV

cut 2 : $\langle\, em0 \,\rangle - 2 \cdot \sigma < em0 < \langle\, em0 \,\rangle + 2 \cdot \sigma$

In table 1 there are shown the results of the measurement for both cuts. From these two measurements we calculated the averaged value (see table 2) as the result value and the deviation we included into the systematic error.

It should be noticed, however, that the ratio of λ_π/λ_p is the same for both methods.

5 Conclusions

We measured the thickness of the first sampling in TileCal Module 0 for pions and protons and calculated the ratio of their interaction lengths.

For this measurement we used 50, 80, 100 GeV pion and proton data from η-scan of Module 0 in July 1998.

The calculated ratio of the interaction length of pions and protons in TileCal Module 0 is shown in table 2 and compared with relevant value calculated in [2].

	final	Ref. [2]
$x(\lambda_p,\ \eta{=}0)$	$1.43 \pm 0.01_{stat} \pm 0.03_{method} + 0.05_{kaons}$	
$x(\lambda_\pi,\ \eta{=}0)$	$1.15 \pm 0.01_{stat} \pm 0.03_{method} + 0.005_{kaons}$	
λ_π/λ_p	$1.25 \pm 0.01_{stat}{}^{+0.04}_{-0.01 kaons}$	1.22 ± 0.05

Table 2: Measured value of the ratio of the pion and proton interaction length compared with the relevant value calculated in [2].

References

[1] Tile Calorimeter TDR, CERN 1996

[2] J.A. Budagov et al.: *Study of the Hadron Shower Profiles with the ATLAS Tile Hadron Calorimeter,* ATLAS internal note, TILECAL-NO-127, 20 October 1997

[3] Particle Data Group: *Review of Particle Properties,* CERN 1998

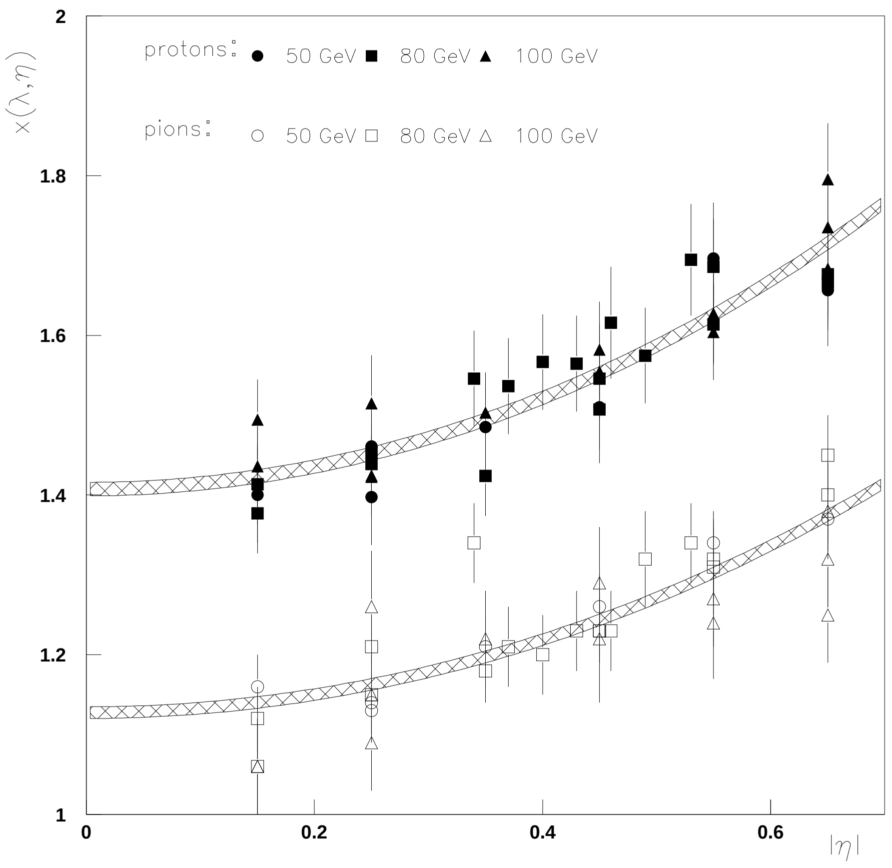

Figure 4: Thickness of the first sampling for various pseudorapidities. Cut used on the energy deposited in Module 0 : $em0 > E_{min}$.

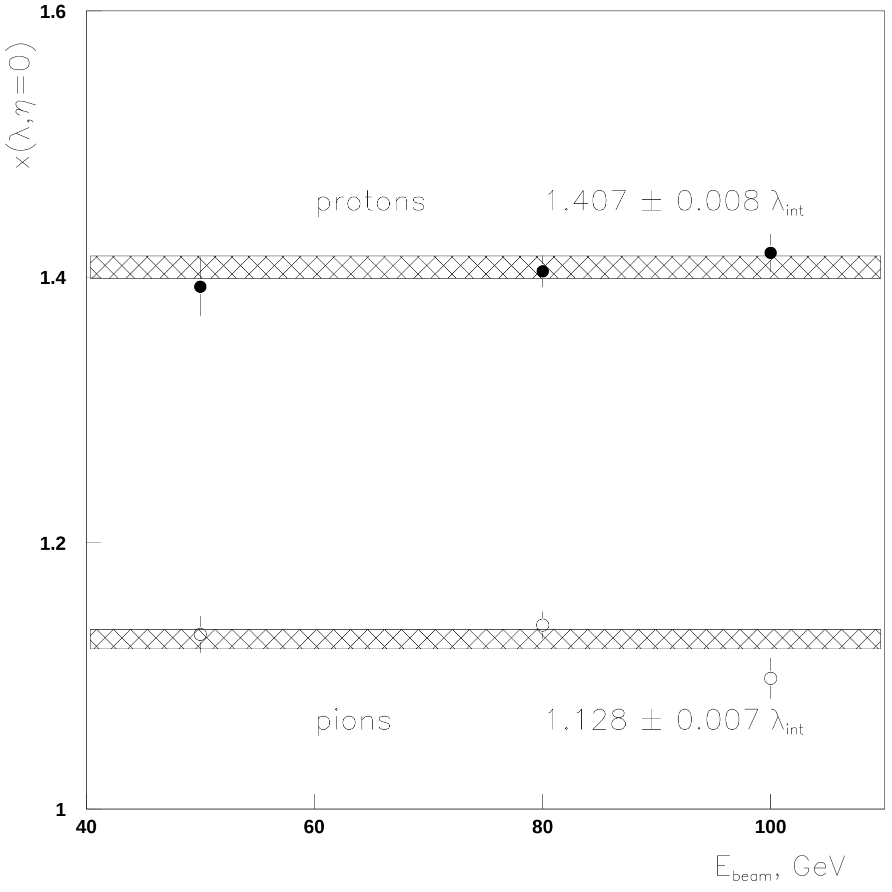

Figure 5: Results of the thickness of the first sampling for energies 50, 80 and 100 GeV. Cut used on the energy deposited in Module 0 : $em0 > E_{min}$.

Appendices

A Thickness of the first sampling of Module 0

The read-out cells of Module 0 are shown in figure 1.

Particles incoming to Module 0 under various pseudorapidities go the various paths through the first sampling (figure 6).

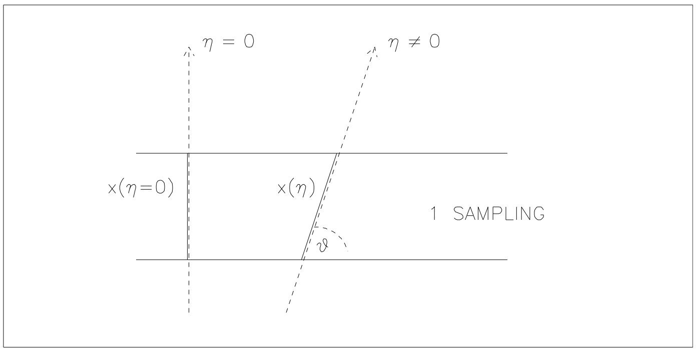

Figure 6: Thickness of the first sampling for various η

The dependence of the thickness of the first sampling on pseudorapidity is described by the following equations:

$$\eta = -\ln\tan\left(\frac{\vartheta}{2}\right)$$

$$\frac{x(\lambda,\eta=0)}{x(\lambda,\eta)} = \sin(\vartheta)$$

$$\frac{x(\lambda,\eta)}{x(\lambda,\eta=0)} = \frac{1}{\sin(2\cdot\arctan(\exp(-\eta)))}$$

where
ϑ is defined by the figure 6
$x(\lambda,\eta)$ is the thickness of the first sampling for η
$x(\lambda,\eta=0)$ is the thickness of the first sampling for $\eta=0$

B The estimation of the interaction length for kaons in TileCal

We estimated the interaction length for kaons in TileCal.

The inelastic cross sections on protons (for 100 GeV particles) is equal to [3]:

protons	:	$\sigma_p(p)$=31 mb
pions	:	$\sigma_\pi(p)$=20 mb
kaons	:	$\sigma_K(p)$=16 mb

We estimated the interaction length for kaons in Tilecal the following equation:

$$\lambda_K(cal) = \lambda_\pi(cal) \cdot \frac{\sigma_\pi(p)}{\sigma_K(p)}$$

where $\lambda_\pi(cal)$=251 cm was calculated in [2].

The estimated interaction length for kaons in TileCal Module 0 is equal to 315 mm.

C Calculation of the influence of the admixture in beam on the results of the interaction length

To measure the interaction length is necessary to separate various kinds of particles (protons, pions, mions, kaons). This is done by cuts on the proper variables. After this separation still remains the certain admixtures of one particles in others. To get the better results is necessary to calculated the corrections.

In this paragraph we use the following variables:
$x(\lambda)$ is the thickness of the first sampling expressed in the interaction length of beam-particles.
$x(\lambda_A)$ is the thickness of the first sampling expressed in the interaction length of admixture-particles.
ε expresses the amount of the admixture-particles in beam

The number of non-interacting particles N and the measured thickness $x(\lambda)$ of the first sampling for the pure beam:

$$N = N_o \cdot e^{-x(\lambda)} \Rightarrow x(\lambda) = \ln(\frac{N_o}{N})$$

The number of non-interacting particles N' and the measured thickness $x'(\lambda)$ of the first sampling for the beam with the admixture-particles:

$$N' = N_o \cdot \varepsilon \cdot e^{-x(\lambda_A)} + N_o \cdot (1-\varepsilon) \cdot e^{-x(\lambda)}$$
$$x'(\lambda) = \ln(\frac{N_o}{N'}) = x(\lambda) - \ln(\varepsilon \cdot e^{-(x(\lambda_A)-x(\lambda))} + 1 - \varepsilon)$$

Then the correction of the measurement of the thickness (expressed in λ) of the first sampling caused by the admixture-particles is equal to:

$$x'(\lambda) - x(\lambda) = -\ln(\varepsilon \cdot e^{-(x(\lambda_A)-x(\lambda))} + 1 - \varepsilon) \quad (5)$$

We used such corrections when we calculated:
* the influence of kaons on the measurement of the interaction length of pions and protons
* the influence of pions, which didn't caused the signal in Cherenkov counter, on the measurement of the interaction length of protons.

D Cherenkov counter

The Cherentov counter was used to separate particles.

In Cherenkov counter the particle, which velocity is bigger than the velocity of light in the medium of Cherenkov counter, cause the production of photons. The intensity of light (the mean value of the produced photons) could be describe by the following equation:

$$I = k \cdot (\Delta n - \Delta\beta)$$

where k is constant for the certain Cherenkov counter, Δn is the threshold for the production of light and $\Delta\beta$ depends on the rest mass m and momentum p of particle incoming the counter like:

$$\Delta\beta = \frac{1}{2}\frac{m^2}{p^2} \tag{6}$$

To get the mean value of the produced photoelectrons (intensity of light) one can fit the response of Cherenkov counter by the Poisson distribution (in ntuples the value of Cherenkov counter is given by the linear amplification of number of photoelectrons to which is added some pedestal).

These fits we did for muons and pions and got the intensities of light I_μ,I_π. We calculated the intensity of light I_K in Cherenkov counter for kaons:

$$\left.\begin{array}{l} I_\mu = k \cdot (\Delta n - \Delta\beta_\mu) \\ I_\pi = k \cdot (\Delta n - \Delta\beta_\pi) \\ I_K = k \cdot (\Delta n - \Delta\beta_K) \end{array}\right\} \Rightarrow I_K = (I_\mu - I_\pi) \cdot (\frac{I_\pi \cdot (\Delta\beta_\pi - \Delta\beta_\mu)}{I_\mu - I_\pi} + \Delta\beta_\pi - \Delta\beta_K)$$

where
I_μ,I_π are the mean values of photoelectron produced in Cherenkov counter by muons and pions. These values are known from fits.
$\Delta\beta_\mu$,$\Delta\beta_\pi$,$\Delta\beta_K$ can be calculated using the equation (6).

With the calculated value I_K we was able to decide if kaons influence the measurement of pions or protons.