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Study of the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ Decay at the NA48/2 Experiment

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Introduction

The present PhD thesis has been carried out within the NA48/2 fixed target experiment, a second upgrade of the NA48 detector located at the CERN-SPS north area with the main purpose to improve information on direct CP violation and study rare decays in the charged kaon sector.

Rare kaon decays offer the possibility of probing high energy scales by doing precise low energy measurements. In particular, radiative kaon decays are sensitive to the non-perturbative aspects of the Standard Model (SM). The only available framework to study these modes is a low effective theory known as Chiral Perturbation Theory (χPT) which parameterizes the ignorance of strong interaction dynamics in terms of a few unknown coupling constants. The $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay provides a stringent test of χPT since there is no tree-level $\mathcal{O}(p^2)$ contribution.

In the first chapter a theoretical introduction to Chiral Perturbation Theory and non-leptonic $K^\pm \rightarrow \pi^\pm \gamma \gamma$ radiative decay is presented together with the current experimental status.

The second chapter gives a detailed description of the novel NA48/2 beam line, experimental apparatus and data acquisition system with particular care to the sub-detectors involved in the analysis.

A Monte-Carlo simulation has been employed to optimize selection cuts, evaluate signal acceptance and analyze the composition of the physical background. In the third chapter the simulation tools are reported and some data/Monte-Carlo comparisons used to validate the official NA48/2 software are shown.

In the fourth chapter the details of the event selection are presented: identification of $K^\pm \rightarrow \pi^\pm \gamma \gamma$ candidate events and decay reconstruction. Special attention has been devoted to the understanding of events that can fake the signal by considering several kaon decay modes.

The fifth chapter focuses on the measurement of the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio. First, how the number of kaon decays in the experimental fiducial volume has been measured and the technique adopted to avoid the low signal statistics

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for trigger efficiency measurements are explained, then some data/Monte-Carlo comparisons for $K^\pm \rightarrow \pi^\pm \gamma\gamma$ events are shown. Several sources of systematics bias are considered using data or Monte-Carlo based approaches. Two different results are reported: a measurement obtained integrating over all the di-photon reconstructed spectrum and another one performed in bin of $m_{\gamma\gamma}$. The Chiral Perturbation Theory coupling constant $\hat{c}$ as been extracted as well.

Chapter 1

Theoretical Introduction

Rare kaon decays offer the possibility of probing high energy scales by doing precise low energy measurements: the precision is obtained by looking at very rare decays and the advantage of the kaon system is the long lifetime of both K_L and $K^\pm$.

Depending on the type of particles involved in the final states, all decays can be grouped in different categories such as radiative, hadronic, leptonic etc.. Radiative kaon decays, dominated by long distance physics, are sensitive to the non-perturbative aspects of the Standard Model (SM) and therefore they cannot be reliably predicted. Lattice calculations could solve the problem but at the moment the only available framework to study these modes is Chiral Perturbation Theory (χPT). Within that model, the ignorance of strong interaction dynamics is parameterized in term of a few unknown coupling constants that can be measured in some processes and then used to predict additional decay modes.

1.1 Chiral Perturbation Theory

Chiral Perturbation Theory [1], as effective formulation of the Standard Model, provides a systematic framework for investigating strong interaction at low energies, as opposed to a perturbative treatment of Quantum Chromo Dynamic (QCD) in terms of the running coupling constant: the only physical states which appear are pseudo-scalar mesons, photons and leptons, and the characteristic momenta involved are small compared to the natural scale of chiral symmetry breaking ($\sim 1\text{ GeV}$).

With n_f massless quark flavours, the QCD Lagrangian is invariant under global $SU(n_f)_L \otimes SU(n_f)_R$ transformations of the left- and right-handed quarks in flavour space. The symmetry group spontaneously breaks down to the diag-

onal sub-group $SU(n_f)_{L+R}$ and $n_f^2 - 1$ pseudo-scalar massless Goldstone bosons appear in the theory. For $n_f = 3$ these particles can be identified with the eight lightest hadronic states (π , K , η). The Goldstone nature of the pseudo-scalar mesons implies strong constraints on their interactions, which can be most easily analyzed on the basis of an effective Lagrangian. Since there is a mass gap separating the pseudo-scalar octet from the rest of the hadronic spectrum, we can build an effective field theory containing only the Goldstone modes. The low-energy effective Lagrangian can be organized in terms of increasing powers of momenta or, equivalently, in terms of increasing number of derivatives. In the low-energy domain the terms with a minimum number of derivatives will dominate. When evaluating the next-to-leading order Lagrangian, a certain number of unknown parameters appear: many of them can be extracted using low energy phenomenology and not all the parameters are necessary to obtain predictions on decay modes.

1.2 Radiative Kaon Decays: $K^\pm \rightarrow \pi^\pm \gamma \gamma$

The $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay provides a stringent test of χPT since there is no tree-level $\mathcal{O}(p^2)$ contribution because of the mismatch between the minimum number of powers of external momenta required by gauge invariance and the powers of momenta that the lowest order effective Lagrangian can provide. The leading contributions start at $\mathcal{O}(p^4)$ [2]. Observation of this decay mode in excess of the SM rate would suggest the existence of new phenomena such as sequential decays of the form $K^\pm \rightarrow \pi^\pm X^0$, $X^0 \rightarrow \gamma \gamma$, where X^0 is a massive short-lived neutral scalar particle [3].

The matrix element of the $K \rightarrow \pi \gamma \gamma$ decay has the general form:

$$\mathcal{M}(K(p) \rightarrow \pi(p_3) \gamma(q_1, \epsilon_1) \gamma(q_2, \epsilon_2)) = \epsilon_{1\mu} \epsilon_{2\nu} \mathcal{M}^{\mu\nu}(p, q_1, q_2)$$

where ϵ_1, ϵ_2 are the photon polarizations and $\mathcal{M}^{\mu\nu}$ contains the four invariant amplitudes:

$$\begin{aligned} \mathcal{M}^{\mu\nu} = & \frac{A(y, z)}{m_{K^+}^2} (q_2^\mu q_1^\nu - q_1 \cdot q_2 g^{\mu\nu}) + \\ & + \frac{2B(y, z)}{m_{K^+}^4} (-p \cdot q_1 p \cdot q_2 g^{\mu\nu} - q_1 \cdot q_2 p^\mu p^\nu + p \cdot q_1 q_2^\mu p^\nu + p \cdot q_2 p^\mu q_1^\nu) + \end{aligned}$$

$$\begin{aligned}
 & + \frac{C(y, z)}{m_{K^+}^2} (\varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}) + \\
 & + \frac{D(y, z)}{m_{K^+}^4} [\varepsilon^{\mu\nu\rho\sigma} (p \cdot q_2 q_{1\rho} + p \cdot q_1 q_{2\rho}) p_\sigma + (p^\mu \varepsilon^{\nu\alpha\beta\gamma} + p^\nu \varepsilon^{\mu\alpha\beta\gamma}) p_\alpha q_{1\beta} q_{2\gamma}]
 \end{aligned}$$

being

$$y = \frac{p \cdot (q_1 - q_2)}{m_{K^+}^2} \quad \text{and} \quad z = \frac{(q_1 + q_2)^2}{m_{K^+}^2} = \frac{m_{\gamma\gamma}^2}{m_{K^+}^2}.$$

The physical region in the adimensional variables y and z is defined to be:

$$0 \leq y \leq \frac{1}{2} \lambda^{1/2}(1, r_\pi^2, z) \quad \text{and} \quad 0 \leq z \leq (1 - r_\pi)^2$$

with

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + ac + bc) \quad \text{and} \quad r_\pi = \frac{m_{\pi^+}}{m_{K^+}}.$$

The invariant amplitudes $A(y, z)$, $B(y, z)$ and $C(y, z)$ have to be symmetric under the interchange of q_1 and q_2 as required by Bose symmetry, while $D(y, z)$ has to be anti-symmetric. In the limit of CP conservation, the amplitudes A and B contribute only to the $K_L \rightarrow \pi^0 \gamma \gamma$ decay while C and D only to the $K_S \rightarrow \pi^0 \gamma \gamma$. In the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ all of them are involved.

The double differential rate for unpolarized photons is given by:

$$\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^+}}{(8\pi)^3} \left[z^2 (|A + B|^2 + |C|^2) + \left(y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 (|B|^2 + |D|^2) \right] \quad (1.1)$$

To lowest non-trivial order $\mathcal{O}(p^4)$ in χPT , only the invariant amplitudes A and C contribute to the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay, because B and D terms are still zero since there are not enough powers of momenta to generate the gauge structure: their leading contribution is $\mathcal{O}(p^6)$ and, as can be seen from Eq. 1.1, they are the only terms contributing to the low z region. Moreover, the leading contribution of the D amplitude is helicity suppressed compared to B , due to its anti-symmetric character under the interchange of q_1 and q_2 .

The dominant amplitude A , corresponding to a $\gamma\gamma$ state with $CP = +1$, is calculated from the loop diagrams (Fig.1.1) and from the tree level counterterms:

$$A^{(4)}(z) = \frac{G_8 m_{K^+}^2 \alpha_{em}}{2\pi z} \left[(z + 1 - r_\pi^2) \cdot F\left(\frac{z}{r_\pi^2}\right) + (z + r_\pi^2 - 1) \cdot F(z) - \hat{c}z \right] \quad (1.2)$$

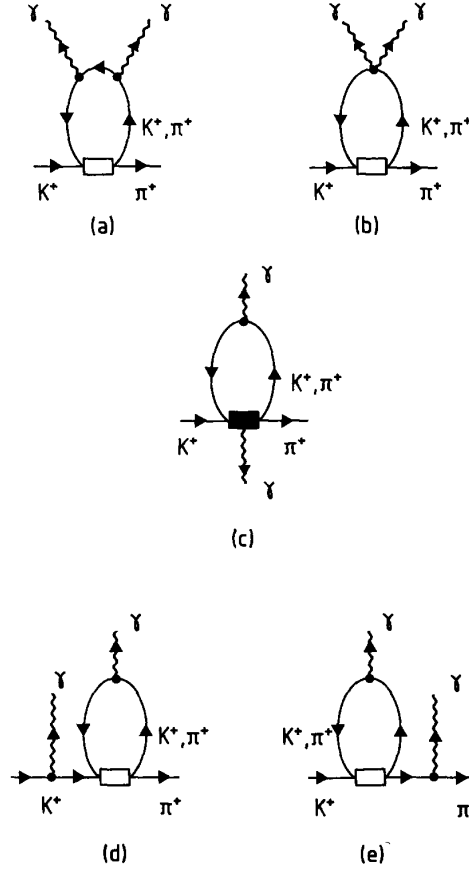


Figure 1.1: One-loop $K^\pm \rightarrow \pi^\pm \gamma \gamma$ diagrams: weak (weak and electromagnetic) vertices denoted by an open (full) box.

being $|G_8| \simeq 9.2 \cdot 10^{-6} \text{ GeV}^{-2}$ the effective weak coupling constant determined from $K \rightarrow \pi\pi$ at $\mathcal{O}(p^2)$ and $F(x)$ a function defined as:

$$F(x) = \begin{cases} 1 - \frac{4}{x} \arcsin^2 \frac{\sqrt{x}}{2} & , x \leq 4 \\ 1 + \frac{1}{x} \left(\ln^2 \frac{1-\beta(x)}{1+\beta(x)} - \pi^2 + 2\pi i \ln \frac{1-\beta(x)}{1+\beta(x)} \right) & , x > 4 \end{cases}$$

where $\beta(x) = \sqrt{1 - \frac{4}{x}}$.

Like in $K_L \rightarrow \pi^0 \gamma \gamma$ decay, the pion loop contribution $\propto F(z/r_\pi^2)$ (Eq. 1.2), dominates by far over the kaon loop amplitude $\propto F(z)$: the resulting loops are finite but χPT allows an $\mathcal{O}(p^4)$ scale independent local contribution that is parameterized by an $\mathcal{O}(1)$ constant:

$$\hat{c} = \frac{128\pi^2}{3} [3(L_9 + L_{10}) + N_{14} - N_{15} - 2N_{18}]$$

being L_9 and L_{10} the strong and N_{14} , N_{15} and N_{18} the weak $\mathcal{O}(p^4)$ couplings,

still not fixed by the phenomenology. They can be only computed in a model dependent way [4]: the Weak Deformation Model (WDM) predicts $\hat{c} = 0$, while the Factorization Model (FM) gives $\hat{c} = -2.3$.

The $\mathcal{O}(p^4)$ contribution to the $C(z, y)$ amplitude, which corresponds to a $\gamma\gamma$ state with $CP = -1$, is generated by the Wess-Zumino-Witten off-shell transition functional [5] $(\pi^0, \eta) \rightarrow \gamma\gamma$ through the sequence $K^+ \rightarrow \pi^+(\pi^0, \eta) \rightarrow \pi^+ \gamma\gamma$:

$$C^{(4)}(z) = \frac{G_8 m_{K^+}^2 \alpha_{em}}{\pi} \left[\frac{z - r_\pi^2}{z - r_\pi^2 + i r_\pi \frac{\Gamma_{\pi^0}}{m_{K^+}}} - \frac{z - \frac{2+r_\pi^2}{3}}{z - r_\eta^2} \right] \quad (1.3)$$

where $r_\eta = m_\eta/m_K$ and $\Gamma_{\pi^0} = \Gamma(\pi^0 \rightarrow \gamma\gamma)$. This contribution amounts roughly to less than 10% of the total width.

The two form factors do not interfere giving for the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ differential decay rate in terms of the normalized invariant mass squared of the photon pair:

$$\frac{d\Gamma}{dz} = \frac{m_{K^+}^5}{2(8\pi)^3} \cdot z^2 \cdot \lambda^{1/2}(1, z, r_\pi) \cdot \left[|A(z)|^2 + |C(z)|^2 \right]$$

The integrated rate can be expressed in the form:

$$\Gamma(K^\pm \rightarrow \pi^\pm \gamma\gamma) = \Gamma_{loop} + \Gamma_{WZW}$$

where

$$\Gamma_{loop} = (2.80 + 0.87 \cdot \hat{c} + 0.17 \cdot \hat{c}^2) \times 10^{-23} \text{ GeV} \quad (1.4)$$

$$\Gamma_{WZW} = 0.26 \times 10^{-23} \text{ GeV}$$

showing the dominance of the loop over the anomalous contribution.

Since the $\hat{c}$ constant is unknown, only a lower bound for the rate can be deduced from Eq. 1.4 ($\hat{c} = -2.6$ (Fig. 1.3)):

$$\Gamma(K^\pm \rightarrow \pi^\pm \gamma\gamma) = \Gamma_{loop} + \Gamma_{WZW} \geq 2 \times 10^{-23} \text{ GeV}$$

The predicted spectrum (Fig.3.5) is very characteristic: the peaking of the distribution at large z is due to the rapidly rising absorptive part of the $\pi\pi$ intermediate state; the shape is very sensitive to the value of $\hat{c}$.

χPT also predicts a correlation between the rate and the spectrum:

$$BR(K^\pm \rightarrow \pi^\pm \gamma\gamma) = (5.26 + 1.64 \cdot \hat{c} + 0.32 \cdot \hat{c}^2 + 0.49) \times 10^{-7} \quad (1.5)$$

giving as lower bound for the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio:

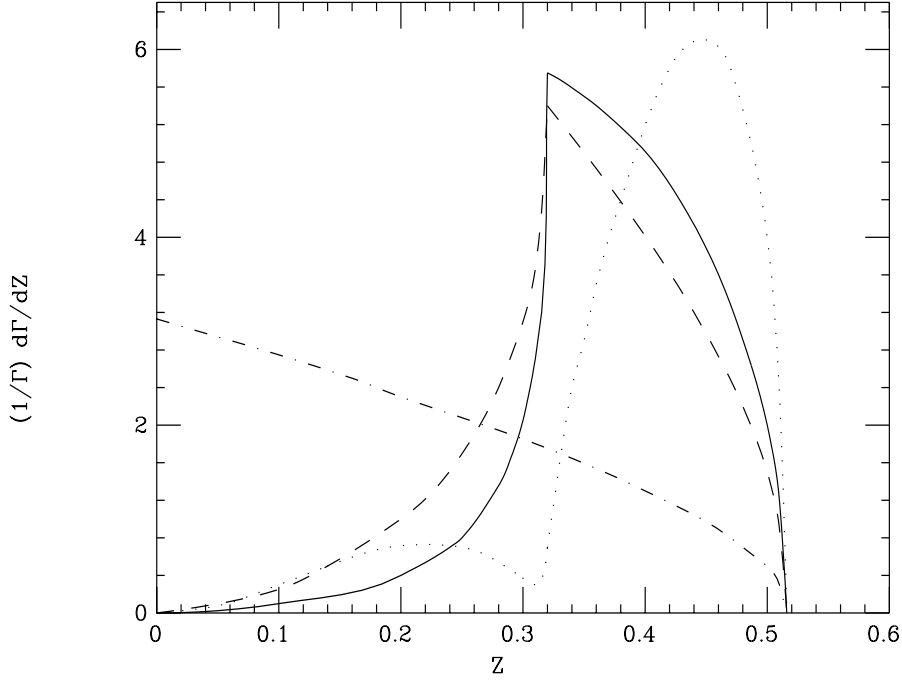


Figure 1.2: Normalized z distribution for $K^\pm \rightarrow \pi^\pm \gamma \gamma$ for $\hat{c} = -4$ (dotted curve), $\hat{c} = 0$ (full curve) and $\hat{c} = 4$ (dashed curve). Pure phase space prediction (dash-dotted curve).

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) \geq 4 \times 10^{-7}$$

1.2.1 $\mathcal{O}(p^6)$ Corrections

While the $\mathcal{O}(p^4)$ predicted spectrum looks in good agreement with the experimental results from $K_L \rightarrow \pi^0 \gamma \gamma$ decay [6], finding no contribution at small di-photon invariant mass, the predicted branching ratio is underestimated by a factor slightly bigger than two ($\sim 2\sigma$ away from the experimental result). These measurements indicate the necessity for next-to-leading order $\mathcal{O}(p^6)$ corrections [7], which can be deduced from an empirical fit of the decay amplitude of $K_L \rightarrow \pi^+ \pi^- \pi^0$.

The same approach has been adopted to evaluate the $\mathcal{O}(p^6)$ corrections to the charged mode: while the vector meson resonance dominated local amplitudes are likely to be negligible [8], the one-loop unitarity corrections from $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ are relevant [9], increasing by about 30 ÷ 40 % the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio (Fig.1.3) compared to the $\mathcal{O}(p^4)$ predictions. The shape of the z distribution is also sensitive to the evaluated corrections (Fig.1.4).

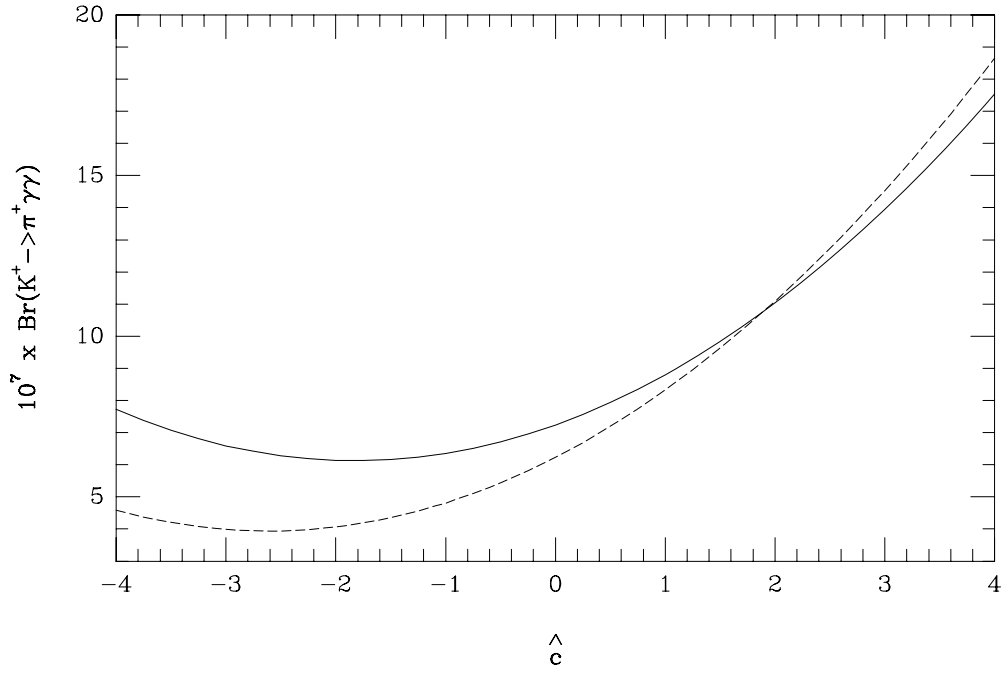


Figure 1.3: $BR(K^\pm \rightarrow \pi^\pm \gamma \gamma)$ as a function of the $\hat{c}$ amplitude: $\mathcal{O}(p^4)$ χPT amplitude (dashed line), amplitude including the $\mathcal{O}(p^6)$ unitarity corrections (full line).

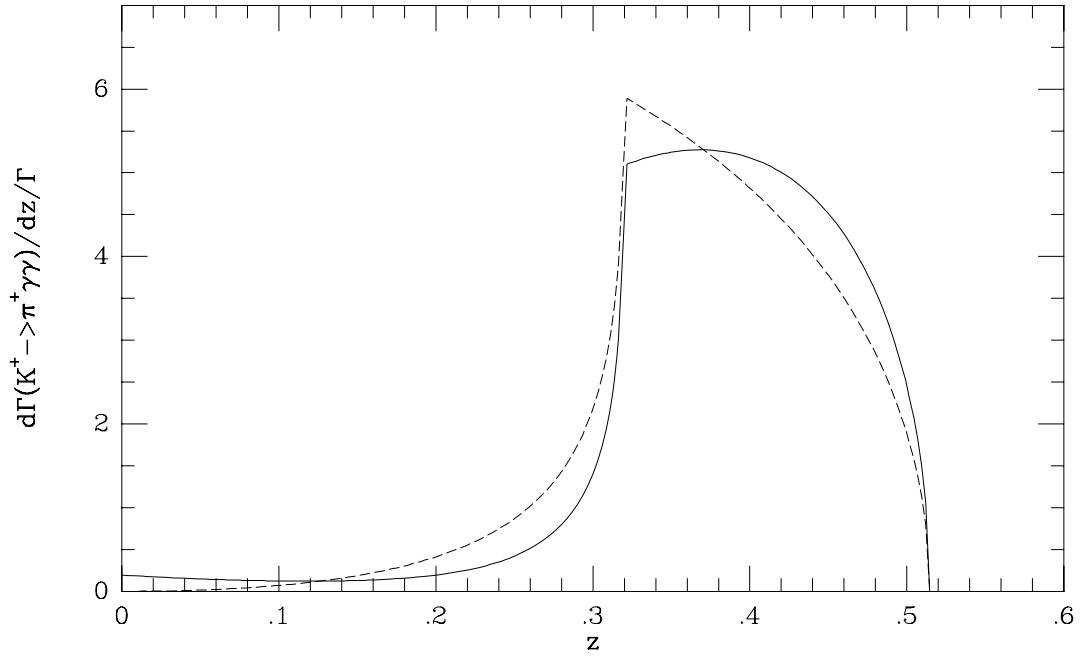


Figure 1.4: Comparison of the normalized z distribution for $K^\pm \rightarrow \pi^\pm \gamma \gamma$ at $\mathcal{O}(p^4)$ (dashed line) with $\mathcal{O}(p^6)$ unitarity corrections for $\hat{c} = 0$ (full line).

1.2.2 CP Violation

An additional feature of the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay is the possibility of searching for CP violation by comparing the two charged modes. The amplitude for $K^- \rightarrow \pi^- \gamma \gamma$ can be obtained from Eq. 1.2 and 1.3 by replacing G_8 and $\hat{c}$ by their complex conjugates. The charge asymmetry has been estimated to be [2] [10]:

$$\frac{|\Gamma(K^\pm \rightarrow \pi^\pm \gamma \gamma) - \Gamma(K^- \rightarrow \pi^- \gamma \gamma)|}{\Gamma(K^\pm \rightarrow \pi^\pm \gamma \gamma) + \Gamma(K^- \rightarrow \pi^- \gamma \gamma)} \lesssim 1 \times 10^{-3}$$

but a sensitivity of 10^{-10} in the branching ratio is necessary to measure that asymmetry.

1.2.3 Experimental Status

The present experimental measurement [11] is based on 31 candidates events with a residual background of 5.1 ± 3.3 events:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma, 100 \text{ MeV}/c < P_{\pi^+} < 180 \text{ MeV}/c) = (6.0 \pm 1.7) \times 10^{-7}$$

which corresponds to:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = (1.10 \pm 0.32) \times 10^{-6}$$

The $\hat{c}$ constant has been also extracted from a fit to the reconstructed $m_{\gamma\gamma}$ spectrum:

$\mathcal{O}(p^6)$ correction	$\hat{c}$
✓	(1.8 ± 0.6)
X	(1.6 ± 0.6)

Table 1.1: $\hat{c}$ measurements with (✓) and without (X) $\mathcal{O}(p^6)$ unitarity corrections.

Chapter 2

NA48/2 Experimental Apparatus

NA48/2 [13] represents the second upgrade of the NA48 fixed target experiment located at the CERN-SPS north area (Fig. 2.1), which adds to the existing detector a novel design for a simultaneous K^+/K^- beam, a new kaon spectrometer and a beam position monitor.

The main purposes are a high statistics study of the charge asymmetry in $K^\pm \rightarrow 3\pi$ decays in order to improve information on direct CP violation, Chiral Perturbation Theory tests with $K^\pm \rightarrow \pi^\pm \gamma \gamma$ and $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$ decays, the extraction of $\pi\pi$ scattering lengths from K_{e4} and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays and tests of V-A theory and $e - \mu$ universality through the ratio of semi-leptonic kaon decays $R_K = \frac{\Gamma(K \rightarrow e \nu)}{\Gamma(K \rightarrow \mu \nu)}$.

2.1 Coordinate System

The coordinate system of the experiment is cartesian: the z axis coincides with the center of the beam pipe and points towards the end of the detector; the y axis goes vertically from bottom to top; the x axis is horizontal and placed in such a way to define a right-handed system.

The position of all sub-detectors is given assuming the origin corresponds to the $K^\pm$ production target, while, at analysis level, the intersection of the axis is placed where the old NA48 K_S target was located ($\sim 120\text{ m}$ downstream the new NA48/2 target and $\sim 19\text{ m}$ from the last collimator).

2.2 Beam Line

A simultaneous K^+/K^- beam (Fig. 2.2 (left)) has been chosen in order to reduce systematic biases in the charge asymmetry measurement.

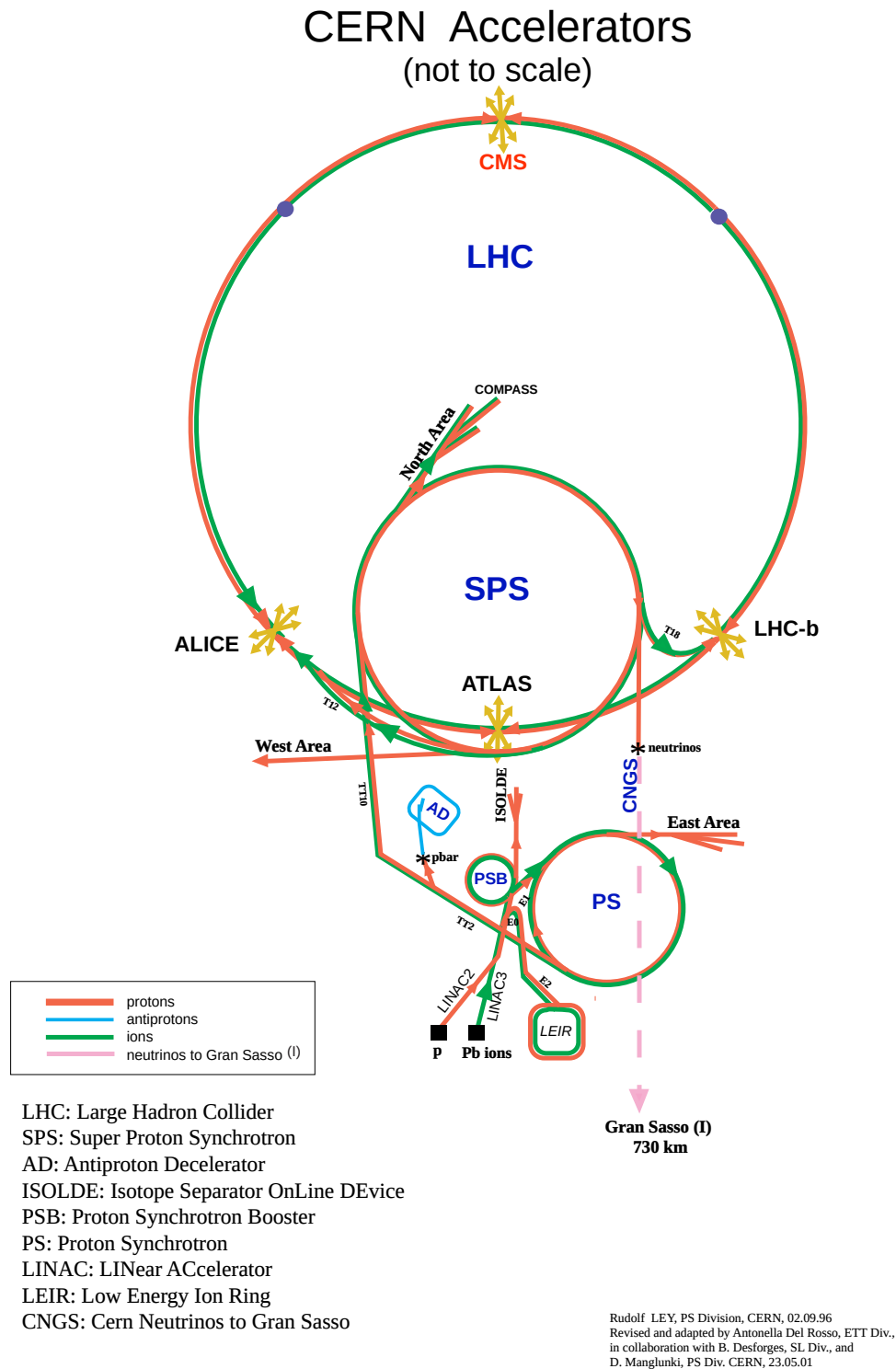


Figure 2.1: CERN accelerator complex. The NA48/2 experiment is located in the SPS north area.

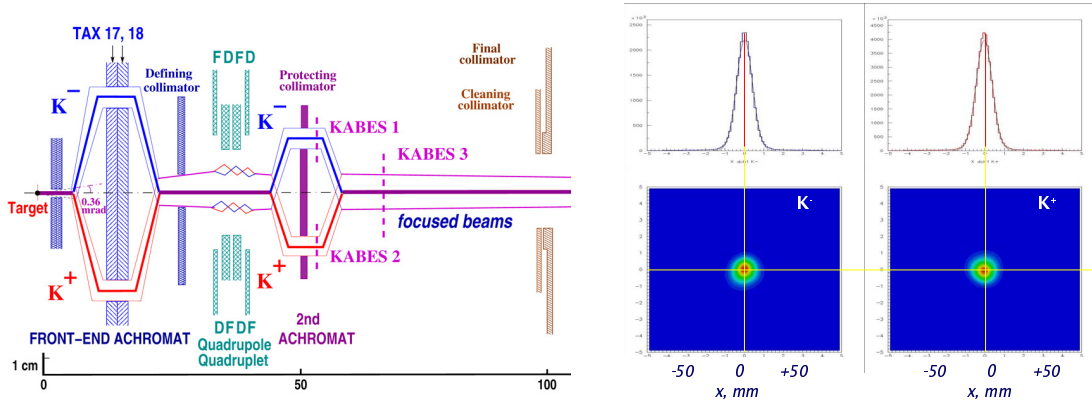


Figure 2.2: Schematic view of the NA48/2 beam line (vertical plane) (left). K^+ and K^- beam spot at the spectrometer position (right).

Two opposite in charge beams are produced with primary protons at $400 \text{ GeV}/c$ from SPS impinging on a 2 mm diameter and 400 mm long beryllium target ($\sim 1 \lambda_{Int}$). The proton beam intensity is $7 \cdot 10^{11}$ particles per burst with a 4.0 s flat top and a 16.8 s cycle. The proton incidence angle onto the target is 0 degrees, while the acceptance angle is defined to be $\pm 0.36 \text{ mrad}$ in both planes by a water cooled copper collimator of 15 mm aperture placed 24 m after the target. The collimator is also designed to absorb large angle secondary particles.

The momentum selection is made for both positive and negative charged particles by their passage through a four dipole magnets system with opposite-sign fields and zero net deflection (*Front-End Achromat*). The collimators placed in the middle of the achromat select a momentum band centered around $60 \text{ GeV}/c$ with an R.M.S. of $\pm 3.8\%$. The achromat is also equipped with dumps (*TAXes* 17 and 18) in order to absorb the remaining primary protons.

The two beams are defined to be "focused" and superimposed within 2 mm by a defining collimator placed $\sim 32 \text{ m}$ from the target, in such a way to have a spot size at the spectrometer position of $\sim 5 \text{ mm}$ (R.M.S.) (Fig. 2.2 (right)). The defining collimator is followed by a second achromat, again separating and recombining the two beams, which serves to block neutral and charged particles produced on *TAXes* (17, 18) and accommodating position sensitive detectors to determine the momentum of individual particles.

The sub-detectors of the experiment are further protected against background around the beams by a cleaning collimator at $\sim 110 \text{ m}$ and a final collimator ending at 114 m from the target. Just upstream of the last collimator, small steering dipole magnets allow to align the two charged beams in such a way to coincide to better than 2 mm at the end of the decay region (Fig. 2.20 (left)).

The K^+ / K^- flux ratio measured with $K^\pm \rightarrow 3\pi$ decays is ~ 1.8 (Tab 5.1).

Particle	Particles per pulse (10^6)	
	+	-
K	2.2	1.3
π	23	17
p	6.1	0.6
e	6.0	6.0
Other	~ 1	~ 1
Total	38	26

Table 2.1: Fluxes of positive and negative particles at the beginning of the decay region.

All magnet settings and collimator positions can be changed to switch the paths of the positive and negative charged beams or to select only one of the two to study systematic effects.

2.3 Beam Spectrometer

The beam spectrometer (*KABES*), a MICROMEGA type detector operating as Time Projection Chamber [14] (Fig. 2.3), has been introduced in order to measure the kaon momentum with sufficient accuracy to improve the study of decays with only one charged particle in the final state or with one or more undetected particles.

The detector is composed by three double stations, each of them recording the time and the space coordinates of the beam particle crossing it. Two stations are placed in the center of the second achromat, where positive and negative beams are vertically displaced, while the third one is located 8 *m* downstream the achromat, where the two beams are again collinear. The momentum of a beam particle is measured by the difference of the vertical coordinates measured in the first or second station, depending on the kaon sign, and the third one. The employed gas mixture is *Ne* 79% + C_2H_6 11% + CF_4 10%. The peak hit rate of the central strips at the third *KABES* station is ~ 2 MHz.

The achieved space resolution of 100 μm provides a measurement of track momentum with a precision better than 1%, while a time resolution better than 1 *ns* allows the charged kaons to be identified with almost no ambiguity (Fig. 2.4).

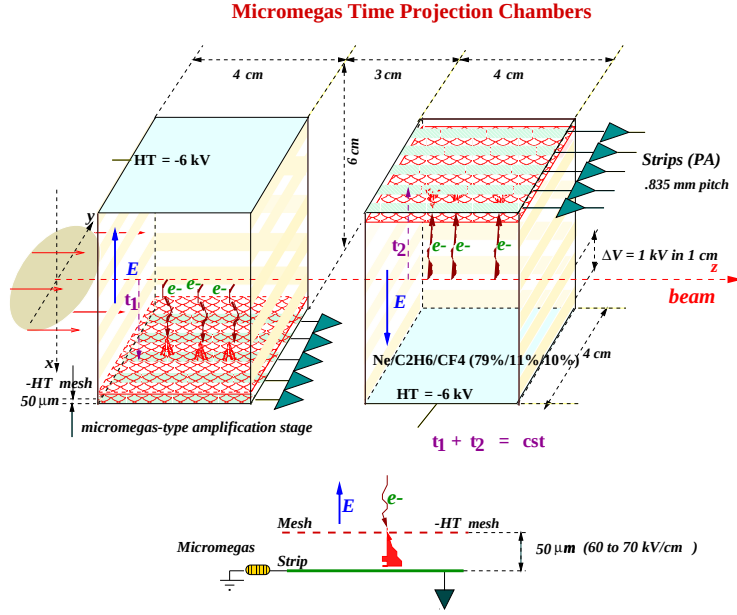


Figure 2.3: Sketch of a double station showing the principle of the MICROMEGAS Time Projection Chamber functioning.

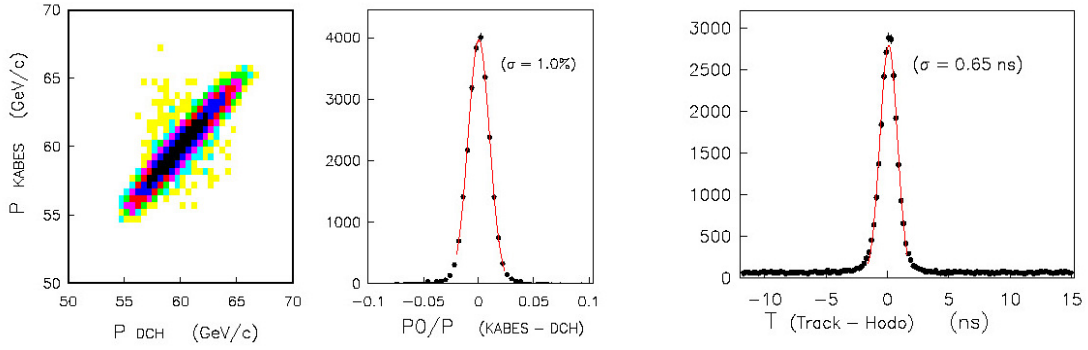


Figure 2.4: *KABES* vs. magnetic spectrometer momentum and *KABES* momentum resolution (left). *KABES* time resolution (right).

2.4 Decay Volume

The NA48/2 fiducial decay region (Fig. 2.5) has been extended by 24 *m* upstream with respect the old NA48 design to compensate for the shorter $K^\pm$ lifetime with respect to the K_L and to increase the detector acceptance for $K^\pm \rightarrow 3\pi$ decays.

The total volume length is ~ 114 *m*. The cylindrical vacuum chamber containing the two beams (*Blue Tube*) has an inner diameter of 1.92 *m*, increased up to 2.4 *m* in the last 48 *m* of the decay region. The volume is evacuated to a pressure $< 10^{-4}$ *mbar* to avoid interactions of kaon decay products before their detection.

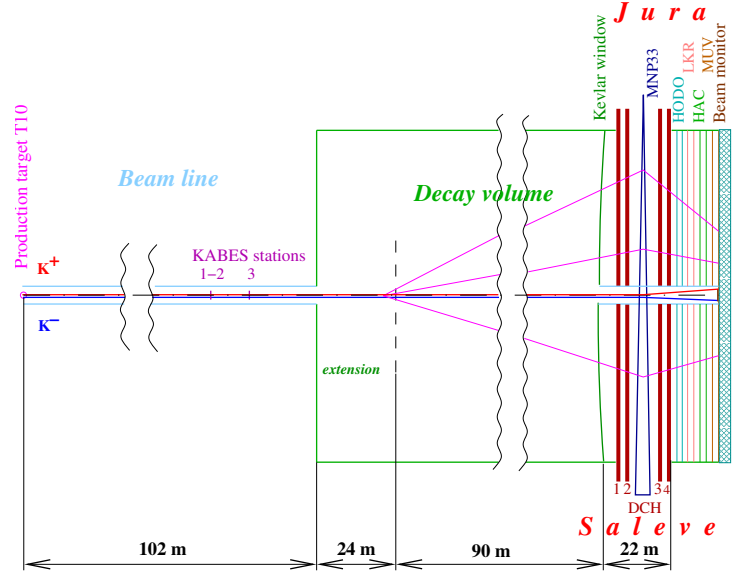


Figure 2.5: Schematic view of the NA48/2 decay volume with the 24 m extension in evidence.

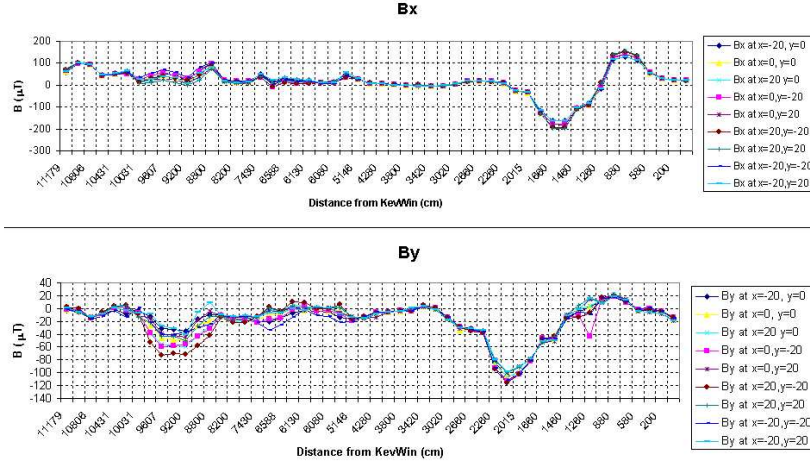


Figure 2.6: x and y component of the residual magnetic field in the blue tube (the different colors correspond to different x and y positions at which the measurement has been performed).

The tank is closed at the end by a 0.8 mm ($\sim 3 \cdot 10^{-3} X_0$) thick convex hemispherical shaped, 1.3 m radius, Kevlar window to separate the vacuum from the following volume, filled with helium gas at atmospheric pressure, which accommodates the drift chambers of the magnetic spectrometer.

In the decay region a small residual magnetic field, mostly due to the Earth field, is present: it has been carefully measured using Hall probes before the 2003 data taking (Fig. 2.6) to allow a posteriori correction on reconstructed tracks and to include its effect in Monte-Carlo simulation.

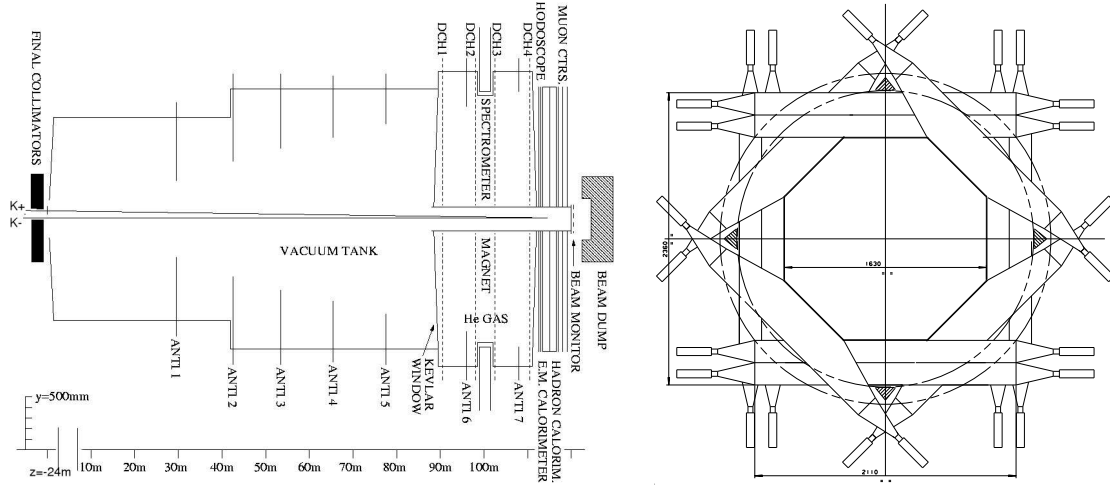


Figure 2.7: *AKL* pockets position (left) and structure of a single station (right).

Downstream the Kevlar window the beam, containing mainly undecayed kaons and pions, travels in vacuum in a carbon fiber pipe of 15.2 cm diameter and 1.2 mm thick.

2.5 Photon Anti-Counter

The large angle anti-counter system (*AKL*) consists of seven rings of iron and scintillator, five placed along the decay region and the last two in the spectrometer (Fig. 2.7 (left)), originally designed to detect photons outside the *LKr* calorimeter acceptance, but very useful also to reduce the trigger rate. Each pocket (Fig. 2.7 (right)) is longitudinally segmented into two layers of 10 mm thick scintillator with a 35 mm thick steel plate in front acting as photons converter. The resulting total photon conversion efficiency is $\sim 95.5\%$. The first four pockets are made of twelve counters while the remaining ones with eight. Each counter is read-out on both sides and a mean-timer is implemented at hardware stage in order to correct for the time difference due to the photon hit position.

The resulting *AKL* time resolution is:

$$\sigma_t \sim 550\text{ ps}$$

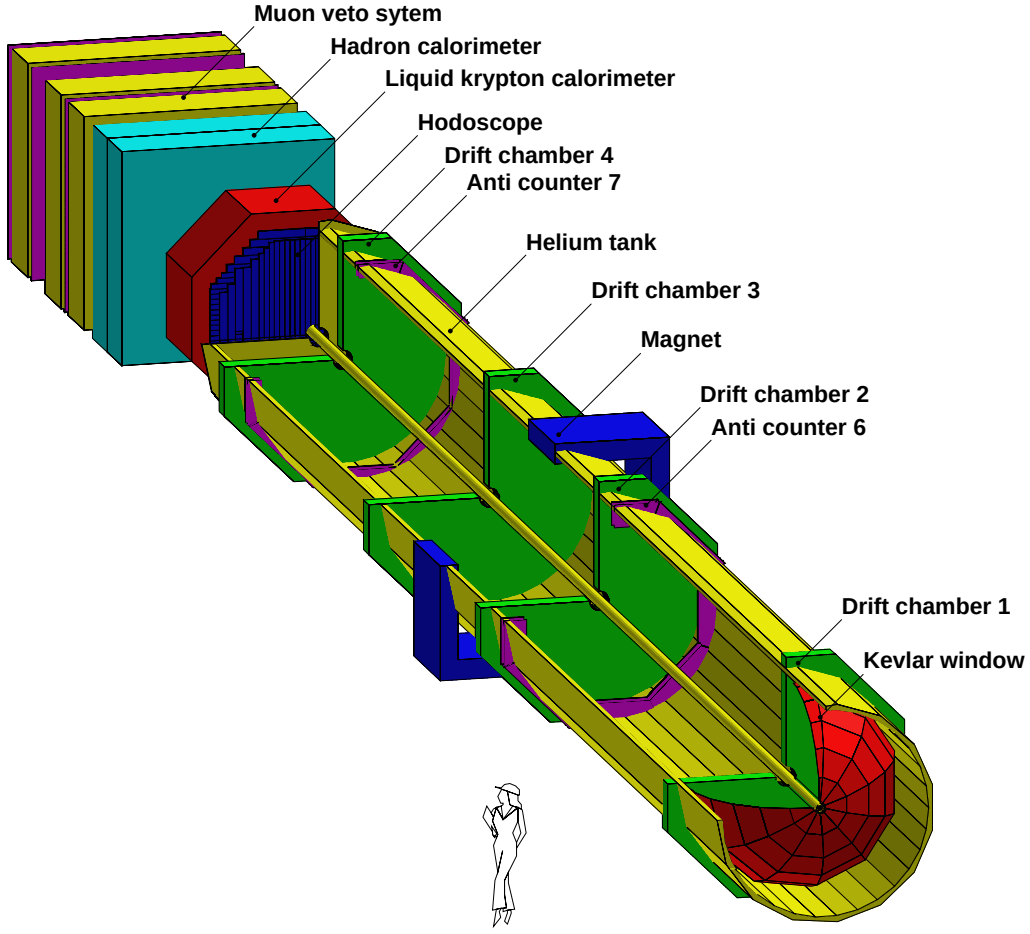


Figure 2.8: Schematic view of the NA48/2 detector.

2.6 Central Detector

No major changes have been made to the central detector setup (Fig. 2.8) with respect to the original NA48 design. The main components are: a magnetic spectrometer, a charged hodoscope, an electromagnetic calorimeter, an hadron calorimeter and a muon veto system.

2.7 Magnetic Spectrometer

The magnetic spectrometer is composed by four drift chambers (*DCH*) and one dipole magnet placed between the second and the third chamber (Fig. 2.9). The central aperture between the magnet poles is $2.45 \times 2.40 \text{ m}^2$ to match the *LKr* acceptance, the horizontal momentum kick is $120 \text{ MeV}/c$ (Fig. 2.10).

The spectrometer is housed in a stainless steel cylindrical vessel, $\sim 23 \text{ m}$ long and 2.8 m internal diameter, kept at atmospheric pressure. The volume is filled

2.7. Magnetic Spectrometer

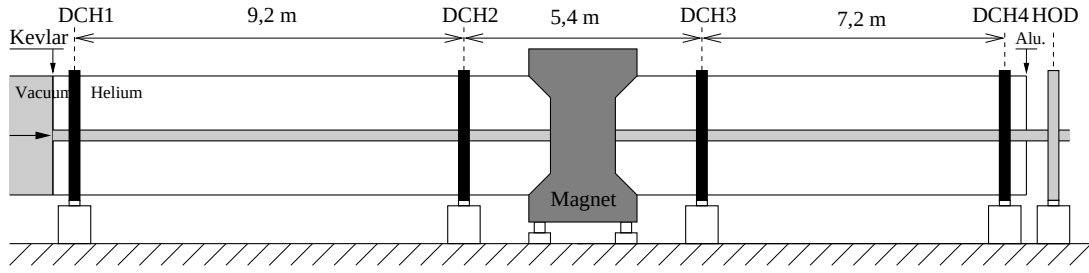


Figure 2.9: Lateral view of the magnetic spectrometer.

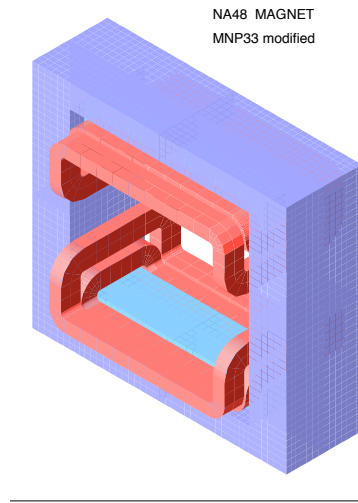


Figure 2.10: Spectrometer dipole magnet.

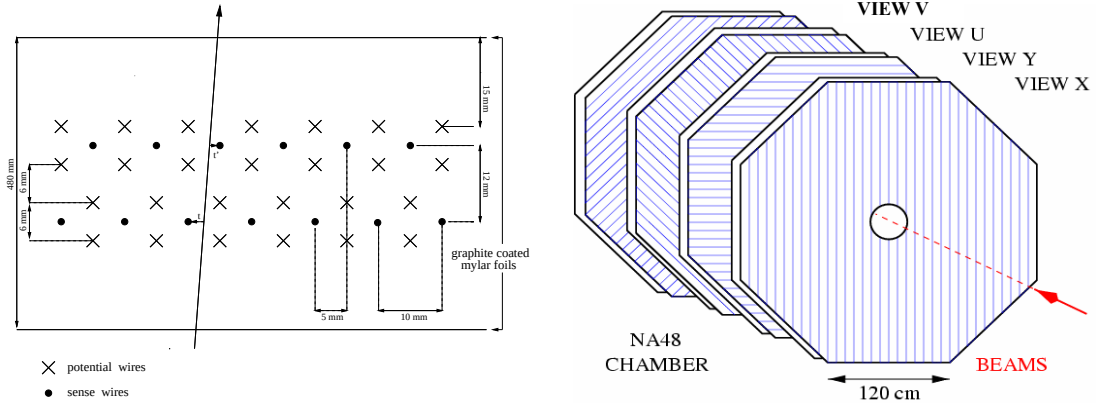


Figure 2.11: Drift cell geometry (left) and *DCH* views orientation (right).

with pure helium to reduce multiple Coulomb scattering and the probability of particle interactions with the medium. The four drift chambers have an octagonal shape with a transverse width of 2.9 m . Each chamber contains eight planes of grounded sense wires (Fig. 2.11 (left)), oriented in four different directions,

orthogonal to the beam axis: 0° (X, X'), 90° (Y, Y'), -45° (U, U') and 45° (V, V') (Fig. 2.11 (right)). Each so called "view" contains two planes staggered by half wire pitch to resolve the left-right ambiguities and to increase the spatial resolution of the reconstructed point. The total number of wires per plane is 256 and the maximum drift time is 100 ns , corresponding to the half wire pitch of 5 mm , obtained operating with a $Ar\ 50\% + C_2H_6\ 50\%$ gas mixture.

The resolution of the spatial position of the reconstructed hit is better than $100\ \mu\text{m}$ and the resulting momentum resolution of the magnetic spectrometer is:

$$\frac{\sigma(p)}{p} = 0.01 \oplus 0.00044 \cdot p$$

where p is in GeV/c . The first term is related to the multiple scattering in the helium tank and drift chambers, while the second one to the spatial point resolution of the chambers. The resolution of track time measurement is $\sim 0.7\text{ ns}$,

2.7.1 Track Reconstruction

The off-line track reconstruction is divided in two steps in order to achieve a more efficient determination of the number of charged particles crossing the detector, their direction, momentum and crossing time with respect to the on-line algorithm:

1. the drift time information is not used in order to reduce the combinatory of the space point finding procedure: tracks are reconstructed using only the hit wire positions; space points on the first and second chambers are connected to form mini-tracks; a complete track is formed if the y projection¹ of the mini-track extrapolation to the fourth chamber is close to a space point to better than 4 cm ; only mini-tracks which intercept an ideal cylinder of 10 cm of diameter along the decay region are reconstructed;
2. the drift time measurements are used to improve the space resolution of the impact points; a quality variable (χ^2) is associated to each track, taking into account the hit position on each view and used to reject bad tracks; momentum and track charge are then calculated employing an accurate map of the magnetic field.

¹The matching is performed on the vertical direction for which the magnet deflection is negligible.

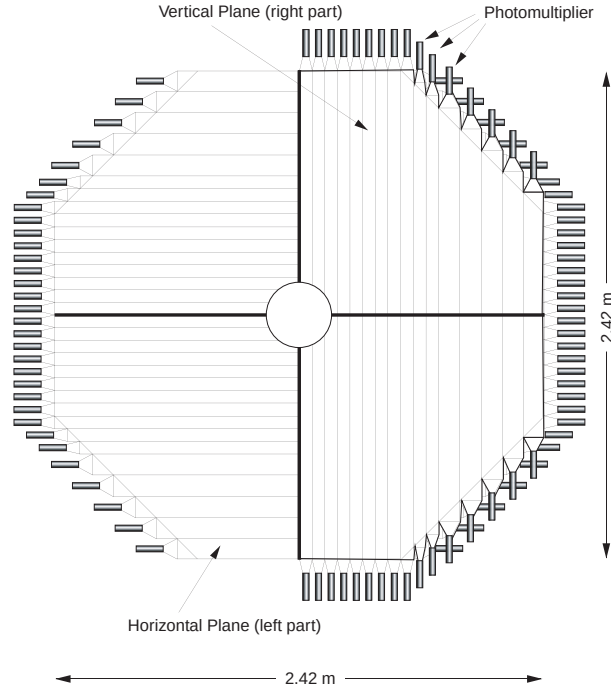


Figure 2.12: Charged hodoscope horizontal and vertical planes.

2.8 Charged Hodoscope

The charged hodoscope (*CHOD*) consists of two planes of plastic scintillator segmented into horizontal and vertical strips and arranged in four quadrants (Fig. 2.12). The thickness of a single counter is 2 cm ($\sim 0.05 X_0$) and the width for counters is 6.5 cm close to the beam pipe and 9.9 cm for the outer ones. The length varied from 0.6 m up to 1.21 m . The radius of the central hole, to let the beam pipe pass, is 10.8 cm .

The distance between the two planes (0.74 m) and the distance of the second plane from the calorimeter (0.8 m) has been chosen in order to reduce the effect of back splash particles from the *LKr* front end.

The detector is divided into four quadrants to produce topological and multiplicity triggers: a single track event will generate a signal (*Q1*) due to time coincidence of the hits in the correspondent quadrant of the two planes.

After off-line corrections the single track *CHOD* time resolution is:

$$\sigma_t \sim 200\text{ ps}$$

Atomic number	36
Mass number	84
Density at 120 K	2.41 g/cm^3
Radiation length	4.7 cm
Nuclear interaction length	60 cm
Molière radius	6.1 cm
Boiling point at 1 bar	119.8 K
Melting point	116.0 K
Critical energy	21.51 MeV
Electron drift velocity at $1(5) \text{ kV/cm}$	$0.27(0.37) \text{ cm}/\mu\text{s}$
Radioactivity	500 Bq/cm^3

Table 2.2: Liquid krypton physical properties.

2.9 Electromagnetic Calorimeter

Liquid krypton has been adopted, in a quasi-homogeneous configuration, allowing for the full ($> 99\%$ containment for a 50 GeV shower) development of electromagnetic showers within a octagonal shaped cylindrical volume of 1.25 m inscribed circle diameter and 1.27 m depth ($\sim 27 X_0$) (Fig. 2.13 (left)).

Thin *Cu-Be* ribbons (Fig. 2.13 (right)) have been chosen to construct the electrodes in the form of longitudinal towers of about $2 \times 2 \text{ cm}^2$ cross-section. The active volume is divided into $13248 \text{ } 2 \times 1 \times 127 \text{ cm}^3$ double ionization cells with the central detector as anode. The transverse dimensions of the cells increase as a function of the distance from the front of the calorimeter up to a maximum of 1.1% at the back. They define a projective geometry of the calorimeter (*LKr*) pointing at about 90 m in front of it, realized in order to achieve the best possible accuracy in the measurement of the angle between the flight path of photons and the beam direction. To ensure a good uniformity of the response over the whole front surface of the calorimeter, the distance between electrodes must be known with high accuracy. For this reason the electrode ribbons are held by spacer plates that fix their transverse position at five longitudinal positions in addition to the front and back planes. The tension of the ribbon is $\sim 2 \text{ N}$. The feed through the spacing plates gives to the electrodes a peculiar zig-zag shape ("Accordion" geometry) that minimizes inefficient ionization of the showers developing along the anode (Fig. 2.14).

The boiling temperature of the *Kr* at normal pressure is 119.8 K and the drift velocity of electrons depends on temperature ($\frac{\Delta v}{v \Delta T} = \frac{-0.87\%}{\text{K}}$) (Tab. 2.2). To precisely control the temperature, the calorimeter has been enclosed in a cryo-

2.9. Electromagnetic Calorimeter

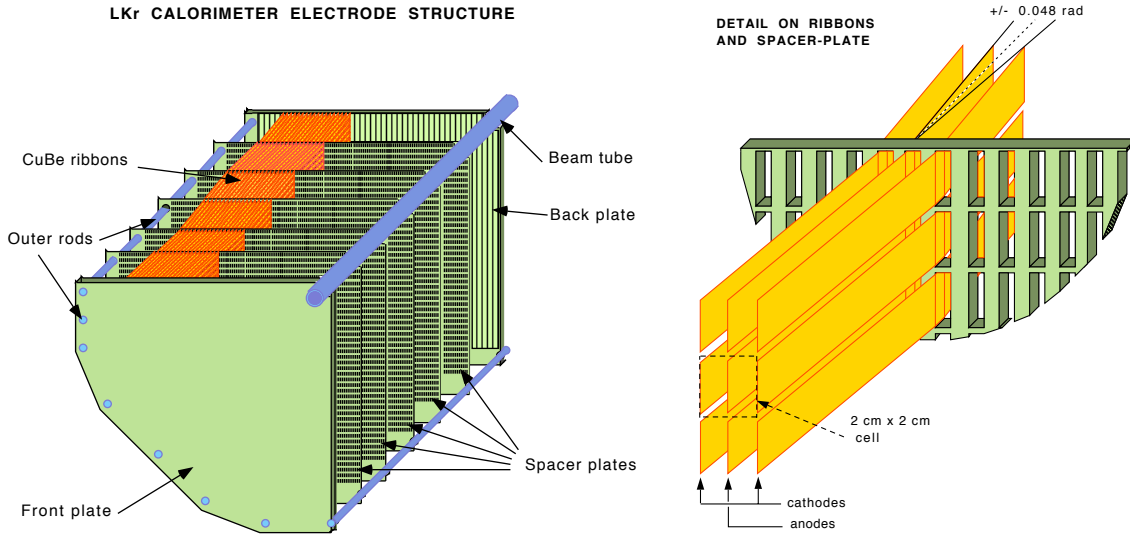


Figure 2.13: *LKr* electrode (left) and cell (right) structure.

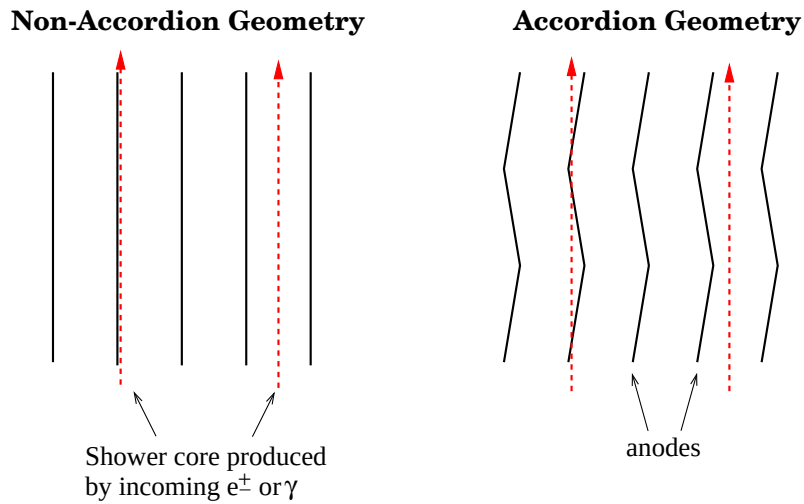


Figure 2.14: "Accordion" geometry of the calorimeter electrodes.

stat, made of an outer aluminium vessel and a vacuum insulated inner stainless steel container: the system keeps the temperature of the *LKr* calorimeter at 121 K within ± 0.1 K. The whole cryostat introduces some passive material ($\sim 0.65 X_0$) in front of the *LKr* that corresponds, on average, to a 50 MeV loss in reconstructed photon energy.

Only about 60 out of 13248 *LKr* cells, known as "dead cells" (Fig. 2.15), has electronic faults (faulty preamplifiers, no calibration, bad pedestal and/or a very unstable response to calibration pulses) preventing their correct utilization.

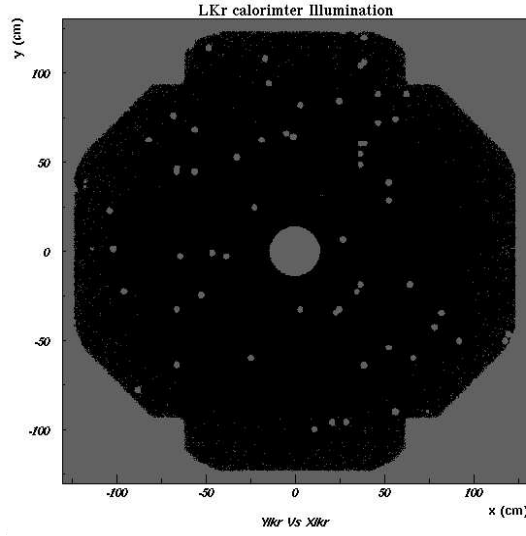


Figure 2.15: "Dead cells" position.

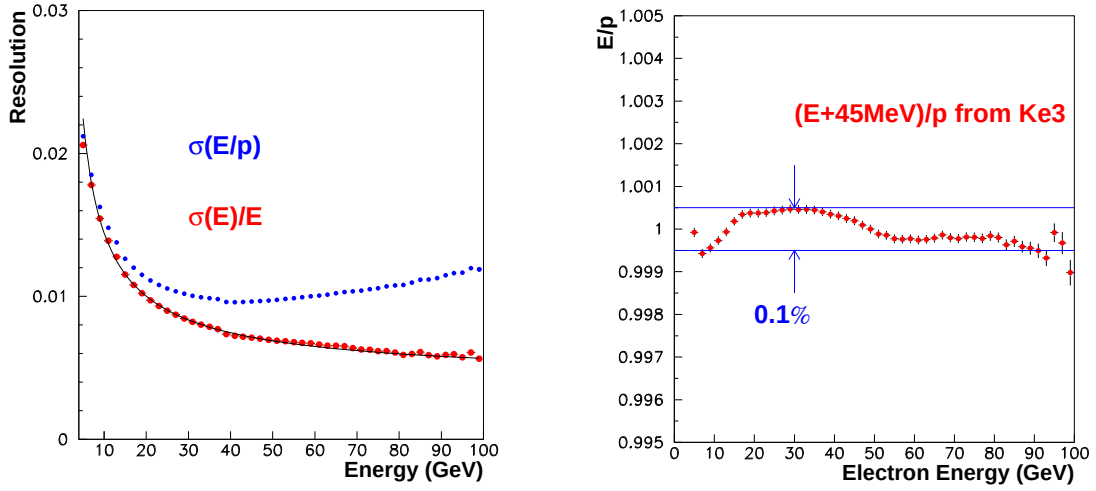


Figure 2.16: Energy resolution (left) and linearity (right) of the electromagnetic calorimeter.

After calibration and corrections the energy resolution (Fig. 2.16) of the *LKr* calorimeter can be parametrized as:

$$\frac{\sigma(E)}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$$

where E is in *GeV*. The first term depends on stochastic sampling fluctuation, the second one on electronic noise and *Kr* natural radioactivity and the last one on inhomogeneities, material in front of the calorimeter and the non perfect inter-calibration of the cells.

Good spatial and time resolutions are achieved from the granularity of the calorimeter:

$$\sigma_{x,y} = \left(\frac{0.42}{\sqrt{E}} \oplus 0.06 \right) cm$$

$$\sigma_t = \left(\frac{2.5}{\sqrt{E}} \right) ns$$

where E is in GeV .

2.9.1 Cluster Reconstruction

A pattern recognition technique, cluster reconstruction, allows to determine which cells belong to the same shower, the energy deposition, crossing time, position and the shower transverse size of crossing particles. A cluster is defined if one cell ("seed") has an energy larger than $0.1 GeV$, if it has more energy than any of the eight surrounding cells and if its energy satisfies the following condition:

$$E_{seed} > 0.18 GeV + 1.8 \cdot E_{average}$$

where E_{seed} and $E_{average}$, the average energy deposition of the eight surrounding cells, are in GeV .

The following steps are applied to extract the physical parameters of the shower.

- The cluster energy is evaluated performing a loop over the clusters, including in each cluster the 121 cells in a $22 \times 22 cm^2$ squared box centered on the seed position; if a cell belongs to more than a cluster, then its energy content is shared among the clusters according to their profile distribution²; the energy of the cluster is corrected for energy loss due to proximity to the hole of the beam pipe and calorimeter borders, dead cells and energy scale of the calorimeter.
- The cluster position is estimated using the centre of gravity of the energy deposition in a 3×3 cell box around the seed position.
- The cluster development size is calculated independently in both x and y directions as the R.M.S. of the energy distribution in a 5×5 cell box around the seed position.

²The shower profile is estimated using GEANT simulation library.

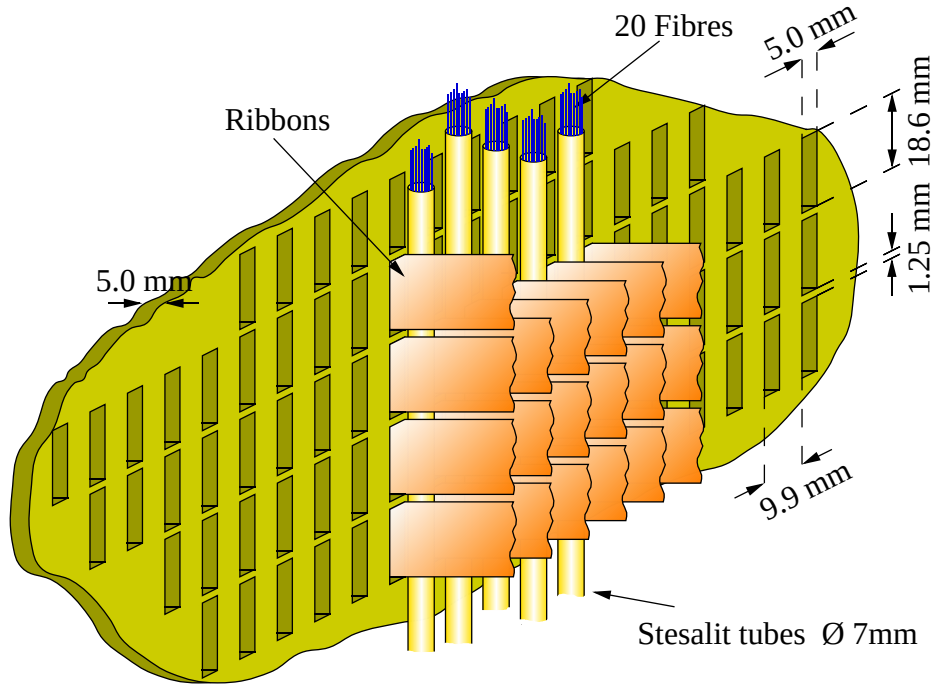


Figure 2.17: Sketch of the neutral hodoscope fibres.

- The cluster time is defined as the average of the event time recorded by the cells in the the 5×5 cell box around the seed cell.

2.10 Neutral Hodoscope

In the inner part of the electromagnetic calorimeter, at the depth of $\sim 9.5 X_0$, a scintillating fiber hodoscope is placed. The *NHOD* is made of 256 vertical bundles of scintillating fibers (Fig. 2.17) contained in an epoxy-fiberglass tube (7 mm in diameter and 2 m in length) and immersed directly in the liquid krypton. The neutral hodoscope provides an independent measurement of the time of the shower and, especially, act as an independent source of minimum bias trigger (*T0N*) to check the efficiency of the neutral trigger systems.

For showers of energy greater than 15 GeV the typical time resolution is:

$$\sigma_t = 250 \text{ ps}$$

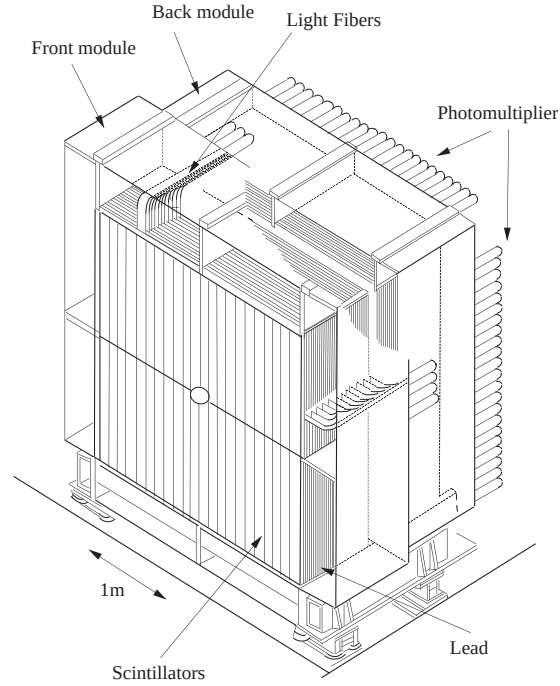


Figure 2.18: Hadron calorimeter layout.

2.11 Hadron Calorimeter

The hadron calorimeter (*HAC*) consists of an iron-scintillator sandwich of 1.2 m total iron thickness ($\sim 6.7 \lambda_{Int}$). It is longitudinally divided into two separate modules (front and back), each consisting of 24 iron plates, 25 mm thick, of dimension $2.7 \times 2.7\text{ m}^2$, alternated with 24 scintillator planes, 4.5 mm thick, each of them divided into 44 half-strips per plane arranged in vertical and horizontal direction (Fig 2.18). It is mainly used for trigger purpose, determining, together with the electromagnetic calorimeter, the total energy of the event.

The *HAC* energy resolution is:

$$\frac{\sigma_E}{E} = \frac{0.65}{\sqrt{E}}$$

where E is in GeV .

2.12 Muon Veto Counter

The complete muon veto counter array (*MUV*) consists of slightly overlapping long flat strip of plastic scintillator arranged in three planes, alternatively in

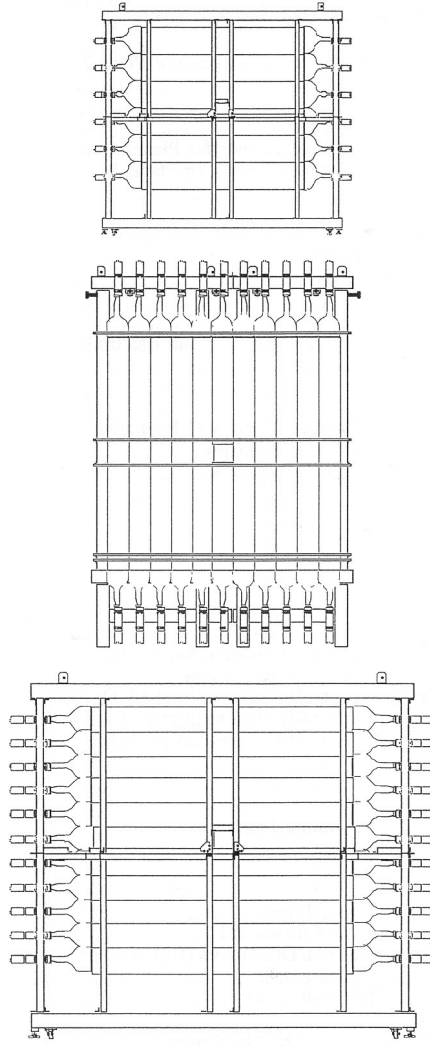


Figure 2.19: Geometry of the muon veto planes.

vertical and horizontal direction, each one preceded by a 0.8 m ($\sim 5\lambda_{Int}$) thick iron wall to provide absorption of hadrons (Fig. 2.19).

The first two scintillators planes are made of eleven plates each 10 mm thick, while the last one is composed by six plates 6 mm thick. The array occupied a longitudinal space of 4.3 m including additional 0.4 m wall behind the third plane to absorb backward-going products of interactions at the rear of the beam line.

After impact point correction (extrapolating the muon position from the *DCH*) the time resolution of this system is:

$$\sigma_t \sim 700\text{ ps}$$

The reconstruction efficiency for single-muon events is $> 99\%$.

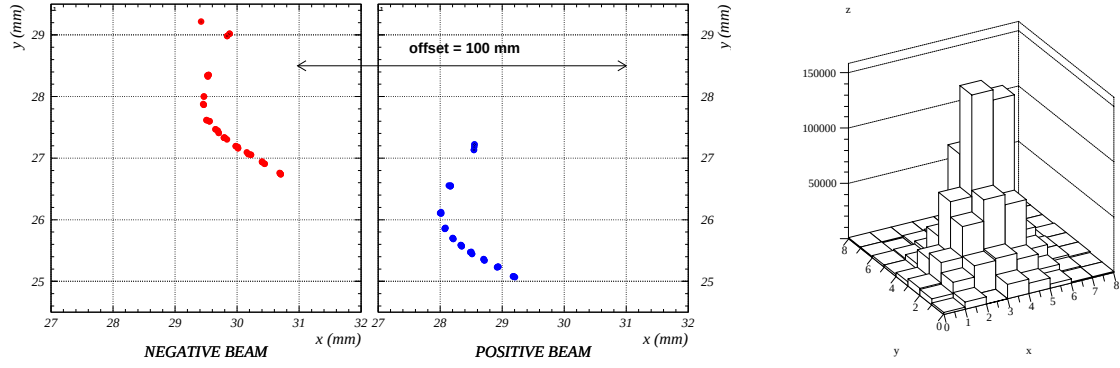


Figure 2.20: Beam movement during the SPS spill (left) and beam profile (right)

2.13 Beam Position Monitor

A beam position monitor has been designed in order to have a fast on-line feedback on the beam stability (Fig. 2.20 (left)). It is placed at the end of the detector, just in front of the beam dump, where, due to the action of the spectrometer magnet, the positive and the negative components of the beam are spatially separated by about 6 cm . The monitor is composed by two 8×8 matrices of plastic scintillator blocks of $6 \times 6\text{ mm}^2$ in transverse dimension and 9 mm thick. The blocks are separated by thin aluminium foils in order to reduce the optical crosstalk. The system is mounted on four independent motors, to allow horizontal (singular and common) and vertical movements. The two detectors are displaced by $\sim 10\text{ cm}$ to intercept the two beams. The resolution on the center of gravity of the beam is $\sim 0.1\text{ mm}$ (Fig. 2.20 (right)).

2.14 Trigger System

The NA48/2 trigger (Fig.2.21) is a multilevel system designed to be in principle dead-time free and to reduce the events rate from $\sim 1\text{ MHz}$, which is the average kaon decay rate in the decay volume, down to $\sim 10\text{ kHz}$. The full acquisition system is pipelined and synchronized by a 40 MHz clock. Every 25 ns the sub-detectors write their output to a circular memory $204.8\text{ }\mu\text{s}$ deep. The system is divided in two parts: the *Charged* and the *Neutral* Trigger. The two sub-systems are controlled by the *Trigger Supervisor (TS)* that collects all the information and takes the final decision to read-out or discard the event.

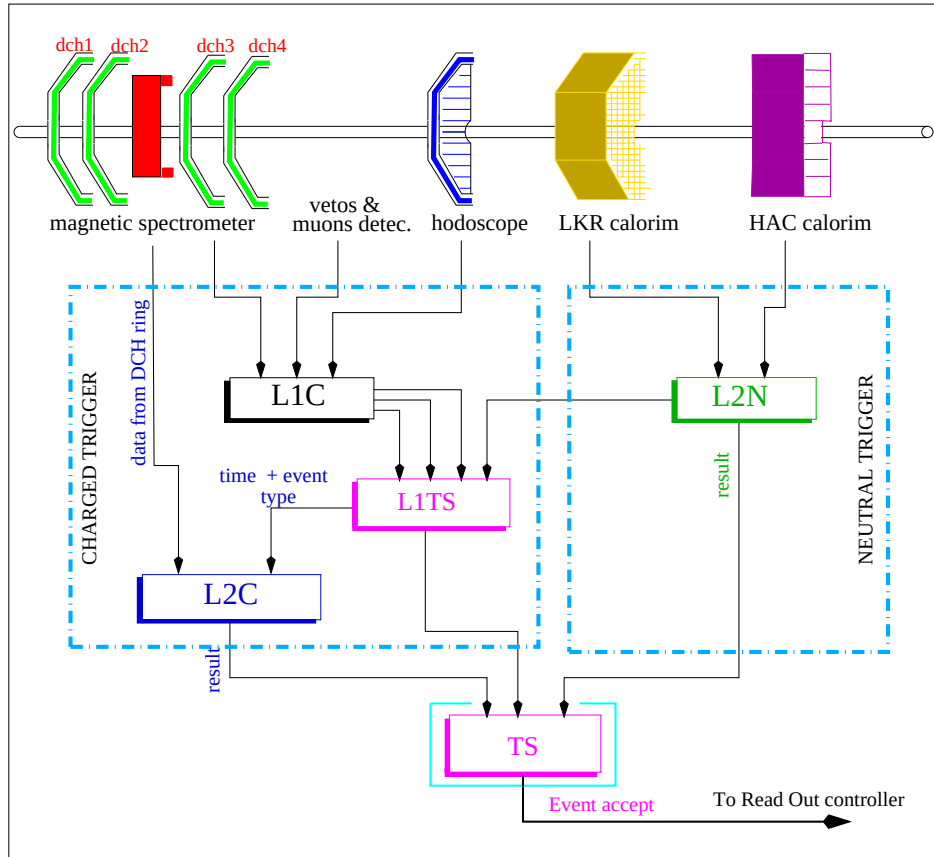


Figure 2.21: Schematic view of the NA48/2 trigger.

2.14.1 Charged Trigger

The Charged Trigger system consists of three levels: the Pre-Trigger (*L1C*), the *L1C* Trigger Supervisor (*L1TS*) and the Mass-Box (*L2C* or *MBOX*).

Pre-Trigger: a fast hardware system that collects information from *AKL*, drift chambers, charged and neutral hodoscopes and synchronizes signals before sending them to the next level;

- the coincidences made within each pocket are summed to obtain the *AKL* trigger condition, that can be used as a veto;
- the *CHOD* provides a simple information on the topology of the event; coincidences of first and second plane identify the quadrant crossed by a charged particle; the signals from the quadrant are combined and the events are split in the two topological classes:

Q_1 : at least one charged particle in one quadrant; it tags decays with at least a charged particle in the acceptance; it is quite noisy and fires easily on accidentals;

Q_2 : a hit in each of two quadrants in the same half-plane (up-down or left-right); it tags decays that have at least two charged particles; the signal is purer than Q_1 , but the efficiency is lower.

- the *NHOD* triggers on a shower in the *LKr*; this signal (*T0N*) is useful as minimum bias trigger for efficiency studies;
- the *MUV* provides informations on the compatibility of the hits in the scintillator with one muon (1μ).

L1C Trigger Supervisor: combines the Pre-Trigger signals with calorimeter energy information coming from the Neutral Trigger; some loose selection based on the topology and energy of the events is made; before the event is sent as input to the Mass-Box, a time alignment of the signals is performed, a 30 *bit* time-stamp is attached to the event and a 3 *bit* code ("strobe") identifying the topology of the event is produced; before going to the *L1TS*, some signals can enter a prescale module to reduce, downscale, of a given factor the number of triggers per burst; the downscaled trigger can be used as minimum bias trigger for efficiency studies;

Mass-Box: a software trigger processor farm that asynchronously handles events on the base of the strobes identification code and produces a response within 100 μ s; the Mass-Box performs a fast on line reconstruction of the events with the data sent from the drift chambers; its capability of performing rather complicated algorithms (like vertex reconstruction and invariant mass calculation) is a key element of the NA48/2 trigger chain. The upgrade to charged beams operated in 2003, required an improvement of the calculation power of the Mass-Box, in order to be able to stand a higher rate of charged events. A processor upgrade of the system increased the upper limit of input events from 120 *kHz* to 170 *kHz*.

2.14.2 Neutral Trigger

The Neutral Trigger is implemented in a 40 *MHz* dead-time free pipeline. The total latency of the pipeline is 128 clock cycles, 3.2 μ s. Every 25 *ns*, the trigger reconstructs on-line a set of physical quantities, like total energy, center of gravity, kaon vertex position and number of *LKr* peaks in both horizontal and vertical

projections. With the reconstructed quantities, it performs a selection and send the information to the Trigger Supervisor and partially also to the Charged Trigger chain.

NT-PEAK: more than two *LKr* cluster peaks in at least one projection (x or y);

NT-NOPEAK: an energy deposition in the *LKr* calorimeter grather than 30 GeV with a center of gravity smaller than 25 cm and a kaon decay position smaller than 90 m ;

LKrMBias: a minimum deposited energy in the electromagnetic calorimeter greater then 10 GeV .

2.14.3 Trigger Supervisor

The Mass-Box and Neutral Trigger results are sent to the Trigger Supervisor which correlates the information coming from different trigger sources and takes the final decision on the selection of the event. It also provides a final trigger word and time-stamp and sends to the Read Out Controllers (ROC) the command to record the event information before the end of the $200 \mu\text{s}$ data persistence time.

2.14.4 $K^\pm \rightarrow \pi^\pm \gamma \gamma$ Trigger Logic

$K^\pm \rightarrow \pi^\pm \gamma \gamma$ events are selected by the one track chain, like $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$, using both Charged and Neutral triggers information.

L1C and L2N:

$$\left(NT-PEAK + \frac{Q_1}{10} * LKrMBias + K_{\mu 3}^{PRE} \right) * (Q_1 + Q_2)$$

where $K_{\mu 3}^{PRE} = Q_1 * \overline{Q_2} * 1\mu * \overline{AKL} * LKrMBias_{15\text{GeV}}$.

L2C: to reduce the $K^\pm \rightarrow \pi^\pm \pi^0$ rate, exploiting the two-body decay signature, only events with an invariant mass defined as

$$m_{fake}^2 = m_{K^\pm}^2 + m_{\pi^\pm}^2 - (P_{K^\pm} - P_{\pi^\pm})^2 = 2m_{K^\pm} E_{\pi^\pm}^* \quad (2.1)$$

smaller then $475 \text{ MeV}/c^2$ are recorded, being $P_{K^\pm}$, $P_{\pi^\pm}$ four-momenta of the nominal kaon and pion respectively and $E_{\pi^\pm}^*$ the pion energy in the kaon rest frame.

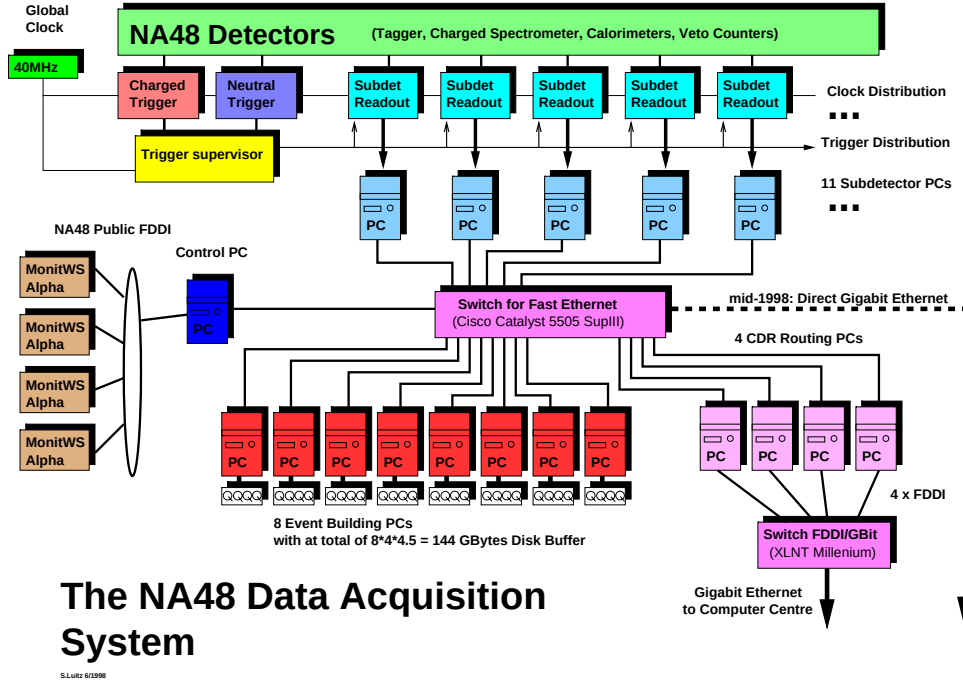


Figure 2.22: Schematic view of the NA48/2 DAQ system.

2.15 Data Acquisition and Format

The NA48/2 data acquisition system (Fig.2.22) is composed by eleven Sub-Sector PCs, eight Event Builders PCs and one Control PC. All PCs are equipped with Linux operating system and they are connected to a Fast Ethernet Switch operating at 200 *Mbit/s*.

Any given Sub-Detector PC stores the data recorded by the connected sub-detector during the SPS burst. Data are assembled, partitioned in eight blocks and sent to the Event Builder PCs in such a way that all the information of any single event are in the same block and go to the same PC. The Event Builders arrange the data in complete *RAW* events that are sent to ten disk-servers (average capacity ~ 1 *TB*) at the CERN computing center via a Giga-Switch connection. In case of an event number mismatch from different sub-detectors, the whole burst is discarded. In normal conditions the amount of transferred data from the experiment to the disks is around ~ 3 *TB/day*. The *RAW* data are processed by a software program (*L3*) running on the CERN Batch System (*LSF*) that performs the event reconstruction, filters the data and creates different output streams. The program outputs are in *COMPACT* [17] format containing reconstructed infor-

mation and physics quantities. Both *COMPACT* and *RAW* files are recorded on tapes. The average time from the data acquisition until the end of the processing is ~ 30 minutes: this allows a quite fast feedback to check the data quality. The overall efficiency of the offline processing is slightly greater than 99%. The typical size of one *RAW* burst is ~ 500 MB while a typical *COMPACT* file is ~ 120 MB. *RAW* data are sometime reprocessed to apply the best recomputed calibration constants. During this process the *SuperCOMPACT* format is produced to reduce the total amount of data and speed up the analysis time. *SuperCOMPACT* bursts are smaller compared to the *COMPACT* ones because, even if no selection is applied, less information are stored. The total *SuperCOMPACT* production is further subdivided into the so called "Charged" (events with at least three well reconstructed tracks for the $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ asymmetry measurements) and "Neutral" (events with one track and one isolated cluster) Splits.

2.16 Data Taking

Data were collected during 2003 and 2004 for a total of ~ 110 days. In order to reduce possible systematic effects due to detector left-right asymmetry, beam lines and spectrometer magnet polarities were frequently reversed. A set of data in which all the four possible magnet setup configurations are present ($\sim$ two weeks of efficient data taking) is called "SuperSample" (SS) and is treated as an independent and self-consistent data sample. Many efforts have been devoted to the alignment and tuning of the drift chambers. Several muon runs were taken in order to adjust the spectrometer geometry relative to the beam line geometry and to investigate drift chamber relative alignment.

2003: the data collection started in June 12th and finished in September 8th; four SuperSamples were collected ($SS0 \div 3$); during the first ten days of data taking beam line, trigger condition and detectors performances were studied and tuned; the spectrometer magnetic field has been cycled and inverted every day; the beam line magnets were inverted on weekly basis, typically during the SPS machine development stops in order to minimize losses of data taking (the procedure was rather long and required a subsequent steering of the beams); the efficiency of the data taking has been about 50% only, mainly due to problems not under the control of the collaboration; more than thirty days could not have been used due to beam problems, power cuts, cooling and vacuum leaks;

2004: the data taking started in May 15th and finished in August 18th; five SuperSamples were collected ($SS4 \div 8$); during the second half of the run the readout of the experiment was modified to discard calorimeter data for a part of the the $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ event in order to increase the band-width available for other decays and increase the trigger collection rate of 20%, up to 60 k triggers per burst; the last week of data taking has been devoted to special runs and to one test run for a future $K^\pm \rightarrow \pi^\pm \nu \bar{\nu}$; in particular it has been collected a 56 hours long run dedicated to the study of leptonic and semi-leptonic decays.

Chapter 3

Monte-Carlo Simulation

Monte-Carlo simulation has been used to optimize selection cuts, evaluate acceptances and analyze the composition of the physical background. The official NA48/2 software (CMC) [15] is based on the *GEANT3 CERNLIB* package [16] and includes:

- a full beam optics and geometry simulation;
- the simulation of the beam movements during the burst and a burst by burst tuning of the beam based on collected data;
- the small residual magnetic field in the decay region upstream of the spectrometer (Sec. 2.4);
- a detailed description of detector materials, geometry and reconstruction, including time collection of light in scintillators, single wire efficiency, electron drift time in *DCHs* and dead cells position;
- the simulation of physical processes such as electron-positron annihilation, bremsstrahlung, Compton scattering, δ ray production, hadronic interactions, continuous energy loss, multiple scattering and photoelectric effect.
- secondary particles production:
 - $\pi \rightarrow \mu\nu$: the charged pion decay ($BR = 0.9998770 \pm 0.0000004$, $c\tau = 7.8045\text{ m}$) can occur within the experimental volume affecting the track reconstruction (direction and momentum);
 - $\pi^0 \rightarrow \gamma\gamma$: due to a short mean free path ($c\tau = 25.1\text{ nm}$), the neutral pion travels very little before decaying ($BR = 0.98798 \pm 0.00032$); as the experimental resolution in the longitudinal decay position is of the

order of 1 m , the distance between the π^0 and the kaon decay point cannot be resolved; therefore the $\pi^0 \rightarrow \gamma\gamma$ decay is assumed to occur at the same position as the kaon decay.

CMC simulates only one charged kaon beam, K^+ or K^- , and only one decay mode, $K \rightarrow \pi\gamma\gamma$ or $K \rightarrow \pi\pi^0$ or etc., per produced sample. A number of events per run proportional to the kaon flux measured with $K^\pm \rightarrow \pi^\pm\pi^0$ decays (Sec. 5.1) has been simulated for each sample. In this way, all the characteristics of the data sample, like the ratio between K^+ and K^- and the ratio between samples of both signs of achromat and spectrometer magnetic fields, are respected in the Monte-Carlo.

Each event is generated in the kaon rest frame, weighted for the corresponding matrix element, boosted to the laboratory frame and then propagated through the detector. Kaon momentum and decay position are simulated in a wider range with respect to the selected one to prevent from resolution effects:

- $50 \text{ GeV}/c \leq P \leq 70 \text{ GeV}/c$
- $-22 \text{ m} \leq z_{\text{decay}} \leq 90 \text{ m}$

Simulated data are recorded in the same format (*SupeCOMpACT*) of the experimental data, allowing the use of the same analysis tools.

3.1 Signal Simulation

$K^\pm \rightarrow \pi^\pm\gamma\gamma$ events are generated according to Eq.???. The $\hat{c}$ value is a free parameter of the simulation in order to evaluate the impact on the acceptance. CMC allows a full treatment of the unitarity correction (Sec 1.2.1).

Several Monte-Carlo samples have been produced, corresponding to different $\hat{c}$ values and with or without the $\mathcal{O}(p^6)$ amplitudes.

3.2 Backgrounds Simulation

Background events can arise from the loss of one or more photons outside the geometrical acceptance of the detector, two coalescent photons at the *LKr* calorimeter or particles mis-identification. In order to optimize the background rejection criteria different kaon decay modes have been simulated and analyzed with the same signal selection code:

- $K^\pm \rightarrow \pi^\pm \pi^0$
- $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ (background mechanism: lost or coalescent photons)
- $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (background mechanism: lost or coalescent photons)
- $K^\pm \rightarrow \pi^0 e \nu$ (background mechanism: e mis-identified as π)
- $K^\pm \rightarrow \pi^0 \mu \nu$ (background mechanism: μ mis-identified as π)

The inner bremsstrahlung, direct emission and interference components of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ radiative decay have been separately simulated and then recombined, taking into account the corresponding branching ratios¹.

3.3 Monte-Carlo Checks

Due to the very low $K^\pm \rightarrow \pi^\pm \gamma \gamma$ statistics ($BR \sim 10^{-6}$), the reliability of the Monte-Carlo simulation has been checked using $K^\pm \rightarrow \pi^\pm \pi^0$ events. This decay mode has been chosen because it has the same topology of the signal: one charged pion and two photons ($\pi^0 \rightarrow \gamma \gamma$). In order to identify $K^\pm \rightarrow \pi^\pm \pi^0$ events, as much similar criteria as possible to the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ selection have been required (Sec. 5.1). Even if a strong downscaling (10000) was applied, $K^\pm \rightarrow \pi^\pm \pi^0$ decays have been selected from a minimum bias data sample (Q_1) to avoid any trigger efficiency correction.

Both the reconstructed beam energy (60.0 ± 2.1) GeV (Fig. 4.12) and longitudinal kaon decay position (Fig. 3.2) show a good agreement between data and Monte-Carlo simulation.

A small shift in the reconstructed invariant masses has been observed (Fig. 3.3): the difference is due to the energy scale of the LKr calorimeter (Sec 5.6).

No other anomalous effects have been found comparing several pion (Fig. 3.4) and photons distributions (Fig. 3.5), validating the Monte-Carlo simulation.

¹In case of $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay, the NA48/2 2003 preliminary results on the direct emission and interference component fractions [19] have been used.

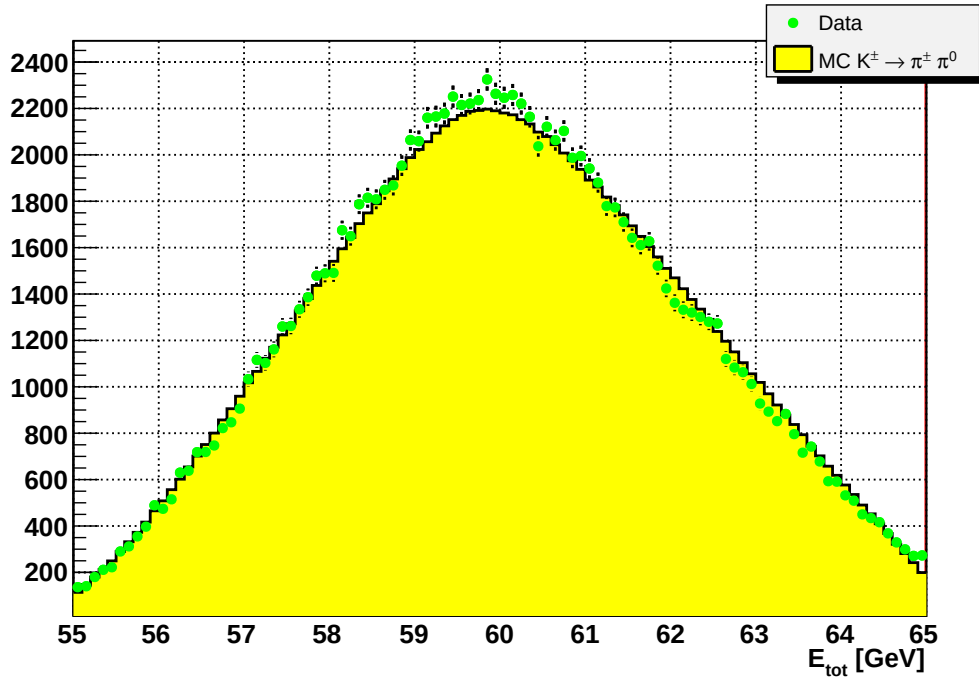


Figure 3.1: Data/Monte-Carlo comparison of the reconstructed total energy.

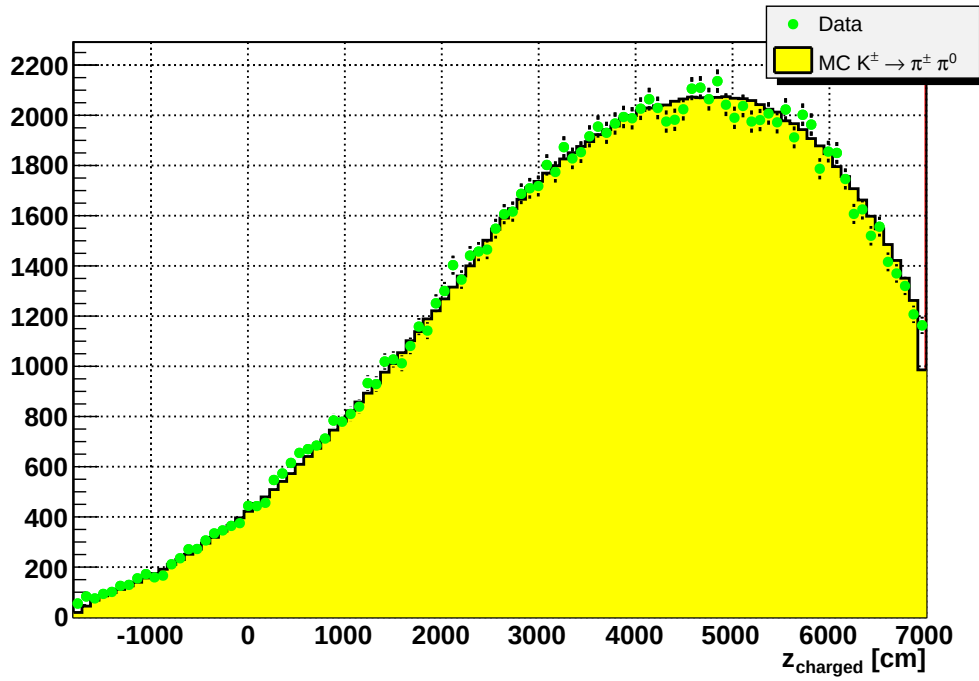


Figure 3.2: Data/Monte-Carlo comparison of the reconstructed decay vertex longitudinal position.

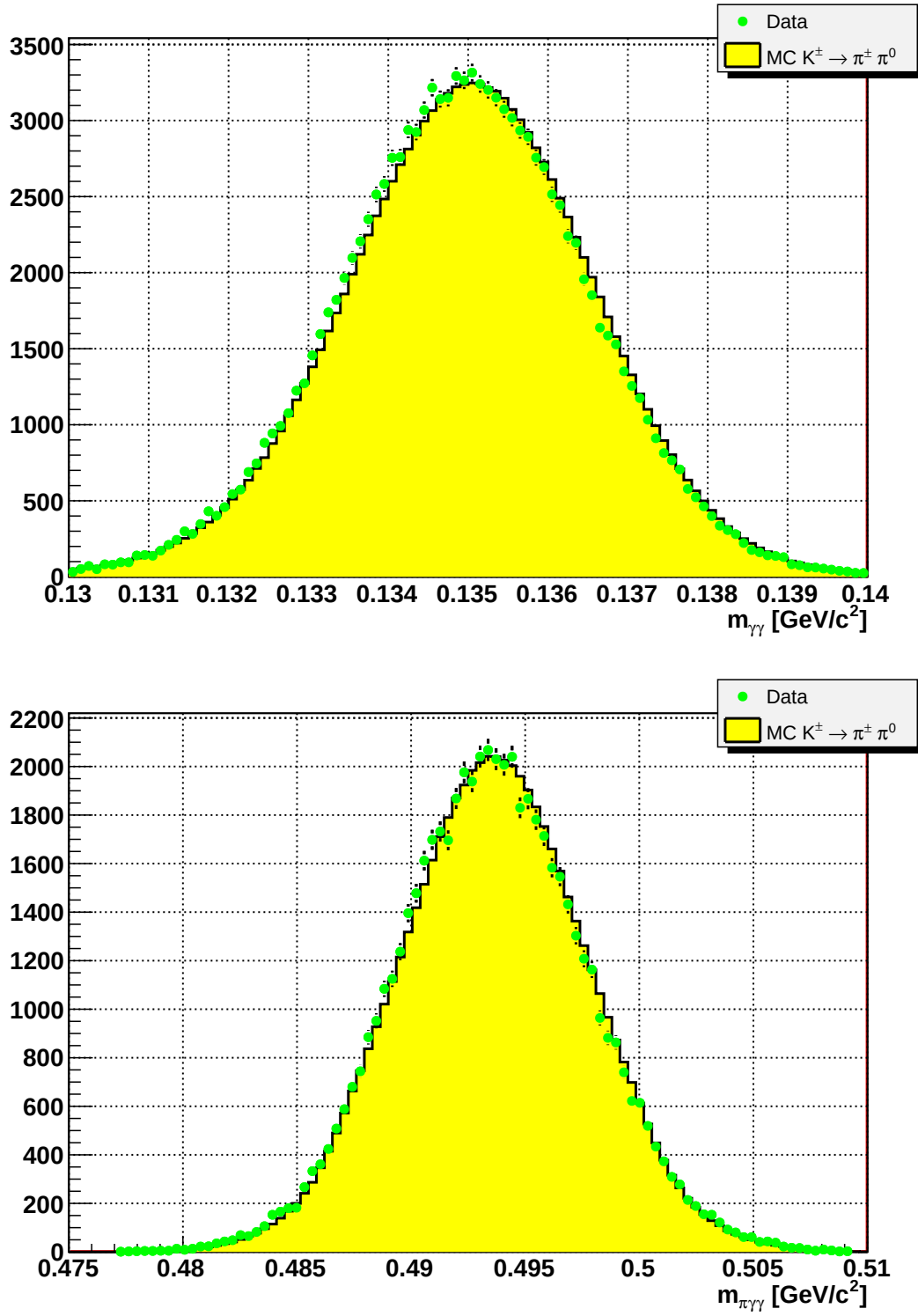


Figure 3.3: Data/Monte-Carlo comparison of the reconstructed π^0 (top) and $K^\pm$ (bottom) invariant mass.

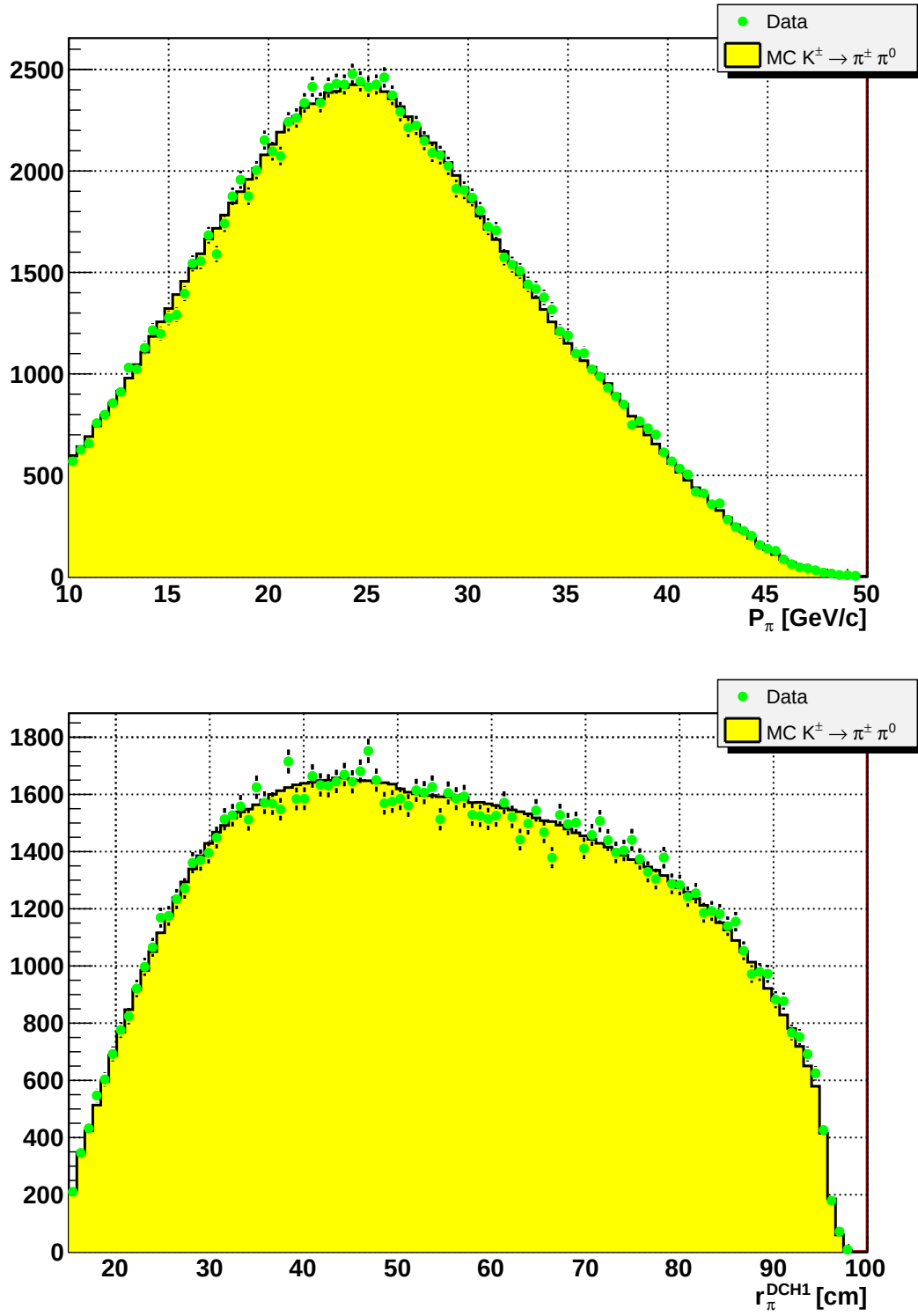


Figure 3.4: Data/Monte-Carlo comparison of the reconstructed $\pi^\pm$ momentum (top) and radial distance from the beam pipe at the first *DCH* (bottom).

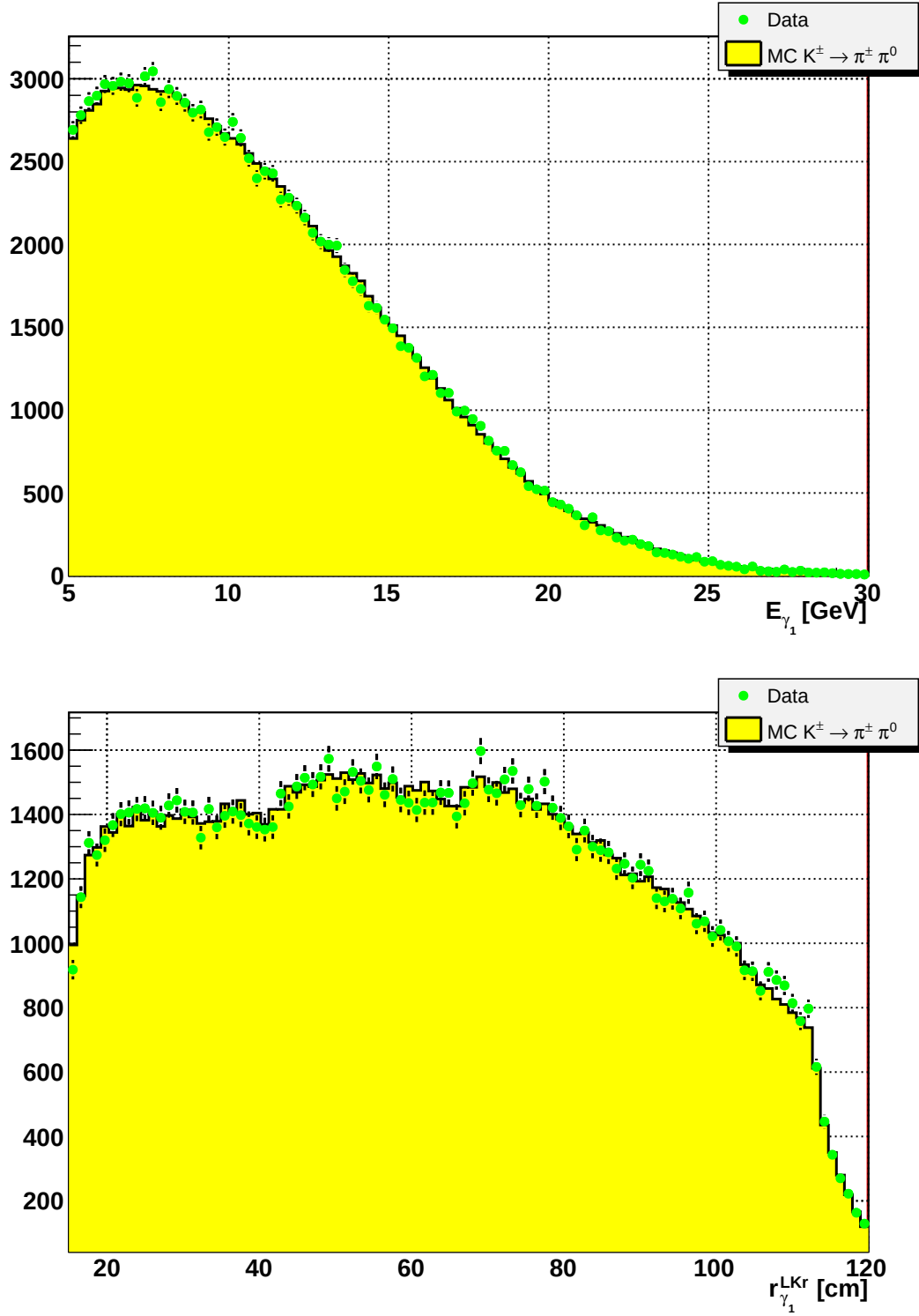


Figure 3.5: Data/Monte-Carlo comparison of the reconstructed γ energy (top) and radial distance from the beam pipe at the LKr (bottom).

Only events with a simulated kaon momentum in the range $(55 \div 65) \text{ GeV}$ and a kaon decay point between -16 m and 70 m have been used to evaluate acceptances. The lower cut on the longitudinal decay position minimizes effects from the presence of the final collimator that could not be well enough modeled in the simulation, while the upper cut rejects events decaying too close to the main detector to be properly reconstructed.

Chapter 4

Event Selection

The official NA48/2 analysis software (*COMPACT*) [17] is based on both *Fortran* and *C* codes and can be implemented in a *PAW* or *ROOT* [18] framework.

To properly evaluate acceptance corrections and measure the amount of residual background, the same selection criteria have been applied to data and Monte-Carlo samples, except for requirements on time which is not simulated by *CMC*.

4.1 Event Reconstruction

Several stages of data compression and filtering, from *RAW* to *COMPACT* data (reduction factor ~ 4) and then to *SuperCOMPACT* format (reduction factor ~ 30), allow to speed up the analysis time.

All the 2003 statistics ($SS0 \div 3$), about 1/3 of the total collected data sample, have been analyzed. To skip non-useful three tracks decays, the event reconstruction has been performed on the "neutral" *SuperCOMPACT* data split (events with at least one track and two isolated cluster). The bursts analyzed are those in which all main sub-detectors whose information have been used in the analysis (*DCHs*, *LKr*, *CHOD*, *NHOD* and *MUV*) and trigger systems (*NT-PEAK* and *MBX*) had an operation status considered suitable. To be as much consistent as possible, discarded periods have been removed also from the Monte-Carlo samples.

A first data selection has been performed at *SuperCOMPACT* level, analyzing events with only one reconstructed track (pion candidate), two not track associated clusters (photon candidates) and any number of additional clusters with a radial distance smaller than 30 *cm* from the track impact point at the electromagnetic calorimeter front face or with a time deviation from the average photon candidates time greater than 3 *ns*. Filtered events have been written on a *ROOT*

TTree which has been used for the final $K^\pm \rightarrow \pi^\pm \gamma \gamma$ event selection, trigger efficiency and flux measurements.

4.1.1 Corrections

To fix different anomalous effects, a set of specific corrections has been applied at *SuperCOMPACT* level to data and/or Monte-Carlo events, before performing the event reconstruction (Tab. 4.1).

Correction	Data	Monte-Carlo
Blue Field	✓	✓
<i>DCH</i> Alpha and Beta	✓	✓
<i>LKr</i> Non-Linearity	✓	✓
<i>LKr</i> Projectivity	✓	X

Table 4.1: Corrections summary (✓ = applied, X = not applied).

“Blue” Field

The small residual magnetic field in the vacuum tank (Sec. 2.4) bends charged decay products so that the direction measured at *DCHs* is slightly different from the one at the decay point.

A precise map of the “blue” field¹ allows to correct track direction before reconstructing the longitudinal position of the kaon decay vertex.

DCH Alpha and Beta

A miscalibration of the spectrometer magnetic field or a misalignment of one of the *DCHs* located downstream the magnet, spoil the momentum measurement inducing a wrong $K^\pm$ mass reconstruction. $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ events have been used to study such effect because they can be fully reconstructed employing *DCH* spectrometer information only.

- *Magnetic field miscalibration*: because $\frac{\Delta p}{p} = \frac{\Delta B}{B}$, it can be demonstrated that $\frac{m_{3\pi} - m_{K^\pm}}{m_{K^\pm}} = 0.2 \cdot \frac{\Delta B}{B}$, being $m_{3\pi}$ the reconstructed and $m_{K^\pm}$ the PDG [12] kaon masses; the effect is independent of the track charge and affects with the same global offset the reconstructed K^+ and K^- mass; the corrected track momentum p can be expressed as:

¹The fact that the cylindrical vacuum chamber is painted blue gives the nickname to the magnetic field.

$$p = p_0 \cdot (1 + \beta)$$

where p_0 is the uncorrected quantity and $\beta = \frac{\Delta B}{B} = \frac{m_{K^\pm} - m_{aver}}{0.1046} \left(m_{aver} = \frac{m_{3\pi^+} + m_{3\pi^-}}{2} \right)$;

- *DCH misalignment*: even if *DCHs* have been regularly aligned each other using straight through tracks (muon halo with no magnetic field), a change in the relative alignment by a tenth of millimeter or less, probably related to temperature oscillations, has been observed during the data taking; the displacement gives opposite effect according to the track sign and the magnetic field direction; the correction can be parameterized as:

$$p = p_0 \cdot (1 + \alpha \cdot q \cdot p_0)$$

where p_0 is the uncorrected momentum, $\alpha = \frac{(m_{3\pi^+} + m_{3\pi^-})}{1.7476}$ and q the particle charge (± 1); as the K^+ is reconstructed from two positive and one negative tracks, its mass is shifted in opposite direction compared to the K^- (two negative and one positive tracks); if the magnet polarity is changed, the sign of the mass splitting is changed as well and the explicit dependence of the correction and determination with the magnetic field sign can be omitted.

The whole data sample has been analyzed in order to evaluate, on a burst by burst basis, the α and β values. The obtained results have been stored on a *SQLite* database: usually, $\sim 8500 K^+ \rightarrow \pi^+ \pi^+ \pi^-$ and $\sim 4600 K^- \rightarrow \pi^- \pi^+ \pi^-$ events per burst are reconstructed. A typical value of β is $\sim 10^{-3}$ which corresponds to $\sim 0.5 \text{ MeV}/c^2$ shift on the reconstructed kaon mass. In the worst period of 2003 a typical value of α is -2.1×10^{-4} , corresponding to a $250 \mu\text{m}$ translation of *DCH4* along x and to a mass difference between K^+ and K^- of $\sim 0.35 \text{ MeV}/c^2$. For later periods, it is at least one order of magnitude smaller. The overall correction is accurate to a few keV/c^2 .

The model has been introduced in the Monte-Carlo simulation in order to reproduce the observed distortions in data.

LKr Non-Linearity

A threshold applied to the calorimeter cells readout introduces a non-linear response between the deposited and the measured energy, which is not reproduced by the Monte-Carlo simulation.

$K_S \rightarrow \pi^0 \pi^0$ decays selected from the 2002 data sample (same threshold as in 2003 and 2004) have been used to develop a correction that has been applied to clusters with an energy smaller than 11 GeV.

LKr Projectivity

The cluster reconstruction algorithm exploits the projective structure of the calorimeter cells (Sec. 2.9) which points to 90 m (z_{proj}) from its entrance: x and y coordinates are extrapolated to the calorimeter front face assuming the shower develop along the projective direction. If the particle generating the cluster was produced at a different coordinate from z_{proj} , the cluster transverse position has to be recalculated.

For a photon cluster with an energy E (in GeV) the shower depth (z_{depth}) can be calculated as:

$$z_{depth} = [20.8 + 4.3 \cdot \ln(E)] \text{ cm}$$

while in case of electrons or pions different constants are needed.

The corrected x (y) cluster coordinate at the *LKr* surface can be extracted according to:

$$x = x_0 \cdot \frac{1 + \frac{z_{depth}}{z_{proj}}}{1 + \frac{z_{depth}}{z_{LKr} - z}}$$

where x_0 is the uncorrected quantity, z_{LKr} the electromagnetic calorimeter position and z the reconstructed kaon decay point.

In case of a photon generated 50 m away from the projective point and with a shower depth of 30 cm, the correction amount roughly to 5 mm ($\sim 5\%$).

The projectivity geometry has been implemented in the *CMC* simulation and must be therefore applied also to Monte-Carlo events.

4.1.2 Decay Topology

High multiplicity events are rejected requiring the right decay topology. Due to the presence of a charged pion in the final state, no cut on the total number of electromagnetic clusters can be applied: shower produced by hadrons can have a fluctuating number of reconstructed clusters which can sometimes be located quite far away from the track impact point. A requirement on the number of photon candidates has been rather adopted to avoid possible discrepancies be-

tween data and Monte-Carlo simulation. As already mentioned, any other cluster located at a radial distance from the LKr pion impact point smaller than 30 cm (hadron shower satellites) or with a time distance from the average photon time greater than 3 ns , have been ignored.

Only charged tracks and electromagnetic clusters reconstructed in a time window of $[120 \div 152]\text{ ns}$ have been considered.

Charged Track Requirements

A charged track must fulfill the following requirements to be compatible with a pion:

- each time a particle crosses the magnetic spectrometer and the corresponding track has been reconstructed, a quality variable based on the number and position of reconstructed hits on each DCH view is computed (Sec. 2.7.1); a minimum track quality of 0.6 has been required;
- to properly define the sensitive sub-detectors area, regions close to the beam pipe and to the edges have been removed; given the track position at $DCH4$ and the direction after the spectrometer magnet, the track impact point at each sub-detector can be extrapolated; checks against the geometrical dimensions of all sub-detectors whose information have been used in the analysis have been performed:
 - cut on the track radial distance from the beam direction at the first and the fourth drift chambers ($DCH1$ and $DCH4$):

$$15\text{ cm} < |\vec{r}_{DCH} - \vec{r}_{beam}| < 100\text{ cm}$$

where $\vec{r}_{DCH}$ is the track and $\vec{r}_{beam}$ the beam position with respect to the beam pipe; $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ events have been used to measure $\vec{r}_{beam}$ on burst by burst basis;

- octagonal shaped cut (Fig. 2.13) and requirement on the minimum track radial distance from the beam pipe at the electromagnetic calorimeter (LKr):

$$r_{LKr} > 15\text{ cm}$$

- cut on the track radial distance from the beam pipe at the charged hodoscope ($CHOD$):

$$15 \text{ cm} < r_{CHOD} < 150 \text{ cm}$$

- squared shaped cut at the muon veto system (MUV):

$$(|x_{MUV}| > 13 \text{ cm} \text{ or } |y_{MUV}| > 13 \text{ cm})$$

and

$$(|x_{MUV}| < 130 \text{ cm} \text{ and } |y_{MUV}| < 130 \text{ cm})$$

- to ensure a full efficiency ($\sim 99.9\%$) of the muon veto system and properly reject events where the pion decayed in flight, a track momentum (p_{DCH}) greater than $10 \text{ GeV}/c$ has been required; to remove non-physical events an upper cut at $60 \text{ GeV}/c$, corresponding to the kaon beam energy, has been applied.

The identification of the charged track has been performed studying the ratio between the energy deposition in the electromagnetic calorimeter (E_{LKr}) and the momentum measured with the magnetic spectrometer (p_{DCH}): in case of electrons, this quantity has a sharp peak at unity because all the energy has been released as electromagnetic shower; for pions and hadrons in general, because they do not deposit all their energy, the distribution is quite broad starting from 0 up to 0.9, while for non-interacting minimum ionizing particles such as muons, it is peaked at small values (Fig. 4.1).

A check on the electromagnetic cluster associated to the charged track is therefore required, to ensure a good separation between pions and electrons:

- the radial distance between the associated cluster candidate and the extrapolated track position at the LKr must be smaller than 5 cm ;
- the cluster-track time difference must be smaller than 5 ns ; the time measurement provided by the charged hodoscope may not be available for one track event, if more than one hit were present; for that reason the magnetic spectrometer information has been preferred.

If no cluster has been found to be compatible with the track, the event is anyway recorded and the pion E_{LKr}/p_{DCH} has been set equal to 0. To reduce the probability for a pion to be mis-identified with an electron it is required that:

$$E_{LKr}/p_{DCH} < 0.8$$

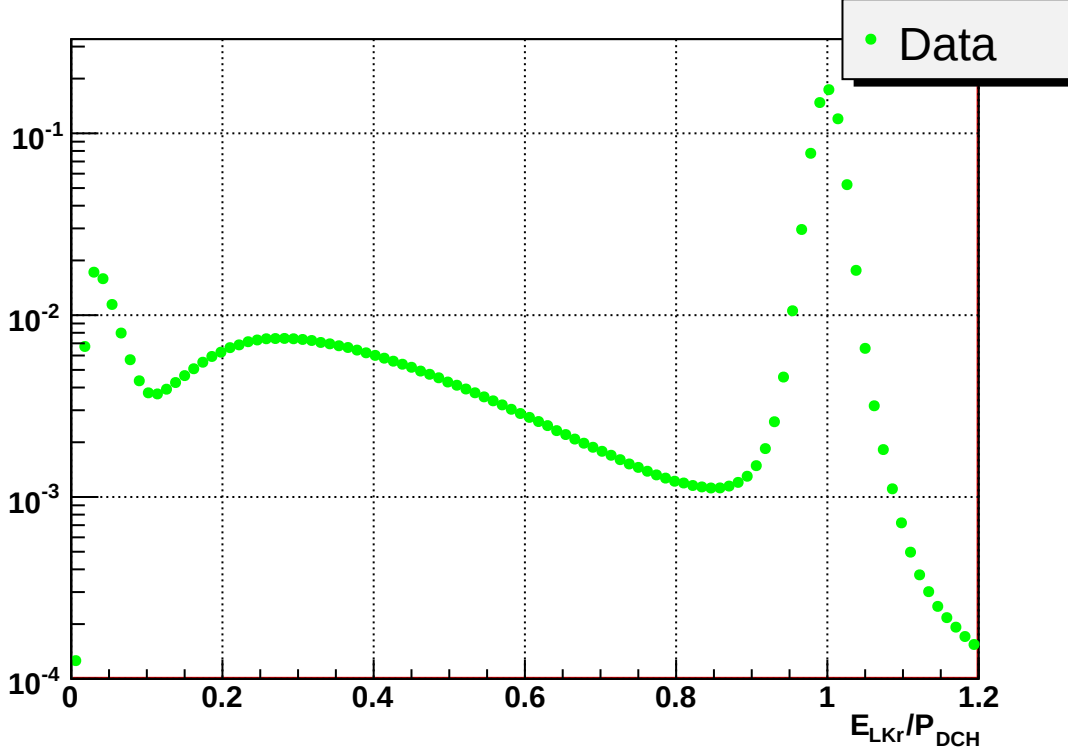


Figure 4.1: Data distribution of the charged track energy deposition in the LKr divided by the momentum measured at $DCHs$.

Events have been anyway accepted if existing extra-tracks have been found to be compatible with fake tracks generated by ambiguities coming from hits with similar y coordinate at $DCH4$ (*ghost tracks*). In that situation the real and the fake tracks are very close, with less than 1 cm separation at $DCH1$. The pion track has been identified requiring the better reconstruction fit quality or, in case of same quality, the closest to the associated electromagnetic cluster has been chosen. In $\sim 4\%$ of cases it has not been possible to distinguish the real from the fake tracks and the event has been rejected.

Electromagnetic Cluster Requirements

Provided the cluster reconstruction (Sec. 2.9.1) has been successfully performed (*reconstruction status bit* < 4), the following conditions must be satisfied by the two photon cluster candidates:

- the cluster must be fully contained within the electromagnetic calorimeter active volume: regions close to the beam pipe ($r_{LKr} < 15\text{ cm}$) and to the edges (octagonal shaped cut (Fig. 2.13)) have been removed;

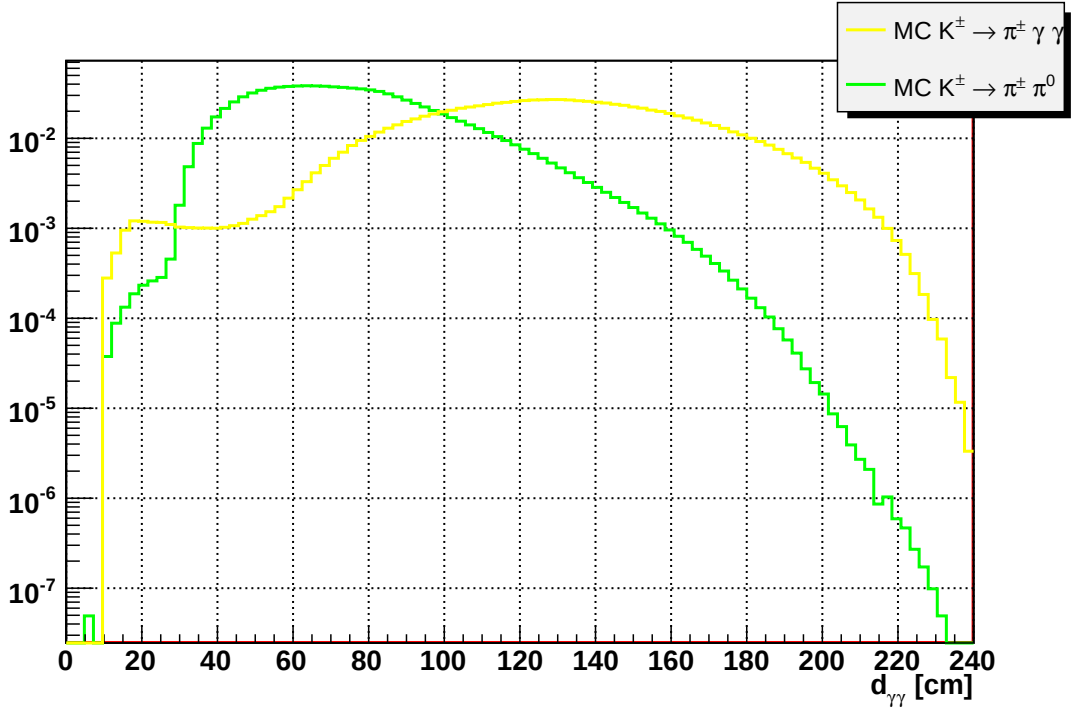


Figure 4.2: Monte-Carlo distributions of the minimum distance between the two photon candidate clusters.

- the distance from the closest *LKr* dead cell must be greater than 2 *cm* to avoid any energy loss and ensure a good energy reconstruction (Fig. 2.15);
- to prevent from hadronic shower contamination, a minimum distance from the pion impact point at the *LKr* equal to 30 *cm* has been required; this condition had been already applied to pre-select *SuperCOMpACT* events;
- to avoid electromagnetic energy sharing, the distance between the two photon candidate clusters has to be greater than 40 *cm*; this cut also improves the background rejection because the opening angle between photons from the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay is bigger than the one from $K^\pm \rightarrow \pi^\pm \pi^0$ events (Fig. 4.2);
- a further requirement on the relative cluster position has been applied to provide a good *NT-PEAK* trigger efficiency: in the assumption of a $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay, at least one between the minimum cluster distance in *x* or *y* projection among any cluster pairs must be greater than 10 *cm* (Sec. 5.2);
- to improve the global Level 1 trigger efficiency (Sec. 5.2) a minimum cluster energy (E_{LKr}) of 5 *GeV/c* has been required; to remove non-physical events

an upper cut at $60 \text{ GeV}/c$, corresponding to the kaon beam energy, has been applied.

In order to have a reliable particle identification, some of the previous cuts must be fulfilled, where present, by the electromagnetic cluster associated to the charged track. All events with a pion cluster not successfully reconstructed, outside of the LKr geometrical acceptance or close to dead cells have been rejected.

Time Requirements

Some triggers can include more than one decay due to close in time production at the target. The following conditions have to be satisfied by the events surviving the previous selection criteria, to guarantee that all the decay products have been generated by the same kaon decay:

- the time difference between the two photon clusters must be smaller than 3 ns ;
- the time difference between the pion and the LKr time, defined as the average time of the two photon clusters, must be smaller than 5 ns (Fig. 4.3); as described for the track-cluster association, the time measurement provided by the magnetic spectrometer has been used instead of the charged hodoscope information.

Only events with one well reconstructed track identified as a charged pion, only two electromagnetic clusters compatible with two photons and no hits in the muon veto counter are further analyzed.

4.1.3 Decay Vertex Reconstruction

The longitudinal position of the kaon decay vertex has been reconstructed in order to define the fiducial decay region and reconstruct quantities such as the di-photon ($m_{\gamma\gamma}$) and the kaon ($m_{\pi\gamma\gamma}$) invariant masses. Two different approaches have been adopted: a "charged" and a "neutral" method.

The "charged" vertex is expected to give best estimate of the kaon decay point, while the "neutral" measurement has been used for background rejection purpose only.

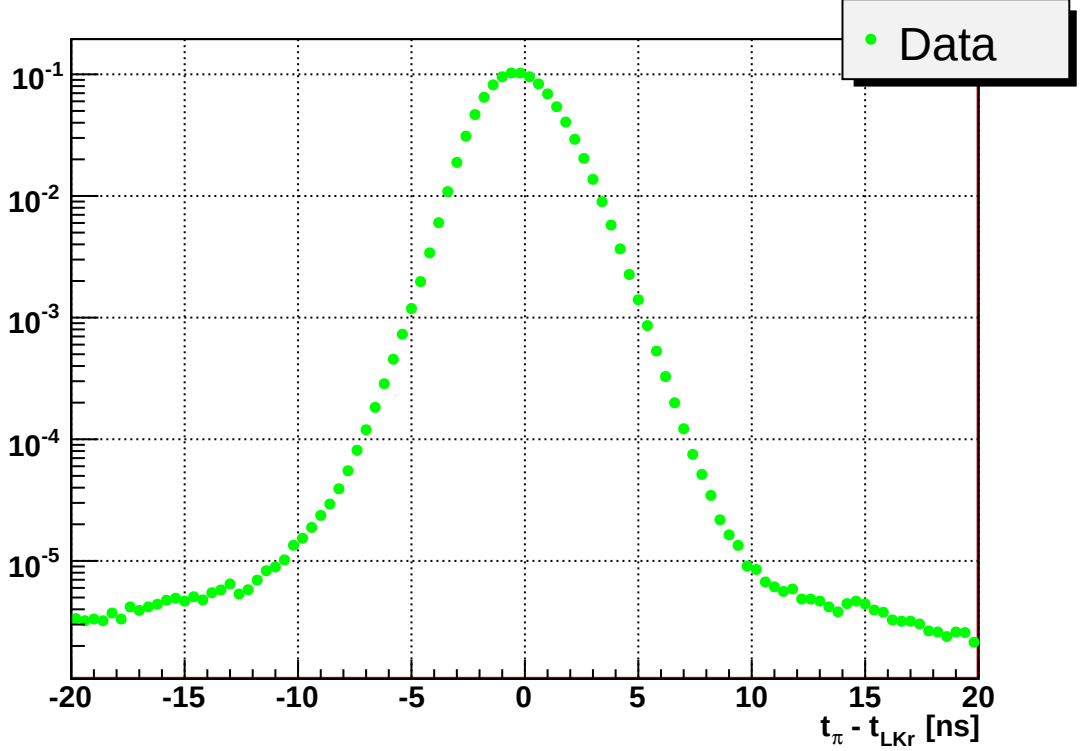


Figure 4.3: Data distribution of the time difference between the pion track and the *LKr* time.

“Charged” Vertex

The so called “charged” vertex has been determined as the point of the closest distance of approach (*CDA*) between the pion track and the line that goes from the final collimator to the energy center of gravity (*COG*) of the event, measured at the electromagnetic calorimeter position (Fig. 4.4).

For events with one charged track and two electromagnetic clusters, the *COG* is defined as:

$$COG = \sqrt{\frac{(\sum_{i=1}^3 E_i \cdot x_i)^2 + (\sum_{i=1}^3 E_i \cdot y_i)^2}{\sum_{i=1}^3 E_i}}$$

where all photons information come from the *LKr* calorimeter, while pion quantities have been reconstructed with the magnetic spectrometer only: the energy is given by $E_{\pi^\pm} = \sqrt{(p_{DCH} \cdot c)^2 + (m_{\pi^\pm} \cdot c^2)^2}$, while $x_{\pi^\pm}$ and $y_{\pi^\pm}$ correspond to the pion impact point coordinates at the *LKr* front face using the slopes as measured before the spectrometer magnet.

If no energy has been lost, mainly due to photons outside the detector accep-

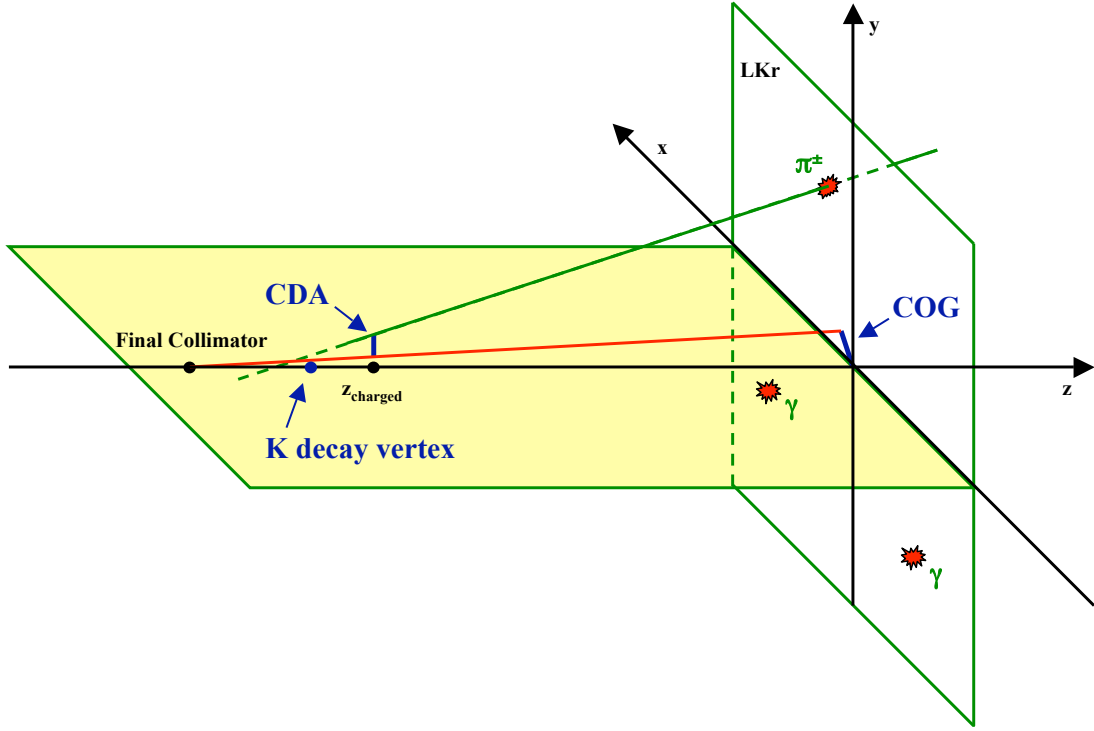


Figure 4.4: Schematic view of the "charged" kaon decay vertex reconstruction.

tance, this quantity will correspond to the kaon position at the LKr surface if this particle would not have been decayed. Due to the fact that the beam path almost coincide with the z axis and a very good focusing, the COG of fully reconstructed events is close to zero.

"Neutral" Vertex

Assuming that the pion ($\pi^\pm$) and the two photons (γ_1 and γ_2) are the only decay products of the parent kaon it is possible, by imposing the kaon mass, to determine the decay vertex position using LKr information (Fig. 4.5):

$$z_{neutral} = z_{LKr} - \frac{\sqrt{\sum_{i,j; i>j} E_i \cdot E_j \cdot r_{i,j}^2}}{m_{K^\pm}^2 - m_{\pi^\pm}^2 \cdot \left(1 + \frac{E_{\gamma_1} + E_{\gamma_2}}{p_{\pi^\pm}}\right)} \quad (4.1)$$

being z_{LKr} the electromagnetic calorimeter longitudinal position, $m_{K^\pm}$ and $m_{\pi^\pm}$ the kaon and pion masses [12], E_i (p_i) the energy (momentum) of the i^{th} particle and $r_{i,j}$ the radial distance between two particles at the LKr surface. The charged pion quantities have been computed with the same algorithm as described for the "charged" vertex reconstruction.

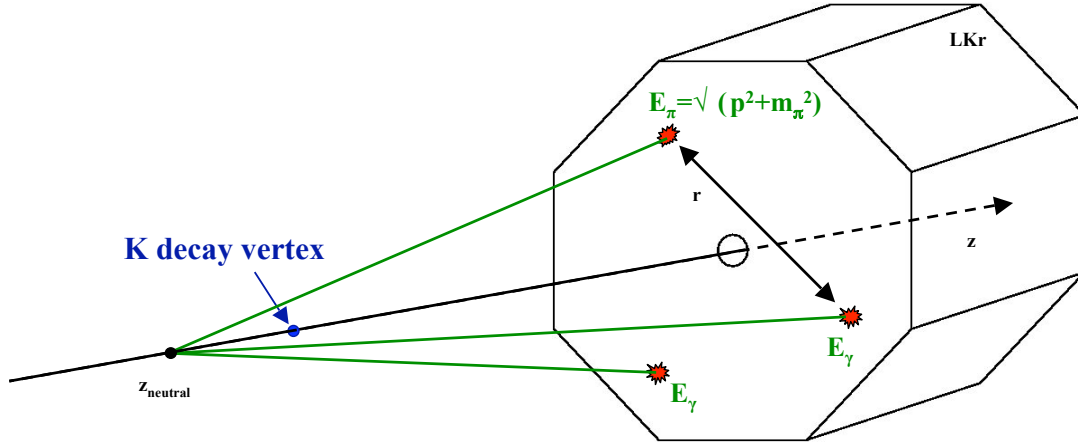


Figure 4.5: Schematic view of the "neutral" kaon decay vertex reconstruction.

The x and y "neutral" coordinates have been assumed to coincide with the pion ones at the $z_{neutral}$ point.

Decay Vertex Quality

As the "charged" vertex has been identified as the best kaon decay point extrapolation, the following cuts have been applied to ensure a good reconstruction quality :

- the energy center of gravity (COG) of the event must be smaller than 2 cm ; as well as providing a good kaon LKr impact point estimate, this requirement also reduce background events with lost energy (Fig. 4.6);
- the closest distance of approach (CDA) between the pion track and the line that goes from the final collimator to the energy center of gravity has to be smaller than 2 cm : if the pion has been really generated by the decay of the parent kaon, the distance between the charged track and the kaon direction must be close to zero (Fig. 4.7); the spread of the CDA distribution is directly related to the quality of the COG measurement.

Only events with a reconstructed kaon decay point between -16 m and 70 m have been further analyzed: the lower cut minimizes effects from the presence of the final collimator that could not be well enough modeled in the simulation, while the upper cut rejects events decaying too close to the main detector to be properly reconstructed.

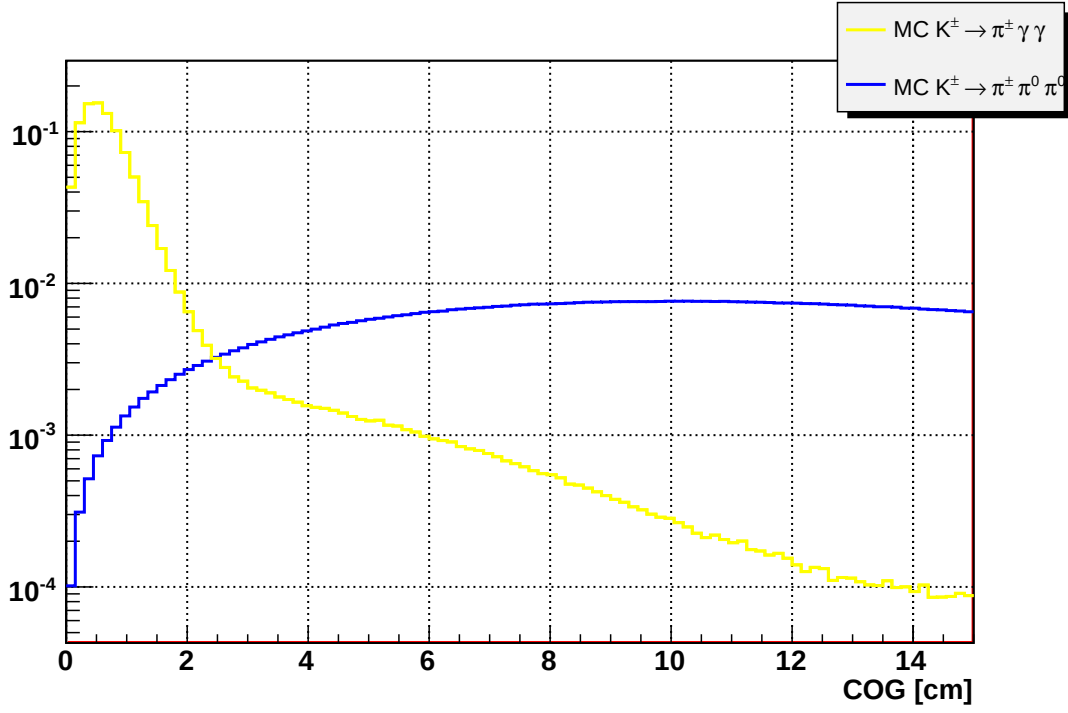


Figure 4.6: Monte-Carlo distributions of the energy center of gravity (COG) measured at the *LKr* position, under the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ assumption.

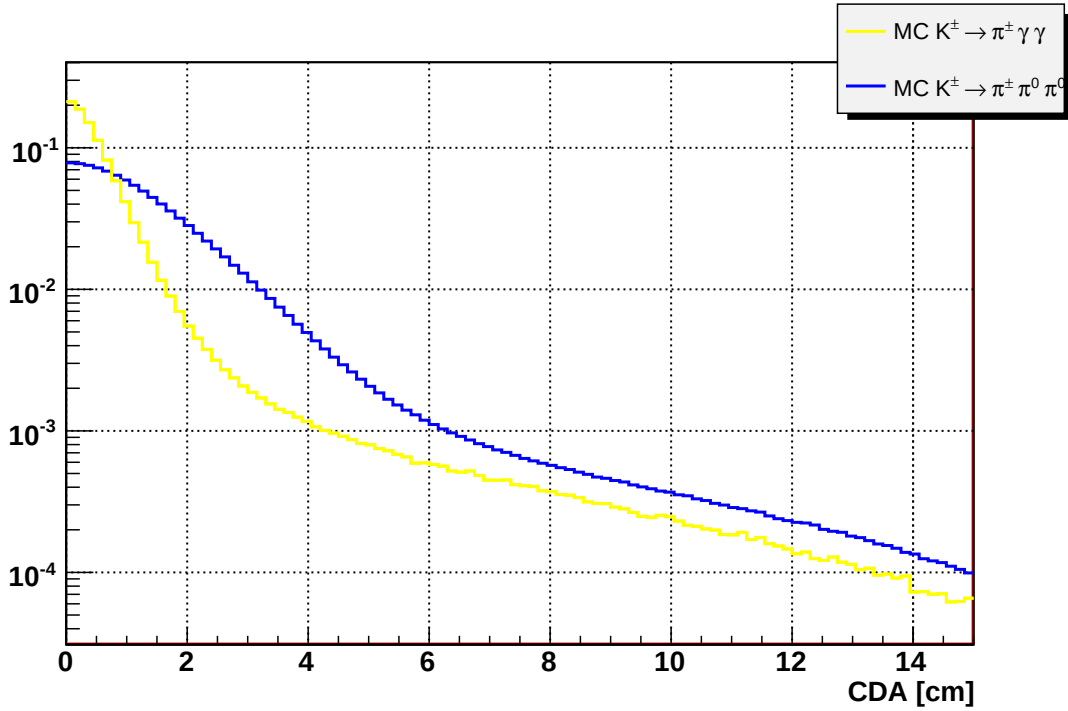


Figure 4.7: Monte-Carlo distributions of the closest distance of approach (CDA) between the pion track and the parent kaon direction.

Interactions at $DCH1$

Photons produced in decays occurring close to the first DCH , may pass through the vacuum pipe or impinge on the chamber flange before reaching the electromagnetic calorimeter. This interaction cannot be well enough modeled in the simulation and therefore the event must be rejected.

Given the kaon decay vertex position ($z_{charged}$), the $DCH1$ flange position can be projected at the LKr surface. The slope needed for a photon to impact on the flange is:

$$\frac{dr^{flange}}{dz} = \frac{r^{flange}}{z_{DCH1} - (z_{charged} + z_{reso})}$$

where $r^{flange} = 11 \text{ cm}$ is the radial flange position, z_{DCH1} the longitudinal position of the first drift chamber and $z_{reso} = 400 \text{ cm}$ have been added to the reconstructed kaon decay vertex point to take into account resolution effects.

Extrapolating according to this direction, the radius of the resulting photon cluster at the calorimeter is:

$$r_{LKr}^{flange} = \frac{dr^{flange}}{dz} \cdot (z_{LKr} - (z_{charged} + z_{reso}))$$

Events are selected only if the radial position of the two photon clusters at electromagnetic calorimeter front face (r_{LKr}) is greater than r_{LKr}^{flange} .

4.1.4 $m_{\gamma\gamma}$ and $m_{\pi\gamma\gamma}$ Invariant Masses

The di-photon ($m_{\gamma\gamma}$) and the kaon ($m_{\pi\gamma\gamma}$) invariant masses in the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ hypothesis have been reconstructed according to:

$$m_{\gamma\gamma}^2 = (E_{\gamma_1} + E_{\gamma_2})^2 - (\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})^2 = (E_{\gamma_1} + E_{\gamma_2})^2 - \sum_{i=1}^3 (p_{\gamma_1}^i + p_{\gamma_2}^i)^2$$

$$\begin{aligned} m_{\pi\gamma\gamma}^2 &= (E_{\pi^\pm} + E_{\gamma_1} + E_{\gamma_2})^2 - (\vec{p}_{\pi^\pm} + \vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})^2 = \\ &= (E_{\pi^\pm} + E_{\gamma_1} + E_{\gamma_2})^2 - \sum_{i=1}^3 (p_{\pi^\pm}^i + p_{\gamma_1}^i + p_{\gamma_2}^i)^2 \end{aligned}$$

where $E_{\gamma_i} = |\vec{p}_{\gamma_i}|$ is the photon energy deposition in the electromagnetic calorimeter of the i^{th} photon candidates ($E_{\gamma_1} < E_{\gamma_2}$) and $E_{\pi^\pm} = \sqrt{(\vec{p}_{\pi^\pm} \cdot c)^2 + (m_{\pi^\pm} \cdot c^2)^2}$

the pion energy reconstructed with magnetic spectrometer information ($|\vec{p}_{\pi^\pm}| = p_{DCH}$).

A cut on the $m_{\gamma\gamma}$ kinematic boundary has been applied:

$$0 \text{ GeV}/c^2 < m_{\gamma\gamma} < m_{K^\pm} - m_{\pi^\pm}$$

being $m_{K^\pm}$ and $m_{\pi^\pm}$ the kaon and charged pion masses [12].

4.2 Background Rejection

Background events can arise from one or more photons outside the geometrical acceptance of the detector, two coalescent photons at the *LKr* calorimeter or charged particle mis-identification. The main background decay channel are listed in Tab 5.4.

Decay Mode	BR [12]	BR/BR($K^\pm \rightarrow \pi^\pm \gamma\gamma$)
$K^\pm \rightarrow \pi^\pm \pi^0$	$(20.92 \pm 0.12)\%$	$\sim 1.9 \times 10^5$
$K^\pm \rightarrow \pi^0 e\nu$	$(4.98 \pm 0.07)\%$	$\sim 4.5 \times 10^4$
$K^\pm \rightarrow \pi^0 \mu\nu$	$(3.32 \pm 0.06)\%$	$\sim 3.0 \times 10^4$
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$	$(1.757 \pm 0.024)\%$	$\sim 1.6 \times 10^4$
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (IB)	$(1.39 \pm 0.08) \times 10^{-3}$	$\sim 1.3 \times 10^3$
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (DE)	$(7.5 \pm 1.1) \times 10^{-6}$	~ 6.8
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (INT)	$(7.4 \pm 3.0) \times 10^{-6}$	~ 6.7

Table 4.2: Summary of the main background decay channels (in case of $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay, the NA48/2 2003 preliminary results on the direct emission and interference component fractions [19] have been used).

A very good background suppression, better than 10^{-8} , is needed in order to select an almost pure $K^\pm \rightarrow \pi^\pm \gamma\gamma$ sample.

The different background components can be identified analyzing the distribution of the di-photon reconstructed invariant mass ($m_{\gamma\gamma}$) as a function of the pion energy in the kaon rest frame ($m_{fake}^2 = 2m_{K^\pm} E_{\pi^\pm}^*$, Eq.2.1) (Fig. 4.8), as populating different regions.

A set of specific cuts have been implemented in order to reduce the background contribution to the final data sample. Some already described requirements, such as *COG*, *CDA* and number of *MUV* hits, partially reduce the number of background events, but a more detailed study is mandatory in order to properly identify the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ signal.

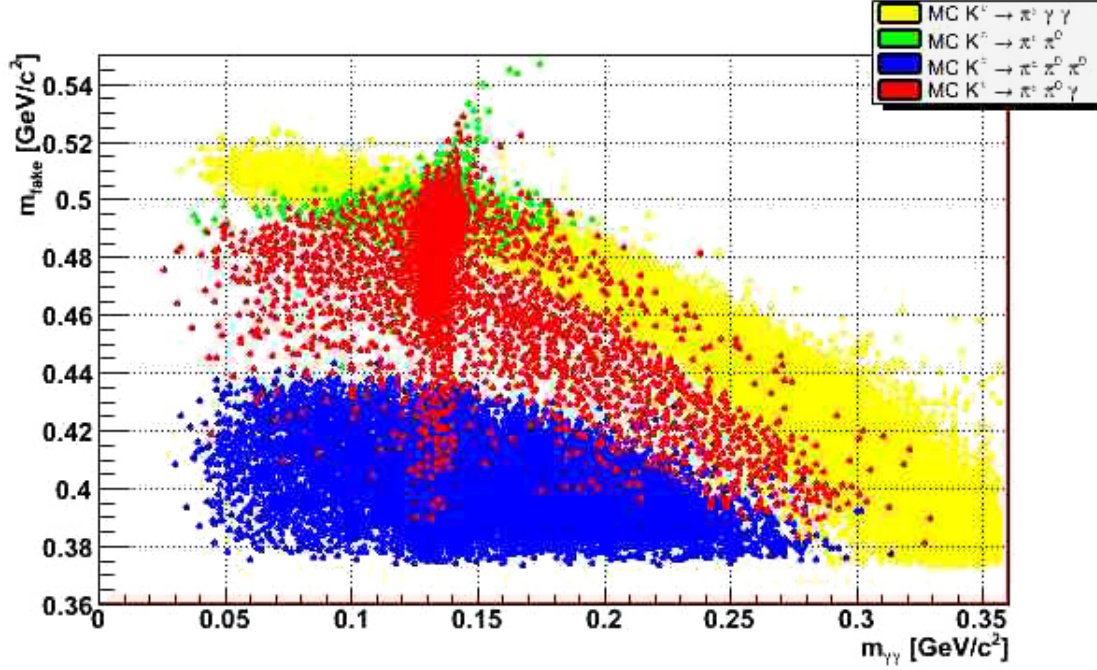


Figure 4.8: Monte-Carlo scatter plot: m_{fake} vs. $m_{\gamma\gamma}$ invariant masses.

4.2.1 $K^\pm \rightarrow \pi^\pm \pi^0$ Decay

Even if the $K^\pm \rightarrow \pi^\pm \pi^0$ decay mode has exactly the same topology as the $K^\pm \rightarrow \pi^\pm \gamma \gamma$, only one charged pion and two photons ($\pi^0 \rightarrow \gamma \gamma$), it can be easily rejected exploiting its two body decay peculiarity: the distribution of the charged pion kinetic energy in the kaon rest frame ($\propto m_{fake}$) is different from signal events (Fig. 4.9). $K^\pm \rightarrow \pi^\pm \pi^0$ events clearly show a peak at $m_{fake} = m_{K^\pm}$.

To decrease the $K^\pm \rightarrow \pi^\pm \pi^0$ acquisition rate during the data taking, a trigger (L2) cut requiring $m_{fake} < 0.48 \text{ GeV}/c^2$ had already been implemented. However, to remove edge effects and further reduce the residual background, a different cut value has been implemented:

$$m_{fake} < 0.46 \text{ GeV}/c^2$$

corresponding to $m_{\gamma\gamma} \gtrsim 0.2 \text{ GeV}/c^2$.

Unfortunately all the low di-photon spectrum is cut away, but it would be anyway almost impossible to study the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay under the π^0 peak due to resolution tails.

A first background study has been based on a large Monte-Carlo sample ($\sim 160 \times 10^6$ events). After applying the signal reconstruction and m_{fake} cut, no events survive, but to reach an adequate rejection factor, a much larger (at least

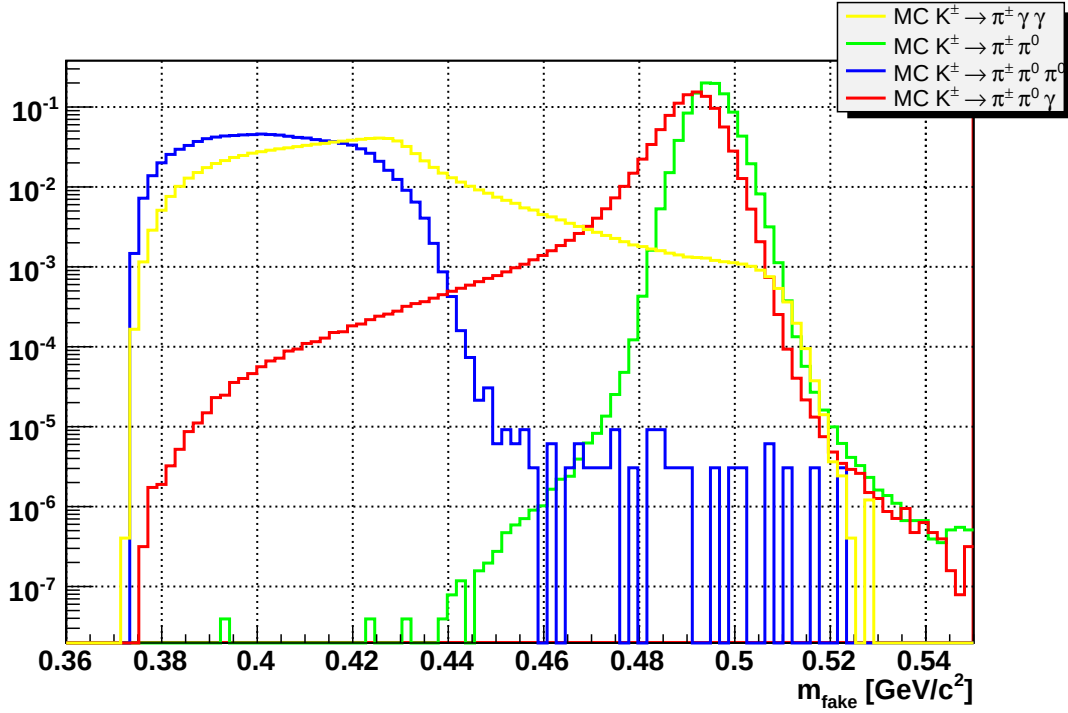


Figure 4.9: Monte-Carlo distributions of the m_{fake} invariant mass.

a factor ~ 100) Monte-Carlo sample would be necessary. Due to the very large CPU time needed to produce such a huge statistics, a different approach has been adopted.

Selecting pure $K^\pm \rightarrow \pi^\pm \pi^0$ data (*NT-PEAK* trigger bit) and Monte-Carlo samples (Sec. 5.1), the $m_{\gamma\gamma}$ reconstructed invariant mass distribution has been studied. Fitting the tail on the right side of the π^0 peak from $0.16 \text{ GeV}/c^2$ up to $0.2 \text{ GeV}/c^2$ with a second order polynomial (Fig. 4.10), it has been possible to measure the probability to find a $K^\pm \rightarrow \pi^\pm \pi^0$ event above $m_{\gamma\gamma} = 0.2 \text{ GeV}/c^2$ according:

$$\mathcal{P}(m_{\gamma\gamma} > 0.2 \text{ GeV}/c^2) = \frac{\int_{0.2 \text{ GeV}/c^2}^{m_{K^\pm} - m_{\pi^\pm}} dm_{\gamma\gamma} \cdot e^{-(p_0 + p_1 \cdot m_{\gamma\gamma} + p_2 \cdot m_{\gamma\gamma}^2)}}{\mathcal{N}_{\pi^\pm \pi^0}}$$

where p_i are the second order polynomial coefficients, $\mathcal{N}_{\pi^\pm \pi^0}$ is the number of reconstructed Monte-Carlo $K^\pm \rightarrow \pi^\pm \pi^0$ events and the integral has been performed up to the $m_{\gamma\gamma}$ kinematic boundary.

Proved that the CMC simulation properly reproduces quite general data distributions (Sec. 3.3), it is important to check if π^0 tails are reproduced as well to validate the method. Comparing data and Monte-Carlo selected events (Fig. 4.11), one can conclude that the agreement is quite good.

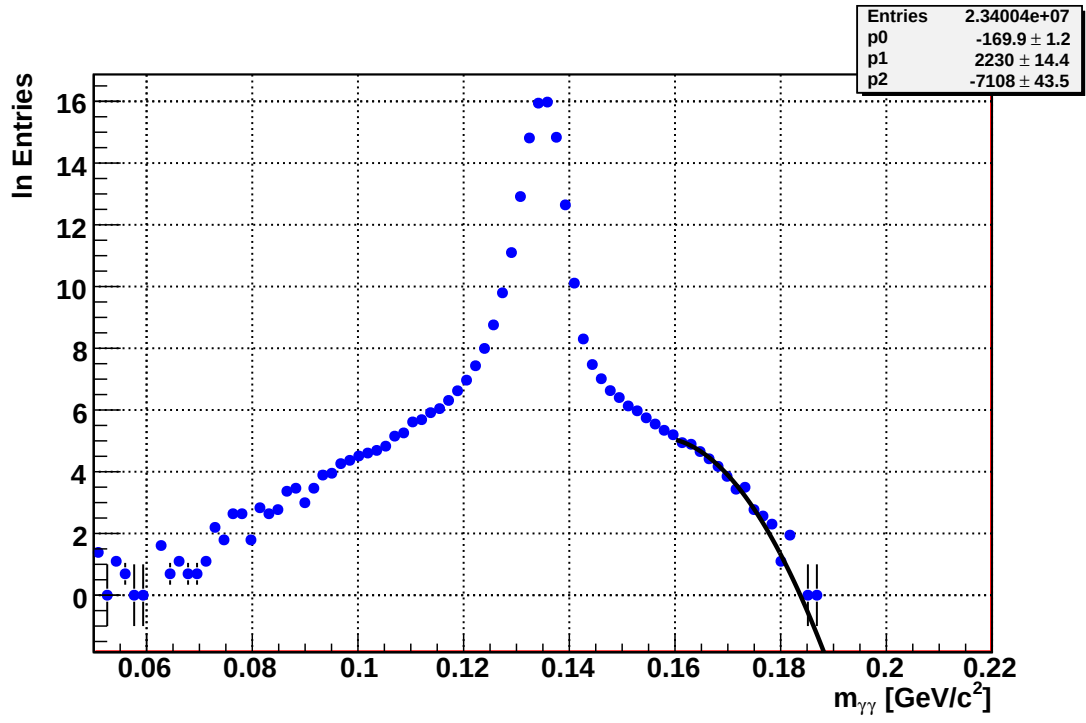


Figure 4.10: Second order polynomial fit to the Monte-Carlo reconstructed $m_{\gamma\gamma}$ invariant mass tail.

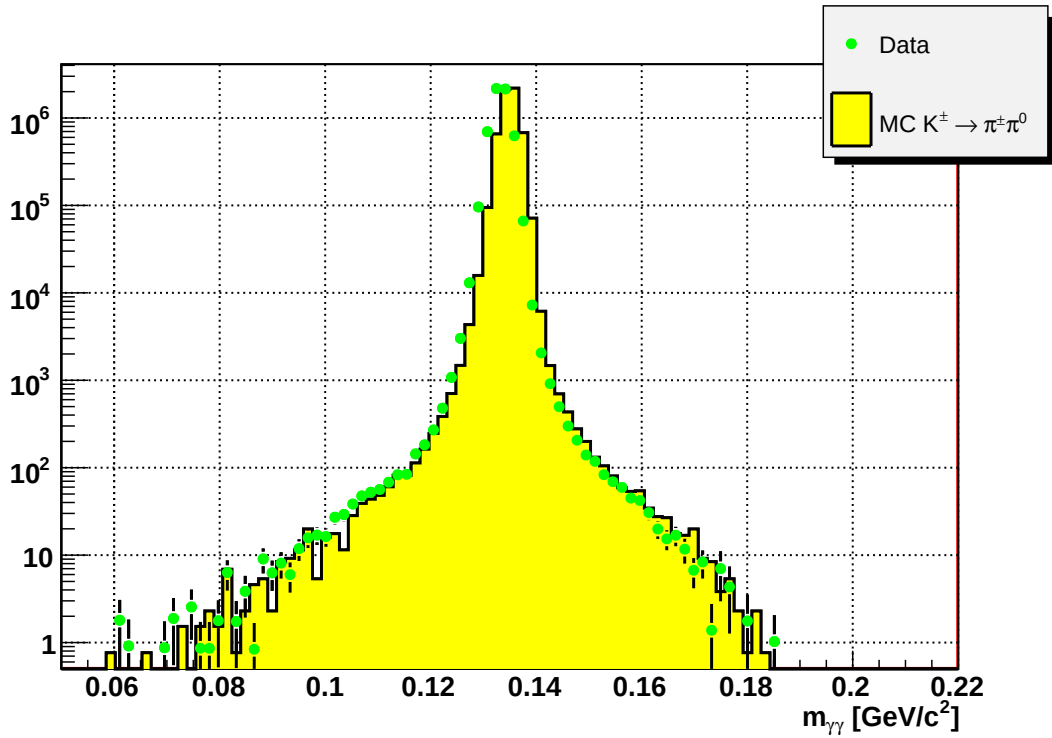


Figure 4.11: Data/Monte-Carlo comparison of the reconstructed π^0 invariant mass (a small shift has been observed (Sec. 3.3)).

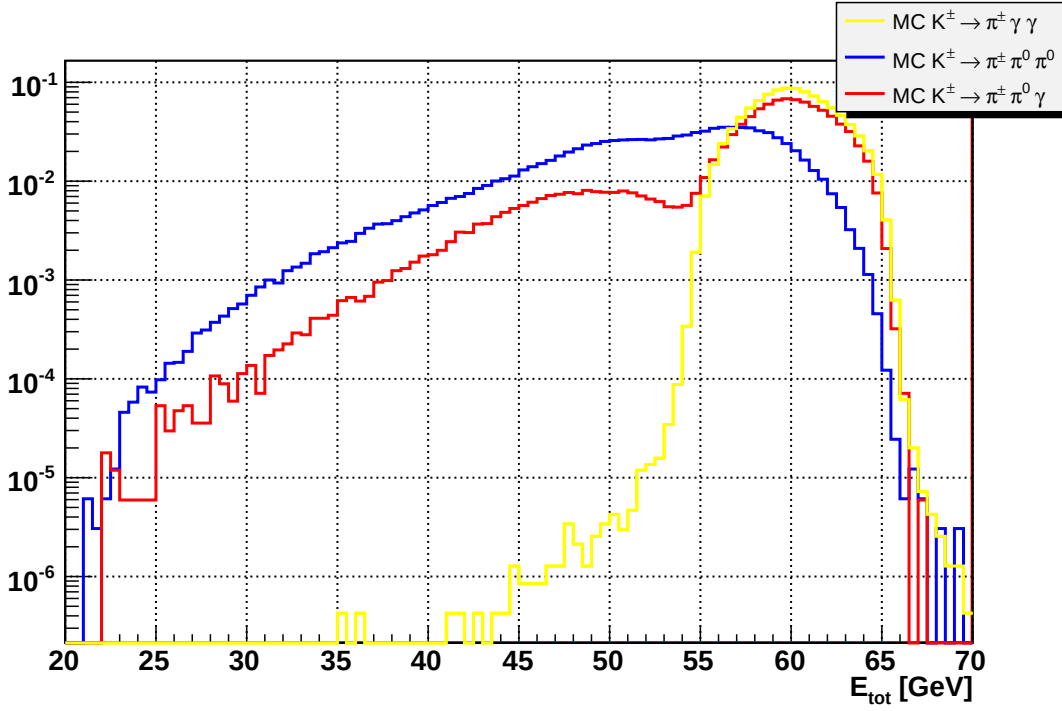


Figure 4.12: Monte-Carlo distributions of the reconstructed total energy under the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ assumption.

The Monte-Carlo based fitting method allows to measure a rejecting factor of $(1 \pm 2) \times 10^{-13}$ ($< 4 \cdot 10^{-13}$ (95% CL)) and conclude that the residual background due to $K^\pm \rightarrow \pi^\pm \pi^0$ events is completely negligible.

4.2.2 Unbalanced Decays

Kaon decays such as $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ where one or two photons are lost, cannot be fully reconstructed because of the undetected energy.

As already mentioned, unbalanced events have been already partially suppressed by the COG requirement applied for the decay vertex reconstruction (Fig. 4.6), but additional conditions have been required to further decrease the amount of residual background:

- the reconstructed total energy of the event under the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ assumption ($E_{tot} = E_{\pi^\pm} + E_{\gamma_1} + E_{\gamma_2}$), must be compatible with the nominal beam energy $E_{beam} = 60 \text{ GeV}$ (Fig. 4.12): $|E_{tot} - E_{beam}| < 5 \text{ GeV}$;
- the kaon reconstructed invariant mass has to be consistent with the PDG kaon mass [12] (Fig. 4.13): $|m_{\pi\gamma\gamma} - m_{K^\pm}| < 0.02 \text{ GeV}/c^2$;

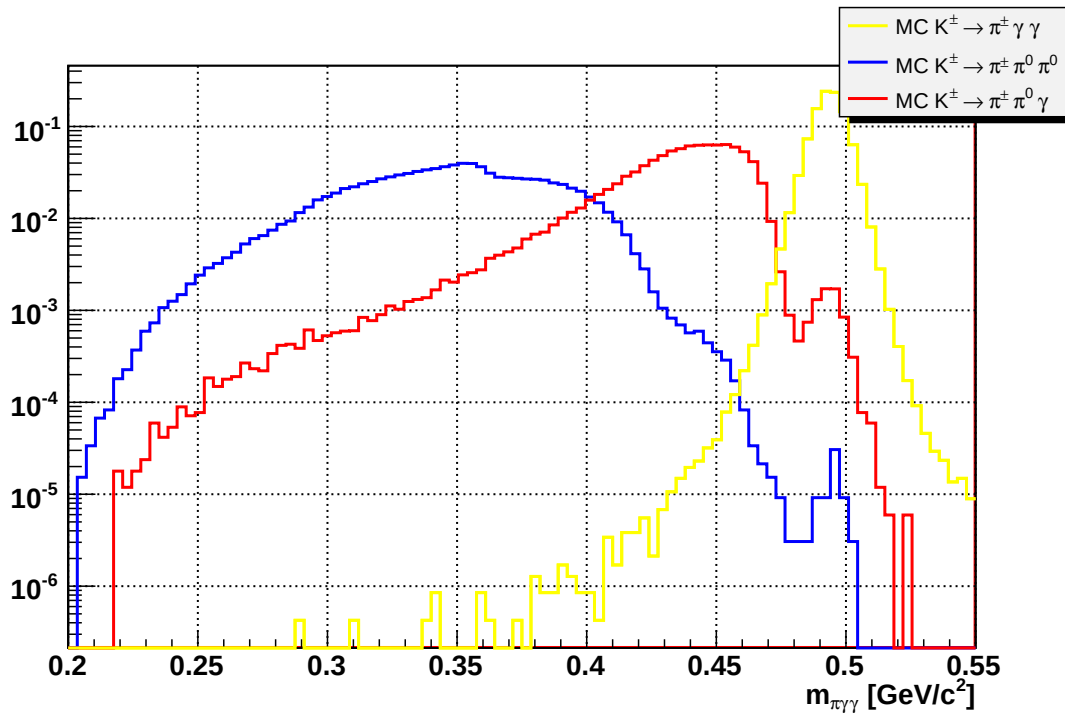


Figure 4.13: Monte-Carlo distributions of the reconstructed kaon invariant mass under the $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ assumption.

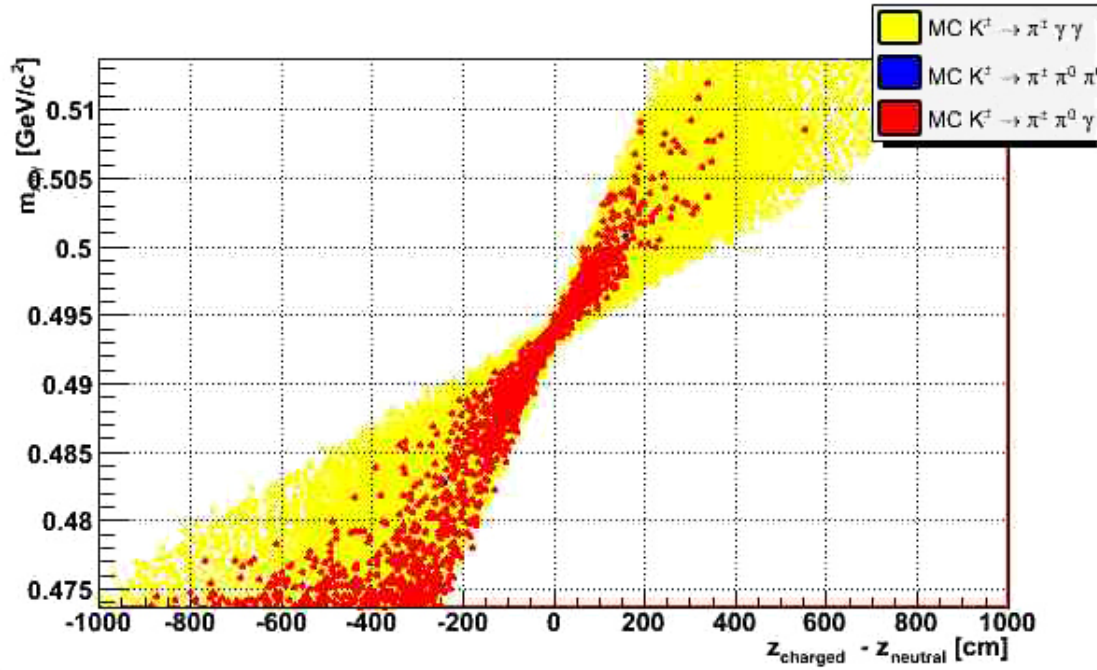


Figure 4.14: Monte-Carlo scatter plot: kaon invariant mass vs. "charged"- "neutral" decay vertex separation.

- the vertex reconstructed with LKr information has to be close to the charged decay vertex (Sec. 4.1.3): $|z_{charged} - z_{neutral}| < 200 \text{ cm}$; even if the "neutral" vertex is by definition correlated to the reconstructed kaon invariant mass, due to resolution effect it allows a supplementary background reduction (Fig. 4.14).

$$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$$

About 160×10^6 $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ simulated decays have been analyzed. Only 2 events survive to the signal reconstruction and background suppression criteria, leading to a rejection factor of $(1.3 \pm 0.9) \times 10^{-8}$.

$$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$$

Several $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ Monte-Carlo samples ($\sim 160 \times 10^6$ inner bremsstrahlung, $\sim 16 \times 10^6$ direct emission and interference components) have been analyzed. The $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ IB decay has been found to be the largest residual background ($\sim 3.2\%$), while DE and INT contributions are at the few ‰ level.

4.2.3 Coalescent Photons

The most problematic background are decays where two photons overlap at the electromagnetic calorimeter and have been reconstructed as a unique cluster with an energy given by the sum of the two. These events cannot be rejected checking the reconstructed kaon invariant mass or the event total energy, because the applied requirement would be by definition satisfied. The only method to identify and reduce them is cutting on the cluster development size.

A small discrepancies in the reconstruction of the shower dimension has been observed between data and simulation (Fig. 4.15), requiring a different cut value implementation for the two samples. Even if the cluster dimension slightly depends on the photon energy (maximum variation $\sim 3\%$), it has been ignored and a fixed cut has been applied:

$$\frac{|r_{cluster} - \langle r_{cluster} \rangle|}{\sigma_{r_{cluster}}} < 3$$

where $\langle r_{cluster} \rangle$ and $\sigma_{r_{cluster}}$ (Tab. 4.3) have been independently measured from data and Monte-Carlo events on a pure $K^\pm \rightarrow \pi^\pm \pi^0$ sample (Sec. 5.1).

From specific studies based on a Monte-Carlo $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ sample, it turns out that $\sim 90\%$ of surviving events belong to the coalescent photons class while

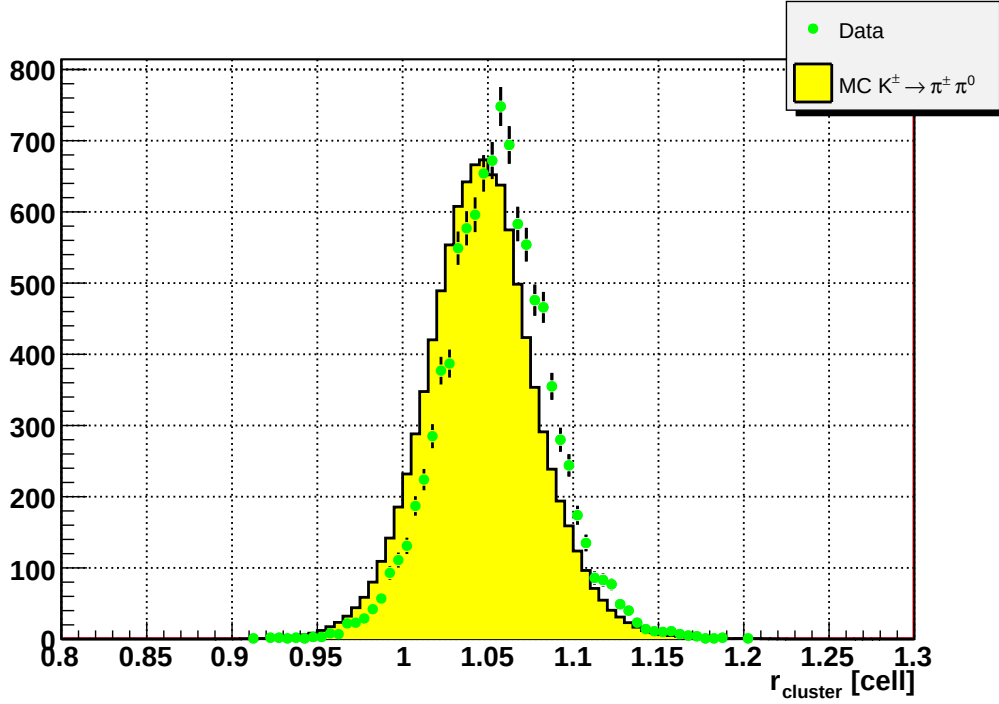


Figure 4.15: Data/Monte-Carlo comparison of the reconstructed shower transverse dimension: a shift of the mean value is clearly visible.

$\langle r_{cluster} \rangle \pm \sigma_{r_{cluster}}$ [cells]		
	Data	CMC
γ_1	1.055 ± 0.031	1.046 ± 0.032
γ_2	1.057 ± 0.022	1.046 ± 0.022

Table 4.3: Data and Monte-Carlo reconstructed cluster dimension: γ_1 and γ_2 are the two photon candidates in the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ hypothesis ($E_{\gamma_1} < E_{\gamma_2}$).

the remaining $\sim 10\%$ have a lost photon (usually the radiative one).

4.2.4 Semi-Leptonic Decays

Because of the missing energy due the presence of a neutrino in the final state, $K^\pm \rightarrow \pi^0 e \nu$ and $K^\pm \rightarrow \pi^0 \mu \nu$ decays are partially suppressed by the requirements applied for the rejection of unbalanced decays. In order to better estimate the amount of residual background a more detailed study has been performed.

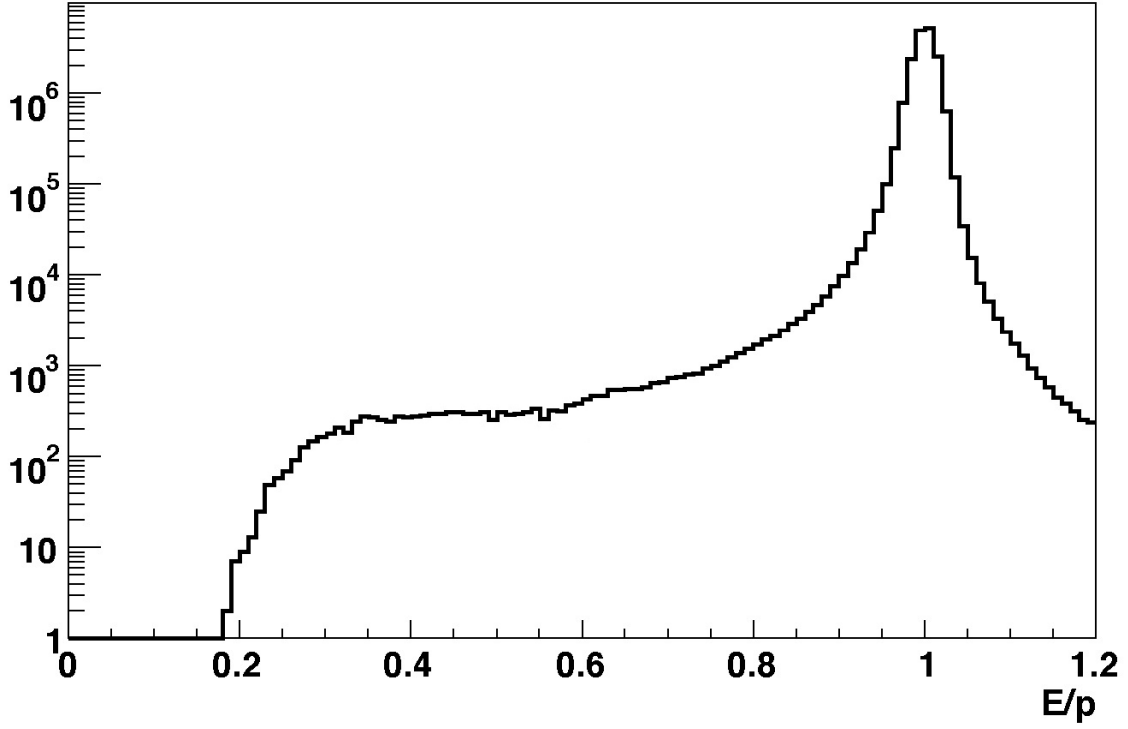


Figure 4.16: Electron E_{LKr}/p_{DCH} distribution for pure $K^\pm \rightarrow \pi^0 e \nu$ events.

$$K^\pm \rightarrow \pi^0 e \nu$$

This decay mode can fake the signal if the electron is mis-identified as a pion. To check such effect, the full data sample has been re-analyzed removing the pion E_{LKr}/p_{DCH} cut. An increase in the signal acceptance of $\sim 1.3\%$ has been observed and a $(4.9 \pm 2.0) \times 10^{-8}$ $K^\pm \rightarrow \pi^0 e \nu$ acceptance has been measured.

Profiting of the electron E_{LKr}/p_{DCH} measurement from pure $K^\pm \rightarrow \pi^0 e \nu$ events (Fig. 4.16), it is possible to evaluate the probability to have an electron with an E_{LKr}/p_{DCH} ratio smaller than the chosen cut value:

$$\mathcal{P}(E_{LKr}/p_{DCH} < 0.8) = (9.12 \pm 0.09) \times 10^{-2}$$

Combining this probability with the acceptance result with no E_{LKr}/p_{DCH} requirement, a $K^\pm \rightarrow \pi^0 e \nu$ rejection factor corresponding to $(4.4 \pm 1.8) \times 10^{-11}$ has been measured.

While studying the $K^\pm \rightarrow \pi^0 e \nu$ decay mode, it has been found that the E_{LKr}/p_{DCH} condition must be applied also for trigger purposes: to avoid the low $K^\pm \rightarrow \pi^\pm \gamma \gamma$ statistic ($BR \sim 10^{-6}$), background events have been used to measure trigger efficiencies (Sec. 5.2); in that situation the fraction of events with an electron

in place of the charged pion, as $K^\pm \rightarrow \pi^0 e \nu$ decays, have a larger probability to fire the *NT-PEAK* trigger with respect to $K^\pm \rightarrow \pi^\pm \gamma \gamma$, faking a bigger efficiency.

$$K^\pm \rightarrow \pi^0 \mu \nu$$

The only way for $K^\pm \rightarrow \pi^0 \mu \nu$ events to simulate a signal event is due to a muon veto system inefficiency. First, about $\sim 16 \times 10^6$ events have been analyzed without the requirement on the number of *MUV* hits: no events survived to the selection, leading to a rejection factor $< 2 \times 10^{-7}$ (95% *CL*). Then, the result has been combined with the *MUV* efficiency of $\sim 99.9\%$, ensured by the cut on the minimum track momentum, giving a $K^\pm \rightarrow \pi^0 \mu \nu$ acceptance $< 2 \times 10^{-10}$ (95% *CL*).

As well as $K^\pm \rightarrow \pi^0 e \nu$, the residual background from $K^\pm \rightarrow \pi^0 \mu \nu$ decays is completely negligible.

4.2.5 Accidental Background

In order to measure the amount of lost events due to accidental photons in the *LKr* acceptance, mainly coming from decay produced by a very close in time proton, the information of the closest in time extra-cluster, when present, has been used.

Only 6 out of 2300 $K^\pm \rightarrow \pi^\pm \gamma \gamma$ candidate events with a not-in-time extra-cluster (time distance from the *LKr* time greater than 4 ns) have been observed, leading to an accidental rate of $\sim 2.3\%$.

4.3 Signal and Background Acceptances

2300 $K^\pm \rightarrow \pi^\pm \gamma \gamma$ candidate events have been reconstructed in the whole 2003 data sample (Tab. 4.4). Unfortunately $\sim 40\%$ of the *SS0* statistics cannot be analyzed because of missing information in the Pattern Unit that prevent to measure the kaon flux (Sec. 5.1).

SS0 and 1 have a bigger acceptance with respect to *SS2* and 3 (Tab. 4.4) because of a different requirement on the minimum cluster distance in x or y projection among any cluster pairs, needed to fix an anomalous trigger efficiency problem related to *NT-PEAK* (Sec. 5.2).

4.3. Signal and Background Acceptances

	SS0	SS1	SS2	SS3
$\mathcal{A}_{\pi^\pm\gamma\gamma} [\%]$	12.768 ± 0.010	12.967 ± 0.025	10.649 ± 0.019	10.69 ± 0.03
$\mathcal{N}_{\pi^\pm\gamma\gamma}$	1207	423	488	182

Table 4.4: $K^\pm \rightarrow \pi^\pm\gamma\gamma$ acceptance and number of candidate events divided according to the SuperSamples.

Signal acceptance has also been studied for each applied cut (Tab. 4.5) according to the following definitions:

$\mathcal{A}_S$ - A single cut acceptance depending only on the specific cut:

$$\mathcal{A}_S = \frac{\mathcal{N}_{Single}^{MC}}{\mathcal{N}_{SC}^{MC}}$$

The number of events surviving the single cut ($\mathcal{N}_{Single}^{MC}$) has been divided by the total number of *SuperCOMPACT* pre-selected events: only one reconstructed track plus any number of ghost tracks, two not track associated clusters plus any number of additional clusters with a radial distance smaller than 30 *cm* from the track impact point at the electromagnetic calorimeter front face or with a time distance from the average photon candidates time greater than 3 *ns* and no hits in the muon veto system ($\mathcal{N}_{SC}^{MC}$);

$\mathcal{A}_C$ - A cumulative acceptance depending on the ordering of the cuts:

$$\mathcal{A}_C = \frac{\mathcal{N}_{Cumulative}^{MC}}{\mathcal{N}_{Total}^{MC}}$$

The number of events surviving the specific and all the previous cuts ($\mathcal{N}_{Cumulative}^{MC}$) has been divided by the total number of simulated events with a kaon momentum in the range (55 ÷ 65) *GeV* and a kaon decay point between -16 *m* and 70 *m* ($\mathcal{N}_{Total}^{MC}$).

After applying all the rejection criteria, the residual background is $\sim 3.5\%$ of the signal (Tab. 4.6), mainly due to inner bremsstrahlung $K^\pm \rightarrow \pi^\pm\pi^0\gamma$ events with two coalescent photons at the electromagnetic calorimeter ($\sim 3.2\%$).

Cut	$\mathcal{A}_S$ [%]	$\mathcal{A}_C$ [%]
<i>SuperCOMPACT Pre-Selection</i>	29.9	29.9
<i>Charged Track (Sec 4.1.2)</i>		
<i>Fit Quality</i> > 0.6	99.99	29.8
<i>Geometrical Acceptance</i>	89.5	26.7
$10 \text{ GeV}/c < p_{DCH} < 60 \text{ GeV}/c$	93.2	24.9
$E_{LKr}/p_{DCH} < 0.8$	94.5	24.2
<i>Electromagnetic Clusters (Sec 4.1.2)</i>		
<i>Reconstruction Status Bit</i> < 4	99.99	24.2
<i>Geometrical Acceptance</i>	81.8	19.7
<i>Dead Cells Distance</i> $> 2 \text{ cm}$	96.9	19.1
$5 \text{ GeV} < E_{LKr} < 60 \text{ GeV}$	94.3	18.3
$\gamma\gamma$ <i>Distance</i> $> 40 \text{ cm}$	98.3	18.9
<i>LKr Peaks Distance</i> $> 10 \text{ cm}$	96.1 (78.6)	17.0 (14.3)
<i>Decay Vertex Reconstruction (Sec 4.1.3)</i>		
<i>COG</i> $< 2 \text{ cm}$	86.6	16.7 (14.0)
<i>CDA</i> $< 2 \text{ cm}$	92.0	16.5 (13.8)
$-16 \text{ m} < z < 70 \text{ m}$	98.4	16.4 (13.8)
<i>DCH1 Interactions</i>	99.6	16.4 (13.8)
$0 \text{ GeV}/c^2 < m_{\gamma\gamma} < m_{K^\pm} - m_{\pi^\pm}$	99.6	16.3 (13.7)
<i>Background Rejection (Sec 4.2)</i>		
$m_{fake} < 0.46 \text{ GeV}/c^2$	93.1	15.4 (12.9)
$ E_{tot} - E_{beam} < 5 \text{ GeV}$	93.0	15.3 (12.8)
$ m_{\pi\gamma\gamma} - m_{K^\pm} < 0.02 \text{ GeV}/c^2$	87.4	15.2 (12.8)
$ z_{charged} - z_{neutral} < 200 \text{ cm}$	68.1	12.8 (10.8)
$ r_{cluster-} < r_{cluster+} < 3 \cdot \sigma_{r_{cluster}}$	94.5	12.8 (10.7)
Total	-	12.8 (10.7)

Table 4.5: Single ($\mathcal{A}_S$) and cumulative ($\mathcal{A}_C$) $K^\pm \rightarrow \pi^\pm \gamma\gamma$ acceptances. Starting from the *LKr Peaks Distance* requirement, because of a different condition on the minimum cluster distances in x or y projection among any cluster pair, two $\mathcal{A}_C$ values have been measured for each cut: the first one refers to SS0 and 1 only, while the second to SS2 and 3.

Decay Mode	$\mathcal{A}$	$BR \cdot \mathcal{A}$
$K^\pm \rightarrow \pi^\pm \gamma \gamma$	$(12.288 \pm 0.008)\%$	$(1.4 \pm 0.4) \times 10^{-7}$
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (IB)	$(3.12 \pm 0.14) \times 10^{-6}$	$(4.3 \pm 0.3) \times 10^{-9}$
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (DE)	$(3.92 \pm 0.16) \times 10^{-5}$	$(3.0 \pm 0.4) \times 10^{-10}$
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (INT)	$(2.53 \pm 0.13) \times 10^{-5}$	$(1.9 \pm 0.8) \times 10^{-10}$
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$	$(1.3 \pm 0.9) \times 10^{-5}$	$(2.2 \pm 1.6) \times 10^{-10}$
$K^\pm \rightarrow \pi^\pm \pi^0$	$< 4 \times 10^{-13}$ (95% CL)	$< 1 \times 10^{-13}$
$K^\pm \rightarrow \pi^0 e \nu$	$(4.4 \pm 1.8) \times 10^{-11}$	$(1.8 \pm 0.8) \times 10^{-12}$
$K^\pm \rightarrow \pi^0 \mu \nu$	$< 2 \times 10^{-10}$ (95% CL)	$< 3 \times 10^{-12}$

Table 4.6: Acceptance summary of all the studied kaon decay modes: Monte-Carlo sub-samples ($SS0 \div 3$) have been combined to obtain a unique acceptance value for each decay channel.

Chapter 5

Results

Taking into account the residual amount of background events ($\sim 3.3\%$ due to $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decays and $\sim 0.2\%$ to $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$), a measurement of the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio has been performed according to the following formula:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = \frac{\mathcal{N}_{\pi^\pm \gamma \gamma} - \mathcal{N}_{bg}}{\Phi(K^\pm) \cdot \mathcal{A}_{\pi^\pm \gamma \gamma} \cdot \varepsilon_{L1} \cdot \varepsilon_{L2}} \quad (5.1)$$

where $\mathcal{N}_{\pi^\pm \gamma \gamma}$ is the number of reconstructed signal candidate decays (Tab. 4.4), $\mathcal{N}_{bg}$ the estimated number of residual background events using the CMC simulation, $\Phi(K^\pm)$ the total kaon flux measured with $K^\pm \rightarrow \pi^\pm \pi^0$ events, $\mathcal{A}_{K^\pm \rightarrow \pi^\pm \gamma \gamma}$ the Monte-Carlo signal acceptance (Tab. 4.4) and ε_{L1} (ε_{L2}) the efficiencies of the first (second) trigger level.

Four independent measurements have been performed on each 2003 Super-Sample ($SS0 \div 3$) and then combined into a final result.

Two different approaches have been adopted: a measurement obtained integrating over all the di-photon reconstructed spectrum and another one performed in bin of $m_{\gamma\gamma}$. In the first case, since the shape of the di-photon invariant mass distribution strongly depends on the $\hat{c}$ constant of the Chiral Perturbation Theory, the signal acceptance correction is model dependent as well as the obtained result. On the other hand, when performing the measurement in bin of $m_{\gamma\gamma}$ the dependence on $\hat{c}$ vanishes.

5.1 Kaon Flux

$K^\pm \rightarrow \pi^\pm \pi^0$ events have been selected to measure the total number of kaon decayed within the experimental fiducial volume. The choice tends to cancel

possible systematic effects related to the data acquisition and detector because the $K^\pm \rightarrow \pi^\pm \pi^0$ decay has same topology as the $K^\pm \rightarrow \pi^\pm \gamma\gamma$: one charged pion and two photons produced by the neutral pion decay ($\pi^0 \rightarrow \gamma\gamma$).

Several data sample collected through different trigger conditions can be used to reconstruct $K^\pm \rightarrow \pi^\pm \pi^0$ events: two minimum bias ("charged" and "neutral") and two control triggers (Sec. 2.14.1, 2.14.2).

C-PRE: the "charged" minimum bias trigger $\left(\frac{Q_1}{100} + Q_2 * \overline{AKL}\right)$ combines the information of the large angle anti-counter system and the charged hodoscope, tagging decays with at least one charged particle in the detector acceptance; in order to not saturate the acquisition bandwidth, a $D = 100$ downscaling factor had been applied; since one track events, such as $K^\pm \rightarrow \pi^\pm \gamma\gamma$ and $K^\pm \rightarrow \pi^\pm \pi^0$, can fire the Q_2 condition only if there is an accidental particle¹ crossing the detector or a photon conversion before the hodoscope, only the Q_1 part of this trigger must be selected (total downscaling: $D = 100 \cdot 100 = 10000$);

T0N: the "neutral" minimum bias signal is derived from the hodoscope placed inside the electromagnetic calorimeter; the downscaling factor had been set to $D = 200$ during the first part of the data taking (*SS0*), while it had been decreased to $D = 100$ for the remaining period ($SS1 \div 3$);

NT-PEAK: the condition on the minimum number of *LKr* cluster peaks on x or y projections ($N_x > 2 + N_y > 2$) is part of the first trigger level (Level 1) that selects $K^\pm \rightarrow \pi^\pm \gamma\gamma$ events, but a pure control sample had been anyway collected to better monitor its behaviour ($D = 50$);

NT-NOPEAK: a different control trigger based on both spectrometer and electromagnetic calorimeter information had been set up to further check the main *NT-PEAK* trigger with a $D = 100$.

Profiting of the high branching ratio, even if a strong downscaling had been applied it has been chosen to select $K^\pm \rightarrow \pi^\pm \pi^0$ events from the Q_1 minimum bias data sample to avoid any trigger efficiency correction. As a crosscheck the kaon flux has been measured with the *NT-PEAK* control trigger as well.

Unfortunately $\sim 38\%$ of the *SS0* statistics cannot be analyzed due to a malfunctioning cable in the Pre-Trigger system that prevent to properly identify Q_1 events in the "charged" minimum bias data sample. This is quite a huge amount

¹Parallel muons in the beam usually do not satisfy the track reconstruction algorithm.

of statistics but it would not be anyway used since the Q_1 sample must be employed in the measurement of the Level 1 trigger efficiency of $K^\pm \rightarrow \pi^\pm \gamma \gamma$ events.

To reduce possible biases from a different selection approach, $K^\pm \rightarrow \pi^\pm \pi^0$ candidate events have been identified applying as much similar criteria as possible to the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ selection. The same event reconstruction (Sec. 4.1) and background rejection (Sec. 4.2) have been adopted, apart a reversed m_{fake} cut, $m_{fake} > 0.46 \text{ GeV}/c^2$, and a condition on the reconstructed $m_{\gamma\gamma}$ invariant mass to be compatible with a π^0 ($|m_{\gamma\gamma} - m_{\pi^0}| < 0.02 \text{ GeV}/c^2$, where m_{π^0} is the π^0 mass [12]).

A dedicated study of background events to the $K^\pm \rightarrow \pi^\pm \pi^0$ decay have been performed: as for $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decays, only events with one or more photons outside the geometrical acceptance of the detector and/or two coalescent photons in the *LKr* calorimeter ($K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$, $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$) or charged particle misidentification ($K^\pm \rightarrow \pi^0 e \nu$, $K^\pm \rightarrow \pi^0 \mu \nu$) can fake the signal. The very small amount of residual background ($\sim 4\%$), mainly due to inner bremsstrahlung $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decays with two coalescent photons ($\sim 2.4\%$), has been completely neglected in the kaon flux measurement.

All data/Monte-Carlo comparisons concerning the pion and photons reconstructed information show a good agreement (Sec. 3.3).

Once $K^\pm \rightarrow \pi^\pm \pi^0$ candidate events have been identified, the number of kaon decays can be extracted according to the formula:

$$\Phi(K^\pm) = \frac{\mathcal{N}_{\pi^\pm \pi^0}}{BR(K^\pm \rightarrow \pi^\pm \pi^0) \cdot \mathcal{A}_{\pi^\pm \pi^0} \cdot \varepsilon / D}$$

being $\mathcal{N}_{\pi^\pm \pi^0}$ the number of reconstructed $K^\pm \rightarrow \pi^\pm \pi^0$ events, $BR(K^\pm \rightarrow \pi^\pm \pi^0) = (20.92 \pm 0.12)\%$ [12], $\mathcal{A}_{\pi^\pm \pi^0}$ the decay acceptance obtained with the Monte-Carlo simulation, ε the efficiency of the chosen trigger and the D the corresponding downscaling factor. In case $K^\pm \rightarrow \pi^\pm \pi^0$ events have been selected from the Q_1 minimum bias data sample, the corresponding efficiency has been assumed to be $100\%^2$ ($D = 10000$), while for *NT-PEAK* it has been directly measured from data ($D = 50$).

The following general procedure has been adopted to measure the trigger efficiency: first, a control sample with no correlated inefficiency to the trigger under investigation has been identified; secondly, the proper event selection has been performed on the chosen data set and finally, whether the studied trigger condi-

²The assumption has been proved to be true in many analysis along the years.

tion had been satisfied or not by the reconstructed decays has been checked.

The efficiency has been defined as the ratio between the number of reconstructed events satisfying the trigger condition and the total number of reconstructed decays in the control sample. The corresponding error has been determined according to the binomial distribution.

Since the Q_1 sample has the advantage of being completely independent from the LKr calorimeter detector, it has been identified as the NT - $PEAK$ control trigger. The corresponding trigger efficiency has been defined as:

$$\varepsilon_{NT-PEAK} = \frac{\mathcal{N}_{Q_1*NT-PEAK}}{\mathcal{N}_{Q_1}}$$

$$\sigma_{\varepsilon_{NT-PEAK}}^2 = \frac{\varepsilon_{NT-PEAK} \cdot (1 - \varepsilon_{NT-PEAK})}{\mathcal{N}_{Q_1}}$$

where $\mathcal{N}_{Q_1*NT-PEAK}$ is the number of reconstructed events satisfying the Q_1 and the NT - $PEAK$ conditions, while $\mathcal{N}_{Q_1}$ the Q_1 only.

Four different flux measurements, one for each SuperSample, have been performed. A discrepancy between the results obtained selecting $K^\pm \rightarrow \pi^\pm \pi^0$ events from the Q_1 minimum bias or from the NT - $PEAK$ control sample has been observed (Tab. 5.1). The disagreement has been investigated but no clear evidence for the source of such effect has been found. The Q_1 based measurement has been assumed to give the best estimate of the number of kaon decays in the fiducial volume and has been used to extract the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio, but a systematic error given by the difference between the two approaches has been added.

	SS0	SS1	SS2	SS3
$\mathcal{A}_{\pi^\pm \pi^0} [\%]$	15.125 ± 0.005	15.623 ± 0.009	12.780 ± 0.006	12.810 ± 0.011
Q_1				
$\mathcal{N}_{\pi^\pm \pi^0}$	60487	20206	27802	10143
$\Phi(K^\pm) \times 10^{-9}$	19.12 ± 0.14	6.18 ± 0.06	10.40 ± 0.09	3.79 ± 0.04
NT - $PEAK$				
$\mathcal{N}_{\pi^\pm \pi^0}$	7551543	2408018	3275506	1208999
$\varepsilon_{NT-PEAK} [\%]$	60.79 ± 0.19	60.9 ± 0.3	59.7 ± 0.3	59.4 ± 0.5
$\Phi(K^\pm) \times 10^{-9}$	19.63 ± 0.14	6.05 ± 0.05	10.26 ± 0.08	3.80 ± 0.04
$\frac{\Delta\Phi(K^\pm)}{\Phi(K^\pm)} [\%]$	~ 2.7	~ 2.1	~ 1.4	~ 0.3

Table 5.1: Q_1 and NT - $PEAK$ based flux measurements divided according to SuperSamples.

5.2 Trigger Efficiencies

The trigger system selecting $K^\pm \rightarrow \pi^\pm \gamma \gamma$ events is divided in two levels. The logic had been designed to collect $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ events with the maximum efficiency and the minimum systematic bias, therefore the implemented conditions are not optimal for $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decays.

To avoid the problems related to the low $K^\pm \rightarrow \pi^\pm \gamma \gamma$ statistics due to the small branching ratio ($\sim 10^{-6}$), trigger efficiencies have been separately measured with all one pion and two photons events, mainly $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ with lost or coalescent photons, without applying the requirements to suppress the background. Only conditions on the quality of the pion reconstruction and photon identification, such as geometrical acceptance, minimum momentum and energy, time checks, have been required. In order to correct for possible discrepancies between signal and background arising from a different kinematic, a Monte-Carlo based re-weighting technique has been adopted.

Assuming a two-dimensional trigger efficiency measurement performed in bin of two given variables x and y , the re-weighted $K^\pm \rightarrow \pi^\pm \gamma \gamma$ efficiency, averaged over the (x, y) space, is defined as:

$$\begin{aligned}
 \langle \varepsilon \rangle &= \frac{\sum_{i,j} \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \cdot \varepsilon(x_i, y_j)}{\sum_{i,j} \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j)} \\
 \sigma_{\langle \varepsilon \rangle}^2 &= \frac{\sum_{i,j} \left[\mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \cdot \sigma_\varepsilon(x_i, y_j) \right]^2}{\left[\sum_{i,j} \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \right]^2} + \\
 &+ \frac{\sum_{i,j} \left[\left[\varepsilon(x_i, y_j) \cdot \sum_{i,j} \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) - \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \cdot \varepsilon(x_i, y_j) \right]^2 \cdot \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \right]}{\left[\sum_{i,j} \mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j) \right]^4}
 \end{aligned} \tag{5.2}$$

being $\mathcal{N}_{\pi^\pm \gamma \gamma}^{\text{MC}}(x_i, y_j)$ the number of Monte-Carlo reconstructed $K^\pm \rightarrow \pi^\pm \gamma \gamma$ events and $\varepsilon(x_i, y_j)$ the first (second) level efficiency measured from data applying the definition as described for $K^\pm \rightarrow \pi^\pm \pi^0$ events (Sec. 5.1).

By applying this technique, regardless of the small branching ratio a reliable measurement of the trigger efficiency with a relative precision of few percent can be achieved. The method is rather general either for what concern the number of parameters either for the parameter choice.

Special care has been taken in monitoring of all possible dependencies of the

trigger efficiencies on the main reconstructed decay information such as pion direction and momentum, photon energy and impact point at the electromagnetic calorimeter and $m_{\gamma\gamma}$ invariant mass.

5.2.1 Level 1

The first trigger level combines charged and neutral information in the following logic condition:

$$\left(NT-PEAK + \frac{Q_1}{10} * LKrMBias + K_{\mu 3}^{PRE} \right) * (Q_1 + Q_2)$$

where *NT-PEAK* requires a minimum number of *LKr* cluster peaks on x or y projections ($N_x > 2 + N_y > 2$), *LKrMBias* corresponds to a minimum energy deposition in the electromagnetic calorimeter of 10 GeV and $K_{\mu 3}^{PRE} = Q_1 * \overline{Q_2} * 1\mu * \overline{AKL} * LKrMBias_{15GeV}$.

The following trigger composition has been observed checking the sample of reconstructed $K^\pm \rightarrow \pi^\pm \gamma\gamma$ events: $\sim 90\%$ of decays come from the *NT-PEAK* condition, while $\sim 20\%$ from the $\frac{Q_1}{10} * LKrMBias$ with $\sim 10\%$ of common events. The $K_{\mu 3}^{PRE}$ part does not give any contribution to the final data sample due to the requirement on zero hits in the muon veto system applied to remove events where the pion decayed in flight.

While the *LKrMBias* behaviour had been stable and fully efficient during all the data taking, the *NT-PEAK* trigger experienced quite a lots of technical problems. As a consequence $\sim 40\%$ of the total number of bursts collected in 2003 have been excluded from the data sample due to hardware malfunctioning on the "neutral" trigger chain: in some periods the *NT-PEAK* had a very high inefficiency (up to 70%) and at some point, to cope with the high rate, the condition had been changed from the standard ($N_x > 2 + N_y > 2$) requirement to ($N_y > 2$) or switched off. To not introduce any systematic bias in the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio measurement, discarded periods have been removed also from the Monte-Carlo samples.

The *NT-PEAK* trigger requires a well defined event topology: more than two *LKr* cluster peaks in at least one projection (x or y). On each projection two calorimeter cells are readout together defining a grid of $4\text{ cm} \times 4\text{ cm}$ boxes. The number of peaks in a given projection corresponds to the number of 4 cm strips fired by the decay products of that particular event. Due to the location of particle showers at the *LKr* surface, for some events, the *NT-PEAK* trigger system can reconstruct only two peaks in one projection even if there are three well separated

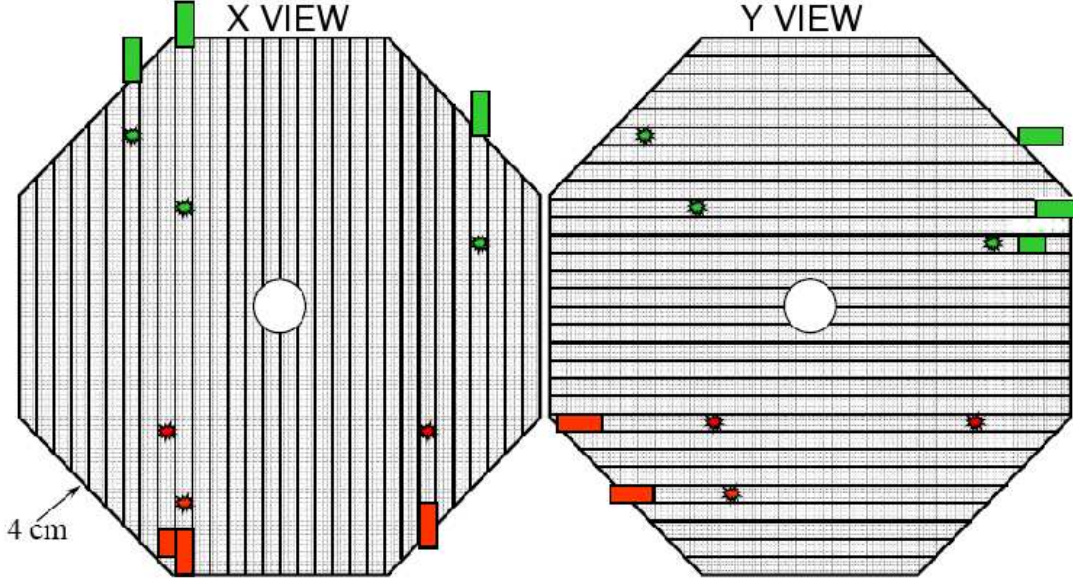


Figure 5.1: Schematic view of *NT-PEAK* projection logic: both event, the green and the red one, have three well separated clusters but for the latter the "neutral" trigger system can reconstruct only two peaks in the y projection.

electromagnetic clusters (Fig. 5.1).

This effect produces an inefficiency which is strictly correlated to the event geometry. In addition, if one of the clusters is not energetic enough to fire the corresponding projection, then an energy dependent inefficiency is produced.

Because of the presence of only two photons, $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay can fire the peaks projection requirement only if the pion produces a shower or not-in-time extra clusters are present.

To study the behaviour of the *NT-PEAK* trigger, $K^\pm \rightarrow \pi^\pm \pi^0$ events selected for the flux measurement from the pure *NT-PEAK* control sample have been used, checking the efficiency dependence with respect to the following quantity:

$$\max(\Delta x_{LKr\ peaks}^{min}, \Delta y_{LKr\ peaks}^{min})$$

where $\Delta x_{LKr\ peaks}^{min}$ ($\Delta y_{LKr\ peaks}^{min}$) is the minimum distance on x (y) projection between two clusters among all the possible combinations in the assumption that the event topology is given by one pion and two photons.

As expected the *NT-PEAK* trigger shows an efficiency drop (Fig. 5.2) for a separation below 10 cm since in that topological configuration the system cannot reconstruct more than two peaks in both x and y projections.

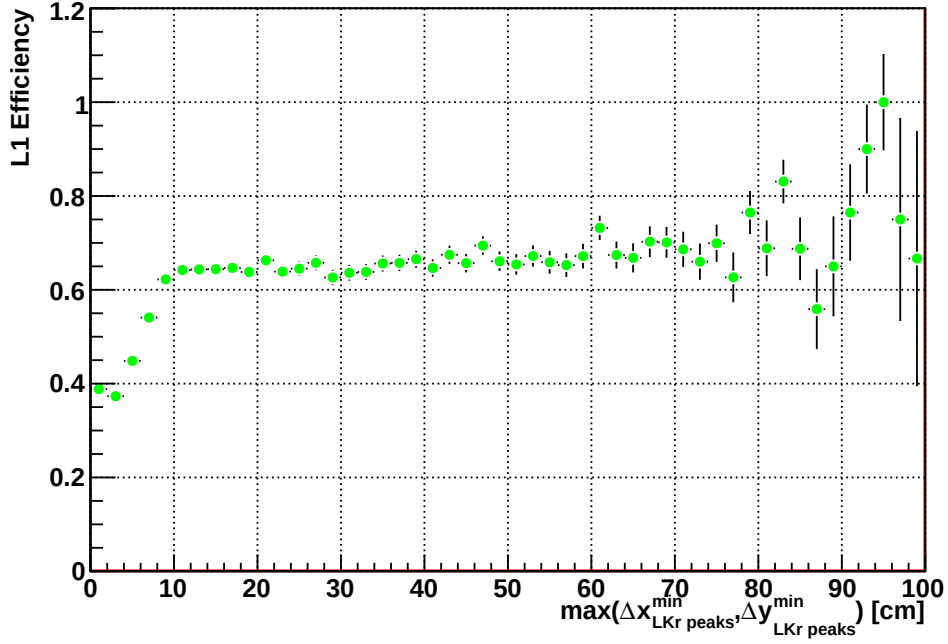


Figure 5.2: *NT-PEAK* efficiency as a function of $\max(\Delta x_{LKr\ peaks}^{min}, \Delta y_{LKr\ peaks}^{min})$.

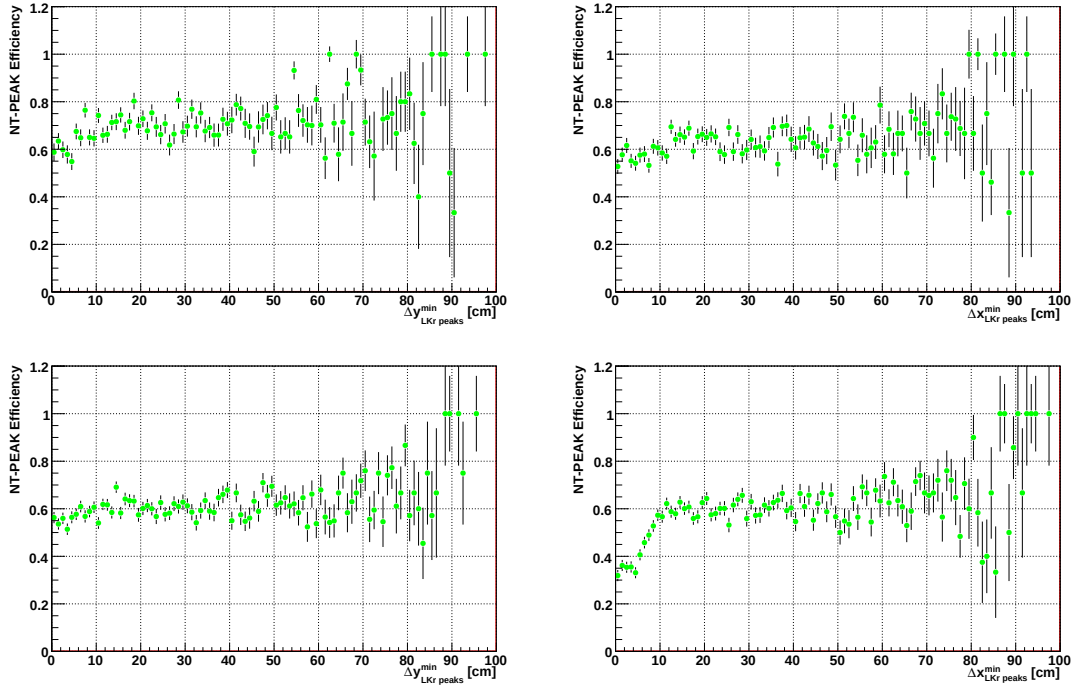


Figure 5.3: *NT-PEAK* efficiency as a function of $\Delta y_{LKr\ peaks}^{min}$ ($\Delta x_{LKr\ peaks}^{min}$) when requiring a $\Delta x_{LKr\ peaks}^{min}$ ($\Delta y_{LKr\ peaks}^{min}$) distance greater than 30 cm. SS0 and 1 (top), SS2 and 3 (bottom).

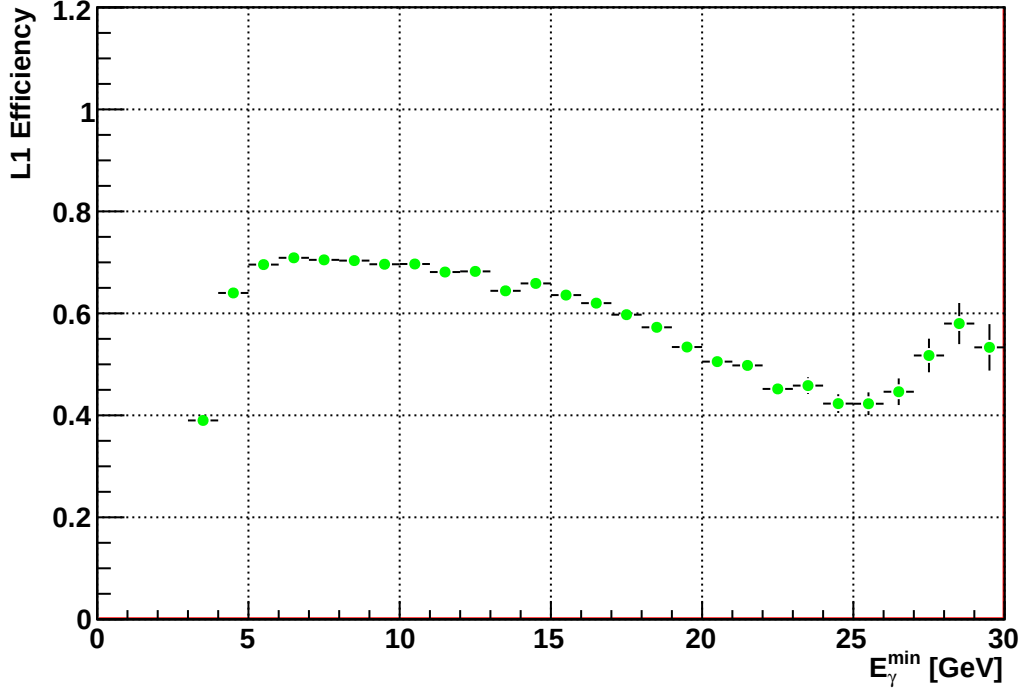


Figure 5.4: *NT-PEAK* efficiency distribution as a function of the minimum γ energy.

Even if the trigger system is expected to be inefficient when both $\Delta x_{LKr\ peaks}^{\min}$ and $\Delta y_{LKr\ peaks}^{\min}$ are smaller than 10 cm, a further check on the two single projection conditions has been performed. Requiring a $\Delta y_{LKr\ peaks}^{\min}$ ($\Delta x_{LKr\ peaks}^{\min}$) distance greater than 30 cm, the efficiency variation has been studied with respect to $\Delta x_{LKr\ peaks}^{\min}$ ($\Delta y_{LKr\ peaks}^{\min}$). While in SS0 and 1 (Fig. 5.3 (top)) both distributions are completely flat, for SS2 and 3 (Fig. 5.3 (bottom)) $\Delta x_{LKr\ peaks}^{\min}$ shows an efficiency decrease below 10 cm, indicating a residual problem in the y projection.

To limit the impact of correction, the requirement on $\max(\Delta x_{LKr\ peaks}^{\min}, \Delta y_{LKr\ peaks}^{\min}) > 10$ cm has been applied to SS0 and 1 only, while for SS2 and 3 a more stringent condition must be fulfilled ($\Delta x_{LKr\ peaks}^{\min} > 10$ cm).

A contribution to the *NT-PEAK* inefficiency is energy dependent and it has been found to increase for low photon energy (Fig. 5.4). A safe cut at $E_{\gamma} > 5$ GeV has been applied.

Because of the strong correlation between Q_2 and *NT-PEAK* due to decays with photon conversions that easily fire the projection requirement, as for the flux measurement, only events of the charged minimum bias triggered by the Q_1 condition have been used as control sample to measure the overall Level 1

efficiency.

Several checks have been performed to study the Level 1 efficiency behaviour but only a high inefficiency for large radial pion position at the first drift chamber (Fig. 5.5) has been observed. A condition requiring a r_{π}^{DCH1} smaller than 100 cm has been implemented.

The Level 1 efficiency has been measured with respect the pion momentum and the minimum photon energy in a 10×10 matrix (Fig: 5.6):

$$\varepsilon_{L1}(p_{\pi}, E_{\gamma}^{min}) = \frac{\mathcal{N}_{Q_1 * (L1 * Mass-Box_{strobe})}(p_{\pi}, E_{\gamma}^{min})}{\mathcal{N}_{Q_1}(p_{\pi}, E_{\gamma}^{min})}$$

being $\mathcal{N}_{Q_1 * (L1 * Mass-Box_{strobe})}$ the number of reconstructed events satisfying the Q_1 and the $L1$ requirement, while $\mathcal{N}_{Q_1}$ is number of events triggered by Q_1 only; the $Mass-Box_{strobe}$ condition ensures that the event has been sent to the second trigger level.

Because the Level 1 efficiency is more sensitive to the pion momentum, this information has been used in place of the $\max(\Delta x_{LKr\ peaks}^{min}, \Delta y_{LKr\ peaks}^{min})$ quantity.

Four different efficiency has been measured (Tab. 5.2) applying the Monte-Carlo based re-weighting technique (Eq. 5.2) to $\varepsilon_{L1}(p_{\pi}, E_{\gamma}^{min})$. The results are quite stable over all SuperSamples.

	SS0	SS1	SS2	SS3
$\mathcal{N}_{Q_1}$	79867	24854	32229	12696
$\varepsilon_{L1} [\%]$	54.7 ± 0.3	55.4 ± 0.5	54.0 ± 0.5	53.6 ± 0.7

Table 5.2: Level 1 trigger efficiencies divided according to SuperSamples. $\mathcal{N}_{Q_1}$ is the total number of reconstructed events in the Q_1 control sample used to perform the measurement.

5.2.2 Level 2

The second trigger level is implemented on a software processor farm (Mass-Box) that performs a fast on line reconstruction of the events with the information sent from the drift chambers.

To reduce the $K^{\pm} \rightarrow \pi^{\pm} \pi^0$ rate, exploiting the two-body decay signature, only events with m_{fake} invariant mass (Eq. 2.1) smaller then $475 \text{ MeV}/c^2$ are recorded. The m_{fake} quantity is directly related to the pion energy in the kaon rest frame ($m_{fake} = 2m_{K^{\pm}} E_{\pi^{\pm}}^{*}$) and thus to the $m_{\gamma\gamma}$ as well.

The *NT-PEAK* trigger has been used as control sample to evaluate the Level 2 trigger efficiency.

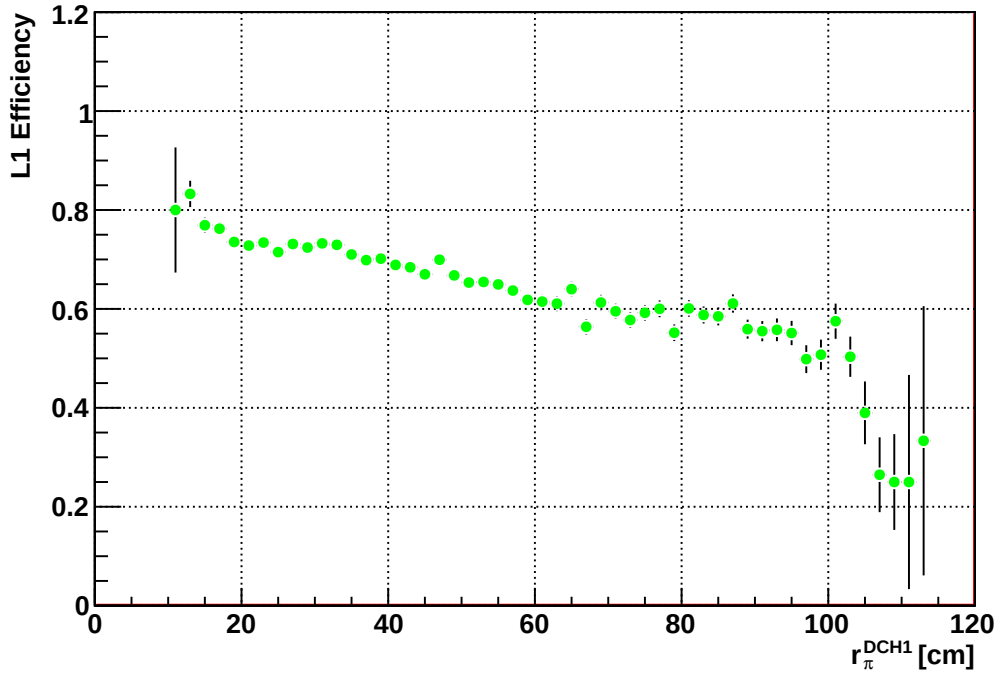


Figure 5.5: Level 1 efficiency distribution as a function of the $\pi^\pm$ radial position at the first drift chamber.

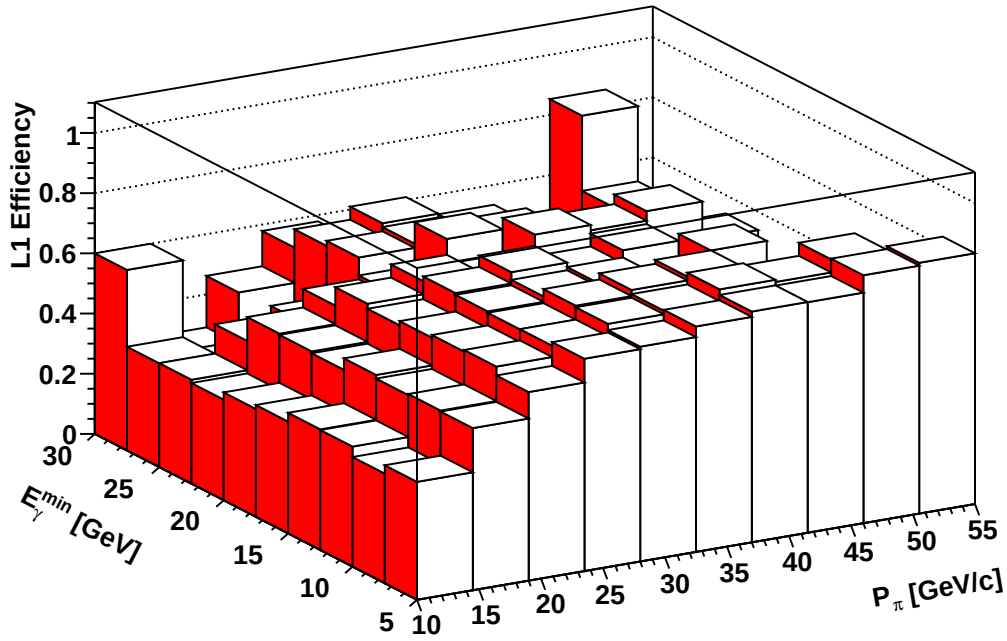


Figure 5.6: Level 1 efficiency distribution as a function of the $\pi^\pm$ momentum and the minimum γ energy.

Since a threshold effect is expected with respect to the m_{fake} variable (Fig. 5.7 (top)), only events with $m_{fake} < 460 \text{ MeV}/c^2$ have been selected. This unfortunately removes all the $m_{\gamma\gamma}$ spectrum below $\sim 0.2 \text{ GeV}/c^2$

A very low Mass-Box efficiency has been observed for small values of the pion track distance from the beam pipe at the first DCH (Fig. 5.7 (bottom)) therefore a cut has been applied requiring for $r_{\pi}^{DCH1} > 15 \text{ cm}$.

The Level 2 efficiency has been measured with respect to the pion momentum and the longitudinal position of the kaon decay vertex (20×20 bins) (Fig: 5.8):

$$\varepsilon_{L2}(p_{\pi}, z_{charged}) = \frac{\mathcal{N}_{NT-PEAK*(L2*L1ON)}(p_{\pi}, z_{charged})}{\mathcal{N}_{NT-PEAK}(p_{\pi}, z_{charged})}$$

where $\mathcal{N}_{NT-PEAK*(L2*L1ON)}(p_{\pi}, z_{charged})$ is the number of reconstructed events satisfying the $NT-PEAK$ and the $L2$ conditions, while $\mathcal{N}_{NT-PEAK}$ the $NT-PEAK$ only; the $L1ON$ condition removes not processed events due to Mass-Box dead time (less than 1‰).

Applying the Monte-Carlo based technique (Eq. 5.2) to $\varepsilon_{L2}(p_{\pi}, z_{charged})$, a quite stable result over the different SuperSamples has been measured (Tab. 5.3).

	SS0	SS1	SS2	SS3
$\mathcal{N}_{NT-PEAK}$	607529	176306	216445	86027
$\varepsilon_{L2} [\%]$	79.99 ± 0.08	81.0 ± 0.2	80.3 ± 0.1	79.9 ± 0.2

Table 5.3: Level 2 trigger efficiencies divided according to SuperSamples. $\mathcal{N}_{NT-PEAK}$ is the total number of reconstructed events in the $NT-PEAK$ control sample used to perform the measurement.

The resulting total trigger efficiency ($\varepsilon_{L1} \cdot \varepsilon_{L2}$) for $K^{\pm} \rightarrow \pi^{\pm} \gamma\gamma$ events is quite low, at the level of $43 \div 45\%$, mainly because of the not optimal $NT-PEAK$ condition for events with only two photons.

5.3 Residual Background

Given the number of kaon decays in the experimental fiducial volume defined between -16 m and 70 m , the number of expected background events can be estimated according to:

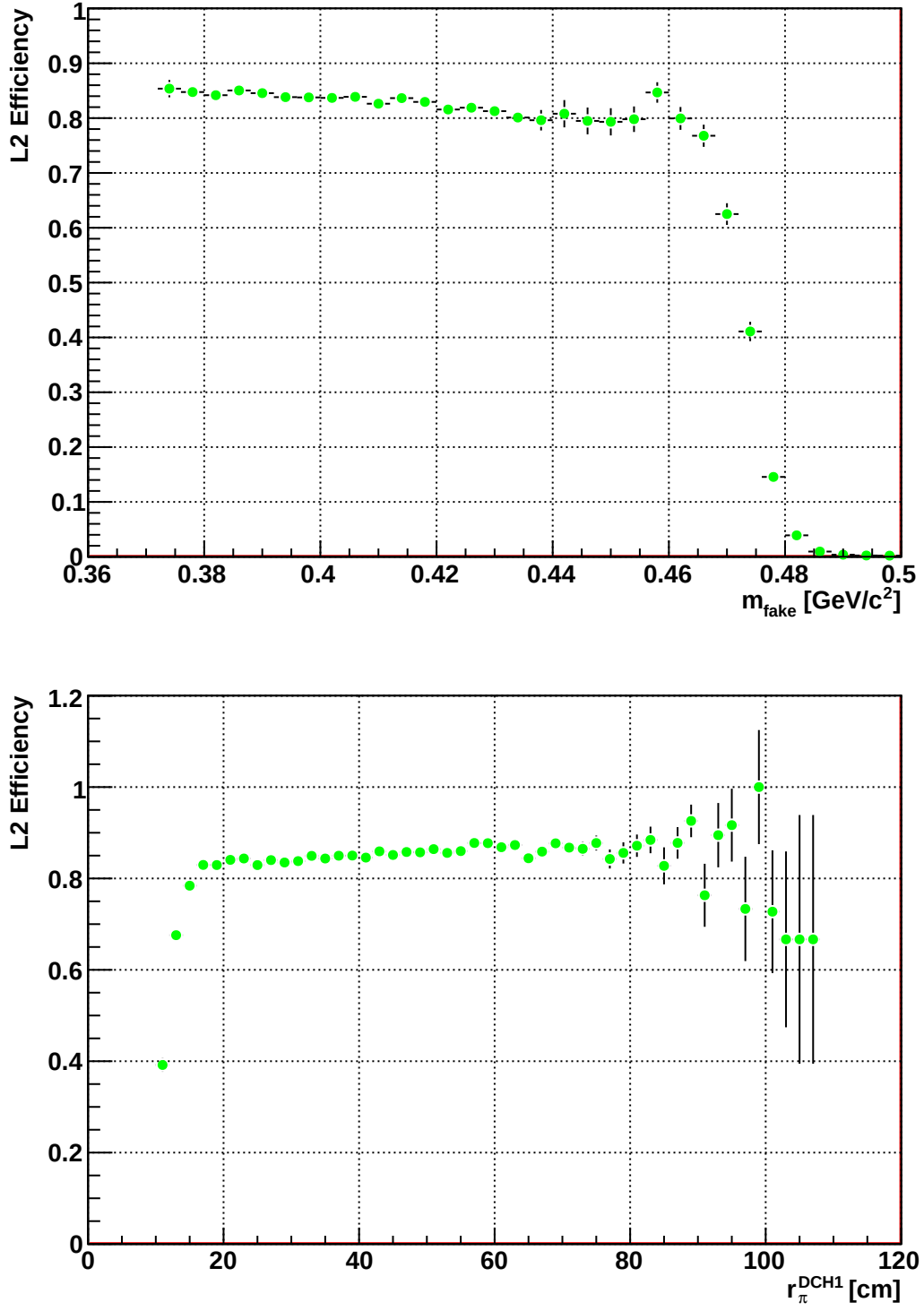


Figure 5.7: Level 2 efficiency distribution as a function of the m_{fake} invariant mass (top) and the $\pi^{\pm}$ radial position at the first drift chamber (bottom).

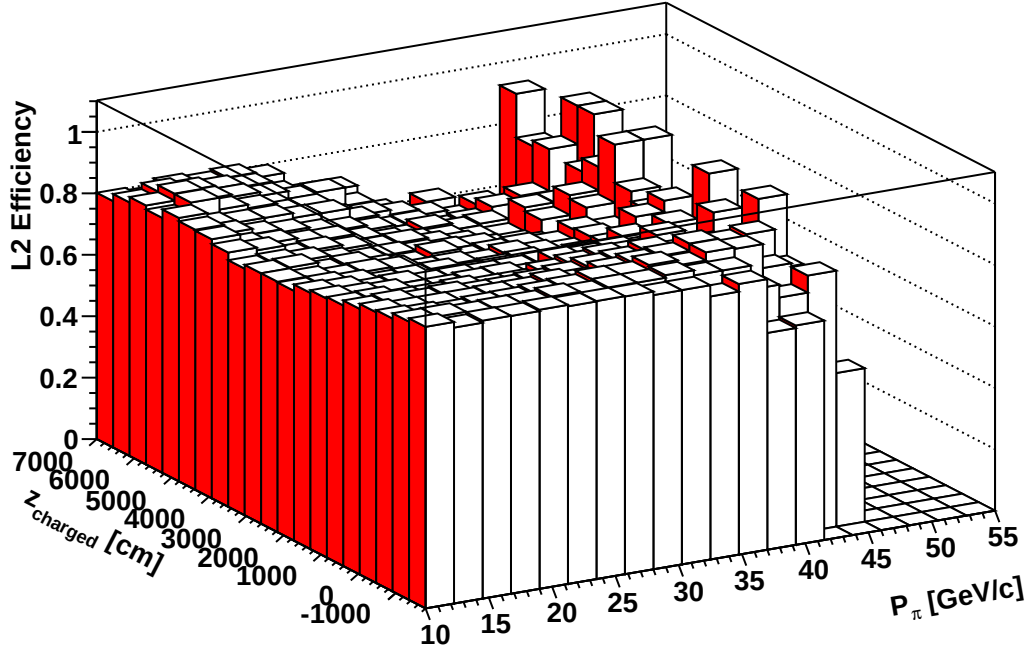


Figure 5.8: Level 2 efficiency distribution as a function of the $\pi^\pm$ momentum and the reconstructed "charged" kaon decay vertex.

$$\mathcal{N}_{bg} = \Phi(K^\pm) \cdot \sum_{bg_i} BR(bg_i) \cdot \mathcal{A}_{bg_i} \cdot \varepsilon_{L1, bg_i} \cdot \varepsilon_{L2, bg_i}$$

being $\Phi(K^\pm)$ the kaon flux extracted with $K^\pm \rightarrow \pi^\pm \pi^0$, $BR(bg_i)$ the single decay channel branching ratio³ [12], $\mathcal{A}_{bg_i}$ the corresponding acceptance (Tab. 4.6) and ε_{L1, bg_i} (ε_{L2, bg_i}) the Level 1 (Level 2) trigger efficiency measured applying the Monte-Carlo based re-weighting technique (Eq. 5.2), where $\mathcal{N}_{\pi^\pm \gamma \gamma}^{MC}(x, y)$ has been replaced by the corresponding number of Monte-Carlo reconstructed background events $\mathcal{N}_{bg_i}^{MC}(x, y)$.

Since $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^0 e \nu$ ($\pi^0 \mu \nu$) semi-leptonic decays have been found to be negligible, only $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ (inner bremsstrahlung, direct emission and interference components) and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ modes have been considered (Tab. 5.4).

³In case of $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay, the NA48/2 2003 preliminary results on the direct emission and interference component fractions [19] have been used.

Decay Mode	SS0	SS1	SS2	SS3
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$	40 ± 3	11.9 ± 0.8	17.7 ± 2.3	5.7 ± 1.4
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$	1.8 ± 1.3	0.6 ± 0.4	1.0 ± 0.7	0.36 ± 0.25
Total	42 ± 4	12.5 ± 1.9	18.7 ± 2.4	6.0 ± 1.4

Table 5.4: Expected background events divided according to the SuperSamples. The $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ components (inner bremsstrahlung, direct emission and interference) have been separately studied and then recombined, taking into account the corresponding branching ratios.

5.4 Data/Monte-Carlo Comparison

The CMC simulation has been already validated by several data/Monte-Carlo checks performed with an almost pure $K^\pm \rightarrow \pi^\pm \pi^0$ sample (residual background at few % level) selected from the Q_1 minimum bias trigger (Sec. 3.3).

Even with a sample characterized by low statistic (2300 candidate events), a crosscheck of the reconstructed $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decays with a pure Monte-Carlo sample is crucial to discover possible systematic effects.

To properly compare data and Monte-Carlo, a global trigger efficiency ($\varepsilon_{L1} \cdot \varepsilon_{L2}$) correction has been applied to data. The following technique has been adopted: starting from the two dimensional efficiency measurement obtained from the sample of one pion and two photons events (mainly $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$), the Monte-Carlo based re-weighting technique (Eq. 5.2) has been applied in bin of the quantity under investigation.

All the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ data/Monte-Carlo distributions show a good agreement (Fig. 5.9, 5.10).

A gaussian fit to the reconstructed kaon invariant mass gives:

$$m_K = (493.7 \pm 4.3) \text{ MeV}/c^2$$

with a $\chi^2/ndf = 25.2/21$, in perfect agreement with the nominal kaon mass [12].

5.5 $K^\pm \rightarrow \pi^\pm \gamma \gamma$ Branching Ratio

A first branching ratio measurement has been performed in each 2003 Super-Sample according to Eq. 5.1, by integrating over all the di-photon reconstructed spectrum (Tab. 5.5).

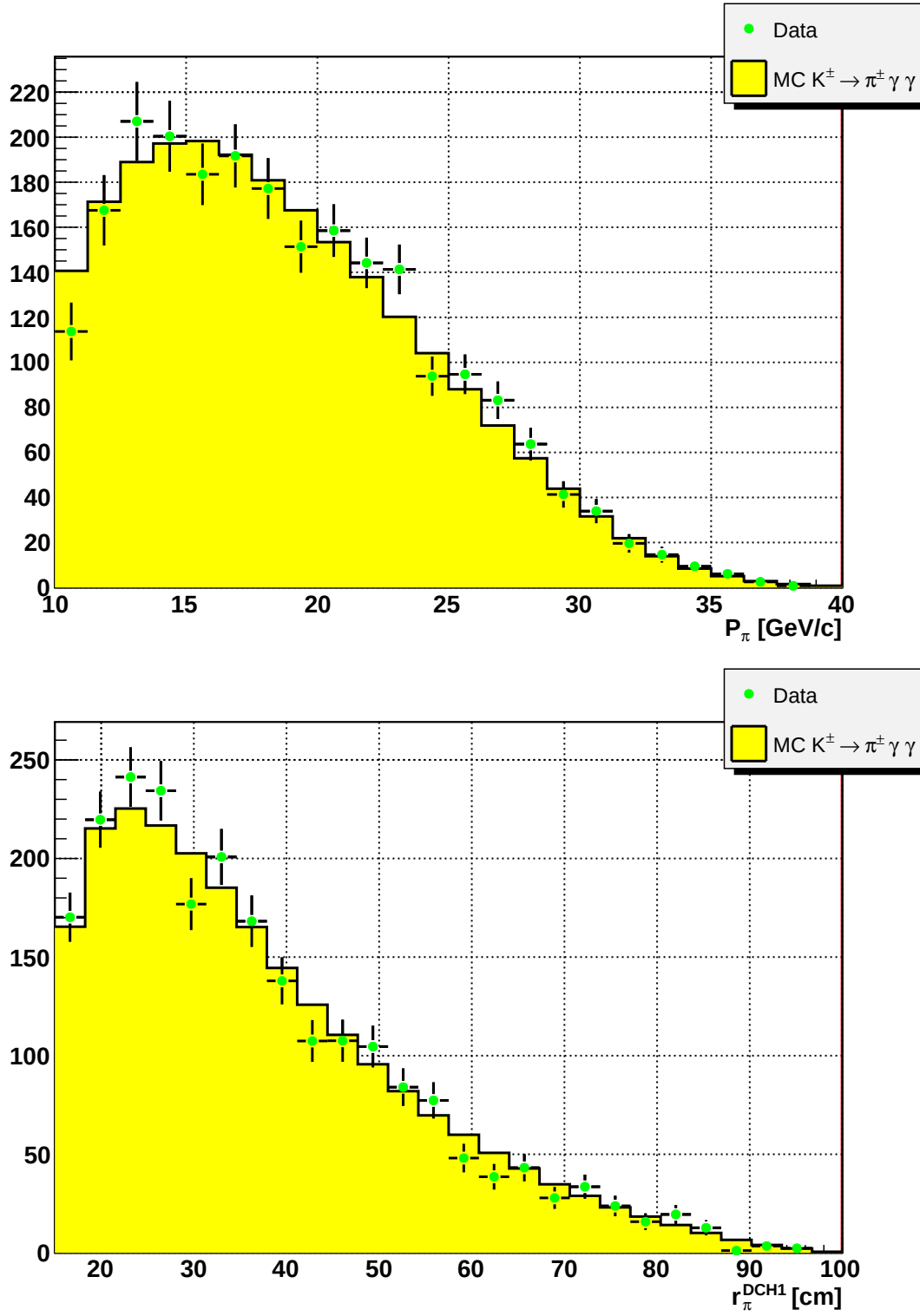


Figure 5.9: Data/Monte-Carlo comparison of the reconstructed $\pi^\pm$ momentum (top) and radial distance from the beam pipe at the first drift chamber (bottom).

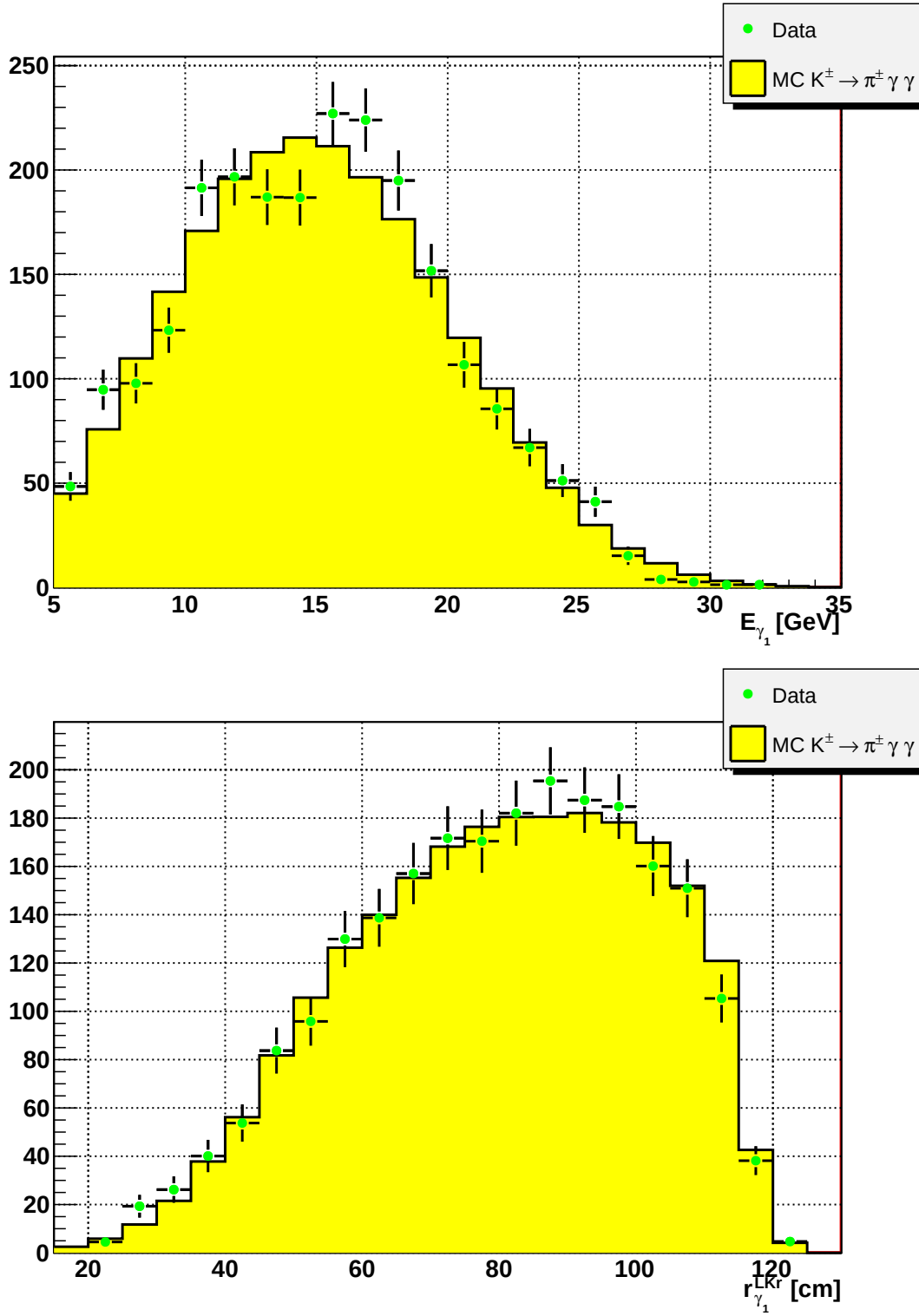


Figure 5.10: Data/Monte-Carlo comparison of the reconstructed γ energy (top) and radial distance from the beam pipe at the electromagnetic calorimeter (bottom).

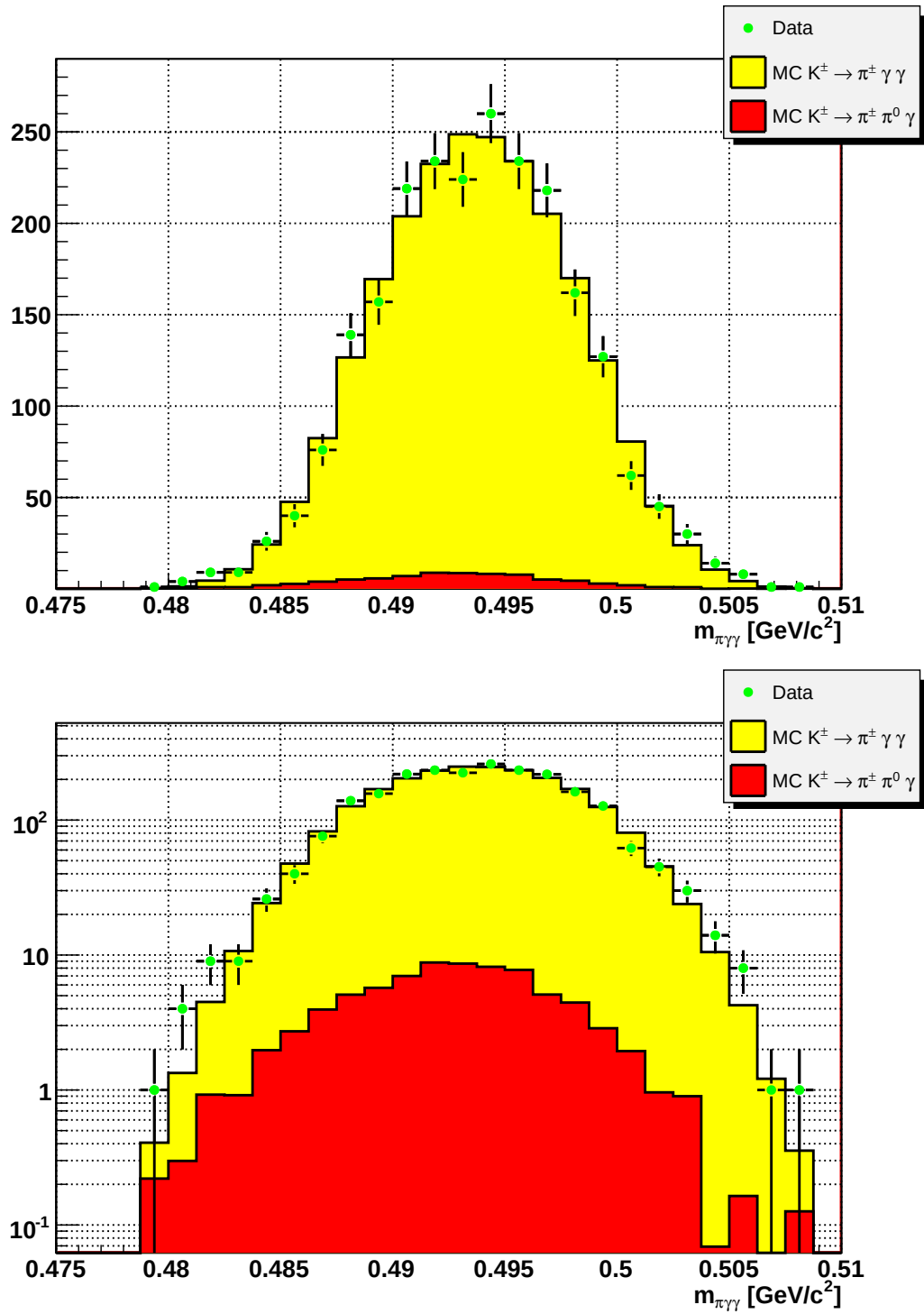


Figure 5.11: Data/Monte-Carlo comparison of the reconstructed kaon invariant mass in linear (top) and logarithmic (bottom) scale. The $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \gamma$ contribution (inner bremsstrahlung, direct emission and interference components) has been added to better understand where the residual background events are located.

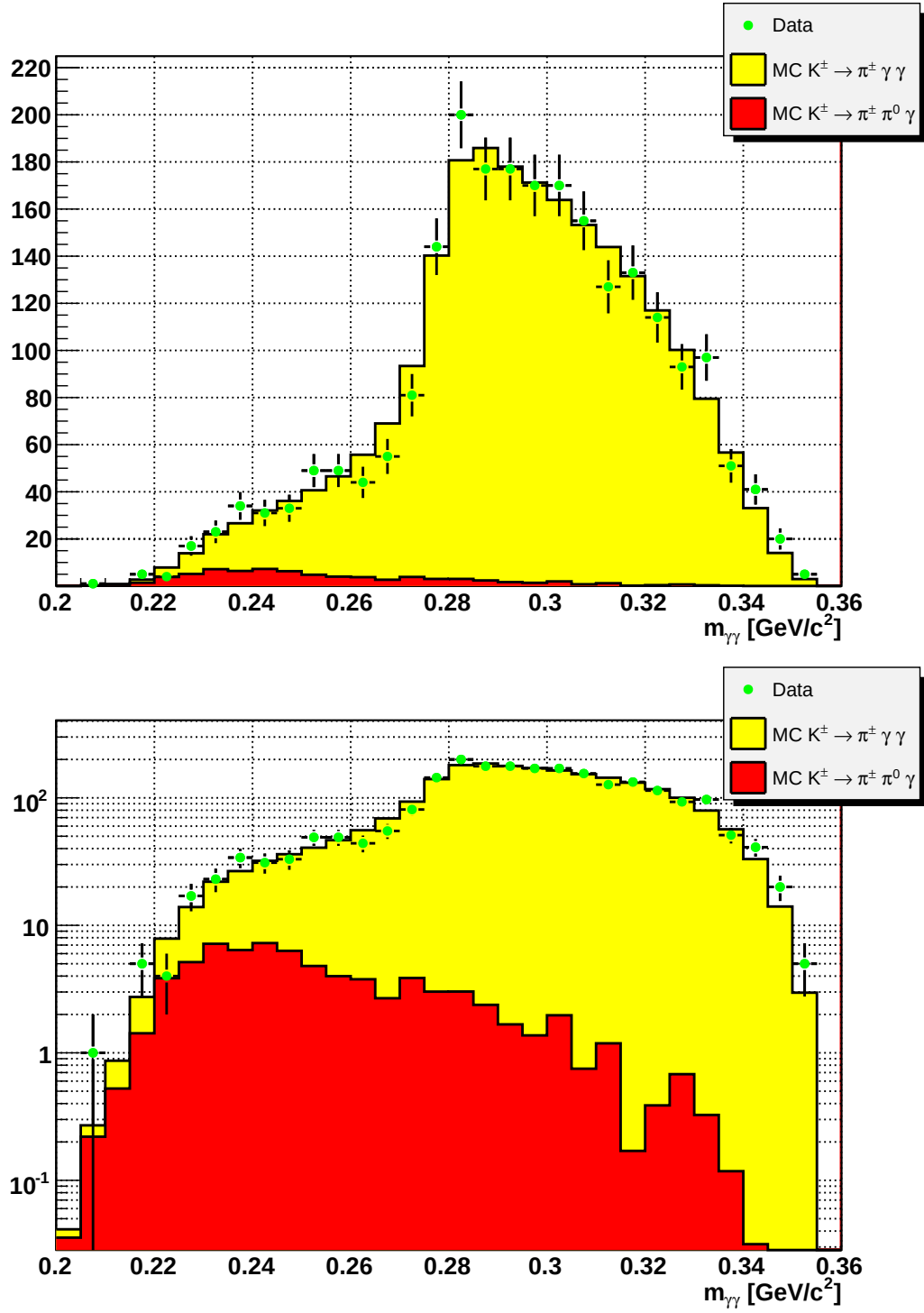


Figure 5.12: Data/Monte-Carlo comparison of the reconstructed di-photon invariant mass in linear (top) and logarithmic (bottom) scale. The $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ contribution (inner bremsstrahlung, direct emission and interference components) has been added to better understand where the residual background events are located.

Chapter 5. Results

	SS0	SS1	SS2	SS3
$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) [10^{-6}]$	1.11 ± 0.04	1.14 ± 0.06	0.98 ± 0.05	1.02 ± 0.08

Table 5.5: Branching ratio measurements divided according to SuperSamples. The uncertainty takes into account the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ statistics, the acceptance correction, the background estimation, the trigger efficiency and the flux error.

The combined result is:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = (1.071 \pm 0.024) \times 10^{-6}$$

where the uncertainty takes into account the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ statistics, the errors on the acceptance correction, background estimation, trigger efficiency and flux measurements.

Since the shape of the di-photon invariant mass distribution, and thus the signal acceptance correction, strongly depends on the $\hat{c}$ constant of the Chiral Perturbation Theory, the obtained result is model dependent.

The integrated equation 5.1 can be rewritten in a more general form as the sum over $m_{\gamma\gamma}$ bins of the partial $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio dependent on the di-photon invariant mass:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = \sum_{i=1}^{\mathcal{N}_{m_{\gamma\gamma}}} \Delta BR_i(K^\pm \rightarrow \pi^\pm \gamma \gamma) \quad (5.3)$$

where $\mathcal{N}_{m_{\gamma\gamma}}$ is the number of $m_{\gamma\gamma}$ bins and

$$\Delta BR_i(K^\pm \rightarrow \pi^\pm \gamma \gamma) = \frac{\mathcal{N}_{\pi^\pm \gamma \gamma}^i - \mathcal{N}_{bg}^i}{\Phi(K^\pm) \cdot \mathcal{A}_{\pi^\pm \gamma \gamma}^i \cdot \epsilon_{L1}^i \cdot \epsilon_{L2}^i}$$

being $\Phi(K^\pm)$ the total kaon flux and $\mathcal{N}_{\pi^\pm \gamma \gamma}^i, \mathcal{N}_{bg}^i, \mathcal{A}_{\pi^\pm \gamma \gamma}^i, \epsilon_{L1}^i, \epsilon_{L2}^i$ the same quantities as defined for Eq. 5.1 but measured in the i^{th} $m_{\gamma\gamma}$ bin.

In this case the acceptance dependence on $\hat{c}$ in each $m_{\gamma\gamma}$ bin is expected to vanish and a model independent branching ratio can be measured.

To prove this assumption, the acceptance variation with respect to $m_{\gamma\gamma}$ has been analyzed for several $\hat{c}$ values. Quite big differences have been observed below $0.220 \text{ GeV}/c^2$ (Fig. 5.13), while a $\sim 5\%$ maximum difference has been found in the range $0.225 \div 0.360 \text{ GeV}/c^2$ therefore a $m_{\gamma\gamma} > 0.225 \text{ GeV}/c^2$ cut has been applied.

As a further check, both Level 1 and Level 2 efficiency have been studied in

5.5. $K^\pm \rightarrow \pi^\pm \gamma \gamma$ Branching Ratio

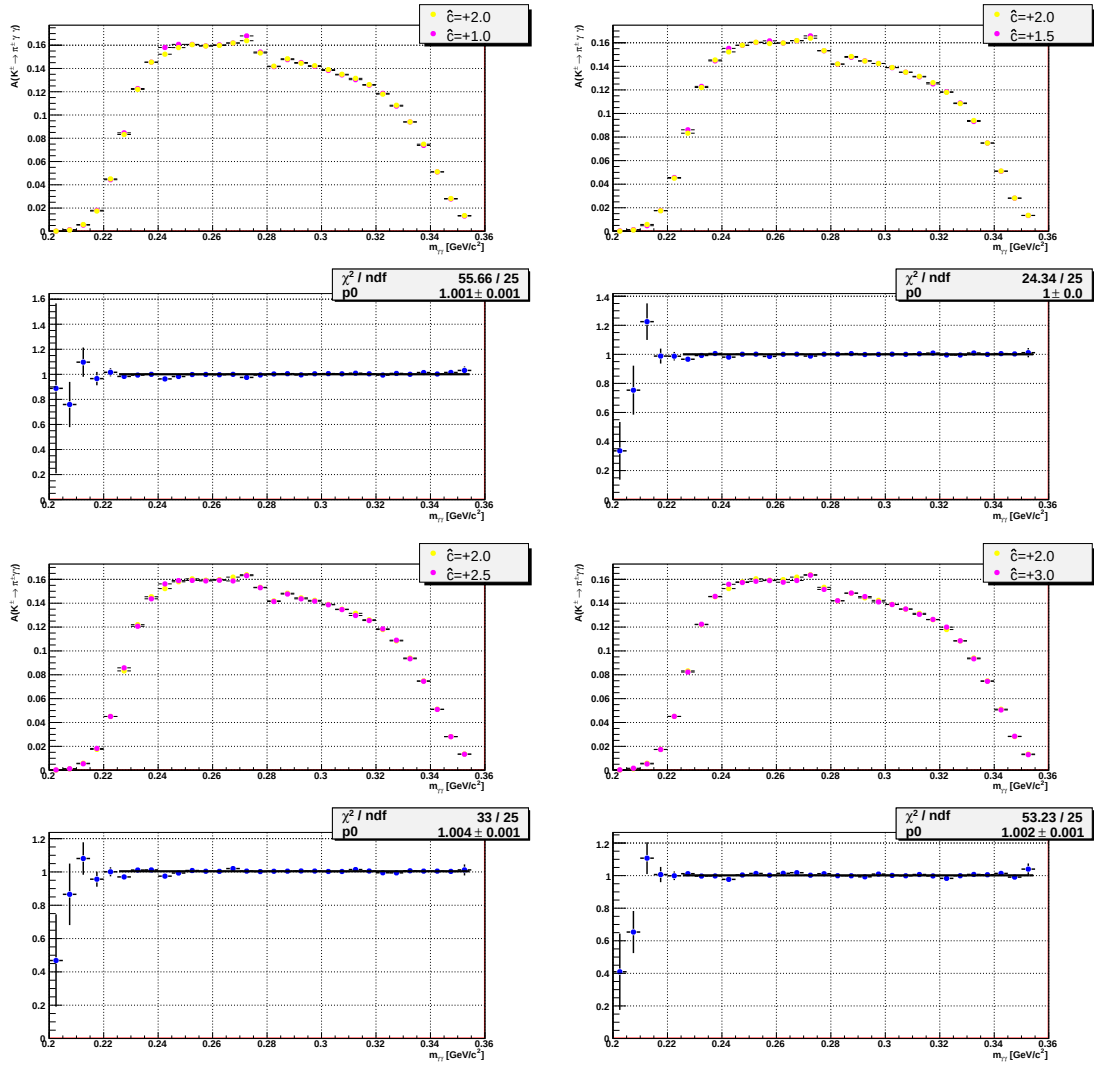


Figure 5.13: $K^\pm \rightarrow \pi^\pm \gamma \gamma$ acceptance distribution as a function of the reconstructed di-photon invariant mass for different $\hat{c}$ values.

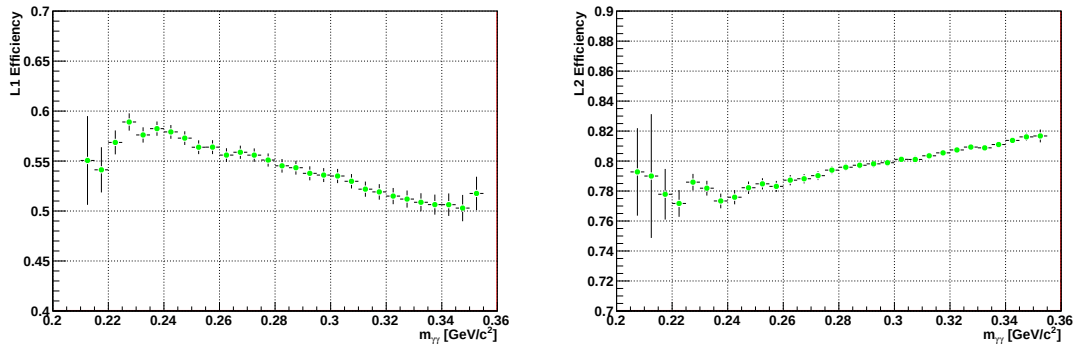


Figure 5.14: Level 1 (left) and Level 2 (right) efficiency distribution as a function of the reconstructed di-photon invariant mass.

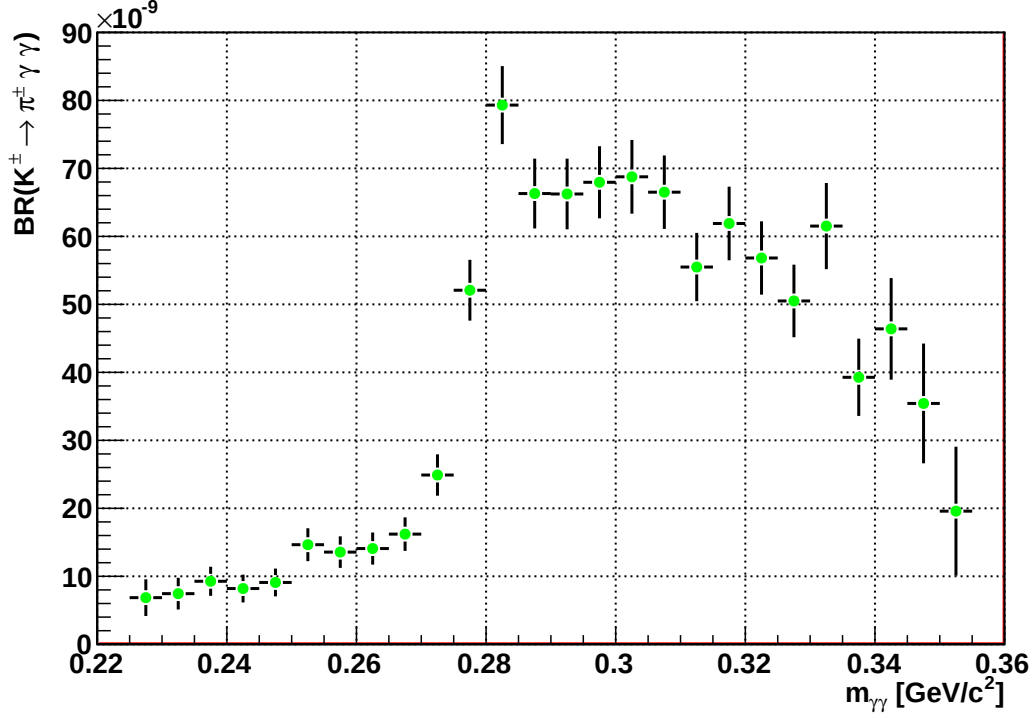


Figure 5.15: Partial $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio distribution as a function of the reconstructed di-photon invariant mass.

bin of $m_{\gamma\gamma}$ (Fig. 5.14). A few percent maximum variation and a quite stable behaviour have been observed.

The $K^\pm \rightarrow \pi^\pm \gamma\gamma$ partial branching ratios $\Delta BR_i(K^\pm \rightarrow \pi^\pm \gamma\gamma)$ are reported in Tab. 5.6 (Fig. 5.15).

Assuming uncorrelated bin to bin errors, the total $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio in the region $225 \text{ MeV}/c^2 < m_{\gamma\gamma} < m_{K^\pm} - m_{\pi^\pm}$ is:

$$BR(K^\pm \rightarrow \pi^\pm \gamma\gamma, m_{\gamma\gamma} > 225 \text{ MeV}/c^2) = (1.018 \pm 0.026) \times 10^{-6}$$

5.6 Systematic Checks

Several systematic checks have been performed to test the stability of the result. This has been done by changing the most relevant cut values or investigating some peculiar aspects of the analysis. In each case all the measurement procedure (event reconstruction, background rejection, flux and trigger efficiencies measurements, residual background subtraction) has been redone.

The error introduced with a given check has been estimated assuming un-

$\Delta m_{\gamma\gamma} [\text{MeV}/c^2]$	$\Delta BR_i [10^{-9}]$	$\Delta m_{\gamma\gamma} [\text{MeV}/c^2]$	$\Delta BR_i [10^{-9}]$
225 ÷ 230	6.9 ± 2.7	290 ÷ 295	66 ± 5
230 ÷ 235	7.5 ± 2.3	295 ÷ 300	68 ± 5
235 ÷ 240	9.3 ± 2.1	300 ÷ 305	69 ± 5
240 ÷ 245	8.2 ± 2.0	305 ÷ 310	67 ± 5
245 ÷ 250	9.1 ± 2.0	310 ÷ 315	56 ± 5
250 ÷ 255	14.7 ± 2.4	315 ÷ 320	62 ± 5
255 ÷ 260	13.6 ± 2.3	320 ÷ 325	57 ± 5
260 ÷ 265	14.1 ± 2.4	325 ÷ 330	51 ± 5
265 ÷ 270	16.2 ± 2.5	330 ÷ 335	62 ± 6
270 ÷ 275	25 ± 3	335 ÷ 340	39 ± 6
275 ÷ 280	52 ± 5	340 ÷ 345	46 ± 8
280 ÷ 285	79 ± 6	345 ÷ 350	35 ± 9
285 ÷ 290	66 ± 5	350 ÷ 355	20 ± 10

Table 5.6: Partial $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratios dependent on the reconstructed di-photon invariant mass. The uncertainty takes into account the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ statistics, the acceptance correction, the background estimation, the trigger efficiency and the flux error.

correlated uncertainties. In this condition the sample is modified by adding or subtracting events when changing a given cut. The uncorrelated error of the branching ratio value obtained for the i^{th} cut variation has been evaluate with respect to the reference one as:

$$\sigma_{i,unrelated}^2 = |\sigma_{reference}^2 - \sigma_i^2|$$

where both $\sigma_{reference}$ and σ_i take into account the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ statistics and the uncertainties on the acceptance correction, background estimation, trigger efficiency and flux measurements.

Almost all the main requirements involved in the event reconstruction (pion and photons identification, trigger related cuts) have been checked (Fig. 5.16, 5.17).

Pion Momentum: the lower cut on the pion momentum implemented to ensure a high muon veto system efficiency has been varied from $5 \text{ GeV}/c$ to $15 \text{ GeV}/c$ (nominal condition: $p_{DCH}^\pi > 10 \text{ GeV}/c$); the results are compatible within uncorrelated errors;

Pion Position at DCH1: the requirements on the pion radial position at the first DCH ($15 \text{ cm} < r_\pi^{DCH1} < 100 \text{ cm}$) needed to avoid trigger efficiency drops, have been varied by $\pm 5 \text{ cm}$; despite a high trigger inefficiencies below 15 cm

and above 100 *cm*, the measurements are still in agreement within uncorrelated errors;

Pion Identification: the condition on the ratio between the energy deposition in the electromagnetic calorimeter and the momentum measured with the magnetic spectrometer (E_{LKr}/p_{DCH}) has been varied from 0.7 up to 0.9 (nominal cut at 0.8) to test the effect of the fraction of events with an electron in place of the charged pion, as $K^\pm \rightarrow \pi^0 e \nu$ decays, on the trigger efficiency;

Minimum Photon Energy: the *NT-PEAK* "neutral" trigger shows a dependence on the minimum photon energy; the nominal cut at 5 *GeV* has been varied from 3 *GeV* up to 7 *GeV*; the results are compatible within uncorrelated errors;

Photon Clusters Separation: the requirement on the relative distance between the two photon showers has been varied from 30 *cm* up to 50 *cm* (nominal cut value at 40 *cm*);

Pion-Photon Clusters Separation: photon clusters have been defined to lie outside a radius of 30 *cm* from the pion impact point at the *LKr* front face in order to minimize a possible contamination from the pion shower and because the hadron shower development cannot be well modeled in the Monte-Carlo simulation; a cut variation of ± 20 *cm* has been performed;

***LKr* Cluster Peak Distance:** the condition on the minimum cluster distance in *x* or *y* projection among any *LKr* cluster pairs in the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ assumption has been changed by ± 5 *cm* from the reference value (10 *cm*);

"Charged" Kaon Decay Vertex: the fiducial decay volume has been defined in a longitudinal range (-16 *m* $\div$ 70 *m*); the lower bound minimizes effects from the presence of the final collimator, while the upper one rejects events decaying too close to the main detector to be properly reconstructed; a variation from the nominal values of ± 500 *cm* has been checked; the results are compatible within uncorrelated errors.

A number of cuts have been checked using the described procedure and for most of them no significant variation of the result has been observed:

Energy Center of Gravity: the COG cut has been moved from the nominal value of 2 *cm* up to 3 *cm*, 4 *cm* and 8 *cm* to check the effect of possible residual contamination in the sample;

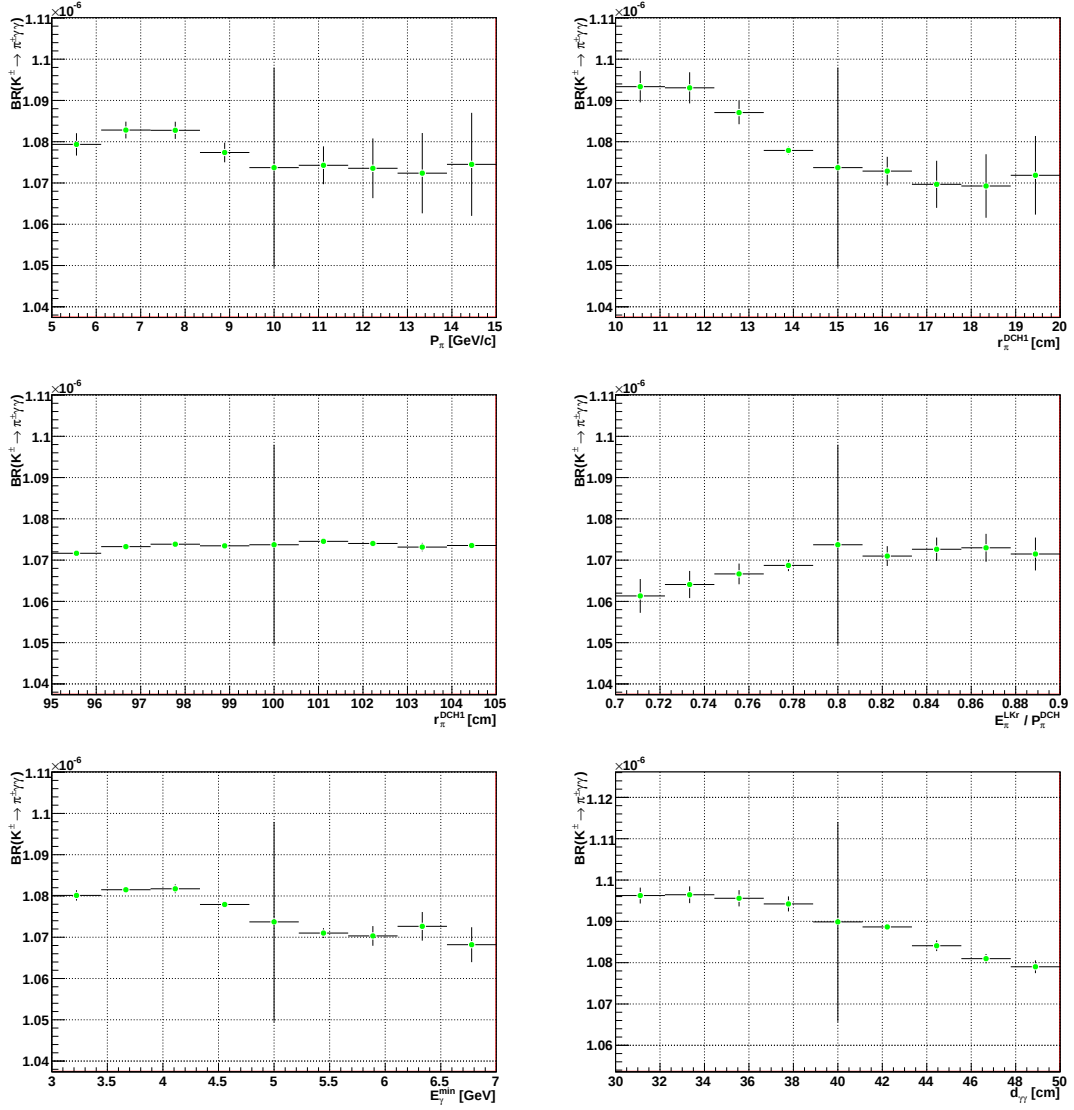


Figure 5.16: Systematic checks.

Closest Distance of Approach: a $CDA < 2\text{ cm}$ ensures a good kaon decay vertex reconstruction; the nominal requirement has been moved to 3 cm , 4 cm and 8 cm ;

“Neutral” Kaon Decay Vertex: the cut on the distance between the “charged” and the “neutral” reconstructed vertices, employed to further suppress $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ background events, has been varied from the standard value (200 cm) up to 300 cm , 400 cm and 800 cm ;

Time Requirements: the cuts on the deviation between the two photon clusters and between the pion and the LKr time have been removed.

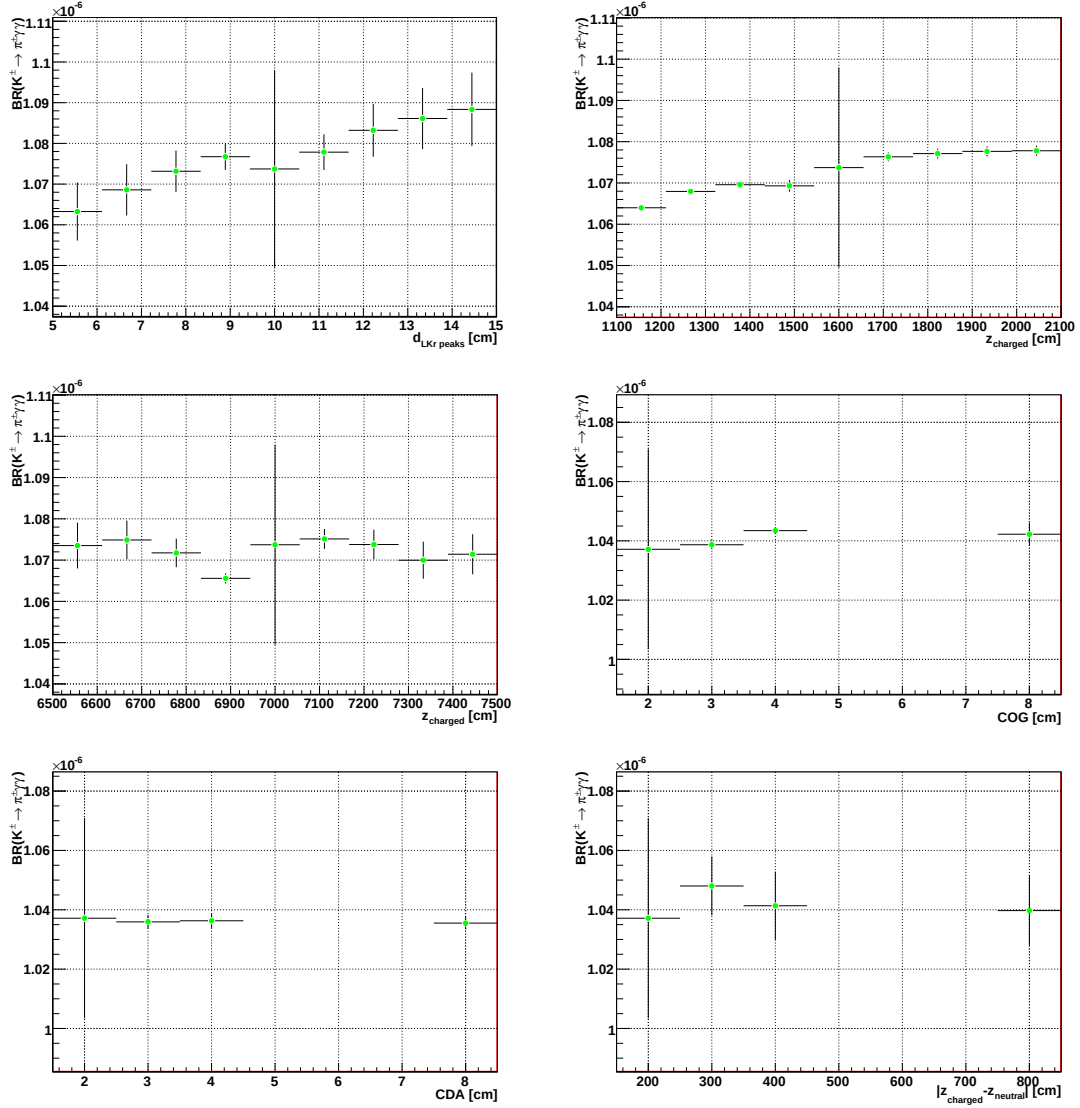


Figure 5.17: Systematic checks.

In addition, other types of effects have been studied:

$K^\pm \rightarrow \pi^\pm \gamma\gamma$ Acceptance

Several $K^\pm \rightarrow \pi^\pm \gamma\gamma$ Monte-Carlo samples, corresponding to different $\hat{c}$ values and with or without the $\mathcal{O}(p^6)$ amplitudes, have been produced in order to evaluate the acceptance variations (Tab. 5.7).

Even if big differences have been observed in the low $m_{\gamma\gamma}$ spectrum only (Fig. 5.13), a 1% systematic error has been added.

$\hat{c}$	$\mathcal{O}(p^6)$	$\mathcal{A}_{\pi^\pm\gamma\gamma}$ [%]	$\Delta\mathcal{A}_{\pi^\pm\gamma\gamma}$ [%]	$\mathcal{O}(p^6)$	$\mathcal{A}_{\pi^\pm\gamma\gamma}$ [%]	$\Delta\mathcal{A}_{\pi^\pm\gamma\gamma}$ [%]
+1.0	✓	12.165	1.0	X	12.315	0.2
+1.5	✓	12.191	0.8	X	12.367	0.6
+2.0	✓	12.288 ± 0.008	-	X	12.409	1.0
+2.5	✓	12.301	0.1	X	12.399	0.9
+3.0	✓	12.307	0.7	X	12.374	0.7

Table 5.7: $K^\pm \rightarrow \pi^\pm\gamma\gamma$ acceptance for different $\hat{c}$ values and with (✓) or without (X) the $\mathcal{O}(p^6)$ unitarity correction. The $\Delta\mathcal{A}_{\pi^\pm\gamma\gamma}$ variation has been evaluated with respect to the $\hat{c} = +2.0$ with $\mathcal{O}(p^6)$ result.

Accidental LKr Clusters

Accidental photons in the LKr acceptance, mainly coming from decay produced by a very close in time proton, can reduce the amount of observed $K^\pm \rightarrow \pi^\pm\gamma\gamma$ events; an accidental rate at the level of $\sim 2.3\%$ has been estimated from data (Sec. 4.2.5).

Kaon Flux

A discrepancy between the flux measurement obtained selecting $K^\pm \rightarrow \pi^\pm\pi^0$ events from the Q_1 minimum bias or from the $NT-PEAK$ control sample has been observed (Tab. 5.1), corresponding to a 1% averaged mean systematic uncertainty.

LKr Energy Scale

An accurate definition of the absolute energy scale of the electromagnetic calorimeter is a crucial issue for the correct reconstruction of photon clusters; special runs ($\eta \rightarrow 2\gamma$, $\eta \rightarrow 3\pi^0$) had been used to measure the overall scale factor which is known to a precision of $\sim 0.1\%$.

To evaluate the effect of such uncertainty, the reconstructed clusters energy have been changed by a fixed amount ($\pm 0.1\%$); the result has been tested on $K^\pm \rightarrow \pi^\pm\pi^0$ events selected for the kaon flux measurement (Sec. 5.1) by checking the variation of the reconstructed π^0 and $K^\pm$ invariant masses (Tab. 5.8).

With nominal calibration parameters the difference between data and Monte-Carlo is $\Delta m_{\pi^0} = 64 \text{ keV}/c^2$ and $\Delta m_{K^\pm} = 116 \text{ keV}/c^2$, while increasing by 0.1% the cluster energy, the it reduces to $\Delta m_{\pi^0} = 34 \text{ keV}/c^2$ and $\Delta m_{K^\pm} = 42 \text{ keV}/c^2$.

Performing a linear interpolation of the π^0 reconstructed invariant masses, the needed correction can be extrapolated: the cluster energy must be decreased

Sample	$\Delta E/E$ [%]	m_{π^0} [MeV/c ²]	$\sigma_{m_{\pi^0}}$ [MeV/c ²]	$m_{K^\pm}$ [MeV/c ²]	$\sigma_{m_{K^\pm}}$ [MeV/c ²]
CMC	-	135.006 ± 0.005	1.562 ± 0.004	493.635 ± 0.012	4.218 ± 0.009
	+0.1	135.106 ± 0.005	1.543 ± 0.004	493.809 ± 0.012	4.151 ± 0.008
	-0.1	134.891 ± 0.005	1.539 ± 0.004	493.499 ± 0.012	4.133 ± 0.008
Data	-	134.942 ± 0.005	1.535 ± 0.004	493.519 ± 0.012	4.186 ± 0.009
	+0.1	135.040 ± 0.005	1.527 ± 0.004	493.677 ± 0.012	4.177 ± 0.009
	-0.1	134.823 ± 0.005	1.520 ± 0.004	493.360 ± 0.012	4.160 ± 0.009

Table 5.8: π^0 and $K^\pm$ reconstructed invariant masses variation after a change of the clusters energy.

by 0.02% in case of Monte-Carlo, while increased by 0.04% in data.

After applying the obtained corrections a difference in the $K^\pm$ invariant mass has still been observed. Because the track momentum scale has been already fixed by the *DCH* Alpha and Beta corrections, the discrepancy has been explained by a worse resolution in the kaon decay vertex determination for one track event with respect to $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$.

The induced variation on the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ branching ratio measurement by a 0.1% increase of the cluster energy is 6×10^{-9} and has been added as systematic error.

Trigger Efficiency

To avoid the low signal statistics a re-weighting technique based on the CMC simulation has been applied to measure the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ trigger efficiencies.

The reliability of the method has been checked on $K^\pm \rightarrow \pi^\pm \pi^0$ decays: the *NT-PEAK* trigger efficiency measured to extract the kaon flux, direct measurement based on data events, has been compared with the Monte-Carlo approach. A very small difference between the two approaches has been observed (Tab. 5.9), validating the re-weighting technique.

A 0.4% averaged mean error has been added for each trigger level, leading to

	SS0	SS1	SS2	SS3
ε_{data} [%]	60.79 ± 0.19	60.9 ± 0.3	59.71 ± 0.29	59.4 ± 0.5
$\varepsilon_{re-weighting}$ [%]	60.96 ± 0.19	61.1 ± 0.3	59.47 ± 0.29	59.1 ± 0.5
$\Delta\varepsilon$ [%]	~ 0.3	~ 0.3	~ 0.4	~ 0.5

Table 5.9: Comparison between *NT-PEAK* trigger efficiency measurement performed on data and the Monte-Carlo based re-weighting technique result.

Check	$\Delta BR [10^{-6}]$	$\Delta BR / BR [\%]$
p_{DCH}^π	0.005	0.5
r_{DCH1}^π	0.012	1.1
$E_{LKr}^\pi / p_{DCH}^\pi$	0.006	0.6
E_{LKr}^γ	0.007	0.6
$\gamma\gamma$ Distance	0.008	0.7
$\gamma\pi$ Distance	0.015	1.4
PeakDistance	0.013	1.2
$z_{charged}$	0.008	0.8
COG	0.002	0.2
CDA	0.0004	0.04
$z_{neutral}$	0.004	0.4
Time	0.00007	0.007
Acceptance	0.011	1.0
Accidental LKr Clusters	0.002	0.2
Kaon Flux	0.010	1.0
LKr Energy Scale	0.006	0.6
Trigger Efficiency	0.006	0.5
Total	0.033	3.1

Table 5.10: Summary of branching ratio stability checks. Half the maximum variation has been quoted.

a global $\sim 0.5\%$ systematic uncertainty.

The total systematic error on the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio has been obtained by summing each individual contribution in quadrature (Tab. 5.10).

5.7 $\hat{c}$ Measurement

A naive extraction of the $\hat{c}$ Chiral Perturbation Theory coupling constant from the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ model independent branching ratio can be performed according to Eq. 1.5, after the measurement has been extrapolated to the full $m_{\gamma\gamma}$ spectrum.

Since the shape of the di-photon invariant mass distribution, and thus the normalization factor, depends on the unknown value of the constant, a systematic error has been added:

$$\hat{c} = 2.06 \pm 0.28 \pm 0.04_{acc}$$

where the first error is due to the statistical and systematic uncertainties on the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ branching ratio determination, while the second one ("acc") the acceptance dependence on $\hat{c}$.

Conclusions

The NA48/2 experiment has collected the largest sample of $K^\pm$ decays ever in the world, opening many challenging opportunities in the kaon sector physics.

2300 $K^\pm \rightarrow \pi^\pm \gamma \gamma$ radiative decays have been reconstructed using the whole 2003 statistics with a residual background at the level of $\sim 3.5\%$. The corresponding branching ratio has been measured following two different approaches.

A first result has been obtained by integrating over all the di-photon invariant mass spectrum:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = (1.071 \pm 0.024_{stat} \pm 0.033_{syst}) \times 10^{-6}$$

with a factor ~ 10 better precision than the previous measurement [11], while a second measurement has been performed in bin of $m_{\gamma\gamma}$:

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma, m_{\gamma\gamma} > 225 \text{ MeV}/c^2) = (1.018 \pm 0.026_{stat} \pm 0.032_{syst}) \times 10^{-6}$$

Since the shape of the di-photon invariant mass distribution strongly depends on the unknown $\hat{c}$ constant of the Chiral Perturbation Theory, the integrated result is model dependent. On the other hand, when performing the measurement in bin of $m_{\gamma\gamma}$ the dependence on $\hat{c}$ vanishes allowing the extraction of the coupling constant:

$$\hat{c} = 2.06 \pm 0.28$$

Conclusions

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