DIRECT CP VIOLATION MEASUREMENTS WITH THE NA48 EXPERIMENT: STATUS AND PERSPECTIVES

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Abstract. Direct CP violation in neutral Kaon system has been studied at NA48 through the measurement of $Re(\epsilon'/\epsilon)$. The decay rates of neutral kaons $K_{L,S}$ in two pions $(\pi^0\pi^0, \pi^+\pi^-)$ were measured using two collinear beams, the four decay modes were collected concurrently. The final result, covering the full data sample collected from 1997 to 2001, is $(14.7 \pm 2.2) \times 10^{-4}$ showing a clean evidence of direct CP violation in neutral Kaon system. Year 2003 data taking has been devoted to high statistics study of charged kaon decays using simultaneous K^+ and K^- beams, and an upgraded NA48 setup: NA48/2. The main goal is to measure the CP-violating asymmetry in the linear slope of the $K^\pm \to \pi^\pm\pi^+\pi^-$ decays with an accuracy of about 10^{-4}.

1 CP violation in Kaon system

1.1 CP violation in neutral Kaon system

If CP is conserved the mass eigenstates K_S and K_L ($c\tau_S = 2.6786cm$, $c\tau_L = 15.51m$ [1]) should be pure CP eigenstates: K_1 $(CP = +1)$ and K_2 $(CP = -1)$. As a consequence K_L should not decays into $\pi\pi$ $(CP = +1)$. But in 1964 the forbidden K_L decays in the opposite CP state $\pi^+\pi^-$ were recorded by Christenson, Cronin, Fitch and Turlay [2]. The observed CP violation effect was of order $\approx 2 \times 10^{-3}$.

The effect, called *Indirect* CP violation, is due to $K^0 - \overline{K}^0$ (flavour eigenstates) mixing. Mass eigenstates are not pure CP eigenstates: $K_S \approx K_1 + \epsilon K_2$, $K_L \approx K_2 + \epsilon K_1$ where $\epsilon \approx 2 \times 10^{-3}$ is the *indirect* CP violation parameter.

If the mixing is the only source of CP violation then the ratios of CP violating/ CP conserving decay amplitudes η_{+-} and η_{00}

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \quad , \quad \eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \tag{1}$$

should be both equal to ϵ. CP violation in neutral kaon system is dominated by mixing but there could also be a *direct* CP violation contribution, occouring in the decay process itself. *Direct* CP violation requires two interfering amplitudes,two different weak phase-shifts and two different strong phase-shifts: in neutral kaon system it can be seen through the interference of $\pi\pi$ final states with different isospin ($\pi\pi$ can have isospin I=0 or I=2).

Taking into account the *direct* CP violation the *CP violating / CP conserving* ratios can be expressed as

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$$\eta_{+-} \approx \epsilon + \epsilon' \quad , \quad \eta_{00} \approx \epsilon - 2\epsilon' \tag{2}$$

where ϵ' is the *direct* CP violation parameter [c]. Therefore direct CP violation can be demonstrated measuring $\epsilon' \neq 0$. Being $\epsilon' \ll \epsilon$ it is convenient to measure the double ratio R, realated to $Re(\epsilon'/\epsilon)$ by [3]:

$$R = |\eta_{00}/\eta_{+-}|^2 = \frac{\Gamma(K_L \to \pi^0\pi^0)\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\Gamma(K_L \to \pi^+\pi^-)} \approx 1 - 6Re(\epsilon'/\epsilon) \tag{3}$$

1.2 CP violation in charged Kaon system

In charged kaon system, free from mixing, a manifestation of direct CP violation would be any difference between the K^+ and K^- decay matrix elements [4]. The matrix element for $K^\pm \to (3\pi)^\pm$ (B.r. $(5.576 \pm 0.031)\%$ [1]) can be parametrized as

$$|M(u,v)|^2 \propto 1 + gu + hu^2 + kv^2 \tag{4}$$

where $u = (s_3 - s_0)/m_\pi{}^2$, $v = (s_1 - s_2)/m_\pi{}^2$, $s_0 = (s_1 + s_2 + s_3)/3$, $s_i = (P_K - P_i)^2$, P_K and P_i the 4-momenta of kaon and pion (i=3 for the odd pion, having opposite sign to the decaying kaon) [4].

In case of CP conservation the coefficient g^+, h^+, k^+ and g^-, h^-, k^-, for K^+ and K^- respectively, must be the same. Direct CP violation can be measured through the asymmetry in the slope descibing the linear dependence of the decay probabilities on the u variable of the Dalitz plot:

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \tag{5}$$

In the analogous way$A_g{}^0$ is the asymmetry parameter for $K^\pm \to \pi^0\pi^0\pi^\pm$ (B.r. $(1.73 \pm 0.04)\%$).

2 NA48: Re(ϵ'/ϵ) measurement

Up to year 2001 Re(ϵ'/ϵ) measurement, through the double ratio R , has been the main NA48 item [5]. In order to achieve a precision of $\approx 2 \times 10^{-4}$ several millions of $K_L \to \pi\pi$ are required ($K_L \to \pi\pi$ are only 0.3% of K_L decays) and systematic uncertainties have to be minimized. In the double ratio R:
- contributions from systematic effects can be canceled if they are symmetric on Long/Short or Charge/Neutral modes

[c] $\epsilon' = \frac{i}{\sqrt{2}} Im \frac{A_2}{A_0} \exp{(i(\delta_2 - \delta_0))}$, where $A(K_0 \to \pi\pi, I) = A_I \exp{(i\delta_I)}$, $A(\overline{K_0} \to \pi\pi, I) = A_I^* \exp{(i\delta_I)}$ and δ_I are strong phases

- fluxes, inefficiency, dead time, accidental effects cancel in case of concurrent decays.

Differencies between K_S and K_L acceptances $a_{L,S}(p,z)$, function of momentum and vertex position along beam direction, can be minimized if K_L and K_S have similar spectra, obtained using kaons with energy in the range (70,170)GeV, and the decays are
- in the same decay volume,
- coming from quasi-collinear beams,

Moreover being $\tau_L \approx 600 \times \tau_S$ the K_S and K_L have very different decay lenghts, this imply a big difference on the total acceptance for K_S and K_L , even if for a given decay position the acceptances are the same. As a consequence a big correction on R would be needed (red stars in Fig. (1)). To avoid this the K_L events are weighted, offline on a event by event basis, by means of a proper lifetime function obtaining similar distributions for K_S and K_L (Fig. (2)). Through the weighting the acceptance correction almost cancels in the double ratio (black dots in Fig. (1)), even if the statistical error on R increases by about 35%. To be insensitive to remaining difference in K_L and K_S spectra, the analysis is performed in bins of kaon energy, 5Gev each.

Summarizing, in order to minimize systematic uncertainties, the experiment has been designed to have collinear K_L and K_S beams and to collect the four decay modes ($K_{L,S} \to \pi^0\pi^0, \pi^+\pi^-$) simultaneously and in the same fiducial volume. Therefore, once subtracted the background, the double ratio reduces to double ratio of number of decays:

$$R = \frac{N(K_L \to \pi^0\pi^0)N(K_S \to \pi^+\pi^-)}{N(K_S \to \pi^0\pi^0)N(K_L \to \pi^+\pi^-)} \tag{6}$$

where the *first order* corrections($\approx 1\%$) have been canceled and the remaining *second order* (few per mille) corrections ΔR due to residual asymmetries (like remaining backgrounds, trigger inefficiency and so on) have to be estimated. In year 2001 run (≈ 90 days) 1.55×10^6 $K_L \to \pi^0\pi^0$ have been collected.

2.1 NA48 beams and detector

NA48, located in the CERN North Area, makes use of protons extracted from SPS to produce the *far* (K_L) and *near* (K_S) beams: the primary protons impingue on a first target producing the *far* beam, while part of the non interacting protons are deviated toward a second target (*near*) slightly displaced on the vertical axis ($\approx 7cm$) w.r.t the far beam axis (Fig. (3)). Along the proton secondary path is placed a tagging station (Tagger) to record the crossing time of each proton going to the K_S target. The coincidence ($\pm 2ns$) between the time of the event (from the detector) and the time of the nearest proton in the Tagger labels the decay as K_S . The two beams enter the same fiducial volume, roughly 6m downstream the *near* target and 126m from *far* target, so that decaying kaons (in $\pi\pi$ channel) are essentially K_S and K_L .

The beginning of the fiducial volume is defined by an anticounter (AKS), located on the K_S beam path, used to reject all the $K_S \to \pi\pi$ decays occured upstream. The two beam axis converge at the center of the electromagnetc calorimeter (LKr) located $\approx 120m$ downstream. Seven rings of counters surround the fiducial volume in order to record escaping photons thus reducing $K_L \to 3\pi^0$ background. Muon counters, at the end of the beam line, are used as a veto to reduce the $K_{\mu 3}$ background. The main subdetectors for charged and neutral decays are (Fig. (4)):

- charged decays: magnetic spectrometer. A dipole magnet providing 265 MeV p_t kick, two drift chambers upstream and two downstream of it. Each drift chamber is equipped with 4 views (2 staggered planes each) orthogonal to the beam axis (Z) and oriented at $0°, 90°, -45°, +45°$. Each plane houses 256 sense wires, 1cm spaced. The track momentum resulution is $\sigma(p)/p = 0.48\% \oplus 0.009p\%$ (p in GeV/c).

- neutral decays: Liquid Krypton electromagnetic calorimeter. It is a quasi-homogeneous detectors filled with an active volume of $\sim 10m^3$ of liquid Krypton. Sever performances are required since $2\pi^0$ decays are reconstructed through their 4γs detection. 13212 cells ($2 \times 2cm^2 \times 127cm$) are defined by electrodes in a structure of longitudinal projective towers pointing toward the center of the decay region. The energy resolution is $\sigma(E)/E = \frac{(3.2\pm0.2)\%}{\sqrt{E}} \oplus \frac{(9\pm1)\%}{E} \oplus (0.42 \pm 0.05)\%$

2.2 $\pi^+\pi^-$ detection and reconstruction

$K_{L,S} \to \pi^+\pi^-$ events are triggered by the two levels *charged trigger* (efficiency $\approx 98.7\%$). The first level reduces the rate to 100kHz by a coincidence of charged hodoscope signals in opposite quadrants, hit multiplicity in the first chamber (integrated over 200ns) and total energy from calorimeters (LKr+HAC). The second level trigger is based on hardware coordinate builder reconstructing tracks from drift chambers (1,2,and 4) data.

Charged selection is based on tracks, momenta and invariant mass. The $\pi^+\pi^-$ invariant mass resolution is about 2.5 MeV (Fig. (5)) and the applied cut is at 3 σ. In november 1999 all the four drift chambers were damaged by the implosion of the beam pipe but they have been rebuilt and were ready for the run in year 2001. The new chambers' resolution, as shown in Fig. (5) is in agreement with 1998 and 1999 data.

In order to reduce effects from uncertainties in magnetic field and multiple scattering in the definition of the fiducial region the kaon energy is calculated by the $\pi^+\pi^-$ opening angle (θ) and tracks energy ratio:

$$E_K^2 = \frac{C}{\theta^2}\left\{m_K^2 - C\ m_\pi^2\right\} \quad , \quad C = 2 + \frac{E_{\pi 1}}{E_{\pi 2}} + \frac{E_{\pi 2}}{E_{\pi 1}} \tag{7}$$

Charged energy understandig is reduced to chambers' geometry knowledge and can be checked reconstructing the position of the AKS anticounter for not vetoed $\pi^+\pi^-$ ($\Delta z = 2$ cm).

The background, due to K_L semileptonic decays in which an electron or a muon is identified as a pion, are suppressed by μ-veto counters and the E/p cut, where E is the energy of the cluster associated to the track in the calorimeter. Λ decays are suppressed cutting on tracks momentum asymmetry while the cut on kaon transverse momentum ($P_T^2 < 200$ (MeV/c)^2) removes three-body decays with a missing neutrino. A detailed description of the cuts can be found in [3,5,6]

2.3 $\pi^0\pi^0$ detection and reconstruction

$K_{L,S} \to \pi^0\pi^0$ events are triggered by the *neutral trigger* which operates on Lkr informations such as energy deposit and number of energy peaks, and distance of the decay vertex from the calorimeter. The electronics is implemented in a pipeline which makes the trigger free from dead time. The efficiency is almost 100% (99.9%) fot both K_S and K_L .

$K_{L,S} \to \pi^0\pi^0$ selection is based on LKr data on photon showers: energy and position, minimum distance between photons, matching of photon pairs invariant mass with nominal π^0 mass. From the four detected photons in the calorimeter, the distance D of the decay from the calorimeter is given by:

$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K} \tag{8}$$

where E_i are the photons energies and r_{ij} the distances between photons in the calorimeter. The two photons invariant mass is:

$$m_{ij} = \frac{\sqrt{E_i E_j}\ .\ r_{ij}}{D} \tag{9}$$

In order to find the best shower pairing a χ^2 variable ($R_{ellipse}$ Fig. (7)) of the two photons invariant masses w.r.t. the π^0 mass is constructed. A cut on the χ^2 is applied to suppress $3\pi^0$ decays with missing or overlapping photons . Events with extra photons in time are rejected.

The calorimeter energy scale is adjusted to match the AKS nominal position, reconstructed from the $K_S \to \pi^0\pi^0$ decay distribution (Fig. (8)).

2.4 *Accidental activity*

Accidental activity in the beams can induce event losses. Being the K_L beam intensity roughly 10^5 times the K_S one the event losses due to K_S beam are negligible. Moreover event losses show a linear dependence on K_L beam instantaneous intensity, as verified in year 2001 data.

The accidental activity effect cancels to first order in R but a difference in losses between charged and neutral or Long and Short can lead to a residual correction to R:

$$\Delta \mathrm{R} \approx \Delta(\pi^+\pi^- - \pi^0\pi^0) \times \Delta(K_L - K_S) \tag{10}$$

The difference between neutral and charged losses is minimized by applying dead time conditions to all the modes. Dead time conditions are due mainly to the drift chamber multiplicity limit, these conditions are recorded and applied offline to all the events. The difference in the accidental activity seen by K_L and K_S events is small by design being the two beams simultaneous.

To estimate residual illumination difference [d] random events overlayed to $\pi\pi$ Montecarlo and data events have been used.

2.5 *Data samples and Results*

Year 2001 has been the last one devoted to $\mathrm{Re}(\epsilon'/\epsilon)$, it has been useful no only to acumulate more statistics but also to perform a better studies on accidental activity effects.

Thanks to the end of LEP activities a longer spill (Table (1)) was infact delivered to NA48 with lower momentum protons (400GeV/c) giving lower instantaneous intensity in the detector. New beam monitors, to study accidental activity at short time scale, and new drift chambers were installed.

	98-99	2001
proton momentum (GeV/c)	450	400
SPS cycle time (s)	14.4	16.8
spill length (effective) (s)	2.4 (1.7)	5.2 (3.6)
duty cycle	0.17	0.31
K_L beam intensity (ppp)	$\approx$ 1.5x10^{12}	$\approx$ 2.4x10^{12}
K_S beam intensity (ppp)	$\approx$ 3x10^7	$\approx$ 5x10^7

Table 1: Beam proprieties, years 1998-99 and 2001

Due to all these imnprovements a better understanding of accidental activity and related items have been reached improving their corrections to R as shown in Table (2)

[d] K_S and K_L beams are still separated by about 1 cm at the first drift chamber: this could induce a difference on charged events from K_L and K_S

	98-99	2001
$\pi^+\pi^-$ background	$16.9 \pm 3.0_{(syst.)}$	$14.2 \pm 3.0_{(syst.)}$
$\pi^0\pi^0$ background	$-5.9 \pm 2.0_{(syst.)}$	$-5.6 \pm 2.0_{(syst.)}$
beam scattering	$-9.6 \pm 2.0_{(syst.)}$	$-8.8 \pm 2.0_{(syst.)}$
Tagging inefficiency α_{SL}	$\pm 3.0_{(syst.)}$	$\pm 3.0_{(syst.)}$
Accidental tagging α_{LS}	$8.3 \pm 3.4_{(stat.)}$	$6.9 \pm 2.8_{(stat.)}$
$\pi^+\pi^-$ scale	$2.0 \pm 2.8_{(syst.)}$	$\pm 2.8_{(syst.)}$
$\pi^0\pi^0$ scale	$\pm 5.8_{(syst.)}$	$\pm 5.3_{(syst.)}$
AKS inefficiency	$1.1 \pm 0.4_{(syst.)}$	$1.2 \pm 0.3_{(syst.)}$
Acceptance	$26.7 \pm 4.1_{(stat.)}$ $\pm 4.0_{(syst.)}$	$21.9 \pm 3.5_{(stat.)}$ $\pm 4.0_{(syst.)}$
$\pi^+\pi^-$ trigger inefficiency	$-3.6 \pm 5.2_{(stat.)}$	$5.2 \pm 3.6_{(stat.)}$
Accidental activity intensity diff. illumination diff.	 $\pm 3.0_{(syst.)}$ $\pm 3.0_{(stat.)}$	 $\pm 1.1_{(syst.)}$ $\pm 3.0_{(stat.)}$
K_S in time activity	$\pm 1.0_{(syst.)}$	$\pm 1.0_{(syst.)}$
Total	$+35.9 \pm 8.1_{(stat.)} \pm 9.6_{(syst.)}$	$+35.0 \pm 6.5_{(stat.)} \pm 9.0_{(syst.)}$

Table 2: Different years corrections on R. Corrections and systematic uncertainties on R are reported in 10^{-4} units.

The corrected double ratio for the 2001 data is $R_{2001} = 0.99181 \pm 0.00147_{stat} \pm 0.00110_{syst}$; where part of the systematic error (± 0.00065) comes from the statistics on control samples. NA48 results are stable along the different samples:

sample	$K_L \to \pi^0\pi^0$	Re(ϵ'/ϵ)
1997	0.5M	$(18.5 \pm 7.3) \times 10^{-4}$ [3]
1998-99	3M	$(15.0 \pm 2.7) \times 10^{-4}$ [6]
2001	1.5M	$(13.7 \pm 3.1) \times 10^{-4}$ [5]

and the final result is Re $(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$ [5]

3 NA48/2: A_g measurement

NA48/2 main goal is to search for CP violation in $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ decays measuring the direct CP violating asymmetry $A_g = (g^+ - g^-)/(g^+ + g^-)$; where $g^{+,-}$ are the slope parameters describing the linear dependence of $K^{+,-}$ decay probabilities on the u kinematic variable of the Dalitz plots. The u variable is linearly related to the energy of the odd pion [e] in the centre of mass system:

$$u = (2M_K/{m_\pi}^2)\dot{(}M_K/3 - {E_\pi}^*) \tag{11}$$

Any variation in the ratio

$$R(u) = \frac{\int dv|M^+(u,v)|^2}{\int dv|M^-(u,v)|^2} \tag{12}$$

[e] the pion having the opposite sign to that of the dacying kaon

as a function of u, would show evidence of direct CP violation [4].

The experiment is designed to reach sensitivity of about 10^{-4}, limited by statistics rather than systematics. The corresponding asymmetry ${A_g}^0$ in $K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}$ will be measured too, with a sensitivity again limited by statistics. Moreover high statistics Ke4 can be analyzed allowing the $\pi - \pi$ scattering lenght parameter ${a_0}^0$ to be measured with an accuracy of better than 1×10^{-2}, which permits to measure the $q\overline{q}$ condensate postulated by the Chiral Perturbation Theory. The present knowledge of several rare decays can be extended as well.

To achieve the required sensitivity, as it has been done for $Re(\epsilon'/\epsilon)$ measurement, all possible sources of asymmetries have to be minimized. In order to do that the simultaneous K^+ and K^- beams are derived from the same target, K^+ and K^- decaying in the same fiducial volume, the field in the spectrometer is frequently alternated in sign.

A new beam line using a novel design has been built downstream the NA48-K_L target position to transport simultaneously the K^+ and K^- beams, produced by the 400GeV/c primary protons from SPS impinguing on the beryllium target (Fig. (9)). The average kaon momentum is 60GeV/c for both K^+ and K^- (r.m.s. $\pm 3.8\%$), selected by their passage through two vertical deflection magnets with opposite-sign field and a pair of collimators (TAX) which have two similar openings and also serve as a dump for the remaining primary protons [4]. Two further vertical deflection magnets return the two beams onto a common axis. A system of quadrupole is used to focused particle of each sign in both planes in order to have small spot size beams at the spectrometer, thus minimizing the transverse scale of any structure within the beam spots. Moreover by regular inversion of the achromats any remaining structures inside the beam spots is exchanged between K^+ and K^- Other improvement have been done and new detectors (KABES, 3 station of TPC-type detector using MICROMEGAS) have been installed (see [7]).

The proposed statistic should be reach with the 2004 run, while analysis is already started on 2003 data corresponding to roughly 50% of the planned statistics. During 2003 run the positive flux at the exit of the final collimator was estimated to be 3.8×10^7 particle per pulse of which 2.2×10^6 were K^+. While negative particle flux was 2.6^7 ppp of which 1.3×10^6 were K^-. The number of charged kaons reconstructed $K^{\pm} \rightarrow (3\pi)^{\pm}$ per spill was roughly 1.3×10^4.

Acknowledgments

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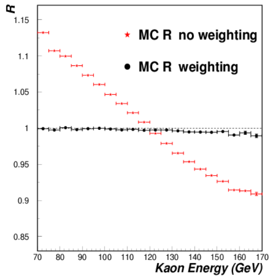

Figure 1: Acceptance effect on R (20 energy bins, 5 Gev each) estimaed by MC

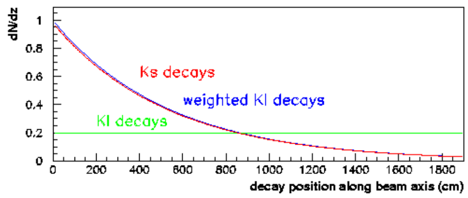

Figure 2: Decays position along beam axis for K_L , K_S and weighted K_L decays

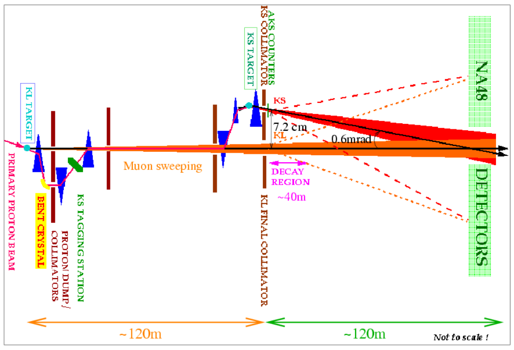

Figure 3: NA48 beams setup

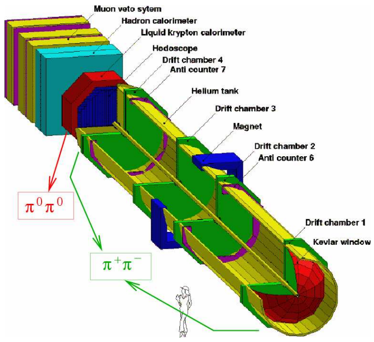

Figure 4: NA48 detector

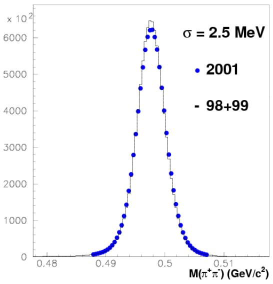

Figure 5: $\pi^+\pi^-$ inv. mass

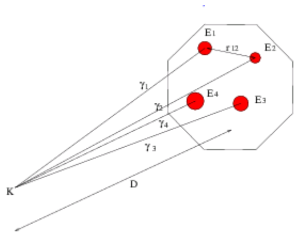

Figure 6: Decay distance D computed from 4 γs in Lkr

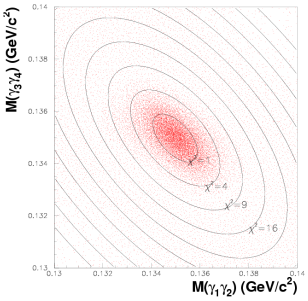

Figure 7: $K_S \to \pi^0\pi^0$ candidates in the the two reconstructed $m_{\gamma\gamma}$ space

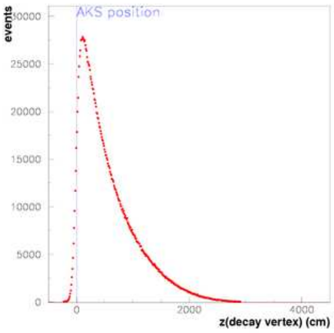

Figure 8: $\pi^0\pi^0$ vertex distribution

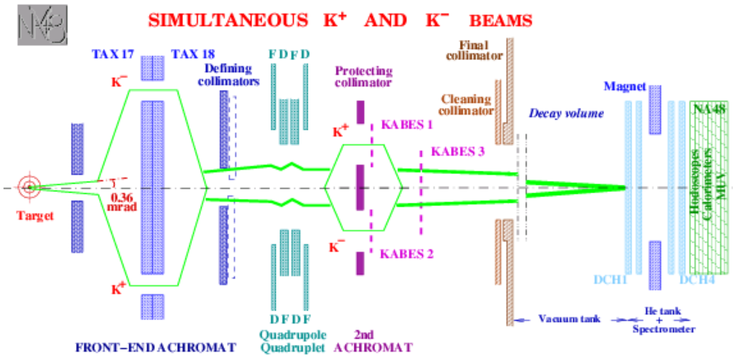

Figure 9: Vertical view of the simultaneous K^+ and K^- beam, not to scale. Outside achromats the beam lines are separated for clarity, in reality displacement is less than 1mm

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