NA48 results on neutral kaon rare decays and prospects for charged kaon physics

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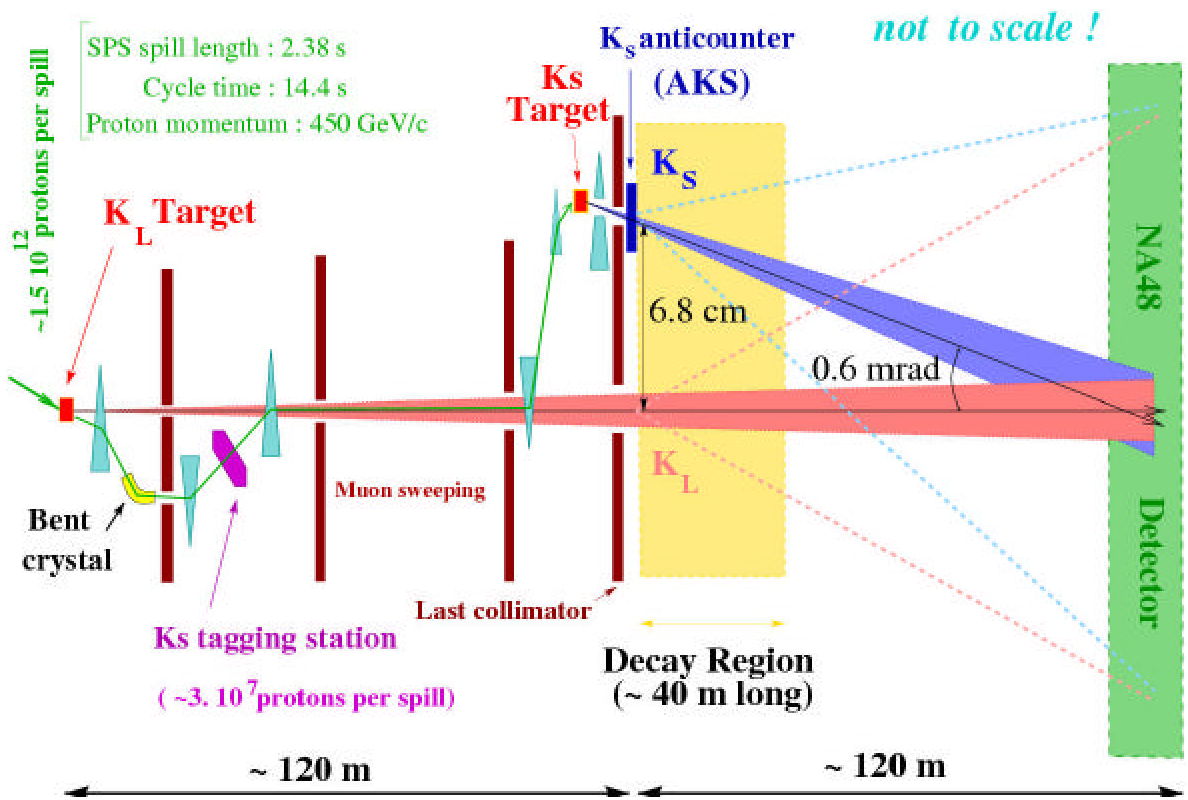
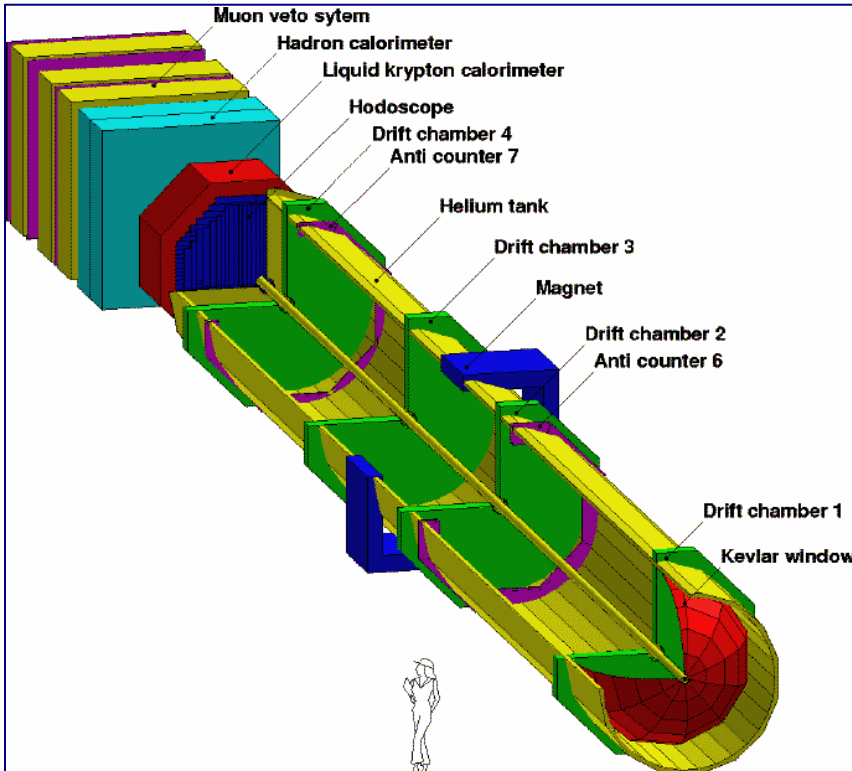
Outline

- 1997-99 data taking for ε'/ε measurement
  - Measure of η mass and K_S lifetime
  - Rare decay studies
  - Hyperon decay measurements
- NA48/1: high intensity K_s
  - Physics motivations
  - Beam and detector upgrade
  - Results from phase 1
- NA48/2: charged kaon physics
  - Motivations
  - Beam and detector upgrade
  - Results from a test run in 2001

The NA48 beams



The NA48 detector



LKr Calorimeter:

s(E)/E @ 3.2%/vE Å 100MeV/E Å 0.42%

Spectrometer:

p_T kick ~250 MeV/c
s(P)/P @ 0.48% Å 0.009 P[GeV/c]%

$s_M(p^0p^0)$ ~ $s_M(p^+p^-)$ ~ 2.5 MeV

Rare kaon decays with ε'/ε data

- Good resolutions in charged and neutral sectors
- Flexible trigger for neutral decays $\Rightarrow$ allows to select decays in any number of γ
- Flexible trigger for charged decays $\Rightarrow$ allows to select events with more than 2 charged tracks
- Enough data acquisition bandwidth to accept a fraction of not ε'/ε triggers
- Intense K_L beam

Data taken for ε'/ε

- 1997-99 ε'/ε data taking
  - 450 GeV/c proton momentum
  - 2.4s/14.4s duty cycle
  - 3*10*^{7} ppp on K_S target $\Rightarrow$ ~3*10^2 K_S
  - 1.5*10*^{12} ppp on K_L target $\Rightarrow$ ~2*10^7 K_L
  - 6.5*10*^{7} K_S/year $\Rightarrow$ SES ~ 1.5*10^{-7}
  - 3.6*10*^{10} K_L/year $\Rightarrow$ SES ~ 3*10^{-10}

1997-2000

- Special runs with π^-/K^- beam along the K_L beam axis to study the performance of the LKr calorimeter with π^0/η produced by charge exchange in a polyethylene target

K^0 and η masses : the method

- Data collected in 2000, K_L only and η going in $3\pi^0$
- For each pion

$$d_{vertex} = \frac{d_{12}}{M_{p^\circ}} \sqrt{E_1 E_2}$$

- For the parent particle

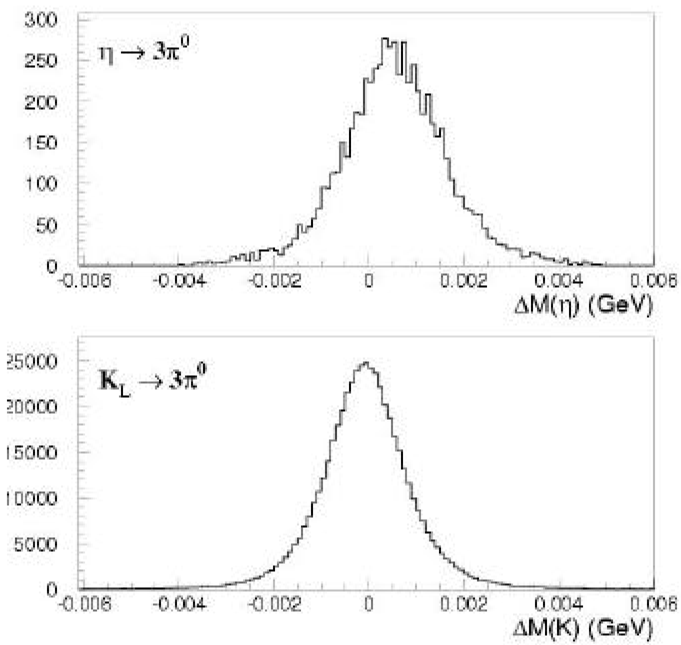
$$M = \frac{1}{< d_{vertex} >} \sqrt{\sum_{ij,i<j} E_i E_j d_{ij}}$$

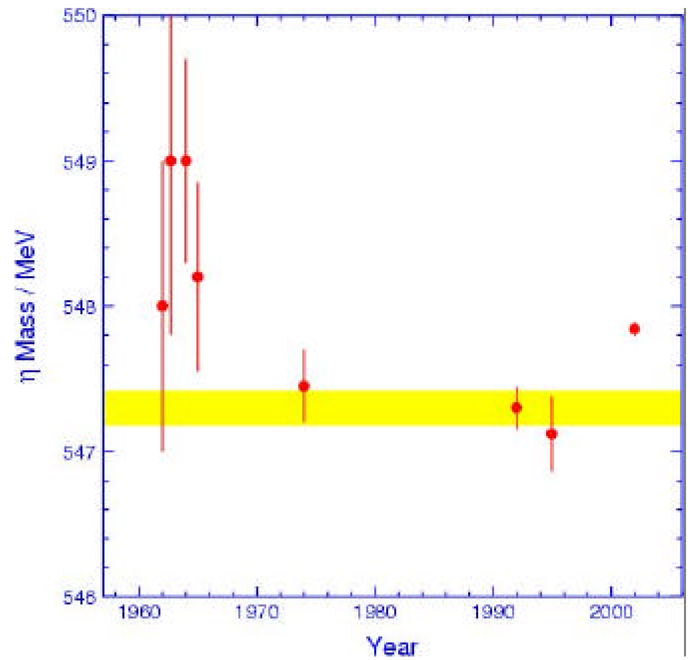
- $\Rightarrow$ Measure $M_{\eta,K} / M_{\pi 0}$
  - $3\pi^0$ mode is background free
  - Indipendent from the energy scale
  - Only sensitive to residual non-linearities in energy or position

K^0 and η masses : the method

- High statistics in K^0 decays allows systematic checks to validate the measurement of the η mass
- Systematic errors are due to
  - Non linearity in energy measurement $\Rightarrow$ reduced using symmetric decays: $0.7 < (E\gamma/\langle E\gamma\rangle) < 1.3$
  - Non uniformity in the calorimeter response
  - Energy leakage from one shower to another
  - Non gaussian tails in the energy response mainly due to hadron photoproduction
- The total systematic error is $\pm$ 41 keV/c^2 for the η mass and $\pm$ 31 keV/c^2 for the K^0 mass

K^0 and η masses : results





η mass: (PDG) = 547.30 ± 0.12 (NA48) = 547.843 ± 0.030_{st} ± 0.045_{sy}

K^0 mass: (PDG) = 497.672 ± 0.031 (NA48) = 497.625 ± 0.001_{st} ± 0.031_{sy}

η mass is 4.2σ off the PDG value with smaller error Phys.Lett. B533 196 (2002)

K^0 mass agrees with the world average within 1.1 σ

K_s lifetime measurement

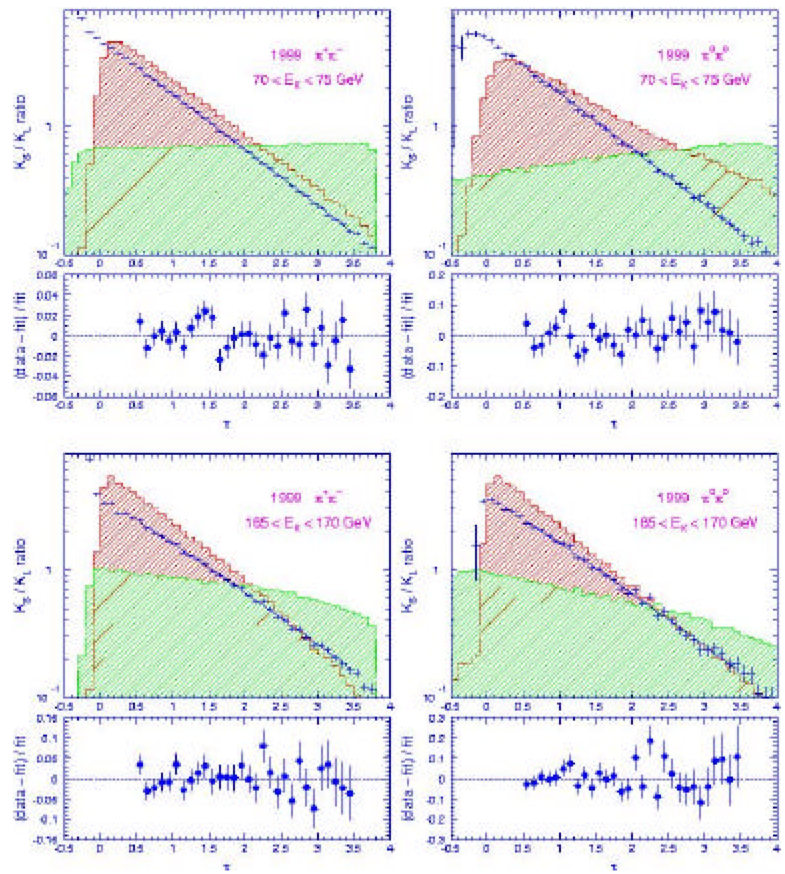
- Method (introduced by NA31)
  - Use the same data sample as for ε'/ε analysis
    - Decay region is defined in $0.5 < \tau/\tau_s < 3.5$
    - Cut at $0.5\ \tau_s$ to avoid detector resolution effects
    - Analysis in 5 GeV energy bins and $0.1\ \tau_s$ lifetime bins
  - Fit the ratio N_L/N_S with the proper function of $\tau_{S,L}$, Δ_m, η, ϕ and dilutions in bins of E and $c\tau_s$
    - Acceptances cancel at first order in the ratio and a small correction from Montecarlo is needed
    - Background from K_L decays (10^{-3} level) is subtracted as in ε'/ε analysis

K_S lifetime measurement

Statistics (in 10^6 events)

$K_L \to \pi^+\pi^-$	12.2
$K_S \to \pi^0\pi^0$	13.2
$K_L \to \pi^+\pi^-$	2.8
$K_S \to \pi^0\pi^0$	3.1

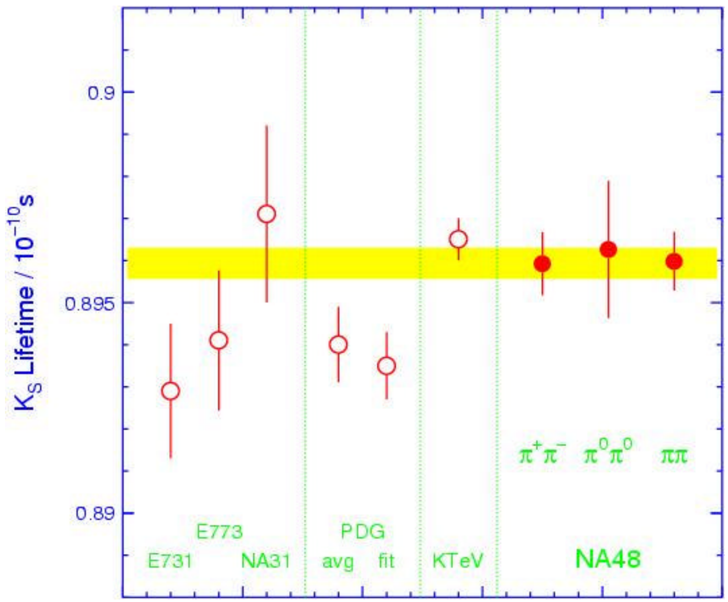
	$\tau_S/10^{-10}$s	χ/dof
$\pi^+\pi^-$ - 1998	0.89578 ± 0.00109	628.2/573
$\pi^0\pi^0$ – 1998	0.89606 ± 0.00247	551.0/573
$\pi^+\pi^-$ - 1999	0.89598 ± 0.00072	601.2/573
$\pi^0\pi^0$ - 1999	0.89635 ± 0.00167	543.5/573



Statistical errors only

K_s lifetime measurement

Systematics dominated by fit method and beam geometry uncertainties



Combined result (CERN-EP/2002-028 - hep-ex/0205008)

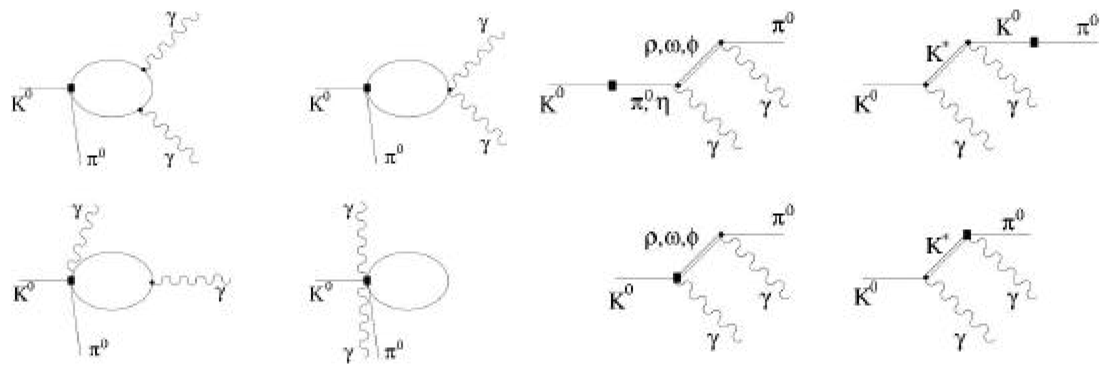
$\tau_s = (0.89598 \pm 0.00048_{st} \pm 0.00043_{sy} \pm 0.00027_{MCst})*10^{-10}s$

$K_L \to \pi^0 \gamma\gamma$ - Physics

- Motivation
  - At one loop χPT ($O(p^4)$) the decay rate is finite, but only gives 1/3 of the measured rate
  - Calculations of $O(p^6)$ including vector meson exchange reproduce the measured rate and allows a tail at low $M\gamma\gamma$
  - VMD contribution parametrized by a_V, to be measured, which determines the CPC amplitude to $K_L \to \pi^0 e^+e^-$

χPT prediction

- $BR(K_L \to \pi^0 \gamma\gamma) = 1.5*10^{-6}$
- a_V = -0.7



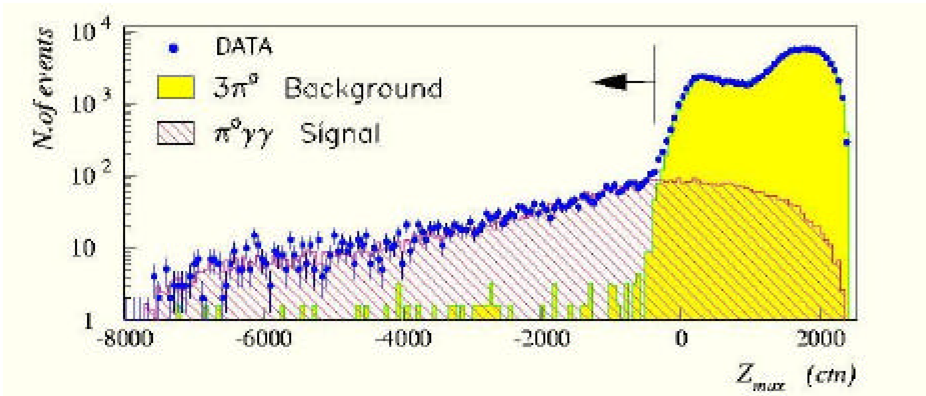
$K_L \rightarrow \pi^0 \gamma \gamma$ - Analysis

- Data selection
  - Signature similar to $K_L \rightarrow \pi^0\pi^0$ (normalization channel)
    - Most systematic uncertainties cancel
    - Both channels collected with the same trigger

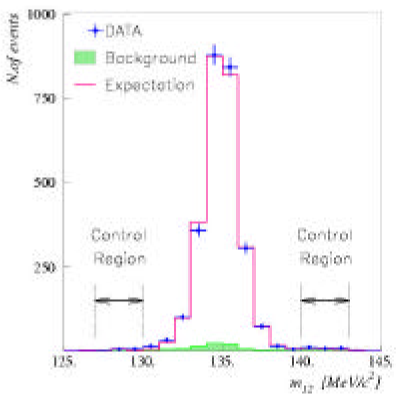
- Background
  - Background from 2 π^0 rejected using invariant mass cuts
    - One pair should be within 3 MeV from the pion mass
    - The other should be outside the 110 MeV-160 Mev window
    - Transverse momentum of the lowest energy unpaired photon should be > 40 MeV/c
    - Remaining background estimated from $K_s \rightarrow \pi^0\pi^0$ tails

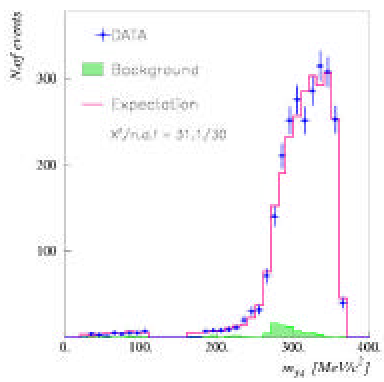
$K_L \to \pi^0 \gamma\gamma$ - Analysis

- Background
  - Background from $3\pi^0$ with missing or overlapping photons are rejected with combinatorial cuts
    - Background gives wrong K vertex with a good π^0 vertex
  - Additional cuts on the shower width of the cluster
  - Good separation using a variable z_{max} set up as the maximum of the reconstructed z of various combinations of photons

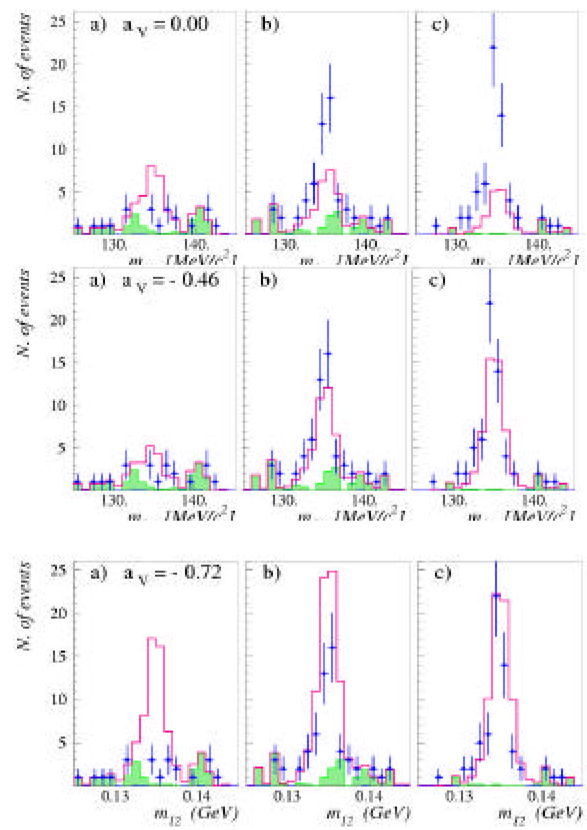


$K_L \rightarrow \pi^0 \gamma \gamma$ - Analysis





$0<m_{34}<0.135$ $0.135<m_{34}<0.24$ $0.24<m_{34}<0.26$



~2500 candidates in the signal region ($132 < m_{12} < 138$ MeV)

$K_L \to \pi^0 \gamma\gamma$ - Results

KTeV

BR ($K_L \to \pi^0\gamma\gamma$) = (1.68± 0.10)

a_V= -0.72 ± 0.08

- Fitting a_V one obtains:

$$a_V = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$$

- Using the fitted a_V the branching ratio is:

$$BR\ (K_L \to \pi^0 \gamma\gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm})*10^{-6}$$

- The systematics of both results are limited by background evaluation and acceptance calculation

- The value of a_V implies a negligible CP conserving contribution to $K_L \to \pi^0 e^+e^-$

$$BR\ (K_L \to \pi^0 e^+e^-)_{CPC} = (4.7 \pm 2.2)*10^{-13}$$

CERN-EP 2002-030 hep-ex/0205010 submitted to Phys. Lett. B

Summary of other analyses

- $K_L \to \pi^+\pi^-e^+e^-$ - CP Violation
  - Asymmetry in the angle between the planes of $\pi^+\pi^-$ / e^+e^-
    - $A = 13.9 \pm 2.7_{st} \pm 2.7_{sy}$ % (KTeV: $A = 3.6 \pm 2.5_{st} \pm 1.2_{sy}$ %)
- $K_S \to \pi^+\pi^-e^+e^-$
  - First observation and prel. $BR = (4.5 \pm 0.2_{st} \pm 0.3_{sy})*10^{-5}$
- $K_S \to \pi^0e^+e^-$
  - Upper limit for the BR: $BR < 1.4*10^{-7}$
- Hyperons
  - $M(\Xi^0) = 1314.82 \pm 0.06_{st} \pm 0.2_{sy}$ MeV/c^2
  - $BR(\Xi^0 \to \Lambda\gamma) = (1.9\pm0.2)*10^{-3}$ $BR(\Xi^0 \to \Sigma^0\gamma) = (3.7\pm0.5)*10^{-3}$
  - 60 events of $\Xi^0 \to \Sigma^+e^-\nu$

NA48/1: High Intensity K_S Physics motivations

- $K_S \rightarrow \pi^0 e^+ e^-$, $K_S \rightarrow \pi^0 \mu^+ \mu^-$
  - Bound indirect CP Violation in the corresponding K_L decays
- Search for CP Violation in K_S decays
  - $K_S \rightarrow 3\pi^0$, $K_S \rightarrow \pi^0 \pi^+ \pi^-$
- Test of Chiral Perturbation Theory
  - $K_S \rightarrow \gamma\gamma$, $K_S \rightarrow \pi^0 \gamma\gamma$, $K_S \rightarrow \pi^0 \pi^0 \gamma\gamma$
- Semileptonic and radiative neutral hyperon decays
  - Improve NA48 results on $\Xi^0 \rightarrow \Sigma^+ e^- \nu$, $\Xi^0 \rightarrow \Sigma^+ \mu^- \nu$, $\Xi^0 \rightarrow \Sigma^0 \gamma$, $\Xi^0 \rightarrow \Lambda\gamma$
  - Put an upper limit to BR ($\Xi^0 \rightarrow p\pi^-$) (double beta decay)
- ....

First step towards NA48/1

- 1999 High Intensity K_S run (40 hours)
  - No K_L beam
  - $6*10^9$ ppp on K_S target (x200)
  - $2.3*10^8$ K_S decays for $60 < E_K < 190$ GeV
  - SES ~ $4*10^{-8}$ with 10% acceptance
  - 40 hours ≡ 3-4 years of ε'/ε operation
- 2000 run – No drift chambers in the spectrometer
  - 400 GeV/c proton momentum
  - Modified production angle, same proton intensity
  - Modified duty cycle (3.2s/14.4s)
  - Far target run (K_L) with magnetic field on
  - Near target run (HIK_S) without magnetic field
  - 10^{10} K_S decays collected in ~40 days

$K_S \rightarrow \gamma\gamma$

- $K_S \rightarrow \gamma\gamma$ is interesting because it is calculable in xPT with no counter-terms and it is sensitive to loops
  - Theoretical prediction: $BR(K_S \rightarrow \gamma\gamma)=(2.1 \pm 0.2)*10^{-6}$
  - Result from NA31: $BR(K_S \rightarrow \gamma\gamma)=(2.4 \pm 0.9)*10^{-6}$
- Data from 1999 HIKs run with dedicated trigger
  - $7.5*10^6$ decays after x100 downscaling
  - Acceptances: 22% for $K_S \rightarrow 2\pi^0$, 49% for $K_S \rightarrow \gamma\gamma$
  - Flux measurement using $K_L \rightarrow 3\pi^0$ and $K_s \rightarrow 2\pi^0$
  - Use $K_S \rightarrow 2\pi^0$ as normalisation channel
  - Subtract K_L events extrapolating at the production target where K_L and K_S fluxes are equal

$K_S \rightarrow \gamma\gamma$

- $K_S \rightarrow \gamma\gamma$ is interesting because it is calculable in χPT with no counter-terms and it is sensitive to loops
  - Theoretical prediction: $BR(K_S \rightarrow \gamma\gamma) = (2.1 \pm 0.2)*10^{-6}$
  - Result from NA31: $BR(K_S \rightarrow \gamma\gamma) = (2.4 \pm 0.9)*10^{-6}$
- Published result from 1999 HIKs run with dedicated trigger
  - $BR(K_S \rightarrow \gamma\gamma) = (2.58 \pm 0.36_{st} \pm 0.22_{sy})*10^{-6}$
  - Phys. Lett. B493 (2000) 29
- New result based on 2000 HIKs run
  - Use data from 2000 far target run
  - Normalise to $K_S \rightarrow \pi^0\pi^0$

$K_S \rightarrow \gamma\gamma$ – Background

- $K_S \rightarrow \pi^0\pi^0$ minimized using a 5 m fiducial region after the K_S collimator. There decays with two lost γ have a maximum invariant mass of 458 MeV and the reconstructed vertex cannot be less than 9 m. Reduction to 5 m is due to the effect of overlapping showers.
- Hadronic interactions in the collimator evaluated from high COG tails and suppressed by Ehac and shower width cut
- Accidental $\gamma\gamma$ pairs eliminated with a cut on cluster time difference

$K_S \to \gamma\gamma$ – Background

- $K_L \to \gamma\gamma$ irreducible $\to$ 1.5 times the $K_S \to \gamma\gamma$ in the decay volume.
  - Use $K_L \to 3\pi^0$ to evaluate K_L flux
  - Use 2000 far target run to measure $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$
  - Need 5 data samples:
    - *Far target: gg, 2p^0, 3p^0*
    - *Near target: gg, 3p^0*
- Dalitz decays K, $\pi^0 \to ee\gamma$ mainly due to closed e^+e^- pairs subtracted using MC

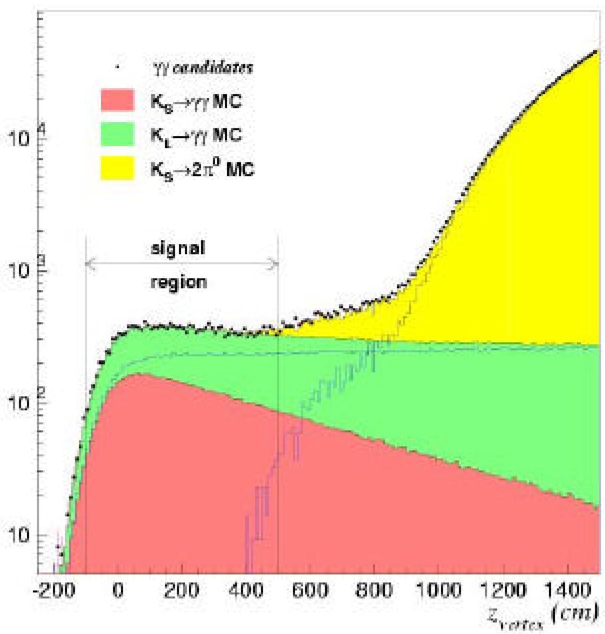
$K_S \to \gamma\gamma$

- Measurement of $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$
  - 2000 far target run: similar detector conditions as in the near target one $\Rightarrow$ detector systematics cancel.
  - Choose the same decay volume as for $K_S \to \gamma\gamma \Rightarrow$ acceptance almost cancels
  - Background handling similar to $K_S \to \gamma\gamma$
  - Result:

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy})*10^{-3}$$

PDG value = $(2.77 \pm 0.08)*10^{-3}$

$K_S \rightarrow \gamma\gamma$ - Result



Global systematic correction

-1.8 ± 1.4 %

Total number of $K_x \rightarrow \gamma\gamma$ 19916

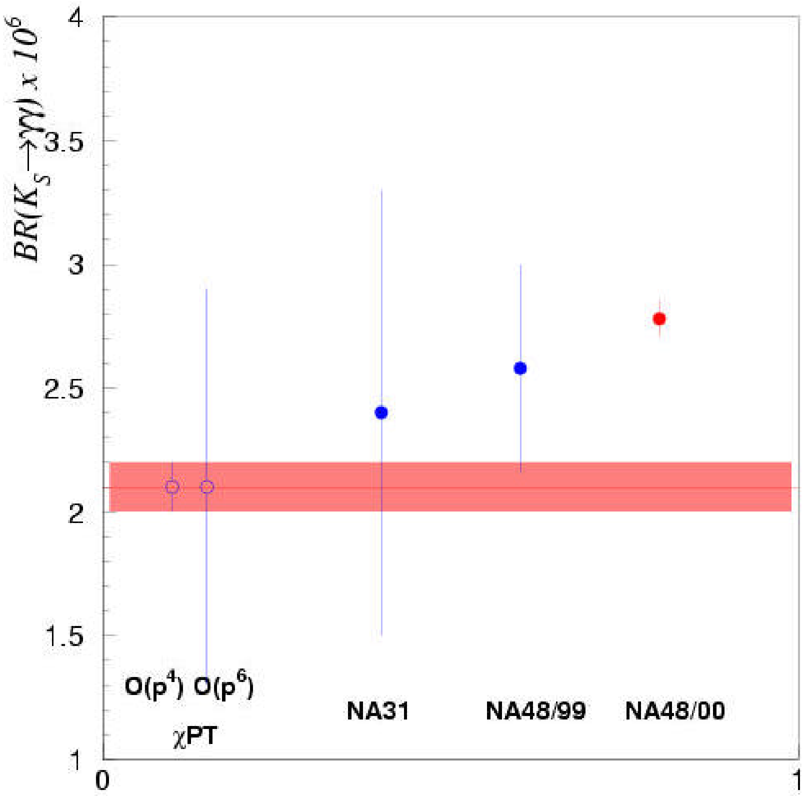
Statistical error ± 2.0 %

Statistical error on MC ± 0.6 %

Preliminary result:

$$BR(Ks \rightarrow \gamma\gamma) = (2.78 \pm 0.06_{st} \pm 0.02_{MCst} \pm 0.06_{sy})*10^{-6}$$

$K_S \rightarrow \gamma\gamma$ – Result



- The NA48 result is compatible with the previous measurements
- It shows 30% difference wrt $O(p^4)$ χPT predictions
- There is an indication for a large $O(p^6)$ contribution

NA48/1 – Phase 2

- Basic motivation is to achieve a SES of $2\text{-}3*10^{-10}$ for the decay $K_S \rightarrow \pi^0 e^+ e^-$
  - Scheduled to run in 2002
  - Asked for 10^{10} ppp $3*10^{10}$ decays in 105 days with 5.2s/16.8s duty cycle
  - Expected SES of $6*10^{-10}$ for 5% acceptance*efficiency with 1999 setup
  - Improvement to the beam and detector will improve SES
  - Expected ~7 events for the improved conditions
- SPS in 2002 will deliver protons to NA48 only for 84 days $\rightarrow$ improved efficiency/few more protons

Beam modifications

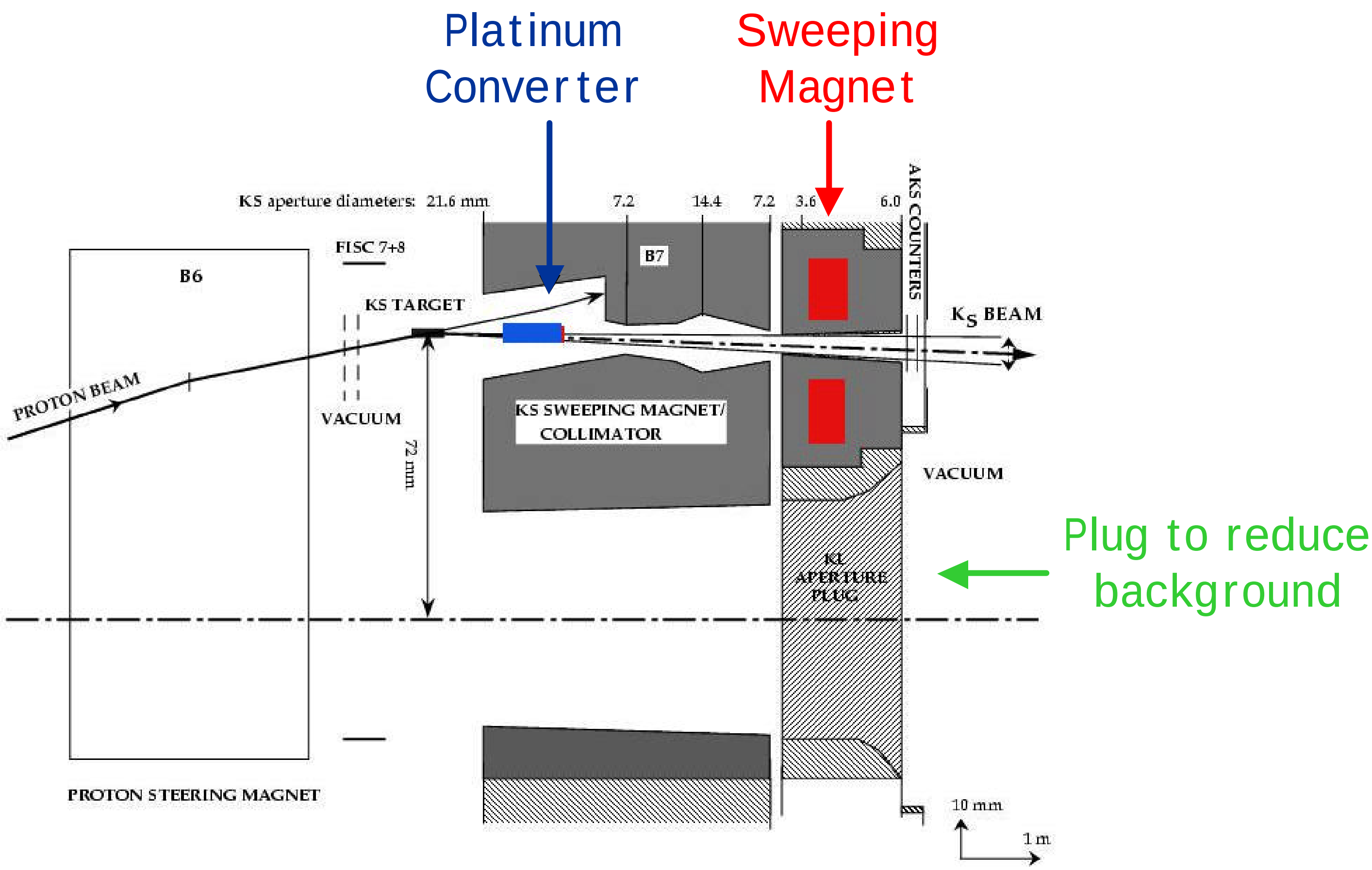
- Upgraded target station
  - Accidental activity measured in 1999 is due to electromagnetic showers generated in the collimator
  - Add a magnetic field in the collimator to sweep out charged particles
  - Add a platinum photon converter downstream of the KS target
  - Accidental reduction of a factor ~2 $\rightarrow$ increase proton intensity to $2*10^{10}$ ppp

Beam/detector modifications

- Upgraded target station
  - Accidental activity measured in 1999 is due to electromagnetic showers generated in the collimator
  - Add a magnetic field in the collimator to sweep out charged particles
  - Add a platinum photon converter downstream of the K_S target
- New Drift Chamber readout
  - Remove overflow losses present in the current readout
    - 30 % overflow in 1999 data
- Upgrade of the LKr readout system
  - New readout mode to gain a factor 2 in the number of events
  - Online PC farm bandwidth upgraded to 1GB/burst

Global increase in SES up to $2*10^{-10}$

Beam modifications



Detector upgrade

- New Drift Chamber readout
  - Remove overflow losses present in the current readout
    - 30 % overflow in 1999 data
- Upgrade of the LKr readout system
  - New format to pack 2 events in one block
  - Factor ~2 gained in the number of events read
  - Online PC farm bandwidth upgraded to 1GB/burst
- Improve on SES by a factor at least 3
  - 1999 configuration: $6 * 10^{-10}$
  - 2002 configuration: $2 * 10^{-10}$

NA48/2 – Motivation

- Measurement of direct CP violation in the decays of charged kaons
  - $K^+ \to \pi^+\pi^+\pi^-$, $K^- \to \pi^-\pi^+\pi^-$, $K^\pm \to \pi^\pm\pi^0\pi^0$
- Study of quark condensate in K_{e4} decay mode measuring the scattering length a_0^0
- Other rare decays of charged kaons
  - $K^\pm \to \pi^\pm(n\gamma)$, $K^\pm \to \pi^\pm\pi^0\gamma$, $K^\pm \to \pi^\pm e^+e^-$
  - $K^\pm \to \pi^\pm\mu\mu$, $K^\pm \to \pi^0 e^\pm\nu\gamma$, ...

Direct CP violation in $K^{\pm}$ decays

- $K^{\pm}$ decay matrix
  - $|M(u,v)|^2 \mu \; 1 + g*u + h*u^2 + k*v^2$
    - u,v Dalitz plot variables $u = (s_3 - s_0)/m_{\pi}^2, v = (s_1 - s_2)/m_{\pi}^2$, where s_3 refers to the odd pion
  - Direct CP violation $\Rightarrow A_g \equiv (g^+ - g^-)/ (g^+ + g^-) \neq 0$
  - Theory predicts values for A_g between 10^{-6} and 10^{-4}
  - $\Delta(A_g) \approx 10^{-4} \approx 3.7*\sqrt{(1/N_+ + 1/N_-)}$
    - Limited mainly by statistics $\Rightarrow 10^{10}$ decays for $\Delta(A_g) \approx 10^{-4}$

Direct CP violation in $K^{\pm}$ decays

- Data taking strategy
  - Measure $$R(u) = \frac{\int dv \left|M^{+}(u,v)\right|^{2}}{\int dv \left|M^{-}(u,v)\right|^{2}} \approx 1 + u * \left(g^{+} - g^{-}\right)$$
  - Data will be taken under the following conditions:
    - Simultaneous K^{+} and K^{-} beams in the same fiducial volume
    - Alternate the spectrometer field to equalise acceptances even if the detector has localised imperfections
    - Ratios are measured in momentum bins and with opposite B polarities. Final average over P and B is independent of acceptances
  - Simulation shows that total systematic error is $\leq 5*10^{-5}$
  - Precision limited by statistics

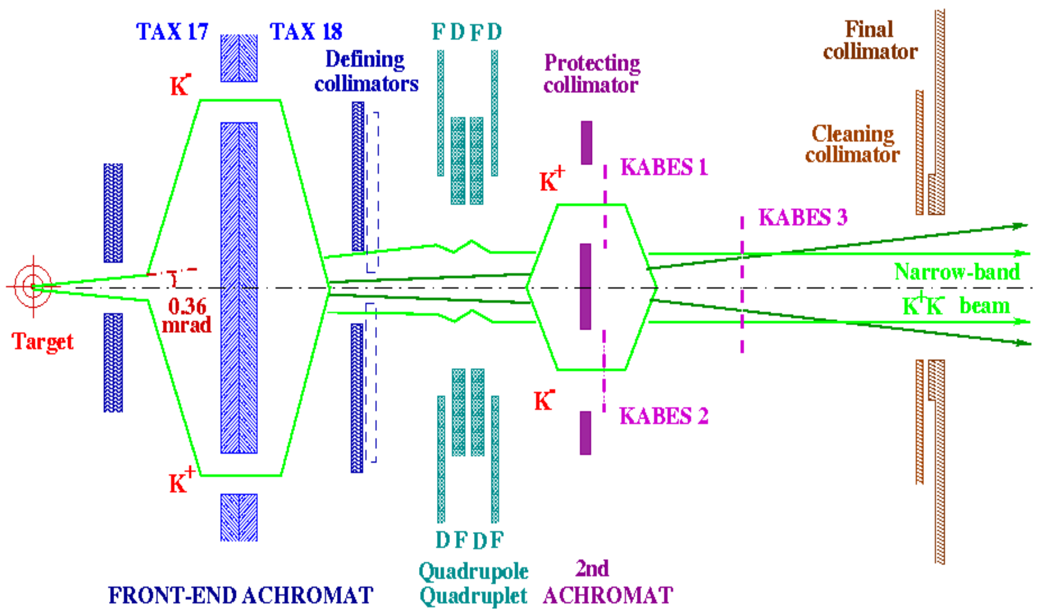
Beam parameters

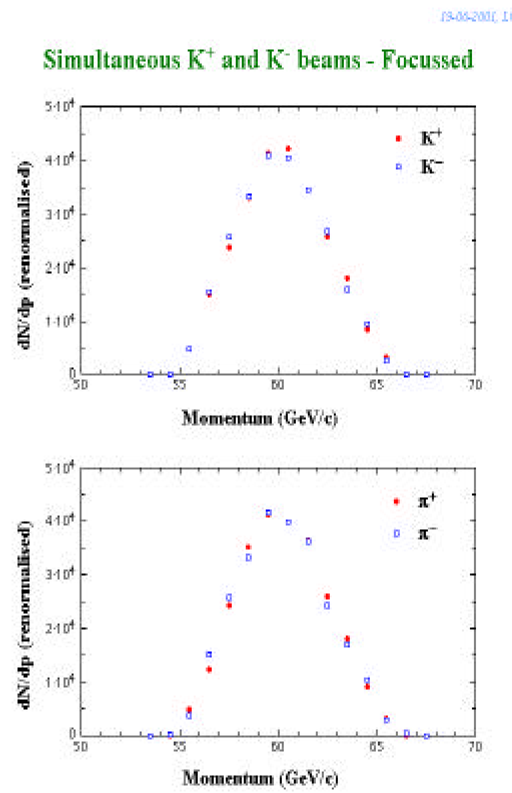
- Simultaneous positive and negative beams
  - Focused beams
  - Narrow band – energy 60 GeV

  - 10^{12} ppp with duty cycle 5.2s/16.8s and 400 GeV energy
  - Kaon flux per pulse: $3.1*10^6$ K^+ and $1.8*10^6$ K^-
  - Kaon decays/year: $7.3*10^9$ K^+ and $4.4*10^9$ K^- with 120 days at 50% efficiency $\rightarrow$ likely to be less

  - Statistical error on $A_g \leq 10^{-4}$
  - Statistical error on $a_0^0 < 0.01$

Simultaneous focused K^+ K^- beams





KAon BEam Spectrometer

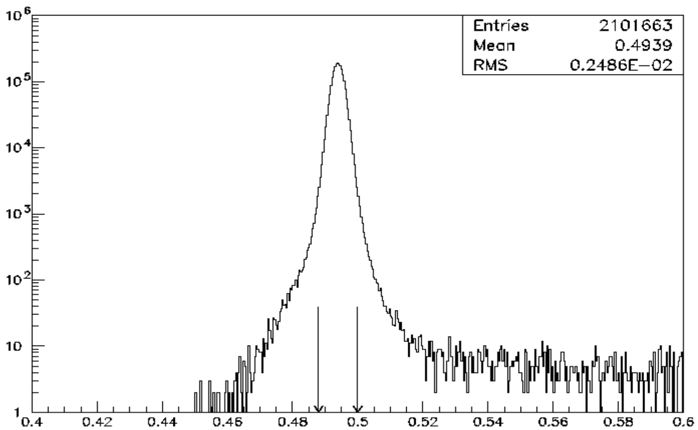
- Purpose
  - Resolve ambiguity in K_{e4} reconstruction
  - Reconstruction of $K^{\pm}$ decays where one pion escaped detection
- Requirements
  - $\delta p/p \approx 1\%$
  - $\theta_{x,y} \leq 2$mrad
  - Expected rate 40 Mhz
  - $\delta t \approx 1$ns
  - $\Delta X/X_0 \approx 10^{-3}$
  - $\delta_{X,Y} \approx 0.25$ mm
- Solution
  - MicroMegas gas chambers with 60 mm drift and 1mm strips, with two coordinate measurement, placed in achromat 2 and downstream

Test run in 2001 - Motivation

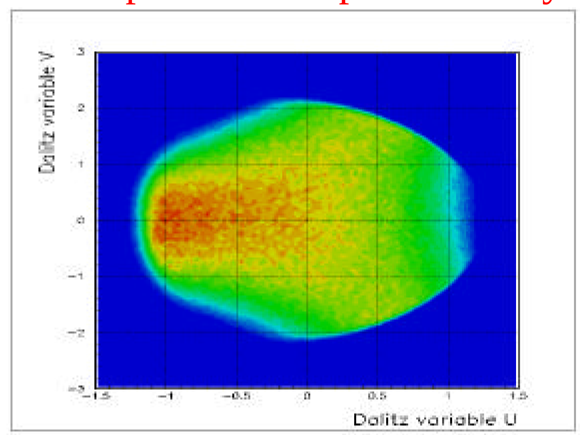
- Few hours of data taking in 2001, using both positive and negative π/K beam with average energy of 60 Gev
- Data taking optimization
  - Optimize pretrigger logic
  - Check rates in the detectors
  - Optimize L2 trigger processor algorithms
  - No restrictions found for rates and trigger inefficiencies
- Practice with data analysis

Test run in 2001 – Results

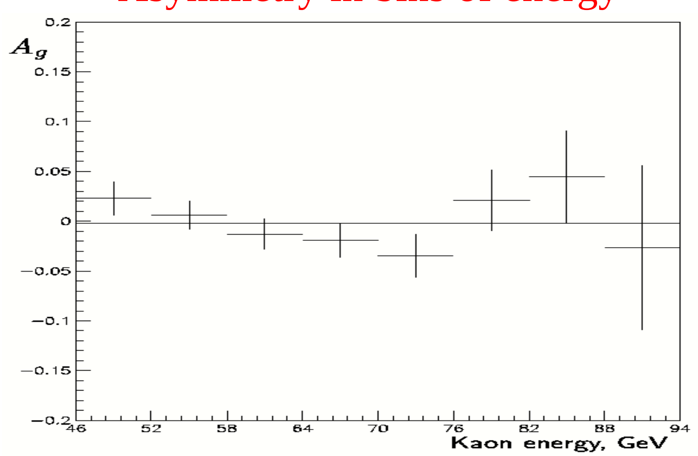
Reconstructed K mass



Dalitz plot for accepted K decays



Asymmetry in bins of energy



Average asymmetry obtained: $(-2\pm7)*10^{-3}$

Best direct measurement (BNL) is $(-7 \pm5)*10^{-3}$

Conclusion

- Data taken during ε'/ε runs have been used for rare decay studies
  - Many channels analyzed, work still in progress
  - Some of them published, but all used for theses
- High intensity K_S proposal already operational
  - Neutral only run in 2000
  - New result on $K_S \rightarrow \gamma\gamma$ announced today
  - Analysis on $K_S \rightarrow \pi^0\gamma\gamma$ and $Ks \rightarrow 3\pi^0$ is progressing
  - 2002 data taking for $K_S \rightarrow \pi^0 e^+ e^-$ will start in 20 days
- Charged kaon proposal
  - Ready for 2003
  - No problems spotted in a test run done in 2001