The final NA48 result on direct CP violation

Massimo Lenti
INFN Firenze

June 25, 2002
EP Seminar, CERN

On behalf of the NA48 Collaboration:
Cagliari Cambridge CERN Dubna Edinburgh
Ferrara Firenze Mainz Orsay Perugia Pisa Saclay
Siegen Torino Vienna Warsaw

.

Plan of the presentation

- Physics motivation
- The 2001 run
- Analysis of 2001 data
- 2001 result and comparison with 97+98+99 value
- Combined result and conclusions

Physics motivation

Strangeness eigenstates:

$$\mathrm{K}^0(\bar{\mathrm{s}}\mathrm{d}) \quad (S=+1)$$
$$\overline{\mathrm{K}^0}(\mathrm{s}\bar{\mathrm{d}}) \quad (S=-1)$$

CP eigenstates:

$$\mathrm{K}_1 = (\mathrm{K}^0 + \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=+1)$$
$$\mathrm{K}_2 = (\mathrm{K}^0 - \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=-1)$$
$$\pi^+\pi^-, \pi^0\pi^0 \quad (CP=+1)$$

Mass and Lifetime eigenstates:

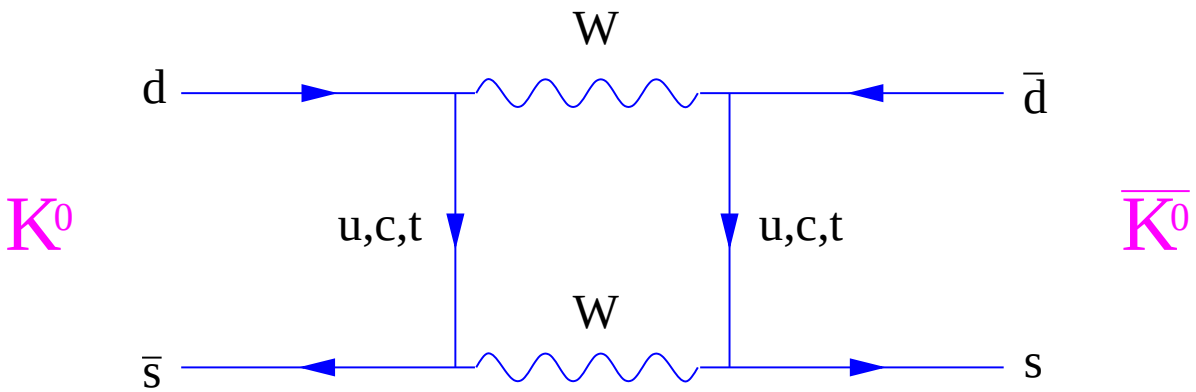
$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \quad (\mathrm{c}\tau_\mathrm{S} = 2.67 \text{ cm})$$
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \quad (\mathrm{c}\tau_\mathrm{L} = 15.5 \text{ m})$$

$\mathrm{K_S}$		$\mathrm{K_L}$	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

$$\varepsilon = (2.27 \pm 0.02) \times 10^{-3}$$

Physics motivation, contd.

$\varepsilon \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing



Is there also a component of CP violation in the decay process?

$$K_L = K_2^{-1} + \varepsilon\, K_1^{+1} \qquad \pi^+\pi^-,\ \pi^0\pi^0$$

$$\mathrm{CP} = +1$$

Need interference of two decay amplitudes

$\pi\pi$ from K^0 can have I=0,2 $\Rightarrow$ amplitudes A_0, A_2

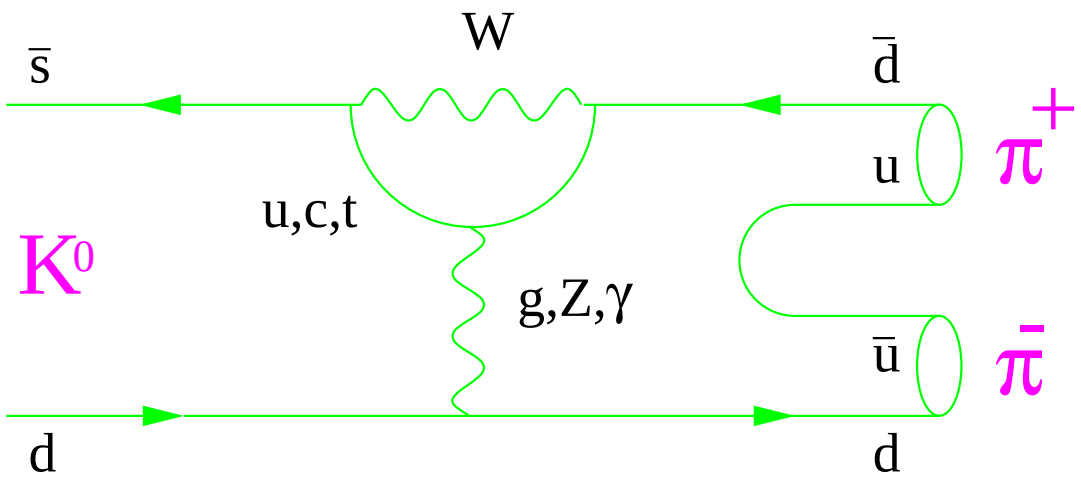
$$A(K^0 \rightarrow \pi\,\pi\,, I) = A_I \exp(i\delta_I)$$

$$A(\overline{K^0} \rightarrow \pi\,\pi\,, I) = A_I^* \exp(i\delta_I)$$

$$\varepsilon' = \frac{i}{\sqrt{2}} \mathfrak{Im} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0))$$

Physics motivation, contd.

$\varepsilon' \Rightarrow$ Direct CP violation:



$$\eta_{+-} \equiv \frac{A(\mathrm{K_L} \to \pi^+\pi^-)}{A(\mathrm{K_S} \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(\mathrm{K_L} \to \pi^0\pi^0)}{A(\mathrm{K_S} \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

$$\mathrm{R} = \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)/\Gamma(\mathrm{K_S} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)/\Gamma(\mathrm{K_S} \to \pi^+\pi^-)} \simeq 1 - 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

IF the 4 modes are taken

- simultaneously
- in the same decay region

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

Experimental results on $\mathrm{Re}(\varepsilon'/\varepsilon)$

First generation of experiments:

- NA31: $(23.0 \pm 6.5) \times 10^{-4}$;
- E731: $(7.4 \pm 5.9) \times 10^{-4}$;

Second generation of experiments:

- KTEV:
  $(28.0 \pm 4.1) \times 10^{-4}$ (96 data, published result)
  $(20.7 \pm 2.8) \times 10^{-4}$ (96+97 data, preliminary)
- NA48: $(15.3 \pm 2.6) \times 10^{-4}$ (97+98+99 data)

World average: $(17.2 \pm 1.8) \times 10^{-4}$, $\chi^2/\mathrm{ndf}=5.5/3$

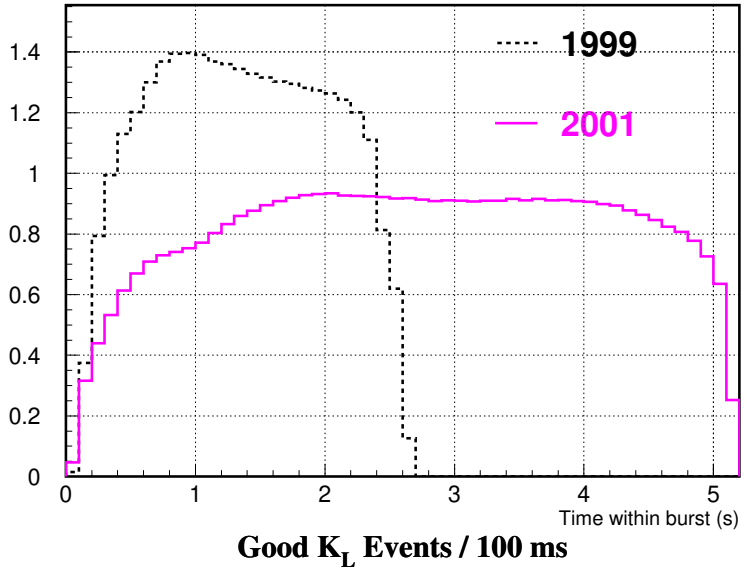
Typical theoretical predictions:
from -1×10^{-3} to about 4×10^{-3}
but recently new lattice calculation appeared:
$-7 \div -2 \times 10^{-4}$ [CP-PACS collaboration]
$-8 \div -4 \times 10^{-4}$ [RBC collaboration]

A little bit of NA48 history

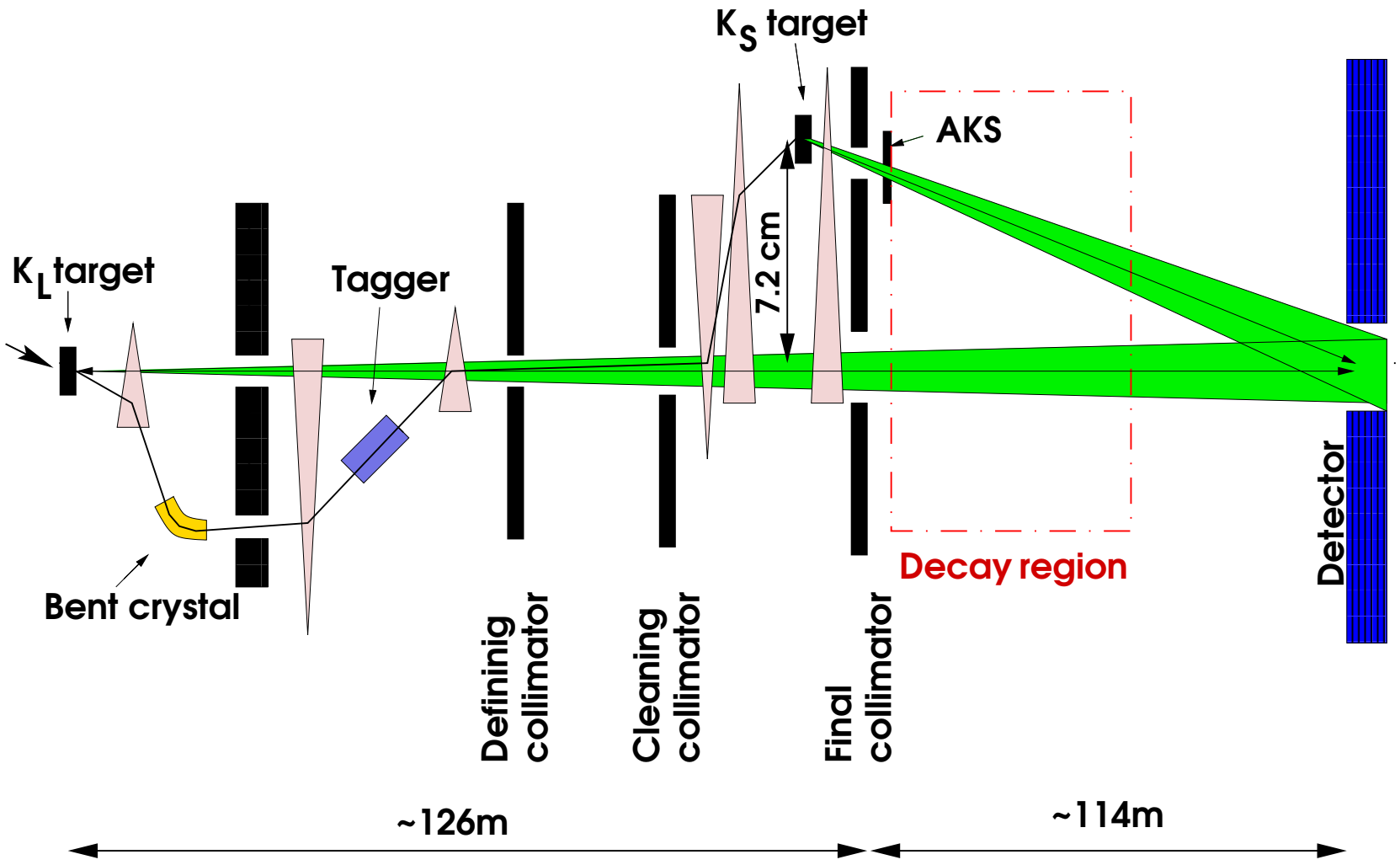
- 1990: NA48 proposal
- 1997: ≈ 0.5 million $K_L \to \pi^0\pi^0$
  Result published in 1999
- 1998: ≈ 1 million $K_L \to \pi^0\pi^0$
  Several improvements (trigger, DAQ, LKr)
- 1999: ≈ 2 million $K_L \to \pi^0\pi^0$
  Further improvements in trigger and DAQ
  better data taking efficiency
- November 1999: Beam tube implosion $\Rightarrow$
  Drift chambers damaged
- 2000: only neutral events data (cross-checks + high intensity K_S runs)
- 2000-2001: Drift chambers being repaired
- 2001: ≈ 1.5 million $K_L \to \pi^0\pi^0$
  - Different beam conditions
    $\Rightarrow$ better duty cycle
    $\Rightarrow$ lower instantaneous intensity
  - Lower dead time

Changed conditions

	98-99	2001
proton momentum	450 GeV/c	400 GeV/c
SPS cycle time	14.4 s	16.8 s
spill length (effective)	2.4 s (1.7 s)	5.2 s (3.6 s)
duty cycle	0.17	0.31
K_L beam intensity	$\approx 1.5 \times 10^{12}$ ppp	$\approx 2.4 \times 10^{12}$ ppp
K_S beam intensity	$\approx 3 \times 10^{7}$ ppp	$\approx 5 \times 10^{7}$ ppp



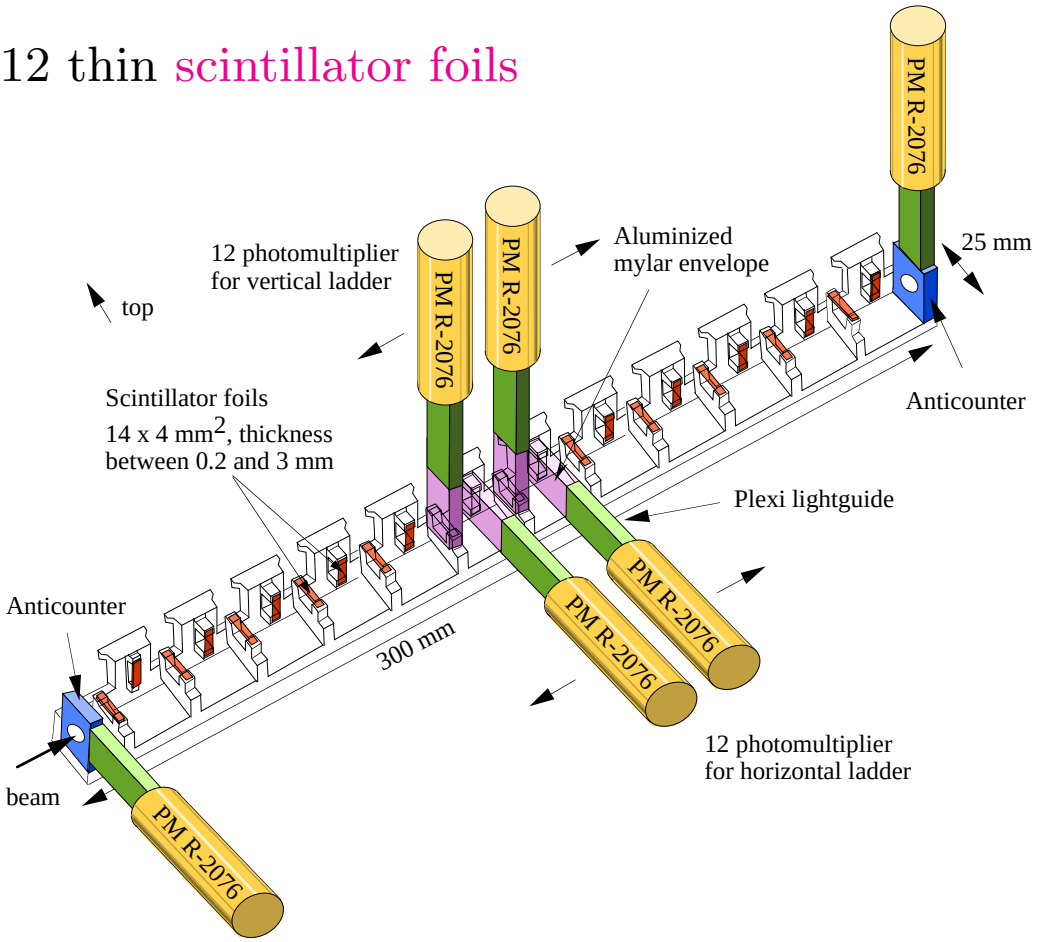
Simultaneous and collinear K_L and K_S beams



K_S and K_L are distinguished by proton tagging upstream of the K_S target

The K_S proton tagger

2×12 thin scintillator foils



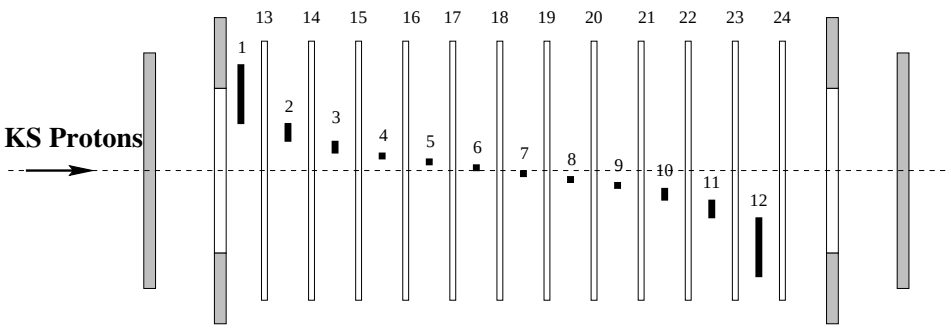
Proton rate: $\approx$ 30 MHz

$\rightarrow$ split the intensity between foils

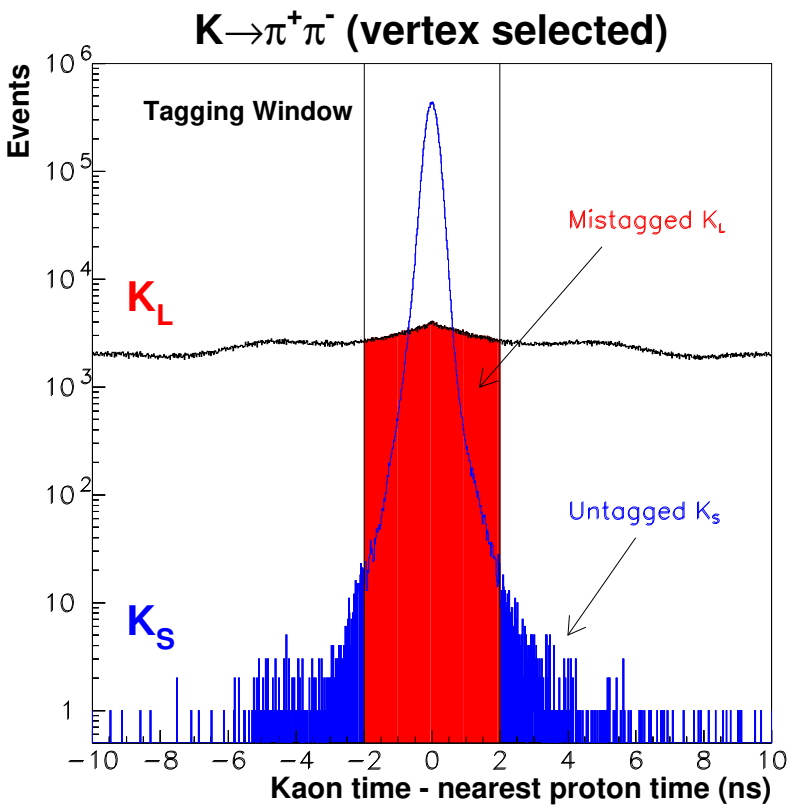
readout by Flash-ADC 8 bits at 960 MHz

$\Rightarrow$ Time resolution: 140 ps

$\Rightarrow$ Double pulse separation: 4 ns



Tagging



IF at least one proton is in coincidence (within ± 2 ns) with the event time
$\Rightarrow$ identified as K_S

ELSE $\Rightarrow$ identified as K_L

Tagging inefficiency
$P(K_S \rightarrow K_L) : \alpha_{SL}^{+-} = (1.12 \pm 0.03) \times 10^{-4}$

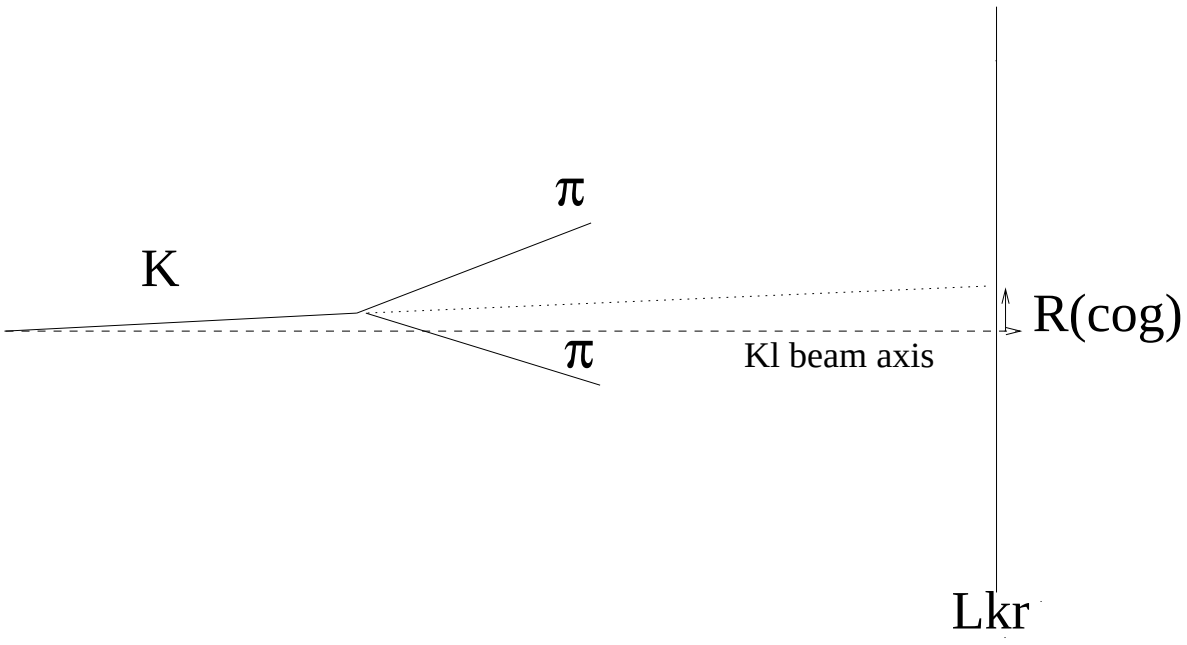
Accidental tagging
$P(K_L \rightarrow K_S) : \alpha_{LS}^{+-} = (8.115 \pm 0.010)\%$
(it was $(10.649 \pm 0.008)\%$ in 98-99)

In the Double Ratio we account for the accidental tagging

Decay region definition

- $0 \leq \tau \leq 3.5$
  - τ = proper time along the beam axis, in K_S lifetime units
  - $\tau = (z_{vertex} - z_0) \frac{M_K}{E_K} \frac{1}{c\tau_{K_S}}$
  - For K_S beginning of decay region is defined by AKS anticounter
- $70 \leq E_K \leq 170$ GeV (K_L/K_S variations$< 20\%$)
- Centre of gravity $R_{COG} \leq 10$ cm

R_{COG} is the K impact point extrapolated to the calorimeter



Lifetime weighting principle

At the same z $\Rightarrow$ Acceptance K_S $= K_L$

But very different decay lenghts: $\tau_{K_L} \approx 600 \times \tau_{K_S}$

$\Rightarrow$ Different total acceptance for K_S and K_L

$\Rightarrow$ large correction on R

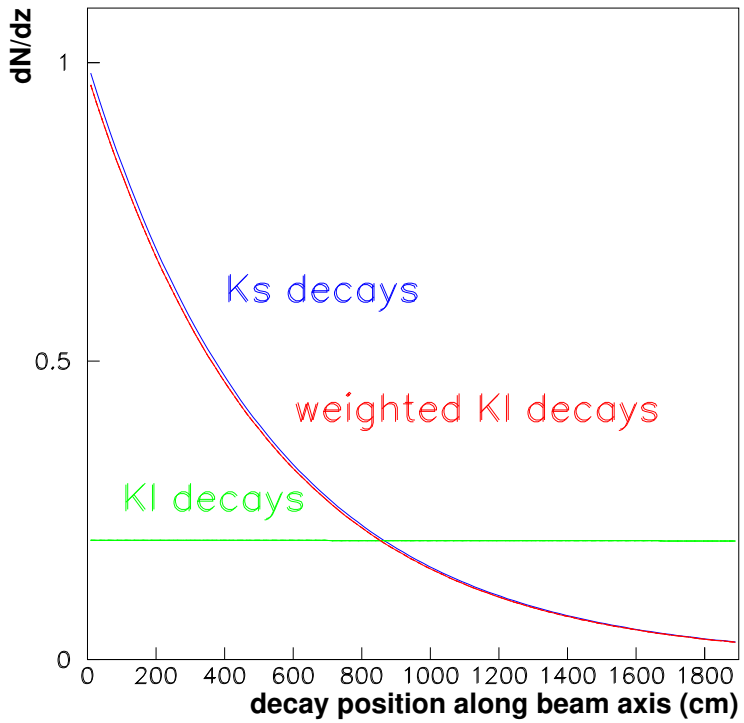
Solution: Weight K_L events with:

$$\frac{\pi\pi \text{ decay rate in } K_S}{\pi\pi \text{ decay rate in } K_L} \approx e^{\frac{-z}{\beta\gamma c}\left(\frac{1}{\tau_{K_S}} - \frac{1}{\tau_{K_L}}\right)} \approx e^{-z/(\beta\gamma c \tau_{K_S})}$$

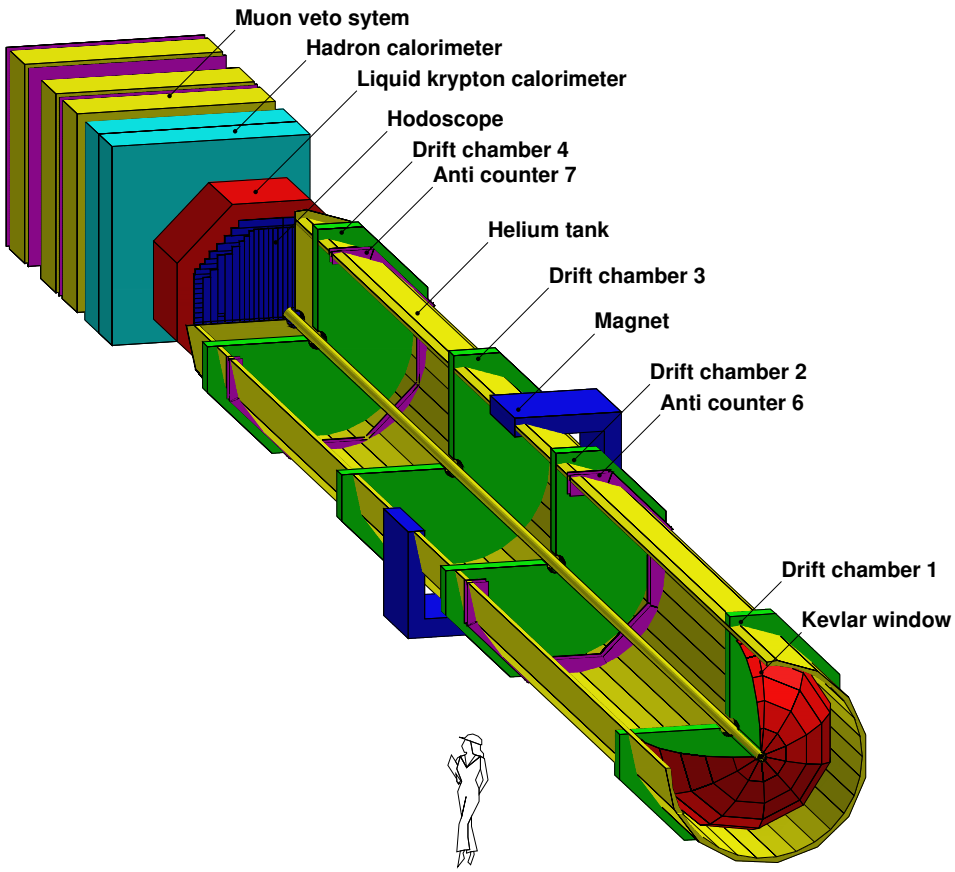
Same decay vertex distribution for K_S and weighted K_L

Acceptance correction cancels

Price: Increase in statistical error ($\approx 35\%$)



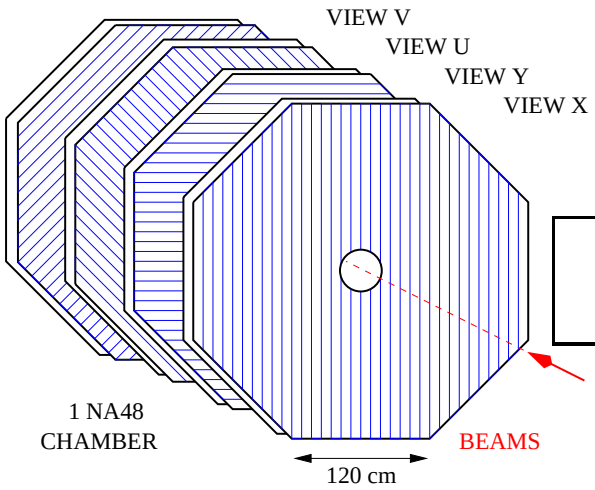
NA48 detectors



- $K_{L,S} \to \pi^+\pi^-$
  - magnetic spectrometer (rebuilt after November 1999 accident)
  - scintillators hodoscope
- $K_{L,S} \to \pi^0\pi^0$
  - quasi-homogeneous Liquid Krypton e.m. calorimeter
  - scintillating fibers hodoscope

Magnetic Spectrometer

$2+2$ drift chambers + magnet $\rightarrow$ 265 MeV p_t kick

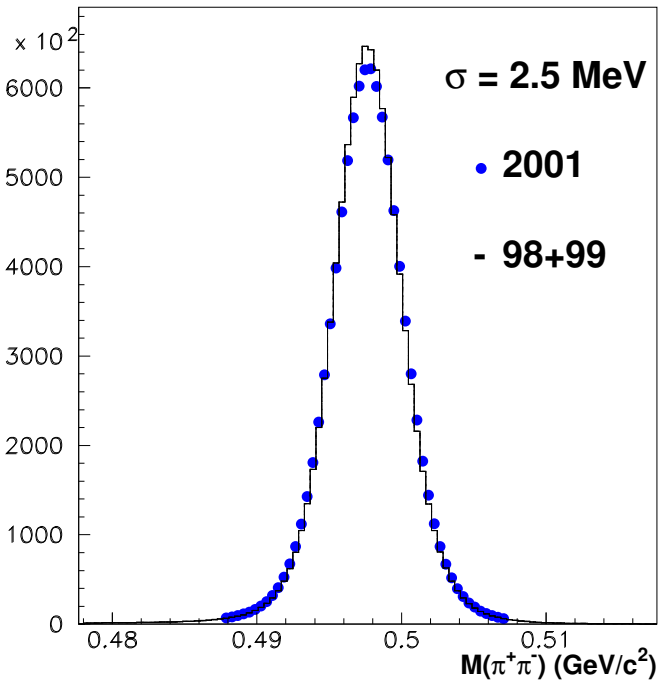


plane efficiency: 99.5%

space resolution: 95 μm

$$\frac{\sigma(p)}{p} \simeq 0.5\% \oplus 0.009\ p\%$$

p in GeV/c



Background rejection:

No hits in the μ counters

$E/p < 0.8$

$|M_{\pi\pi} - M_K| < 3\sigma$

$\frac{|p_1 - p_2|}{p_1 + p_2} < f(E_K)$

$P'_T \Rightarrow \mathrm{K_L} - \mathrm{K_S}$ "symmetric" transverse momentum:

P_K component $\perp$ line target $\leftrightarrow$ K^0 X-point at DCH1

$P'^2_T < 200\ (\mathrm{MeV/c})^2$

$\pi^+\pi^-$ Reconstruction

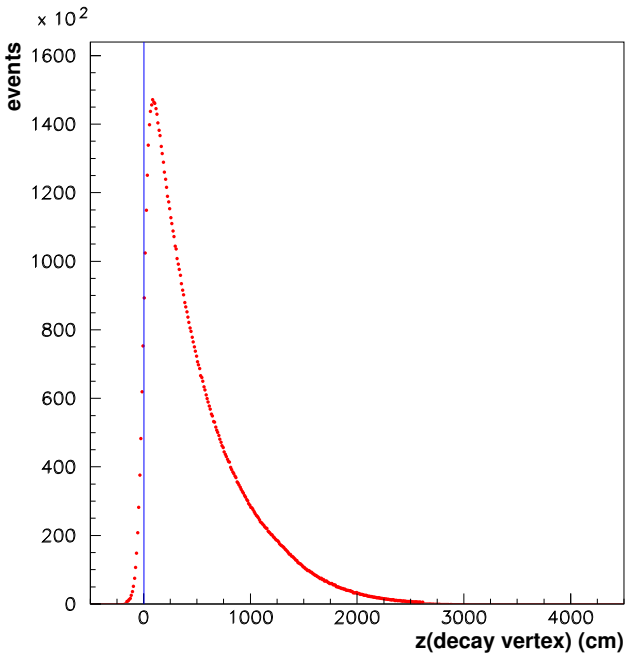
K^0 energy in $\pi^+\pi^-$ decay

$\Rightarrow$ opening angle and tracks energy ratio

$E_K^2 = (C/\theta^2)\left\{m_K^2 - C\ m_\pi^2\right\}$

$C = 2 + E_{\pi 1}/E_{\pi 2} + E_{\pi 1}/E_{\pi 2}$

$\Rightarrow$ geometry of the drift chambers

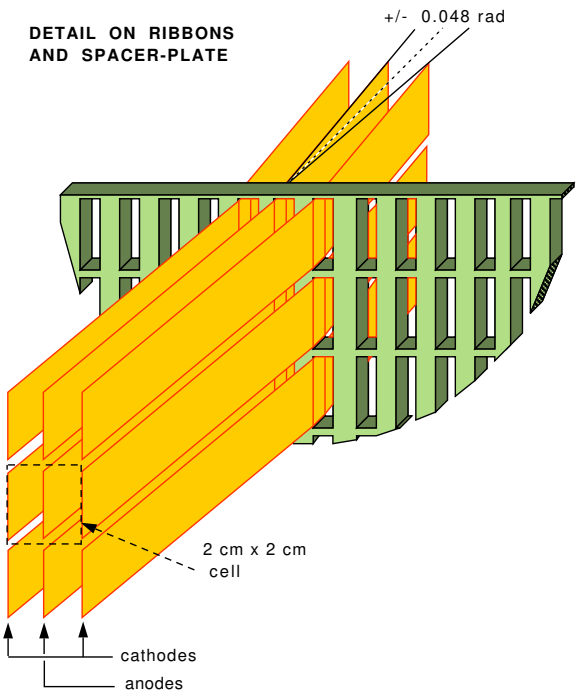


check of geometry: reconstruct the AKS position in $K_S \to \pi^+\pi^-$

$\Rightarrow |\Delta z| < 1$ cm

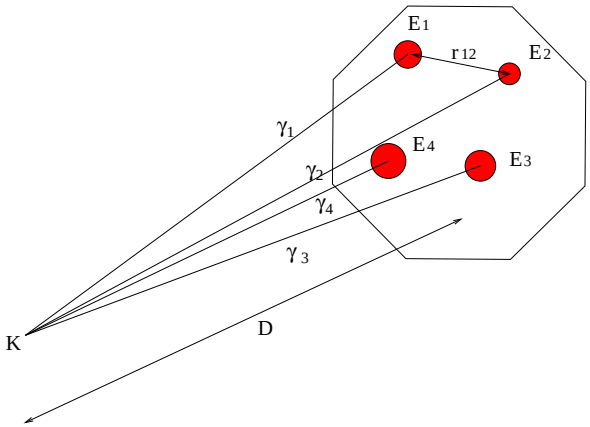
Liquid Krypton Calorimeter

- Quasi-homogeneous detector: 10 m^3 lkr ($X_0 = 4.7$ cm)
- 13212 cells
  - Granularity $2 \times 2 cm^2$
  - Depth 1.25 m ($\approx 27\ X_0$)
- Projective geometry pointing to decay region ($\approx$ 114 m upstream)
- Accordion geometry



$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.42\% \quad \text{(E in GeV)}$$

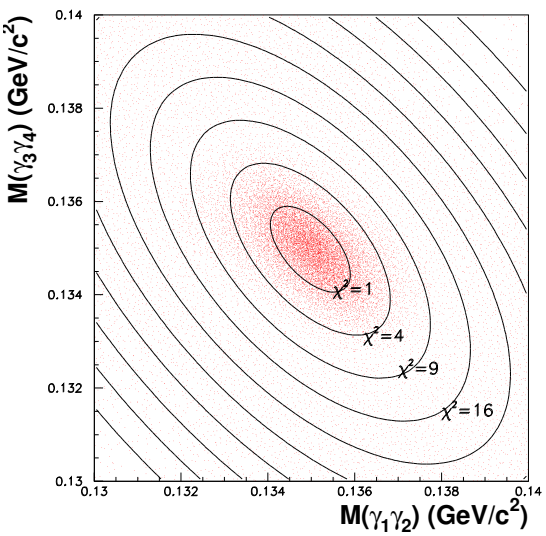
$K^0 \rightarrow 2\ \pi^0 \rightarrow 4\gamma$

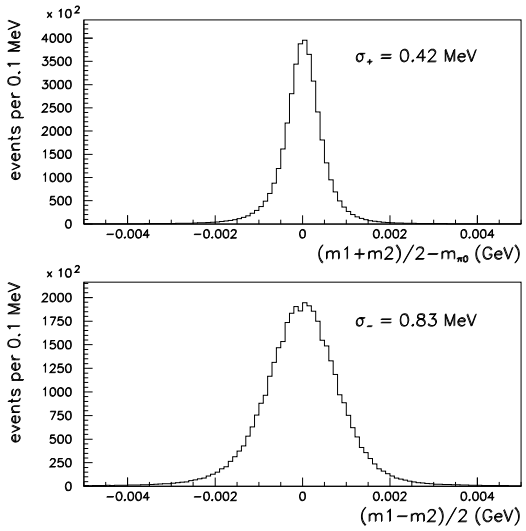


$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K}$$

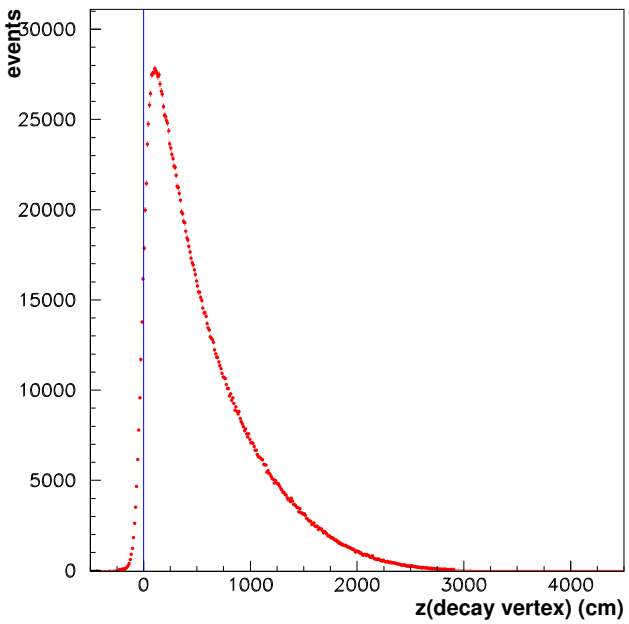
$$m_{ij} = \frac{\sqrt{E_i E_j} \cdot r_{ij}}{D}$$

$\pi^0\pi^0$ Reconstruction





- Cut on χ^2 from π^0 masses
- Veto events with 5th cluster in time

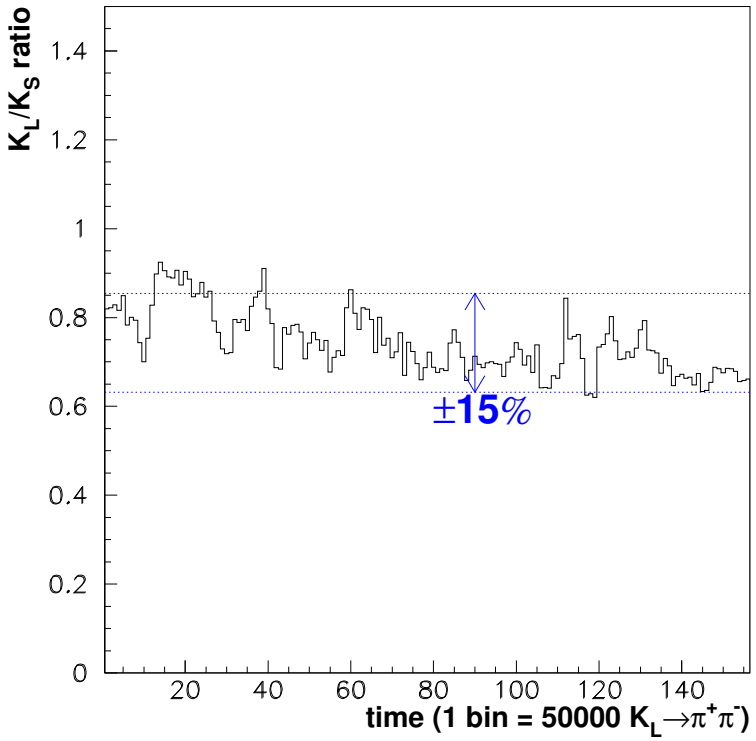


Use K_S events to adjust energy scale $\Rightarrow$ match the AKS nominal position

energy$\Rightarrow$geometry

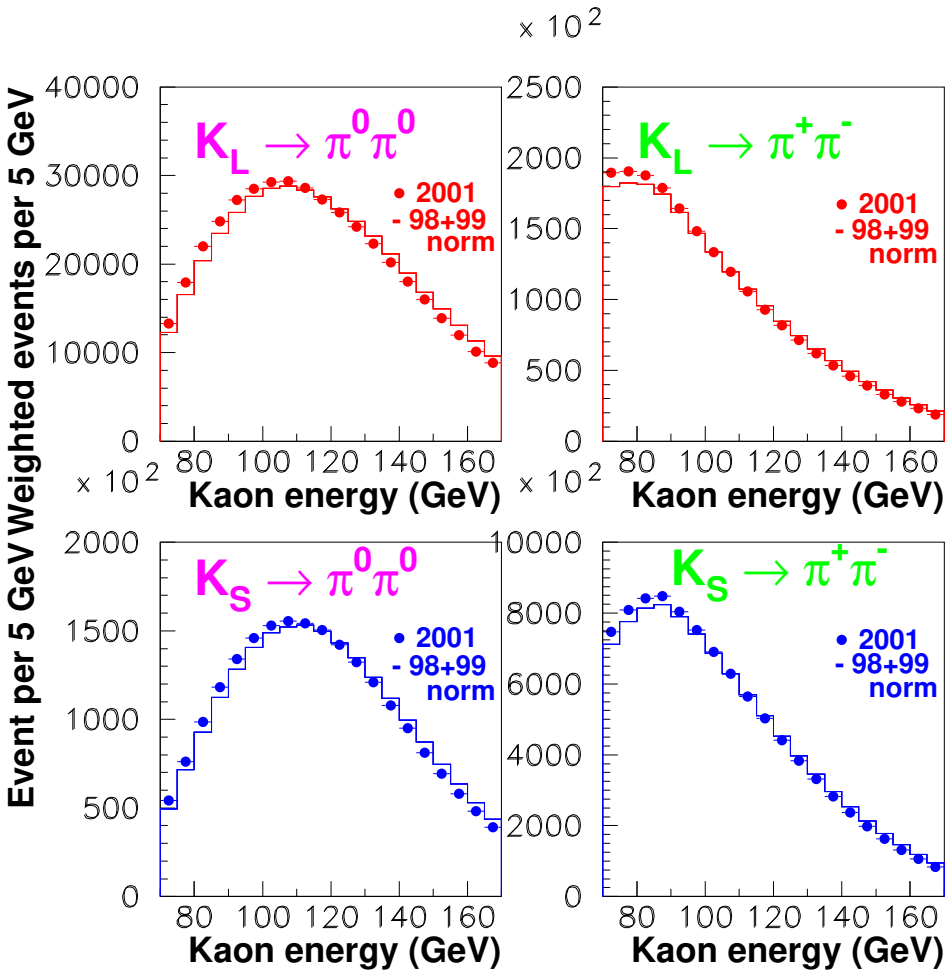
Final Analysis Strategy

- Measure R in Kaon energy bins (5 GeV wide)
  $\Rightarrow$ insensitive to $K_S - K_L$ energy spectrum difference
- Record dead time conditions
  $\approx 0.3\%$ from $\pi^+\pi^-$ trigger (it was 1.5% in 98-99)
  $\approx 11\%$ from drift chamber multiplicity limit
  (it was 20% in 98-99)
  and apply them offline to all events
- Account for K_S/K_L variations
  $\Rightarrow$ reweight K_S events to keep K_S/K_L constant
  $\Rightarrow$ cancel bias due to occasional coupling of K_S/K_L and neutral/charged variation



- The first 200 ms where not used for the 2001 analysis due to the very strong beam structure

Data Sample



2001 Statistics:
(corrected for mistagging)

$K_L \to \pi^0\pi^0$: 1.55×10^6, $K_S \to \pi^0\pi^0$: 2.16×10^6
$K_L \to \pi^+\pi^-$: 7.14×10^6, $K_S \to \pi^+\pi^-$: 9.61×10^6

Corrections

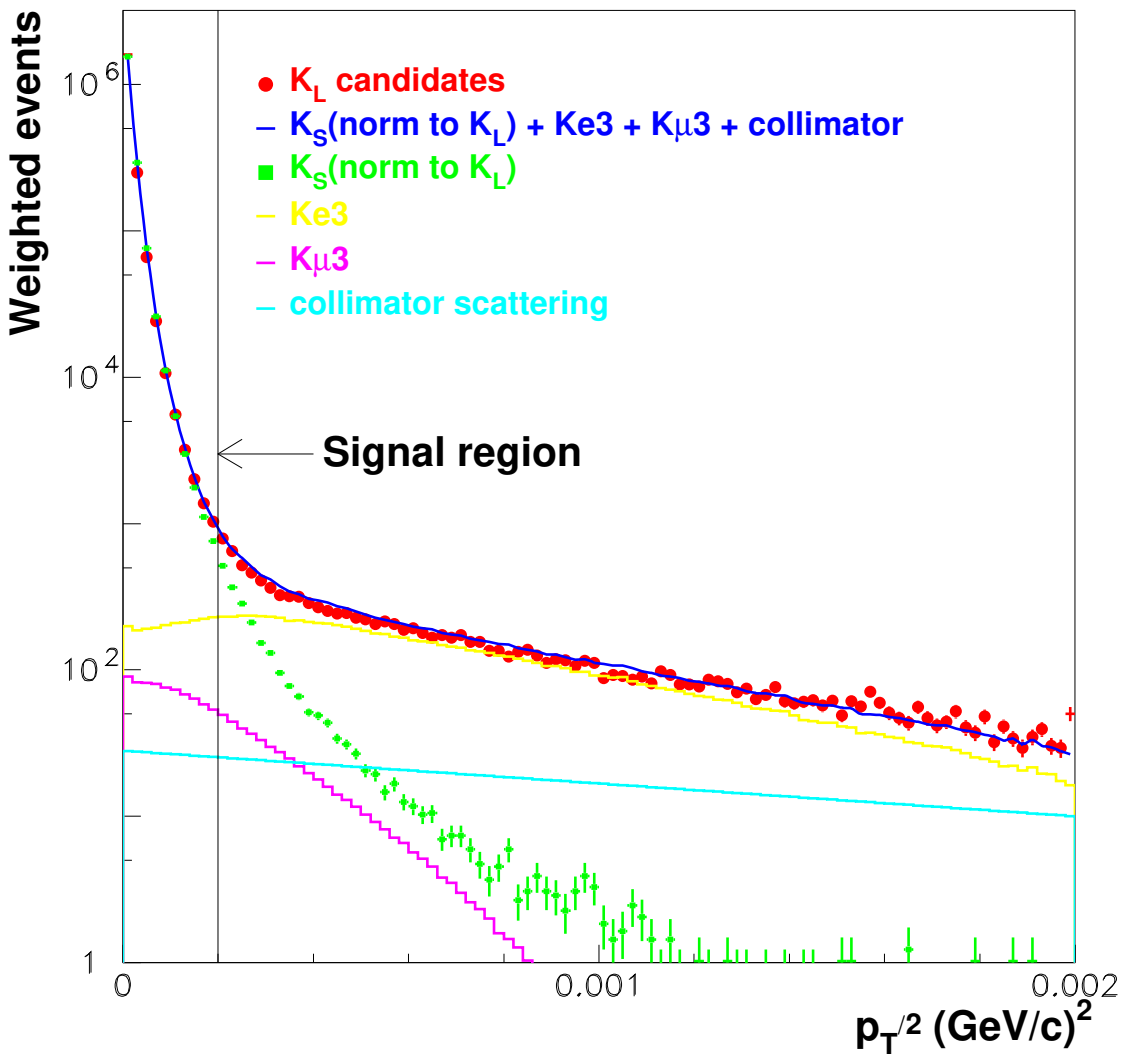
Corrections to be applied

- Charged Background
- Neutral Background
- Beam Scattering Background
- Tagging (Neutral-Charged difference)
- Triggers inefficiency
- AKS veto inefficiency
- Energy scale uncertainty
- Acceptance
- Accidental activity induced losses

$\pi^+\pi^-$ background subtraction

The residual K_L background is estimated:

- using control region in $M_{\pi\pi}$ and $P_T'^2$;
- using sample of identified $Ke3$ and $K\mu3$ decays



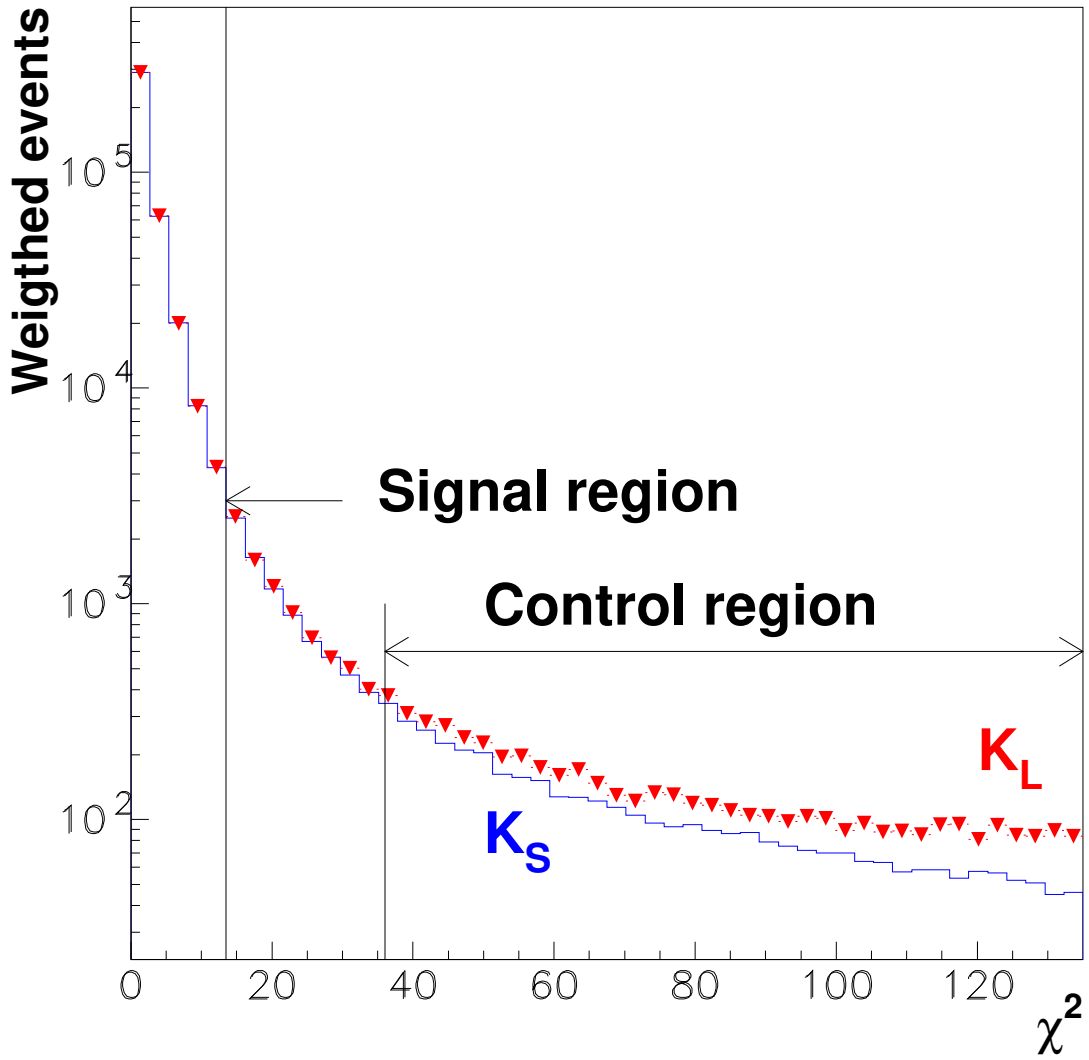
$$\text{Background} = (14.2 \pm 3.0) \times 10^{-4}$$

(systematic error: variation of control regions, modelling of $P_T'^2$ shape)

$\pi^0\pi^0$ background subtraction

The residual K_L background is estimated:

- using control region in χ^2
  ($3\pi^0$ background is almost flat)
- using K_S events to evaluate resolution tails



Background $= (5.6 \pm 2.0) \times 10^{-4}$

(systematic error: uncertainty in background extrapolation from MC)

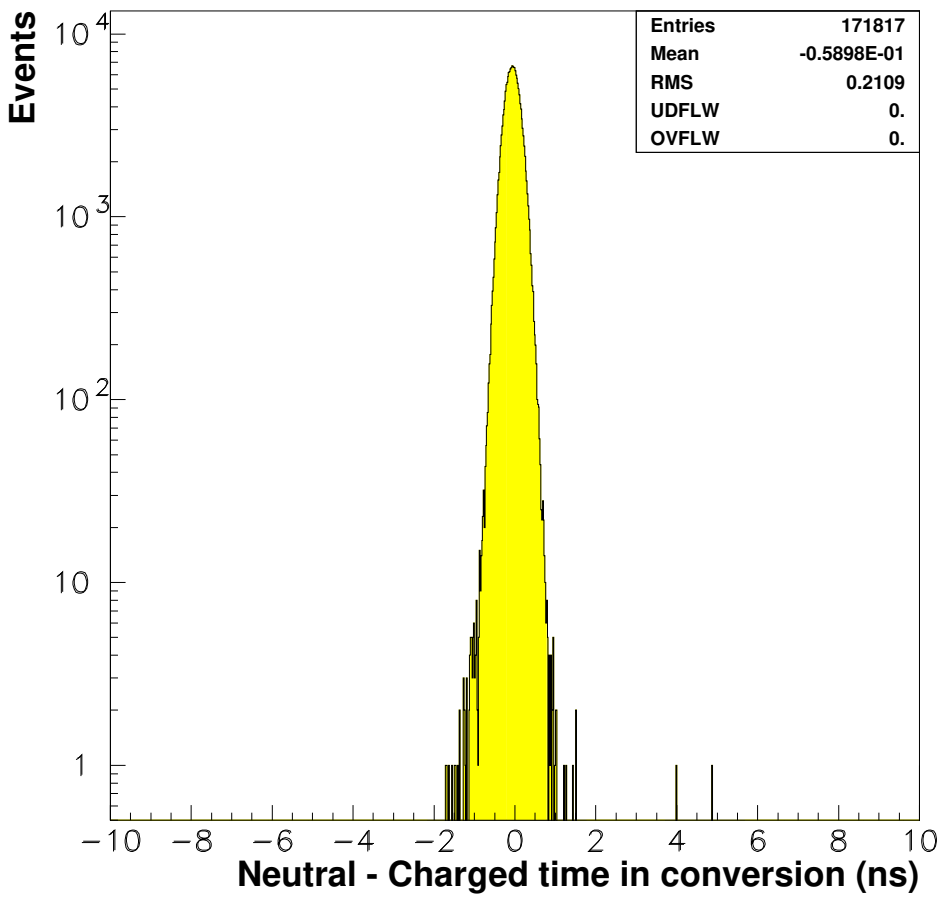
Tagging Inefficiency

$\mathrm{P}(\mathrm{K_S} \rightarrow \mathrm{K_L}) : \alpha_{\mathrm{SL}}^{+-} = (1.12 \pm 0.03) \times 10^{-4}$

$\alpha_{\mathrm{SL}}^{+-}$ dominated by tagger inefficiency
($\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric)

$\Delta\alpha_{\mathrm{SL}} = \alpha_{\mathrm{SL}}^{00} - \alpha_{\mathrm{SL}}^{+-} \Rightarrow$ Difference in tails between $\pi^+\pi^-$ and $\pi^0\pi^0$ event time measurements

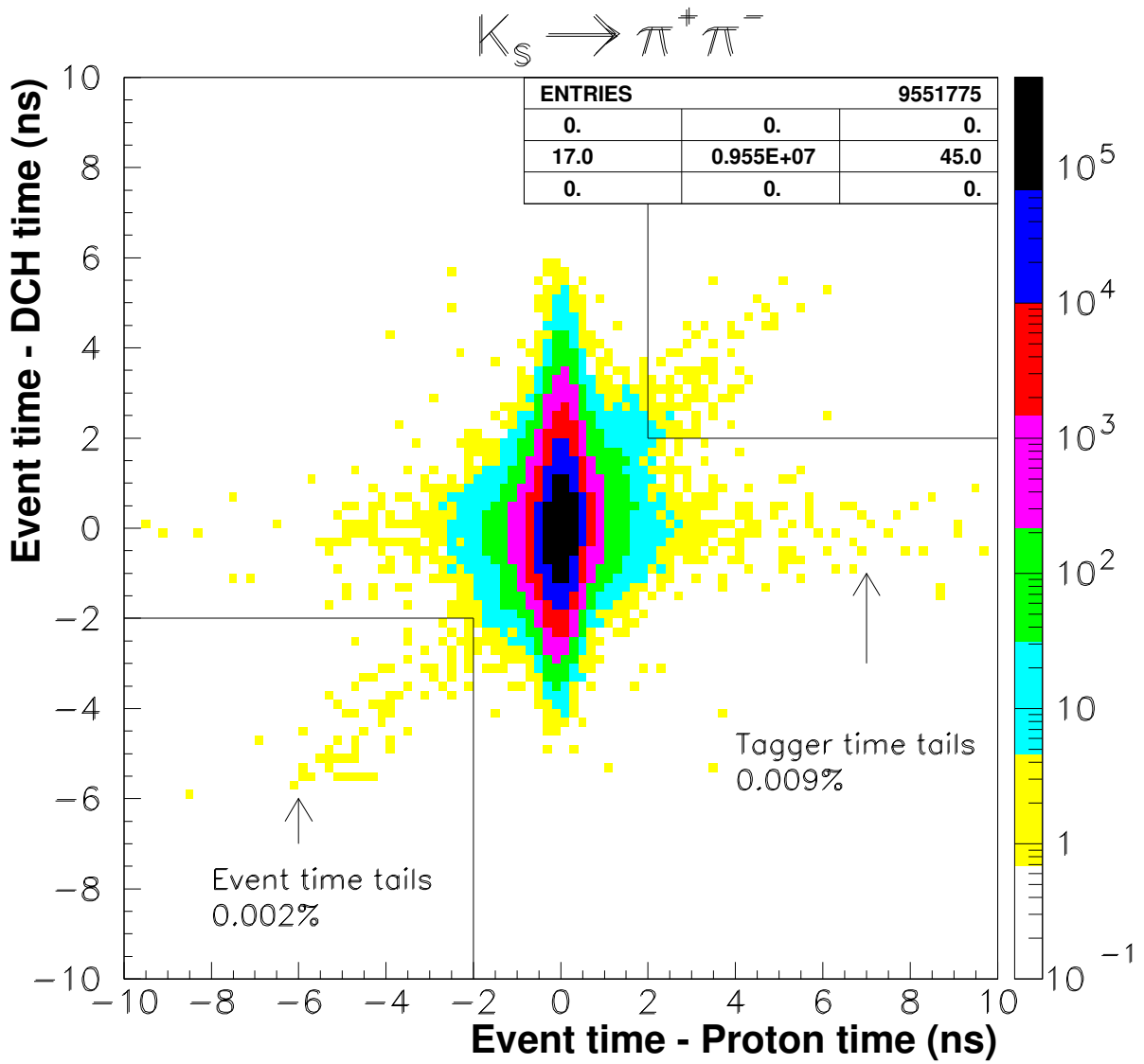
$\Rightarrow$ Compare directly charged and neutral measurements using events with γ's and e^+e^-



$$\Delta\alpha_{\mathrm{SL}} = (0 \pm 0.5) \times 10^{-4}$$

$$\boxed{\Delta \mathrm{R} = (0 \pm 3.0) \times 10^{-4}}$$

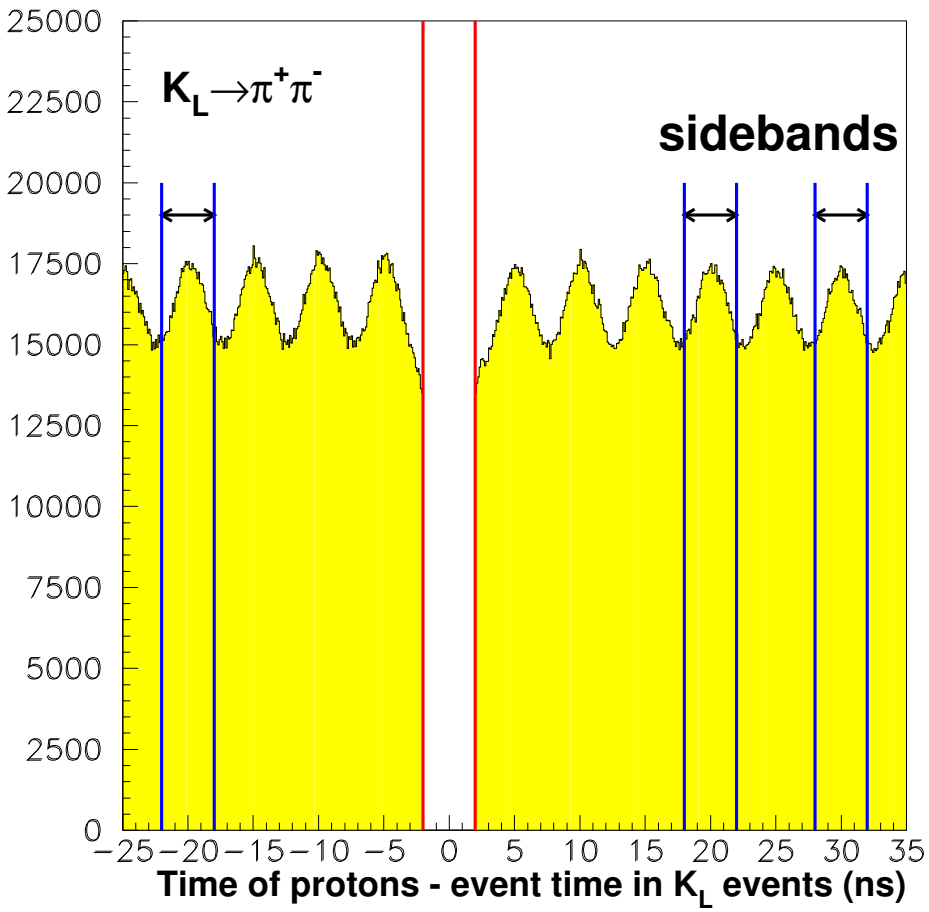
Tagging: time measurement tails



Accidental Tagging

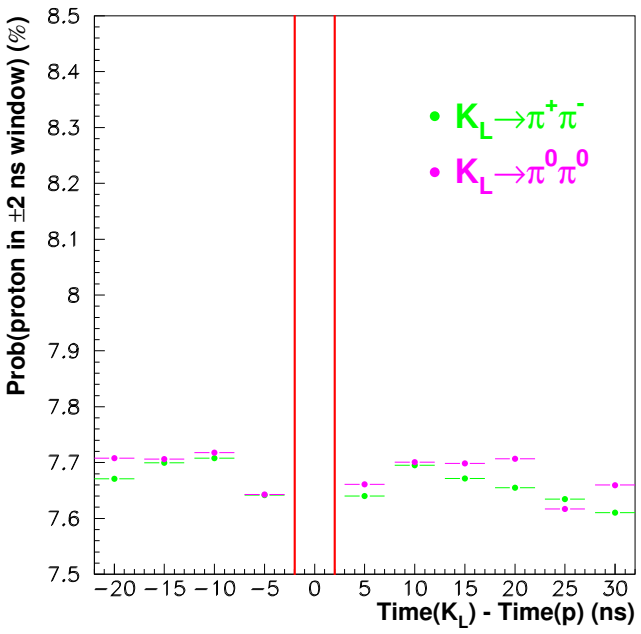
$P(K_L \rightarrow K_S) : \alpha_{LS}^{+-} = (8.115 \pm 0.010)\%$

α_{LS} comes from accidental coincidence in tagger
it should depend only on proton intensity
$\Rightarrow$ estimate $\Delta\alpha_{LS} = \alpha_{LS}^{00} - \alpha_{LS}^{+-}$ using
coincidence rate in tagging windows offset from
the event time ("sidebands")

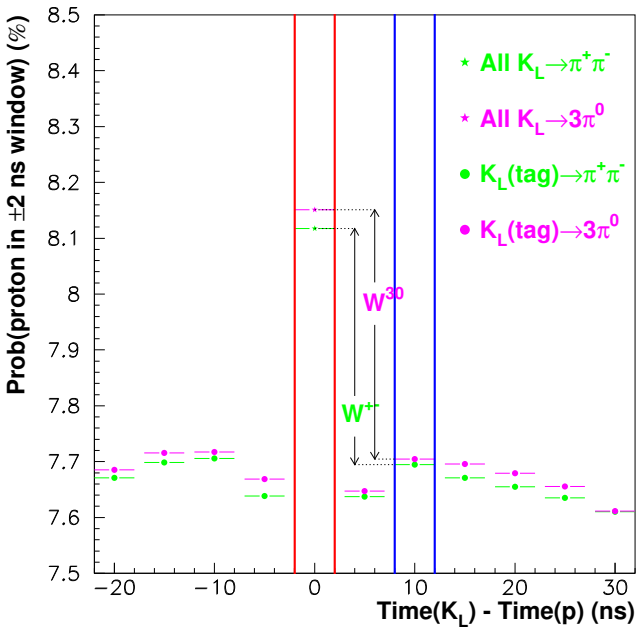


This is done for events tagged as K_L
(no proton in the central window)

Accidental Tagging, cont'd



Using sidebands of tagger selected K_L to $\pi^0\pi^0$ and $\pi^+\pi^-$:
$\Delta\alpha_{LS}^{\text{sidebands}} = (2.1 \pm 0.7) \times 10^{-4}$



Extrapolation to central window (W)
$\pi^+\pi^-$: use vertex selected K_L
$\pi^0\pi^0$: use $3\pi^0$ events (only K_L)
$\Delta W = (1.3 \pm 1.3) \times 10^{-4}$

$$\Delta\alpha_{LS} = (3.4 \pm 1.4) \times 10^{-4}$$

$$\boxed{\Delta R = (6.9 \pm 2.8) \times 10^{-4}}$$

Triggers inefficiency

Rate of K_L decays $\approx$ 500 kHz

$\pi^0\pi^0$ trigger

- Based on LKr infos summed into projections
- Cut on total energy, decay vertex, R_{COG} and number of γ's
- Fully pipelined, no dead time
- Output rate $\approx$ 2 kHz
- Efficiency: 99.9%

$\pi^+\pi^-$ trigger

Level 1:

- Scintillator hodoscope + Total energy + hits in drift chamber 1
- Output rate $\approx$ 100 kHz

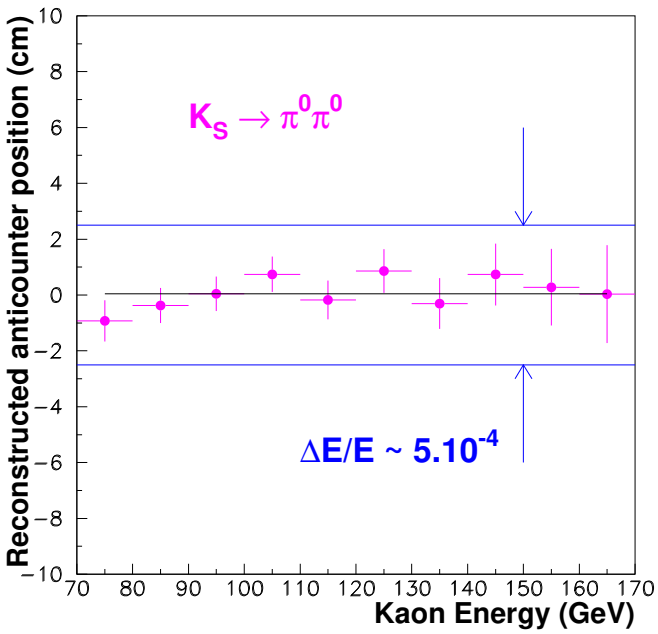
Level 2:

- Fast track reconstruction
- Cut on decay vertex position and $M_{\pi\pi}$
- Output rate $\approx$ 2 kHz

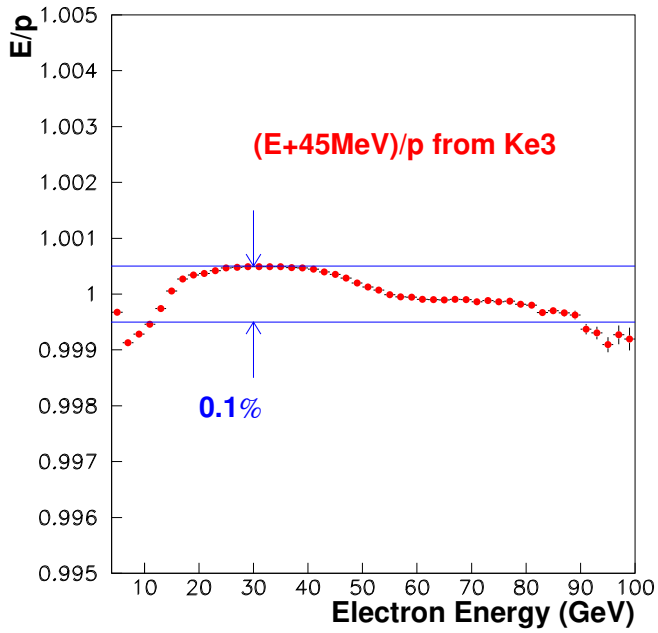
Efficiency: $(98.697 \pm 0.017)\%$,
it was $(97.782 \pm 0.021)\%$ in 98-99

$$\Delta R = (+5.2 \pm 3.6) \times 10^{-4}$$

Energy scale checks

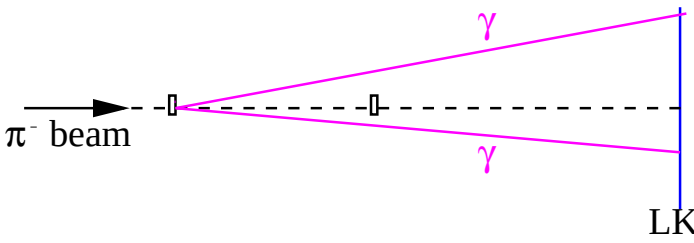


$\pi^0\pi^0$: energy scale independent of Kaon energy (non linearity check)



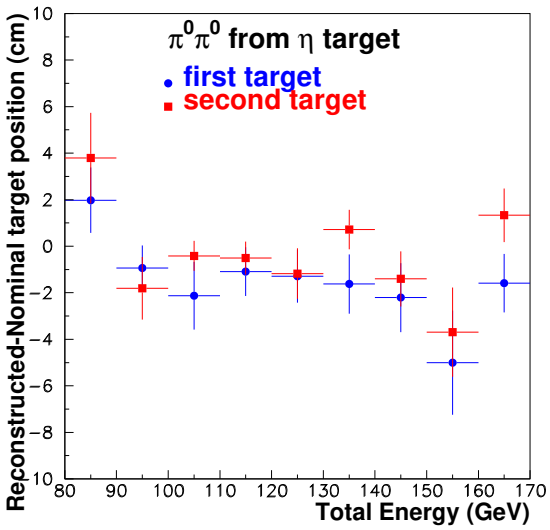
Electrons from Ke3 decays E/p constant within $\approx 0.1\%$ between a few GeV and 100 GeV

Energy scale checks, contd.



Special run π^- beam directed to two thin targets

- Produce π^0 and η with known decay position
- Use $\gamma\gamma$ decays to reconstruct vertex (assuming π^0 or η masses)

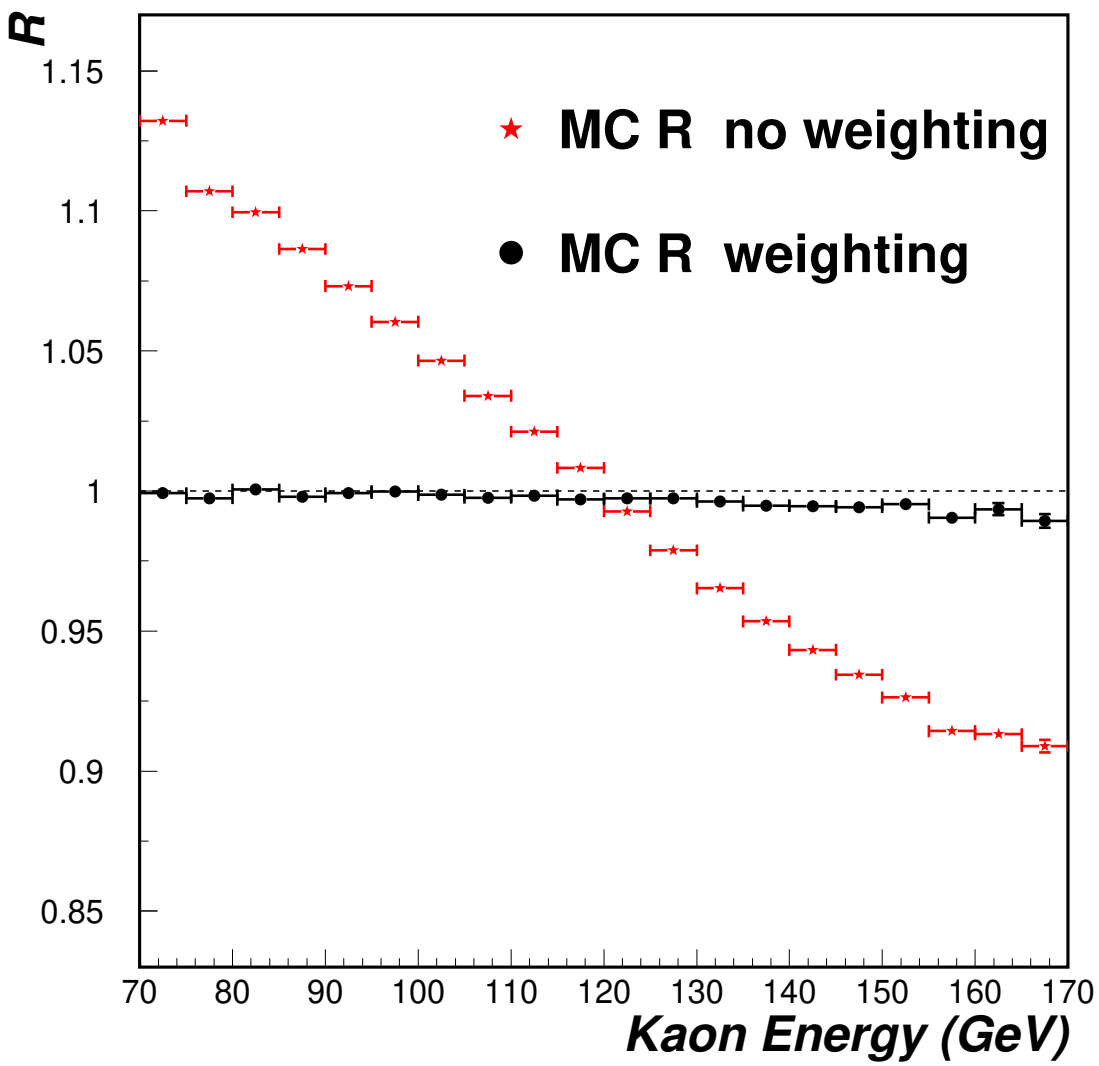


Use also $\pi^0\pi^0$ events with invariant mass close (but not equal) to the kaon mass

Total uncertainties on neutral energy scale

$$\Delta R = \pm 5.3 \times 10^{-4}$$

Acceptance Correction



$$\Delta R = (21.9 \pm 3.3_{\mathrm{MCstat}} \pm 4.0_{\mathrm{syst}}) \times 10^{-4}$$

Systematic error comes from:

- beam positions and shapes knowledge
- comparison of fast MC/GEANT based simulation

Accidental activity

Accidental activity from beam $\Rightarrow$ Event losses

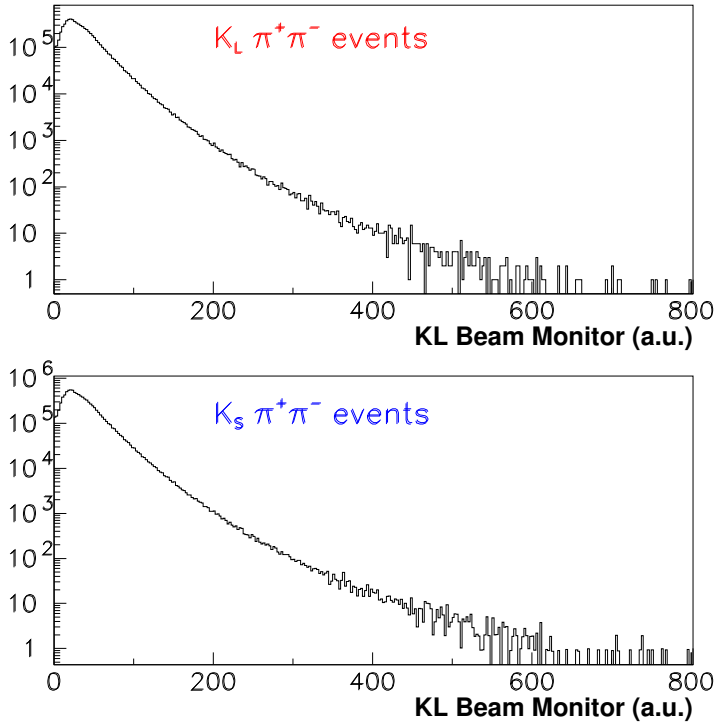
Cancel at first order in R

Residual effects:

- Intensity difference:
  $\Delta R \approx \Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) \times \Delta I(K_L - K_S)/I$
  - $\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0)$: difference between charged and neutral losses; minimized by applying dead time conditions to all modes;
  - $\Delta I(K_L - K_S)/I$: difference in accidental activity seen by K_L and K_S; $\Rightarrow$ small by design of the experiment:
    - Simultaneous beams $\Rightarrow$ K_L and K_S events should see the same activity
- Illumination difference
  - $K_L - K_S$ detectors illumination difference
  - different detector parts $\Leftrightarrow$ different losses
    - Lifetime weighting $\Rightarrow$ K_L and K_S events should see the same parts of the detector

Beam Monitors

BM integrators are used to measure K_L or K_S beam intensity



In 2001 BM integrators rates have been collected with integration times of 200 ns, 1 μs, 3 μs, 15 μs

The Overlay Technique

BM triggers downscaled and delayed by 69 μs (3 SPS revolutions) record the accidental activity proportionally to K_L or K_S beam intensity

- $\pi^+\pi^-$ and $\pi^0\pi^0$ are overlayed with BM triggers
- overlayed events undergoe standard reconstruction and analysis selection
- loss and gain probabilities are estimated
- $\pi^+\pi^-$ and $\pi^0\pi^0$ from data and MC are used

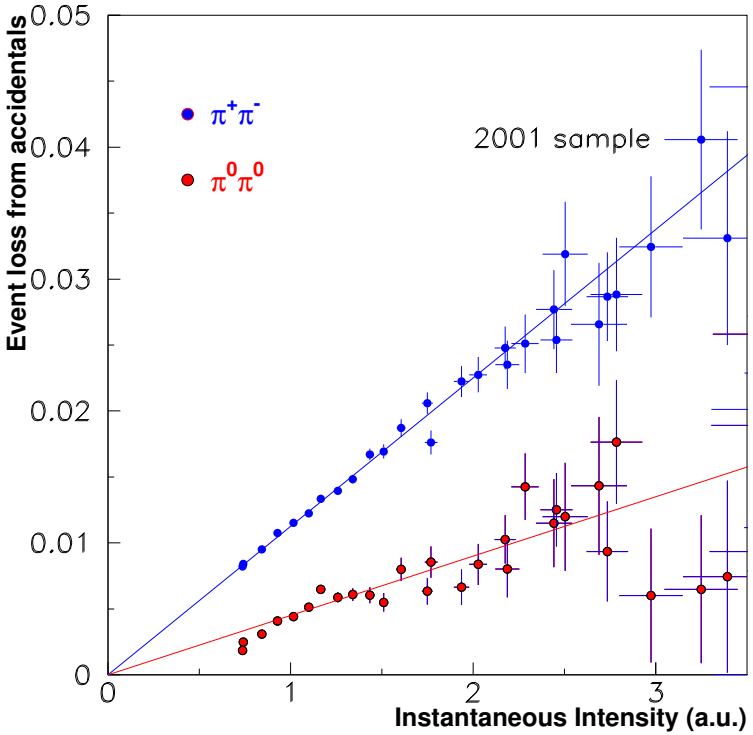
Intensity difference

Method	$\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0)$
data events overlayed with BM triggers	1.0%
MC events overlayed with BM triggers	0.65%
$\pi^0\pi^0/\pi^+\pi^-$ in $K_L + K_S$ w.r.t. pure K_S runs	$(0.9 \pm 0.6)\%$
variation of $\pi^0\pi^0/\pi^+\pi^-$ vs K_L beam intensity	$\approx 1\%$
final estimate	$(1.0 \pm 0.5)\%$

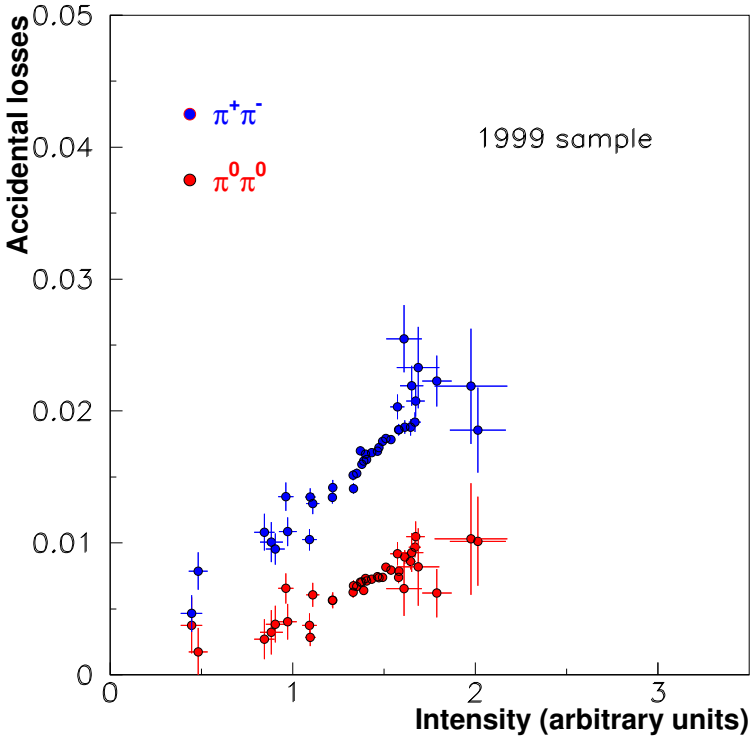
Method	$\Delta I(K_L - K_S)/I$
Lkr extra cluster in good $\pi^+\pi^-$	$(+0.4 \pm 0.4_{stat})\%$
DCH extra tracks in good $\pi^+\pi^-$	$(+0.6 \pm 0.3_{stat})\%$
BM rates (200 ns int. time) in good $\pi^+\pi^-$	$(-0.08 \pm 0.04_{stat})\%$
BM rates (15 μs) correlation in flat triggers	$\approx -1\% \pm \approx 1\%$
final estimate	$0 \pm 1\%$

Intensity difference $\Rightarrow \Delta R = (0 \pm 1.1) \times 10^{-4}$
(it was $(0 \pm 3) \times 10^{-4}$ in 98-99)

Losses vs intensity

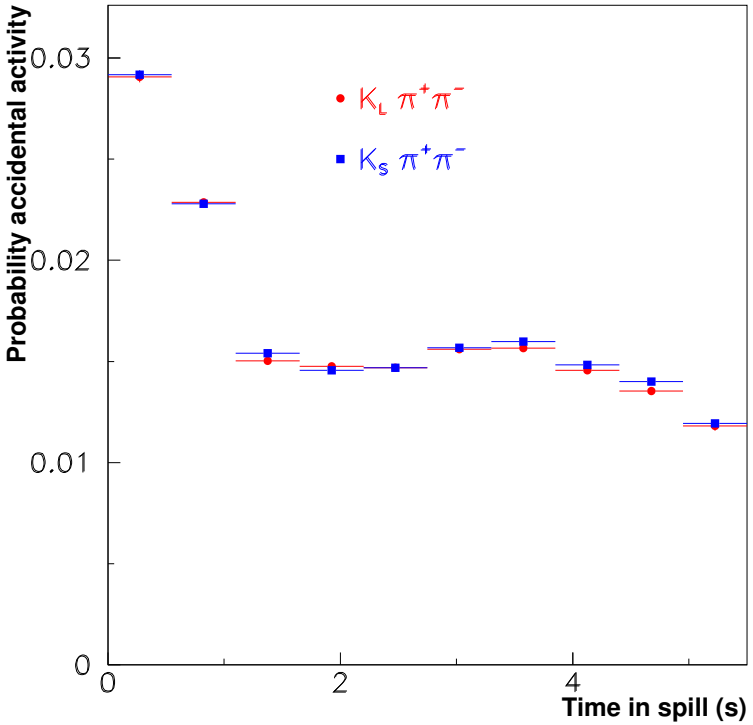


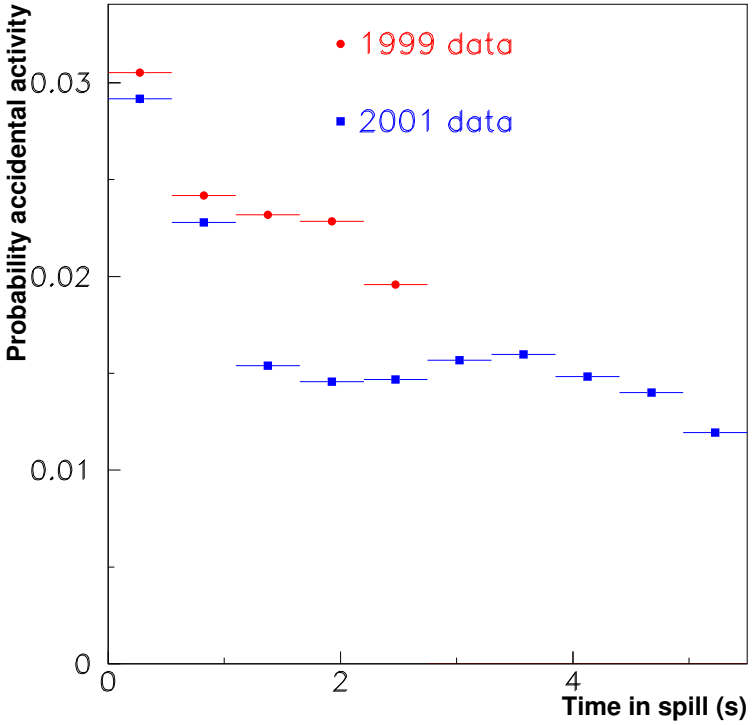
$\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.0 \pm 0.5)\%$
in 2001



$\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.4 \pm 0.7)\%$
in 98-99

Intensity difference





$$\Delta I(\mathrm{K_L} - \mathrm{K_S})/I = 0 \pm 1\%$$

Illumination difference

Method	Illumination difference
data overlay	$(+0.9 \pm 3.5) \times 10^{-4}$
MC overlay (1st MC)	$(+3.4 \pm 3.3) \times 10^{-4}$
MC overlay (2nd MC)	$(-0.6 \pm 3.3) \times 10^{-4}$
final estimate	$0 \pm 3 \times 10^{-4}$

Illumination difference $\Rightarrow \Delta R = (0 \pm 3) \times 10^{-4}$

Cross-check of Intensity and Illumination difference at the same time:

- K_S events overlayed by K_S BM triggers
- K_L events overlayed by K_L BM triggers

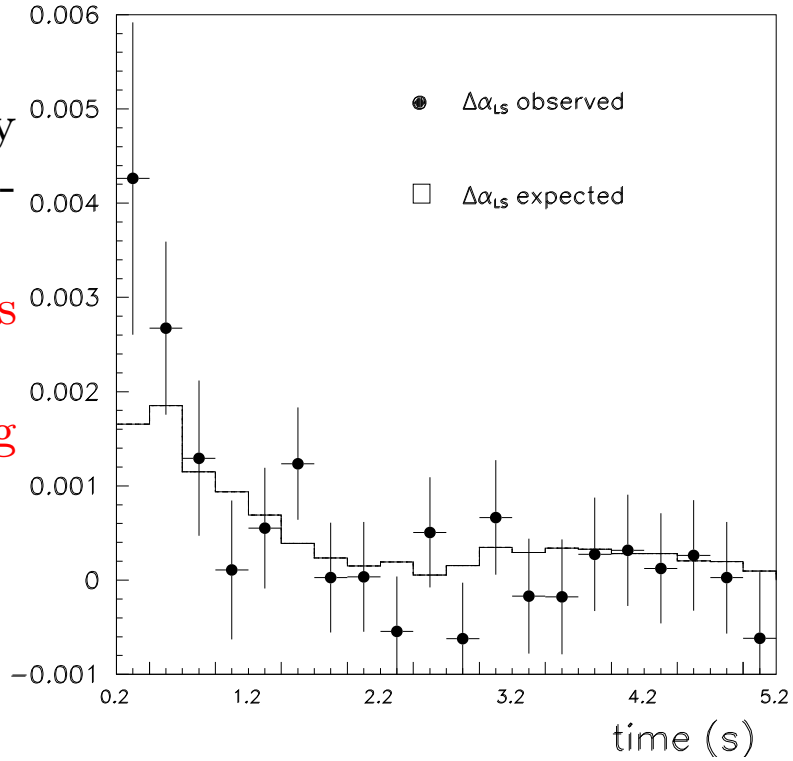
$\Delta R = (4.7 \pm 4.9) \times 10^{-4}$

Origin of $\Delta\alpha_{LS}$

The accidental tagging probability α_{LS} depends on the proton beam intensity, but

- IF accidental activity losses higher for $\pi^+\pi^-$ than for $\pi^0\pi^0$
- IF the beam intensity is varying with time

$\Rightarrow \alpha_{LS}(\pi^0\pi^0) > \alpha_{LS}(\pi^+\pi^-)$



$$\alpha_{LS}^{observed} = \alpha_{LS}^{true} - P(losses) \times \delta\alpha_{LS}(losses)$$

$\Delta\alpha_{LS}(\text{predicted}) = (+3.5 \pm 0.4) \times 10^{-4}$ [losses estimated by data overlay]
$\Delta\alpha_{LS}(\text{predicted}) = (+2.0 \pm 0.4) \times 10^{-4}$ [losses estimated by MC overlay]
$\Delta\alpha_{LS}(\text{predicted}) = (+0.4 \pm 0.2) \times 10^{-4}$ [from trigger inefficiency]
$\Delta\alpha_{LS}(\text{observed}) = (+3.4 \pm 1.4) \times 10^{-4}$

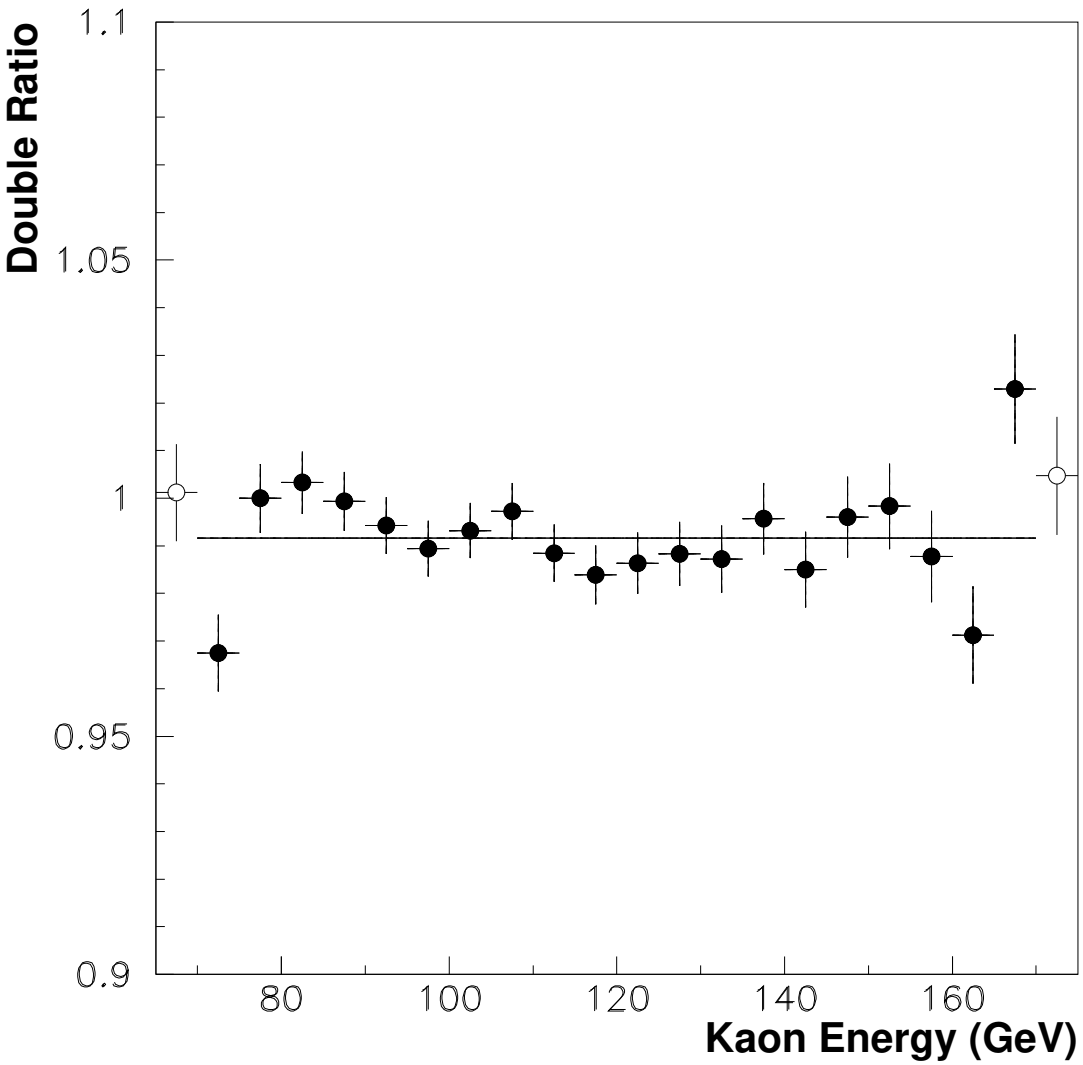
Corrections Summary

Corrections and systematic uncertainties on R (Units = 10^{-4}); errors are pure stat or pure syst		
	2001	98-99
$\pi^+\pi^-$ background	14.2 ± 3.0	16.9 ± 3.0
$\pi^0\pi^0$ background	-5.6 ± 2.0	-5.9 ± 2.0
beam scattering	-8.8 ± 2.0	-9.6 ± 2.0
Tagging inefficiency	± 3.0	± 3.0
Accidental tagging	6.9 ± 2.8	8.3 ± 3.4
$\pi^+\pi^-$ scale	± 2.8	2.0 ± 2.8
$\pi^0\pi^0$ scale	± 5.3	± 5.8
AKS inefficiency	1.2 ± 0.3	1.1 ± 0.4
Acceptance	21.9 ± 3.5	26.7 ± 4.1
	± 4.0	± 4.0
$\pi^+\pi^-$ trigger	5.2 ± 3.6	-3.6 ± 5.2
Accidental activity		
intensity diff.	± 1.1	± 3.0
illumination diff.	± 3.0	± 3.0
K_S in time activity	± 1.0	± 1.0
Total	+35.0 ± 6.5	+35.9 ± 8.1
	± 9.0	± 9.6

$$R = 1 - (1.169 \pm 0.147)\% + (0.350 \pm 0.111)\%$$

- First term after 1: effect of the ratio of the 4 numbers;
- Second term after 1: corrections.

The Double Ratio

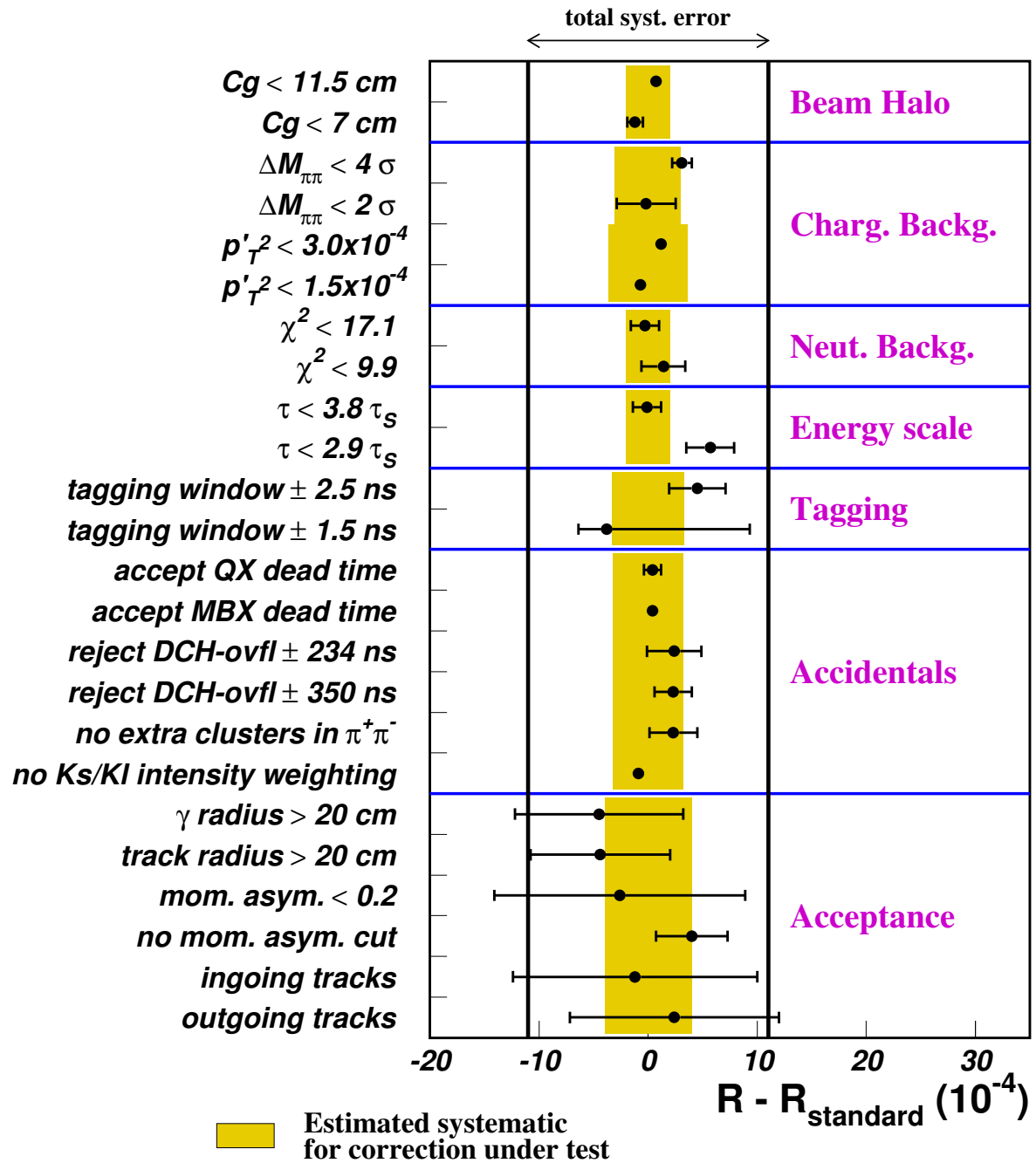


$$R = 0.99181 \pm 0.00147_{stat} \pm 0.00110_{syst}$$

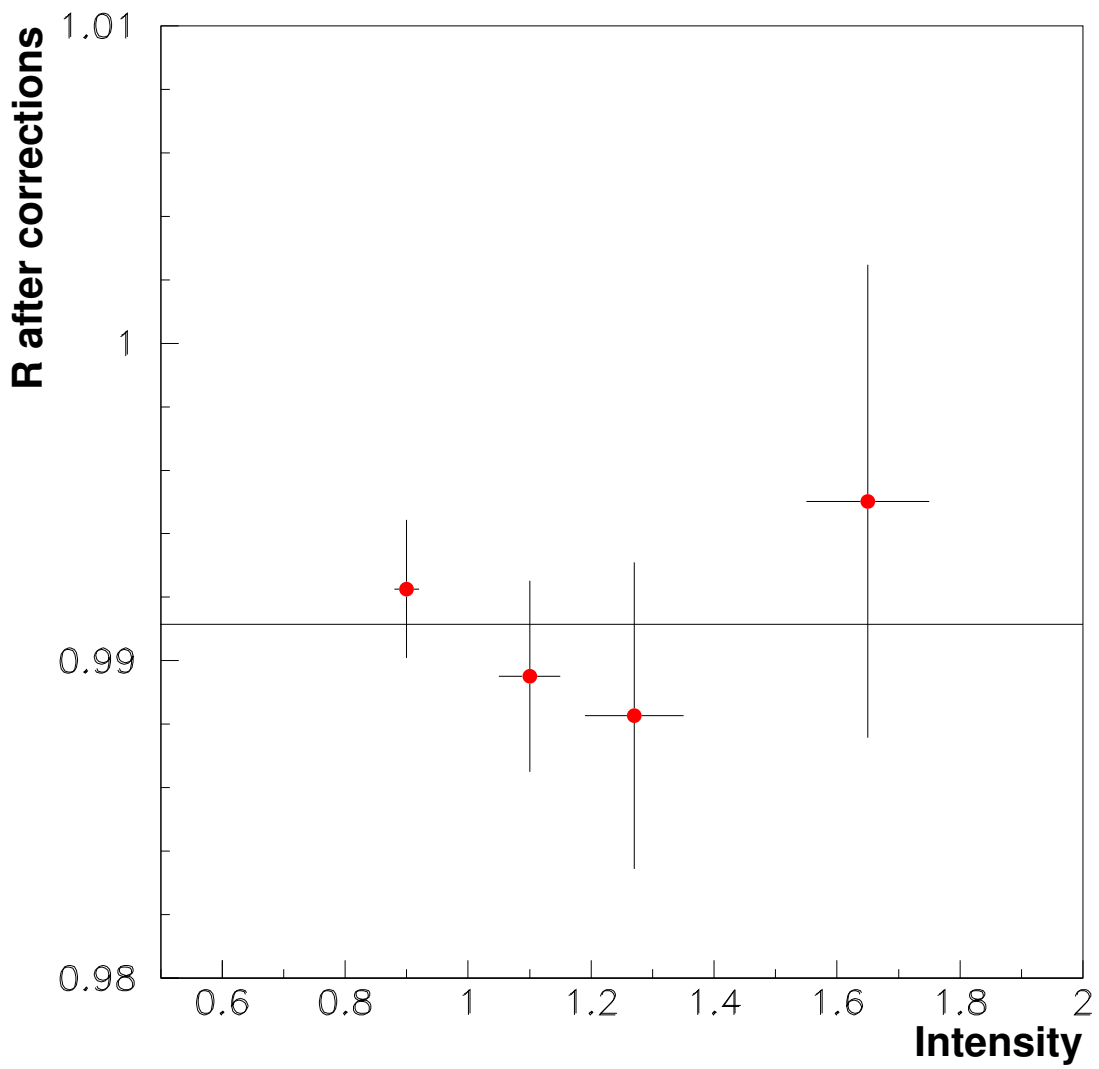
where in the systematic error ± 0.00065 comes from the statistics of the control samples

Checks

R stability against cut variations



Double Ratio versus beam intensity



Final Result

From 2001 data:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 3.1) \times 10^{-4}$$

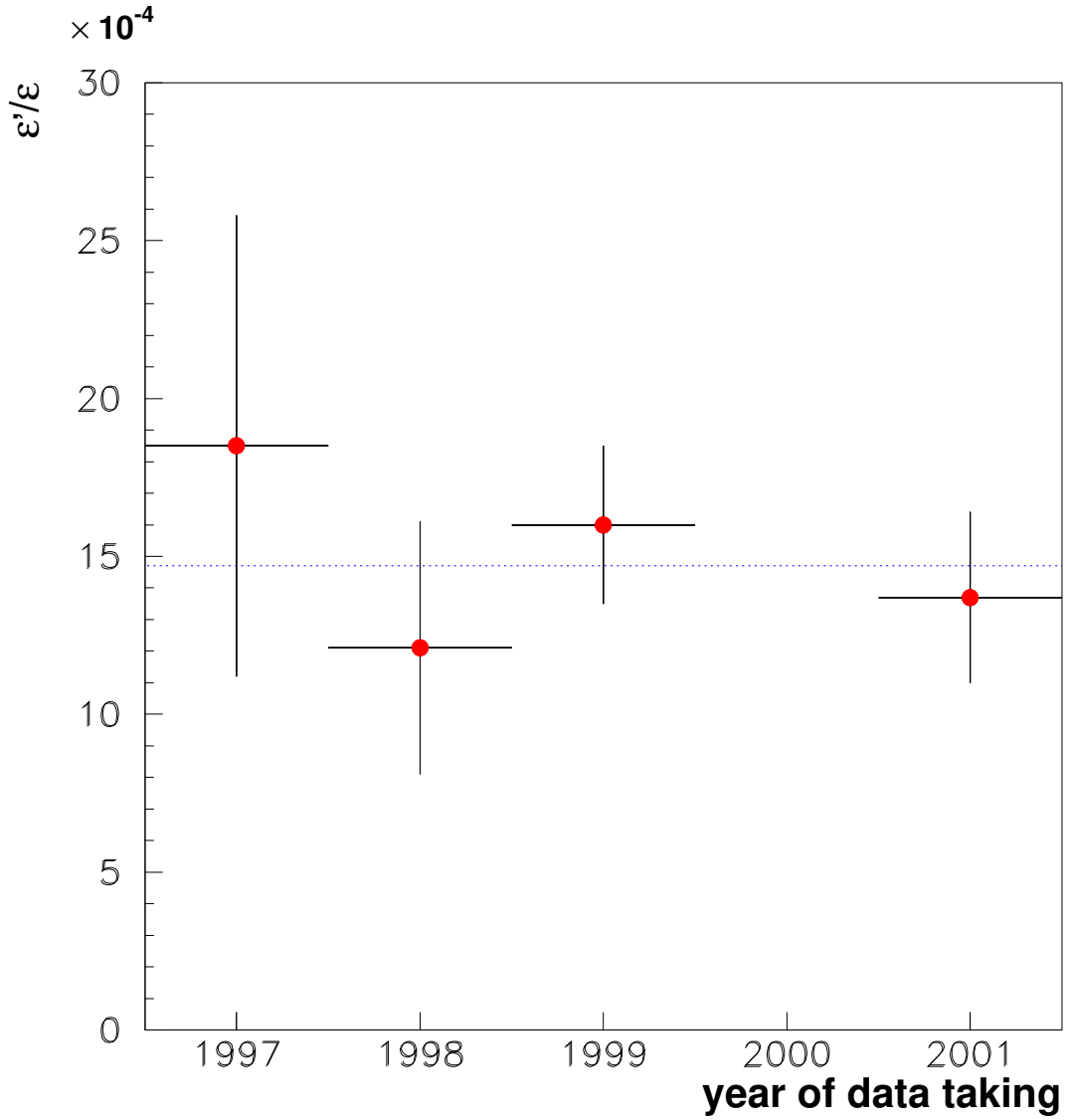
Combining with 97+98+99 result
$(15.3 \pm 2.6) \times 10^{-4}$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}}$$

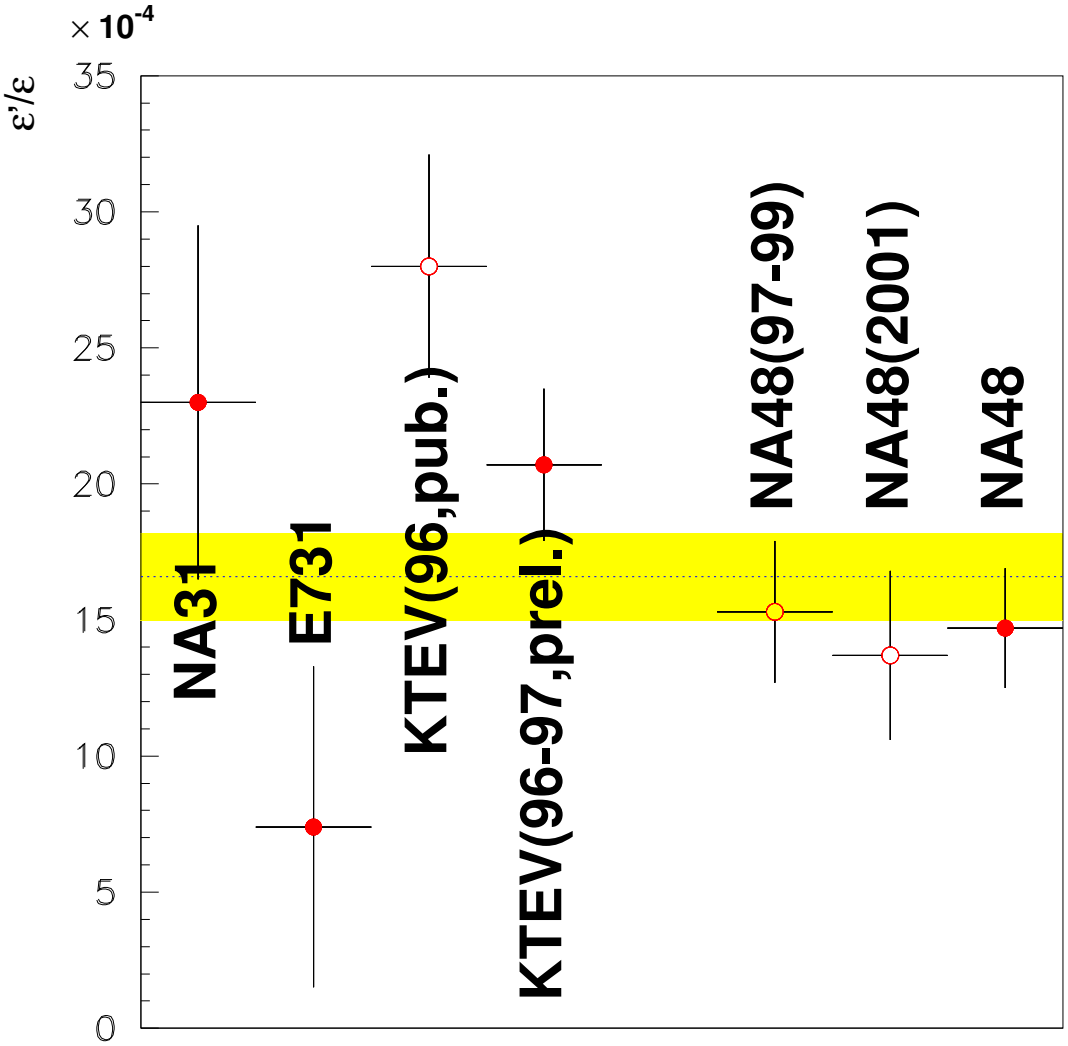
(6.7σ away from 0, it was 5.9σ in the 97-99 result)

- 2001 measurement in good agreement with 97-99 result
  (data collected in different conditions)
- proposal goal reached
- a paper is coming

$\mathrm{Re}(\varepsilon'/\varepsilon)$ vs run period



Experimental result comparison



World average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$
with χ^2/ndf=6.2/3

Spare Slides

K_S lifetime effect on R

NA48 use the PDG $c\tau_S = 2.676$ cm

KTeV and NA48 results are about 0.4% higher

The K_S lifetime has 3 effects:

- The K_S and interference term in K_L beam:
  small terms in NA48
  $\Rightarrow$ negligible effect on R
- The lifetime weight:
  acceptance cancellation not perfect
  0.4% error on $c\tau_S$ $\Rightarrow$ 0.5×10^{-4} error on R
- The energy scale setting (AKS position) is sensitive to MC $c\tau_S$:
  0.4% error on $c\tau_S$ $\Rightarrow$ 1 cm on z
  (accounted for in ± 3 cm uncertainty on z)
  $\Rightarrow \lesssim 10^{-4}$ on R

K_S lifetime measurement

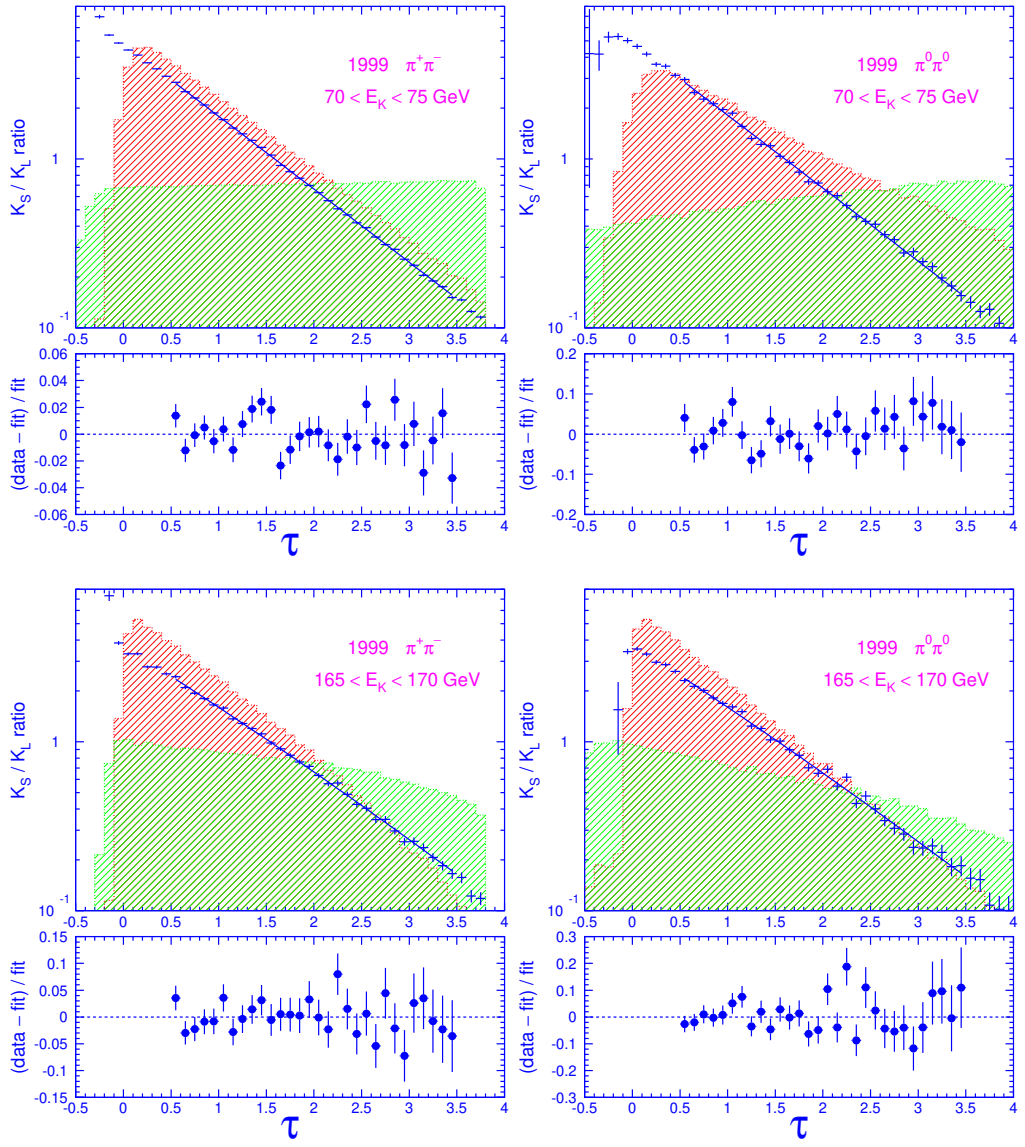
- Use the same samples as for $\mathrm{Re}(\varepsilon'/\varepsilon)$ analysis from 1998 and 1999 runs.
- Decay region is defined in $0.5 < \tau/\tau_S < 3.5$.
  Cut at $0.5\tau_S$ avoids detector resolution effects.
- Analysis is done in 5 GeV energy bins and 0.1 τ_S lifetime bins.
- Both $\pi^+\pi^-$ and $\pi^0\pi^0$ are used. Lifetime is calculated separately and subsequently combined.

$\Rightarrow$ Statistics used:

Decay	$K_S \to \pi^+\pi^-$	$K_L \to \pi^+\pi^-$	$K_S \to \pi^0\pi^0$	$K_L \to \pi^0\pi^0$
Stat. in 10^6	13.2	12.2	3.1	2.8

K_S lifetime measurement

- The measurement relies least possible on MC: K_L samples are used to measure the acceptance.
- Only the residual acceptance differences between K_S and K_L due to beam geometry are corrected using MC.
- Background (at 10^{-3} level only in K_L samples) is subtracted using data



K_S lifetime measurement

	$\pi^+\pi^-$		$\pi^0\pi^0$	
	$\tau_S/10^{-10}$s	χ^2/dof	$\tau_S/10^{-10}$s	χ^2/dof
1998	0.89578 $\pm$ 0.00109	628.2/573	0.89606 $\pm$ 0.00247	551.0/573
1999	0.89598 $\pm$ 0.00072	601.2/573	0.89635 $\pm$ 0.00167	543.5/573

Statistical uncertainties only

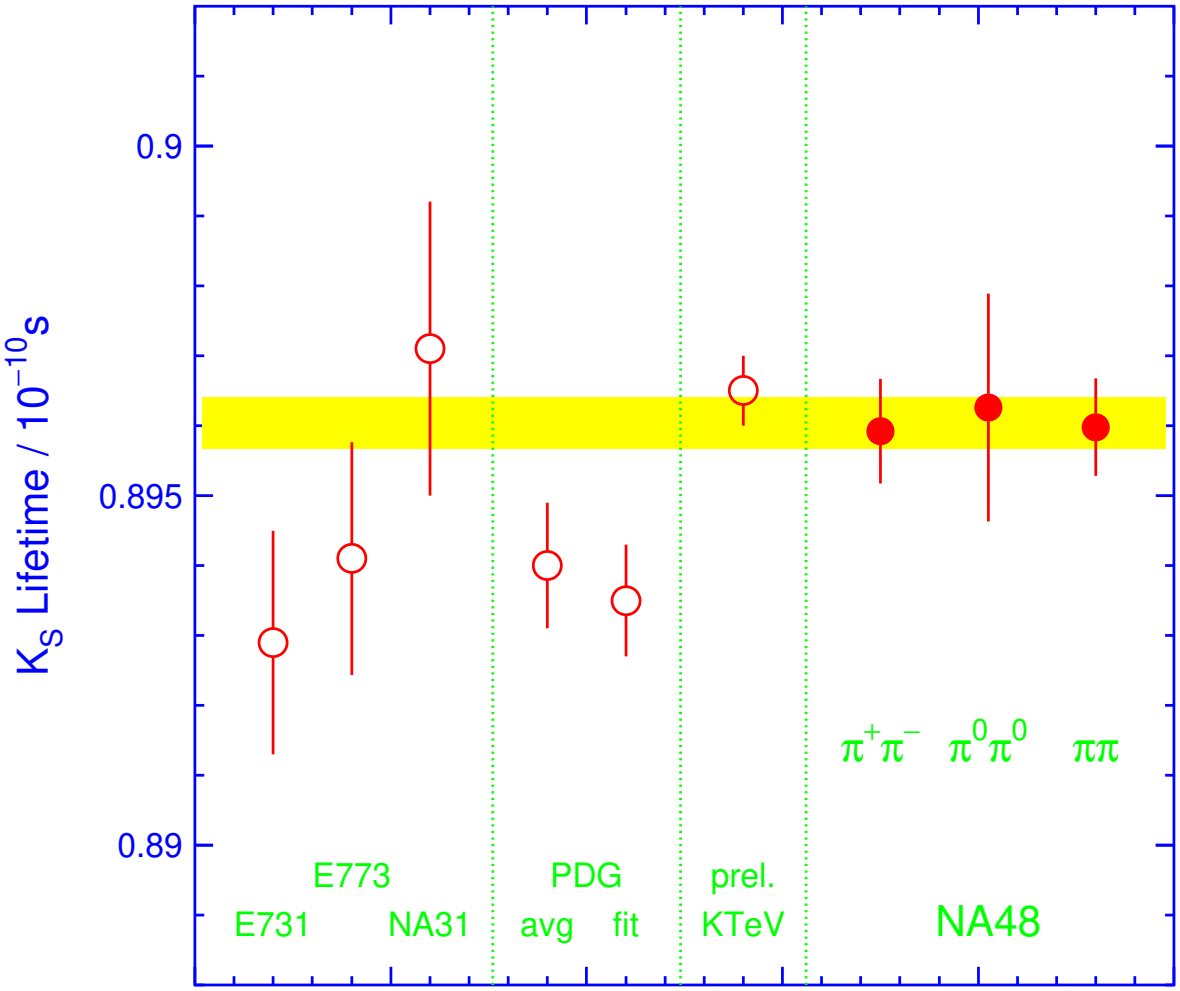
$\Rightarrow$ Combined result:

$$\tau_S = (0.89598 \pm 0.00048_{stat} \pm 0.00043_{syst} \pm 0.00027_{MCstat}) \times 10^{-10} \text{ s}$$

Systematics dominated by fit method and beam geometry uncertainties

Preprint: CERN-EP/2002-028 - hep-ex/0205008

K_S lifetime measurement



Our result differs by 1.7 σ from current PDG average

World average: $\tau_S = (0.89605 \pm 0.00038) \times 10^{-10}$ s $\chi^2/\mathrm{dof} = 6.3/4$

using also preliminary KTeV value

η and K^0 mass measurements

- Data taken during the 2000 run, in absence of the spectrometer.
- Using $\eta(\mathrm{K_L}) \to 3\pi^0$ decays - background free.
- $\mathrm{K_L}$'s are produced in absence of $\mathrm{K_S}$ beam.
- η's are produced with π^- beam at two polyethylene targets 2cm thick. Used to calibrate the energy scale with $\eta \to \gamma\gamma$ decays.

π^0 mass constraint

$$d_{vertex} = \frac{1}{M_{\pi^0}}\sqrt{E_1 E_2} d_{12} \quad M = \frac{1}{d_{\pi^0}}\sqrt{\Sigma_{ij,i<j} E_i E_j d_{ij}}$$

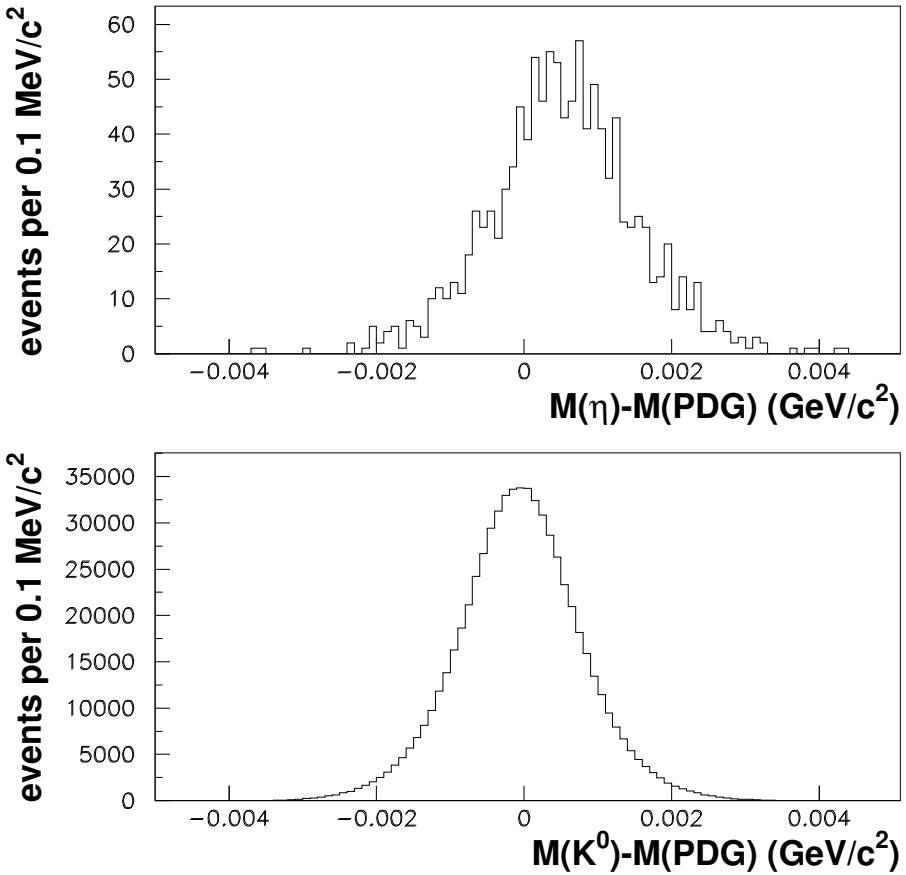
average from $3\pi^0$'s

η and K^0 mass measurements

$$\Delta M \equiv M_{\mathrm{NA48}} - M_{PDG}$$

- M independent of the global energy scale
- main systematics from non-linearities in the energy measurement
- sensitivity to non-linearities reduced by using only symmetric π^0 decays:

$$0.7 < \frac{E_\gamma}{<E_\gamma>} < 1.3$$

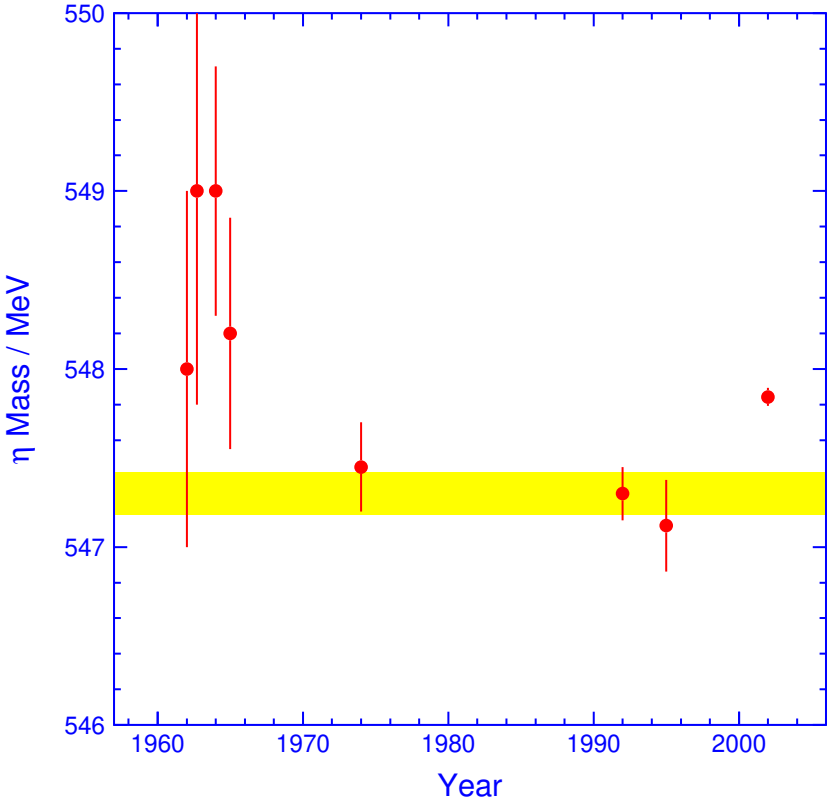


η and K^0 mass measurements

$$M_\eta = (547.843 \pm 0.030_{stat} \pm 0.041_{syst} \pm 0.005_{MCstat})$$

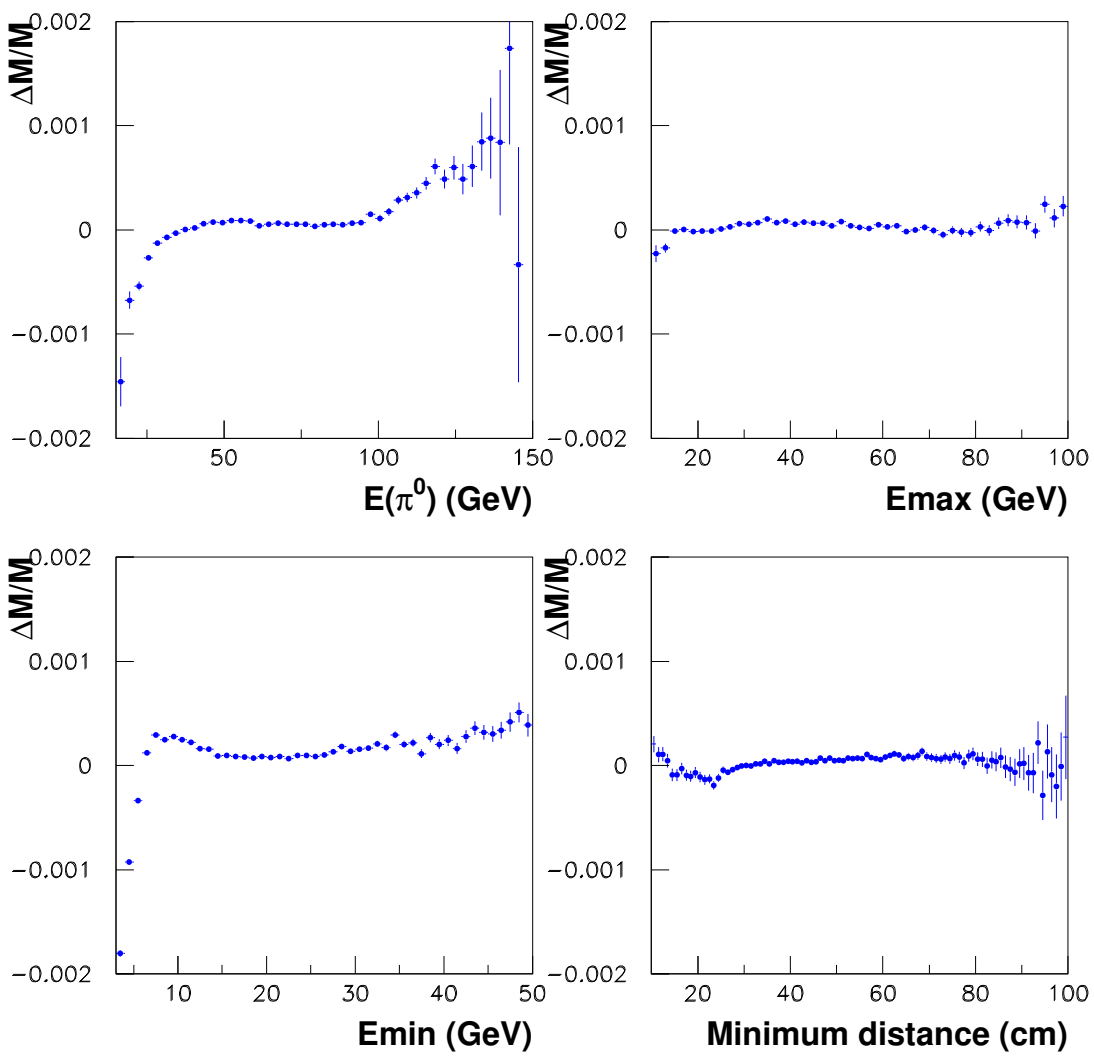
$$M_{K^0} = (497.625 \pm 0.001_{stat} \pm 0.031_{syst} \pm 0.003_{MCstat})$$

Preprint: CERN-EP/2002-025 - hep-ex/0204008

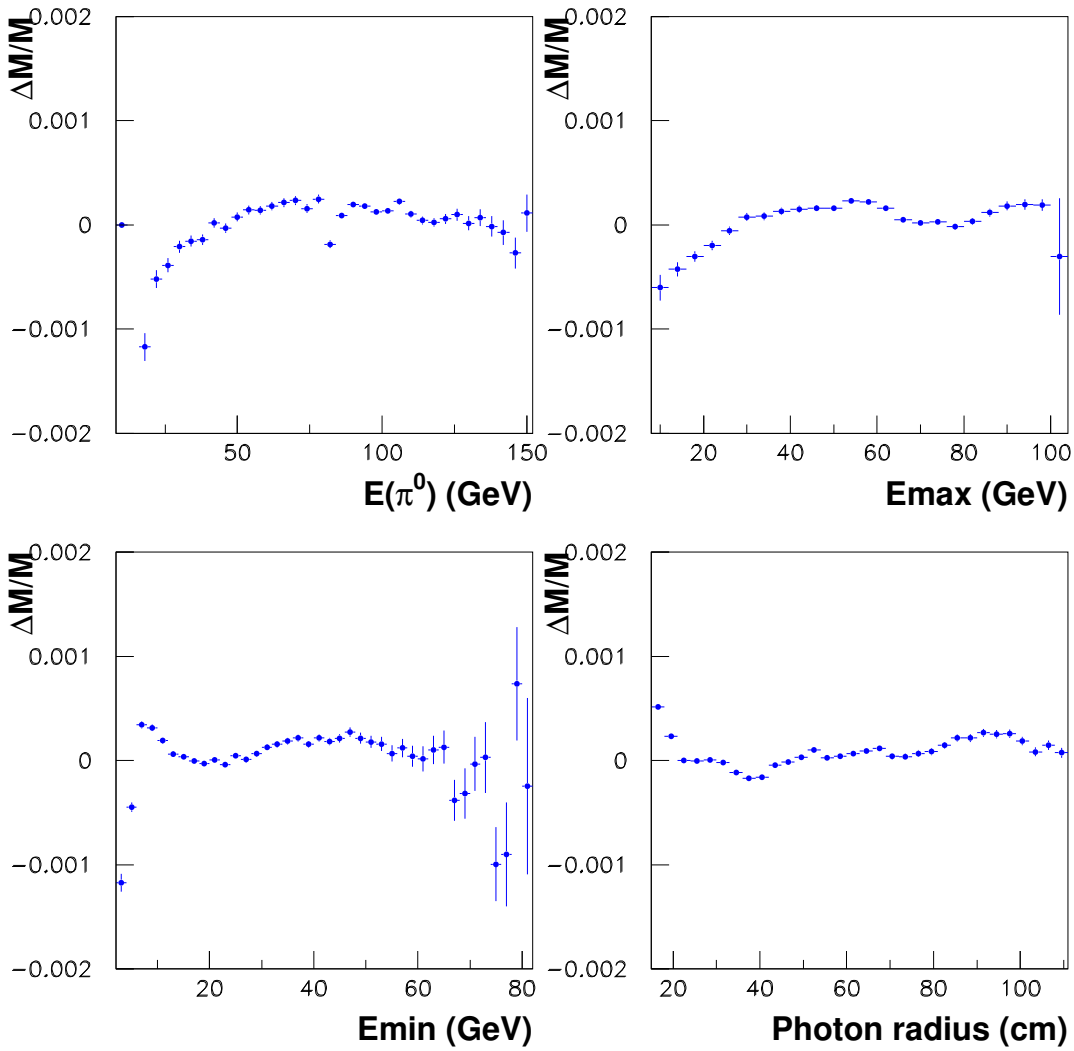


- η mass differs from world average by 4.2 σ (0.1% of its value) the uncertainty is 2.4 times smaller
- K^0 mass agrees with the world average within 1.1 σ, and has similar uncertainty

Non linearity check: π^0 mass vs energy



π^0 mass variation for $\pi^0 \to \gamma\gamma$ in η run



$\pi^0\pi^0$ reconstruction uncertainties

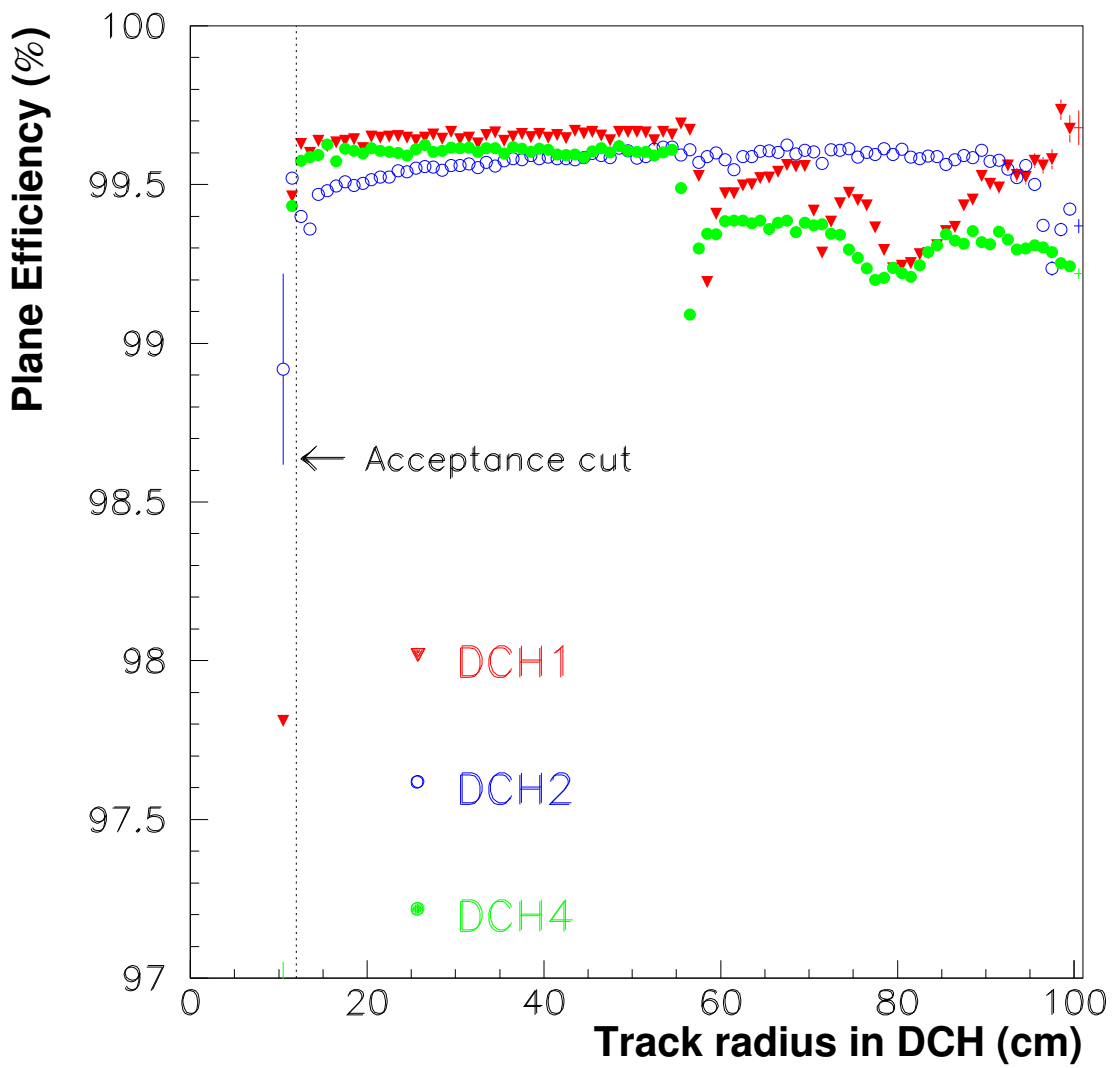
Systematic uncertainties on R (Units = 10^{-4})		
	2001	98-99
Energy scale	$\pm$ 2.0	$\pm$ 2.0
Non-linearities	$\pm$ 3.8	$\pm$ 3.7
Non-uniformities	$\pm$ 1.6	$\pm$ 1.5
Cluster energy sharing	$\pm$ 1.1	$\pm$ 2.0
Transverse size	$\pm$ 1.6	$\pm$ 2.5
Shower maximum	$\pm$ 1.6	$\pm$ 1.2
Non-gaussian tails	$\pm$ 1.0	$\pm$ 1.2
Total	$\pm$ 5.3	$\pm$ 5.8

The AKS veto

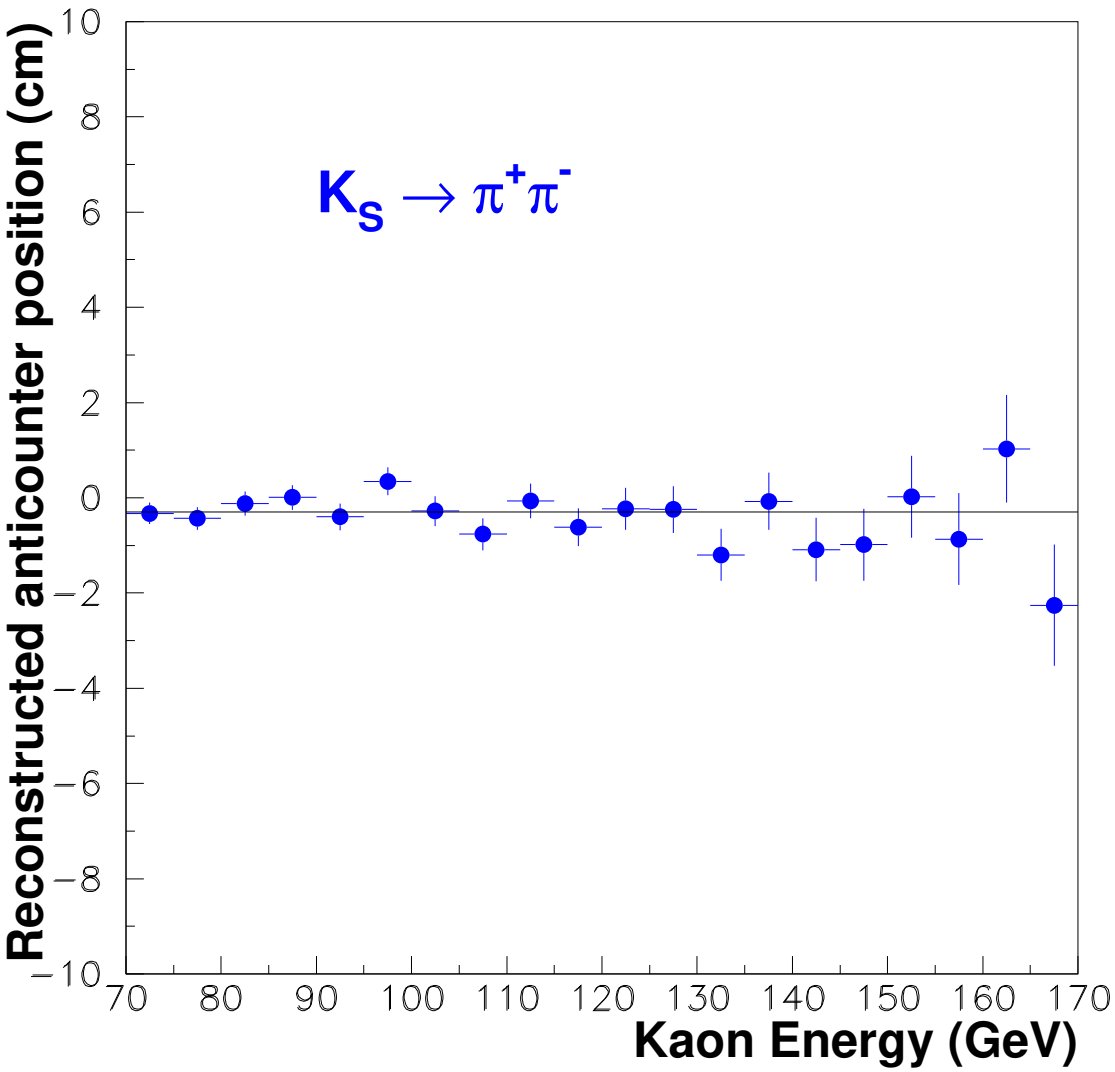
- Defines beginning of decay region for $\pi^+\pi^-$ and $\pi^0\pi^0$ K_S decays
- Used to fix the energy scale for $\pi^0\pi^0$ events
- Photon converter:
  - iridium cristal 3 mm thick, (22 ± 0.5) mm upstream of counter
  - 1.79 X_0 at 0 angle (instead of 0.98 X_0 for amorphous iridium)
- very small veto inefficiency

$$\Delta R = (1.2 \pm 0.3) \times 10^{-4}$$

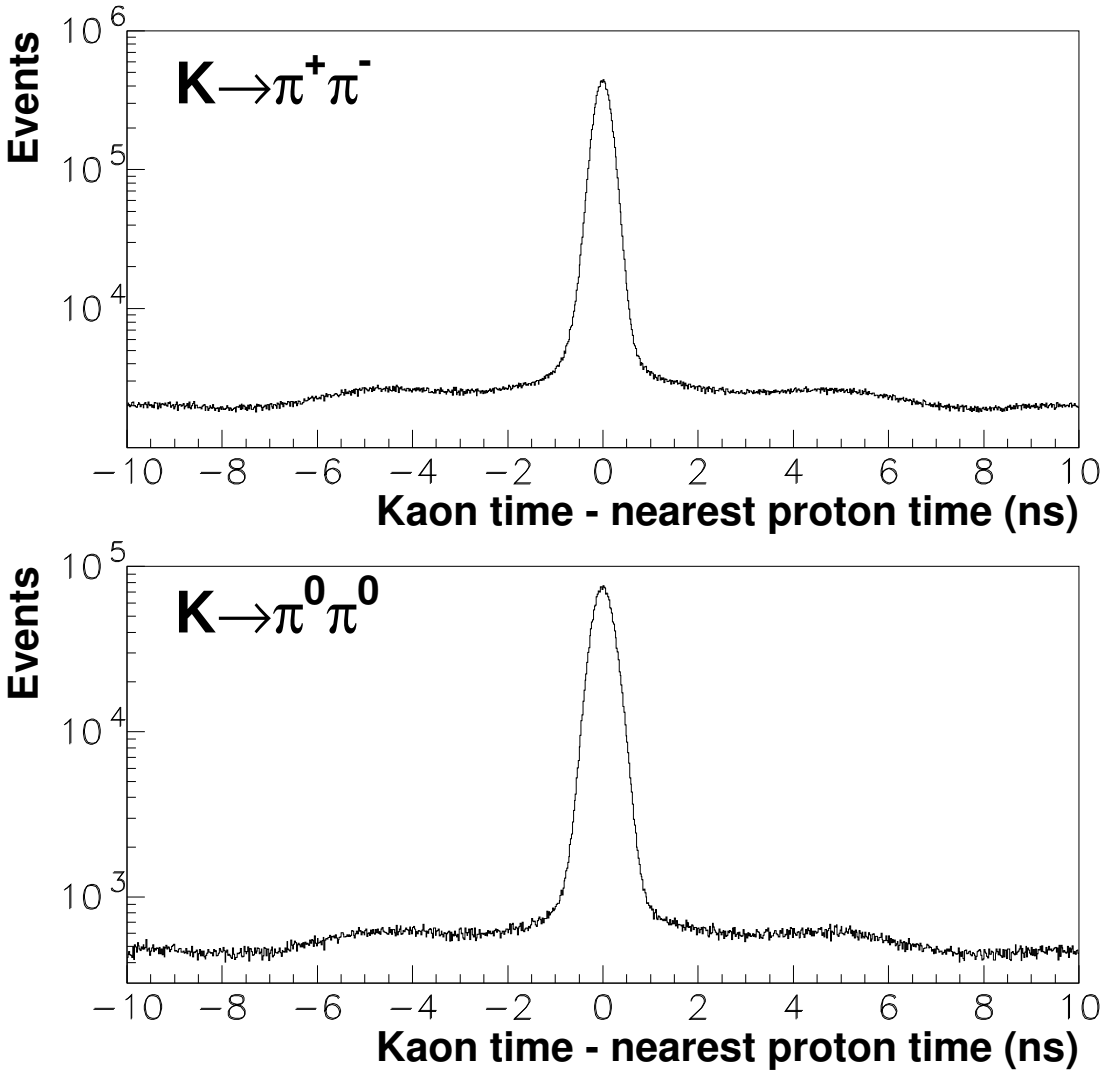
DCH efficiency



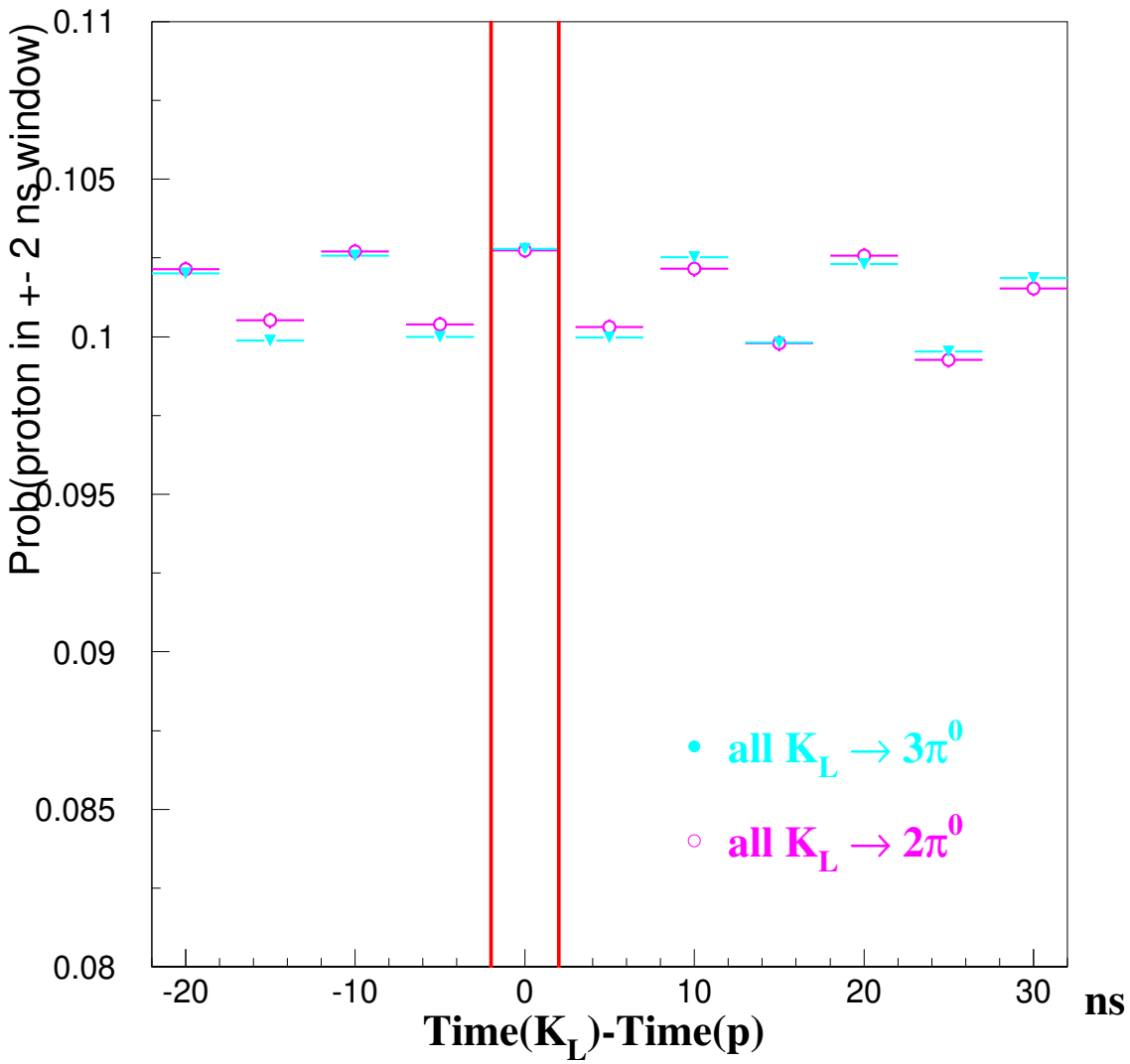
AKS position from $K_S \to \pi^+\pi^-$



Tagging: all events

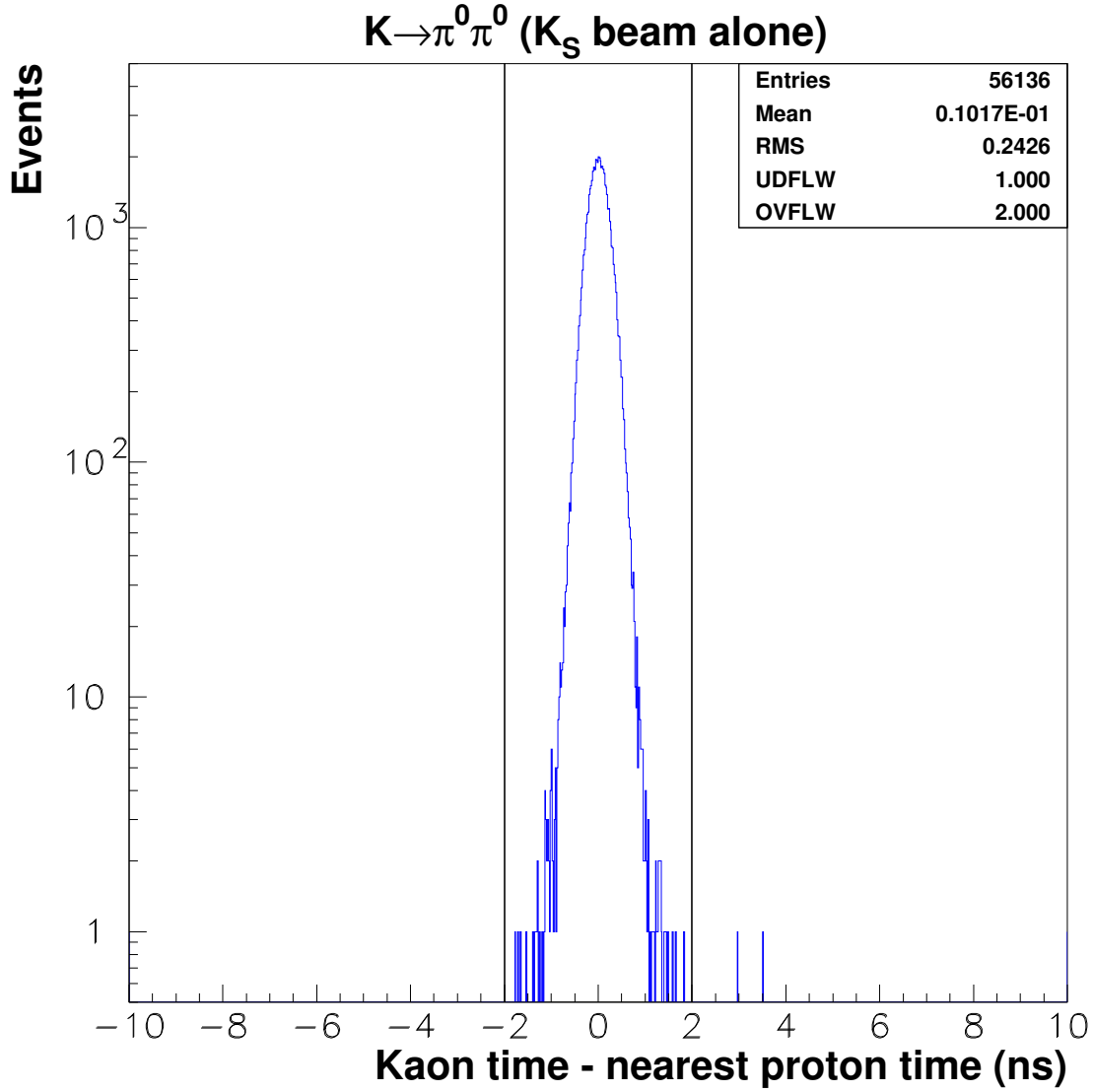


Tagging: check from 2000 run



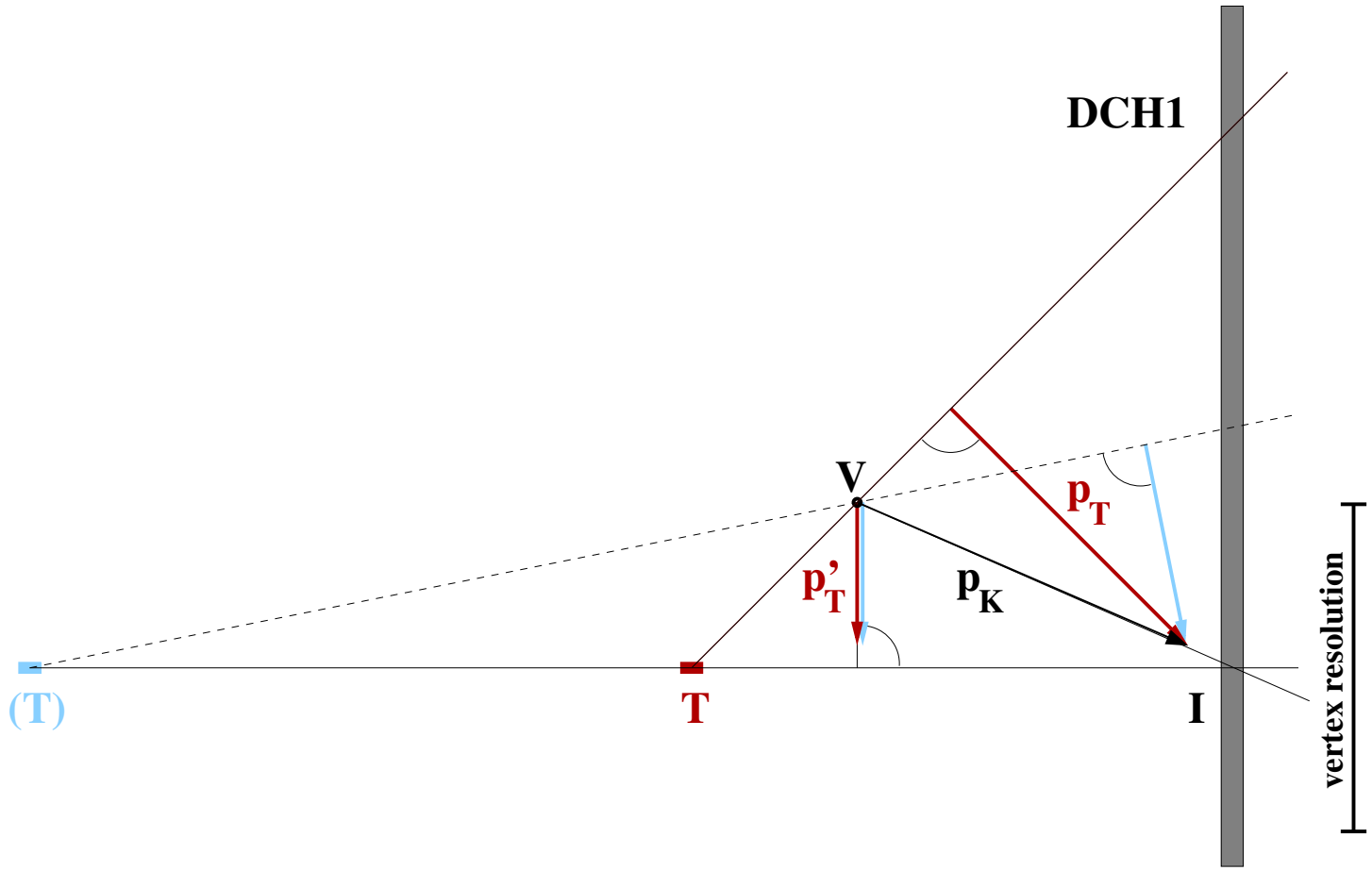
$$\Delta W(2\pi^0 - 3\pi^0) = (-0.8 \pm 2.9) \times 10^{-4}$$

K_S only beam for $\pi^0\pi^0$ events tagging



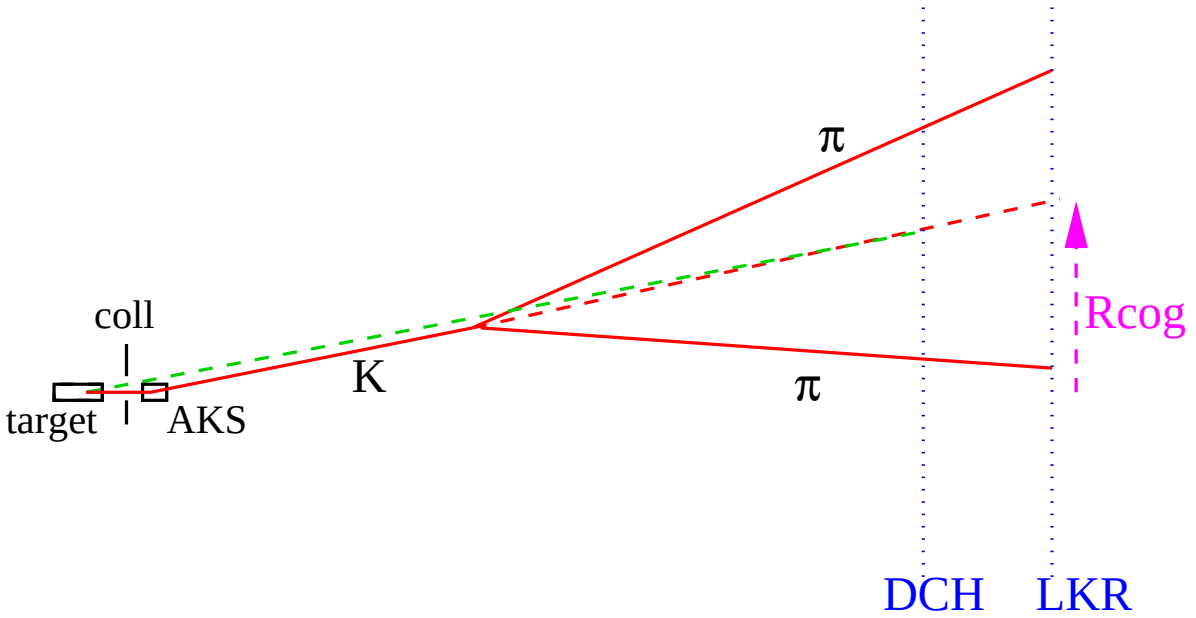
$$\alpha_{SL}^{00} = (0.89 \pm 0.40_{stat}) \times 10^{-4}$$

$P_T'^2$ definition

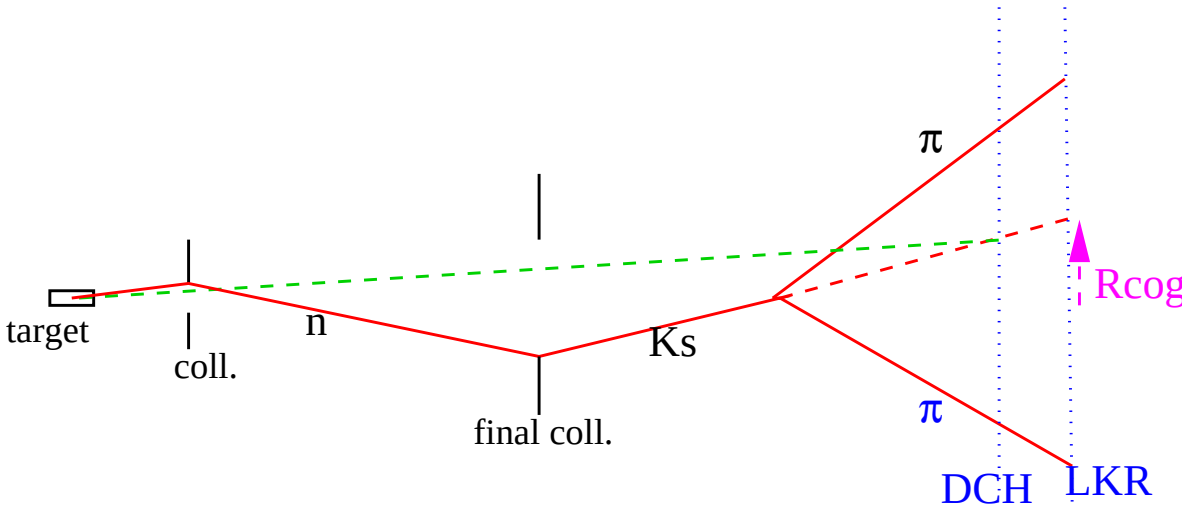


- Targets distance is ≈120 m ⇒ very different for K_S and K_L
- $P_T'^2$: same resolution for K_S and K_L (dominated by vertex resolution)

Beam Scattering Background



K_S scattering removed by R_{COG} cut
$\Rightarrow$ $\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric $\Rightarrow$ no effect on R

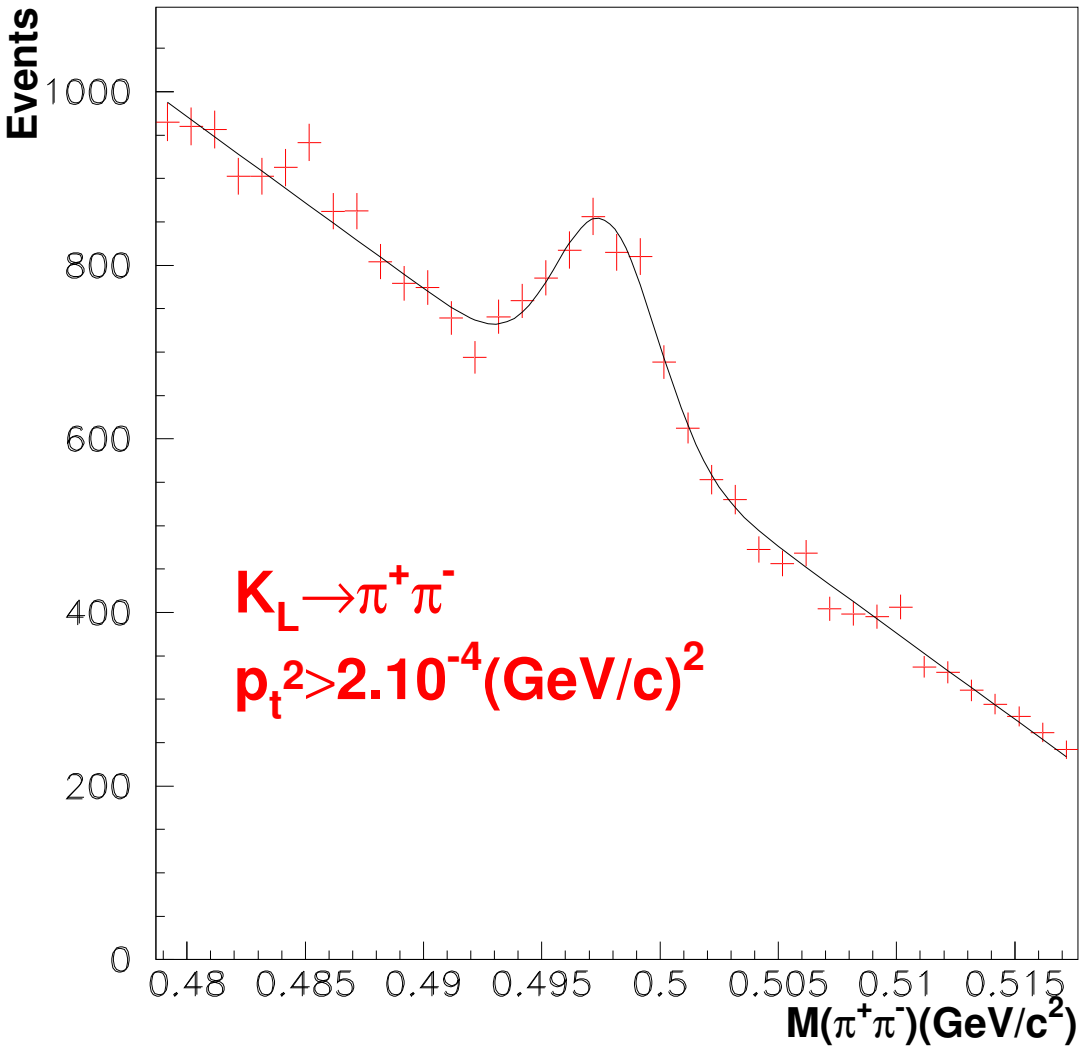


Background from beam scattering produces
K_S in final collimator
Removed by $\pi^+\pi^-$ sample by $P_T'^2$ cut
Kept in $\pi^0\pi^0$ sample $\Rightarrow$ correction on R

Beam Scattering Background, cont'd

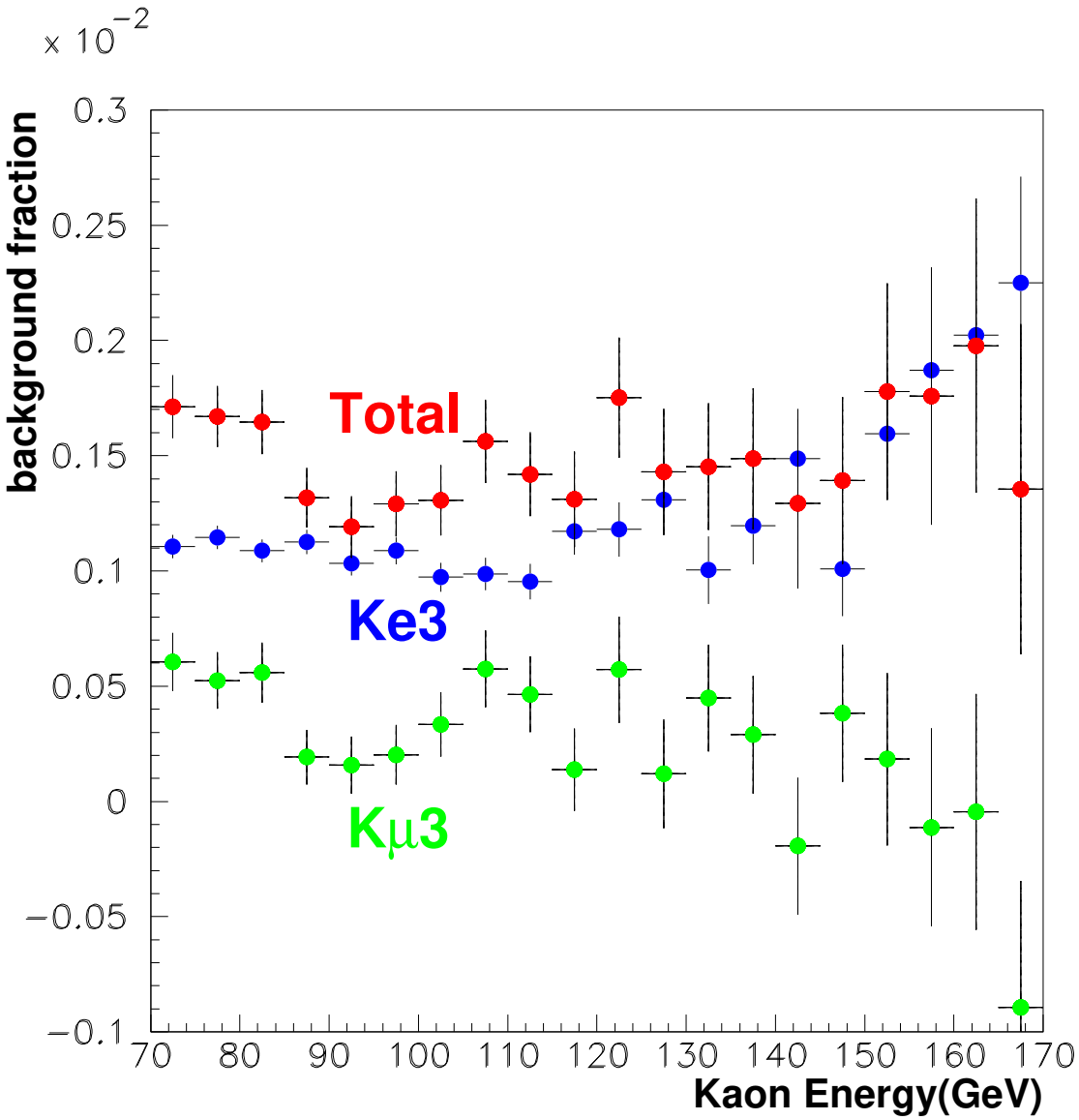
The collimator background is estimated:

- using $\pi^+\pi^-$ events with $P_T'^2 > 200$ (MeV/c)^2 with $M_{\pi\pi} = M_K$
- cross-check in $\pi^0\pi^0$ $\mathrm{R_{COG}}$ distribution

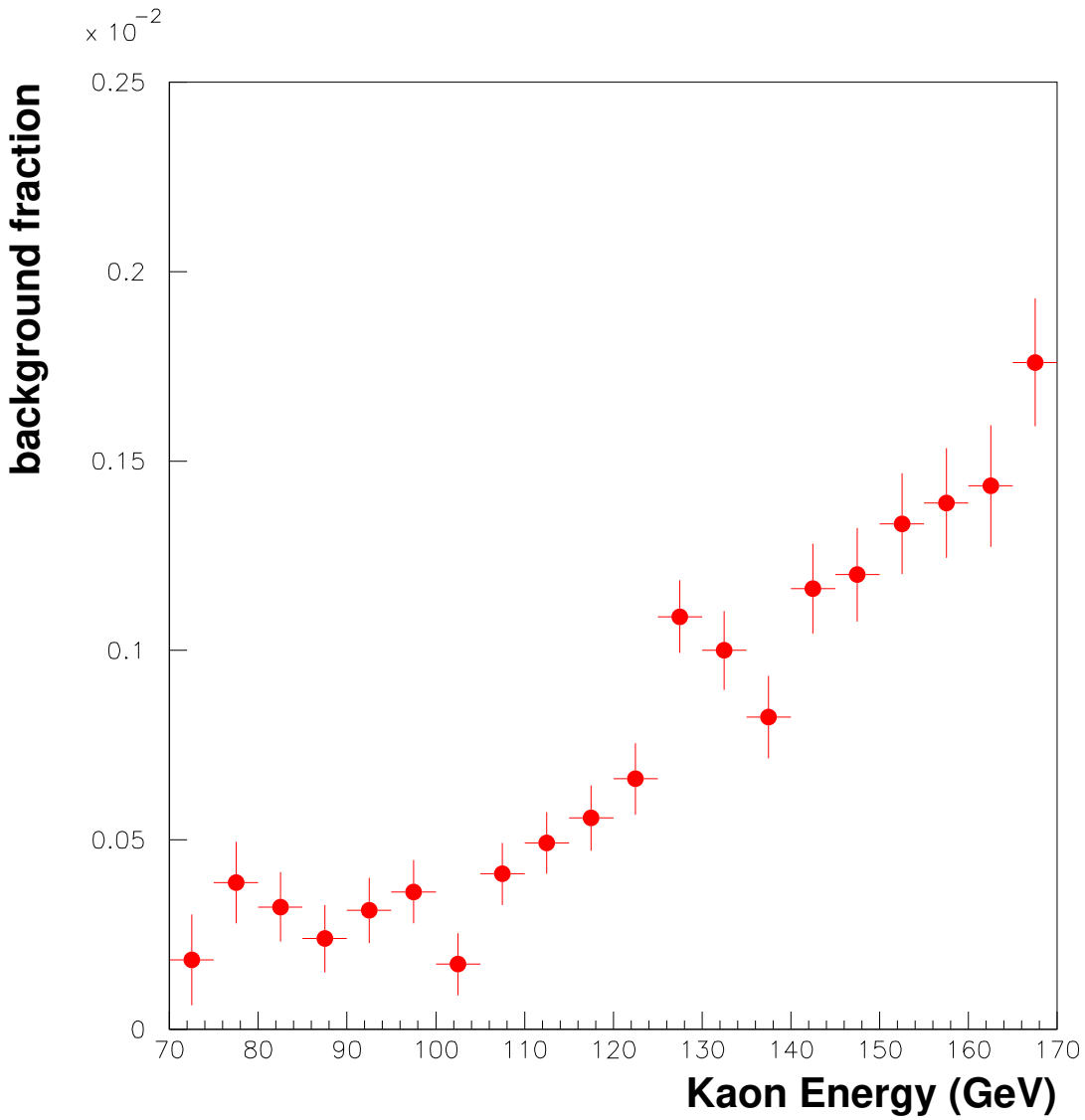


Background in $\pi^0\pi^0 = (8.8 \pm 2.0) \times 10^{-4}$

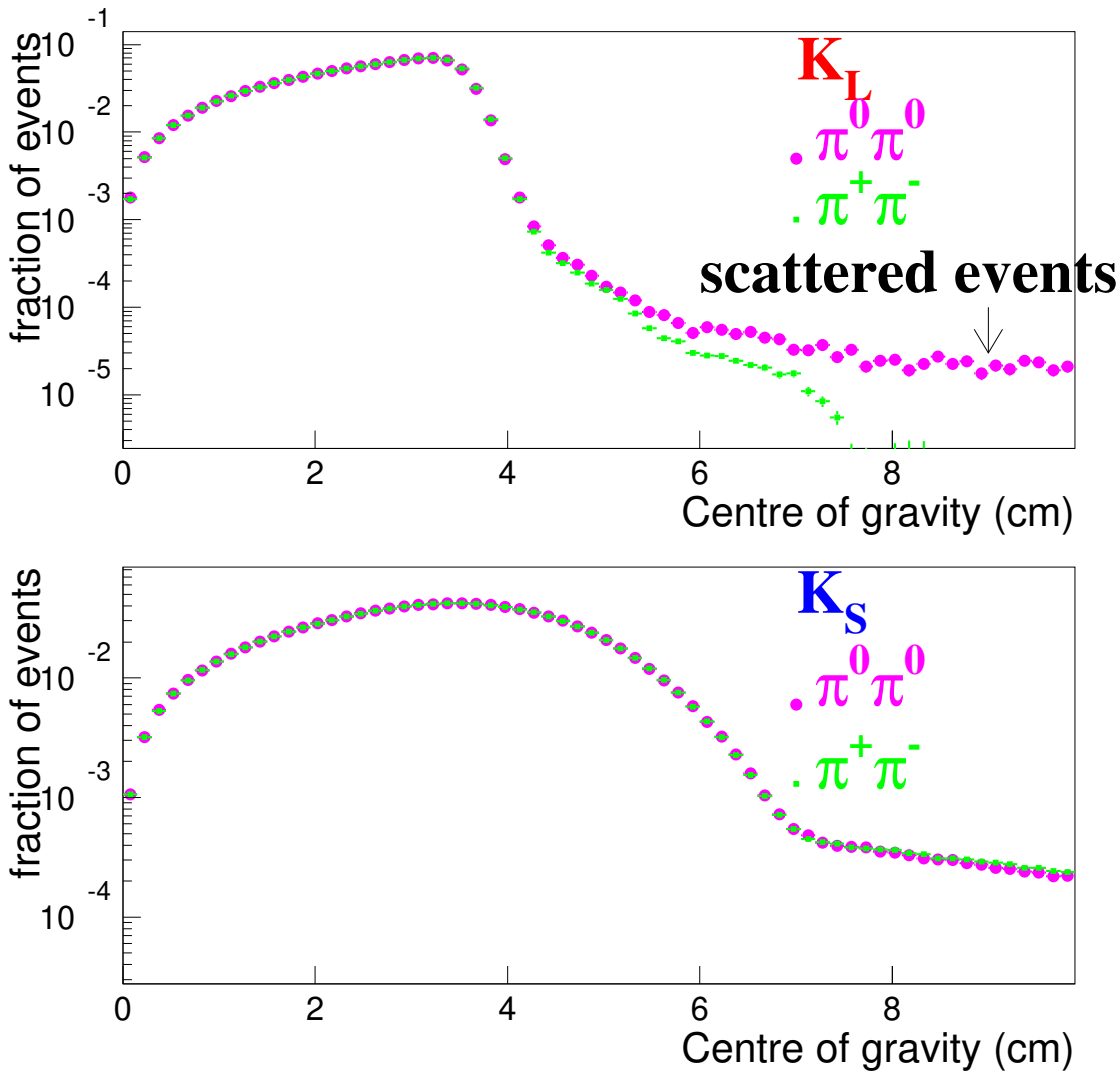
$\pi^+\pi^-$ background vs Energy



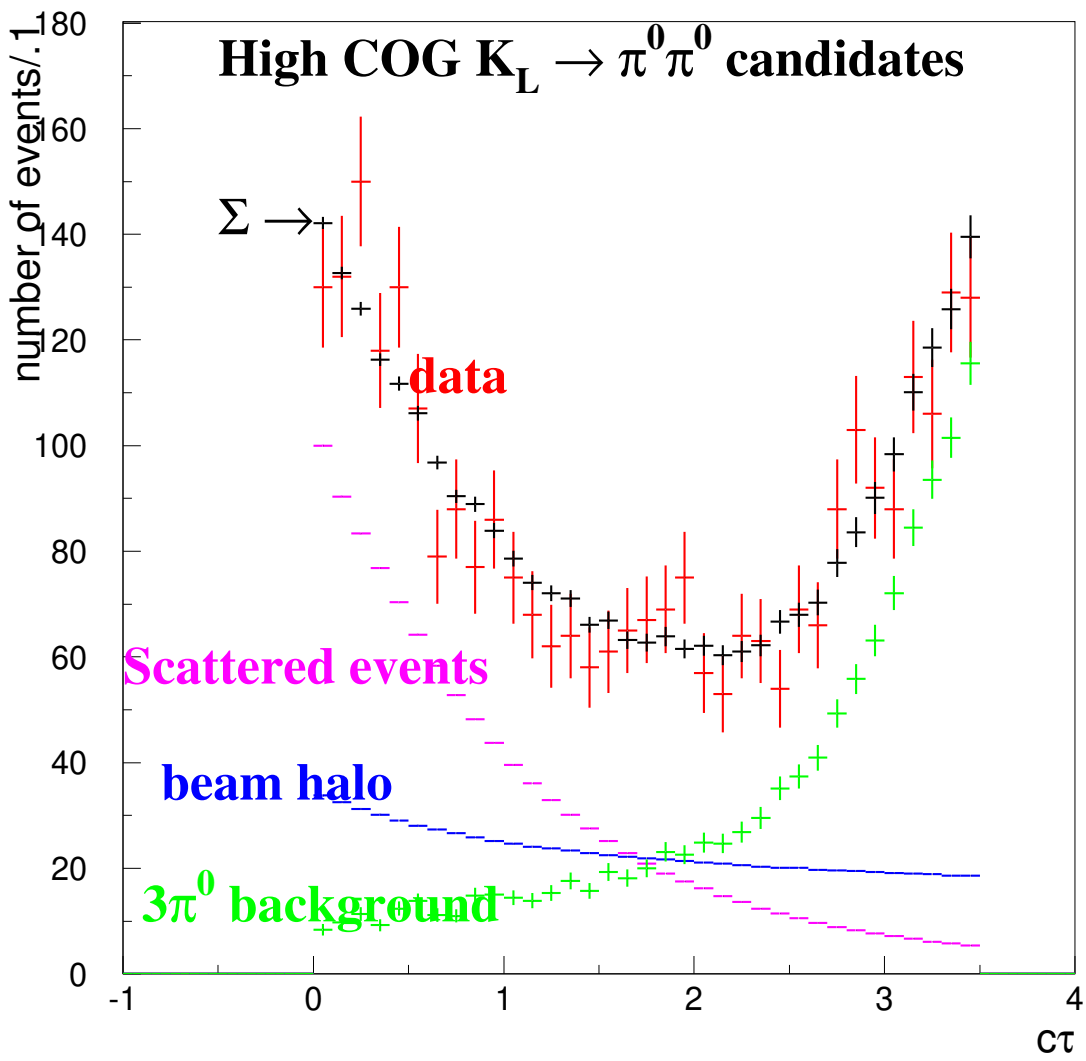
$\pi^0\pi^0$ background vs Energy



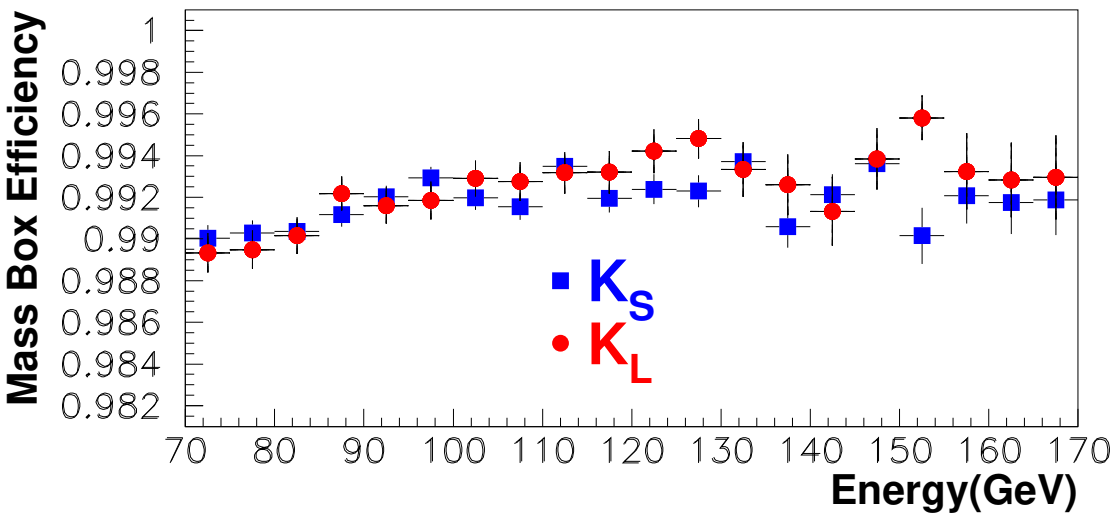
R_{cog} distributions for K_S and K_L

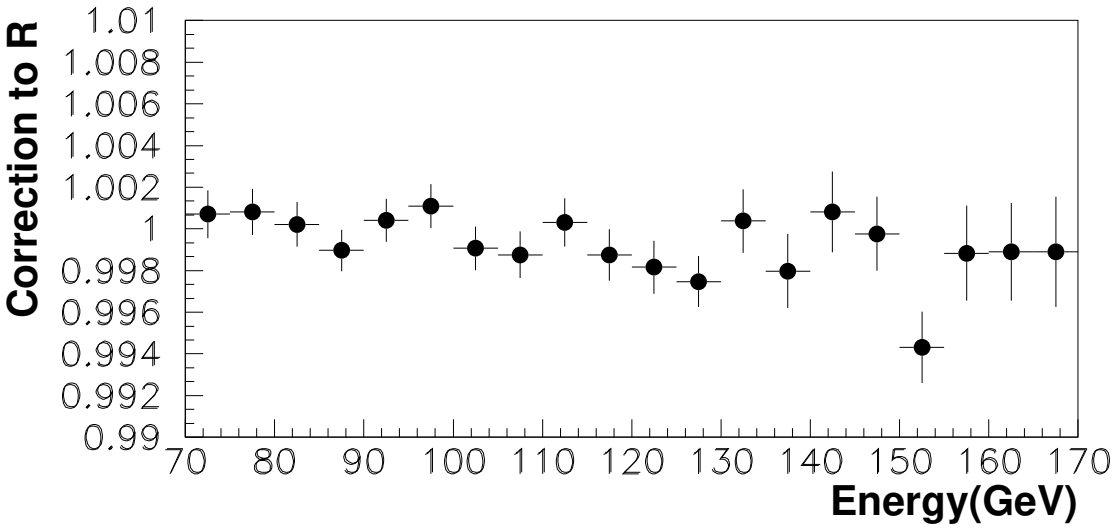


High pt events: estimate from $\pi^0\pi^0$



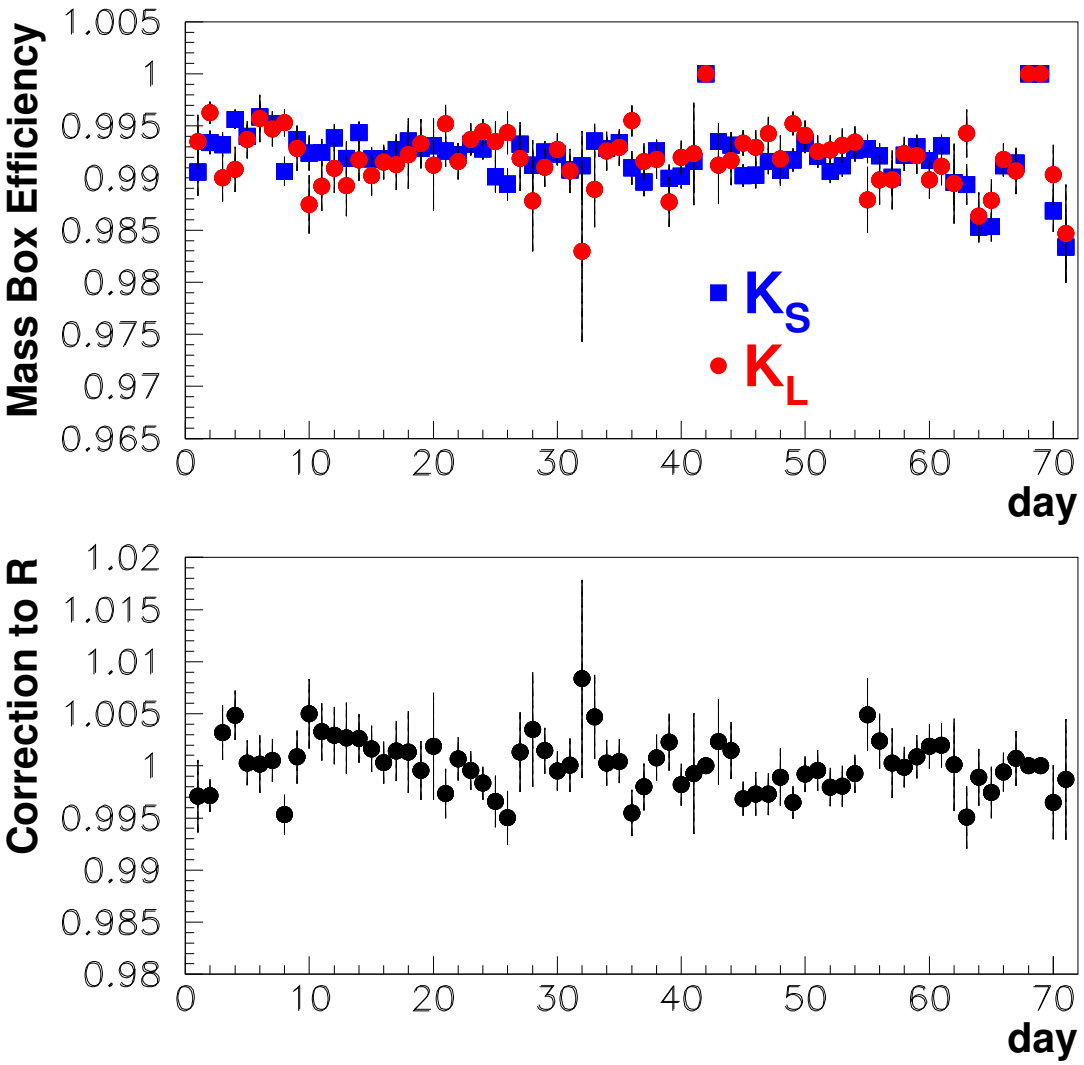
Mass box inefficiency vs Kaon energy



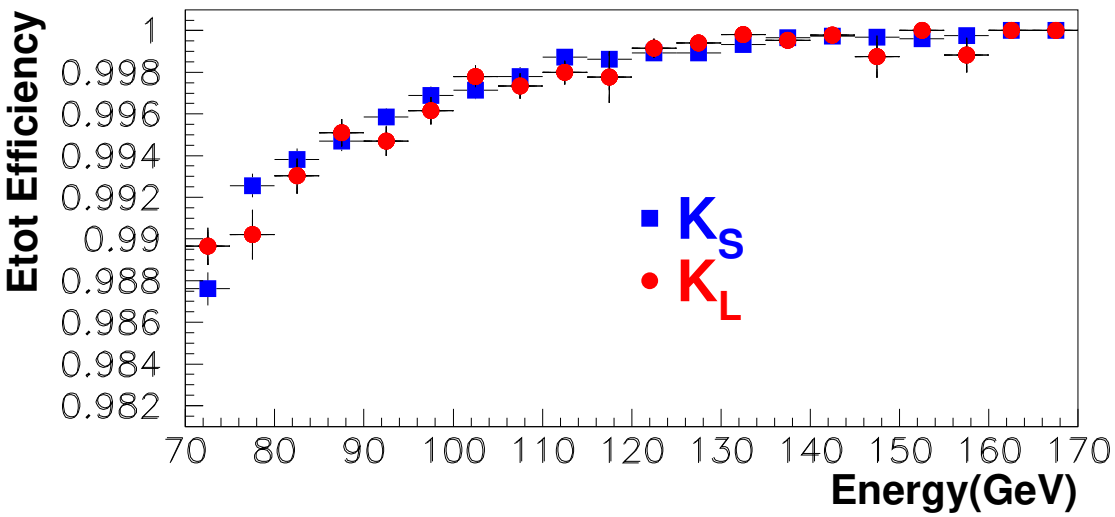


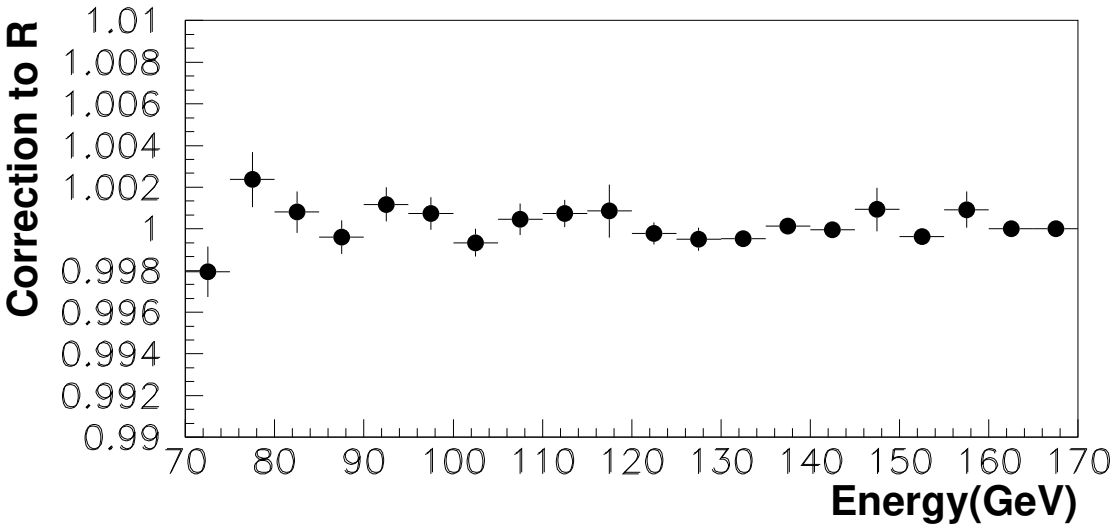
$$\Delta R = (6.5 \pm 3.0) \times 10^{-4}$$

Mass box inefficiency along the run



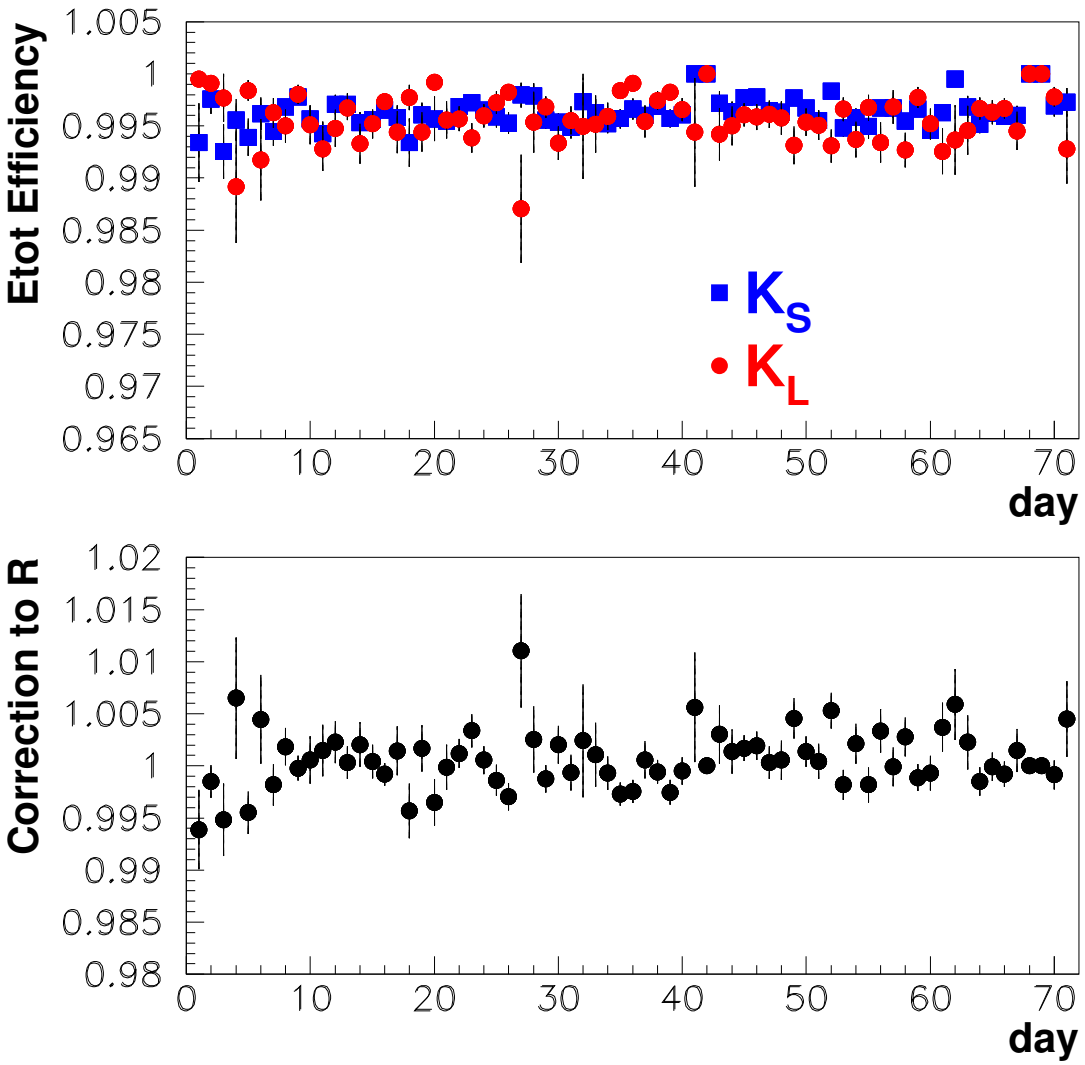
Etot inefficiency vs Kaon energy



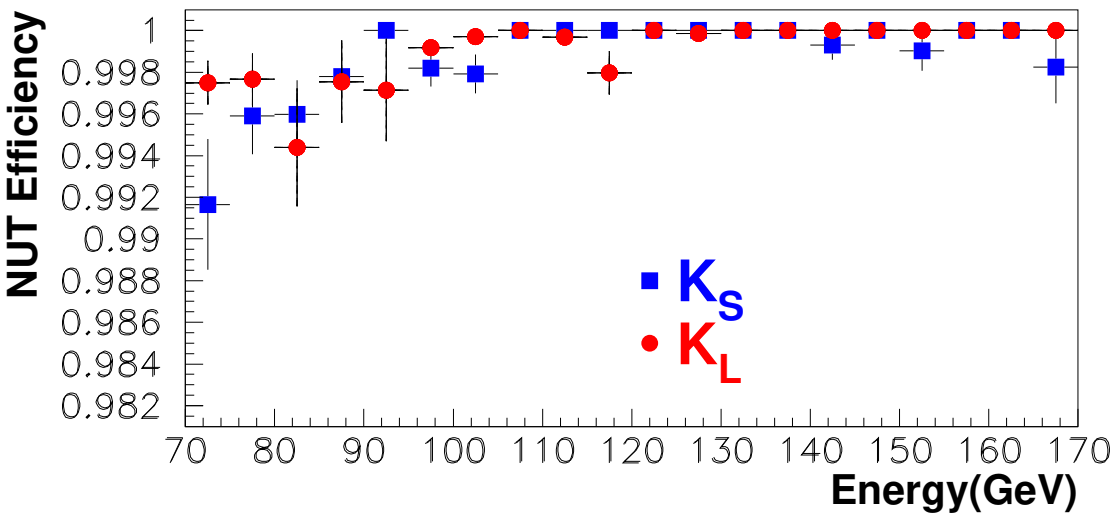


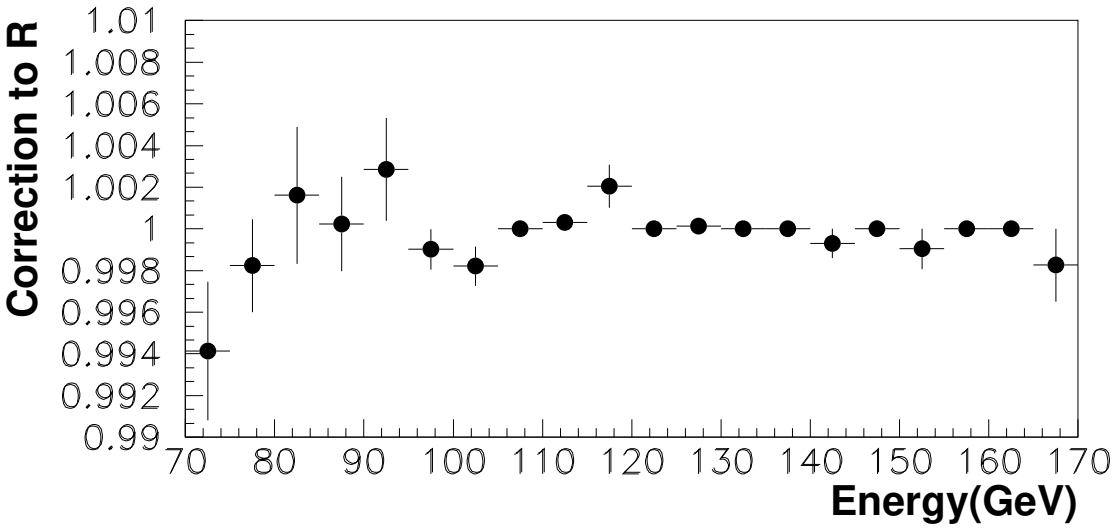
$$\Delta R = (-3.0 \pm 1.9) \times 10^{-4}$$

Etot inefficiency along the run

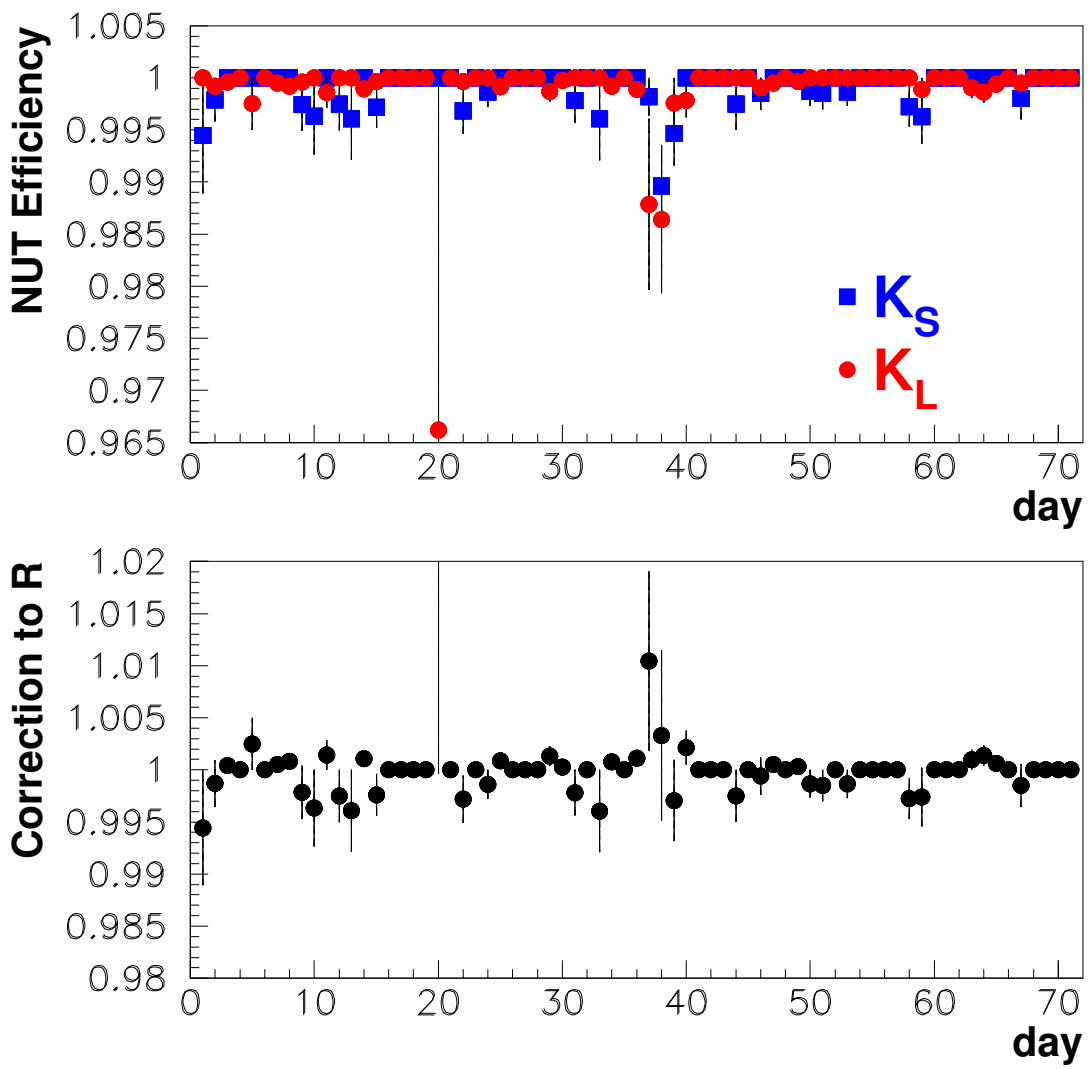


NUT inefficiency vs Kaon energy



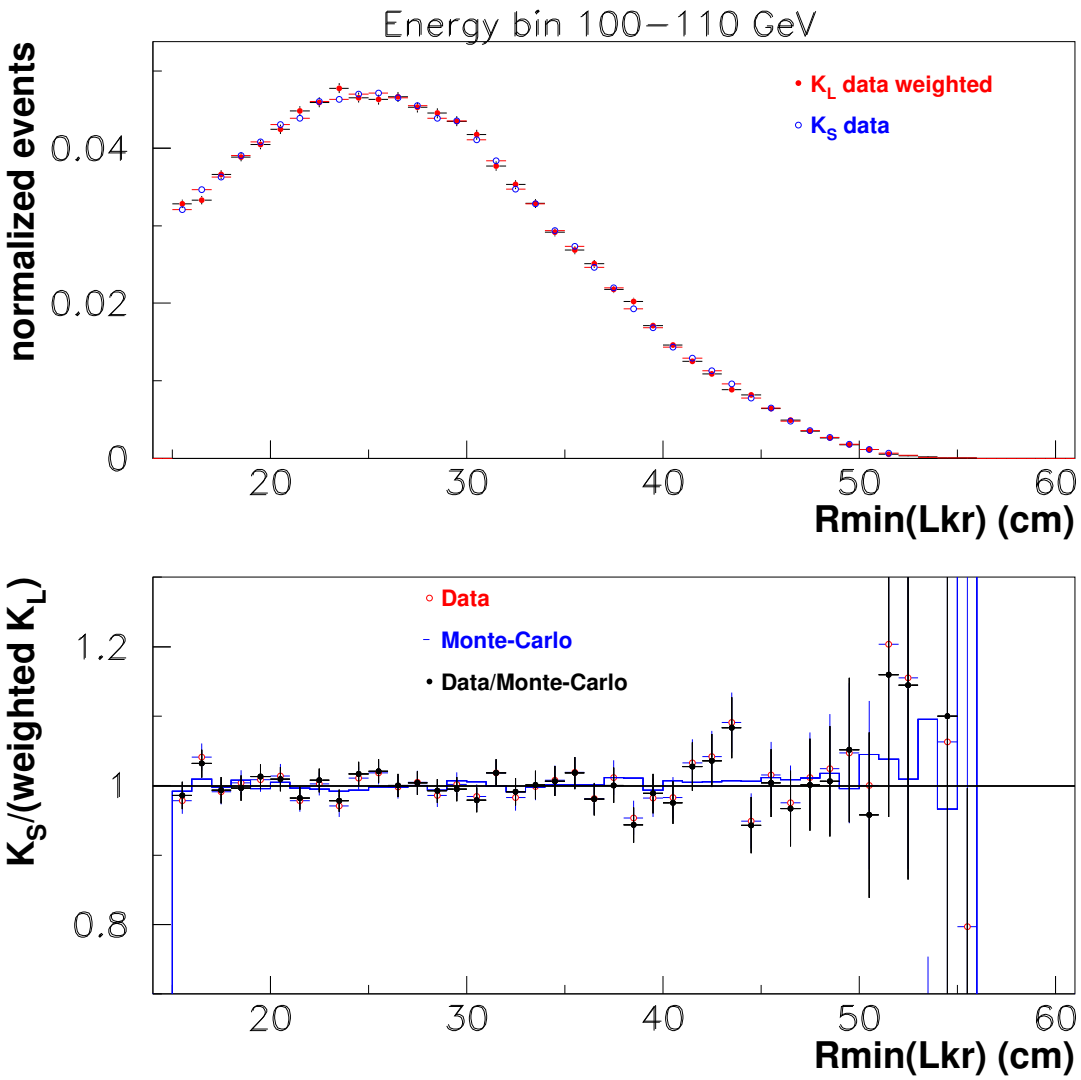


NUT inefficiency along the run

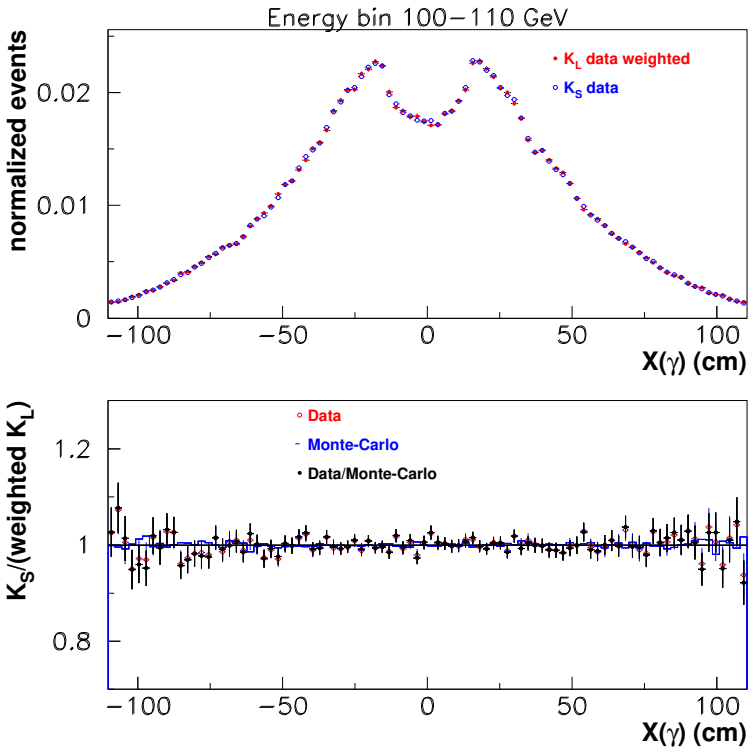


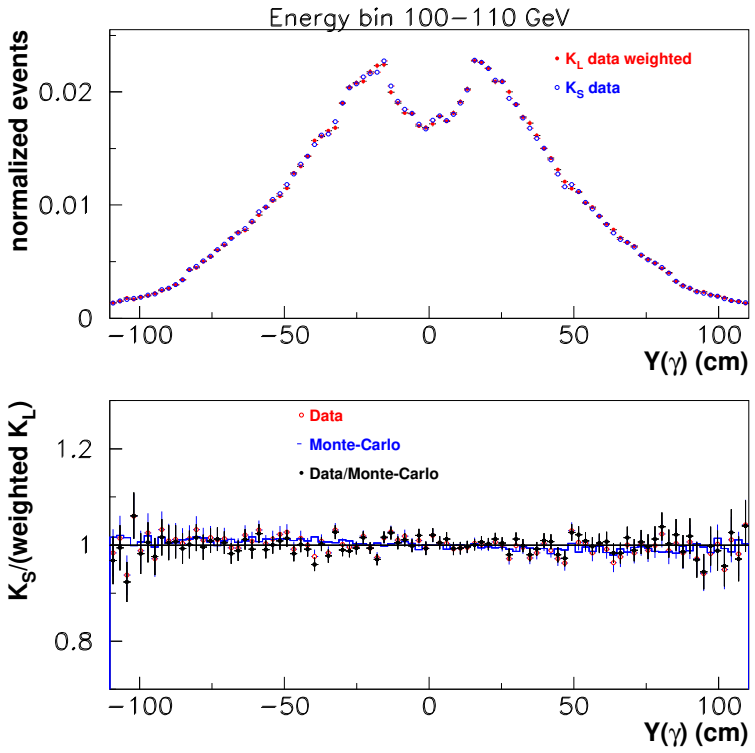
Acceptance Correction: $\pi^0\pi^0$

K_L lifetime weighting
$\Rightarrow$ minimize $K_L - K_S$ detector illumination difference and acceptance correction



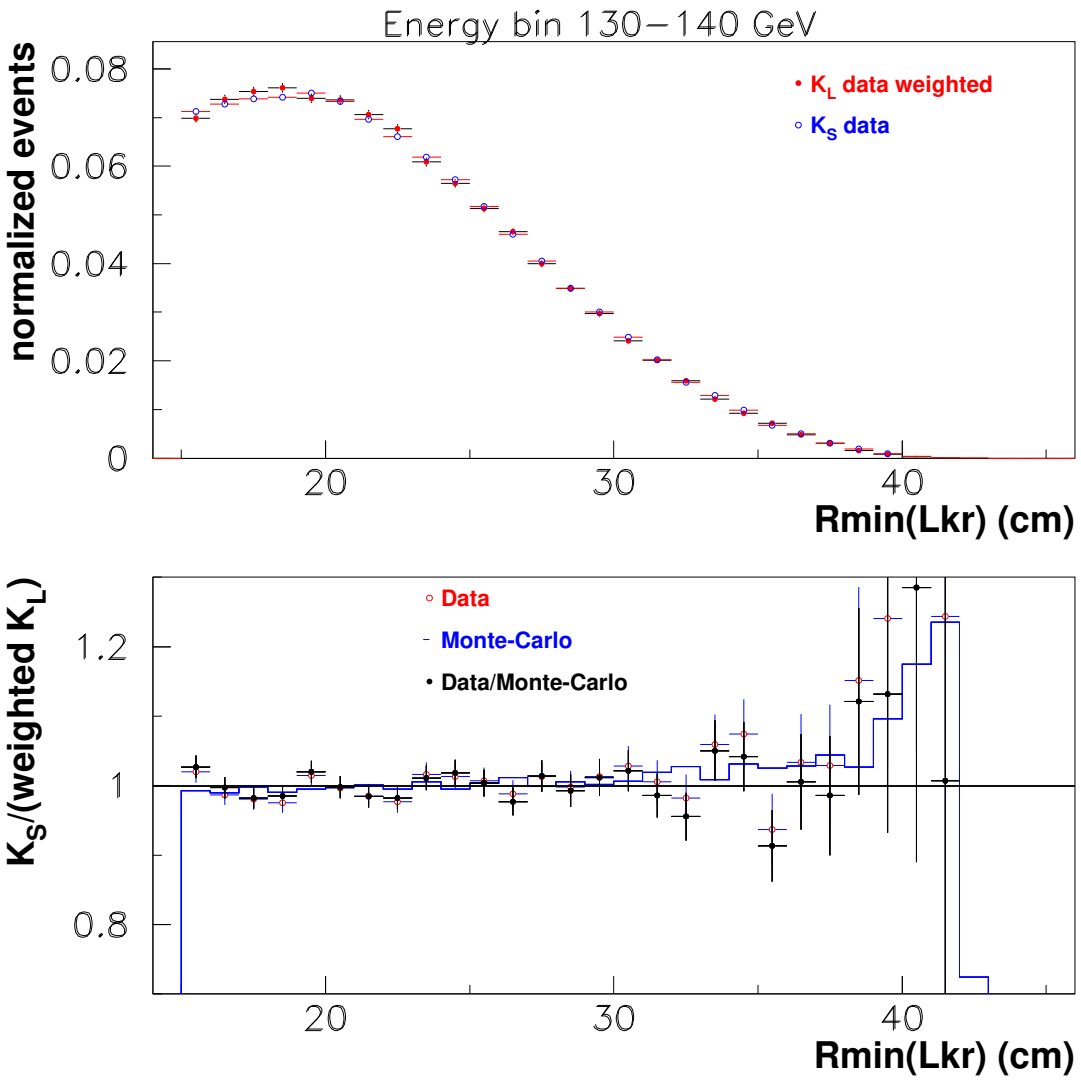
Acceptance Correction: $\pi^0\pi^0$



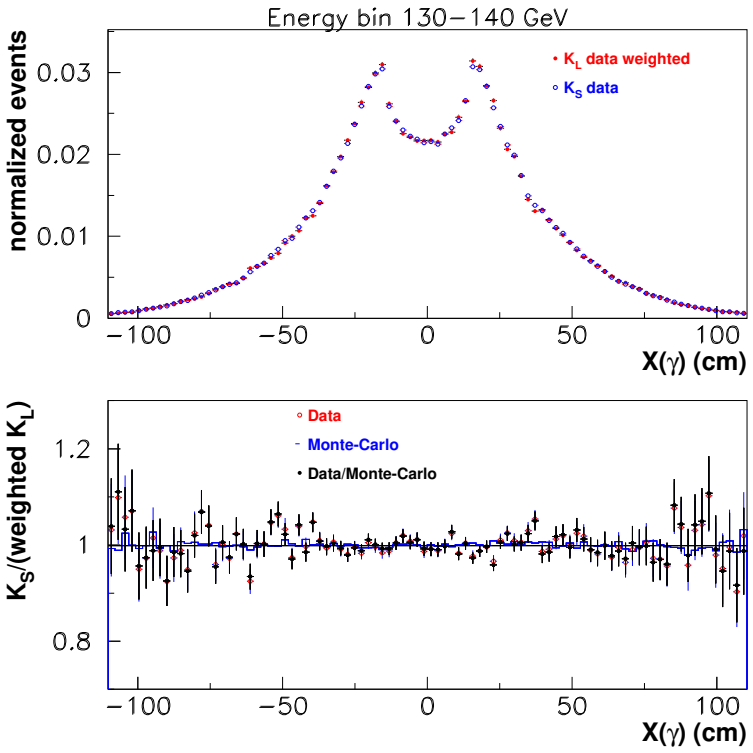


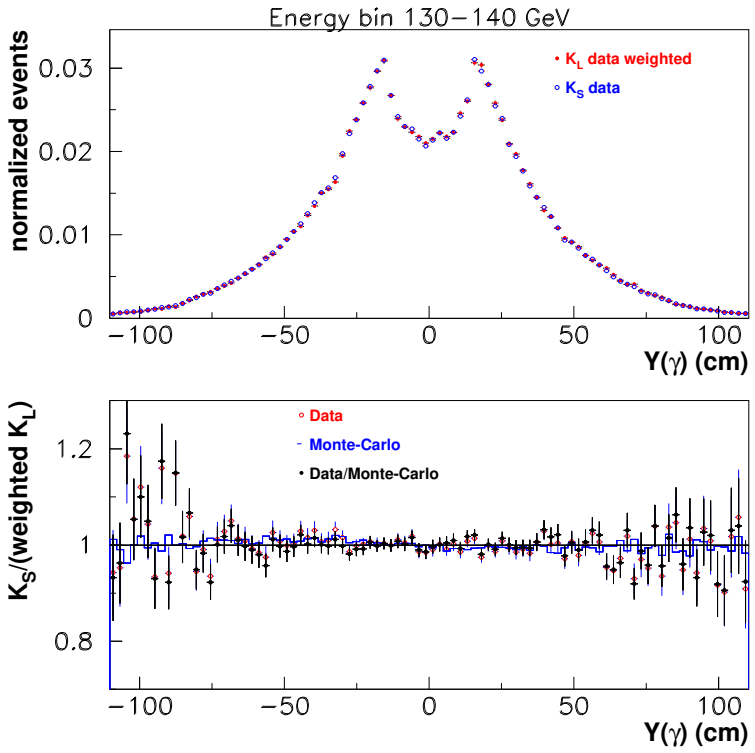
Acceptance Correction: $\pi^0\pi^0$

K_L lifetime weighting
$\Rightarrow$ minimize $K_L - K_S$ detector illumination difference and acceptance correction



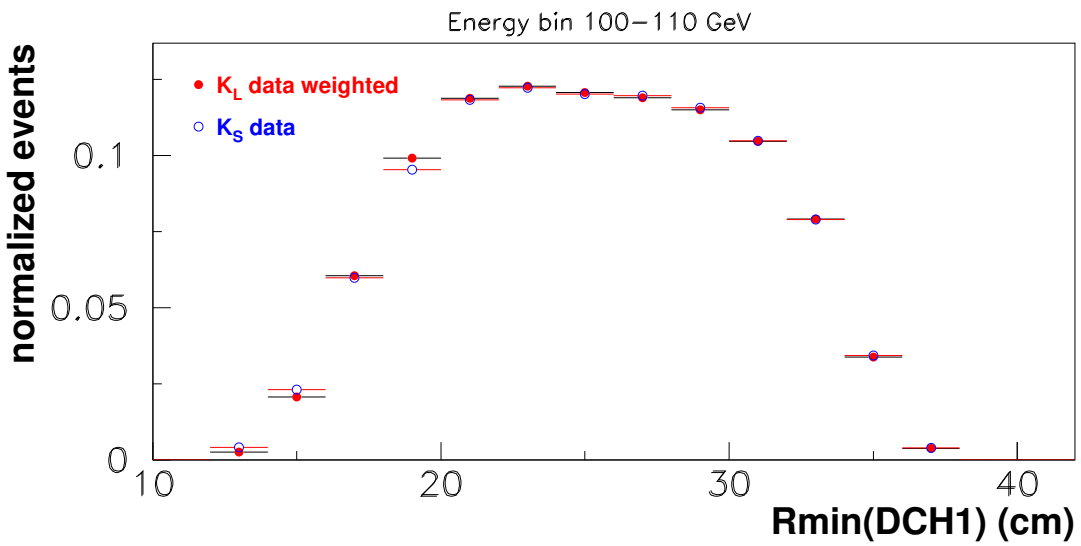
Acceptance Correction: $\pi^0\pi^0$

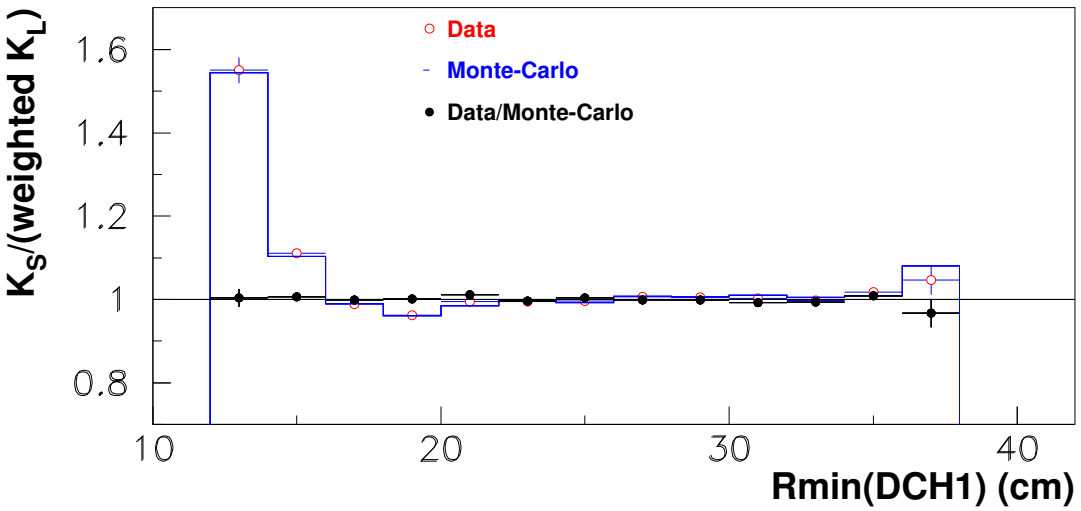




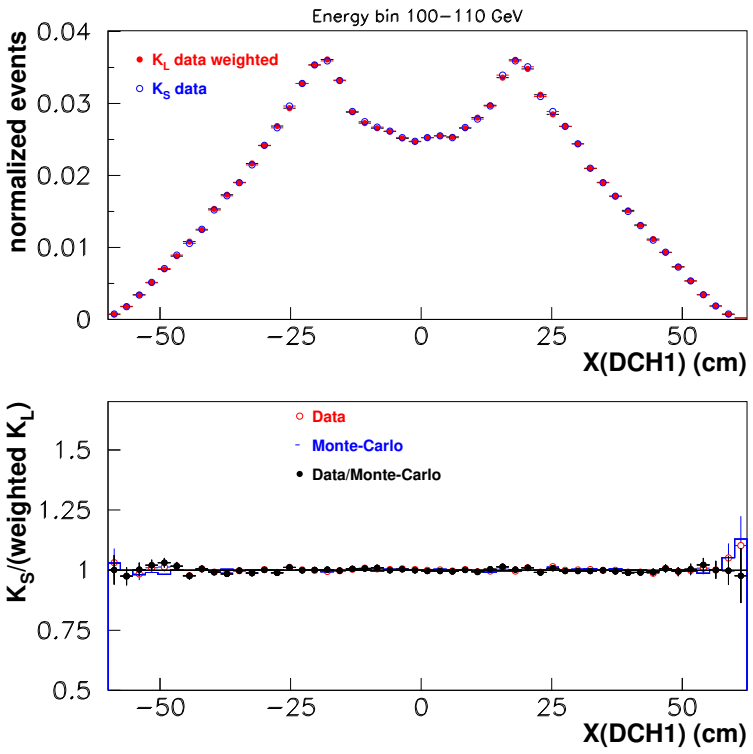
Acceptance Correction: $\pi^+\pi^-$

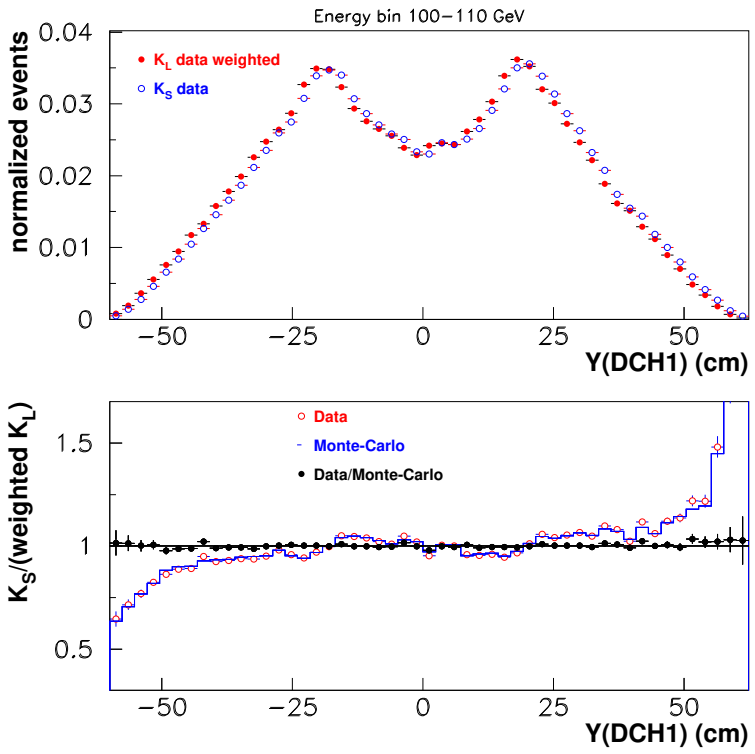
Small residual effect from 0.6 mrad angle between K_L and K_S beams





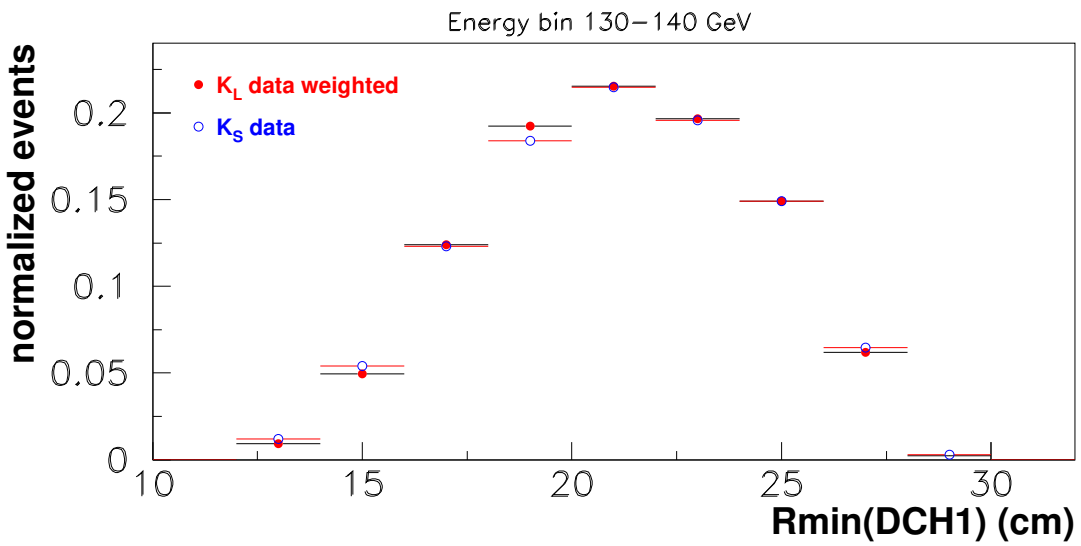
Acceptance Correction: $\pi^+\pi^-$

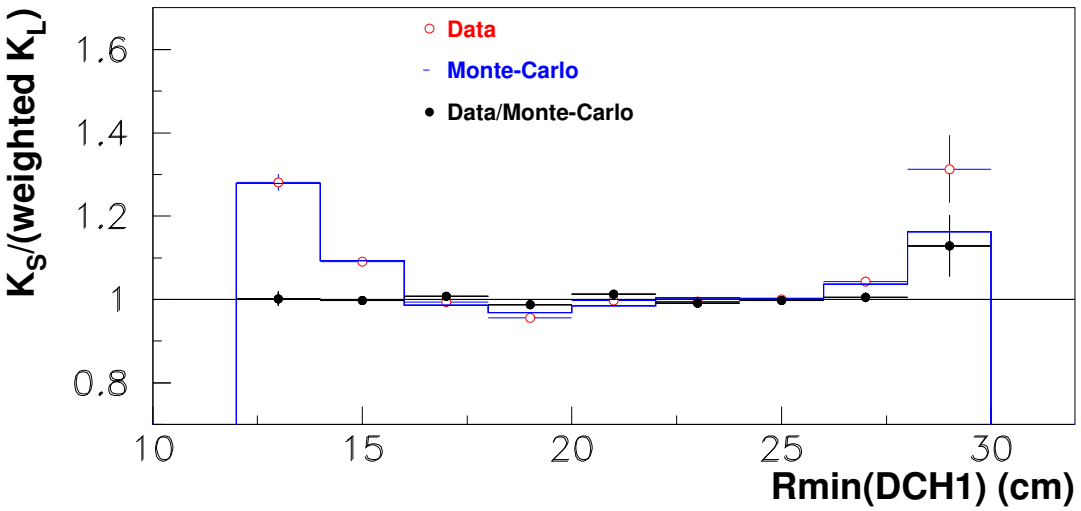




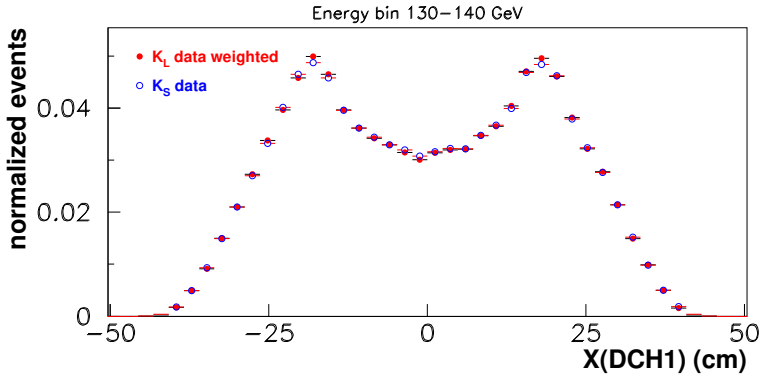
Acceptance Correction: $\pi^+\pi^-$

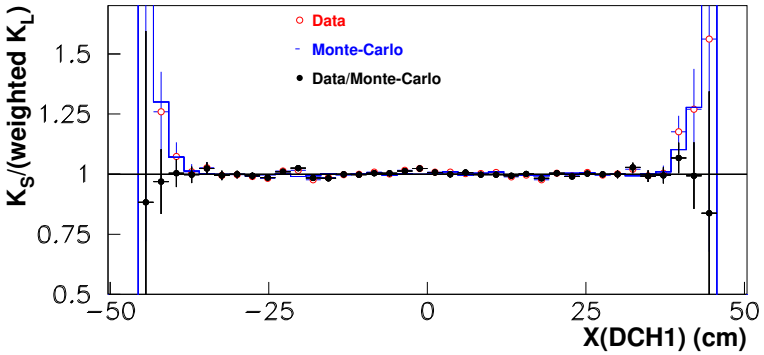
Small residual effect from 0.6 mrad angle between K_L and K_S beams

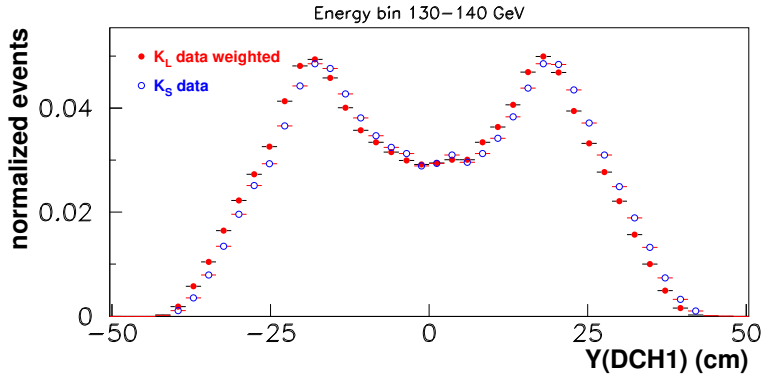


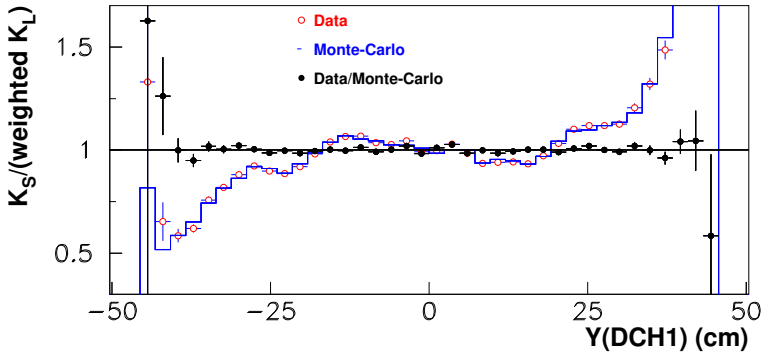


Acceptance Correction: $\pi^+\pi^-$

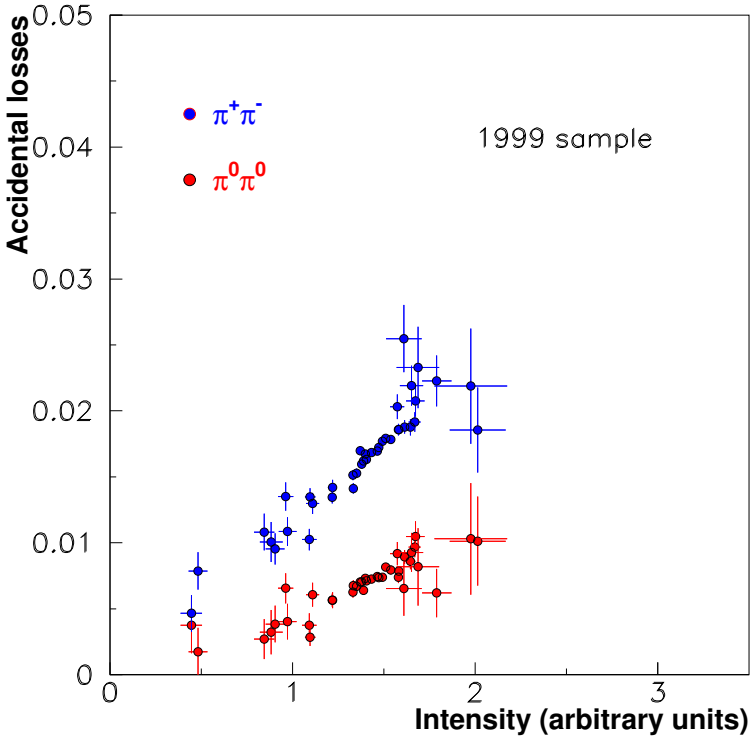




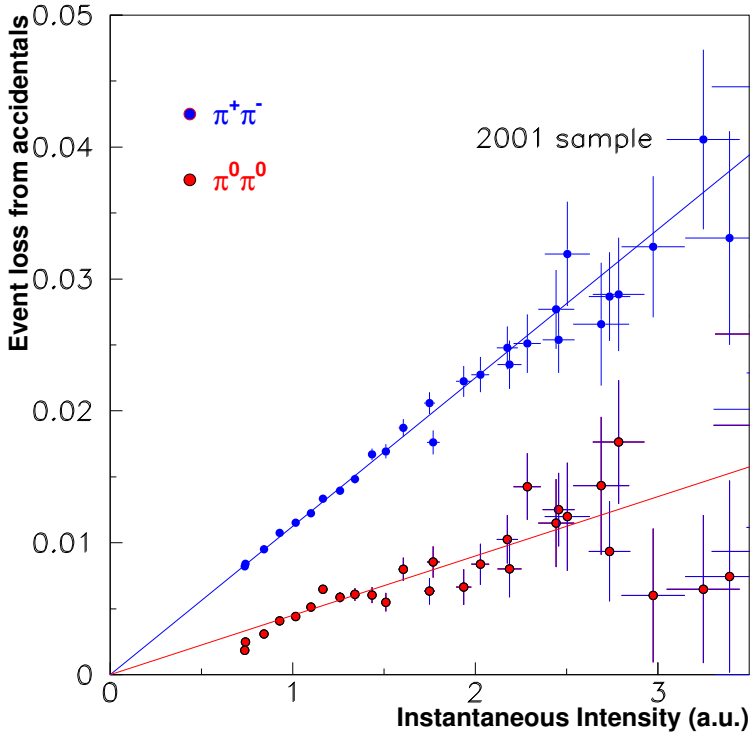




Accidental effects



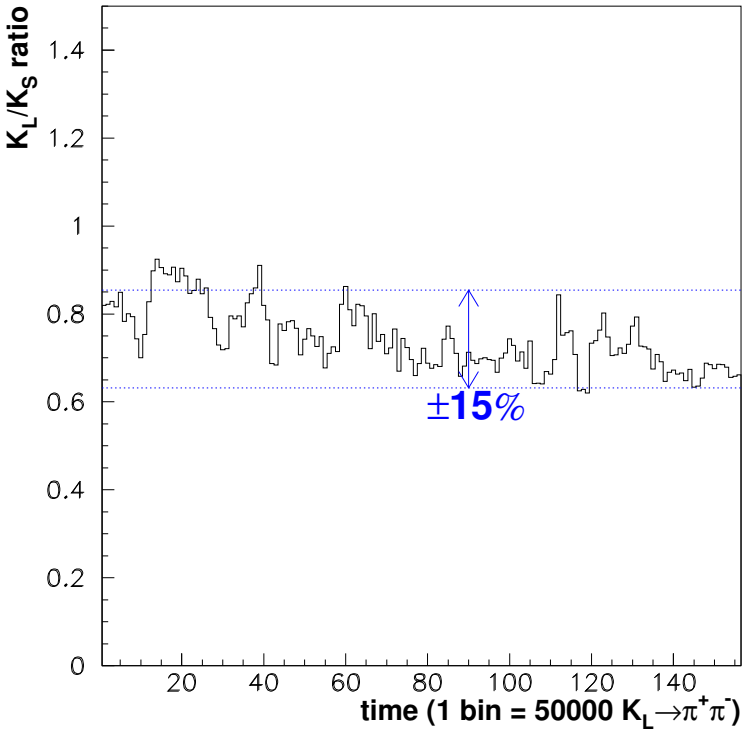
$\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.4 \pm 0.7)\%$
in 98-99



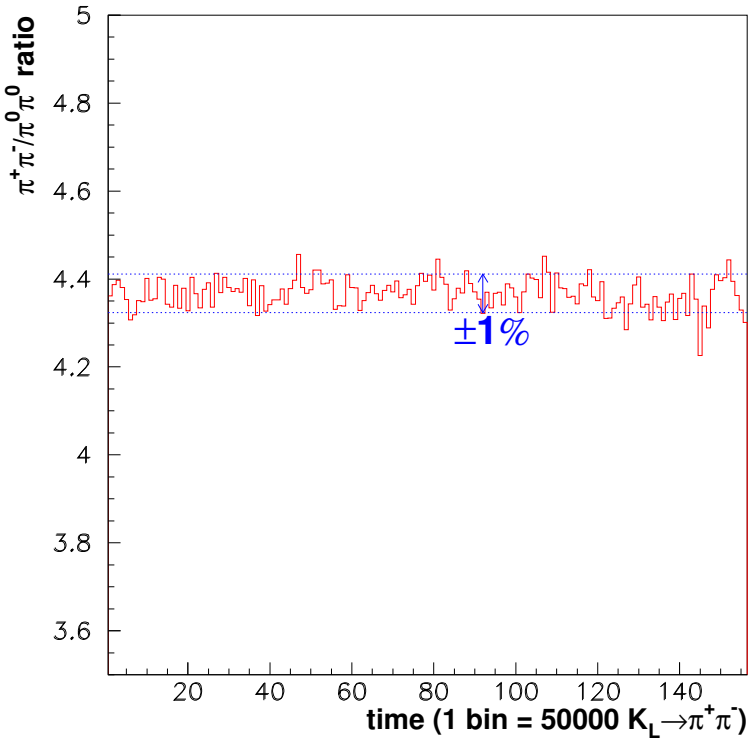
$\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.0 \pm 0.5)\%$
in 2001

K_L /K_S and $\pi^+\pi^-$ / $\pi^0\pi^0$ stability vs time

K_S events before reweighting



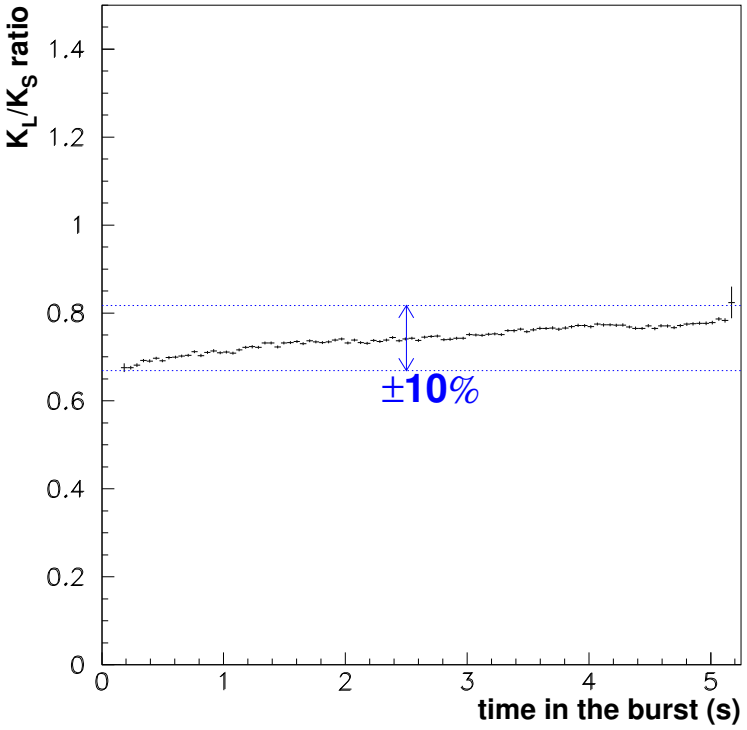
Variation in K_L /K_S with time
(RMS $\approx$ 10%)



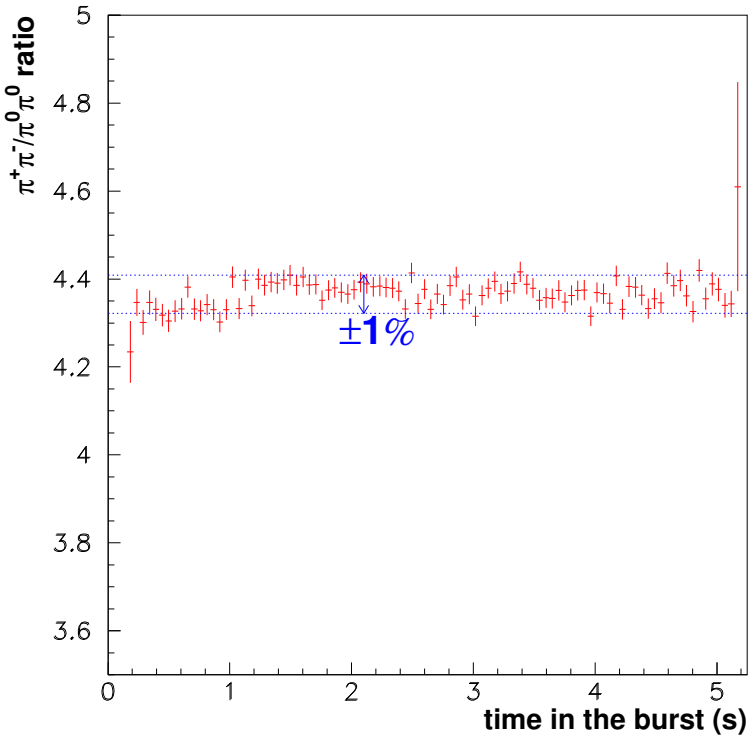
Variation in $\pi^+\pi^-/\pi^0\pi^0$ with time

K_S reweighting is a small effect on R ($\approx 0.9 \times 10^{-4}$, it was $\approx 3 \times 10^{-4}$ in 98-99)

K_S /K_L and $\pi^+\pi^-$ / $\pi^0\pi^0$ stability vs time in the burst



Variation in K_L /K_S with time



Variation in $\pi^+\pi^-/\pi^0\pi^0$ with time

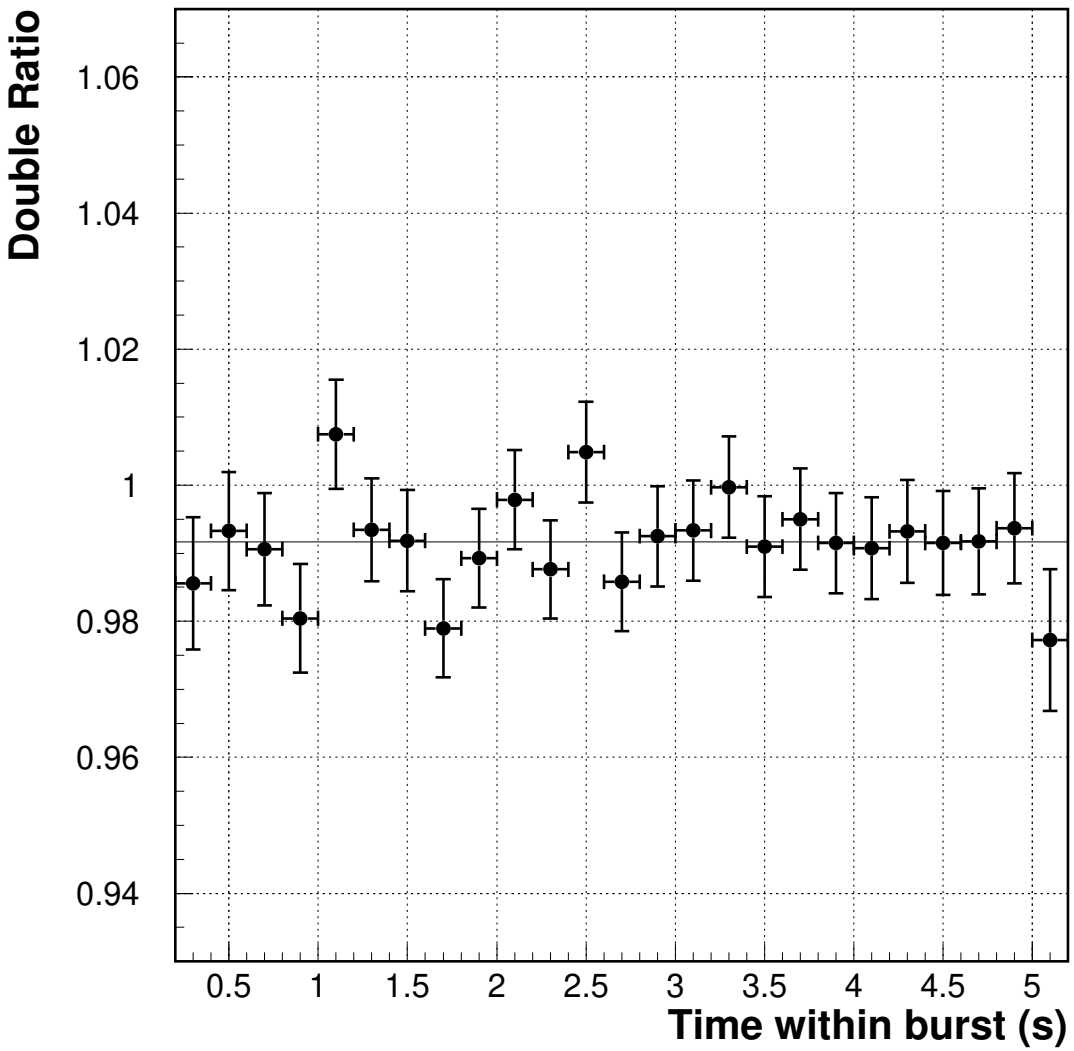
$\Delta\alpha_{LS}$ origin

α_{LS} seen by BM triggers and probability of losses and gains

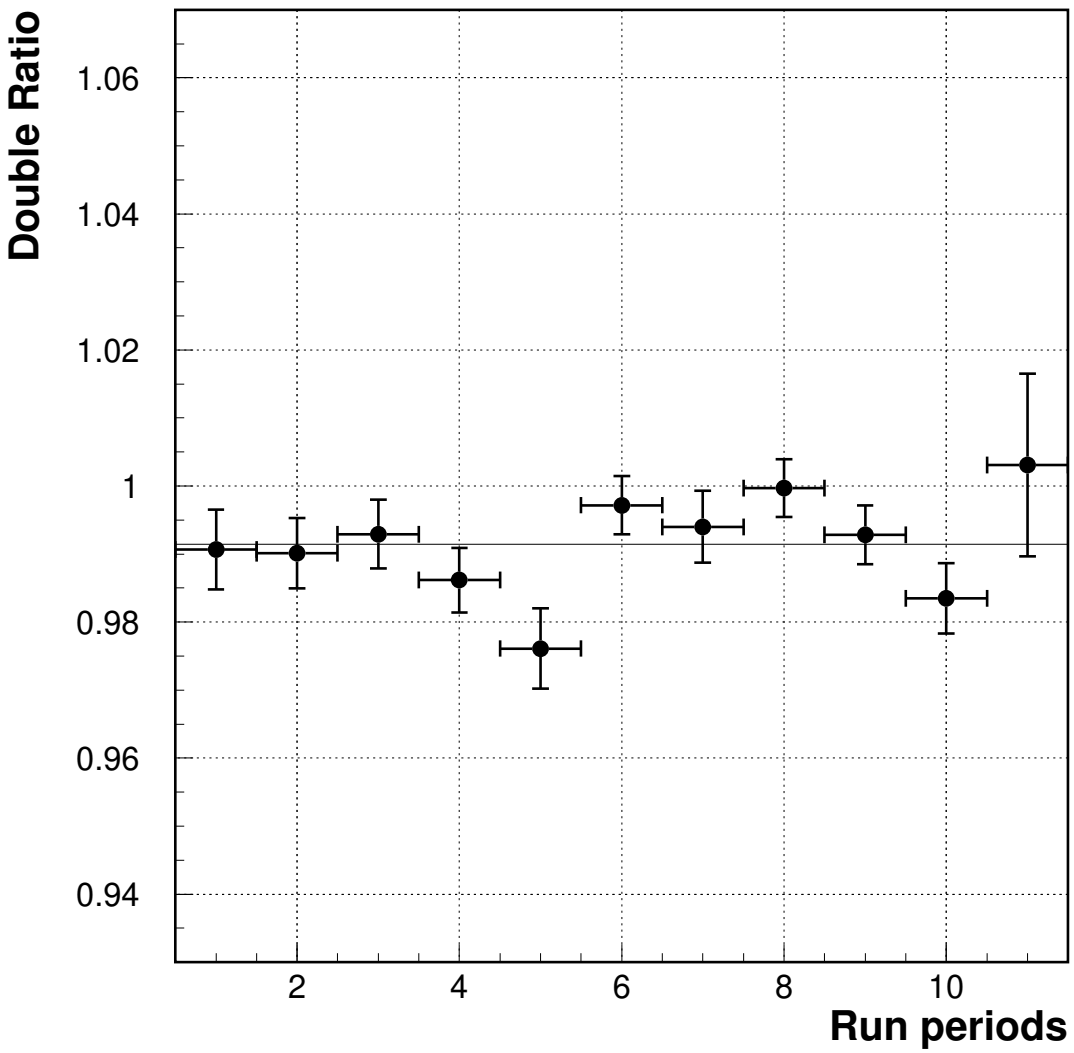
α_{LS} all BM triggers used	7.57%
α_{LS} BM triggers inducing losses of $\pi^+\pi^-$	$(10.72 \pm 0.05)\%$
Probability of loss for $\pi^+\pi^-$	2.05%
α_{LS} BM triggers inducing gains of $\pi^+\pi^-$	$(8.35 \pm 0.21)\%$
Probability of gain for $\pi^+\pi^-$	0.14%
α_{LS} BM triggers inducing losses of $\pi^0\pi^0$	$(8.19 \pm 0.03)\%$
Probability of loss for $\pi^0\pi^0$	4.78%
α_{LS} BM triggers inducing gains of $\pi^0\pi^0$	$(7.63 \pm 0.04)\%$
Probability of gain for $\pi^0\pi^0$	2.57%

$\Delta\alpha_{LS}(\text{predicted}) = (+3.5 \pm 0.4) \times 10^{-4}$ [losses and gains from data overlay]
$\Delta\alpha_{LS}(\text{predicted}) = (+2.0 \pm 0.4) \times 10^{-4}$ [losses and gains from MC overlay]
$\Delta\alpha_{LS}(\text{predicted}) = (+0.4 \pm 0.2) \times 10^{-4}$ [from trigger inefficiency]
$\Delta\alpha_{LS}(\text{observed}) = (+3.4 \pm 1.4) \times 10^{-4}$

Double Ratio versus time in burst



Double Ratio versus run periods



Final Result

From 2001 data:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 2.5_{\mathrm{stat}} \pm 1.1_{\mathrm{syst,stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-4}$$

Combining with 97+98+99 result

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 1.6_{\mathrm{stat}} \pm 1.3_{\mathrm{syst,stat}} \pm 1.6_{\mathrm{syst}}) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst,stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-4}}$$