NA48 Result on Direct CP Violation

Ivan Mikulec
CERN, Geneva

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

Outline

- Measurement principles and experimental setup
- Data analysis
- Result and checks
- Conclusions and perspectives

The presented result (to be published) is based on data collected in 1998 and 1999 runs

The statistics is almost 7 times larger than our last published result based on 1997 data - Phys. Lett. B 465 (1999)

Measurement principles

Measure double ratio:

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

by counting the four 2π decay rates.

⟹ Statistics: need millions of $K_L \to \pi^0\pi^0$ events using high intensity K_L beam with fast detectors and powerful trigger, DAQ and computing farm

⟹ Systematics: systematic biases in the event counting are made symmetric between $\pi^0\pi^0$ and $\pi^+\pi^-$, or K_L and K_S, so they cancel in R.

Basic principle:

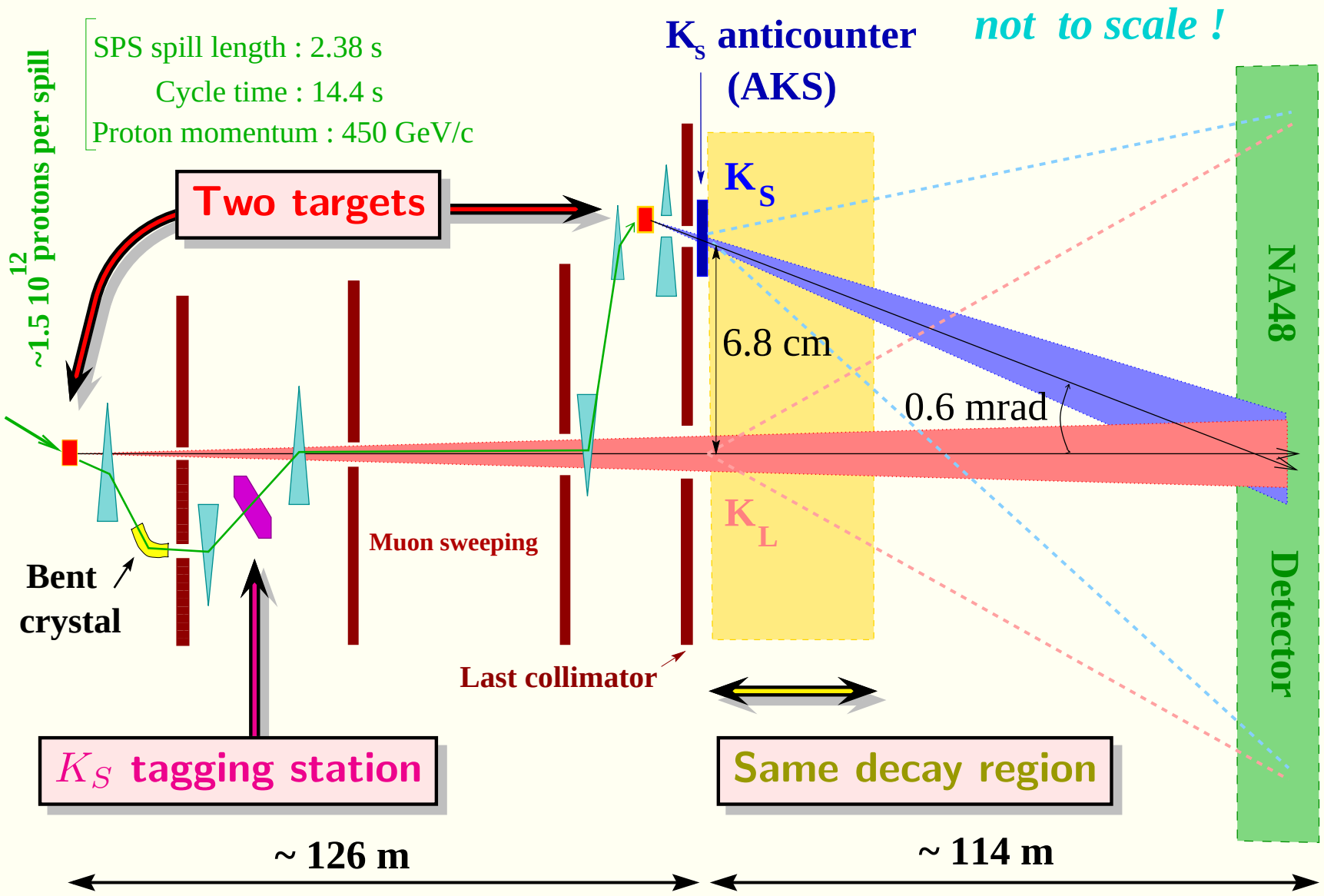
Better symmetry:

⟹ better cancellation

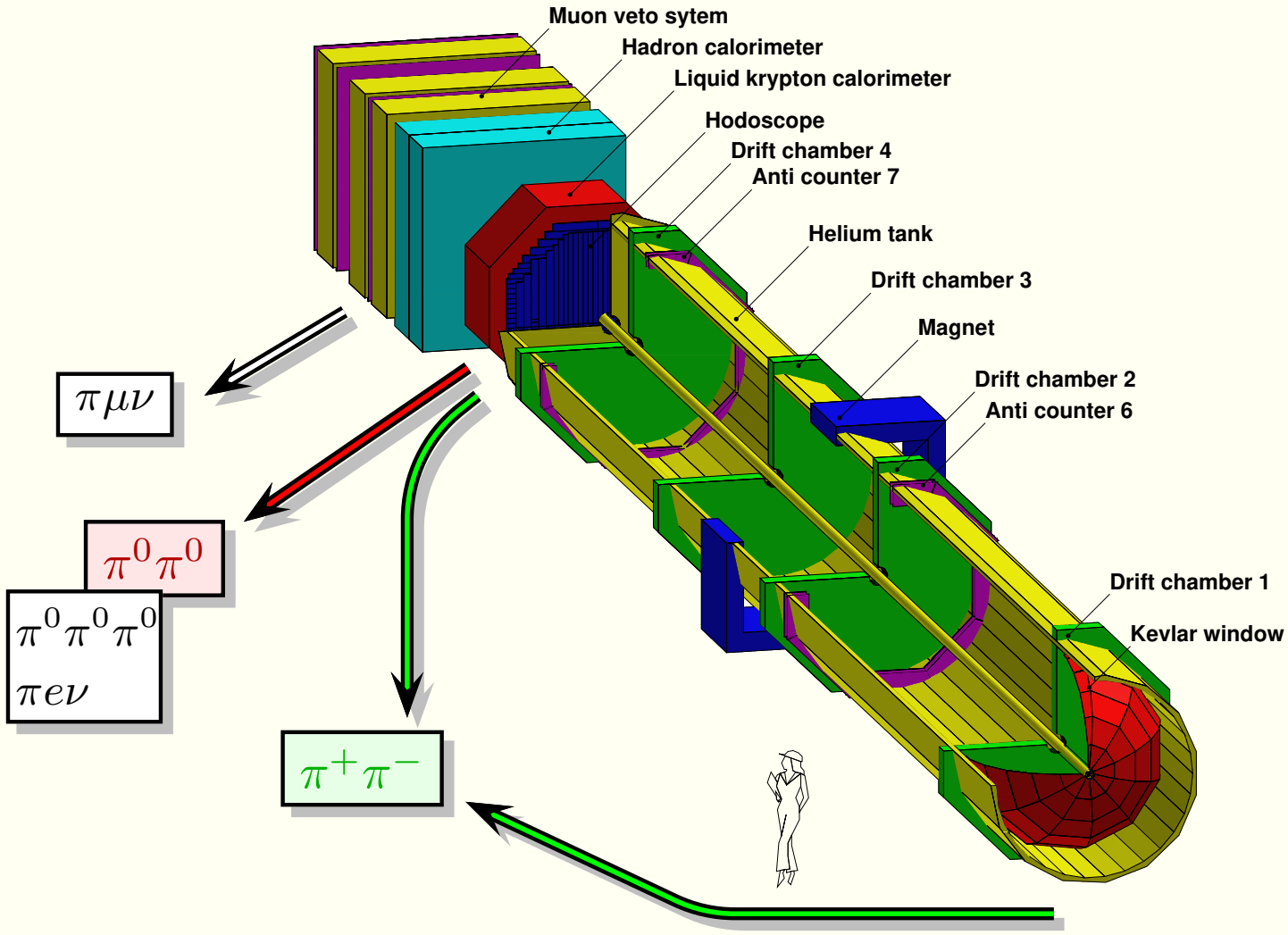
⟹ smaller correction

⟹ smaller systematic uncertainty.

NA48 beam lines



NA48 detector

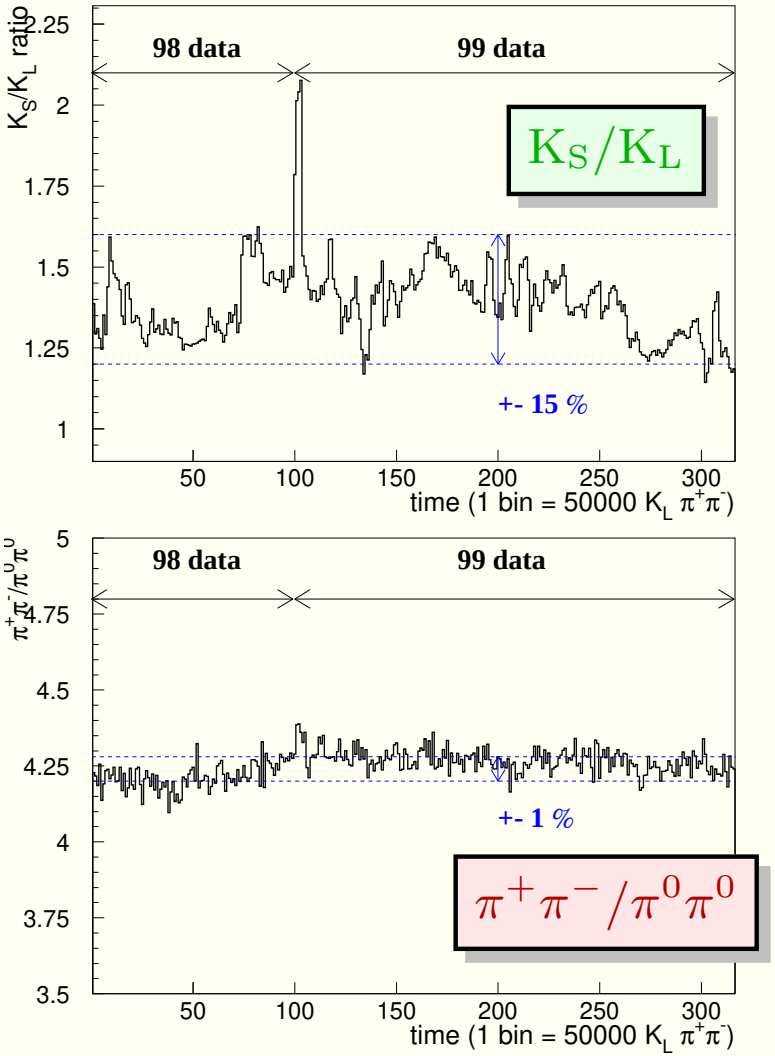


Symmetry in the time variations

➡ All four decays are collected at the same time by using simultaneous K_S and K_L beams. They are derived from the same primary proton beam using two targets with different distances to the decay volume.

➡ K_S events are weighted with K_L/K_S intensity ratio

➡ in case of dead-time (∼20%) in one decay mode no events are counted also in the other mode

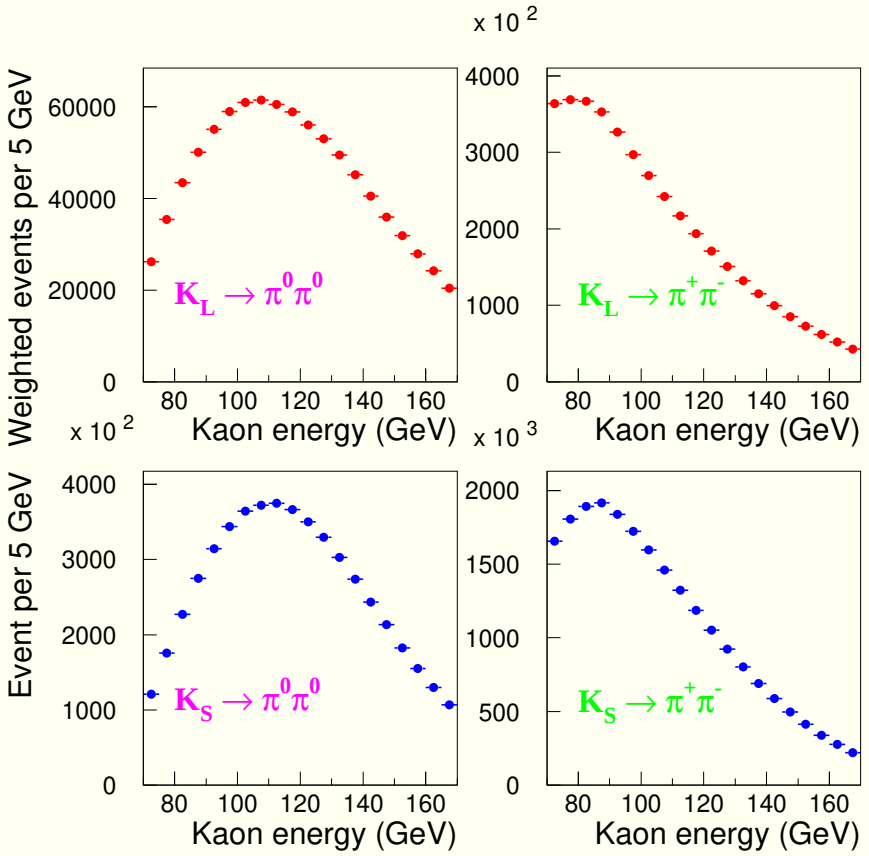


Symmetry in the kaon energy

Kaon energy spectra:

➡ the targeting angles are tuned to deliver similar decay spectra in the chosen decay volume and in the energy interval 70 to 170 GeV

➡ residual differences in the $\mathrm{K_S}$ and $\mathrm{K_L}$ decay spectra are reduced by performing the analysis in twenty 5 GeV bins



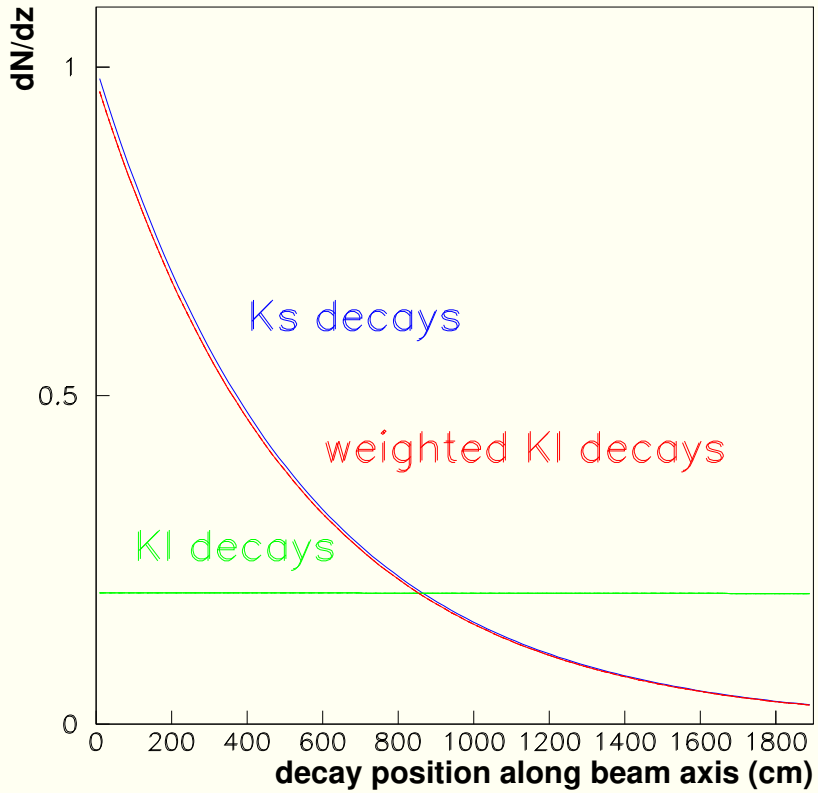
Symmetry in the detector illumination

➡ the two beams converge in the center of the detector

➡ all four decays are collected from the same decay volume extending 3.5 $\mathrm{K_S}$ life times downstream the final collimator

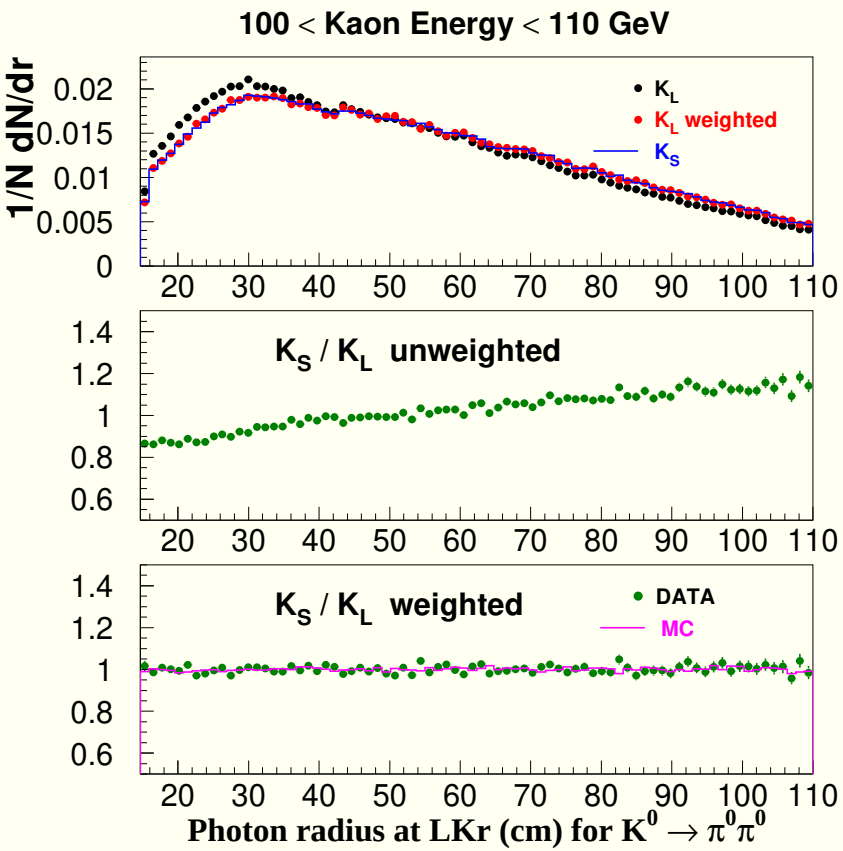
➡ $\mathrm{K_L}$ events are weighted with $\frac{\mathrm{K_S}-target}{\mathrm{K_L}-target}$ 2π decay rate ratio (proper time weighting) $\Rightarrow$ distances between the decay vertex and the detector become the same as for $\mathrm{K_S}$

proper time weighting:

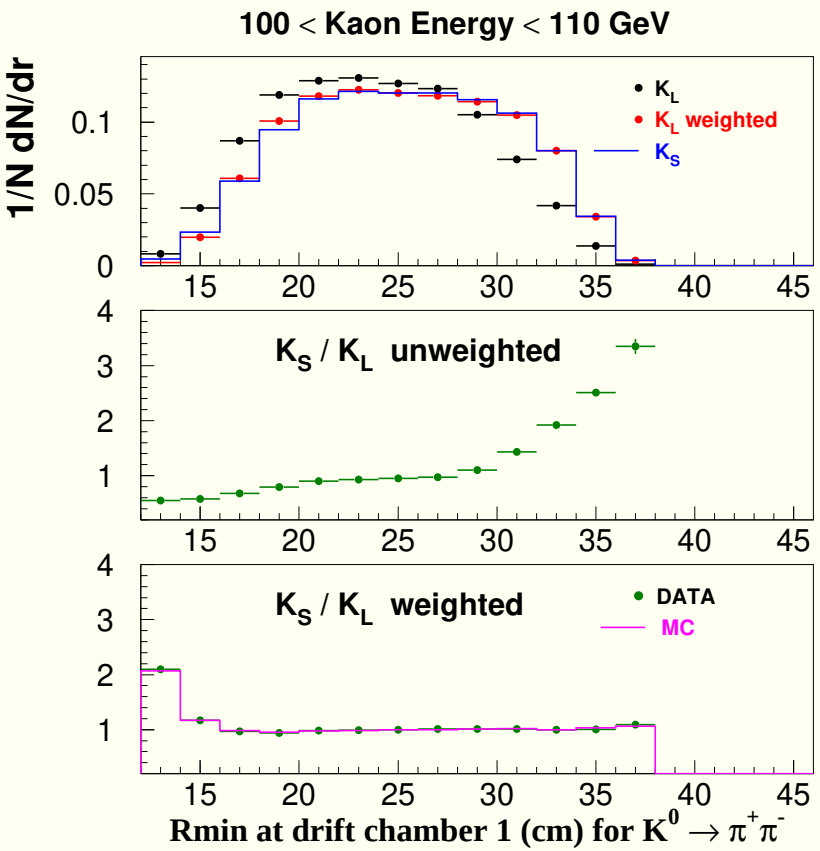


Symmetry in the detector illumination

$\pi^0\pi^0$:



$\pi^+\pi^-$:



Illumination as a function of distance to the beam axis

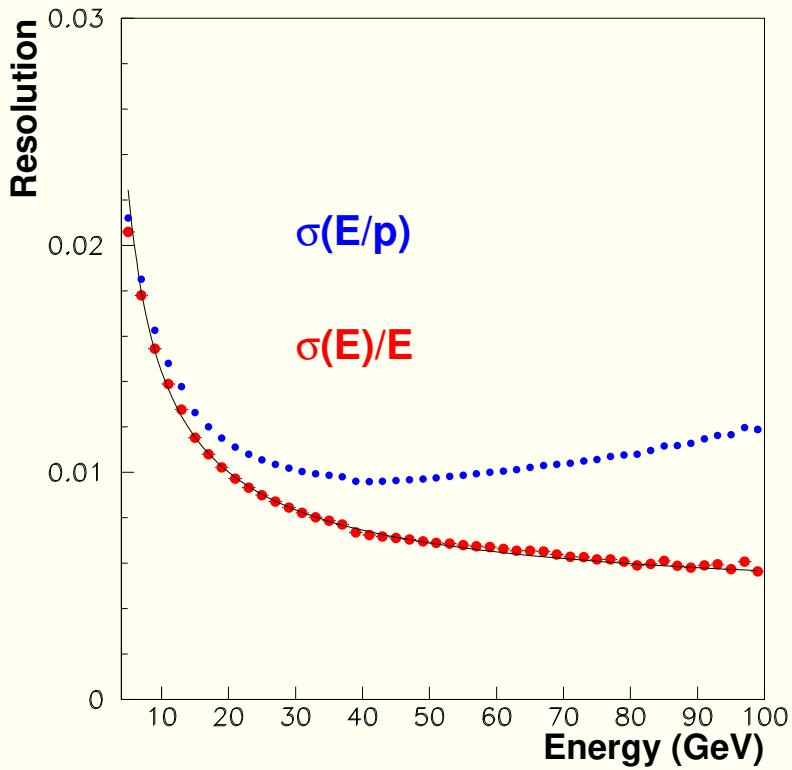
Symmetry in the decay identification

backgrounds do not cancel - detectors with good resolutions are used - backgrounds are reduced to $\simeq 10^{-3}$ level:

- $\pi^0\pi^0$: LKr calorimeter resolutions:
  energy ~1% for 25 GeV photons
  position ~1 mm for 25 GeV photons
  time ~0.22 ns/$\pi^0\pi^0$

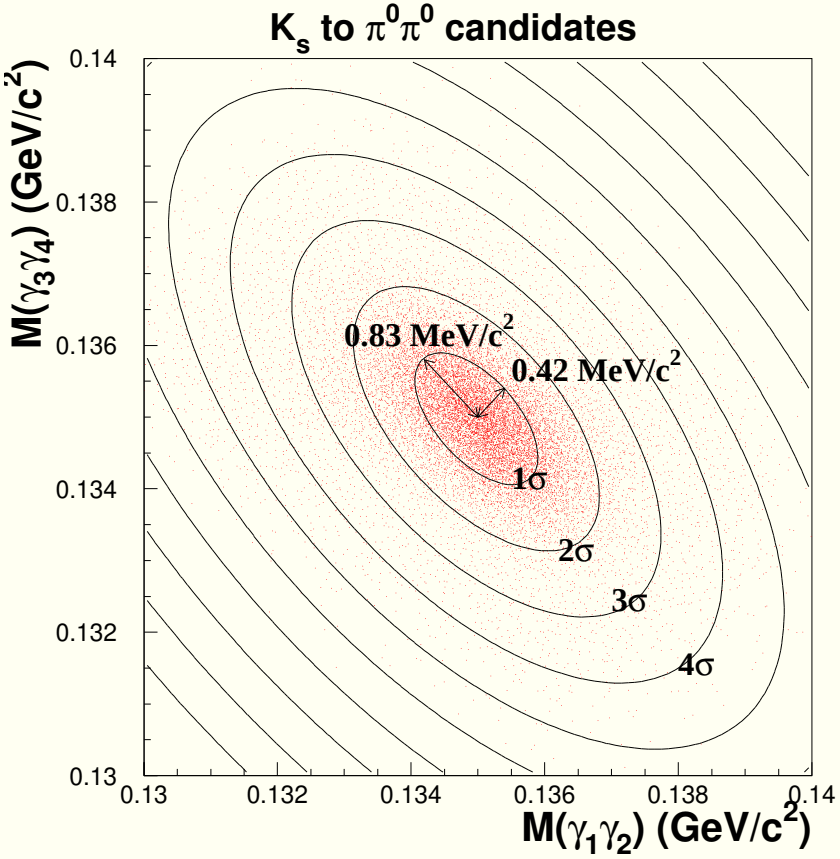
- $\pi^+\pi^-$: Spectrometer resolutions:
  momentum ~1% for 100 GeV pion
  position ~100 μm/plane
  Hodoscope time res. ~0.15 ns/$\pi^+\pi^-$

LKr calorimeter energy resolution:

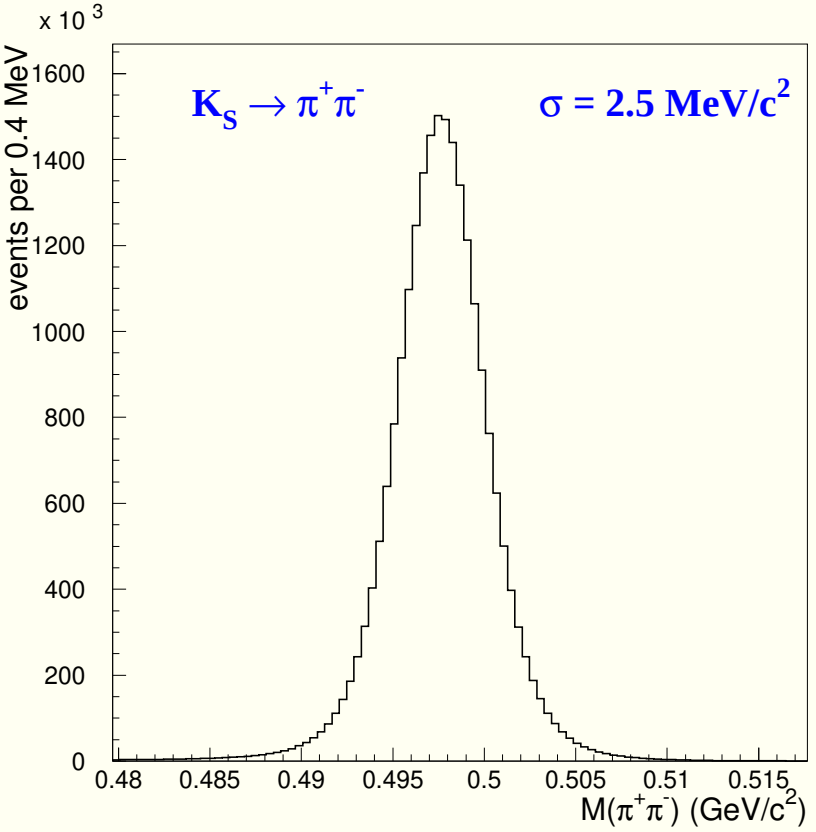


Invariant mass resolutions

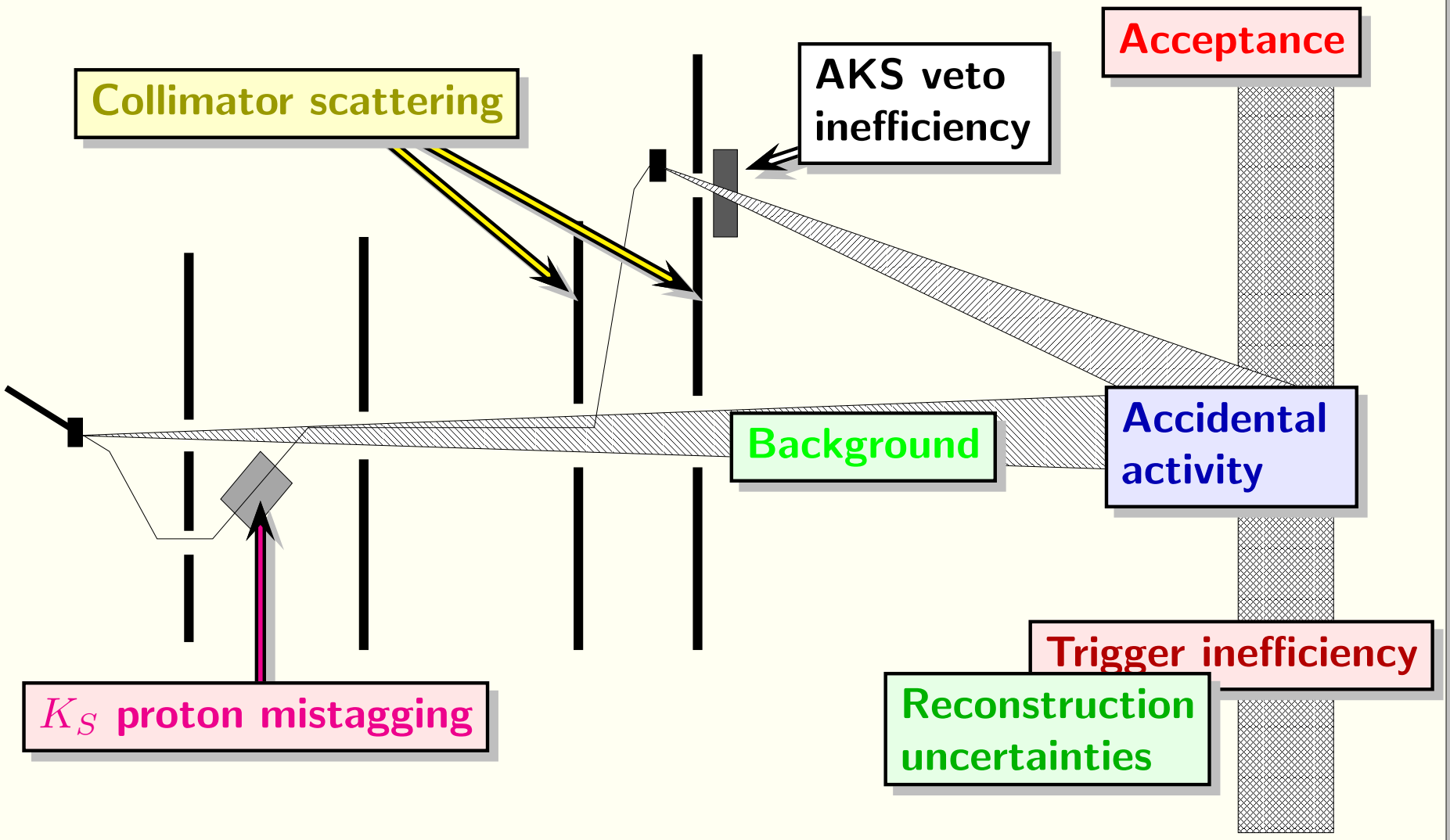
$m_{\gamma\gamma}$



$m_{\pi\pi}$



Sources of systematics



Trigger efficiency

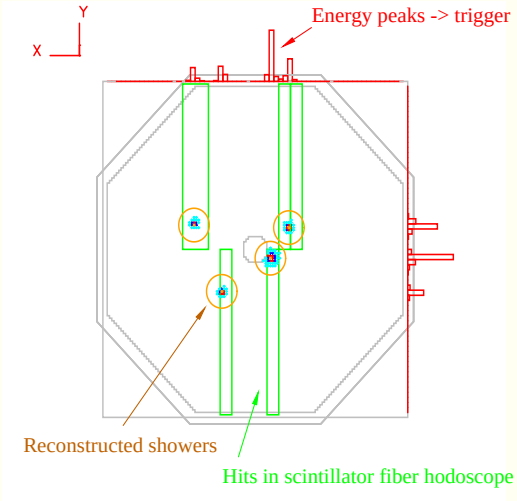
$K_S - K_L$ cancellation

$\pi^0\pi^0$:

- Fully pipelined system using LKr cell information to compute energy, centre of gravity, proper lifetime and number of showers
- Output rate ~ 2 kHz
- No dead time

→ Efficiency : $(99.920 \pm 0.009)\%$

ΔR negligible



$\pi^+\pi^-$:

- Level 1:
  - Energy in calorimeters
  - Two track topology in hodoscope
  - Two track multiplicity in drift chamber 1

→ Efficiency: $(99.535 \pm 0.011)\%$

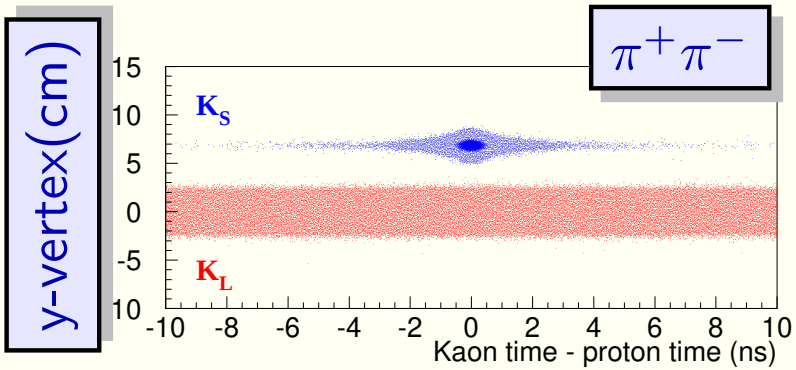
- Level 2: on-line processing of vertex position and $\pi\pi$ invariant mass from spectrometer hits
  - Output rate ~ 2 kHz
  - Dead Time: 1.1% monitored and applied to $\pi^0\pi^0$

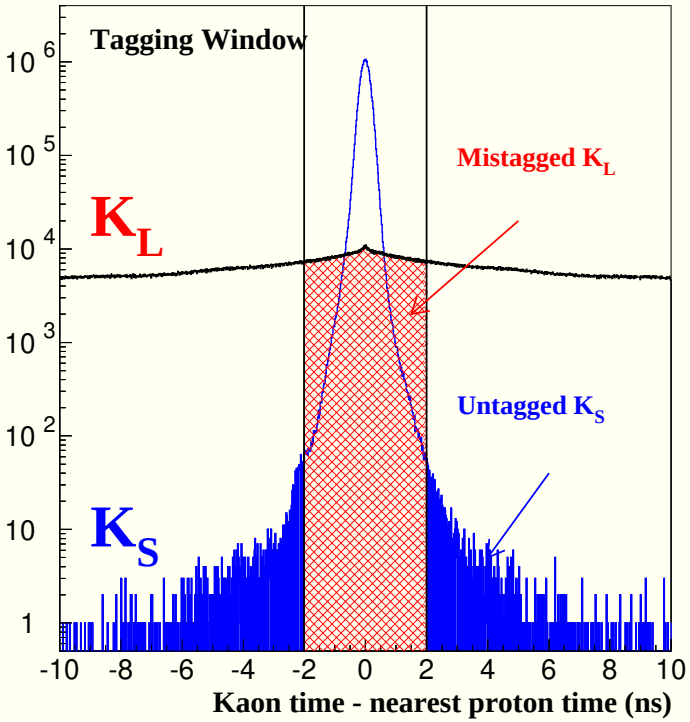
→ Efficiency: $(98.353 \pm 0.022)\%$

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

K_S/K_L identification

$\pi^0\pi^0 - \pi^+\pi^-$ cancellation





→ in both decay modes K_S tagged by comparing the event time to proton times as they pass through tagging station

→ in $\pi^+\pi^-$ kaons are also identified through y-vertex

→ two ways of misidentification:

- Tagging inefficiency: α_{SL}
  tails in time measurement
  $$\Delta R \simeq 6\left(\alpha_{SL}^{00} - \alpha_{SL}^{+-}\right) = 6\Delta\alpha_{SL}$$
- Accidental tagging: α_{LS}
  proton rate in the tagging station
  $$\Delta R \simeq 2\left(\alpha_{LS}^{00} - \alpha_{LS}^{+-}\right) = 2\Delta\alpha_{LS}$$

K_S/K_L misidentification

$\pi^0\pi^0 - \pi^+\pi^-$ cancellation

$\Delta\alpha_{SL}$

$$\alpha_{SL}^{+-} = 1.6 \times 10^{-4}$$

dominated by tagging station inefficiency

→ $\Delta\alpha_{SL}$ is measured from $2\pi^0$ and $3\pi^0$ events with conversion - by comparing the hodoscope time (from e^+e^-) with LKr time (from photon showers)

→ other methods confirm the result

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

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

$\Delta\alpha_{LS}$

$$\alpha_{LS}^{+-} = (10.649 \pm 0.008)\%$$

→ $\Delta\alpha_{LS}$ is measured by looking at the probability to see a random proton in a false coincidence using untagged $\pi^0\pi^0$ and $\pi^+\pi^-$

→ the correspondence to the true coincidence for $\pi^0\pi^0$ is measured with $K_L \to 3\pi^0$ decays

$$\Delta\alpha_{LS} = 4.3 \pm 1.8 \times 10^{-4}$$

$$\Delta R = (8.3 \pm 3.4) \times 10^{-4}$$

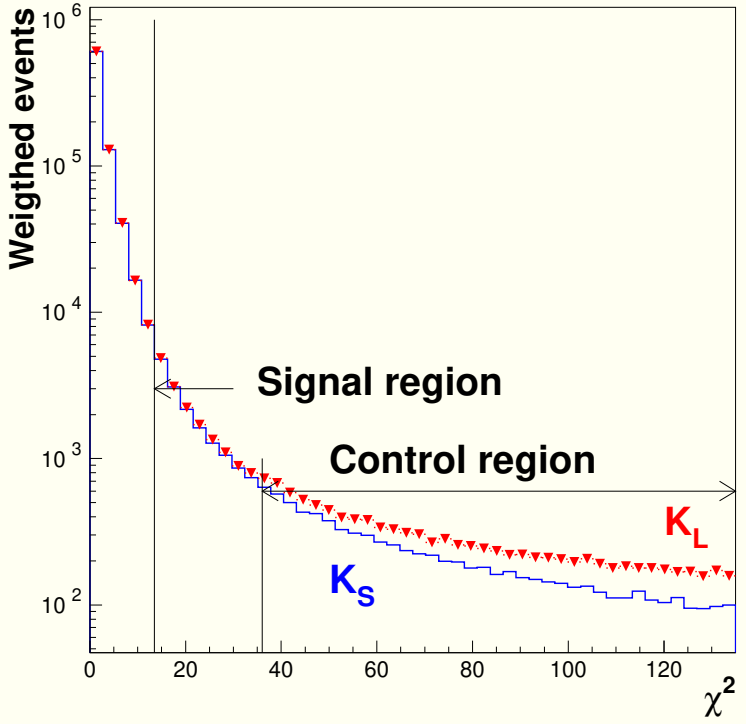
Background in $\pi^0\pi^0$

$\mathrm{K_S}$ - no background

$\mathrm{K_L}$ - background source:

$$\mathrm{K_L} \to 3\pi^0$$

- rejected by:
  - requiring no extra showers in-time (1.5 ns)
  - χ^2 from the two π^0 masses < 13.5
- rest subtracted:
  - extrapolating from χ^2 control region
  - extrapolation checked by MC



$$\Delta R = (-5.9 \pm 2.0) \times 10^{-4}$$

Background in $\pi^+\pi^-$

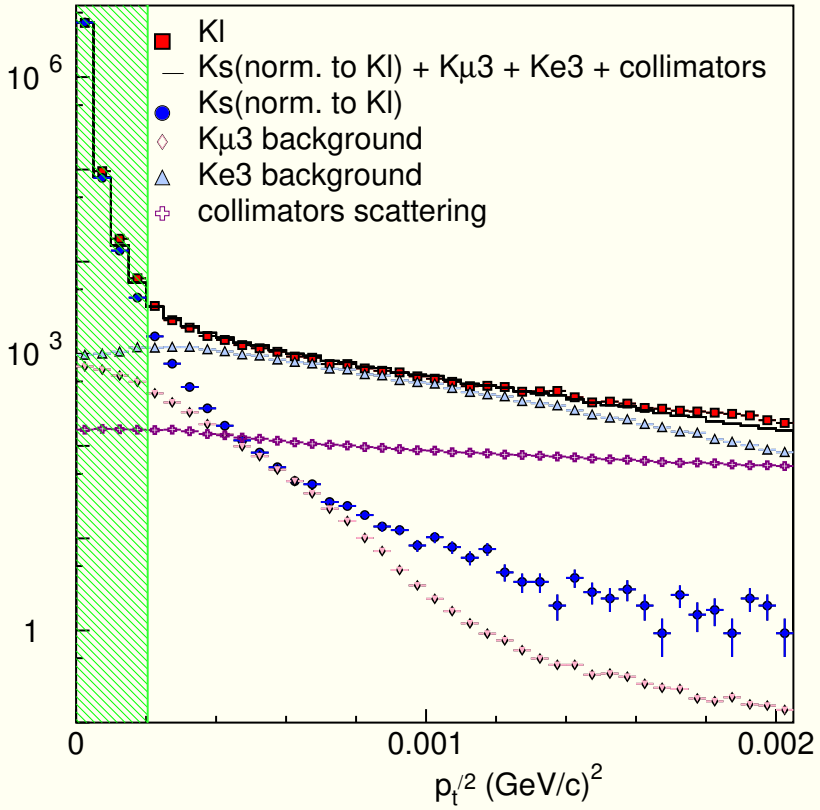
$\Rightarrow$ $\mathrm{K_S}$ - no background

Λ's rejected by momentum asymmetry cut

$\Rightarrow$ $\mathrm{K_L}$ - background source:

$$\mathrm{K_L} \to \pi e \nu, \pi \mu \nu$$

- rejected by:
  - requiring $E/p < 0.8$ and no associated hit in muon veto
  - cutting in invariant mass $(m_{\pi\pi})$ and transverse momentum $({p_T}'^2)$
- rest subtracted:
  - modeling the $m_{\pi\pi}$–${p_T}'^2$ distribution of $\mathrm{K_L} \to \pi^+\pi^-$ with $\mathrm{K_S}$, $\pi e \nu$ and $\pi \mu \nu$ samples in two control regions



$$\Delta R = (16.9 \pm 3.0) \times 10^{-4}$$

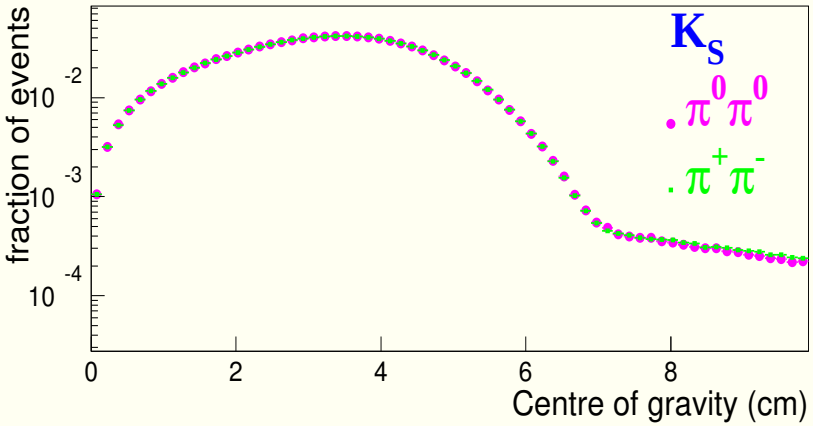
Collimator scattering

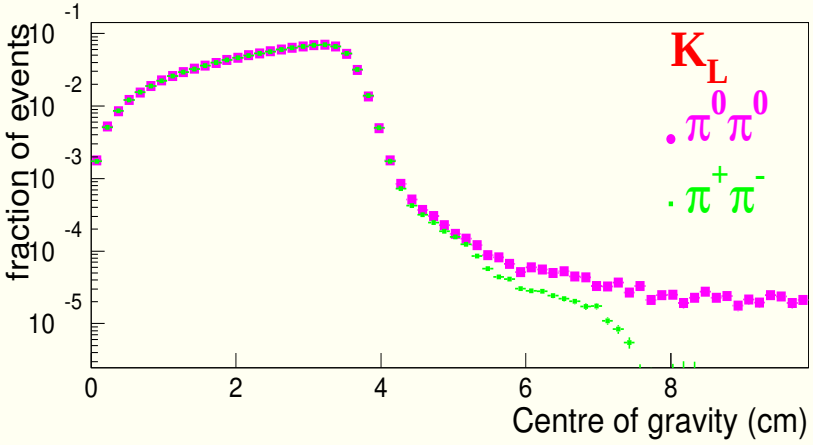
$\rightarrow K_S$ - symmetrically cut at 10 cm radius of centre of gravity (COG = virtual impact point of the kaon at the LKr calorimeter)

$\pi^0\pi^0 - \pi^+\pi^-$ cancellation

$\rightarrow K_L$ - in $\pi^+\pi^-$ mode events scattered at final and cleaning collimator cut by ${p_T}'^2$ $\rightarrow$ must be subtracted in $\pi^0\pi^0$ decay mode:

- calculated from $m_{\pi\pi}$ distribution of $\pi^+\pi^-$ decays at high ${p_T}'^2$
- cross-checked from tails of COG in $\pi^0\pi^0$ (taking into account background and scattering at defining collimator)





$$\Delta R = (-9.6 \pm 2.0) \times 10^{-4}$$

Acceptance correction

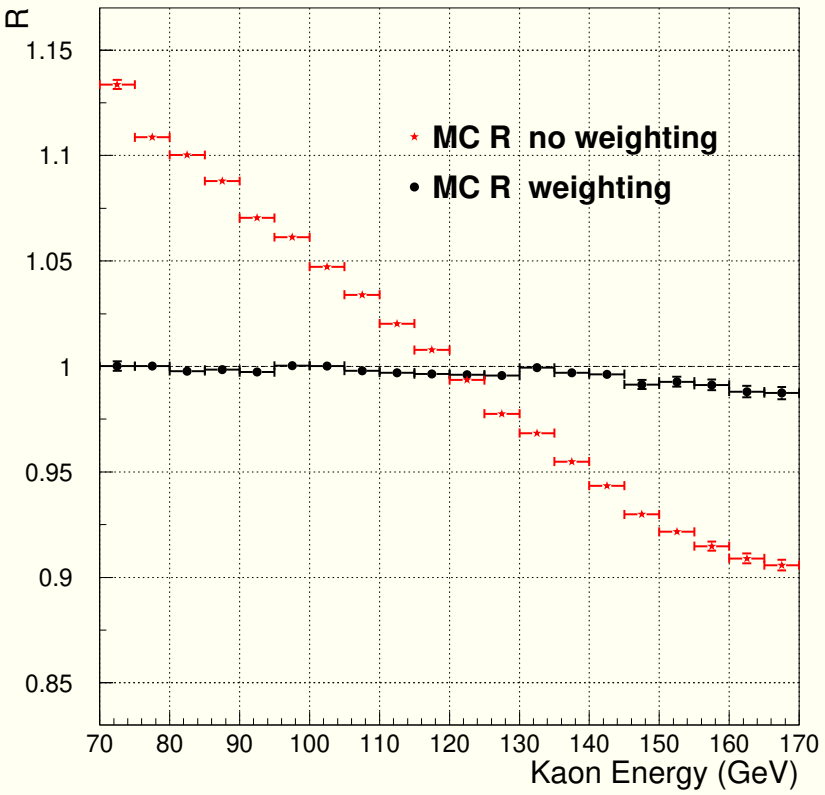
$K_S - K_L$ cancellation

➡ small due to symmetric illumination – consequence of proper time weighting

➡ residual effect in $\pi^+\pi^-$ due to small beam separation at the spectrometer

➡ computed by fast MC with GEANT-generated shower library and $\pi^+\pi^-$ mode checked with GEANT MC

➡ systematic uncertainty mainly from beam geometry uncertainties and fast MC – GEANT MC comparison



$$\Delta R = (26.7 \pm 4.1_{MCstat} \pm 4.0_{syst}) \times 10^{-4}$$

Accidental activity

$\pi^0\pi^0 - \pi^+\pi^-$
$\mathrm{K_S} - \mathrm{K_L}$
cancellation

losses due to beam particles and noise:

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

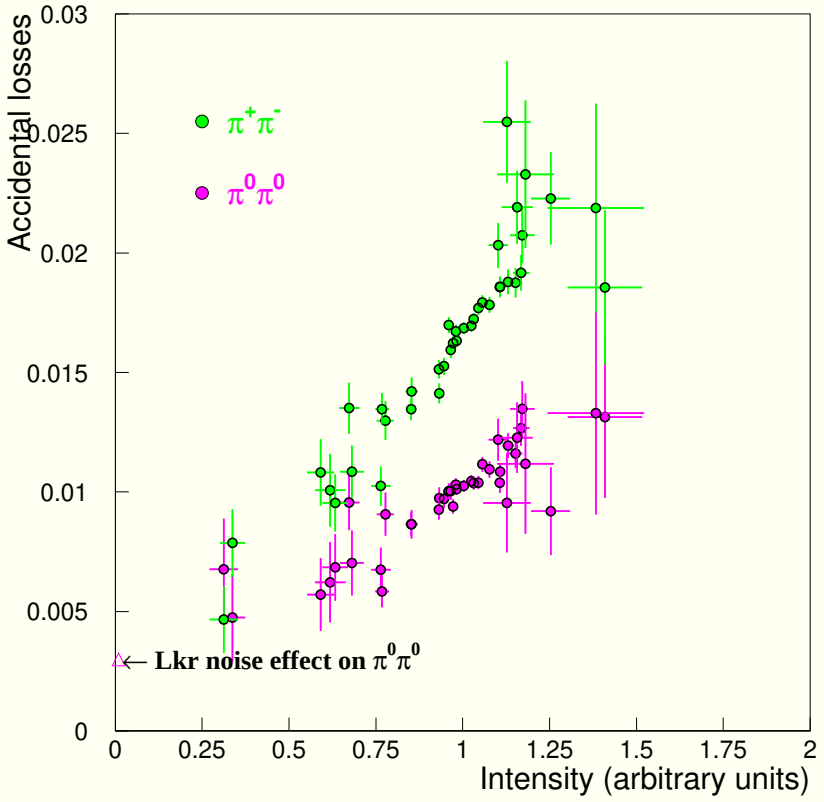
$\Delta(\pi^0\pi^0 - \pi^+\pi^-) = (1.4 \pm 0.7)\%$

- measured by overlaying beam monitor triggers on signal candidates
- minimised by:
  dead-time symmetrisation

$\Delta(\mathrm{K_L} - \mathrm{K_S}) \lesssim 1\%$

beam correlation

- checked from extra activity
  $\sim$100 ns around the event
  and from beam monitors
- minimised by:
  simultaneous data collection
  illumination symmetry $\pm 3 \times 10^{-4}$



$$\Delta R = (\pm 3_{Intensity} \pm 3_{Illumination} \pm 1_{In-time}) \times 10^{-4}$$

Reconstruction uncertainty

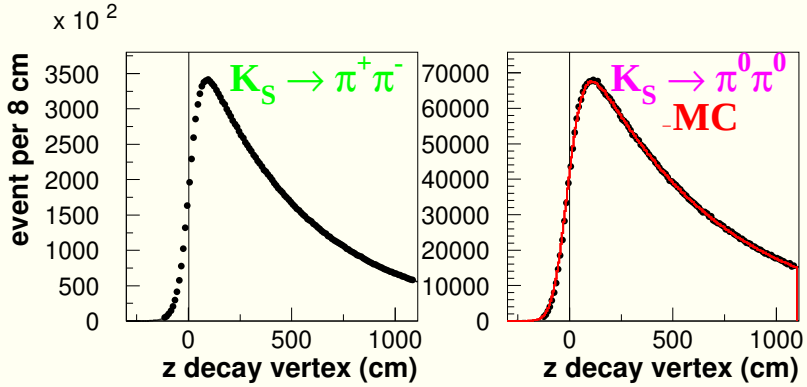
Enters R computation mainly through decay volume definition - distance scale

$\pi^+\pi^-$:

→ depends on geometry of drift chambers before the magnet (straight track extrapolation to vertex)

→ checked by: AKS position measurement

$$\Delta R = (2 \pm 2.8) \times 10^{-4}$$



$\pi^0\pi^0$:

→ depends on energy scale and calorimeter geometry

→ energy scale adjusted by measurement of AKS position

→ uncertainties from: energy scale, transverse size, non-linearities, non-uniformities, non-Gaussian tails etc.

$$\Delta R = \pm 5.8 \times 10^{-4}$$

→ checks from special samples: electrons, η's (using new η mass measurement to be published), π^0, $3\pi^0$, MC

Statistical uncertainty

Statistics in millions			
$K_L \to \pi^0\pi^0$	3.29	$K_L \to \pi^+\pi^-$	14.45
$K_S \to \pi^0\pi^0$	5.21	$K_S \to \pi^+\pi^-$	22.22

Statistical error on R: 10.1×10^{-4}

(Increase due to proper time weighting is $\sim$1.3)

Systematic uncertainties

		on R in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency		-3.6	$\pm$ 5.2
AKS inefficiency		+1.1	$\pm$ 0.4
Reconstruction	of $\pi^0\pi^0$	—	$\pm$ 5.8
	of $\pi^+\pi^-$	+2.0	$\pm$ 2.8
Background	to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
	to $\pi^+\pi^-$	+16.9	$\pm$ 3.0
Beam scattering		-9.6	$\pm$ 2.0
Accidental tagging		+8.3	$\pm$ 3.4
Tagging inefficiency		—	$\pm$ 3.0
Acceptance	statistical	+26.7	$\pm$ 4.1
	systematic		$\pm$ 4.0
Accidental activity		—	$\pm$ 4.4
Long term variations of K_S /K_L		—	$\pm$ 0.6
Total		+35.9	$\pm$ 12.6

→ some uncertainties depend on statistics of control samples or MC

Result

From 98 and 99 data:

$$R = 0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst}$$

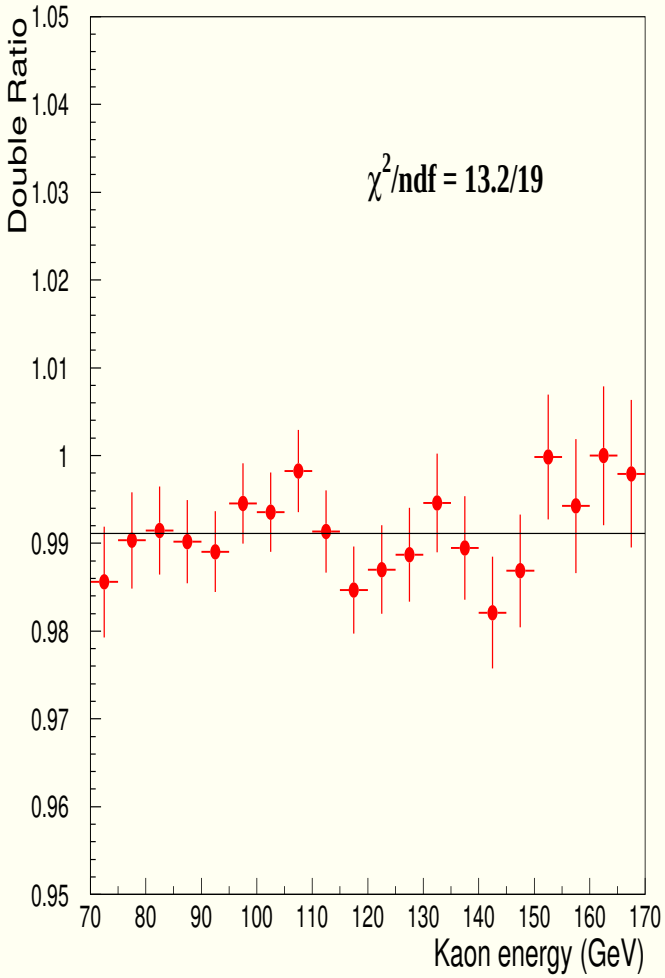
$$\Re\mathrm{e}\frac{\varepsilon'}{\varepsilon} = (15.0 \pm 2.7) \times 10^{-4}$$

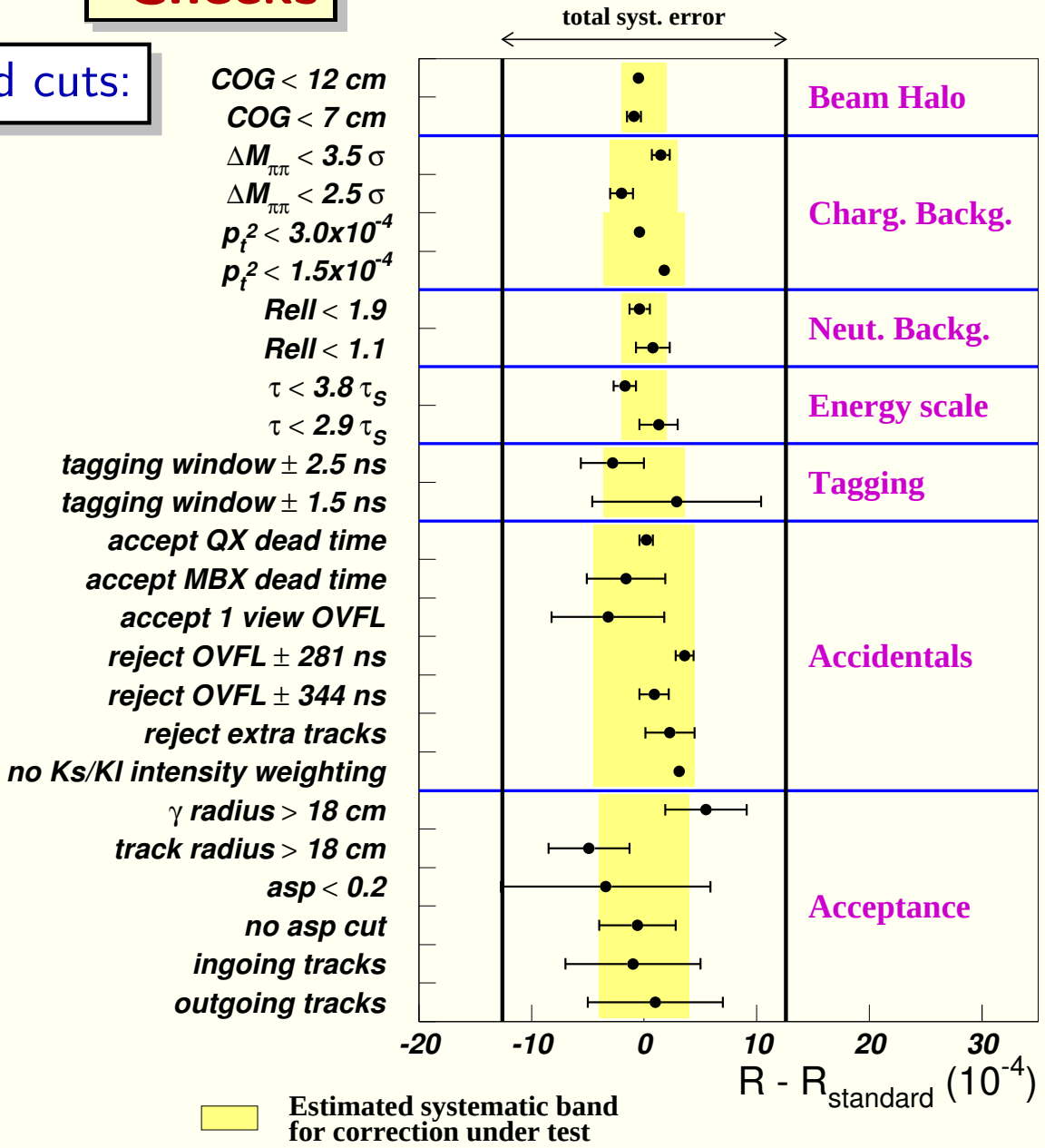
Combined with $\Re\mathrm{e}\frac{\varepsilon'}{\varepsilon} = (18.5 \pm 7.3) \times 10^{-4}$ from 97 data:

$$\Re\mathrm{e}\frac{\varepsilon'}{\varepsilon} = (15.3 \pm 2.6) \times 10^{-4}$$

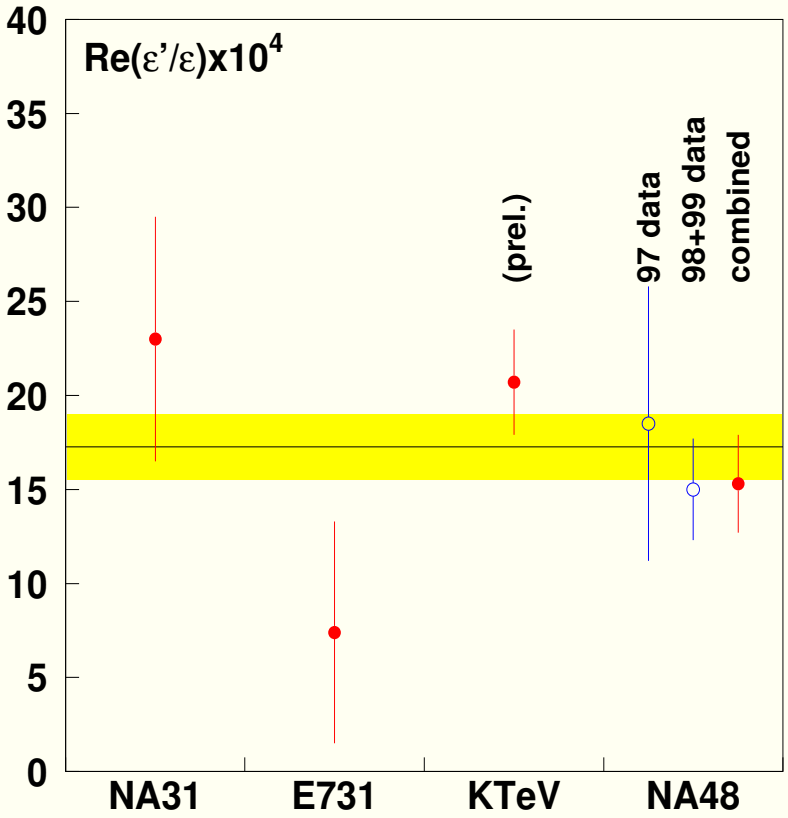
Checks

Stability with kaon energy and cuts:





Conclusions and prospects



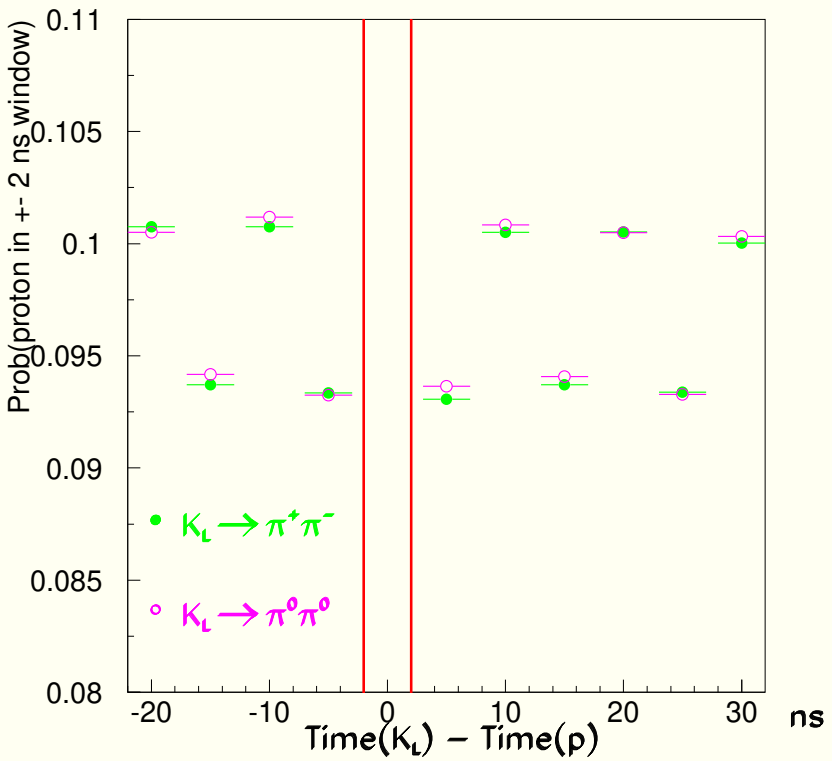
➡ After 3 years of data taking NA48 measures direct CP violation 5.9 σ from zero

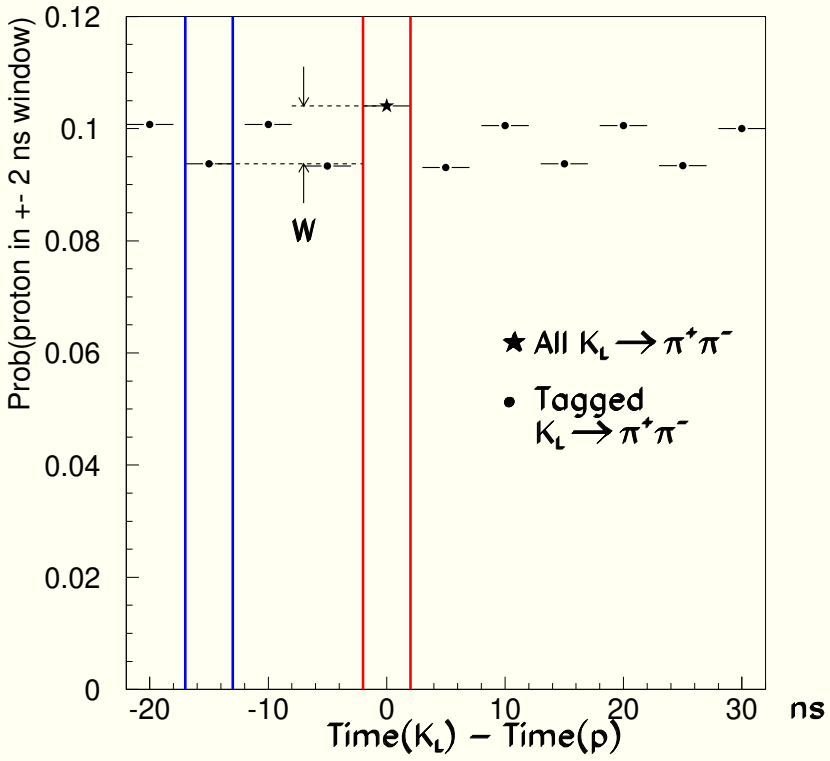
➡ Run 2001 will complement the statistics (expect 1.5M $\mathrm{K_L} \to \pi^0\pi^0$) and add data in changed conditions:

- lower beam energy
- longer spill
- lower instantaneous intensity
- rebuilt spectrometer

spare transparencies

Estimate of $\Delta\alpha_{LS}$





Using sidebands of tagger selected K_L to $\pi^0\pi^0$ and $\pi^+\pi^-$:

$$\Delta = (3.0 \pm 1.0) \times 10^{-4}$$

Extrapolation to central window (W)

$\pi^+\pi^-$: use vertex selected K_L

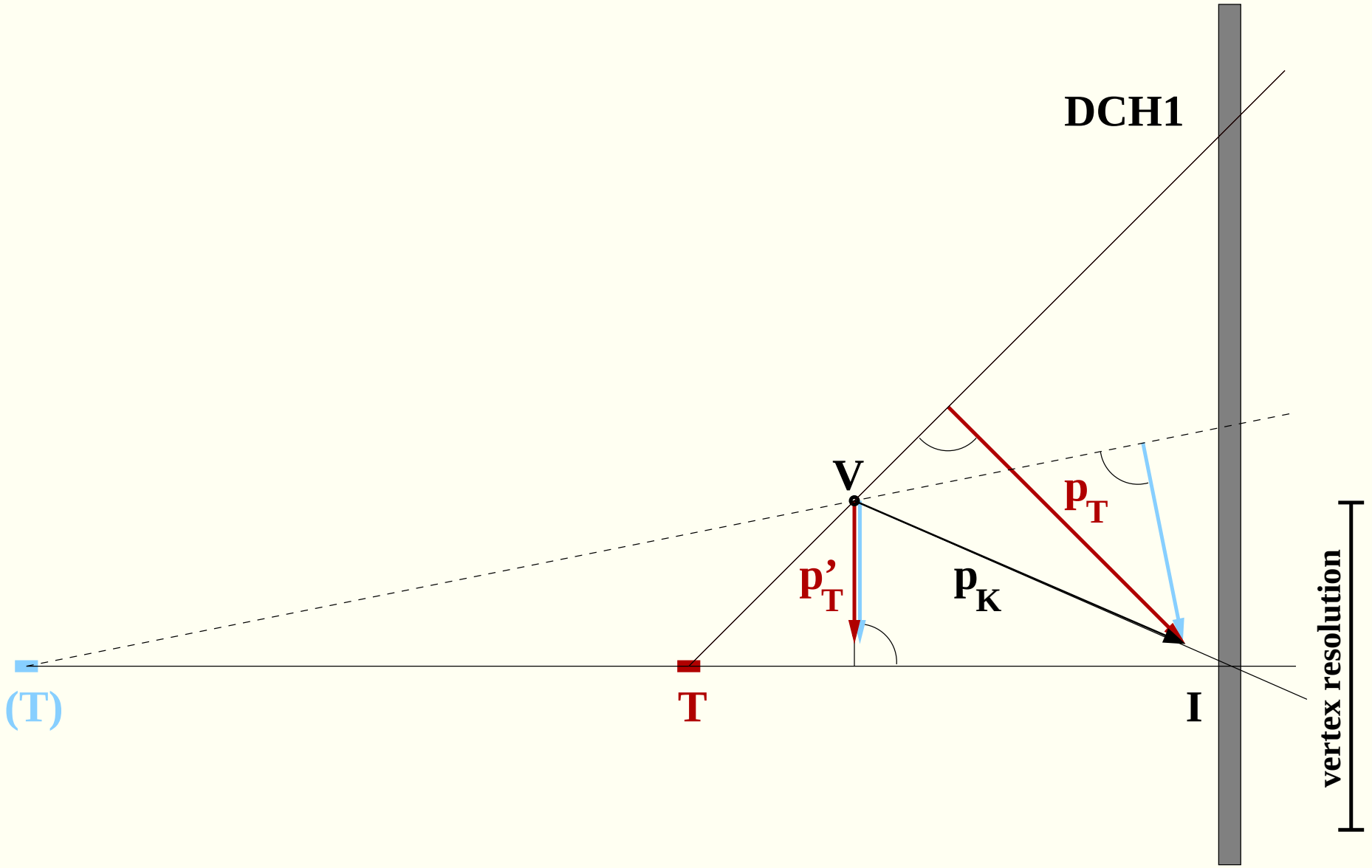
$\pi^0\pi^0$: use $3\pi^0$ events (only K_L)

$$\Delta W = (1.3 \pm 1.1) \times 10^{-4}$$

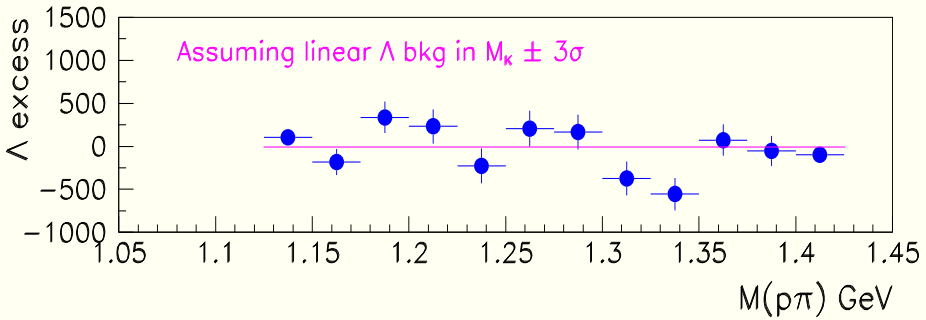
$$\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$$

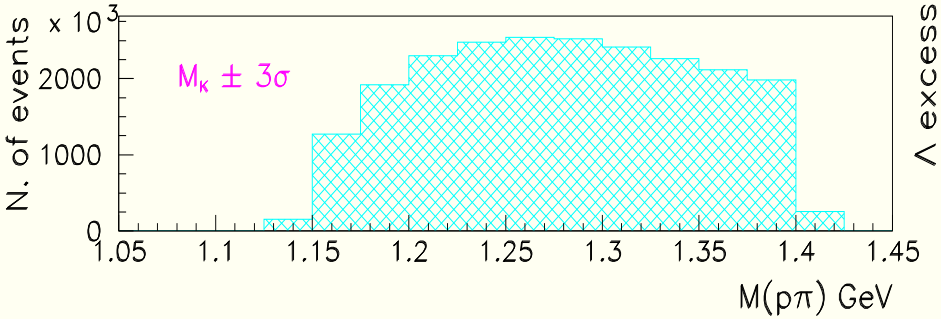
(adding systematic error from choice of sideband windows: $\pm 1.0 \times 10^{-4}$)

Transverse momentum calculation



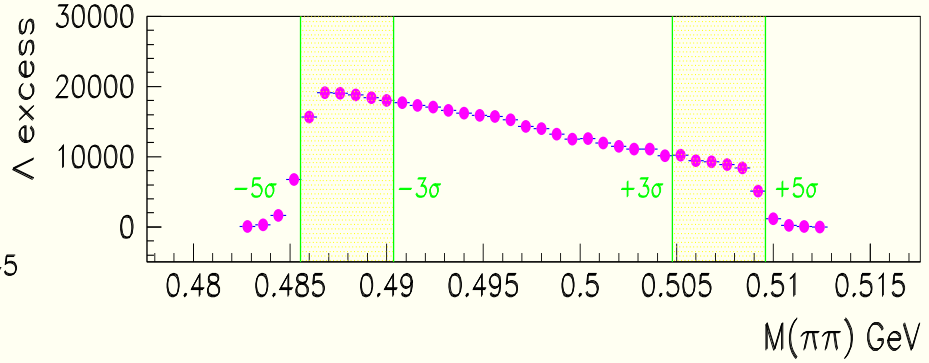
Λ contamination measurement

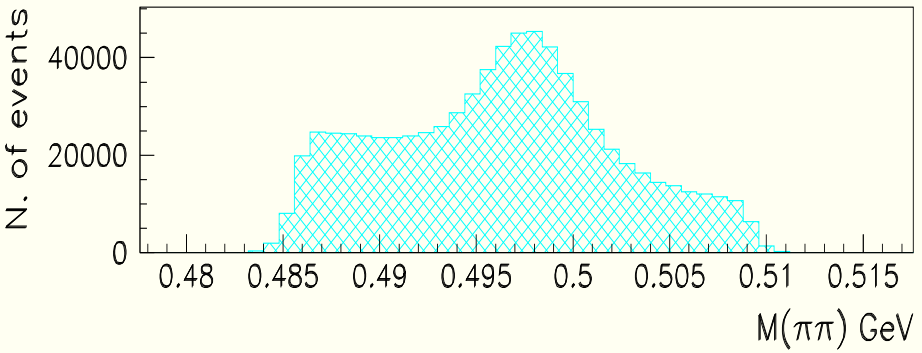




Λ enriched sample

check on linearity of Λ background :

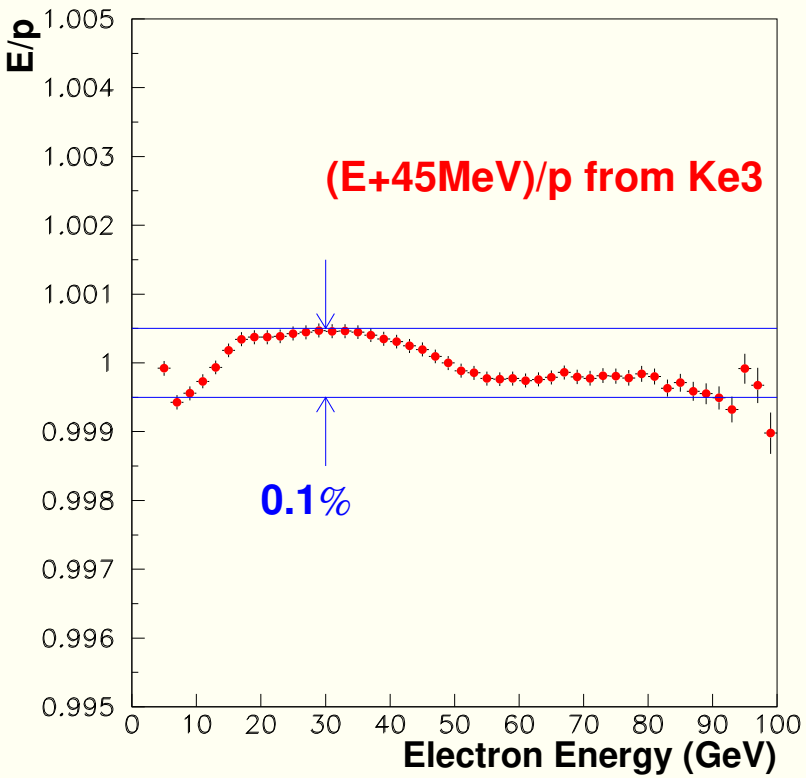


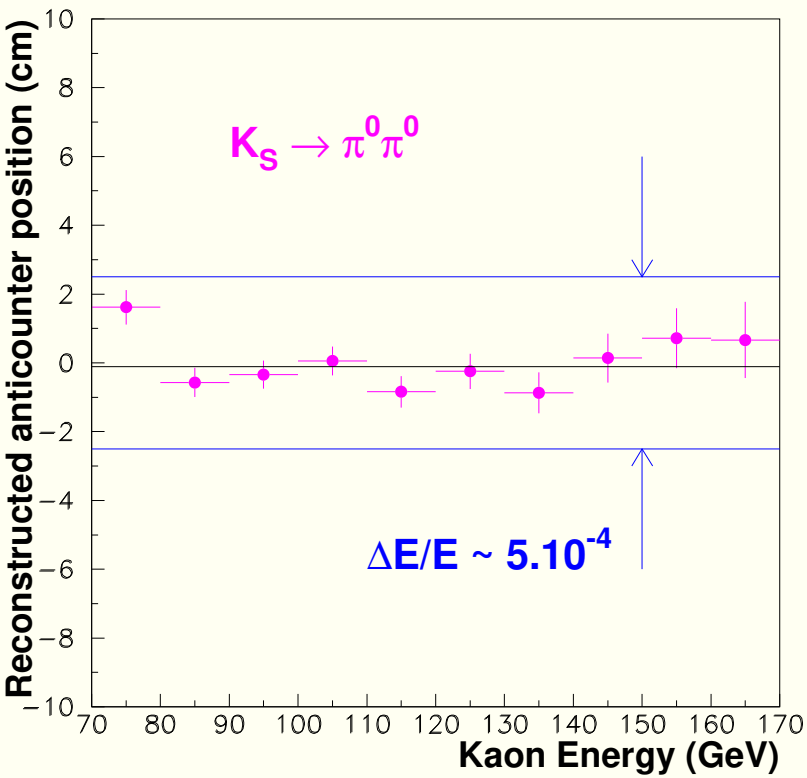


Combined 1998−1999 $\Lambda \rightarrow p\pi$ background limit on $K_s \rightarrow \pi^+\pi^-$ sample :

$(-0.48 \pm 0.41) \times 10^{-4}$

Non linearity checks



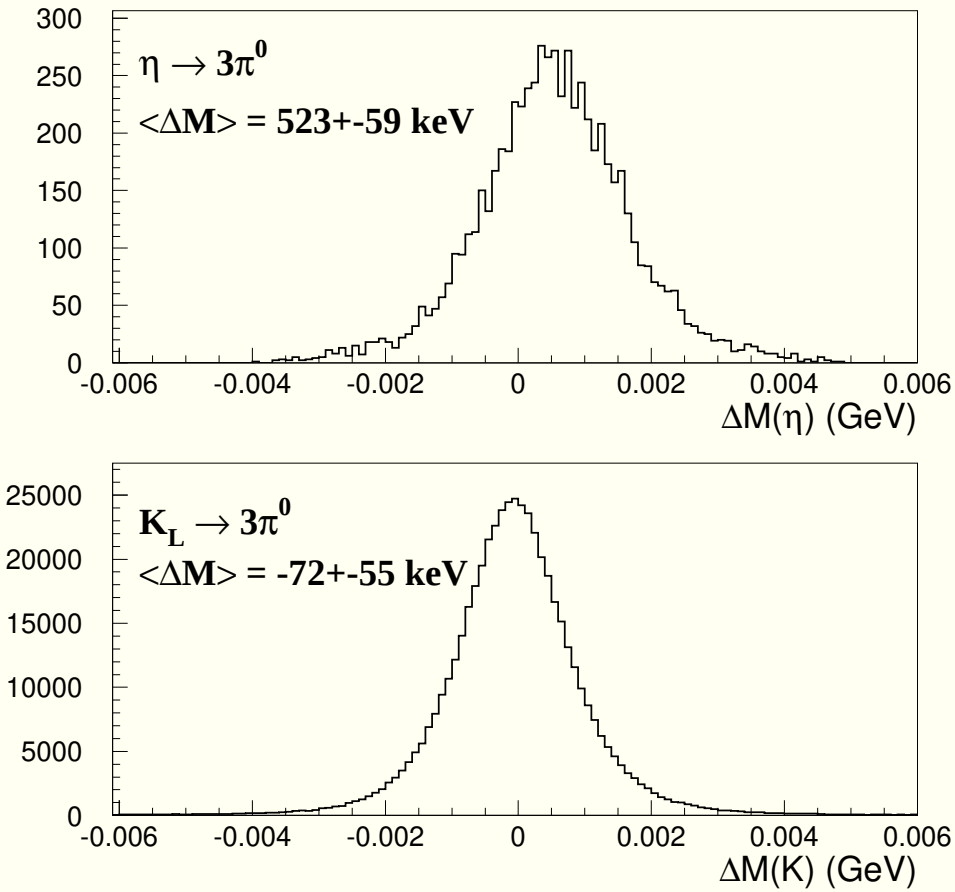


Electrons from Ke3 decays :
E/p constant within $\approx 0.1\%$
between a few GeV and 100 GeV

Overall Check :
Reconstructed AKS position
independent of K energy

η mass measurement

PDG: $M_\eta = 547.30 \pm 0.12$ MeV



- Use $\eta \to 3\pi^0 \to 6\gamma$ decays
- Decay vertex from π^0 mass constraint

  $\Rightarrow$ Measure M_η / M_{π^0}

  Independent of energy scale!
- Check method on $K_L \to 3\pi^0$
- $\Delta M \equiv M_{\mathrm{NA48}} - M_{PDG}$

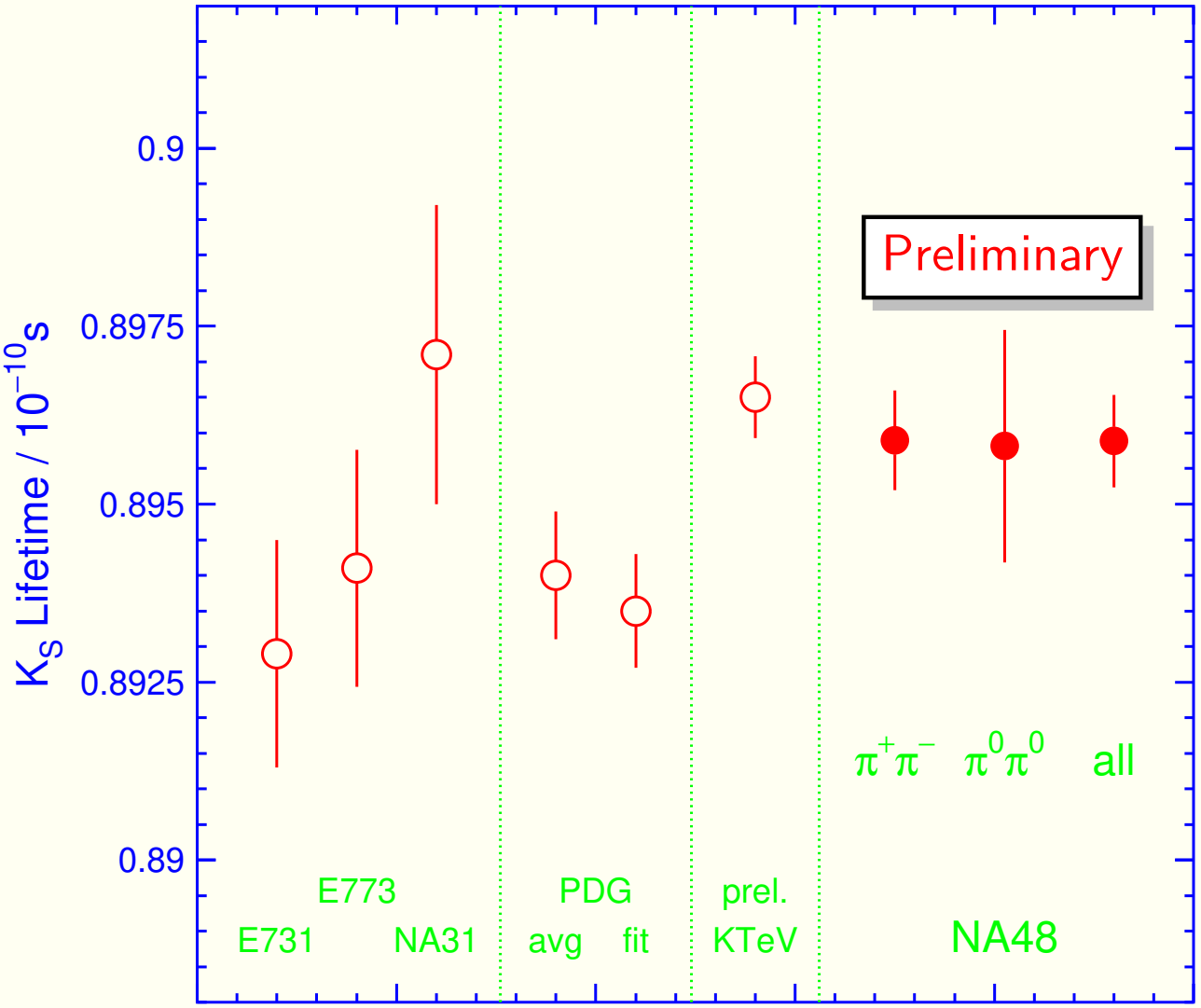
NEW Preliminary result $M_\eta = 547.823 \pm 0.020_{stat} \pm 0.055_{syst}$ MeV

Use this measurement to check energy scale with $\eta \to \gamma\gamma$

Reconstruction uncertainties

	$\Delta(R)$ (in 10^{-4} units)
$\pi^+\pi^-$	
AKS position	± 2.0
Non-gaussian tails	± 2.0
Total	± 2.8
$\pi^0\pi^0$	
Energy scale	± 2.0
Non-linearities	± 3.8
Transverse size	± 2.5
Non-uniformities	± 1.5
Non-gaussian tails	± 1.2
Others	± 2.3
Total	± 5.8

K_S lifetime


0.9
0.8975
0.895
0.8925
0.89
K_S Lifetime / 10^{-10}s
Preliminary
E731
E773
NA31
PDG
avg
fit
prel.
KTeV
$\pi^+\pi^-$
$\pi^0\pi^0$
all
NA48

1998 Systematics prel./final

Corrections and syst. uncertainties on R			(Units = 10^{-4})	
Source	1998 prel.		1998 final	
Charged trigger	–1	± 11	–2.6	± 11.4
Accidental tagging	+1	±8	16.1	± 5.4
Tagging efficiency	–	± 3	–	± 3
Neutral rec. systematics	–	±10	–	±5.8
Charged vertex	+2	±2	+2	±2.8
Acceptance	+31	±9	+23.4	±8.3
Neutral BKG	–7	±2	–6.3	±2
Charged BKG	+19	±3	+17.6	±3
Beam scattering	–10	±3	–9.6	±2
Accid. activity	+2	±12	–	±7.1
Total	+37	±24	+40.6	±18.6
R	9926.7	±29.4	9927.4	±25.8

$$\Re\mathfrak{e}\frac{\varepsilon'}{\varepsilon} = \frac{1}{6} \times (1 - R)$$