Results on CP Violation from the NA48 experiment at CERN

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LP01 Rome 23-28 July 2001

$\boxed{\text{Main goal of NA48 experiment}}$

$$\Downarrow$$

Precise measurement of Direct CP Violation in the Neutral Kaon System: parameter Re(ε'/ε).

- Data taking in 97, 98 and 99
- 1999: published result on 97 data
  Phys.Lett.B 465, 335-348 (1999)
- May 2001: announced result on 98+99 data $\Leftarrow$ Today

$\boxed{\text{also}}$

$$\Downarrow$$

Study of a wide range of K_L and K_S rare decays, collected in parallel or in special runs.

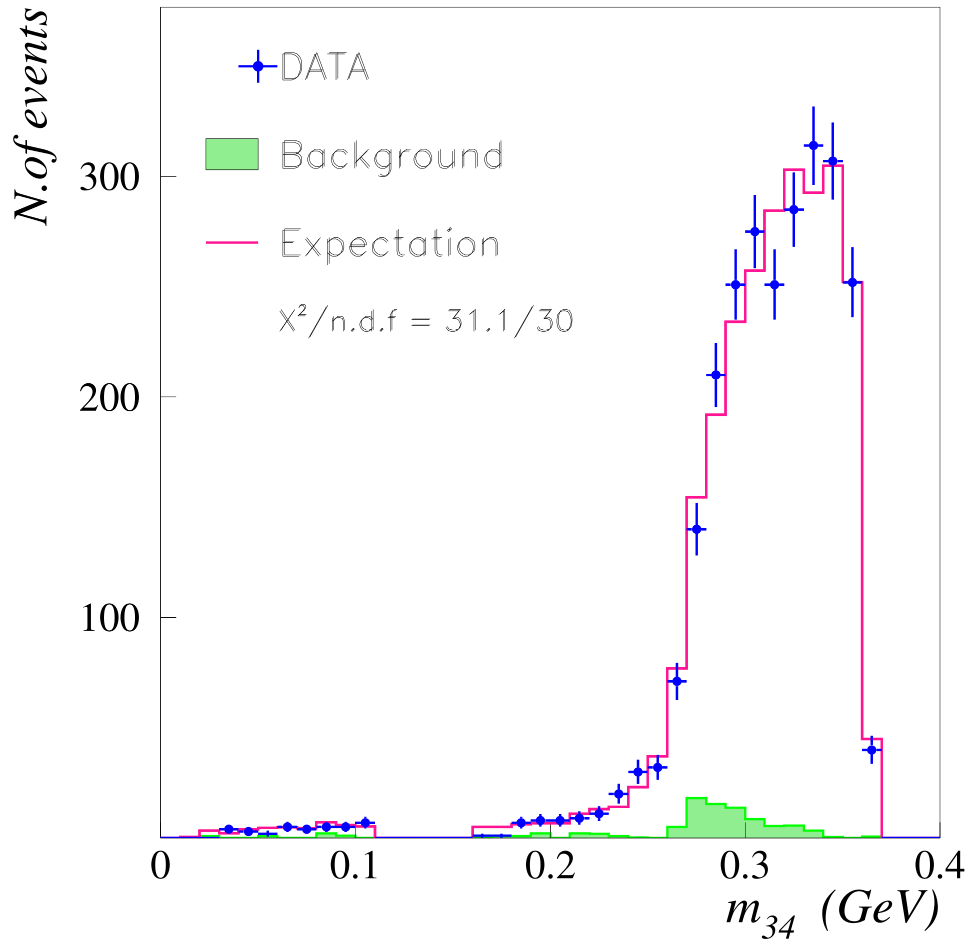
RARE KAON DECAYS in NA48

Allow study of χPT theory, CP Violation, SM checks etc

- $K_L \rightarrow \pi^0 \gamma\gamma$ BR=$(1.36\pm0.05)\times10^{-6}$ 2588 events
  a_V=-0.46$\pm$.05 NEW!!!
- $K_S \rightarrow \pi^0 e^+ e^-$ BR $< 1.4\times10^{-7}$ (90% CL)
- $K_S \rightarrow \gamma\gamma$ BR=$(2.58\pm0.42)\times10^{-6}$ 149 events
- $K_S \rightarrow \pi^+\pi^- e^+ e^-$ BR=$(4.3\pm0.4)\times10^{-5}$ 921 events
- $K_L \rightarrow \pi^+\pi^- e^+ e^-$ BR=$(3.1\pm0.2)\times10^{-7}$ 1337 events
- $K_L \rightarrow e^+ e^- e^+ e^-$ BR=$(3.7\pm0.4)\times10^{-8}$ 139 events
- $K_L \rightarrow e^+ e^- \gamma$ BR=$(1.06\pm0.05)\times10^{-5}$ 6864 events
- $K_L \rightarrow e^+ e^- \gamma\gamma$ BR=$(6.3\pm0.5)\times10^{-7}$ 1543 events

NEW RESULT: $K_L \to \pi^0 \gamma\gamma$

- χPT :Needs to include O(p^6) and Vector meson contribution to reproduce the observed rate
- Gives constraints to the CP-Conserving amplitude to $K_L \to \pi^0 e^+e^-$.
- Low $m_{\gamma\gamma}$: sensitive to the amount of VM $\propto a_V$
- 2588 events with 3.3% background



$$Br=(1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10^{-6}$$
$$a_V=-0.46 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.02_{the}$$

MENU

- Direct CP Violation
- Presentation of NA48
- Analysis for Re(ε'/ε) measurement
- The new result
- Conclusions

DIRECT CP VIOLATION

In the Kaon System, CP Violation manifests in the observation of the CP-forbidden $K_L \to 2\pi$ decay.

- In the Standard Model, an irreducible phase in CKM matrix is the source of CP Violation
- Two components: Indirect CP Violation (ε), due to CP-states mixing, and Direct CP Violation (ε') acting in the decay and depending on decay channel

K_1: CP=+1 eigenstate

K_2: CP=-1 eigenstate

$$K_S = K_1 + \varepsilon K_2$$

$$K_L = K_2 + \varepsilon K_1$$

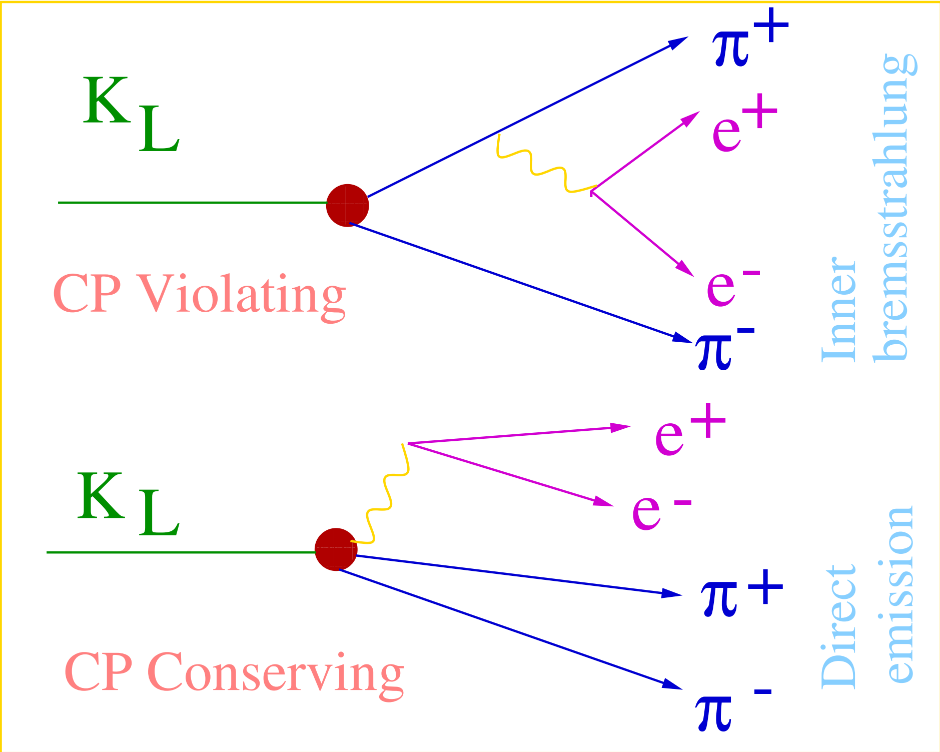
DIRECT CP VIOLATION(cntd)

- Indirect CP Violation (ε) known since '64 ($\approx 2 \times 10^{-3}$).
- Direct CP Violation (ε') is small wrt Indirect
  $\Rightarrow$ convenient to measure Re(ε'/ε).
- The measurable quantity Re(ε'/ε) is connected to the ratio R of four observable decay rates:

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

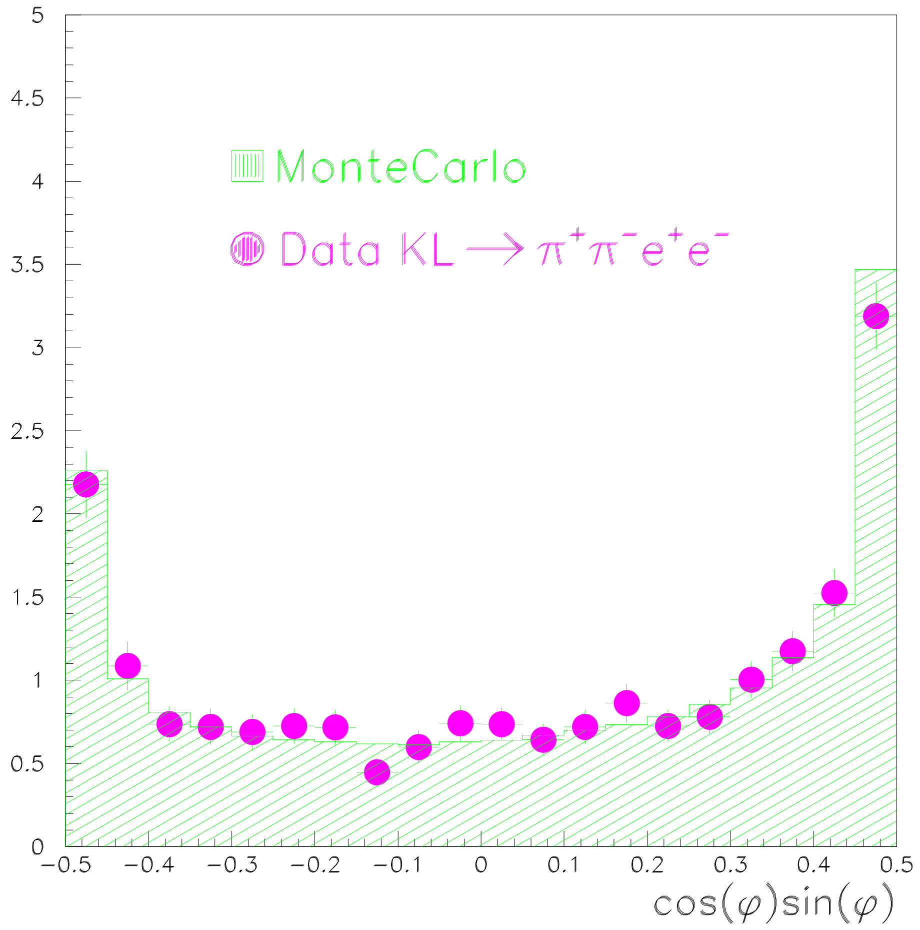
- From theory : Re(ε'/ε) in the range 5 - 30×10^{-4}

PAUSE : large effects of CP Violation in the Kaon System $\Rightarrow$ the decay $K_L \rightarrow \pi^+\pi^- e^+ e^-$



- K_L decays to $\pi^+\pi^- e^+ e^-$ through two diagrams
- CP-Viol./CP-Cons. $\approx \eta\times(2M_K/E_\gamma)^2 \sim 1$
- Interference visible in $\sin(\phi)\cos(\phi)$ where ϕ is the angle between the $\pi^+\pi^-$ and e^+e^- planes in Kaon rest frame.

PAUSE :the decay $K_L \rightarrow \pi^+\pi^-e^+ e^-$ (cntd)



~1300 observed events

BR($K_L \rightarrow \pi^+\pi^- e^+e^-$)=
$(3.1\pm0.1_{stat}\pm0.2_{syst})\times 10^{-7}$

CPV Asymmetry=
$(13.9\pm2.7_{stat}\pm2.0_{syst})\%$

Theory: A~14%
P.Heiliger and L.M.Sehgal
KTeV:
$A=(13.6\pm2.5_{stat}\pm1.2_{syst})\%$

RESUME: DIRECT CP VIOLATION(cntd)

The formula:

$$R=\frac{\Gamma(K_L\to\pi^0\pi^0)}{\Gamma(K_S\to\pi^0\pi^0)}\Big/\frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_S\to\pi^+\pi^-)}\approx 1\text{-}6\times\mathrm{Re}(\varepsilon'/\varepsilon)$$

becomes in the experiment:

$$R^{meas}=\frac{Nb(K_L\to\pi^0\pi^0)}{Nb(K_S\to\pi^0\pi^0)}\Big/\frac{Nb(K_L\to\pi^+\pi^-)}{Nb(K_S\to\pi^+\pi^-)}\approx 1\text{-}6\times\mathrm{Re}(\varepsilon'/\varepsilon)^{meas}$$

where Nb($K_{L,S}\to$final state)=counted Nb of events within the acceptance.

$$\Rightarrow \boxed{R = R^{meas} + A_{corr}}$$

$\boxed{\text{To measure precisely } \mathrm{Re}(\varepsilon'/\varepsilon)} \Rightarrow \boxed{\text{Measure precisely } A_{corr}}$

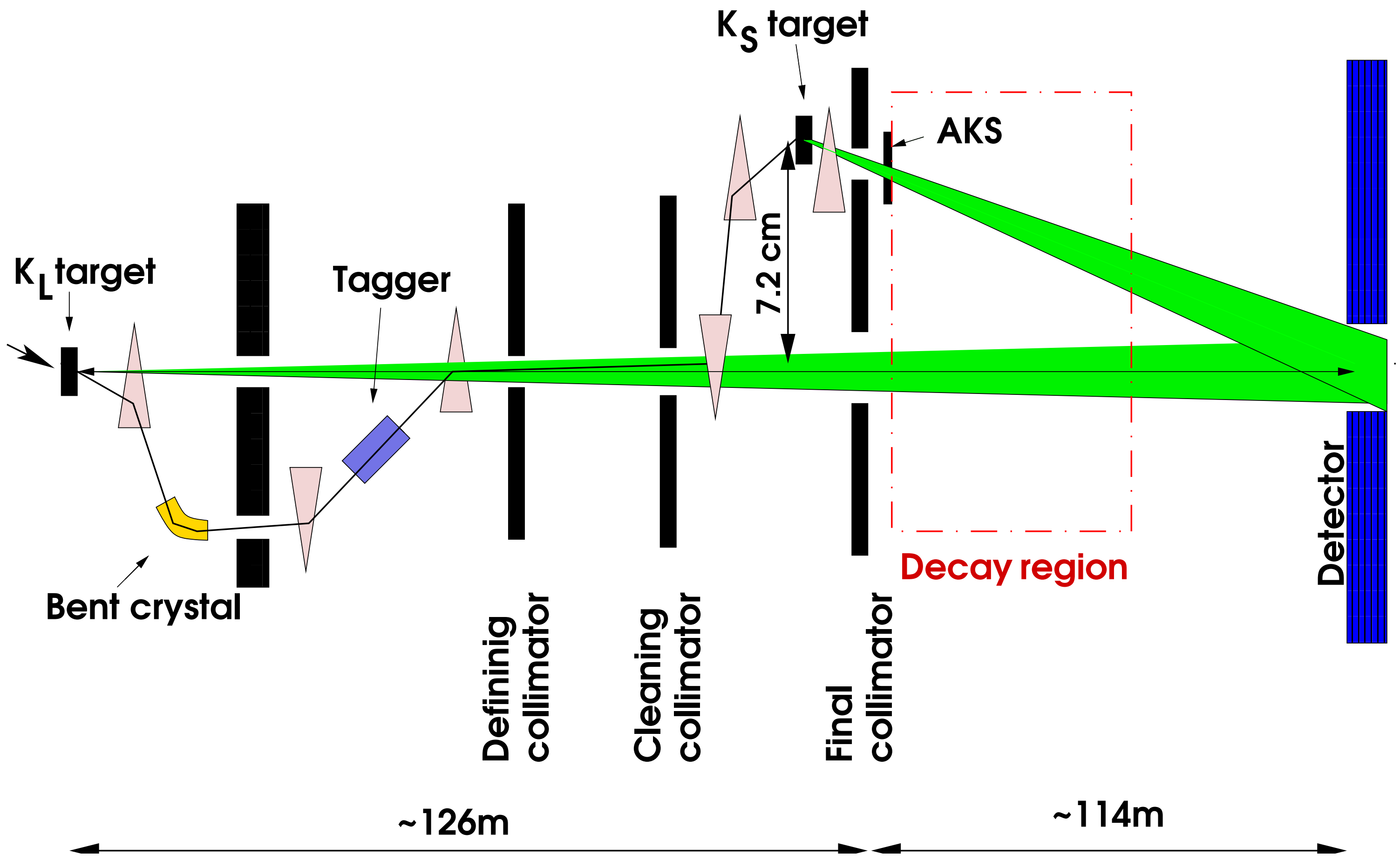
PRESENTATION of NA48

- The Beams

- The Detector

- The Analysis Method

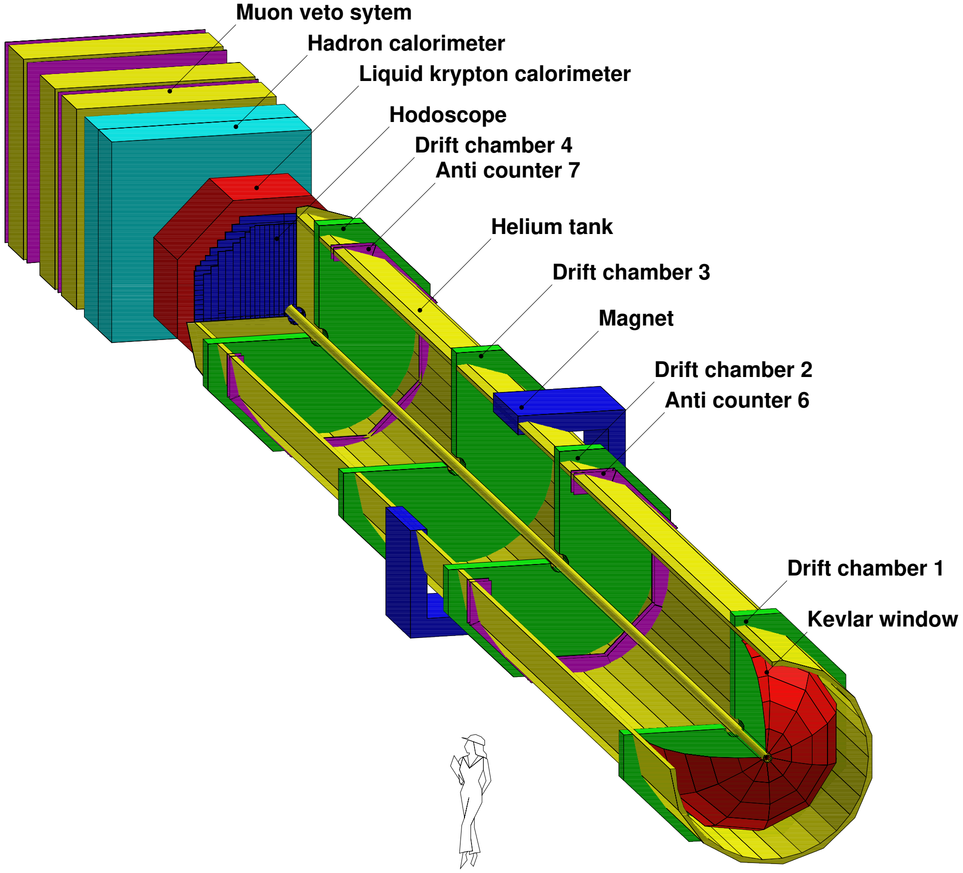
PRESENTATION of NA48:The Beams



Simultaneous K_S and K_L beams.

Sligthly converging, to hit the same detector region.

PRESENTATION of NA48:The Detector



High resolution detectors to identify 3body background

- $\pi^+\pi^-$:Magnetic Spectrometer with P_T kick=265MeV/c
- $\pi^0\pi^0$: Liquid Krypton Calorimeter leading to $\sigma(\pi^0)\sim$1MeV
- Decay time known to $\sim$200ps allows an accurate K_S–K_L identification

PRESENTATION of NA48:The Method

$$\mathrm{R}=\mathrm{R}^{meas} + \mathrm{A}_{corr}=\frac{Nb(K_L\rightarrow\pi^0\pi^0)}{Nb(K_S\rightarrow\pi^0\pi^0)}/\frac{Nb(K_L\rightarrow\pi^+\pi^-)}{Nb(K_S\rightarrow\pi^+\pi^-)}+\mathrm{A}_{corr}$$

•Fully exploit the double ratio technique

$\Rightarrow$ Do such that all effects are common either to K_S and K_L or to $\pi^0\pi^0$ and $\pi^+\pi^-$, to obtain cancellation in R.

$\Rightarrow\Rightarrow$ Simultaneous data taking of four modes:Variation of fluxes, trigger inefficiencies, detector instabilities etc, vanish at first order

•Minimise the amount of residual corrections (A_{corr})

$\Rightarrow$ Weight K_L decay distribution to obtain $\sim$ similar K_S and K_L acceptances $\Rightarrow$ small correction on R

ANALYSIS for Re(ε'/ε)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L using Tagging
- Subtract the remaining background from K_L samples
- Evaluate A_{corr} and systematics
- Checks and stability of the result

!!! All given effects are on the double ratio R !!!

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1-R)/6$$

$$\sigma(\mathrm{Re}(\varepsilon'/\varepsilon)) = \sigma(R)/6$$

ANALYSIS for Re(ε'/ε)

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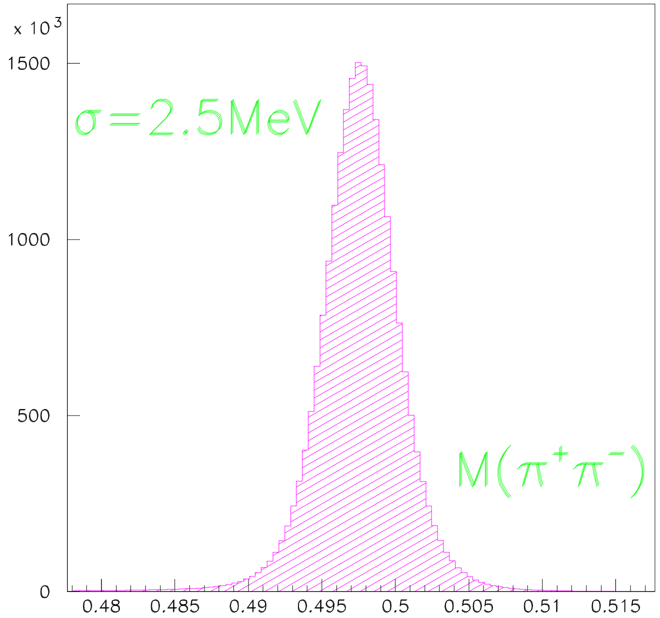
ANALYSIS for Re(ε'/ε): 2π counting

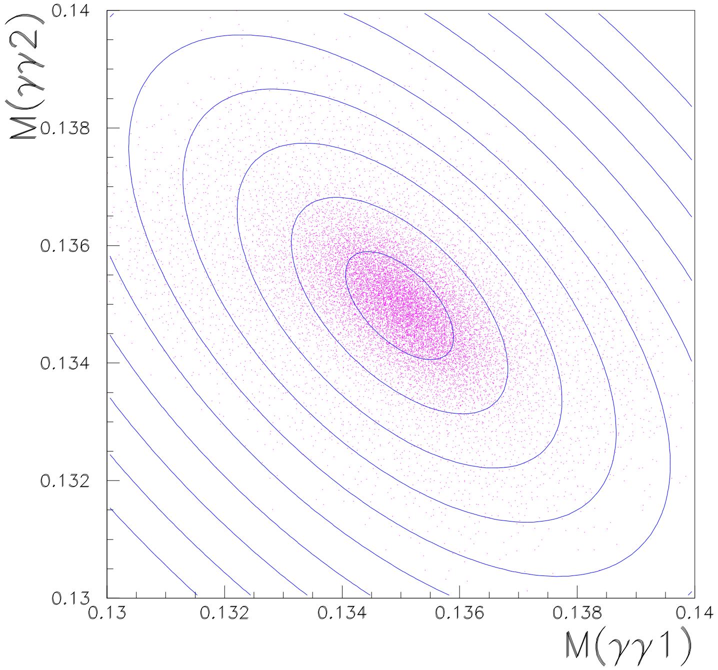
$K_S, K_L \rightarrow \pi^+\pi^-$ sample

- Decay vertex and M($\pi^+\pi^-$) reconstructed by the spectrometer
- Decay time from hodoscope ($\sigma \approx$140ps)

$K_S, K_L \rightarrow \pi^0\pi^0$ sample

- E_i, x_i and y_i of the four photons in LKr $\Rightarrow$ two M($\gamma\gamma$) and decay vertex
- Decay time from LKr calorimeter ($\sigma \approx$200ps)





ANALYSIS for Re(ε'/ε): 2π counting (cndt)

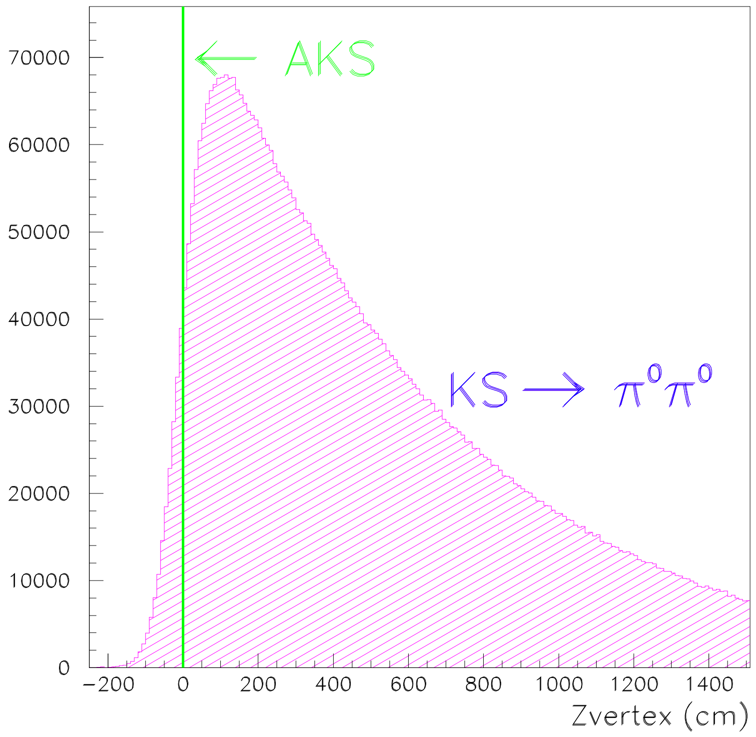
Common decay region for $\pi^0\pi^0$ and $\pi^+\pi^-$
to cancel beam flux variations
$70 \leq E_K \leq 170$GeV and $\tau \leq 3.5\ \tau_S$

In $\pi^0\pi^0$: Decay Volume defined by energy from LKr

$\Downarrow$

Check energy scale looking at the reconstructed AKS position

$\pm 10^{-4}$ on E $\Leftrightarrow$ $\pm 10^{-4}$ on R

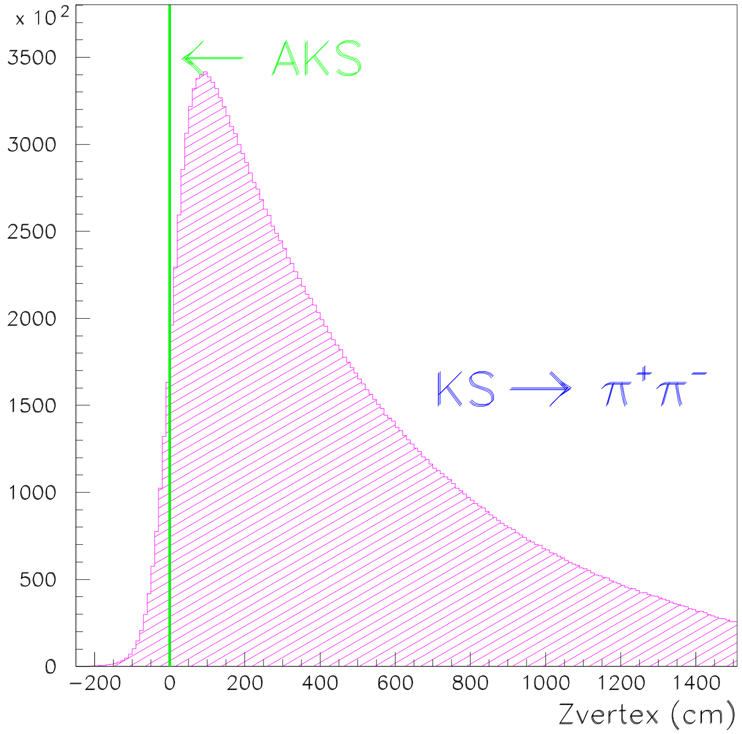


ANALYSIS for Re(ε'/ε): 2π counting (cndt)

In $\pi^+\pi^-$:Decay Volume defined by geometry of the chambers

Also check reconstructed AKS position

$\pm$1cm on Z $\Leftrightarrow$ $\pm 10^{-4}$ on R



Same Intensity conditions for all modes

Record and apply dead time

ANALYSIS for Re(ε'/ε)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L using Tagging
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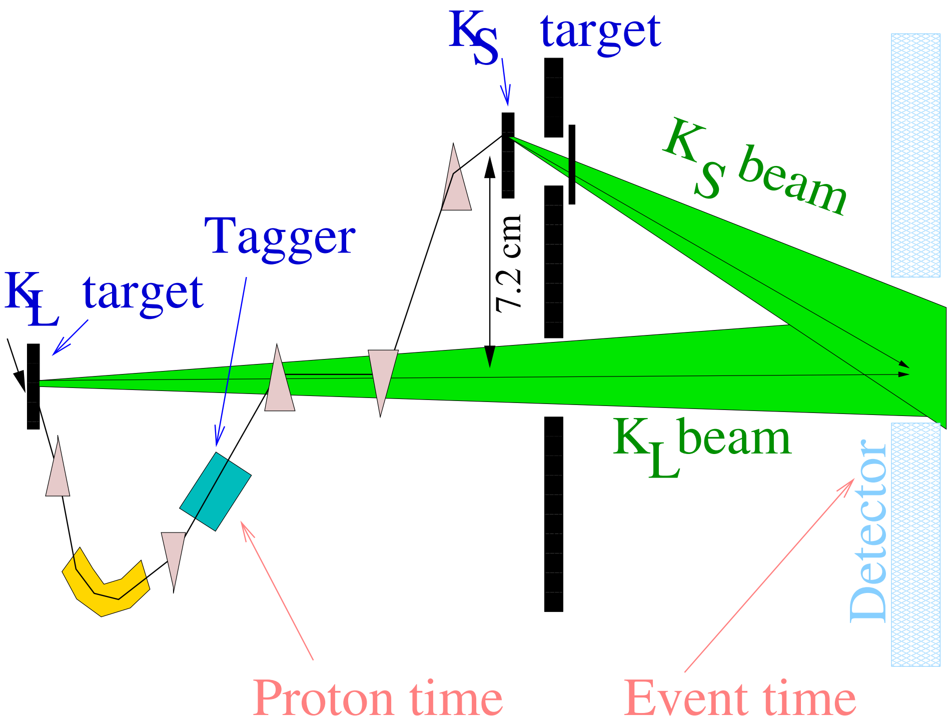
- Evaluate A_{corr} and systematics
- Checks and stability of the result

ANALYSIS for Re(ε'/ε): Disentangle K_S from K_L



K_S and K_L beams hit the same detector region$\Rightarrow$

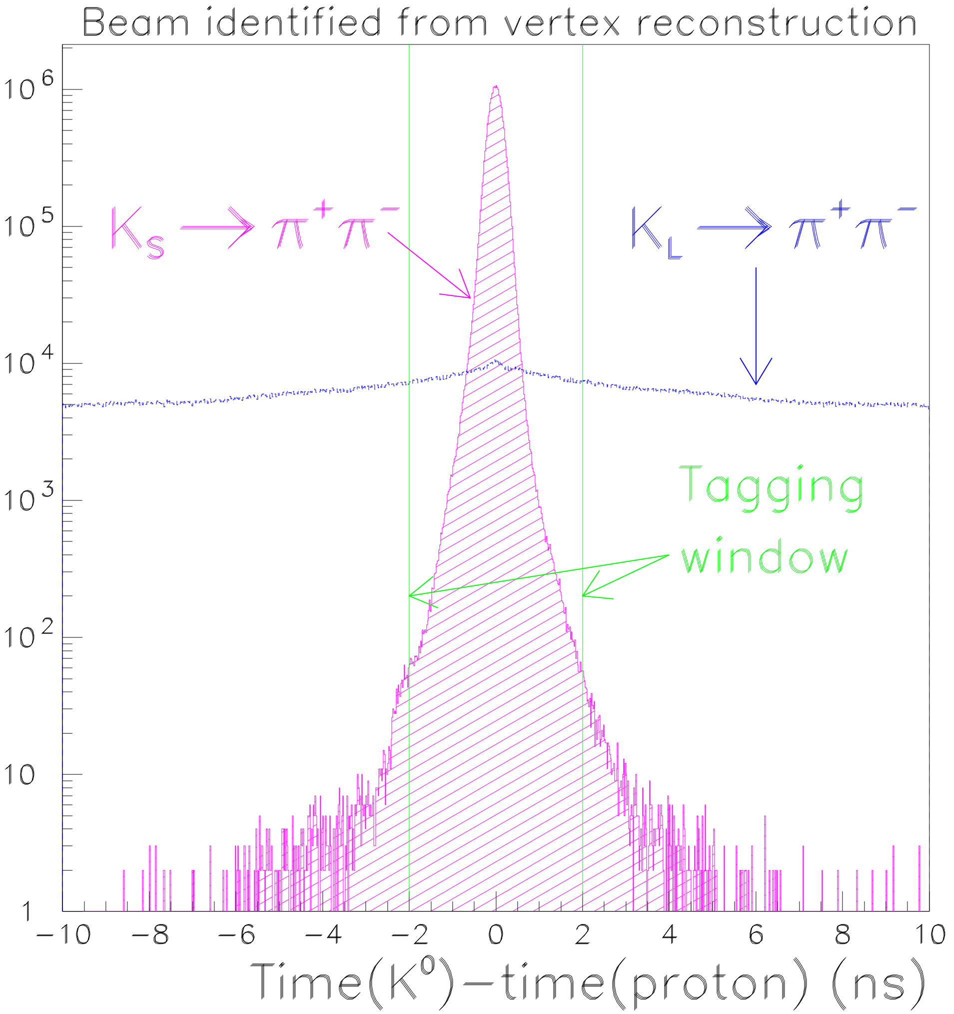
Identify K_S decays:

- Compare event time with the closest proton time in tagger.
- If compatible $\Rightarrow$event comes from K_S beam

Tagging applied to both, $\pi^+\pi^-$ and $\pi^0\pi^0$.

In $\pi^+\pi^-$ $\Rightarrow$ beam also known from vertical vertex position

ANALYSIS: Disentangle K_S from K_L (cntd)



Tagging window ±2ns

Two kinds of misidentification:

- K_S identified as K_L : called α_{SL}, due to misreconstruction
- K_L identified as K_S : called α_{LS}, due to accidental coincidence of a K_L decay with a proton in tagger

ANALYSIS: Disentangle K_S from K_L :α_{SL}

$$\boxed{\alpha_{SL}^{+-}=(1.64\pm0.03)\times10^{-4}}$$

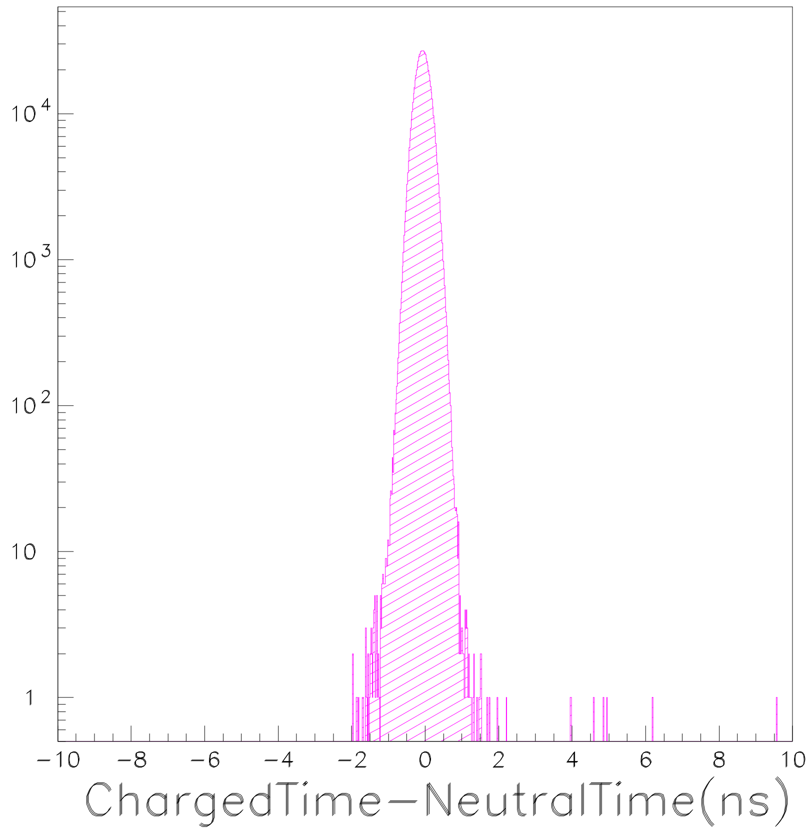
measured in $K_S\rightarrow\pi^+\pi^-$ identified from vertex.

Dominated by proton time misreconstruction$\Rightarrow$ $\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric

$$\boxed{\Delta\alpha_{SL}=\alpha_{SL}^{00}\text{-}\ \alpha_{SL}^{+-}}$$

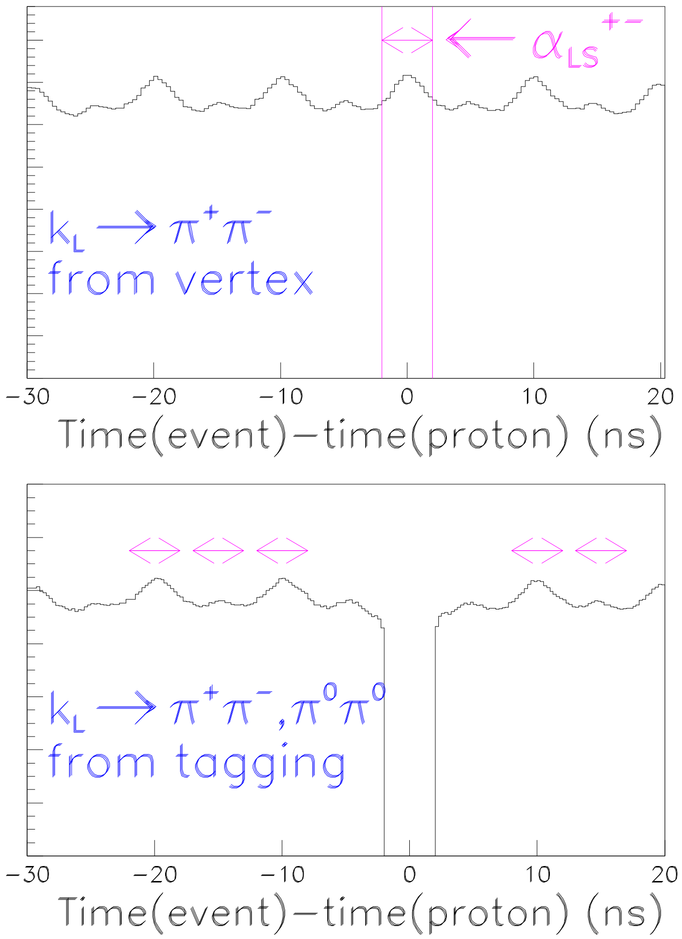
$$\boxed{\Delta\alpha_{SL}=(0\pm0.5)\times10^{-4}}$$

comparing charged and neutral times in $2\pi^0$ and $3\pi^0$ events with conversions



$$\boxed{\Rightarrow\ \Delta R=(0\pm3)\times10^{-4}}$$

ANALYSIS: Disentangle K_S from K_L :α_{LS}



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

measured in $K_L \rightarrow \pi^+\pi^-$ identified from vertex.

Small difference between α_{LS}^{+-} and α_{LS}^{00} because of different sensitivities of $\pi^+\pi^-$ and $\pi^0\pi^0$ to the intensity.

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

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

ANALYSIS for Re(ε'/ε)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
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- Subtract the remaining background from K_L samples
- Evaluate A_{corr} and systematics
- Checks and stability of the result

ANALYSIS: Background subtraction

K_L decays dominated by the CP-conserving 3-body decays

- $K_L \to \pi e \nu$ (39%)
- $K_L \to \pi \mu \nu$ (27%)
- $K_L \to 3\pi^0$ (21%)
- $K_L \to \pi^+\pi^-\pi^0$ (13%)

$\Leftarrow$ Can mimic $\pi^+\pi^-$and $2\pi^0$

Hunted K_L CP-violating modes: $2\pi^0$(0.1%) and $\pi^+\pi^-$ (0.2%)

Also check for scattered events

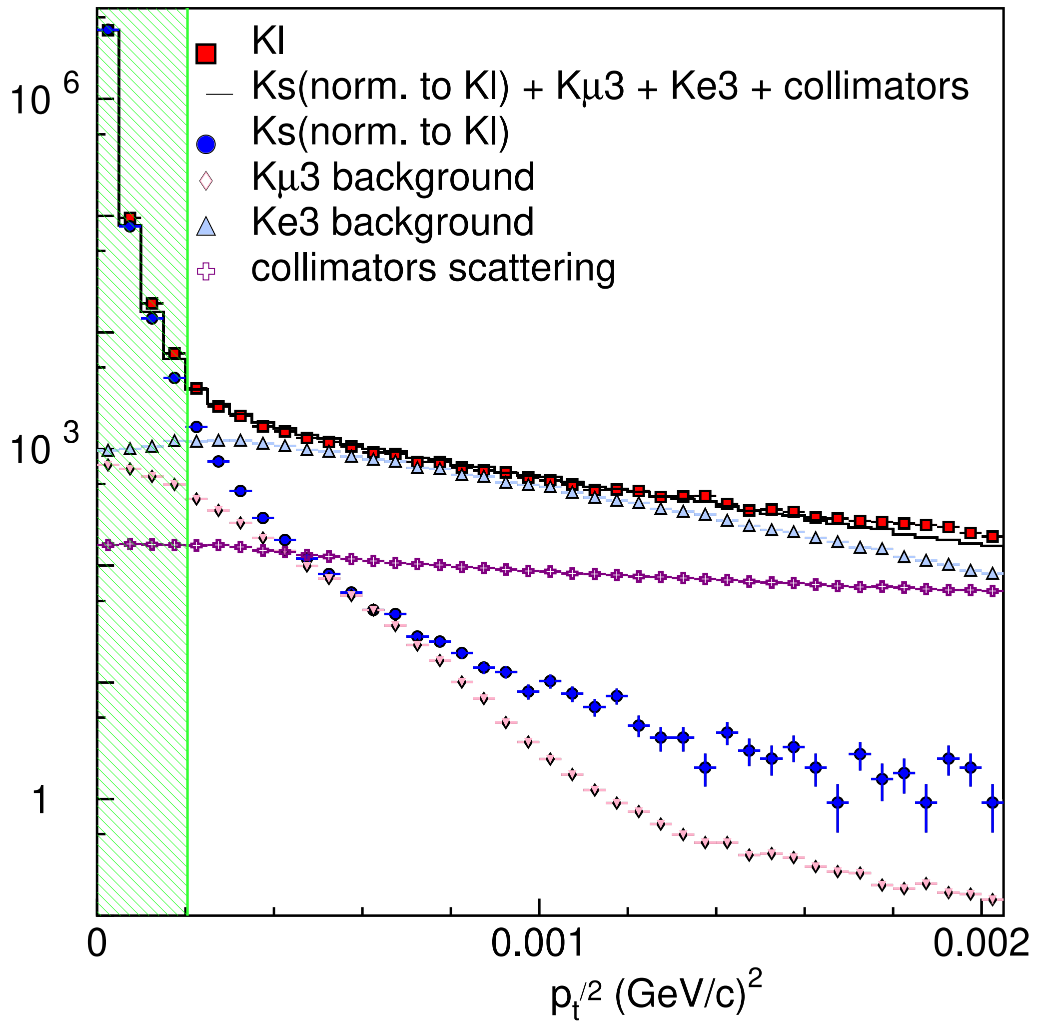
ANALYSIS: Background in $\pi^+\pi^-$

CP-conserving decays, $K_L \to \pi\mu\nu$ and $\pi e\nu$, are strongly suppressed by muon Vetoes and E/P respectively.

The remaining misidentified events are studied in the $P_T'^2$ vs $M_{\pi^+\pi^-}$ and subtracted statistically under the signal.

$\Downarrow$

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



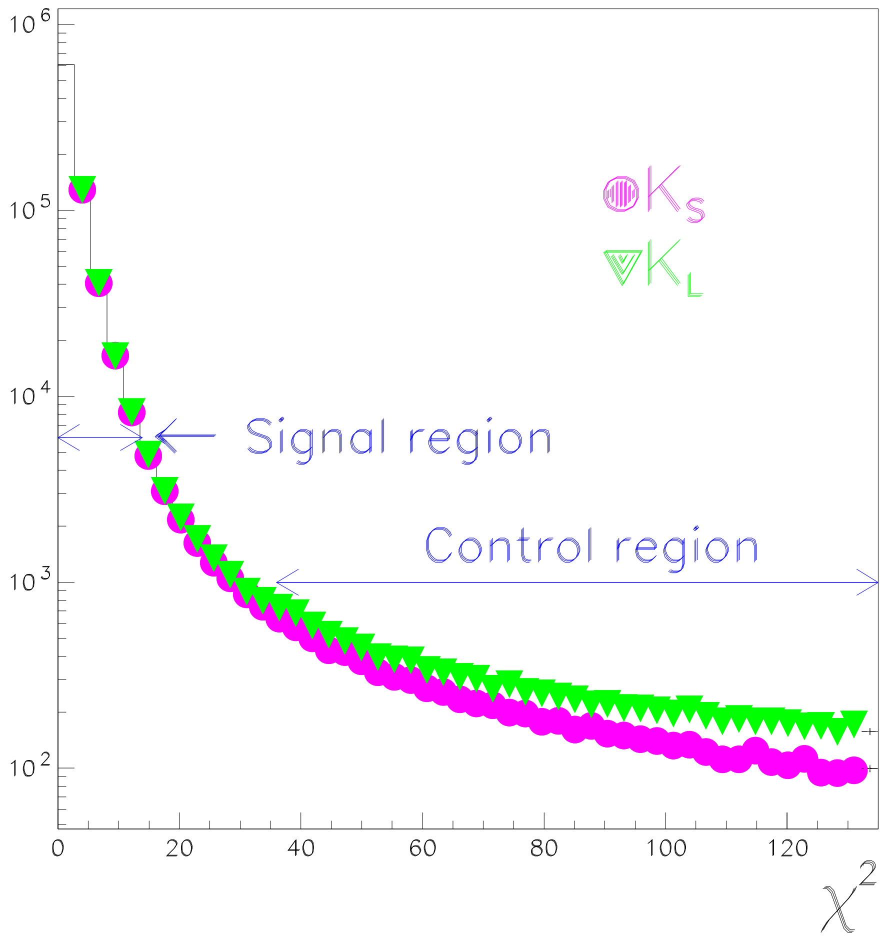
ANALYSIS: Background in $\pi^0\pi^0$

CP-conserving $K_L \rightarrow 3\pi^0$ with lost or fused γ(s).

Compatibility of the two $\gamma\gamma$ pair masses with $m(\pi^0)$ described by a χ^2 function

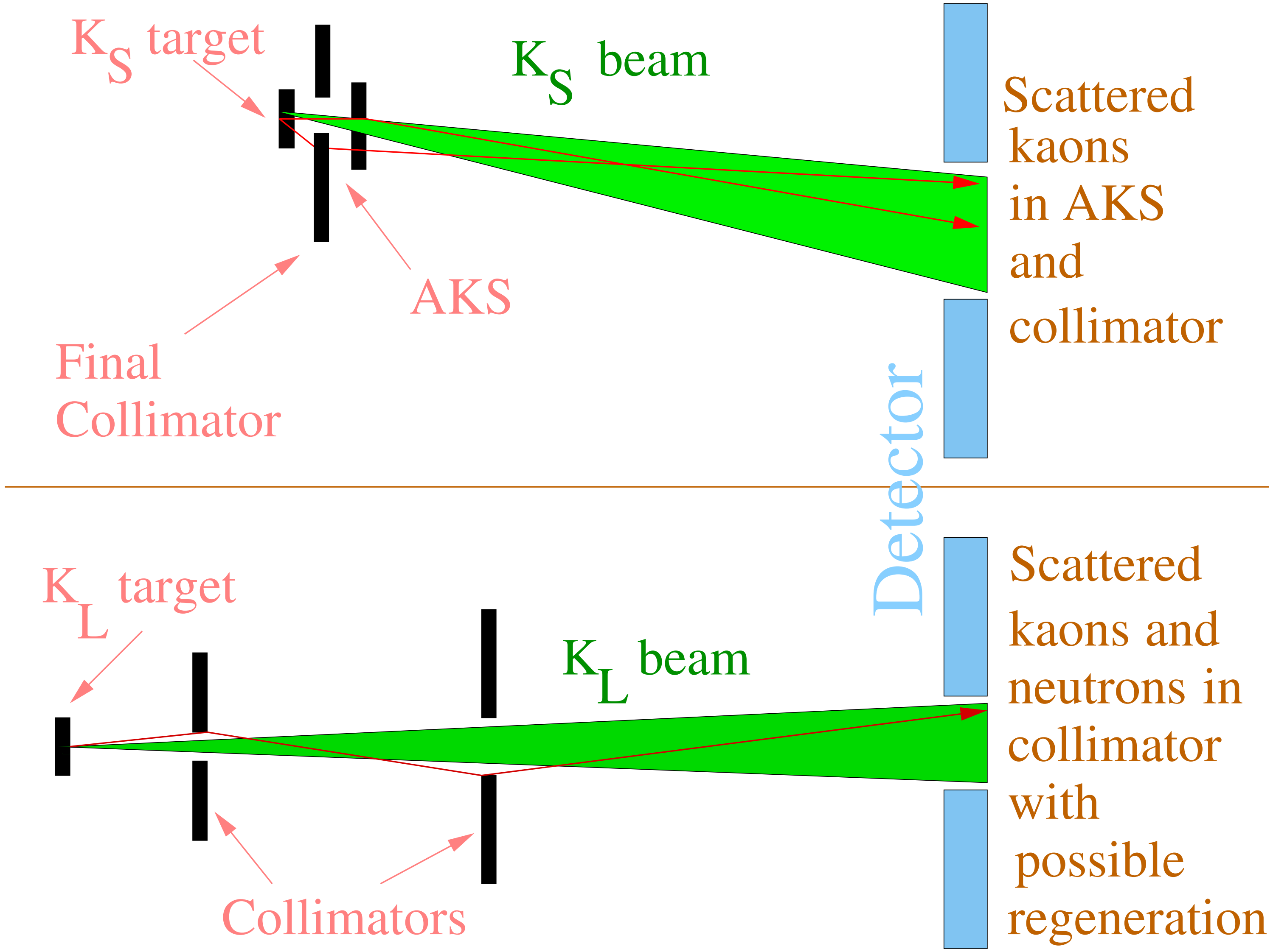
Events with extra clusters within 3ns are rejected

Remaining background studied in control region and subtracted under the signal

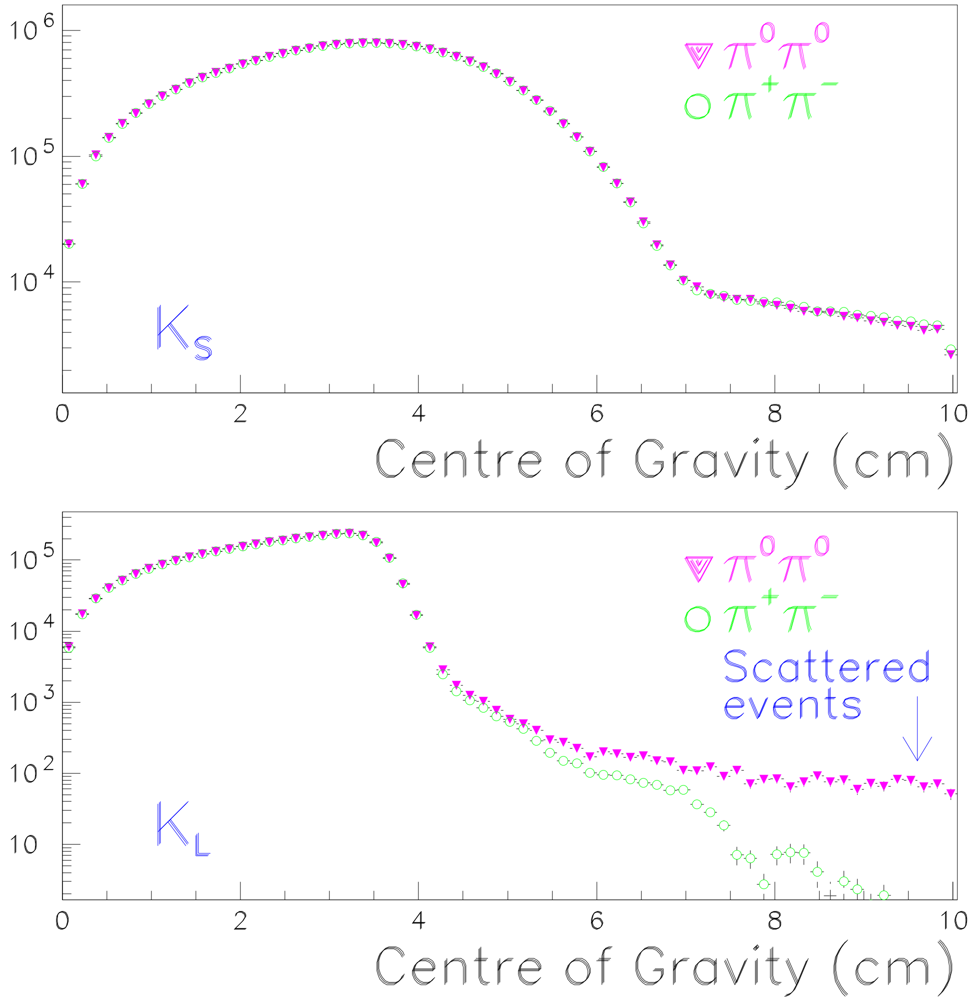


$$\Delta R = (-5.9 \pm 2.0) \times 10^{-4}$$

ANALYSIS: Scattering effects



ANALYSIS: Scattering effects (cntd)



In K_S , scattered events are symmetrically rejected in $\pi^+\pi^-$ and $\pi^0\pi^0$.

In K_L case, $P_T^{2'}$ cut (in $\pi^+\pi^-$) is stronger than CoG cut (in $\pi^0\pi^0$).

This resulting asymmetry in the halos in $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow 2\pi^0$ leads to a correction on R:

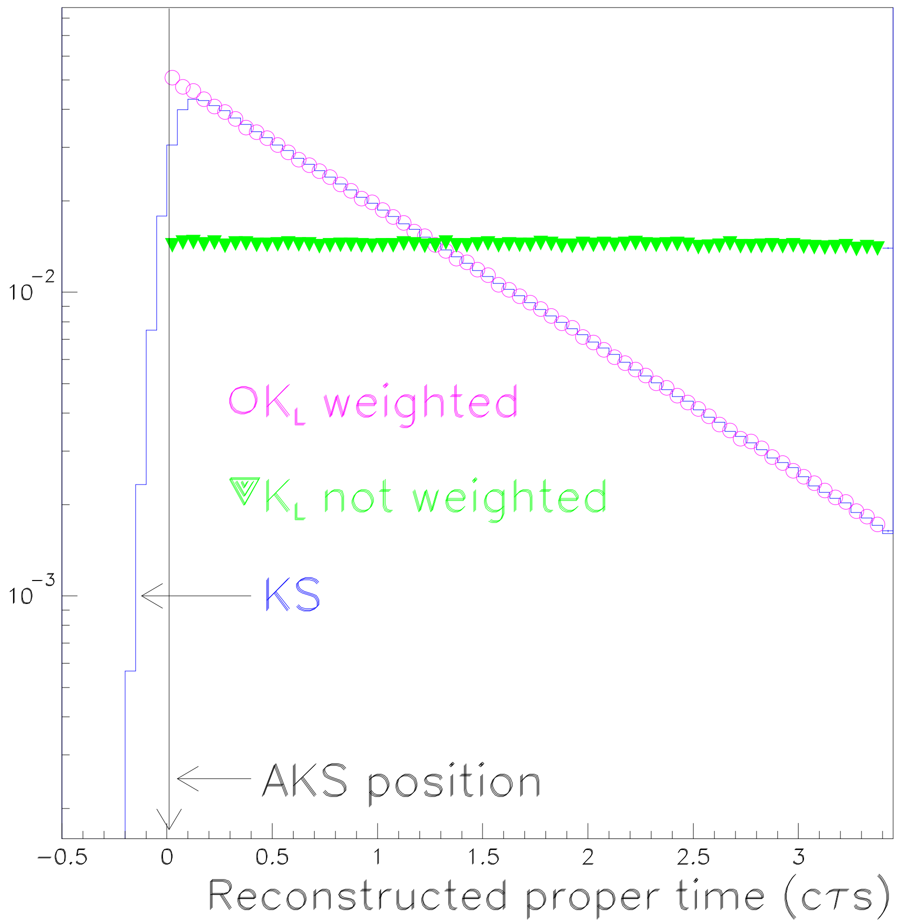
$\Downarrow$

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

ANALYSIS for Re(ε'/ε)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L using Tagging
- Subtract the remaining background from K_L samples
- Evaluate A_{corr} and systematics
- Checks and stability of the result

ANALYSIS: Acceptance correction

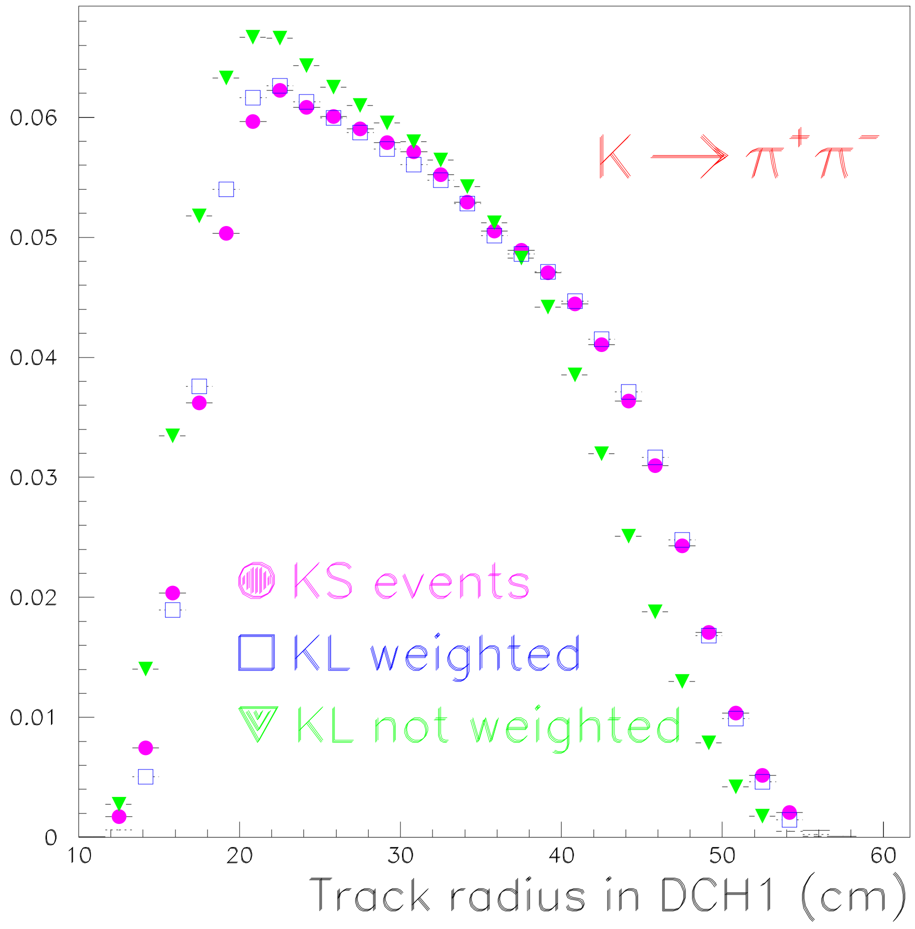


Because $\tau_L \neq \tau_S$, K_L and K_S decays illuminate differently the detector.

This would lead to an acceptance correction on R up to $\pm 10\%$ depending on the kaon energy

Weighting K_L events by the $K_S\ /K_L$ 2π-decay ratio $\Rightarrow$ K_S and K_L decay distributions become identical and illuminations similar

ANALYSIS: Acceptance correction (cntd)



Small remaining acceptance correction

Slightly converging beams$\Rightarrow$

For $\pi^+\pi^-$ events small acceptance difference in first chamber close to the beam tube.

$\Downarrow$

$$\boxed{\Delta R = (26.7 \pm 5.7) \times 10^{-4}}$$

ANALYSIS: Summary of A$_{corr}$

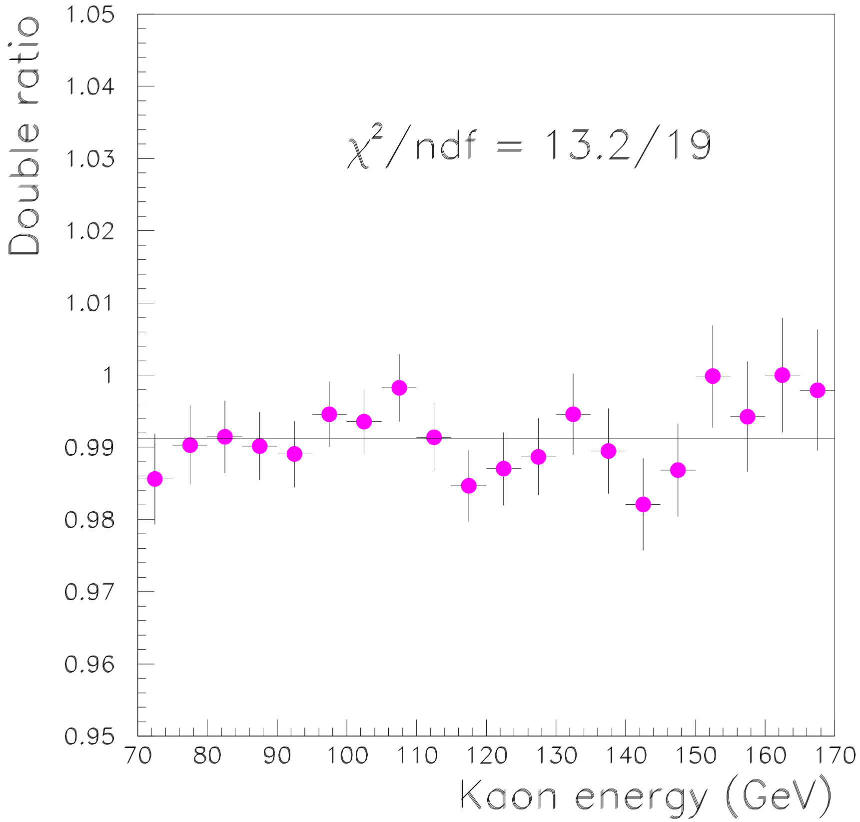
		in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency		-3.6	$\pm$ 5.2
AKS inefficiency		$+1.1$	$\pm$ 0.4
Reconstruction	of $\pi^0\pi^0$	—	$\pm$ 5.8
	of $\pi^+\pi^-$	$+2.0$	$\pm$ 2.8
Background	to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
	to $\pi^+\pi^-$	$+16.9$	$\pm$ 3.0
Scattering		-9.6	$\pm$ 2.0
Tagging : $\Delta\alpha_{LS}$		$+8.3$	$\pm$ 3.4
Tagging : $\Delta\alpha_{SL}$		—	$\pm$ 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 correction on R		$+35.9$	$\pm$ 12.6

Total correction on Re(ε'/ε)= -A$_{corr}$/6= (-6.0$\pm$2.1)$\times 10^{-4}$

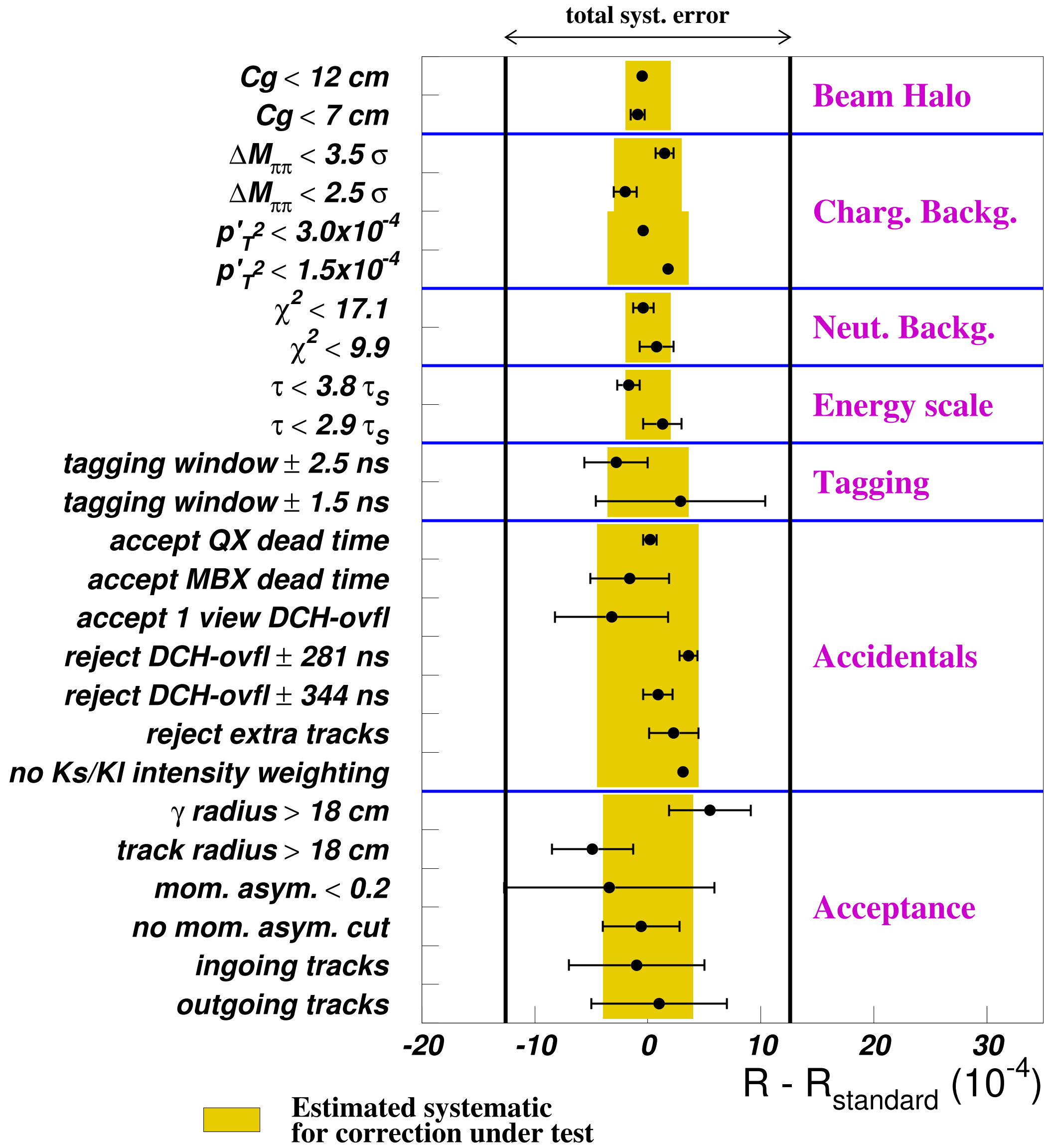
ANALYSIS for Re(ε'/ε)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L using Tagging
- Subtract the remaining background from K_L samples
- Evaluate A_{corr} and systematics
- Checks and stability of the result

ANALYSIS: Stability of the result



R computed in 5GeV bins



THE RESULT

$$R=0.99098 \pm .00101_{stat} \pm 0.00126_{syst}$$

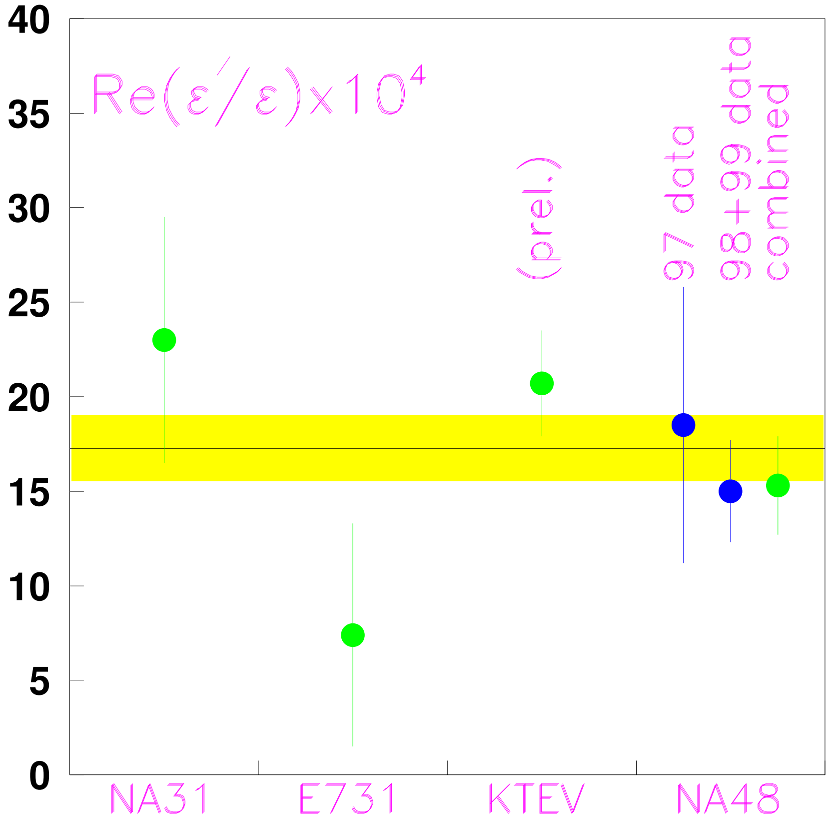
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1\text{-}R)/6$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon)=(15.0 \pm 1.7_{stat} \pm 2.1_{syst}) \times 10^{-4}}$$

extracted from the analysis of the 98+99 statistics of:

$$K_L \rightarrow \pi^0\pi^0 \; : 3290 \times 10^3$$
$$K_L \rightarrow \pi^+\pi^- \; : 5209 \times 10^3$$
$$K_S \rightarrow \pi^0\pi^0 \; : 14453 \times 10^3$$
$$K_S \rightarrow \pi^+\pi^- \; : 2222 \times 10^3$$

CONCLUSIONS



Combined NA48 result :

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

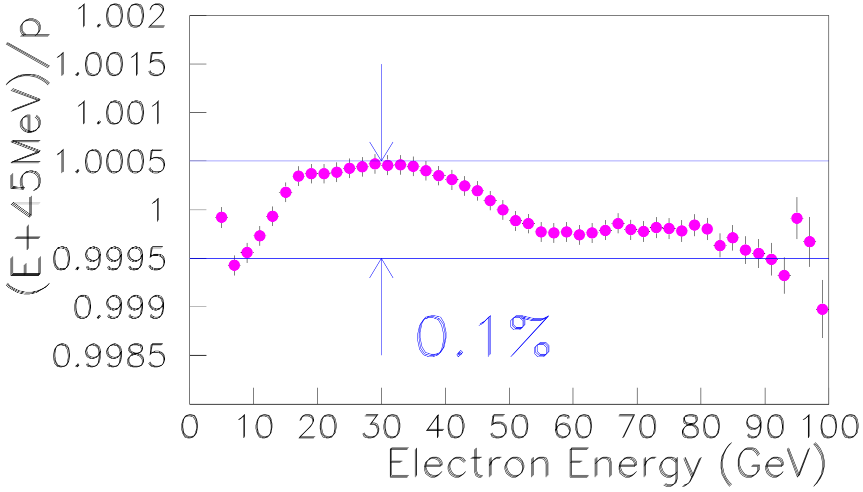
World average of NA31, E731, KTeV and NA48:

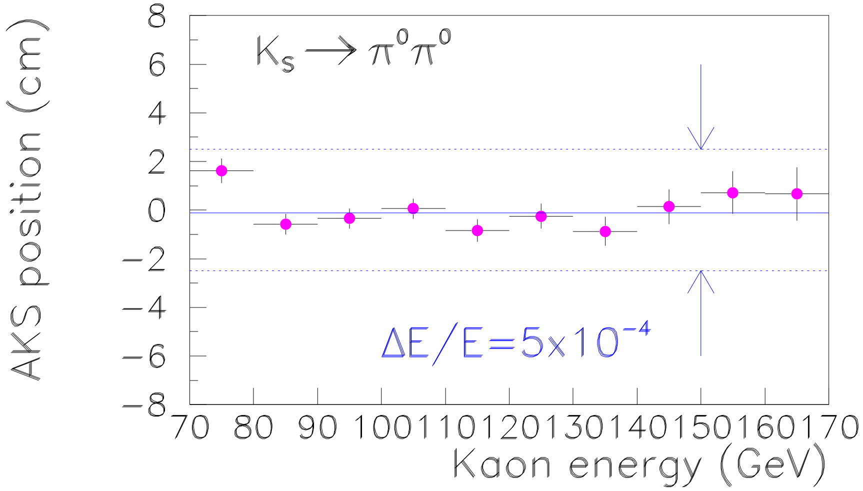
$$Re(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$$

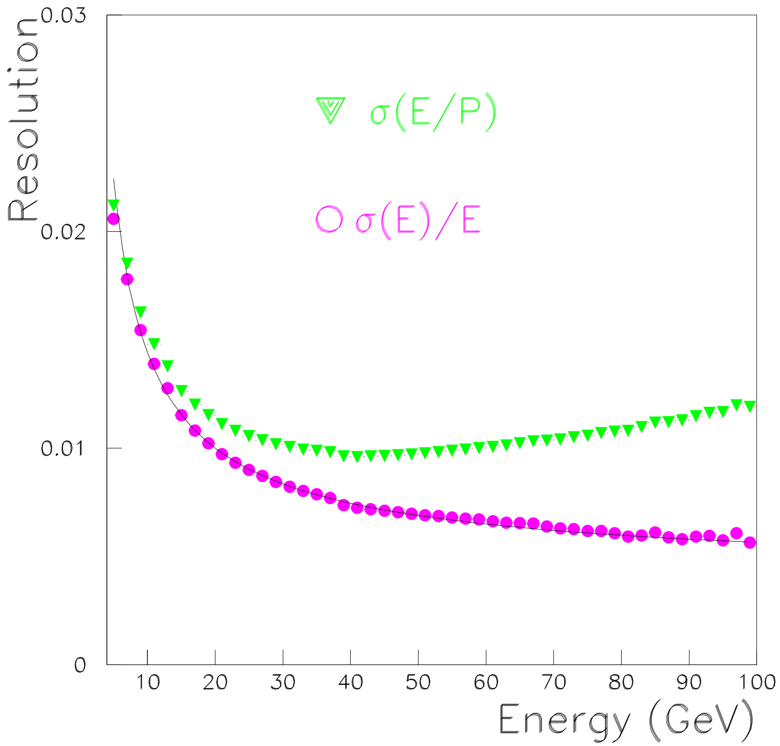
$\Rightarrow$ Both Indirect and Direct CP Violation components discovered, measured and confirmed in the kaon system

Spares

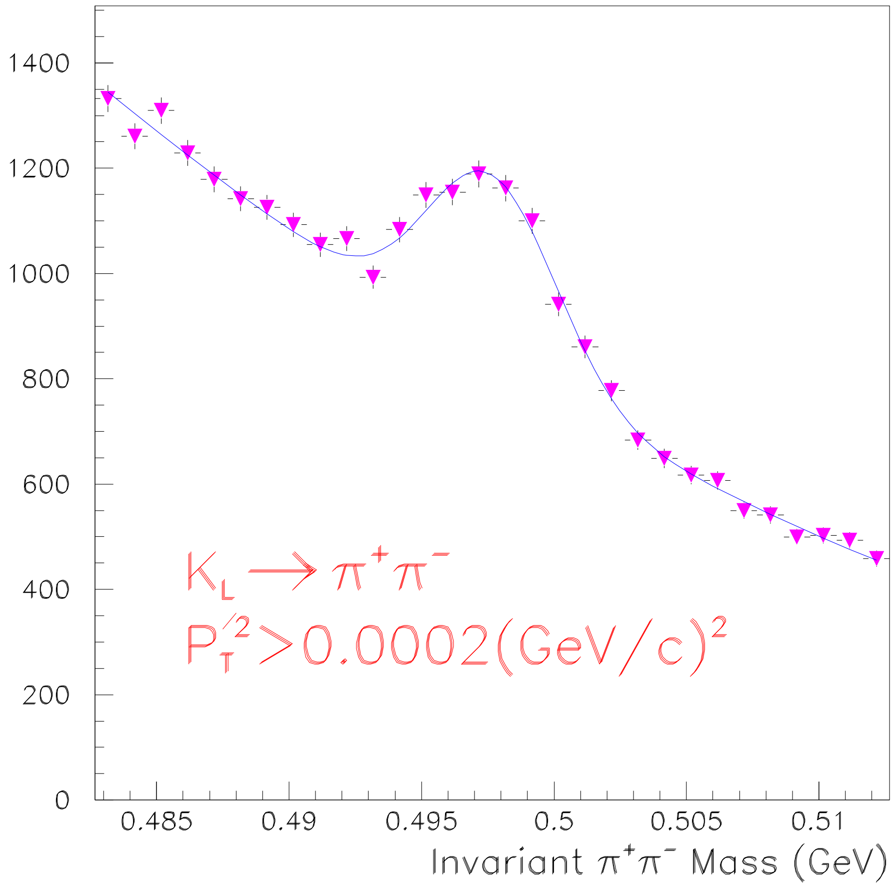
LKr Performances and energy scale

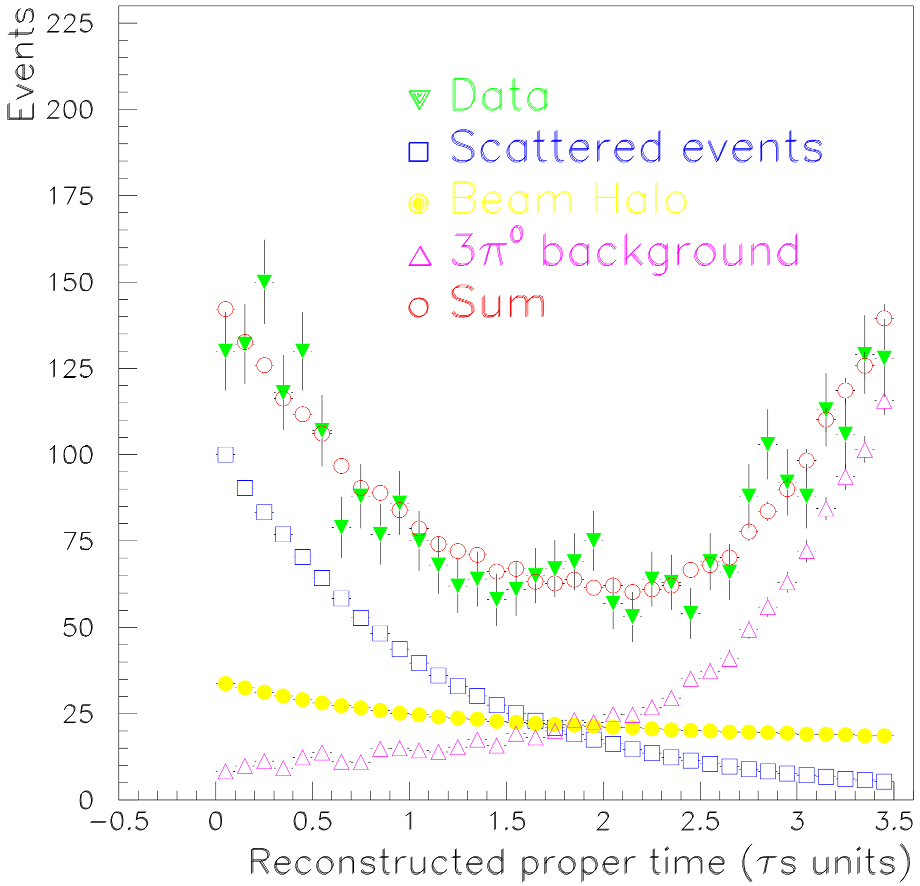




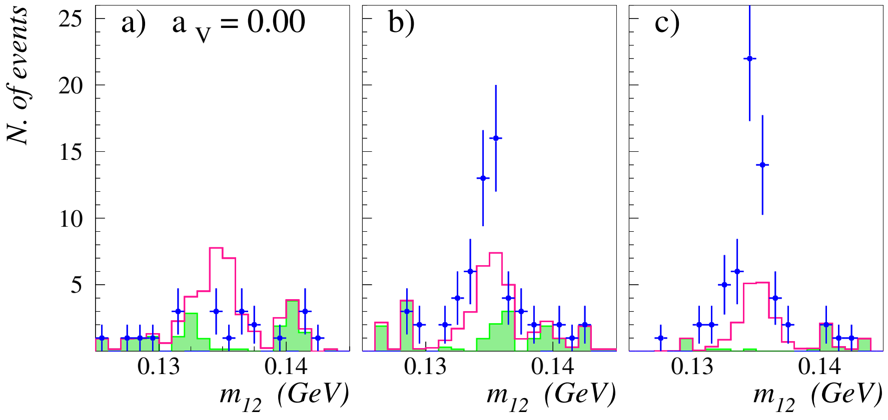


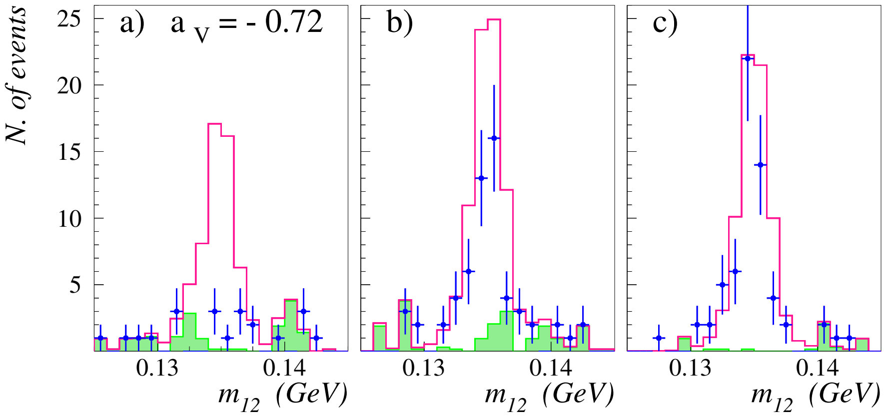
Scattering in K_L collimators

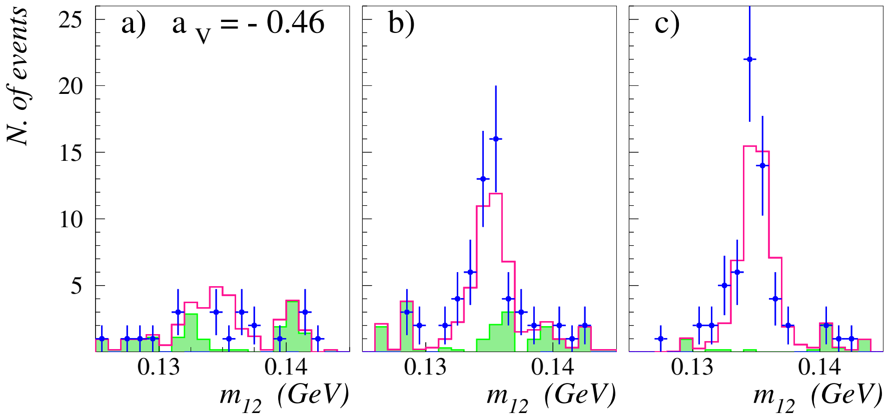


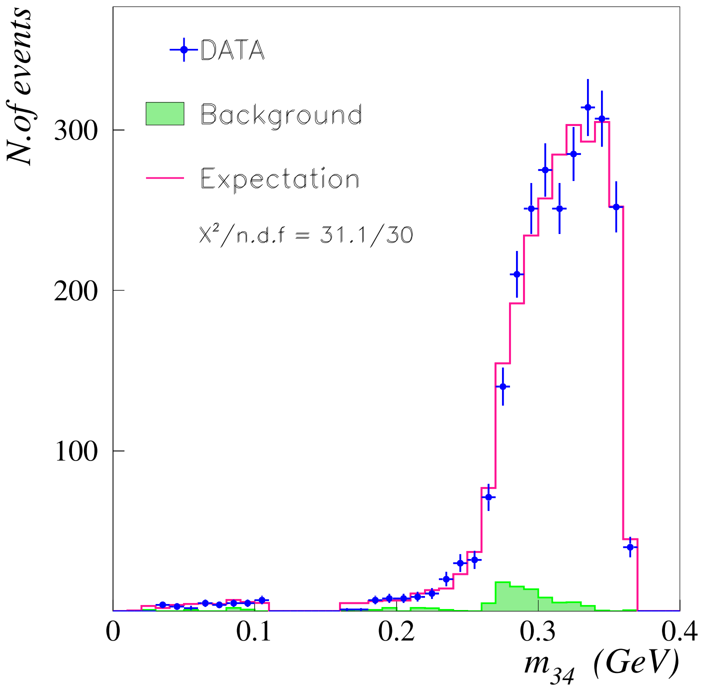


$K_L \to \pi^0 \gamma\gamma$







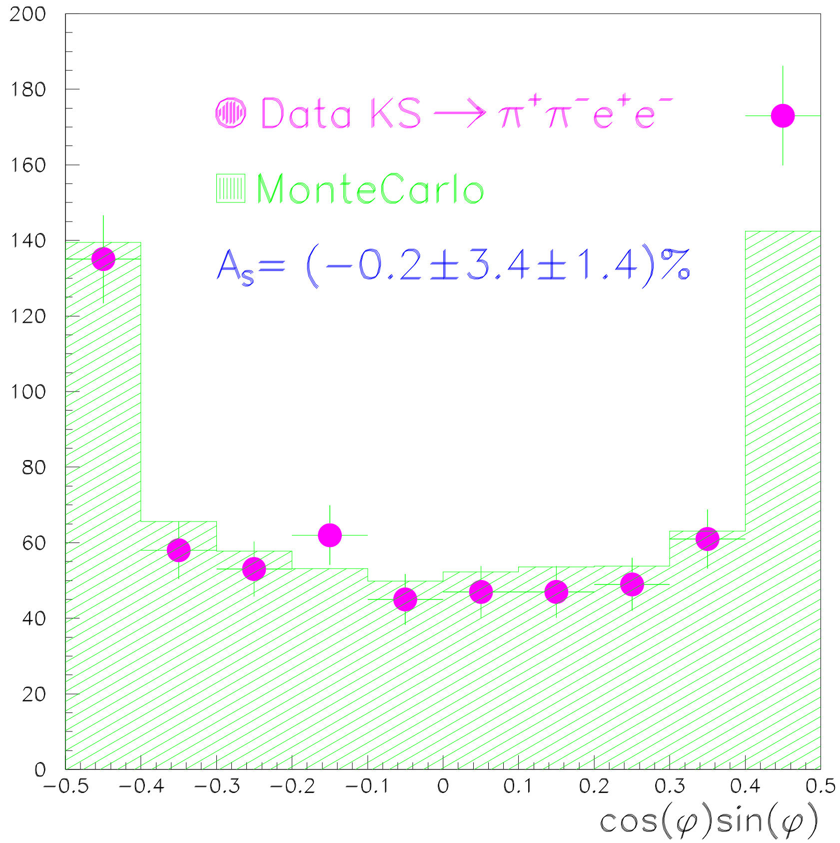


a: $30\text{MeV} \leq m_{\gamma\gamma} \leq 110\text{MeV}$

b: $160\text{MeV} \leq m_{\gamma\gamma} \leq 240\text{MeV}$

c: $240\text{MeV} \leq m_{\gamma\gamma} \leq 260\text{MeV}$

$K_S \to \pi^+\pi^- e^+ e^-$



- Dominant inner bremsstr. contribution
- 921 events observed
- A_S=-0.2±3.4$_{stat}$±1.4$_{syst}$ %
- $\Rightarrow$ No CP-Asymmetry

BR=(4.3±0.2$_{stat}$±0.3$_{syst}$)×10^{-5} $\Rightarrow$ BR($K_L \to \pi^+\pi^- e^+ e^-)_{IB}$

First Observation!!!!