New Measurement of Direct CP Violation Parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ by the NA48 Experiment at CERN

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- CP violation
- NA48 method
- Analysis of 1998 data and result
- Perspectives

NA48 COLLABORATION

Cagliari - Cambridge - CERN - Dubna - Edinburgh - Ferrara- Firenze - Mainz - Orsay - Perugia - Pisa - Saclay - Siegen - Torino - Vienna - Warsaw

CP violation in the neutral Kaon system

- Before 1964, neutral kaon system was described by:

$$K_1{}^{+1} \text{ and } K_2{}^{-1} \text{ CP eigenstates}$$
$$CP|K_1{}^{+1}\rangle = +|K_1{}^{+1}\rangle, \; CP|K_2{}^{-1}\rangle = -|K_2{}^{-1}\rangle$$

$$K^0 \text{ and } \overline{K^0} \text{ flavour eigenstates:}$$
$$|K_1{}^{+1}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K^0}\rangle)$$
$$|K_2{}^{-1}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K^0}\rangle)$$

- In 1964 CP violation discovery: $'\mathrm{K_L}' \rightarrow \pi^+\pi^-(CP = +1)$

CP eigenstate ($K_1{}^{+1}$ and $K_2{}^{-1}$) are not pure mass eigenstates $\mathrm{K_L}$ and $\mathrm{K_S}$:

$$\mathrm{K_S} \simeq K_1{}^{+1} + \varepsilon K_2{}^{-1}$$
$$\mathrm{K_L} \simeq K_2{}^{-1} + \varepsilon K_1{}^{+1}$$

$$|\varepsilon| = (2.28 \pm 0.02) \times 10^{-3}$$

- Indirect CP $\overline{K^0}$-K^0 asymetric mixing:

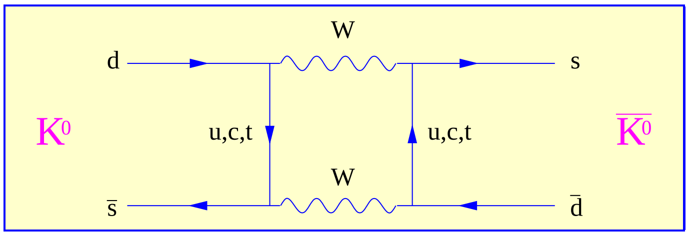
$$K^0 \rightarrow \overline{K^0} \neq \overline{K^0} \rightarrow K^0$$
$$\varepsilon \simeq \frac{\langle\overline{K^0}|H|K^0\rangle - \langle K^0|H|\overline{K^0}\rangle}{2(m_L - m_S) - i(\Gamma_L - \Gamma_S)}$$

- Direct CP in decay: $\varepsilon' \neq 0$

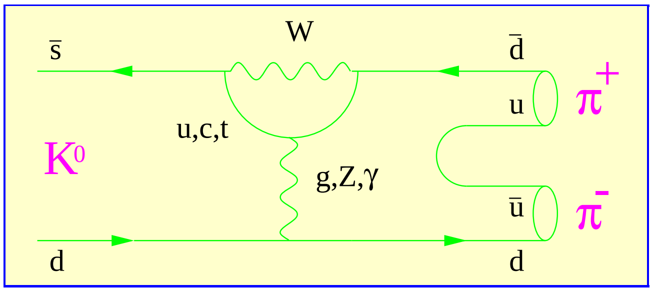
$$K^0 \rightarrow \pi^+\pi^- \neq \overline{K^0} \rightarrow \pi^+\pi^-$$
$$K^0 \rightarrow \pi^0\pi^0 \neq \overline{K^0} \rightarrow \pi^0\pi^0$$
$$\varepsilon' = -\frac{e^{i(\delta_2 - \delta_0 + \frac{\pi}{2})}}{\sqrt{2}} \frac{\omega}{\mathfrak{Re}A_0}[\mathfrak{Im}A_0 - \frac{1}{\omega}\mathfrak{Im}A_2]$$

In the standard model

Indirect CP violation
through mixing
$K^0/\overline{K^0}$ oscillations
$(\Delta S = 2)$
$\Rightarrow \varepsilon$ parameter



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



Direct violation
through decay
penguin diagrams
$(\Delta S = 1)$
$\Rightarrow \varepsilon'$ parameter

$$\frac{\varepsilon'}{\varepsilon} \cdot 10^4 = \frac{|V_{ub}||V_{cb}|\sin\delta}{1.34 \cdot 10^{-4}} \cdot 18 \cdot [\frac{110MeV}{m_s(2GeV)}]^2 \cdot$$

$$[\ 0.75 \cdot B_6 - 0.4(\frac{m_{top}}{165GeV})^{2.5} \cdot B_8] \cdot (\frac{\Lambda_{\bar{MS}}}{340MeV})$$

B_6 QCD pinguin operator

B_8 electoweak pinguin operator

(from A. Buras academic training at CERN - spring 2000)

SM Calculations and experimental results

$\mathrm{Re}(\varepsilon'/\varepsilon)$ in Standard Model

- B_6 and B_8: $\approx$ same size
- Difficulties is in the computation of B_6 (QCD pinguins)
- $\mathrm{Re}(\varepsilon'/\varepsilon) \simeq 10 \times 10^{-4}$
- Range $\simeq \pm 10 \times 10^{-4}$, depending on scheme.
- Hope in the coming months from lattice calculations

$\mathrm{Re}(\varepsilon'/\varepsilon)$ in experiments

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

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

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) \simeq \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right)}$$

Previous Measurements of $\mathrm{Re}(\varepsilon'/\varepsilon) \times 10^4$		
	NA31	23.0 ± 6.5
	E731	7.4 ± 5.9
	KTEV	28.0 ± 4.1
	NA48	18.5 ± 7.3

NA48 method and analysis

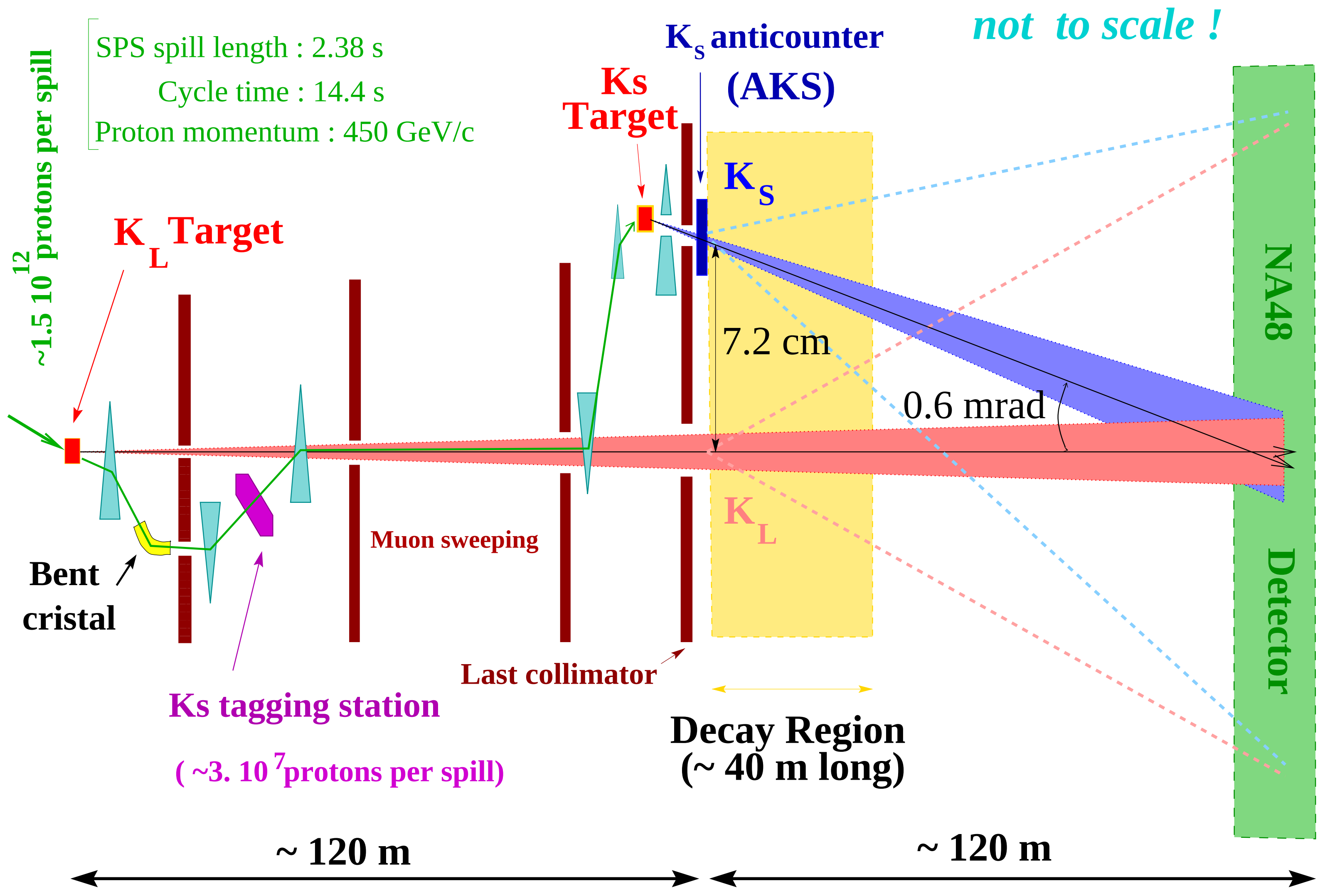
- Goal : measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with a precision $\simeq 2 \times 10^{-4}$
- Mean : measure the double ratio of the four modes

$$R = \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}$$

$$\simeq 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon)$$

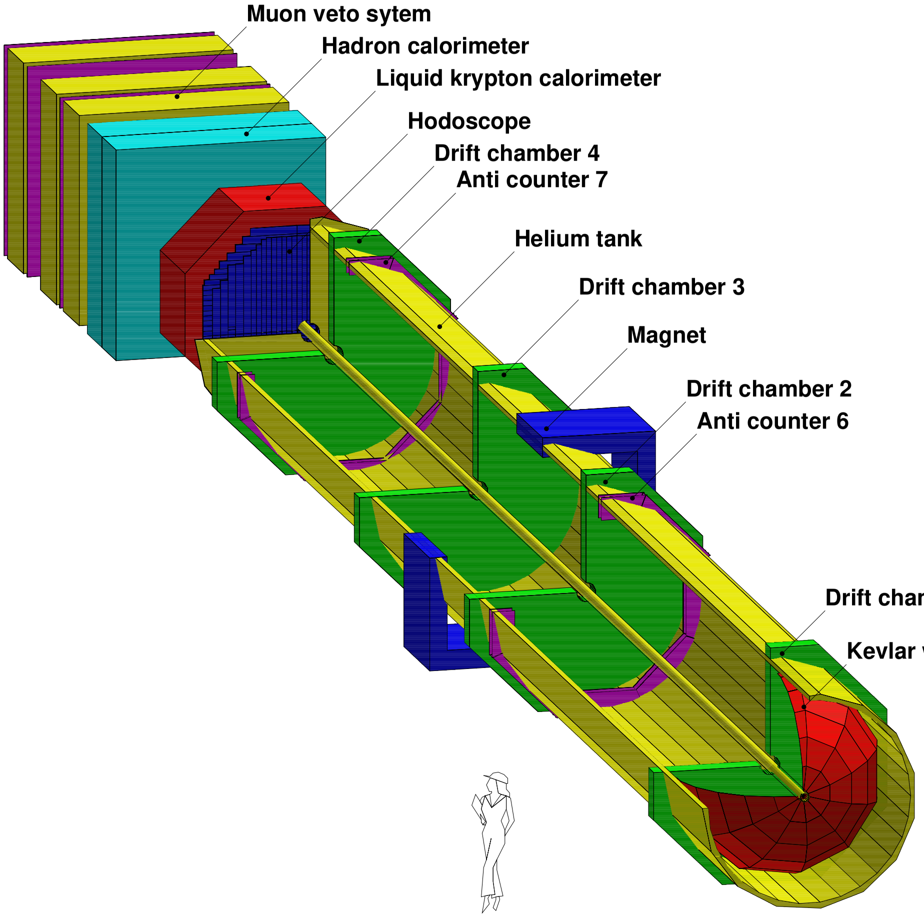
- High statistics
  - ◇ $BR(\mathrm{K_L} \to \pi^0\pi^0) = 0.0936\%$
  - ◇ $BR(\mathrm{K_L} \to \pi^+\pi^-) = 0.2067\%$
  - ◇ $BR(\mathrm{K_L} \to \pi^0\pi^0\pi^0) \simeq 21\%$
  - ◇ $BR(\mathrm{K_L} \to \pi^\pm\mu^\mp\nu_\mu + \pi^\pm e^\mp\nu_\mathrm{e}) \simeq 66\%$
- To minimize corrections the 4 modes are measured:
  - ◇ simultaneously: cancellation of fluxes, inefficiencies, dead time, accidental activity)
  - ◇ from the same fiducial volume (life time $< 3.5 \times \tau_S$), applying lifetime weighting to equalize longitudinal vertex distribution: small acceptance correction
  - ◇ with high resolution: magnetic spectrometer for $\pi^+\pi^-$ mode and homogeneous Liquid Krypton calorimeter for $\pi^0\pi^0$ mode to reject backgrounds.
  - ◇ in bins of energy to account for differences of $\mathrm{K_S}$ and $\mathrm{K_L}$ energy spectra (20 bins 70–170 GeV)

NA48 simultaneous and collinear K_S and K_L beams



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

NA48 detector



- $K_{S,L} \to \pi^+\pi^-$
  - ◇ Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu$m, $\sigma_{mass} \sim 2.5 MeV/c^2$)
  - ◇ Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - ◇ μ veto to reject $\pi\mu\nu$ background.
- $K_{S,L} \to \pi^0\pi^0$
  - ◇ Liquid Krypton electromagnetic calorimeter ($\sigma_t \sim 270\ ps$)
  - ◇ $\frac{\sigma(E)}{E} < 1GeV$ for $E_\gamma > 20GeV$
  - ◇ $\sigma_{mass} \simeq 1.1 MeV/c^2$

NA48 data and analysis

- 1997 data: published result (0.49×10^6 $K_L \to \pi^0\pi^0$)
  Phys. Lett. B 465 (1999) 335-348

$$1997\ \mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5(stat.) \pm 5.8(syst.)) \times 10^{-4}$$

Statistics (millions)	1997	1998
$K_L \to \pi^0\pi^0$	0.49	1.14
$K_S \to \pi^0\pi^0$	0.98	1.80
$K_L \to \pi^+\pi^-$	1.07	4.87
$K_S \to \pi^+\pi^-$	2.09	7.46

- 1998 data: this new preliminary result
  (1.14×10^6 $K_L \to \pi^0\pi^0$)

- Count events in the four modes and correct:
  - ◇ trigger inefficiencies
  - ◇ kaon misidentification
  - ◇ acceptance
  - ◇ backgrounds
  - ◇ accidental activities
- Control systematics effects

NA48 corrections and uncertainties

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}$$

- Effects a priori cancel in the double ratio.
- Measure differential effects K_S vs K_L, neutral vs charged.

$$\Downarrow$$

$$\boxed{\text{small corrections}}$$

- Corrections to R (units of 10^{-4}):

◇ Charged trigger (K_S vs K_L)	-1 ± 11
◇ Accidental tagging (neutrals vs charged)	$+1 \pm 8$
◇ Acceptance	$+31 \pm 9$
◇ Neutral background	7 ± 2
◇ Charged background	$+19 \pm 3$
◇ Beam scattering (neutrals vs charged)	-10 ± 3
◇ Accidental activity	$+2 \pm 12$

- Uncertainties on R (units of 10^{-4}):

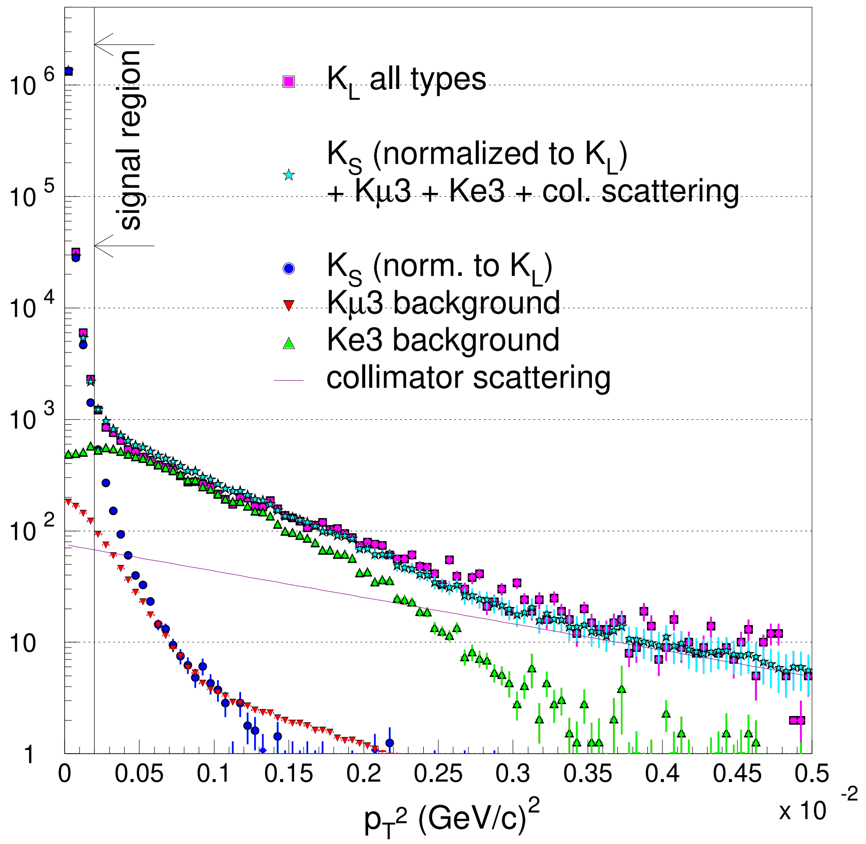
◇ Tagging efficiency	± 3
◇ Neutral energy scale	± 10

- Total:

37 ± 24

Charged background

Background dominated by $K_L \to \pi\mu\nu$ and $K_L \to \pi e\nu$
(70% vs 0.2% for signal)



Signal selection

$\pi\mu\nu$ no hit in μ veto

$\pi e\nu$ $\frac{E_{LKr}}{P_{DCh}} < 0.8$

$\pi\pi$ mass within 3σ

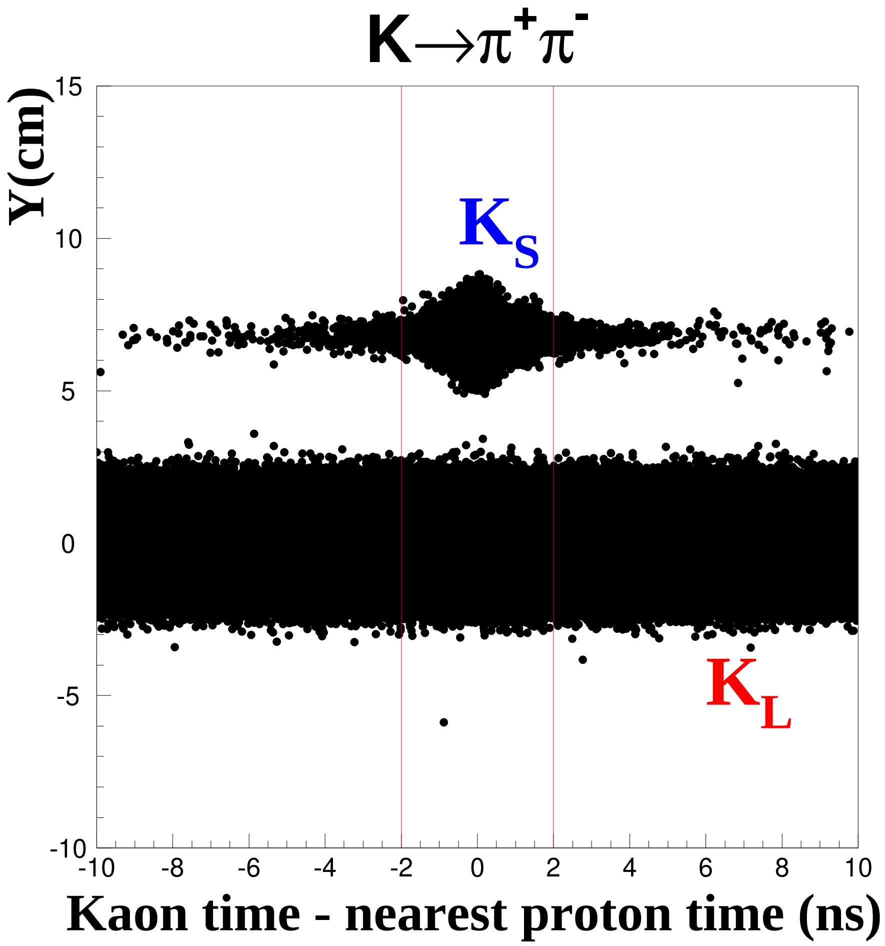
$p_t^2 < 200\ (MeV/c)^2$

Background subtraction

Fit K_L distribution as $\pi^+\pi^-(K_S) + \pi\mu\nu + \pi e\nu$ in a wide $(m_{\pi\pi}, p_t^2)$ control region

- Overall background $\Rightarrow$ $\boxed{\Delta R = (19 \pm 3) \times 10^{-4}}$
- Contribution from scattering in collimators (rejected in charged but not in neutral) correction: $\Delta R = (-10. \pm 3.) \times 10^{-4}$

K_S vs K_L tagging



- Tagging inefficiency: $\alpha_{\rm SL}$

  $\rightsquigarrow$ K_S identified as a K_L

  - ◇ $\pi^0\pi^0$ time measured with Liquid Krypton calorimeter.
  - ◇ $\pi^+\pi^-$ time measured with charged hodoscope.

$$\Delta R \simeq 6 \times \left(\alpha_{SL}^{00} - \alpha_{SL}^{+-}\right) = 6 \times \Delta\alpha_{\rm SL}$$

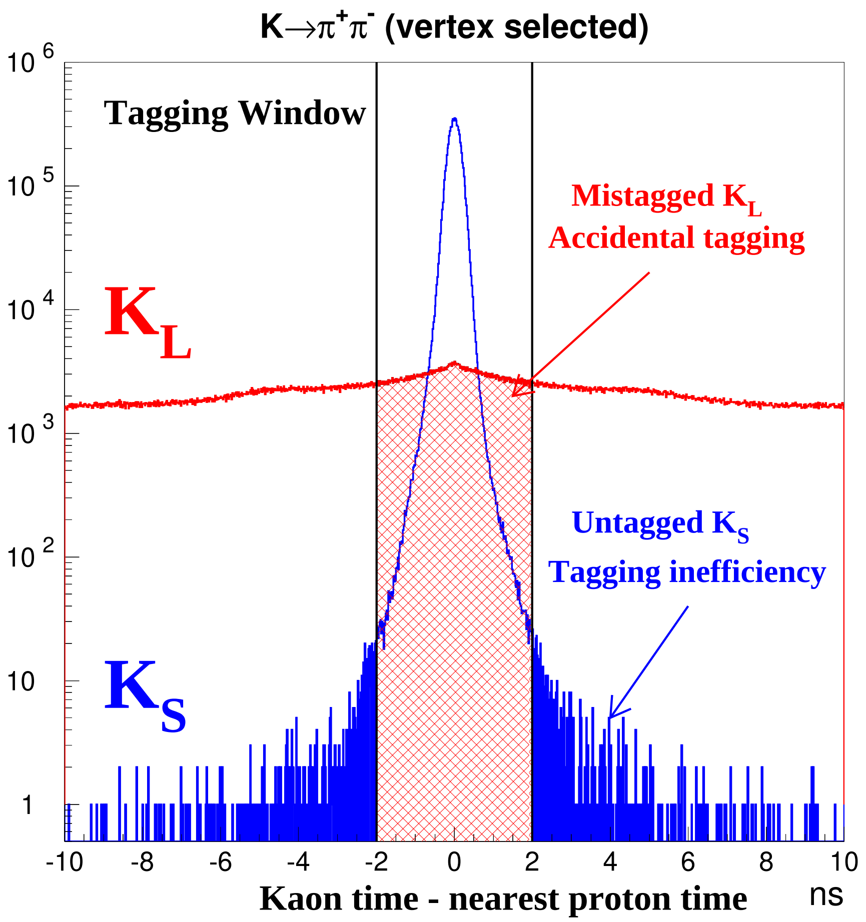
- Accidental tagging $\alpha_{\rm LS}$

  $\rightsquigarrow$ K_L identified as a K_S

  - ◇ Accidental proton inside tagging window

$$\Delta R \simeq 2 \times \left(\alpha_{LS}^{00} - \alpha_{LS}^{+-}\right) = 2 \times \Delta\alpha_{\rm LS}$$

Tagging Performances



- Tagging inefficiency: $|\alpha_{SL}^{+-} - \alpha_{SL}^{00}| < 0.5 \times 10^{-4}$

$$\Rightarrow \boxed{\Delta R < 3 \times 10^{-4}}$$

- Accidental tagging:
  - ◇ measure difference between charged and neutral rates in 4ns wide side bands:
  $$\beta_{LS}^{00} - \beta_{LS}^{+-} = (5.3 \pm 1.6) \times 10^{-4}$$
  - ◇ measure difference of activity between central and side bands with $K_L \to 3\pi^0$ and $K_L \to \pi^+\pi^-$:
  $$W^{00} - W^{+-} = (-5.0 \pm 3.9) \times 10^{-4}$$

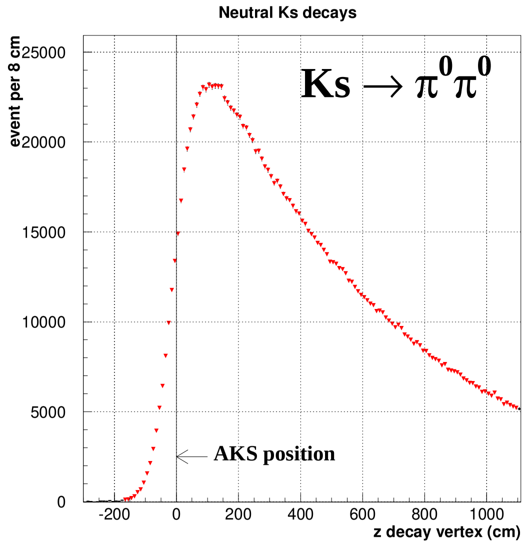
$$\Rightarrow \boxed{\Delta R = (+1 \pm 8) \times 10^{-4}}$$

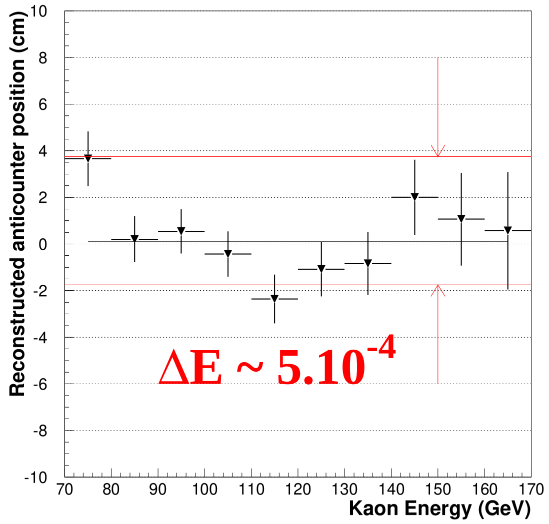
Calorimeter energy scale and non linearitiy

Energy scale

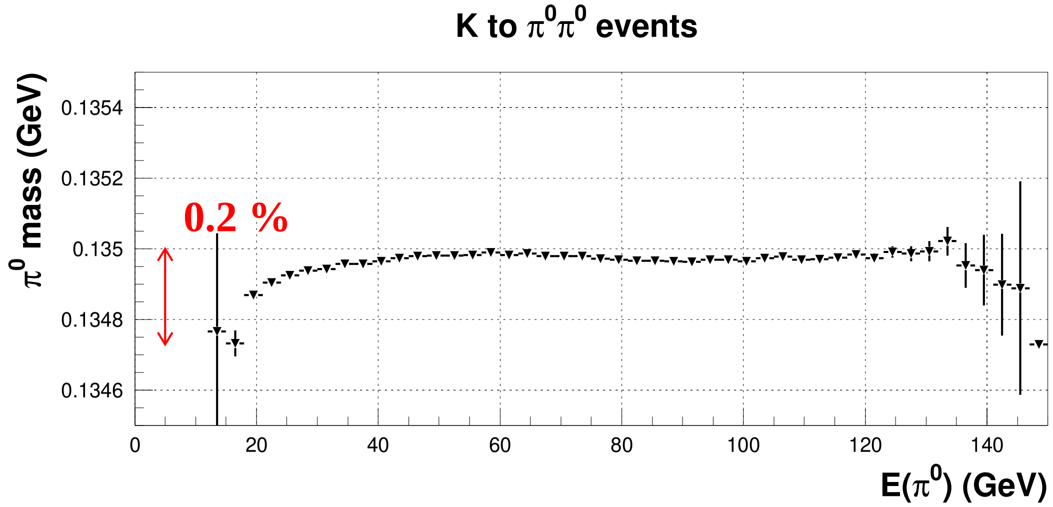
In neutral mode : $D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \;/M_K$

Fit of the Anti-K_S counter position $\rightarrow$ energy scale





Non-linearity

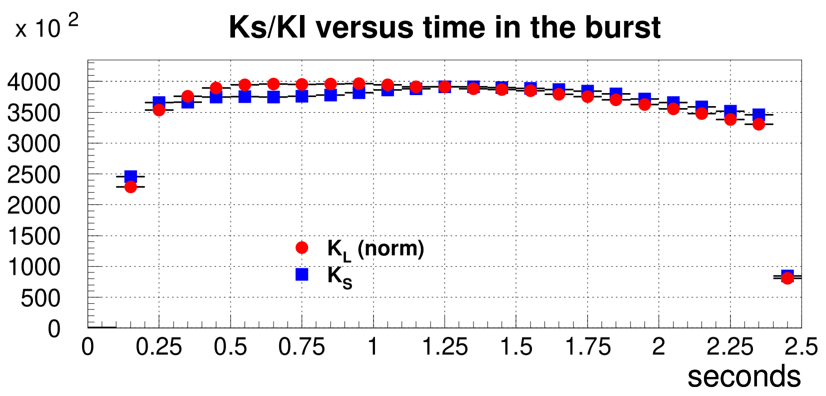


Non-linearity $(5.10^{-4}) \oplus$ energy scale $(3.10^{-4}) \oplus$ transverse scale $(3.10^{-4}) \oplus$ non-gaussian tails $(5.10^{-4}) \oplus$...

$\Rightarrow$ $\boxed{\text{Uncertainty on } R : \; 10 \times 10^{-4}}$

Accidental activity

- Beams simultaneity reduces differential accidental loss.



- Accidental activity (extra clusters and tracks) is found to be identical within 1 % between $K_S$et K_L.
- Correction for accidental activity
  - ◇ Superimpose events triggered proportionally to the beam intensity on top of $\pi\pi$ candidates.
  - ◇ Count gains and losses: $\Delta R = (+2.0 \pm 6.4) \times 10^{-4}$)
- Uncertainty on accidental corection
  - ◇ High multiplicity in DCH causes losses of $\pi^-\pi^+$ events.
  - ◇ We cut both $\pi^+\pi^-$ and $\pi^0\pi^0$ when such an overflow occurs, to symmetrize the loss.

$$\Downarrow$$

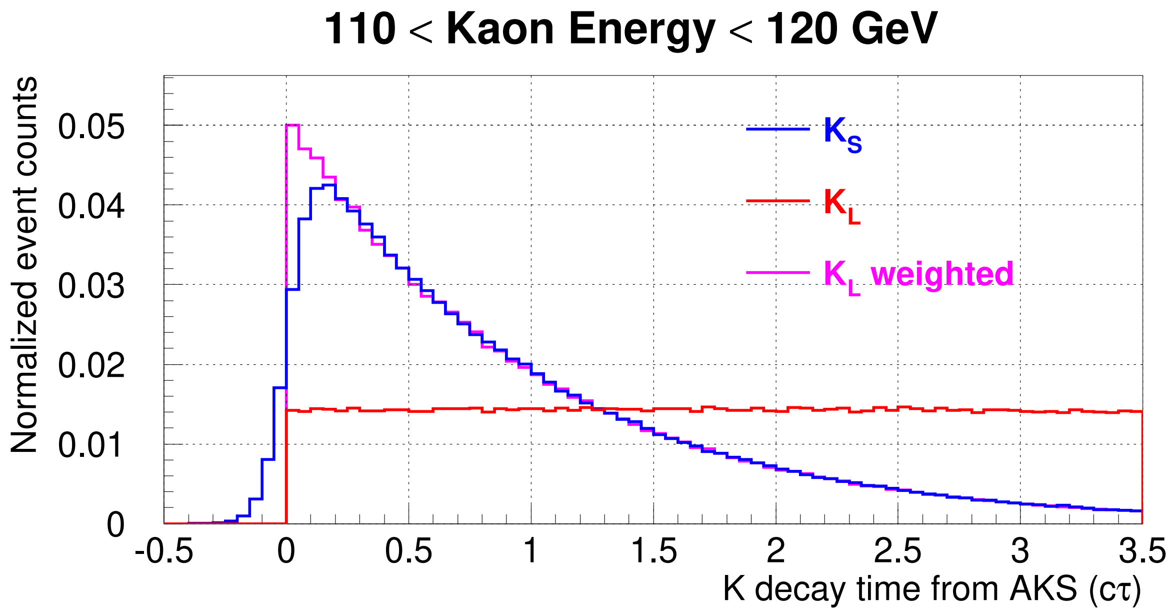
$$\boxed{\Delta R = (+2. \pm 12.) \times 10^{-4}}$$

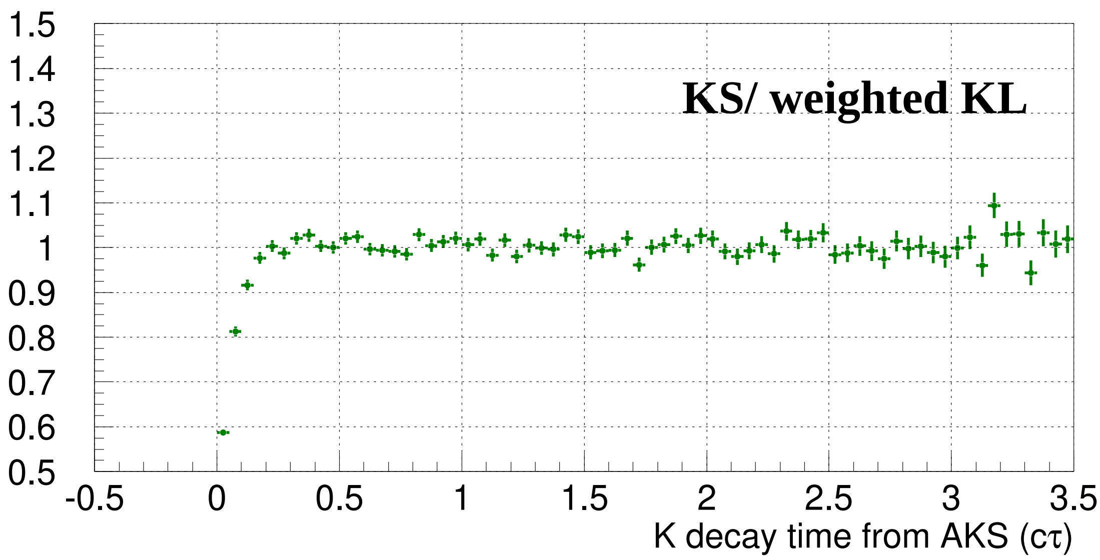
Work in going on to reduce uncertainty.

Acceptance : weighting procedure

We weight the $\mathrm{K_L}$ events by $exp(-c\tau/c\tau_S)$

$\Rightarrow$ z-distributions look similar





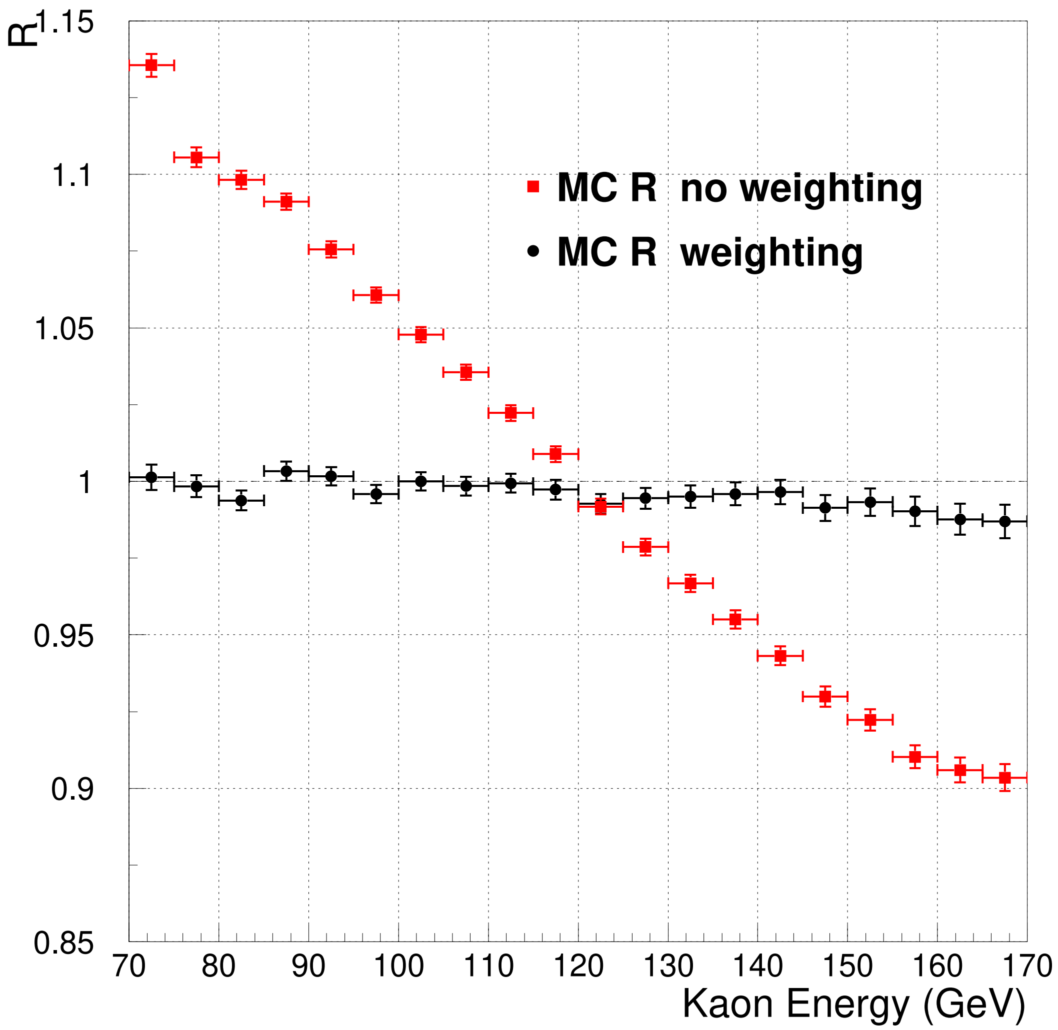
z=0 is defined by

- an Anti-Counter in the $\mathrm{K_S}$beam
- a cut on reconstructed z for $\mathrm{K_L}$

Acceptance : R correction

A detailed montecarlo simulation is used to correct the remaining effect of acceptances.

MC sample $\sim 5 \times$ data sample



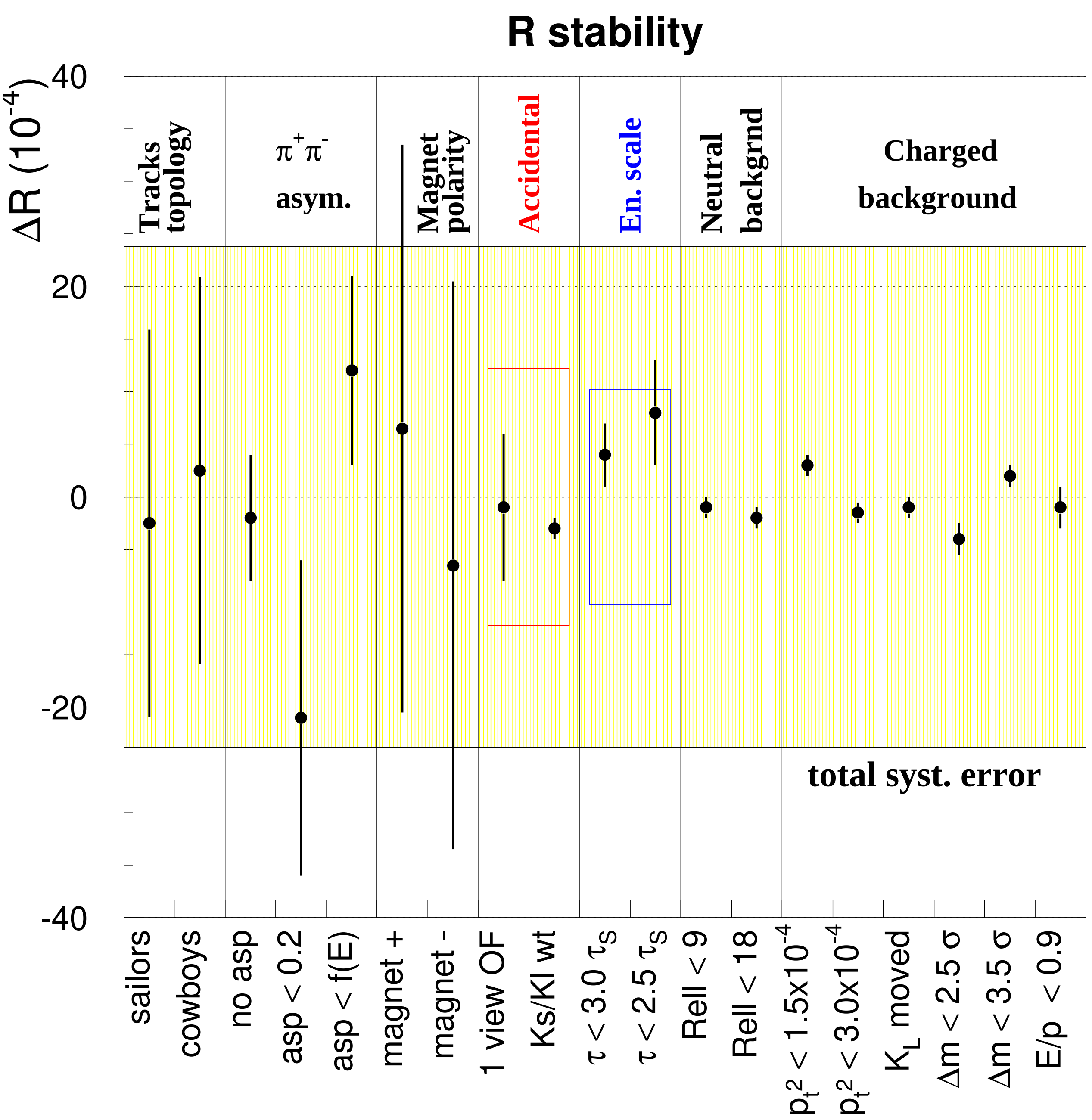
$\Rightarrow$ Bin by bin correction to R :

$$\boxed{\Delta R = 31. \pm 6. \text{ (MC stat.) } \pm 6. \text{ (syst.) } \times 10^{-4}}$$

Price : statistical error increase by $\sim 35\%$

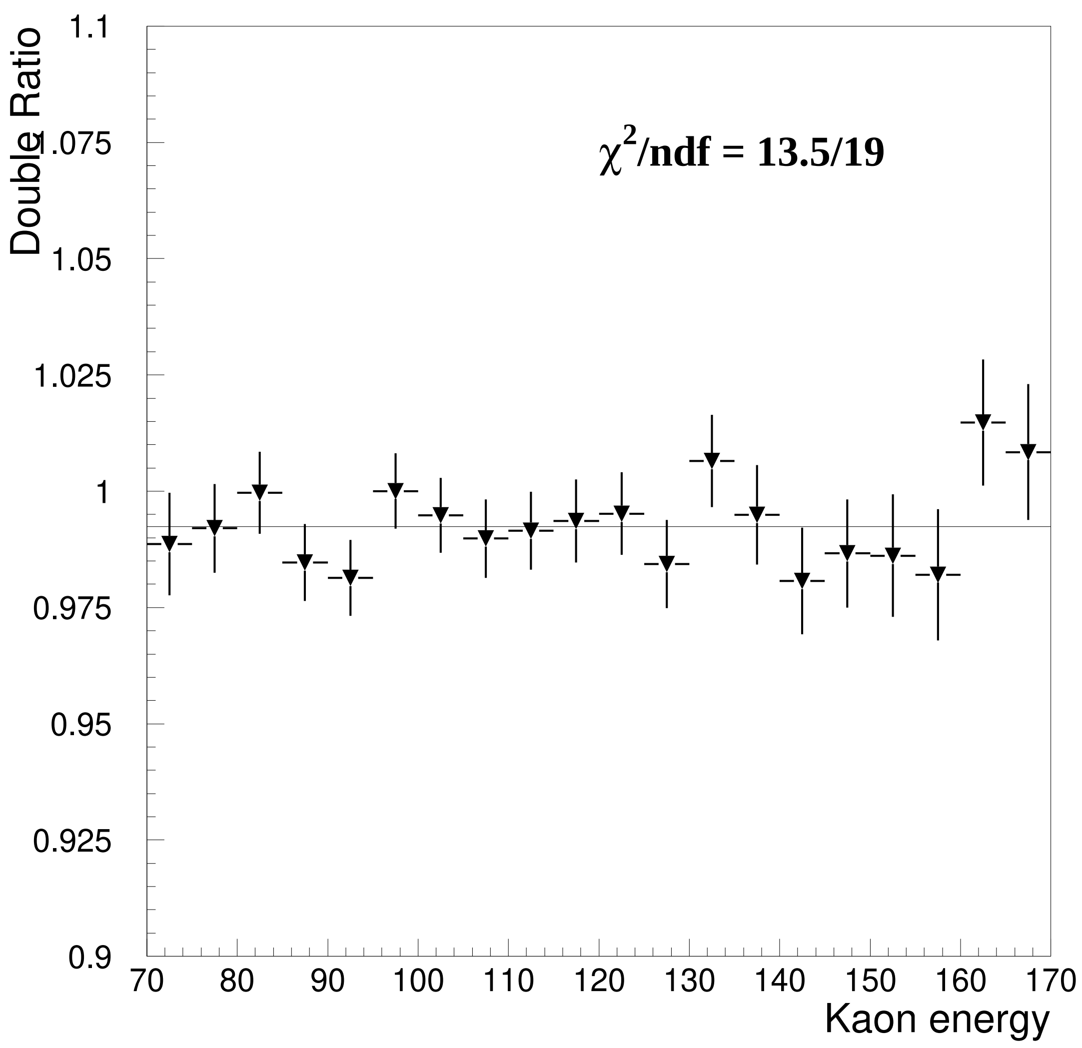
$\Delta R \simeq 200$ without weigting

R stability with cuts



Result from 1998 data

PRELIMINARY RESULT ON 1998 DATA



$$R = 0.99267 \pm 0.00173(stat.) \pm 0.00238(syst.)$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9\ (\mathrm{stat.}) \pm 4.0\ (\mathrm{syst.})) \times 10^{-4}$$

Comparison of NA48 with previous measurements

- 1997 data: published result (0.49×10^6 $K_L \to \pi^0\pi^0$)

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5(stat.) \pm 5.8(syst.)) \times 10^{-4}$$

- 1998 data: preliminary result (1.14×10^6 $K_L \to \pi^0\pi^0$)

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9(stat.) \pm 4.0(syst.)) \times 10^{-4}$$

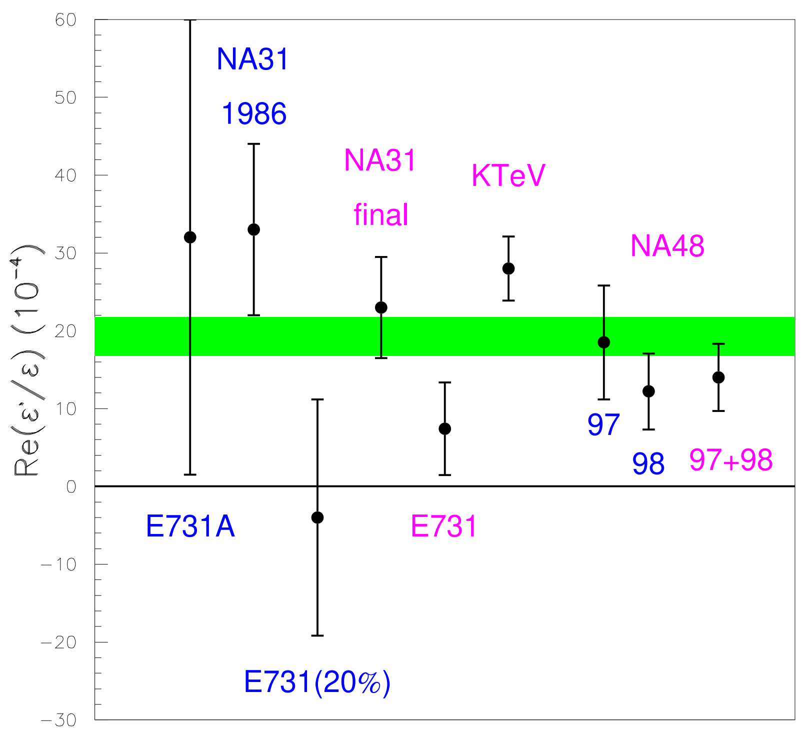
- Combining 1997 and 1998 data

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}$$

- Comparing with previous measurements

World average of 4 most precise results

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.5) \times 10^{-4}$$
$$(\chi^2/ndf = 10.4/3)$$



Perspectives in NA48 for $\mathrm{Re}(\varepsilon'/\varepsilon)$ analysis

- Refine systematic errors with 1998 data
  - ◇ Accidental tagging
  - ◇ Accidental activity

- 1999 data Analysis is in progress (2×10^6 $K_L \to \pi^0\pi^0$)

- 2000 run Started yesterday (24-05-2000): $\simeq$ 100 days recording neutral decays only as the 4 drift chambers were destroyed last fall (beam pipe implosion).
  - ◇ Accidental tagging with K_L only beam
  - ◇ Data to study in more details neutral energy scale
  - ◇ $\simeq$ 60 days to test futur rare decay program (K_S high intensity)

- 2001 run Three of the four drift chambers will be in place.
  - ◇ Study stability of $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement as a function of beam intensity

- Rare decays program Proposal submitted to CERN

Conclusions

- New preliminary measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ by NA48, based on 1998 data sample

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9(stat.) \pm 4.0(syst.)) \times 10^{-4}}$$

- Combined 1997 and 1998 NA48 result:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}}$$

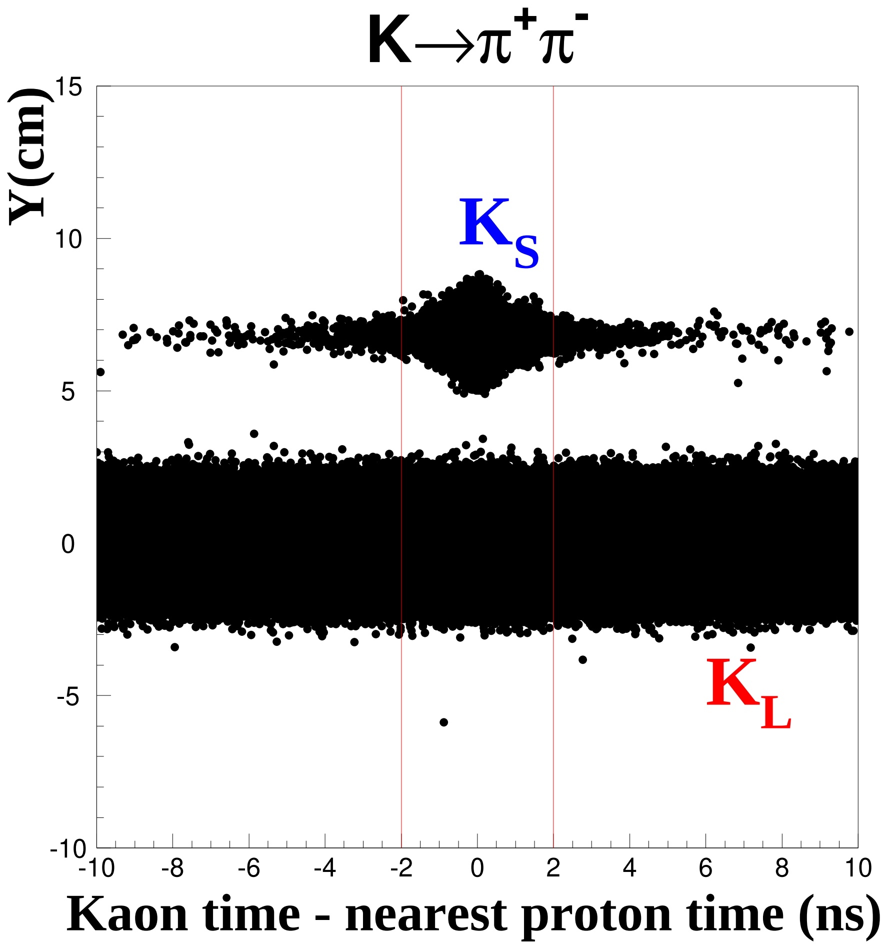
- This result confirms a non-zero positive value for $\mathrm{Re}(\varepsilon'/\varepsilon)$

- Work in progress to improve NA48 results: 1999 data analysis and refined systematic studies in progress.

- Theoretical predictions: Expect improvement in coming months (lattice calculations)

Corrections and syst. uncertainties on R (Units = 10^{-4})				
Source	1997 sample		1998 sample	
Charged trigger	$+9$	$\pm$ 23	-1	$\pm$ 11
Accidental tagging	$+18$	± 9	$+1$	± 8
Tagging efficiency	–	± 6	–	$\pm$ 3
Neutral rec. systematics	–	± 12	–	± 10
Charged vertex	–	± 5	$+2$	± 2
Acceptance	$+29$	± 12	$+31$	± 9
Neutral BKG	-8	± 2	-7	± 2
Charged BKG	$+23$	± 4	$+19$	± 3
Beam scattering	-12	± 3	-10	± 3
Accid. activity	-2	± 14	$+2$	± 12
Total	$+57$	± 35	$+37$	± 24

K_S vs K_L tagging



- Tagging inefficiency: $\alpha_{\rm SL}$

  $\rightsquigarrow$ K_S identified as a K_L

  ◇ $\pi^0\pi^0$ time measured with Liquid Krypton calorimeter.

  ◇ $\pi^+\pi^-$ time measured with charged hodoscope.

$$\Delta R \simeq 6 \times \left(\alpha_{SL}^{00} - \alpha_{SL}^{+-}\right) = 6 \times \Delta\alpha_{\rm SL}$$

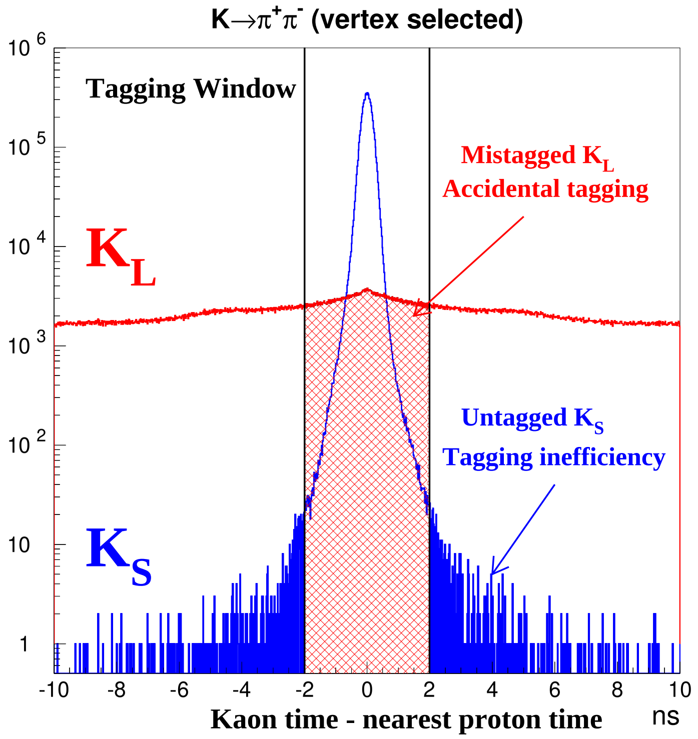
- Accidental tagging $\alpha_{\rm LS}$

  $\rightsquigarrow$ K_L identified as a K_S

  ◇ Accidental proton inside tagging window

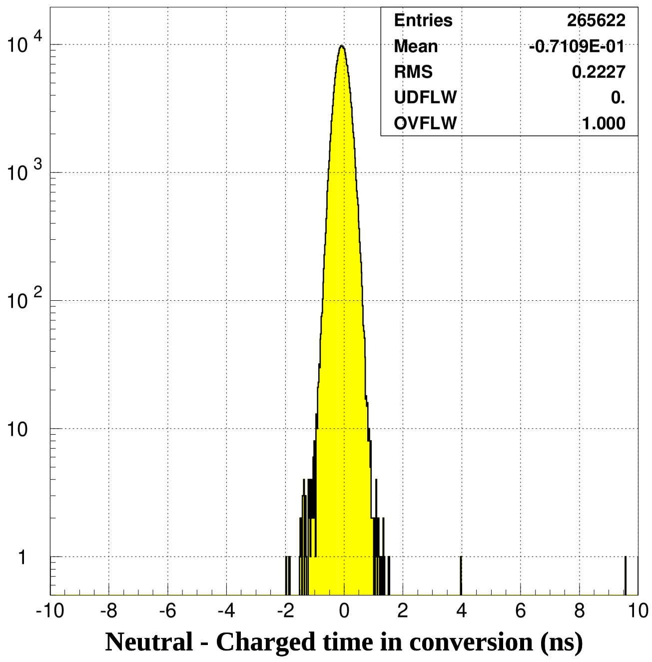
$$\Delta R \simeq 2 \times \left(\alpha_{LS}^{00} - \alpha_{LS}^{+-}\right) = 2 \times \Delta\alpha_{\rm LS}$$

Tagging inefficiency: K_S identified as a K_L



- Charged:
  - ◇ $\sigma_t^{hodoscope} \simeq 200ps$
  - ◇ events selected by vertex
  - ◇ $\alpha_{SL}{}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$

- Neutrals:
  - ◇ $\sigma_t^{LKR} \simeq 270ps$
  - ◇ $2\pi^0$, $3\pi^0$ with one converted photon
  - ◇ $|\alpha_{SL}^{+-} - \alpha_{SL}^{00}| < 0.5 \times 10^{-4}$

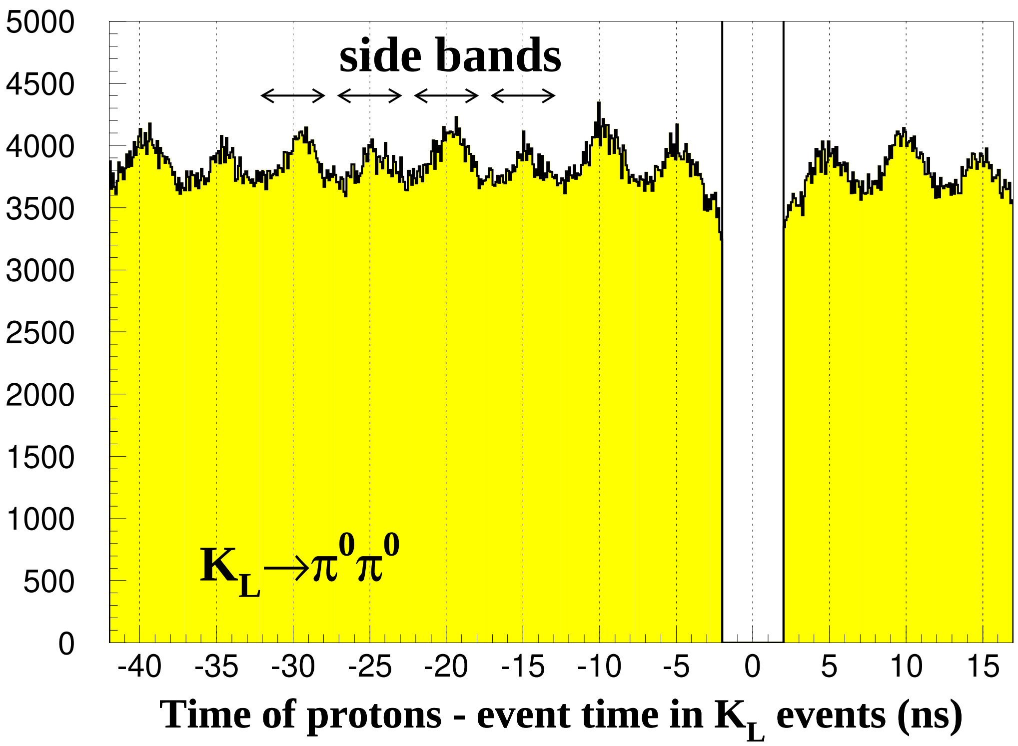


$\Rightarrow \boxed{\Delta R < 3 \times 10^{-4}}$

Accidental tagging: K_L identified as a K_S

- With tagged $K_L \to 2\pi$ (no proton), we compute the difference between charged and neutral rates in 4 ns wide SIDE-BANDS :

$$\beta^{00}_{LS} - \beta^{+-}_{LS} = (5.3 \pm 1.6) \times 10^{-4}$$



- Differences of activity between central and side bands estimated with $K_L \to 3\pi^0$ and $K_L \to \pi^+\pi^-$ vertex-id.

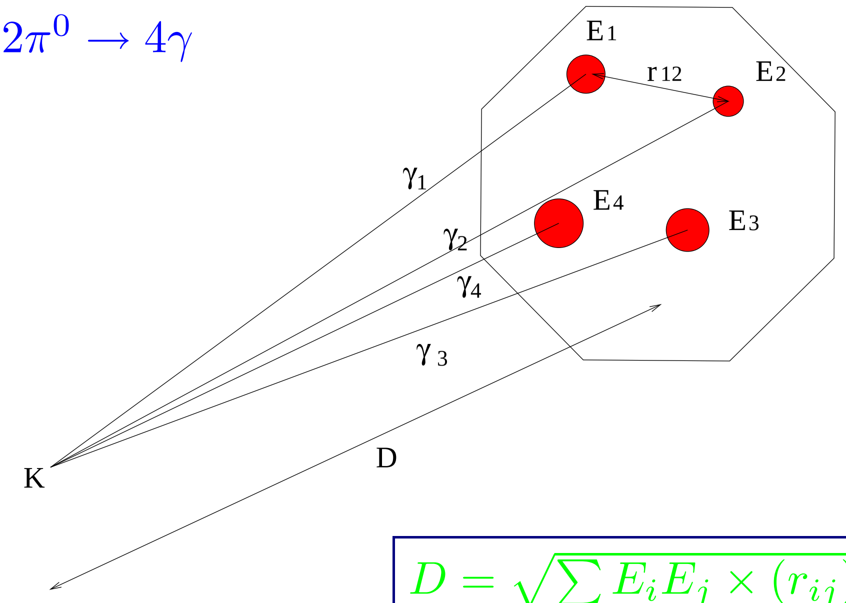
$$W^{00} - W^{+-} = (-5.0 \pm 3.9) \times 10^{-4}$$

(Improvement to come from more $3\pi^0$ processing)

$$\Rightarrow \boxed{\Delta R = (+1 \pm 8) \times 10^{-4}}$$

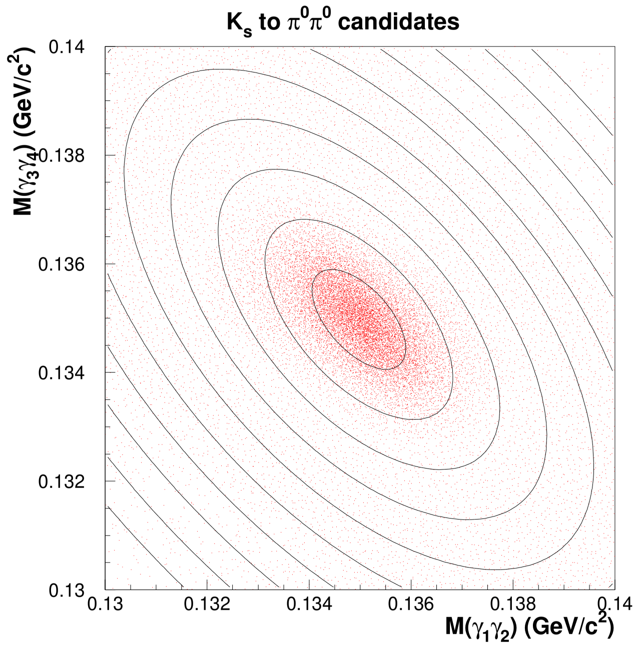
$K^0 \rightarrow \pi^0\pi^0$ identification

$K_{\mathrm{L,S}} \rightarrow 2\pi^0 \rightarrow 4\gamma$



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

- Vertex position under kaon mass assumption
- γ pairing for best π^0 masses: $m_{ij} = \sqrt{E_i E_j} \, . \, r_{ij}/D$



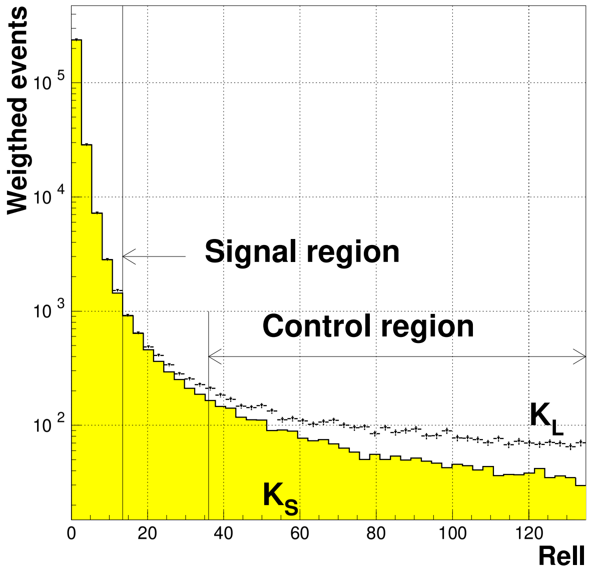
$\sigma_+ = 0.42 MeV$

$\sigma_- = 0.83 MeV$

define χ^2 variable R_{ell}

$$R_{ell} \equiv \left\{ \left(\frac{\frac{m_1+m_2}{2} - m_{\pi^0}}{\sigma_+} \right)^2 + \left(\frac{\frac{m_1-m_2}{2}}{\sigma_-} \right)^2 \right\}$$

Neutral background: $K_L \to 3\pi^0$

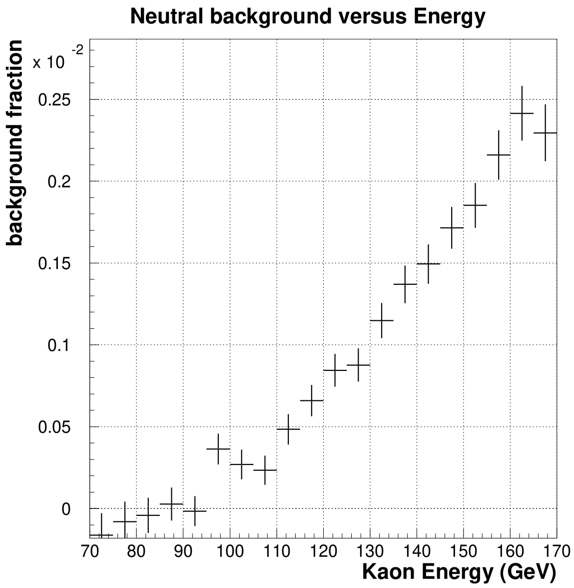


Background estimation

Signal region :
$R_{ell} < 13.5$

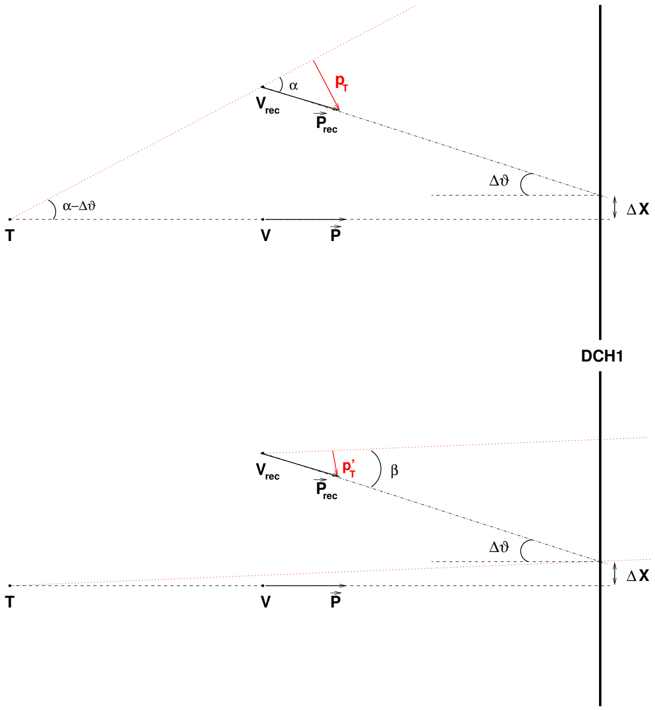
$K_L - K_S$difference
in control region

- Reject events with extra intime ($\pm 3ns$) cluster ($E > 1.5$ GeV)
- Background fraction in energy bins



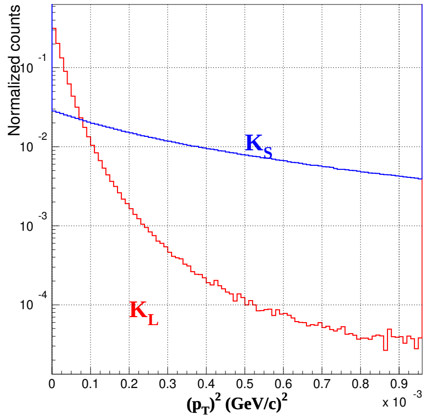
$$\boxed{\Delta R = (-6.6 \pm 2.0).10^{-4}}$$

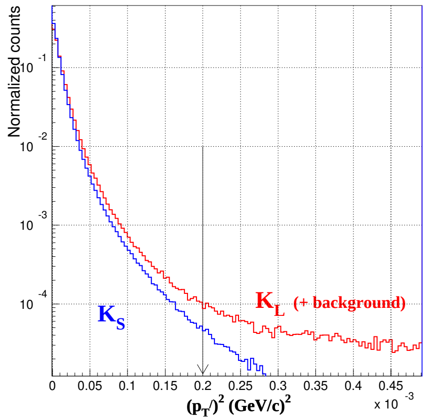
Charged background : P'^2_T



$$p_T \simeq P_K \frac{\Delta X + \Delta\theta(Z_{DCH1} - Z_V)}{Z_V - Z_T}$$
$$\simeq P_K \frac{\Delta\theta(Z_{DCH1} - Z_V)}{Z_V - Z_T}$$

$$p'_T \simeq P_K \left(\Delta\theta + \frac{\Delta X}{Z_{DCH1} - Z_T}\right)$$
$$\simeq P_K \Delta\theta$$





Neutral systematic

Neutral reconstruction systematics

Source	ΔR (units 10^{-4})
Non linearity	$\pm$ 5
Non Gaussian tails in σ_E	$\pm$ 5
Transverse scale	$\pm$ 3
Intercalibration	$\pm$ 3
Distance/Energy scale	$\pm$ 3
Other sources	$\pm$ 4
Total	$\pm$ 9.5

- We employ a π^- beam and two 3.5cm thick polyethylene targets, to produce $\eta, \pi^0 \rightarrow \gamma\gamma$ decays to cross check the distance scale using the published π^0 and η masses.
- A discrepancy at the level of 2 σ is found reconstructing the vertex for $\eta \rightarrow \gamma\gamma$

A dedicated η run will take place later this year to verify the effect

For the time being, we have increased the scale and/or the non linearity error to also cover the $\eta \rightarrow \gamma\gamma$ result.

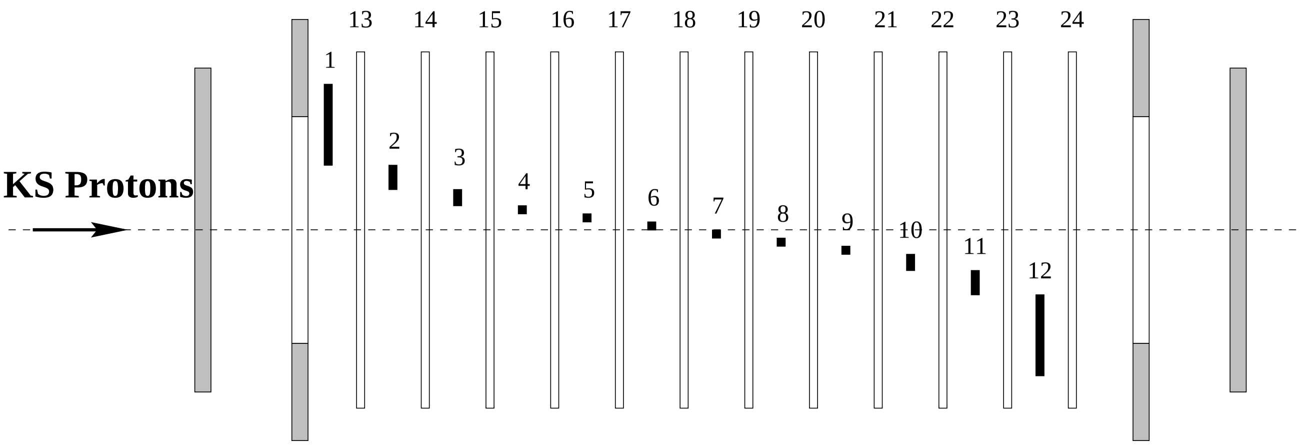
$\boxed{\text{Uncertainty on } R : \pm 10.2 \times 10^{-4}}$

K_S Tagger

T.O.F. between the proton in the Tagger and the detected Kaon decay products:

$$|t_K - t_{tagger}| < 2\text{ns} \Rightarrow K_S$$
$$|t_K - t_{tagger}| > 2\text{ns} \Rightarrow K_L$$

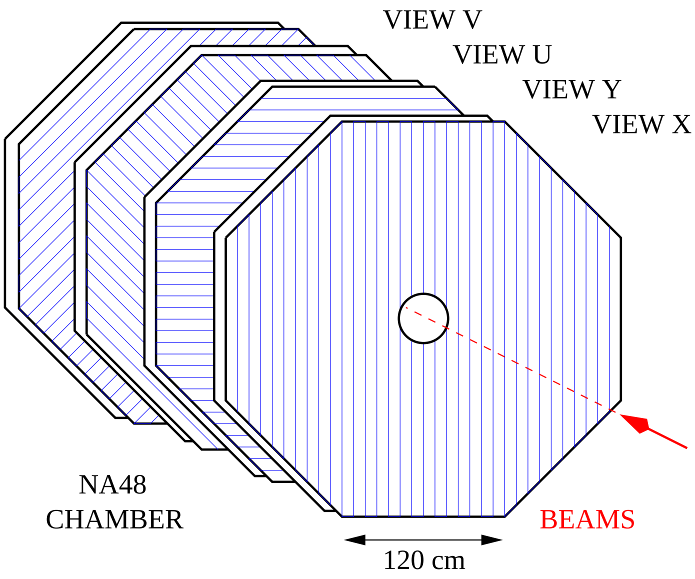
Tagger from side view



▮ : Vertical ladder ▯ : Horizontal ladder

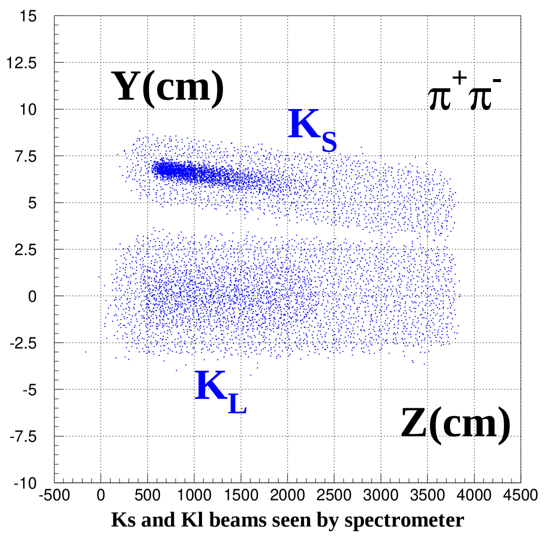
- 8-bit 960MHz FADC read-out
- 200ps time resolution per counter
- 4ns double pulse separation

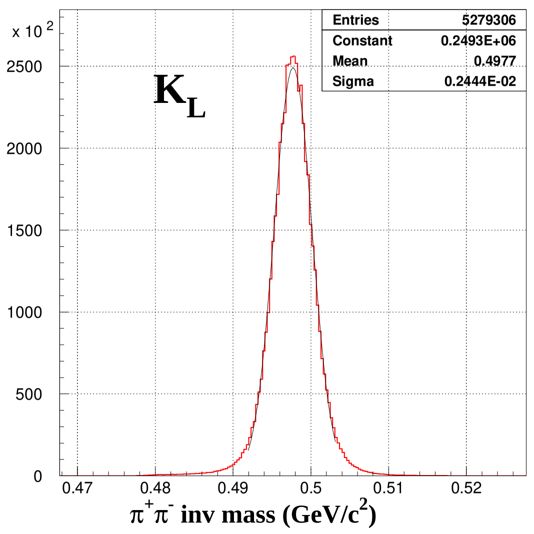
Magnetic spectrometer



Per Chamber:

- 8 planes of 256 wires
- Positioning of wires to $\leq 100\mu\text{m}/\text{m}$
- Argon/Ethane
- Gain $\sim 8.10^4$



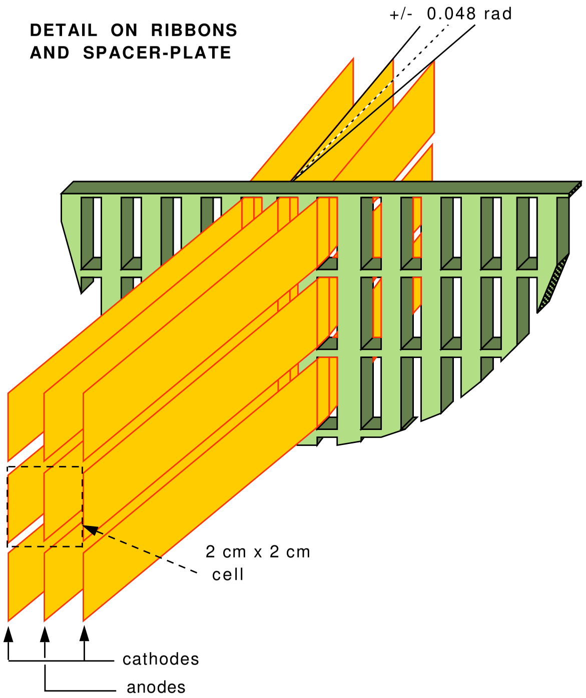


Vertex reconstruction allows beam separation

Kaon mass resolution ~ 2.5 MeV/c^2

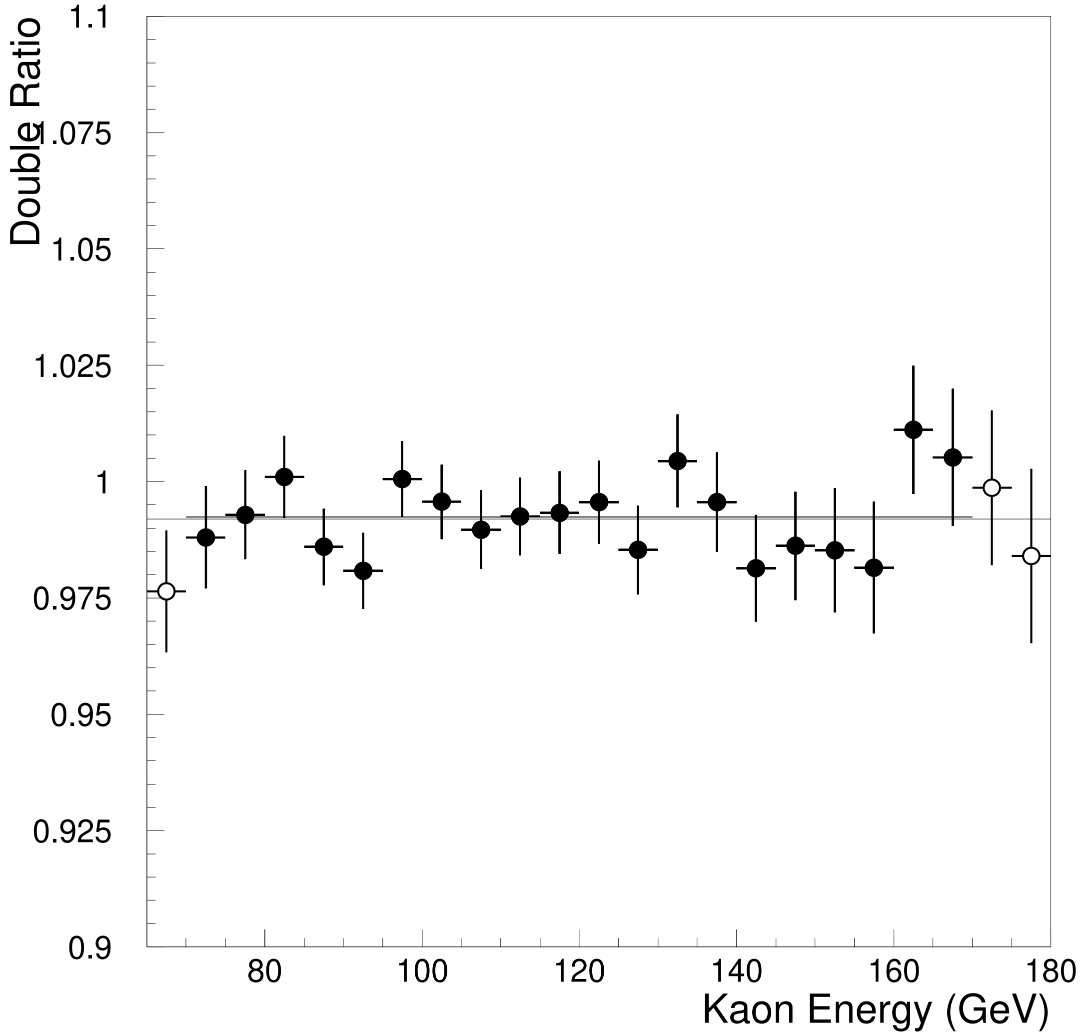
$$\sigma(p)/p \simeq 0.5\,\% \oplus 0.009\,p[\text{GeV/c}]\,\%$$

Liquid Krypton calorimeter



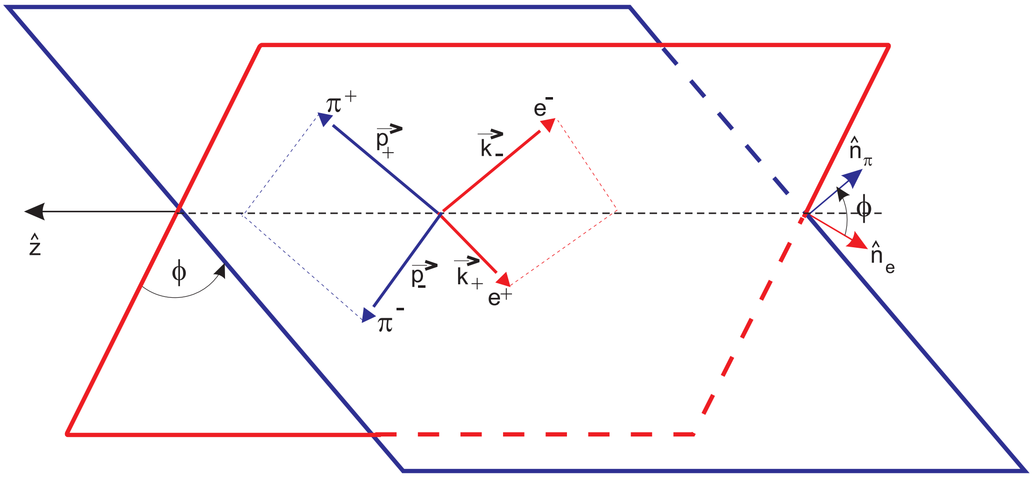
- Contains $\approx 9m^3$ LKr
- Cu-Be electrodes
- Bias HV: +3 KV/cm
- Cell: 2cm×2cm×127cm
- Five Spacer plates
- Electrodes: ± 48mrad zig-zag in each spacer
- Geometry controlled to ≈0.2mm/1m

Result 1998: checks



$\mathrm{K_L} \rightarrow \pi^+\pi^-e^+e^-$ Model

- Expected to proceed mainly through $\mathrm{K_L} \rightarrow \pi^+\pi^-\gamma^*$ intermediate state
- 2 dominant components:
  - ◇ CP violating $\mathrm{K_L} \rightarrow \pi^+\pi^-$ with inner bremsstrahlung (IB)
  - ◇ CP conserving M1-direct emission (DE)
- Interference between the two amplitudes
  $\rightarrow$ CP-violating circular polarization of the γ^*
- Probe polarization by studying correlation of e^+e^- plane relative to $\pi^+\pi^-$: Φ angle (T_{odd})



$$Decay\ rate: \frac{d\Gamma}{d\phi} = \Gamma_1 cos^2\phi + \Gamma_2 sin^2\phi + \Gamma_3 cos\phi sin\phi$$

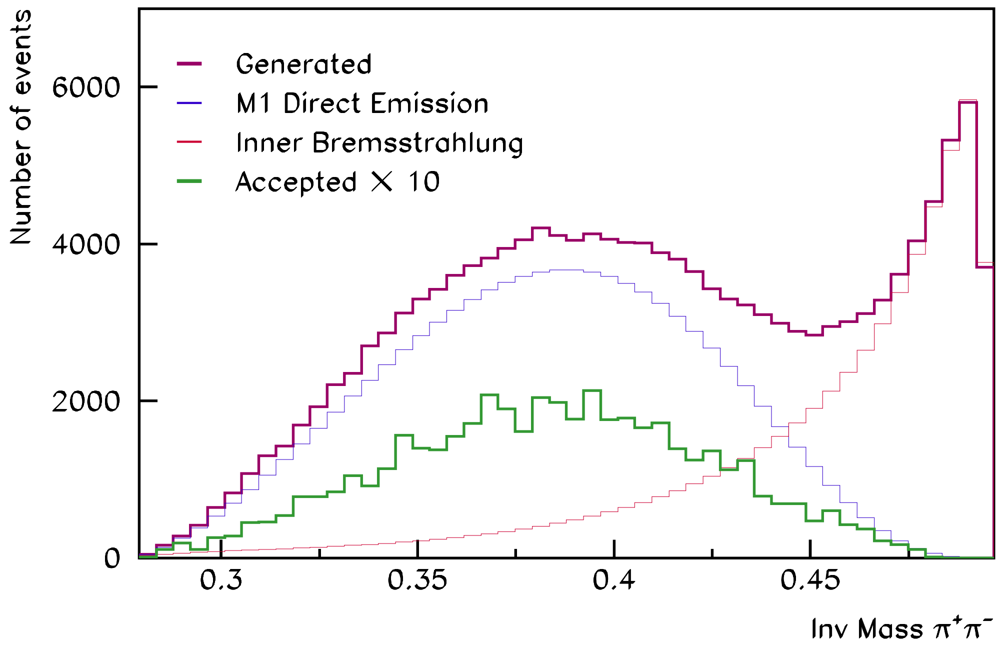
where: $\cos\phi \sin\phi = (\mathbf{n}_e \times \mathbf{n}_\pi)\ \hat{z}\ (\mathbf{n}_e \cdot \mathbf{n}_\pi)$ Visible effect in the asymmetry defined as:

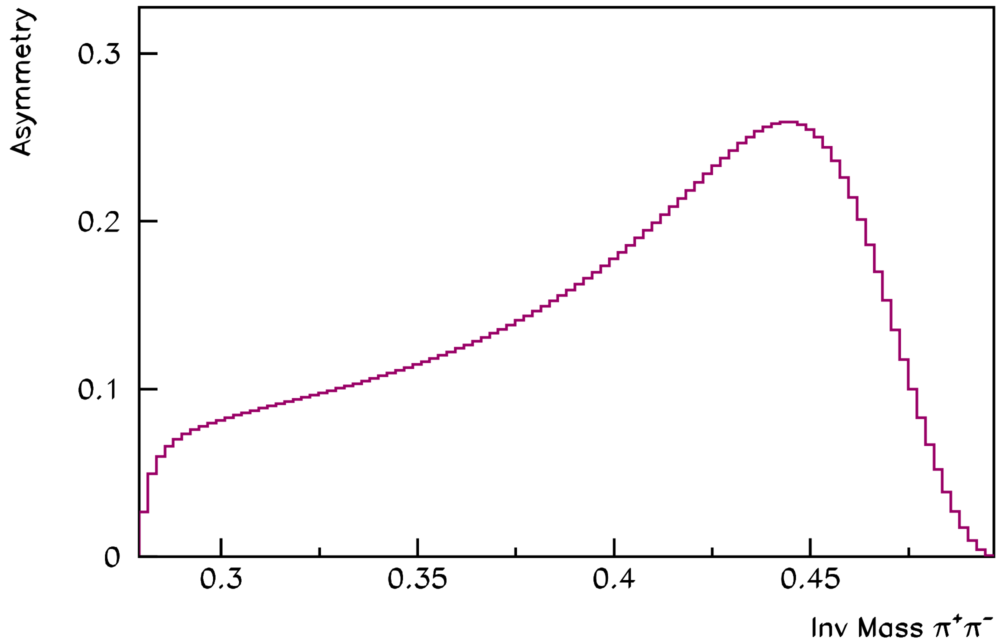
$$Asymmetry = \frac{N_{\cos\phi\sin\phi>0} - N_{\cos\phi\sin\phi<0}}{N_{\cos\phi\sin\phi>0} + N_{\cos\phi\sin\phi<0}}$$

Theoretical expectation: $\sim 14.4\%$ (Sehgal and Wanniger)

$K_L \to \pi^+\pi^-e^+e^-$: Observed asymmetry

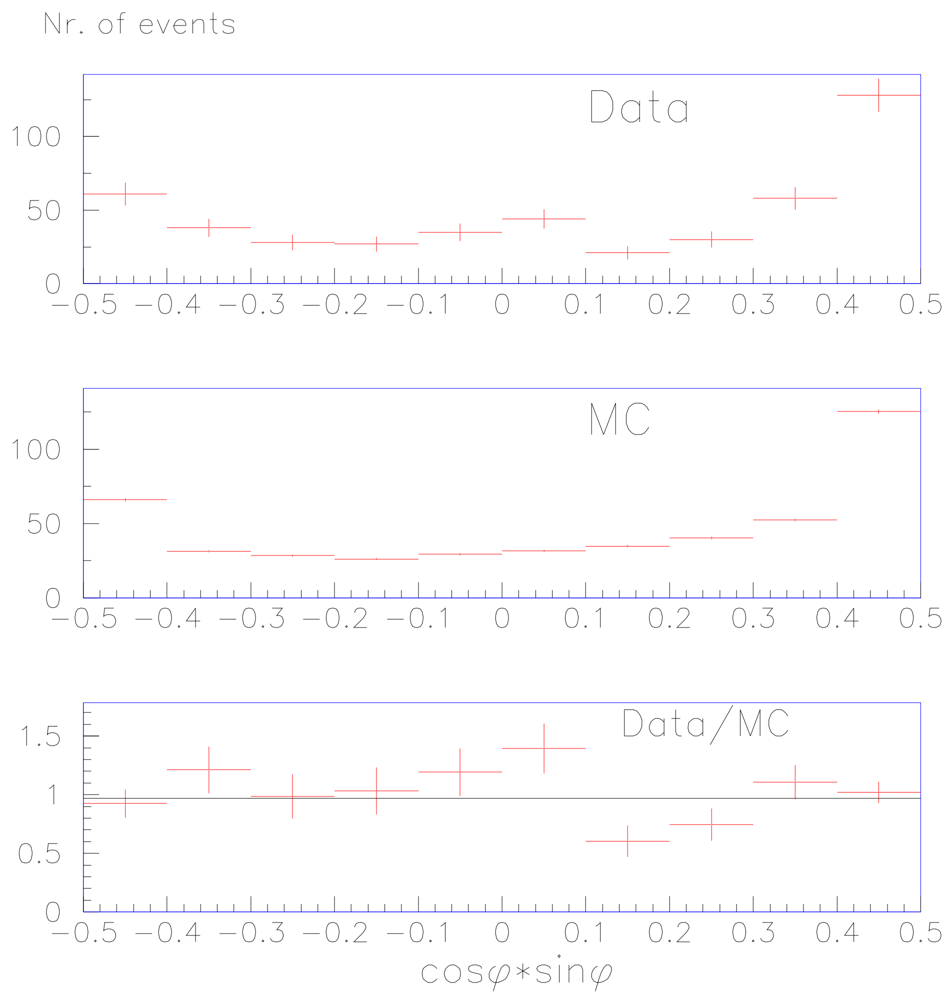
Asymmetry maximal where maximum interference:





Observed asymmetry enhanced by experimental acceptance

$\mathrm{K_L} \to \pi^+\pi^-e^+e^-$: Preliminary asymmetry



Asymmetry studies:

- Monte Carlo:

  generated 0% $\Rightarrow$ Reconstructed 0%

  generated 14% $\Rightarrow$ Reconstructed 22%

- Data: Observed asymmetry= $(20 \pm 5)\%$

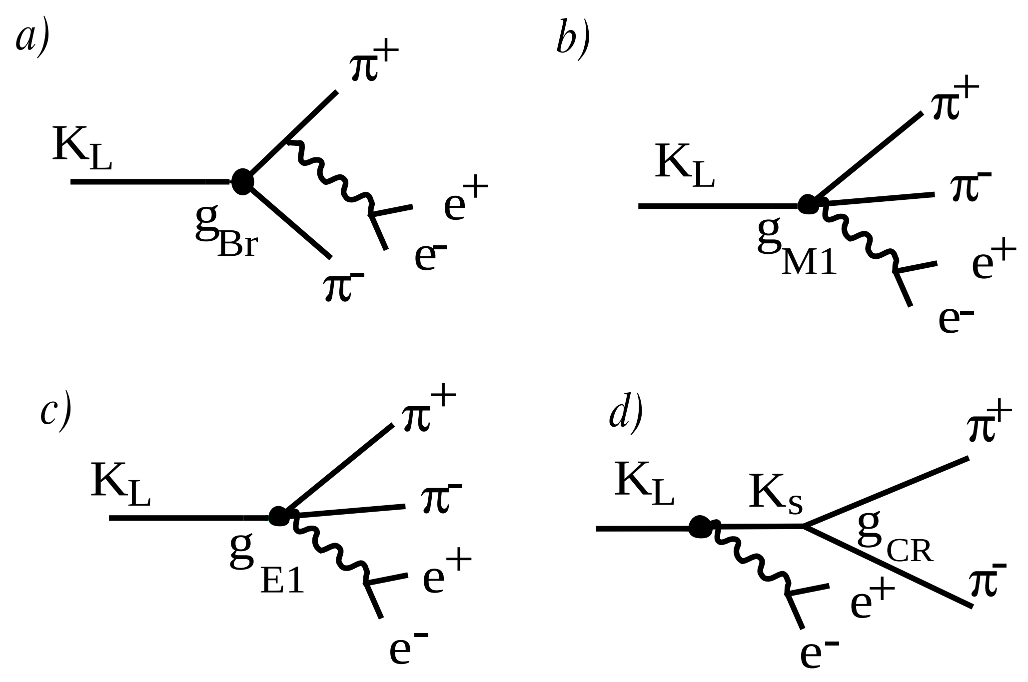
KTeV Observed asymmetry= $23.3 \pm 2.3\%$ (1811 events)
Acceptance corrected: $13.6 \pm 2.5(stat) \pm 1.2(syst)\%$

$\mathrm{K_L} \to \pi^+\pi^-e^+e^-$ Process

$\mathrm{K_L} \to \pi^+\pi^-e^+e^-$ seen as a conversion process related to $\mathrm{K_L} \to \pi^+\pi^-\gamma$.

Processes contributing to $\mathrm{K_L} \to \pi^+\pi^-e^+e^-$:

- CP-violating bremsstrahlung (IB)
- CP-concerving M1 γ emission (DE)
- CP-violating E1 γ emission very small
- Charge radius process very small



The conversion process $\mathrm{K_L} \to \pi^+\pi^-e^+e^-$ may be viewed as a means of probing the CP-violating circular polarization of the γ^*.

Asymmetry effect arising entirely from bremsstrahlung of the K_1 admixture in the $\mathrm{K_L}$: CP-violation.