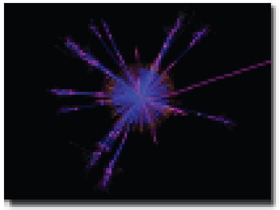

CP Violation Results From the NA48 Experiments

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on Behalf of the NA48 and NA48/2 Collaboration

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CRIMEA -07, Yalta September 15-22, 2007

OUTLINE

- NA48: the CP violation experiment
- History
- Apparatus
- Na48: the CP violation parameter $|\eta\pm|$
- Na48/2: direct CP violation in $K^{\pm} \rightarrow 3\pi$ decays
- Conclusions

OVERVIEW

NA48 (1997-2001)

- Direct CP violation in neutral kaon decays.

  $Re(\varepsilon'/\varepsilon)=(14.7\pm2.2)x10^{-4}$

- Measurement of CP violation parameter $|\eta_{+-}|$

  New result! (presented)

NA48/1 (2002)

- Rare K_S decays.

  $BR(K_S \rightarrow \pi^\circ e^+e^-)=(5.8^{+2.8}_{-2.3}\pm0.8)x10^{-9}$

  $BR(K_S \rightarrow \pi^\circ \mu^+\mu^-)=(2.8^{+1.5}_{-1.2}\pm0.2)x10^{-9}$

NA48/2 (2002)

- Search for direct CP violation in $K^\pm \rightarrow 3\pi$ decays

  Final result (presented)

1997	ε'/ε run	$K_L + K_S$
1998	ε'/ε run	$K_L + K_S$
1999	ε'/ε run $K_L + K_S$	K_S Hi. Int.
2000	K_L only	K_S High Intensity
	NO Spectrometer	
2001	ε'/ε run $K_L + K_S$	K_S High Int.
2002	K_S High Intensity	
2003	$K^\pm$ High Intensity	
2004	$K^\pm$ High Intensity	

The NA48 Detector

Main detector components:

- Magnetic spectrometer (4 DCHs):

  4 views: redundancy ⇒ efficiency
  $\sigma(p)/p$ 1.0% + 0.044% p [GeV/c]
  Trasversal resolution of decay point ≈ 2mm

- Hodoscope:

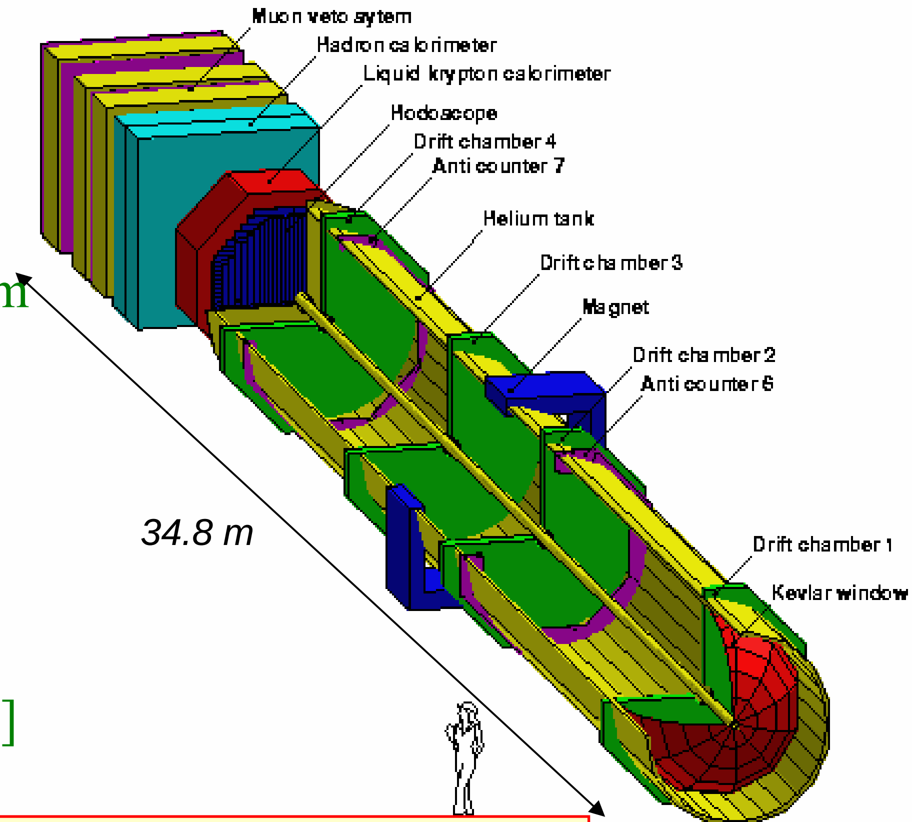
  fast trigger and
  precise time measurement (150ps)

- Liquid Krypton e.m. calorimeter:

  High granularity, quasi−homogeneous
  $\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

- Hadron calorimeter, photon vetos,

  muon veto counters



NIM A 574 (2007) 433-471

CP violation parameter η_{+-} – NA48

CP violation parameter η+ –

The parameter η+- → fundamental observable of CP violation defined as the ratio of K_L to K_S CPV decay amplitudes

related to indirect and direct CPV parameters

$$\eta+- = \varepsilon + \varepsilon'$$

$$\eta+- = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

Method:

- Measure the ratio of the decay rates → $\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)}$
- Compute → $BR(K_L \to \pi^+\pi^-)$ $\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)} BR(K_L \to \pi^\pm e^\mp \nu)$
- Extract → $|\eta+-| = \sqrt{\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\dfrac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \dfrac{\tau_{KS}}{\tau_{KL}}}$

CP violation parameter η+ –

$$|\eta_{\pm}| = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \times \frac{\tau_{KS}}{\tau_{KL}}}$$

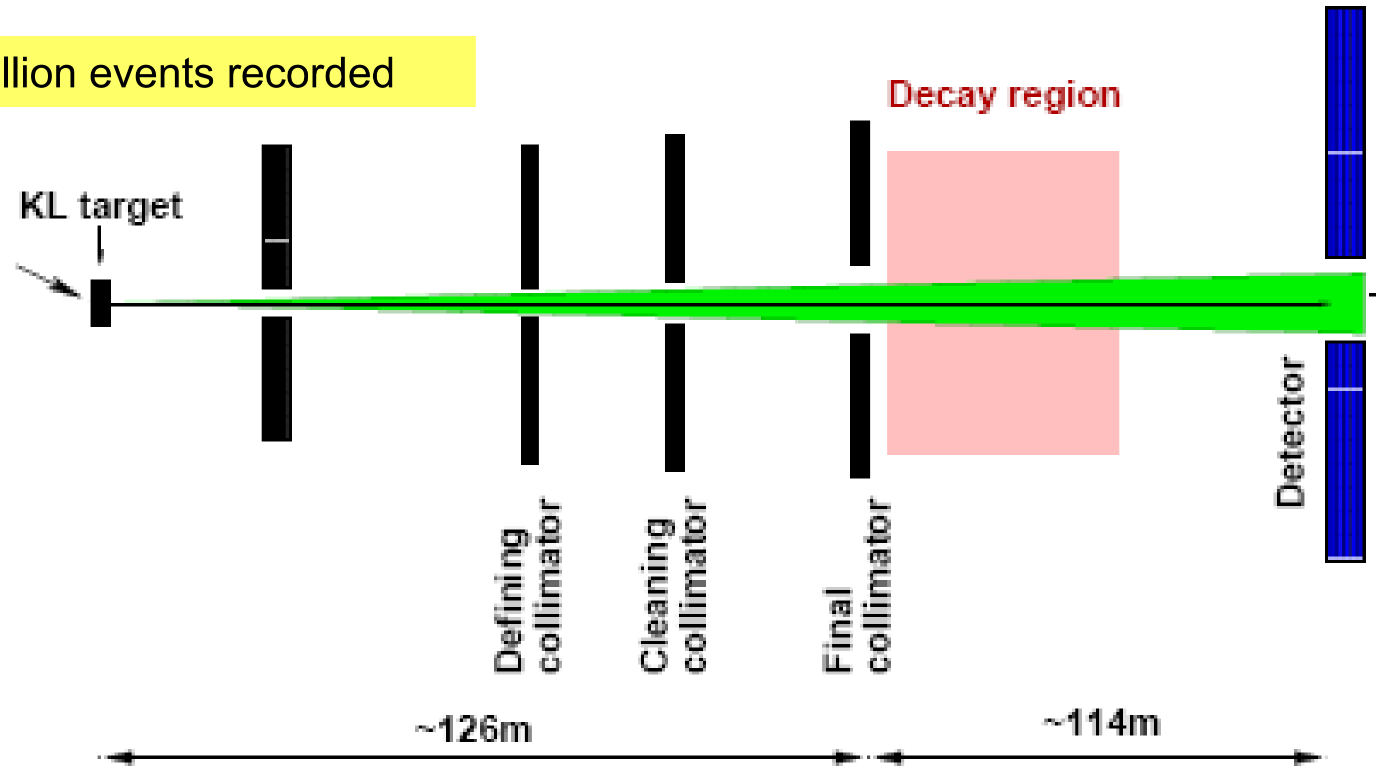
- External input: best single measurements
  - → K_S lifetime: $\tau_{KS} = (0.89598 \pm 0.00070) \times 10^{-10}$ s (NA48 '02);
  - → K_L lifetime: $\tau_{KL} = (5.084 \pm 0.023) \times 10^{-8}$ s (KLOE '06);
  - → $BR(K_L \to \pi e \nu) = 0.4022 \pm 0.0031$ (NA48 '04 + improved $K_L \to 3\pi^0$: KTeV, KLOE);
  - → $BR(K_S \to \pi^+\pi^-) = 0.69196 \pm 0.00051$ (KLOE '06).

NA48 beam line for pure K_L beam

✓Special run (2 days in 1999) with pure K_L beam at low intensity.

✓Minimum bias trigger to select only events with 2 charged tracks

~ 80 million events recorded

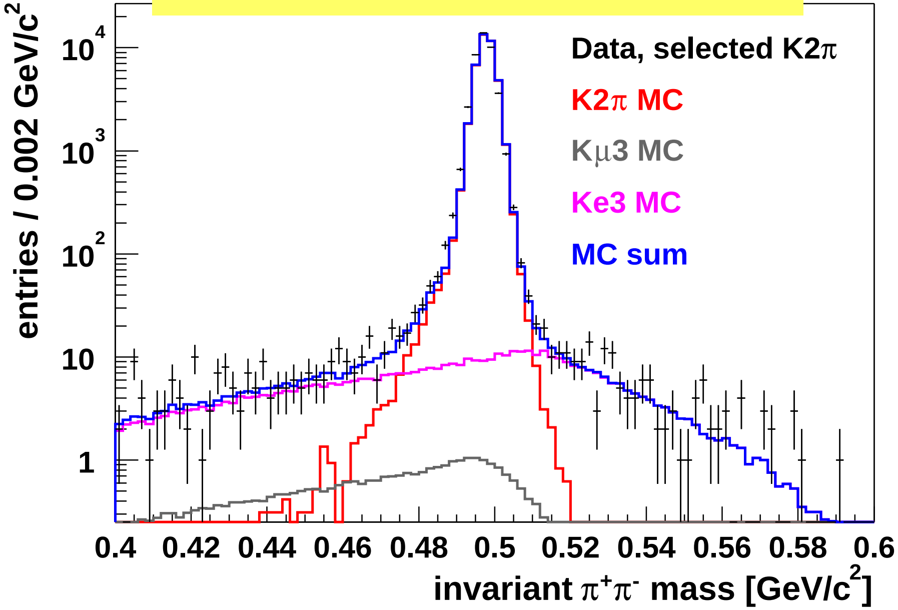


$\Gamma_{K2\pi}/\Gamma_{Ke3}$ event selection

$K_L \rightarrow \pi^+\pi^-$

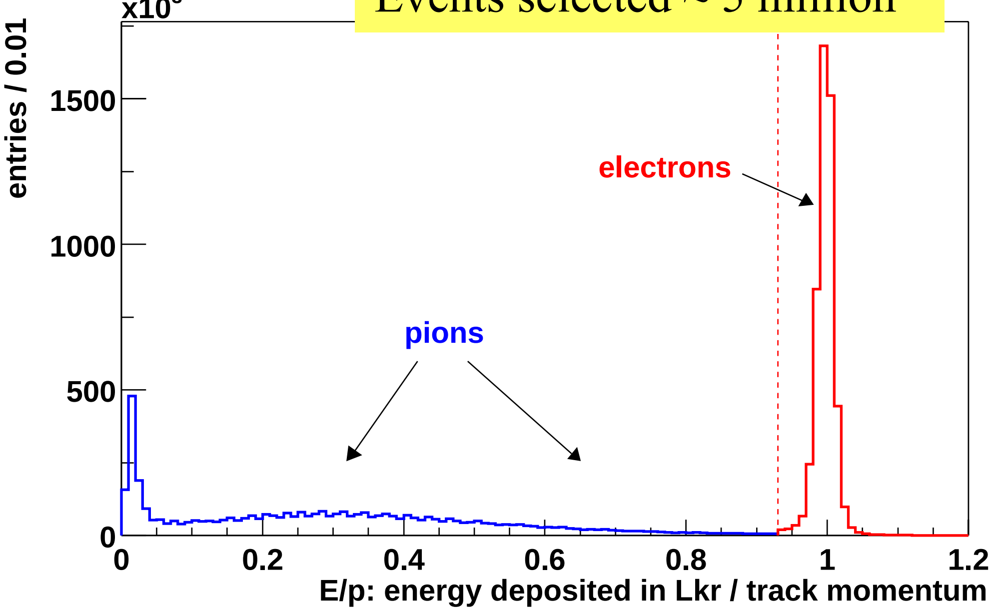
- CP violating process, suppress main channels by 4-5 order of magnitude
- Small background ~0.5%
- Data well described by MC

Events selected ~ 47000



$K_L \rightarrow \pi e \nu$

- Select K_{e3} decays via the ratio E/p (energy in electromagnetic calorimeter over track momentum). → E/p ~ 1 for electrons.
- Small background ~ 0.5%



Results (Published in Phys.Lett. B645:26-35,2007)

The directly measured value:

$R = BR(K_L \to \pi^+\pi^-) / BR(K_L \to \pi e \nu) = (4.835 \pm 0.022_{stat.} \pm 0.016_{syst.}) \times 10^{-3}$

Corrections and uncertainties on R

Uncertainty source	Correction	Uncertainty
Particle ID	+1.34%	0.05%
$K_{2\pi}$ background	–0.49%	0.03%
Muon ID	+0.48%	0.18%
Trigger	–1.29%	0.11%
Energy spectrum		0.20%
Radiative corrections		0.10%
MC statistics		0.10%
Totally	+0.04%	0.33%

Branching fraction:

$BR(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}$

→ Includes the $\pi^+\pi^-\gamma$ (IB) component;

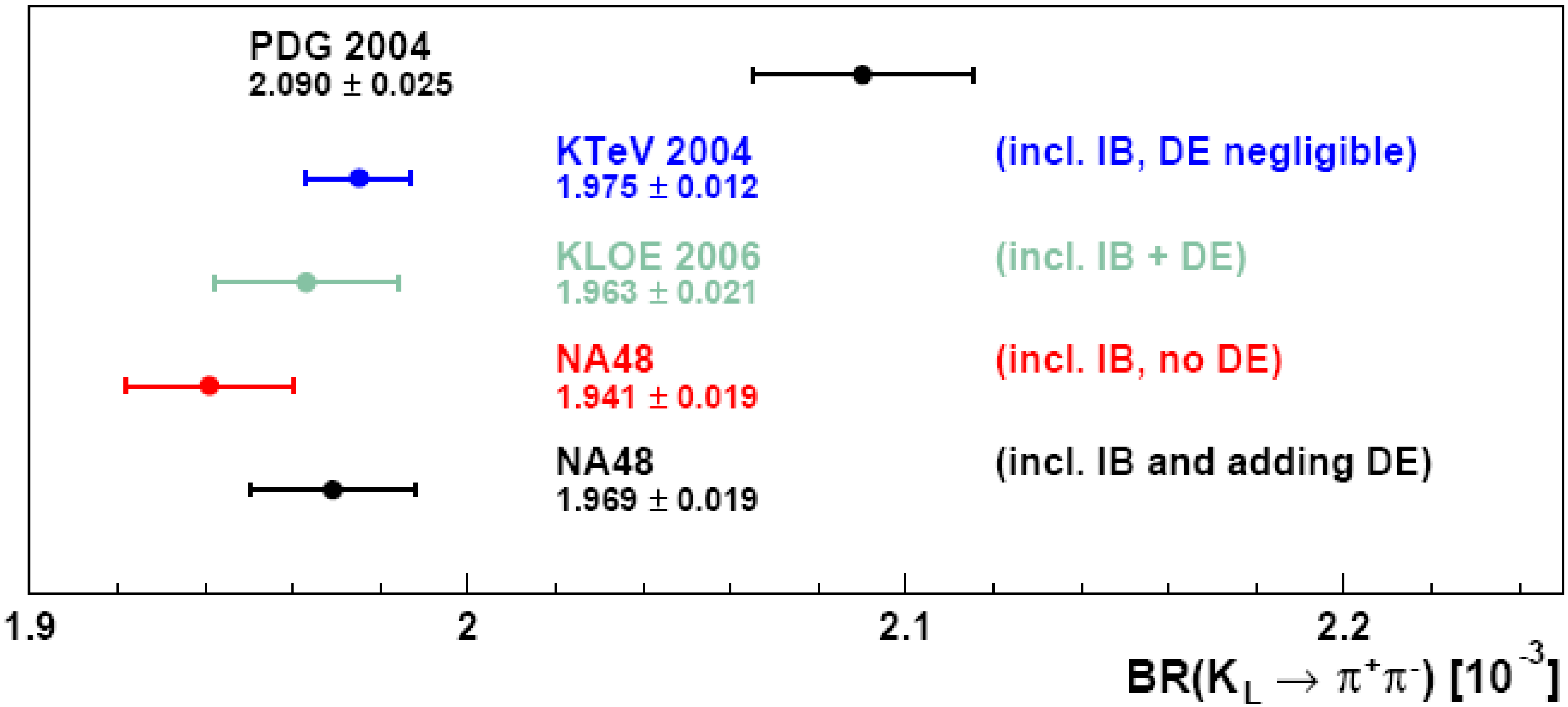
→ Direct emission (CP conserving) component was subtracted.

The CP violation parameter:

$$|\eta_\pm| = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}} = (2.223 \pm 0.012) \times 10^{-3}$$

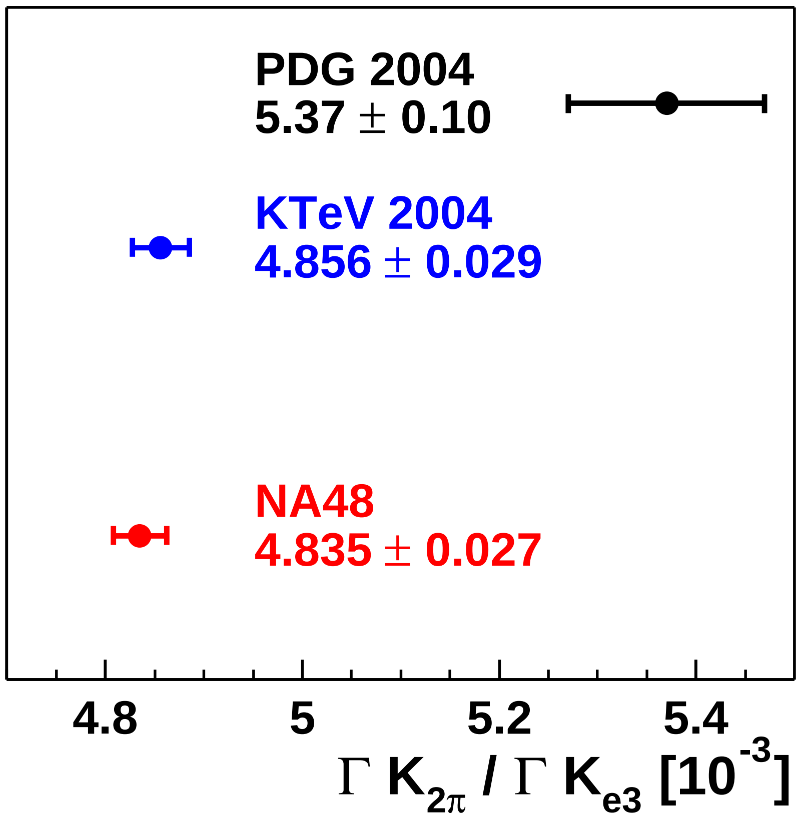
Comparison of results

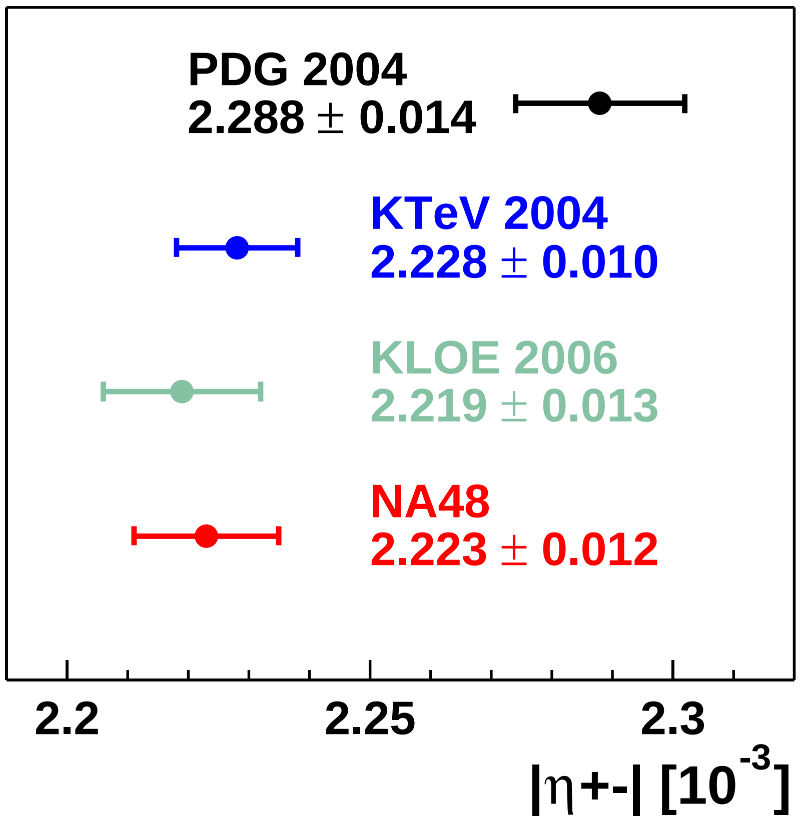
$$BR(K_L \to \pi^+\pi^-)$$



For comparison it is important to point out the treatment of radiative decays (IB +DE).

Comparison of results





→ Good agreement with KTEV and KLOE

→ Experiments contradict PDG 2004

CP violation in $K^{\pm} \rightarrow 3\pi$ decays NA48

CP- violating asymmetry in $K^{\pm} \rightarrow 3\pi$

Why look for direct CP violation in $K^{\pm} \rightarrow 3\pi$ decays ?

(only direct CPV in $K^{\pm}$ possible – no mixing)

- Potentially large statistics.

  (BR ($K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$)= 5.57%; BR ($K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$)= 1.73%

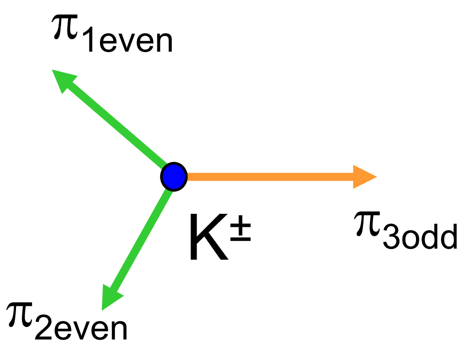
- Simple selection
- Low background

Method:

No absolute kaon flux measurement

→ Compare only Dalitz plot shapes between K^{+}/K^{-}

Dalitz variables



Matrix element:

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

With $|h|, |k| \ll |g|$

Kinematics:

$$s_i = (P_K - P_{\pi i})^2,\ i=1,2,3\ (3=\text{odd } \pi);$$
$$s_0 = (s_1+s_2+s_3)/3;$$
$$u = (s_3 - s_0)/m_\pi^2;$$
$$v = (s_2 - s_1)/m_\pi^2.$$

Kaon rest frame:

$$u = 2m_K \cdot (m_K/3 - E_{odd})/m_\pi^2;$$
$$v = 2m_K \cdot (E_1 - E_2)/m_\pi^2.$$

Direct CP violation observable A_g

$$A_g \equiv \frac{g_+ - g_-}{g_+ + g_-} = \frac{\Delta g}{2g}$$

$g_+ \rightarrow K^+$ decays
$g_- \rightarrow K^-$ decays

1. Measure **Δg**
2. Use known value of **g**
3. Compute **A_g**

$A_g \neq 0$ → **Direct CP violation**

$K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ $g = (-21.134 \pm 0.017)\%$
$h = (1.848 \pm 0.040)\%$
$k = (-0.463 \pm 0.014)\%$

Phys. Lett. B649 (2007) 349-358

Na48/2 Results for Slopes

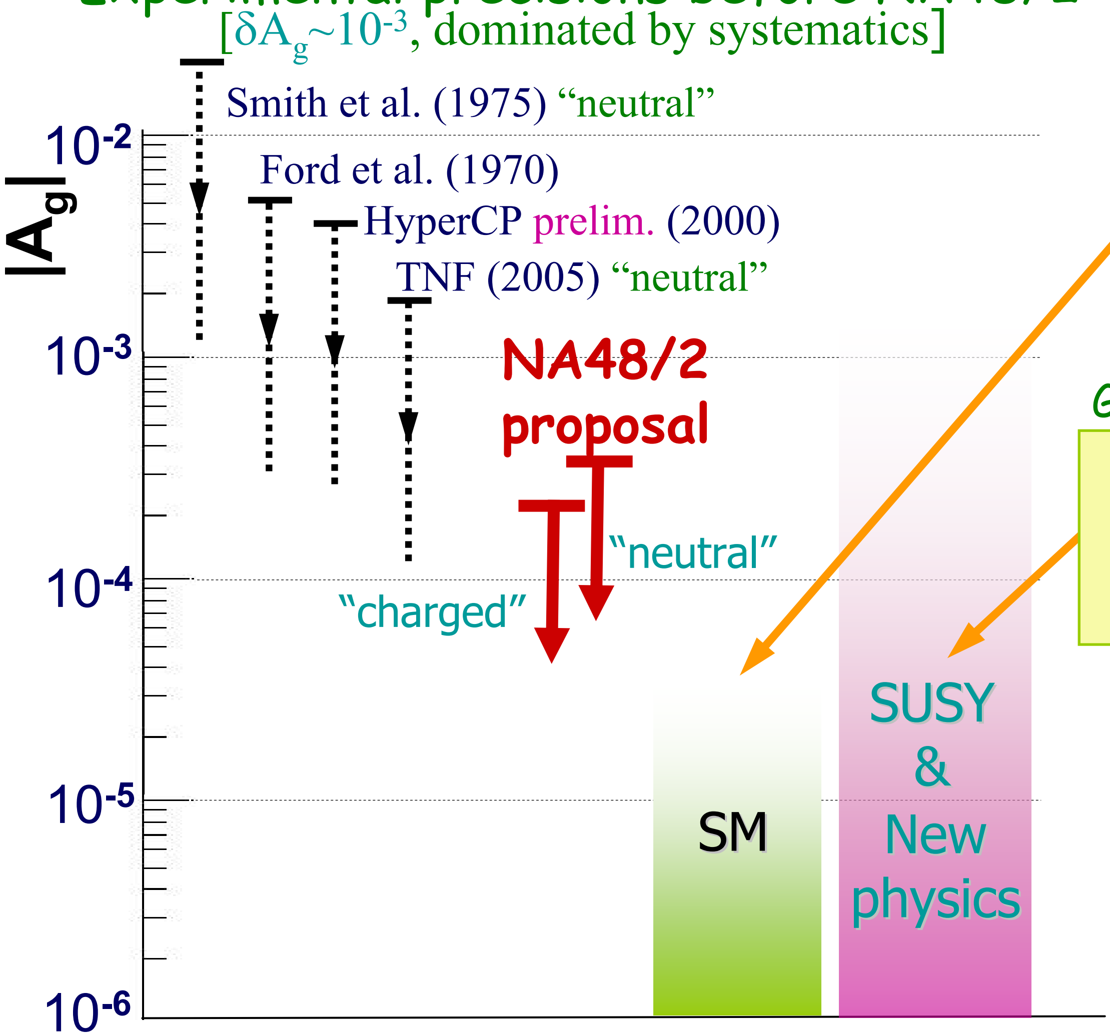
- agreement with PDG
- factor 10 smaller uncertainties
- first evidence of **h≠0**

$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ $g = (62.6 \pm 0.7)\%$

PDG value

Theory & Experiments

Experimental precisions before NA48/2:



E. Gámiz et al., JHEP 10 (2003) 42

SM estimate (NLO ChPT):
$A_g^c = (-1.4 \pm 1.2) \times 10^{-5}$;
$A_g^n = (1.1 \pm 0.7) \times 10^{-5}$.

G. D'Ambrosio et al., PLB480 (2000) 164

Models beyond the SM predict substantial enhancement partially within the reach of NA48/2.

Asymmetry of integrated decay widths is strongly suppressed.

Goal and method

➢ Primary Na48/2 goal

Measure slope asymmetries in **charged** and **neutral** modes with high accuracy (few 10^{-4}).

➢ Central idea

To measure a tiny asymmetry one must garantee perfect charge symmetrization in the experimental setup and eliminate the remaining acceptance differences by a smart analysis tecnique.

Goal and method

•Experimental realization

- –Two simultaneous K^+ and K^- beams, superimposed in space, with narrow momentum spectra.
- – Equalise averaged K^+ and K^- acceptances by frequently alternating the polarities of the relevant magnets.

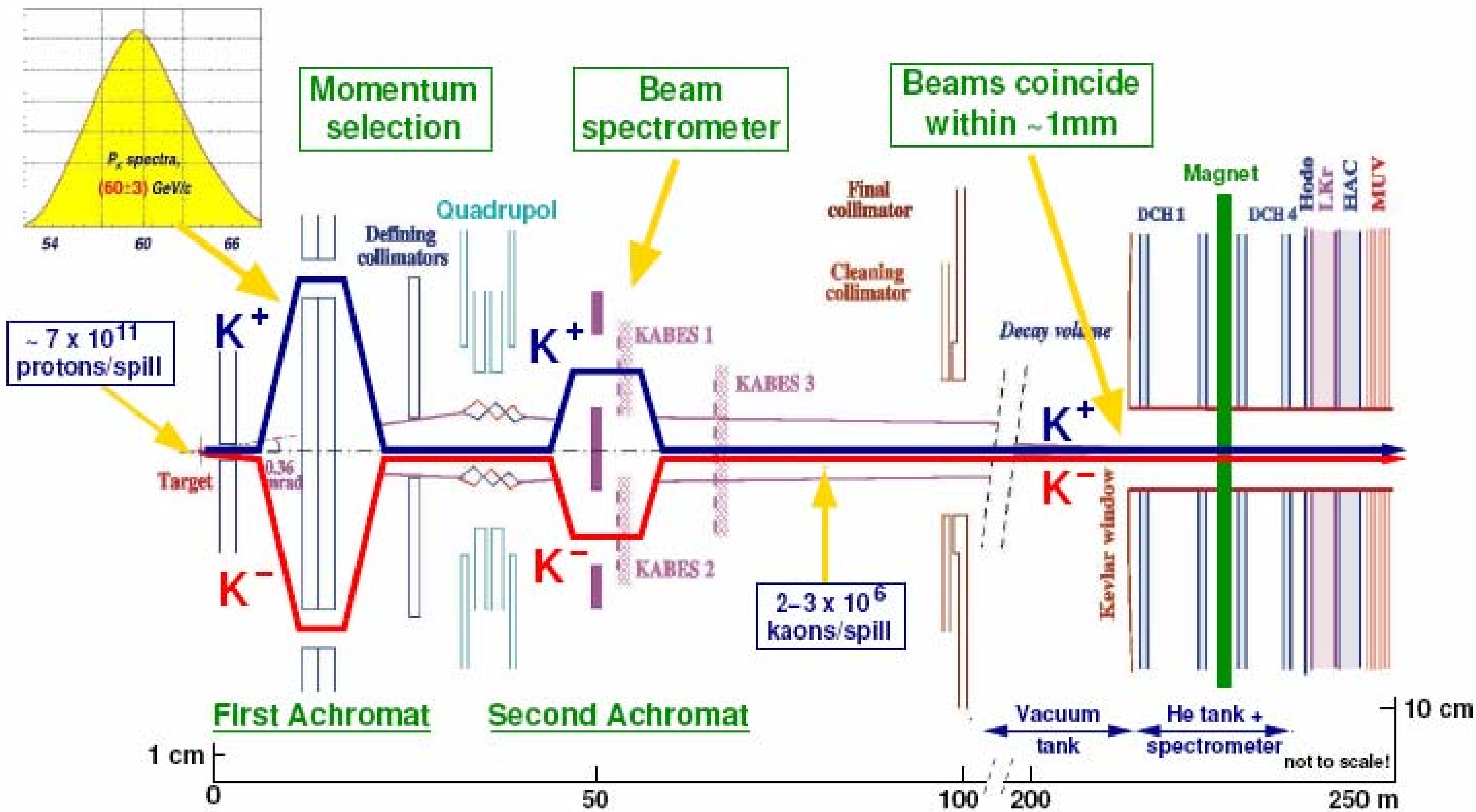
•Event selection

- – Require simplicity and charge symmetry
- – In $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ selection used only spectrometer information
- – In neutral mode mainly information from charge blind LKr detector

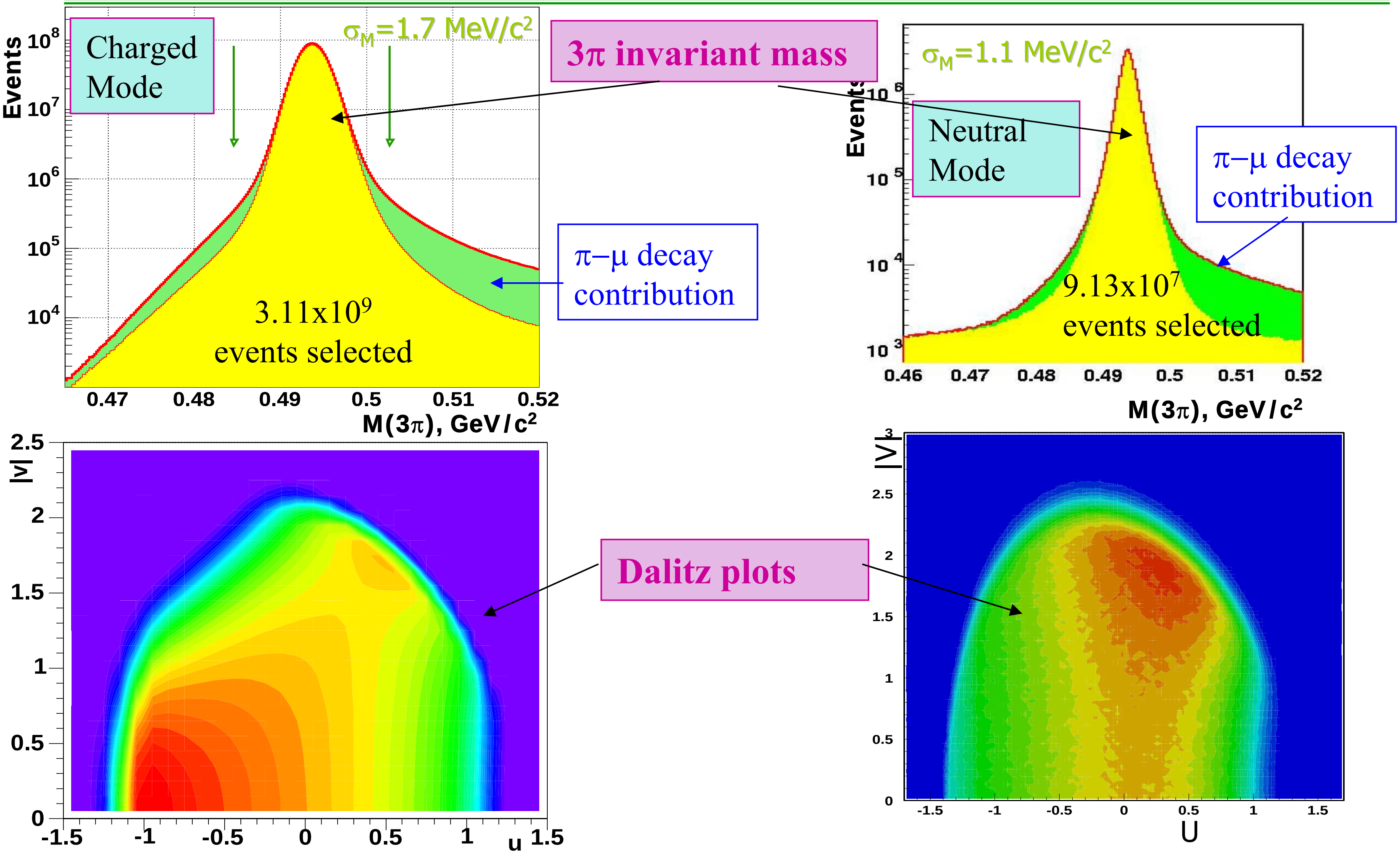
•Extraction of A_g

- – Take the u projection of the Dalitz plot to extract information about A_g
- – Compare the u spectra of K^+ and K^- decays

The K^+/K^- simultaneous beam setup



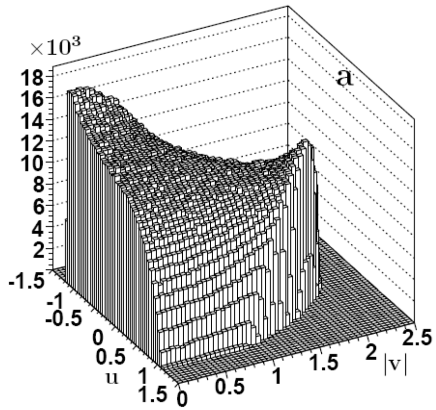
Selected events properties

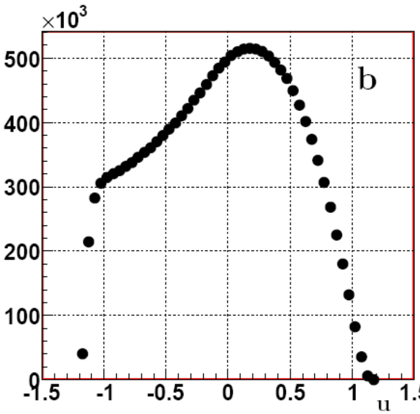


Method to extract A_g

- Make u projection of the Dalitz plot for K^+ and K^-: $N^+(u)$, $N^-(u)$
- Compute R(u), the ratio of the above distributions
- Fit R(u) with afunction to extract Δg
  (This holds only if the acceptance for K+ and K- is the same)

$$R(u) = \frac{N^+(u)}{N^-(u)} \approx 1 + \frac{\Delta g \cdot u}{1 + gu + hu^2}$$





☹ **But:** there are experimental asymmetries that do not cancel in the simple ratio R(u)! (mainly due to the presence of magnetic fields)

To cancel the charge asymmetry in the detector and beam optics

➔ Beam line (achromat) polarity (A) is reversed on weekly basis

➔ Spectrometer magnet polarity (B) is reversed on few hours basis

The 4 ratios

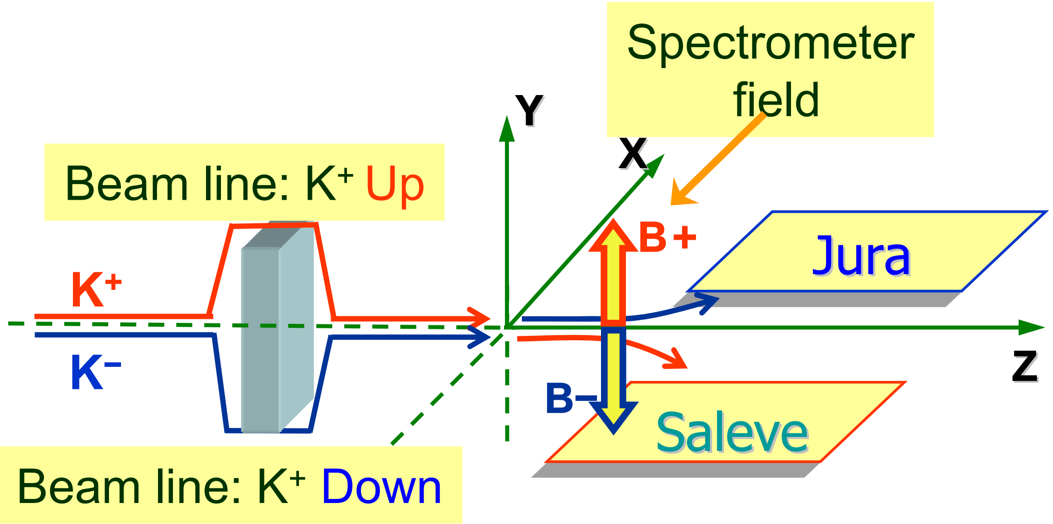
Define 4 u-ratios $R_{xy}(u)$ with the 4 possible combinations of magnetic field polarities.

$$R_{US} = \frac{N(A+B+K+)}{N(A+B-K-)}$$

$$R_{UJ} = \frac{N(A+B-K+)}{N(A+B+K-)}$$

$$R_{DS} = \frac{N(A-B+K+)}{N(A-B-K-)}$$

$$R_{DJ} = \frac{N(A-B-K+)}{N(A-B+K-)}$$



Indexes correspond to: beamline polarity (U/D) left/right direction of kaon deviation in spectrometer (S/J)

K samples in numerator and denominator illuminate the same parts of the detector

Detector left/right asymmetry cancels in the 4 ratios of K^+/K^- distributions defined above

Quadruple ratio

- Use a quadruple ratio :

$$\mathbf{R_4} = R_{US}R_{UJ}R_{DS}R_{DJ} \sim 1+4\cdot\Delta g\cdot u$$

  - ⇨ Cancellation of global time instabilities + local beamline biases
  - ⇨ Cancellation of left-right detector asymmetries
  - ⇨ Cancellation of effect of permanent stray fields (earth, vacuum tank magnetization)

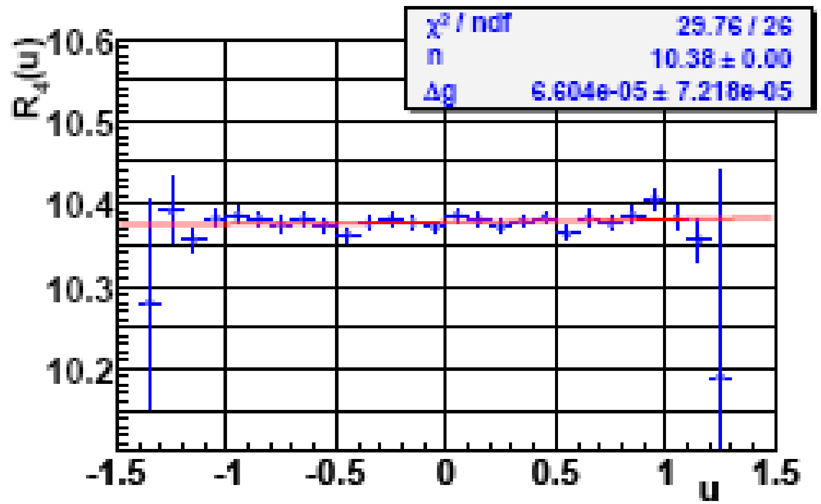
- Extract Δg fitting the quadruple ratio with a function

$$f(u) = n \cdot \left(1 + \frac{\Delta g u}{1 + gu + hu^2}\right)^4$$

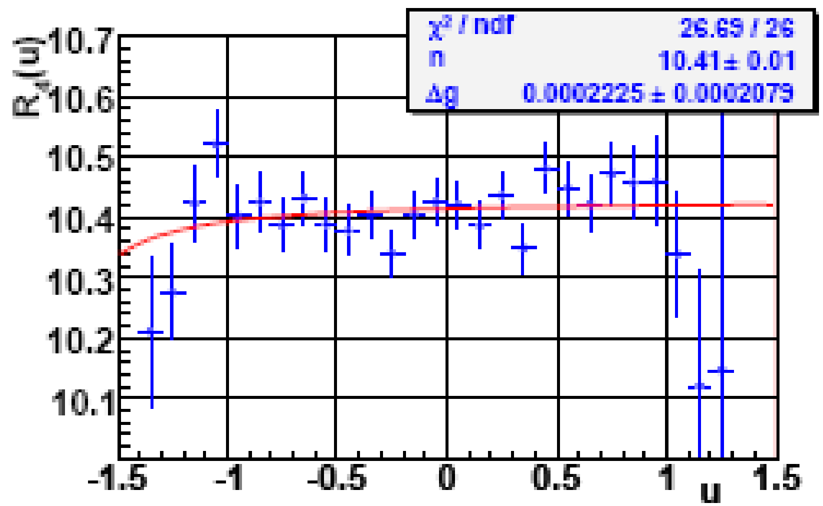
- Advantages :
  - ⇨ Result sensitive only to time variation of asymmetries in short time intervals
  - ⇨ The method is independent of K^+/K^- flux ratio
  - ⇨ The analysis does not rely on a detailed MC to calculate acceptances.

Quadruple ratios in bins of u

Charged mode
$(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})$



Neutral mode
$(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0})$



Final Results

Data samples

Data taking: 2003 + 2004
Effective days: ~ 50 + ~ 60
Amount of data recorded: ~ $16 \cdot 10^9$ triggers ~200 TB

Charged mode (3.11×10^9 selected $K^\pm \rightarrow p^\pm p^+ p^-$)

$$A_g = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \times 10^{-4} = (-1.5 \pm 2.1) \times 10^{-4}$$

Neutral mode (9.13×10^7 selected $K^\pm \rightarrow p^\pm p^0 p^0$)

$$A_g = (1.8 \pm 1.7_{stat} \pm 0.9_{syst}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}$$

- ✓Charged and neutral results are consistent
- ✓Statistical error dominates in both cases
- ✓10 times more precise than previous experiments
- ✓Design goal reached
- ✓Results compatible with SM predictions

No evidence for direct CP violation at the order of 10^{-4}

Spare

$\Gamma_{K2\pi}/\Gamma_{Ke3}$ event selection

Basic two track selection :

1. Two tracks with opposite charge
2. CDA $\leq$ 3 cm
3. Vertex longitudinally between 8 m and 33 m from the finel collimator
4. 15 GeV/c $\leq p_{trac} \leq$ 100 GeV/c

$\pi^+\pi^-$ selection :

1. $M_{\pi\pi}$ compatible with the K mass
2. $p^2_{tK} < 3 \times 10^{-4}$ GeV/c^2
3. E/p < 0.93

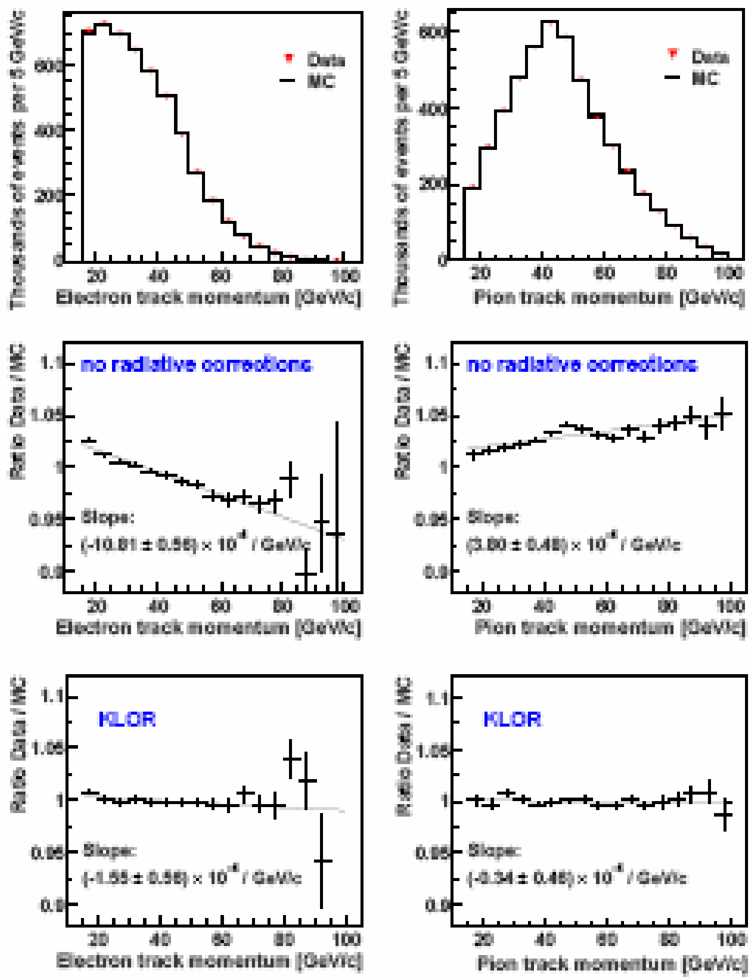
$\pi e \nu$ selection :

1. E/p > 0.93 → electron

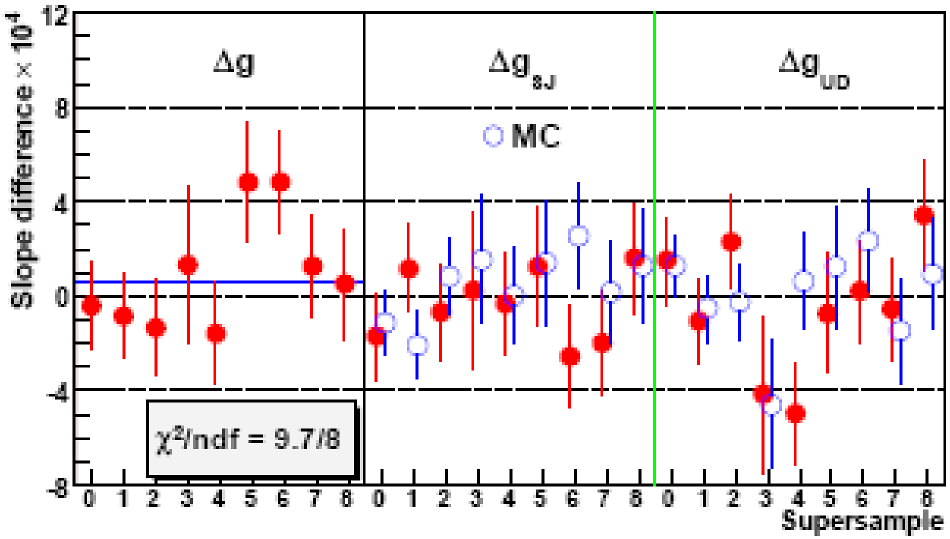
$\Gamma(K \rightarrow 2\pi)/\Gamma(Ke3)$ systematics

	Correction [%]	Uncertainty [%]
E/p cut	$+1.34$	0.05
Background in $K_{2\pi}$	-0.49	0.03
Muon cut	$+0.48$	0.18
Trigger efficiencies	-1.29	0.11
Energy spectrum	-	0.20
Radiative corrections	-	0.10
MC statistics	-	0.10
Total correction	$+0.04$	0.33

Radiative corrections in Ke3



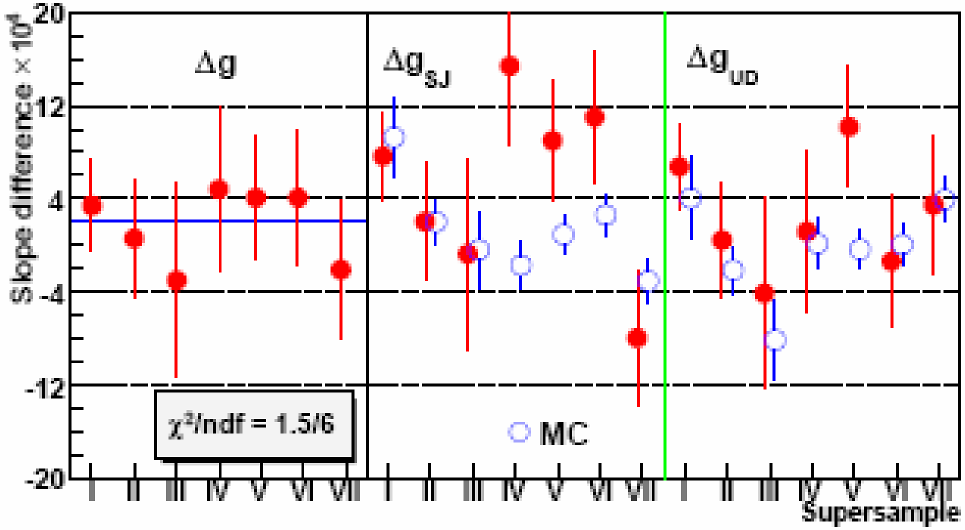
$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ asymmetry :stability



- Δg extracted from quadruple ratio as function of supersamples 0-8
- Δg_{SJ} and Δg_{UD} extracted from corresponding double ratios in which not all asymmetries cancel intrinsically
  - $R_{SJ}(u) = R_S(u)/R_J(u)$: effects by global time-dependent detector variations
  - $R_{UD}(u) = R_U(u)/R_D(u)$: effects by differences of the two beam paths

⇒ Our detector is really symmetric !

$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ asymmetry :stability



- Δg extracted from quadruple ratio as function of supersamples I-VII
- Δg_{SJ} and Δg_{UD} extracted from corresponding double ratios in which not all asymmetries cancel intrinsically
  - $R_{SJ}(u) = R_S(u)/R_J(u)$: effects by global time-dependent detector variations
  - $R_{UD}(u) = R_U(u)/R_D(u)$: effects by differences of the two beam paths

$\Rightarrow$ Our detector is really symmetric !

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ asymmetry : systematics

Systematic effect	Correction, uncertainty $\delta(\Delta g^c) \times 10^4$
Spectrometer misalignment	± 0.1
Spectrometer magnetic field	± 0.3
Beam geometry and stray magnetic fields	± 0.2
Pile-up	± 0.2
Resolution and fitting	± 0.2
Total purely systematic uncertainty	± 0.5
L1 trigger inefficiency	± 0.3
L2 trigger inefficiency	-0.1 ± 0.3

$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ asymmetry : systematics

Systematic effect	Uncertainty $\delta(\Delta g^{n}) \times 10^{4}$
Overlap of LKr showers	± 0.5
LKr resolution	± 0.1
LKr non-linearity	± 0.1
Photon pairing in reconstruction	± 0.1
L1 HOD trigger inefficiency	± 0.1
L1 LKr trigger inefficiency	± 0.1
L2 trigger inefficiency	± 0.3
Stray magnetic fields	± 0.1
Pile-up	± 0.2
Total systematic uncertainty	± 0.7