Measurement of $|\eta_{+-}|$ and search for direct CPV charge asymmetries in $K^{\pm} \rightarrow 3\pi$ decays

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on behalf of the NA48 and NA48/2 collaborations

Cagliari, Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze,

Mainz, Northwestern, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warsaw, Wien

KAON’07, Frascati

NA48 - the CP violation experiment

NA48 (1997-2001)

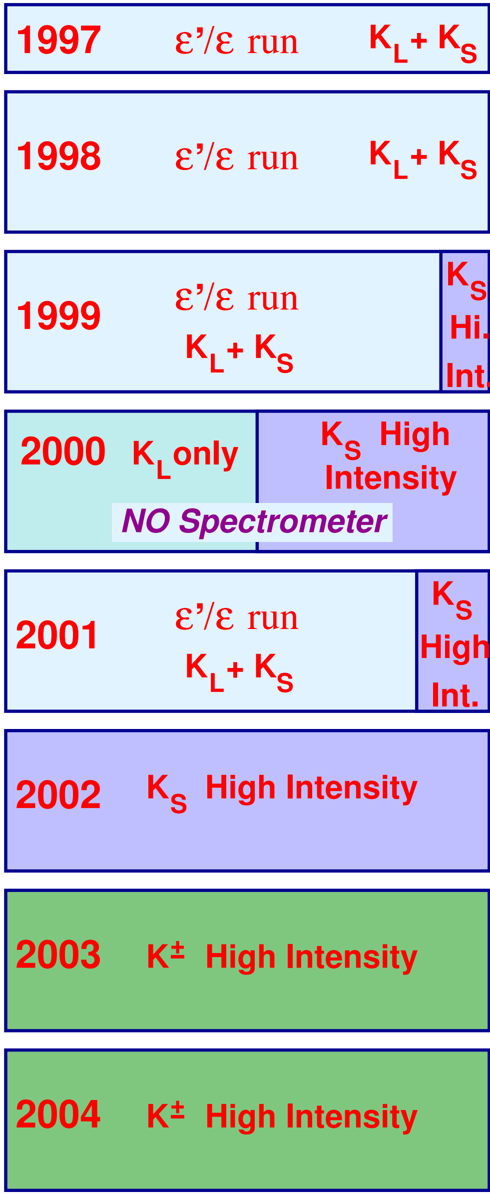
- Direct CP violation in neutral kaon decays
  $\mathrm{Re}(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$
- New !
  Measurement of CP violation parameter $|\eta_{+-}|$

NA48/1 (2002)

- Rare K_S decays
  $BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$
  $BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$

NA48/2 (2003-2004)

- Final results !
  Search for direct CP Violation in $K^\pm \to 3\pi$ decays



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

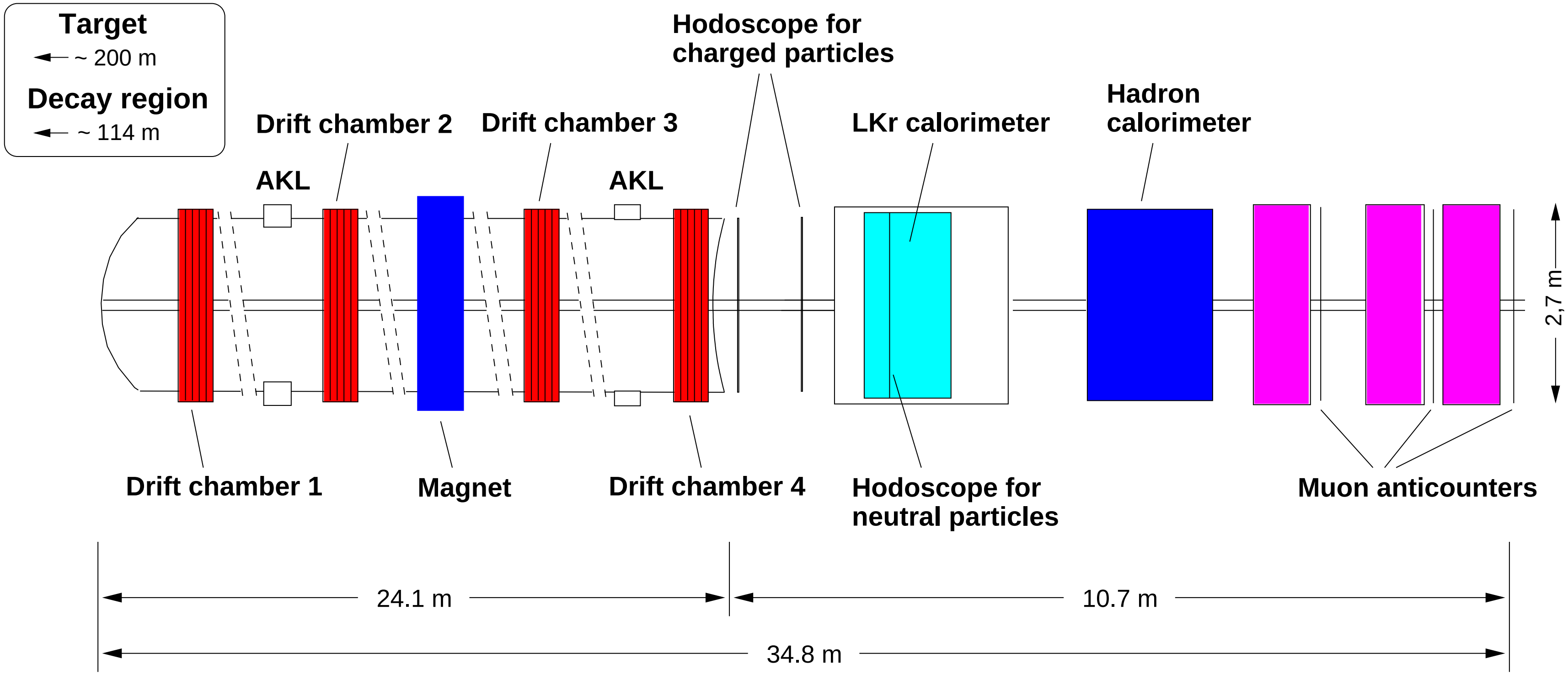
2001 ε'/ε run $K_L + K_S$ | K_S High Int.

2002 K_S High Intensity

2003 $K^\pm$ High Intensity

2004 $K^\pm$ High Intensity

The NA48 detector



Magnetic spectrometer

- Four drift chambers with central dipole magnet
- Good momentum and time resolution
- Transversal resolution of reconstructed decay point (vertex) $\sim 2\,$mm

Electromagnetic calorimeter

- Structure: 13248 cells of $2 \times 2\text{cm}^2$ along beamline in $\sim 10\,\text{m}^3$ liquid krypton (27 X_0 deep)
- Energy resolution $\sim 1\,\%$ and spatial resolution $\sim 1\,$mm (at 20 GeV)

CP violation parameter η_{+-}

Definition

Parameter η_{+-} = fundamental observable of CP violation, defined as the CP-violating ratio of the neutral kaon decaying into two charged pions

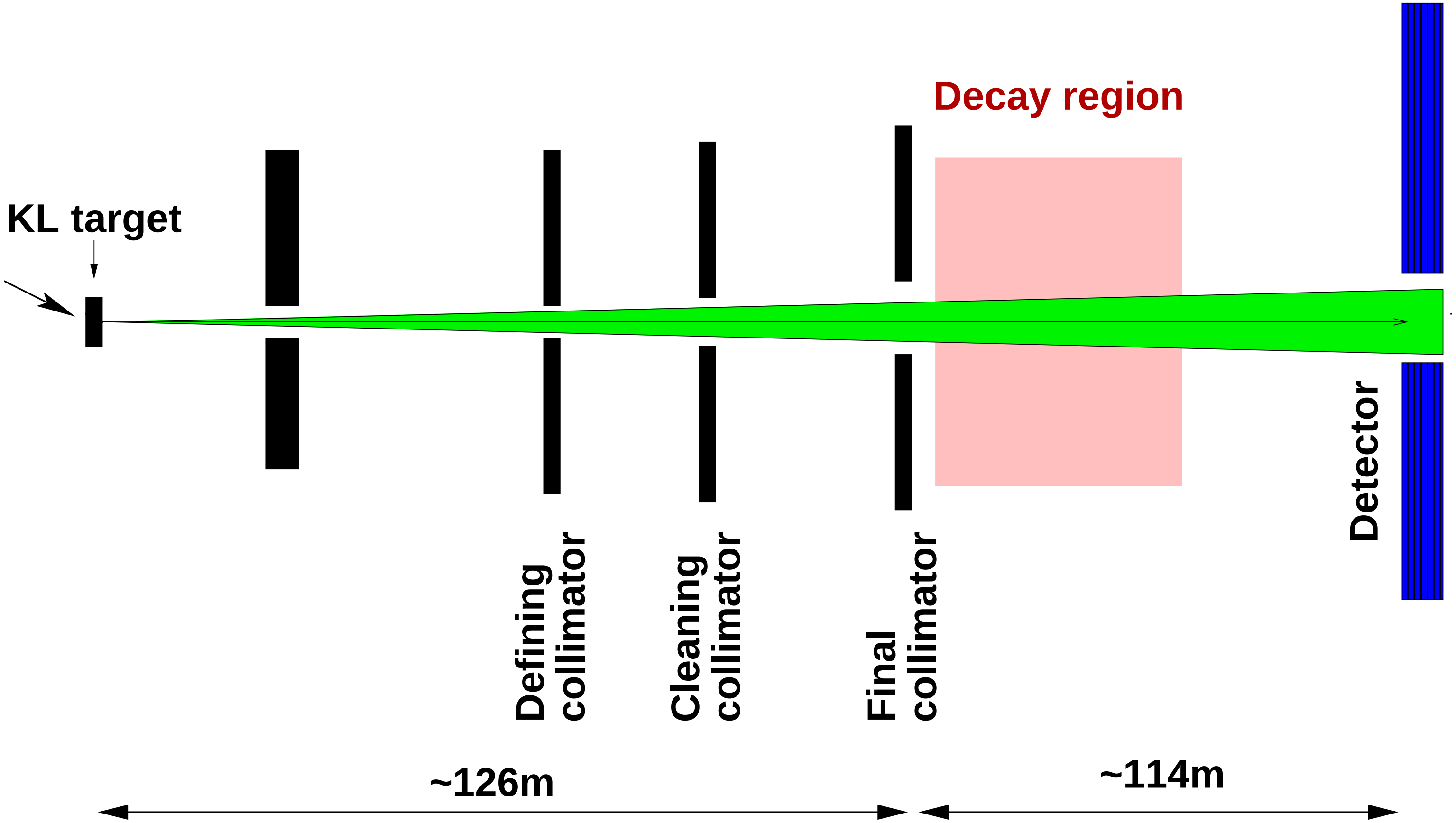
$$\eta_{+-} := \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \qquad \eta_{+-} = \epsilon + \epsilon'$$

What we measure

- Determine $|\eta_{+-}|$ via the ratio of decay rates $\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)}$
- $BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e \nu)} \cdot BR(K_L \to \pi e \nu)$
- $|\eta_{+-}| \equiv \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}}$

NA48 beam line for pure K_L beam

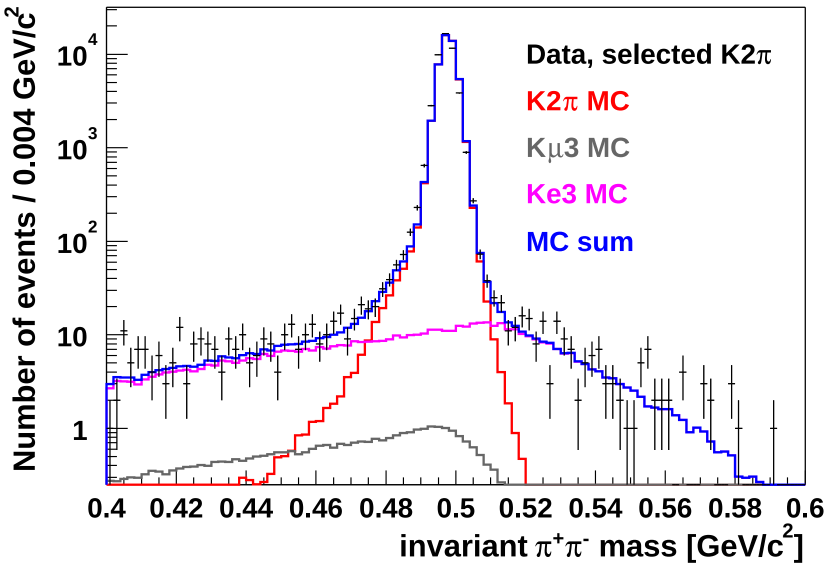
- Special run 1999 (two days) with pure K_L beam at low intensity
- Simple trigger condition: minimum bias trigger to select only events with two charged tracks ($\sim$80 million events)



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

$K_L \to \pi^+\pi^-$

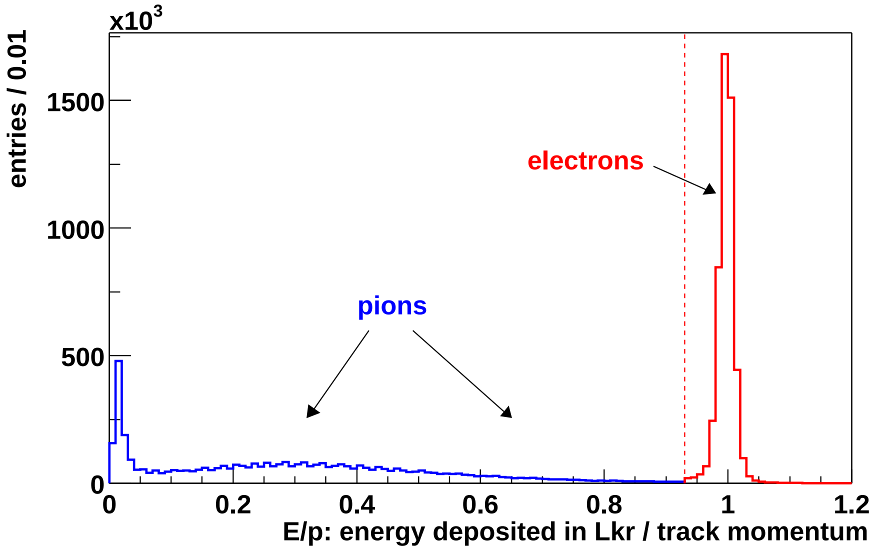
- Need to suppress main decay channels by 4-5 orders of magnitude
- Only small background of $\sim 0.5\,\%$
- Data are well described by MC
- About 47000 selected $\pi^+\pi^-$ events



$K_L \to \pi^\pm e^\mp \nu$

- Selection of K_{e3} decays via ratio E/p (energy in electromagnetic calorimeter over track momentum)

  $\to$ E/p ~ 1 for electrons
- About 5 million K_{e3} events selected with small background of $\sim 0.5\,\%$



Results (published in Phys.Lett.B 645:26-35, 2007)

- $$\frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^\pm e^\mp\nu)} = (4.835 \pm 0.022_{stat.} \pm 0.016_{syst.}) \times 10^{-3} = (4.835 \pm 0.027) \times 10^{-3}$$

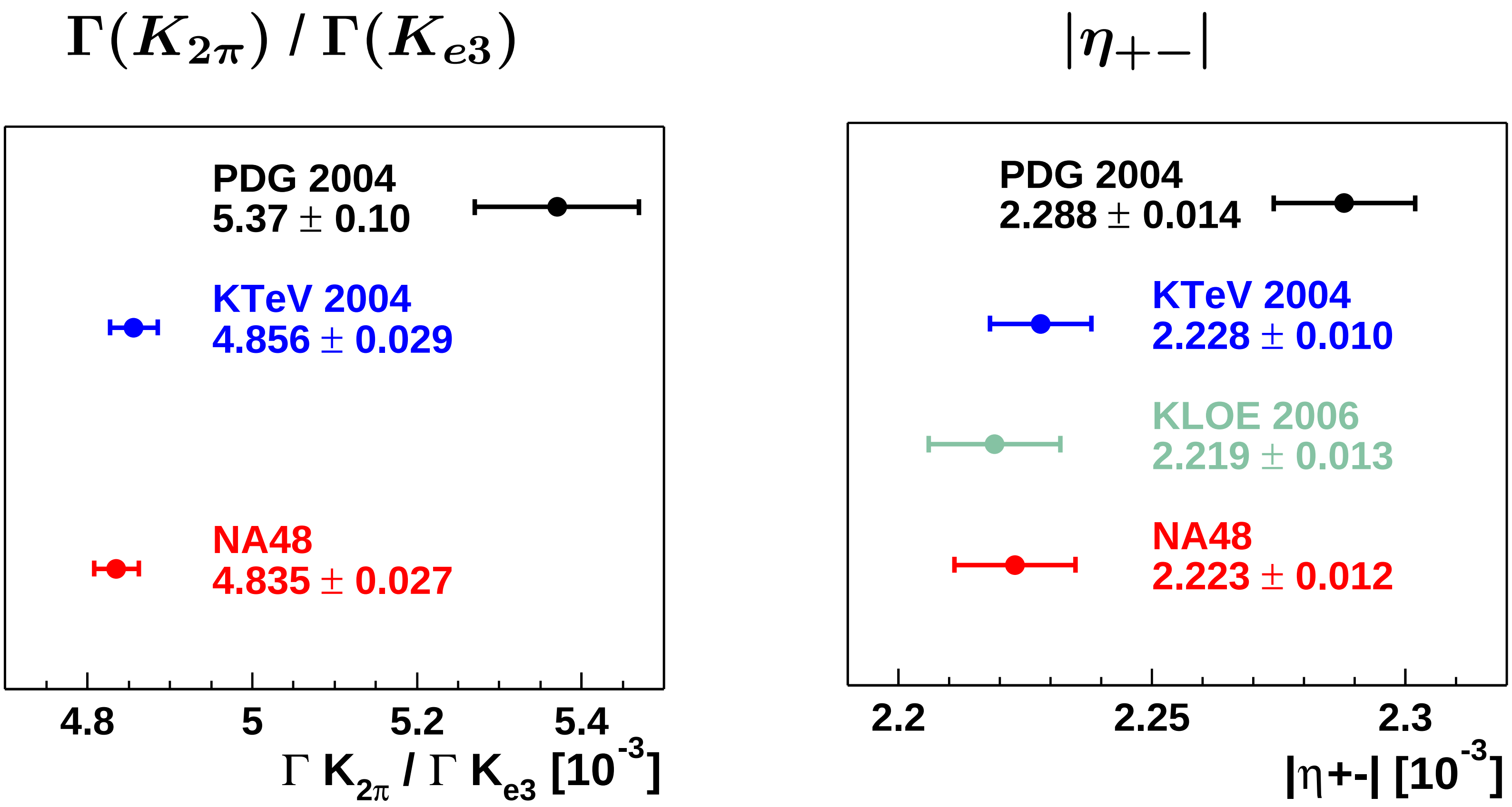
- $$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_L\to\pi e\nu)} \cdot BR(K_L \to \pi e\nu) = (1.941 \pm 0.019) \times 10^{-3}$$

  - Includes $\pi^+\pi^-\gamma(IB)$ component, IB = Inner Bremsstrahlung
  - Direct Emission (DE) component, which is (mostly) CP-conserving, was subtracted
  - Take updated NA48 result $BR(K_L \to \pi e\nu) = 0.4022 \pm 0.0031$ due to better knowledge of $BR(K_L \to 3\pi^0)$

    (published in Phys.Lett.B 602:41-51, 2004)

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

Comparison of results



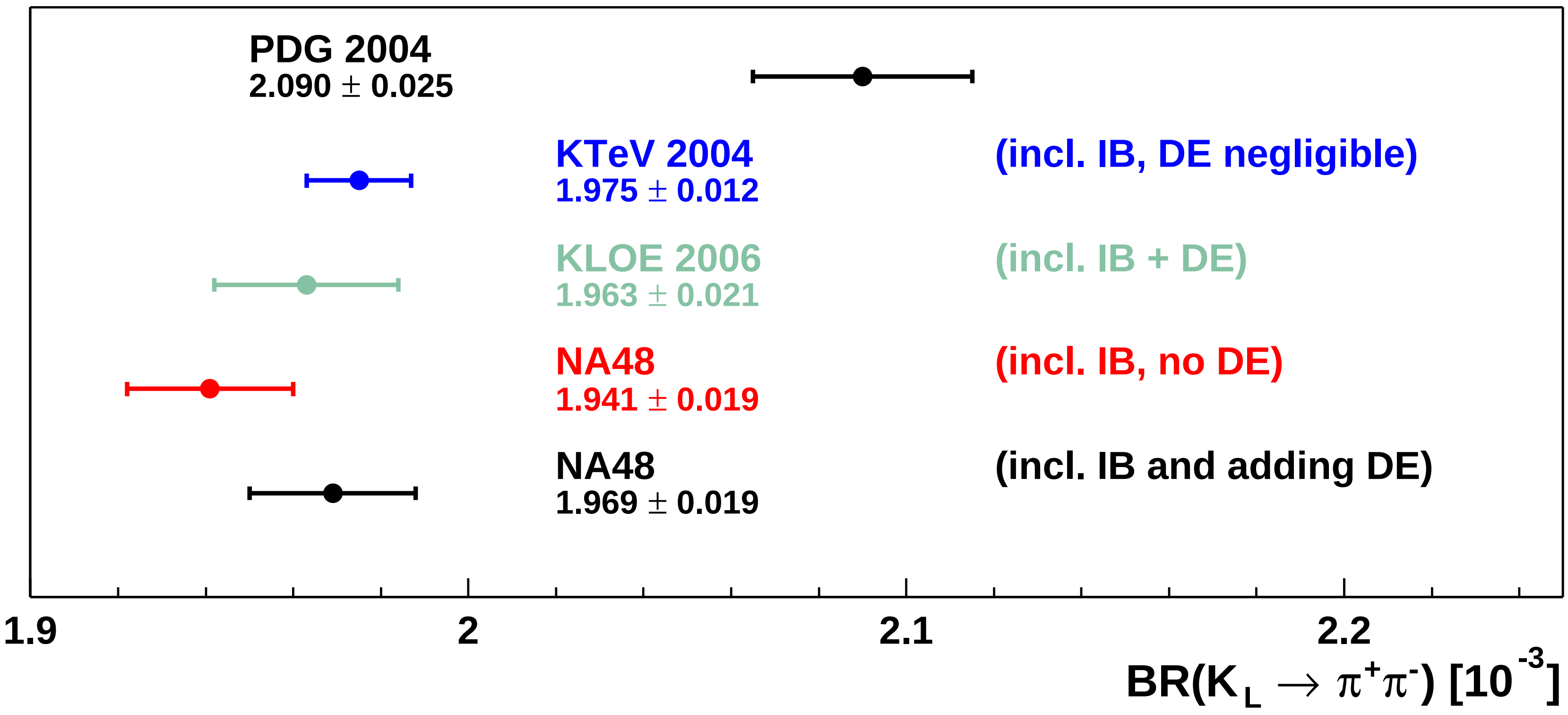
$\Gamma(K_{2\pi})$ / $\Gamma(K_{e3})$

$|\eta_{+-}|$

- Good agreement with results from KTeV and KLOE
- Experiments commonly contradict PDG 2004

Comparison of results

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



- For comparison it's important to point out the treatment of radiative decays (IB + DE)

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

Why look at $K^{\pm} \to 3\pi$ decays ?

- 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^{-}
- The matrix element as function of the Dalitz variables u, v

$$|M(u,v)|^2 \propto 1 + g\,u + h\,u^2 + k\,v^2$$

with parameters $|h|, |k| \ll |g|$ and

$u = \frac{s_3 - s_0}{m_\pi^2}$, $v = \frac{s_1 - s_2}{m_\pi^2}$ π = charged pion

$s_i = (P_K - P_{\pi_i})^2,\ i = 1,2,3$ (3 = odd π); $s_0 = 1/3\,(s_1 + s_2 + s_3)$

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

Observable for direct CPV

- Measure the slope asymmetry : $\boxed{A_g = \frac{g^+ - g^-}{g^+ + g^-}}$

$\Rightarrow$ **Any value of $A_g \neq 0$ is a manifestation of direct CP violation !**

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

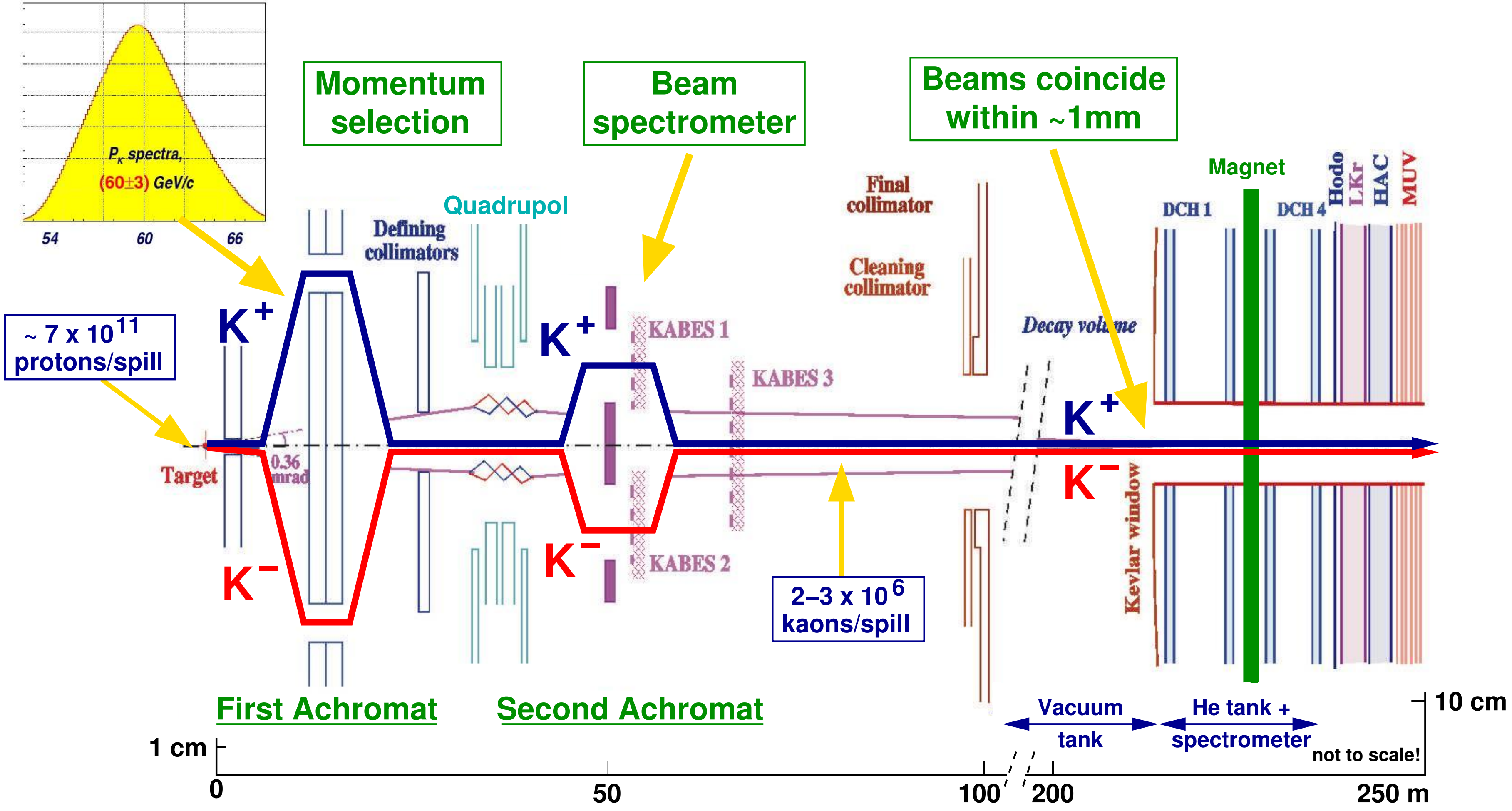
- SM prediction for A_g between 10^{-6} und 10^{-5}
- Theoretical calculations involving processes beyond the SM do not exclude enhancements of the asymmetry A_g up to a few 10^{-4}
$\rightarrow$ within the reach of this experiment, can test on New Physics !

Experimental situation

- Previous experiments set upper limits on A_g at the level of a few 10^{-3}
(limited by systematic effects !)
- Main goal of NA48/2: measure A_g with a precision at least one order of magnitude better (both for charged and neutral mode)

NA48/2 beams setup in 2003 + 2004

- Simultaneous K^+ and K^- beams with flux ratio K^+ / K^- ~1.8
- ~100 days of data taking, 18×10^9 triggers and 200 TB recorded



Asymmetry measurement in $K^{\pm} \rightarrow 3\pi$ decays

Central idea

- To measure a tiny asymmetry, one must guarantee perfect charge symmetrization in the experimental setup and eliminate the remaining acceptance differences by a smart analysis technique !

Experimental realization

- Simultaneous superimposed K^{+} and K^{-} beams with similar momentum spectra
- Reverse regularly the polarities of all magnets in beam transport (achromat) + spectrometer magnet

Event selection

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

$K^{\pm} \to 3\pi$ decays: extraction of A_g

Take the u-projection of the Dalitz plot to extract information about A_g

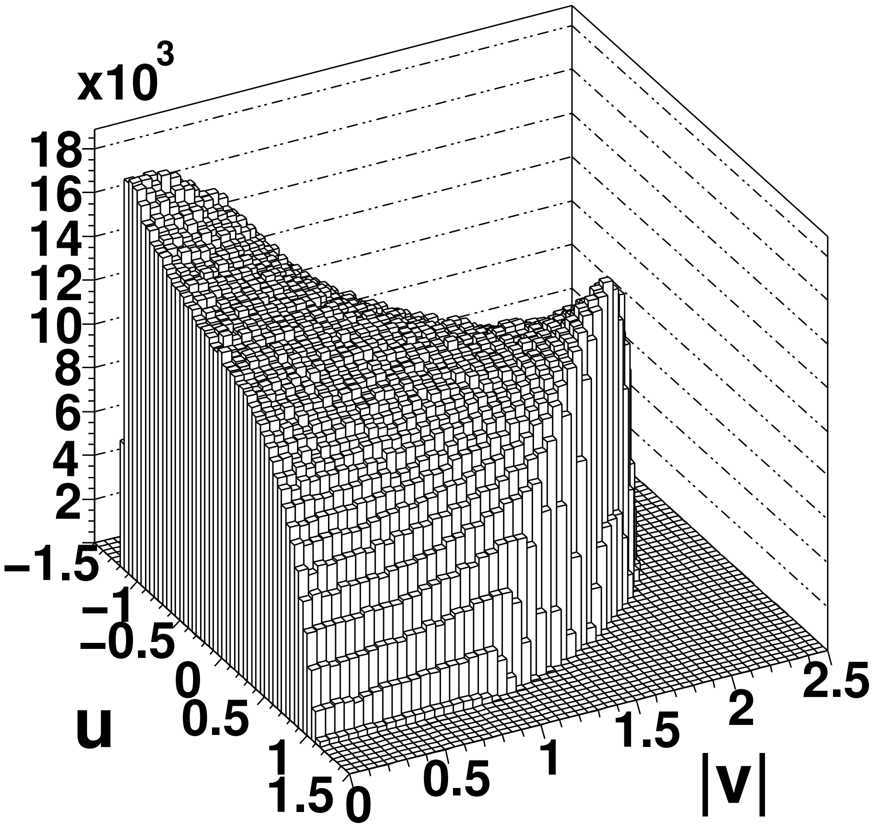
- Compare the reconstructed u-spectra of K^+ and K^- decays

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

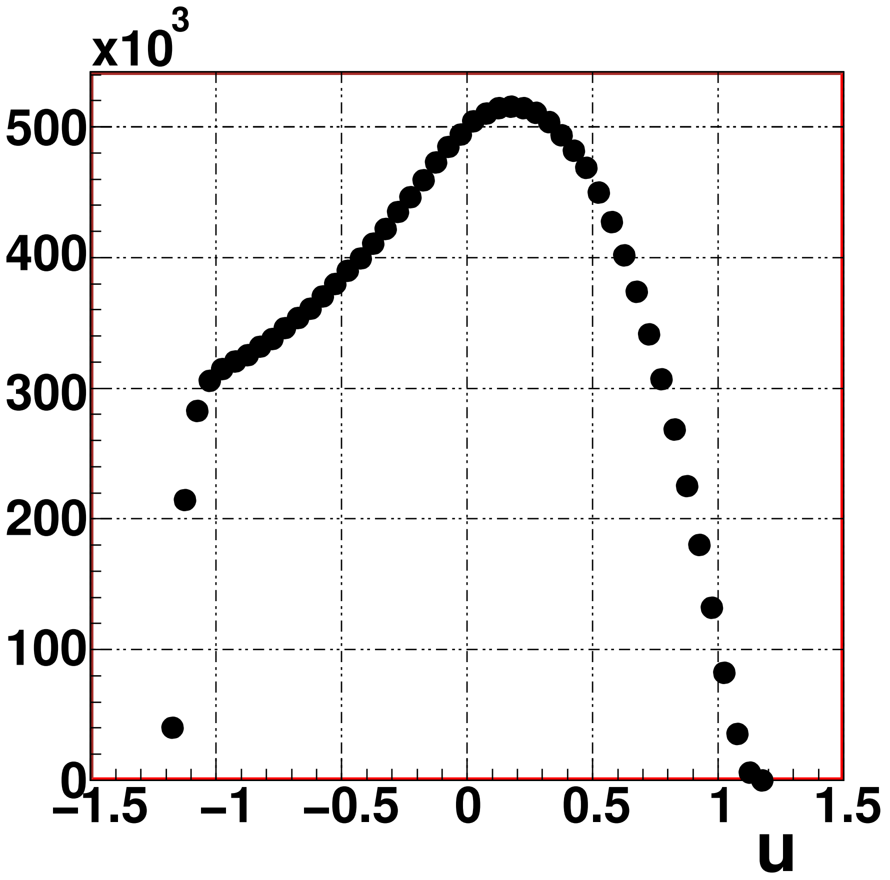
$K^{\pm} \rightarrow 3\pi$ decays: Dalitz plot

Charged mode $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

Selected events in the kinematic variables $(u, |v|)$



Projection to the u axis



$K^\pm \to 3\pi$ decays: extraction of A_g

Take the u-projection of the Dalitz plot to extract information about A_g

- Compare the reconstructed u-spectra of K^+ and K^- decays

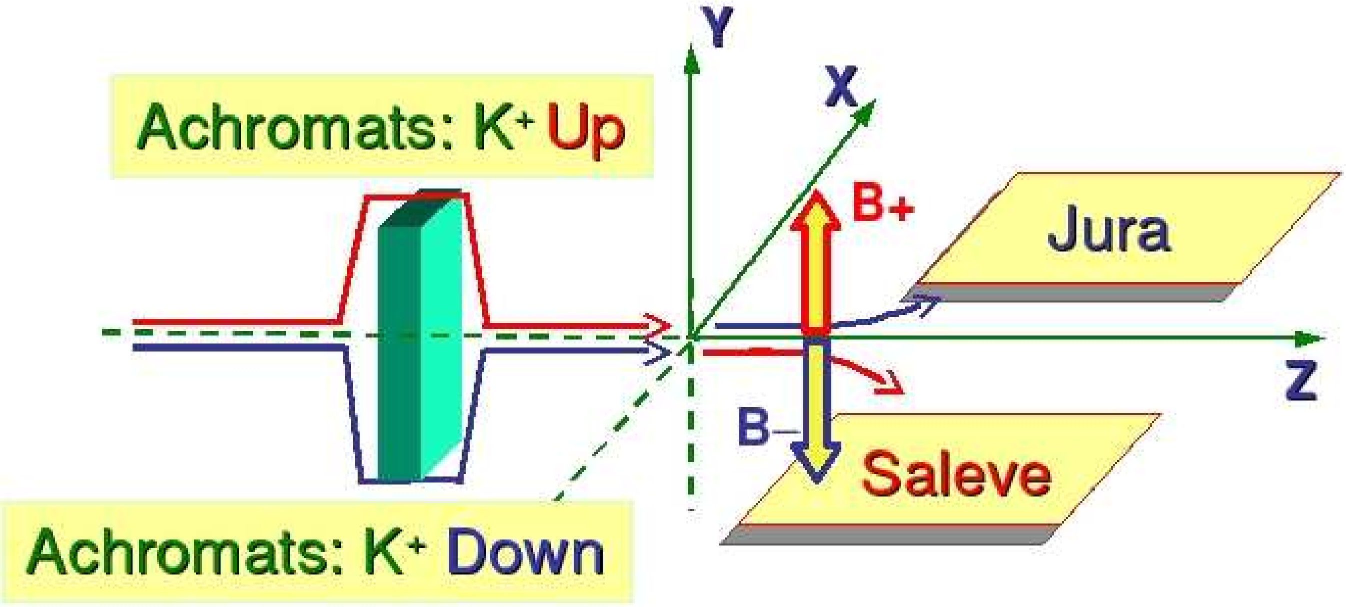
$$R(u) = \frac{N^+(u)}{N^-(u)} \sim 1 + \frac{\Delta g\, u}{1 + gu + hu^2}$$

- Extract the slope difference Δg from a fit to $R(u)$, with
  - $g(\pi^\pm\pi^+\pi^-) = -0.21134 \pm 0.00017$ new NA48/2 measurement !
    $h(\pi^\pm\pi^+\pi^-) = 0.01848 \pm 0.00039$ see talk by Evgueni Goudzovski
  - $g(\pi^\pm\pi^0\pi^0) = 0.626 \pm 0.007; \quad h(\pi^\pm\pi^0\pi^0) = 0.052 \pm 0.008$
- Evaluate A_g: $A_g = \frac{g^+ - g^-}{g^+ + g^-} \approx \frac{\Delta g}{2g}$

But: there are experimental asymmetries which do not cancel in the simple ratio ! (mainly due to presence of magnetic fields)

$K^{\pm} \rightarrow 3\pi$ decays: Quadruple ratio

- Define four u-ratios $R_{xy}(u)$ with the four possible combinations of magnetic field polarities
  - Achromat: $x = U(up), D(down)$
  - Spectrometer: $y = J(\mathrm{Jura} = \mathrm{left}), S(\mathrm{Saleve} = \mathrm{right})$



$K^{\pm} \rightarrow 3\pi$ decays: Quadruple ratio

- Define four u-ratios $R_{xy}(u)$ with the four possible combinations of magnetic field polarities
  - Achromat: $x = U(up), D(down)$
  - Spectrometer: $y = J(\mathrm{Jura} = \mathrm{left}), S(\mathrm{Saleve} = \mathrm{right})$
- Quadruple ratio $\boldsymbol{R_4(u) = R_{US}(u) \cdot R_{UJ}(u) \cdot R_{DS}(u) \cdot R_{DJ}(u)}$

⇒ Cancellation of global time instabilities + local beamline biases

⇒ Cancellation of left-right detector asymmetries

- Extract Δg by fitting the quadruple ratio with a function

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

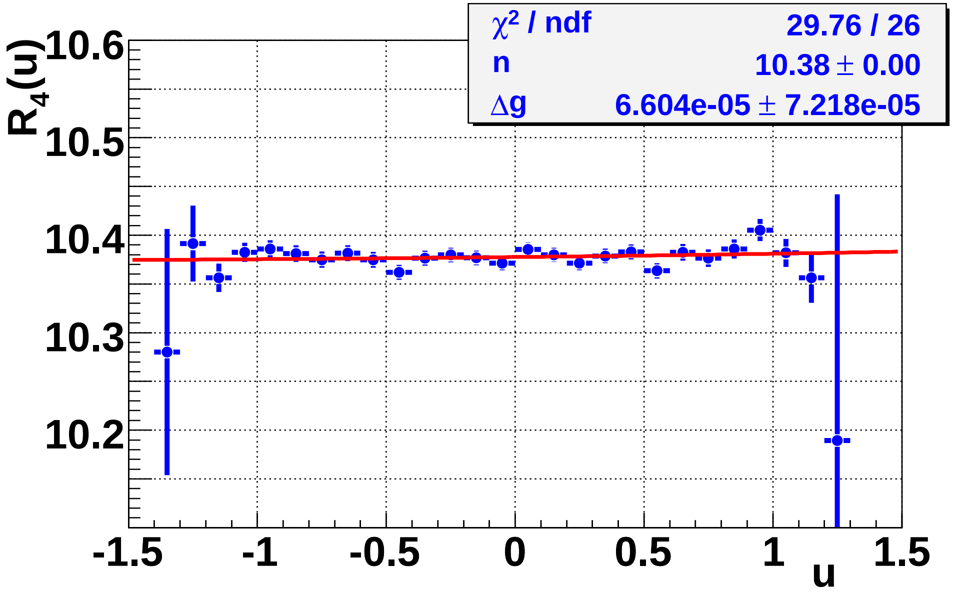
Further advantages

- The method is independent of K^+/K^- flux ratio
- The analysis does not rely on a detailed Monte-Carlo to calculate acceptances (MC only used to study systematic effects)

Quadruple ratio in bins of u

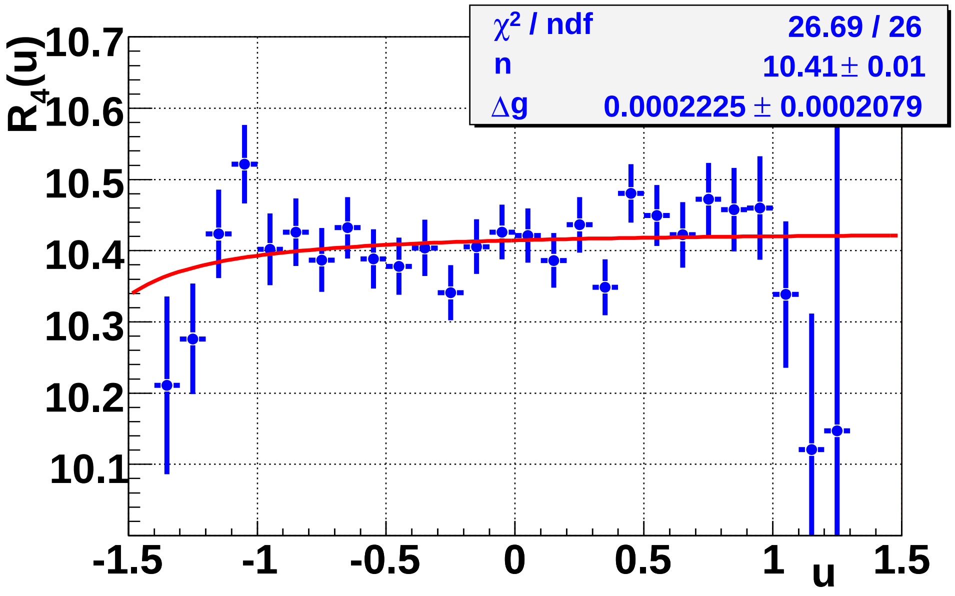
Charged mode

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



Neutral mode

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



Final results for 2003 + 2004

Charged mode $(3.11 \times 10^9$ selected $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-})$

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

Neutral mode $(9.13 \times 10^7$ selected $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0})$

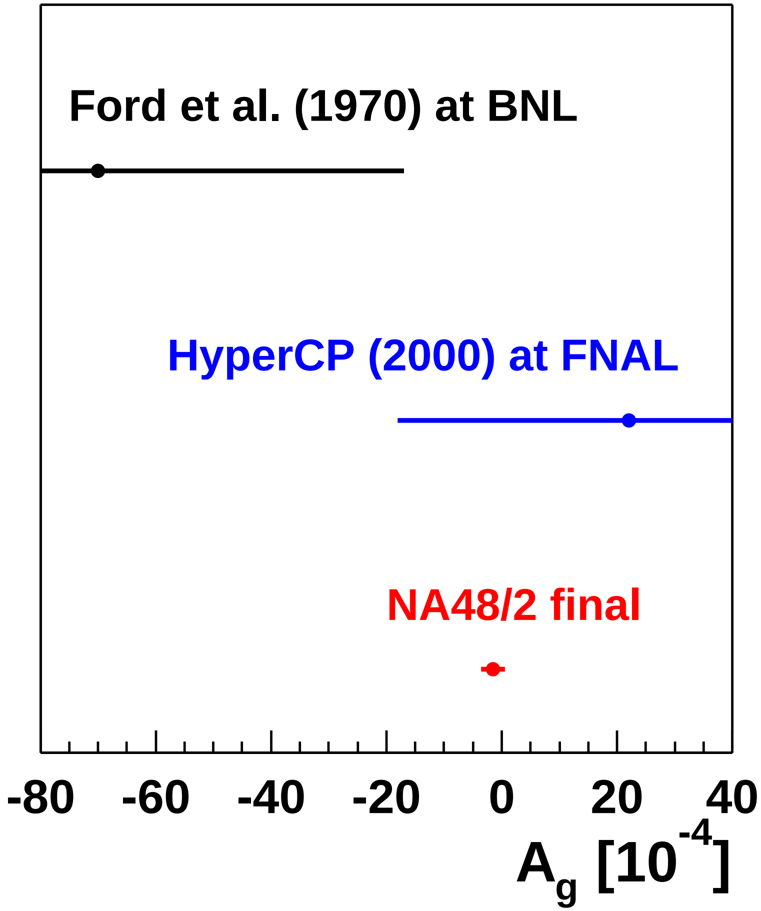
$$\boxed{A_g = (1.8 \pm 1.7_{stat.} \pm 0.9_{syst.}) \times 10^{-4} \ = \ (1.8 \pm 1.9) \times 10^{-4}}$$

- The design goal has been reached!
- About 10x more precise than previous measurements
- Charged and neutral results are consistent
- Statistical errors dominate in both cases
- Results are compatible with the SM model predictions,
  $\Rightarrow$ no evidence for direct CP violation of the order 10^{-4}

Comparison of results

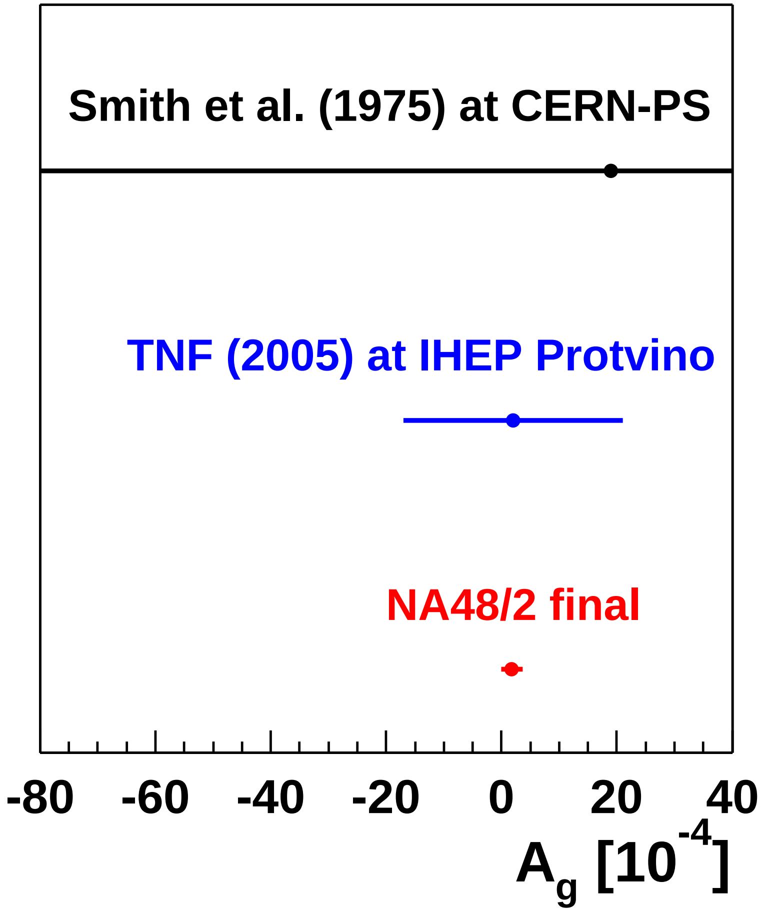
Charged mode

$(K^\pm \to \pi^\pm\pi^+\pi^-)$



Neutral mode

$(K^\pm \to \pi^\pm\pi^0\pi^0)$

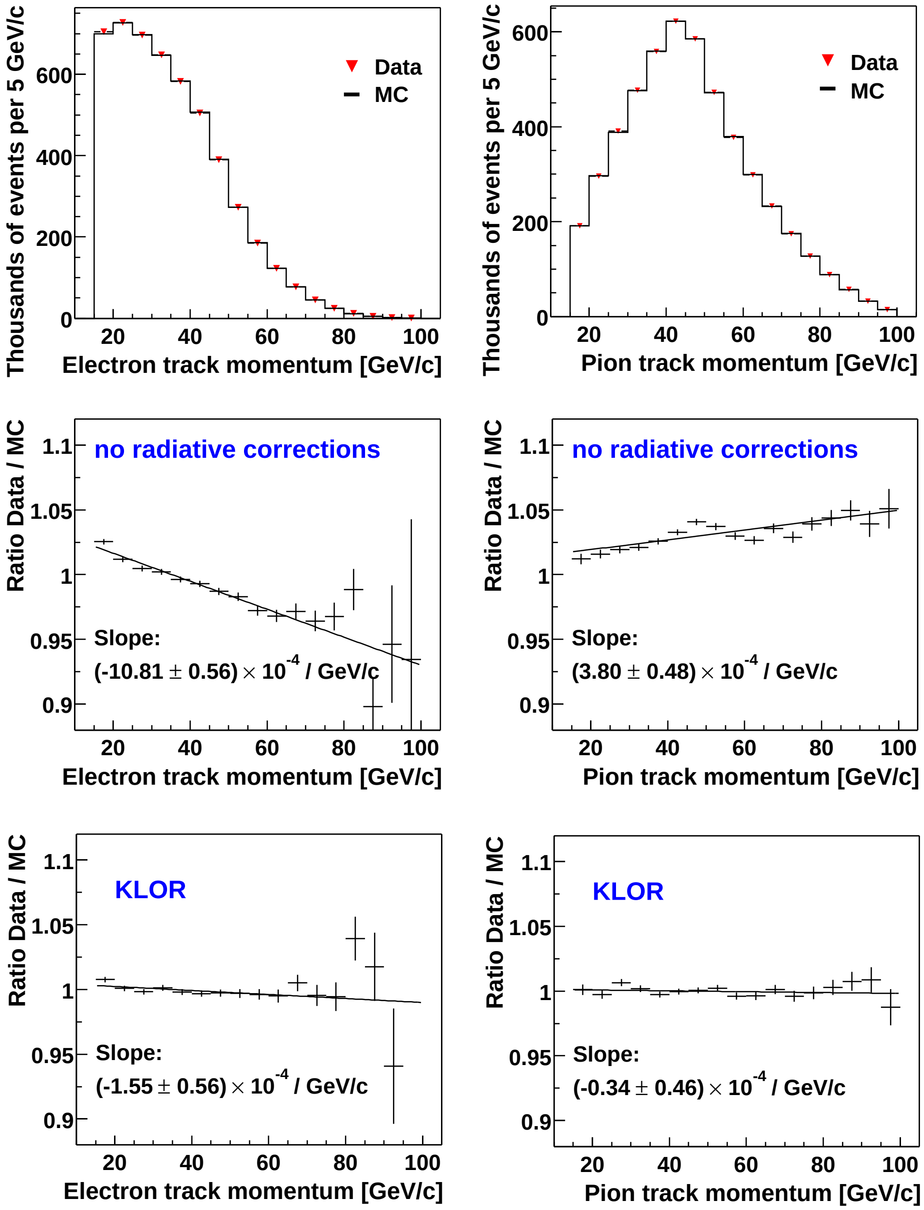


Spare Slides

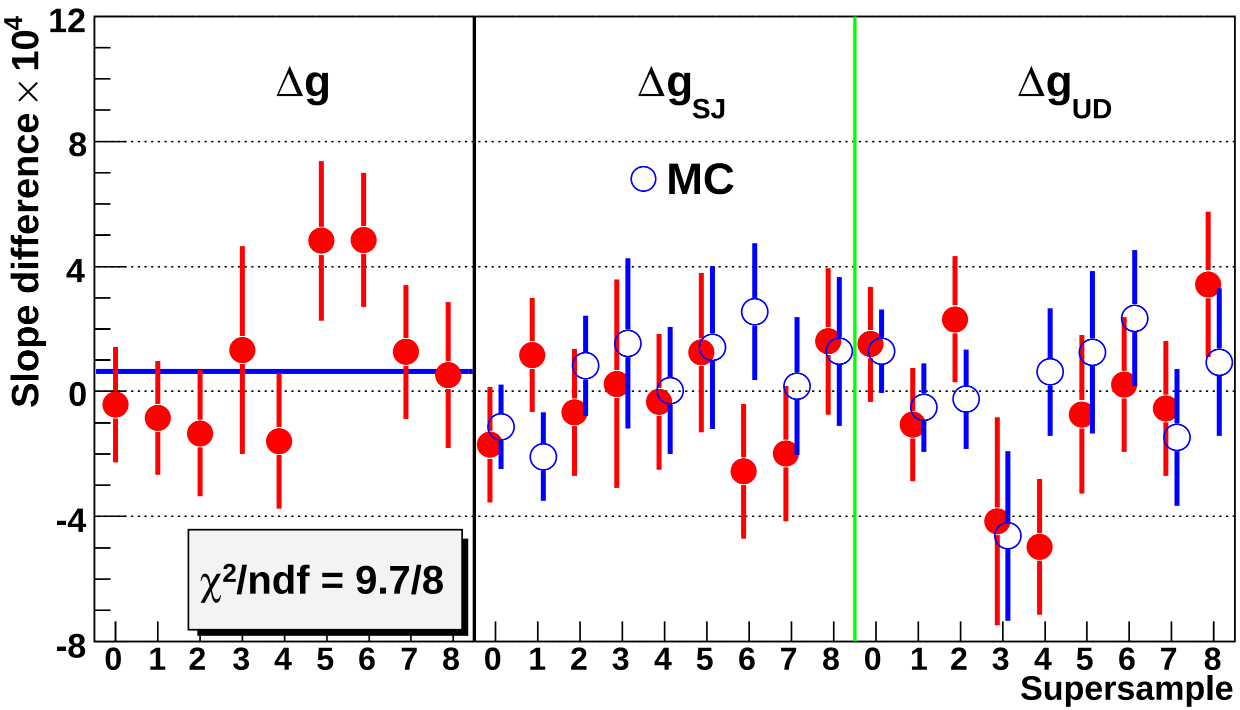
$\Gamma_{K2\pi}/\Gamma_{Ke3}$: Systematics

	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

$\Gamma_{K2\pi}/\Gamma_{Ke3}$: radiative Corrections in K_{e3}



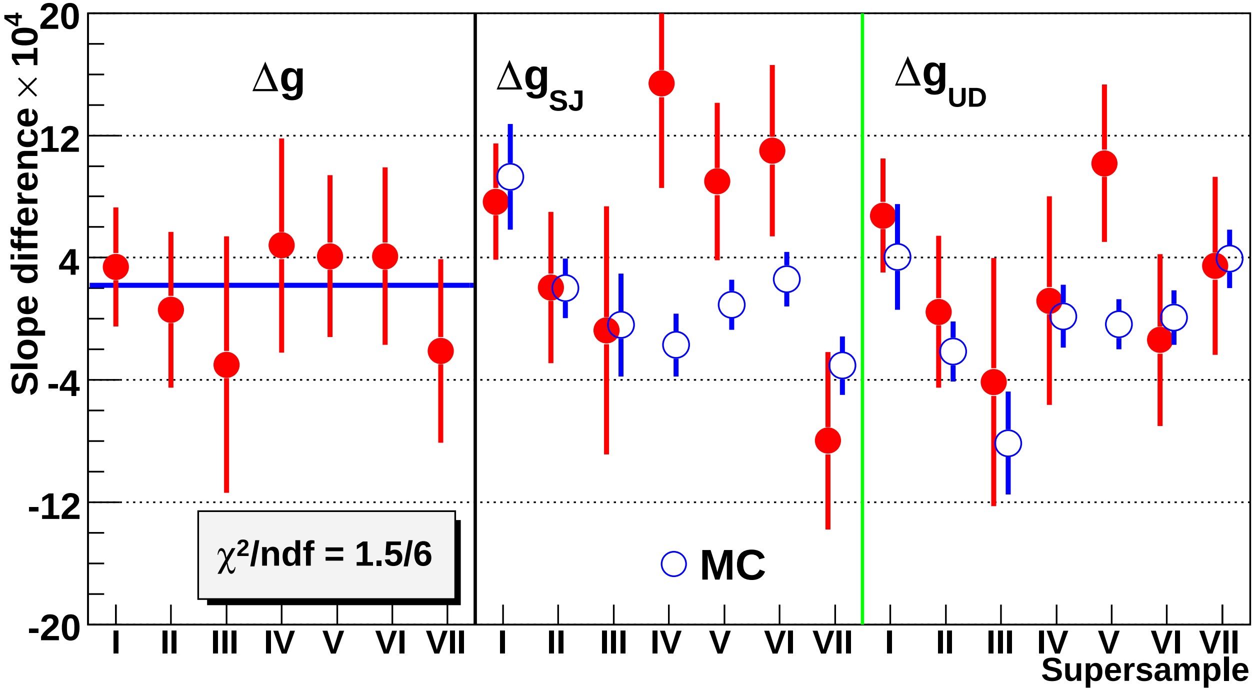
Asymmetry in $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$: stability checks



- 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 !

Asymmetry in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$: stability checks



- 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

⇒ Our detector is really symmetric !

Asymmetry in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$: 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

Asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$: 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