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# 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**

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**KAON'07, Frascati**

# NA48 - the CP violation experiment

## NA48 (1997-2001)

- Direct CP violation in neutral kaon decays

$$\text{Re}(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$$

- **New!**

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

## NA48/1 (2002)

- Rare  $K_S$  decays

$$\text{BR}(K_S \rightarrow \pi^0 e^+ e^-) = (5.8_{-2.3}^{+2.8} \pm 0.8) \times 10^{-9}$$

$$\text{BR}(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.8_{-1.2}^{+1.5} \pm 0.2) \times 10^{-9}$$

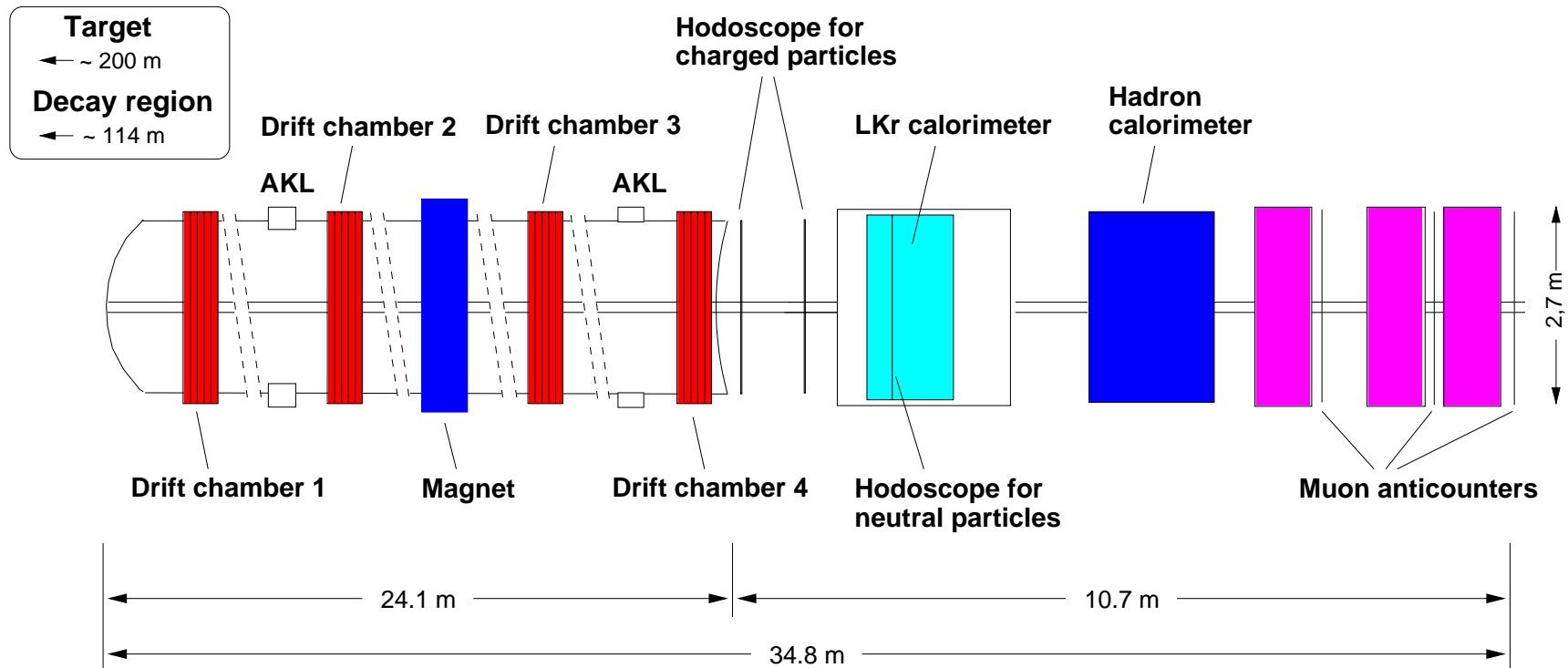
## NA48/2 (2003-2004)

- **Final results!**

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

1997	$\epsilon'/\epsilon$ run	$K_L + K_S$
1998	$\epsilon'/\epsilon$ run	$K_L + K_S$
1999	$\epsilon'/\epsilon$ run $K_L + K_S$	$K_S$ Hi. Int.
2000	$K_L$ only	$K_S$ High Intensity NO Spectrometer
2001	$\epsilon'/\epsilon$ 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 $\eta_{+-}$

## Definition

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

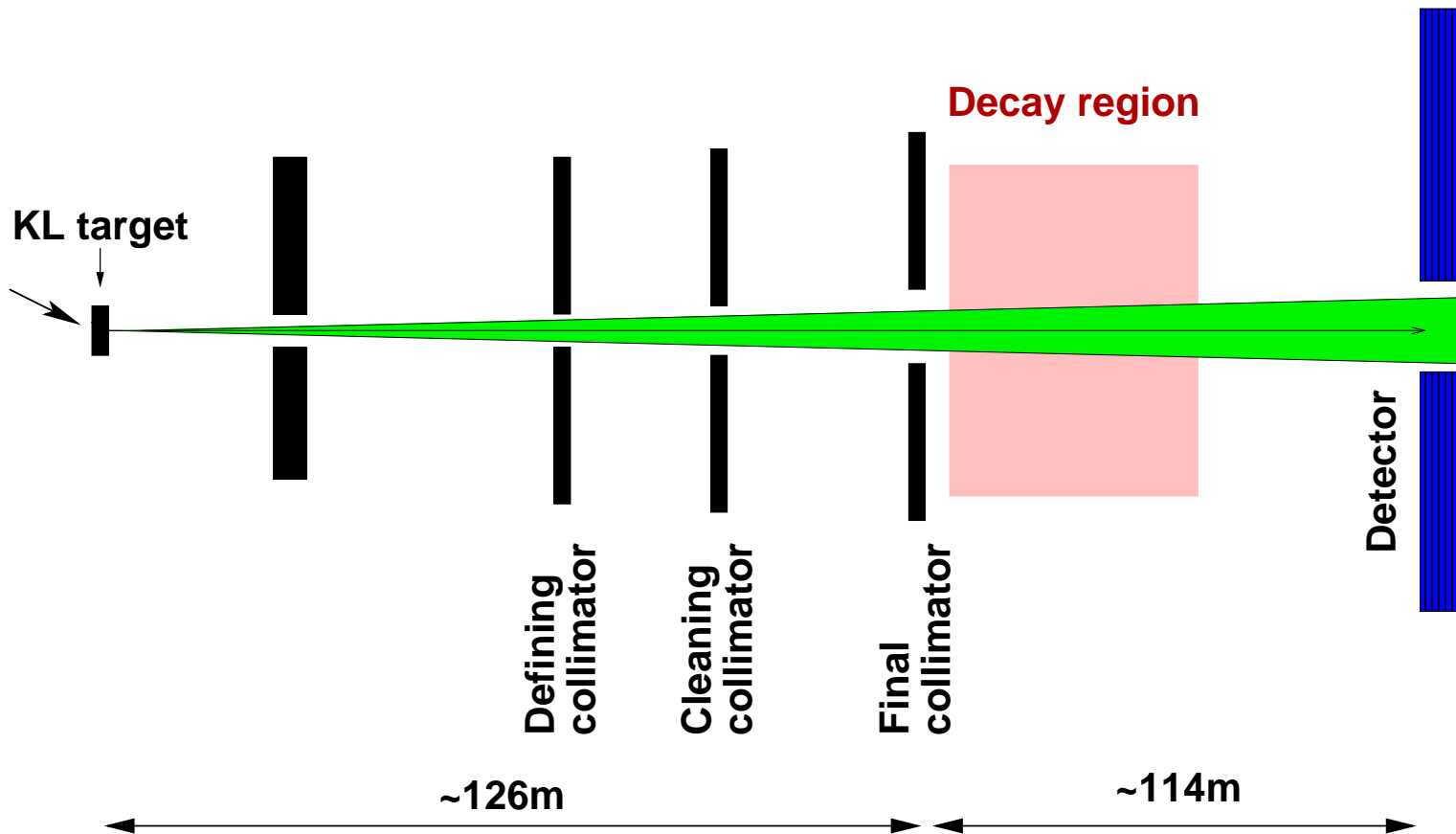
$$\eta_{+-} := \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \qquad \eta_{+-} = \epsilon + \epsilon'$$

## What we measure

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

# NA48 beam line for pure $K_L$ beam

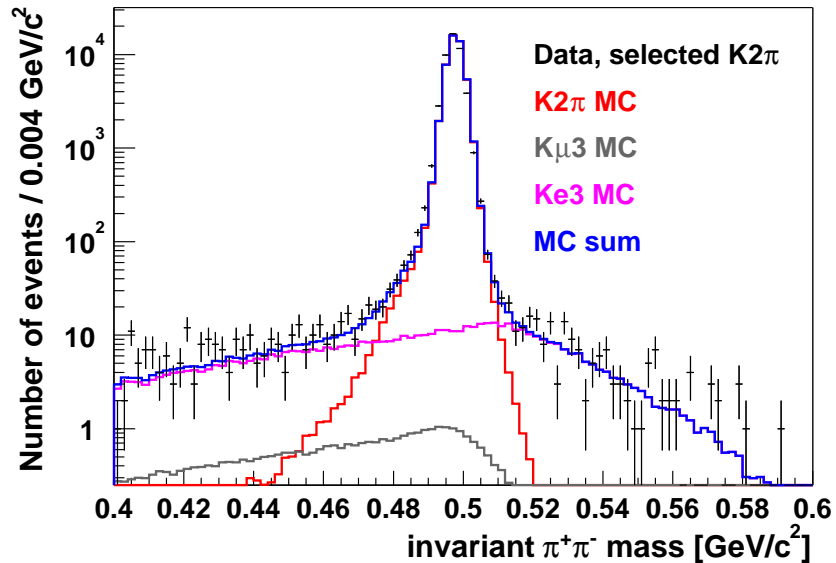
- Special run 1999 (two days) with **pure  $K_L$  beam** at low intensity
- Simple trigger condition: minimum bias trigger to select only **events with two charged tracks** ( $\sim 80$  million events)



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

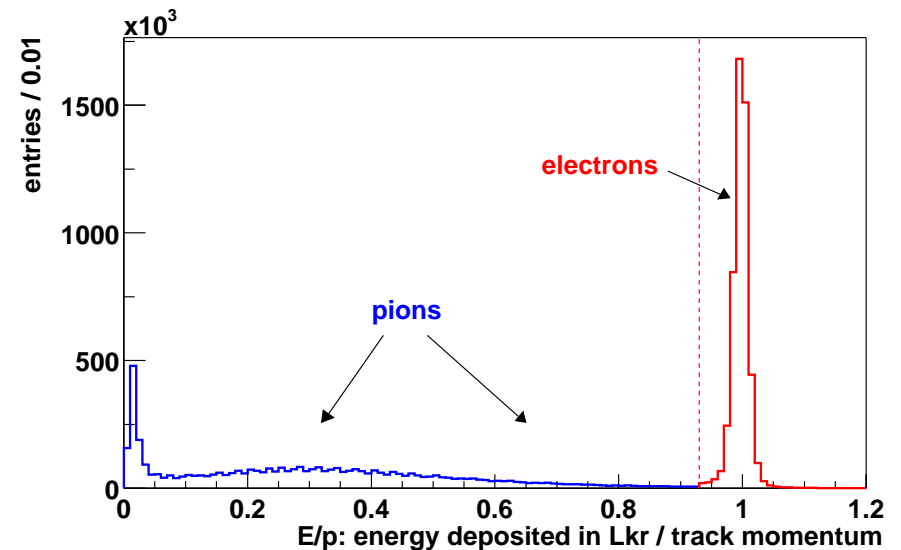
$$\underline{K_L \rightarrow \pi^+ \pi^-}$$

- 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



$$\underline{K_L \rightarrow \pi^\pm e^\mp \nu}$$

- Selection of  $K_{e3}$  decays via ratio E/p (energy in electromagnetic calorimeter over track momentum)  
→ E/p  $\sim 1$  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)

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

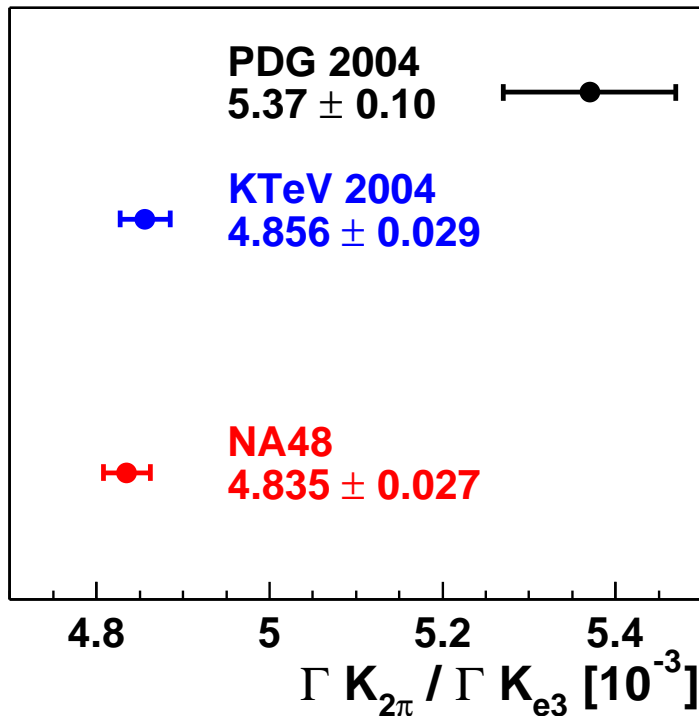
$$BR(K_L \rightarrow \pi^+ \pi^-) = \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi e \nu)} \cdot BR(K_L \rightarrow \pi e \nu)$$
$$= (1.941 \pm 0.019) \times 10^{-3}$$

- Includes  $\pi^+ \pi^- \gamma$  (IB) component, IB = Inner Bremsstrahlung
- Direct Emission (DE) component, which is (mostly) CP-conserving, was subtracted
- Take updated NA48 result  $BR(K_L \rightarrow \pi e \nu) = 0.4022 \pm 0.0031$  due to better knowledge of  $BR(K_L \rightarrow 3\pi^0)$   
(published in Phys.Lett.B 602:41-51, 2004)

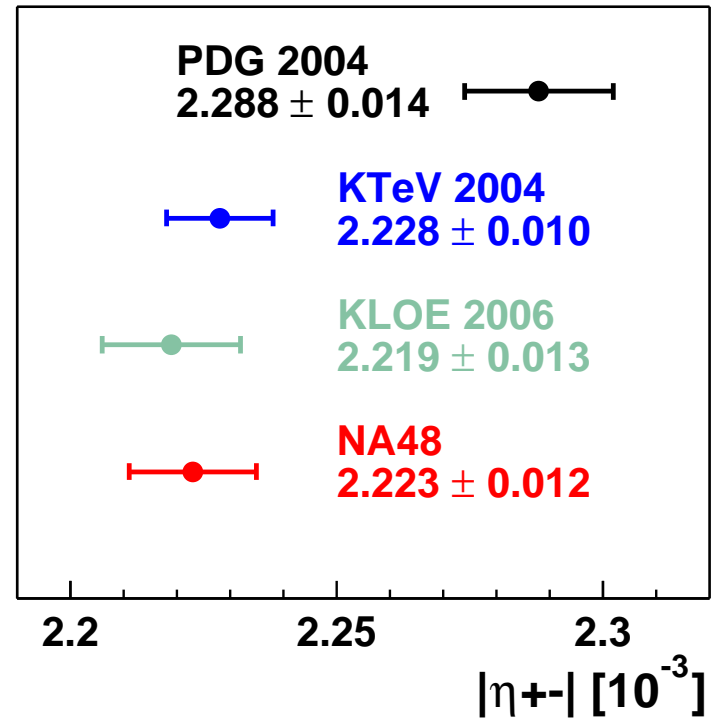
$$|\eta_{+-}| = \sqrt{\frac{\tau_{KS}}{\tau_{KL}} \cdot \frac{BR(K_L \rightarrow \pi^+ \pi^-)}{BR(K_S \rightarrow \pi^+ \pi^-)}} = (2.223 \pm 0.012) \times 10^{-3}$$

# Comparison of results

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



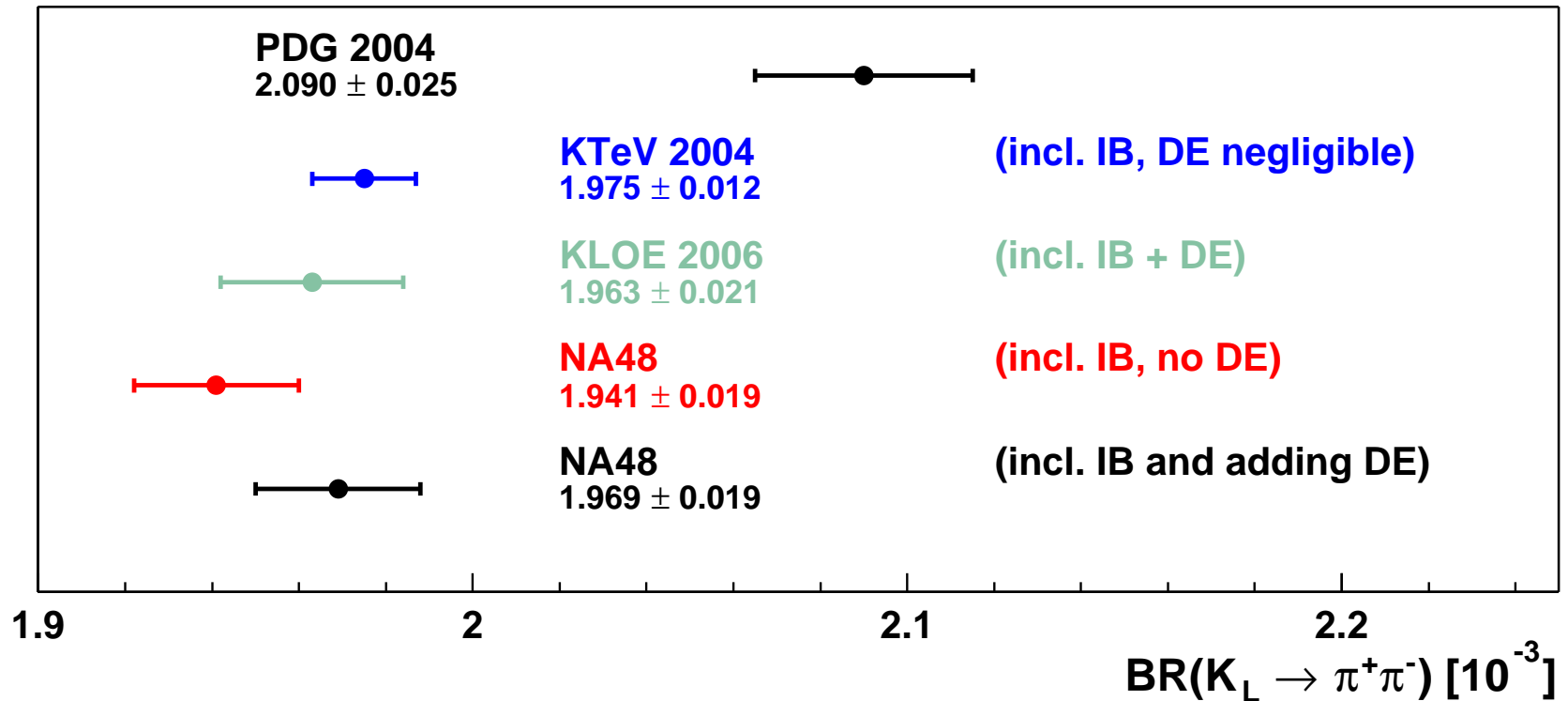
$$|\eta_{+-}|$$



- 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 $K^\pm \rightarrow 3\pi$

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## Why look at $K^\pm \rightarrow 3\pi$ decays ?

- Potentially large statistics  
( $BR(K^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = 5.57\%$ ;  $BR(K^\pm \rightarrow \pi^\pm \pi^0 \pi^0) = 1.73\%$ )
- 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

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

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

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

## Observable for direct CPV

- Measure the slope asymmetry :

$$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

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

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

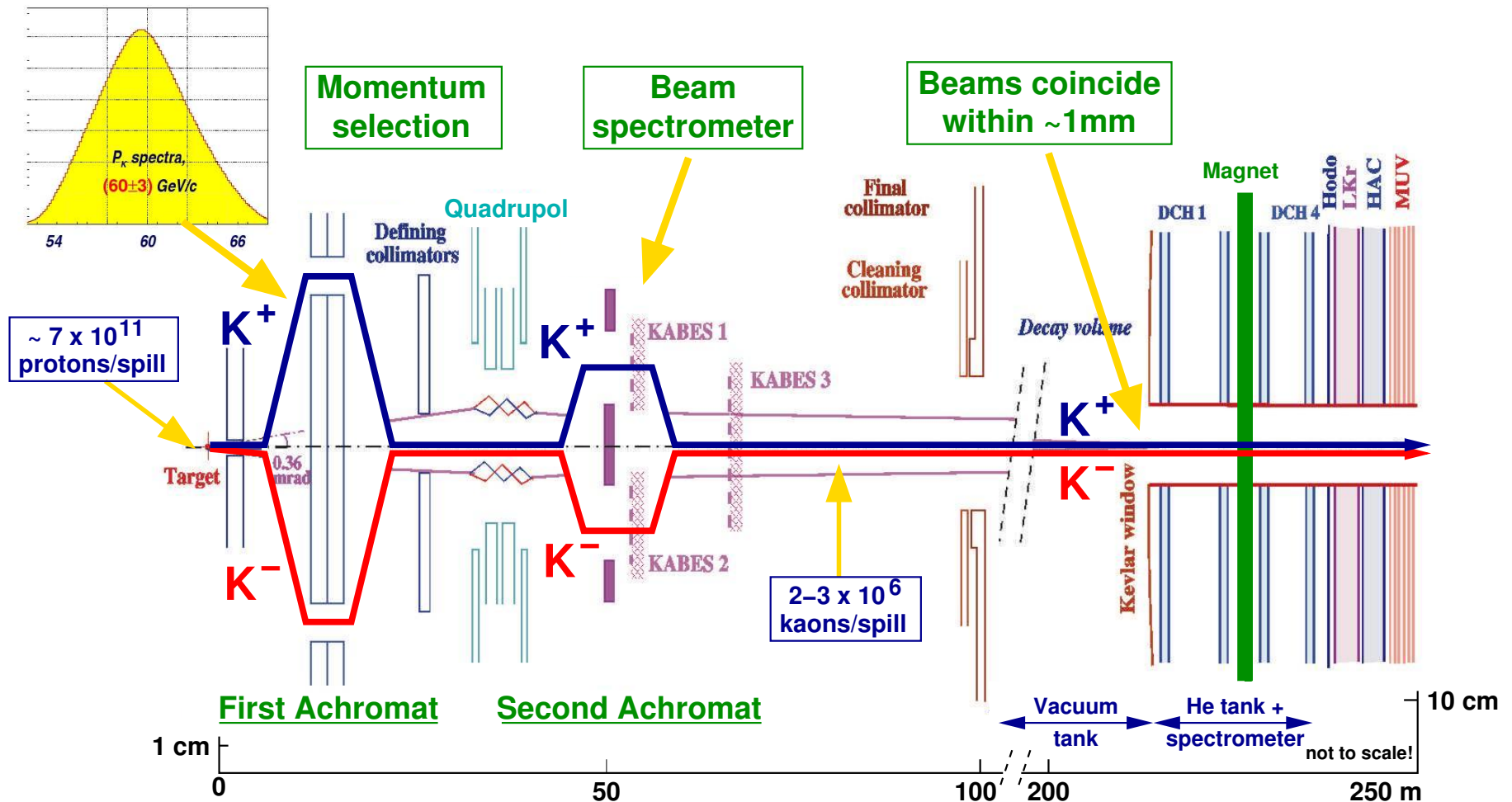
- SM prediction for  $A_g$  between  $10^{-6}$  und  $10^{-5}$
- Theoretical calculations involving processes beyond the SM do not exclude enhancements of the asymmetry  $A_g$  up to a few  $10^{-4}$   
→ within the reach of this experiment, can test on New Physics !

## 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  $K^+ / K^- \sim 1.8$
- $\sim 100$  days of data taking,  $18 \times 10^9$  triggers and 200 TB recorded



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

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## 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

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

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

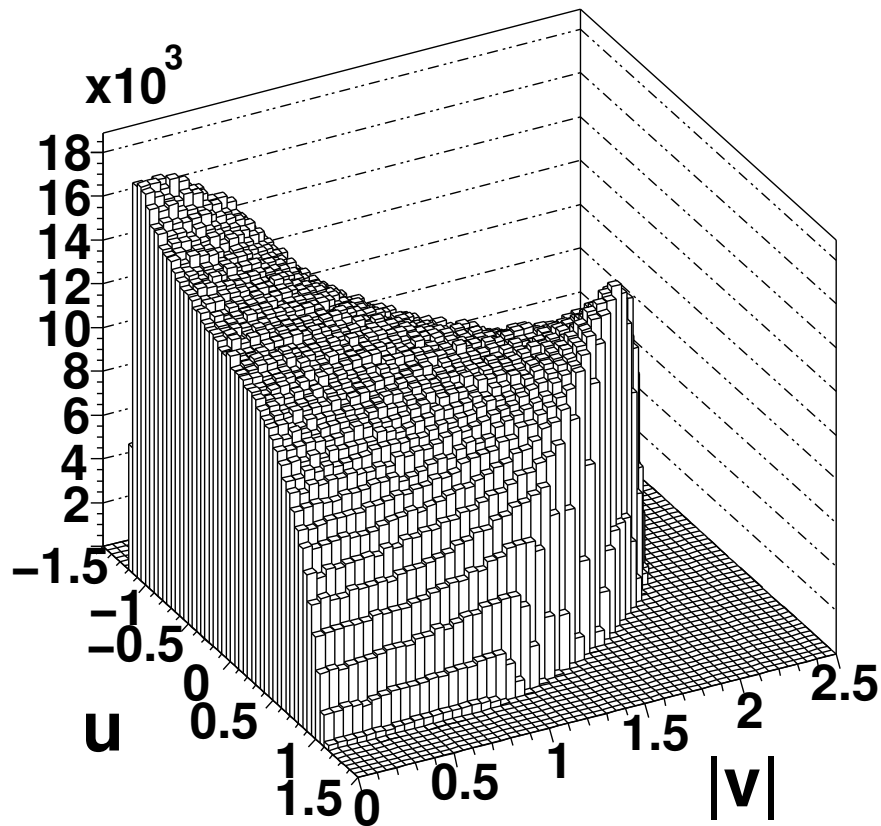
- Compare the reconstructed  $u$ -spectra of  $K^+$  and  $K^-$  decays

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

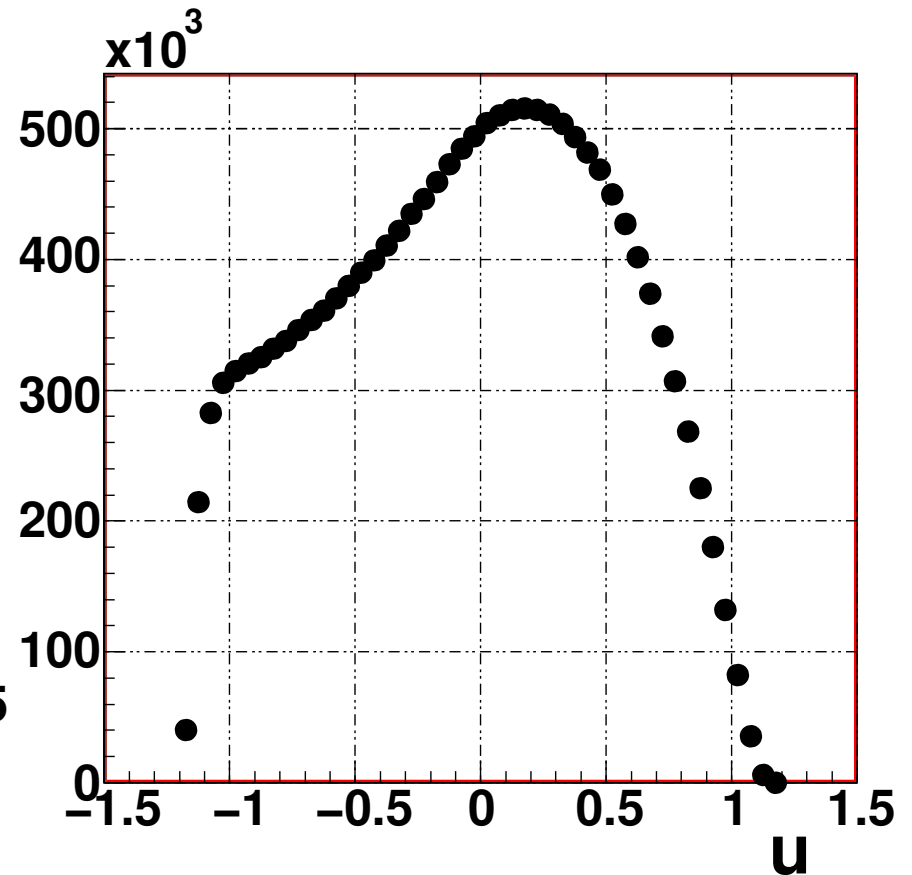
# $K^\pm \rightarrow 3\pi$ decays: Dalitz plot

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

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



Projection to the  $u$  axis



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

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

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

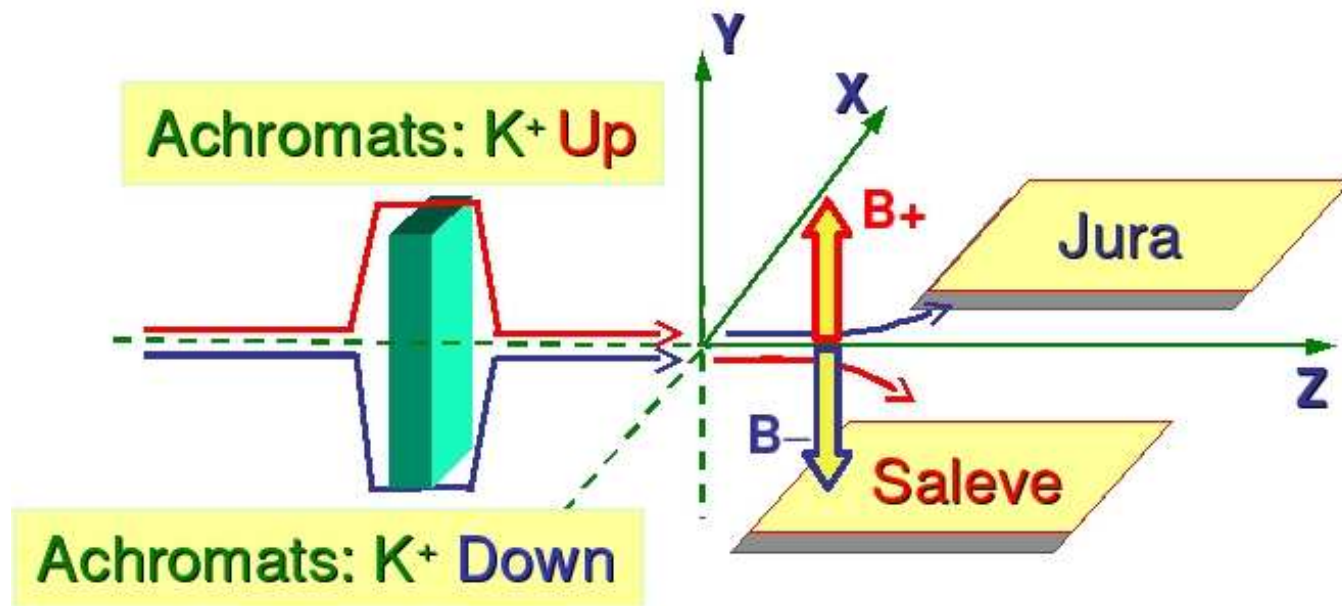
$$R(u) = \frac{N^+(u)}{N^-(u)} \sim 1 + \frac{\Delta g u}{1 + gu + hu^2}$$

- Extract the slope difference  $\Delta g$  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
  - $g(\pi^\pm\pi^0\pi^0) = 0.626 \pm 0.007$ ;     $h(\pi^\pm\pi^0\pi^0) = 0.052 \pm 0.008$
- 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:  $x = U(\text{up}), D(\text{down})$
  - Spectrometer:  $y = J(\text{Jura} = \text{left}), S(\text{Saleve} = \text{right})$



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

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- Define four  $u$ -ratios  $R_{xy}(u)$  with the four possible combinations of magnetic field polarities
  - Achromat:  $x = U(\text{up}), D(\text{down})$
  - Spectrometer:  $y = J(\text{Jura} = \text{left}), S(\text{Saleve} = \text{right})$
- Quadruple ratio  $R_4(u) = R_{US}(u) \cdot R_{UJ}(u) \cdot R_{DS}(u) \cdot R_{DJ}(u)$ 
  - ⇒ Cancellation of global time instabilities + local beamline biases
  - ⇒ Cancellation of left-right detector asymmetries
- Extract  $\Delta g$  by fitting the quadruple ratio with a function

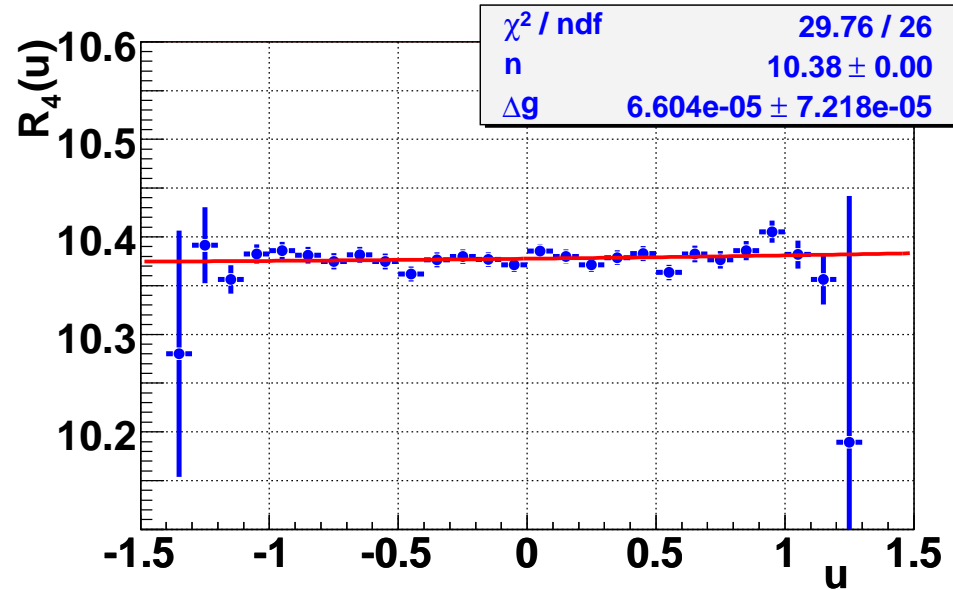
$$f(u) = n \cdot \left( 1 + \frac{\Delta g u}{1 + gu + hu^2} \right)^4$$

## Further advantages

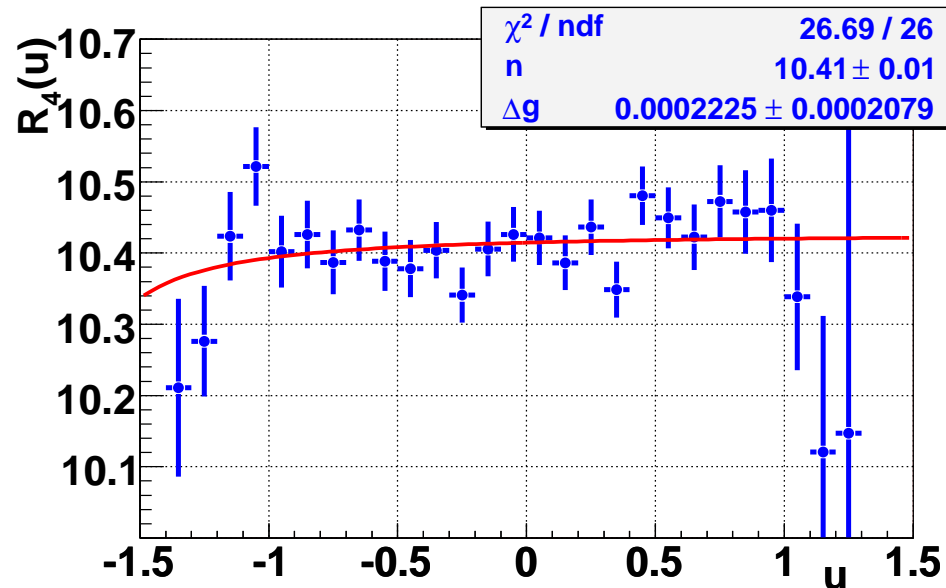
- The method is independent of  $K^+/K^-$  flux ratio
- The analysis does not rely on a detailed Monte-Carlo to calculate acceptances (MC only used to study systematic effects)

# Quadruple ratio in bins of $u$

Charged mode  
( $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ )



Neutral mode  
( $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ )



# Final results for 2003 + 2004

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

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

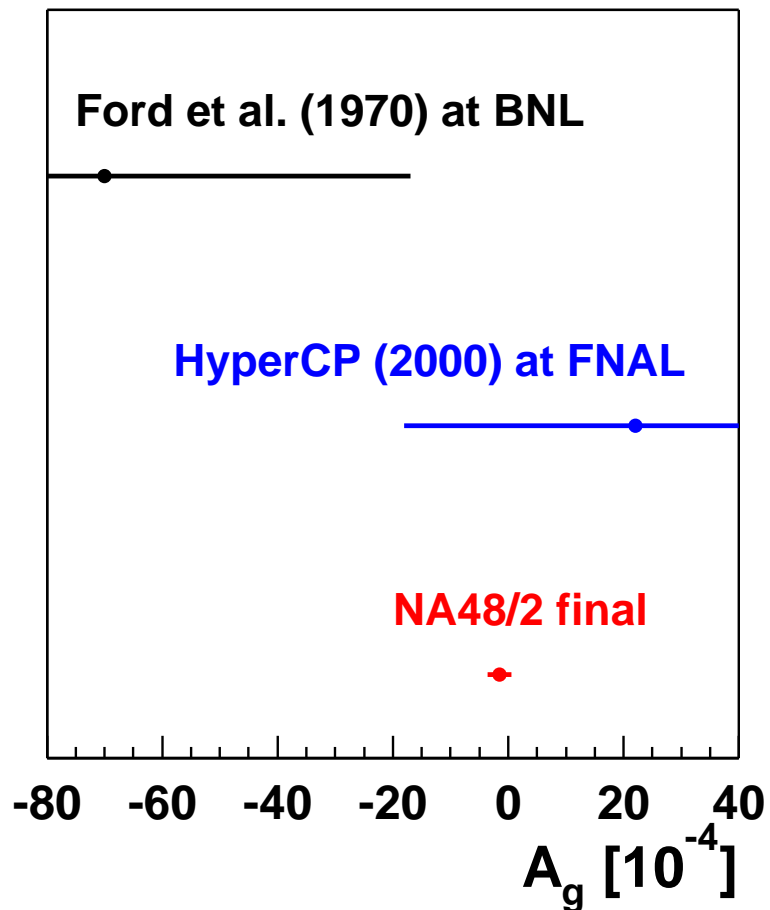
**Neutral mode** ( $9.13 \times 10^7$  selected  $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ )

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

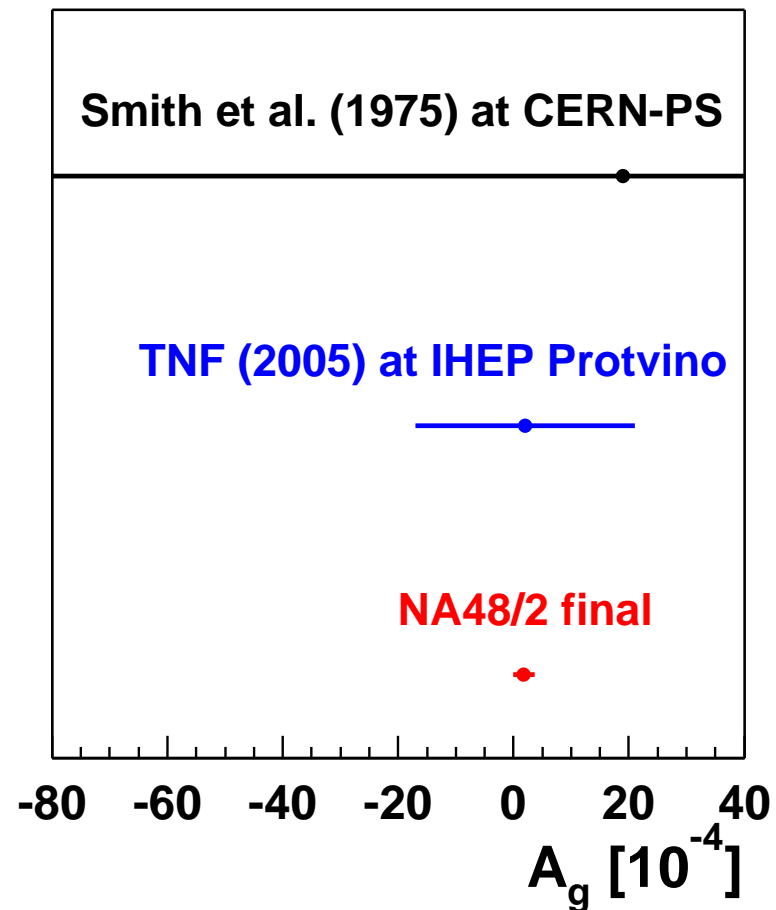
- The design goal has been reached!
- About 10x more precise than previous measurements
- Charged and neutral results are consistent
- Statistical errors dominate in both cases
- Results are compatible with the SM model predictions,  
⇒ no evidence for direct CP violation of the order  $10^{-4}$

# Comparison of results

Charged mode  
( $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ )



Neutral mode  
( $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ )



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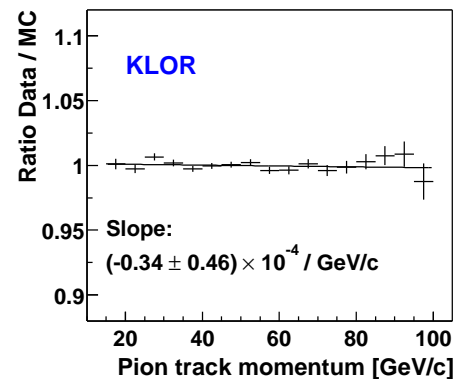
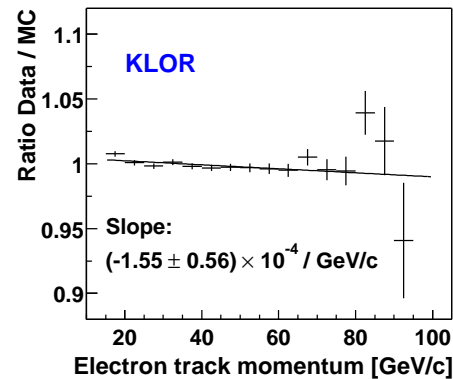
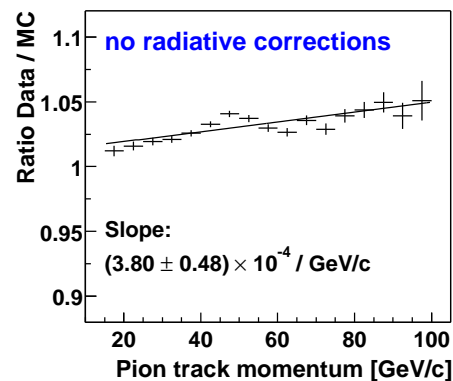
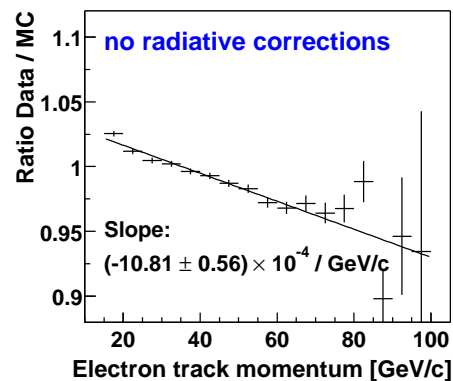
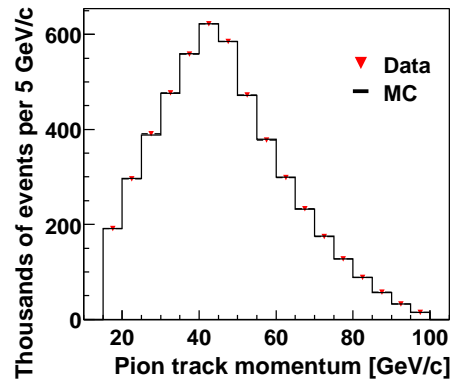
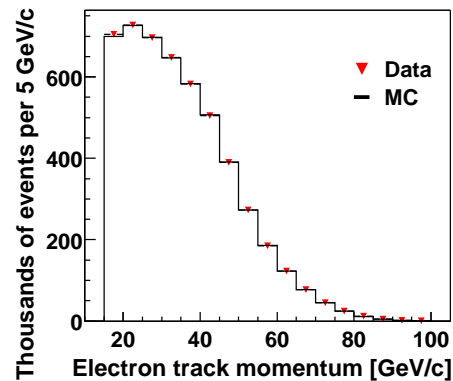
# Spare Slides

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

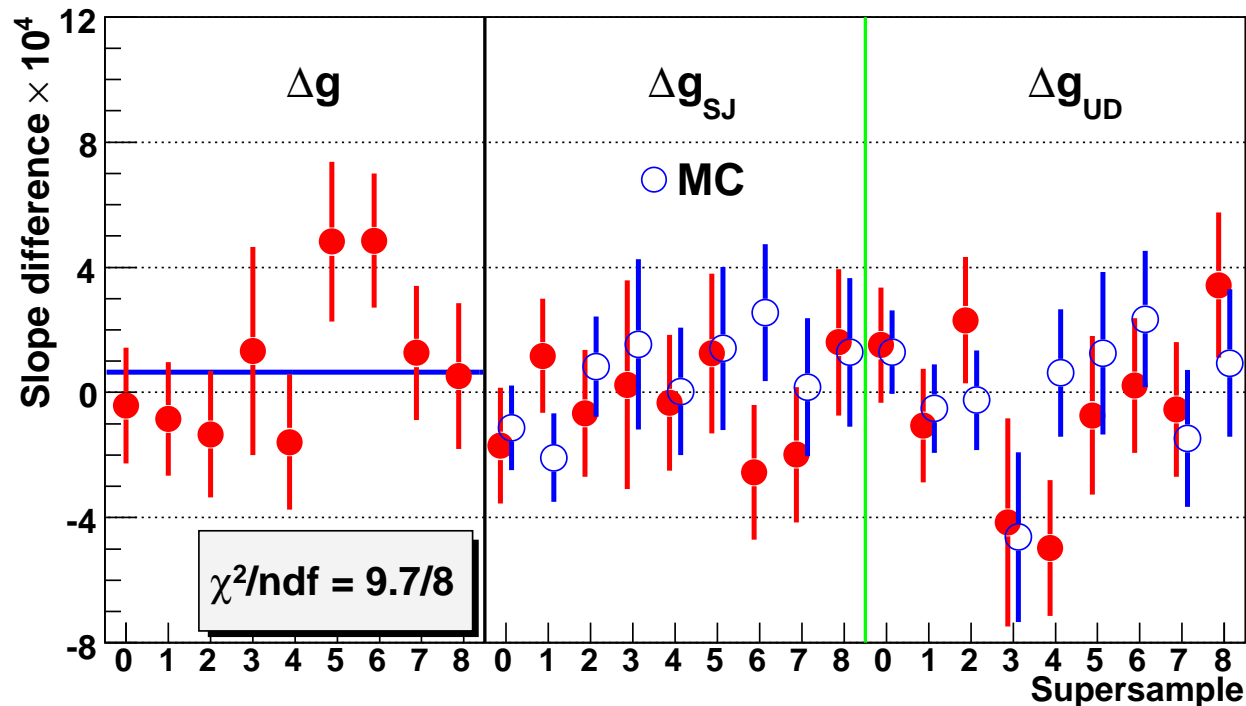
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	Correction [%]	Uncertainty [%]
$E/p$ cut	+ 1.34	0.05
Background in $K_{2\pi}$	- 0.49	0.03
Muon cut	+ 0.48	0.18
Trigger efficiencies	- 1.29	0.11
Energy spectrum	-	0.20
Radiative corrections	-	0.10
MC statistics	-	0.10
Total correction	+ 0.04	0.33

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



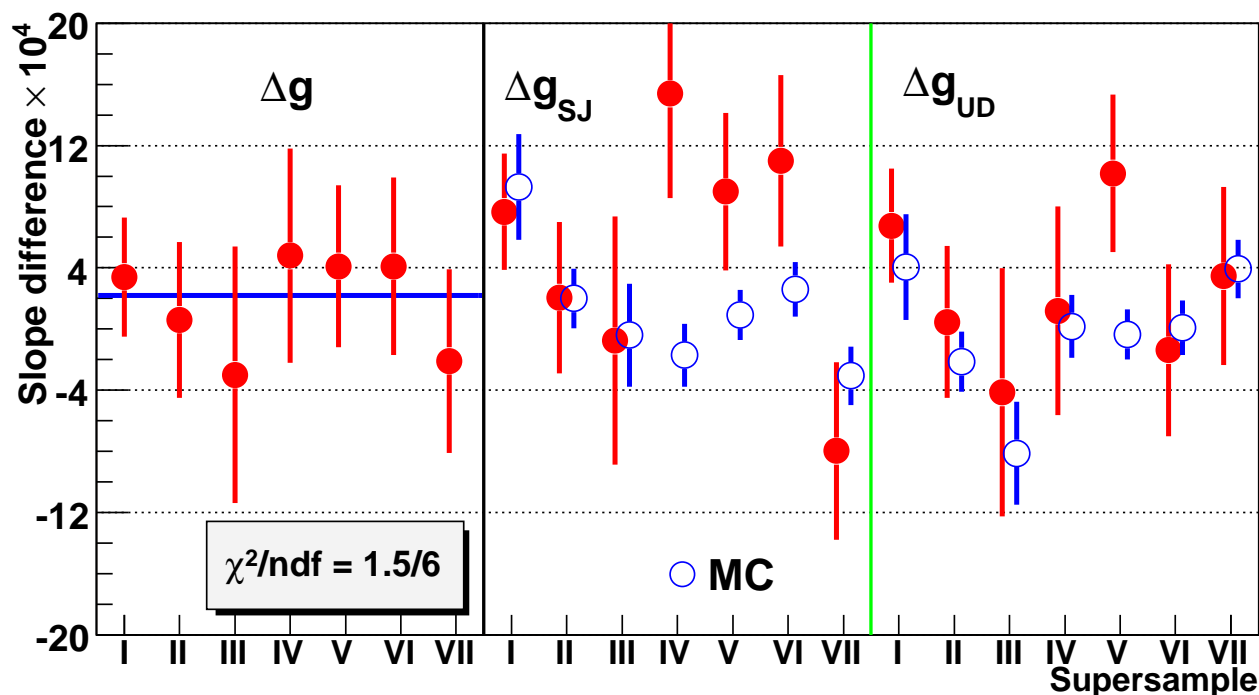
# Asymmetry in $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ : stability checks



- $\Delta g$  extracted from quadruple ratio as function of supersamples 0-8
- $\Delta g_{SJ}$  and  $\Delta g_{UD}$  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



- $\Delta g$  extracted from quadruple ratio as function of supersamples I-VII
- $\Delta g_{SJ}$  and  $\Delta g_{UD}$  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	$\pm 0.1$
Spectrometer magnetic field	$\pm 0.3$
Beam geometry and stray magnetic fields	$\pm 0.2$
Pile-up	$\pm 0.2$
Resolution and fitting	$\pm 0.2$
Total purely systematic uncertainty	$\pm 0.5$
L1 trigger inefficiency	$\pm 0.3$
L2 trigger inefficiency	$-0.1 \pm 0.3$

# Asymmetry in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ : Systematics

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