

# ***CP Violation Results From the NA48 Experiments***

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# OUTLINE

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- 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.

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

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

**New result! (presented)**

## NA48/1 (2002)

- Rare  $K_S$  decays.

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

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

## NA48/2 (2002)

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

**Final result (presented)**

1997	$\varepsilon'/\varepsilon$ run	$K_L + K_S$
1998	$\varepsilon'/\varepsilon$ run	$K_L + K_S$
1999	$\varepsilon'/\varepsilon$ run $K_L + K_S$	$K_S$ Hi. Int.
2000	$K_L$ only	$K_S$ High Intensity <i>NO Spectrometer</i>
2001	$\varepsilon'/\varepsilon$ 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  $\Rightarrow$  efficiency  
 $\sigma(p)/p = 1.0\% + 0.044\% p [\text{GeV}/c]$   
Transversal resolution of decay point  $\approx 2\text{mm}$

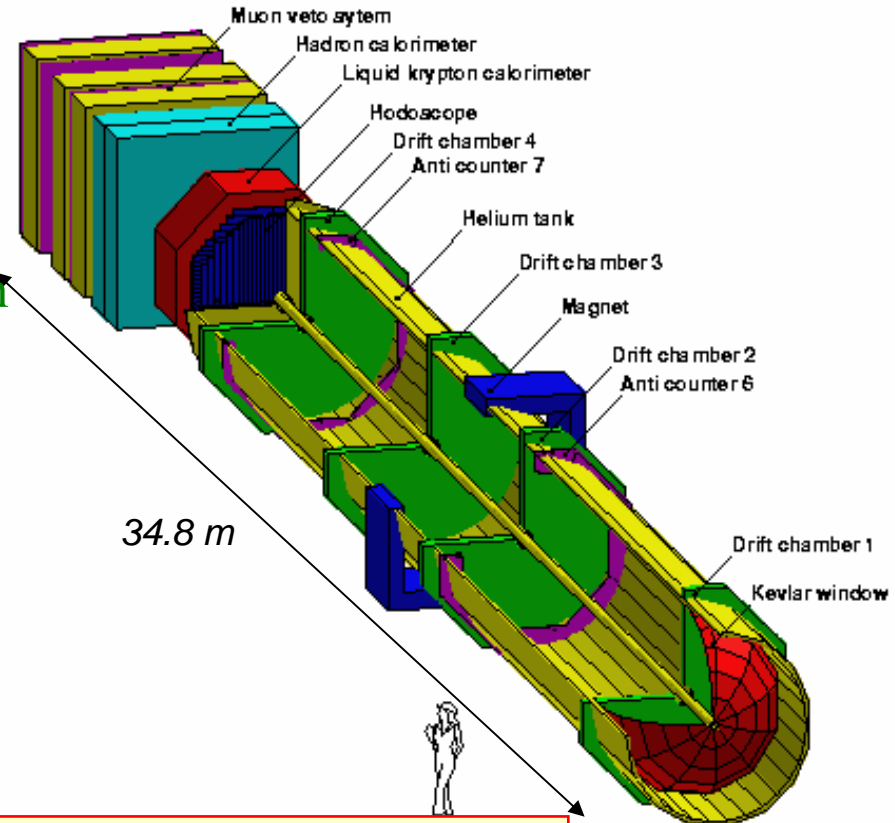
### ❖ Hodoscope:

fast trigger and  
precise time measurement (150ps)

### ❖ Liquid Krypton e.m. calorimeter:

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

### ❖ Hadron calorimeter, photon vetos, muon veto counters



# CP violation parameter $\eta_{+-}$ NA48

# CP violation parameter $\eta_{+-}$

The parameter  $\eta_{+-}$   $\longrightarrow$  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

$$\eta_{+-} = \varepsilon + \varepsilon'$$

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

## Method:

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

# CP violation parameter $\eta_{+-}$

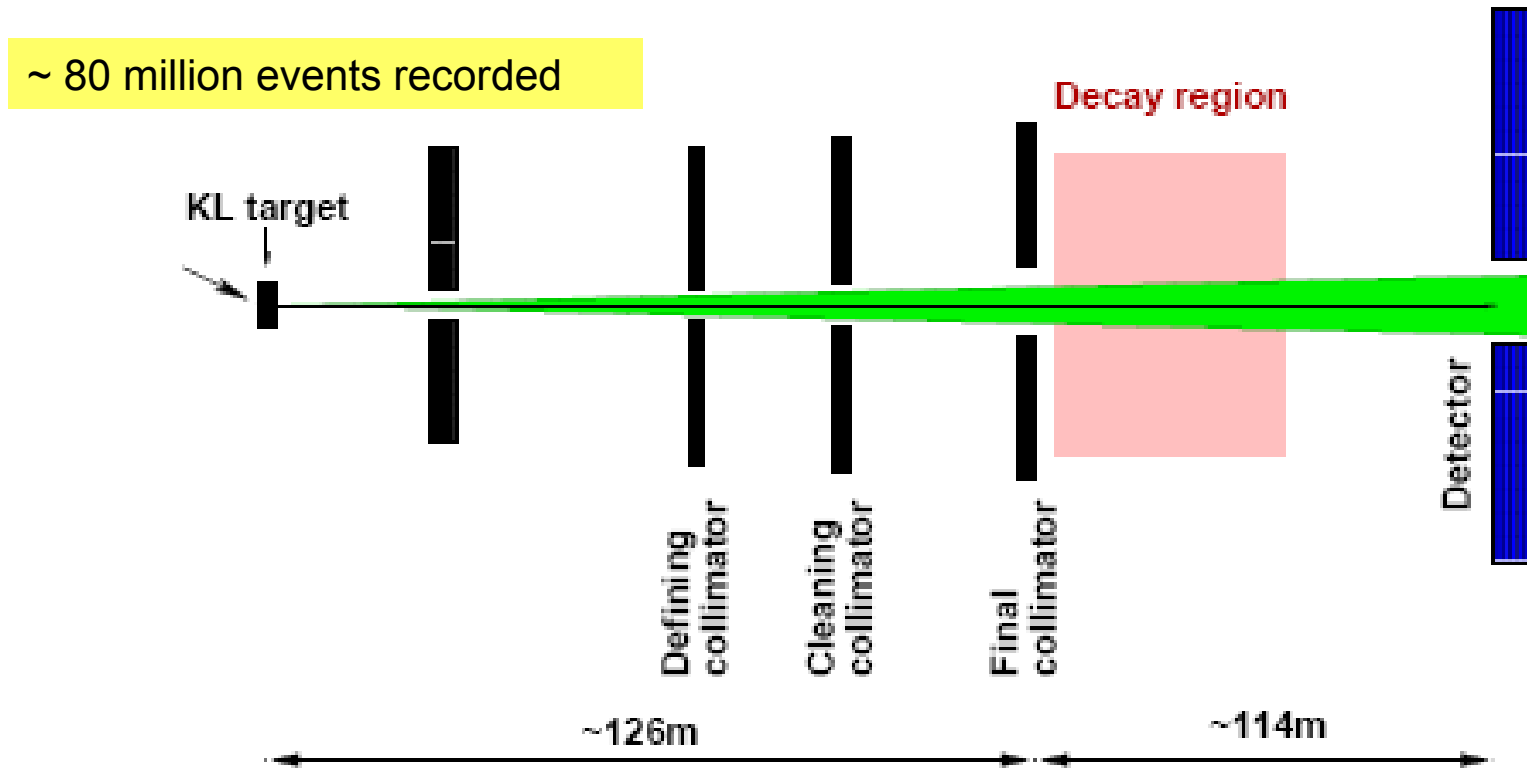
$$|\eta_{\pm}| = \sqrt{\frac{BR(K_L \rightarrow \pi^+ \pi^-)}{BR(K_S \rightarrow \pi^+ \pi^-)} \times \frac{\tau_{KS}}{\tau_{KL}}}$$

- 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);
- $BR(K_L \rightarrow \pi e \nu) = 0.4022 \pm 0.0031$  (NA48 '04 + improved  $K_L \rightarrow 3\pi^0$ : KTeV, KLOE);
- $BR(K_S \rightarrow \pi^+ \pi^-) = 0.69196 \pm 0.00051$  (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



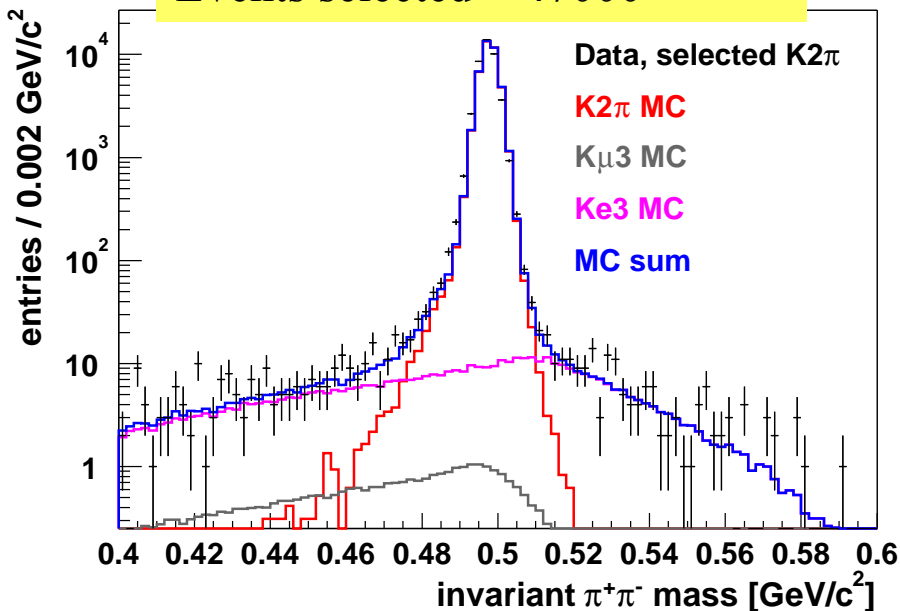


# $\Gamma_{K2\pi}/\Gamma_{Ke3}$ event selection

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

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

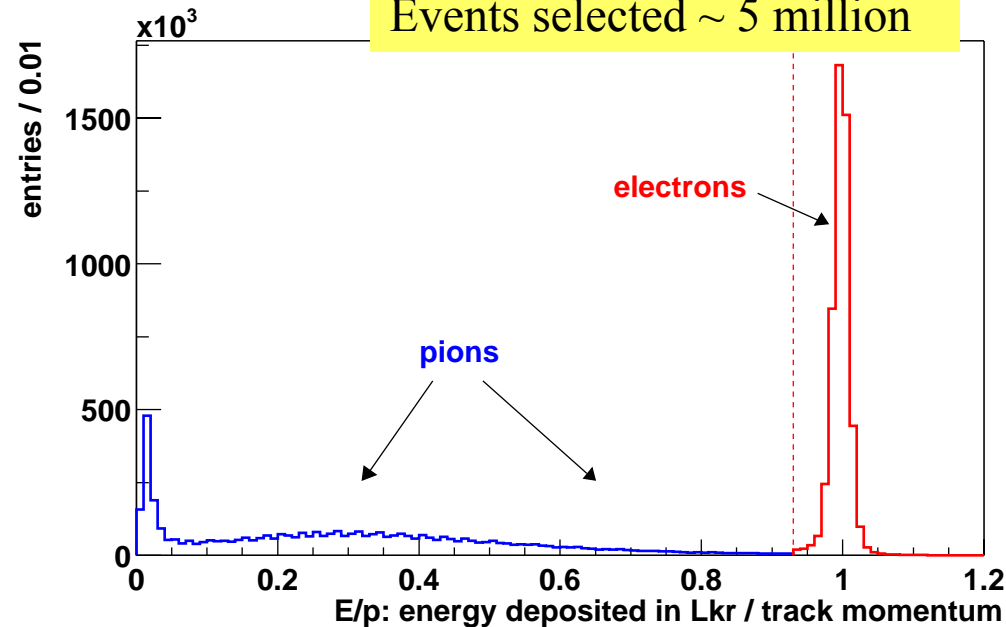
Events selected  $\sim 47000$



## $K_L \rightarrow \pi e \nu$

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

Events selected  $\sim 5$  million



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

The directly measured value:

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

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:

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

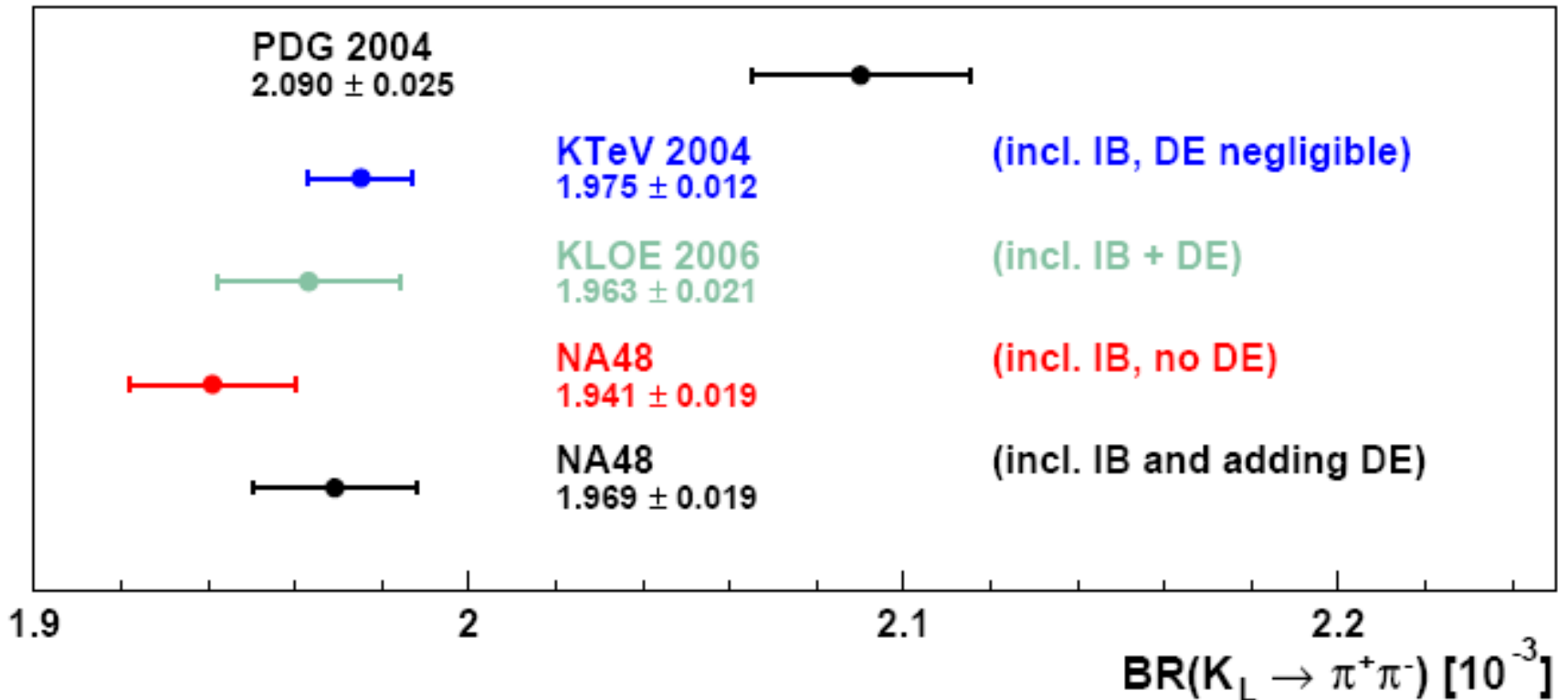
- Includes the  $\pi^+ \pi^- \gamma$  (IB) component;
- Direct emission (CP conserving) component was subtracted.

The CP violation parameter:

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

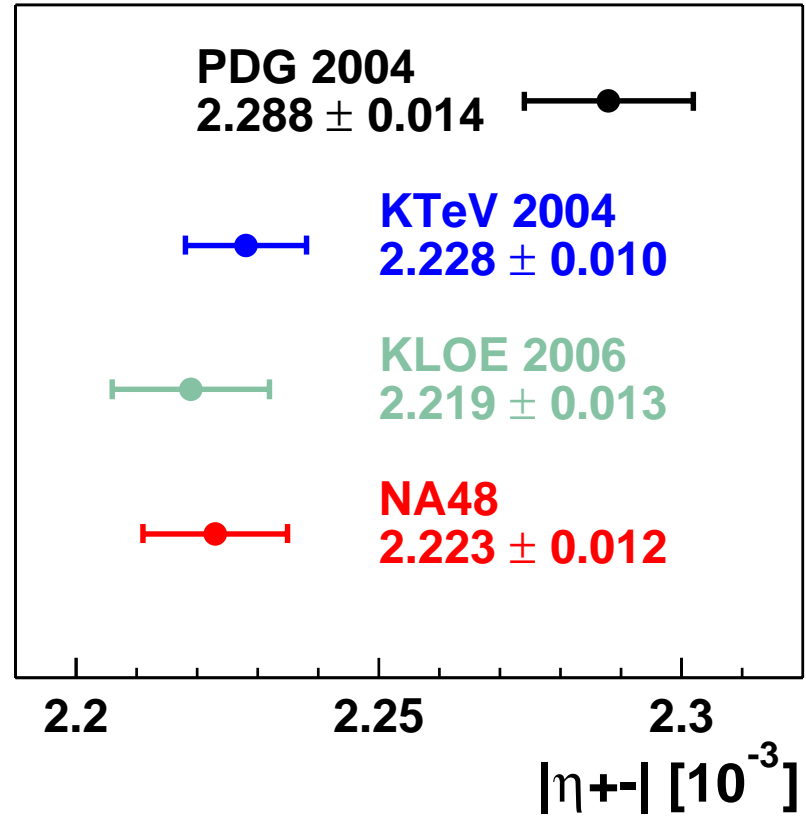
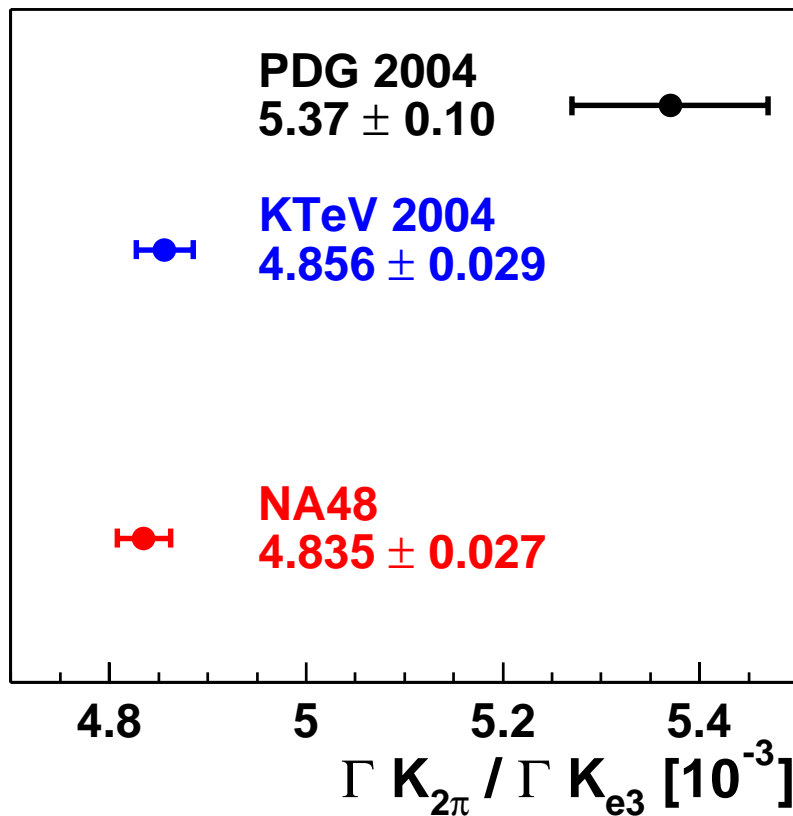
# Comparison of results

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



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 $K^\pm \rightarrow 3\pi$

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

➤ Simple selection

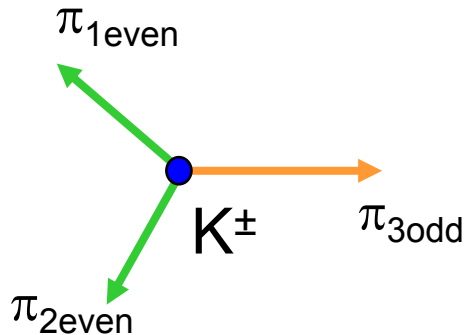
➤ Low background

### Method:

No absolute kaon flux measurement

➔ Compare only Dalitz plot shapes between  $K^+/K^-$

# Dalitz variables



## Matrix element:

$$|\mathbf{M}(\mathbf{u}, \mathbf{v})|^2 \sim 1 + \mathbf{g}\mathbf{u} + \mathbf{h}\mathbf{u}^2 + \mathbf{k}\mathbf{v}^2$$

With  $|\mathbf{h}|, |\mathbf{k}| \ll |\mathbf{g}|$

## Kinematics:

$$s_i = (P_K - P_{\pi_i})^2, \quad i=1,2,3 \quad (3=\text{odd } \pi);$$

$$s_0 = (s_1 + s_2 + s_3)/3;$$

$$\mathbf{u} = (s_3 - s_0)/m_\pi^2;$$

$$\mathbf{v} = (s_2 - s_1)/m_\pi^2.$$

## Kaon rest frame:

$$\mathbf{u} = 2m_K \cdot (m_K/3 - E_{\text{odd}})/m_\pi^2;$$

$$\mathbf{v} = 2m_K \cdot (E_1 - E_2)/m_\pi^2.$$

# 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  $\Delta g$
2. Use known value of  $g$
3. Compute  $A_g$

$$A_g \neq 0$$



Direct CP violation

$$\begin{aligned}
 K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \quad & g = (-21.134 \pm 0.017)\% \\
 & h = (1.848 \pm 0.040)\% \\
 & k = (-0.463 \pm 0.014)\%
 \end{aligned}$$

Phys. Lett. B649 (2007) 349-358

## Na48/2 Results for Slopes

- agreement with PDG
- factor 10 smaller uncertainties
- first evidence of  $h \neq 0$

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

PDG value



# Theory & Experiments

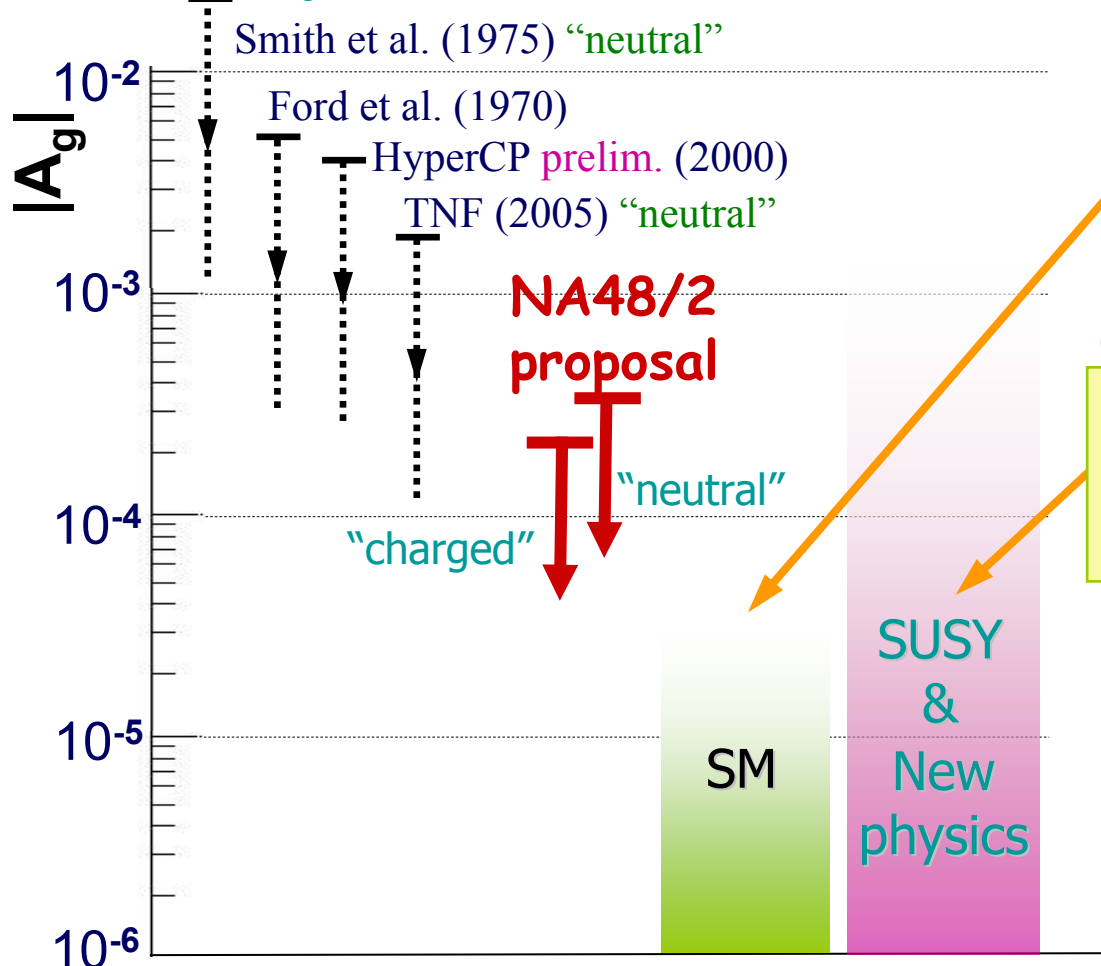
Experimental precisions before NA48/2:  
 $[\delta A_g \sim 10^{-3}, \text{ dominated by systematics}]$

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

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## ➤ 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 guarantee perfect charge symmetrization in the experimental setup and eliminate the remaining acceptance differences by a smart analysis technique.

# Goal and method

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## •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.

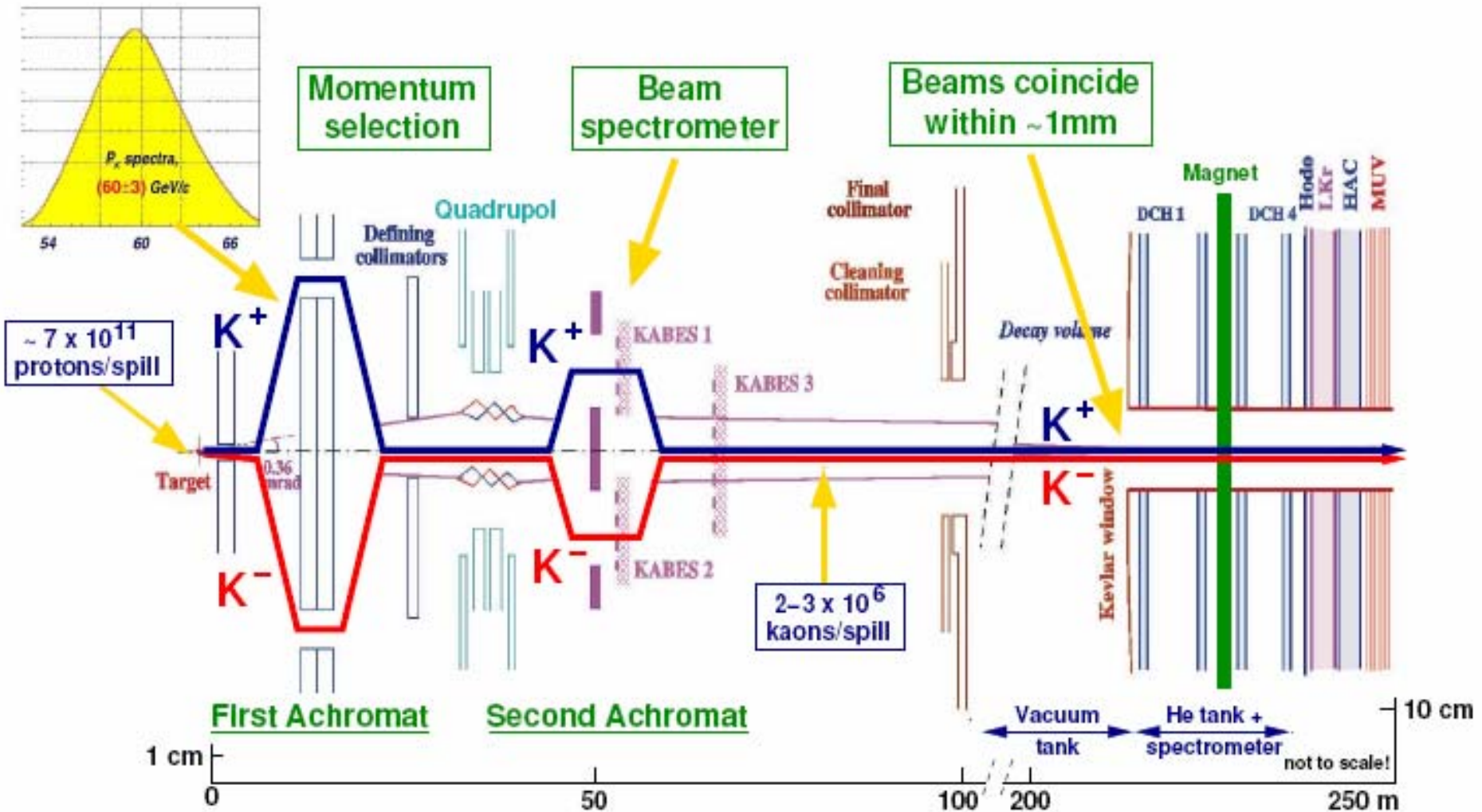
## •Event selection

- 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**

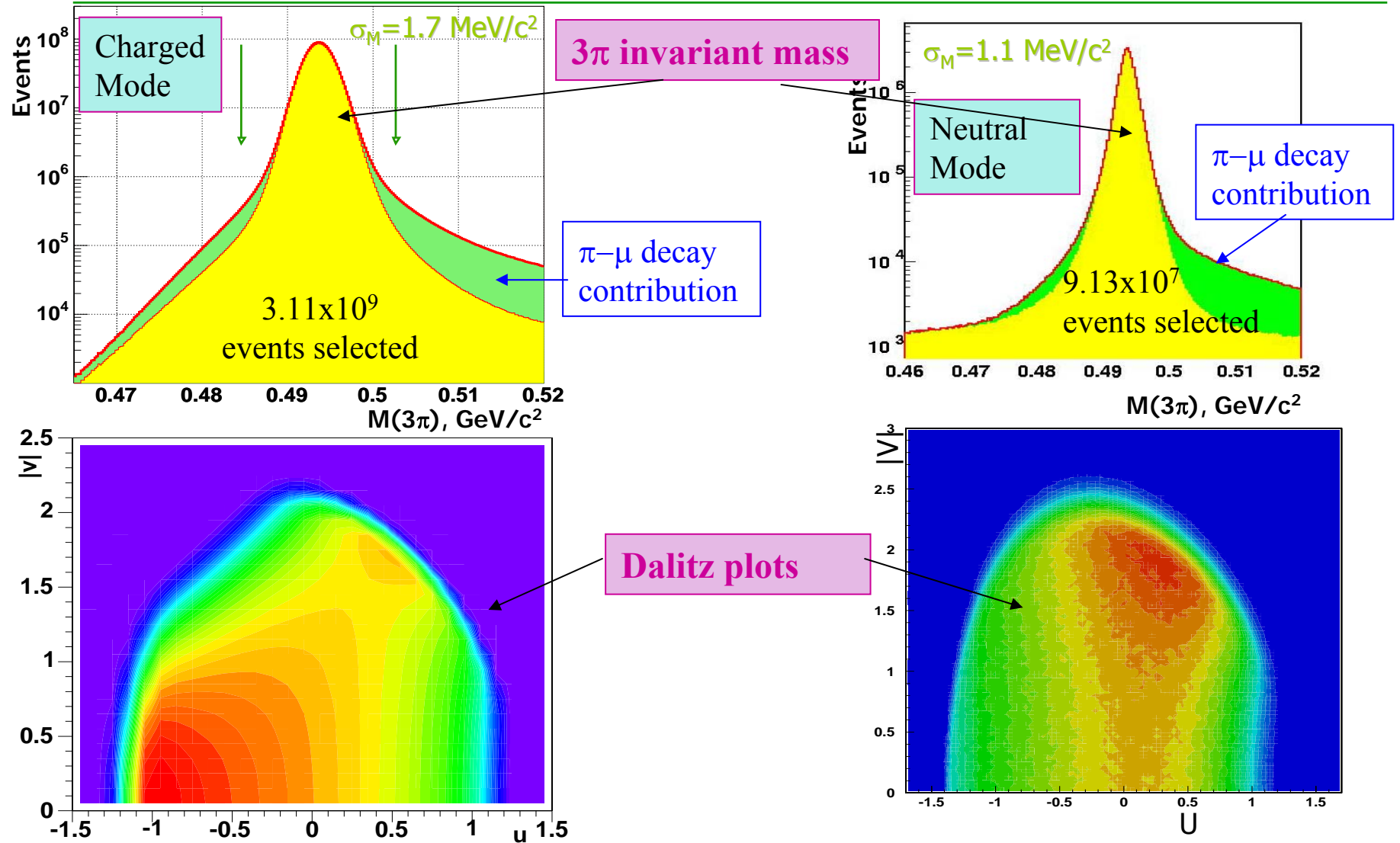
## •Extraction of $A_g$

- 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



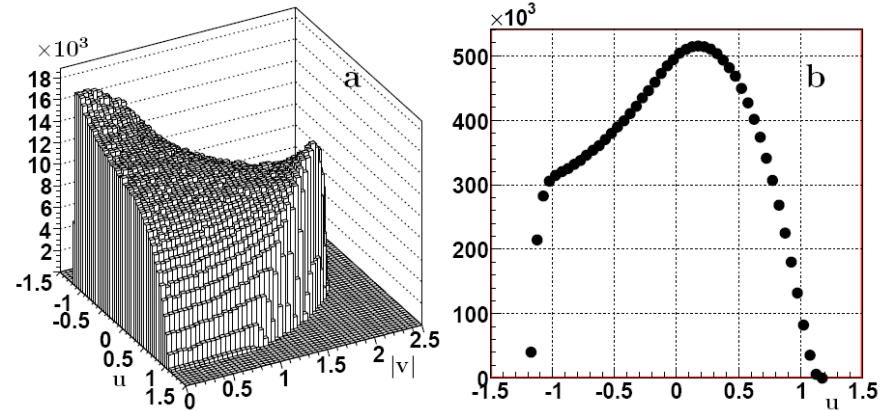
# Selected events properties



# 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 a function to extract  $\Delta g$   
(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

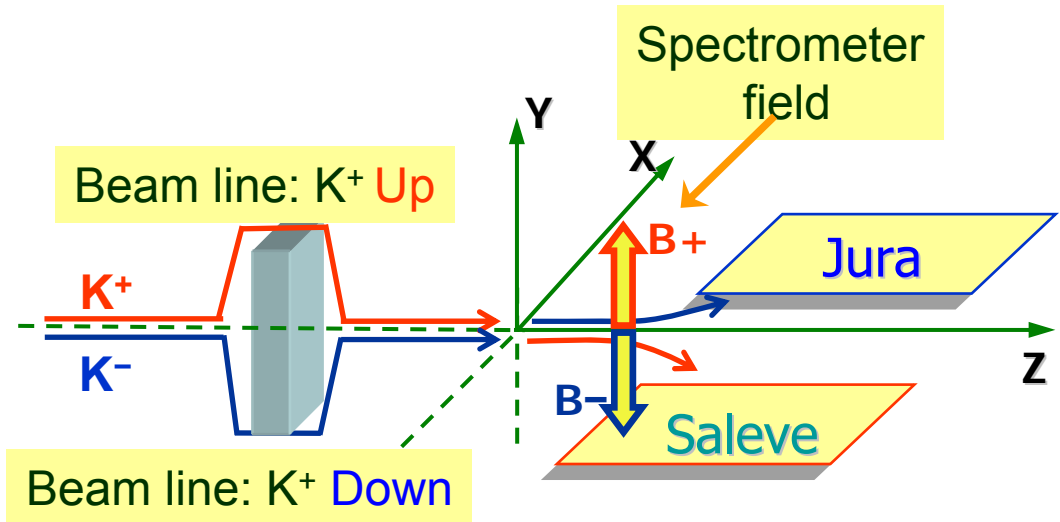
Define 4  $u$ -ratios  $R_{xy}(u)$  with the 4 possible combinations of magnetic field polarities.

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

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

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

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



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  $\Delta g$  fitting the quadruple ratio with a function

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

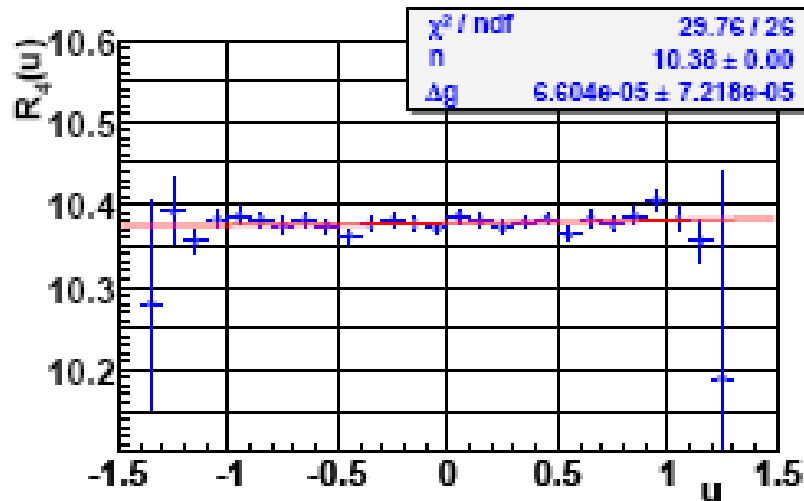
- ◆ Advantages :

- ⇒ 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.

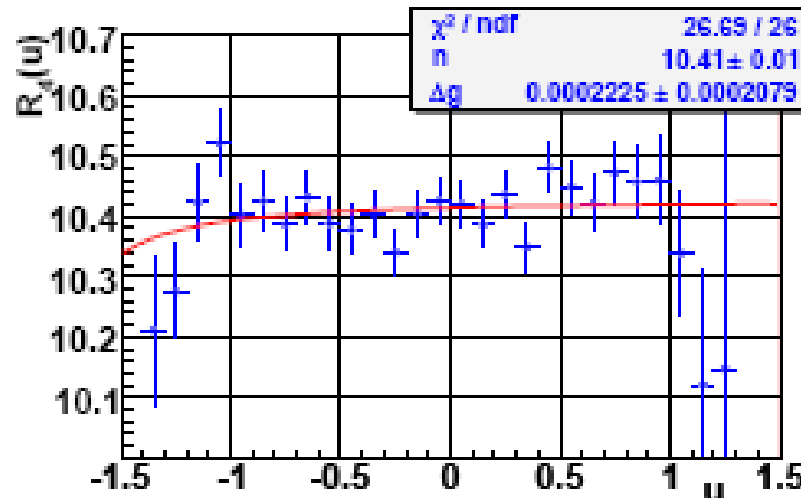


# Quadruple ratios in bins of $u$

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

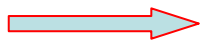


Neutral mode  
( $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ )



# 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 ( $3.11 \times 10^9$  selected  $K^\pm \rightarrow p^\pm p^+ p^-$ )

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

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

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

- ✓ 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

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

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## 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 final collimator
4.  $15 \text{ GeV}/c \leq p_{\text{trac}} \leq 100 \text{ GeV}/c$

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

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

## $\pi e \nu$ selection :

1.  $E/p > 0.93 \rightarrow$  electron

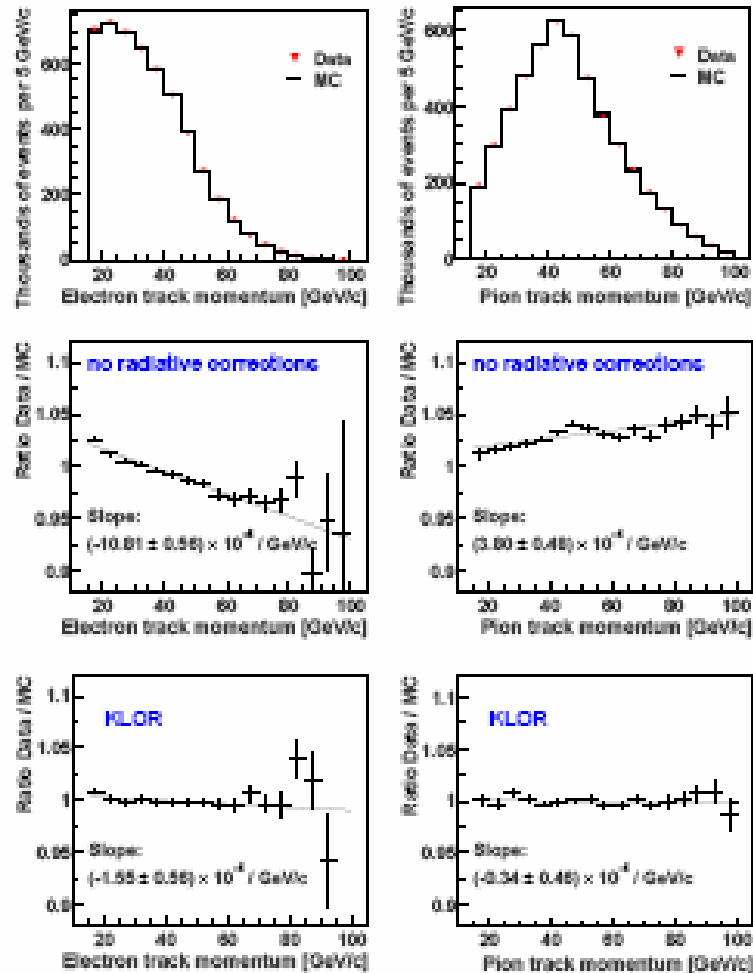
# $\Gamma(K \rightarrow 2\pi)/\Gamma(Ke3)$ systematics

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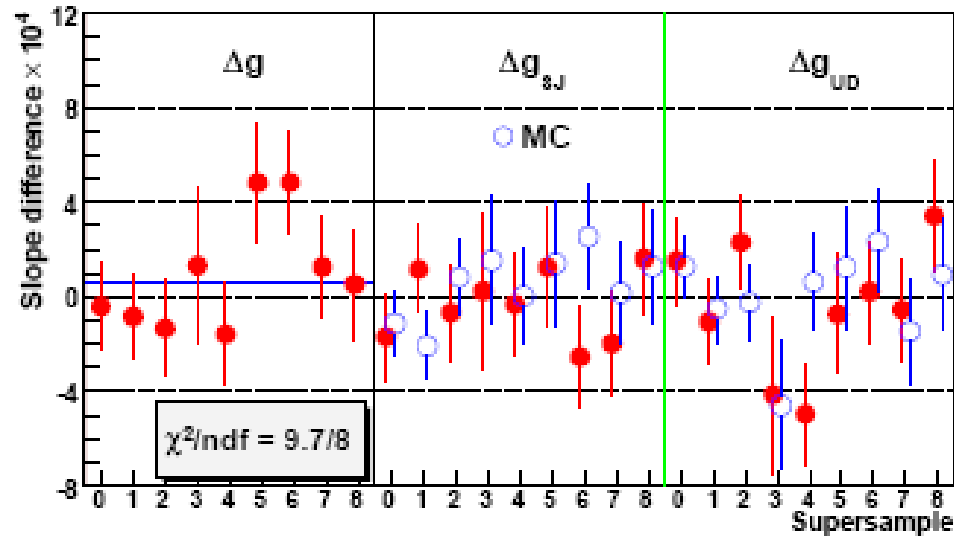
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	Correction [%]	Uncertainty [%]
<i>E/p</i> cut	+ 1.34	0.05
Background in $K_{2\pi}$	- 0.49	0.03
Muon cut	+ 0.48	0.18
Trigger efficiencies	- 1.29	0.11
Energy spectrum	-	0.20
Radiative corrections	-	0.10
MC statistics	-	0.10
Total correction	+ 0.04	0.33

# Radiative corrections in Ke3



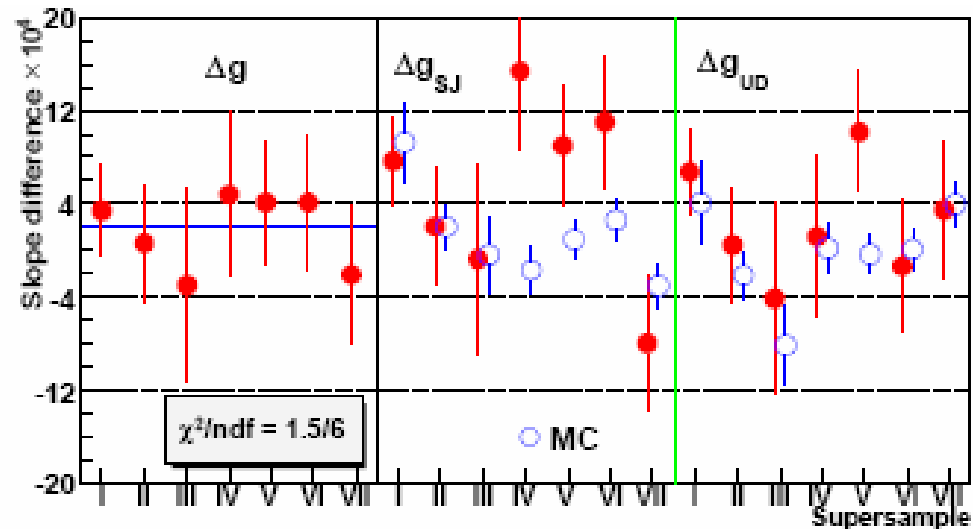
# $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ asymmetry : stability



- $\Delta g$  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 !

# $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ asymmetry : stability



- $\Delta g$  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 !



# $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ asymmetry : systematics

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Systematic effect	Correction, uncertainty $\delta(\Delta g^e) \times 10^4$
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	$-0.1 \pm 0.3$

# $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ asymmetry : systematics

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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	$\pm 0.7$