Symmetry tests in NA48 with kaons

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(on behalf of the NA48 collaboration)

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NA48 - the CP violation experiment

NA48 (1997-2001)

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

NA48/1 (2002)

- Rare K_S and hyperon decays

NA48/2 (2003-2004)

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

Future experiments: NA62 / P326 (2007,...)

- Measurement of $\Gamma(K^{\pm} \to e^{\pm}\nu_e)/\Gamma(K^{\pm} \to \mu^{\pm}\nu_\mu)$
- Measurement of $BR(K^{\pm} \to \pi^{\pm}\nu\bar{\nu})$

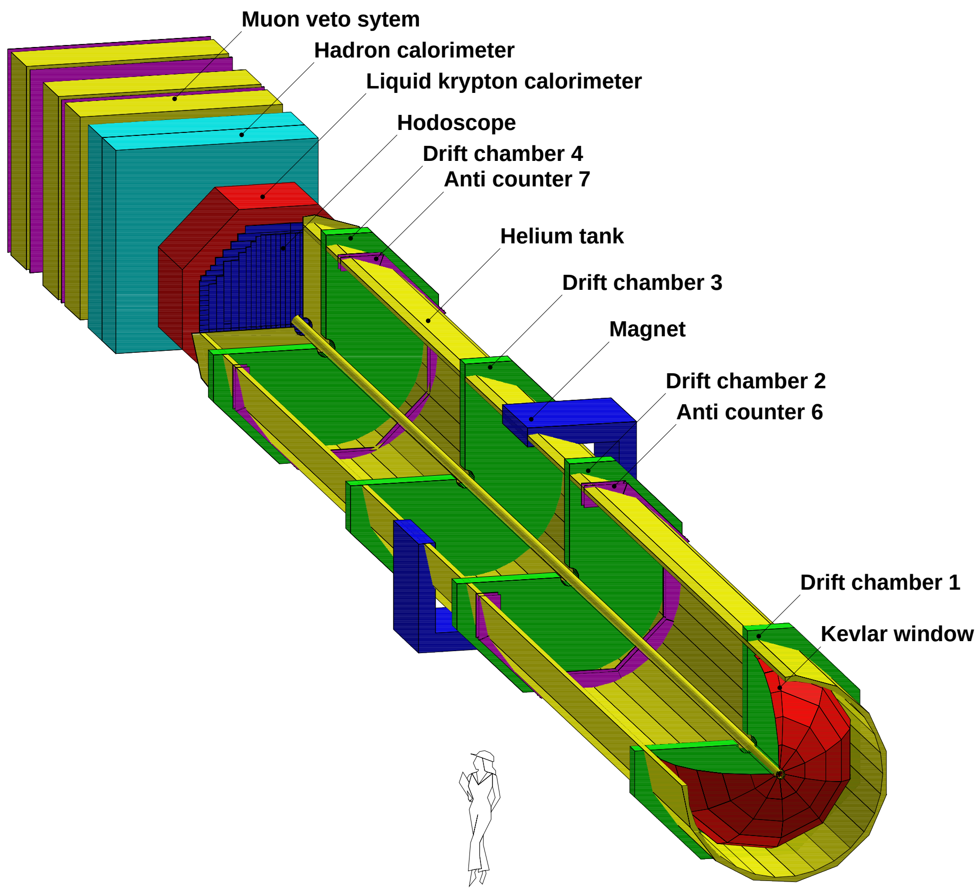
1997	ε'/ε run, $K_L + K_S$
1998	ε'/ε run, $K_L + K_S$
1999	ε'/ε run, $K_L + K_S$; K_S Hi. Int.
2000	K_L only; K_S High Intensity; *NO Spectrometer*
2001	ε'/ε run, $K_L + K_S$; K_S High Int.
2002	K_S High Intensity
2003	$K^{\pm}$ High Intensity
2004	$K^{\pm}$ High Intensity

The NA48 Detector at CERN-SPS

- **Magnet spectrometer**
  with 4 drift chambers
  $$\frac{\sigma(p)}{p} \approx 1-2\%, \quad \text{for typical } p$$

- **Liquid Krypton Calorimeter**
  with ~ 13300 cells
  $$\frac{\sigma(E)}{E} \approx 1\%, \quad \text{for } E \approx 20\,\text{GeV}$$

- **Scintillator hodoscope**
  $$\sigma(t) \approx 200\,\text{ps}$$



CP violation

- CP violation found 1964 by Christensen, Cronin, Fitch and Turlay through decay $K_L \to \pi\pi$

  (In case of CP invariance: $CP(K_L) = -1$ and $CP(\pi\pi) = +1 \quad \Rightarrow \quad K_L \not\to \pi\pi$)

- Why we are interested in CP violation?
  - e.g., the universe consists only of matter, not of matter and anti-matter
  - Sacharov (1967): existence of our universe requires CP violation
  - but: CP violation in SM is too small to explain the matter anti-matter asmmetry in our universe

$\Rightarrow$ What is wrong with the universe, CP violation, SM,... ?

CP violation parameter η_{+-}

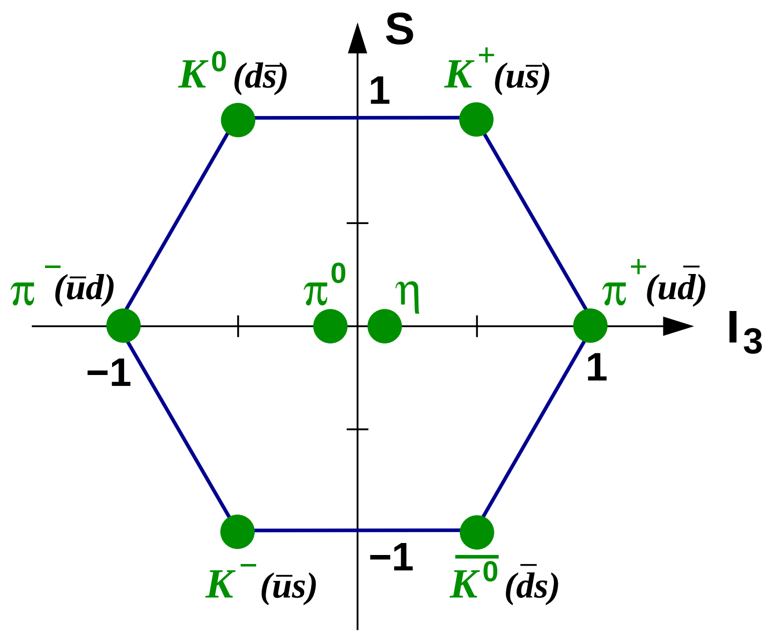
Parameter η_{+-} = fundamental observable of CP violation, defined as the CP-violating ratio of the neutral kaon decaying into two charged pions

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

new measurements (KTeV, 2004 and KLOE, 2006) disagree with PDG

short reminder:

- observed kaons: $K_S = K_1 + \varepsilon K_2$,
  $K_L = K_2 + \varepsilon K_1$
- CP eigenstates: $K_1 = K^0 + \overline{K^0}$, $CP(K_1) = +1$
  $K_2 = K^0 - \overline{K^0}$, $CP(K_2) = -1$
- indirect CP violation: $K_L = K_2 + \varepsilon K_1 \Rightarrow \varepsilon$ ($K_1 \hookrightarrow \pi\pi$)
- direct CP violation: $K_L = K_2 + \varepsilon K_1 \Rightarrow \varepsilon' \; (\ll \varepsilon)$ ($K_2 \hookrightarrow \pi\pi$)



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

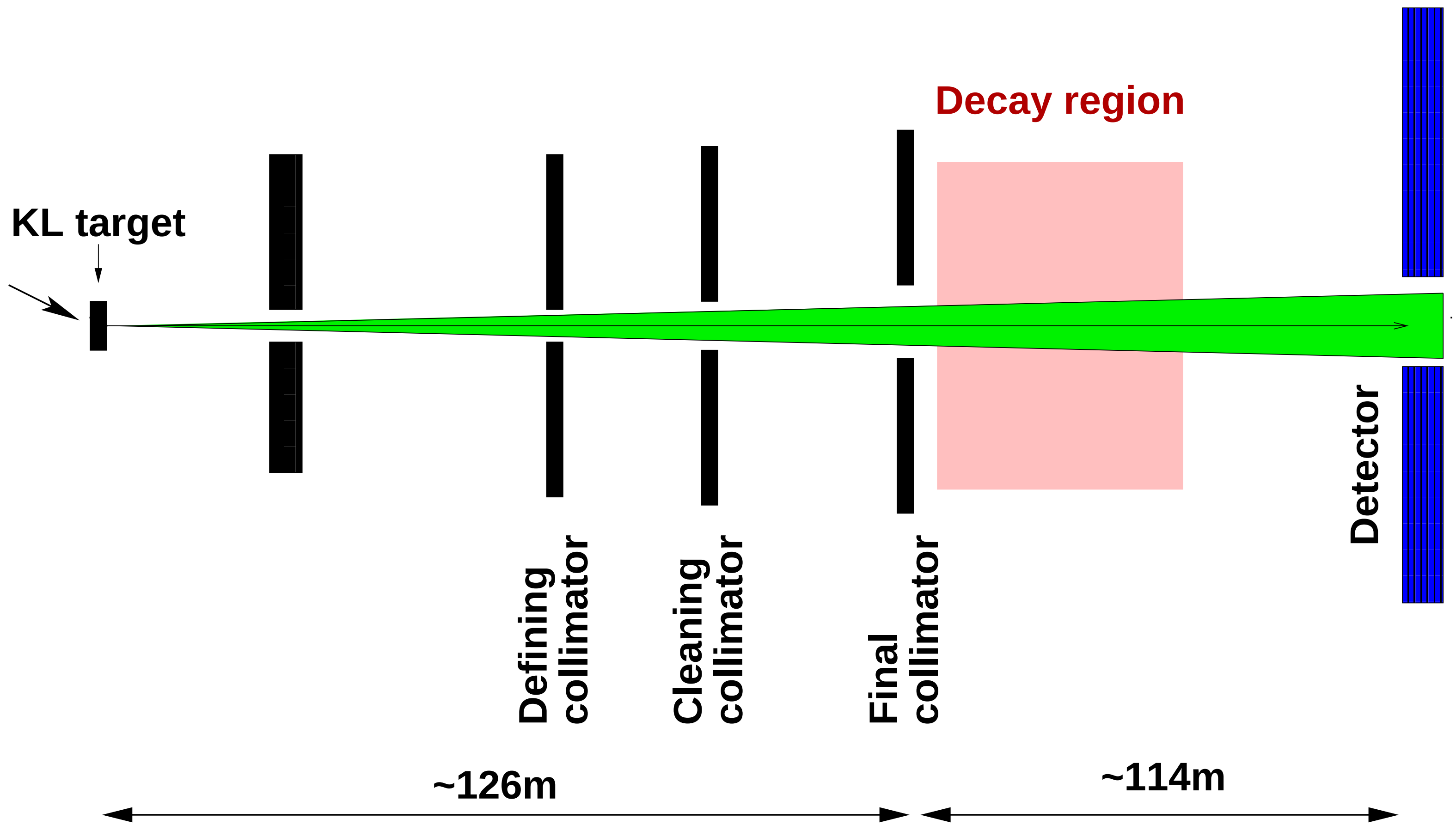
new measurements (KTeV, 2004 and KLOE, 2006) disagree with PDG

What we measure

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

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

- Special run 1999 (two days) with pure K_L beam at low intensity and simple trigger condition to select events with two charged tracks

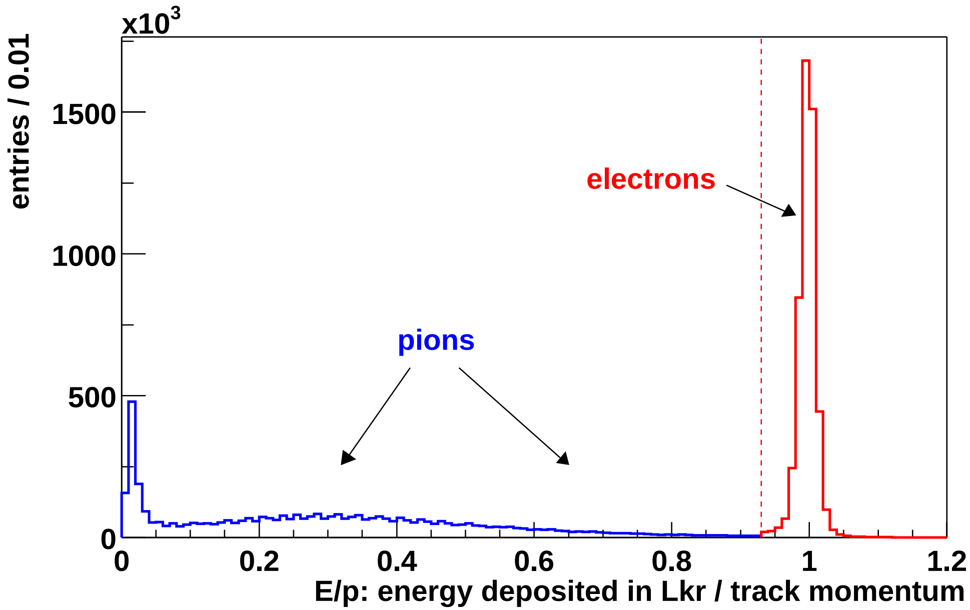


$\Gamma_{K2\pi}/\Gamma_{Ke3}$: event selection

- Special run 1999 (two days) with pure K_L beam at low intensity and simple trigger condition to select events with two charged tracks

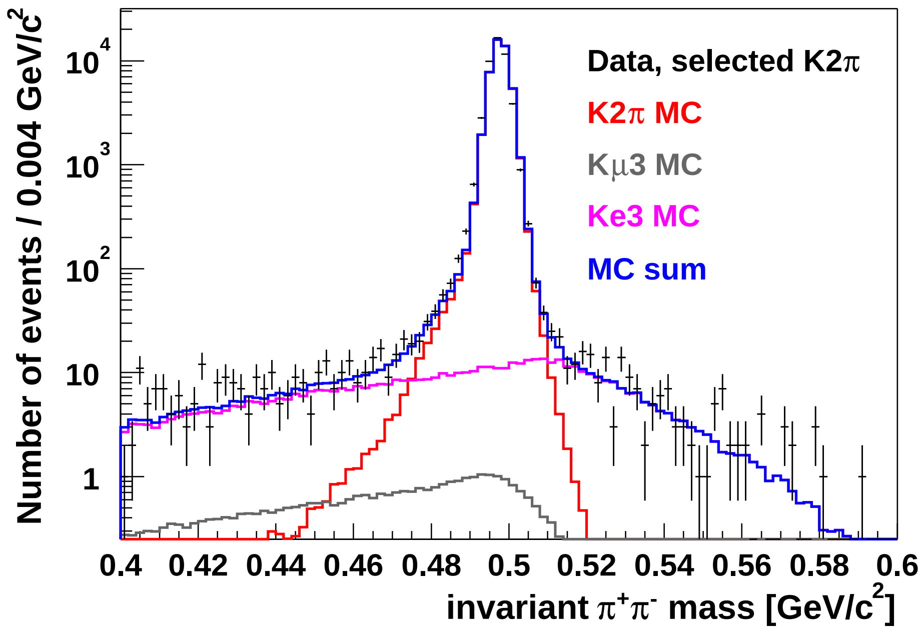
$K_L \to \pi^{\pm} e^{\mp} \nu$

- Selecting 2 tracks with one electron ($\to E_{LKr}/p_{trk} \approx 1$)
- About 5 million K_{e3} events selected with $\sim 0.5\,\%$ background



$K_L \to \pi^{\pm}\pi^{\mp}$

- Selecting 2 tracks, no e or μ
- ~ 47000 selected $\pi^+\pi^-$ events with $\sim 0.5\,\%$ background



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

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

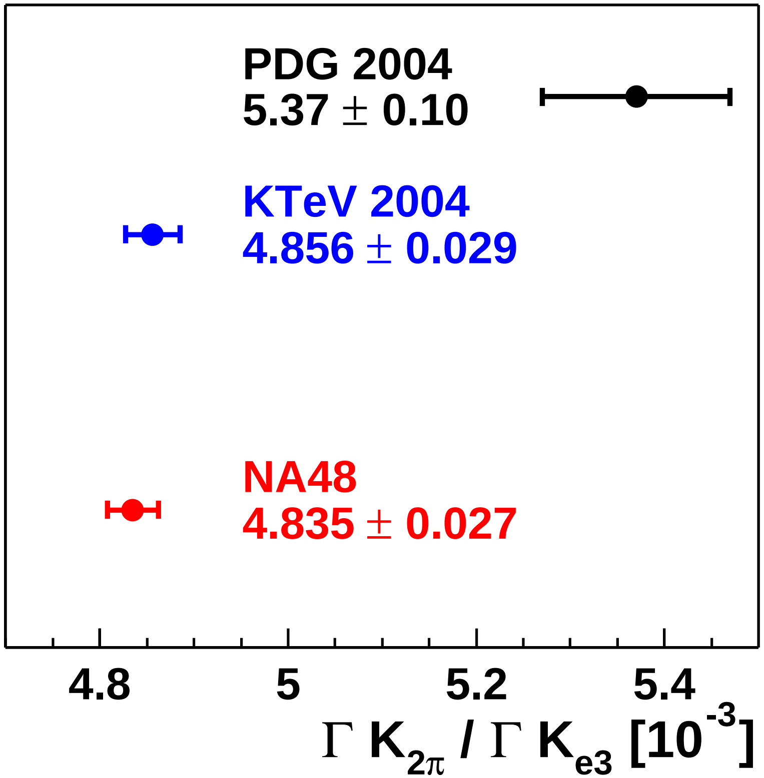
- $$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^\pm e^\mp\nu)} \cdot BR(K_L \to \pi^\pm e^\mp \nu) = (1.941 \pm 0.019) \times 10^{-3}$$

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

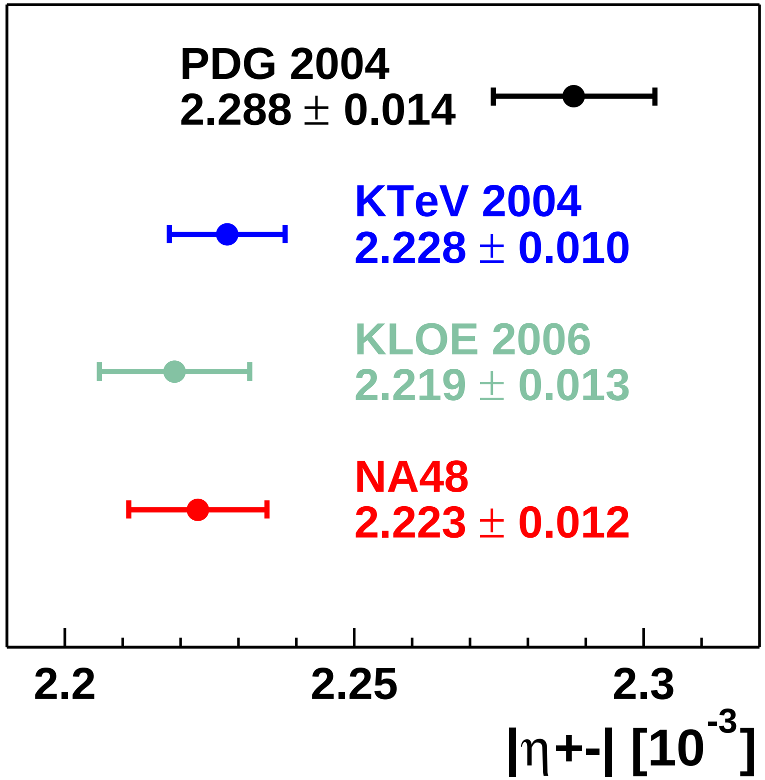
- $$|\eta_{+-}| = \sqrt{\frac{\tau_{KS}}{\tau_{KL}} \cdot \frac{BR(K_L\to\pi^+\pi^-)}{BR(K_S\to\pi^+\pi^-)}} = (2.223 \pm 0.012) \times 10^{-3}$$

Comparison of results

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



$|\eta_{+-}|$



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

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

Observable for direct CPV

- 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 $u = \frac{s_3 - s_0}{m^2_{\pi^\pm}}$, $v = \frac{s_1 - s_2}{m^2_{\pi^\pm}}$

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

- Define slope asymmetry : $$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

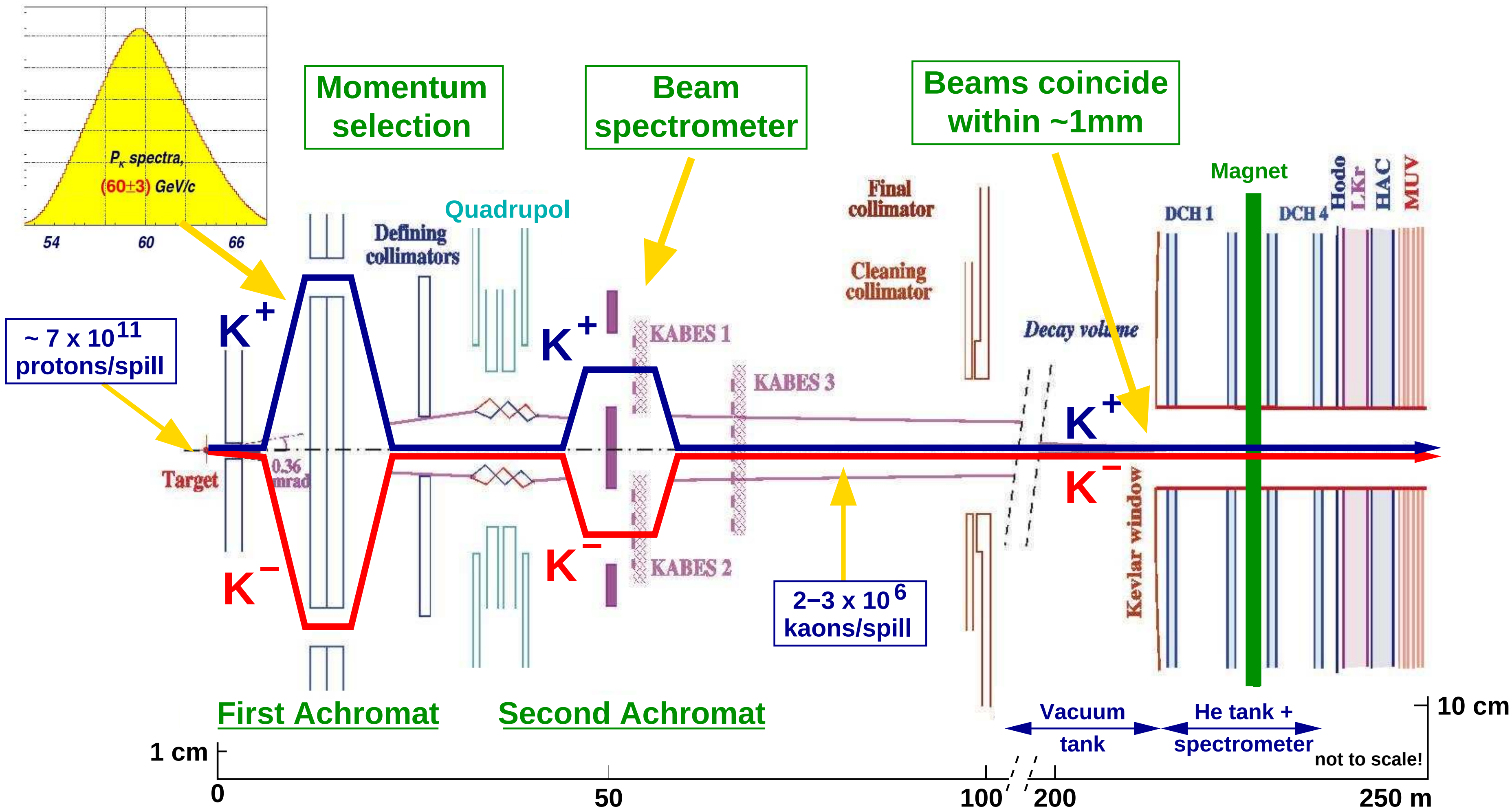
$\Rightarrow$ **Any value of $A_g \neq 0$ is a manifestation of direct CP violation !**
(only direct CPV in $K^\pm$ possible - no mixing !)

- SM prediction for A_g between 10^{-6} und 10^{-5}, processes beyond the SM do not exclude enhancements of the asymmetry A_g up to a few 10^{-4}

- Experimental limits on A_g at a few 10^{-3},
NA48: measurement of A_g at 10^{-4} level $\to$ test on New Physics !

NA48/2 beams setup in 2003 + 2004

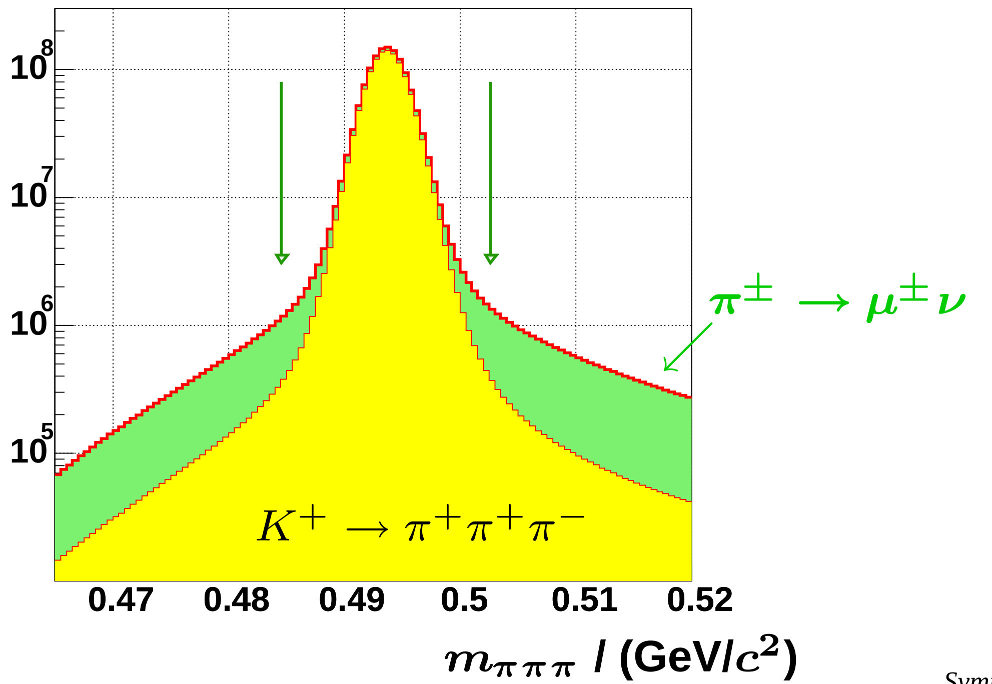
- Simultaneous K^+ and K^- beams with similar momentum spectra
- Polarities of magnets (beam + spectrometer) regularly reversed

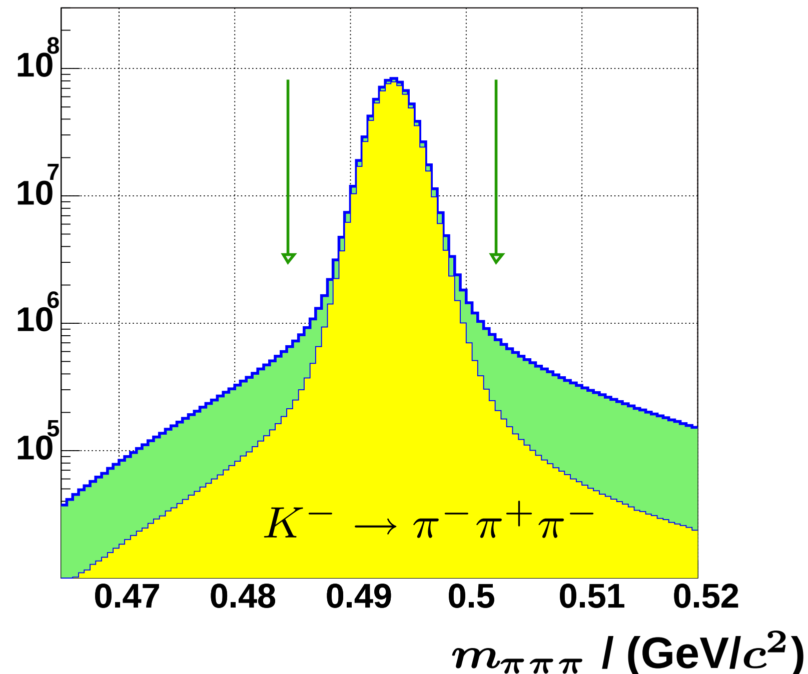


Event selection in $K^{\pm} \to 3\pi$ decays

Event selection

- Require simplicity and charge symmetry
- In $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ selection only spectrometer information used
  $\Rightarrow\ 3.11 \times 10^{9}$ events
- In neutral mode, mainly information from charge-blind LKr detector
  $\Rightarrow\ 9.13 \times 10^{7}$ events





Extraction of A_g: Quadruple ratio

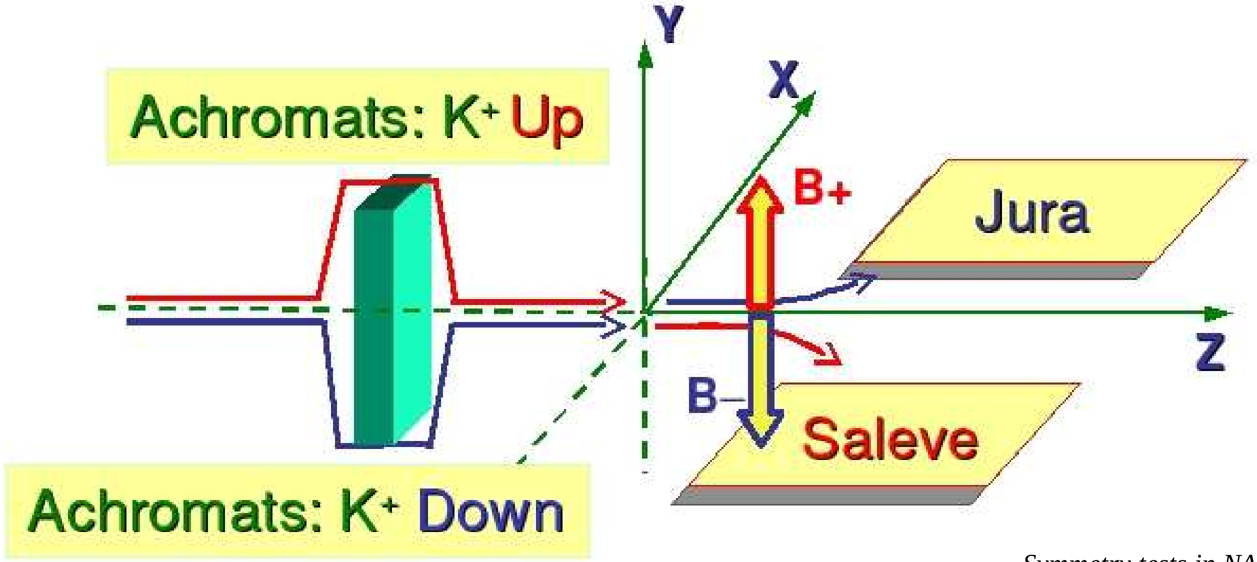
- Compare the reconstructed u-spectra of K^+ and K^- decays in

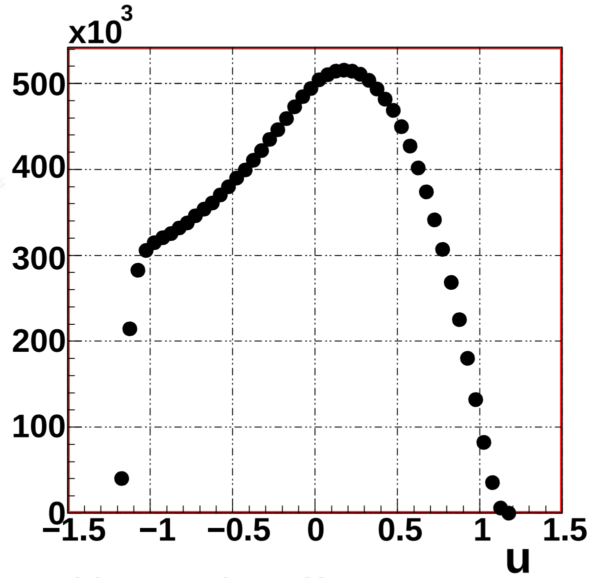
four u-ratios:
$$R_{xy}(u) = \frac{N^+_{xy}(u)}{N^-_{xy}(u)} \sim 1 + \frac{\Delta g\, u}{1 + gu + hu^2}$$

with the four possible combinations of magnetic field polarities

  - Achromat: $x = U(up), D(down)$
  - Spectrometer: $y = J(\mathrm{Jura} = \mathrm{left}), S(\mathrm{Saleve} = \mathrm{right})$

Not all experimental asymmetries (beamline and left-right asymmetries) cancel in one simple ratio but in the product of all four ratios!





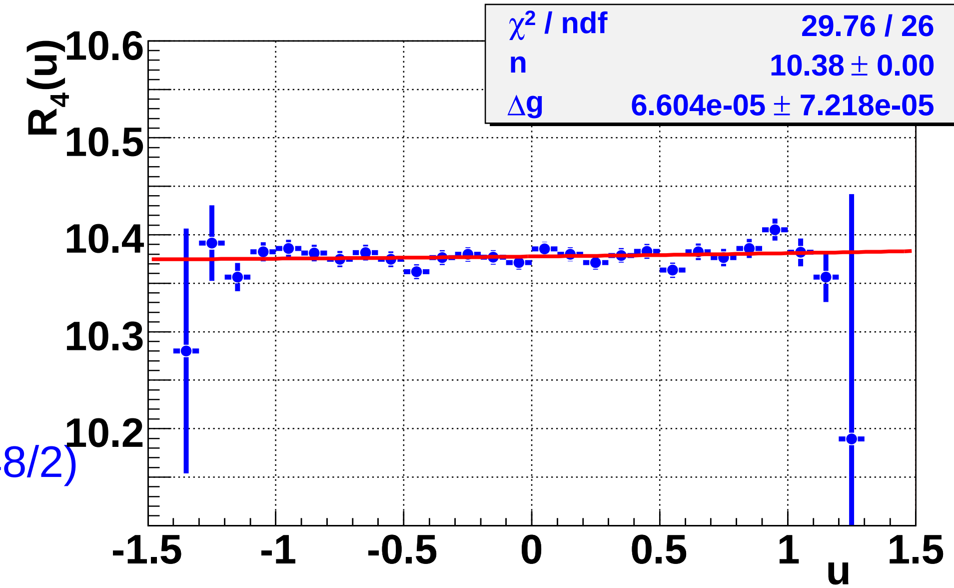
Extraction of A_g: Quadruple ratio

- Define quadruple ratio $R_4(u) = R_{US}(u) \cdot R_{UJ}(u) \cdot R_{DS}(u) \cdot R_{DJ}(u)$
- Extract Δg by fitting the quadruple ratio with a function

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

$$\Rightarrow \quad A_g = \frac{g^+ - g^-}{g^+ + g^-} \approx \frac{\Delta g}{2g}$$

  - $g_{\pi^\pm\pi^+\pi^-} = -0.21134 \pm 0.00017;$
    $h_{\pi^\pm\pi^+\pi^-} = 0.01848 \pm 0.00039$ (NA48/2)
  - $g_{\pi^\pm\pi^0\pi^0} = 0.626 \pm 0.007;$
    $h_{\pi^\pm\pi^0\pi^0} = 0.052 \pm 0.008$



- The analysis does not rely on a detailed Monte-Carlo to calculate acceptances (MC only used to study systematic effects)

Final results for 2003 + 2004

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

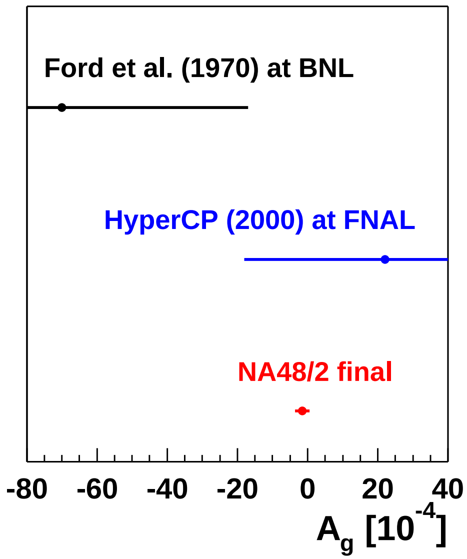
$$A_g = (-1.5 \pm 1.5_{stat.} \pm 0.9_{trig.} \pm 1.1_{syst.}) \times 10^{-4} \; = \; (-1.5 \pm 2.1) \times 10^{-4}$$

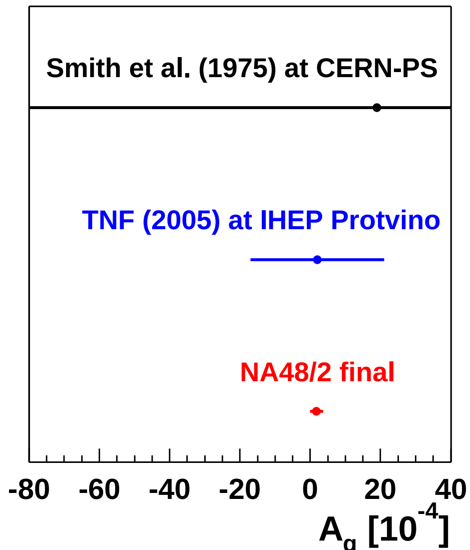
Neutral mode $(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0})$

$$A_g = (1.8 \pm 1.7_{stat.} \pm 0.5_{syst.}) \times 10^{-4} \; = \; (1.8 \pm 1.8) \times 10^{-4}$$

$\Rightarrow$ no evidence for direct CP violation of the order 10^{-4}
(About 10x more precise than previous measurements)

Charged mode



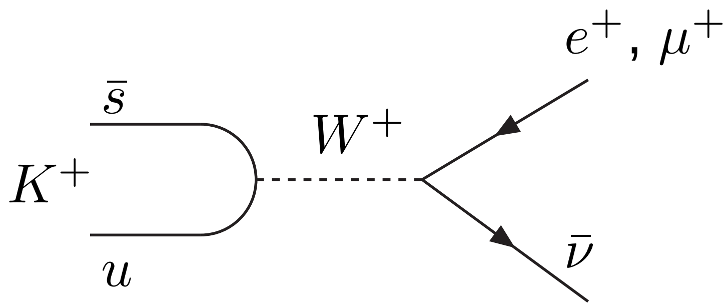


Neutral mode

NA62: Testing $e-\mu$ universality with $K^\pm \to l^\pm \nu$

Within the SM:

$$R_K = \frac{\Gamma(K \to e\nu_e(\gamma))}{\Gamma(K \to \mu\nu_\mu(\gamma))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta R_K)$$



with radiative corrections:

$$\delta R_K = (-3.78 \pm 0.04)\%$$

$$\Rightarrow R_K = (2.477 \pm 0.001) \cdot 10^{-5}$$

(Cirigliano, Rosell (2007))

- LFV in SUSY could change R_K by up to $\pm 3\%$.
  (Masiero, Paradisi, Petronzio (2006))

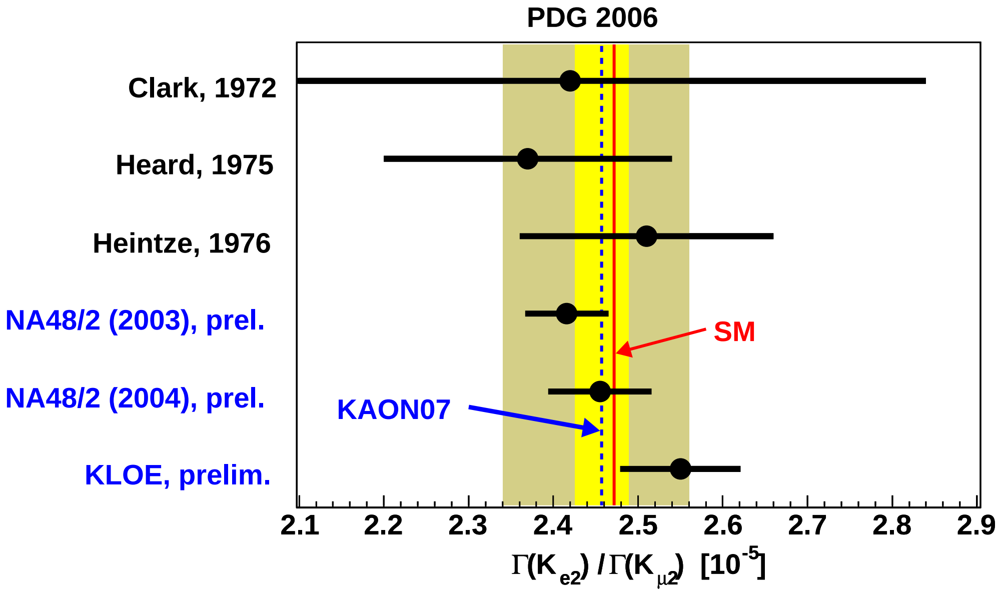
$\Rightarrow$ precise measurement provides sensitive test on SM and $e-\mu$ universality

$\Rightarrow$ experimental error more than one order of magnitude larger than theoretical one

NA62: Testing $e - \mu$ universality with $K^\pm \to l^\pm \nu$

Three new **preliminary measurements**:

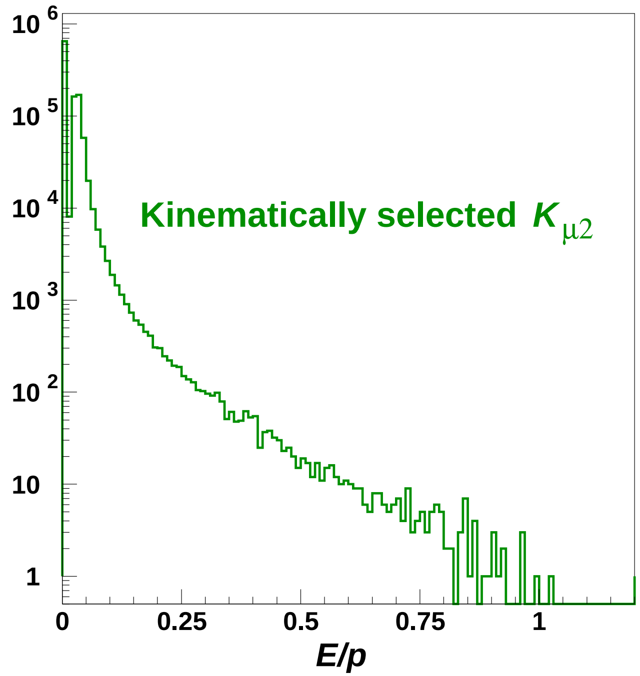
- KLOE, presented at KAON07:
  About 8000 signal events: $\mathbf{R_K = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}}$
- NA48/2 (2003 data), presented in 2005:
  About 4000 signal events from normal running period:
  $\mathbf{R_K = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5}}$
- NA48/2 (2004 data), presented at KAON07:
  About 4000 signal events from special minimum bias trigger
  $\mathbf{R_K = (2.455 \pm 0.045 \pm 0.041) \times 10^{-5}}$

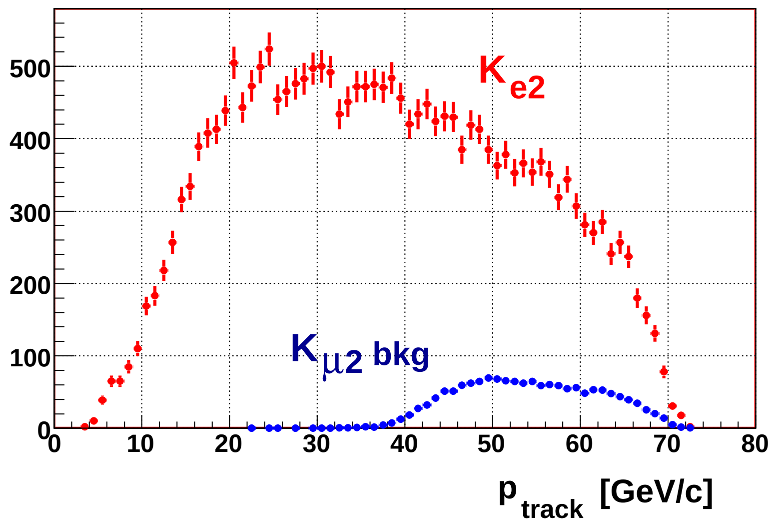


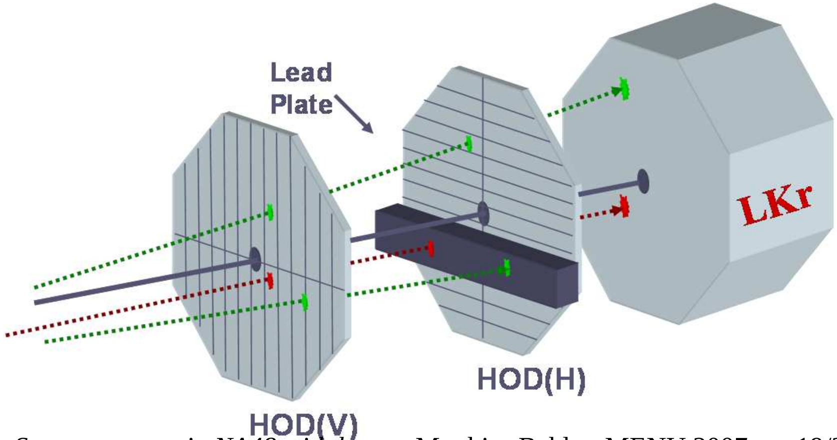
NA62: Testing $e-\mu$ universality with $K^{\pm} \to l^{\pm}\nu$

NA62: data taking in 2007 (June 19th - beginning of October)

- Goal: $\sim 150,000\ K^{\pm} \to e^{\pm}\nu_e$ events and $\sigma_{R_K} \sim 0.3\%$
- using existing NA48 detector
- minimun bias trigger
- experiences from 2004: all systematics $< 0.2\%$ except background from $K^{\pm} \to \mu^{\pm}\nu$ (measured from data)







Conclusions

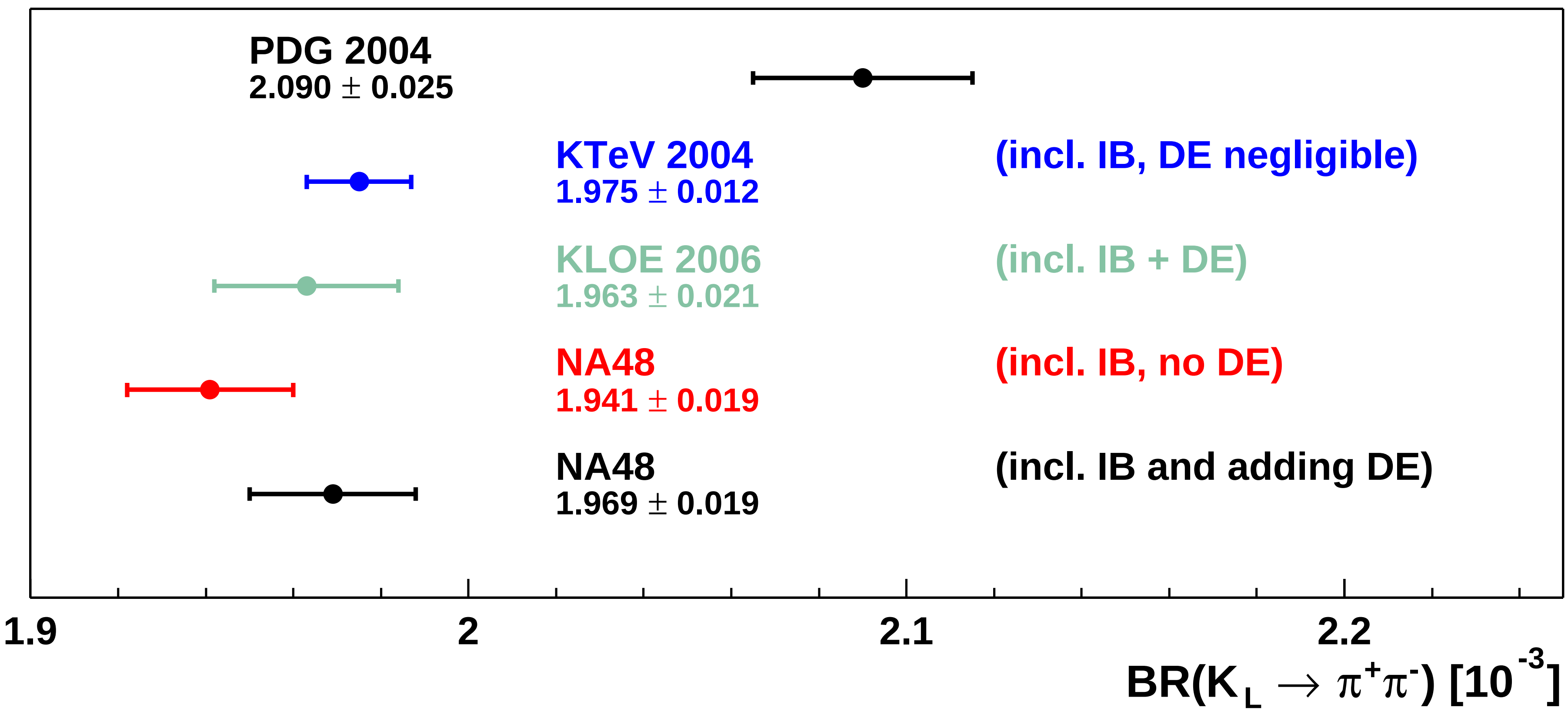
- New measurements from NA48 of
  - the CP violation parameter $|\eta_{+-}| = (2.223 \pm 0.012) \times 10^{-3}$
    $\Rightarrow$ in agreement with KTeV and KLOE
  - the CP-violating asymmetry in $K^{\pm} \rightarrow 3\pi$:
    $A_g(K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}) = (-1.5 \pm 2.1) \times 10^{-4}$
    $A_g(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}) = (1.8 \pm 1.8) \times 10^{-4}$

    $\Rightarrow$ no evidence for direct CP violation of the order 10^{-4}
    (About 10x more precise than previous measurements)
- running / future experiments:
  - **NA62:** is taking data to measure $R_K = \frac{\Gamma(K^{\pm} \rightarrow e^{\pm}\nu_e(\gamma))}{\Gamma(K^{\pm} \rightarrow \mu^{\pm}\nu_\mu(\gamma))}$
    with $\sigma_{R_K} \sim 0.3\%$
  - **P326:** Measurement of $BR(K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}) \sim 10^{-11} - 10^{-10}$,
    data taking in 2011

Spares

Comparison of results

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

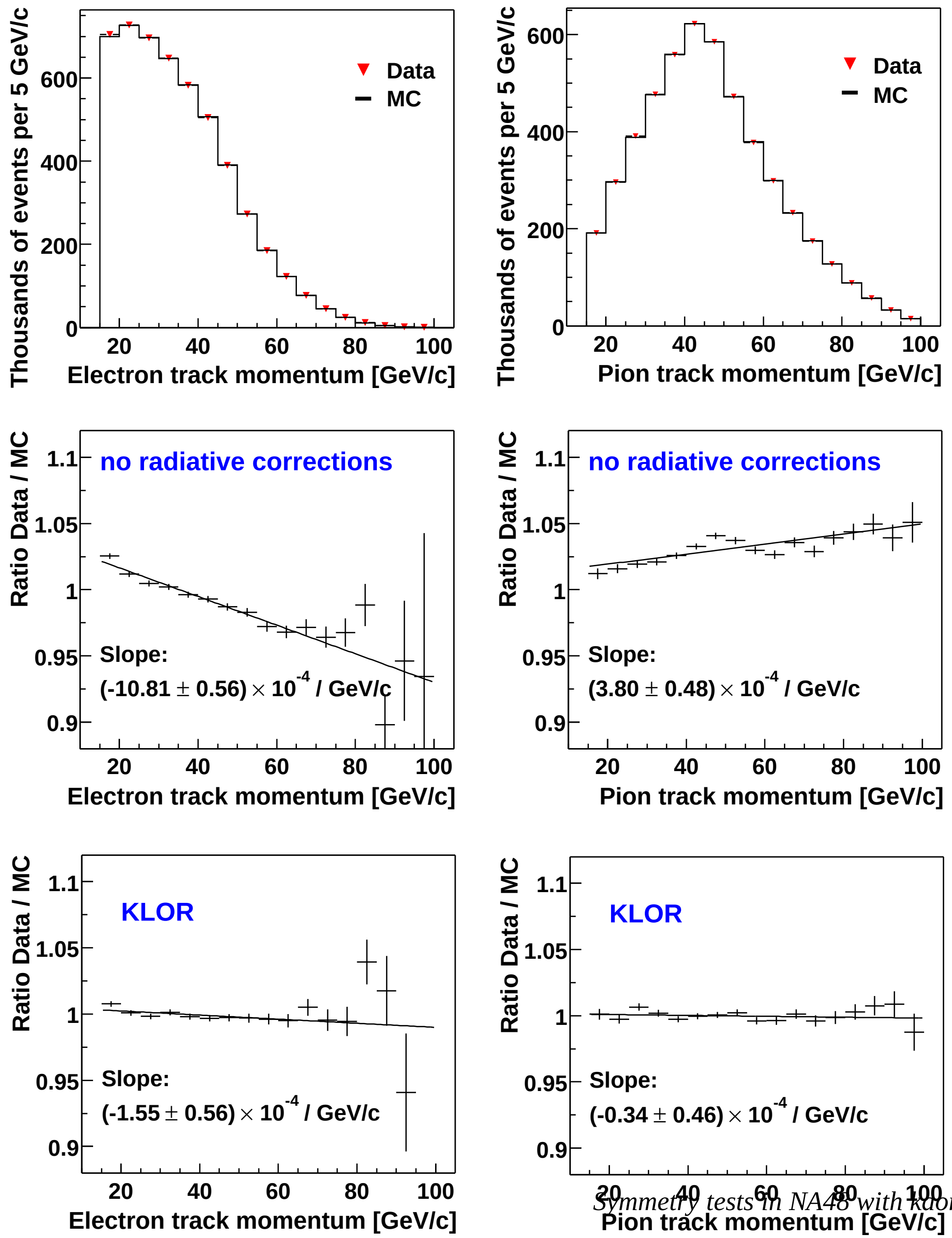


- For comparison it’s important to point out the treatment of radiative decays (IB + DE)

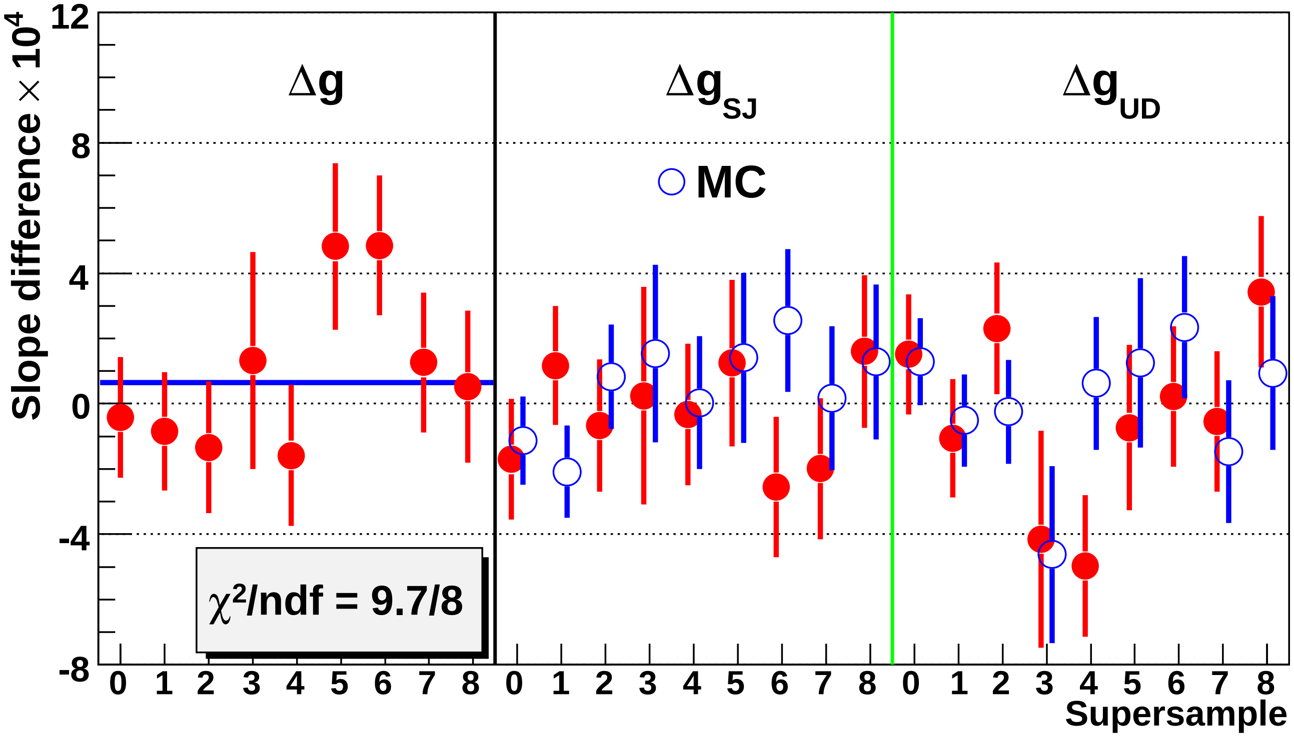
$\Gamma_{K2\pi}/\Gamma_{Ke3}$: Systematics

	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}



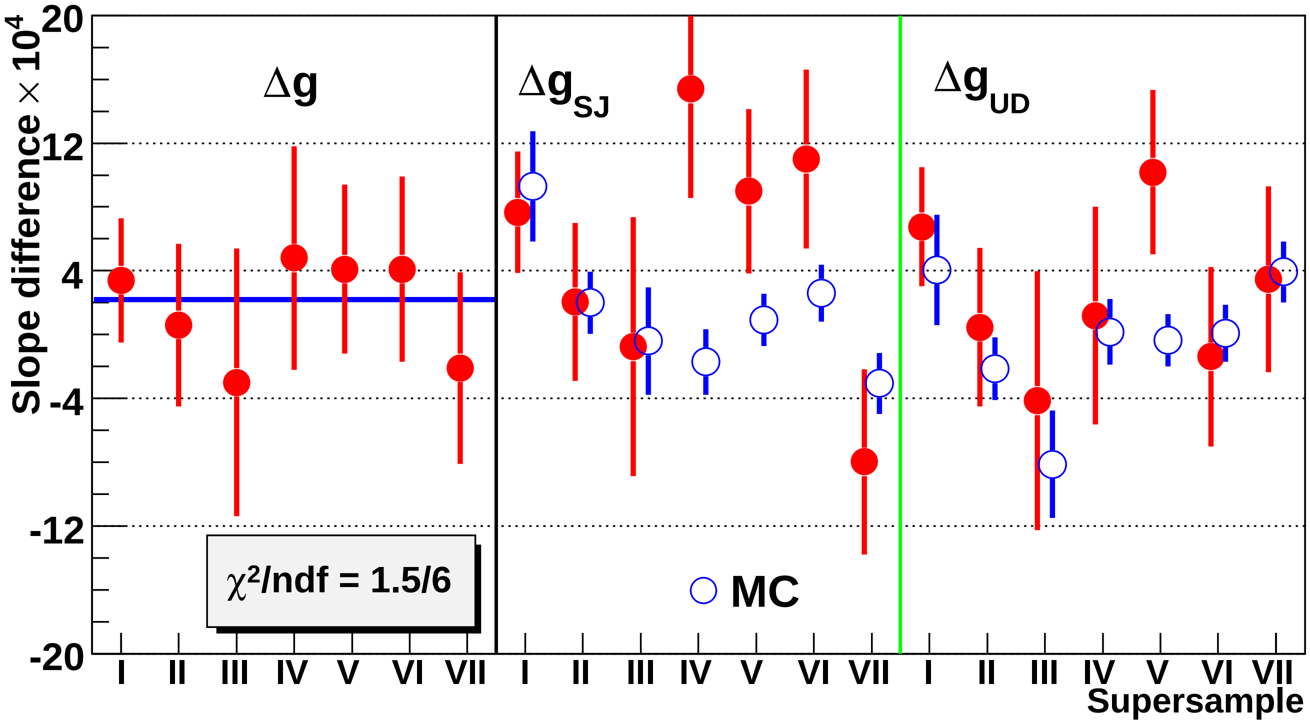
Asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: stability checks



- 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

$\Rightarrow$ Our detector is really symmetric !

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

$\Rightarrow$ Our detector is really symmetric !

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