# Search for CP violation in $K^{\pm} \rightarrow 3\pi$ decays by the NA48/2 experiment at CERN

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**For the NA48/2 Collaboration :**

**Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna**

# Outline

- **CP-violating charge asymmetries in $K^{\pm} \to 3\pi$ decays**
- **The NA48/2 experimental method**
- **The $K^{\pm}$ beam line and detector**
- **Measurement of the $A_g$ parameter in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays**
- **$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays**
- **Conclusions**

# CP Violation in $K^{\pm} \to 3\pi$ decays

*Only direct CP violation is involved in charged kaon decays!*

***Matrix element:***

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

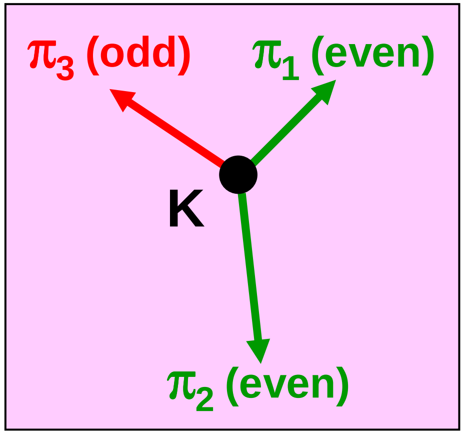
$u = 2m_K(m_K/3 - E_3^*)/m_\pi^2$

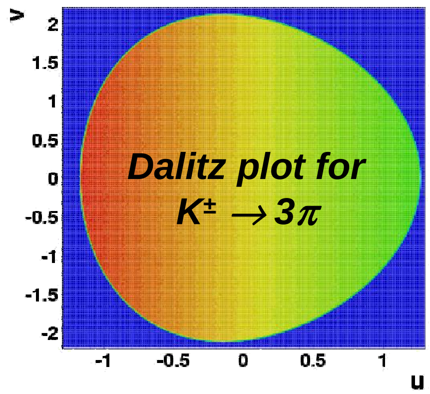
$v = 2m_K(E_1^* - E_2^*)/m_\pi^2$

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ : $g = -0.2154 \pm 0.0035$

$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ : $g = 0.638 \pm 0.020$

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




***If CP invariance holds:***

$$g_{K^+} = g_{K^-},\ h_{K^+} = h_{K^-},\ k_{K^+} = k_{K^-}$$

***Asymmetry parameter:***

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

If $A_g \neq 0 \Rightarrow$ *Direct CP Violation*

***SM predictions:*** $A_g \lesssim 10^{-4}$

If $A_g > 10^{-4} \Rightarrow$ ***SUSY, New Physics?***

# The NA48/2 approach

- ***NA48/2 main goal:***

  - Measure linear slope ($g$) asymmetries for $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ decays with accuracies $\delta A_g < 2.2\times10^{-4}$ and $\delta A_g^0 < 3.5\times10^{-4}$, respectively.

  $\Rightarrow$ *significant improvement w.r.t. present measurements*

$$A_g = \begin{cases} (-70\pm53)\times10^{-4} & \textit{BNL AGS (1970)} \\ (22\pm40)\times10^{-4} & \textit{Hyper CP (2000) prelim.} \end{cases}$$

$$A_g^0 = \begin{cases} (19\pm125)\times10^{-4} & \textit{CERN PS (1975)} \\ (2\pm19)\times10^{-4} & \textit{Protvino IHEP (2005)} \end{cases}$$

  - Need more than $2\times10^{9}$ $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ and $10^{8}$ $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ reconstructed events

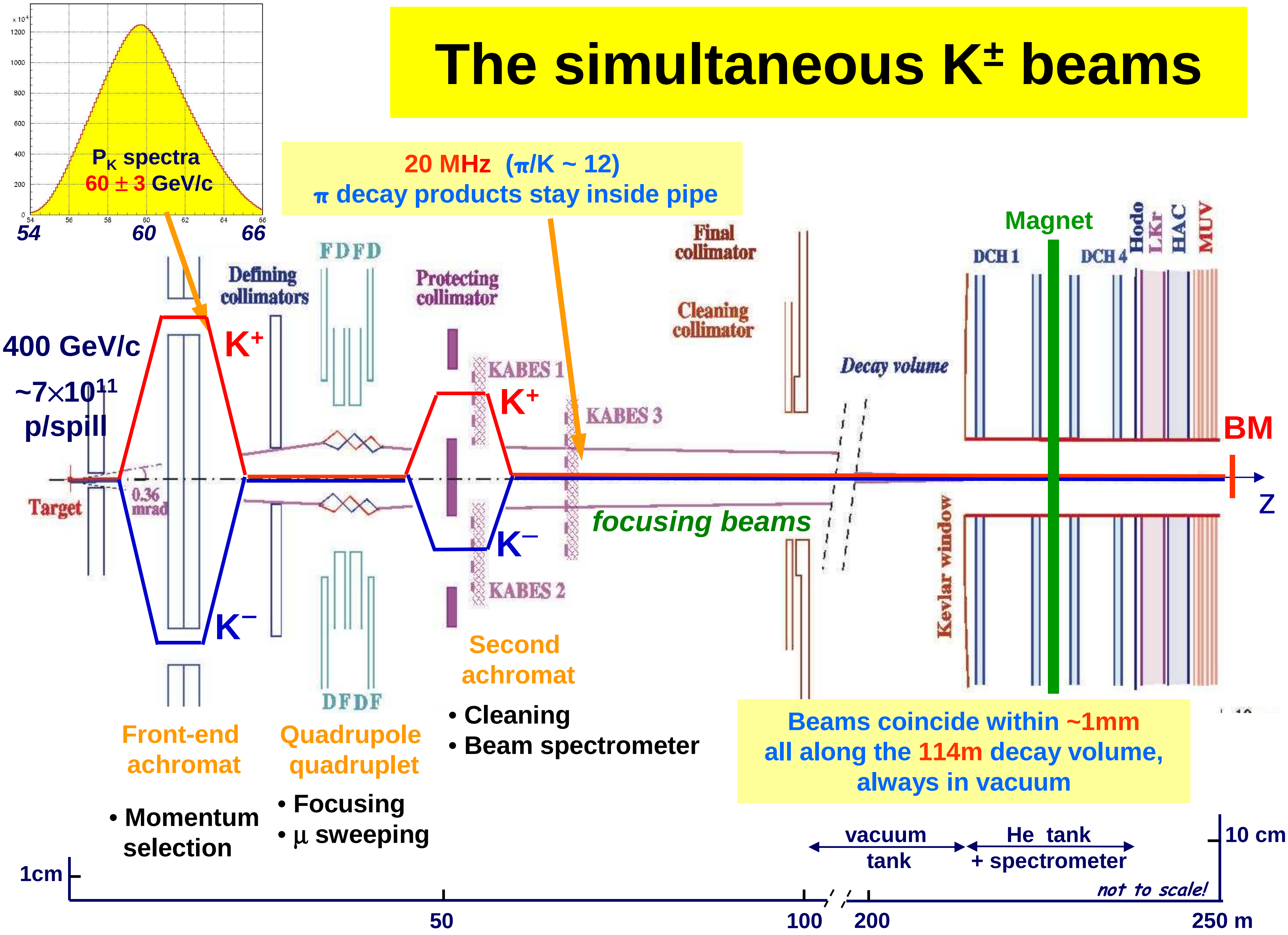
- ***NA48/2 method:***

  - Use of intense simultaneous $K^+$ and $K^-$ beams, superimposed in space, with narrow $P_K$ spectra
  - Equalization of averaged $K^+$ and $K^-$ acceptances by frequent alternations of magnet polarities (magnetic spectrometer, $K^{\pm}$ beam lines)
  - Measurement of asymmetry from slopes of normalized $u$-distribution ratios (*no MC acceptance correction required!* ) :

$$R(u) = N^+(u)/N^-(u) \approx n(1+\Delta g\, u)$$
$$A_g = \Delta g / 2g$$

*Induced instrumental asymmetry can only be due to charge-asymmetric and u-dependent effects that vary with time*

# The simultaneous K± beams



# The NA48 detector

- **Magnetic spectrometer**
  4 high-resolution DCHs

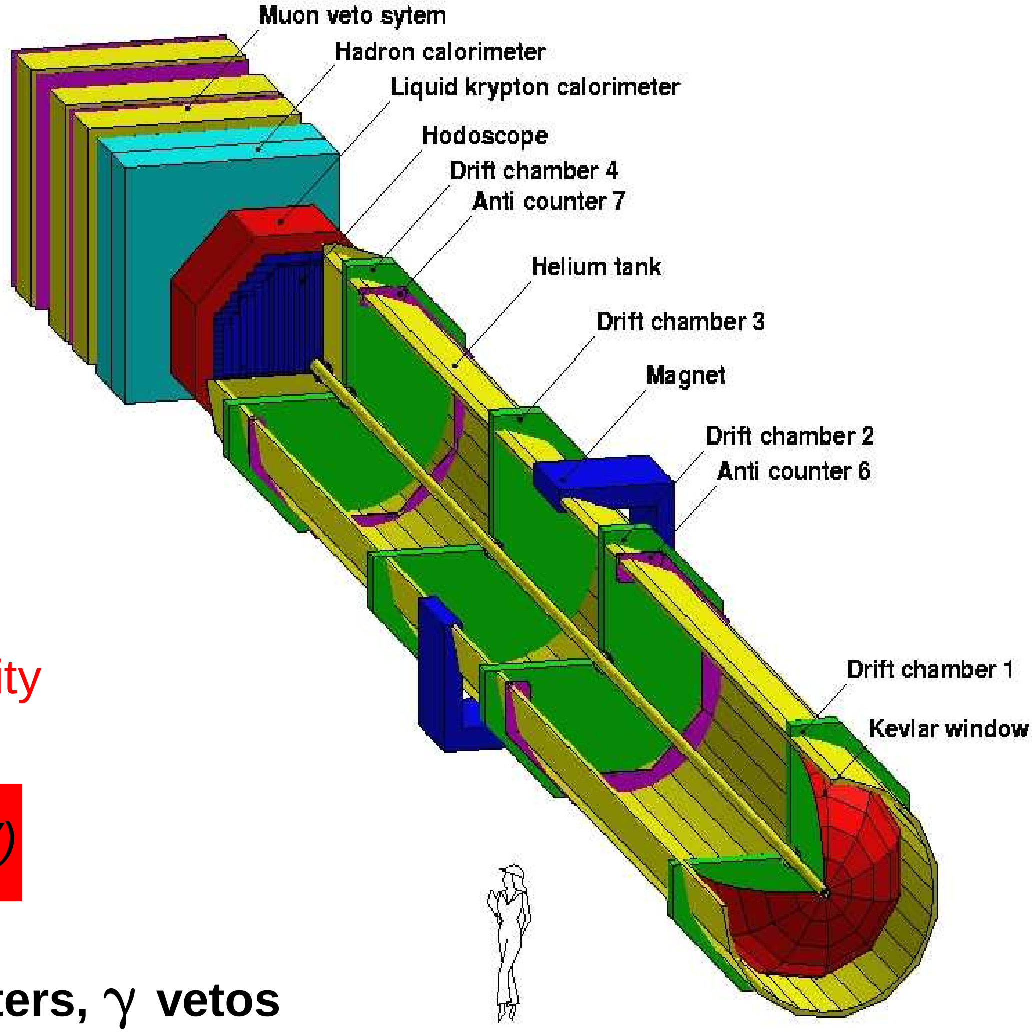
$$\frac{\sigma_p}{p} = (1.0 \oplus 0.044\ p)\% \quad (p \text{ in GeV/c})$$

- **Scintillator hodoscope**
  150 ps time resolution - fast trigger

- **LKr electromagnetic calorimeter**
  Quasi-homogeneous, high granularity
  e/$\pi$ discrimination

$$\frac{\sigma_E}{E} = \left(\frac{3.2}{\sqrt{E}} \oplus \frac{9.0}{E} \oplus 0.42\right)\% \quad (E \text{ in GeV})$$

- **Hadron calorimeter, $\mu$ veto counters, $\gamma$ vetos**



# NA48/2 data taking completed

**2003 run: ~ 50 days**
**2004 run: ~ 60 days**

**Total statistics in 2 years:**

**$K^\pm \to \pi^\pm \pi^0 \pi^0$ : $\gtrsim 1 \times 10^8$ decays**

**$K^\pm \to \pi^\pm \pi^+ \pi^-$ : ~ $4 \times 10^9$ decays**

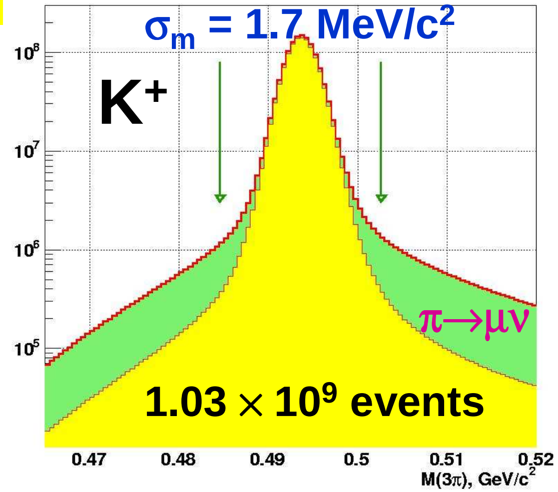
**~ 200 TB of data recorded**

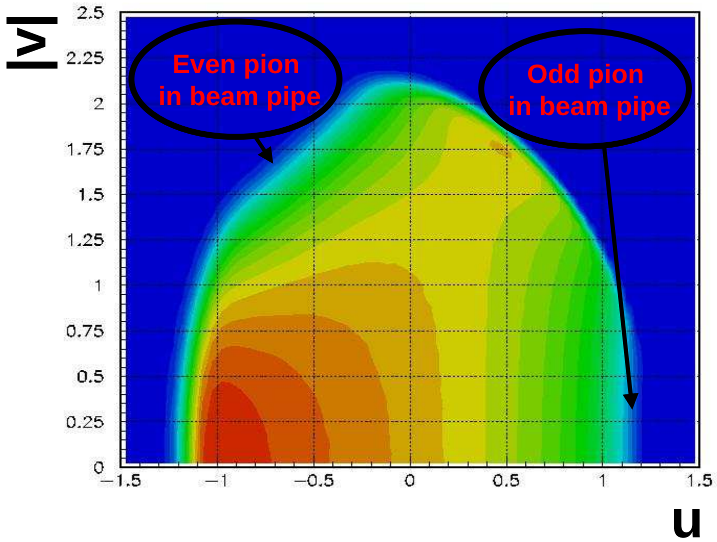
***Preliminary result based on 2003 $K^\pm \to \pi^+ \pi \pi^\pm$ sample***

# Selection of $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ events

*Based only on Hodoscope and Magnetic Spectrometer*

- **2-level trigger:**
  - L1 : fast signals from hodoscope
  - L2 : at least one good vertex made of two tracks in DCHs
- **Offline reconstruction based on magnetic spectrometer only**
  - 3-track vertex in decay volume
  - time, quality cuts, ghost track suppression, etc…
- **Acceptance limited mostly by beam pipe through DCHs**

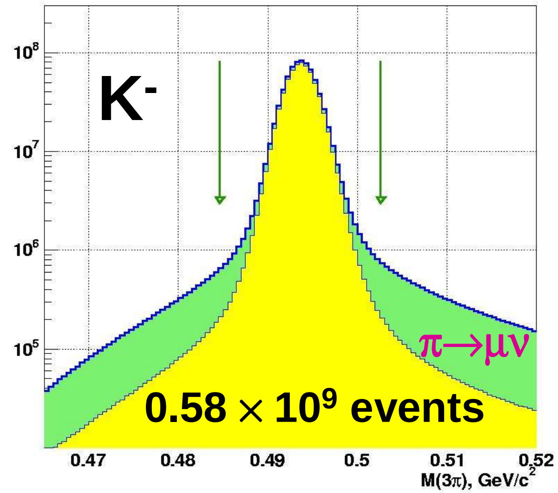



***Negligible $\pi\rightarrow\mu\nu$ background***

*$\sim 1.6\times10^9$ events in 2003 data sample*

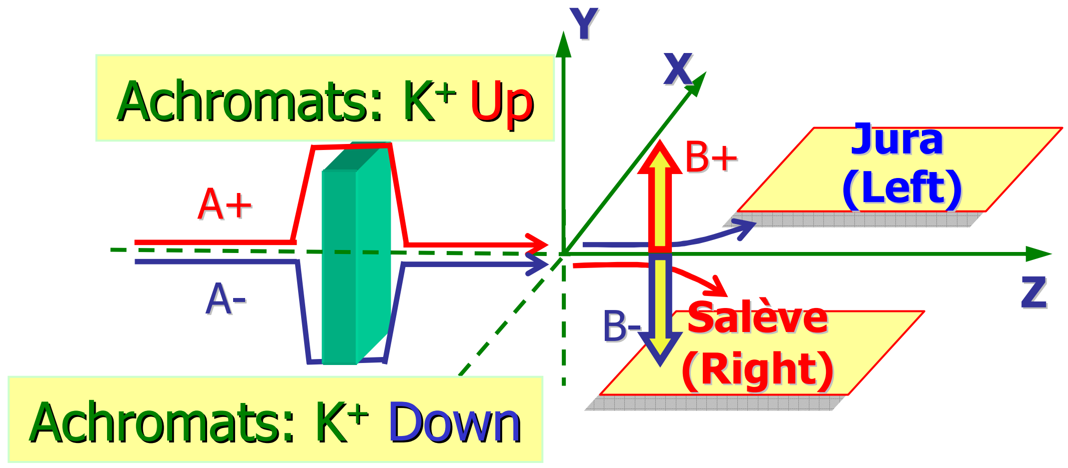
*$K^+ / K^- \sim 1.8$*



# Acceptance equalization for $K^+$ and $K^-$

**Detector Left-Right asymmetry cancellation in the 4 $K^+/K^-$ ratios:**

- $R_{US}(u) = \dfrac{N^+(A+,B+,u)}{N^-(A+,B-,u)}$
- $R_{UJ}(u) = \dfrac{N^+(A+,B-,u)}{N^-(A+,B+,u)}$
- $R_{DS}(u) = \dfrac{N^+(A-,B+,u)}{N^-(A-,B-,u)}$
- $R_{DJ}(u) = \dfrac{N^+(A-,B-,u)}{N^-(A-,B+,u)}$




**Quadruple ratio:**

$$R(u) = R_{US}(u) \times R_{UJ}(u) \times R_{DS}(u) \times R_{DJ}(u) \propto (1 + 4\,\Delta g\, u)$$

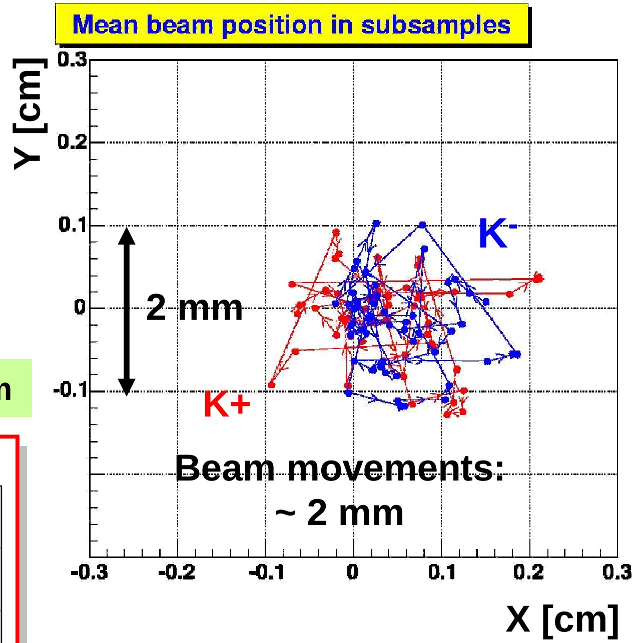
***Cancellation of systematic biases:***

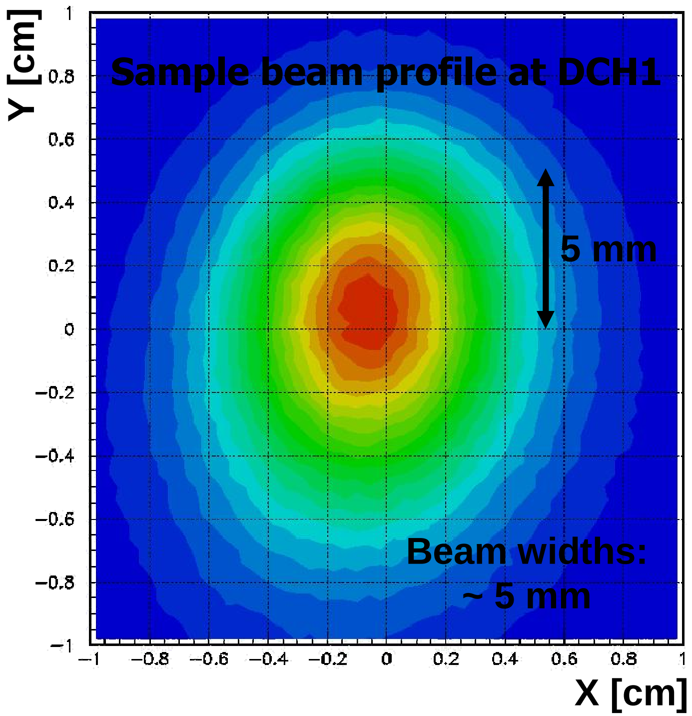
- **Detector L-R asymmetries ( $K^+ \to$ Salève / $K^- \to$ Salève and $K^+ \to$ Jura / $K^- \to$ Jura )**
- **Beam line biases ( $K^+$ beam Up / $K^-$ beam Up and $K^+$ beam Down / $K^-$ beam Down)**
- **Global time-variable biases ($K^+$ and $K^-$ simultaneously recorded)**

***Fit of R(u) is sensitive only to the time variation of asymmetries in experimental conditions with characteristic time smaller than corresponding field alternation periods (beam$\leftrightarrow$week, detector$\leftrightarrow$day) $\Rightarrow$ 2003 data taken in 4 SUPER-SAMPLES of 2 weeks each***

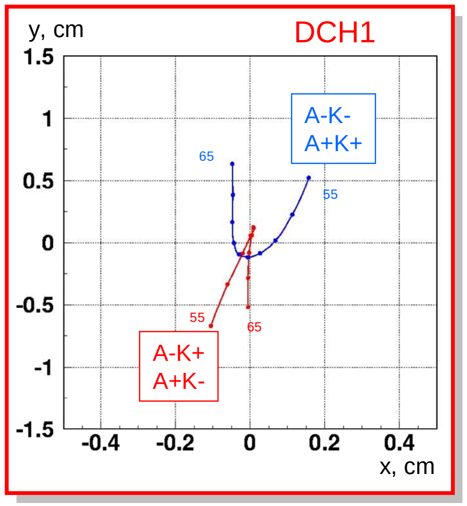
# Time variations of beam geometry

- Acceptance mostly defined by $\Phi \approx 20$ cm central beam pipe
- Apply larger acceptance cut centered on averaged beam positions as a function of time, $K^{\pm}$ charge and momentum



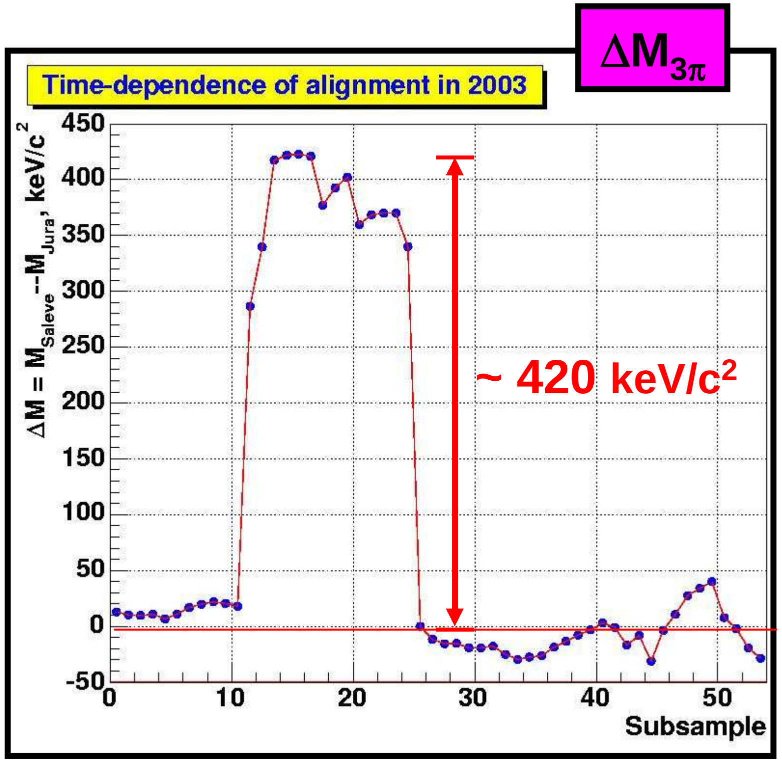




Beam (x, y) -vs- K± momentum



# Time variation in the calibration of the Magnetic Spectrometer

**Relative alignment of DCHs fine tuned by imposing mean reconstructed invariant $M_{3\pi}$ masses to be equal for $K^+$ and $K^-$**




**e.g. sensitivity to DCH4 horizontal shift:**
**$\Delta M/\Delta x \approx 1.5$ keV/c²/μm**

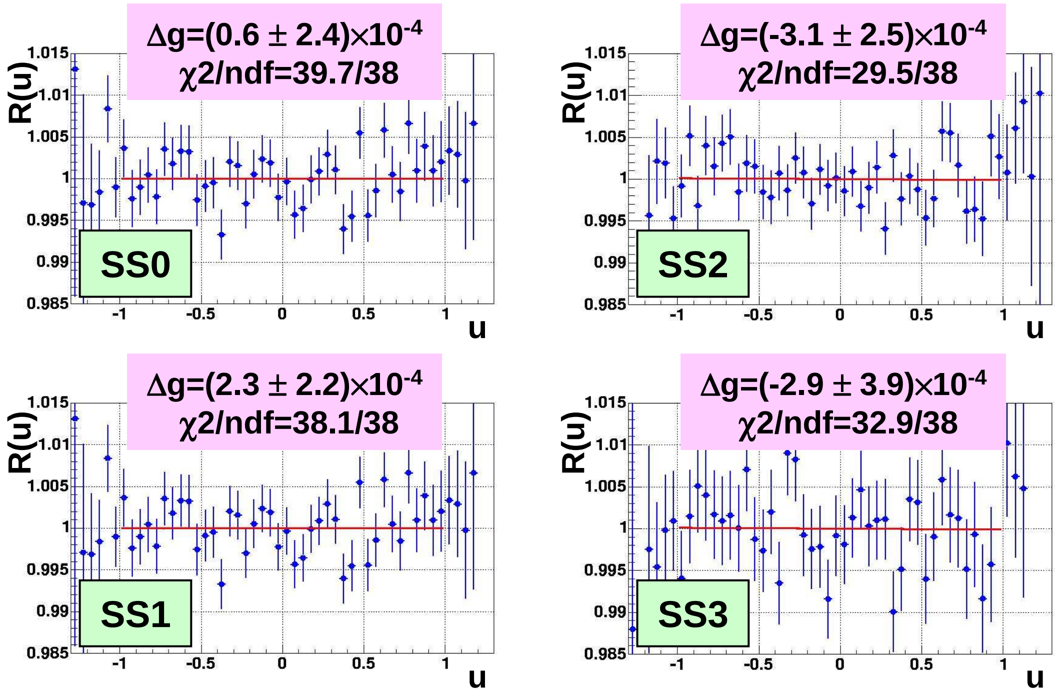
***Momentum scale*** **variation due to limited control of spectrometer magnet current ($10^{-3}$) cancels (simultaneous beams)**

**Sensitivity to $10^{-3}$ error in field integral:**
**$\Delta M \approx 100$ keV/c²**

***Momentum scale*** **adjusted by imposing PDG value of $M_{K\pm}$**

# Δg: 2003 result

*Asymmetry fits (from one of the 3 independent analyses)*




*Combined result contains L2 trigger correction with conservative systematic uncertainty (obtained from downscaled control events)*

⇒

$\chi^2$/ndf = 3.2/3

*Systematic uncertainties*

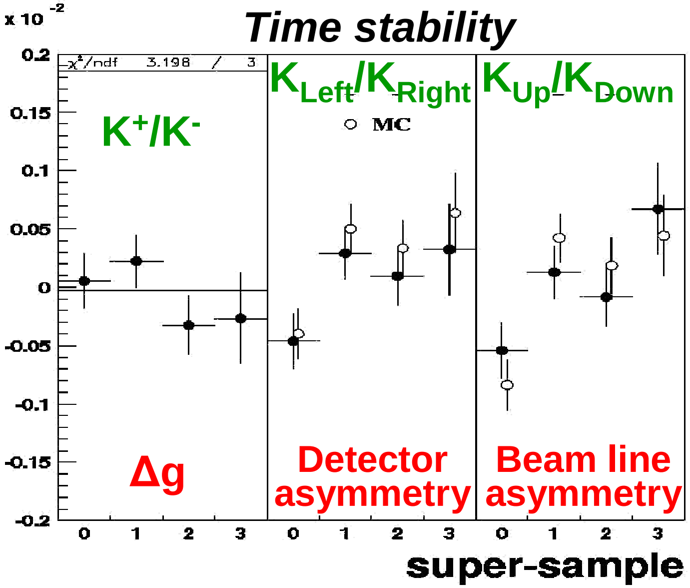
| Source | δΔg ($10^{-4}$) |
|---|---|
| Acceptance and beam geometry | 0.5 |
| Spectrometer alignment | 0.1 |
| Spectrometer magnetic field | 0.1 |
| $\pi \to \mu\nu$ decay | 0.4 |
| Calculation of « u » and fitting | 0.5 |
| Accidental activity | 0.3 |
| Source of statistical nature | |
| L1 trigger efficiency | 0.4 |
| L2 trigger efficiency | 0.8 |
| Total | 1.3 |

*Statistics and result*

| Sample | $K^+\to\pi^+\pi^+\pi^-$ ($10^6$) | $K^-\to\pi^-\pi^-\pi^+$ ($10^6$) | Δg ($10^{-4}$) |
|---|---|---|---|
| SS0 | 431 | 240 | 0.5 ± 2.4 |
| SS1 | 258 | 144 | 2.2 ± 2.2 |
| SS2 | 253 | 141 | -3.0 ± 2.5 |
| SS3 | 95 | 53 | -2.6 ± 3.9 |
| Total | 1036 | 577 | -0.2 ± 1.3 |

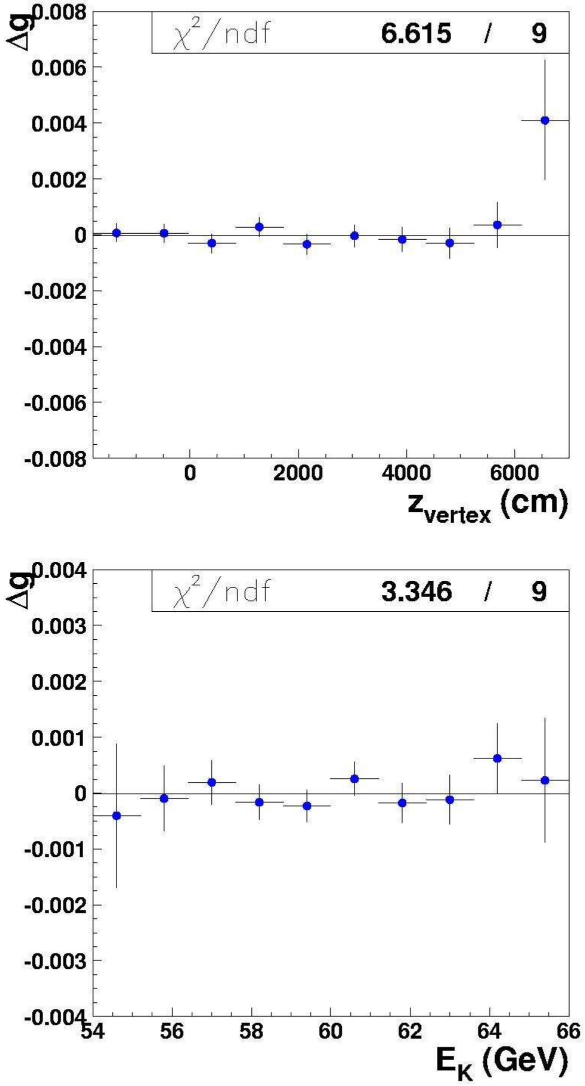
# $A_g$ preliminary result (2003 data)

$$\Delta g = (-0.2 \pm 1.0_{stat.} \pm 0.9_{stat.\,(trig.)} \pm 0.9_{syst.}) \times 10^{-4}$$




- 4 super-samples give consistent results
- Detector and beam line asymmetry effects at a few $10^{-4}$ level, reproduced by MC

**Result stability**




$$A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.\,(trig.)} \pm 2.1_{syst.}) \times 10^{-4}$$

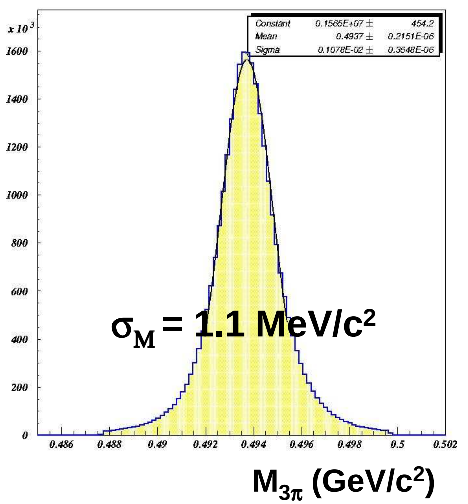
$$A_g = (0.5 \pm 3.8) \times 10^{-4}$$

# $A_g^0$ asymmetry in $K^\pm \to \pi^\pm\pi^0\pi^0$ decays

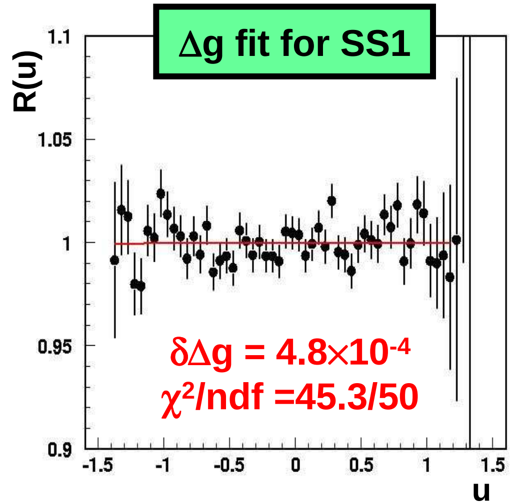
- The « u » variable can be reconstructed from LKr calorimer only (very good resolution at low u)
- Statistics available in 2003: $31 \times 10^6$ $K^+$ and $17 \times 10^6$ $K^-$ decays $\Rightarrow$ $\delta A_g^0{}_{(stat)} \sim 1.7 \times 10^{-4}$

*Lower statistics compensated by higher slope value ( g = 0.638 )*
*and more favourable Dalitz plot distribution*

- Extrapolation to 2003 + 2004 data: $\delta A_g^0{}_{(stat)} \lesssim 1.3 \times 10^{-4}$
- Negligible background ($\pi \to \mu\nu$ decay, wrong $\gamma$ pairings)
- Different sources of systematics w.r.t. $K^\pm \to \pi^\pm \pi^+\pi^-$ decays (radial acceptance, trigger …)




*Preliminary result on $A_g^0$ with 2003 data will be presented at CERN on Nov. 1st , 2005*



# Conclusions

- 2003 preliminary result on the CP-violating charge asymmetry in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ decays:

$$A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.\,(trig.)} \pm 2.1_{syst.}) \times 10^{-4}$$

- 10 times better precision than previous measurements
- Result consistent with SM predictions
- Still room to decrease systematic uncertainties (e.g. trigger)
- $A_g^0$ measurement in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays has comparable sensitivity

  *Preliminary result will be presented at CERN on Nov. 1st, 2005*
- Inclusion of 2004 data will more than double total statistics

  *Better quality of 2004 data due to more frequent alternation of magnets polarity*
- Design goal is within reach for both decay modes