Search for direct CP-violation in $K^\pm \to \pi^\pm \pi^+ \pi^-$ decays by NA48/2

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Overview

- Direct CP violation in $K^\pm \to 3\pi$ decays
- NA48/2 experimental setup
- Measurement principle
- Systematic effects
- Preliminary result in $K^\pm \to \pi^\pm \pi^+\pi^-$ decay mode
- Outlook for $K^\pm \to \pi^\pm \pi^0\pi^0$ analysis
- Conclusions
Brief history of CP violation

1964 - CP violation in $K^0$ (Cronin, Christenson, Fitch, Turlay)
1993-99 - Direct CP violation in $K^0$ (NA31, NA48, KTeV)
2001 - CP violation in $B^0$ (Babar, Belle)
2004 - Direct CP violation in $B^0$ (Belle, Babar)

CP violation and especially direct:
A window to physics beyond SM

Complementary observables in Kaons: $\varepsilon'/\varepsilon \leftrightarrow A_g \leftrightarrow$ rare decays
⇒ Look for direct CP violation in $K^\pm$!
(only direct CPV in $K^\pm$ possible – no mixing)
Direct CP-violation observable $A_g$

$K^{\pm} \rightarrow 3\pi$ matrix element:

$$M(u, v) = 1 + g u + h u^2 + k v^2$$

$K \rightarrow \pi^+ \pi^- \pi^\pm$: $g = -0.2154$
$K \rightarrow \pi^0 \pi^0 \pi^\pm$: $g = 0.652$

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

Dalitz variables

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

$$s_i = (p_K - p_{\pi i})^2$$
$$s_0 = \frac{1}{3} \sum s_i$$

$i = 3$ odd pion

$K^+ - K^-$ asymmetry in $g$:

$$A_g = \frac{g_+ - g_-}{g_+ + g_-}$$

if $A_g \neq 0$ \Rightarrow Direct CP violation
Asymmetry in decay widths $A_T$ expected to be smaller than in Dalitz-plot slopes $A_g$ (SM: $\sim 10^{-7}...10^{-6}$).

SM estimates of $A_g$ vary within an order of magnitude (few $10^{-6}...8\times10^{-5}$).

Models beyond SM predict substantial enhancements partially within the reach of NA48/2. (theoretical analyses are by far not exhaustive by now)
Goals and method

Primary NA48/2 goals:

- Measure slope asymmetries in “charged” and “neutral” modes with precisions $\delta A_g < 2.2 \times 10^{-4}$, and $\delta A_g^0 < 3.5 \times 10^{-4}$, respectively.

- Statistics required for this measurement: $>2 \times 10^9$ in “charged” mode and $>10^8$ in “neutral” mode.

NA48/2 method:

- Two simultaneous $K^+$ and $K^-$ beams, superimposed in space, with narrow momentum spectra;

- Detect asymmetry exclusively considering slopes of ratios of normalized U distributions;

- Equalise $K^+$ and $K^-$ acceptances by frequently alternating polarities of relevant magnets.
Experimental setup

- $P_K$ spectra, 60±3 GeV/c

- Front-end achromat
  - Momentum selection
- Quadrupole quadruplet
  - Focusing
  - $\mu$ sweeping
- Defining collimators
- Protecting collimator
- Cleaning collimator
- Final collimator

- Analysing magnet

- Target
- Beam pipe
- KABES 1
- KABES 2
- KABES 3

- Vacuum tank
- He tank + spectrometer

- Beams coincide within ~1mm all along 114m decay volume

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Data taking

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

Total statistics in 2 years:
$K^\pm \rightarrow \pi^-\pi^+\pi^\pm$: $\sim 4 \times 10^9$
$K^\pm \rightarrow \pi^0\pi^0\pi^\pm$: $\sim 2 \times 10^8$

$\sim 200$ TB of data recorded

First result based on 2003 $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ sample will be presented here
Accepted statistics

Data-taking 2003:
$1.61 \times 10^9$ $K^\pm \to \pi^\pm \pi^+ \pi^-$ events

Even pion in beam pipe

Odd pion in beam pipe

Invariant $\pi \pi \pi$ mass

$\sigma_M = 1.7$ MeV/c$^2$

$K^+ : 1.03 \times 10^9$ events
$K^- : 0.58 \times 10^9$ events

$K^+/K^- \approx 1.8$
Principle of the experiment

- Build $u$-distributions of $K^{+}$ and $K^{-}$: $N^{+}(u), N^{-}(u)$
- Make a ratio of these distributions: $R(u)$
- Fit a linear function to this ratio: normalised slope $\approx \Delta g$

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

- e.g. uncertainty $\delta A_g < 2.2 \cdot 10^{-4}$ corresponds to $\delta \Delta g < 0.9 \cdot 10^{-4}$

But, achromat and spectrometer magnet ⇒ unavoidable sources of apparatus asymmetry!
Four ratios

\[ \frac{R_{US}}{R_{UJ}} = \frac{\frac{N(A+B+K+)}{N(A+B-K-)}}{\frac{N(A+B-K+)}{N(A+B+K-)}} \]

\[ \frac{R_{DS}}{R_{DJ}} = \frac{\frac{N(A-B+K+)}{N(A-B-K-)}}{\frac{N(A-B-K+)}{N(A-B+K-)}} \]

\textbf{Achromats: K}^+ \text{ Up}

\textbf{Achromats: K}^+ \text{ Down}

Indices of R's correspond to:
- beamline polarity (U/D)
- kaon deviation in spectrometer mag. field (S/J).

Supersample data taking strategy:
- achromat polarity (A) was reversed on weekly basis;
- spectrometer magnet polarity (B) was reversed on daily basis.

1 Supersample \sim 2 \text{ weeks} \Rightarrow 2003 \text{ data 4 supersamples}
Quadruple ratio

\[ R = R_{US} R_{UJ} R_{DS} R_{DJ} \sim 1 + 4 \Delta g \cdot u \]

3-fold cancellation of systematic biases:
1) Global time-variable biases (K\(^+\), K\(^-\) simultaneously recorded)
2) Beam line biases (K\(^+\) beam up / K\(^-\) beam up etc.)
3) Detector asymmetries (K\(^+\) toward Saleve / K\(^-\) toward Saleve etc.)

In addition, acceptance is defined respecting azimuthal symmetry
4) Effects of permanent stray fields (earth, vacuum tank magnetisation) cancel

The result is sensitive only to time variation of asymmetries in experimental conditions with a characteristic time smaller than corresponding field-alternation period (beam-week, detector-day)
Monte Carlo simulation

Due to acceptance cancellations, the analysis does not rely on Monte-Carlo to calculate acceptance.

Still MC is used to study systematics. MC features:

- Based on GEANT;
- Full detector geometry and material description;
- Local DCH inefficiencies simulated;
- Variations of beam geometry and DCH alignment are followed;
- Simulated statistics similar to experimental one.

Example of data/MC agreement: mean beam positions @DCH1
Beam systematics

Time variations of beam geometry

Acceptance largely defined by central beam hole edge (~10 cm radius)

Acceptance cut defined by (larger) “virtual pipe” centered on averaged beam positions as a function of charge, time and K momentum
**Spectrometer systematics**

**Time variations of spectrometer geometry** - Alignment is fine tuned by forcing mean reconstructed invariant $\pi\pi\pi$ masses to be equal for $K^+$ and $K^-$.

E.g. sensitivity to DCH4 horizontal shift: $\Delta M/\Delta x \approx 1.5$ keV/\(\mu\)m

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

In addition, it is adjusted by forcing mean reconstructed invariant $\pi\pi\pi$ masses to PDG value of $M_{K^+}$.
Trigger systematics

Inefficiencies measured using control data from low bias triggers. Rate-dependent parts of trigger inefficiencies assumed to be symmetric.

L1 trigger (2 hodoscope hits): stable and small inefficiency
\[ 1 - \varepsilon \approx 0.7 \times 10^{-3} \]
(no correction)

L2 trigger (online vertex reconstruction):
- time-varying inefficiency (local DCH inefficiencies)
  \[ 1 - \varepsilon \approx 0.2\% \text{ to } 1.8\% \]
  - flat in \( u \) within measurement precision
  - \( u \)-dependent correction applied

<table>
<thead>
<tr>
<th>L2 correction ( \delta \Delta g \times 10^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS0</td>
</tr>
<tr>
<td>SS1</td>
</tr>
<tr>
<td>SS2</td>
</tr>
<tr>
<td>SS3</td>
</tr>
</tbody>
</table>

Statistical uncertainty from control sample

Possibility to use MC studied
Other systematics

Residual effects of **stray magnetic fields**
(magnetised vacuum tank, earth field)
minimised by explicit field map correction

Further systematic effects studied:

- Bias due to **resolution** in $u$ calculation
- Sensitivity to **fitting interval and method**
- Effects connected to $\pi \rightarrow \mu \nu$ decay
- Effects due to event **pile-up**
- $\pi^+ / \pi^-$ interactions in material
- Track charge **misidentification**

Field map in decay volume: $Y$ projection

Decay volume: $Z$ coordinate

$\phi$-dependence of kaon mass

No magnetic field correction

Magnetic field corrected for
Fit linearity – four supersamples

SS0: $\Delta g = (0.6 \pm 2.4) \times 10^{-4}$, $\chi^2 = 39.7/38$

SS1: $\Delta g = (2.3 \pm 2.2) \times 10^{-4}$, $\chi^2 = 38.1/38$

SS2: $\Delta g = (-3.1 \pm 2.5) \times 10^{-4}$, $\chi^2 = 29.5/38$

SS3: $\Delta g = (-2.9 \pm 3.9) \times 10^{-4}$, $\chi^2 = 32.9/38$
Time stability

Quadruple ratio with

\[ \Delta g \]

4 supersamples give consistent results

control of detector asymmetry

control of beam line asymmetry

By regrouping the components in quadruple ratio – check residual detector and beam line asymmetries (~few \(10^{-4}\)) – they cancel safely in \(\Delta g\) fits

MC can reproduce these apparatus asymmetries
Systematics summary and result

<table>
<thead>
<tr>
<th>Preliminary estimates of systematic uncertainties</th>
<th>Effect on Δgx10⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance and beam geometry</td>
<td>0.5</td>
</tr>
<tr>
<td>Spectrometer alignment</td>
<td>0.1</td>
</tr>
<tr>
<td>Analyzing magnet field</td>
<td>0.1</td>
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<tr>
<td>π⁺→μν decay</td>
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<tr>
<td>U calculation and fitting</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.3</td>
</tr>
<tr>
<td>Syst. errors of statistical nature</td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency: L2</td>
<td>0.8</td>
</tr>
<tr>
<td>Trigger efficiency: L1</td>
<td>0.4</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Combined preliminary result:
in Δgx10⁴ units
(3 independent analyses)
Including L2 trigger correction

<table>
<thead>
<tr>
<th></th>
<th>Raw</th>
<th>Corrected for L2 eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS0</td>
<td>0.0±1.5</td>
<td>0.5±2.4</td>
</tr>
<tr>
<td>SS1</td>
<td>0.9±2.0</td>
<td>2.2±2.2</td>
</tr>
<tr>
<td>SS2</td>
<td>-2.8±2.2</td>
<td>-3.0±2.5</td>
</tr>
<tr>
<td>SS3</td>
<td>2.0±3.4</td>
<td>-2.6±3.9</td>
</tr>
<tr>
<td>Total</td>
<td>-0.2±1.0</td>
<td>-0.2±1.3</td>
</tr>
<tr>
<td>χ²</td>
<td>2.2/3</td>
<td>3.2/3</td>
</tr>
</tbody>
</table>

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Preliminary result $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ (2003 data)

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

$\Delta g = (-0.2 \pm 1.7) \times 10^{-4}$

Converted to asymmetry:

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

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

- This is a preliminary result with conservative estimate of systematic uncertainties
- Extrapolated statistical uncertainty 2003+2004: $\delta A_g = 1.6 \times 10^{-4}$
- Expect smaller systematic effects in 2004 data (due to more frequent polarity alternation, better L2 performance).
Comparison $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$

This preliminary result is already an order of magnitude better than previous experiments.
**$K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$ analysis**

- $u$ can be reconstructed with LKr calorimeter only
- Statistics analyzed: **$28 \times 10^6$ events** (1 month of 2003)
- Statistical error with analyzed data: $\delta A_g(\text{stat}) = 2.2 \times 10^{-4}$
- Extrapolation to 2003+2004 data: $\delta A_g(\text{stat}) = 1.3 \times 10^{-4}$
- Similar statistical precision as in “charged” mode
- Possibly larger systematic errors

**Statistical precision in $A_g^0$ similar to “charged” mode:**

- Ratio of “neutral” to “charged”
  - statistics: $N^0/N^{\pm} \sim 1/20 \ (\sqrt{s}=1/4.5)$
- Ratio of slopes: $|g^0/g^{\pm}| \sim 3$
- More favourable Dalitz-plot distribution
  (gain factor $f \sim 1.5$)
Observation of $\pi\pi$ scattering effect in $K \rightarrow 3\pi$ decays

Charge exchange process $\pi^+\pi^- \rightarrow \pi^0\pi^0$ not negligible under $2m_\pi$ threshold, destructive interference generates a cusp in the Dalitz plot, not seen earlier by lower precision experiments.

Great potential for a new accurate measurement of $\pi\pi$ scattering lengths from this data.

New preliminary result at Moriond QCD!
Conclusions

- **Preliminary NA48/2 result (2003 data)** on direct CP-violating charge asymmetry in $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays is
  
  $A_g = (0.5 \pm 2.4_{\text{stat.}} \pm 2.1_{\text{stat.(trig.)}} \pm 2.1_{\text{syst.}}) \times 10^{-4}$

- >10 times better precision than previous measurements
- Further room to decrease systematic uncertainties
- 2004 data contain another $2 \times 10^9 K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ events, with higher quality

- Neutral mode asymmetry: complementary, comparable sensitivity
- Design goal is within reach in both decay modes

- Other interesting results will follow ($\pi\pi$ scattering lengths, other CP asymmetries, rare decays)