Measurements of direct CP-violating asymmetries in $K^{\pm} \rightarrow 3\pi$ decays in NA48/2

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For the **NA48/2** collaboration

4th NA48 Kaon physics mini-workshop – CERN - May 2nd 2005

Outline

- Asymmetries in $K^{\pm}\to 3\pi$ decays
- The NA48/2 beam and experiment
- The measurement method
- Preliminary result (2003 data)
- Other measurements and perspectives

Rationale

• Charged K: direct CP violation only

• Differences between CP-conjugate particles:
most “straightforward” CP effect…

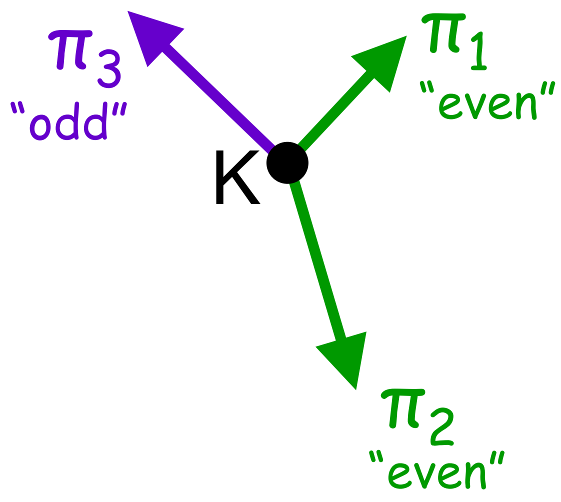
… not the most fashionable for connecting to the parameters of the underlying fundamental theory (e.g. SM)

• *A priori* larger effects than in K^0 (ε'/ε) could be expected

$K_{\pi 3}$ decays

$BR(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}) = 5.57\%$ "charged"

$BR(K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}) = 1.73\%$. "neutral"



Kinematics:

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

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

$u = (s_3-s_0)/m_\pi^2 = 2m_K\,(m_K/3-E^*_{odd})/m_\pi^2$

$v = (s_2-s_1)/m_\pi^2 = 2m_K(E^*_1-E^*_2)/m_\pi^2$

Matrix element:

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

$K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$	$g = -0.2154 \pm 0.0035$
$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$	$g = 0.652 \pm 0.031$

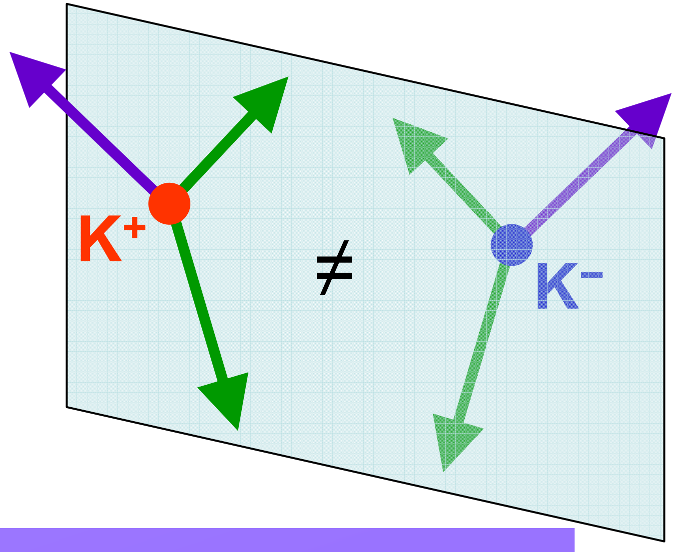
$|h|, |k| << |g|$

CP violation in $K_{\pi 3}$ (how)

Potentially large statistics

Simple selection

Low backgrounds



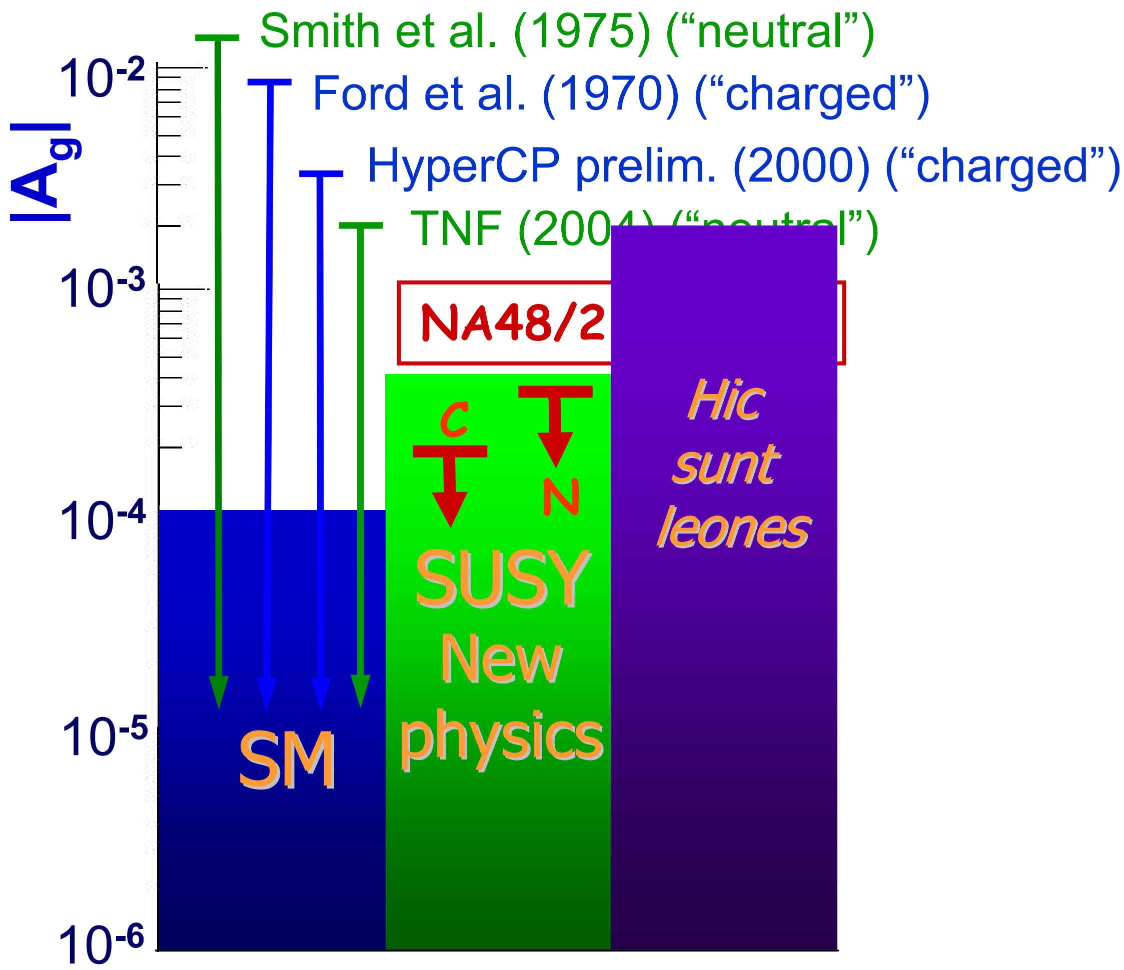
No absolute K flux measurement: compare only Dalitz plot shapes

Measured CP−violating quantity:

$$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0$$

Both 3π decay modes are available (with different statistics)

$K^{\pm}$ asymmetries: status



EXPERIMENT:

Few measurements in the '70s with rather limited statistics (few with both K charges in the same apparatus)

Some more recent measurements as byproducts

Larger statistics require adequate control of systematics: cancellations

No other experiment has simultaneous K+/K- beams

$K^{\pm}$ asymmetries: predictions

The "poor experimentalist's view"

Rate asymmetries (little – not zero - sensitivity in NA48/2) very suppressed

SM contribution now agreed to be rather tiny
several theoretical estimates, differing by ≈ 1 order of magnitude but
Ag ~ 10^{-5} or below *(actually good!)*

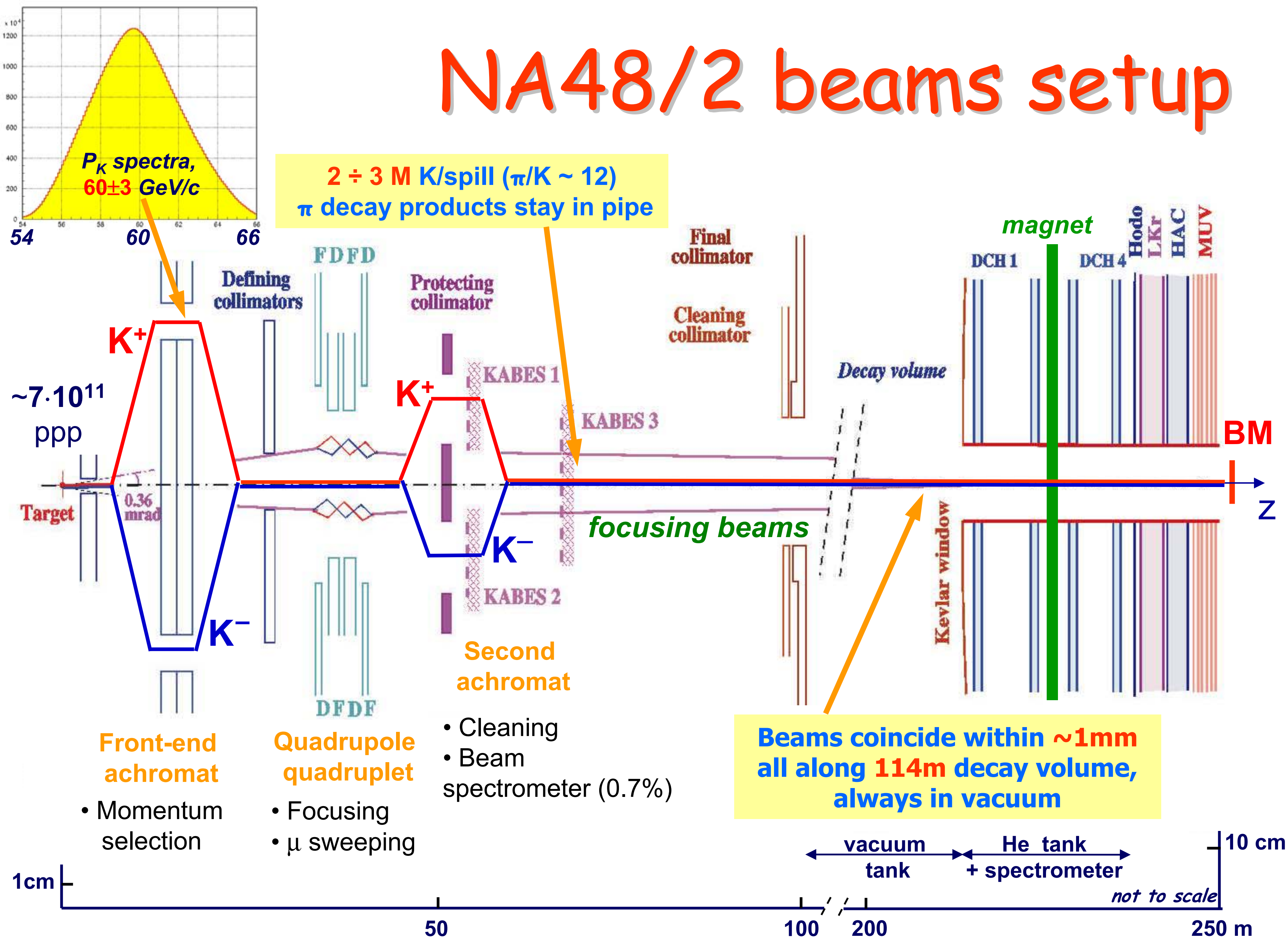
Large uncertainties (unknown phases)
especially for "neutral" mode ($K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$)

Beyond SM some enhancements seem possible.
Few explicit estimates, though.
D'Ambrosio, Isidori, Martinelli: chromo-magnetic operator in SUSY plus K^0 constraints roughly limits **Ag < $1 \cdot 10^{-4}$**

The NA48/2 approach

- ***NA48/2 main goal:***
  - Measure linear slope asymmetries "charged" and "neutral" modes with accuracies $\delta A_g < 2.2\cdot10^{-4}$ and $\delta A_g < 3.5\cdot10^{-4}$ respectively
  - Required statistics: $>2\cdot10^{9}$ in "charged" mode and $>10^{8}$ in "neutral" mode
- ***NA48/2 method: maximal cancellations (robustness)***
  - Two simultaneous K^{+} and K^{-} beams, superimposed in space, with narrow momentum spectra
  - Detect asymmetry only from slopes of ratios of normalized u distributions
  - Equalize averaged K^{+} and K^{-} acceptances by frequently alternating polarities of relevant magnets

NA48/2 beams setup



The NA48 detector

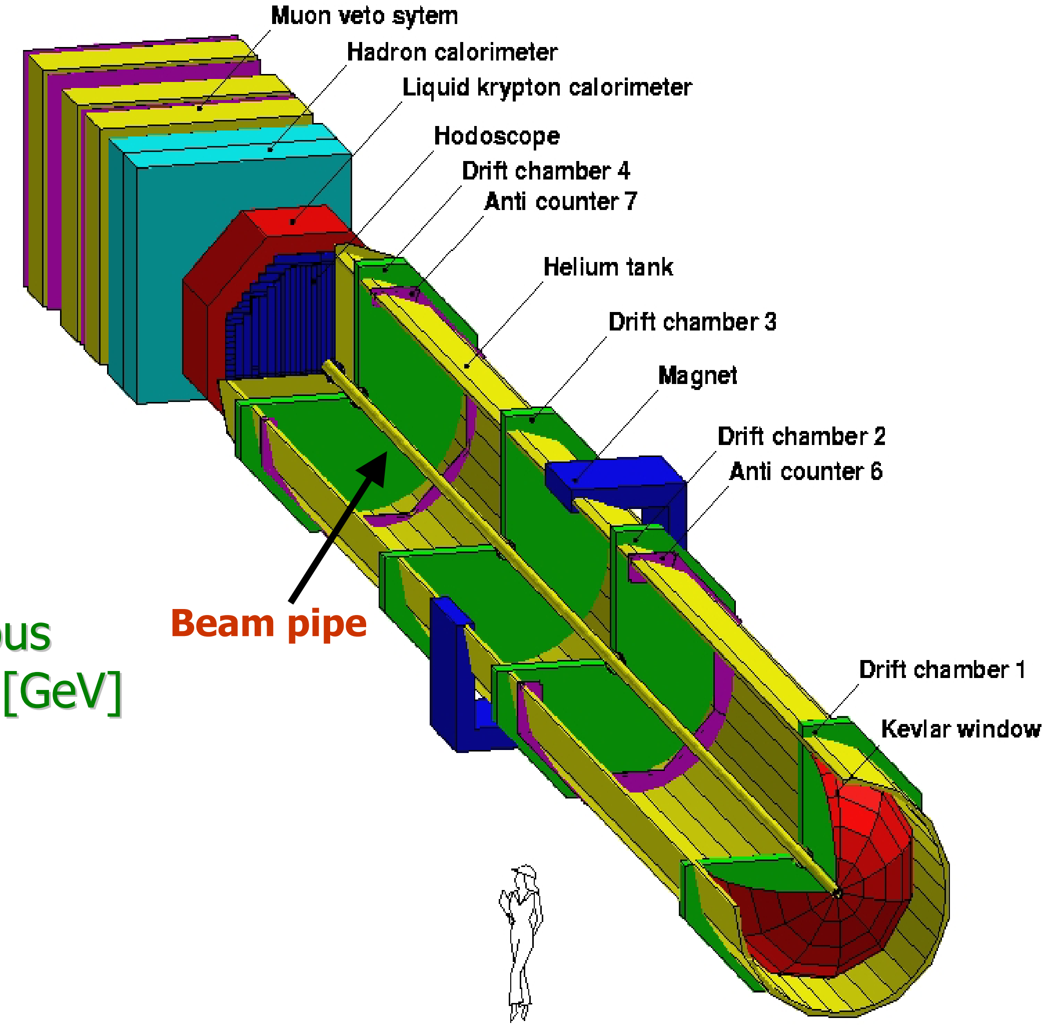
Main detector components:

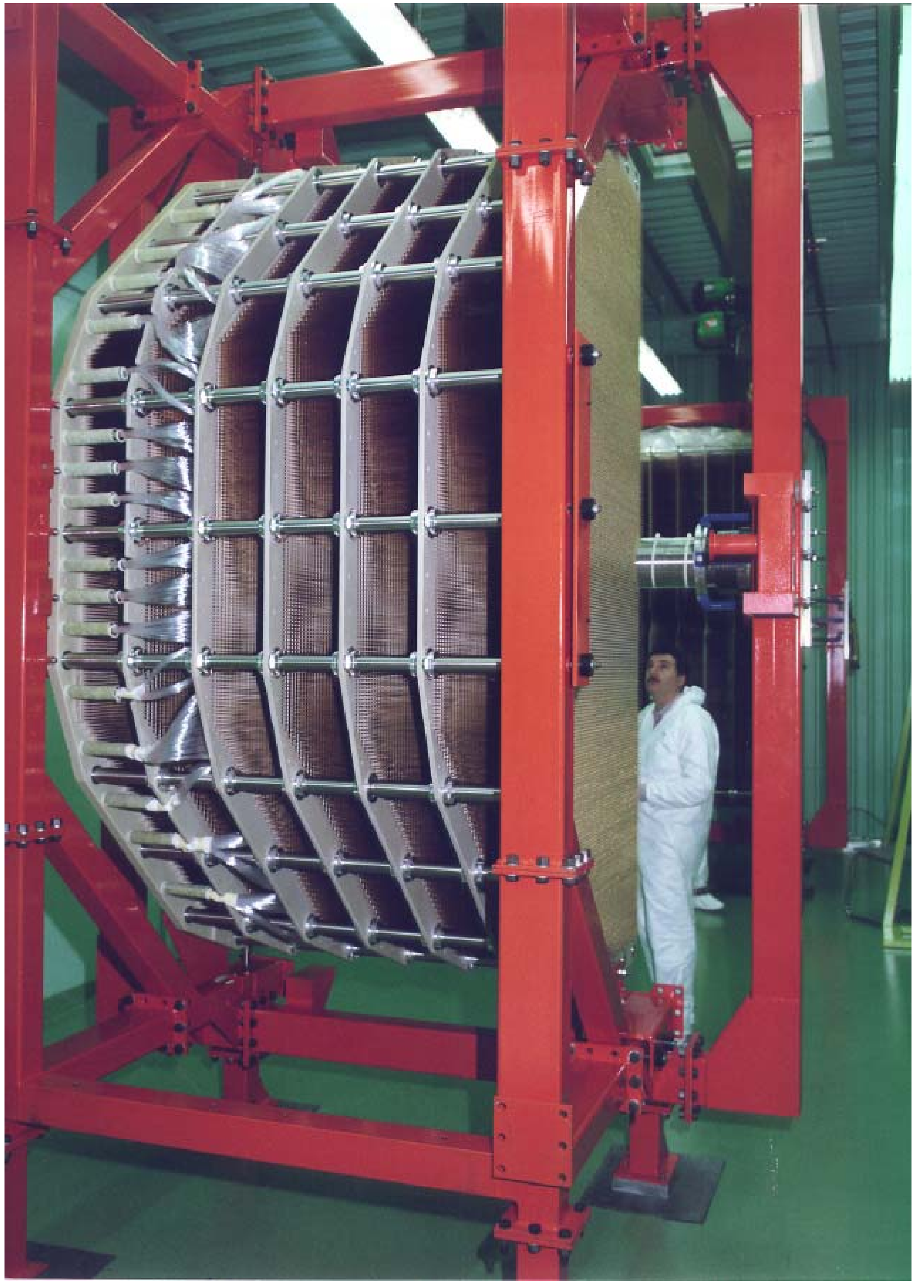
- Magnetic spectrometer (4 DCHs):
  4 views: redundancy ⇒ efficiency
  $\sigma_p/p = 1.0\% + 0.044\%\ p$ [GeV/c]

- Hodoscope
  fast trigger
  precise time measurement (150ps)

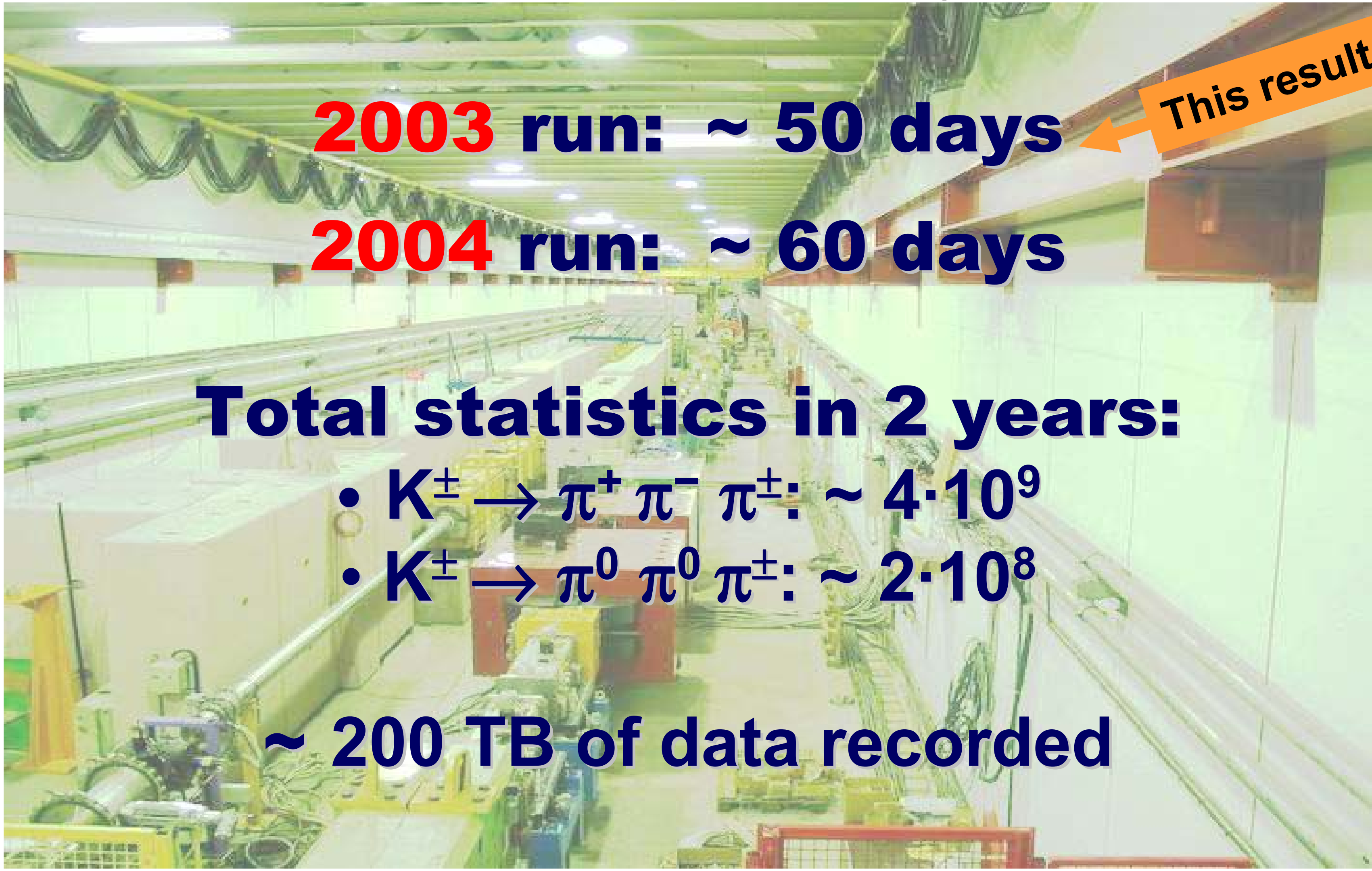
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi–homogeneous
  $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]
  e/π discrimination

- Hadron calorimeter, photon vetos,
  muon veto counters





Data taking: completed



2003 run: ~ 50 days ← This result

2004 run: ~ 60 days

Total statistics in 2 years:

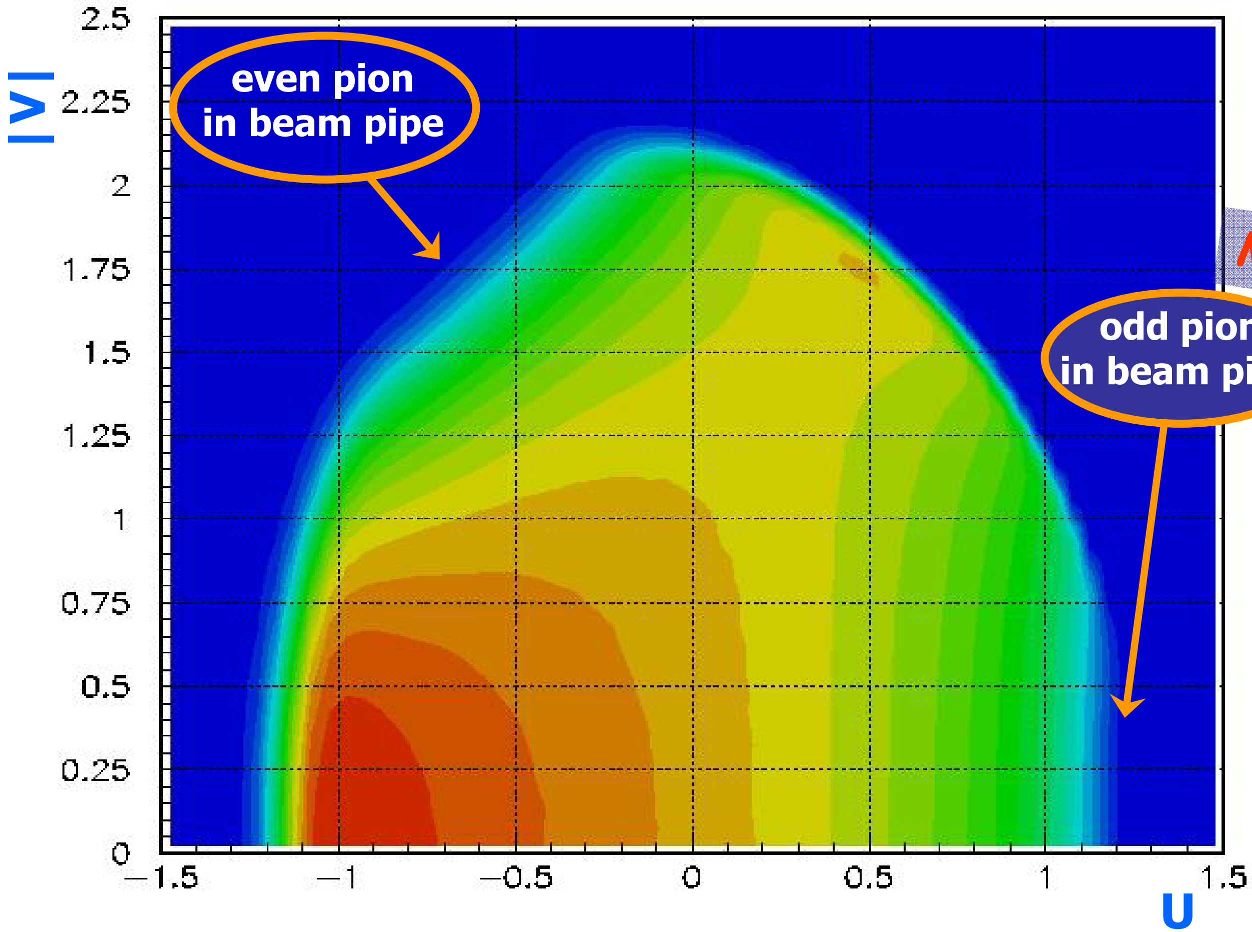
- $K^\pm \to \pi^+ \pi^- \pi^\pm$: ~ $4 \cdot 10^9$
- $K^\pm \to \pi^0 \pi^0 \pi^\pm$: ~ $2 \cdot 10^8$

~ 200 TB of data recorded

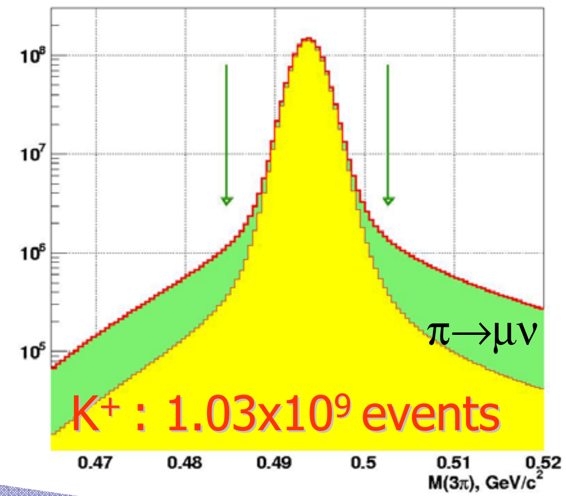
Selected data 2003

Data-taking 2003:

1.61x10^9 *events selected (K$^+$ / K$^-$ ≈ 1.8)*

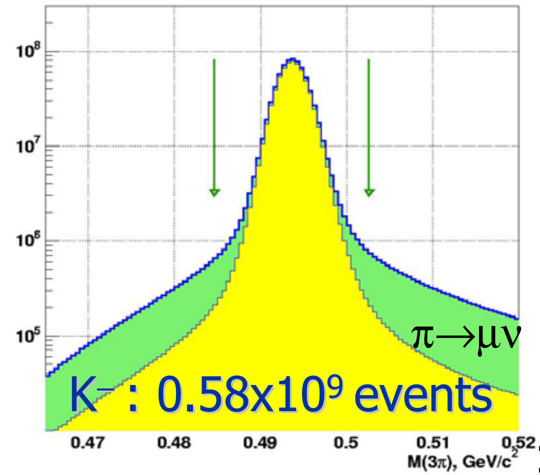


σ_M=1.7 MeV/c^2



Magnetic spectrometer only

No significant background



The experimental method

Project Dalitz plot onto u-axis

Neglect asymmetries in quadratic slopes h, k

If acceptance is equal for K^+ and K^-

$$R(u) = N^+(u)/N^-(u) \approx$$

$$\approx n\cdot(1+g_+u)/(1+g_-u) \approx$$

$$\approx n\cdot(1+ \Delta g\, u)$$

$A_g = \Delta g/2g$ can be extracted from a linear fit of the ratio of u-distributions

Instrumental asymmetries:

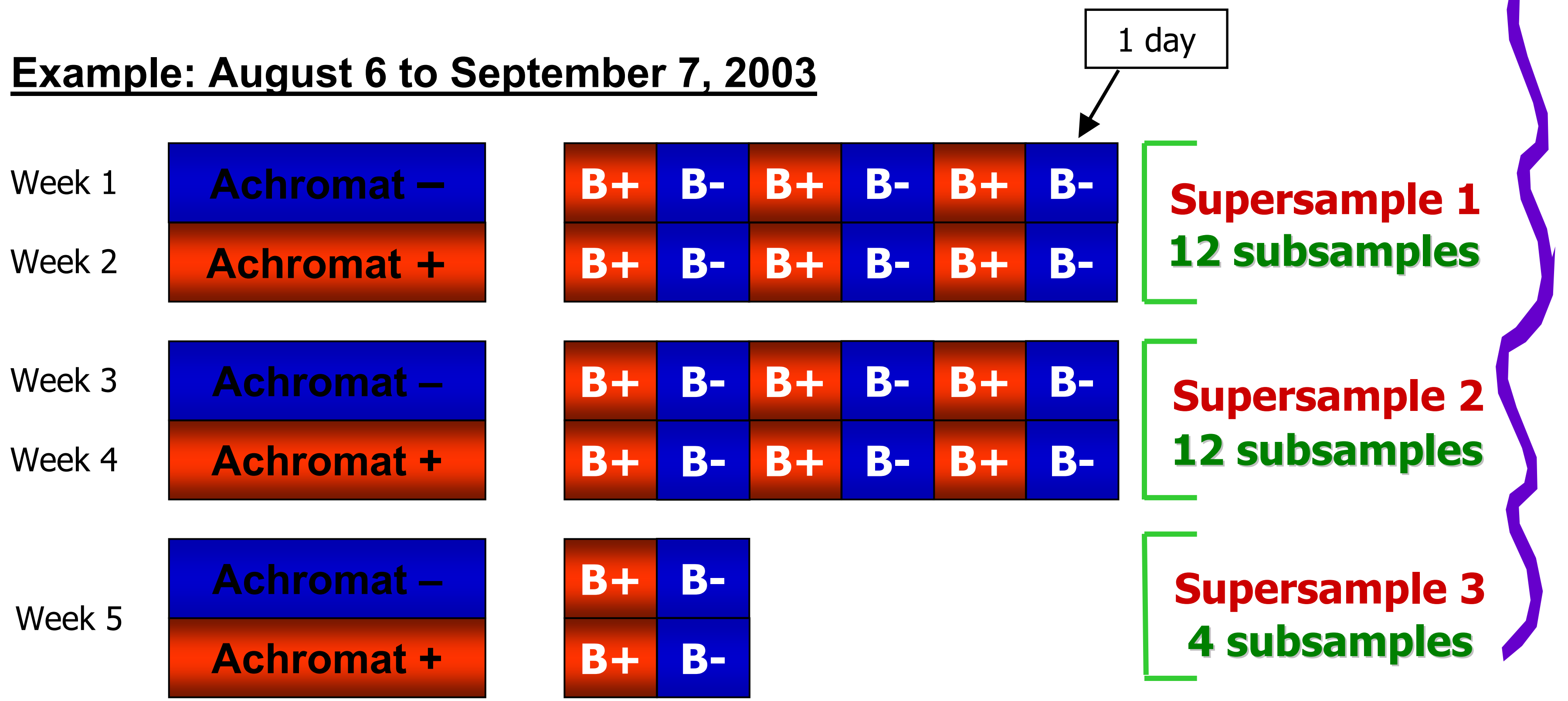
1. Detector acceptance asymmetry
2. Time variation of detector response
3. Charge-dependent beam optics
4. Time variation of beams' properties
5. Spurious magnetic fields
6. Charge-asymmetric interactions

Any imperfection has to be <u>charge-asymmetric</u> AND <u>non-flat in u</u> to induce an effect

Addressing the acceptance

- **Beam line** (achromat) polarity (A) reversed on weekly basis
- **Spectrometer magnet** polarity (B) reversed on daily basis

Example: August 6 to September 7, 2003



Acceptance cancellation
within supersample

Detector left-right asymmetry cancels

in 4 ratios of K^+ over K^- u distributions:

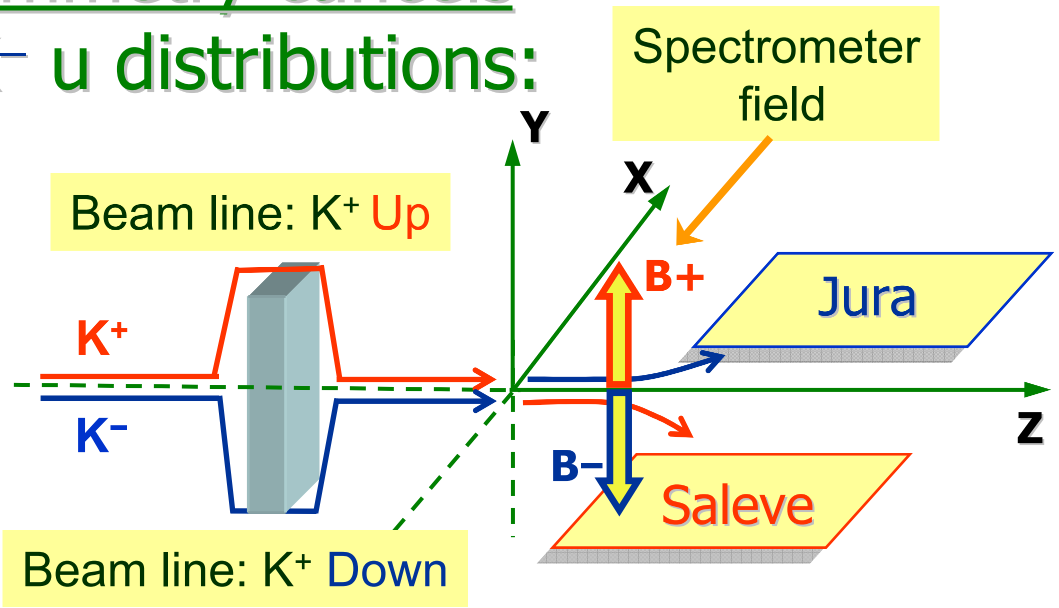
(same deviation by spectrometer in numerator and denominator)

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

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

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

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



Indexes correspond to
- beamline polarity (U / D)
- direction of kaon deviation in spectrometer (S / J)

More cancellations

Double ratio cancellation of **global time instabilities** (rate effects, *simultaneous beams*):

K+ and K− recorded at the same time

Double ratio cancellation of **beam geometry difference** effects:

K+ and K- both passing through upper (lower) beam line

Double ratio cancellation of (possibly large) **detector asymmetry** effects: K+ and K- both illuminating same detector regions

Fit with **quadruple ratio**:

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

n: Normalization; Δg: Slope difference

The fit result is sensitive only to time variation of left-right asymmetries of experimental conditions on a time-scale of ~1 subsample

$$\Delta g = 2g\,A_g \approx -0.43\,A_g$$

$$\delta A_g < 2.2 \cdot 10^{-4} \leftrightarrow \delta\Delta g < 0.9 \cdot 10^{-4}$$

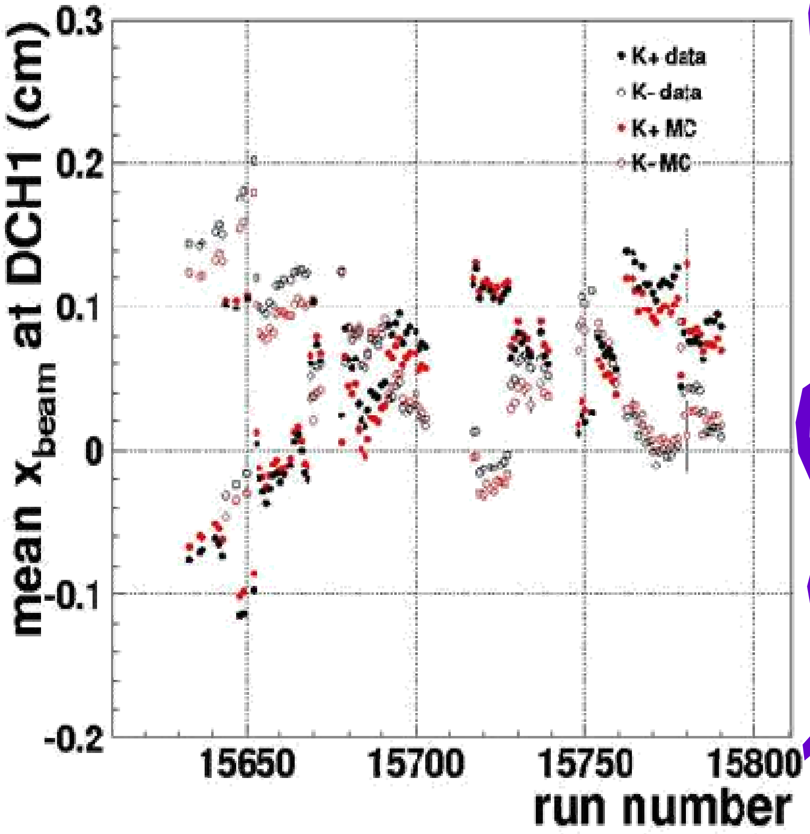
Simulation

Robust technique implies that
ANALYSIS DOES NOT RELY ON MONTE CARLO SIMULATION
of detector imperfections (asymmetries)

Still, a full GEANT-based MC is used to study the sensitivity to different systematic effects

Statistics comparable to data

Local detector imperfections simulated as well as their time evolution



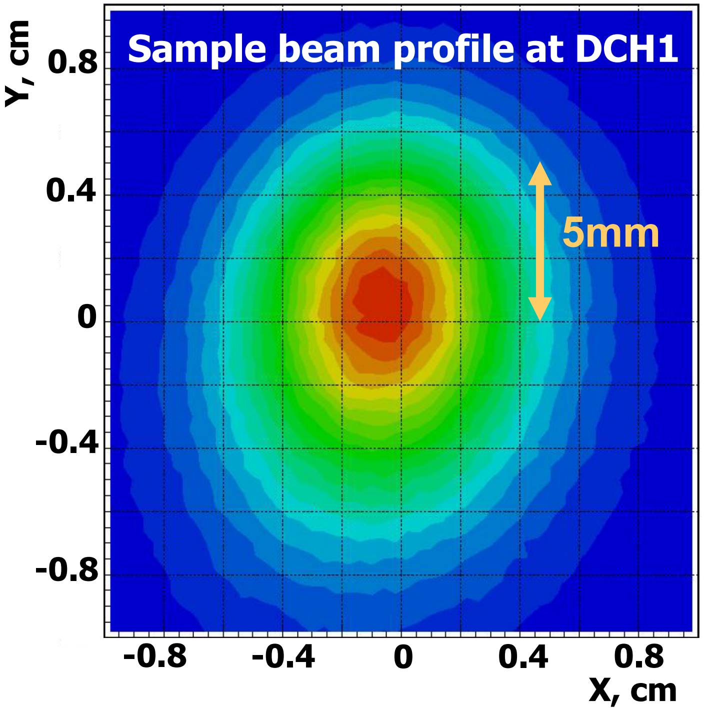
Example of data/MC agreement
Average beam positions at first chamber

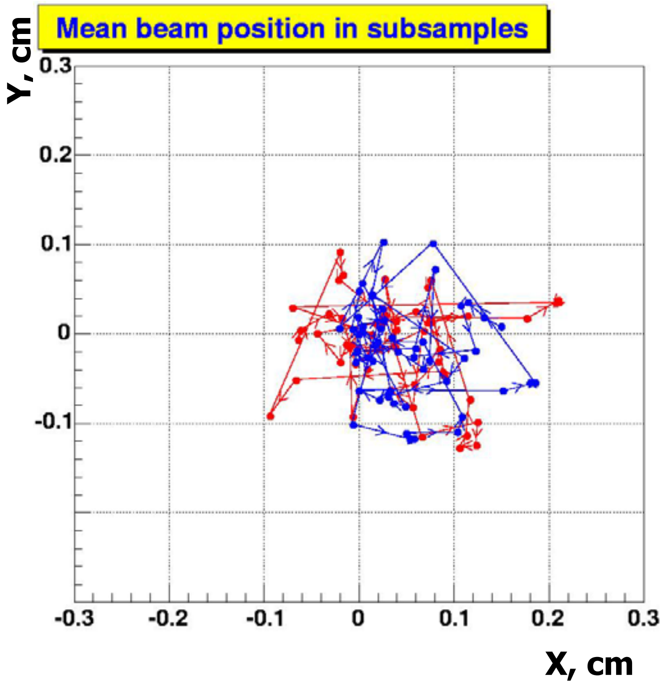
Systematics: beams

Time variations of beam geometry

Acceptance largely defined by central hole edge (12 cm radius)

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





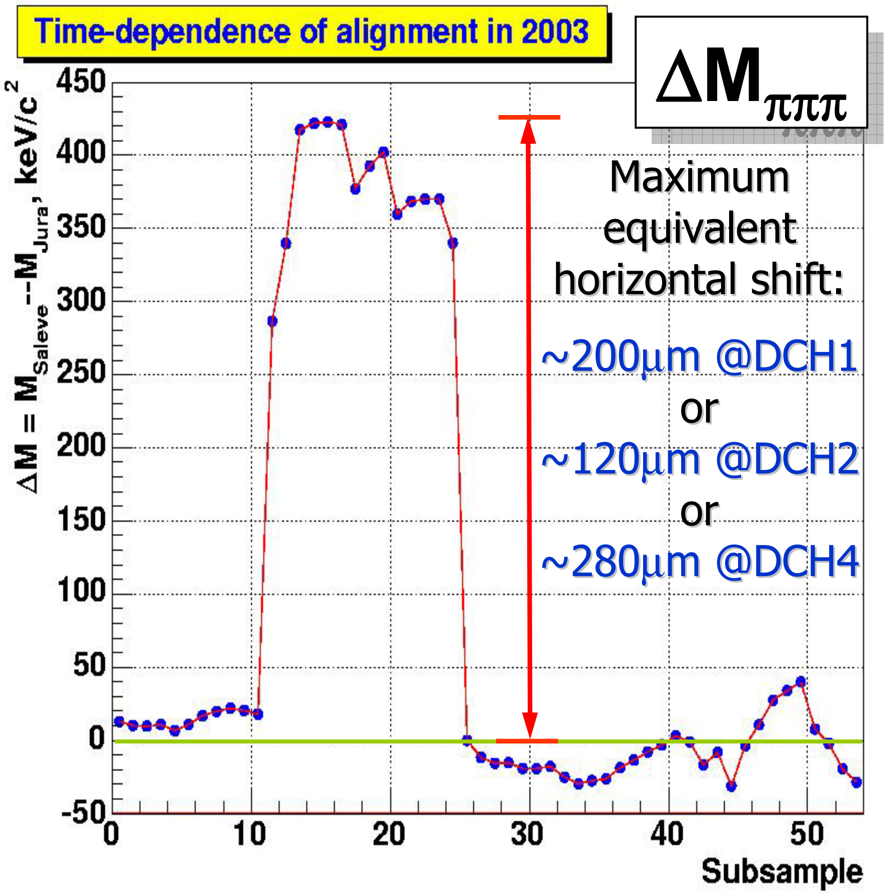
Beam widths:
~ 5 mm
Beam movements:
~ 2 mm

Also corrects for differences in the two beam paths

Systematics: spectrometer

Time variations of spectrometer geometry

Alignment fine tuning by equalizing reconstructed average K^+,K^- masses



Sensitivity to DCH4 horizontal shift:
$\Delta M/\Delta x \approx 1.5$ keV/μm

Effect of **imperfect inversion of spectrometer field** cancels in double ratio (simultaneous beams)

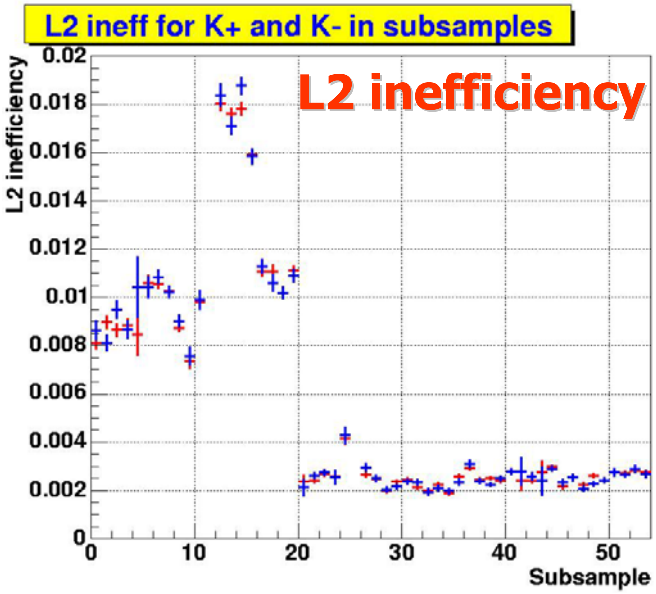
Momentum scale adjusted anyway by constraining average reconstructed K masses to PDG value

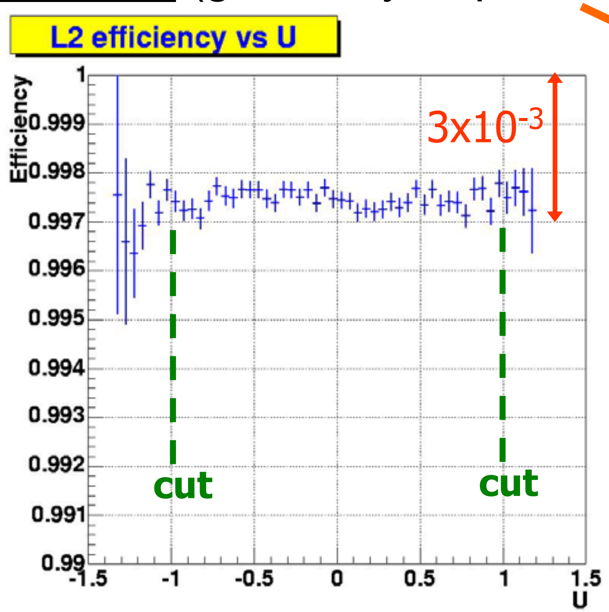
Sensitivity to 10^{-3} error on field integral:
$\Delta M \approx 100$ keV

Systematics: trigger

L1 trigger (2 hodoscope hits):
stable inefficiency ≈ $0.7 \cdot 10^{-3}$ charge-symmetric, flat in u:
no correction

L2 trigger (online vertex reconstruction on DCH data):
time-varying inefficiency (local DCH inefficiencies) 0.2% to 1.8%,
charge-symmetric and flat in u within measurement precision
(control triggers): u-dependent **correction** (geometry-dependent part only)



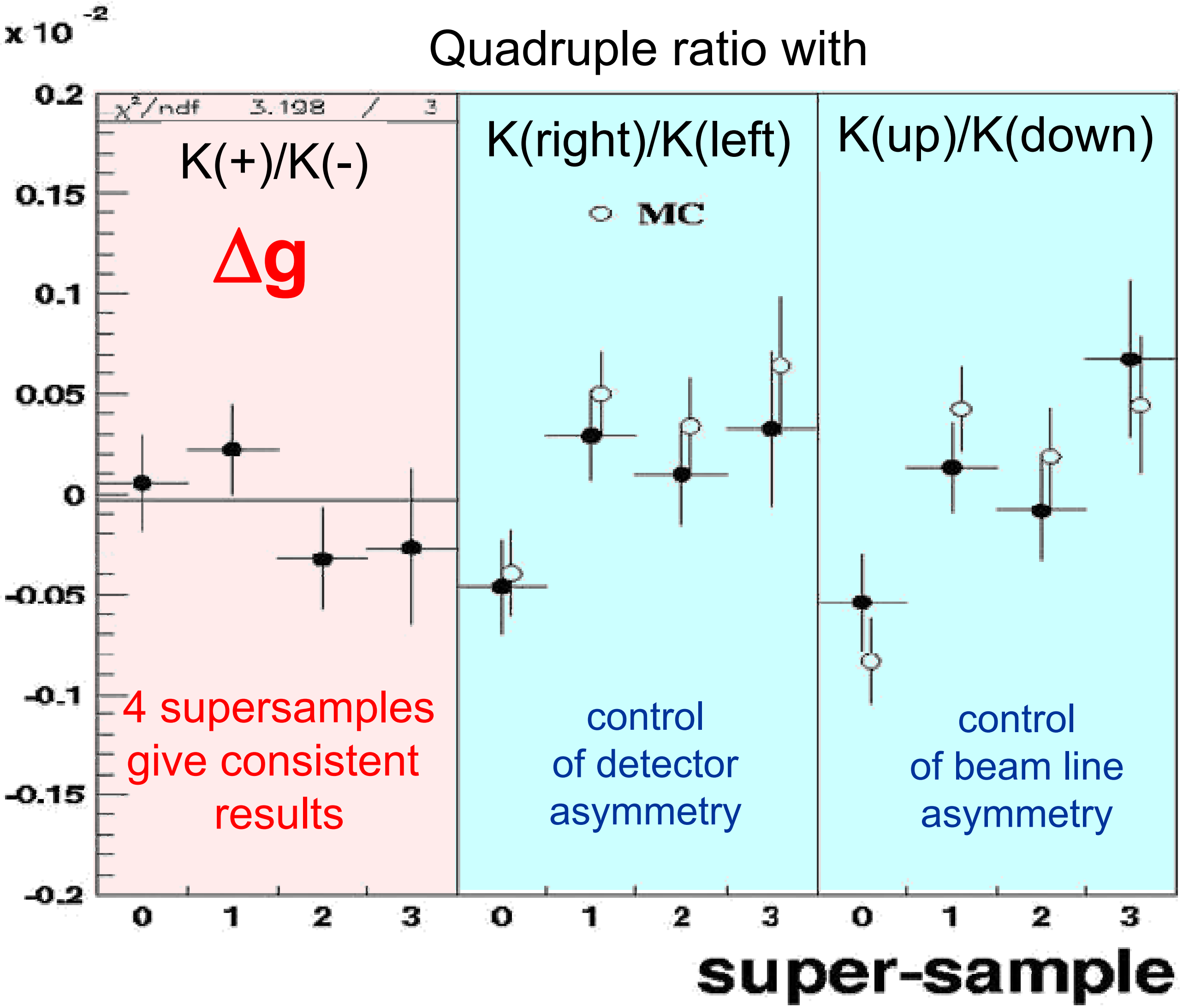


Correction introduces *statistical error* from control sample

More systematics…

- Accuracy in **time-tracking** of beam movements, changes in beam widths
- **Inhomogeneities** in spectrometer misalignment, different misalignments
- Effect of **stray magnetic fields**: Earth's magnetic field, vacuum tank magnetization (measured): 10^{-4} of spectrometer kick
- Coupling of **π decay** to other effects
- **Accidental** (pile-up) effects
- Charge-asymmetric **π interactions**
- Track charge **mis-identification**
- **Fitting** region and method sensitivity

Time stability



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

MC can reproduce these apparatus asymmetries

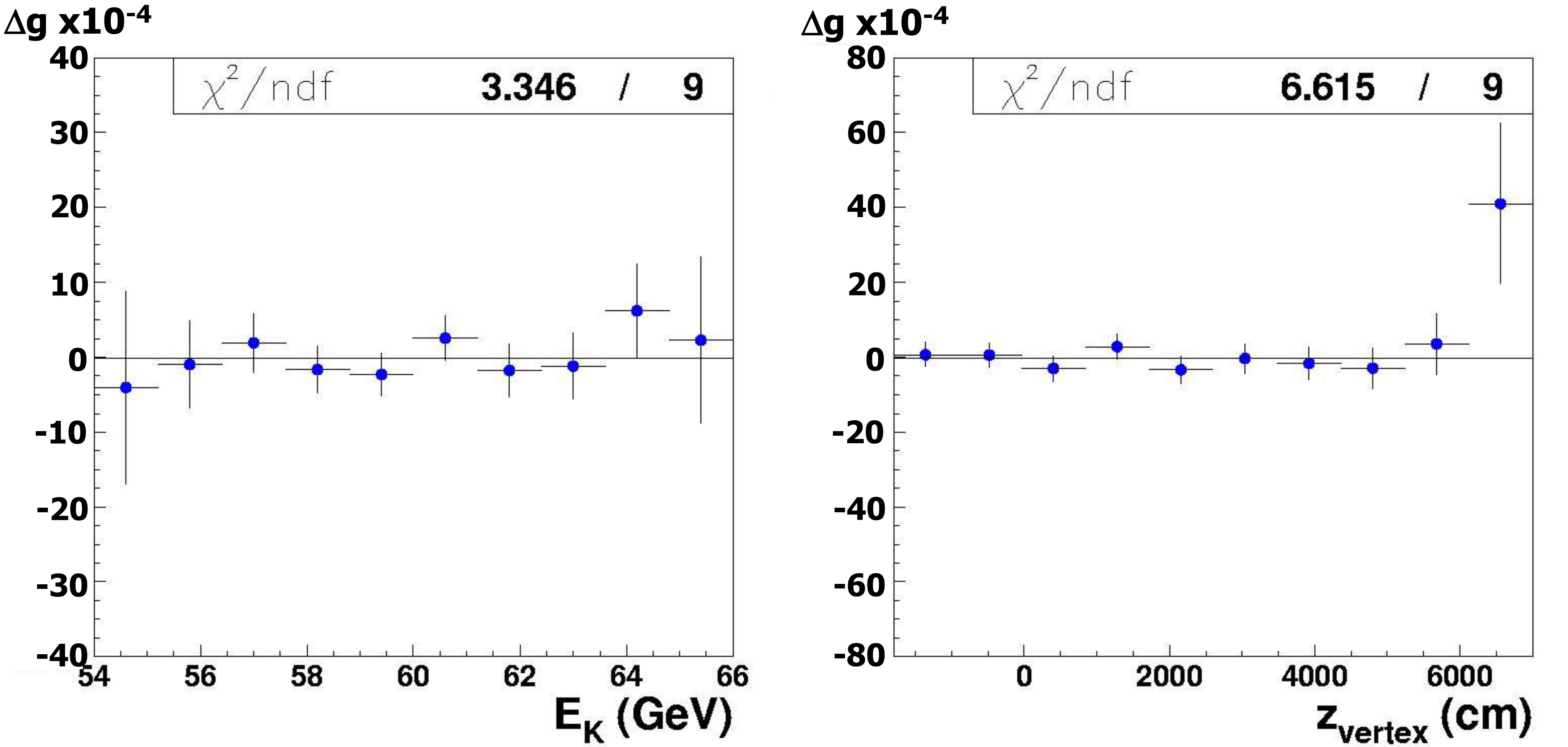
Result and errors

Combined result: $\Delta g \times 10^4$
(3 independent analysis)
L2 trigger systematics included

Sample	Raw	Corrected for L2 eff
SS0	0.0 ± 1.5	0.5 ± 2.4
SS1	0.9 ± 2.0	2.2 ± 2.2
SS2	-2.8 ± 2.2	-3.0 ± 2.5
SS3	2.0 ± 3.4	-2.6 ± 3.9
Total	**-0.2 ± 1.0**	**-0.2 ± 1.3**
χ^2	2.2 / 3	3.2 / 3

Conservative estimate of systematic errors	Effect on $\Delta g \times 10^4$
Acceptance, beam geometry	0.5
Spectrometer alignment	0.1
Spectrometer magnet field	0.1
$\pi \to \mu\nu$ decay	0.4
U calculation and fitting	0.5
Accidental activity	0.3
Syst. errors of statistical nature	
Trigger efficiency: L2	0.8
Trigger efficiency: L1	0.4
Total systematic error	**1.3**

Result stability



Preliminary result: 2003 data

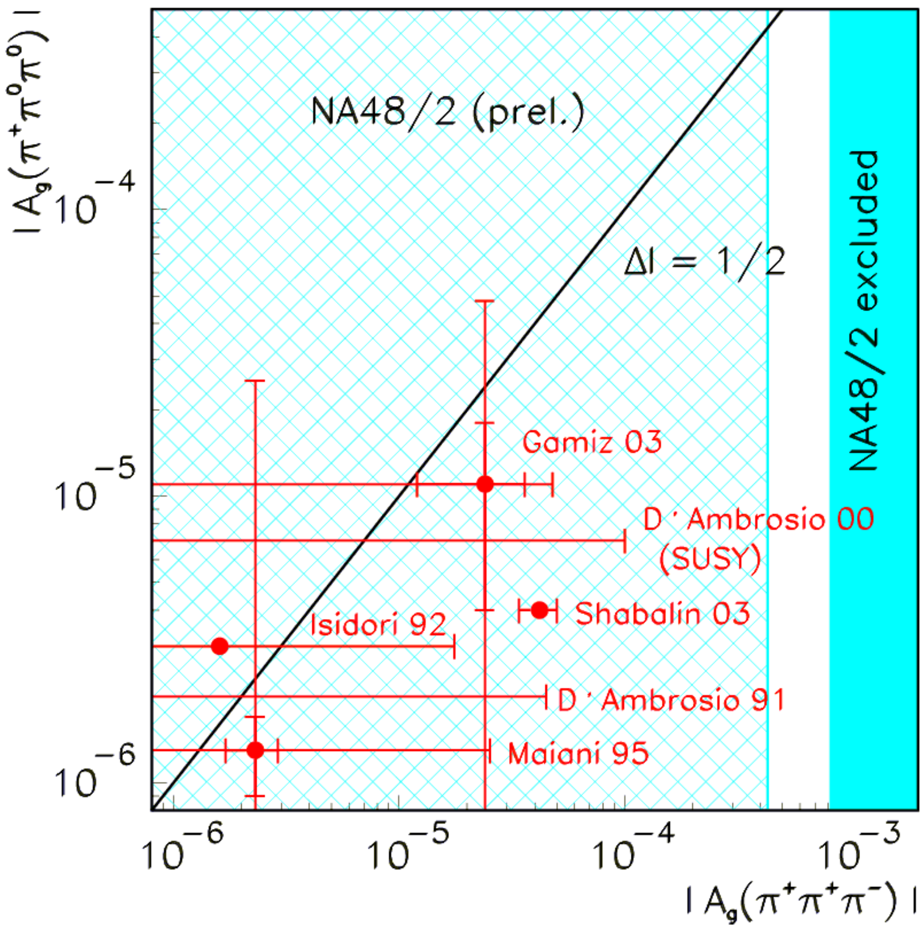
$$A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.(trig.)} \pm 2.1_{syst.}) \times 10^{-4}$$

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

- Preliminary result with conservative systematic errors

- Extrapolated final statistical error (2003+2004): $\delta A_g = 1.6 \times 10^{-4}$

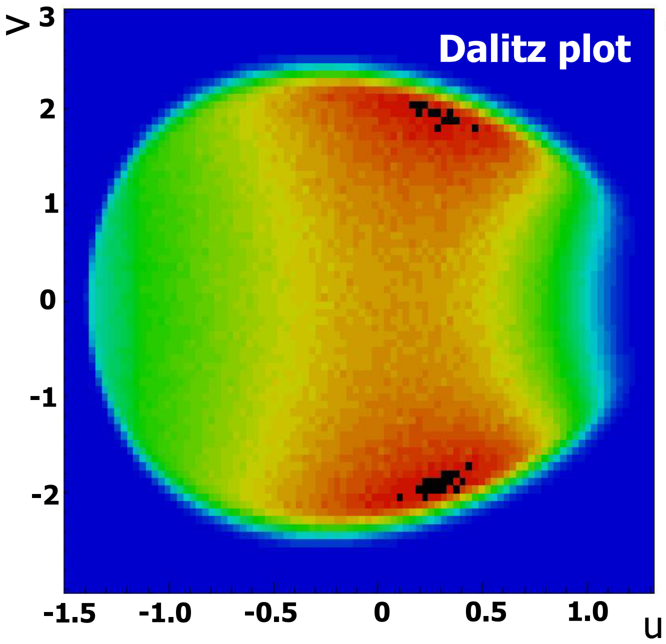
- 2004 data: expect smaller systematic effects (more frequent polarity alternation, better beam steering)

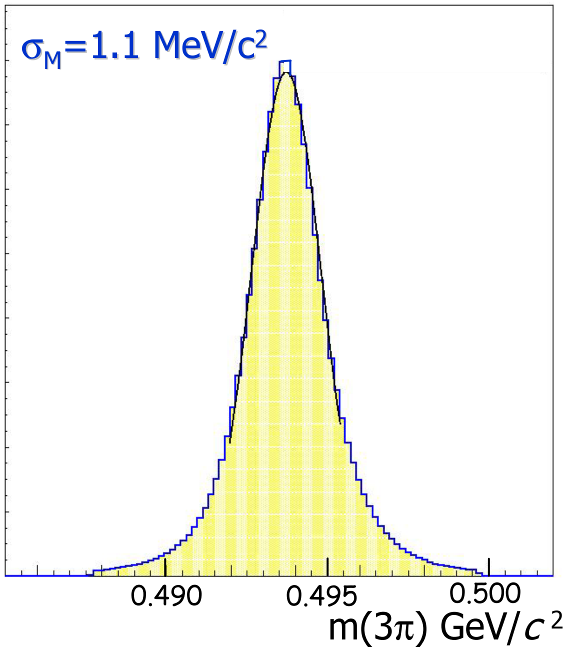


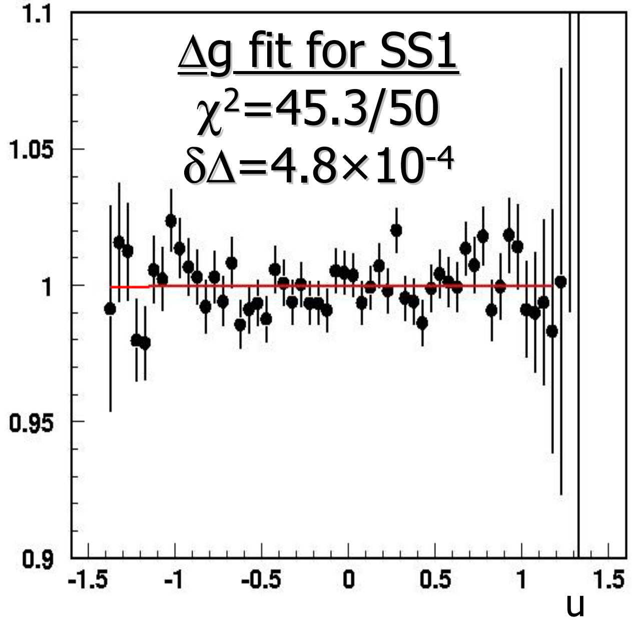
“Neutral” mode asymmetry

$K^\pm \to \pi^\pm \pi^0 \pi^0$

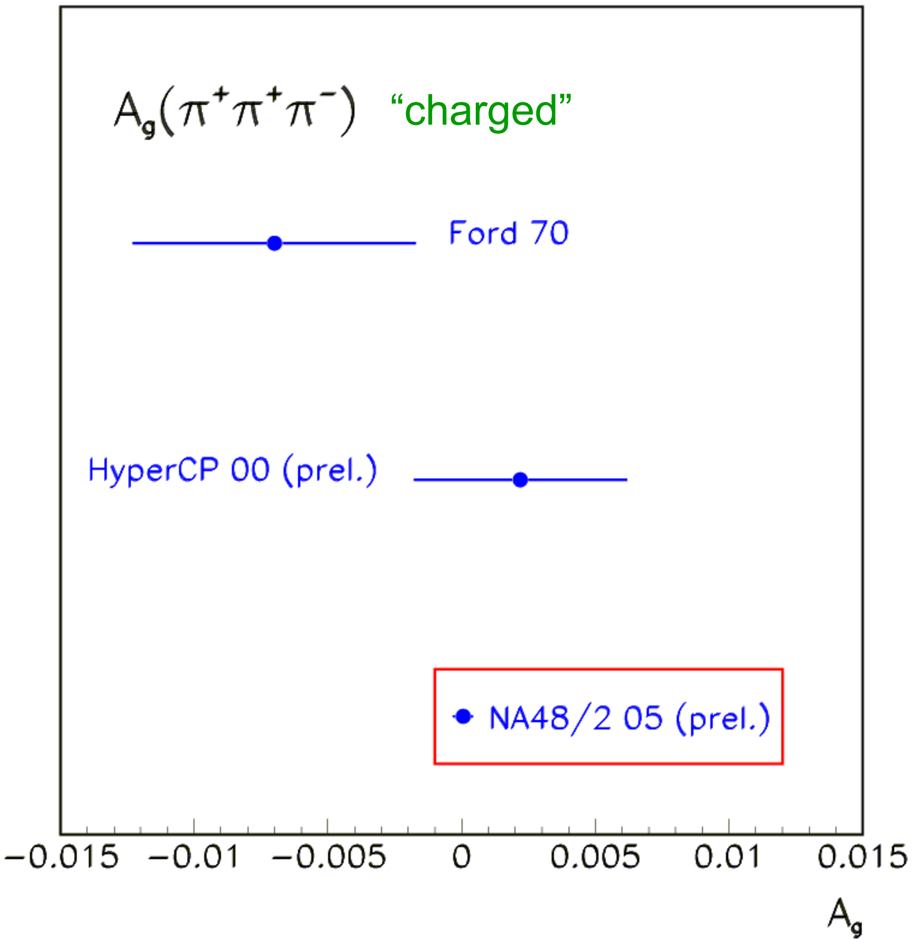
- u can be reconstructed with LKr calorimeter only
- Statistics analyzed: **28 × 10⁶ events** (1 month of 2003)
- Higher statistical power
- Statistical error with analyzed data: $\boldsymbol{\delta A_{g(stat)} = 2.2 \times 10^{-4}}$
- Extrapolation to 2003+2004 data: $\boldsymbol{\delta A_{g(stat)} = 1.3 \times 10^{-4}}$
- Possibly larger systematic errors



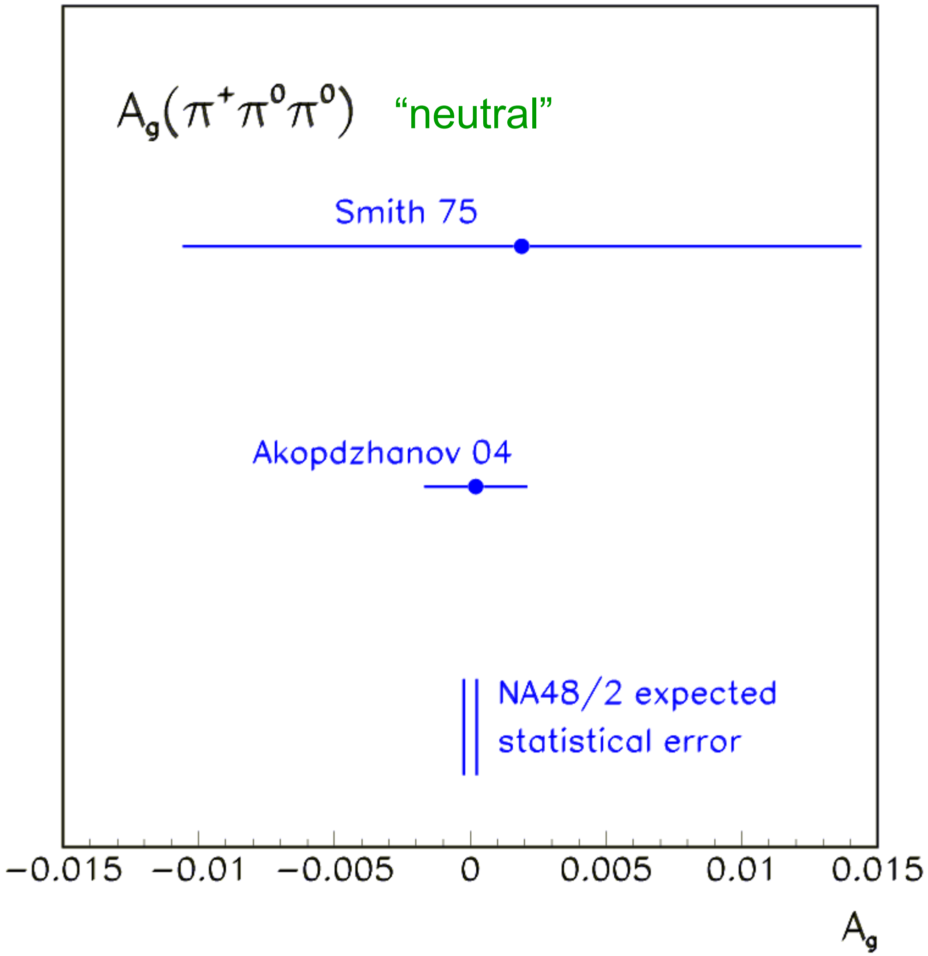




Experiment



$A_g(\pi^+\pi^+\pi^-)$ "charged"
Ford 70
HyperCP 00 (prel.)
NA48/2 05 (prel.)
−0.015 −0.01 −0.005 0 0.005 0.01 0.015
A_g



$A_g(\pi^+\pi^0\pi^0)$ "neutral"
Smith 75
Akopdzhanov 04
NA48/2 expected
statistical error
−0.015 −0.01 −0.005 0 0.005 0.01 0.015
A_g

NA48/2 asymmetry highlights

- Unprecedented statistics
- First experiment with *simultaneous* K^+/K^- beams: robust cancellations of systematics
- Both 3π decay modes available:
  comparable statistical power
  complementary and uncorrelated systematics
  ("charged" mode uses only magnetic spectrometer, "neutral" mode can use almost exclusively EM calorimeter)
- Almost *all* charged K decay modes collected

$K^{\pm}$ asymmetries: questions

More explicit investigation of other models beyond SM?

Are there other possible enhancements mechanisms?

NA48/2 has the potential to close the very wide gap between experimental limits and the edges of the explicit predictions *(significance of a non-zero result…):*

Can this measurement rule out some parts of parameter space?

Can the connection between the two 3π decay modes be exploited?

Can the connection with K0 (ε'/ε) be exploited?

Are there other interesting asymmetries (in these or other decay modes)?

Conclusions

- Preliminary NA48/2 result (2003 data) on direct CP−violating charge asymmetry in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$:

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

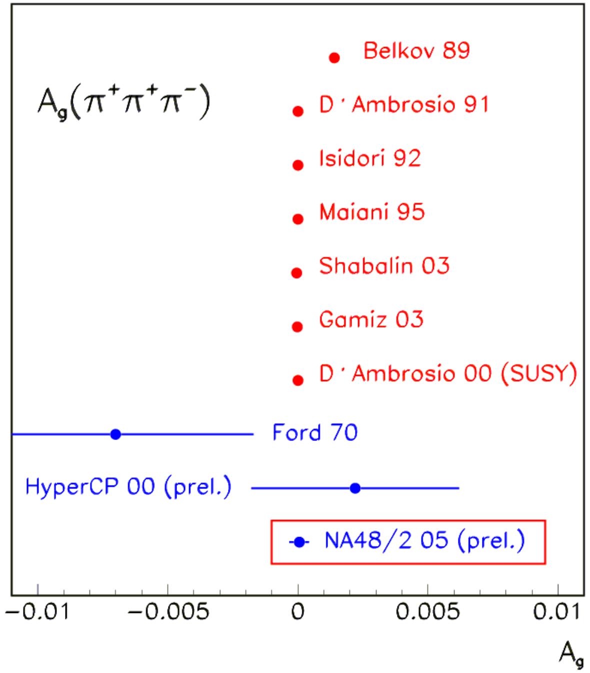
- 10 times better precision than previous measurements
- Room to decrease systematic error (*trigger efficiency*)
- 2004 data contain another 2×10^{9} charged events, with higher quality
- Design goal within reach
- More detector information (beam spectrometer) available
- Neutral mode asymmetry: complementary, comparable sensitivity

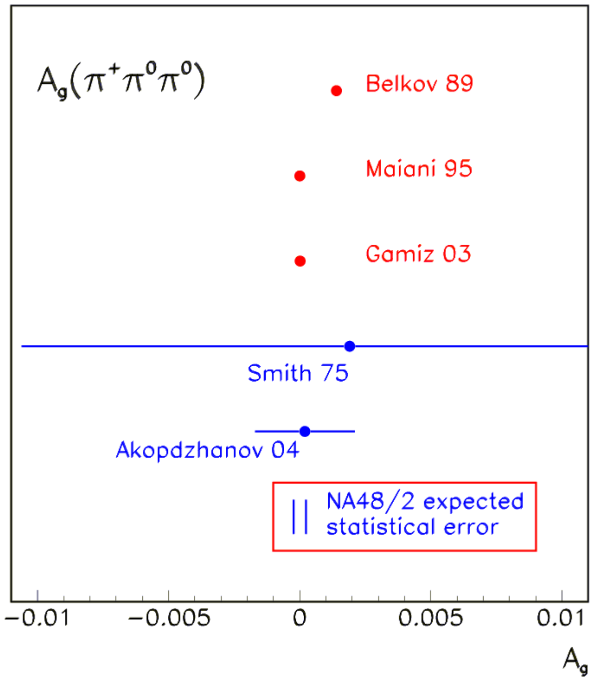
SPARE SLIDES

Experimental status

"Charged" mode $K^{\pm}\rightarrow 3\pi^{\pm}$

- Ford et al. (1970) at BNL
  A_g=(-7.0±5.3)·10^{-3}
  Statistics: 3.2M $K^{\pm}$
- HyperCP prelim. (2000) at FNAL
  A_g=(2.2±1.5±3.7)·10^{-3}
  Statistics: 390M K^{+}, 1.6M K
  Preliminary, published as PhD thesis





"Neutral" mode $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$

- Smith et al. (1975) at CERN-PS
  A_g=(1.9±12.3)·10^{-3}
  Statistics: 28000 $K^{\pm}$
- TNF (2004) at IHEP Protvino
  A_g=(0.2±1.9)·10^{-3}
  Statistics: 0.52M $K^{\pm}$

Theoretical predictions of A_g

Standard Model	L.Maiani, N.Paver '95	$(2.3\pm0.6)\times10^{-6}$
	A. Bel'kov '95	$<4\times10^{-4}$
	G.D'Ambrosio, G.Isidori '98	$<10^{-5}$
	E.Shabalin '01	$<3\times10^{-5}$
	E.Gamiz, J.Prades, I.Scimemi '03	$(-2.4\pm1.2)\times10^{-5}$
	E.Shabalin '05 (La Thuile'05)	$<8\times10^{-5}$
Beyond SM	G.D'Ambrosio, G.Isidori, G.Martinelli	$\sim10^{-4}$
	E.Shabalin '98 [Weinberg model of extended Higgs doublet]	$\sim4\times10^{-4}$
	I.Scimemi '04	$>3\times10^{-5}$