High precision study of charge asymmetry in $K^{\pm} \rightarrow 3\pi^{\pm}$ decays by NA48/2 at CERN SPS

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on behalf of the **NA48/2** Collaboration:

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

Les Rencontres de Physique de la Vallée d'Aoste

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Overview

- Direct CP violation in $K^{\pm}\rightarrow 3\pi$ decays;
- NA48/2 experimental setup;
- Measurement principle;
- Systematic effects;
- The preliminary result in the $K^{\pm}\rightarrow 3\pi^{\pm}$ mode based on the full collected statistics;
- Status of the $K^{\pm}\rightarrow \pi^{0}\pi^{0}\pi^{\pm}$ analysis;
- Conclusions.

DCPV in $K_{3\pi}$ decays

DCPV: a window to physics beyond the SM

The two decay modes: $BR(K^\pm \to \pi^\pm\pi^+\pi^-)=5.57\%$; $BR(K^\pm \to \pi^\pm\pi^0\pi^0)=1.73\%$.
"charged" **"neutral"**

Kinematics:

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

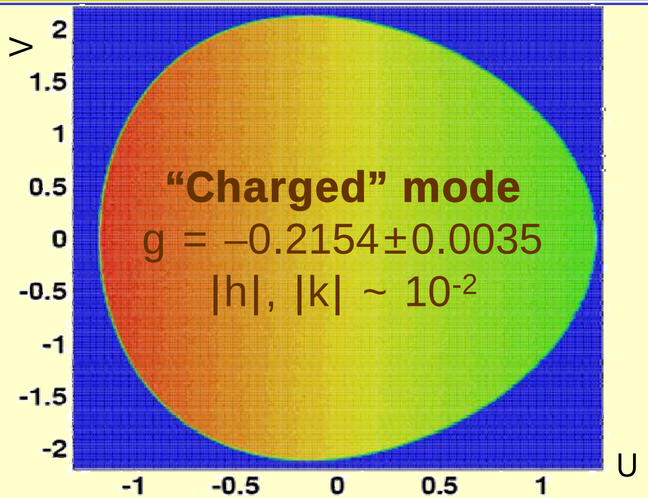
$s_0 = (s_1+s_2+s_3)/3$;

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

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

Matrix element:

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



Kaon rest frame:

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

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

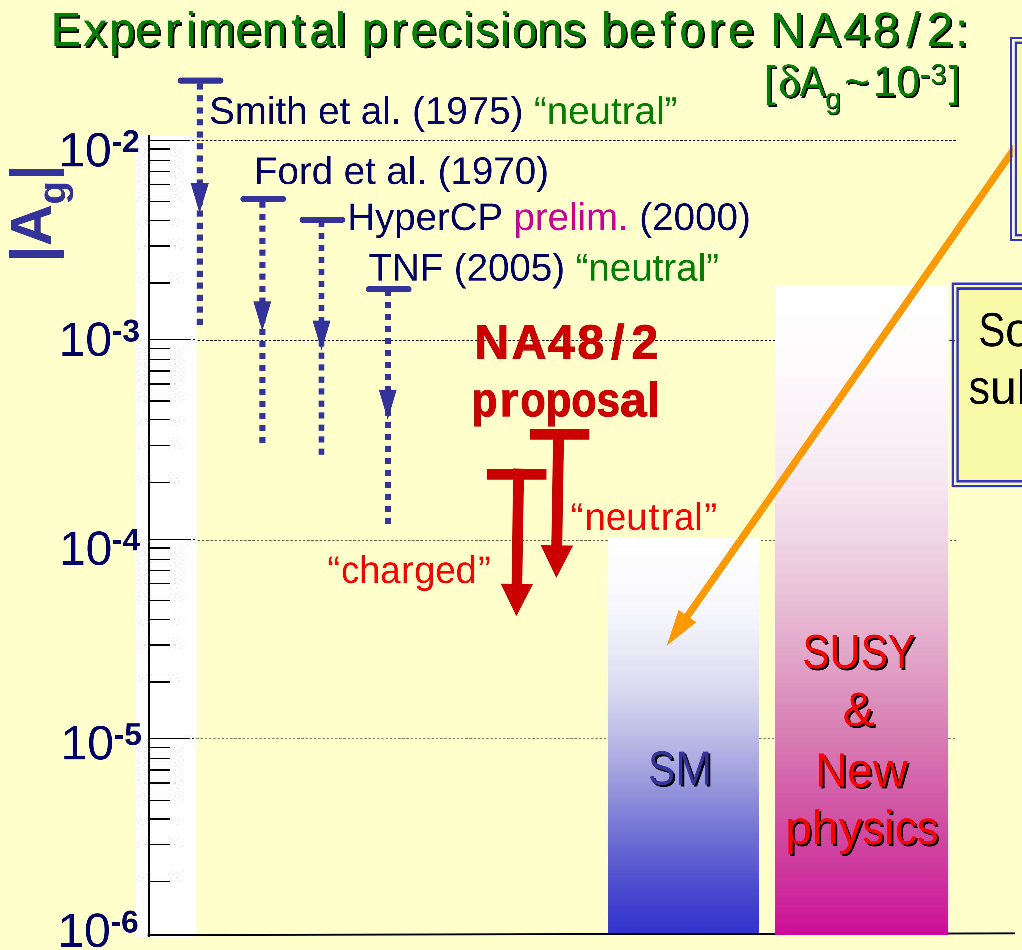
Direct CP-violating quantity: the slope asymmetry

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

Measurements before NA48/2

- ***"Charged" mode*** ($K^{\pm} \rightarrow 3p^{\pm}$)
  - Ford et al. (1970) at BNL: $A_g = (-7.0 \pm 5.3) \times 10^{-3}$
    Statistics: 3.2M $K^{\pm}$
  - HyperCP prelim. (2000) at FNAL: $A_g = (2.2 \pm 1.5 \pm 3.7) \times 10^{-3}$
    Statistics: 41.8M K^{+}, 12.4M K^{-}
    Systematics due to knowledge of magnetic fields
    Published as PhD thesis W.-S.Choong LBNL-47014 Berkeley 2000
- ***"Neutral" mode*** ($K^{\pm} \rightarrow p^{\pm} p^{0} p^{0}$)
  - Smith et al. (1975) at CERN-PS: $A_g^{0} = (1.9 \pm 12.3) \times 10^{-3}$
    Statistics: 28000 $K^{\pm}$
  - TNF (2005) at IHEP Protvino: $A_g^{0} = (0.2 \pm 1.9) \times 10^{-3}$
    Statistics: 0.62M $K^{\pm}$

Theoretical expectations



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

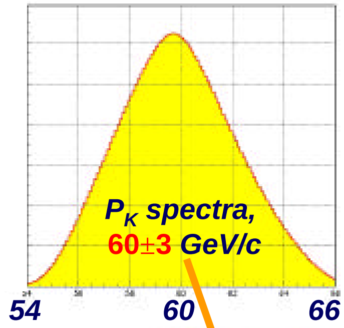
Some models beyond SM predict substantial enhancement partially within the reach of NA48/2.

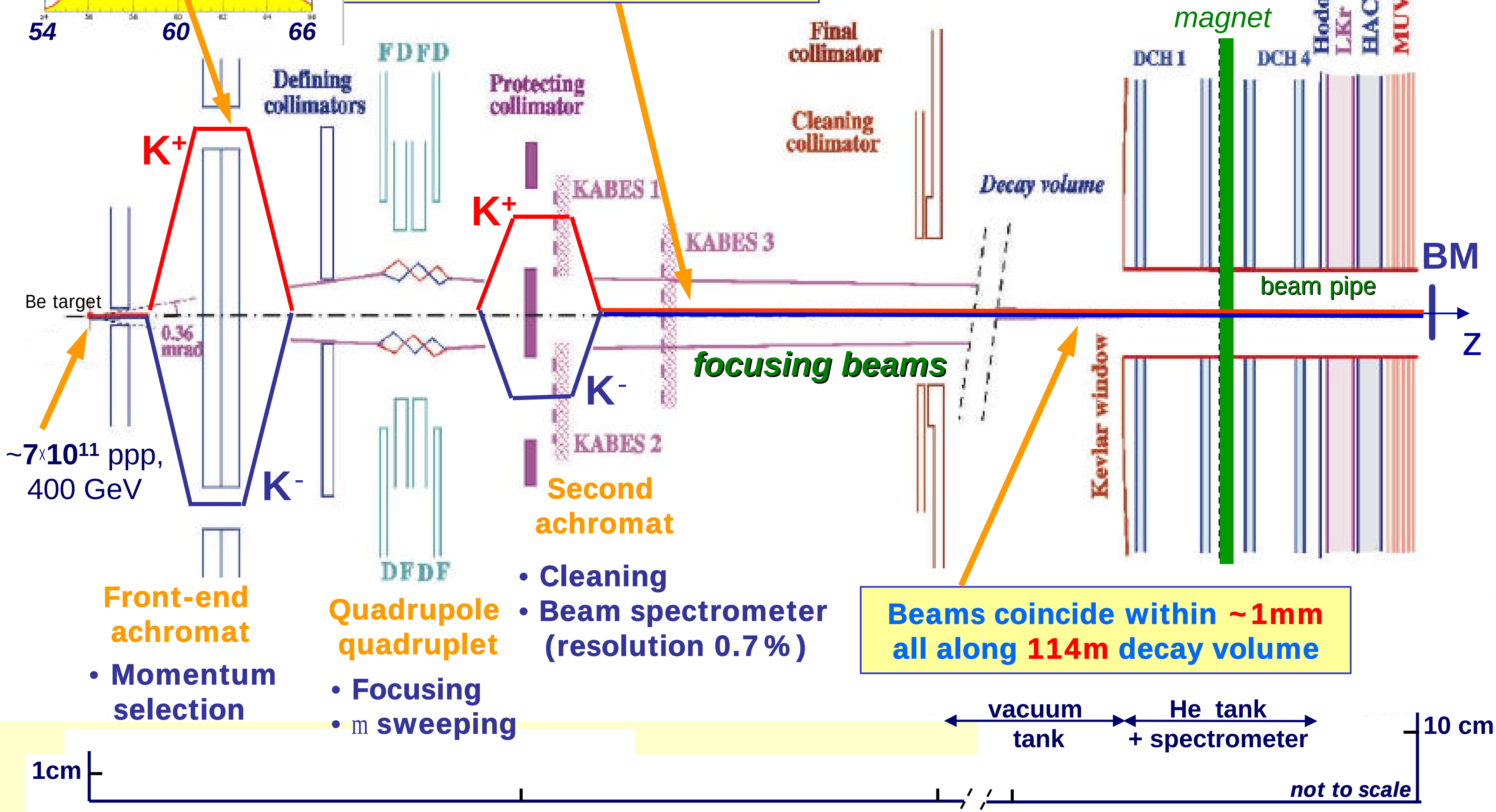
Asymmetry in decay widths expected to be smaller than in Dalitz-plot slopes (SM: $\sim10^{-7}$...10^{-6}).

NA48/2 beams setup

2-3M K/spill (p/K~10),
p decay products stay in pipe.
Flux ratio: K^+/K^- » 1.8

Simultaneous K^+ and K^- beams:
large **charge symmetrization** of experimental conditions





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

The NA48 detector

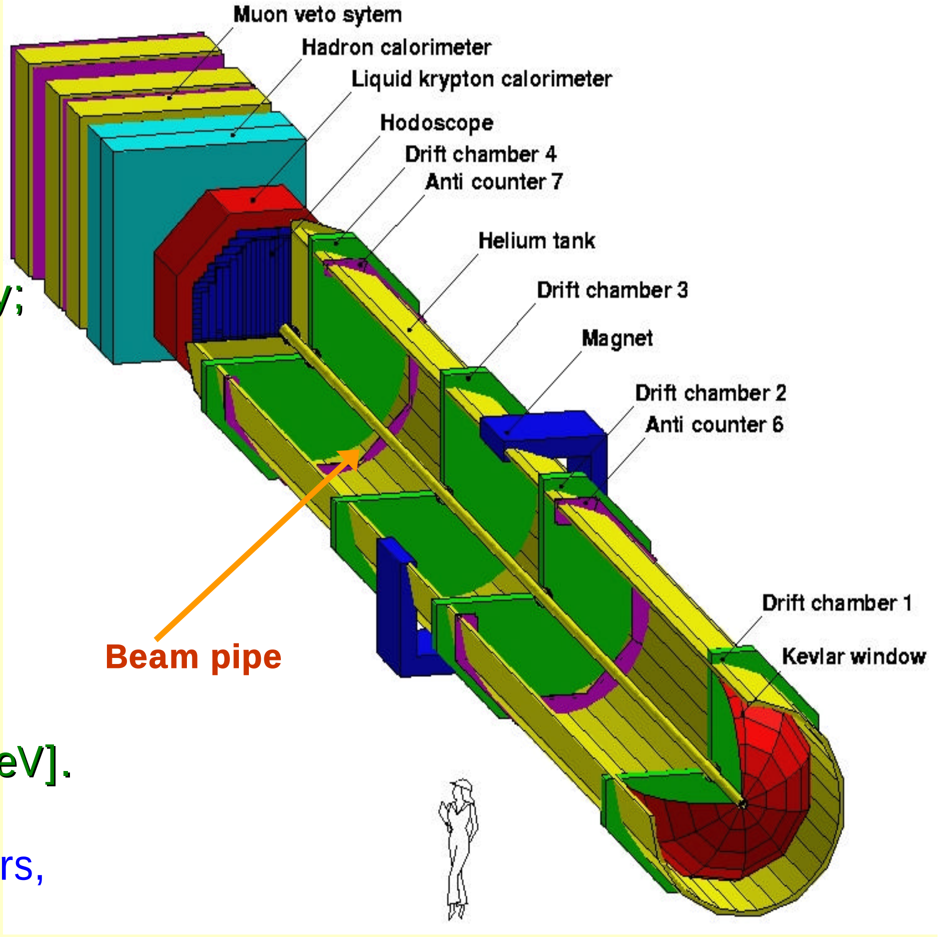
Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy ⇒ efficiency;
  ?p/p = 1.0% + 0.044%*p [GeV/c]

- Hodoscope
  fast trigger;
  precise time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogenious;
  $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV].

- Hadron calorimeter, muon veto counters, photon vetoes.



NA48/2 data taking: completed

A view of the NA48/2 beam line

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

Total statistics in 2 years:

K$^{\pm}$ ® p^{-}p^{+}p$^{\pm}$**: ~3·10^{9}**

K$^{\pm}$ ® p^{0}p^{0}p$^{\pm}$**: ~1·10^{8}**

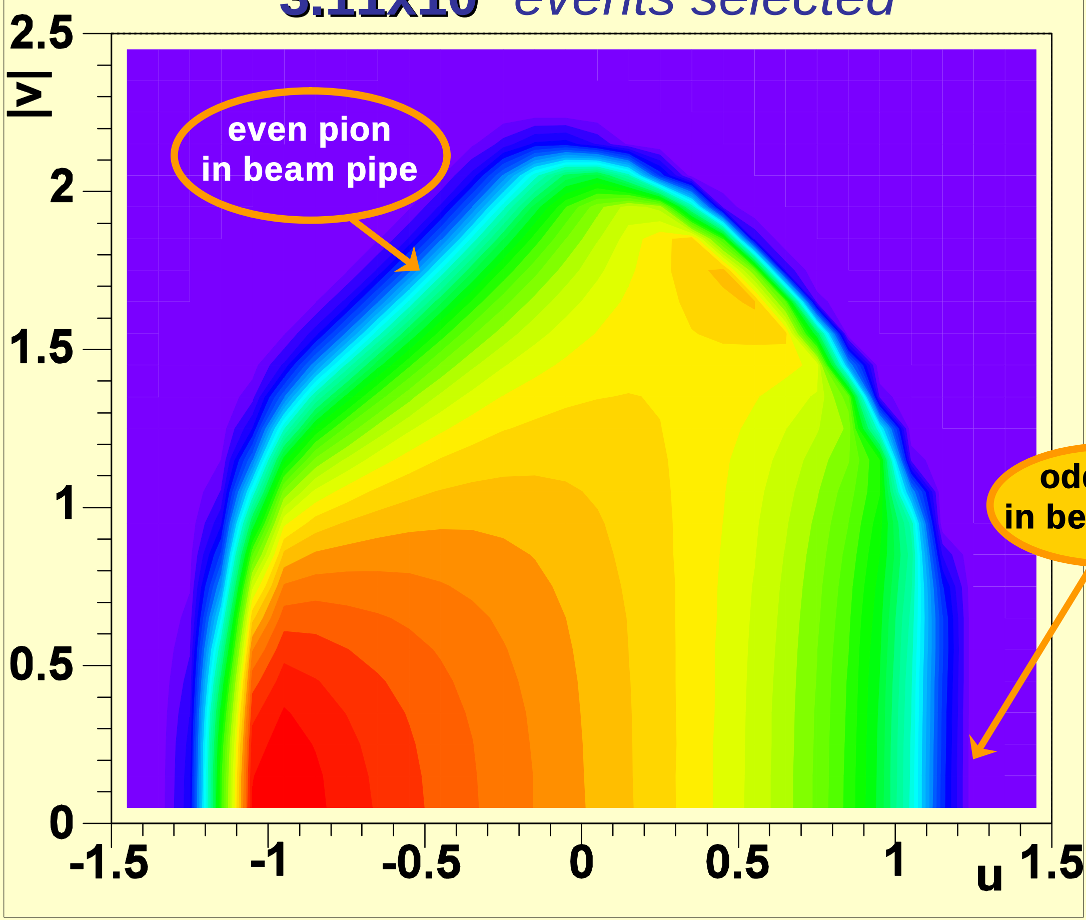
Rare K$^{\pm}$ decays:
BR's down to 10^{-9}
can be measured

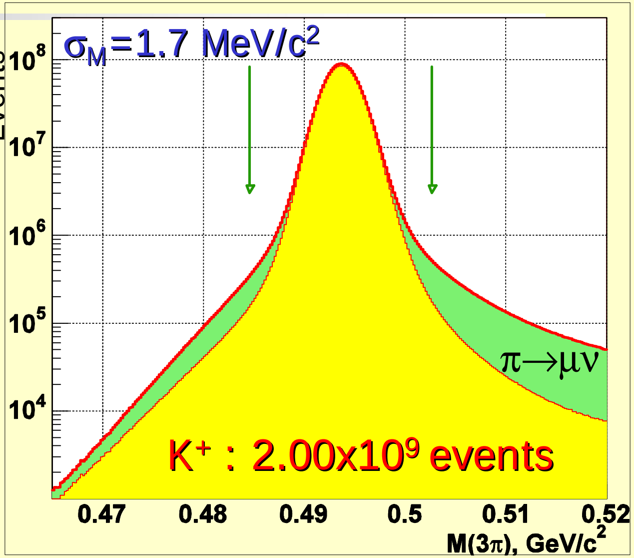
>200 TB of data recorded

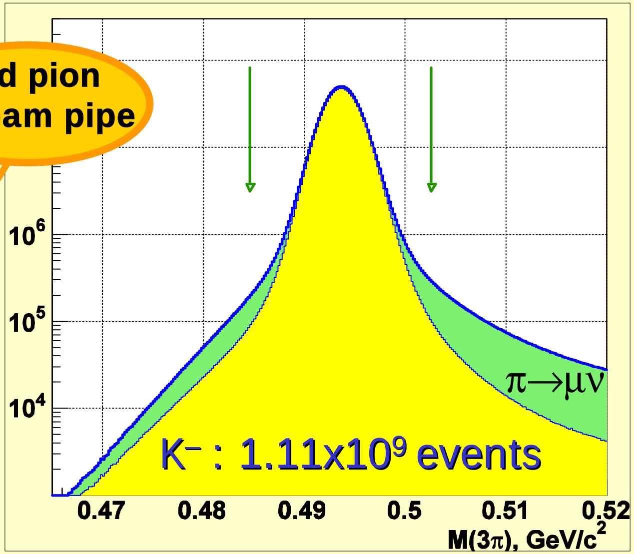
Selected statistics

The final 2003+2004 data sample:

3.11x10^{9} *events selected*







Δg measurement: fitting method

analysis of 1-dimensional U spectra

If K^+ and K^- acceptances are made sufficiently similar, in general case Δg can be extracted fitting the 2D-ratio $R(u,v)$ with a non-linear function:

$R_2(u,v)=N^+(u,v)/N^-(u,v)$

(normalization is a free parameter)

$$f(u,v) = n\frac{1 + (g+\Delta g)u + hu^2 + kv^2}{1 + gu + hu^2 + kv^2}$$

However, given the (small) slopes in the "charged" mode, 1D-ratio $R(u)$ and linear function are suffcient approximations:

$R_1(u)=N^+(u)/N^-(u)$

$$f(u) = n\cdot(1+\Delta g u)$$

The "charged" mode:

$g = -0.2154\pm0.0035$

$|h|, |k| \sim 10^{-2}$

Addressing the acceptance

- Magnetic fields present in both beam line and spectrometer:
  - This leads to residual charge asymmetry of the setup;
- Supersample data taking strategy:
  - Beam line (achromat) polarity (A) reversed on weekly basis;
  - Spectrometer magnet polarity (B) reversed on a more frequent basis (~daily in 2003, ~3 hours in 2004)

Example: Data taking from August 6 to September 7, 2003

Week	Achromat							Supersample
Week 1	Achromat –	B+	B–	B+	B–	B+	B–	Supersample 1 12 subsamples
Week 2	Achromat +	B+	B–	B+	B–	B+	B–	
Week 3	Achromat –	B+	B–	B+	B–	B+	B–	Supersample 2 12 subsamples
Week 4	Achromat +	B+	B–	B+	B–	B+	B–	
Week 5	Achromat –	B+	B–					Supersample 3 4 subsamples
	Achromat +	B+	B–					

Acceptance cancellation
within supersample

Detector left-right asymmetry cancels
in 4 ratios of K^+ over K^- U-spectra:

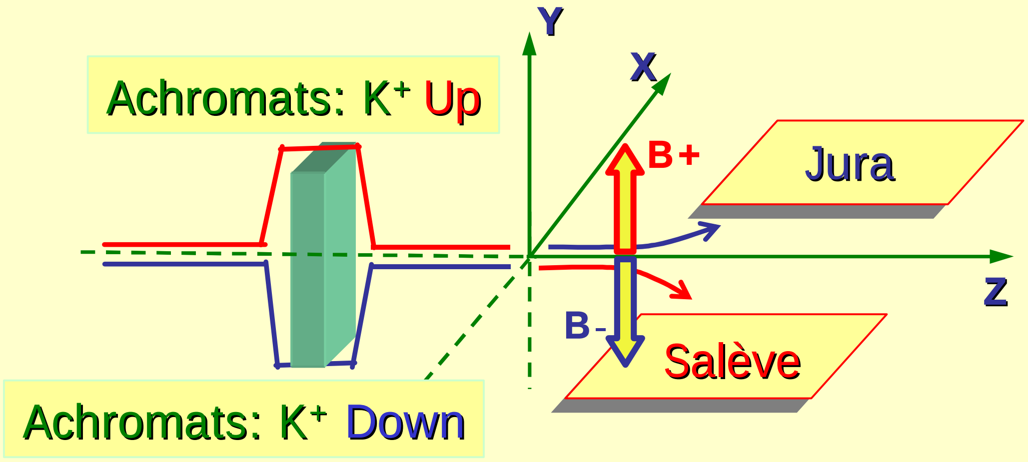
- same deviation direction by spectrometer magnet in numerator and denominator;
- data from 2 different time periods used at this stage.

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

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

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

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



Indices of **R**'s correspond to
- beam line polarity (U/D);
- direction of kaon deviation in spectrometer magnet field (S/J).

More cancellations

(1) **Double ratio:** cancellation of **global time instabilities**

(rate effects, analyzing magnet polarity inversion): [IMPORTANT: SIMULTANEIOUS BEAMS]

$R_U = R_{US} \times R_{UJ}$ ⇒ $f_2(u)=n\cdot(1+?g_U\cdot u)^2$

$R_D = R_{DS} \times R_{DJ}$ ⇒ $f_2(u)=n\cdot(1+?g_D\cdot u)^2$

(2) **Double ratio:** cancellation of **local beam line biases** effects

(slight differences in beam shapes and momentum spectra):

$R_S = R_{US} \times R_{DS}$ ⇒ $f_2(u)=n\cdot(1+?g_S\cdot u)^2$

$R_J = R_{UJ} \times R_{DJ}$ ⇒ $f_2(u)=n\cdot(1+?g_J\cdot u)^2$

(3) **Quadruple ratio**: both cancellations

$R = R_{US}\times R_{UJ}\times R_{DS}\times R_{DJ}$ ⇒ $f_4(u)=n\cdot(1+\Delta g\cdot u)^4$

Normalization (n) — Slope difference (Δg)

The method is independent of
K^+/K^- flux ratio and
relative sizes of the samples collected

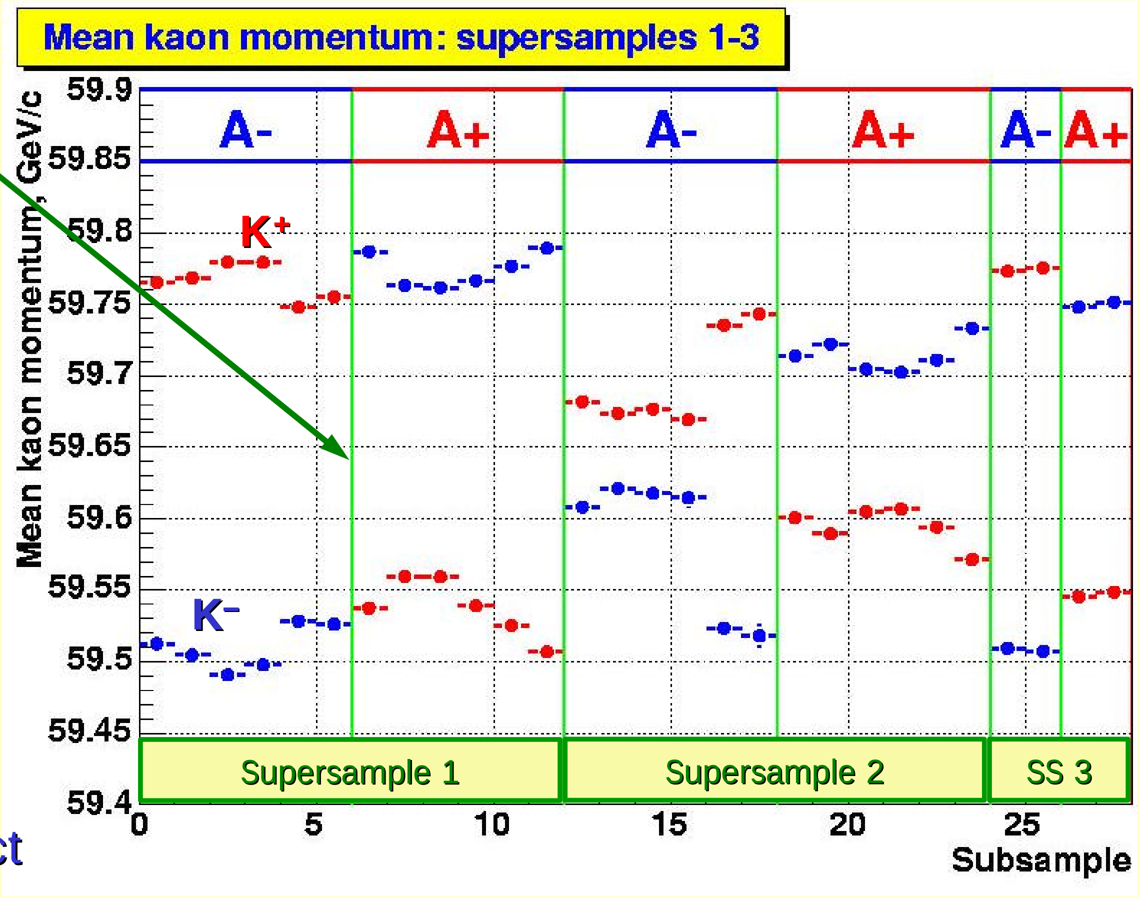
$?g = 2g\cdot A_g$ ˜ $-0.43\cdot A_g$

Beam spectra difference

(an example of cancellation)

Beam line polarity reversal almost reverses K^+ and K^- beam spectra

Systematic differences of K^+ and K^- acceptance due to beam spectra <u>mostly cancel</u> in $R_U \times R_D$



<u>Systematic check:</u>

Reweighting K^+ events so as to equalize momentum spectra leads to a negligible effect $\delta(?g)=0.03\times10^{-4}$

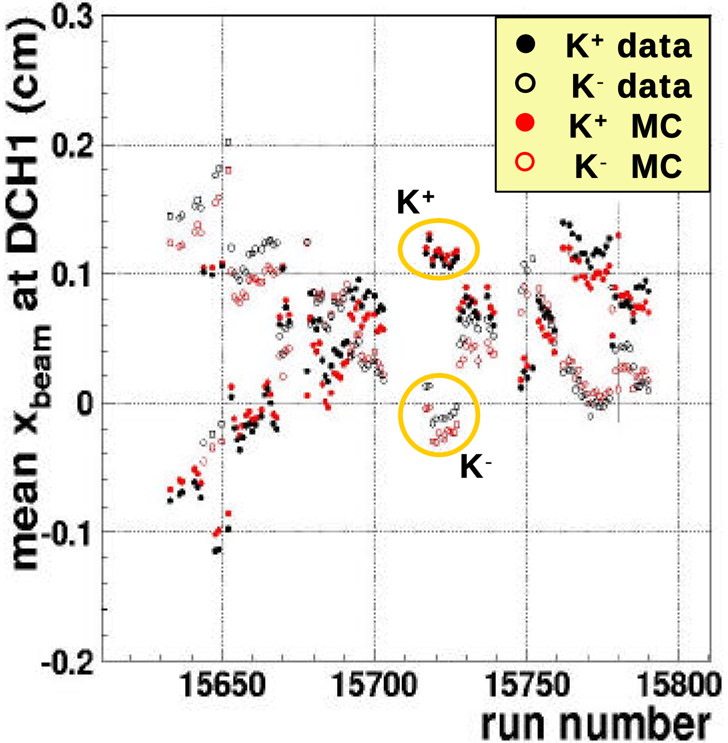
Monte-Carlo simulation

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

Still Monte-Carlo is used to study systematic effects.

- 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.

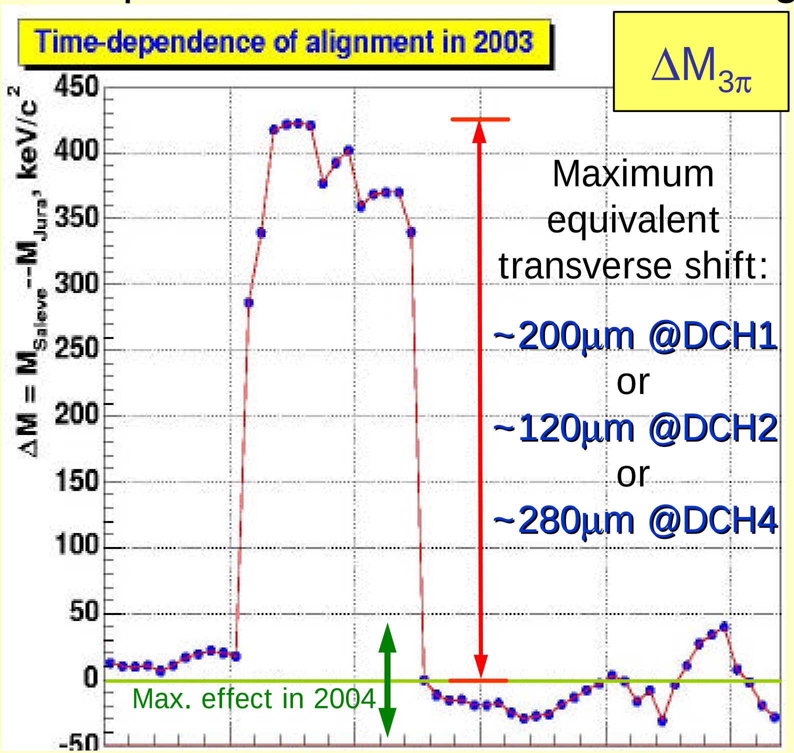
Example of data / MC agreement: mean beam positions @DCH1



Systematics: spectrometer

Transverse alignment

Time variations of spectrometer geometry: do not cancel in the result. Alignment is fine-tuned by scaling momenta (charge-asymmetrically) to equalize the reconstructed average K^+,K^- masses



→ Much more stable alignment in 2004!

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

Magnetic field

The effect of **imperfect inversion of spectrometer field** cancels in double ratio [simultaneous beams]

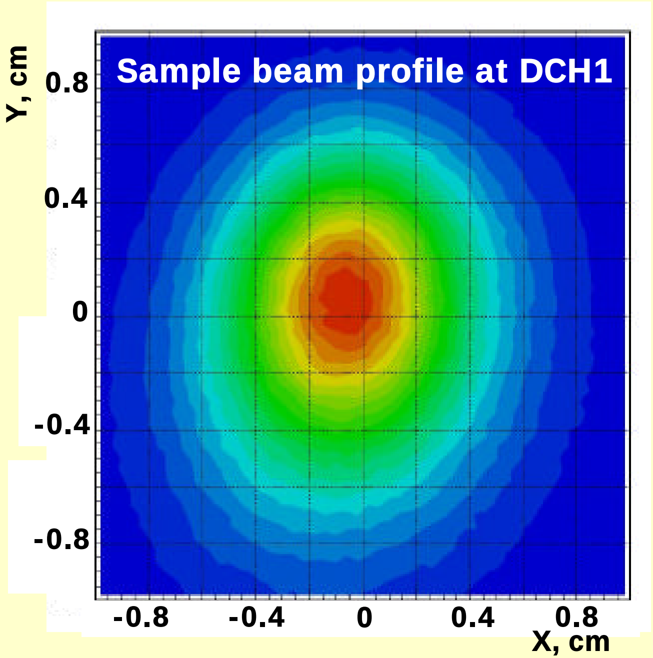
Momentum scale adjusted anyway by constraining average reconstructed K masses to the PDG value

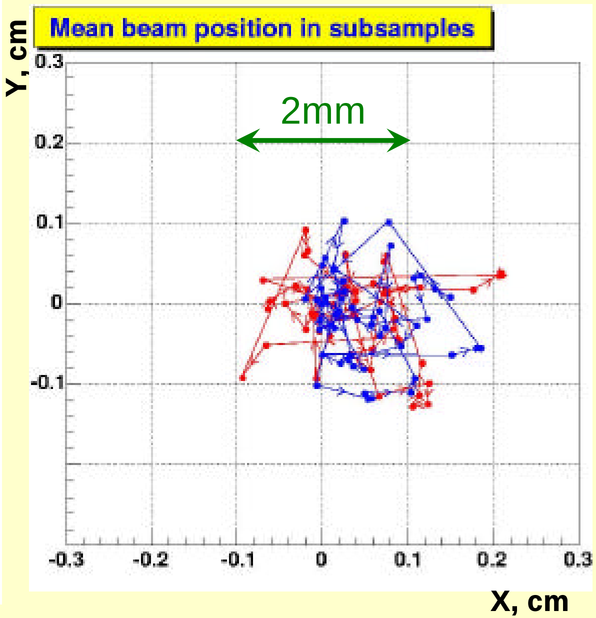
Sensitivity to 10^{-3} error on field integral:
$\Delta M \approx$ **100 keV**

Systematics: beam geometry

- Acceptance largely defined by central hole edge (R≈10cm);
- Geometry variations, non-perfect superposition: asymmetric acceptance.
- Additional acceptance cut defined by a **"virtual pipe"** (R=11.5cm) centered on averaged reconstructed beam position as a function of charge, time and K momentum ⇒ Statistics loss: 12%

[Special treatment of permanent magnetic fields effect on measured beam positions]





Beam widths:
~ 1 cm
Beam movements:
~ 2 mm

"Virtual pipe" also corrects for the differences between the upper and lower beam paths

Systematics: trigger

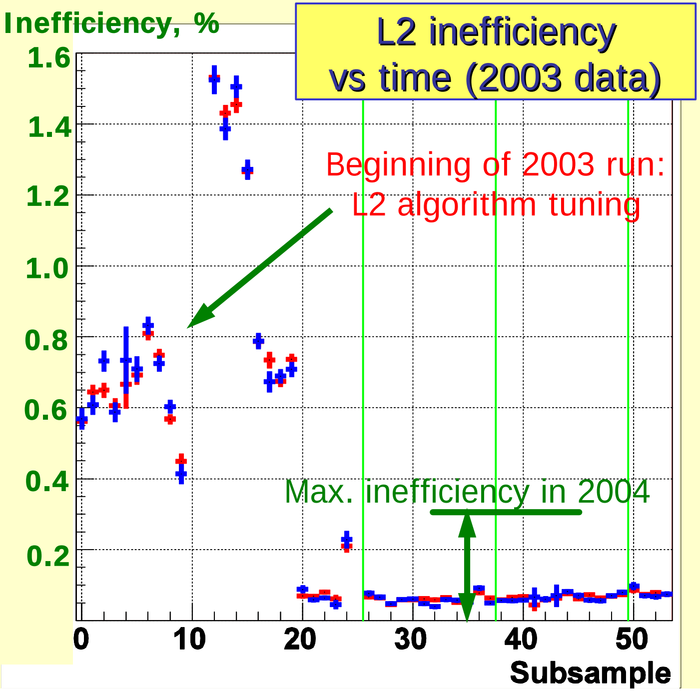
Only charge-asymmetric trigger inefficiency dependent on u can bias the result

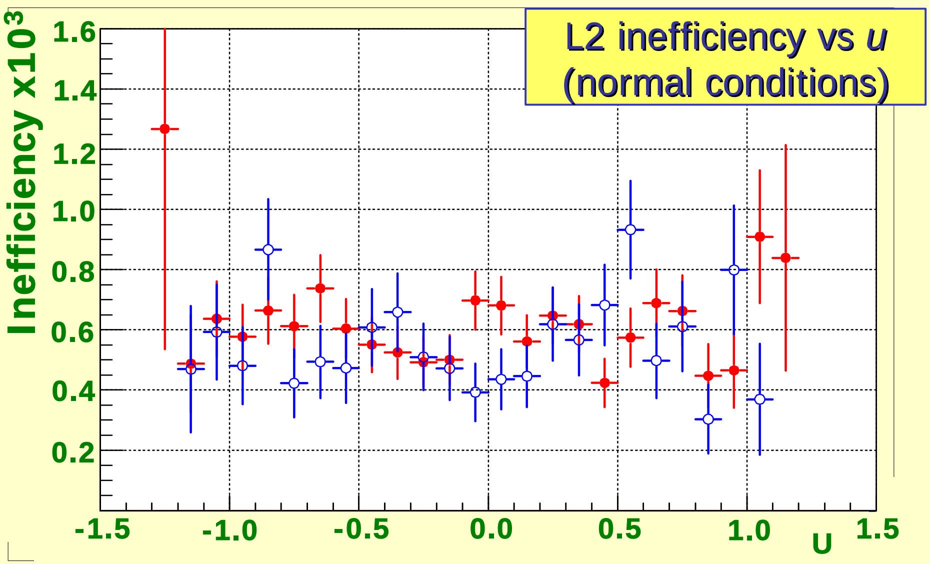
Trigger efficiencies measured using control data samples triggered by downscaled low bias triggers

L1 trigger [2 hodoscope hits]
small and stable inefficiency
$1-\varepsilon \sim 0.9\times10^{-3}$
(no correction)

L2 trigger [online vertex reconstruction on DCH data]
time-varying inefficiency (local DCH inefficiencies, tuning)
$1-\varepsilon$ = 0.06% to 1.5%
u-dependent correction applied

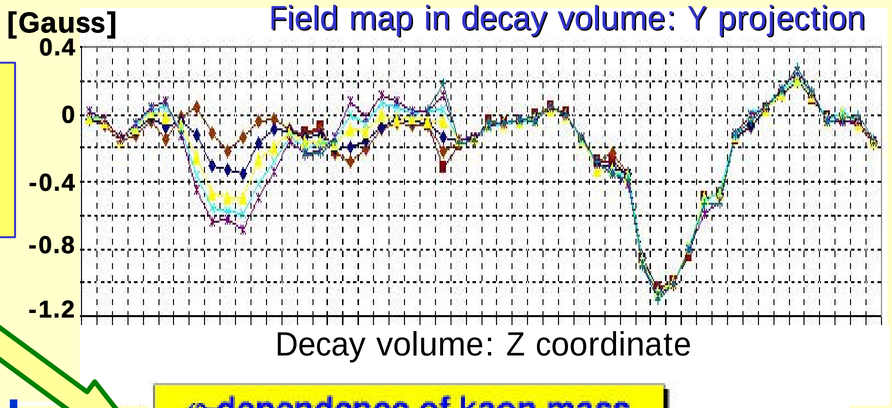
Statistical errors due to limited sizes of the control samples are propagated into the result





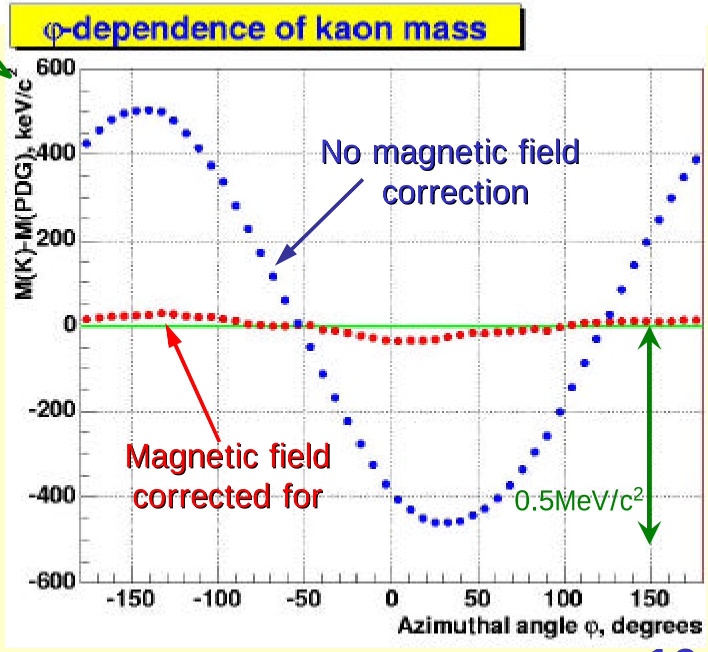
Other systematics

Residual effects of stray magnetic fields (magnetized vacuum tank, earth field) minimized by explicit field map correction



Further systematic effects studied:

- Accuracy of beam tracking, variations of beam widths;
- Bias due to resolution in u;
- Sensitivity to fitting interval and method;
- Coupling of $\pi\to\mu\nu$ decays to other effects;
- Effects due to event pile-up;
- π^+/π^- interactions with the material.



Supersamples collected

Supersample: **a minimal independent self-consistent set of data**
(including all magnetic field polarities)

Run	Supersample	Dates	Subsamples	$K_{3\pi}$ events selected (millions)
2003	0	22/06 – 25/07	26	697.69
	1	06/08 – 20/08	12	421.50
	2	20/08 – 03/09	12	413.37
	3	03/09 – 07/09	4	134.13
2004	4	16/05 – 07/06	87	362.07
	5	27/06 – 07/07	48	221.74
	6	07/07 – 19/07	86	301.83
	7	24/07 – 01/08	66	304.98
	8	01/08 – 11/08	62	255.29
		Total	349	3112.59

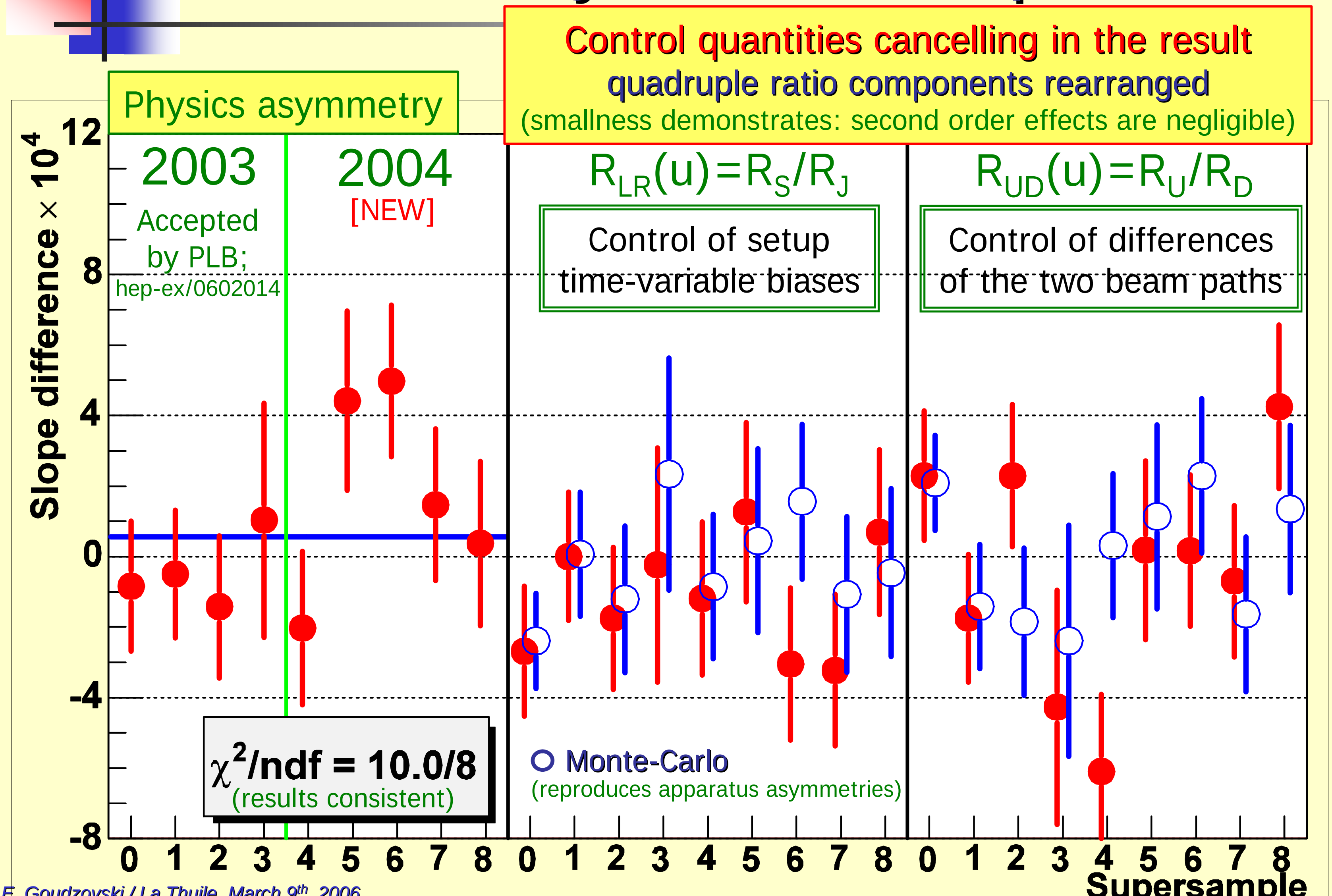
Δg fits in supersamples

(quadruple ratios corrected for L2 trigger efficiency)

Results in supersamples

Run	Supersample	$\Delta g \times 10^4$ "raw"	$\Delta g \times 10^4$ L2-corrected	χ^2 of the $R_4(u)$ fit (L2-corrected)
2003 Accepted by PLB; hep-ex/0602014	0	0.5±1.4	–0.8±1.8	30/26
	1	–0.4±1.8	–0.5±1.8	24/26
	2	–1.5±2.0	–1.4±2.0	28/26
	3	0.4±3.2	1.0±3.3	19/26
2004 [NEW]	4	–2.8±1.9	–2.0±2.2	18/26
	5	4.7±2.5	4.4±2.6	20/26
	6	5.1±2.1	5.0±2.2	26/26
	7	1.7±2.1	1.5±2.1	10/26
	8	1.3±2.3	0.4±2.3	23/26
Combined		0.7±0.7	0.6±0.7	

Time-stability & control quantities



Systematics summary

Systematic effect	Effect on $\Delta g \times 10^4$
Spectrometer alignment	±0.1
Momentum scale	±0.1
Acceptance and beam geometry	±0.2
Pion decay	±0.4
Accidental activity (pile-up)	±0.2
Resolution effects	±0.3
Total systematic uncertainty	±0.6
L1 trigger: uncertainty only	±0.3
L2 trigger: correction	–0.1±0.3
Total trigger correction	–0.1±0.4
Systematic & trigger uncertainty	±0.7
Raw Δg	0.7±0.7
Δg corrected for L2 inefficiency	0.6±0.7

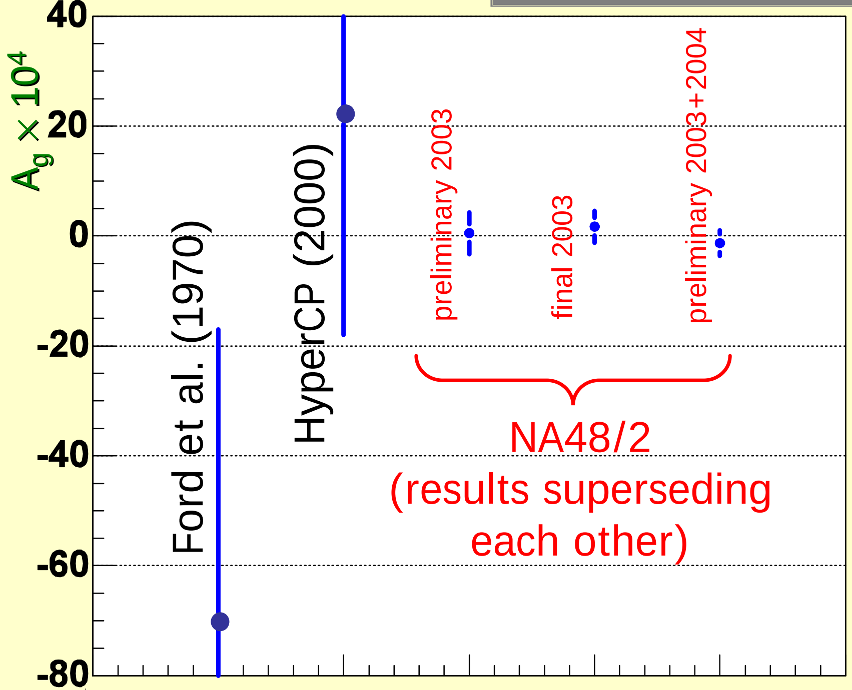
The preliminary result

A NEW RESULT
based on the full statistics accumulated in 2003 and 2004 runs

$$\Delta g = (0.6 \pm 0.7_{stat} \pm 0.4_{trig} \pm 0.6_{syst}) \times 10^{-4}$$
$$= (0.6 \pm 1.0) \times 10^{-4}$$

$$A_g = (-1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \times 10^{-4}$$
$$= (-1.3 \pm 2.3) \times 10^{-4}$$

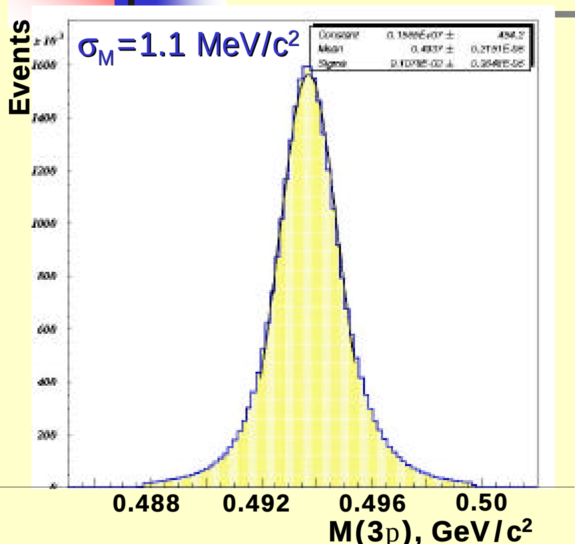
Measurements of A_g

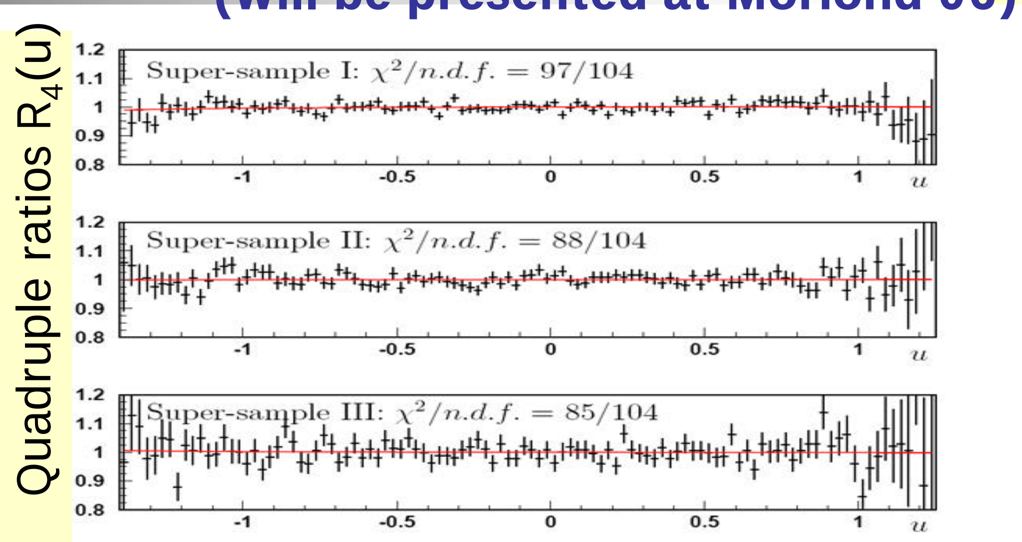


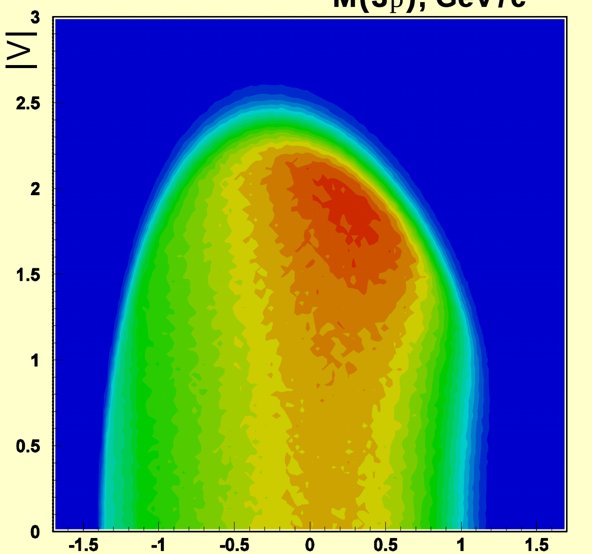
- More than an order of magnitude better precision that the previous measurements;
- Uncertainties dominated by those of statistical nature;
- Result compatible with the Standard Model predictions;
- The design goal reached! There is still some room to improve the systematic uncertainties.

The "neutral" mode analysis

(will be presented at Moriond'06)







Statistical precision in $\mathbf{A_g^0}$ similar to "charged" mode:

- Ratio of "neutral" to "charged" statistics: $N^0/N^{\pm}\sim 1/30$;
- Ratio of slopes: $|g^0/g^{\pm}|\approx 1/3$;
- More favourable Dalitz-plot distribution (gain factor $f\sim 1.5$).

The final result with the 2003 sample

(based on $\sim 48\times 10^6$ events)

[a new result superseding the old one!]

$$A_g^0 = (1.8\pm 2.6)\times 10^{-4}$$

Conclusions

- New NA48/2 results on direct CP-violating charge asymmetry in $K^{\pm}\to 3\pi$ slopes:

"Charged" mode $K^{\pm}\to 3\pi^{\pm}$
Full data set, preliminary

$$A_g = (-1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \times 10^{-4}$$
$$= (-1.3 \pm 2.3) \times 10^{-4}$$

"Neutral" mode $K^{\pm}\to \pi^0\pi^0\pi^{\pm}$
~½ of data set, final result

$$A_g^0 = (1.8 \pm 2.2_{stat} \pm 1.0_{trig} \pm 0.8_{syst} \pm 0.2_{ext}) \times 10^{-4}$$
$$= (1.8 \pm 2.6) \times 10^{-4}$$

- ~10 times better precisions than previous measurements, still dominated by statistical contributions;
- The NA48/2 design goal reached, however further improvements of the analysis possible.

Spare slides

Consistency of 2003 & 2004 results

Slope difference

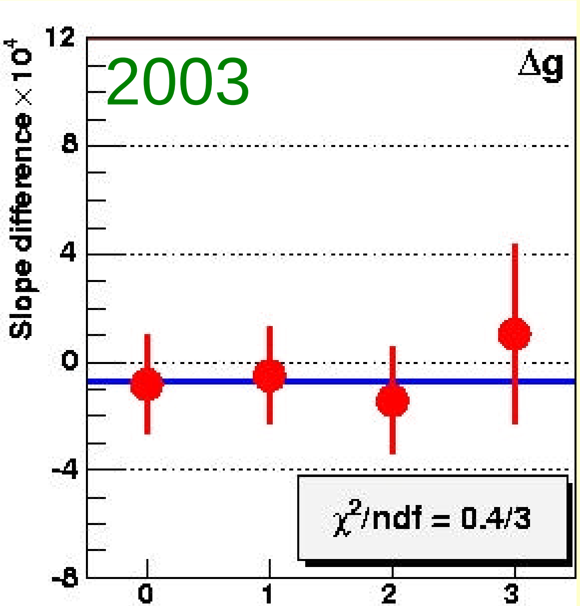
2003: $\Delta g = (-0.7 \pm 0.9_{stat} \pm 0.6_{trig} \pm 0.6_{syst}) \times 10^{-4} = (-0.7 \pm 1.3) \times 10^{-4}$

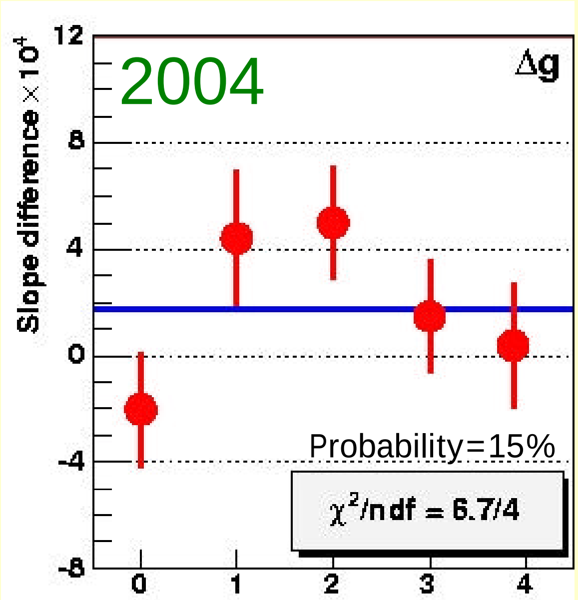
2004: $\Delta g = (1.8 \pm 1.0_{stat} \pm 0.5_{trig} \pm 0.6_{syst}) \times 10^{-4} = (1.8 \pm 1.2) \times 10^{-4}$

Slope asymmetry

2003: $A_g = (1.6 \pm 2.1_{stat} \pm 1.4_{trig} \pm 1.4_{syst}) \times 10^{-4} = (1.6 \pm 2.9) \times 10^{-4}$

2004: $A_g = (-4.1 \pm 2.2_{stat} \pm 1.1_{trig} \pm 1.4_{syst}) \times 10^{-4} = (-4.1 \pm 2.8) \times 10^{-4}$





Raw (L2-corrected) 2003 and 2004 results are 1.4σ (1.7σ) away