Results on direct CP Violation in $K^{\pm} \rightarrow 3\pi$ decays from the NA48/2 experiment at CERN

Giuseppina Anzivino
University of Perugia and INFN

On behalf of the NA48/2 collaboration:
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

New Trends in High Energy Physics
Yalta, 10-17 September 2005

Outline

- 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
- Outlook for $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ analysis
- Neutral mode "Cusp effect"
- Conclusions

Brief history of CP violation

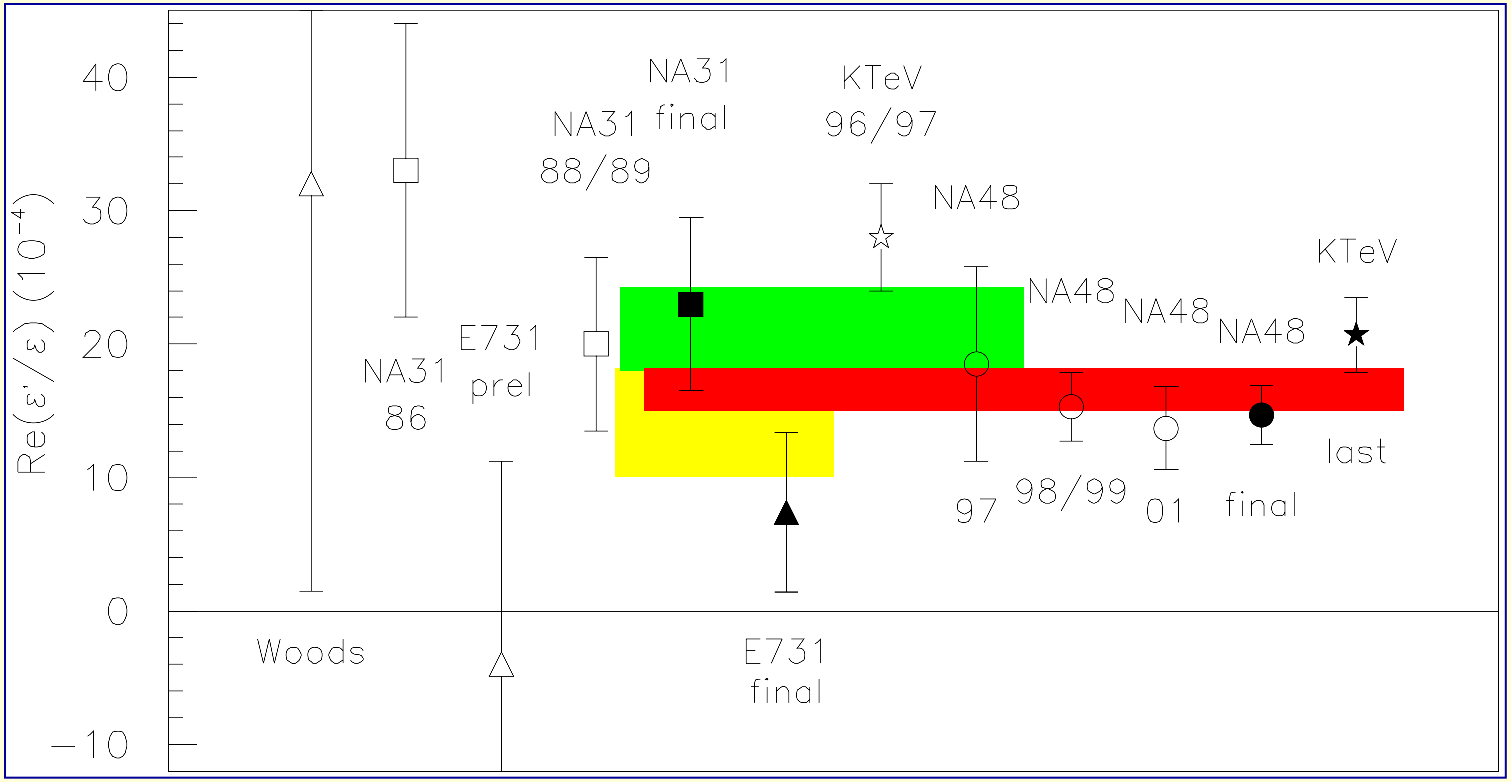
1964 - CP violation in K^0 (Cronin, Christenson, Fitch, Turlay)
1993-99 - Direct CP violation in K^0 (NA31, NA48, KTeV)
2001 - CP violation in B^0 mixing (Babar, Belle)
2004 - Direct CP violation in B^0 (Belle, Babar)

Direct CP Violation, also known as CPV in decay amplitudes, is the most “straightforward” CP effect

- ➔ Hard to detect experimentally
- ➔ Hard to connect to the parameters of the underlying fundamental theory (i.e. SM)

But it is a crucial window to physics beyond SM
because possible non-SM enhancements to heavy quark loops are just at the core of DCPV processes

Direct CPV in $K^0 \to \pi\pi$ decays

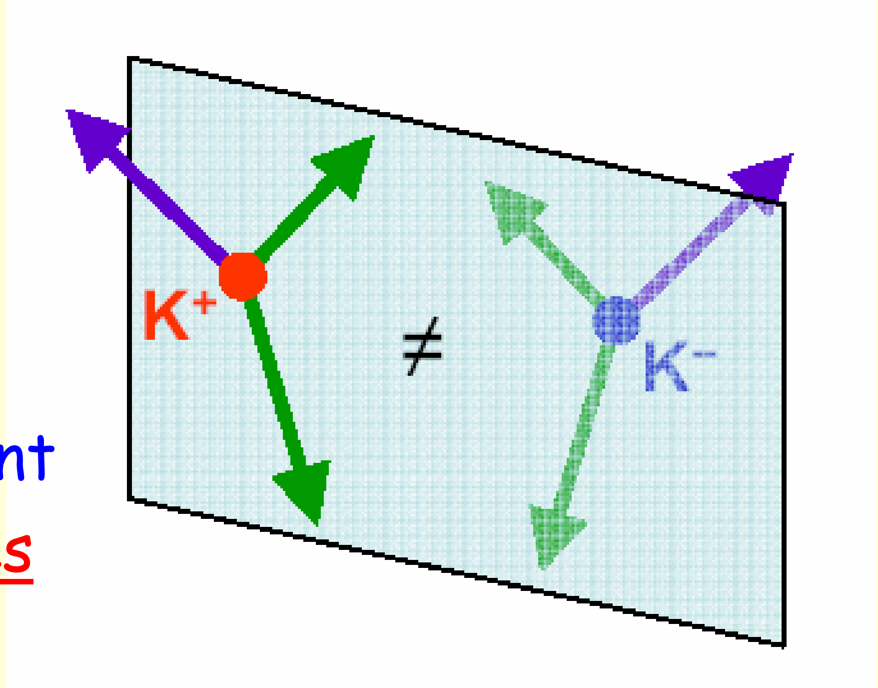


Final NA48 result

$\varepsilon'/\varepsilon = (14.7 \pm 2.2) \times 10^{-4}$

CP violation in $K^{\pm}_{3\pi}$ decays

- Potentially large statistics
- Simple selection
- Low background



No absolute K flux measurement

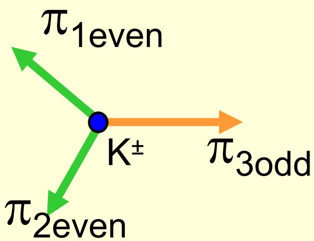
Compare only Dalitz plot shapes

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



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

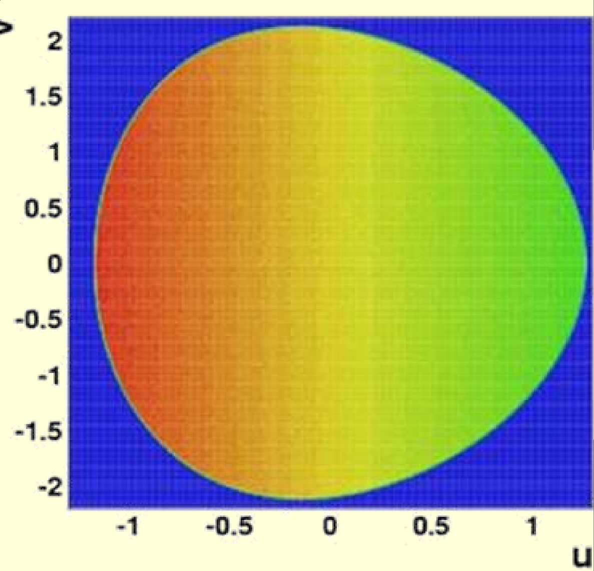
$$u = \frac{s_3 - s_0}{m_\pi^2}$$

$$v = \frac{s_2 - s_1}{m_\pi^2}$$

$$s_i = (P_K - p_{\pi i})^2$$

$$s_0 = \tfrac{1}{3}\sum s_i$$

i=3 odd pion



$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

BR = 5.57% ; g = -0.2154 ± 0.035

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

BR = 1.73% ; g = 0.652 ± 0.031

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

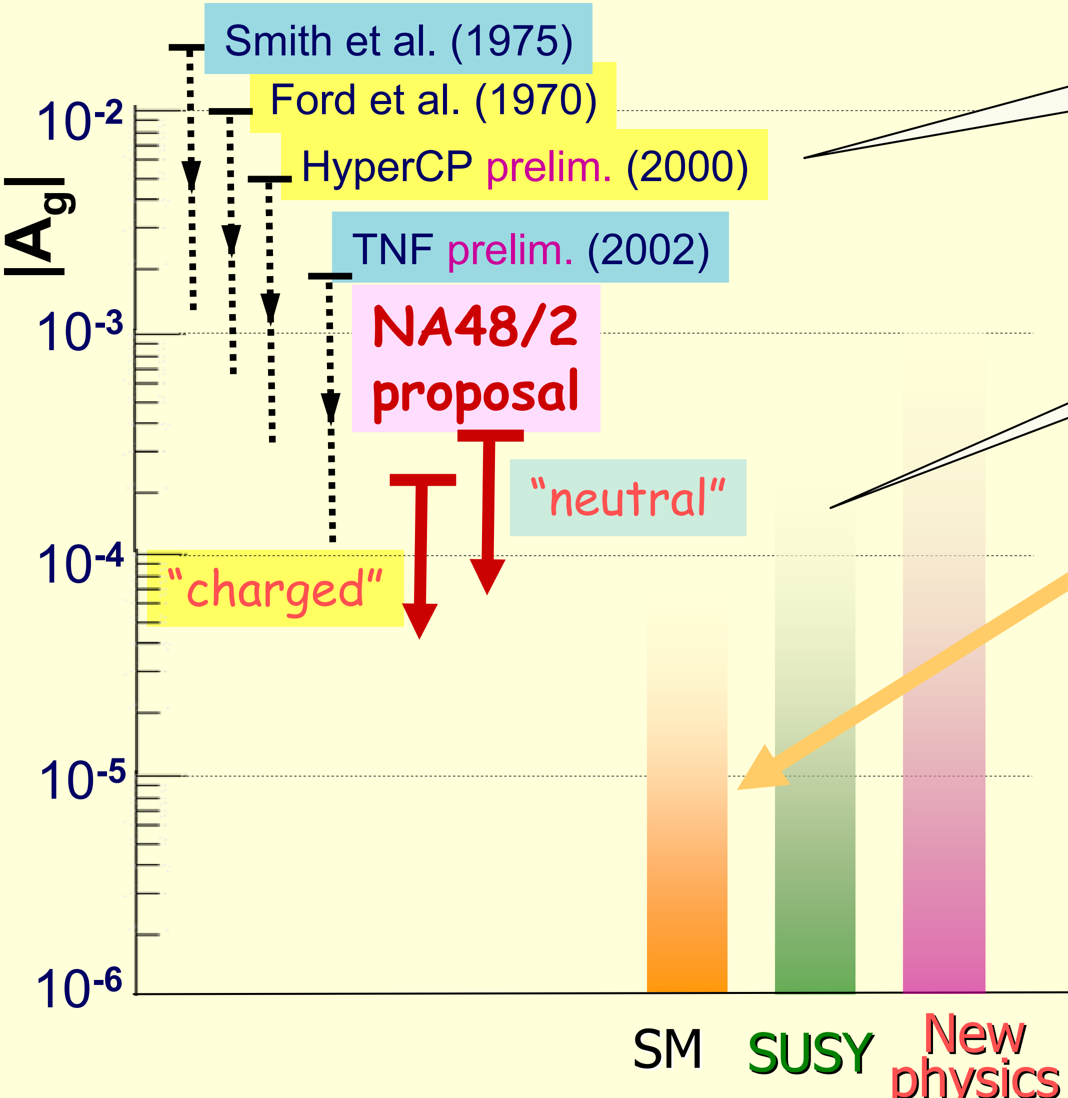
$$A_g = \frac{g_+ - g_-}{g_+ + g_-} = \frac{\Delta g}{2g} = -\frac{\Delta g}{0.43}$$

$A_g < 5 \times 10^{-5}$ compatible with SM

$A_g > 1 \times 10^{-4}$ SUSY/new physics

$A_g \neq 0$ → Direct CP violation

Experimental and theoretical status



Experimental results

Theory

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

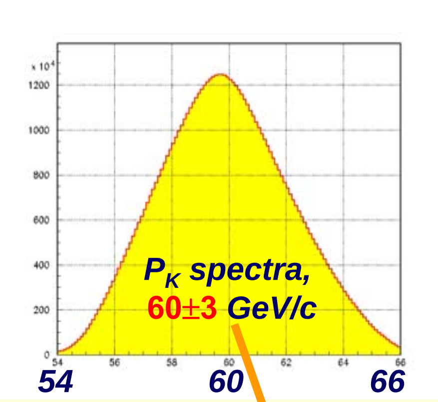
Models beyond SM predict substantial enhancements partially within the reach of NA48/2.
(theoretical analyses are by far not exhaustive by now)

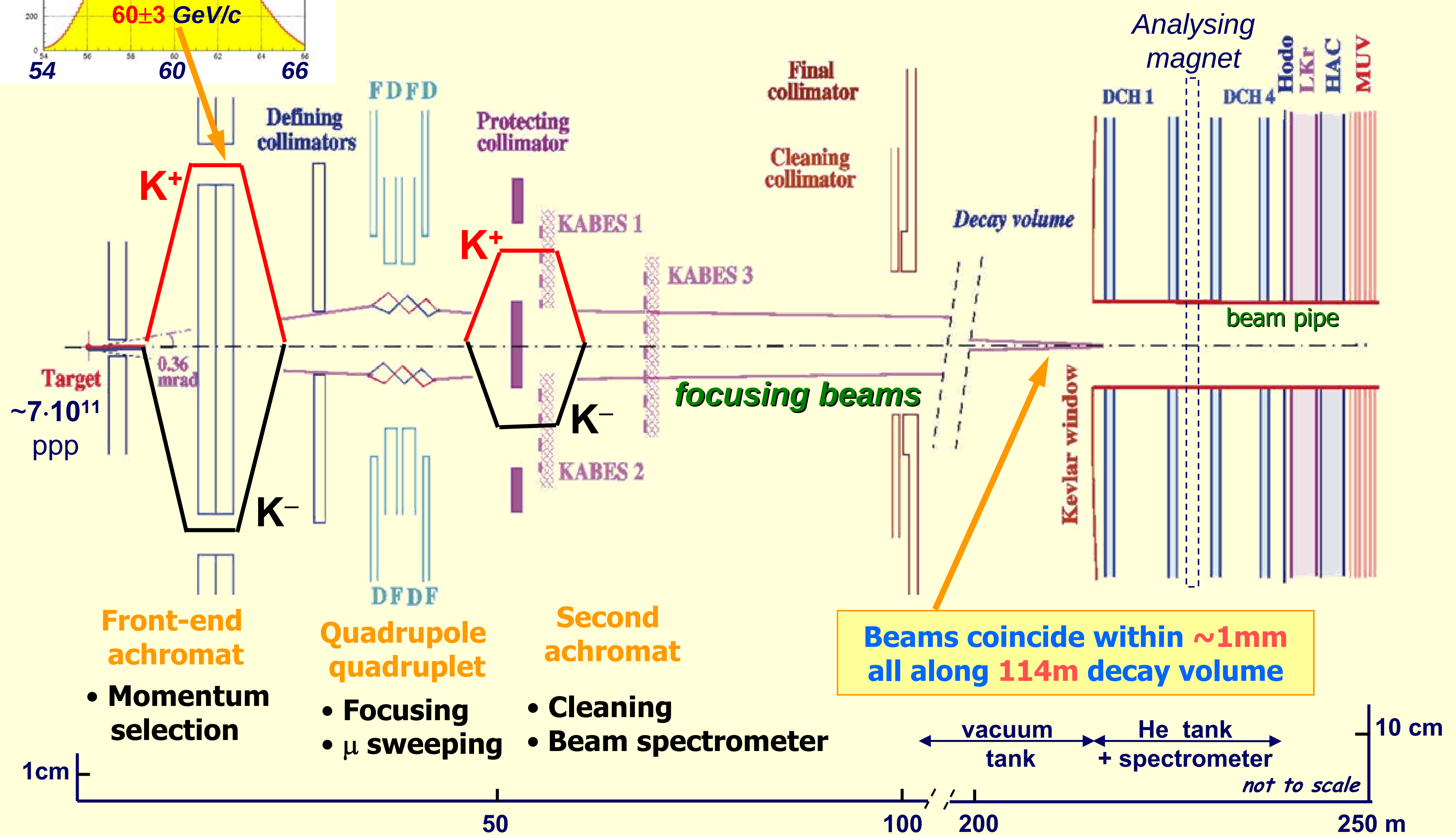
Goals and method

- **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 averaged K^+ and K^- acceptances by frequently alternating the polarities of the relevant magnets.

Experimental 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 and

  precise time measurement (150ps)

- Liquid Krypton e.m. calorimeter:

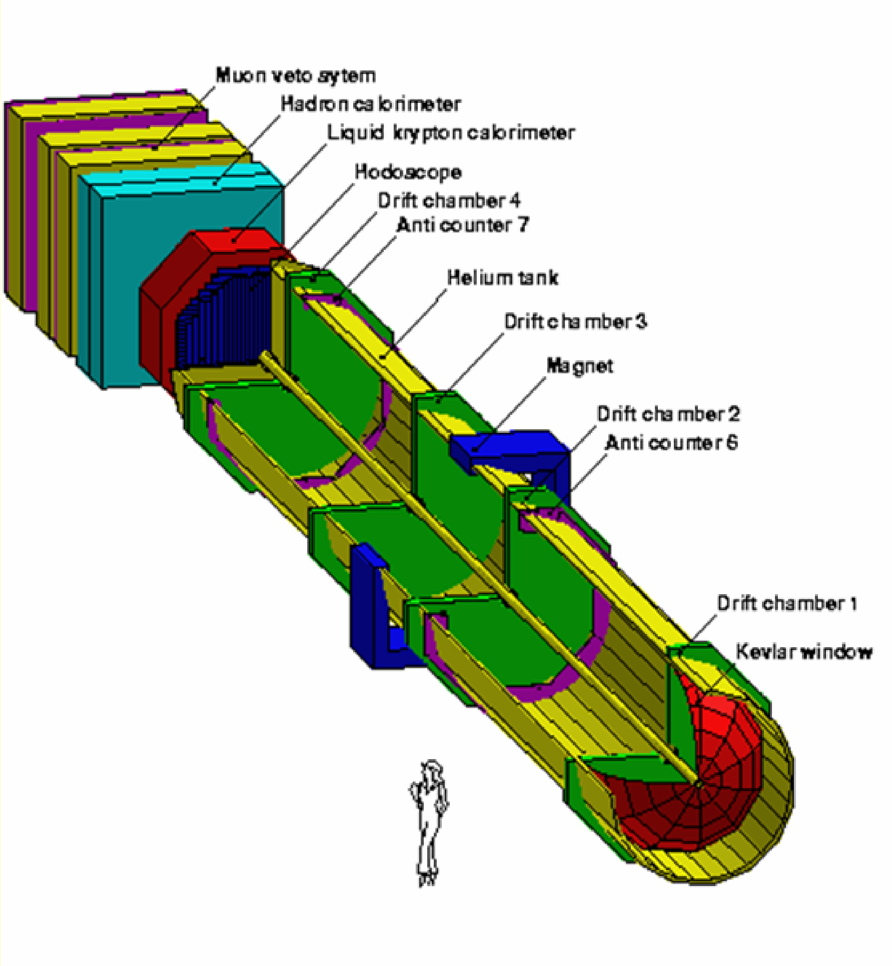
  High granularity, quasi-homogeneous

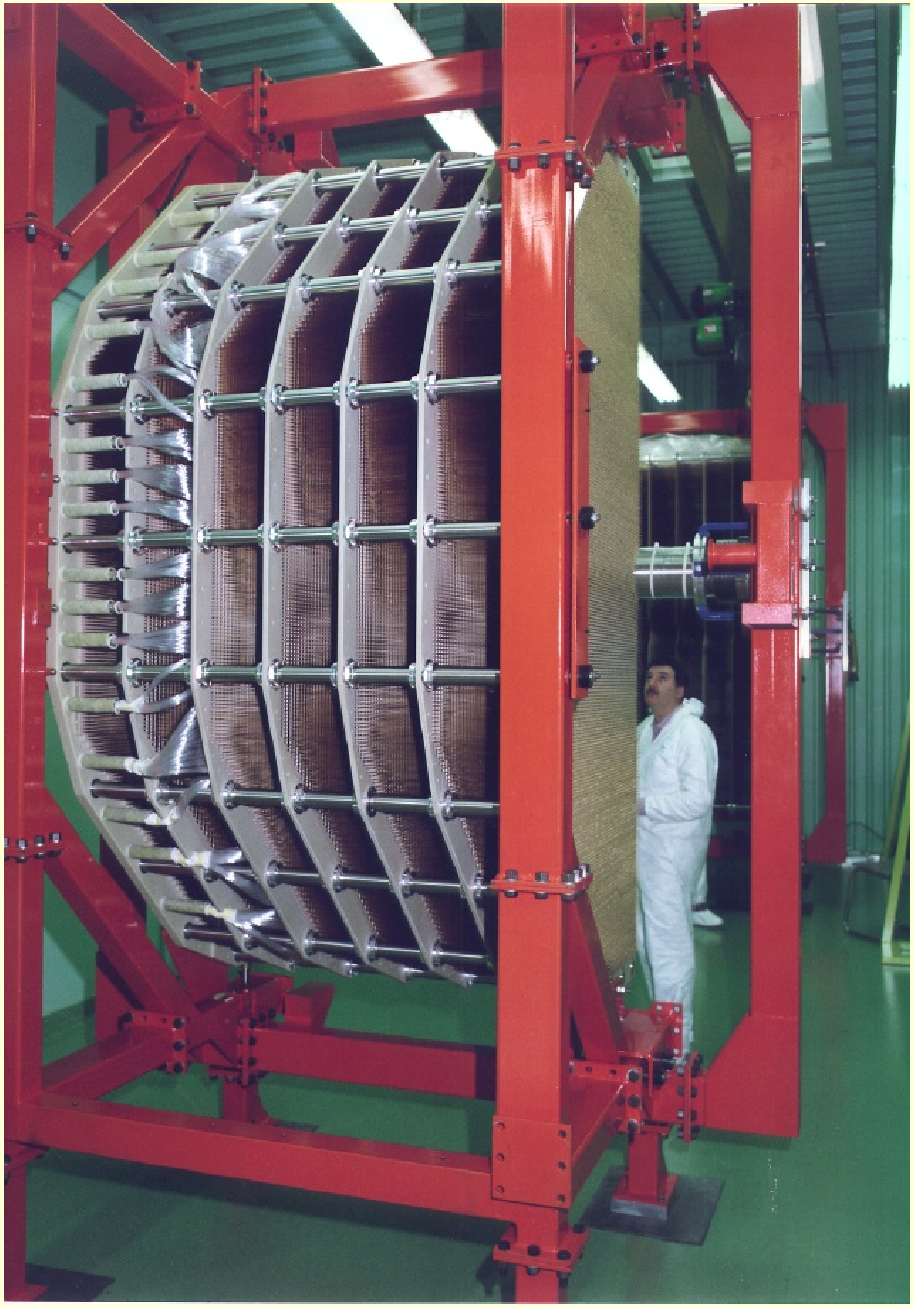
  $\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

  e/π discrimination

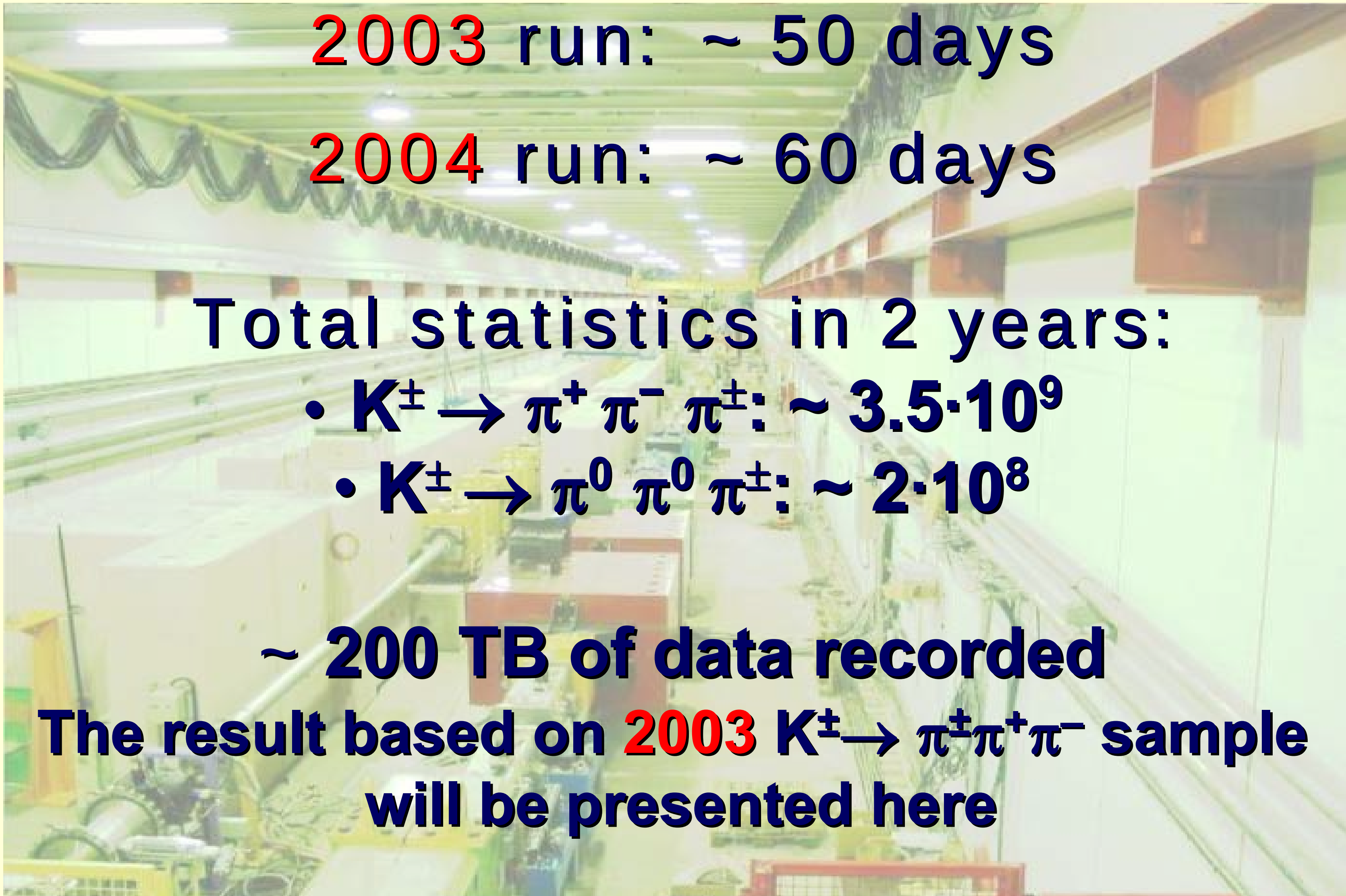
- Hadron calorimeter, photon vetos,

  muon veto counters





Data taking: completed



2003 run: ~ 50 days

2004 run: ~ 60 days

Total statistics in 2 years:

- $K^{\pm} \rightarrow \pi^{+} \pi^{-} \pi^{\pm}$: ~ $3.5 \cdot 10^{9}$
- $K^{\pm} \rightarrow \pi^{0} \pi^{0} \pi^{\pm}$: ~ $2 \cdot 10^{8}$

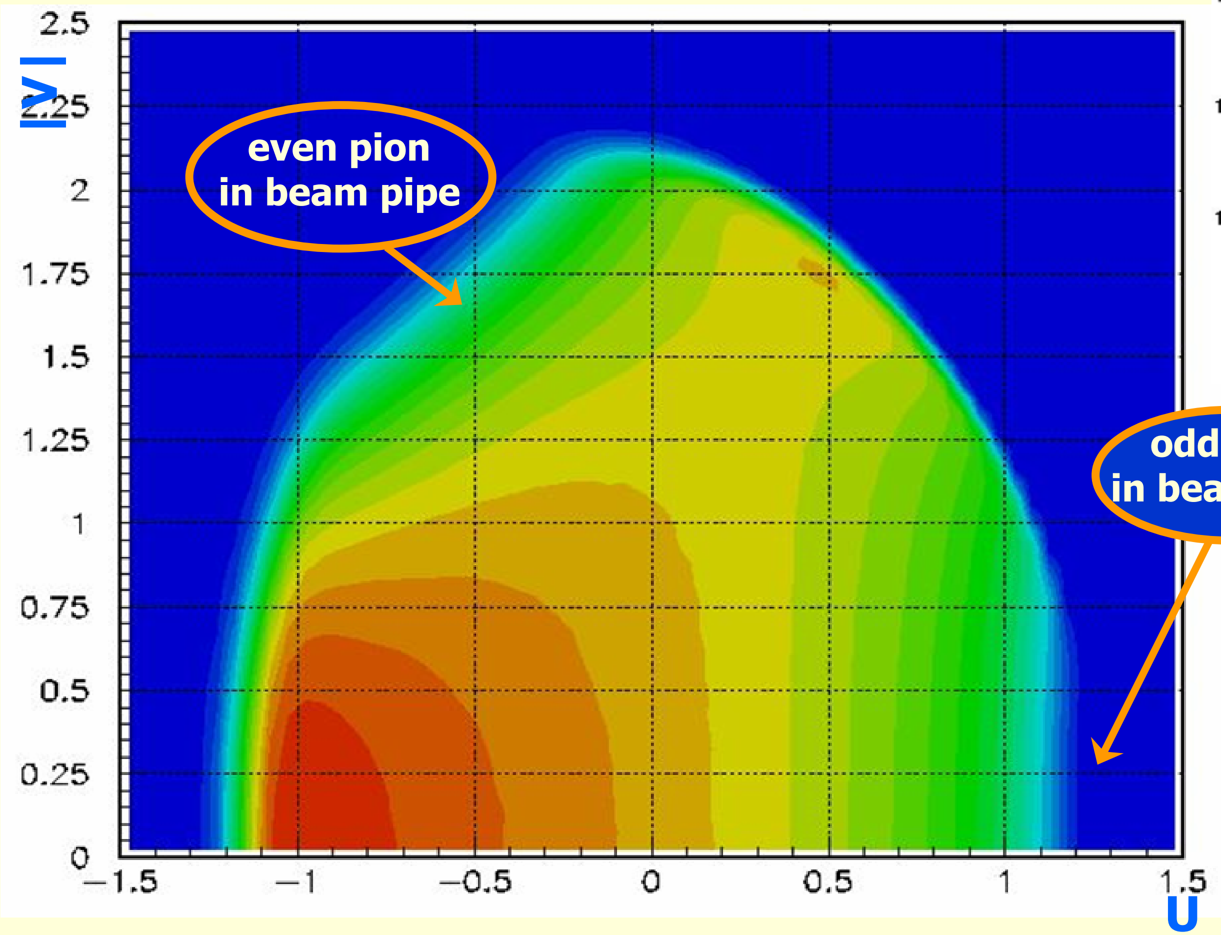
~ 200 TB of data recorded

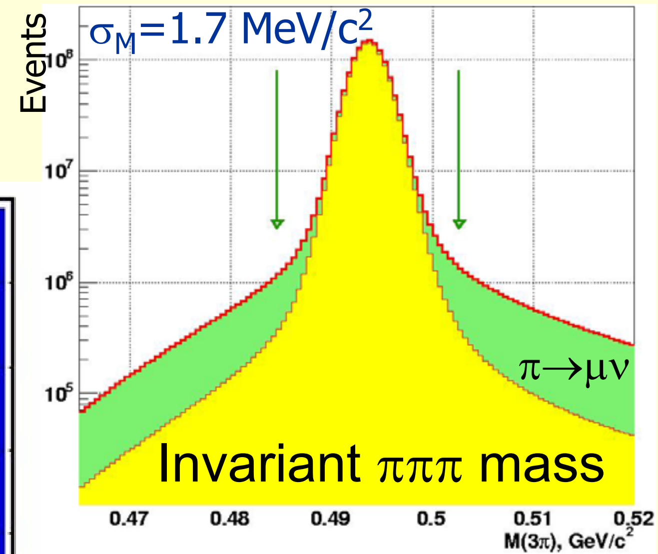
The result based on 2003 $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ sample will be presented here

Accepted statistics

Data-taking 2003:

1.61×10^9 $K^\pm \to \pi^\pm \pi^+ \pi^-$ events





K^+: 1.03×10^9 events

K^- : 0.58×10^9 events

$K^+/K^- \approx 1.8$

Method to extract A_g

- Build u projections of the Dalitz plot for K^+ and K^-: $N^+(u)$,$N^-(u)$
- Make the ratio of these two distributions: R(u)
- Fit a linear function to this ratio to extract $\Delta g = g+ - g-$

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

$$A_g = \frac{\Delta g}{2g}$$

This holds only if the acceptance for K^+ and K^- is the same

$\delta A_g < 2.2 \cdot 10^{-4}$

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

The **magnetic fields** (achromat and spectrometer) are *intrinsic sources of charge asymmetry* in the detector!!!

Instrumental asymmetries

In real life

- ✓ Detector acceptance asymmetries
- ✓ Time variation of detector response
- ✓ Charge-dependent beam optics
- ✓ Time variation of beams' properties
- ✓ Spurious magnetic fields
- ✓ Charge-asymmetric interactions

Strategy of data taking

Beam line (achromat) polarity (A) reversed on weekly basis

Spectrometer magnet polarity (B) reversed on daily basis

Example: August 6 to September 7, 2003

Week	Achromat	Spectrometer magnet						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

Detector left-right asymmetry cancels in 4 ratios of K^+/K^- distributions:

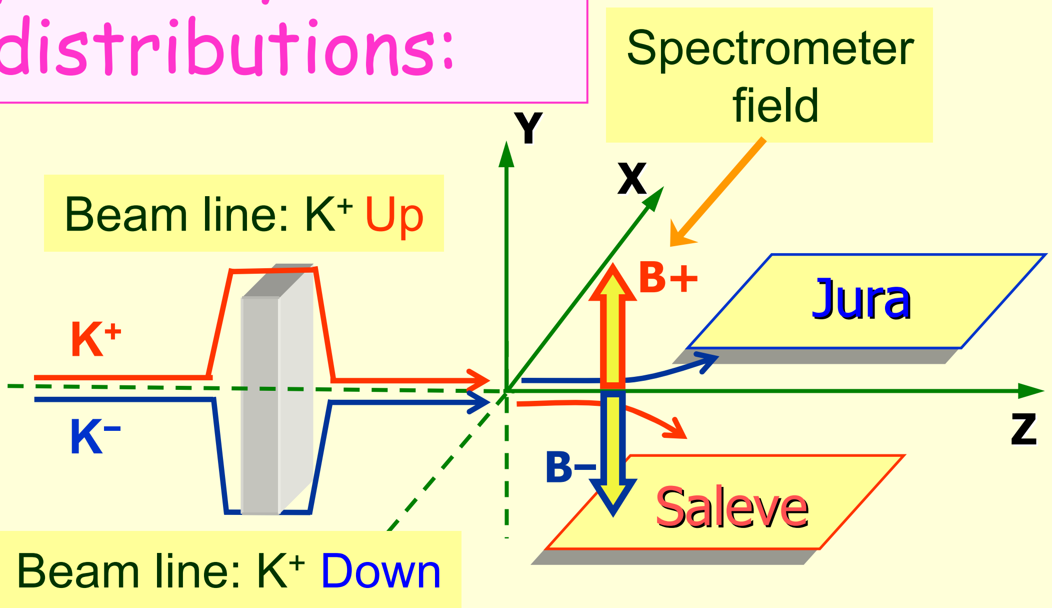
(same deviation by spectrometer in numerator and denominator)

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

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

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

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



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

Quadruple ratio

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

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.)
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)

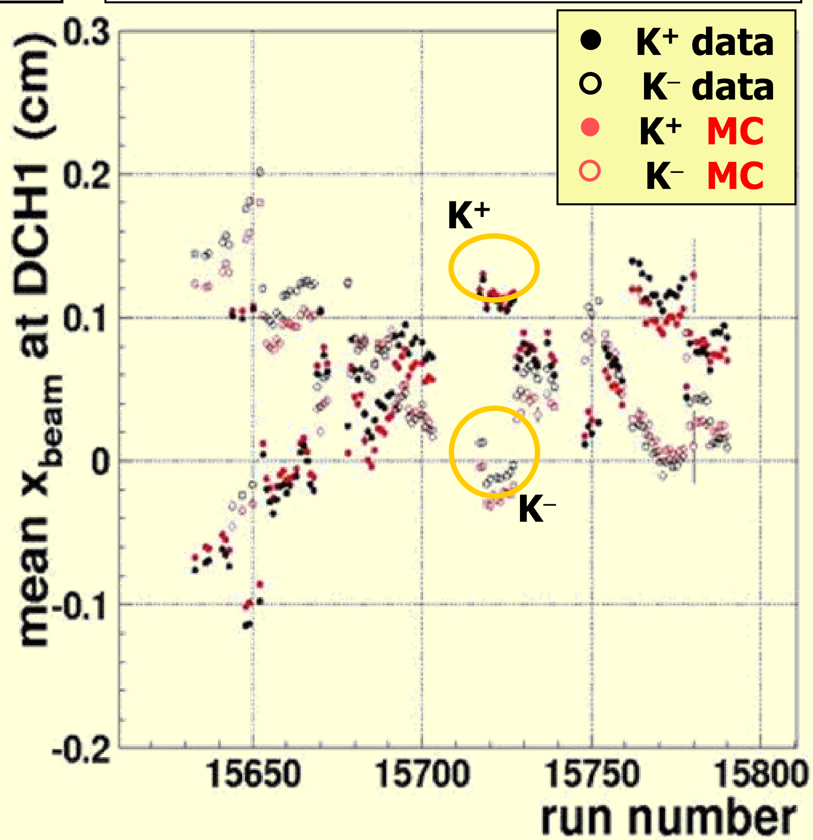
Monte Carlo simulation

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



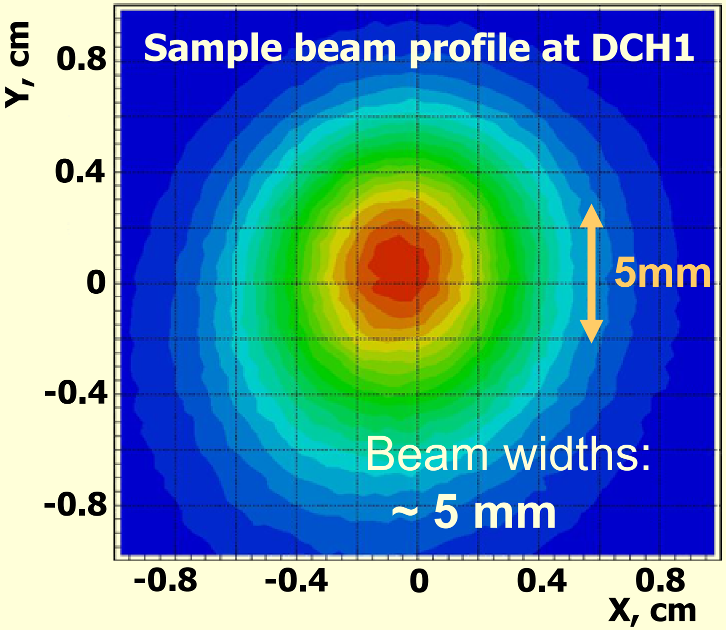
Beam systematics

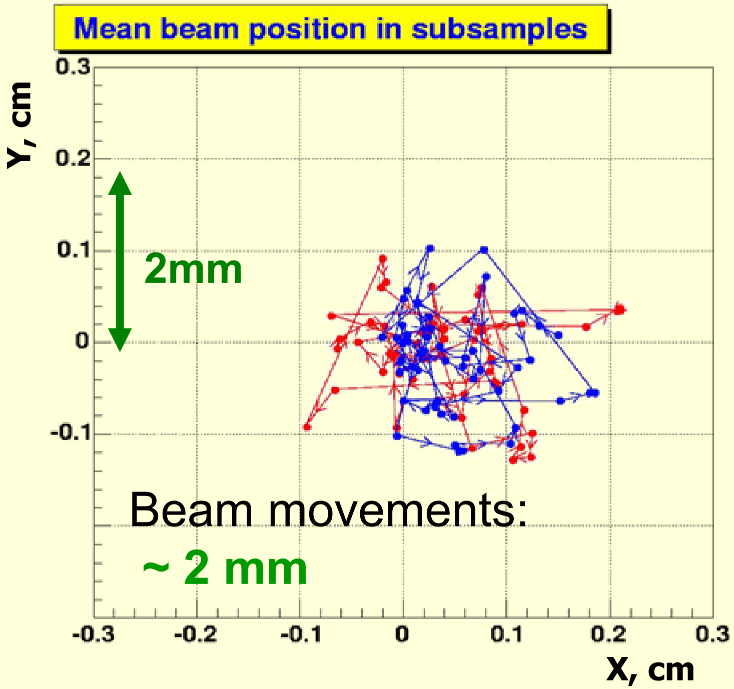
<u>**Time variations of beam geometry**</u>

Acceptance largely defined by central beam hole edge.

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

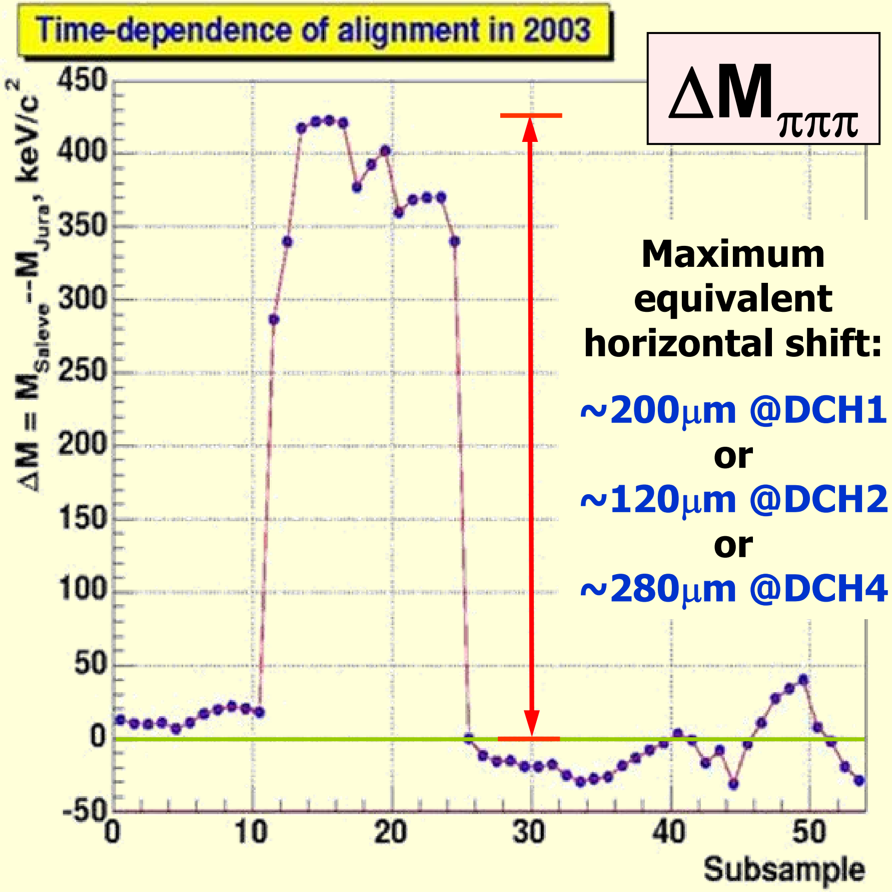
Effects due to beam movements and not perfect overlap corrected





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/μm

Momentum scale

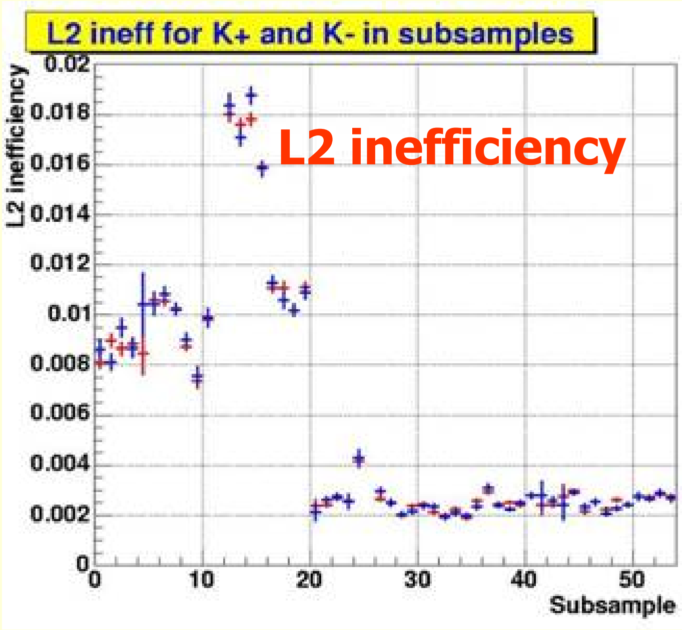
variation due to limited control of spectrometer magnet current (10^{-3}) cancels due to simultaneous beams

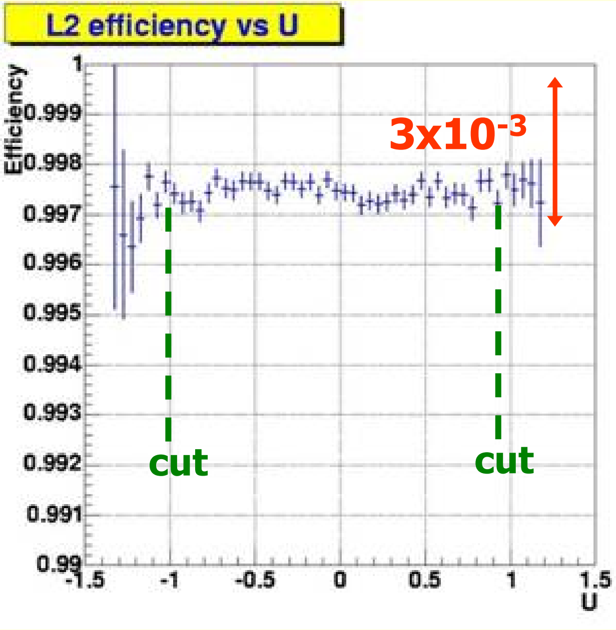
In addition, it is adjusted by forcing mean reconstructed invariant $\pi\pi\pi$ masses to PDG value of M_{K+}

Trigger systematics

L1 trigger (2 hodoscope hits): stable and small inefficiency: $1\text{-}e \approx 0.7 \cdot 10^{-3}$, charge-symmetric, flat in u NO CORRECTION NEEDED

L2 trigger (online vertex reconstruction on DCH data):
time-varying inefficiency (local DCH inefficiencies) $1\text{-}e \approx 0.2\%$ to 1.8% , flat in u within measurement precision u-dependent CORRECTION APPLIED

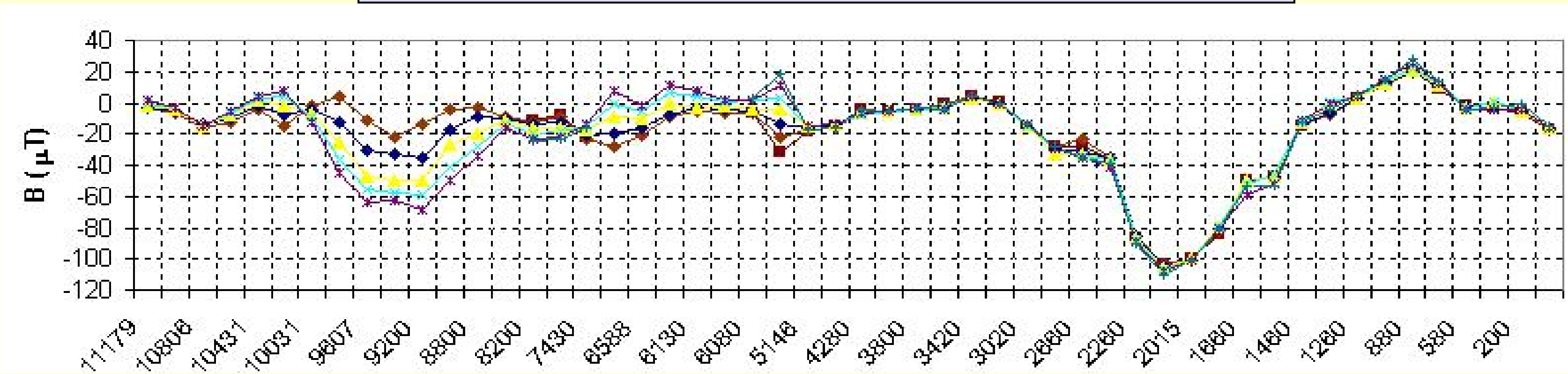




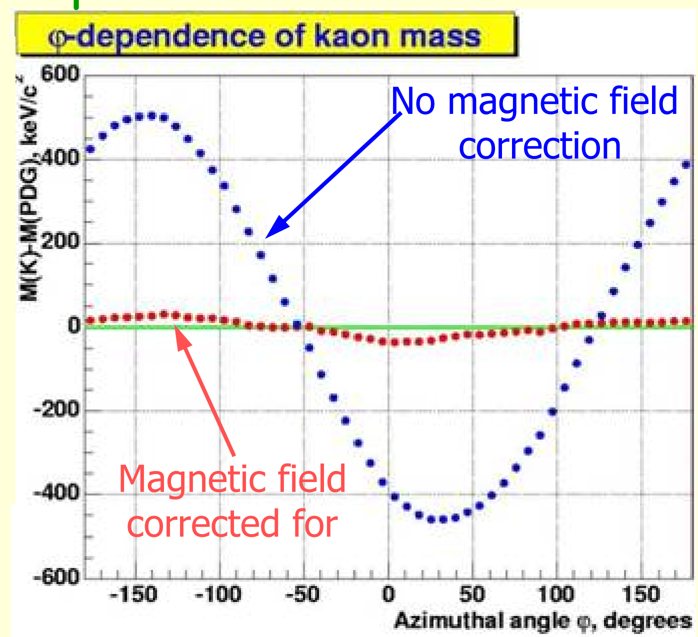
	L2correction $\delta\Delta g \times 10^4$
SS0	0.5±1.8
SS1	1.4±1.0
SS2	-0.2±1.2
SS3	-4.5±1.9

statistical uncertainty from control sample

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
- π^+/π^- interactions in material
- Track charge misidentification

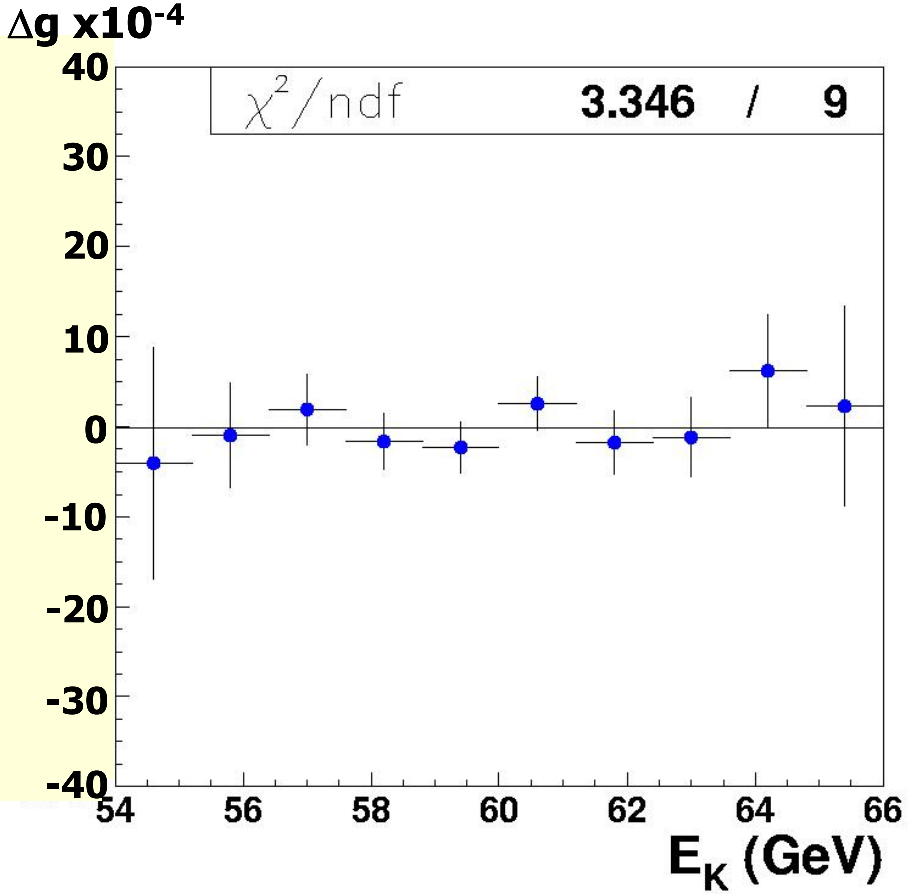
Systematics summary and result

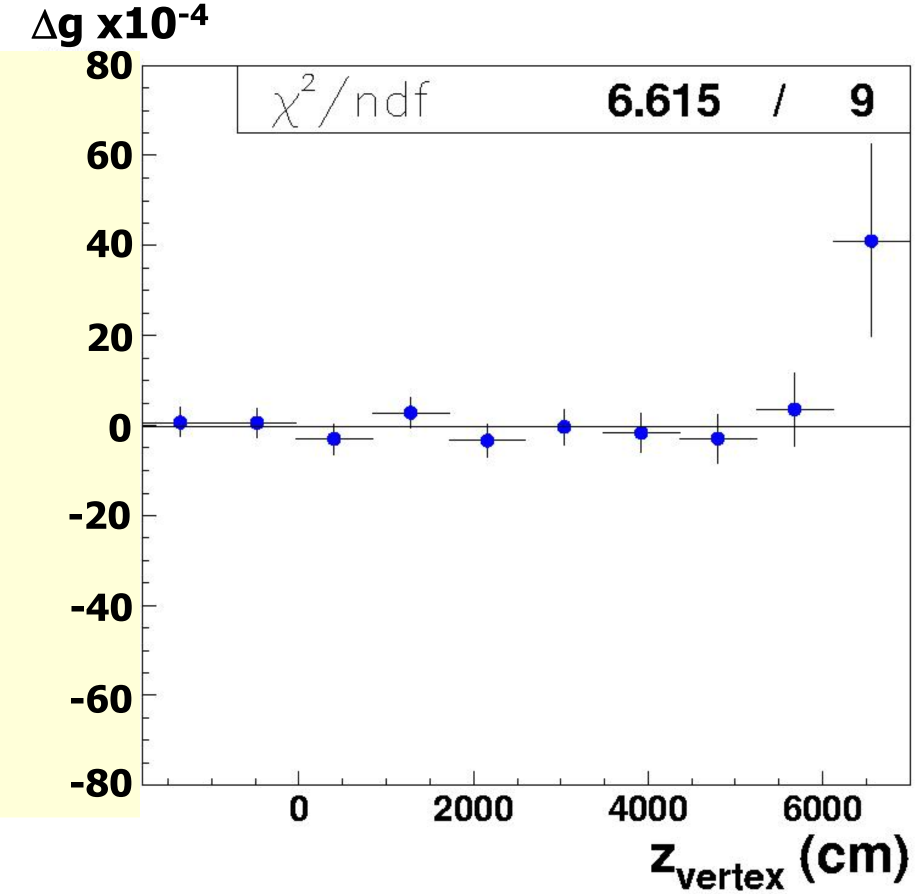
Conservative estimations of systematic errors	Effect on $\Delta x 10^4$
Acceptance and beam geometry	0.5
Spectrometer alignment	0.1
Analyzing magnet field	0.1
$\pi^{\pm} \rightarrow \mu\nu$ decay	0.4
U calculation and fitting	0.5
Pile-up	0.3
Syst. errors of statistical nature	
Trigger efficiency: L2	0.8
Trigger efficiency: L1	0.4
Total systematic error	1.3

Combined preliminary result:
in $\Delta g \times 10^4$ units
(3 independent analyses)
Including L2 trigger correction

	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

Result stability





Preliminary result (2003 data)

slope difference

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

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

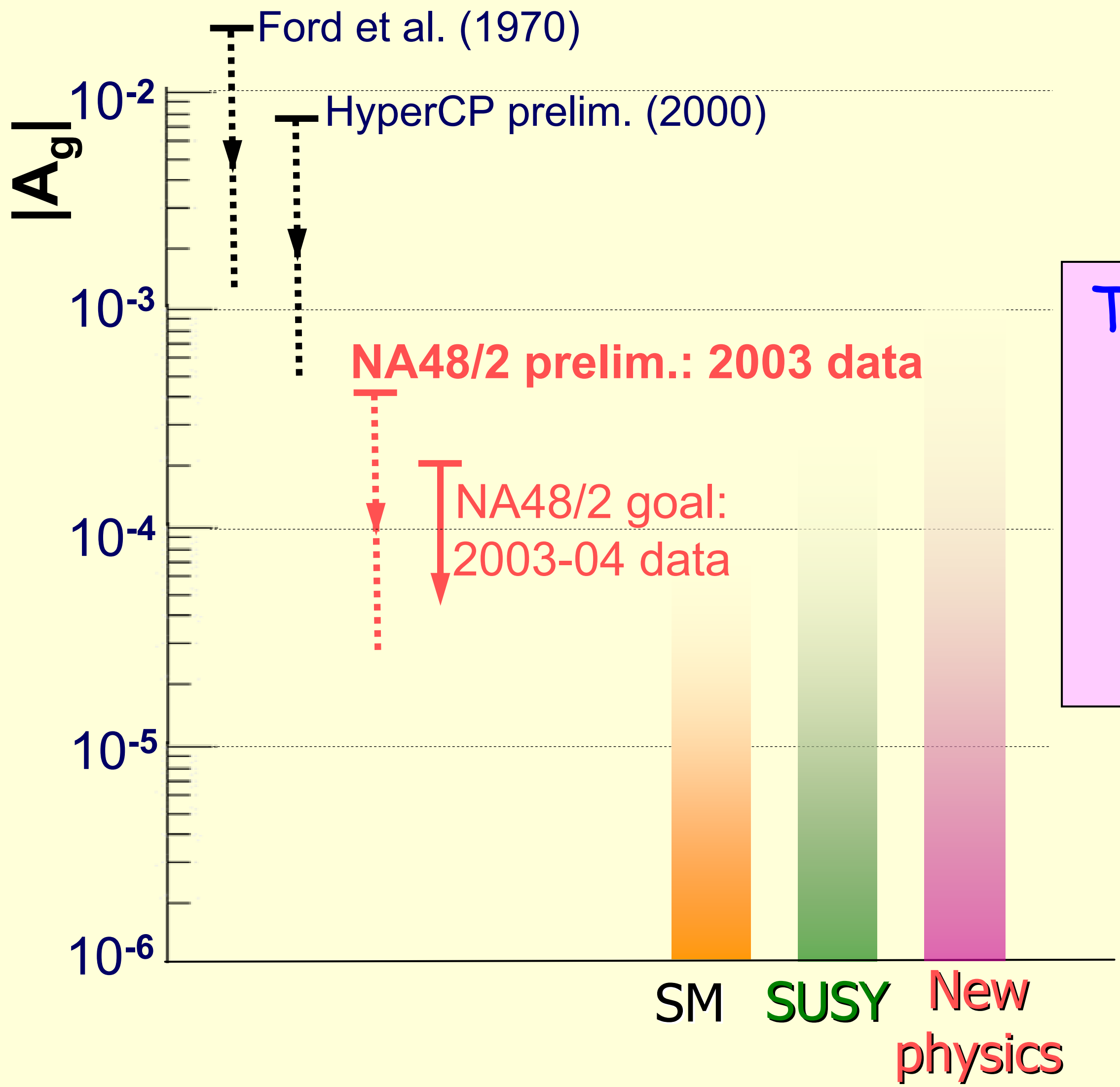
charge asymmetry

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

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

- 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).

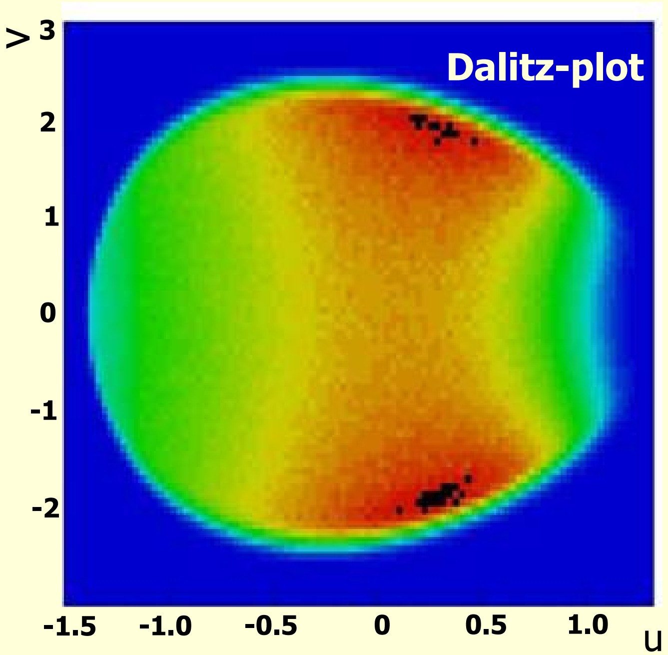
Comparison $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



This preliminary result is already an order of magnitude better than previous experiments

$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ analysis

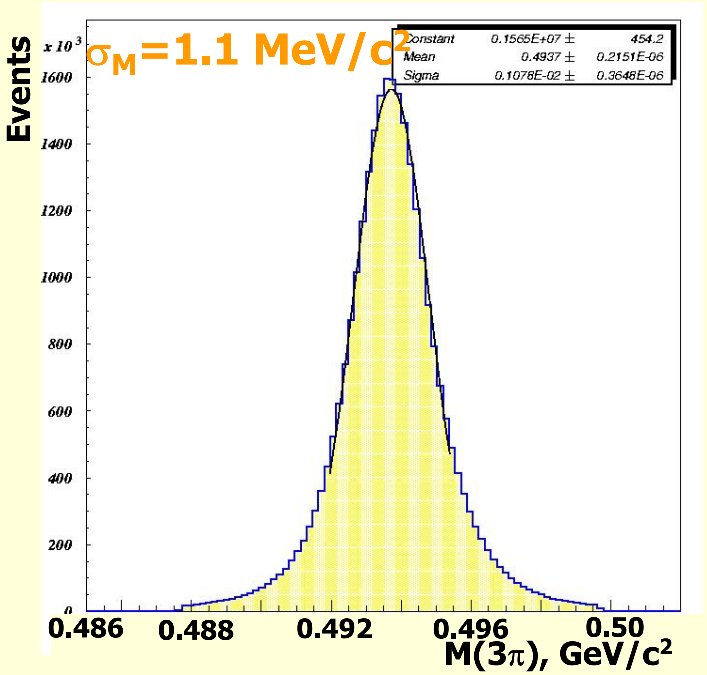
"neutral" mode wrt "charged"



- Same stategy of analysis
- Only the Lkr used to define u
- Totally different systematics
- Statistical precision in A_g^0 similar
  - ✓ Ratio of "neutral" to "charged" statistics: $N^0/N^{\pm}\sim 1/20(\surd=1/4.5)$
  - ✓ Ratio of slopes: $|g^0/g^{\pm}|\approx 3$
  - ✓ More favourable Dalitz-plot distribution (gain factor $f\sim 1.5$)

Status of analysis

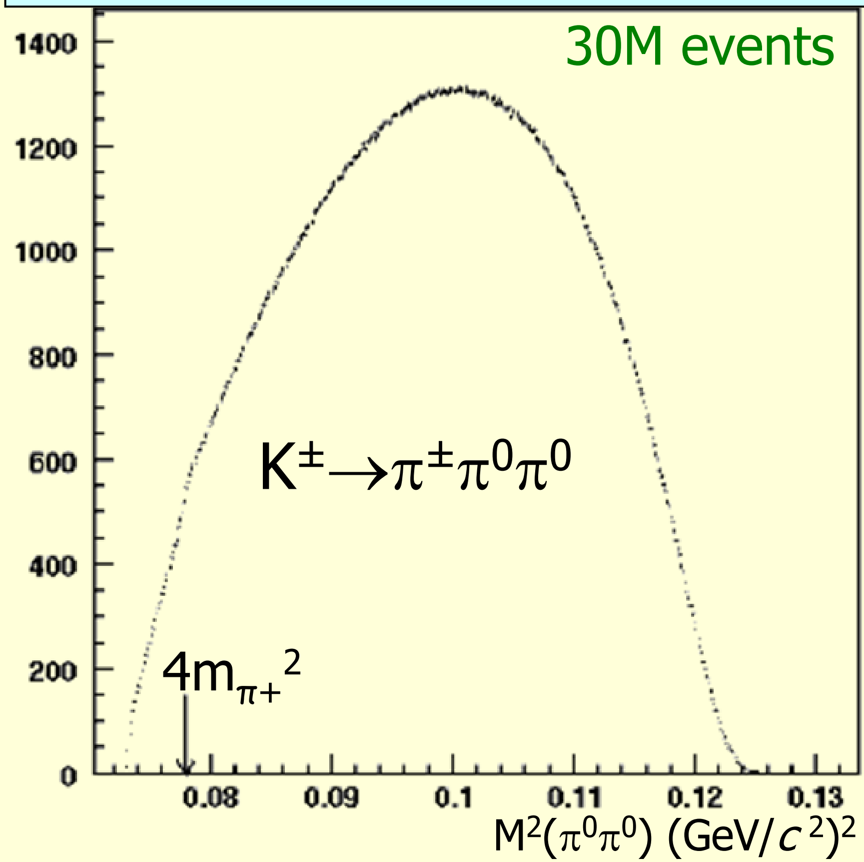
- Statistics analyzed:
  50 × 10^6 events
- Statistical error with analyzed data:
  δA_g(stat)= 1.7 × 10^{-4}
- Extrapolation to 2003+2004 data (115 × 10^6)
  δA_g(stat)= 1.1 × 10^{-4}

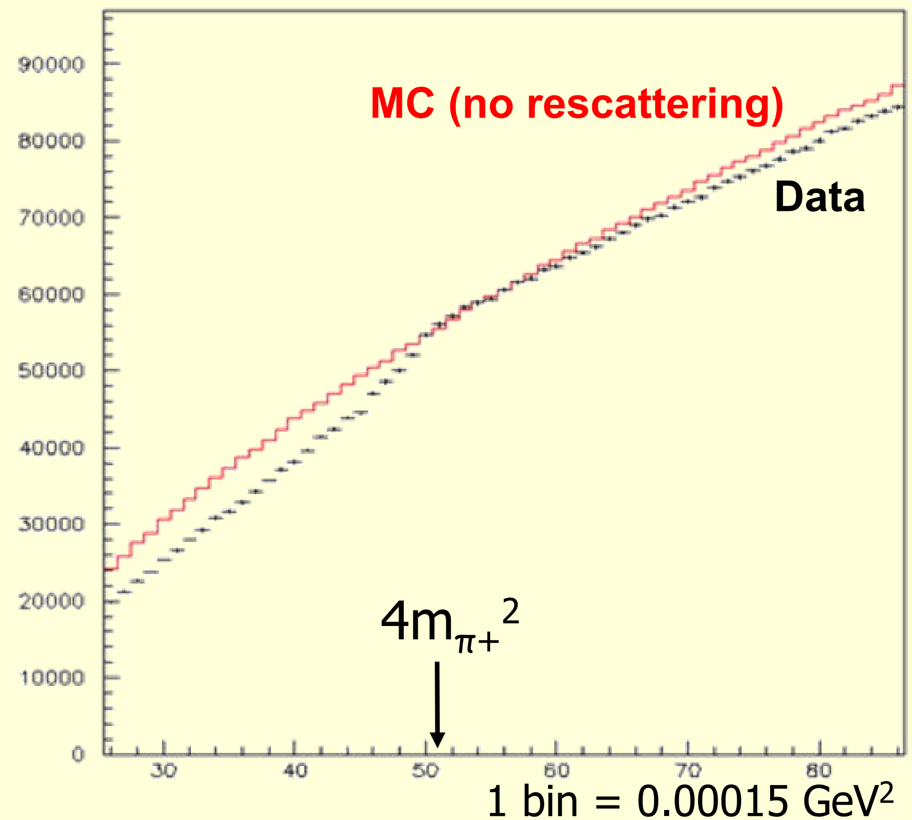


Preliminary results will be announced soon

Observation of ππ scattering effect in K→3π decays

Thanks to the large statistics in the neutral mode we can see (for the first time) the contribution of the charge exchange process $\pi^+\pi^-\to\pi^0\pi^0$ in the $K^\pm\to\pi^0\pi^0\pi^\pm$ decay. This effect stimulated some theoretical work



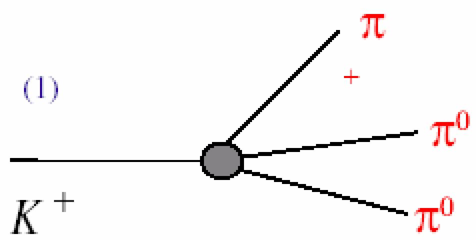


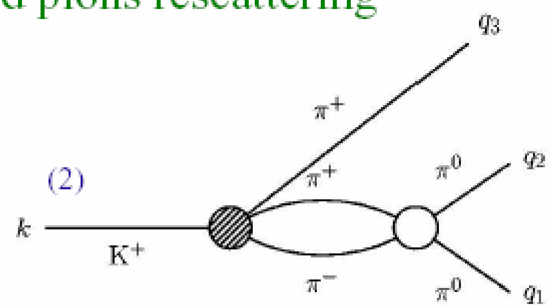
$(a_0 - a_2)$ determination in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

Two processes contribute to $K^+ \to \pi^+ \pi^0 \pi^0$

1) Direct emission of $\pi^+ \pi^0 \pi^0$

2) $\pi^0 \pi^0$ produced in charged pions rescattering





$$\mathcal{M}_0 = 1 + gu/2$$

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

$g = 0.638 \pm 0.020$

(present PDG value)

$$\mathcal{M}_1 \propto (a_0 - a_2)$$

- Small Pionium formation also expected

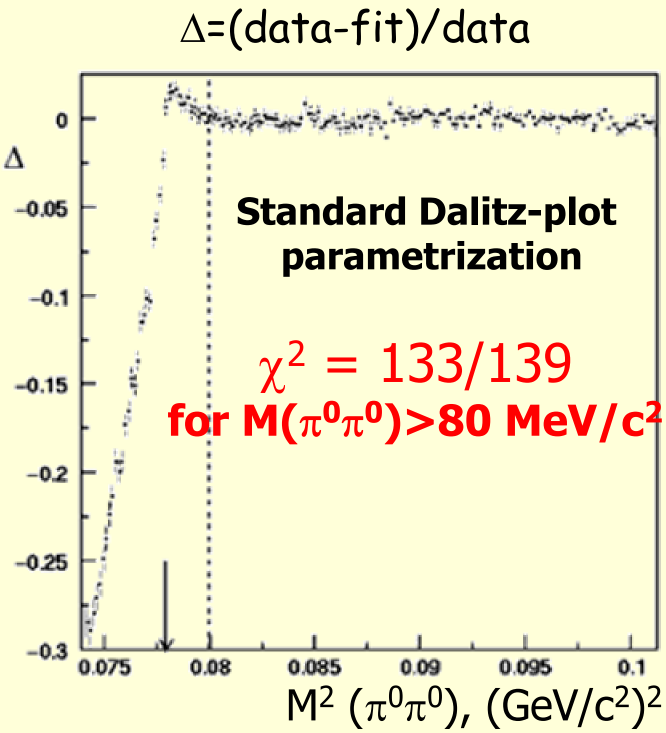
$$d\Gamma/dm_{\pi\pi} \propto |\mathcal{M}_0 + \mathcal{M}_1|^2$$

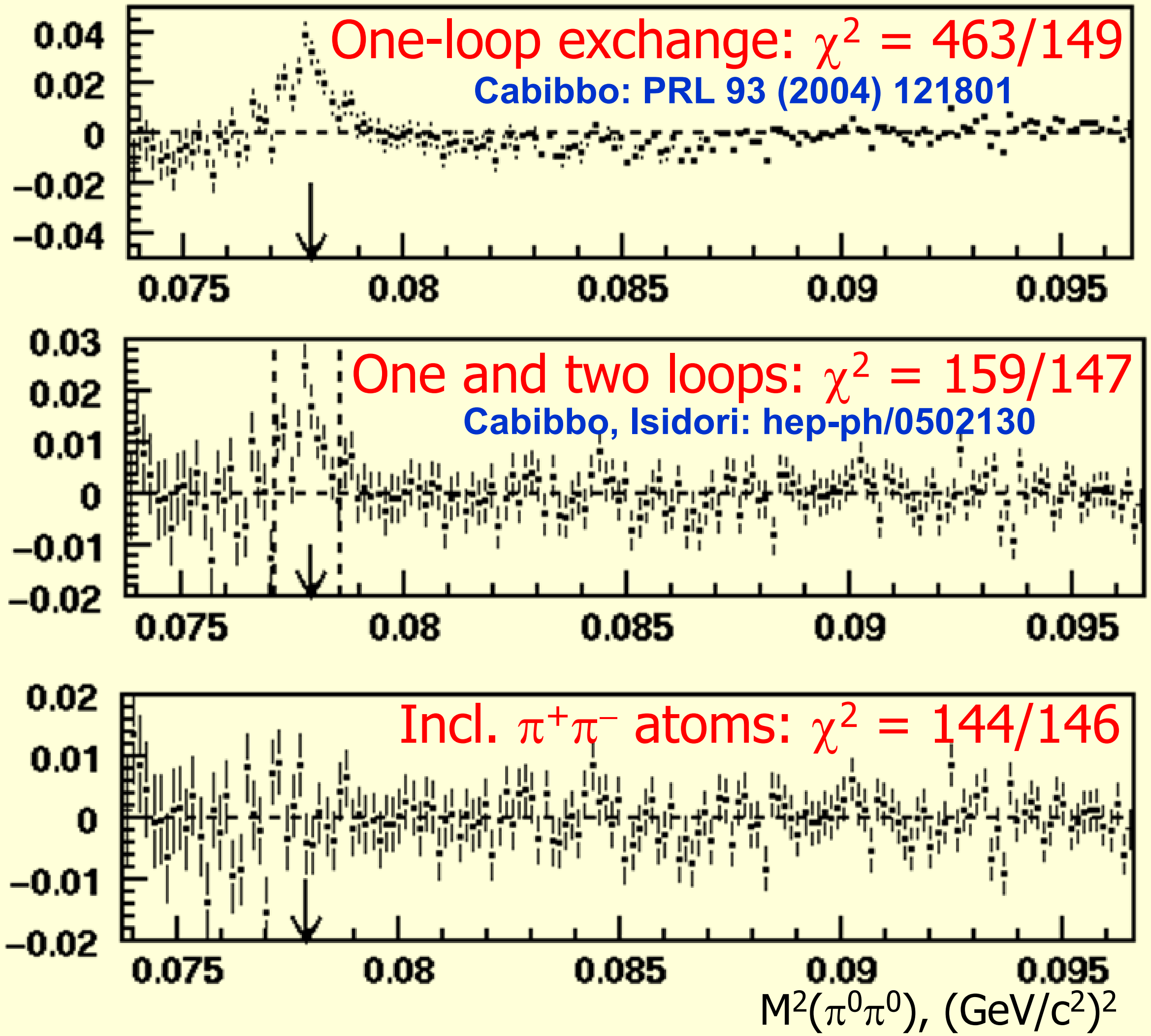
Interference is expected

N. Cabibbo, hep-ph/0405001 Phys. Rev. Lett. ***93****, 121801 (2004) one loop calculation*

N. Cabibbo and G. Isidori, hep-ph/0502130 Phys. Rev. Lett. ***93****, 121801 (2005) two loops*

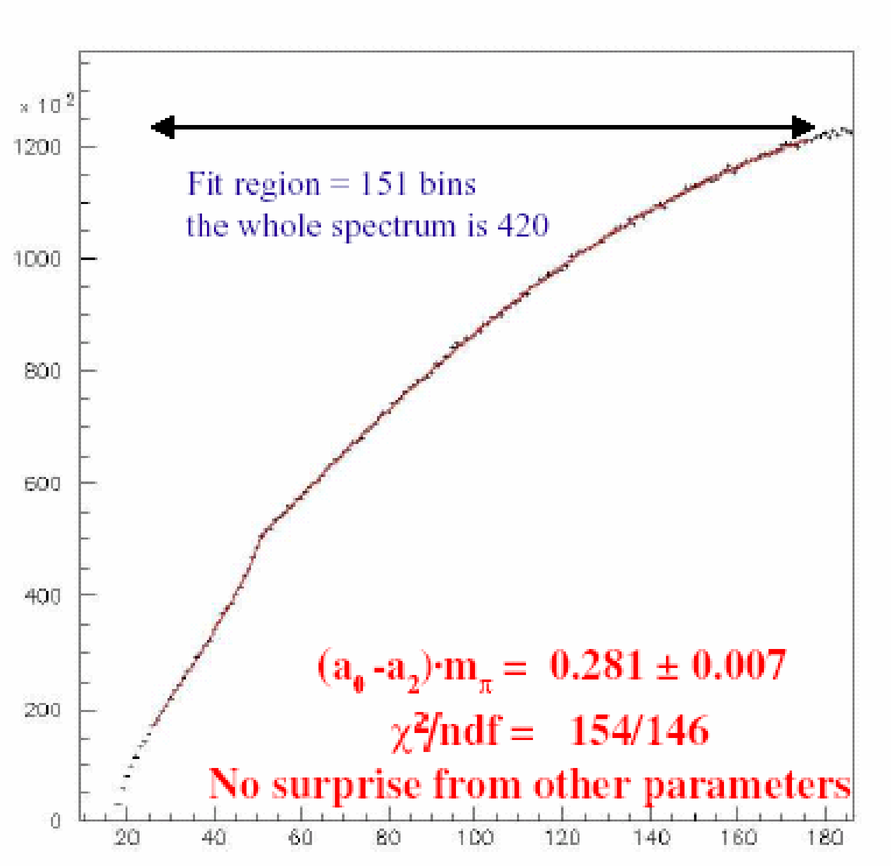
Fits to the "cusp" effect in $K^\pm \to \pi^\pm \pi^0 \pi^0$





The best fit obtained with two loops adding a small amount of pionium to improve the χ^2

Preliminary result



the pionium contribution has been fixed to the prediction:
Z.K. Silagadze, hep-ph/9411382

$$\frac{K^+ \to \pi^+ + pionium}{K^+ \to \pi^+ \pi^+ \pi^-} \approx 7.4 \times 10^{-6}$$

$(a_0 - a_2) m_+$ ➡ has low sensitivity to pionium

$(a_0 - a_2) m_+ = 0.281 \pm 0.007(stat) \pm 0.014(syst) \pm 0.014(theor)$

In agreement with theory $(a_0 - a_2) m_+ = 0.265 \pm 0.004$ (Colangelo 2001)

Conclusions

- Preliminary NA48/2 result (only 2003 data) on direct CP–violating charge asymmetry in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ decays is
  $A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.(trig.)} \pm 2.1_{syst.}) \times 10^{-4}$
- x 10 times better precision than previous measurements
- Further room to decrease systematic error (trigger efficiency)
- 2004 data contains another 2×10^{9} $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ events, possibly with higher quality $\rightarrow$ Design goal within reach
- $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ neutral asymmetry: complementary, comparable sensitivity
- "Cusp" effect: determination of the $\pi\pi$ scattering lengths
- A lot of other interesting results coming (other CP asymmetries, rare decays)

SPARE SLIDES

$K^{\pm}_{3\pi}$ 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"

Kinematic variables

Lorentz-invariants

$$u = (s_3 - s_0)/m_\pi^2;$$
$$v = (s_2 - s_1)/m_\pi^2;$$
$$s_i = (P_K - P_{\pi i})^2,\ i=1,2,3\ (3=\text{odd } \pi);$$
$$s_0 = (s_1 + s_2 + s_3)/3.$$

Centre of mass frame

$$u = 2m_K \cdot (m_K/3 - E_{odd})/m_\pi^2;$$
$$v = 2m_K \cdot (E_1 - E_2)/m_\pi^2.$$

Matrix element

parameterized in terms of slopes

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

Measured quantity sensitive to direct CP violation:

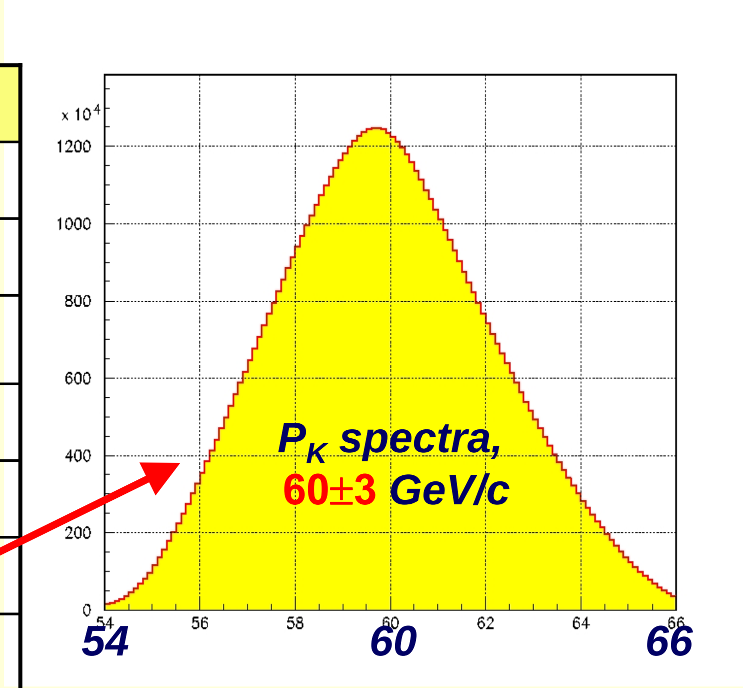
Slope asymmetry:

$$A_g = (g_+ - g_-) / (g_+ + g_-)$$

NA48/2 narrow-band beams

simultaneous, coaxial, focused

Beam	Positive	Negative
Primary proton momentum	400 GeV/c	
Duty cycle	5.2 s / 16.8 s	
Protons on target per cycle	10^{12}	
Production angle	0	
Beam acceptance	±0.36 mrad	
Beam momentum	(60 ± 3) GeV/c	
Beamline length	102 m	
p / $\bar{p}$ per cycle (10^6)	8.6	0.9
π^+ / π^- per cycle (10^6)	33.2	24.6
K^+ / K^- per cycle (10^6)	3.1	1.8
Decay region	115 m	



⇒ Pion decay products stay in beam pipe...

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)	$<8\times10^{-5}$
SUSY	G.D'Ambrosio, G.Isidori, G.Martinelli	$\sim10^{-4}$
New physics	E.Shabalin '98 [Weinberg model of extended Higgs doublet]	$\sim4\times10^{-4}$
	I.Scimemi '04	$>3\times10^{-5}$

More cancellations

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

$R_U = R_{US} \times R_{UJ}$ ⇒ $R(u)=n\cdot(1+2\,\Delta g_U\,u)$

$R_D = R_{DS} \times R_{DJ}$ ⇒ $R(u)=n\cdot(1+2\,\Delta g_D\,u)$

(2) **Double ratio** cancellation of **beam geometry difference** effects:

$R_S = R_{US} \times R_{DS}$ ⇒ $R(u)=n\cdot(1+2\,\Delta g_S\,u)$

$R_J = R_{UJ} \times R_{DJ}$ ⇒ $R(u)=n\cdot(1+2\,\Delta g_J\,u)$

(3) 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 asymmetries in experimental conditions on a time-scale of ~ 1 subsample

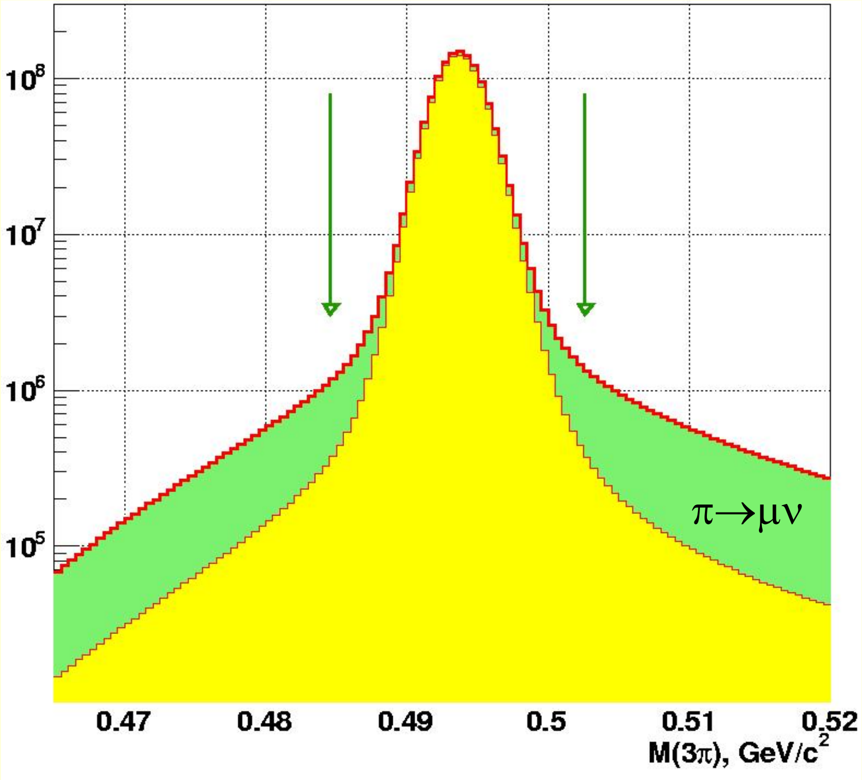
Break down of $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ statistics

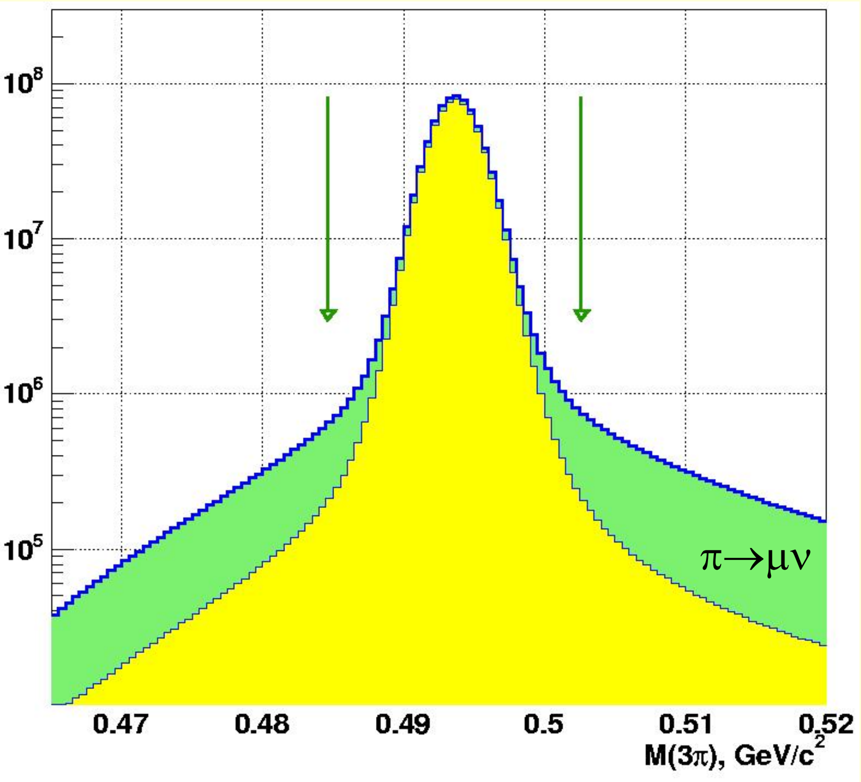
Statistics selected for A_g measurement, events x10^6

	Dates	Sub-samples	Achromat A+		Achromat A–	
			K^+	K^-	K^+	K^-
0	22.06-25.07	26	229.6	125.9	201.0	114.0
1	6.08-20.08	12	122.5	68.1	135.1	75.4
2	20.08-3.09	12	147.2	81.8	105.5	58.9
3	3.09-7.09	4	40.6	22.6	54.5	30.4
	Total	54	Total events selected			1613.2

Invariant πππ mass

σ_M=1.7 MeV/c^2



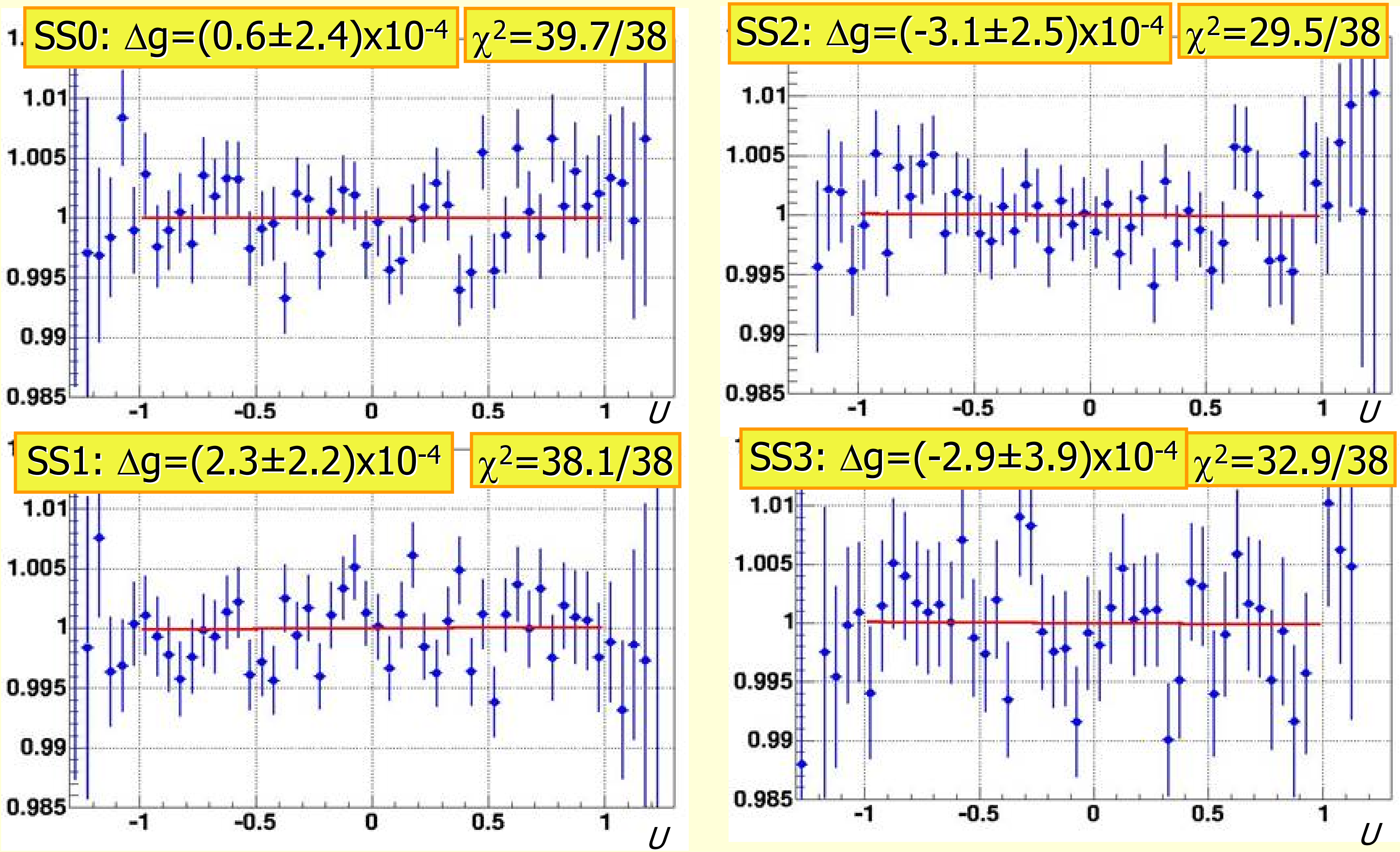


K^+ : 1.03x10^9 events

No significant background

K^- : 0.58x10^9 events

Fit linearity – four supersamples

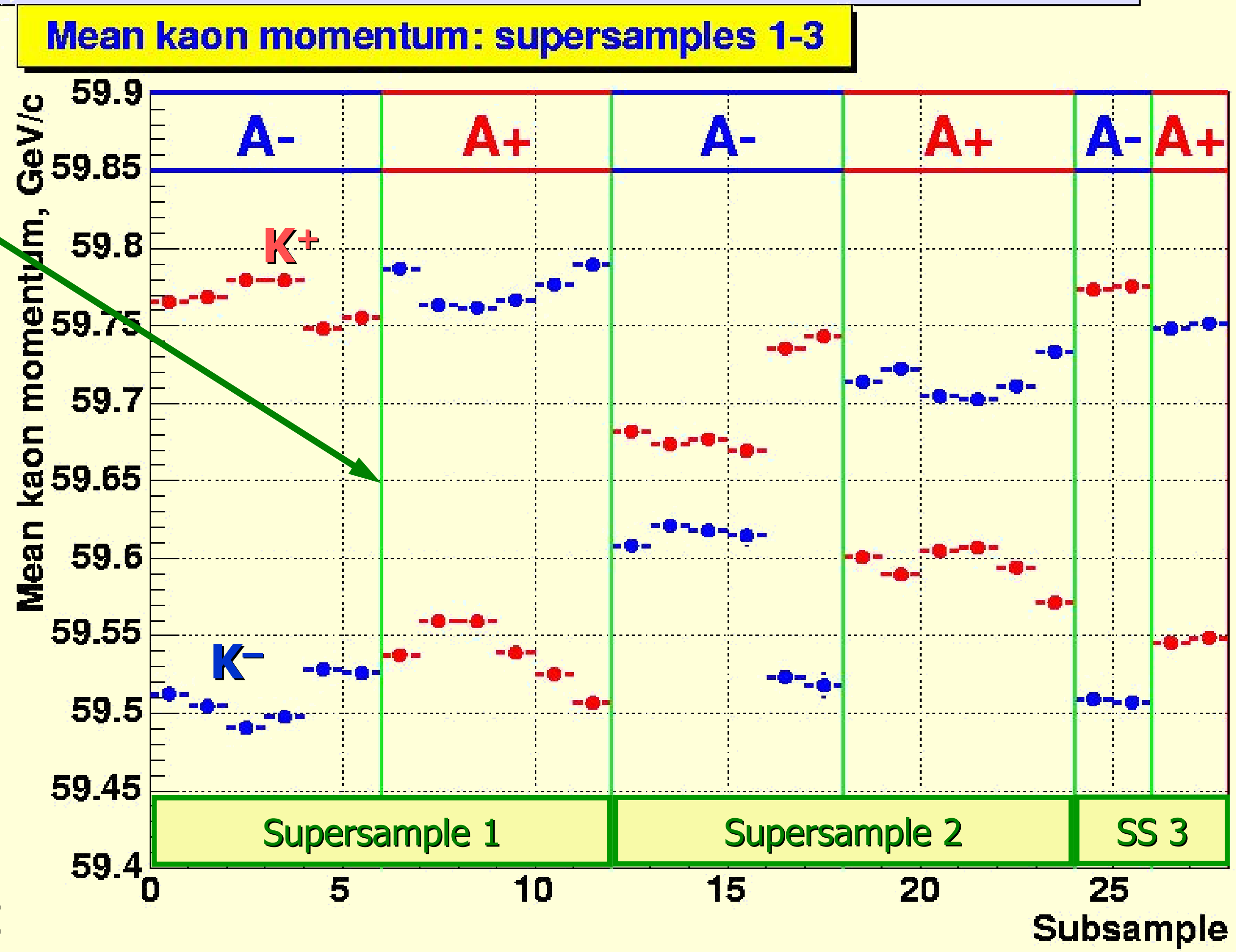


Cancellation of beam spectra

Achromat reversal reverses K^+ and K^- beam spectra

Systematic differences of K^+ and K^- acceptance due to beam spectra mostly cancel in R_U*R_D

Systematic check:
Reweighting K^+ events so as to equalise momentum spectra leads to negligible effect $\delta\Delta g=0.03\times10^{-4}$



Theoretical predictions

Weinberg (1966)
Effective field theory for strong interaction at low E

$$a_0 m_{\pi^+} = \frac{7 m_{\pi^+}^2}{16\pi f_\pi^2} = 0.159$$

$$a_2 m_{\pi^+} = \frac{-m_{\pi^+}^2}{8\pi f_\pi^2} = -0.045$$

Most recently
Colangelo (2001)
χpt -theory two loops
Ref: hep- ph/0103088

$$a_0 m_{\pi^+} = 0.220 \pm 0.005$$

$$a_2 m_{\pi^+} = -0.0444 \pm 0.0010$$

$$(a_0 - a_2) m_{\pi^+} = 0.265 \pm 0.004$$

- **2% level of accuracy:** quite unusual for hadronic physics
  experiments have not yet reached the same level

Experimental status

1977: measurement by Genève/Saclay experiment @ **20% accuracy**

2003: **BNL E865** extracts a_0 at **5% accuracy** by measuring the form factors of the decay K --> $\pi\pi e\nu$ with 400,000 events

$$a_0 m = 0.216 \pm 0.013(stat.) \pm 0.002(syst.) \pm 0.002(theor.)$$

Ref. Pislak et al. (2003) hep-ex/0301040

Present: Cern experiment **DIRAC,** with a sophisticated technique, aims to measure the pionium lifetime @ **10% accuracy**

$$\tau \sim 40 \cdot (a_0 - a_2)^2 \cdot 10^{-15} \text{ sec}$$