First results on direct CP-violating asymmetries in $K^{\pm} \rightarrow 3\pi$ decays from 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

Les Rencontres de Physique de la Vallée d'Aoste 2005

Outline

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

Direct CP violation

a.k.a. CP violation in decay amplitudes

Direct CP violation in K^0: ε'/ε (1999)

CP violation in B^0 decays with oscillations (2001)

Direct CP violation measured in B^0 (2004)

The most "straightforward" CP effect…

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

Charged K: direct CP violation only

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

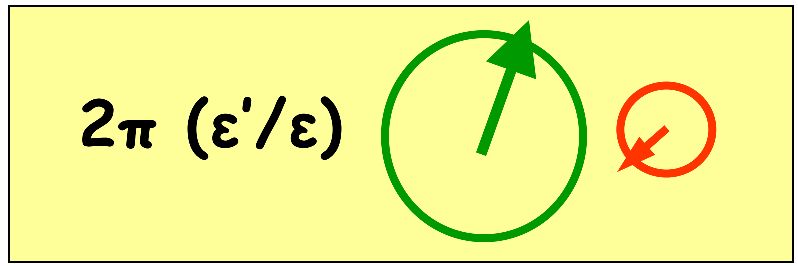
Kaons: a (relatively) simple system

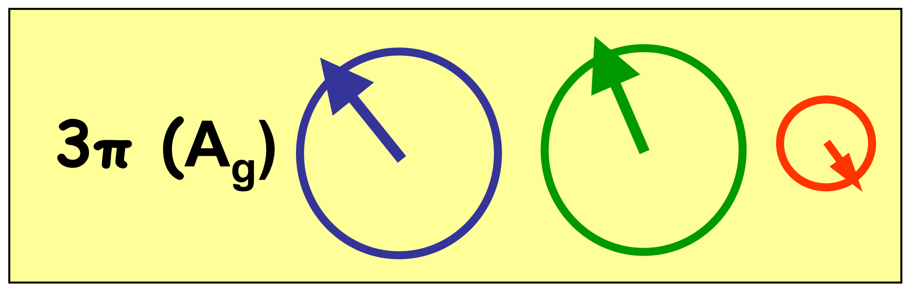
$K^\pm \to \mu^\pm \nu$ ✗

$K^\pm \to \pi^\pm \pi^0$ ✗

$K^\pm \to 3\pi$ ✓

No intrinsic ΔI=1/2 amplitude suppression (as for ε'/ε)





But…

Hadronic uncertainties

Small rescattering phases

→ Small in SM

Width asymmetries suppressed

$K_{\pi 3}$ 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"

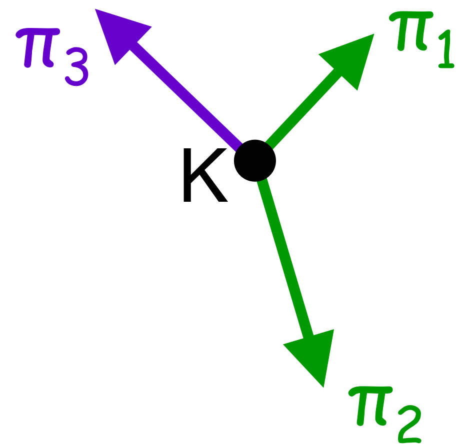
Kinematics:

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

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

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

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



Matrix element:

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

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

$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ $g = 0.652 \pm 0.031$

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

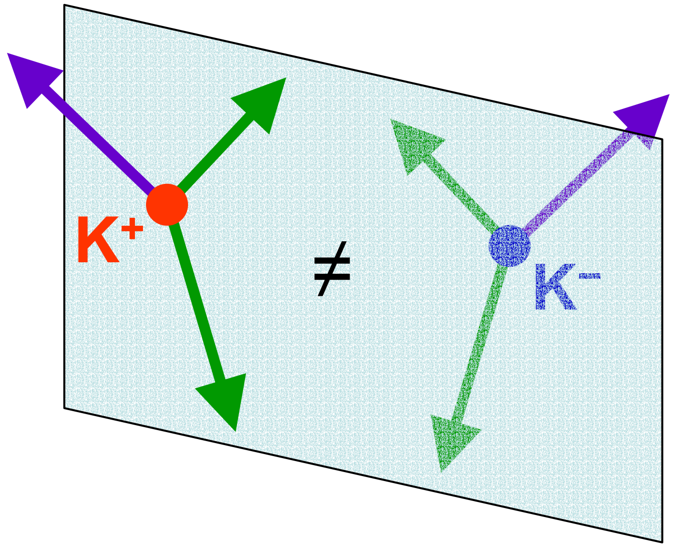
CP violation in $K_{\pi 3}$ (how)

Potentially large statistics

Simple selection

Low backgrounds

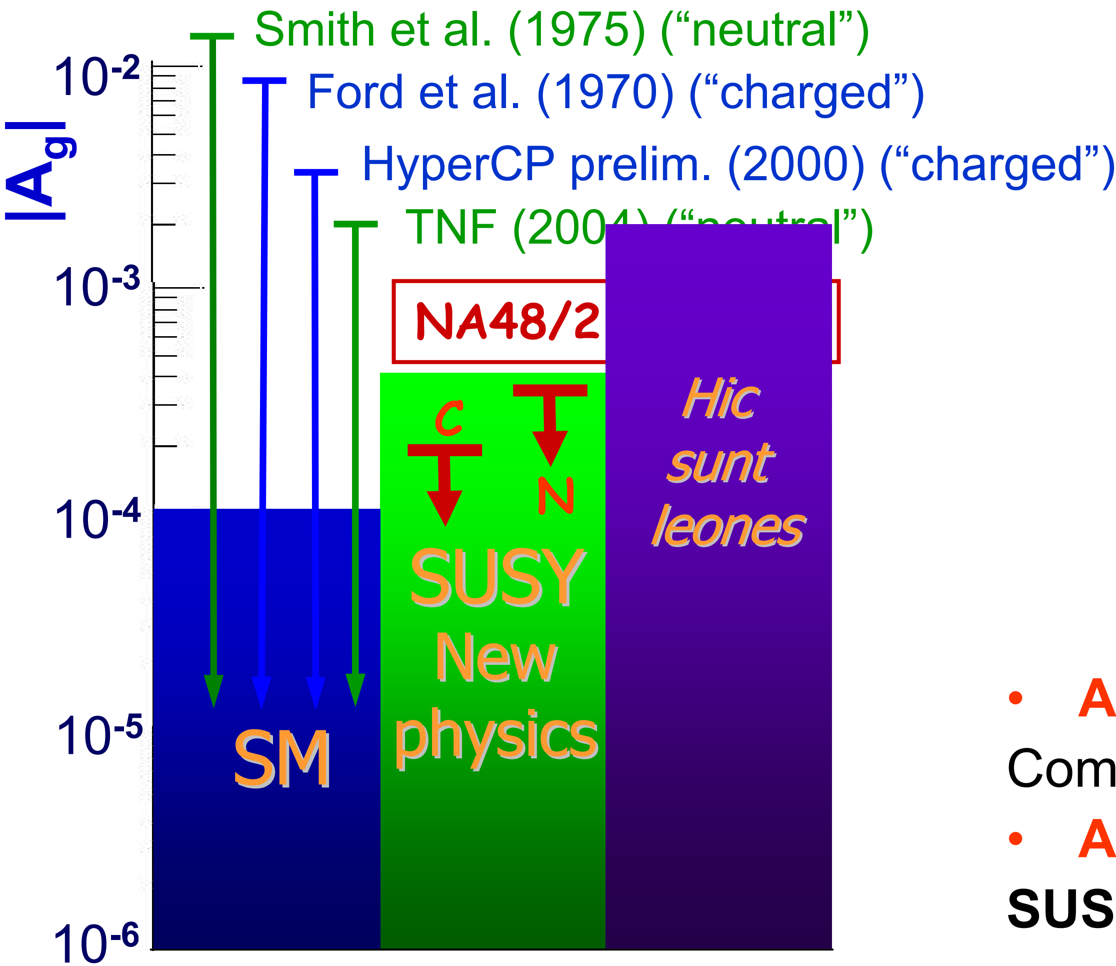
No absolute K flux measurement: compare only Dalitz plot shapes



Measured CP−violating quantity:

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

K± asymmetries: status



THEORY:

SM contribution: many theoretical computations from several groups
Large uncertainties (~1 order of magnitude) esp. for "neutral"

Some enhancements possible **beyond SM**

- **$A_g \sim 10^{-5}$**

Compatible with SM

- **$A_g > 1 \cdot 10^{-4}$**

SUSY / New Physics

The NA48/2 approach

NA48/2 main goal:

– Measure linear slope asymmetries "charged" and "neutral" modes with accuracies $\delta A_g < 2.2 \cdot 10^{-4}$ and $\delta A_g < 3.5 \cdot 10^{-4}$ respectively

– Required statistics: $>2 \cdot 10^9$ in "charged" mode and $>10^8$ in "neutral" mode

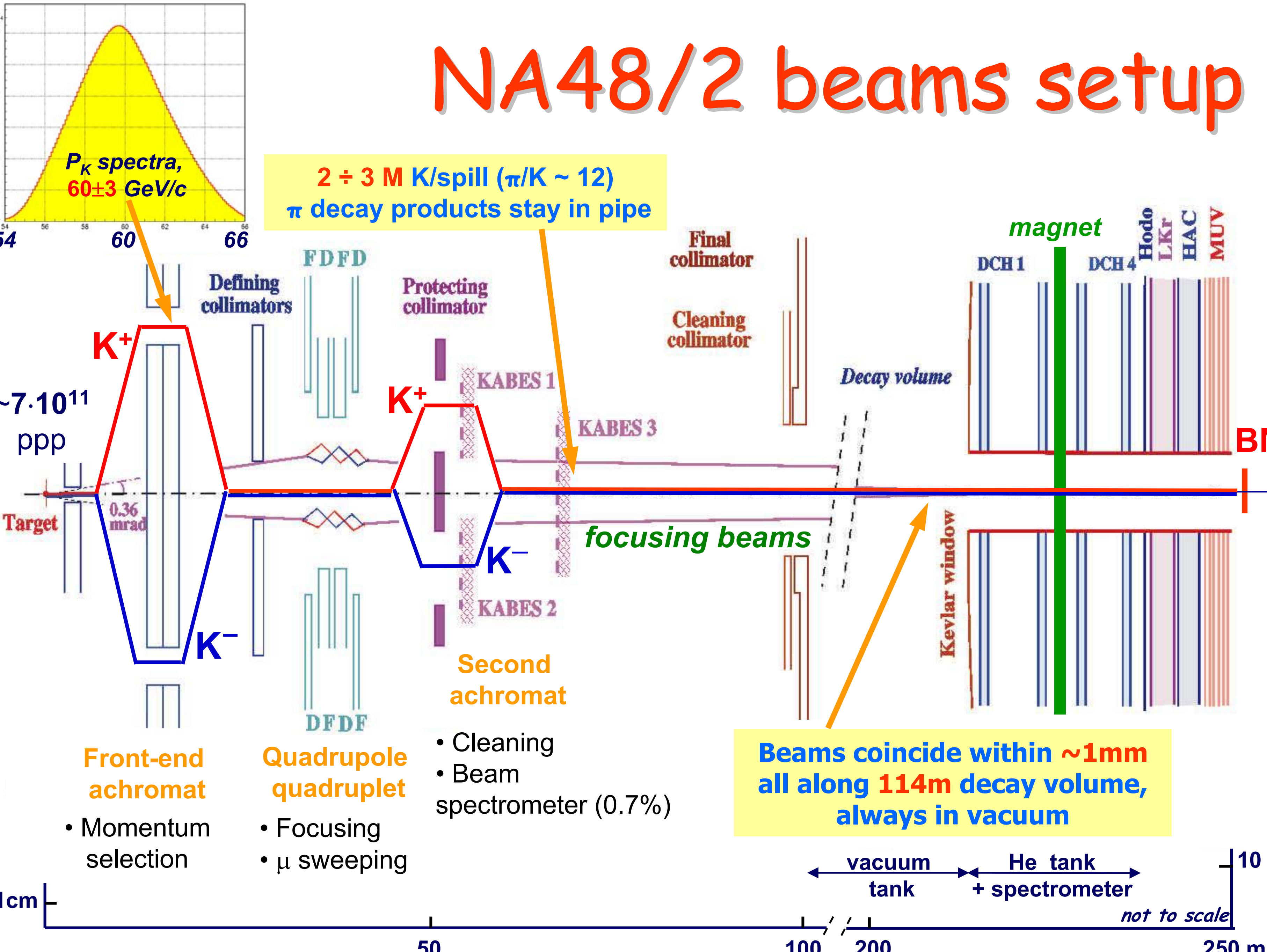
NA48/2 method: maximal cancellations (robustness)

– 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

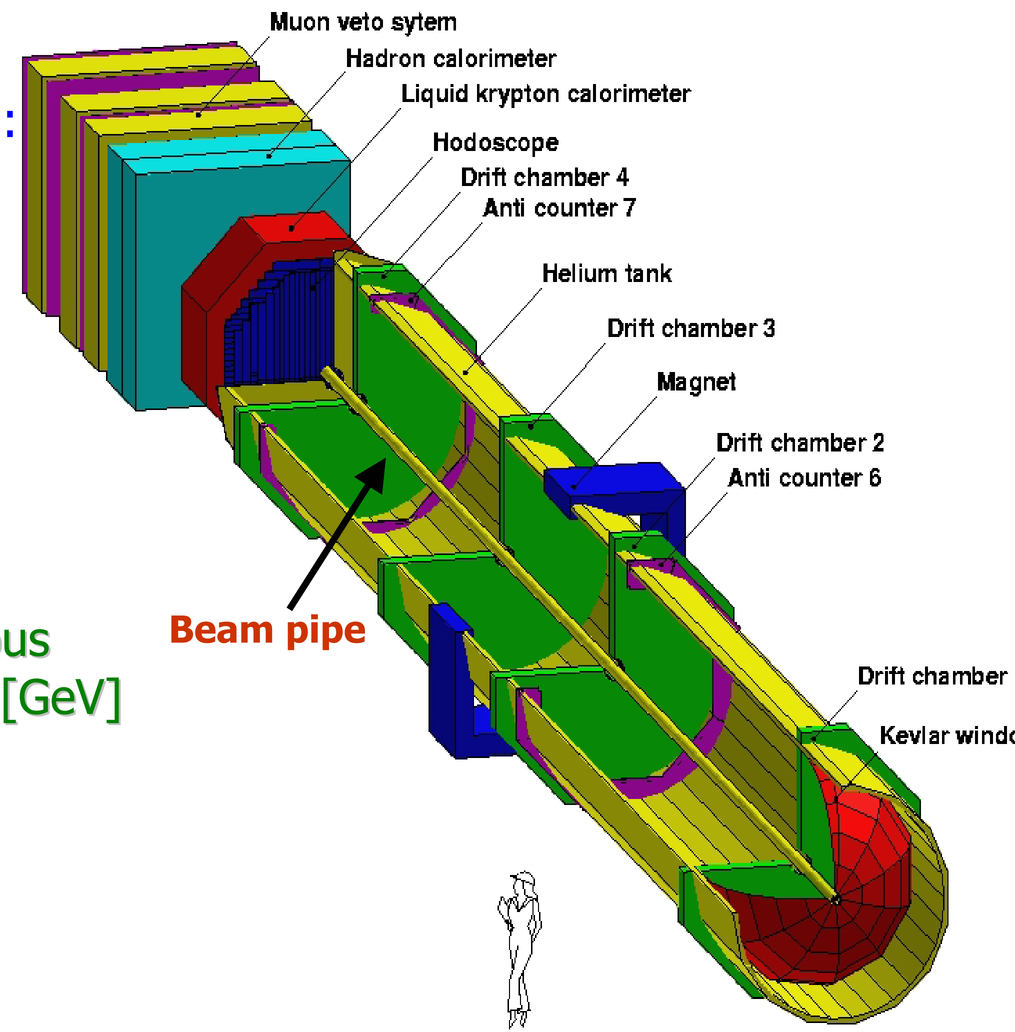
Main detector components:

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

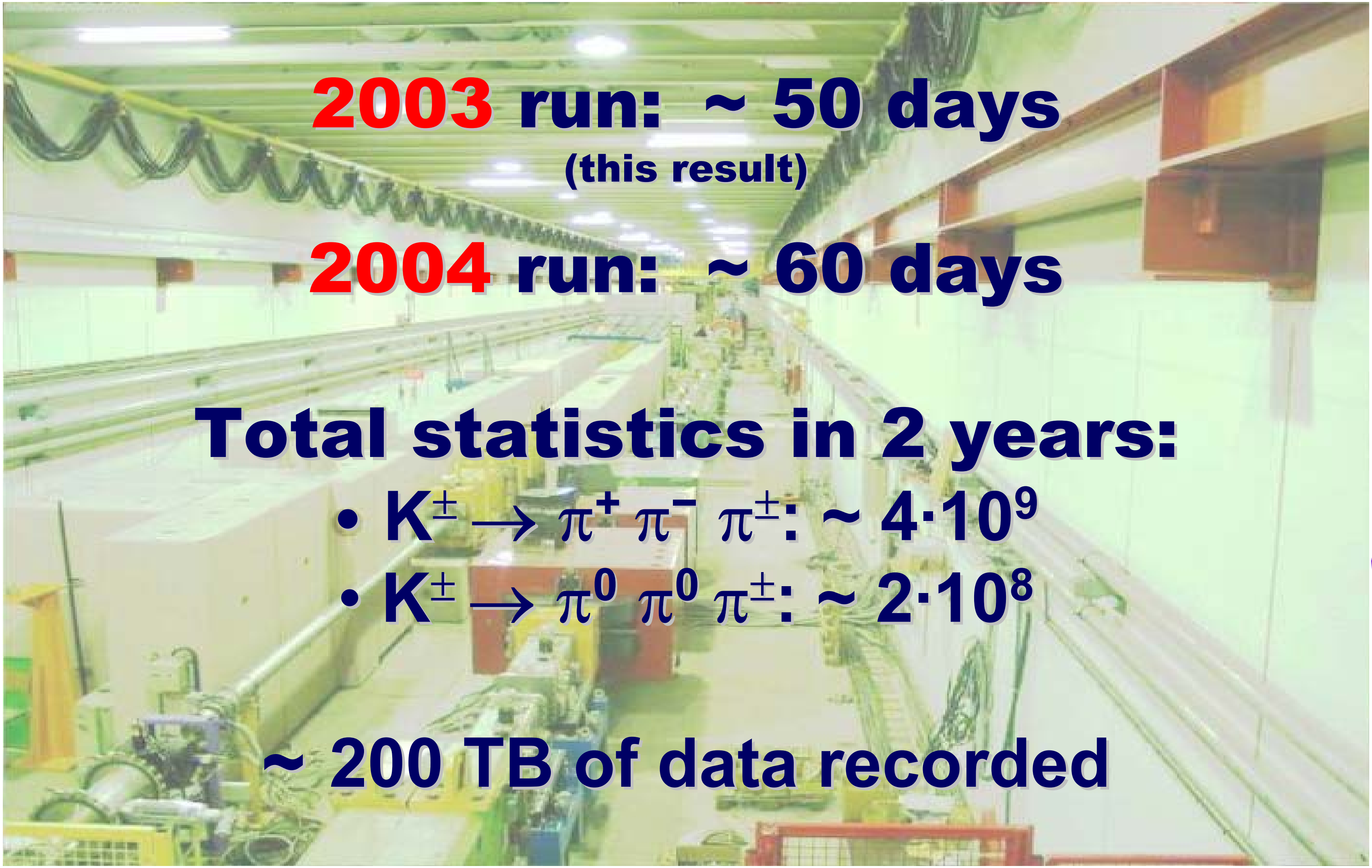
- Hodoscope
  fast trigger
  precise time measurement (150ps)

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

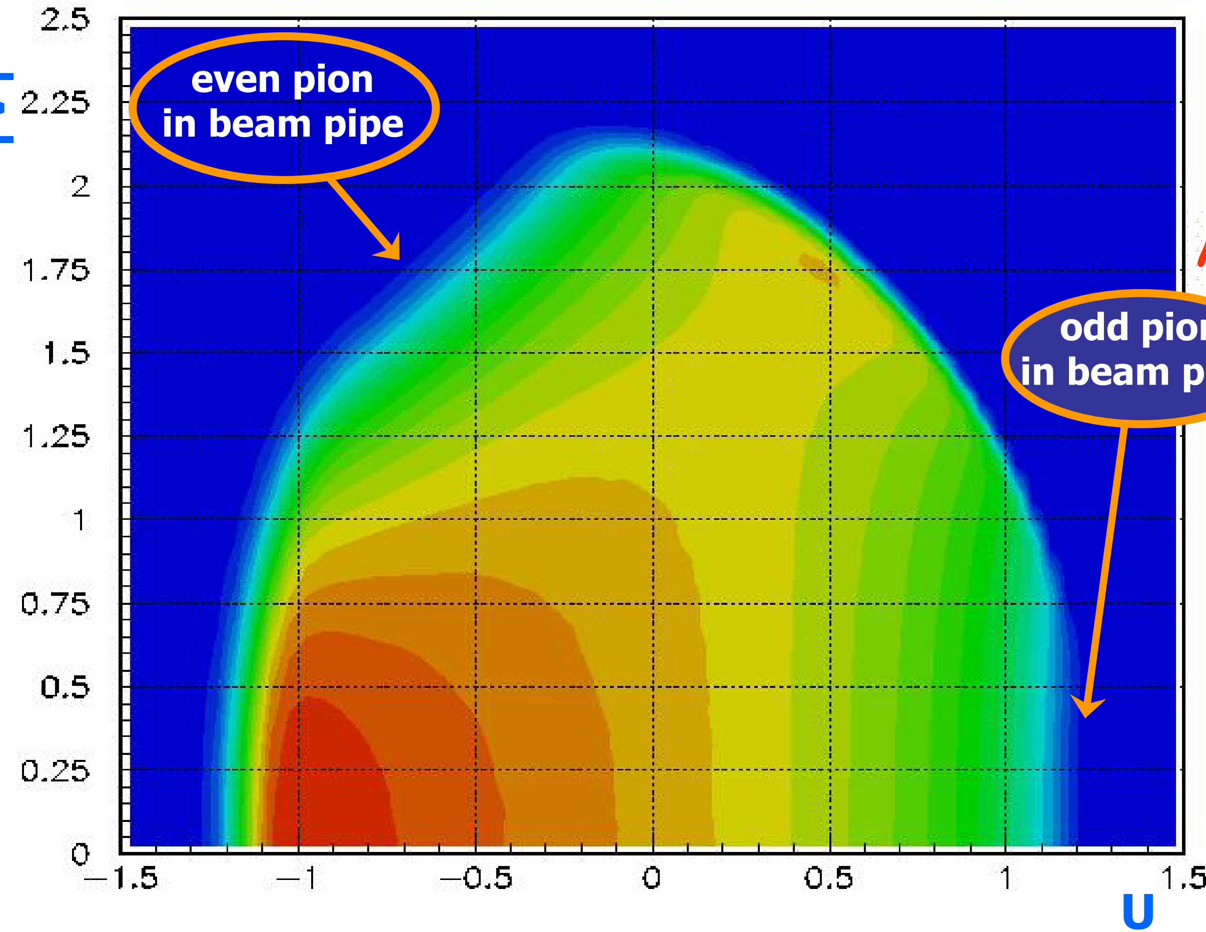
- $K^{\pm} \rightarrow \pi^{+} \pi^{-} \pi^{\pm}$: ~ $4 \cdot 10^{9}$
- $K^{\pm} \rightarrow \pi^{0} \pi^{0} \pi^{\pm}$: ~ $2 \cdot 10^{8}$

~ 200 TB of data recorded

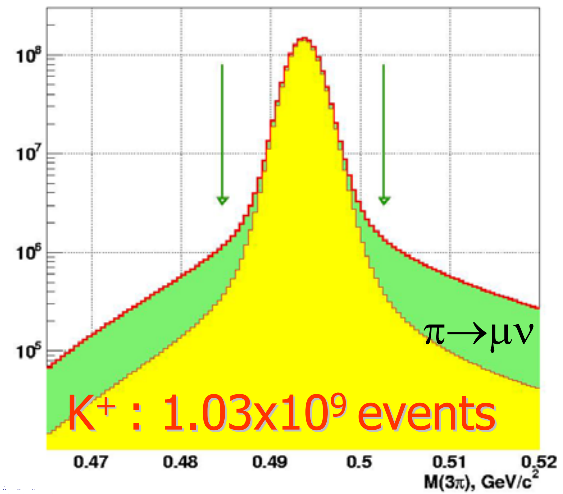
Selected data 2003

Data-taking 2003:

1.61x10⁹ *events selected (K⁺ / K⁻ ≈ 1.8)*

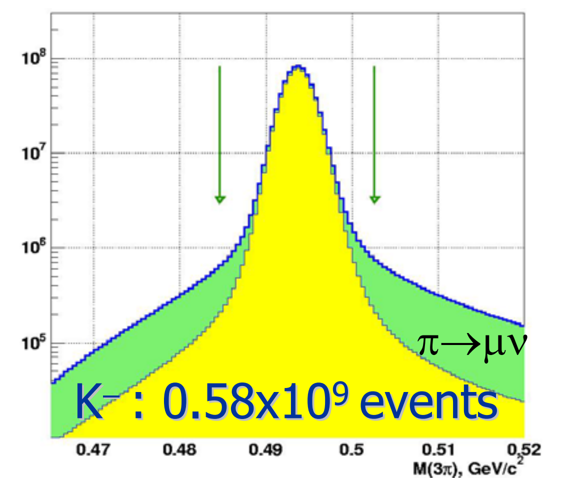


σ_M=1.7 MeV/c²



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 charge-asymmetric AND non-flat in 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

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 distributions:

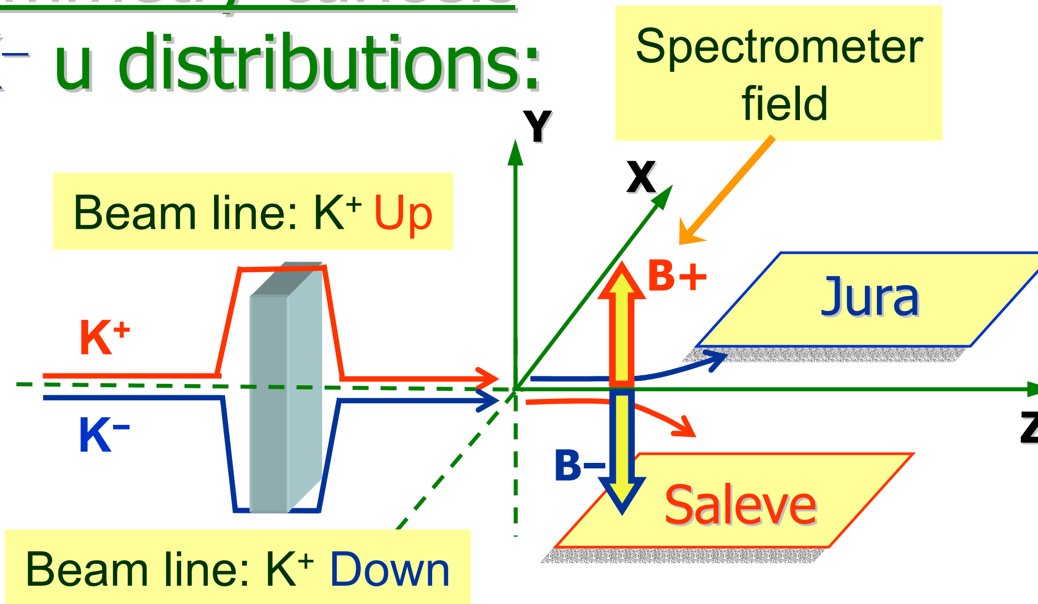
(same deviation by spectrometer in numerator and denominator)

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

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

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

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



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

More cancellations

(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**:

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

Normalization (n) — Slope difference (Δg)

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

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

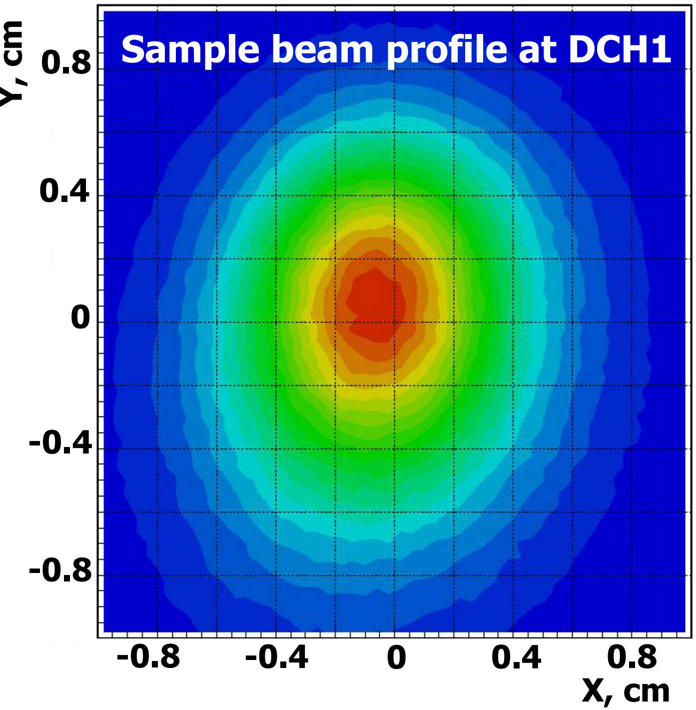
The fit result is sensitive only to
time variation of left-right asymmetries
of experimental conditions
on a time-scale of ~1 subsample

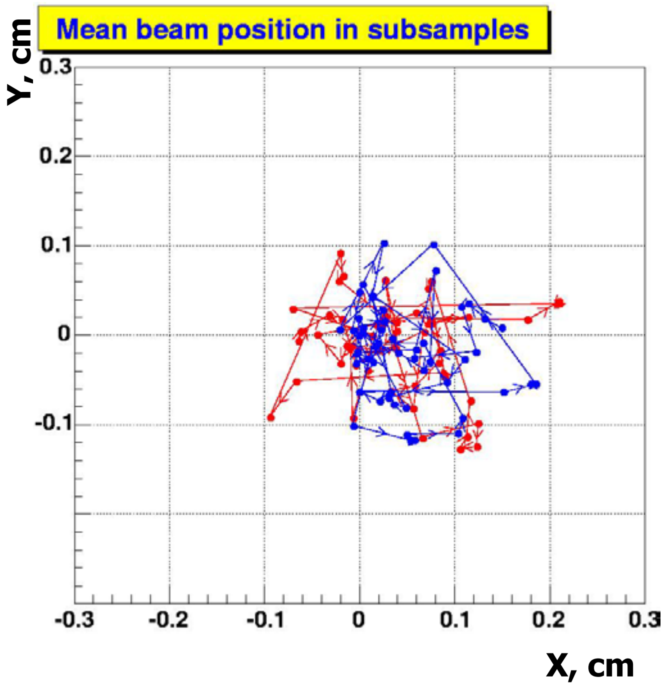
Systematics: beams

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*





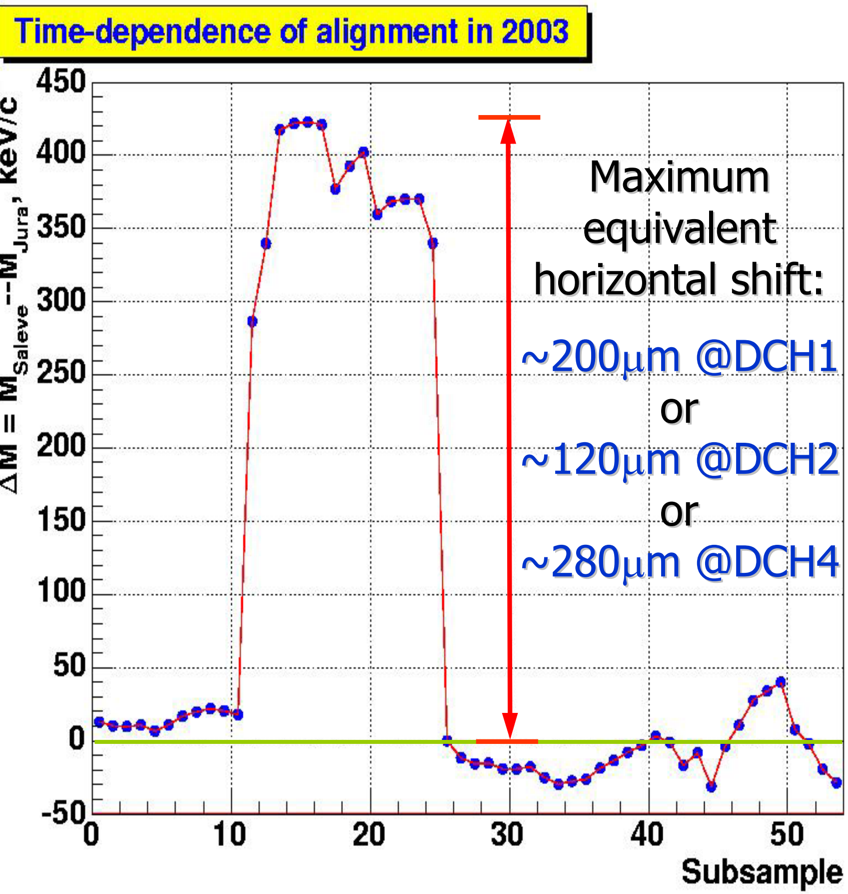
Beam widths:
~ 5 mm
Beam movements:
~ 2 mm

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)

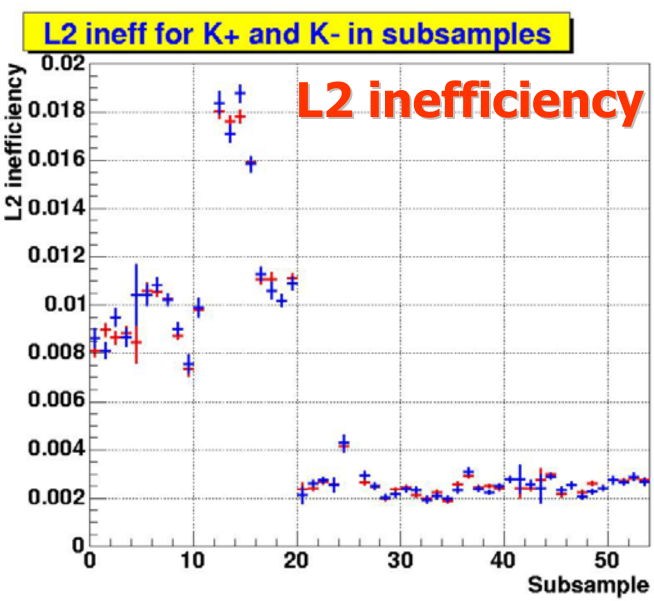
Momentum scale adjusted anyway by constraining average reconstructed K masses to PDG value

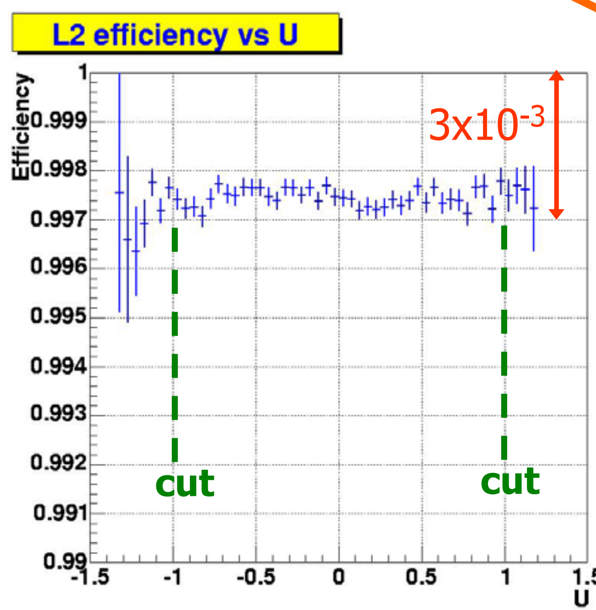
Sensitivity to 10^{-3} error on field integral:
$\Delta M \approx$ **100 keV**

Systematics: trigger

L1 trigger (2 hodoscope hits):
stable inefficiency ≈ $0.7\cdot10^{-3}$ 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** for 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
- Simulation not required.

Full **MonteCarlo** (GEANT, following misalignments, local DCH inefficiencies) with same statistics as data used for systematic checks

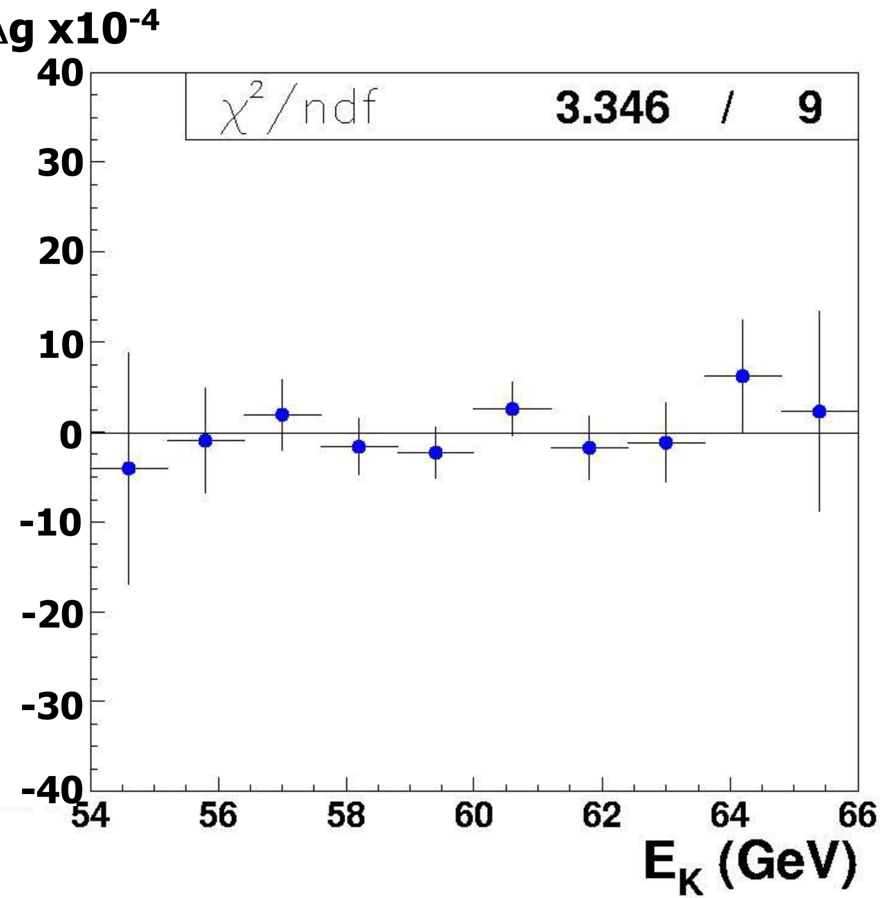
Result and errors

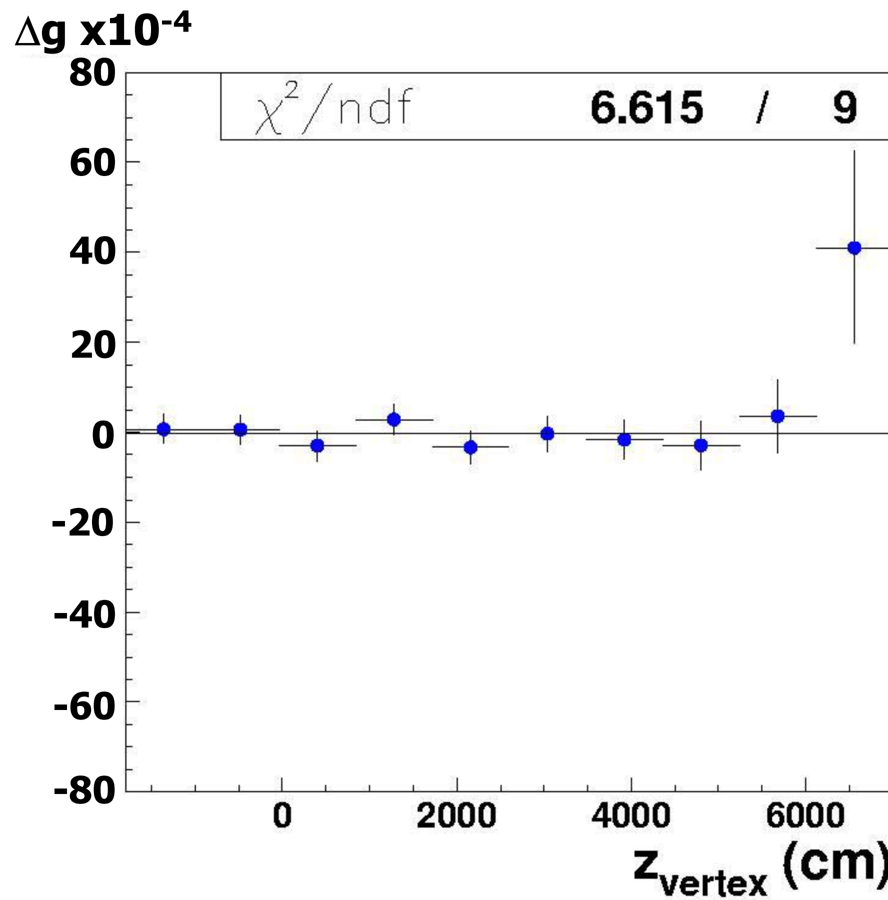
Combined result: $\Delta g \times 10^4$
(3 independent analysis)
L2 trigger systematics included

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



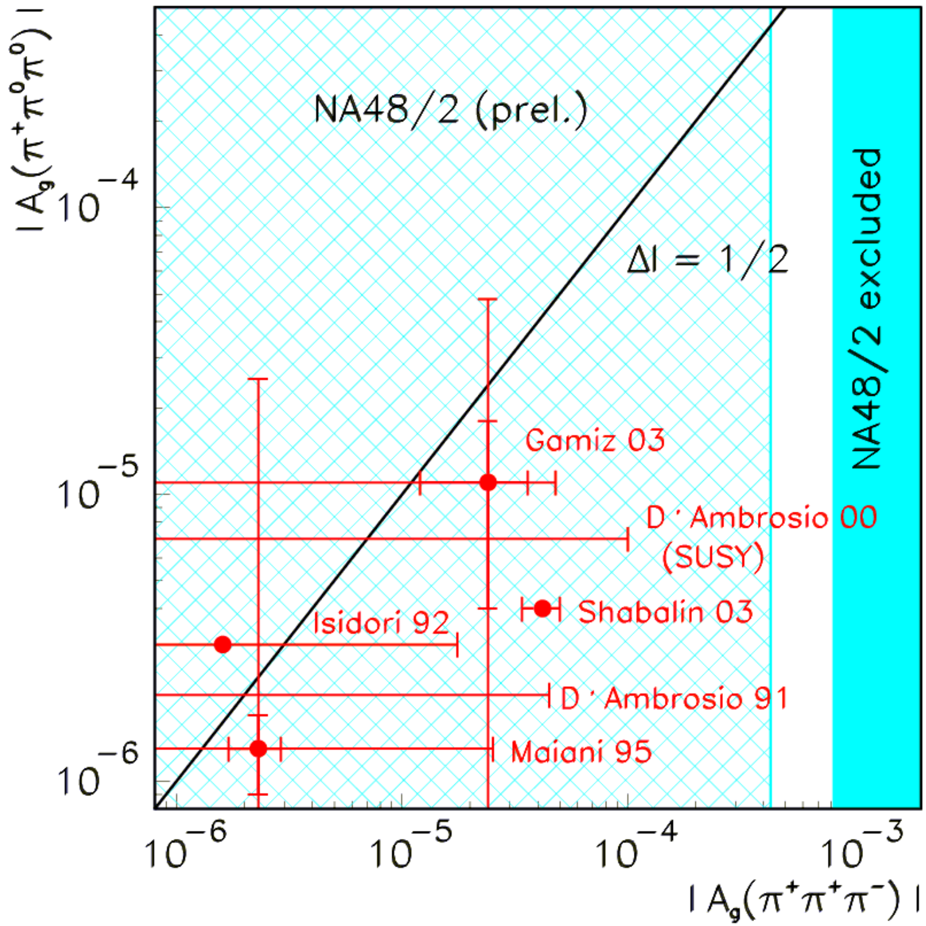


Preliminary result: 2003 data

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

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

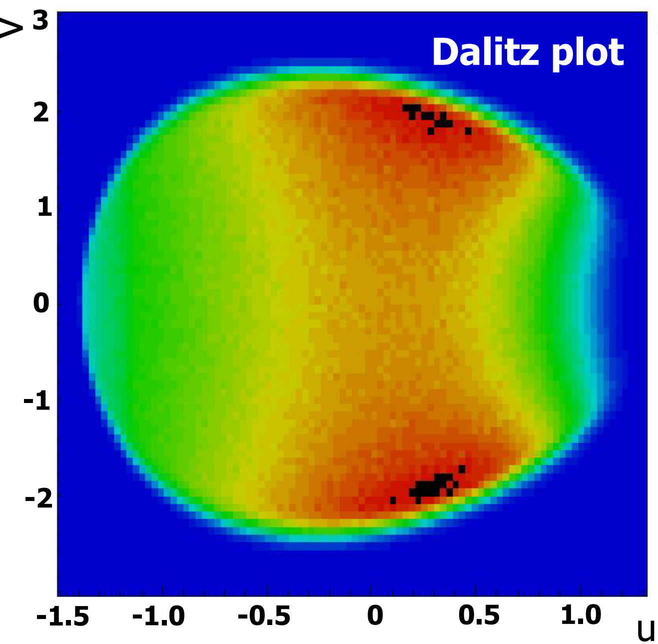
- Conservative systematic errors for preliminary result
- Extrapolated final statistical error (2003+2004): $\delta A_g = 1.6 \times 10^{-4}$
- 2004 data: expect smaller systematic effects (more frequent polarity alternation, better beam steering)

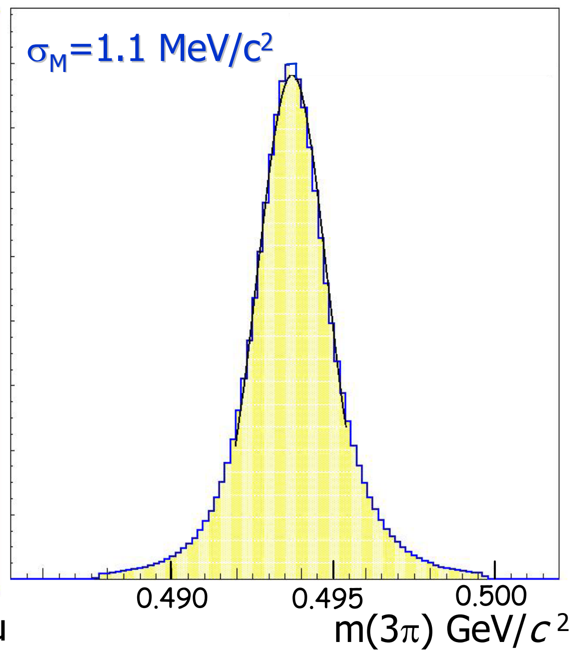


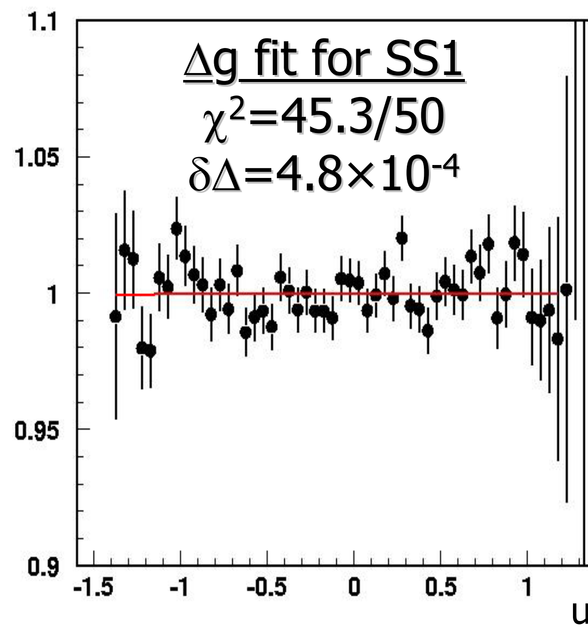
“Neutral” mode asymmetry

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

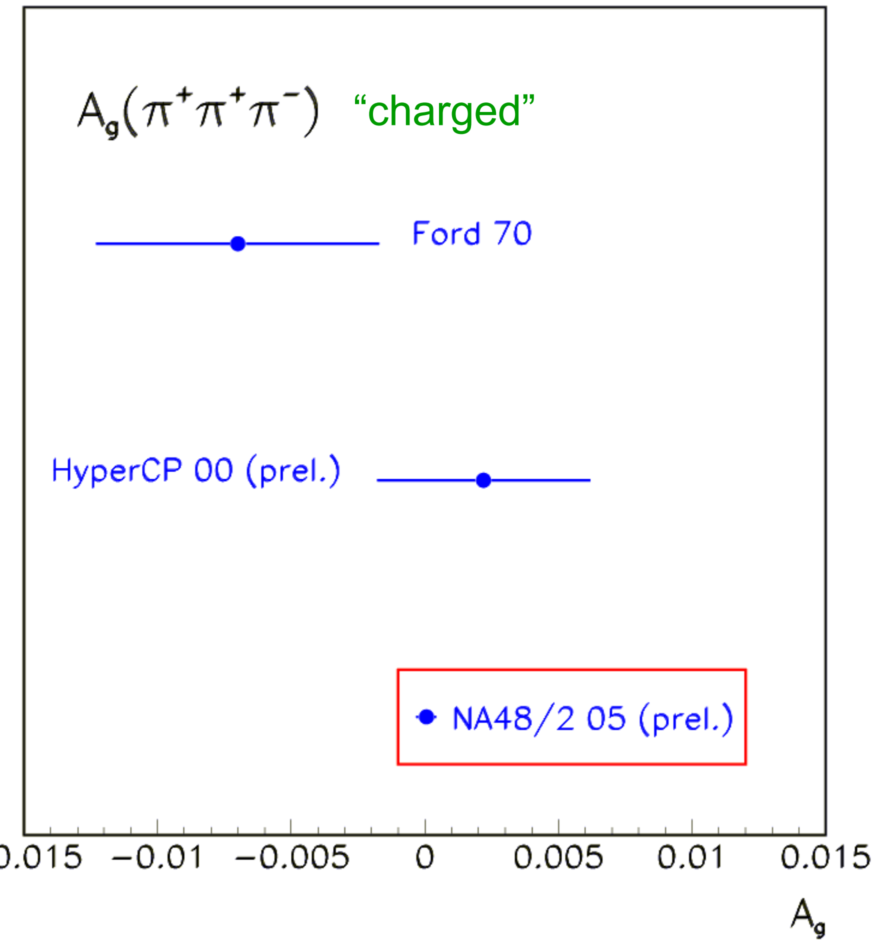
- u can be reconstructed with LKr calorimeter only
- Statistics analyzed: **28 × 10^{6} events** (1 month of 2003)
- Higher statistical power
- Statistical error with analyzed data: $\delta A_{g(stat)}$**= 2.2 × 10^{-4}**
- Extrapolation to 2003+2004 data: $\delta A_{g(stat)}$**= 1.3 × 10^{-4}**
- Possibly larger systematic errors

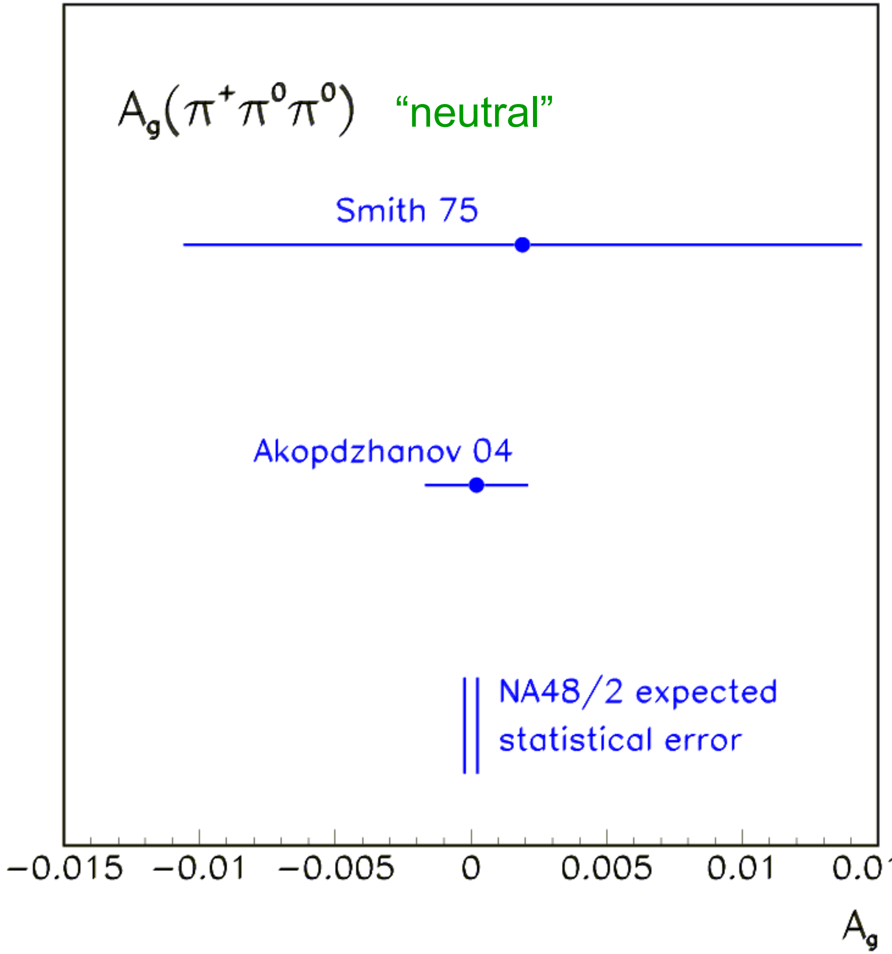






Experiment

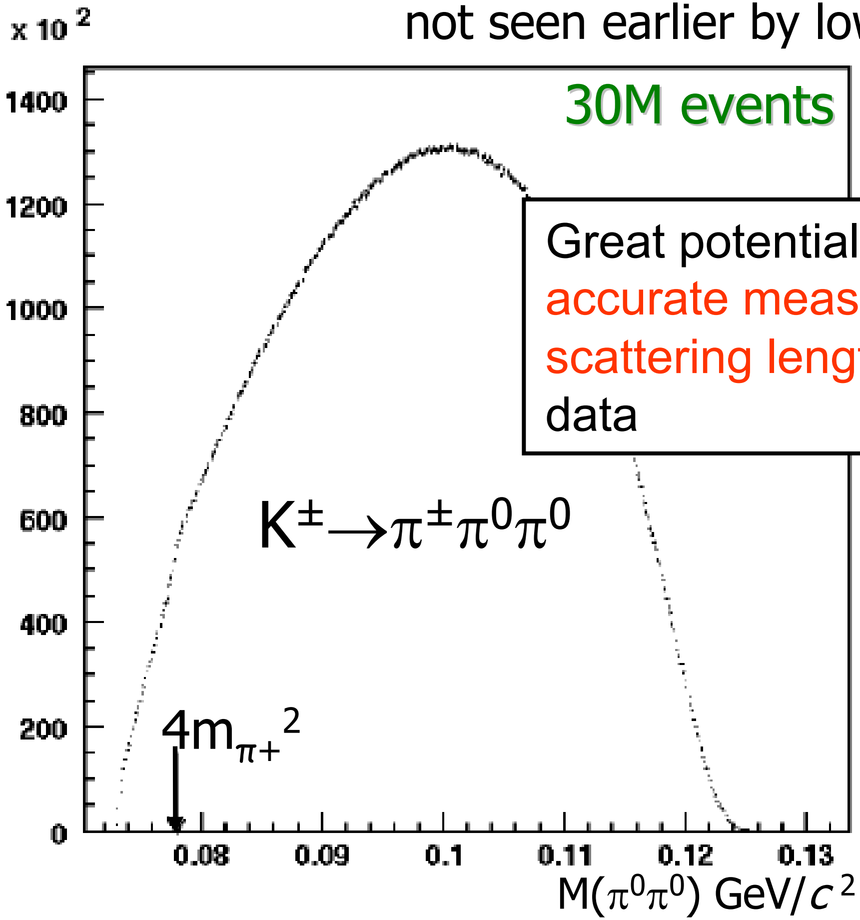




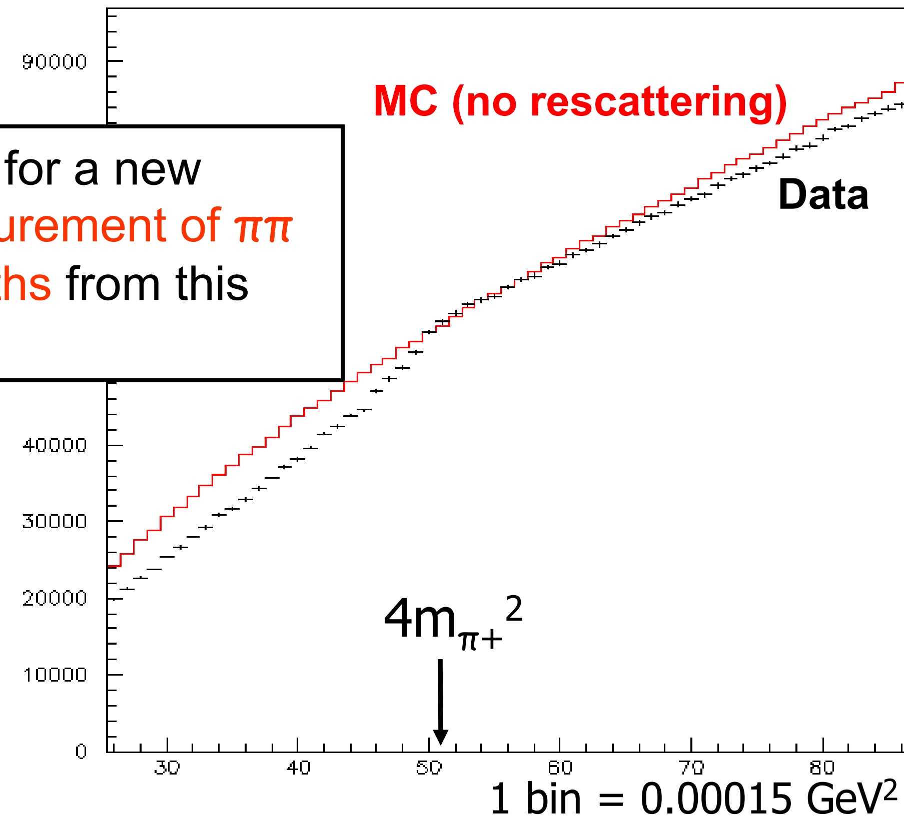
Other experiments will join: KLOE, OKA…

Observation of ππ scattering effect in $K \to 3\pi$ decays

Charge exchange process $\pi^+\pi^- \to \pi^0\pi^0$ not negligible under 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 ππ scattering lengths from this data



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
- *A lot of other physics coming too ($\pi\pi$ scattering lengths, other CP asymmetries, rare decays)*

Thank-you