CP violation in K-->3π @ NA48-CERN

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On behalf of the NA48 experiment:

Cambridge, Cern, Dubna, Edimburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa,Saclay, Siegen, Torino, Warsaw, Wien

Summary

- K--> 3p generalities (kinematics, dynamics)
- CP violating observables
- Theoretical predictions and experimental results
- NA48 brief history and (few) old results
- New K+/K- beams, detector
- Strategy for CP violation
- Most important systematics
- Statistics and statistical error
- A surprise from $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$
- Conclusions

K--> 3π decays

$$s_i = (p_k - p_i)^2 \qquad u = (s_3 - s_0)/M_\pi^2$$

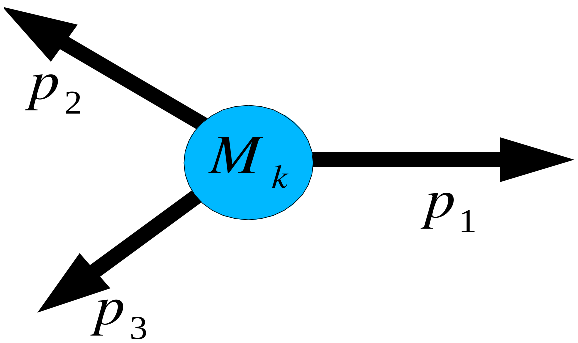
$$s_0 = \frac{1}{3}\sum s_i \qquad v = (s_1 - s_2)/M_\pi^2$$

Two Isospin amplitudes:

ΔI=1/2 dominant, ΔI=3/2

$$|A(K \to 3\pi)|^2 \propto 1 + gu + hu^2 + kv^2$$

Kinematics



$$-1.2 < u < 1.2$$

Dynamics

$$\frac{BR(K^\pm \to \pi^\pm \pi^+ \pi^-)}{BR(K^\pm \to \pi^\pm \pi^0 \pi^0)} = \frac{(5.57 \pm 0.03)}{(1.73 \pm 0.04)}$$

$$\Delta I = \frac{1}{2} \to 4:1 \qquad \Delta I = \frac{3}{2} \to 1:1$$

Mixture with ΔI = ½ dominance

$$\omega = \frac{A_{3/2}}{A_{1/2}} \sim \frac{1}{20}$$

Linear slope g

$$\left|A\left(K \rightarrow 3\pi\right)\right|^2 \propto 1 + g \times u + hu^2 + kv^2$$

Phase space is small --> the expansion in u,v is rapidly convergent

Linear slope g dominates on h,k

$$g^c = g\left(K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}\right) \sim -0.2 \qquad h = O\left(10^{-2}\right)$$

$$g^n = g\left(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}\right) \sim 0.6 \qquad k = O\left(10^{-2}\right)$$

Charged mode is statistically favored but neutral g is 3 times larger

CP VIOLATION IN K--> 3π
Standard Model Predictions

Neglecting (small) quadratic slopes h,k ---> 2 CP violating observables:

2 linear slope asymmetries considering separately K+ and K-

$$A_g^{c,n} = \frac{(g_+ - g_-)}{(g_+ + g_-)}$$

C : charged mode
N: neutral mode

$(2 \sim 4) \times 10^{-4}$ Belkov (1989-1995)

$(2.3 \pm 0.6) \times 10^{-6}$ Maiani (1995)

$\sim 10^{-5}$ Scimemi (2003)

$$A_g^c = A_g^n [1 + O(\omega)] \qquad \omega = \frac{A_{3/2}}{A_{1/2}} \sim \frac{1}{20}$$

CP VIOLATION IN K--> 3π
experimental results

BNL (1970):

$$A_g^c = (-7.0 \pm 5.3)10^{-3}$$

Statistics: 3.2M K+-

HyperCP (E731) at FNAL :

$$A_g^c = (2.2 \pm 1.5 \pm 3.7)10^{-3}$$

Statistics: 390M K+ and 1.6M K- (10% only used)

Important systematic due to the knowledge of magnetic fields

(Choong W-S., PhD *Thesis* LBNL-47014, *Berkeley*, 2000)

ISTRA+ at Protvino:

$$A_g^c = (-0.3 \pm 2.5)10^{-3}$$

Statistics: 0.5M K+- (50% only used)

(Denisov S.P., *talk at Frontier Science 2002, Frascati , October 2002*)

Na48 history

1997
Kl + Ks
ε'/ε run
0.5M $K_L \to \pi^0 \pi^0$

1998
Kl + Ks
ε'/ε run
1.0M $K_L \to \pi^0 \pi^0$

1999
Kl + Ks
ε'/ε run
2.0M $K_L \to \pi^0 \pi^0$

Kl
K_{e3}
K_{μ}

Ks
HI
test

2000
No DCH (implosion nov. 99)
Neutral reconstruction checks
$K_l, \eta \to 3\pi^0$

Ks
HI

2001
Kl + Ks
ε'/ε run
1.5M $K_L \to \pi^0 \pi^0$

2002
Ks High intensity

2003
K+ K- new beam line
Kabes, beam monitor

2004
K+ K-
Running

Some results (not exhaustive list)

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

$$BR(Ks \to \pi^0 e\, e) = (5.8^{+2.8}_{-2.3} \pm 0.8)10^{-9}$$

$$BR(Ks \to \pi^0 \mu\, \mu) = (2.9^{+1.4}_{-1.2} \pm 0.2)10^{-9}$$ *

*So far the two smallest branching ratios ever measured at CERN-SPS

$$BR(K_S \to \gamma\, \gamma) = (2.78 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.02_{norm})10^{-6}$$

...and many other test of CHPT, rare decays, hyperons decay, etc...

$$M_\eta = (547.843 \pm 0.030_{stat} \pm 0.041_{syst} \pm 0.005_{MC})\, MeV/c^2$$

Very proud of our Liquid Krypton calorimeter !!!

NA48: K+ K- beam optics

SPS 400 GeV primary intensity 10^{12} protons per pulse beam
Simultaneous collinear unseparated focused K+ K- beams 60 ± 3 GeV
enter the fiducial decay volume every 16.8 sec.

$\sim 5\times10^{5}$ K per pulse

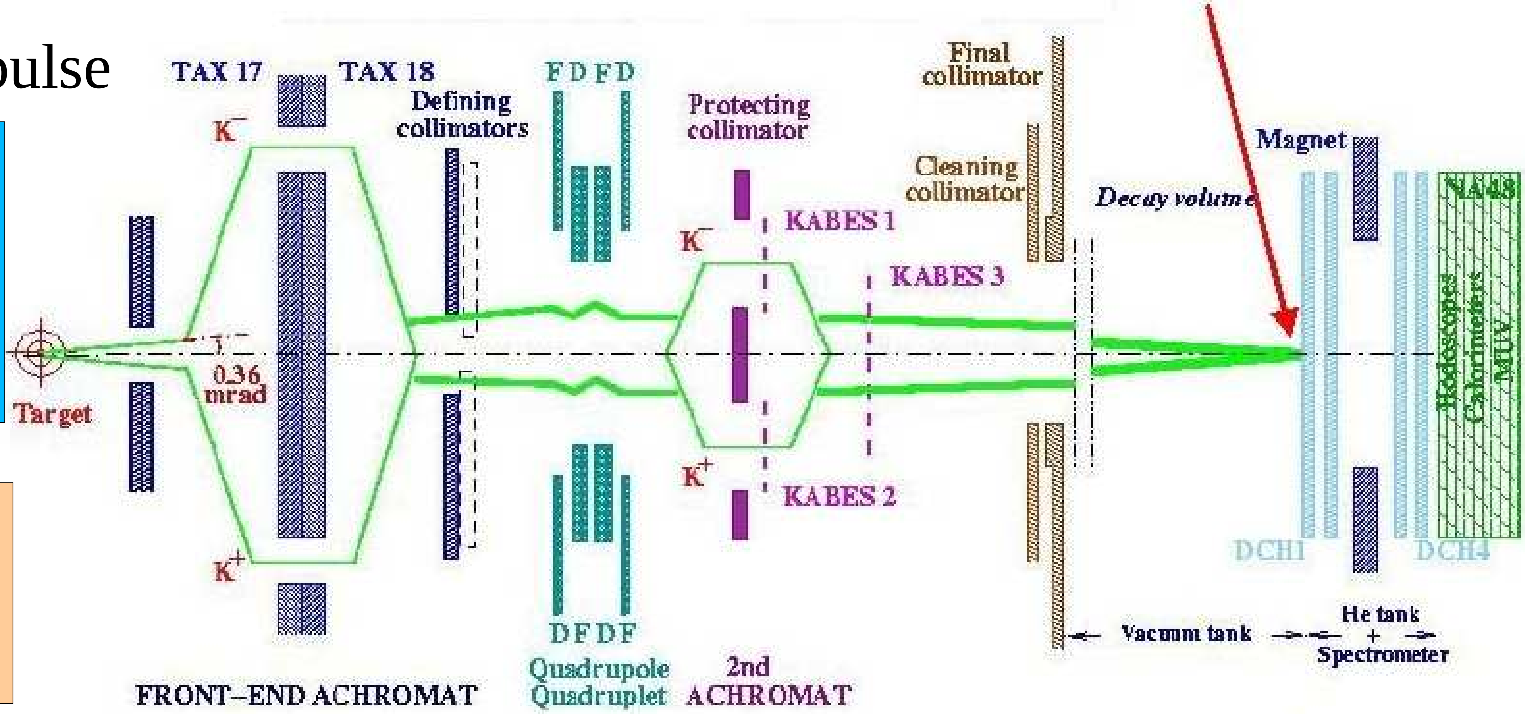
$$\frac{N(K^+)}{N(K^-)} \sim 1.8$$

Asymmetry in strong production in the target

1% Ek resolution by Kabes

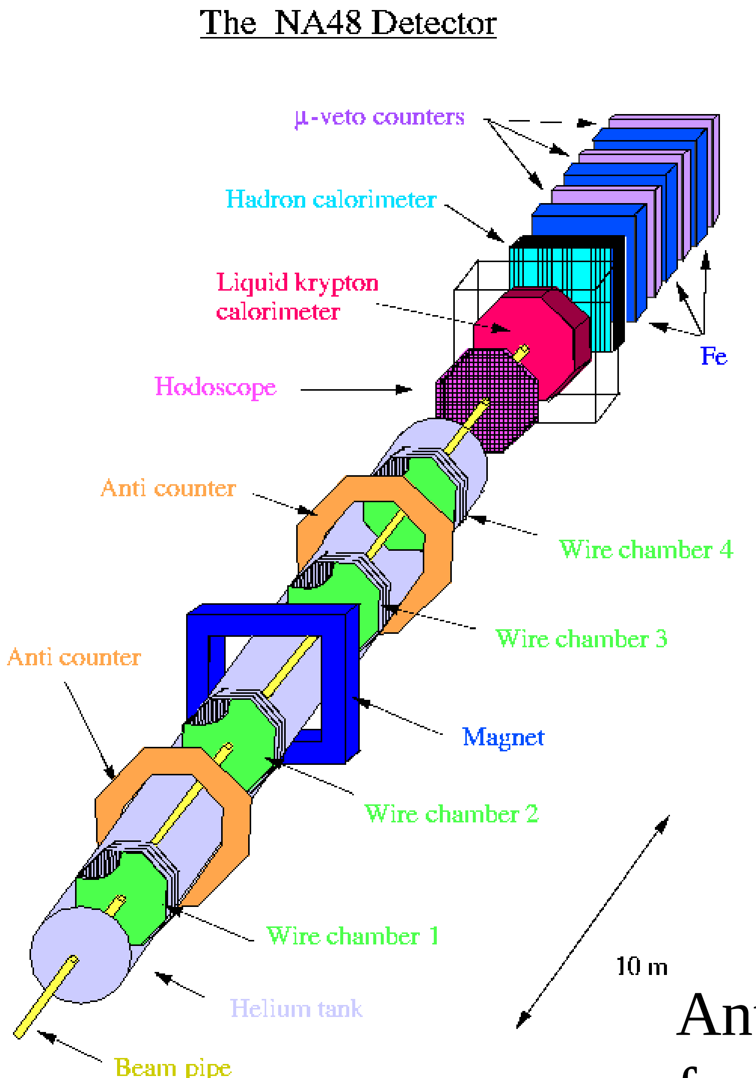
$K \to \pi\,\pi\,e\,\nu$

axes are steered to coincide within ≤ 1 mm



not to scale

NA48: DETECTOR



Lkr calorimeter: γ detection

$$1.5 < E < 100 \quad \text{GeV}$$

$$\frac{\sigma(E)}{E} = \frac{0.090}{E} \oplus \frac{0.032}{\sqrt{E}} \oplus 0.0042$$

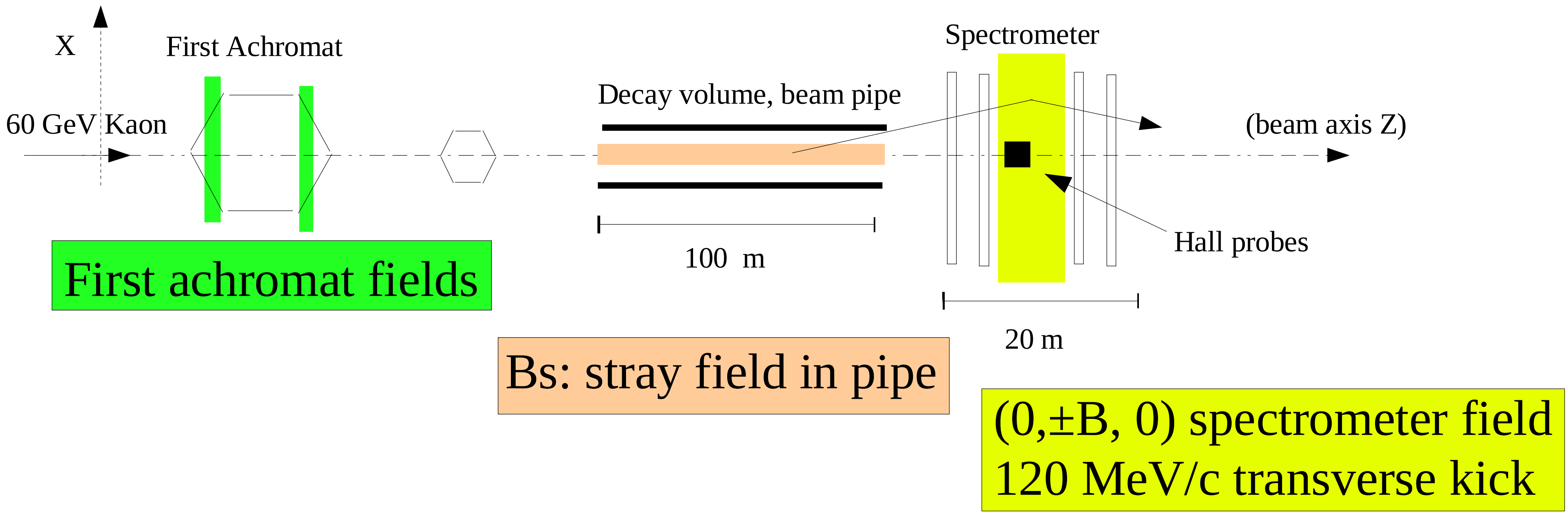
4 drift chambers + magnet dipole

π tracking and momentum measurement

$$\frac{\sigma(p)}{p} = 0.005 \oplus 0.009 \times p$$

Anti counter, hodoscope, HAC and μ-veto used for on line triggering and particle ID

Which magnetic fields are present?



- B is monitored by measuring the current in the dipole, several Hall probes are also used for redundancy
- Bs has been measured in spring 2003

NA48: strategy for Ag

Data taken with all the 4 combinations of achromat and spectrometer magnetic field B orientation. Dipole reversed every day, Achromat each week

$$|A(K \to 3\pi)|^2 \propto 1 + gu + hu^2 + kv^2 \qquad u = \frac{2M_k}{m_\pi^2} \times (\frac{M_K}{3} - E_\pi^{odd})$$

CP violation would appear as a linear slope
in the K+/K- u distribution ratio

$$\frac{P(u, K^+, B_{up})}{P(u, K^-, B_{down})} = N \frac{1 + g_+ u}{1 + g_- u} \sim N(1 + 2g_+ A_g u)$$

Small h, k
are neglected
$gu \ll 1$

2 independent measurements if up <--> down swapped
The final Ag obtained by averaging the 2 results

BASIC PRICIPLE OF THE MEASUREMENT:

"Since (K+, B=UP/DOWN) *and* (K-,B=DOWN/UP) *illuminate detector in the same way, acceptance effects cancel out in the crossed ratio"*

Deviations from the first principle

Non perfect symmetry of the detector is dangerous if coupled with the following effects and may create a fake CP violation signal

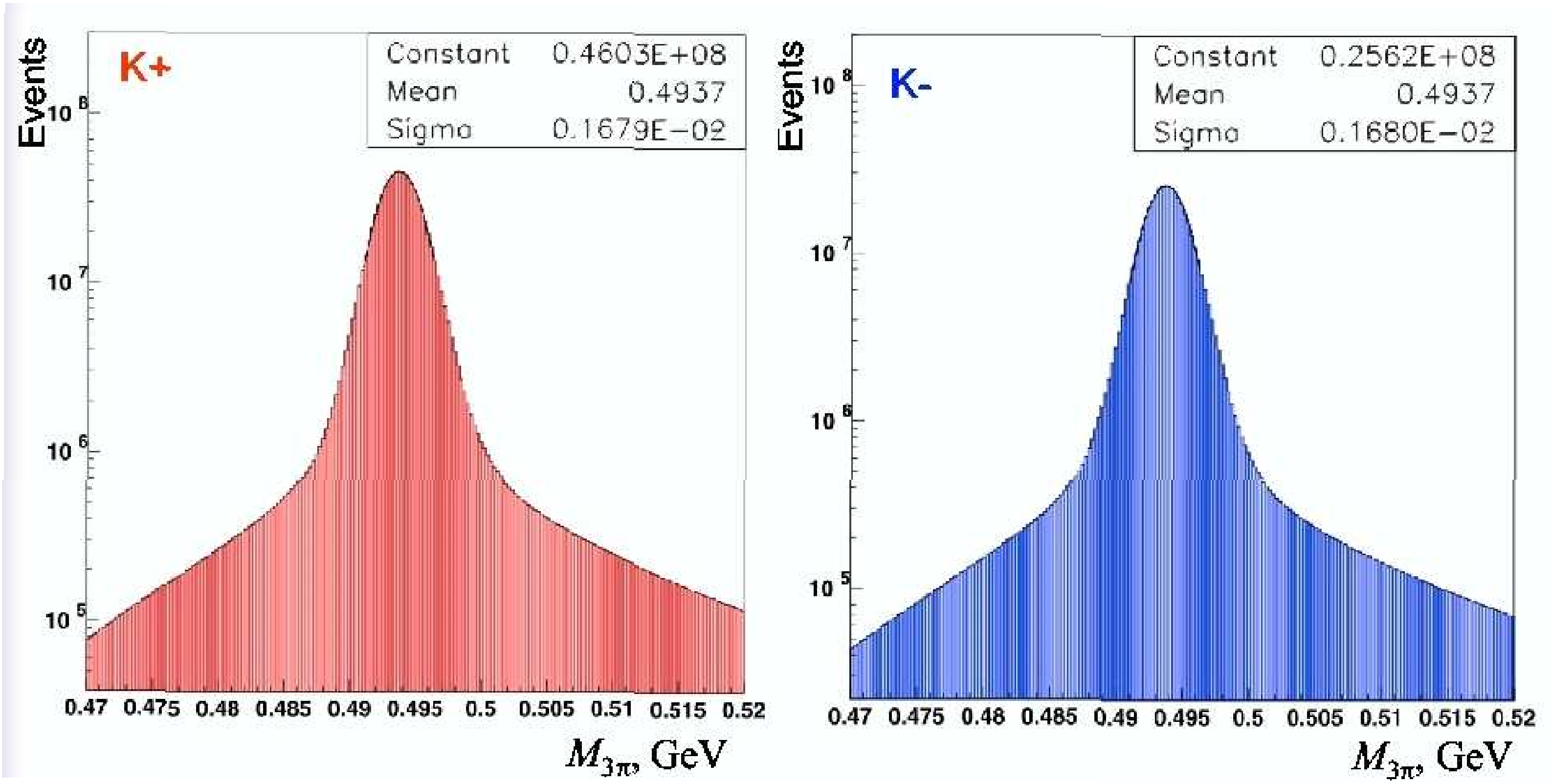
1) $B_{up} \neq B_{down}$ Non perfect inversion with respect nominal value assumed in the reconstruction

2) Presence of stray magnetic fields: earth field or residual magnetisation of the beam iron pipe along the decay region.
(Iron everywhere. Bad experience with Carbon Fiber !!!)

3) Non perfect coaxiality of the K+ K- beams

4) Since UP/DOWN orientations are realized at different time, any time instability of the detector and of trigger efficiency may be dangerous

NA48: KAON mass spectrum



$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ Reconstructed Kaon mass Resolution 1.7 MeV

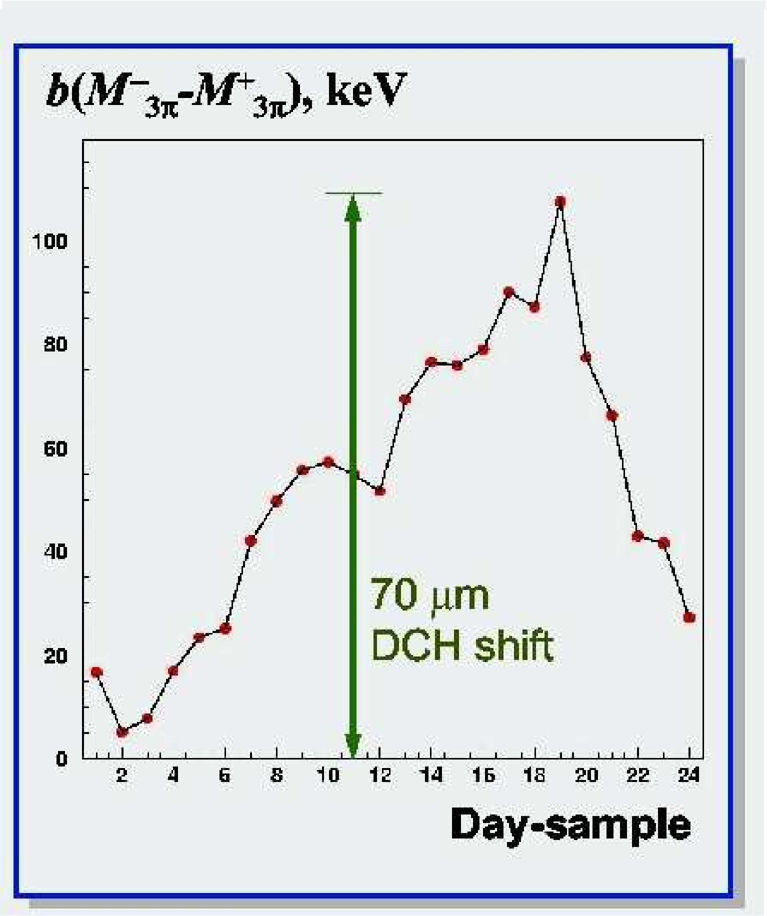
Good tool to calibrate and to monitor the small instabilities of the spectrometer.

Spectrometer corrections

Apply α and β corrections

$P = p(1+\alpha)(1+\beta qbp)$

P – real track momentum
p – observed track momentum
q – charge of the track
b – sign of magnetic field B

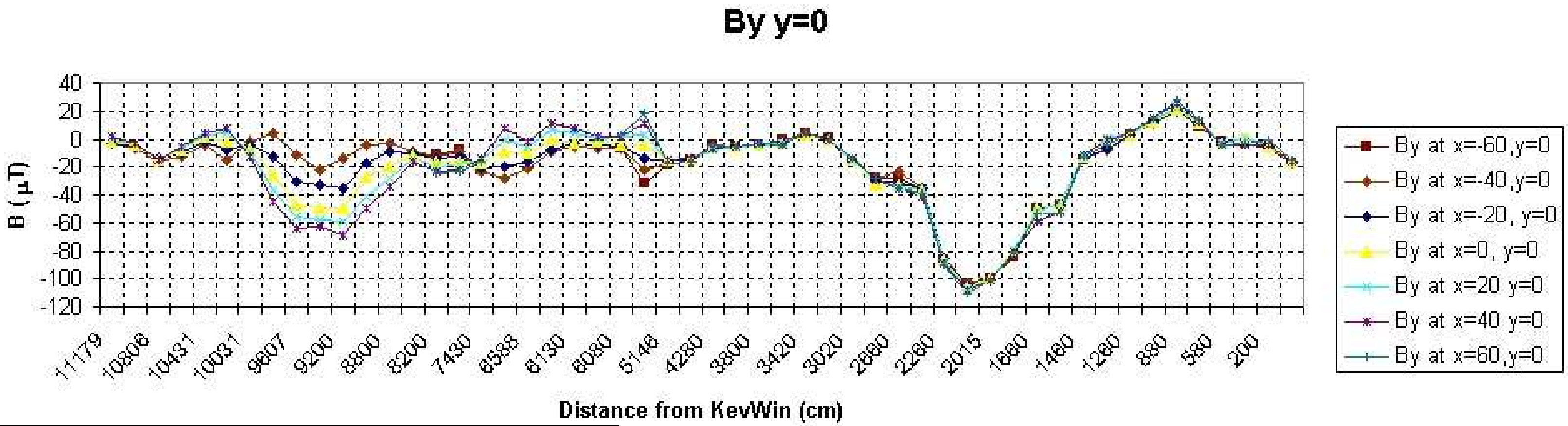


$\alpha \rightarrow$ Correct for DCH misalignment by putting to zero $M^{+}_{3\pi} - M^{-}_{3\pi}$

$\beta \rightarrow$ Corrects for magnetic field by putting the observed Kaon mass at the PDG value

Stray magnetic fields

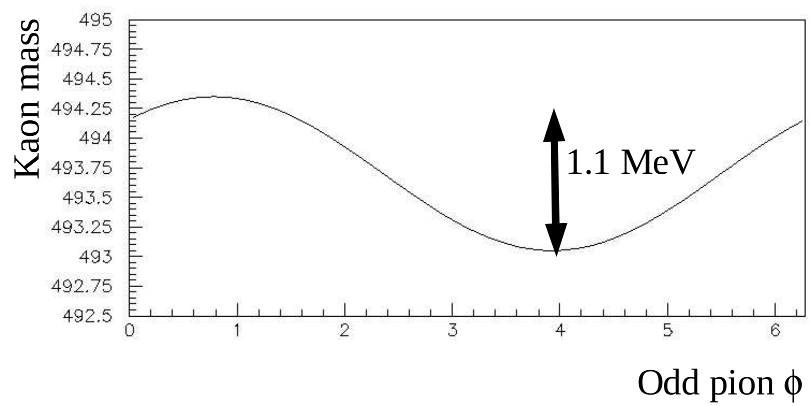
Several measurements of magnetic field Bs along the decay volume
A map of the field is plugged in the reconstruction program.



$$\frac{p_{kick}(stray\ field)}{p_{kick}(spectrometer)} \sim 10^{-4}$$

Quality of the correction checked looking at Mk VS odd pion ϕ

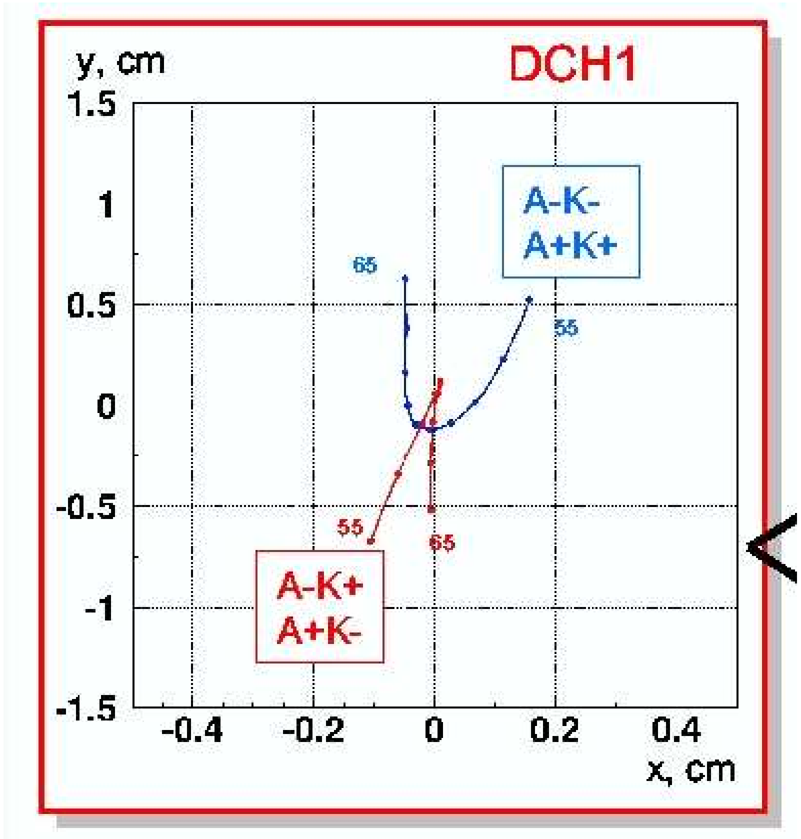
90% of the effect recovered



ΔM = 1.1 MeV compared with σ = 1.7 MeV resolution

Systematic on Ag on study ($< 10^{-5}$ expected)

K+/K- coaxiality



A radial cut necessary because at
R< 10 cm the spectrometer is insensitive

At a given Z position, the center of the circular cut is set at the barycenter (cog) of the positive (negative) Kaon beam as seen by the detector.

$$x_{cog} \equiv \frac{\sum_{i=1}^{3} x_i \times p_i}{\sum_{i=1}^{3} p_i}$$

X= pion transverse coordinate
p = pion momentum

(similar for Y)

Dynamical and charge dependent center --> symmetric K+/K- acceptances

- The achromat orientation is changed every week
- Analysis done in 10 Kaon momentum beam, 1 GeV each

Statistics and statistical error

- In 2003 we had 50 effective days of data taking
- A 30 days subset has been processed (calibration, alignment,etc..)
- People are mainly concentrated on $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ (charged mode)

Stat. (millions of events)	
$K^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$	720
$K^{-} \rightarrow \pi^{-}\pi^{+}\pi^{-}$	400
$K^{+} \rightarrow \pi^{+}\pi^{0}\pi^{0}$	36
$K^{-} \rightarrow \pi^{-}\pi^{0}\pi^{0}$	13

$$\sigma(A_g) = \frac{F}{\sqrt{N}} \times \frac{1+r}{\sqrt{r}}$$

$$\sigma(A_g^c) = 2.7 \times 10^{-4}$$

$$\sigma(A_g^n) = 6.5 \times 10^{-4}$$

N = N(K+) + N(K-)

r = N(K+)/N(K-) = 1.8

F(charged) = 3.8 (from data)

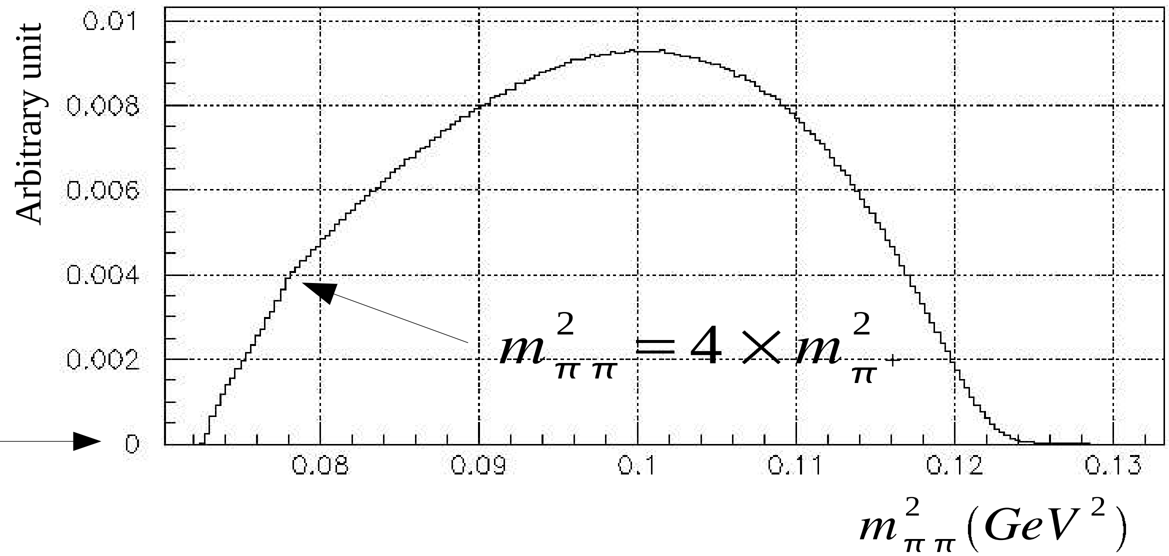
F(neutral) = 0.7 (from Montecarlo)

F(neutral) is favored because

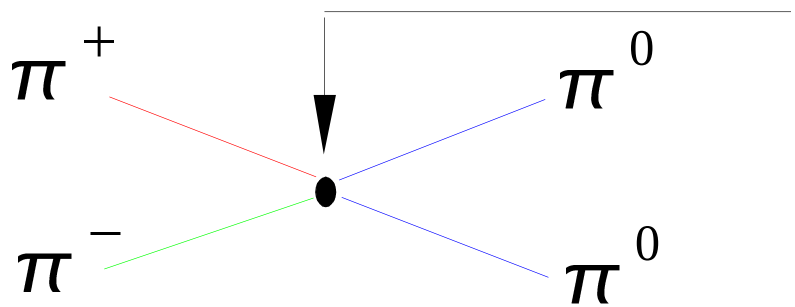
- Neutral g is larger
- Phase space is (not so much) bigger
- Larger range for u

A surprise from ππ (neutral)

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



Under the threshold, the charge exchange process is not negligible and interferes (destructively) with the direct emission. (N. Cabibbo's idea)



Coupling constant:
Pion scattering length
CHPT prediction:

$$(a_0 - a_2) m_\pi = (0.265 \pm 0.004)$$

What is going on: 2004 run

- 2004 is our last run. Next year SPS shutdown for LHC
- So far, analysis does not show large systematics errors
- People are mainly concentrated on the analysis of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ but interest for the neutral channel is growing
- K--> 3π program will continue
- A more frequent alternation of achromat and spectrometer dipole is desirable to dilute possible time instabilities.
- 60 days of data taking are scheduled
- A doubling of statistics is expected

- Other analysis in progress: Ke2, Ke3, Ke4

CONCLUSIONS

- At the end of the story we will produce a result on Ag with an accuracy of 10^-4 (statistically dominated)
- If theoretical predictions are correct, we will not see the S.M.

BUT

The new world average of $\Re(\epsilon'/\epsilon) = (16.7 \pm 2.3) \times 10^{-4}$ *is higher than the predictions of most theoretical evaluations and can be considered to be in disagreement with the Standard Model or at least to indicate significant problems in the calculation of non perturbative parameters of decay matrix element.*