Recent results from NA48/2 on Ke4 and $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays
Interpretation in terms of $\pi\,\pi$ scattering lengths

Brigitte Bloch-Devaux

CEA Saclay, DAPNIA-SPP

XLIInd Rencontres de Moriond

(QCD AND High Energy Hadronic Interactions)

La Thuile, 17-24 March 2007

On behalf of the NA48/2 collaboration:

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

Outline

- The NA48/2 experiment : an introduction
  beams, detector and performances

- Ke4 decays in charged ($K^{\pm} \to e^{\pm} \nu \pi^{+}\pi^{-}$) and neutral ($K^{\pm} \to e^{\pm} \nu \pi^{0}\pi^{0}$) : modes : variables and Form Factors

- Ke4 results : Form Factors and phase shift in charged decays
  Form Factor and Branching fraction in neutral mode

- K3pi neutral decays ($K^{\pm} \to \pi^{\pm} \pi^{0}\pi^{0}$) : the "cusp" effect and Form Factors in the Dalitz plot

- Interpretation in terms of $\pi\pi$ scattering lengths

- Conclusion and prospects

The NA48/2 experiment: an introduction

The primary goals :

Search for CP-violating charge asymmetries (K^+ K^-) in $K^\pm \rightarrow 3\pi$ decays

Two measurements : "charged" $\pi^\pm \pi^+\pi^-$ and "neutral" $\pi^\pm \pi^0\pi^0$ asymmetries both modes with large BR's of (2-5) 10^{-2}

(presented by M.Raggi in last week EW session)

but also

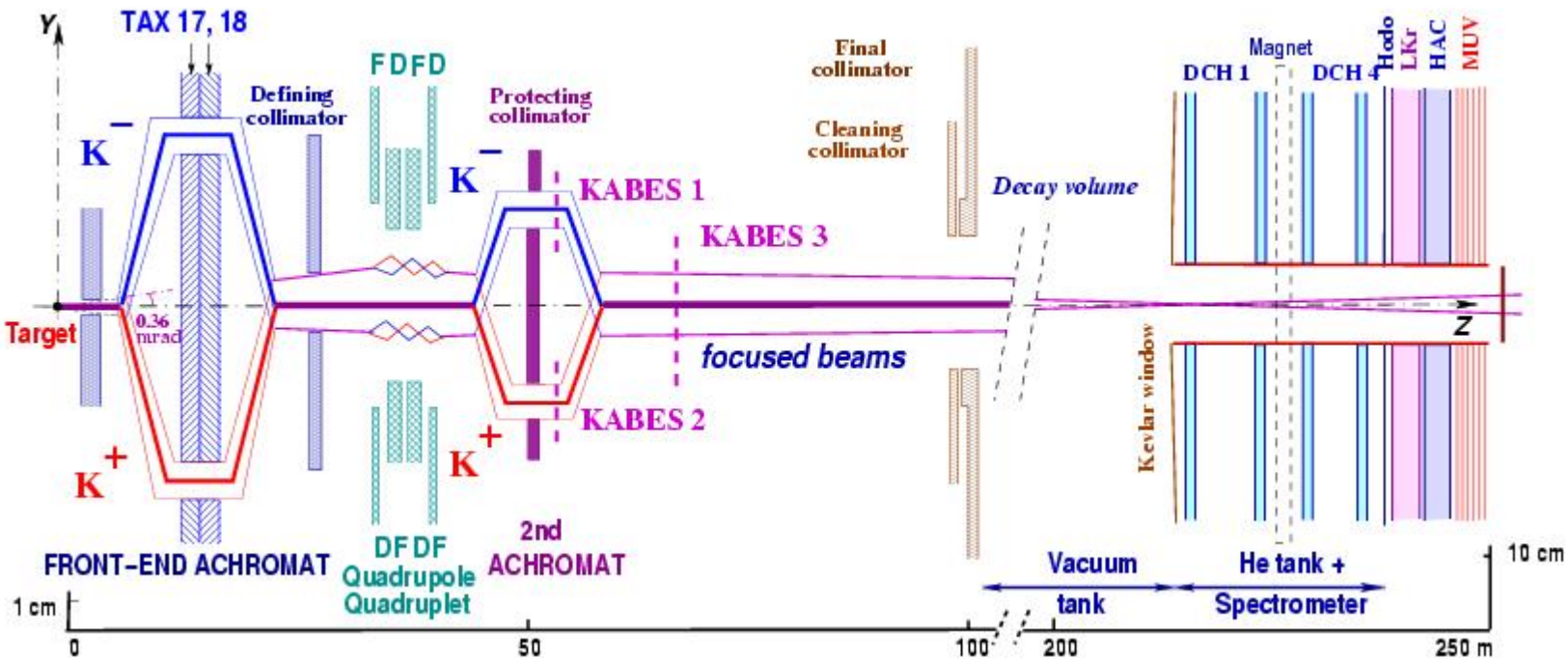
Study of many rare decays , in particular Ke4 in the "charged" $\pi^+\pi^-e^\pm\nu$ (and "neutral" $\pi^0\pi^0e^\pm\nu$) final state, both modes with small BR's of few 10^{-5} .

In the $\pi\pi$ scattering process, it is possible to relate amplitudes with different Isospin using dispersion relations (Roy equations) which depend essentially on two parameters, the scattering lengths a_0^0 and a_0^2

Chiral PT predictions for low energy $\pi\pi$ interaction introduce further constrains between a_0^0 and a_0^2 which are related to the size of the quark condensate.

The NA48/2 experiment: beams and detector

Simultaneous K^+/K^- beams : (60 ± 3) GeV/c

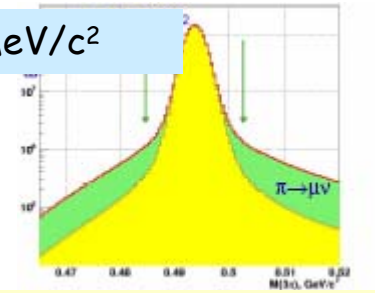


2003 Run ~50 days

2004 Run ~60 days

The NA48/2 experiment: detector performances

$\sigma = 1.7$ MeV/c^2



$(\pi^{\pm}\,\pi^{+}\pi^{-})$ mass GeV/c^2

Most important components for Ke4/K3pi analysis :

Magnetic spectrometer : 4 high-resolution DCH's

$\Delta p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)

→ Very good resolution for charged invariant masses (Kaon)

LKr electromagnetic calorimeter : quasi-homogenous and high granularity

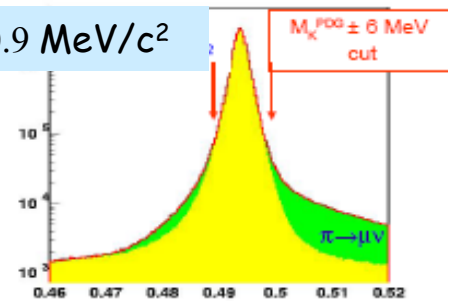
$\Delta E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)

$\sigma_x = \sigma_y \sim 1.5$ mm for E=10 GeV

→ Very good resolution for neutral invariant masses (π^0)

→ E/p ratio for e/π discrimination

$\sigma = 0.9$ MeV/c^2



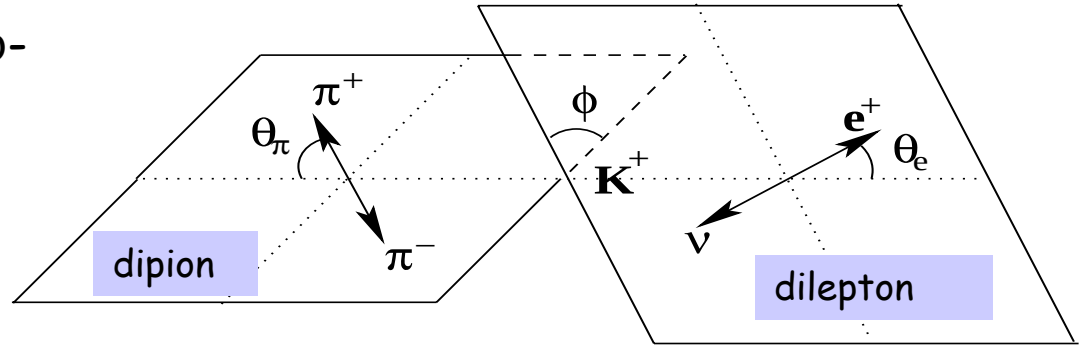
$(\pi^{\pm}\,\pi^{0}\pi^{0})$ mass GeV/c^2

Ke4 charged decays : formalism

Five kinematic variables (Cabibbo-Maksymowicz):

$S_\pi\ (M^2_{\pi\pi})$, $S_e\ (M^2_{e\nu})$,

$\cos\theta_\pi$, $\cos\theta_e$ and ϕ.



partial wave expansion of the amplitude:

F, G = Axial Form Factors

$F = F_s\, e^{i\delta s} + F_p\, e^{i\delta p} \cos\theta_\pi$ + d-wave term...

$G = G_p\, e^{i\delta g}$ + d-wave term...

H = Vector Form Factor

$H = H_p\, e^{i\delta h}$ + d-wave term...

expansion in powers of q^2 , Se

($q^2 = (S_\pi/4m_\pi^2 - 1)$)

$$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e\left(S_e/4m_\pi^2\right) + ..$$

$$F_p = f_p + f_p' q^2 + ..$$

$$G_p = g_p + g_p' q^2 + ..$$

$$H_p = h_p + h_p' q^2 + ..$$

The fit parameters are : F_s F_p G_p H_p and $\delta = \delta_s - \delta_p$

Ke4 decays: event selection and background rejection

Signal ($\pi^+\pi^-e^\pm\nu$) Topology : 3 charged tracks , two opposite sign pions, 1 electron (LKr info E/p), some missing energy and p_T (neutrino)

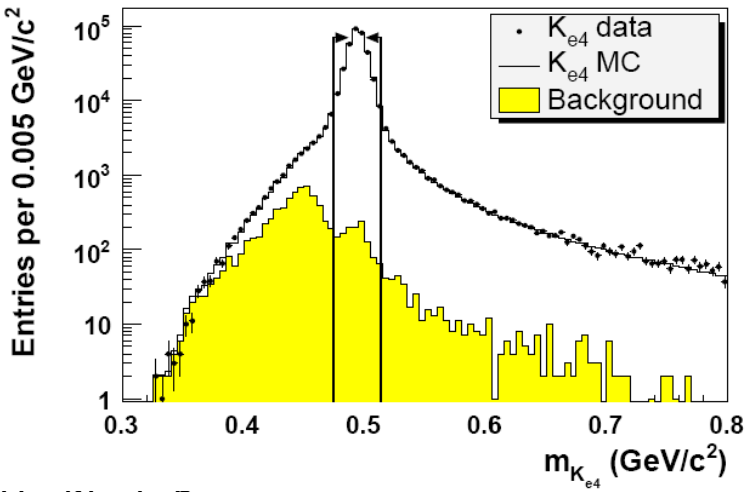
Background : main sources

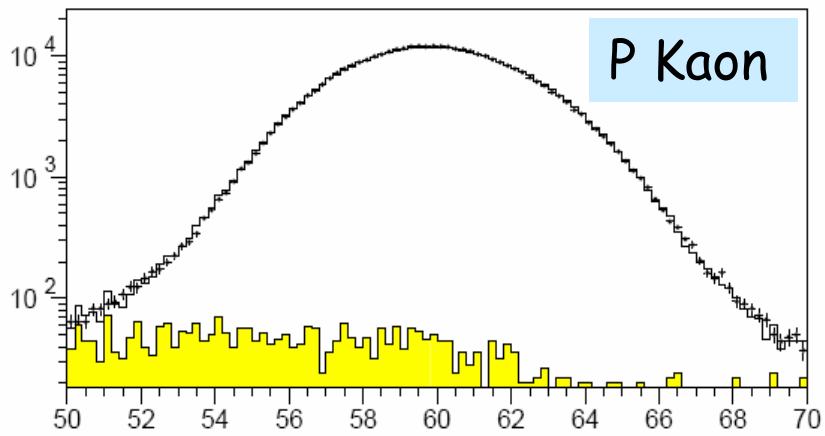
$\pi^\pm\ \pi^+\ \pi^-$ decay + $\pi \rightarrow e\ \nu$ decay (dominant) or + π misidentified as e

$\pi^\pm\ \pi^0(\pi^0)$ decay + π^0 Dalitz decay ($e^+e^-\gamma$) + e misidentified as π and γ (s) undetected

Control from data sample : Wrong Sign events have the same total charge but e^- and $\pi^+\ \pi^+$ for K^+ decays (e+ and $\pi^-\ \pi^-$ for K^- decays). Depending on the process, background events appear in Right Sign events with the same rate or twice the rate of the WS events

Total background level can be kept at ~ 0.5 % relative level





Ke4 charged decays : Form Factor determination

Using iso-populated bins in the 5-dimension space of the C.M. variables, ($M_{\pi\pi}$, $M_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$ and ϕ) one defines a grid of

10x5x5x5x12=15000 boxes.

The set of Form Factor values is used to minimize a log-likelihood estimator well suited for small numbers of data events/bin and taking into account the statistics of the simulation (simulated and expected events/bin).

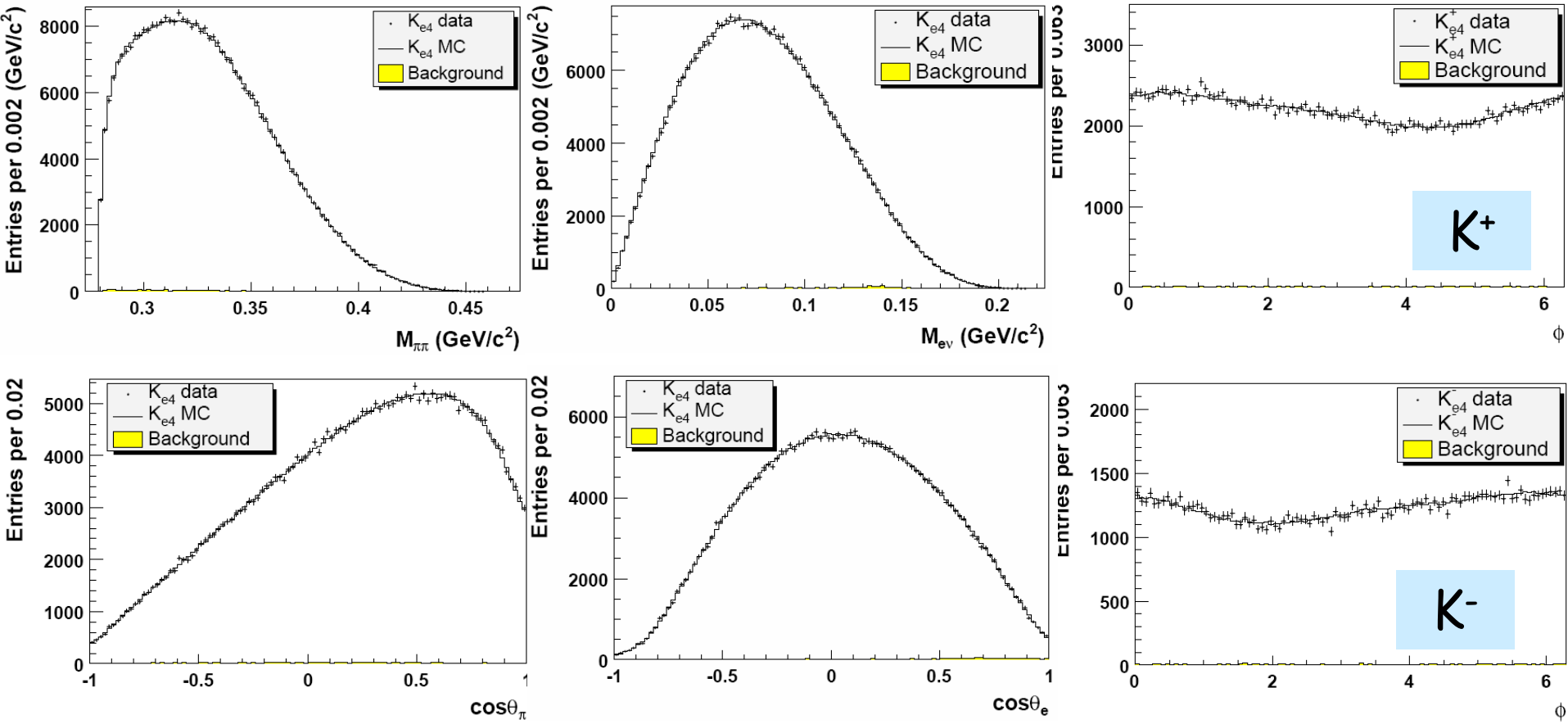
K^+ sample (235000 events)	16 events/box
K^- sample (135000 events)	9 events/box
MC K+ sample (5.5 Millions events)	~370 events/box
MC K- sample (3.0 Millions events)	~200 events/box

Ratio K+/K- ~ 1.8 both in Data and MC (run by run basis)
Ratio MC/Data ~ 23. both for K+ and K- (run by run basis)

Ke4 charged decays : the 5 distributions

CP symmetry : $(K^+)\ \phi$ distribution is opposite of $(K^-)\ \phi$ distribution

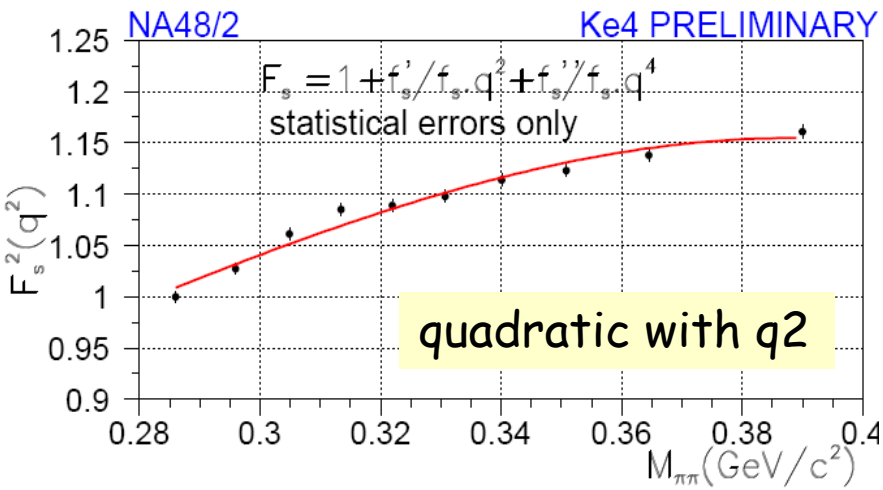
K^+ and K^- samples fitted separately, results combined

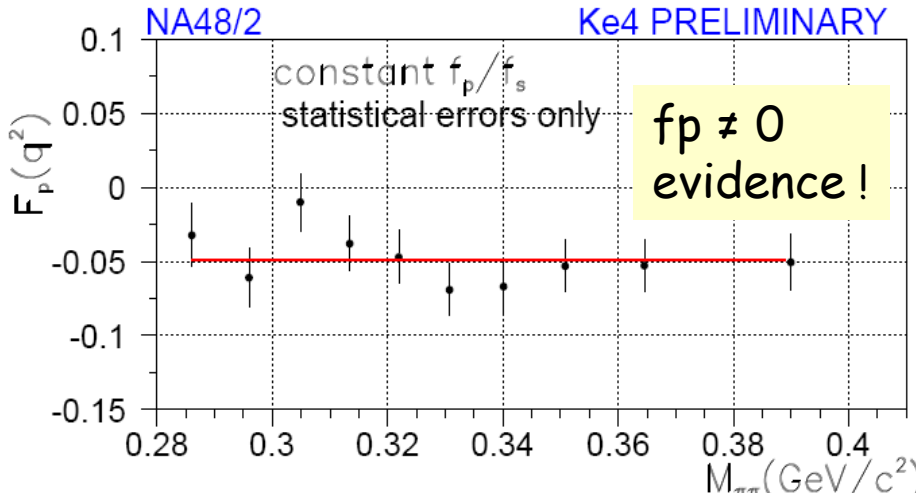


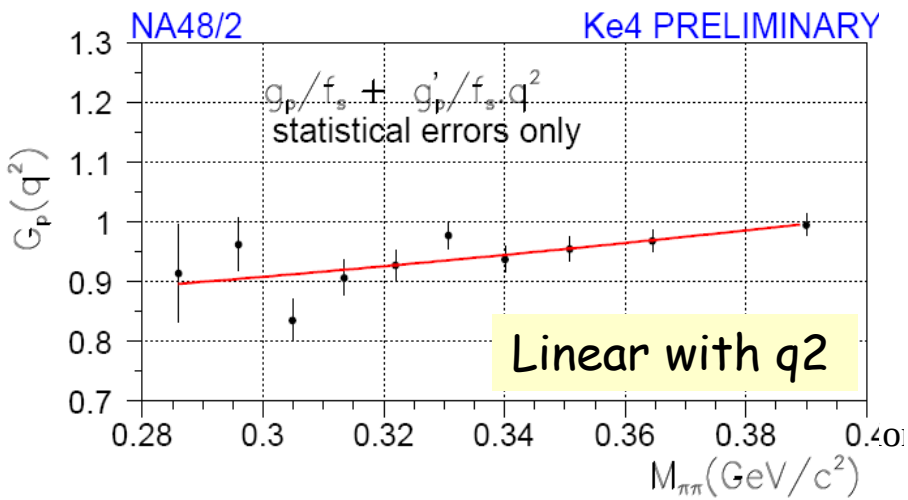
Ke4 charged decays : F,G,H form factors

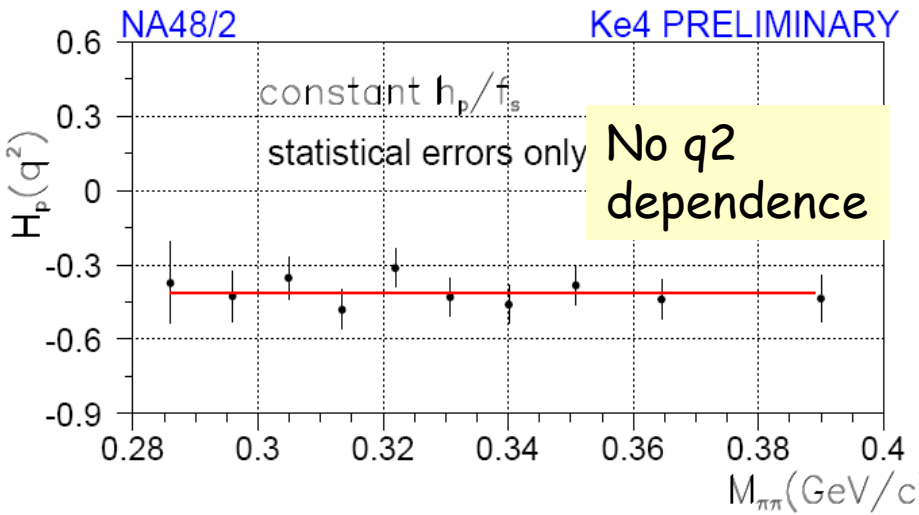
Ten independent fits, one in each $M_{\pi\pi}$ bin, assuming ~constant form factors over each box. This allows a model independent analysis.

Without the overall normalization (Branching fraction), one can quote relative form factors and their variations with q^2,q^4 ($q^2 = (S_\pi/4m_\pi^2 - 1)$)



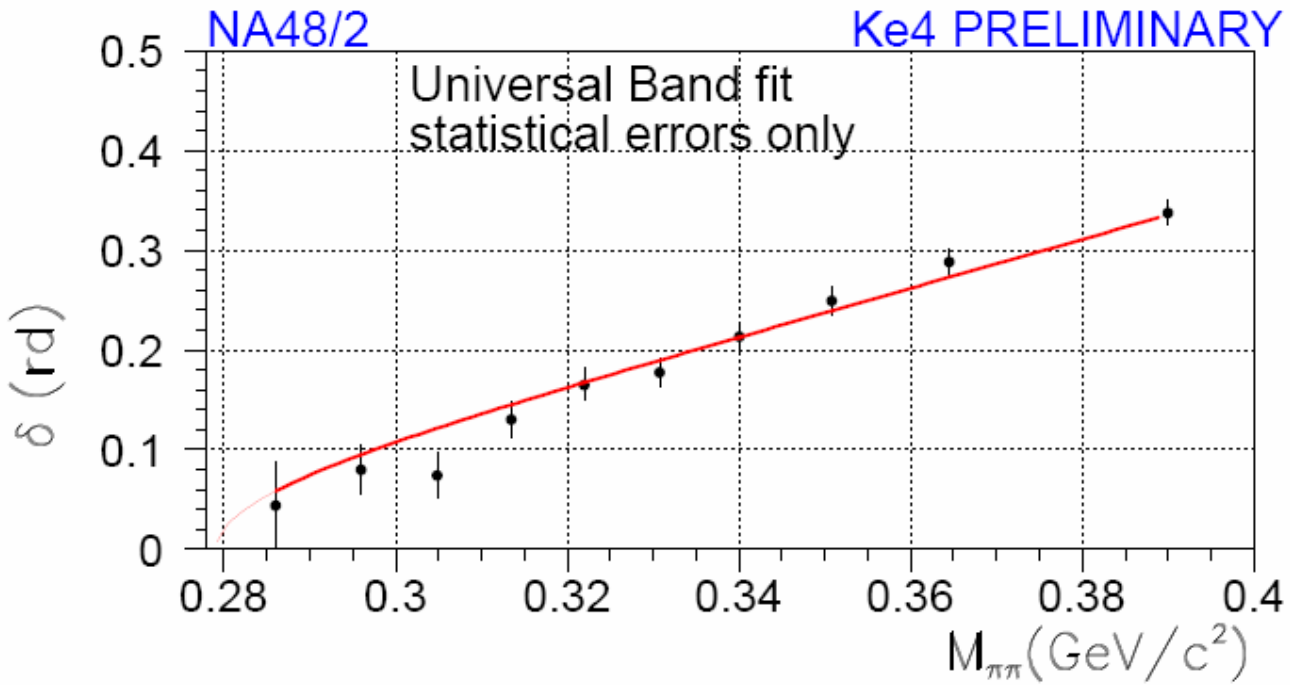






Ke4 charged decays : δ form factor and a_0^0

To extract information from the $\delta = (\delta_0^0 - \delta_1^1)$ variation, some external data (I=2 $\pi\pi$ data @Higher energy) and theoretical work are needed : the numerical solution of Roy equations (*ACGL Phys. Rep.353 (2001), DFGS EPJ C24 (2002)*) relates δ and (a_0^0 , a_0^2) . The Universal Band parameterization corresponds to a 1-parameter fit with $a_0^2 = f(a_0^0)$.



Ke4 charged decays : preliminary results (370 000 decays)

Snapshot on systematics :

- Two independent analyses with slightly different approaches (binning, trigger efficiency, fit method..)
- Acceptance control
- Background level and shape control :
- Electron identification control
- Radiative corrections implementation
- Neglected S_e dependence

Form Factors K^+ and K^- combined

f_s'/f_s	$= 0.169 \pm 0.009 \pm 0.034$
f_s''/f_s	$= -0.091 \pm 0.009 \pm 0.031$
f_p/f_s	$= -0.047 \pm 0.006 \pm 0.008$
g_p/f_s	$= 0.891 \pm 0.019 \pm 0.020$
g_p'/f_s	$= 0.111 \pm 0.031 \pm 0.032$
h_p/f_s	$= -0.411 \pm 0.027 \pm 0.038$
a_0^0	$= 0.256 \pm 0.008 \pm 0.007$
	± 0.018 Theory (Universal Band)

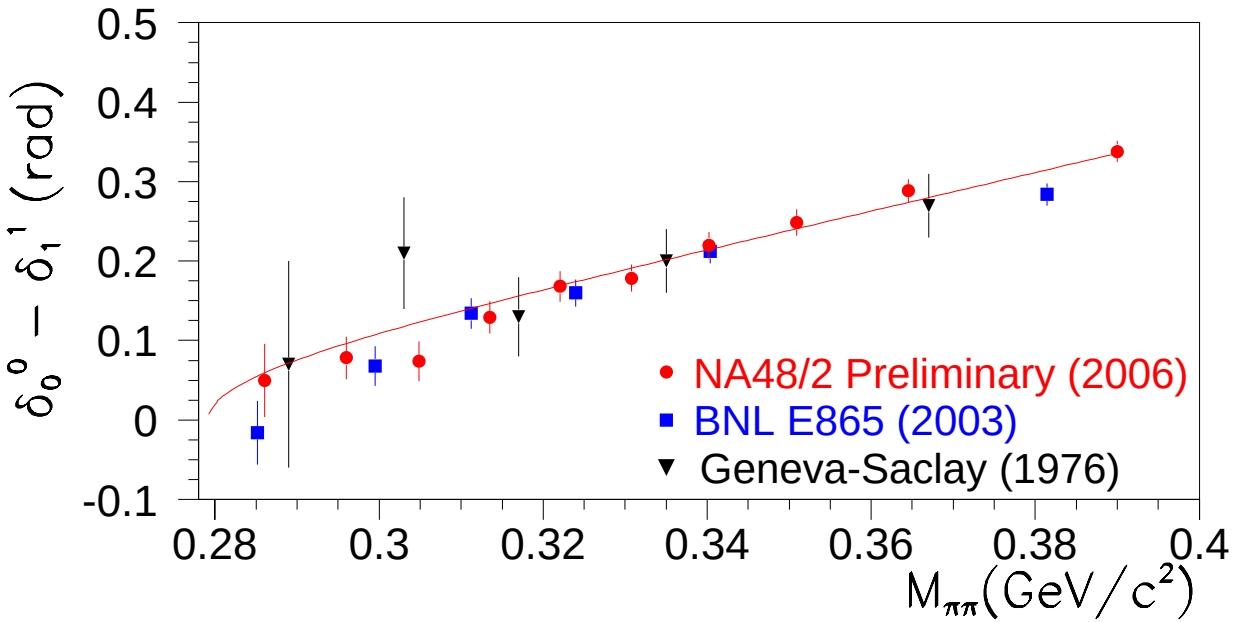
Corresponding to $a_0^2 = -0.031 \pm 0.002 \pm 0.002$
± 0.009 Theory (full UB width)

Ke4 charged decays : towards $\pi\,\pi$ scattering lengths

Comparison with previous published Ke4 results :

- CERN/PS Geneva-Saclay ~30000 decays (K^+) (Phys. Rev. D15 (1977))
- BNL E865 ~390 000 decays (K^+) (PRL 87 (2001), Phys. Rev. D67 (2003)
- CERN/SPS NA48/2 : prelim. result from ~370 000 decays (K^+/K^-) significant acceptance at larger $m_{\pi\pi}$ values, high resolution and low background level.

  Universal Band centre line shown (stat. + experimental syst. errors added)



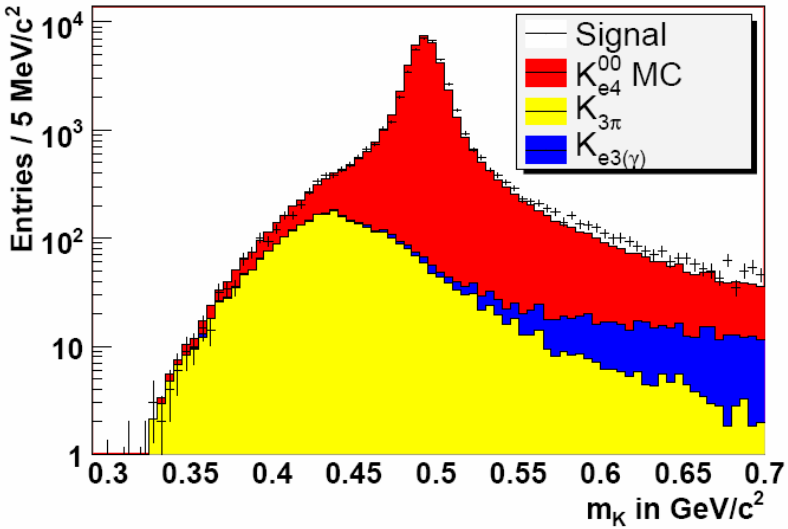
Ke4 neutral decays : Branching fraction

Signal $\pi^0\ \pi^0\ e^{\pm}\ \nu$ Topology : 1 charged track , 2 π^0s (reconstructed from 4γ's in LKr), 1 electron (LKr info E/p), some missing energy and p_T (neutrino)

2003 data : ~10000 signal events (with ~3% background events)
2004 data : ~30000 signal events (with ~2% background events)

Background : main sources estimated from data by reverting cuts
$\pi^{\pm}\ \pi^0\ \pi^0$ decay + π misidentified as e (dominant)
$\pi^0\ e^{\pm}\ \nu\ \gamma$ decay + accidental γ

Systematics from acceptance, trigger, electron id



Branching fraction (2003 data, K^+ and K^-) using ($\pi^{\pm}\ \pi^0\ \pi^0$) as normalization

Br(Ke4 neutral) = (2.587 $\pm$ 0.026 stat $\pm$ 0.019 syst $\pm$ 0.029 ext) 10^{-5}

10 times more precise than previous measurement :

KEK E470 based on 216 signal events (2.29 $\pm$ 0.33) 10^{-5}

Ke4 neutral decays : Form Factor

(two identical π^0 ➔ only ONE Form Factor F_s, no p-wave !)

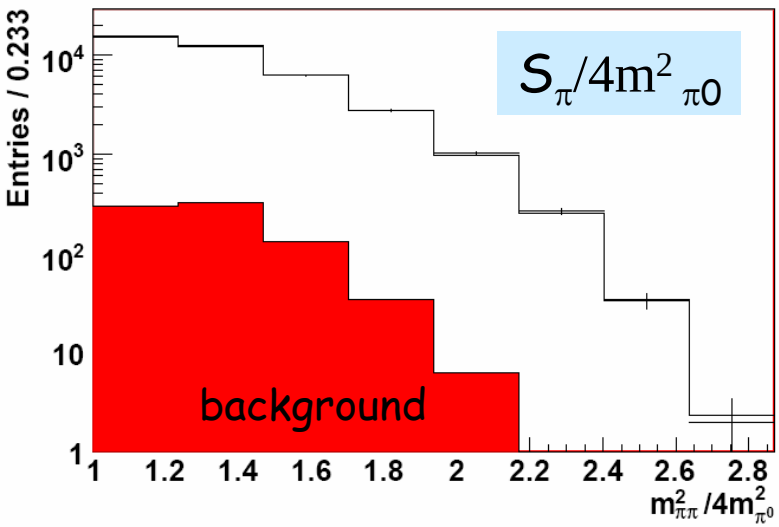
$$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e\left(S_e/4m_{\pi}{}^2\right) + ..$$

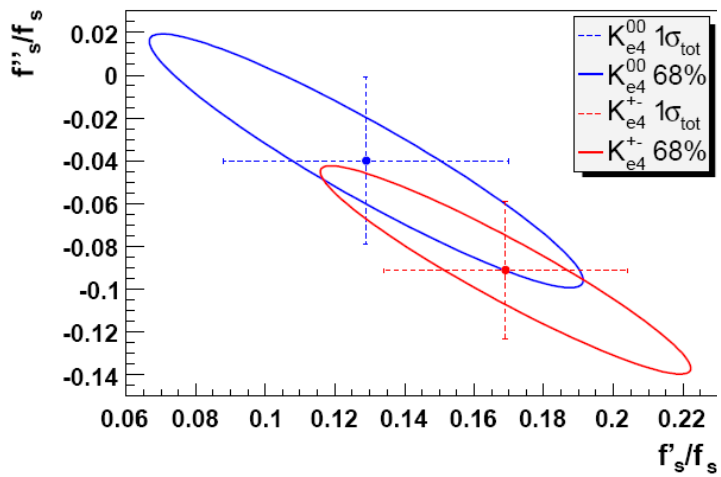
Form factors (2003 +2004 data, K^+ and K^-)

S_e dependence measurement consistent with 0.

$$f_s'/f_s = 0.129 \pm 0.036_{stat} \pm 0.020_{syst}$$

$$f_s''/f_s = -0.040 \pm 0.034_{stat} \pm 0.020_{syst}$$



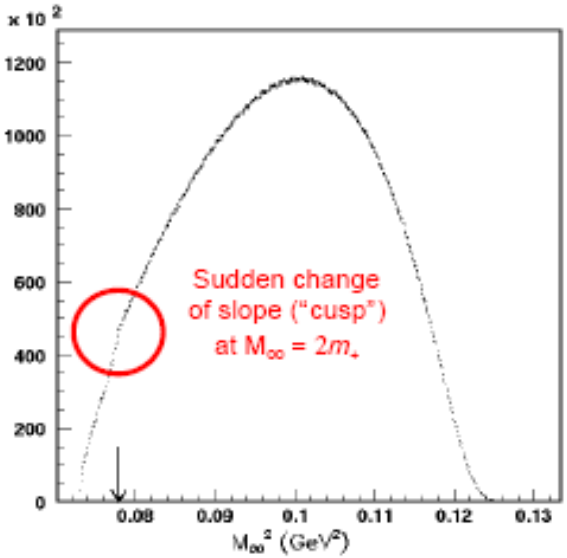


Ke4 charged and neutral FF consistent

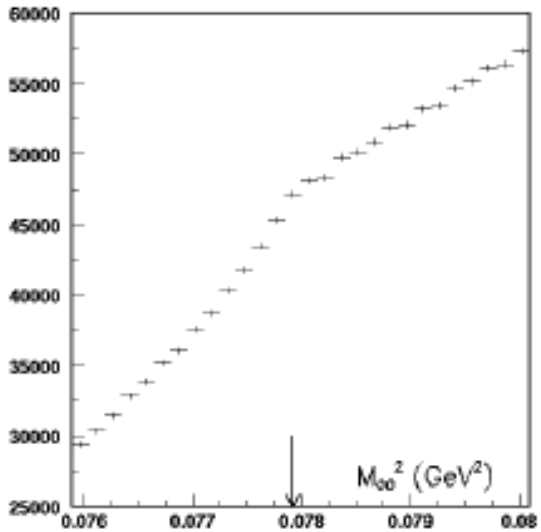
The cusp effect in $K^{\pm} \to \pi^{\pm} \pi^0 \pi^0$ decays

Result published in Phys. Lett. B633 (2006)

Reminder: from 23×10^6 ($\pi^{\pm} \pi^0 \pi^0$) decays , the M^2_{00} shows a sudden change of slope at $M_{00} = 2m_{\pi^{\pm}}$



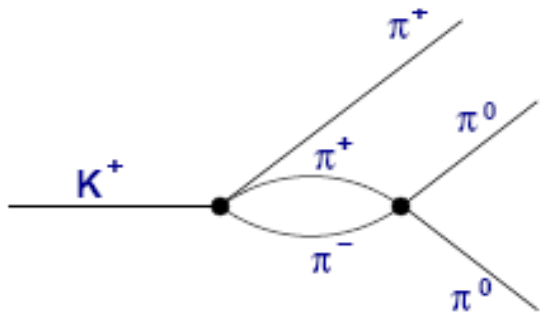
"Zoom" on the cusp region



The cusp effect : fit method and results

Principle: 1-dimension fit to the M^2_{00} distribution based on the improved rescattering model of Cabibbo-Isidori (JHEP 0503 (2005))

In the Dalitz plot, g_0 and h' are free parameters while parameter k is set to 0.



$$M_0 = A_0\left(1+\frac{1}{2}g_0 u+\frac{1}{2}h'u^2+\frac{1}{2}kv^2\right)$$

Form Factors as in Phys.Lett.B633(2006)

g_0 = $0.645 \pm 0.004_{stat} \pm 0.009_{syst}$

h' = $-0.047 \pm 0.012_{stat} \pm 0.011_{syst}$

a_2 = $-0.041 \pm 0.022_{stat} \pm 0.014_{syst}$

(a_0-a_2) = $0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$

Correlation

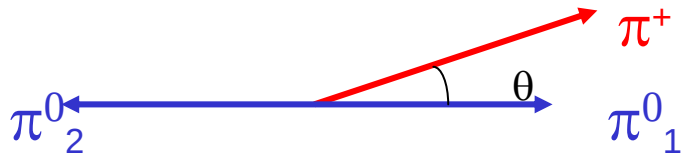
$\rho(a_0-a_2,a_2) = -0.858$

if the a_2 value predicted/preferred by ChPT is fixed,

$(a_0-a_2) = 0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$

The cusp effect : more investigations for a k term

Going to a 2D fit would imply to use (M^2_{00}, M^2_{+0}) variables. An alternate choice is $(M^2_{00}, \cos\theta)$ where θ is the angle between the charged π and the direction of the π^0's in their rest frame.

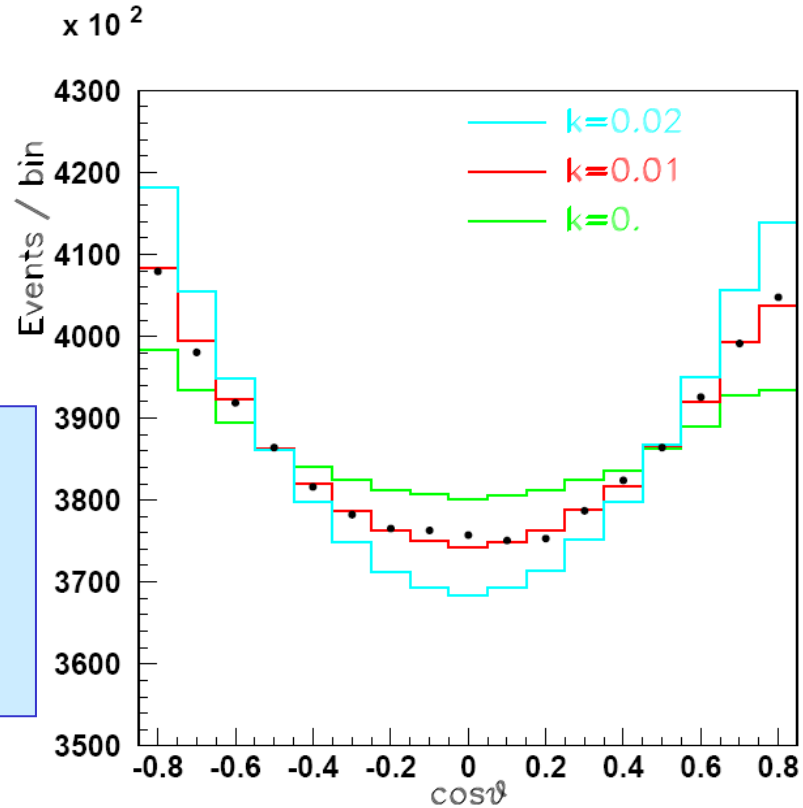


Use a modified matrix element :

$$M_0 = A_0\left(1+\frac{1}{2}g_0 u+\frac{1}{2}h' u^2+\frac{1}{2}k' \mathrm{v}^2\right)$$

re-fit in M^2_{00} range [0.082, 0.097] $(GeV/c^2)^2$)

no incidence on previous (a_0-a_2) result.



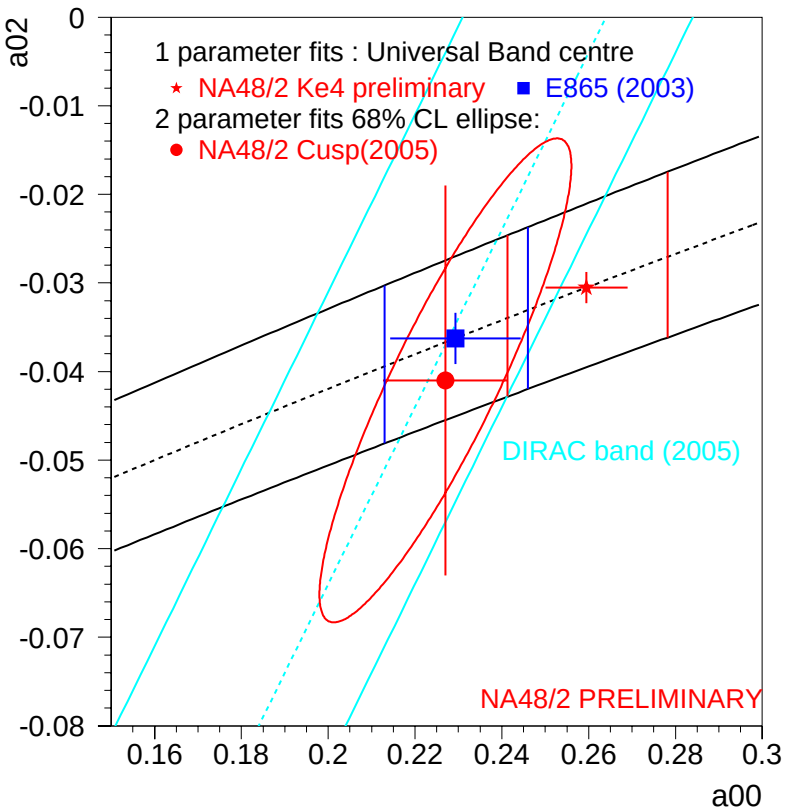
Preliminary result (2003 data, K^+ and K^-)

$$k' = 0.0097 \pm 0.0003_{stat} \pm 0.0008_{syst}$$

Note: the different meaning (g_0,h',k') wrt PDG (g_0,h,k)

π–π scattering lengths in NA48/2 : Summary and prospects

NA48/2 uses 2 independent channels to access π-π scattering lengths: phase shift from the Ke4 decays and the cusp effect in $\pi^{\pm}\,\pi^0\,\pi^0$ decays.



Other measurements (E865 Ke4, DIRAC pionium τ) also available

They maybe compared BUT beware of (implicit) theoretical frameworks !

Future Improvements from NA48 in a few months (KAON 07 in May)

Cusp : 70 M events (2003+2004) + improved theory input

Ke4 : ~0.65 M events (2003) + more elaborated theory input

Conclusions

Ke4

Using partial data samples recorded in 2003-2004, Na48/2 has improved measurements of the Ke4 form factors in the charged and neutral modes (5 to 30% stat. precision). Non zero fp term observed

$BR(Ke4^{00}) = (2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{theo}) \cdot 10^{-5}$

(10 times better than current PDG value)

Using a conservative theoretical approach, a preliminary value of a_0^0 is obtained with 3% precision (both stat. and syst.). More constrained result in progress with help from theorists.

$a_0^0 = 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{theo}$ (Universal Band width)

New measurements of Matrix element and $\pi\pi$ scattering length in K3pi decays

Cusp

$a_0^0 - a_0^2 = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{theo}$

First evidence for a non-zero k' term

$k' = 0.0097 \pm 0.0003_{stat} \pm 0.0008_{syst}$

More stringent constrains in the (a_0^0, a_0^2) plane to be expected soon