

Recent results from NA48/2 on K_{e4} and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays
Interpretation in terms of $\pi\pi$ scattering lengths



Brigitte Bloch-Devaux
CEA Saclay, DAPNIA-SPP

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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, Wien

Outline

- The NA48/2 experiment : an introduction
beams, detector and performances
- Ke4 decays in charged ($K^\pm \rightarrow e^\pm \nu \pi^+ \pi^-$) and neutral ($K^\pm \rightarrow e^\pm \nu \pi^0 \pi^0$) :
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 ($K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$) : 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

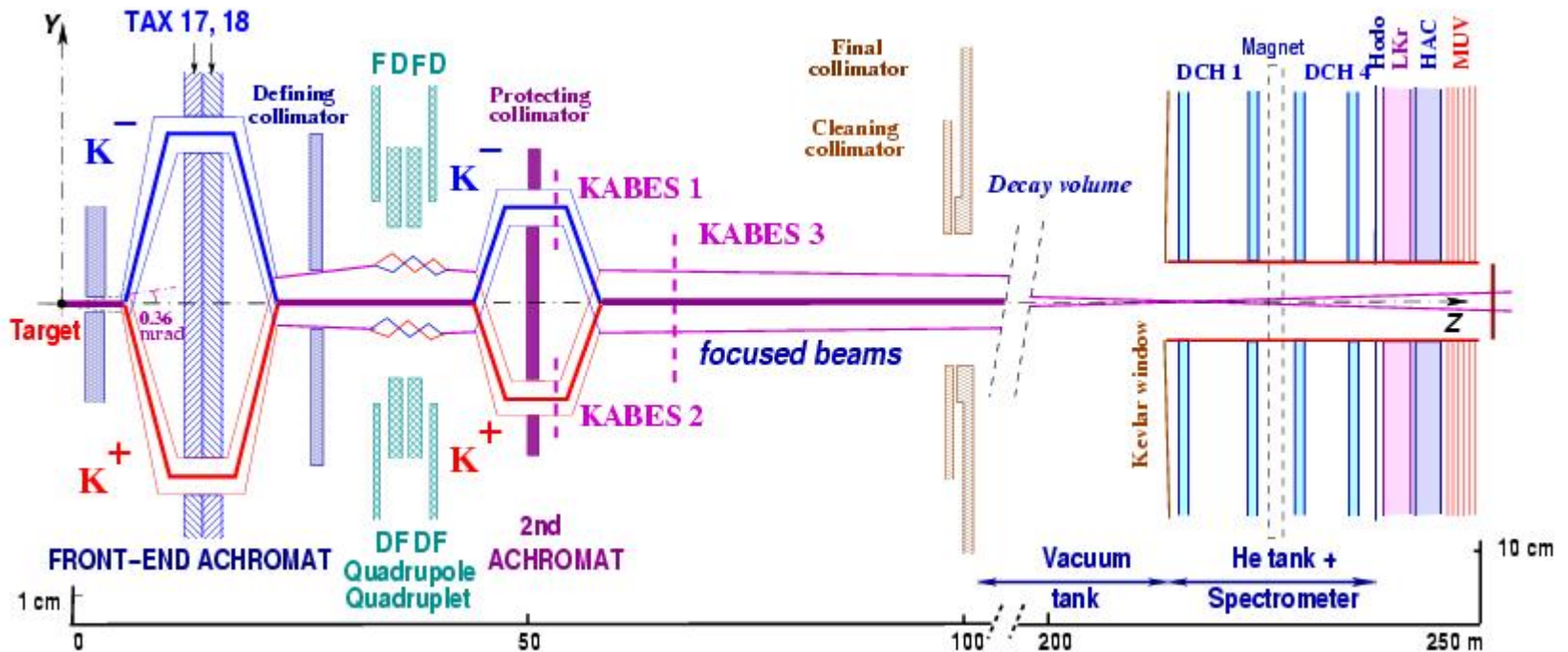
Study of many **rare decays** , in particular **Ke4** in the "charged" $\pi^+ \pi^- e^\pm \nu$ (and "neutral" $\pi^0 \pi^0 e^\pm \nu$) final state, both modes with small **BR's of few 10^{-5}** .

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 : $(60 \pm 3) \text{ GeV}/c$



2003 Run ~50 days

2004 Run ~60 days

The NA48/2 experiment: detector performances

Most important components for $K_{e4}/K_{3\pi}$ analysis :

Magnetic spectrometer : 4 high-resolution DCH's

$$\Delta p/p = (1.0 \oplus 0.044 p)\% \quad (p \text{ in } \text{GeV}/c)$$

→ Very good resolution for **charged invariant masses** (Kaon)

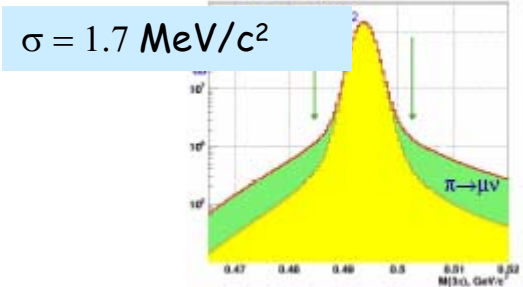
LKr electromagnetic calorimeter : quasi-homogenous and high granularity

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

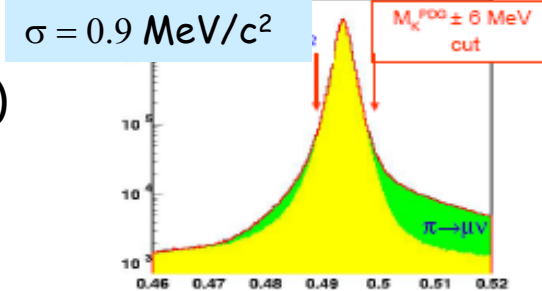
$$\sigma_x = \sigma_y \sim 1.5 \text{ mm for } E=10 \text{ GeV}$$

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

→ E/p ratio for **e/π discrimination**



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



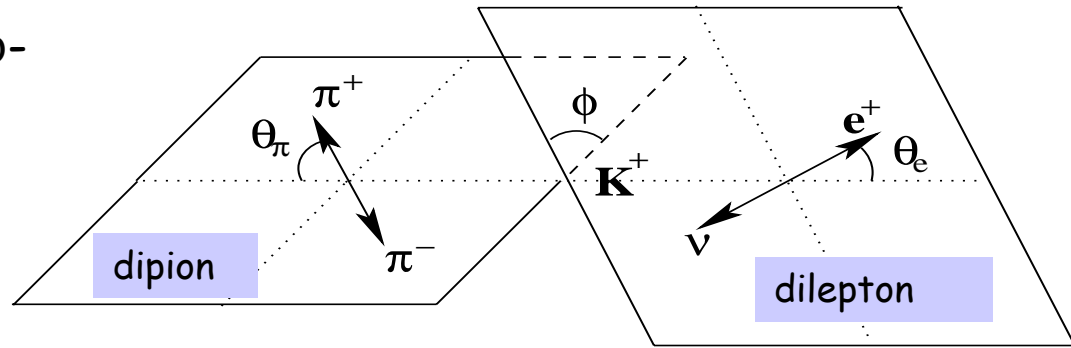
$(\pi^\pm \pi^0\pi^0)$ mass GeV/c^2

Ke4 charged decays : formalism

Five kinematic variables (Cabibbo-Maksymowicz):

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

$$\cos\theta_\pi, \cos\theta_e \text{ and } \phi.$$



partial wave expansion of the amplitude:

$F, G =$ Axial Form Factors

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p} \cos\theta_\pi + \text{d-wave term...}$$

$$G = G_p e^{i\delta_g} + \text{d-wave term...}$$

$H =$ Vector Form Factor

$$H = H_p e^{i\delta_h} + \text{d-wave term...}$$

expansion in powers of q^2 , S_e

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

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

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

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

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

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)

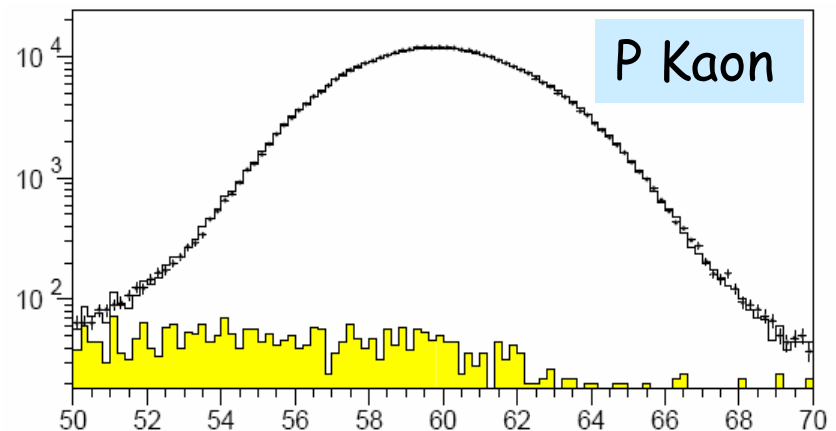
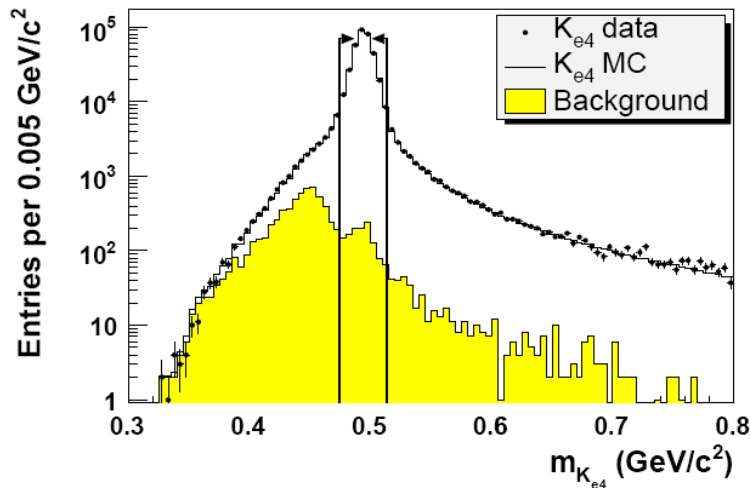
Background : main sources

$\pi^\pm\pi^+\pi^-$ 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 $\sim 0.5\%$ 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

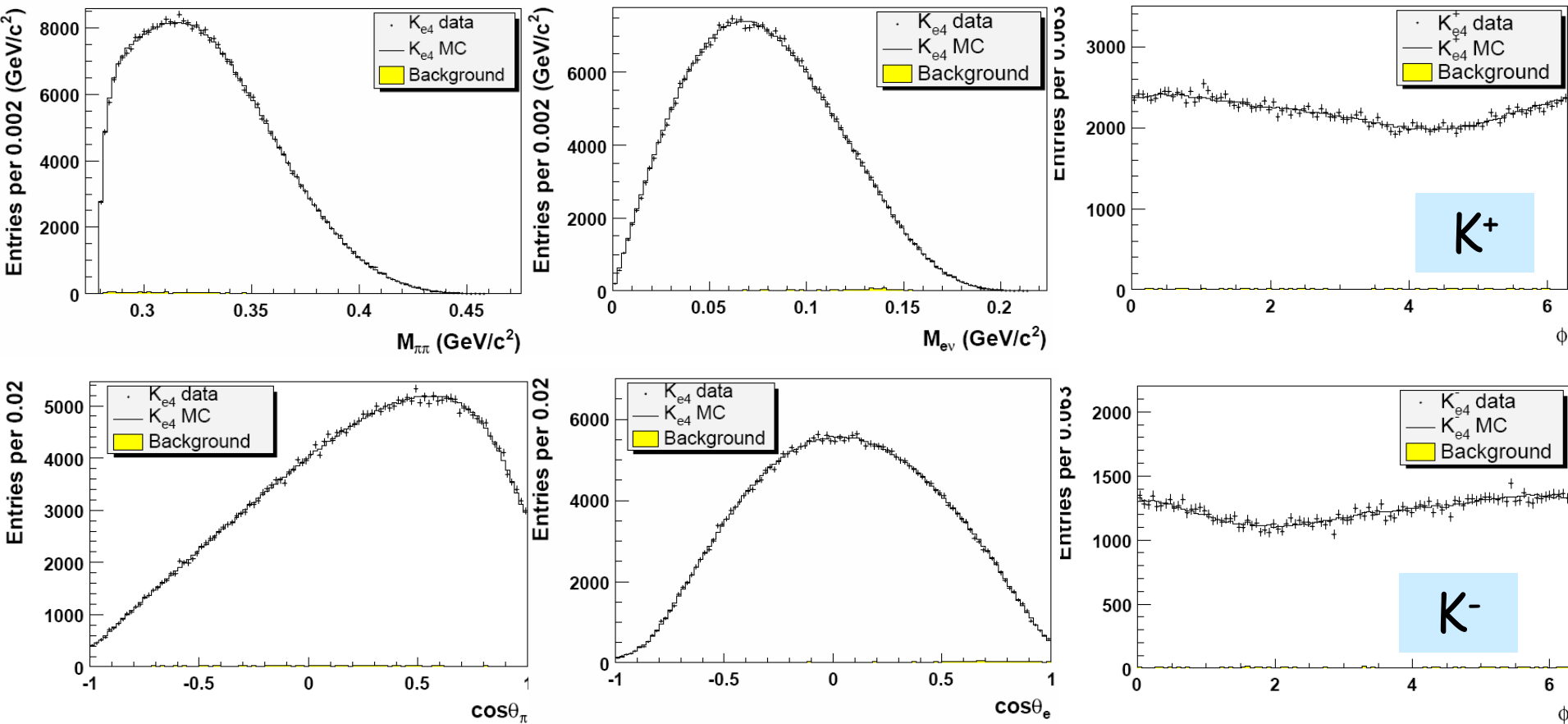
Ratio **K⁺/K⁻** ~ 1.8 both in Data and MC (run by run basis)

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

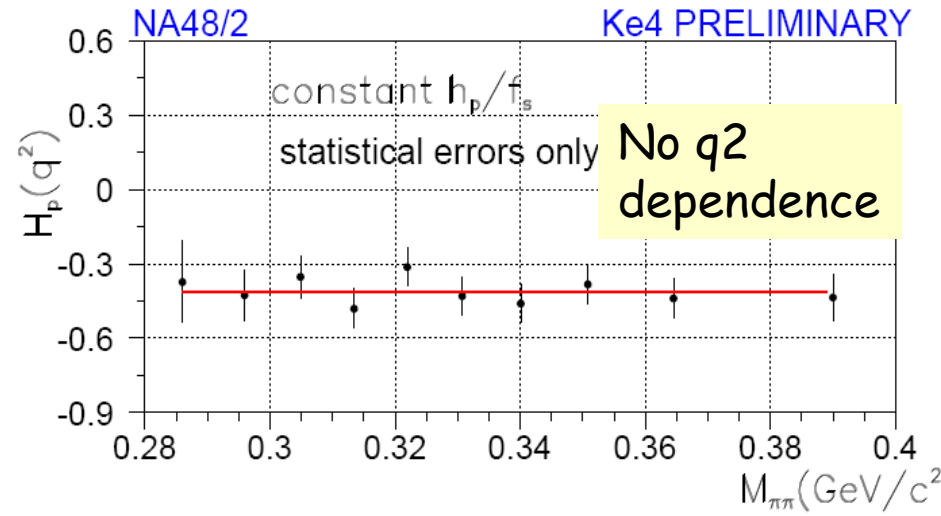
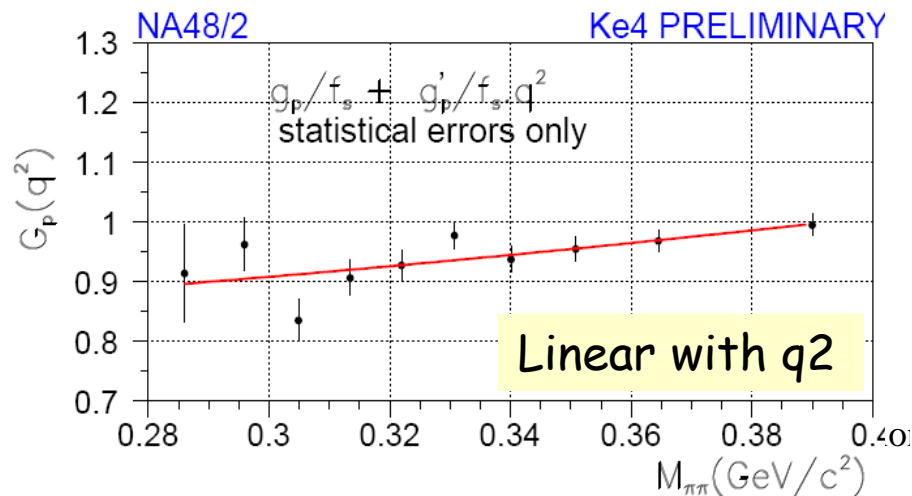
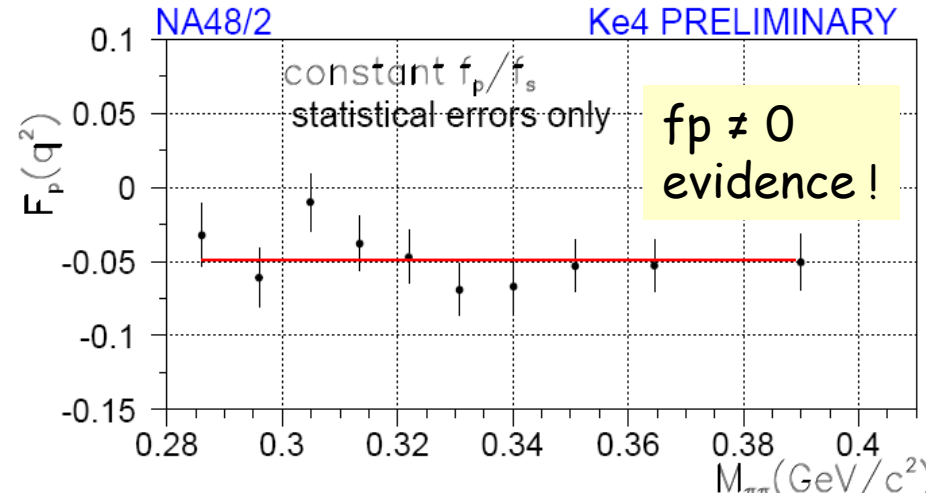
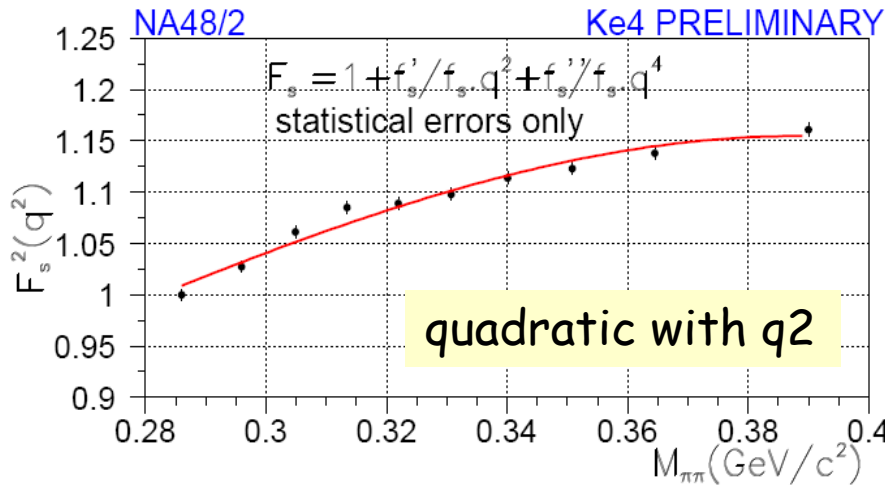
K^+ and K^- samples fitted separately, results combined



Ke4 charged decays : F,G,H form factors

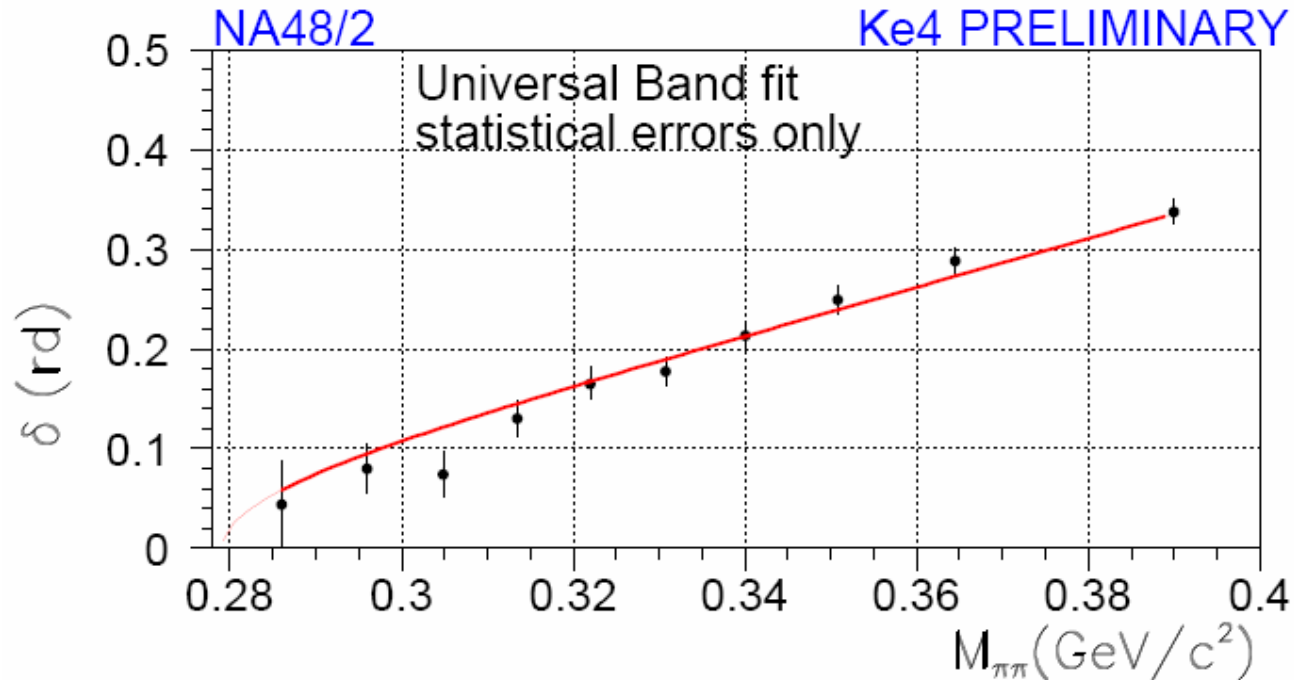
Ten independent fits, one in each $M_{\pi\pi}$ bin, assuming \sim constant form factors over each box. This allows a model independent analysis.

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

$$f'_s / f_s = \mathbf{0.169 \pm 0.009 \pm 0.034}$$

$$f''_s / f_s = \mathbf{-0.091 \pm 0.009 \pm 0.031}$$

$$f_p / f_s = \mathbf{-0.047 \pm 0.006 \pm 0.008}$$

$$g_p / f_s = \mathbf{0.891 \pm 0.019 \pm 0.020}$$

$$g'_p / f_s = \mathbf{0.111 \pm 0.031 \pm 0.032}$$

$$h_p / f_s = \mathbf{-0.411 \pm 0.027 \pm 0.038}$$

$$a_0^0 = \mathbf{0.256 \pm 0.008 \pm 0.007}$$

± 0.018 Theory (Universal Band)

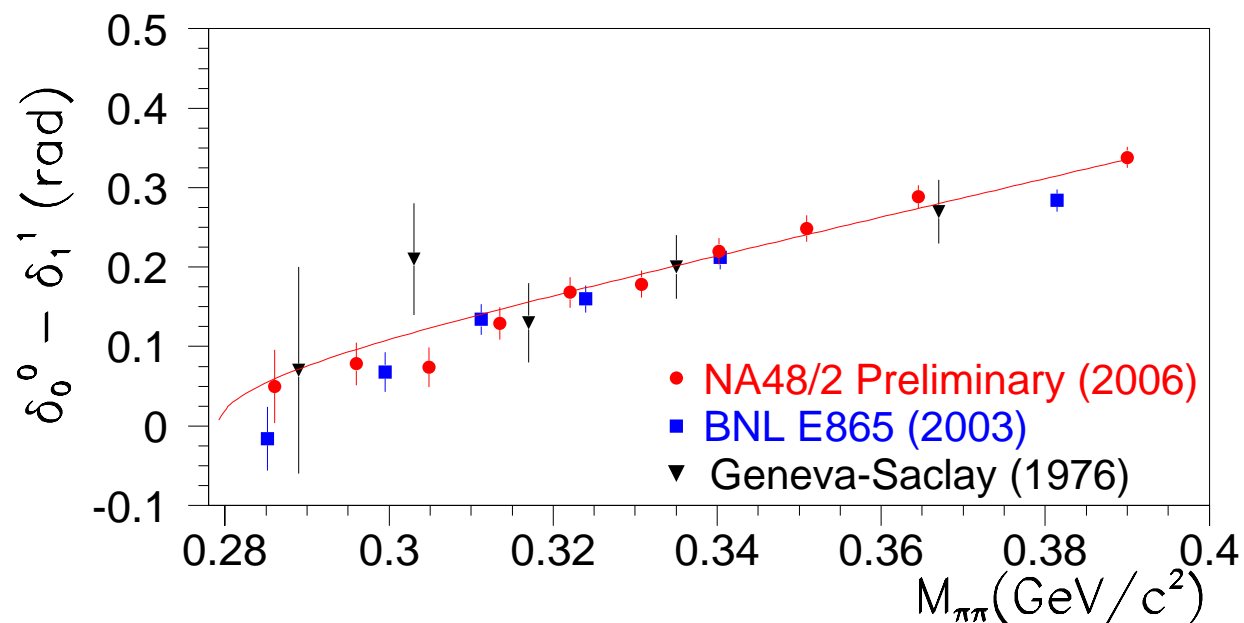
Corresponding to $a_0^2 = \mathbf{-0.031 \pm 0.002 \pm 0.002}$
 ± 0.009 Theory (full UB width)

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 $\sim 390\,000$ decays (K^+) (PRL 87 (2001), Phys. Rev. D67 (2003))
- CERN/SPS NA48/2 : prelim. result from $\sim 370\,000$ 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^0 's (reconstructed from 4 γ '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)

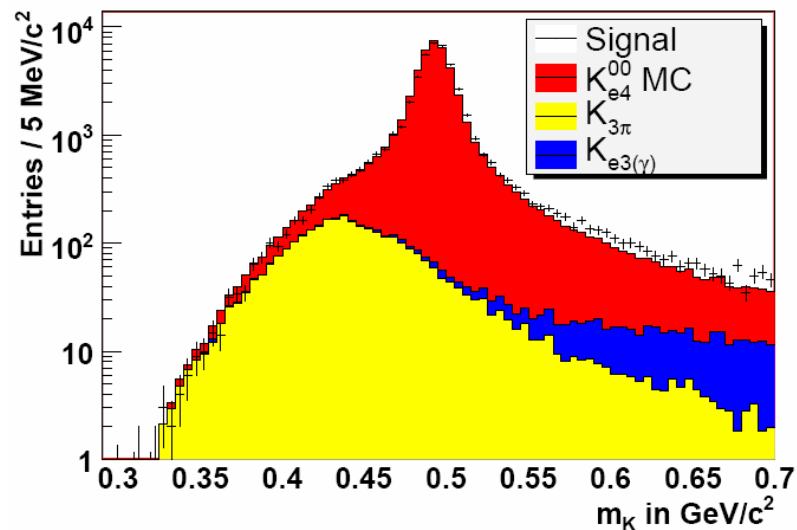
2004 data : ~30000 signal events (with ~2% background events)

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

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

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 $\pi^0 \rightarrow$ only **ONE** Form Factor F_s , no p-wave !)

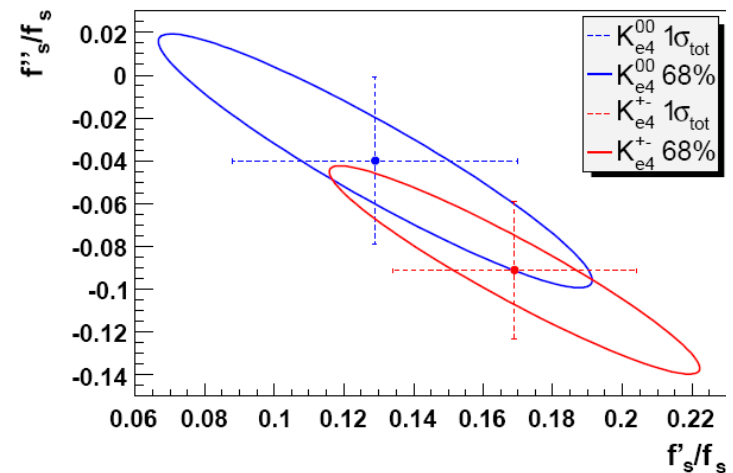
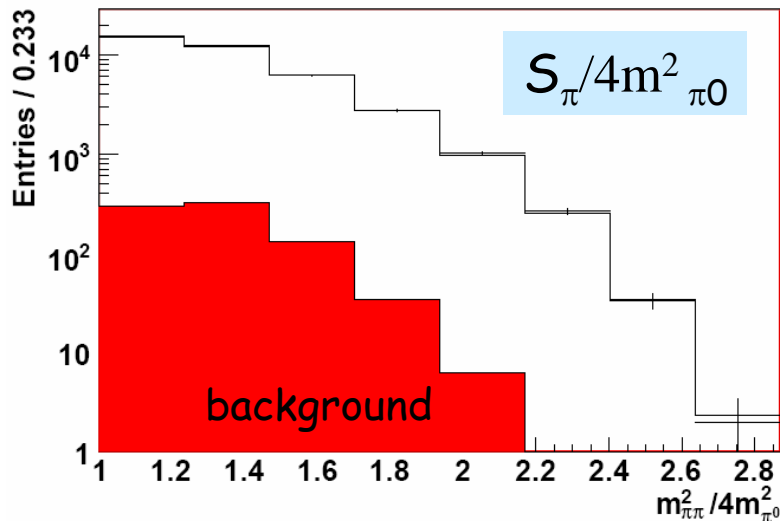
$$F_s = f_s + f'_s q^2 + f''_s q^4 + f_e \left(S_e / 4m_\pi^2 \right) + ..$$

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

S_e dependence measurement consistent with 0.

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

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

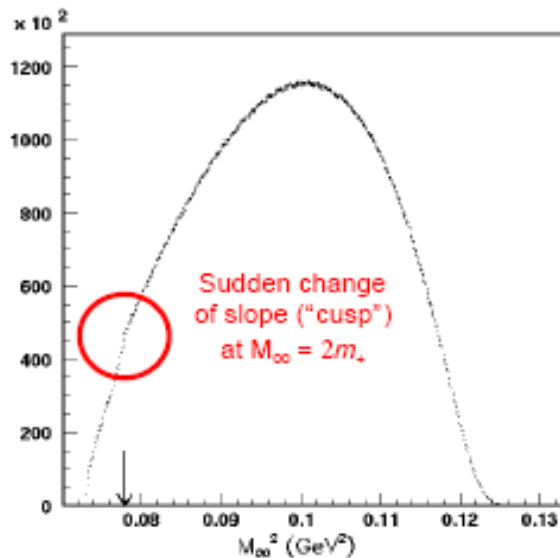


Ke4 charged and neutral FF consistent

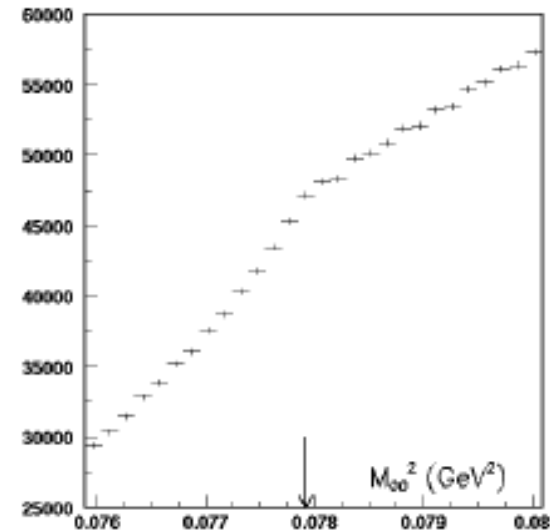
The cusp effect in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays

Result published in Phys. Lett. B633 (2006)

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



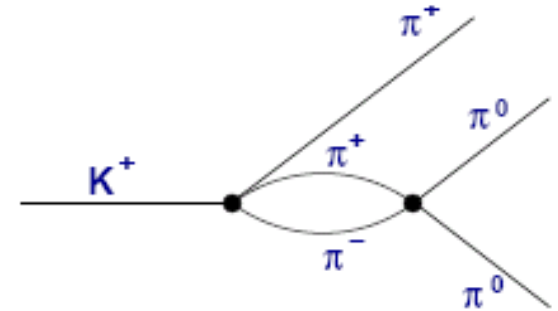
"Zoom" on the cusp region



The cusp effect : fit method and results

Principle: 1-dimension fit to the M_{00}^2 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.**



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

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

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

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

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

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

Correlation

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

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

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

The cusp effect : more investigations for a k term

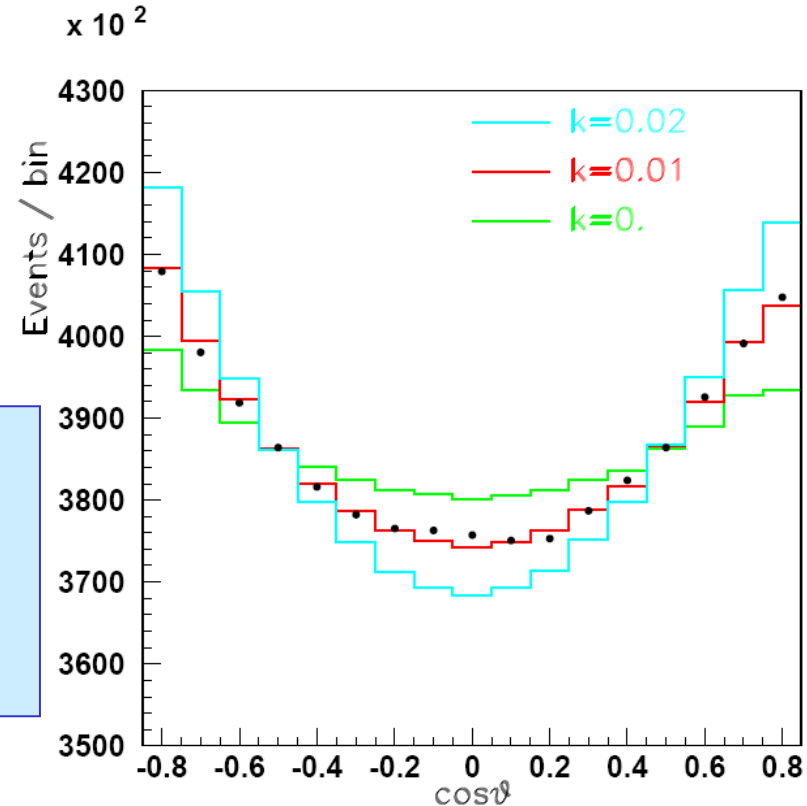
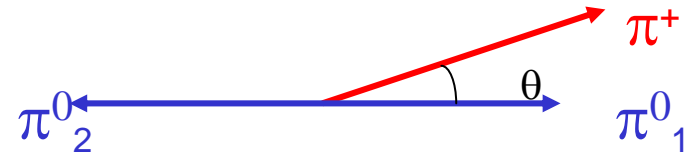
Going to a 2D fit would imply to use (M_{00}^2, M_{+0}^2) variables. An alternate choice is $(M_{00}^2, \cos\theta)$ where θ is the angle between the charged π and the direction of the π^0 's in their rest frame.

Use a modified matrix element :

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

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

no incidence on previous $(a_0 - a_2)$ result.



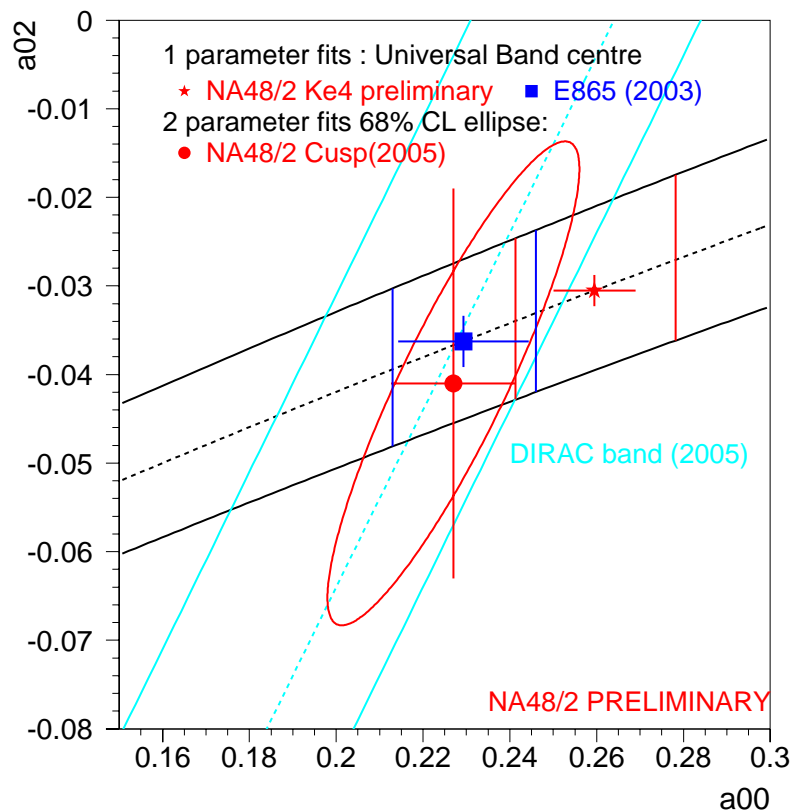
Preliminary result (2003 data, K^+ and K^-)

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

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

$\pi\text{-}\pi$ scattering lengths in NA48/2 : Summary and prospects

NA48/2 uses 2 independent channels to access $\pi\text{-}\pi$ 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**

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

(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.

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

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

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

First evidence for a non-zero k' term

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

Cusp

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