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

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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 : goals, beams, detector, performances
- Ke4 charged decays ($K^{\pm} \to e^{\pm} \nu \pi^{+}\pi^{-}$) : formalism, event selection, form factors
- Ke4 neutral decays ($K^{\pm} \to e^{\pm} \nu \pi^{0}\pi^{0}$) : event selection, form factors, Branching fraction
- K3pi neutral decays ($K^{\pm} \to \pi^{\pm} \pi^{0}\pi^{0}$) : the "cusp" effect, form factors
- Interpretation in terms of $\pi\pi$ scattering lengths
- Conclusion

The NA48/2 experiment: goals

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 R. Arcidiacono)

and also

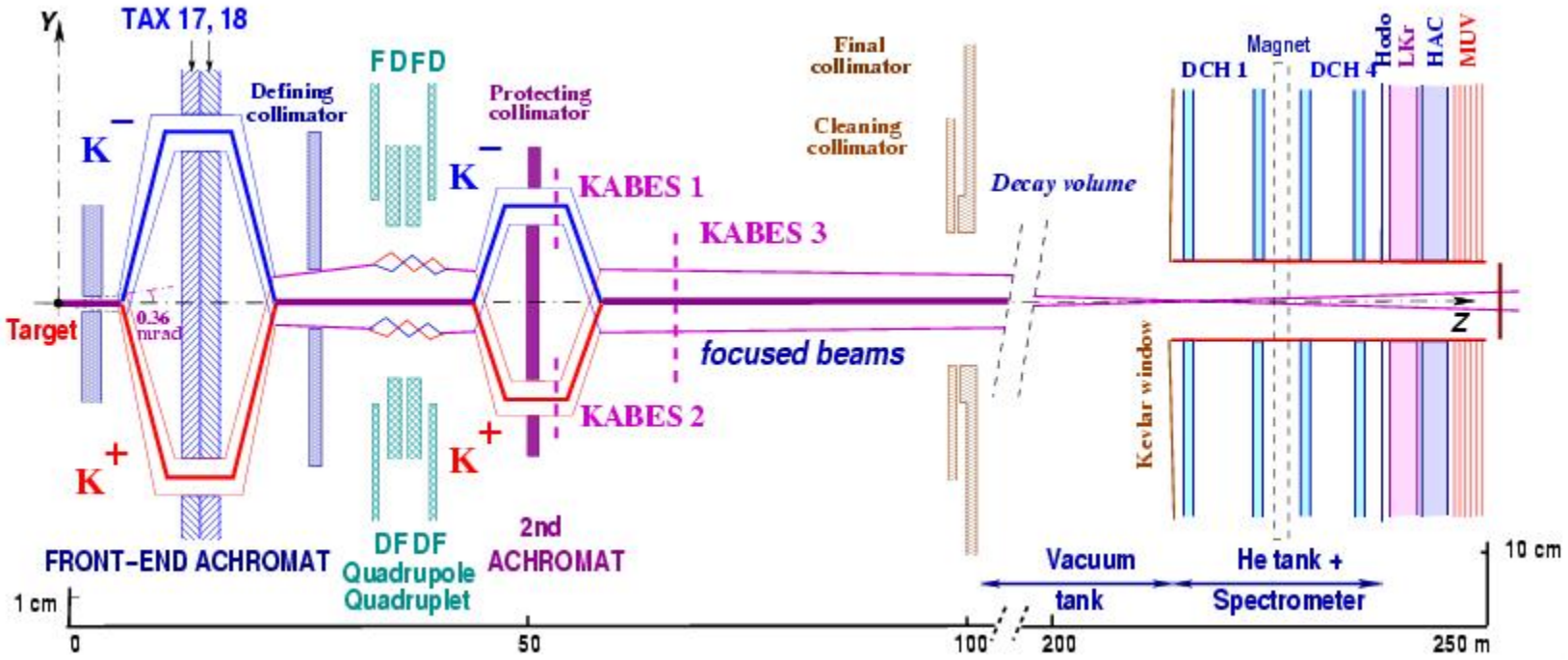
Study of rare decays like Ke4 in the "charged" $\pi^+\pi^-e^\pm\nu$ and "neutral" $\pi^0\pi^0e^\pm\nu$ final states

both modes with small BR's of few 10^{-5}

ChPT predictions exists for low energy $\pi\pi$ interaction (qq condensate)

The NA48/2 experiment: beams and detector

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



The NA48/2 experiment: data taking

2003 Run ~50 days | 2004 Run ~60 days

Total statistics :

~4.10^9 $\pi^{\pm}\pi^+\pi^-$ decays

~1.10^8 $\pi^{\pm}\pi^0\pi^0$ decays

~1.10^6 $\pi^+\pi^- e^{\pm}\nu$ decays

~4.10^4 $\pi^0\pi^0 e^{\pm}\nu$ decays

Preliminary results based on

charged K_{e4} 370 000 decays

(30 days in 2003)

neutral K_{e4} 37 000 decays

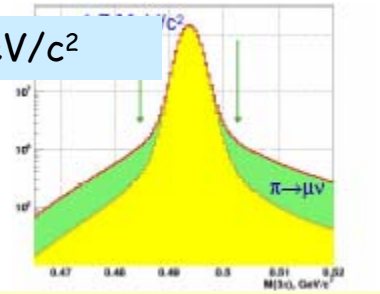
(full statistics of 2003-2004)

neutral K_{3pi} 23 000 000 decays

(30 days in 2003)

The NA48/2 experiment: detector performances

$\sigma = 1.7$ MeV/c²



$(\pi^{\pm}\,\pi^{+}\pi^{-})$ mass GeV/c²

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

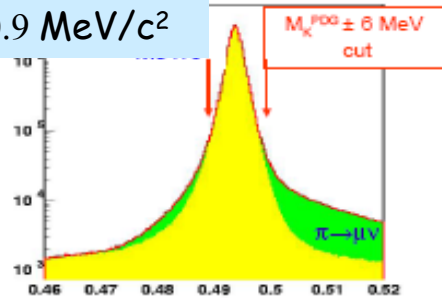
$\Delta E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)

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

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

→ E/p measurement for e/π discrimination

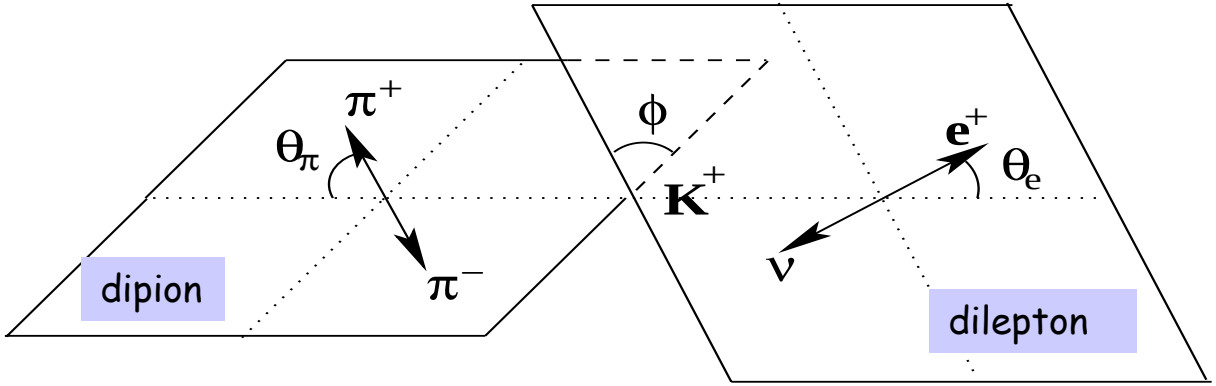
$\sigma = 0.9$ MeV/c²



$(\pi^{\pm}\,\pi^{0}\pi^{0})$ mass GeV/c²

Ke4 charged decays : formalism

The Ke4 decay are described using 5 kinematic variables (defined by Cabibbo-Maksymowicz): S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$), $\cos\theta_\pi$, $\cos\theta_e$ and ϕ.



The form factors which appear in the decay rate can be determined from a fit to the experimental data distribution of the 5 variables provided the binning is small enough.

Several formulations of the form factors appear in the literature, we have considered two of them, proposed by Pais and Treiman (Phys.Rev. 168 (1968)) and Amoros and Bijnens (J.Phys. G25 (1999)) which can be related.

Ke4 charged decays : formalism

Using a partial wave expansion:

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

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

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

Keeping only s and p waves (S_π is small in Ke4) , rotating phases by δ_p and assuming $(\delta_g-\delta_p) = 0$ and $(\delta_h-\delta_p) = 0$, only 5 form factors are left:

$F_s \quad F_p \quad G_p \quad H_p$ and $\delta = \delta_s - \delta_p$

developing in powers of q^2 ($q^2 = (S_\pi/4m_{\pi^+}^2 - 1)$), S_e…

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

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

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

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

Ke4 charged decays: event selection and background rejection

Signal $\pi^+\pi^- e^\pm \nu$ Topology : 3 charged tracks ,two opposite sign pions, one 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 (dominates with same topology as signal)
+ π misidentified as e

$\pi^\pm \pi^0(\pi^0)$ decay + π^0 Dalitz decay ($e^+e^-\gamma$) with 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 as in WS events or twice the rate

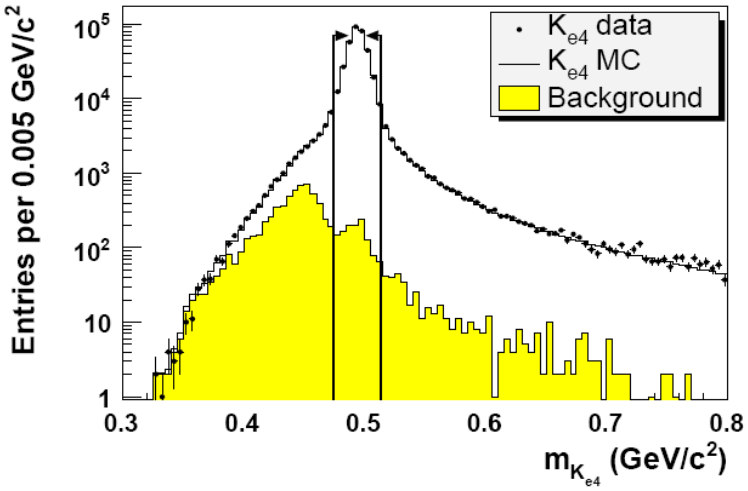
Total background level can be kept at ~ 0.5 % relative level

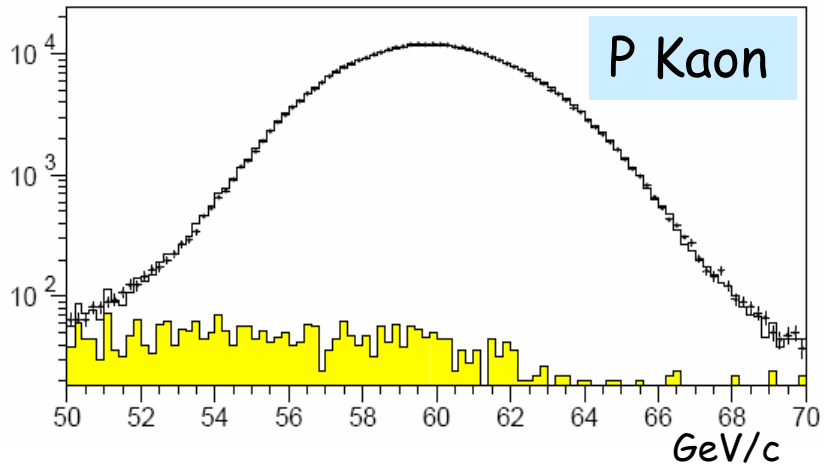
Ke4 charged decays : event reconstruction

Reconstruction of the C.M. variables : Two options

- use ν constrain to solve energy-momentum conservation equations and get P_K
- assume a 60 GeV/c Kaon , assign the missing p_T to the ν and compute the mass of the system

Then boost particles to the Kaon rest frame and dipion/dilepton rest frames to get the angular variables.





Ke4 charged decays : form factor determination

Using equal population 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

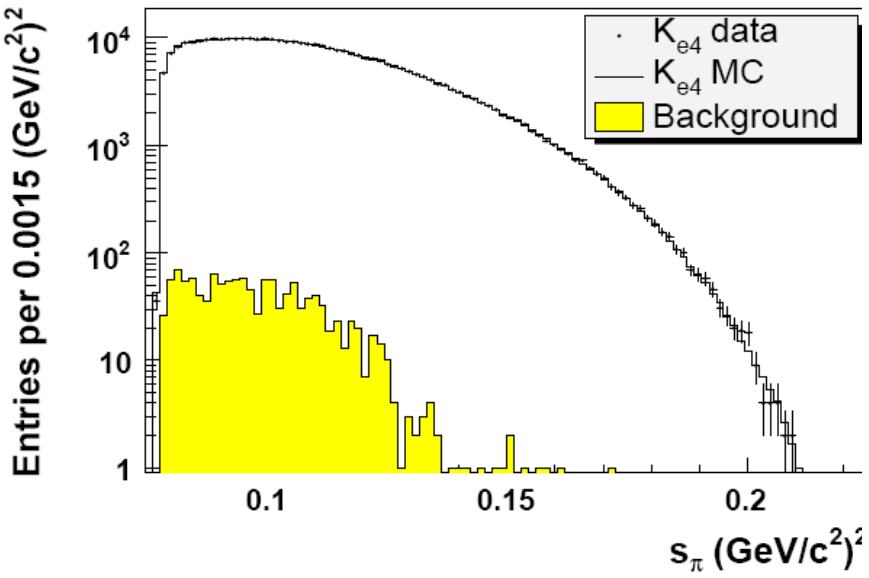
10x5x5x5x12=15000 boxes.

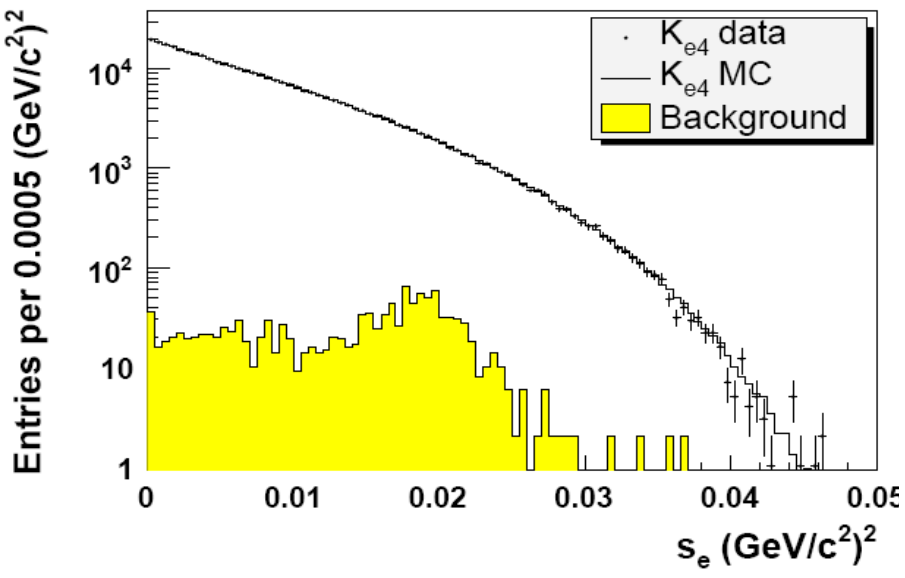
The set of form factor values are used to minimize the T^2, a log-likelihood estimator well suited for small numbers of data events/bin Nj and taking into account the statistics of the simulation = Mj simulated events/bin and Rj expected events/bin.

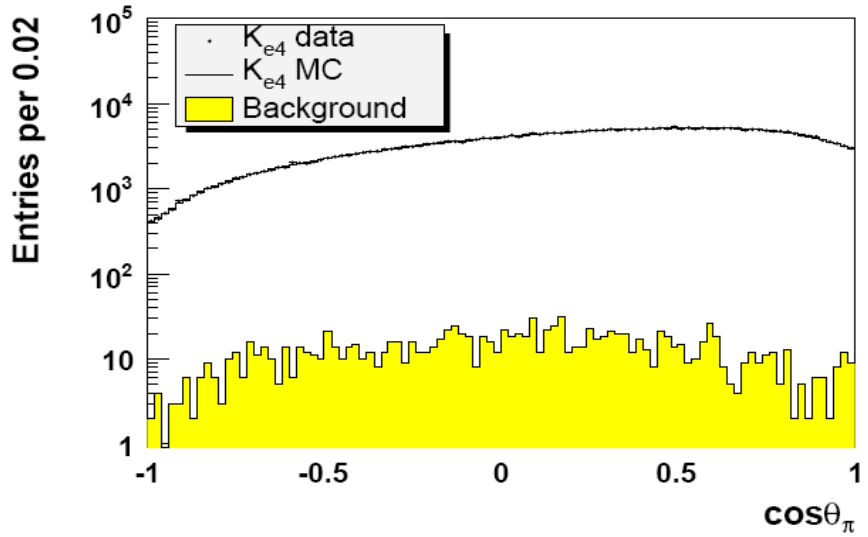
$$T^2 = 2\sum_{J=1}^{S}\left\{ N_j \, Log\left[\frac{N_j}{R_j}\left(1-\frac{1}{Mj+1}\right)\right] + (N_j + M_j + 1)\, Log\left[\frac{1+\frac{R_j}{M_j}}{1+\frac{N_j}{M_j+1}}\right]\right\}$$

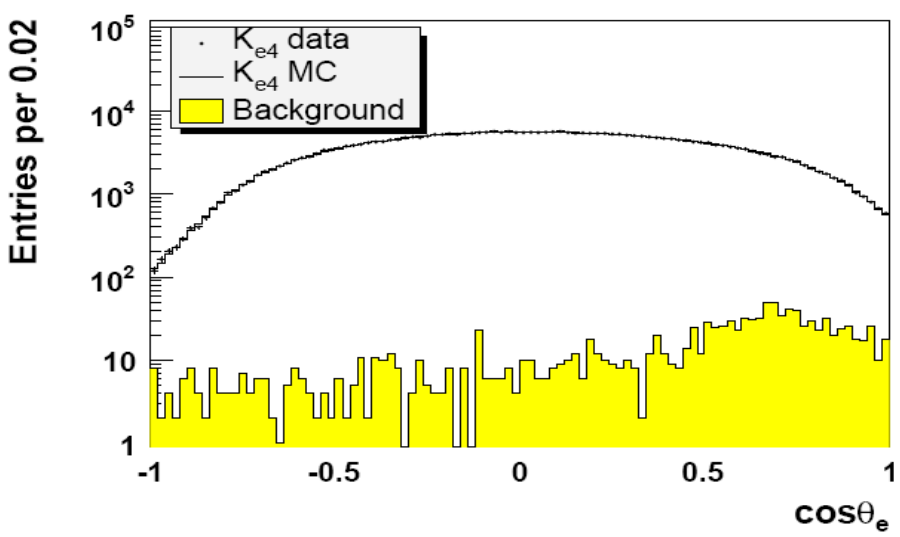
K^+ sample (235000 events)	16 events/bin
K^- sample (135000 events)	9 events/bin

Ke4 charged decays : 4 C.M. distributions (log scale)



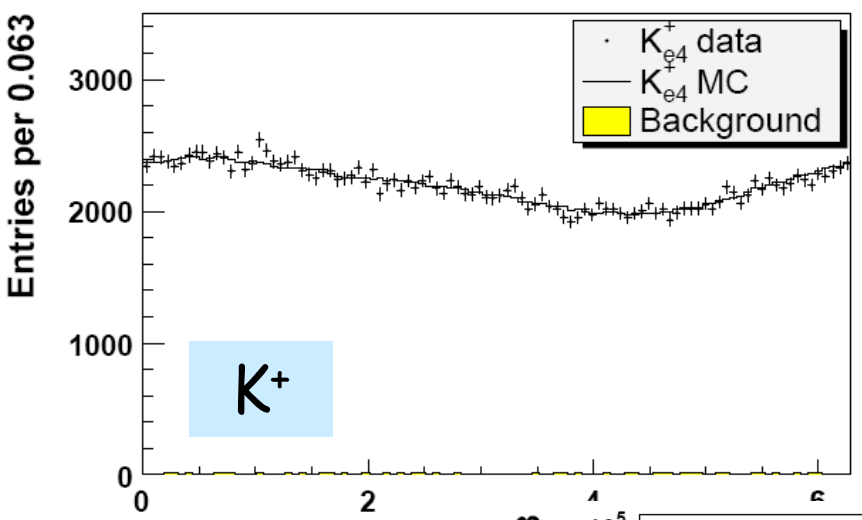


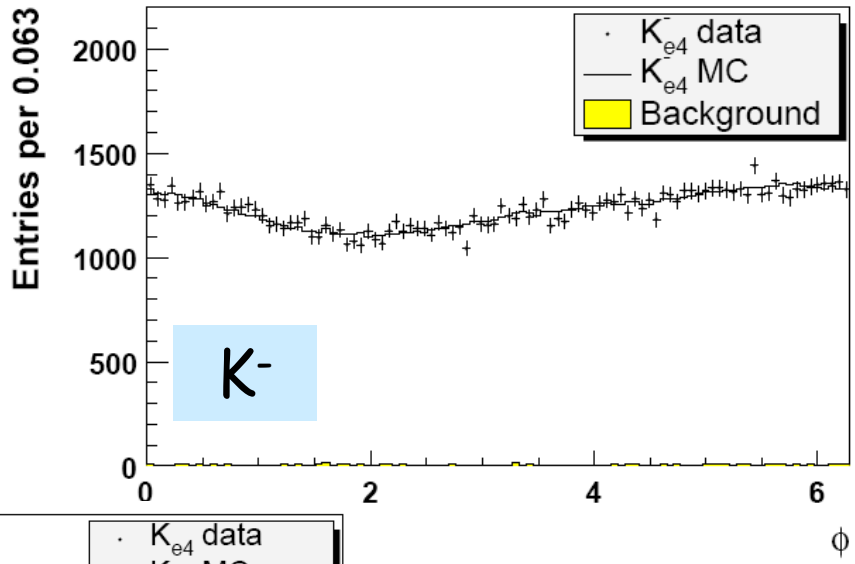


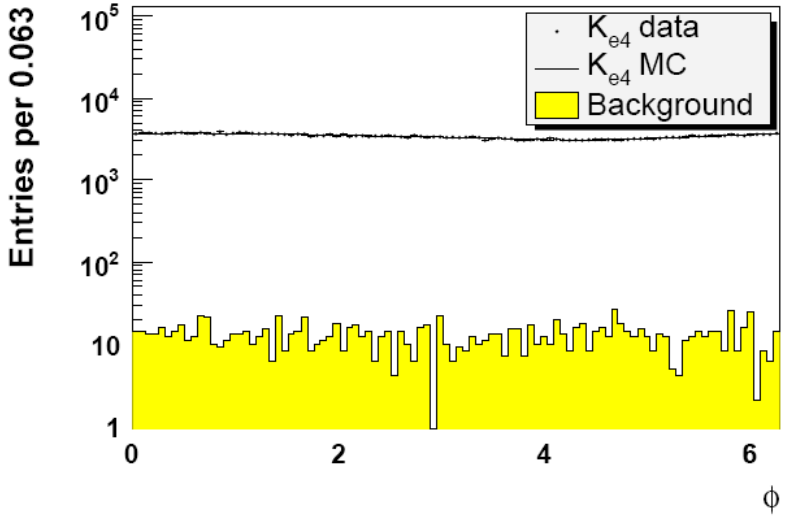


Ke4 charged decays : the 5th distribution ϕ

CP symmetry : (K^{+}) ϕ distribution is opposite of (K^{-}) ϕ distribution





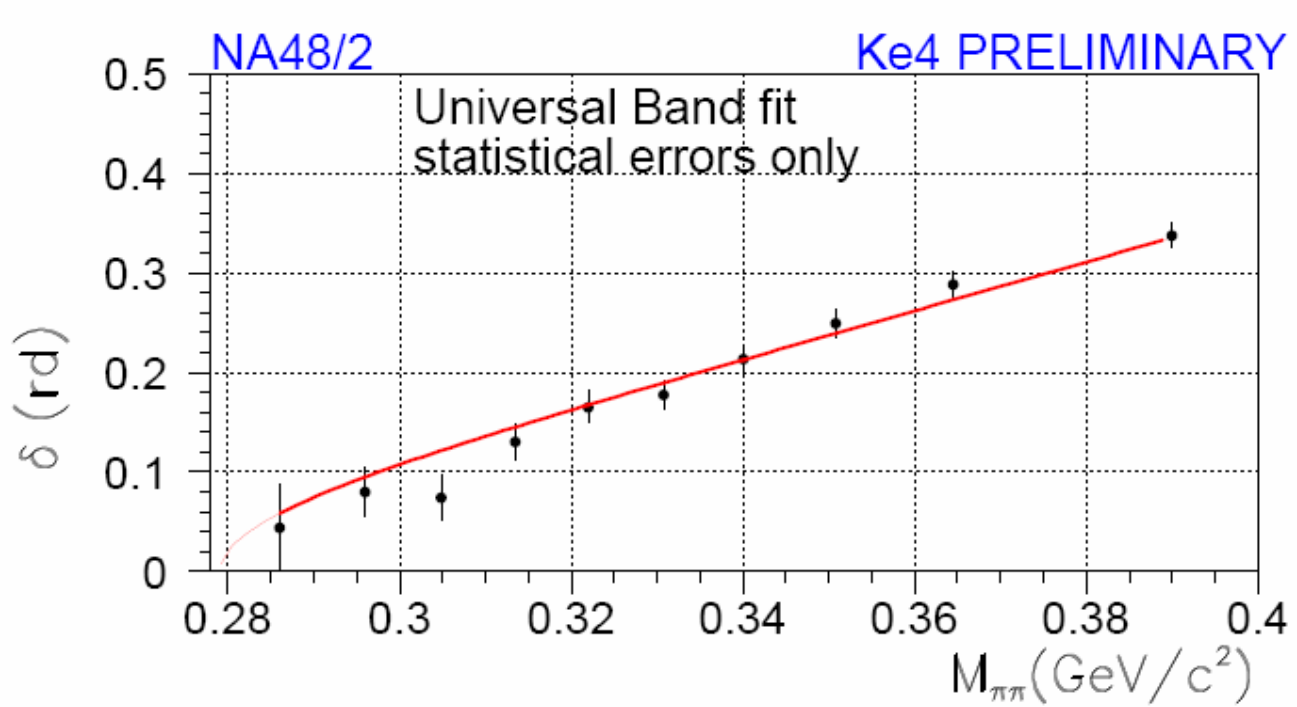


$K^{+}(\phi) + K^{-}(-\phi)$

Note the log scale to see the background!

Ke4 charged decays : δ form factor and a_0^0

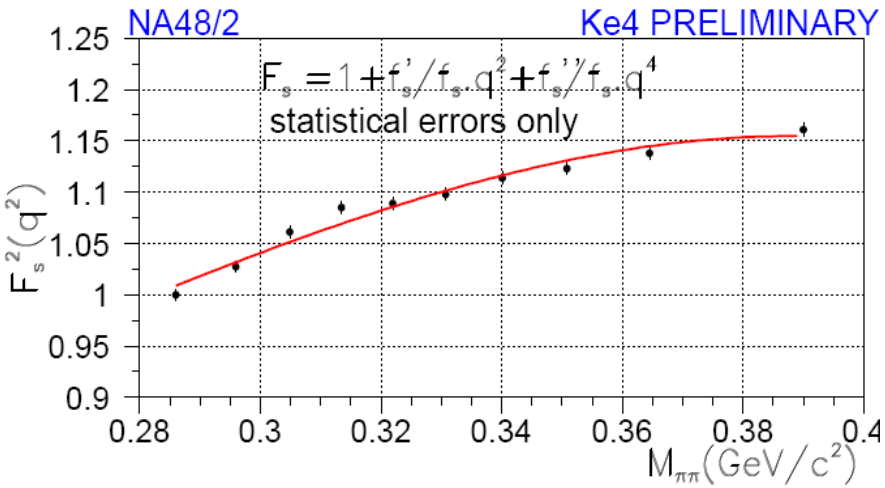
- Ten independent fits, one in each $M_{\pi\pi}$ bin, assuming ~constant form factors over each bin.
- Use the Universal Band parameterization to extract one parameter a_0^0 with $a_0^2 = f(a_0^0)$ (numerical solution of Roy equations as Phys. Rep.353 (2001)) from $\delta = (\delta_0^0 - \delta_1^1)$ distribution

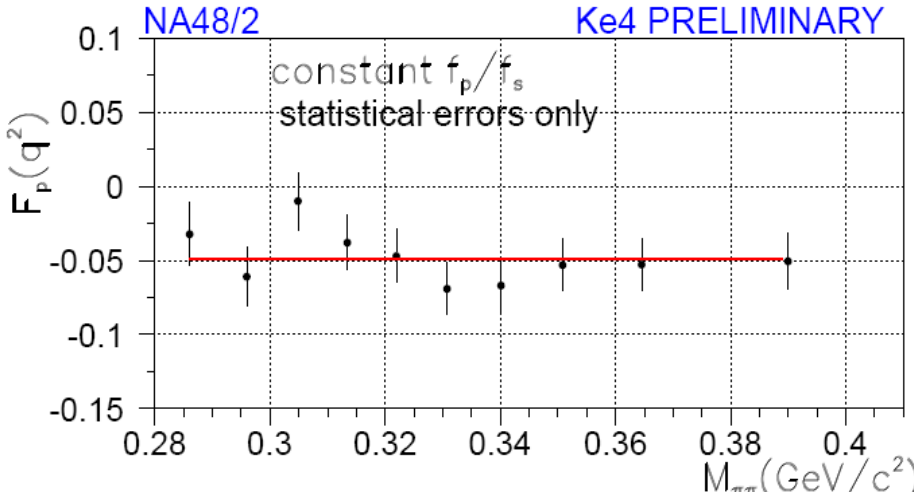


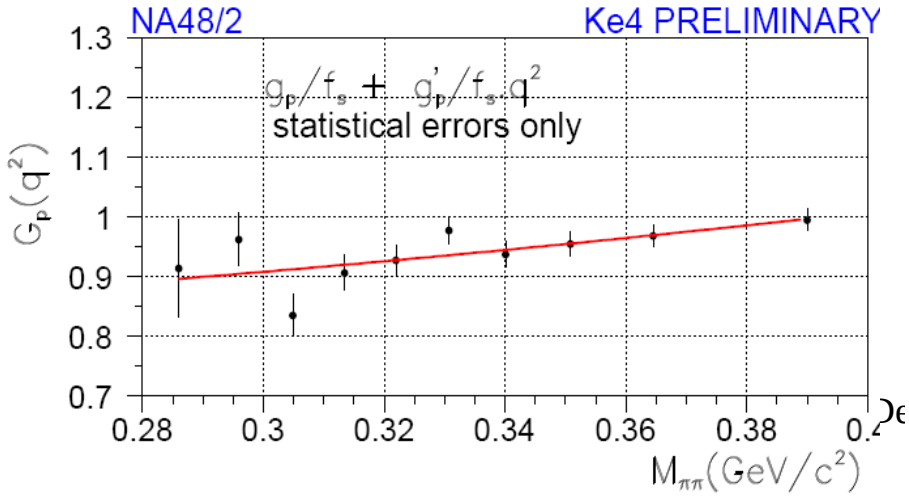
Ke4 charged decays : F,G,H form factors

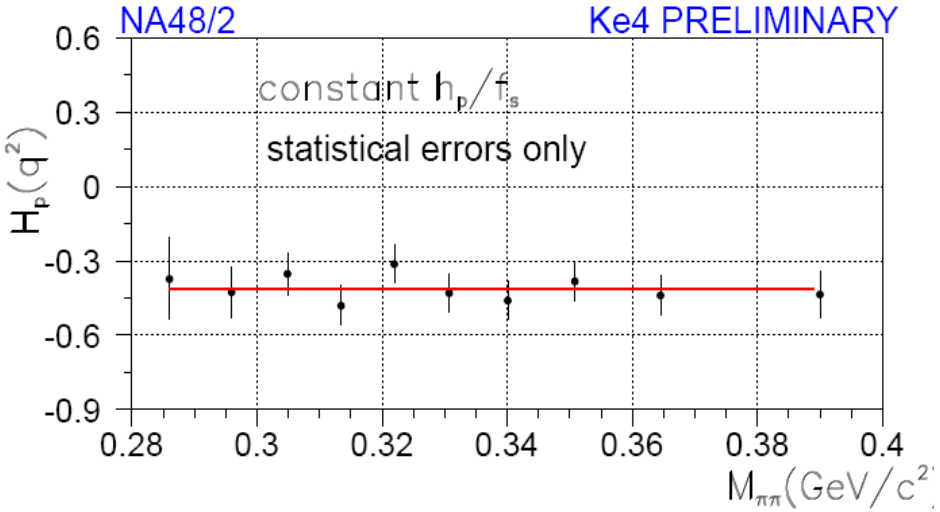
-Not giving (yet) the overall normalization from the Branching fraction, one can quote relative form factors and their variations with q^2,q^4 (q^2= (S_π-4m_π^2)/4m_π^2)

-Se dependence measurement consistent with 0.









Ke4 charged decays : systematics and preliminary results

Snapshot on systematic checks :

- Two independent analyses with slightly different selections, different Kaon reconstruction, detector corrections and fit methods. Residual differences quoted
- Stability of acceptance versus time: variation of simulated beam conditions
- Background level control : estimated both with data (varying cuts) and MC (absolute normalization of various sources).
- Electron identification : variation of the e-π rejection efficiency
- Radiative corrections precision : PHOTOS generator used, fraction of full effect quoted
- Neglected Se dependence : full effect from test simulated event sample quoted

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	$= 0.256 \pm 0.008 \pm 0.007 \pm 0.018$ Theory (Universal Band)

Corresponding to $a_0^2 = -0.031 \pm 0.002 \pm 0.002 \pm 0.009$ Theory

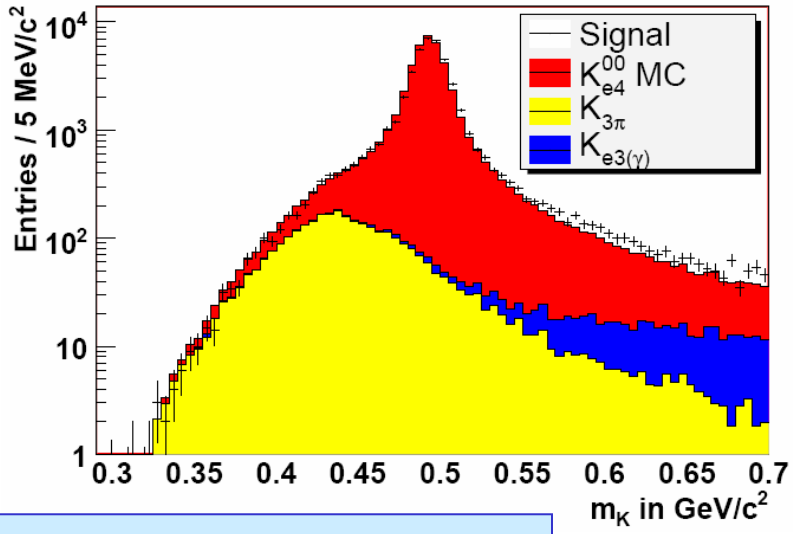
Ke4 neutral decays : Branching fraction

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
$\pi^{\pm}\ \pi^0\ \pi^0$ 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-)

$$BR\left(K^{00}_{e4}\right) = \left(2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext}\right) \times 10^{-5}$$

($\pi^{\pm}\ \pi^0\ \pi^0$) as normalization

Ke4 neutral decays : Form Factor

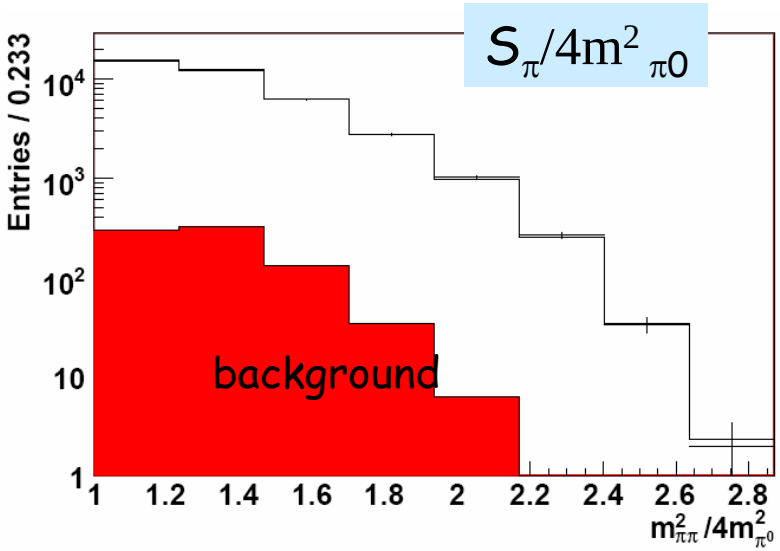
Two identical π^0 → only ONE form factor F (no p wave)

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

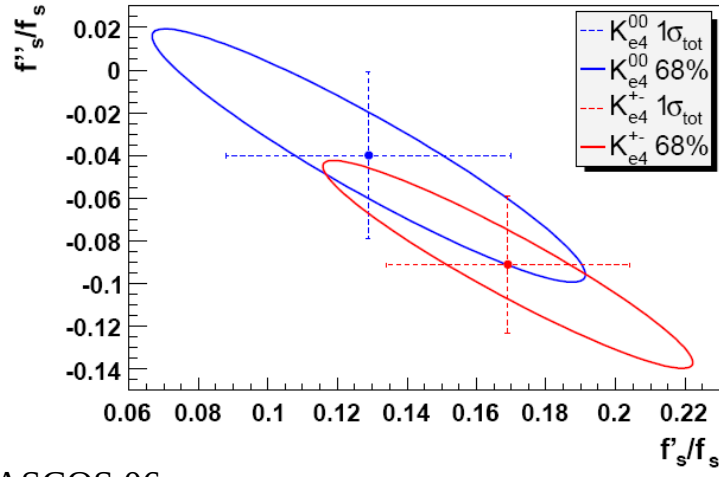
Form factors (2003 +2004 data,K+ and K-)
Se dependence measurement consistent with 0.

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

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



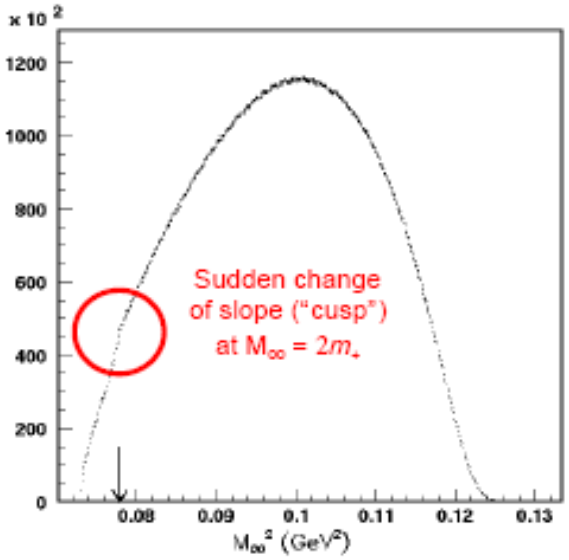
Ke4 charged and neutral FF consistent

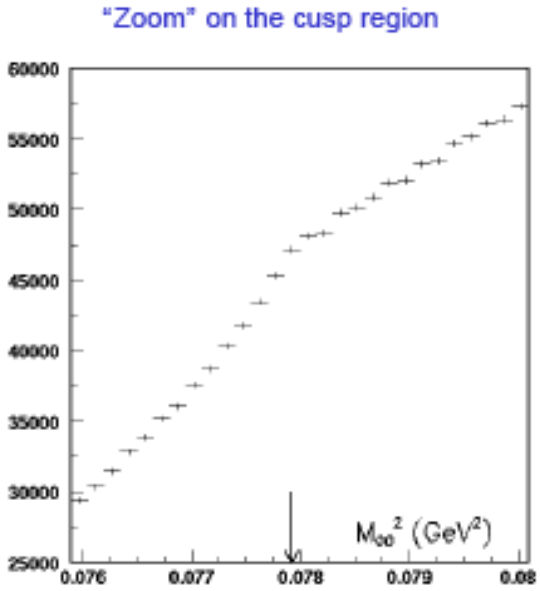


The cusp effect in $\pi^{\pm}\ \pi^0\ \pi^0$ decays

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 $M_{00} = 2m_{\pi^{\pm}}$





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)

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

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

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

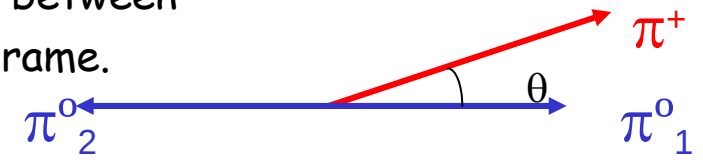
$(a_0-a_2) = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$

if the correlation between a_0 and a_2 predicted by ChPT is taken into account,

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

The cusp effect : more investigations for a k term

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

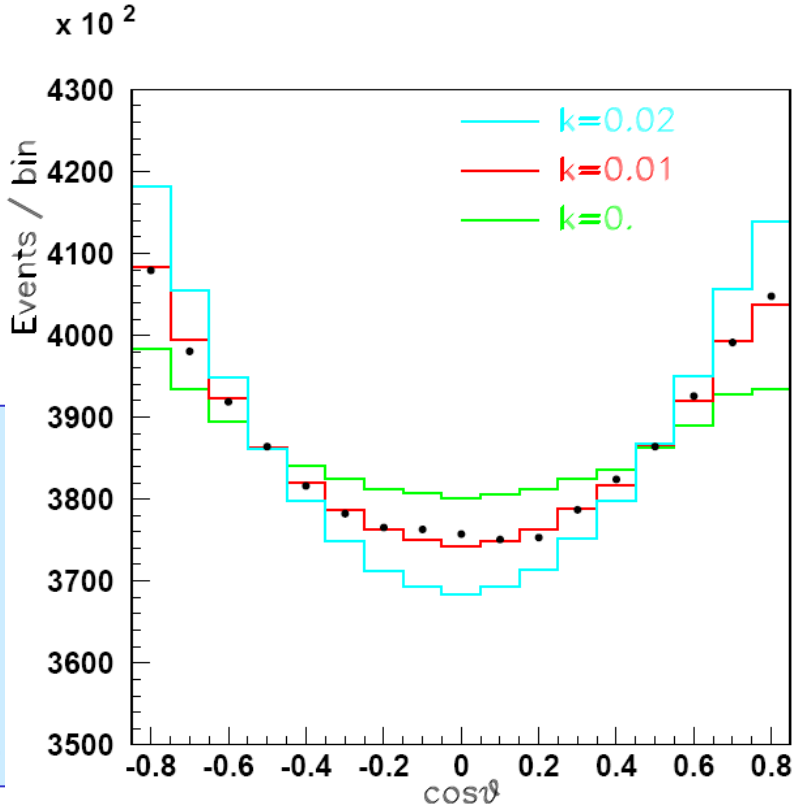


Use a modified matrix element :

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

re-fit in M^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 new meaning of g_0 and h'

-the different meaning (h',k') wrt PDG (h,k)

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

Comparison with previous published Ke4 results : same framework needed !

- CERN/PS Geneva-Saclay ~30000 decays (K^+) (Phys. Rev. D15 (1977))
- BNL E865 ~400 000 decays (K^+) (Phys. Rev. Lett. 87 (2001), Phys. Rev. D67 (2003)
- CERN/SPS NA48/2 : prelim. result from ~370 000 decays ($K^{+/-}$)

use the same Universal Band function (stat. + syst. errors added):

CERN/PS Geneva-Saclay

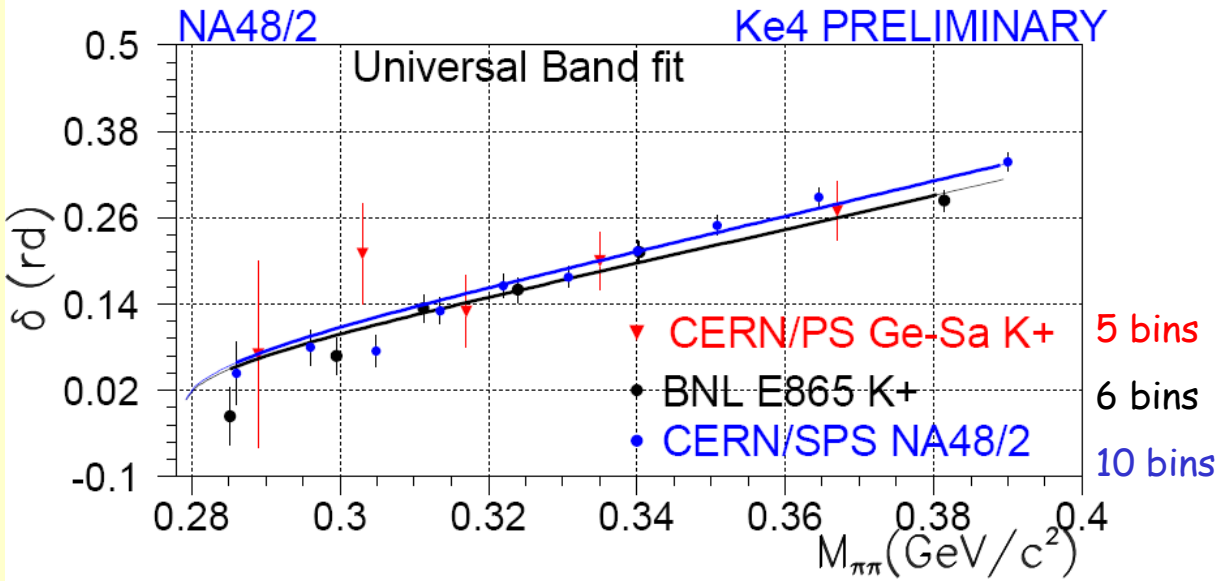
a_0^0 0.253 ± 0.040

BNL E865

a_0^0 0.229 ± 0.015

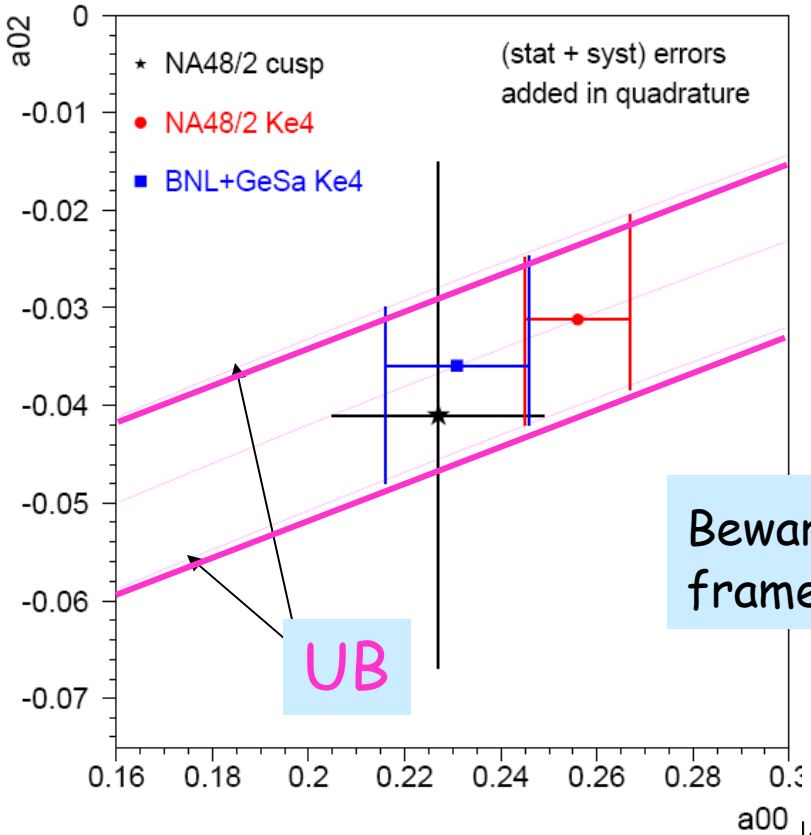
CERN/SPS NA48/2

a_0^0 0.256 ± 0.011



π–π scattering lengths in NA48/2

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



They maybe compared together and to other experimental measurements if in the same theoretical framework

Beware of different theoretical frameworks… work in progress !

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).

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

(10 times better than current PDG)

Using a conservative theoretical approach, a preliminary value of a_0^0 is obtained with 3% precision (both stat. and syst.).

$a00 = 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{theo}$ (Universal Band)

Cusp

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

$a00 - a20 = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{theo}$

First evidence for a non-zero k' term

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

A joint study of Ke4 and Cusp analyses will provide stringent constrains in the (a_0^0, a_0^2) plane (with help from theorists!)