# 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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**For the NA48/2 collaboration:**
**Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna**

# Outline

- The NA48/2 experiment : goals, beams, detector, performances
- Ke4 charged decays : formalism, event selection, form factors
- Ke4 neutral decays : event selection, form factors, Branching fraction
- $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0$ decays : the "cusp" effect
- 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 A.Norton)

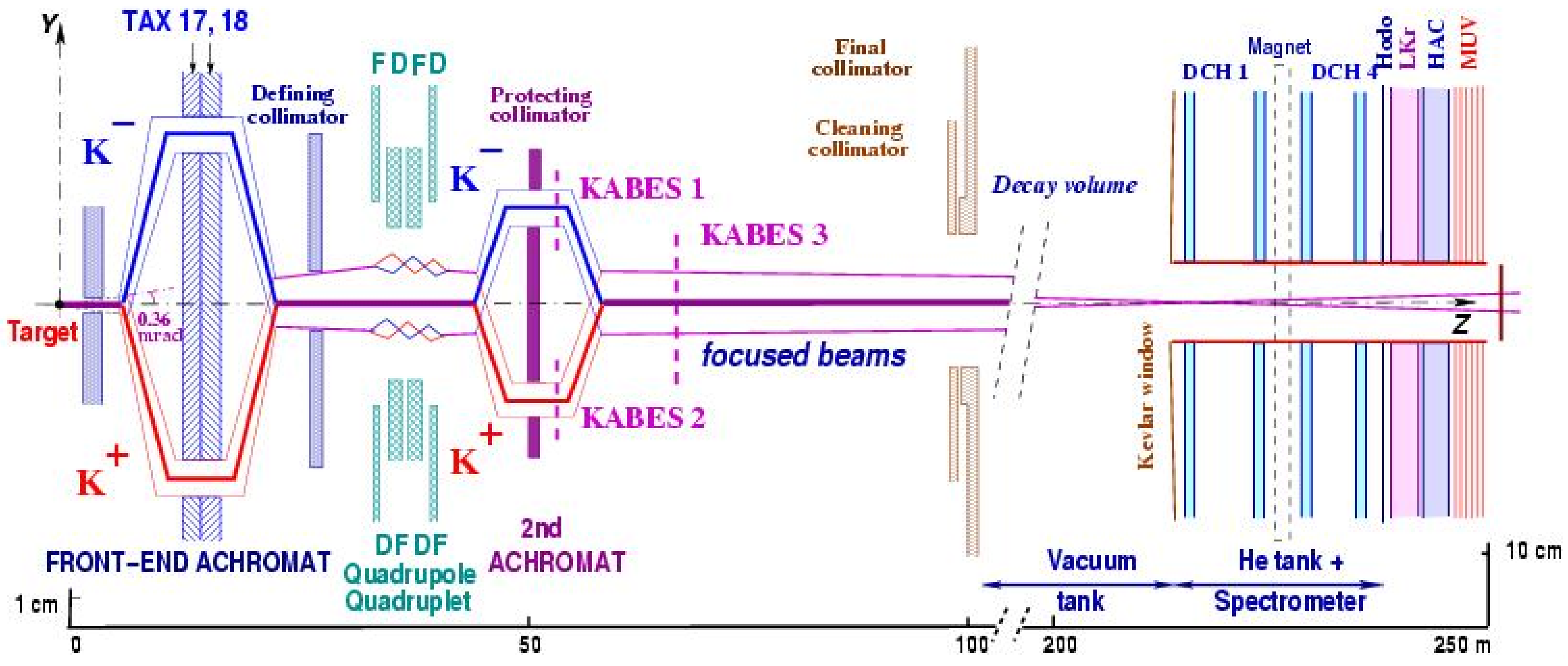
and also

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

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

# The NA48/2 experiment: beams and detector

Simultaneous $K^+/K^-$ beams : $(60 \pm 3)$ 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

~3.10$^4$ $\pi^0\pi^0 e^\pm \nu$ decays

Preliminary charged $K_{e4}$ results based on 370000 decays

(30 days in 2003)

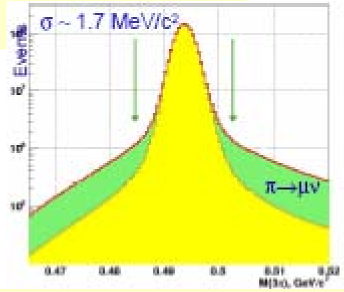
# The NA48/2 experiment: detector performances

Most important components for Ke4 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)




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

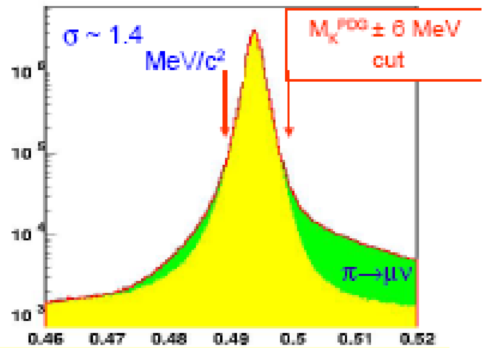
LKr electromagnetic calorimeter : quasi-homogenous and high granularity

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

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

→ Very good resolution for neutral invariant masses ($\pi^0$)

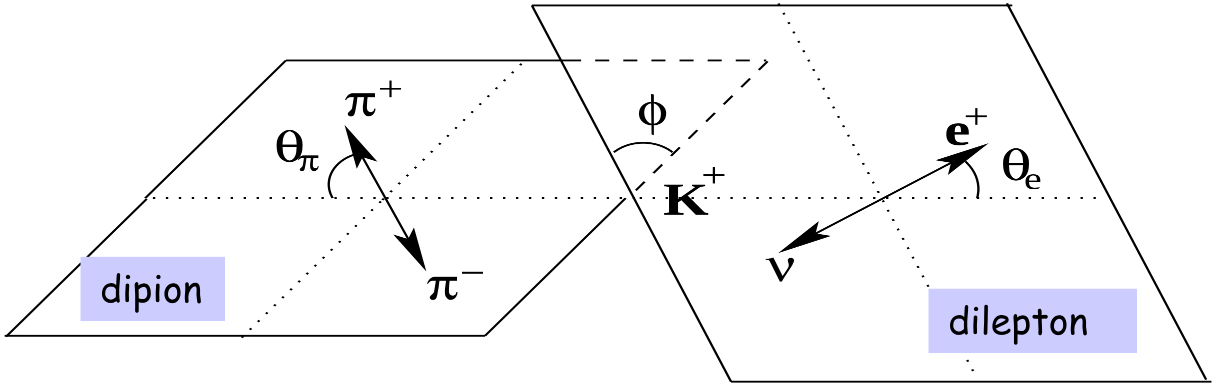
→ E/p measurement for e/π discrimination




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

# Ke4 charged decays : formalism

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




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 ($S_\pi$ is small in Ke4) , rotating phases by $\delta_p$ 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 $q^2$ ($q^2 = (S_\pi - 4m_\pi^2)/4m_\pi^2$), $S_e$…

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

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

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

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

# Ke4 charged decays : event selection

**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

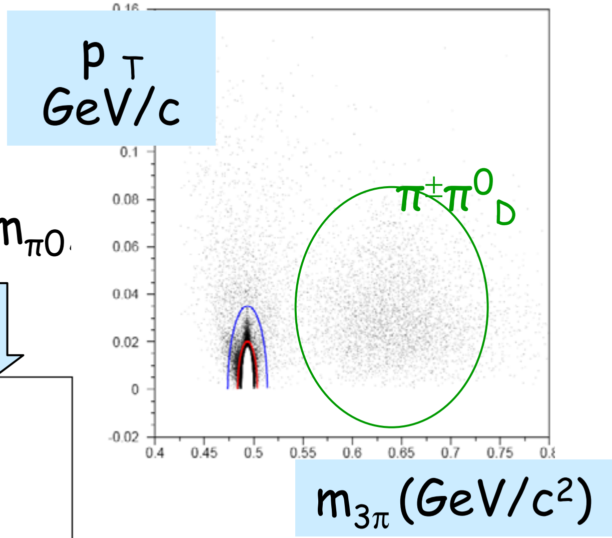
$\pi^{\pm}\pi^+\pi^-$ decay + $\pi \rightarrow e\nu$ decay (dominates with same topology as signal)
+ $\pi$ misidentified as e

$\pi^{\pm}\pi^0(\pi^0)$ decay + $\pi^0$ Dalitz decay ($e^+e^-\gamma$) with e misidentified as $\pi$ and $\gamma$ (s) undetected

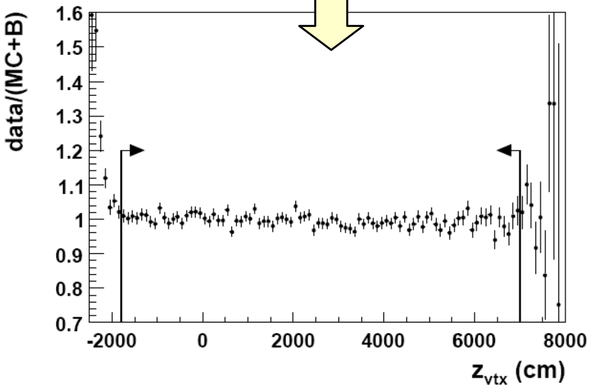
**Control from data sample** : Wrong Sign events have the same total charge but $e^-$ and $\pi^+\pi^+$ for $K^+$ decays ($e+$ and $\pi^-\pi^-$ for $K^-$ decays). Depending on the process, background events appear in Right Sign events with the same rate as in WS events or twice the rate

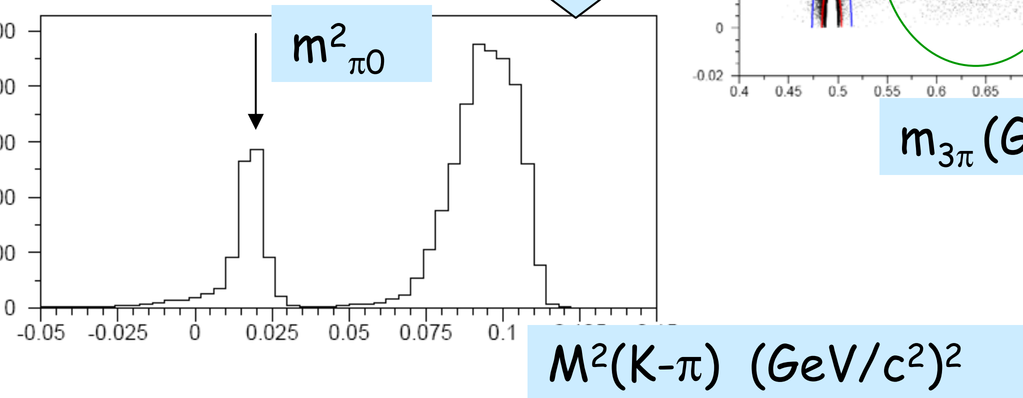
# Ke4 charged decays : background rejection

- Against $\pi^{\pm}\,\pi^{+}\,\pi^{-}$ : elliptic cut in the plane ($m_{3\pi}$, $p_T$) assigning $m_\pi$ to each particle




- Against $\pi^{\pm}\pi^{0}_{D}$: missing mass to ($K^{\pm}$ - $\pi^{\pm}$) larger than $m_{\pi 0}$, reconstructed vertex away from last collimator




- Additional e-π rejection from Linear Discrimant Analysis (LDA) or Neural network (NN) methods using shower shape variables

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

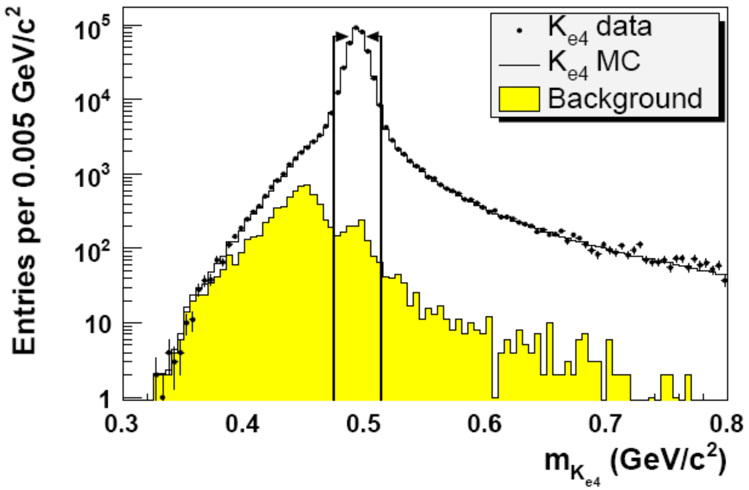
# Ke4 charged decays : event reconstruction

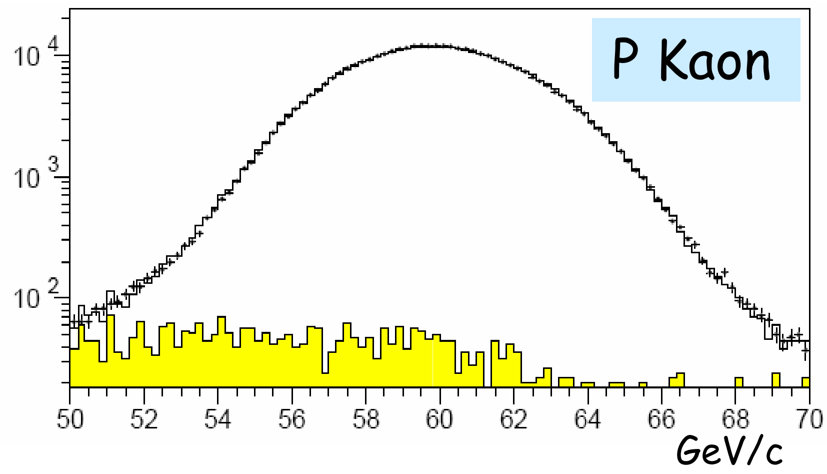
Reconstruction of the C.M. variables : Two options

• 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 $\phi$) one defines a grid of **10x5x5x5x12=15000 boxes**.

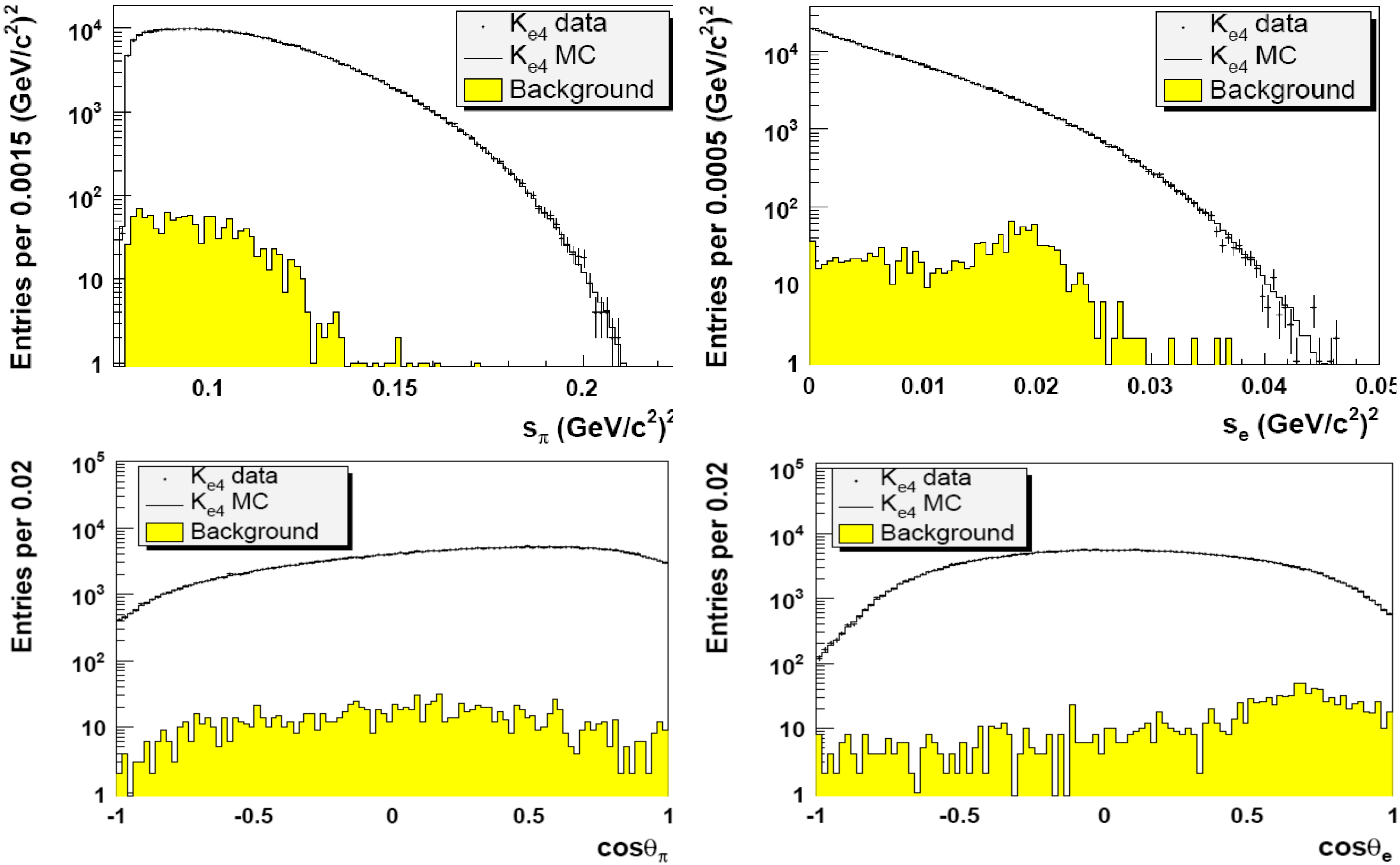
The set of form factor values are used to minimize the $T^2$, a log-likelihood estimator well suited for small numbers of data events/bin Nj and taking into account the statistics of the simulation = Mj simulated events/bin and Rj expected events/bin.

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

For the $K^+$ sample (235000 events), there are 16 events/bin

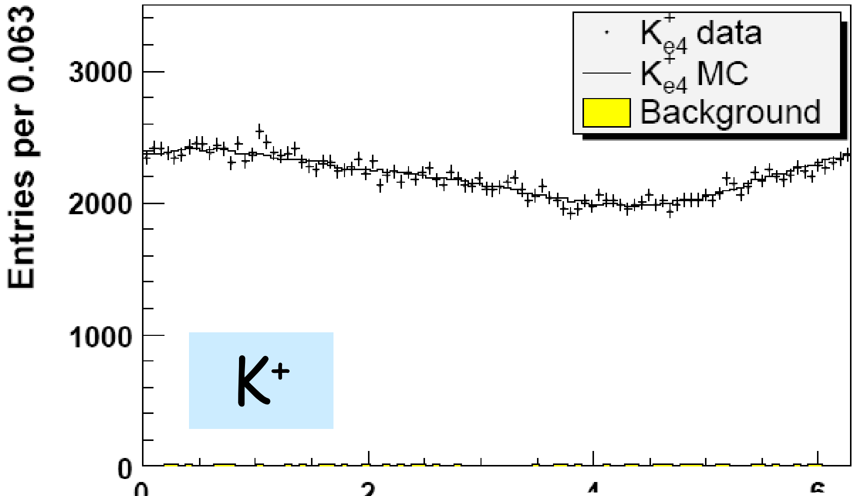
For the $K^-$ sample (135000 events), there are 9 events/bin

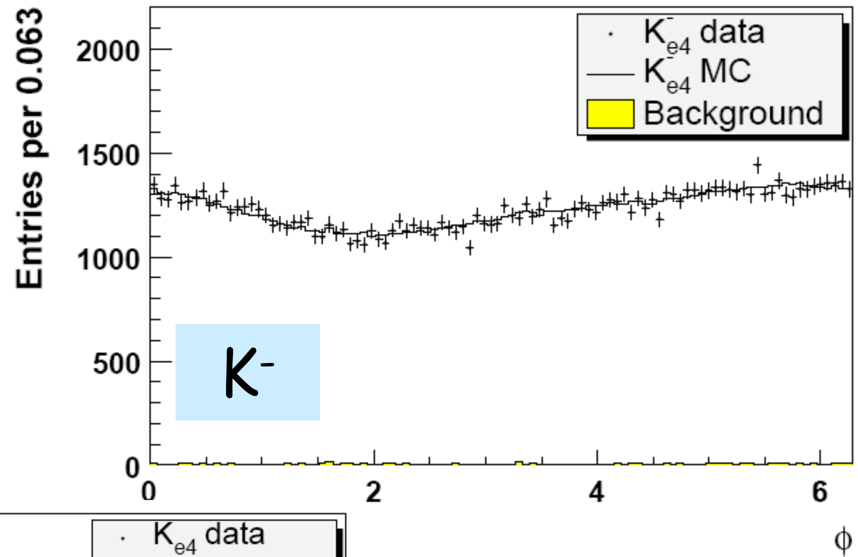
# Ke4 charged decays : the 5 C.M. distributions

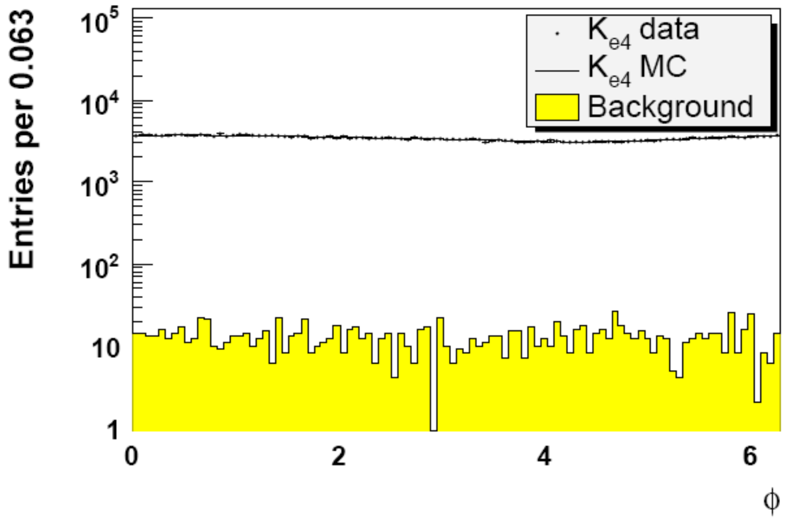


# Ke4 charged decays : the 5 fit distributions

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



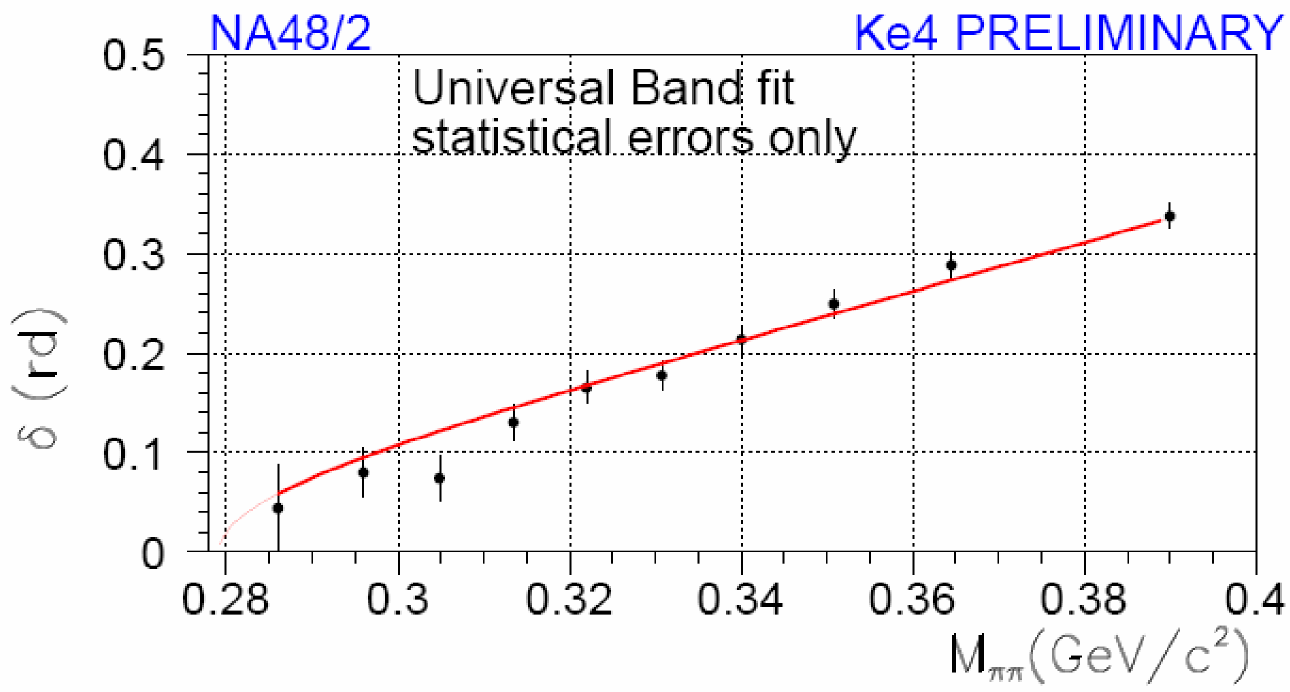




K$^+$($\phi$) + K$^-$(-$\phi$)

Note the log scale to see the background!

# Ke4 charged decays : form factors

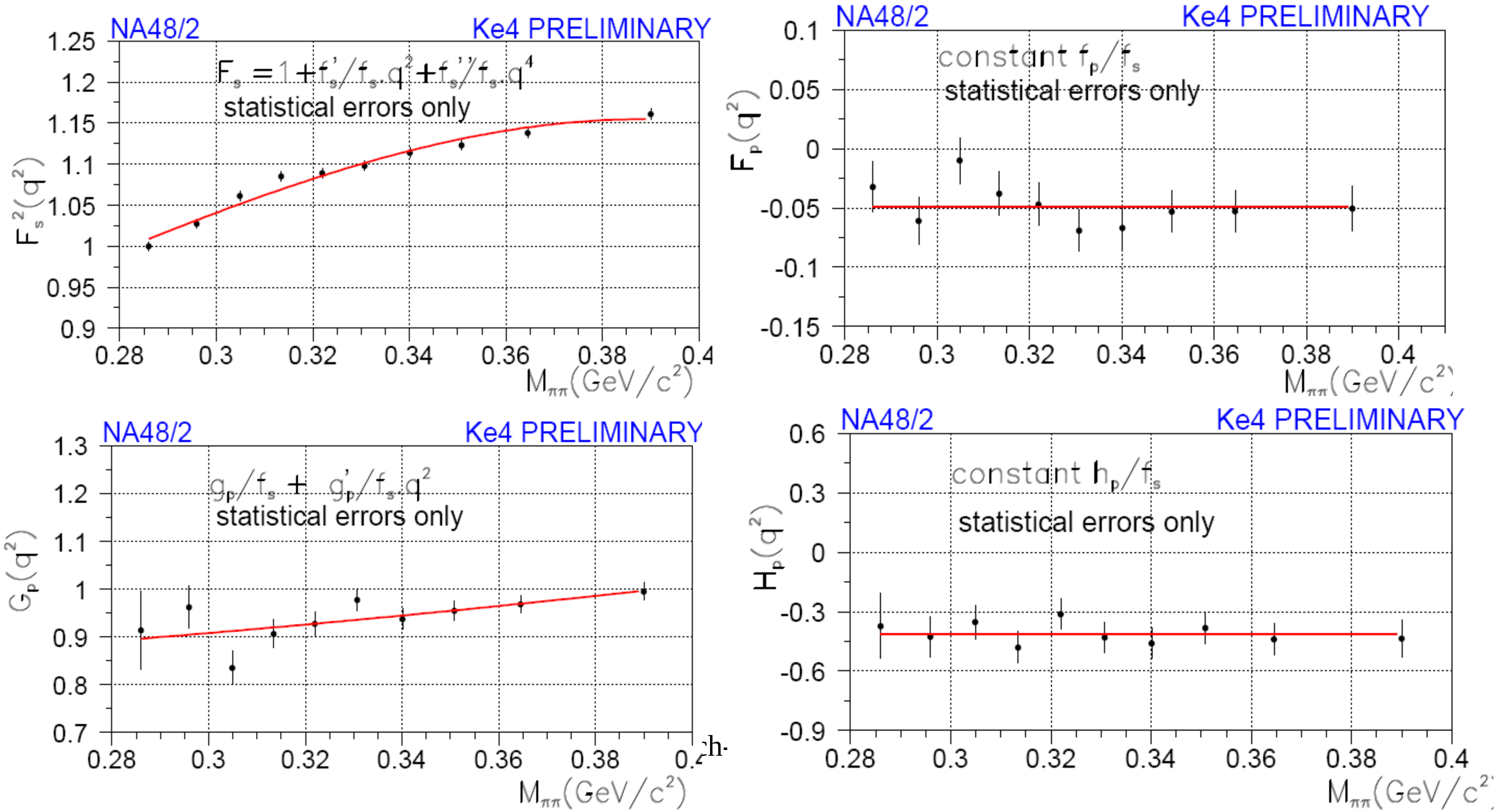
- **Ten independent fits**, one in each $M_{\pi\pi}$ bin, assuming ~constant form factors over each bin.
- **Use the Universal Band** parameterization to extract $a_0^0$ with $a_0^2 = f(a_0^0)$ (Ananthanarayan et al. Phys. Rep.353 (2001), Descotes et al. EPJ C24 (2002) )



# Ke4 charged decays : form factors

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

Se dependence measurement consistent with 0.



# Ke4 charged decays : form factors systematics

Snapshot on preliminary systematic uncertainties :

•Two independent analyses with slightly different selections, different K reconstruction, detector corrections and fit methods give consistent results. Residual differences quoted as systematics.

•Beam simulation versus time (acceptance): estimated by varying beam conditions of the simulated events

•Background level control : estimated both with data (varying cuts) and MC (absolute normalization of various sources).

•Electron identification : varying the efficiency of e-$\pi$ rejection, largest difference quoted

•Radiative corrections precision : PHOTOS generator used, fraction of full effect quoted

•Possible Se dependence of the form factors: full effect from simulated event sample quoted

# Ke4 charged decays : form factors

| | | $K^+$ and $K^-$ combined | |
|---|---|---|---|
| | result | statistical error | systematic error |
| $f_s^{'}/f_s$ | 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 |
| $a_0^0$ (UB)<br>implying<br>$a_0^2$(UB) | 0.256<br><br>-0.031 | $\pm$ 0.008<br><br>$\pm$ 0.015 | $\pm$ 0.007<br>$\pm$ 0.018 Theory<br>$\pm$ 0.015<br>$\pm$ 0.009 Theory |

## Ke4 charged decays: Summary

A large sample of 370000 Ke4 decays has been analyzed

Form factor variations with $q^2(q^4)$ have been measured with an improved precision, dominated by the systematic uncertainty.

A high sensitivity to $a_0^0$ is achieved with similar statistics and systematic uncertainties (3% relative each) due to significant acceptance at large $m_{\pi\pi}$ values, high resolution and low background level.

The external error from the theory (7% relative) is expected to be reduced by models more elaborated than the Universal Band

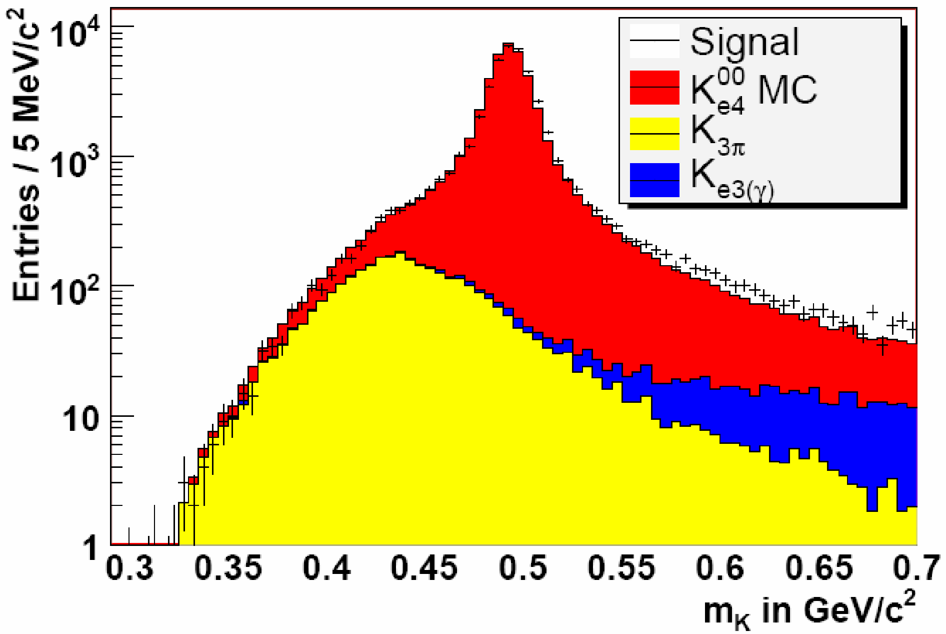
# Ke4 neutral decays

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

**Background** : main sources

$\pi^{\pm}\pi^0\pi^0$ decay + π misidentified as e (dominant)

$\pi^0 e^{\pm}\nu\gamma$ decay + accidental γ



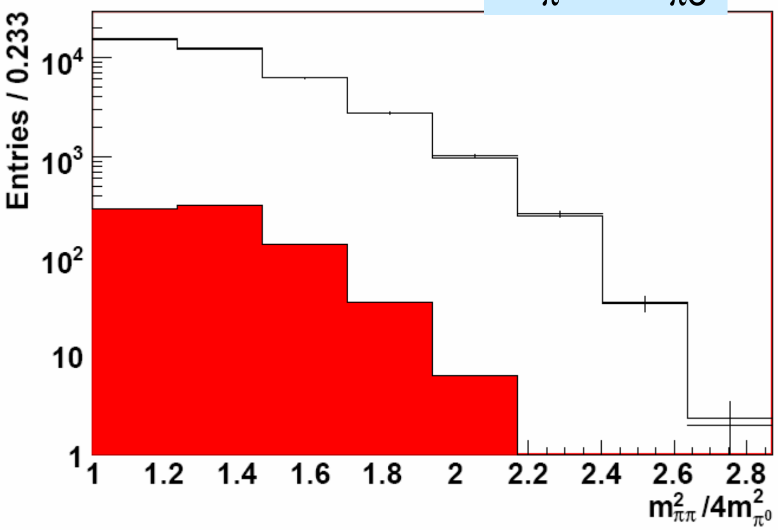
# Ke4 neutral decays : formalism

Branching fraction measurement

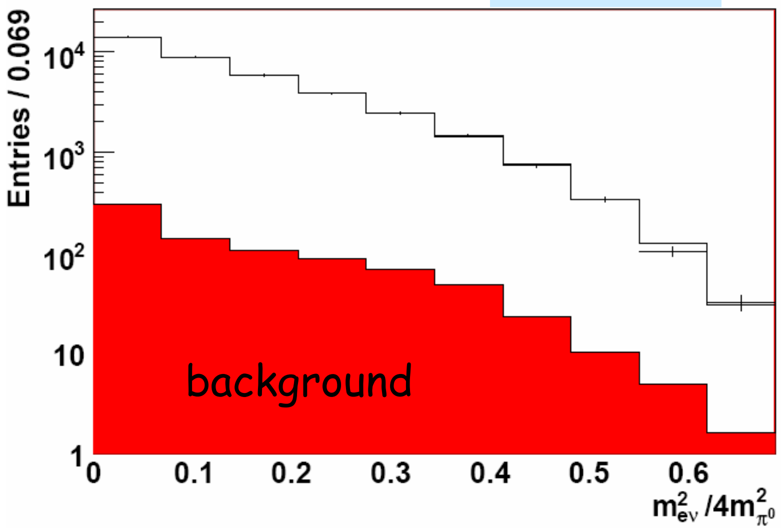
Two identical $\pi^0$ → only ONE form factor F

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

$S_\pi/4m^2_{\pi 0}$




$S_e/4m^2_{\pi 0}$



# Ke4 neutral decays : results

Branching fraction : using 2003 data and ($\pi^{\pm}\ \pi^0\ \pi^0$) as normalization channel, 9642 signal events (276 ± 94 background events)

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

Form factors (2003+2004 data = ~37000 events):
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 neutral decays : summary

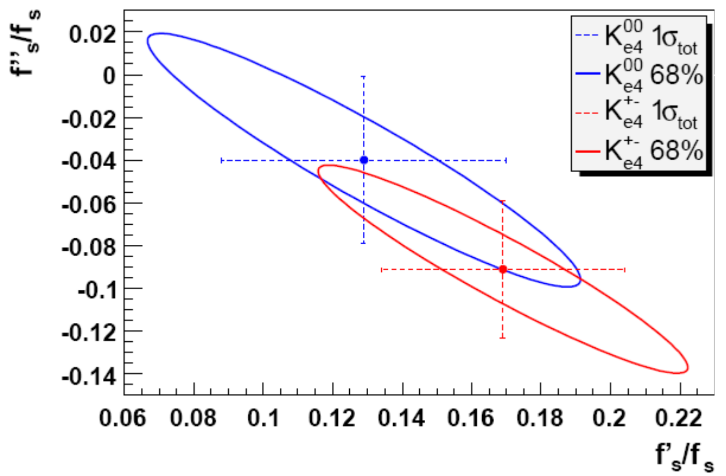
An improved measurement of the BR has been achieved, to be compared with recent published value

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

This measurement :

$$(2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext})\ 10^{-5}$$

Form factor are measured, consistent with the charged Ke4 measurement



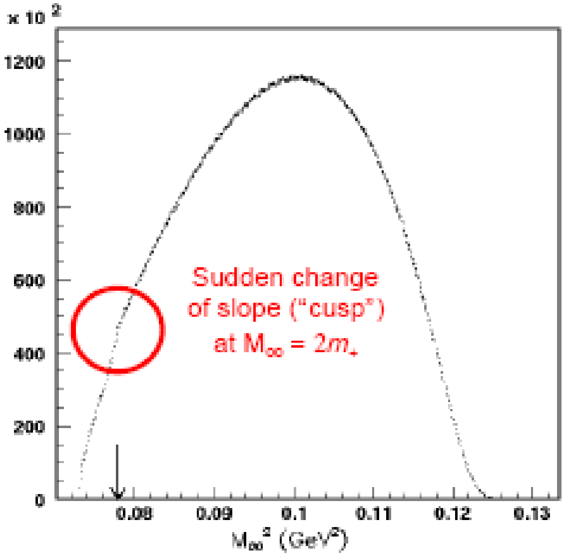

Errors are stat. + syst. assuming same correlation for both.

Using full statistics, the dominant error on BR will be the external error.

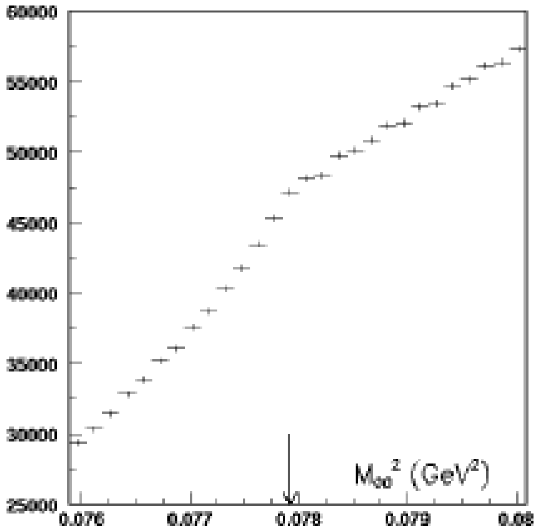
# The cusp effect in $\pi^{\pm}\,\pi^0\,\pi^0$ decays

Result presented as preliminary last year at QCD05 and now 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 $M_{00} = 2m_+$




"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.

$$M_{+00} = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2 + \frac{1}{2} k v^2 + \ldots$$

The scattering length difference is found to be :

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

and

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

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

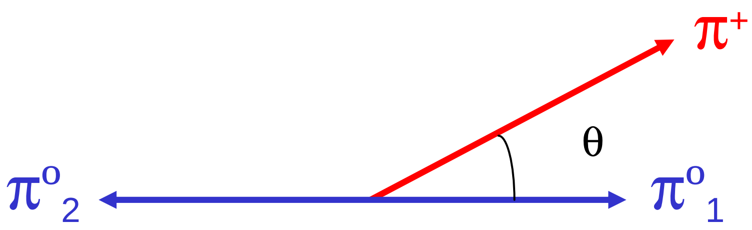
$$(a_0 - a_2)\, m_+ = 0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

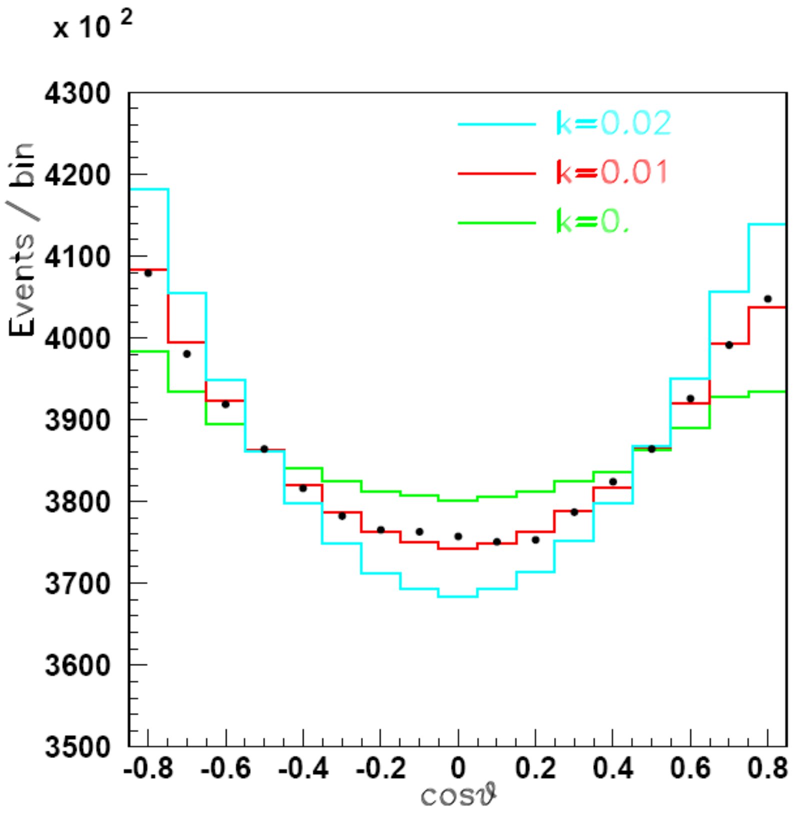
From the same fit the following slope parameters are extracted:

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

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

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 $\cos\theta$ where $\theta$ is the angle between the charged $\pi$ and the direction of the $\pi^0$'s in their rest frame.




A comparison of data distribution with MC, generated with different k values, favors a non-zero k value (for $M^2_{00}$ in the range [0.082, 0.097] $(GeV/c^2)^2$) but has no incidence on previous **$(a_0-a_2)$ $m_+$** result.

# Ke4 charged decays : π π scattering lengths

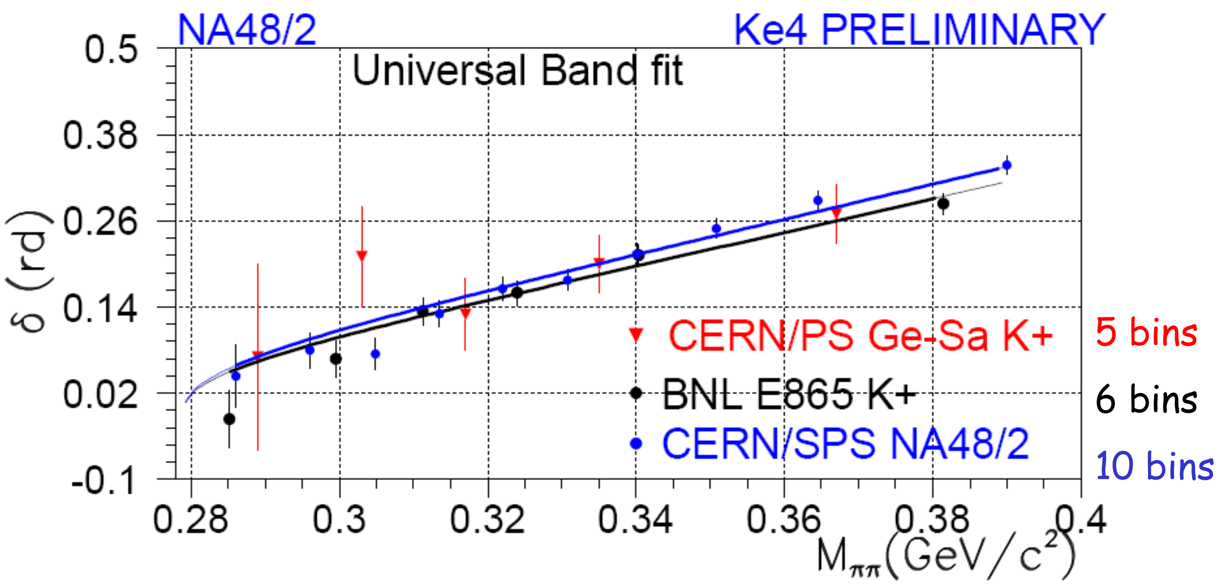
Comparison with previous published Ke4 results : same framework needed !

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

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

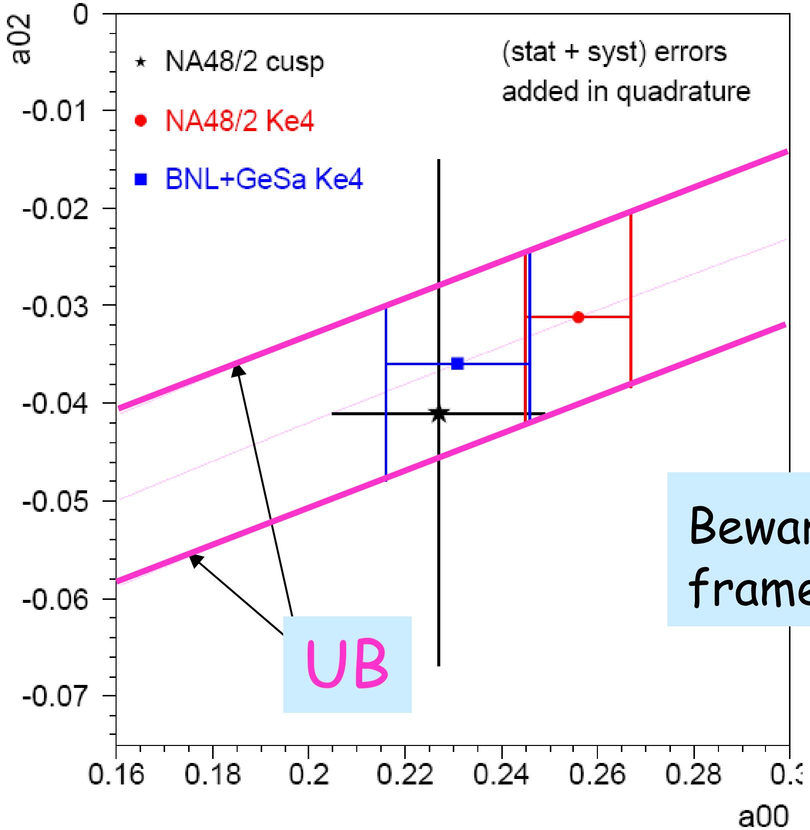
BNL E865 + CERN/PS Geneva-Saclay: $a_0^0 = 0.231 \pm 0.015$

CERN/SPS NA48/2 $a_0^0 = 0.256 \pm 0.011$



# 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… To be worked out !

# Final conclusion

Using part of the data 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).

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

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