# Measurements of $K^{\pm}\rightarrow\pi^{+}\pi^{-}e^{\pm}\nu$ (Ke4) and $K^{\pm}\rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays at NA48/2.

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# Overview

- Introduction to NA48
- The NA48/2 experiment: goal, beam line, detector

- The $K^{\pm}\rightarrow\pi^{+}\pi^{-}e^{\pm}\nu$ (Ke4) decay
  - Introduction
  - Selection, reconstruction
  - Form factor and ππ scattering length measurements
- The $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ decay
  - Selection, reconstruction
  - Cusp effect and interpretation
  - Form factors and ππ scattering length measurements

- Summary and Conclusions

# Introduction

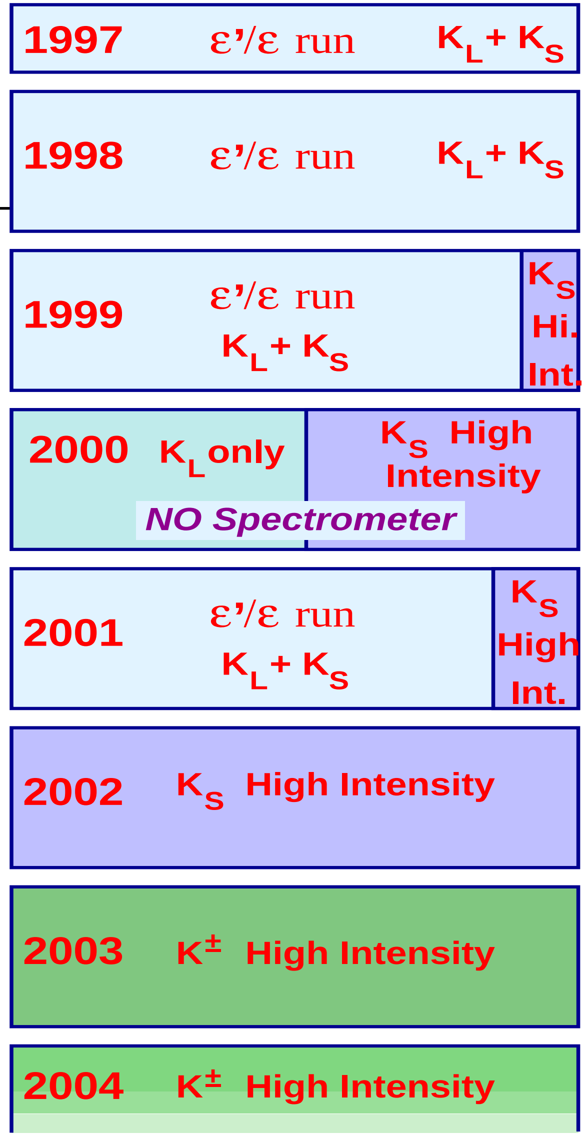
- **NA48: 1997-2000.** DCPV in neutral K
  - $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2)\ 10^{-4}$

- **NA48/1: 2002.** Rare Ks decays
  - $Br(Ks \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8)\ 10^{-9}$
  - $Br(Ks \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2)\ 10^{-9}$

- **NA48/2: 2003-2004.** DCPV in $K^\pm \to 3\pi$
  - $A_g\ (K^\pm \to \pi^\pm \pi^+ \pi^-) = (-1.3 \pm 2.3)\ 10^{-4}$ (La Thuile 06)
  - $A_g\ (K^\pm \to \pi^\pm \pi^0 \pi^0) = (\ 2.1 \pm 1.9)\ 10^{-4}$ (ICHEP 06)

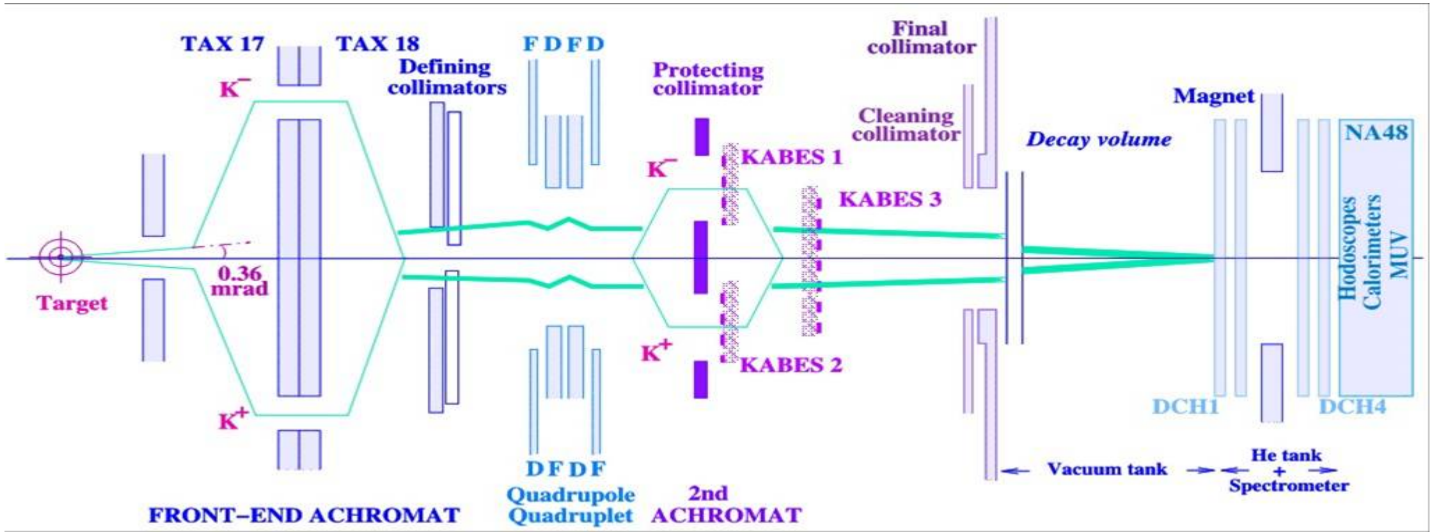
- **In addition many results on rare kaon decays and on hyperon decays.**

- **Results from a partial sample of NA48/2 2003 data will be shown**



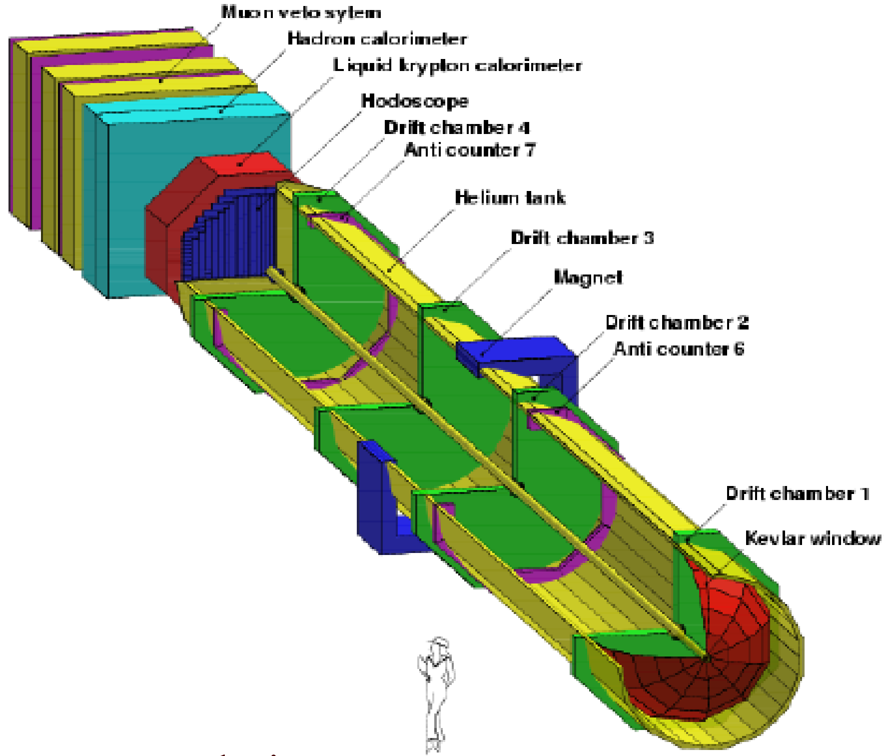
# The NA48/2 Beam Line

- Simultaneous, coaxial and focused $K^+$ and $K^-$ beams
- Central kaon momentum of 60 GeV/c and a spread of ± 3.8% (rms)
- Beam line and spectrometer magnet polarities periodically inverted



# The NA48 Detector

- Magnetic spectrometer
  - 4 DCHs, 4 views, 2 planes/view + dipole magnet
  - $\sigma(p)/p=(1.02 \oplus 0.044p)\%$
  - $P_t$ kick=120 MeV/c
  - $\sigma(t)$ = 1.4 ns
- Charged hodoscope
  - $\sigma(t)$ = 200 ps
- LKr electromagnetic calorimeter
  - 27 $X^0$ with 13212 2x2 $cm^2$ cells
  - $\sigma(E)/E=(3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$
  - $\sigma(x)=\sigma(y)=0.42/\sqrt{E} \oplus 0.06$ cm
  - $\sigma(t)$ = 265 ps
- Muon Counters
  - 2+1 planes 25x25 $cm^2$ $\sigma(t)$ = 350 ps

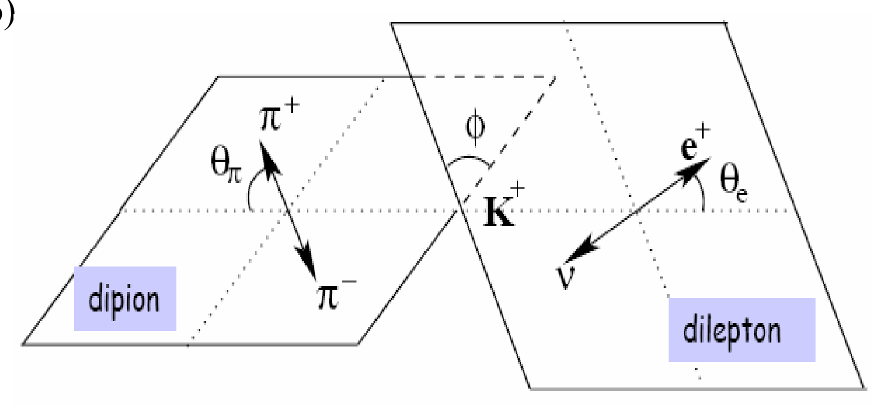



Mass resolutions

$\sigma(\pi^{\pm}\pi^{+}\pi^{-})$= 1.7 MeV/$c^2$ $\sigma(\pi^{\pm}\pi^{0}\pi^{0})$=1.4 MeV/$c^2$

# The $K^{\pm}e4$ decay: Introduction

- $Br(Ke4)=(4.08\pm0.09)\ 10^{-5}$ (PDG06)
- Kinematic variables:
  - $S_\pi\ (M^2_{\pi\pi})$
  - $S_e\ (M^2_{e\nu})$
  - $\cos\theta_\pi$
  - $\cos\theta_e$
  - $\phi$




- Form factors determined by fitting the data distributions.

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p}\cos\theta_\pi$$
$$G = G_p e^{i\delta_g}$$
$$H = H_p e^{i\delta_h}$$

Expanding in terms of $q^2$ ( $\propto S_\pi$), $S_e$

$$F_s = f_s + f_s^{'} q^2 + f_s^{''} q^4 + f_e\left(S_e / 4m_\pi^2\right) + \ldots$$
$$F_p = f_p + f_p^{'} q^2 + \ldots$$
$$G_p = g_p + g_p^{'} q^2 + \ldots$$
$$H_p = h_p + h_p^{'} q^2 + \ldots$$

- **Fit $F_s$, $F_p$, $G_p$ , $H_p$ and $\delta = \delta_s - \delta_p$**

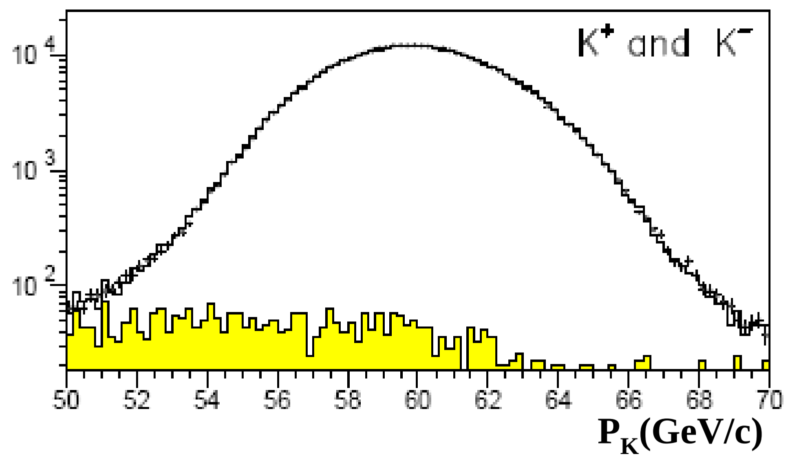
# The $K^{\pm}e4$ decay: Selection

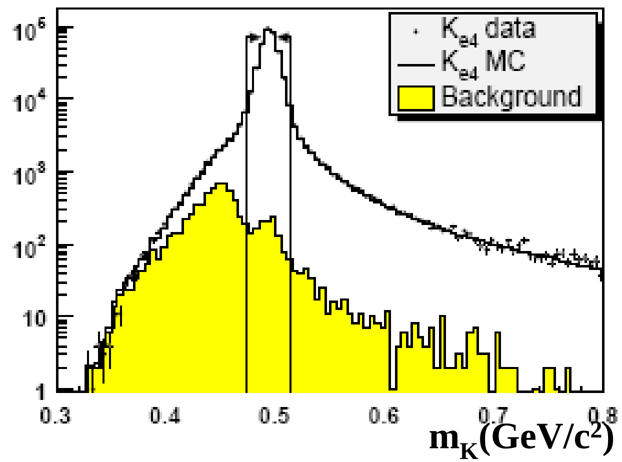
- Selection:
  - Three tracks, two opposite charged pions, one electron, missing energy and $p_t$ (separation $\pi$ /e given by LDA: linear discriminator analysis)
- Background:
  - $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ with $\pi \rightarrow e\nu$ is dominant

    $\pi$ misidentified as electron
  - $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}(\pi^{0})$ with $\pi^{0}$ Dalitz decay ($e^{+}e^{-}\gamma$) with e misid. as $\pi$ , and $\gamma$ undetected
  - Estimation using MC and data ('Wrong sign' events) in agreement
    - In data 'Wrong sign' events (e different sign than kaon) can be only due to background. Scaling factor depending on process.
  - Total background level ~ 0.5%

# The $K^{\pm}e4$ decay: Reconstruction

- Reconstruction. Two approaches:
  - Use constrain given by ν to solve energy-momentum conservation equations and get kaon momentum. Take solution closest to 60 GeV/c
  - Assume a 60 GeV/c kaon along the z axis, assign the missing $p_t$ to the ν and compute the resulting kaon invariant mass. Take events within ± 20 MeV/$c^2$

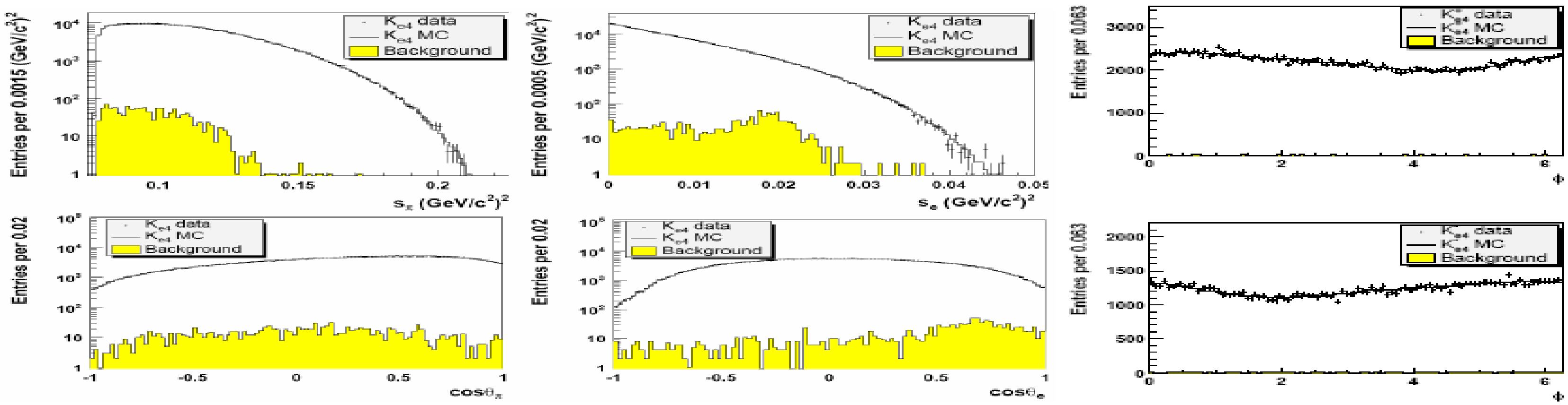



- Statistics: 30 days in 2003, 370000 events

# The K$^{\pm}$e4 decay: Kinematic Distributions

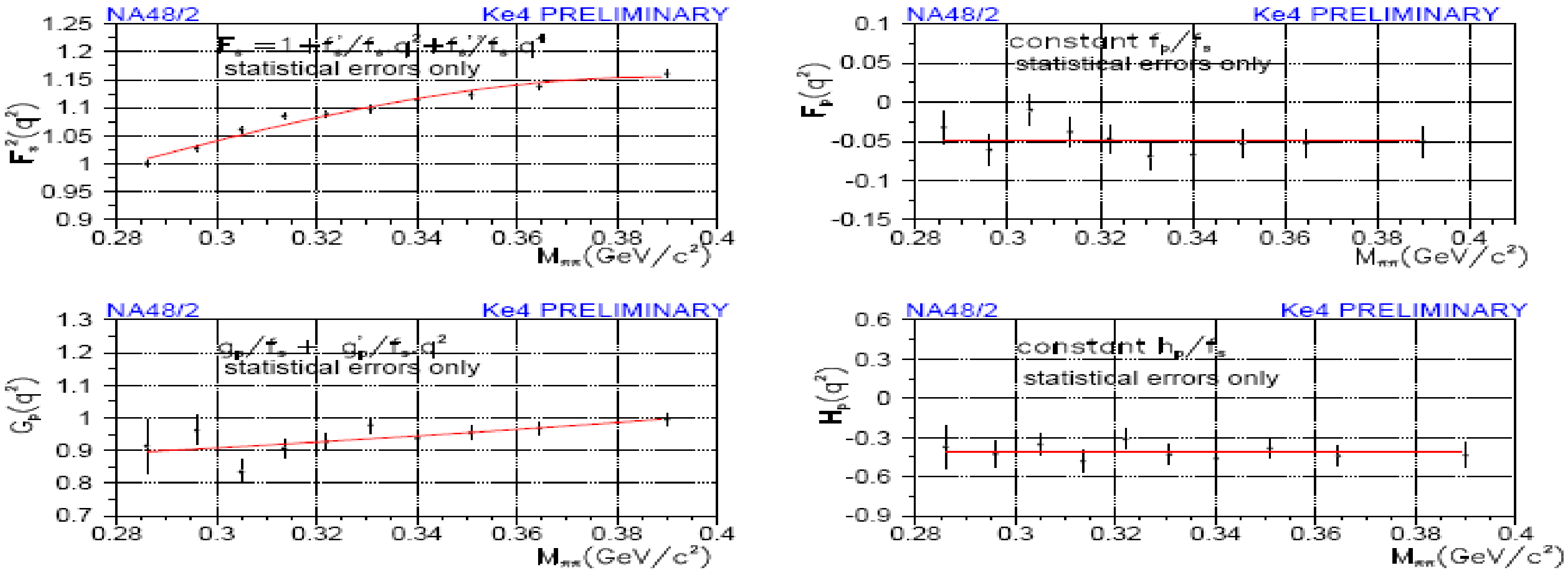
- Distribution of kinematic variables for data and MC
- Background distribution taken from data
- $\phi$ distribution shown separately for K+ and K-




- Fitting of form factors:
  - Define 10x5x5x5x12 iso-populated bins in ($M_{\pi\pi}$ , $M_{e\nu}$ , cos $\theta_{\pi}$ , cos $\theta_{e}$ , $\phi$ )
  - 10 independent fits (one fit per $M_{\pi\pi}$ bin) of 4 par (+ norm) in 4D space.

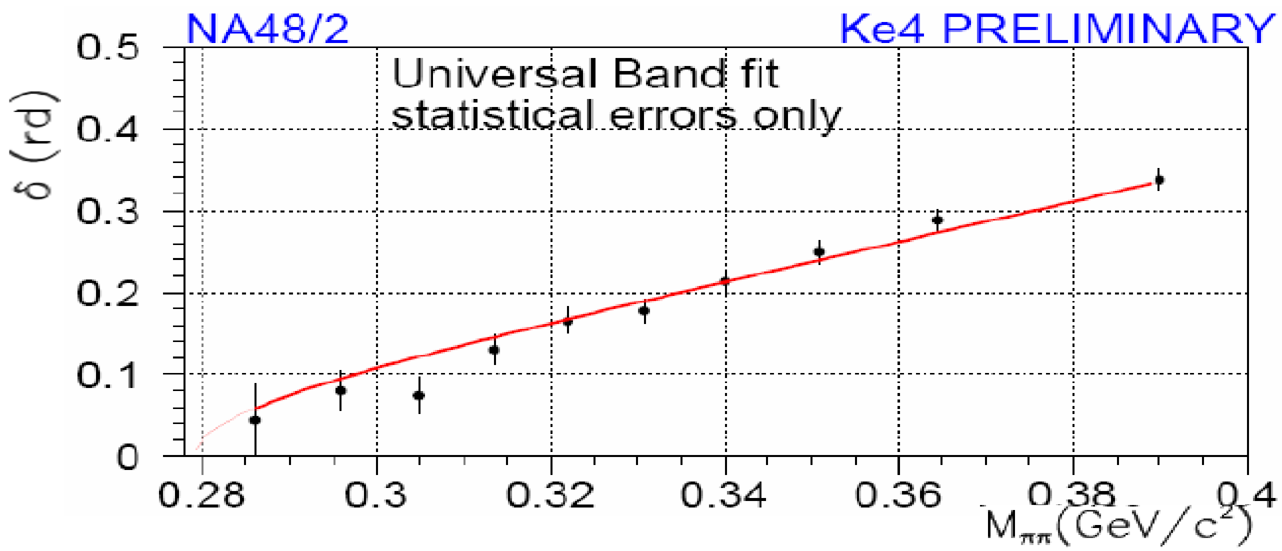
# The $K^{\pm}e4$ decay: Form Factors

- Results for $F^2s$ (normalization), and relative form factors Fp, Gp , Hp
- No absolute normalization available for the moment
- Check dependences: variation with $q^2$ is shown, no variation with $S_e$ found



# The $K^{\pm}e4$ decay: Form Factors

- The $\delta = \delta_s - \delta_p$ variation with $M_{\pi\pi}$ was fitted using Universal Band (numerical solution of Roy equations (A, Phys. Rep. 353 (2001) 207)
- 1 parameter function to extract $a_0$ with $a_2=f(a_0)$ in center of UB
- High sensitivity due to good acceptance for high $M_{\pi\pi}$



# The $K^{\pm}e4$ decay: Results

- Systematic checks
  - Two analysis with different reconstructions, acceptance corrections, fitting methods
  - Beam simulation (acceptance changes)
  - Background level
  - Electron identification
  - Radiative corrections
  - Possible $S_e$ dependence

**NA48/2 Preliminary: 2003 data**

$f'_s / f_s = 0.169 \pm 0.009_{stat} \pm 0.034_{syst}$

$f''_s / f_s = -0.091 \pm 0.009_{stat} \pm 0.031_{syst}$

$f_p / f_s = -0.047 \pm 0.006_{stat} \pm 0.008_{syst}$

$g_p / f_s = 0.891 \pm 0.019_{stat} \pm 0.020_{syst}$

$g'_p / f_s = 0.111 \pm 0.031_{stat} \pm 0.032_{syst}$

$h_p / f_s = -0.411 \pm 0.027_{stat} \pm 0.038_{syst}$

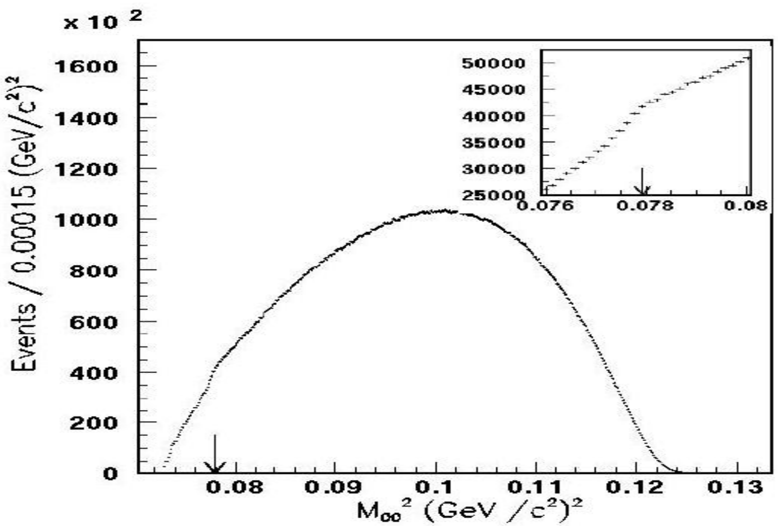
$a_0$ (UB)$= 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{th}$

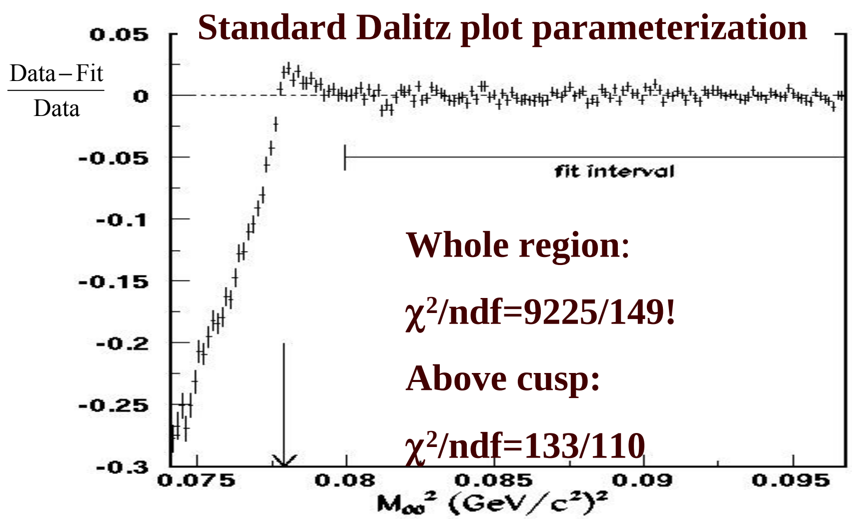
$\rightarrow a_2 = -0.031 \pm 0.015_{stat} \pm 0.015_{syst} \pm 0.019_{th}$

- Prediction for $a_0$ in **ChPT $a_0 = 0.220 \pm 0.005$** **(CGL, PLB 488 (2000) 261)**

# The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decay: Cusp effect

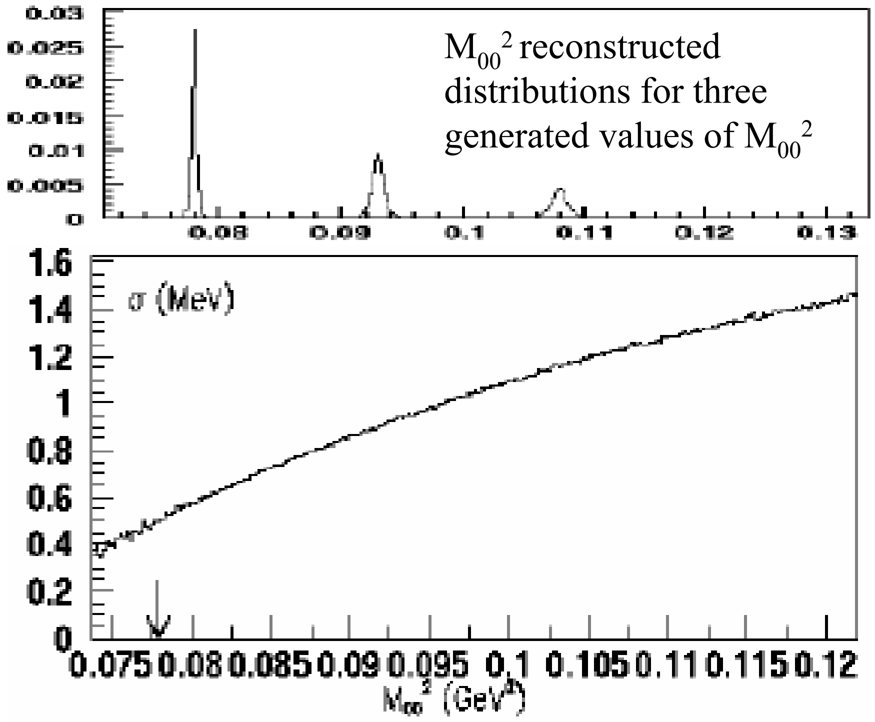
- Reconstruction:
  - At least 4 clusters 15 cm away from any track and 10 cm away from other clusters. Select photon pairs with smallest distance between vertexes. $M_{00}^2$ computed using average vertex of two $\pi^0$
- In sample of 23 $10^6$ events sudden slope variation seen at $M_{00}^2=(2m_{\pi+})^2$
- Standard Dalitz plot parameterization shows deficit in data before cusp



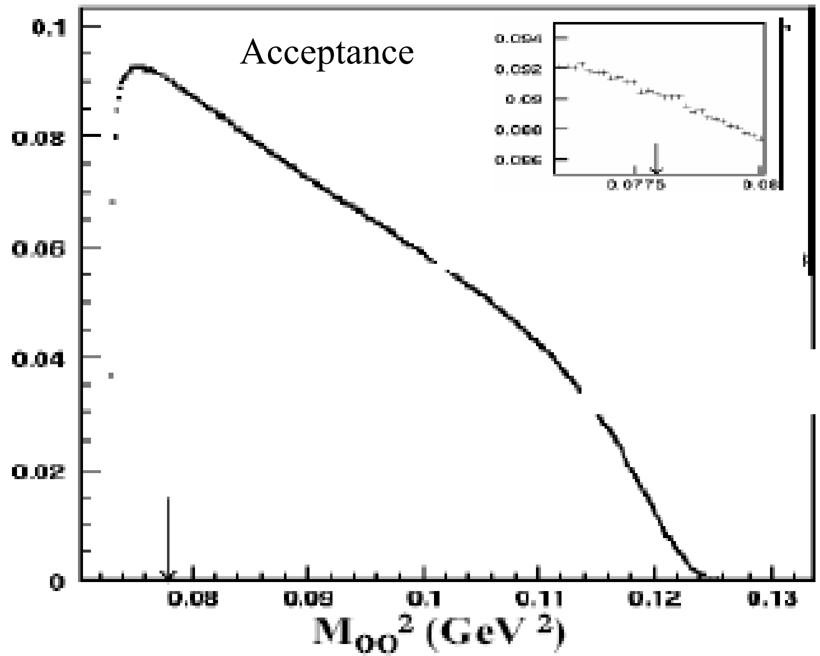



# Cusp on $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$. Checks for instrumental effects

- Good resolution near cusp region

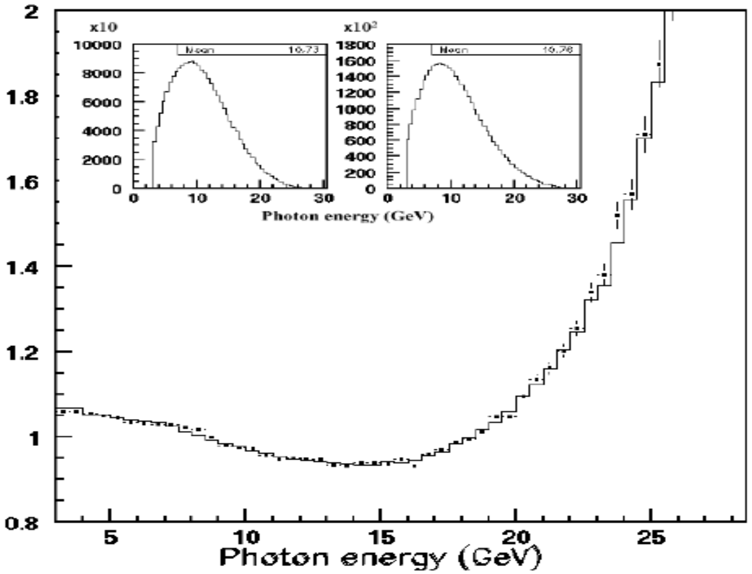


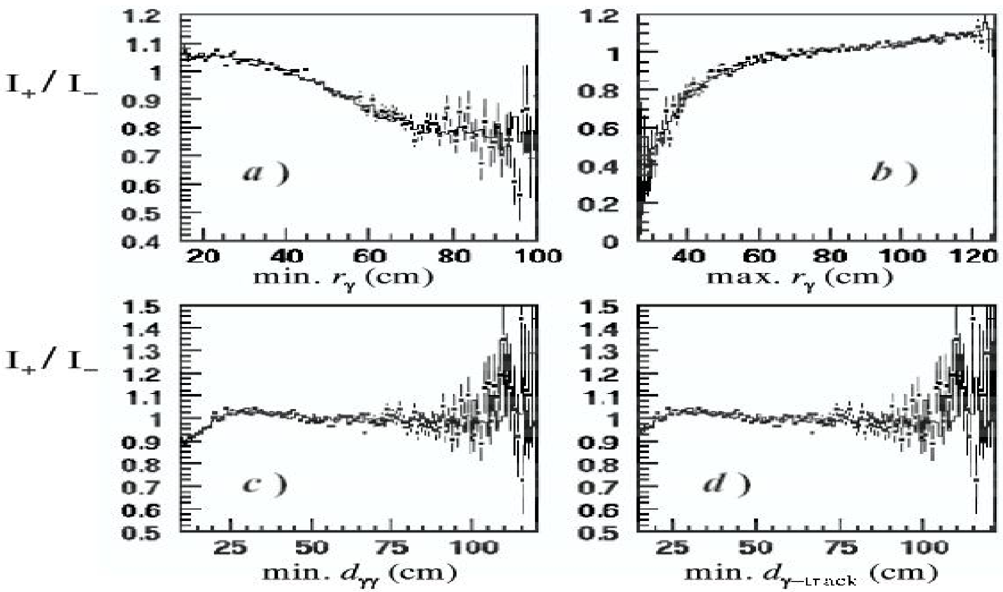

- Acceptance linear near the cusp



# Cusp on $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$. Checks for instrumental effects

- Data-MC comparisons above and below cusp
- MC simulation describes well the of detector efficiency around cusp. Event deficit is real effect



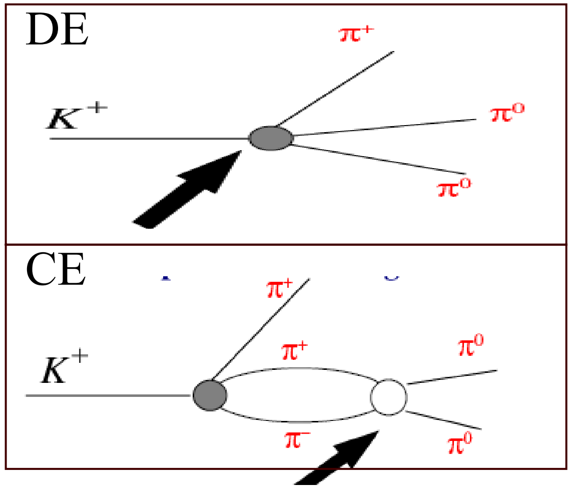



# Cusp on $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$. Interpretation

- Two amplitudes contribute to $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$
  - Direct emission
    - Given by $M_0$

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

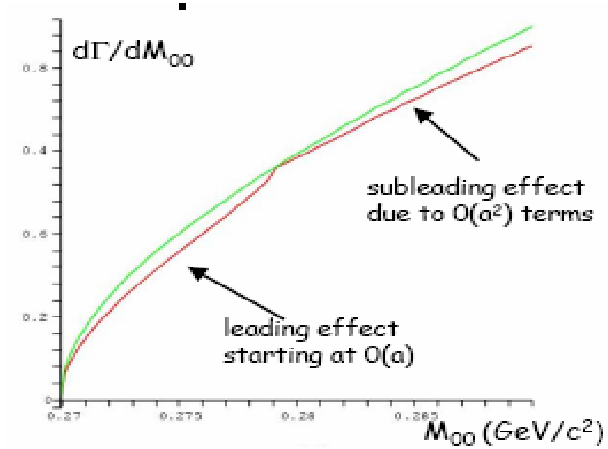
(N.B. g,h' are not same as in PDG)



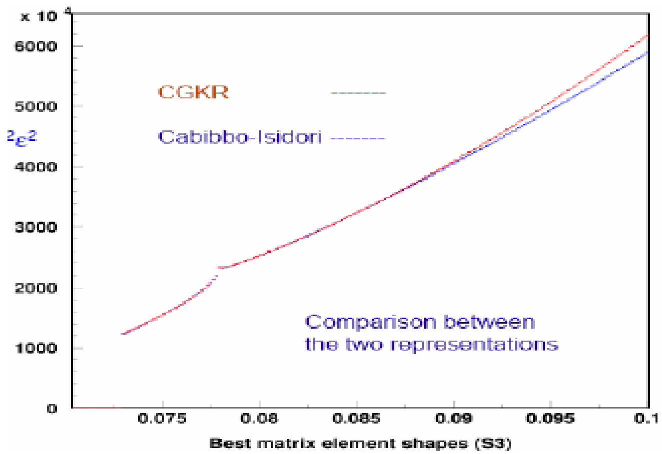

  - Charge exchange ($\pi^+\pi^- \rightarrow \pi^0\pi^0$) in final state of $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi$
    - Given by $M_1$, proportional to $M_+$ and to one extra parameter $a_x = (a_0 - a_2)/3$ in limit of exact isospin symmetry
- These amplitudes interfere destructively below threshold
- Rescattering model at one-loop **(C, PRL 93 (2004) 121801)**

# Cusp on $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$. Interpretation

- More complete formulation of the model includes all re-scattering processes at one-loop and two-loop level **(CI, JHEP 0503 (2005) 21)** has been used to extract NA48/2 result.
  - More parameters than just $a_x$
  - Isospin correction applied in order to extract $a_0$ and $a_2$ from fits to data.
  - Theoretical uncertainty of ~ 5% but radiative corrections and three-loops can be computed to reach ~1%




- Effective field theory model **(CGKR hep-ph 0604084)** valid in whole decay region. Experimental work in progress:
  - Re-analyzing $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ NA48/2 data.
  - Study of $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ cusps

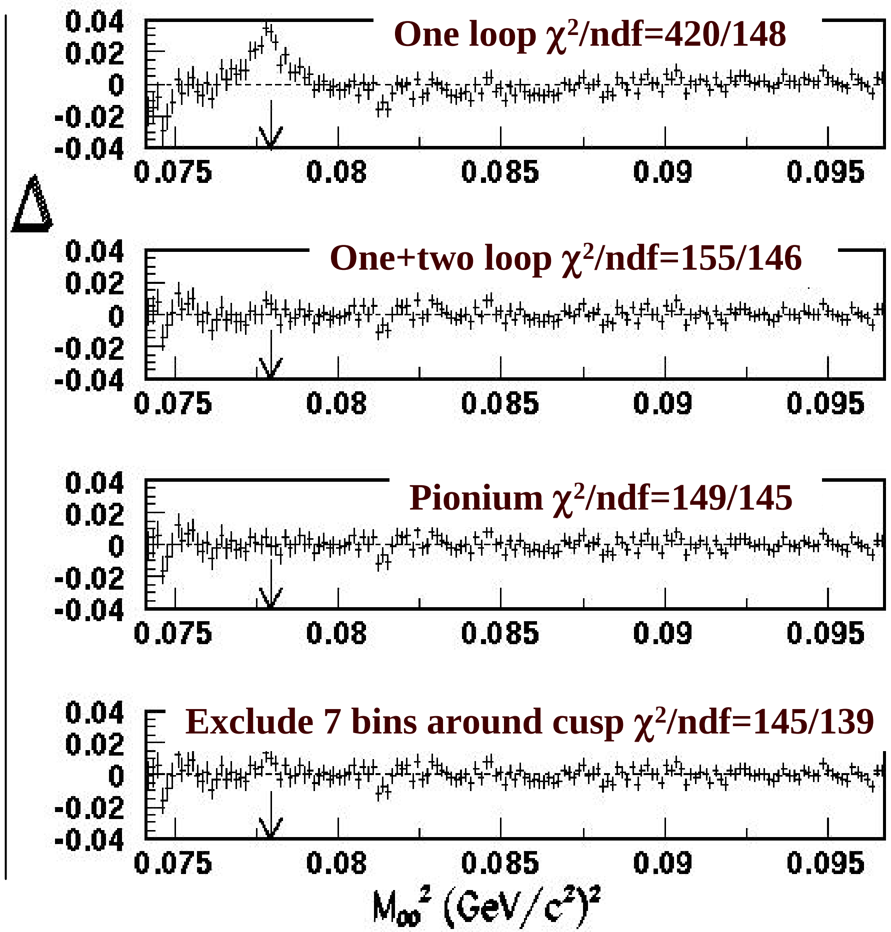


# Cusp on $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$: Results

- Try fitting different theoretical models to $M_{00}^2$ distribution and evaluate

$$\Delta = \frac{\text{Data} - \text{Fit}}{\text{Data}}$$

- Fitting up to 0.097 (GeV/$c^2$)
- Fits 2 and 4 have 5 parameters: norm, g, h', $a_0$- $a_2$ and $a_2$
- For final result pionium set to theoretical expectation and 7 bins around cusp excluded from the fit in order to reduce sensitivity to Coulomb corrections and pionium.



# Cusp on $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$. Results

- **NA48/2 results on partial sample of 2003 data (PLB 633 (2006))**
- Systematic effects: Acceptance determination, trigger efficiency, fitting interval

$$g = 0.645 \pm 0.004_{stat} \pm 0.009_{syst}$$
$$h' = -0.047 \pm 0.012_{stat} \pm 0.011_{syst}$$

$$a_0 - a_2 = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$
$$a_2 = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

- Prediction for a2 **in ChPT a2 = -0.0444 ± 0.0010 (CGL, PLB 488 (2000) 261)**
- Prediction for a0-a2 **in ChPT a0 -a2 = 0.265 ± 0.004 (CGL, PLB 488 (2000) 261)**

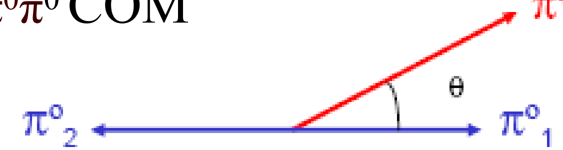
  **using disper. rel. = 0.278 ± 0.016 (PY, PRD 71 (2005) 074016)**
- Fit imposing ChPT constrain between $a_0$ and $a_2$ **(CGL, PRL 86 (2001) 5008)**

$$a_0 = 0.220 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.011_{ext}$$
$$\to a_0 - a_2 = 0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

# The $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decay. Quadratic term

- Change of Dalitz variables, from ($s_3$, $s_2$-$s_1$ ) to ($s_3$, cosθ)

- Define θ as angle between $\pi^{\pm}$ and $\pi^{0}$ in $\pi^{0}\pi^{0}$ COM

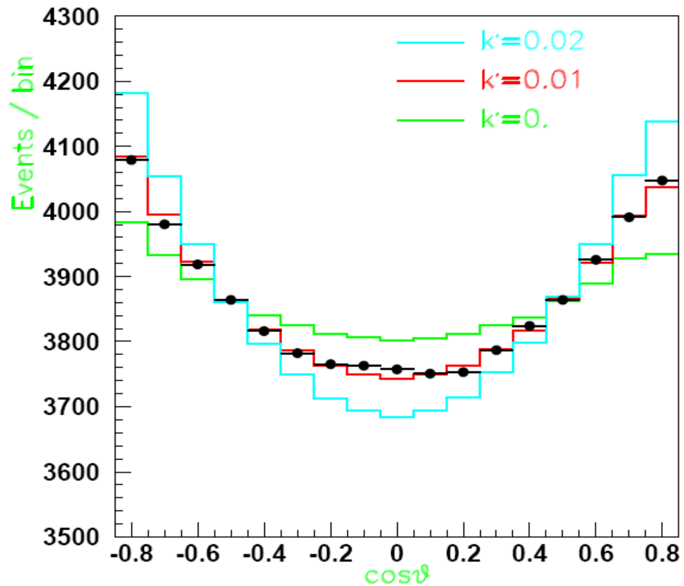



- Fitting new Dalitz plot above cusp

| NA48/2 Preliminary: 2003 data |
|---|
| k' = 0.0097 ± $0.0003_{stat}$ ± $0.0008_{syst}$ |

- Change in value and meaning of g and h' with respect to previous matrix element
- No change of $a_0$-$a_2$ and $a_2$

- Data-MC comparison for cosθ for different k' values



# Summary and conclusions

- Pion scattering lenghts have been measured in NA48/2 with two independent channels:
  - From $K^{\pm}e4$

$$a_0\ (UB) = 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{th}$$

  - From cusp on $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

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

  - **But with different theoretical frameworks!**
- Form factors for $K^{\pm}e4$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ have been measured
  - Non zero quadratic term in $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

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

For comparison evaluation of $a_0$ for previous experiments using center of UB:

**Geneva Saclay:**

$a_0(UB) = 0.253 \pm 0.037_{(stat+syst)} \pm 0.014_{th}$

**E865:**

$a_0\ (UB) = 0.229 \pm 0.012_{stat} \pm 0.004_{syst} \pm 0.014_{th}$