Low Energy QCD and ChPT Tests in the NA48/2 Experiment

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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, Vienna

New Trends In High-Energy Physics

Yalta - Crimea (Ukraine), September 15th – 22nd 2007

Outline

- NA48/2 Experimental Setup
- Low Energy QCD:
  - K_{e4}: Form Factors and $\pi\pi$ Scattering Length
  - $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$: "Cusp" Effect and $\pi\pi$ Scattering Length
- ChPT Tests:
  - $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: First Evidence of Interference Term
  - $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$: First Observation


NA48/2
Experimental Setup

History

NA48 (1997-2000): Direct CP-Violation in neutral K

> $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2)\cdot 10^{-4}$

NA48/1 (2002): Rare K_S decays

> $BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8)\cdot 10^{-9}$

> $BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2)\cdot 10^{-9}$

NA48/2 (2003-2004): Direct CP-Violation in charged K

> $A_g(K^\pm \to \pi^\pm \pi^+ \pi^-) = (-1.5 \pm 2.1)\cdot 10^{-4}$

> $A_g(K^\pm \to \pi^\pm \pi^0 \pi^0) = (1.8 \pm 1.8)\cdot 10^{-4}$

...and many other results on kaon and hyperon decays

1997	ε'/ε run	$K_L + K_S$
1998	ε'/ε run	$K_L + K_S$
1999	ε'/ε run $K_L + K_S$	K_S Hi. Int.
2000	K_L only	K_S High Intensity
	NO Spectrometer	
2001	ε'/ε run $K_L + K_S$	K_S High Int.
2002	K_S High Intensity	
2003	$K^\pm$ High Intensity	
2004	$K^\pm$ High Intensity	

Simultaneous Beam

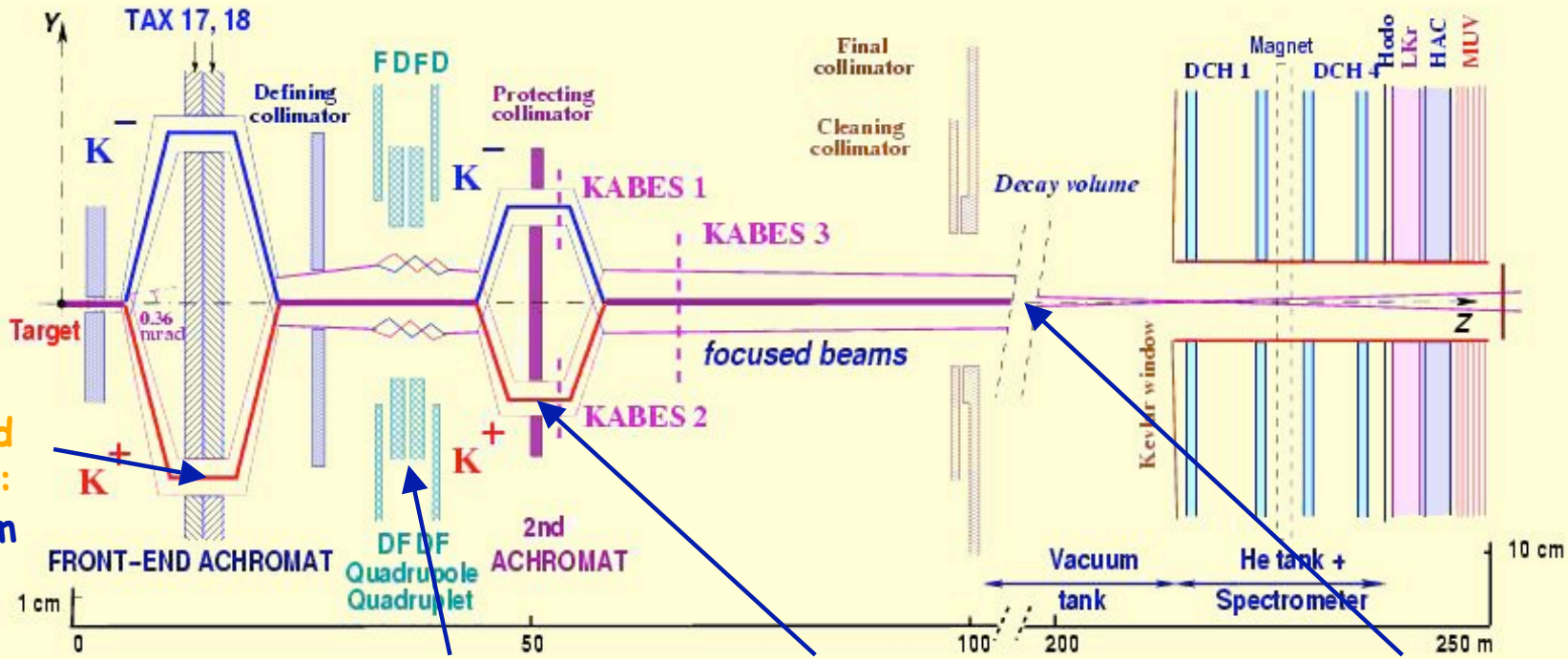
2-3M K/spill (π/K ~ 10)
π decay products stay in pipe
Flux ratio: K^+/K^- ~ 1.8

Simultaneous K^+ and K^- beams:
large charge symmetrization
of experimental conditions

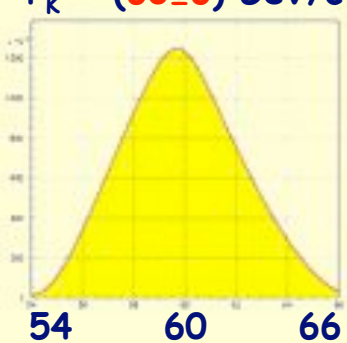
Beams coincide within ~1mm
all along 114m decay
volume

~$7\cdot10^{11}$
p/spil
400 GeV/c

Front-end
achromat:
Momentum
selection



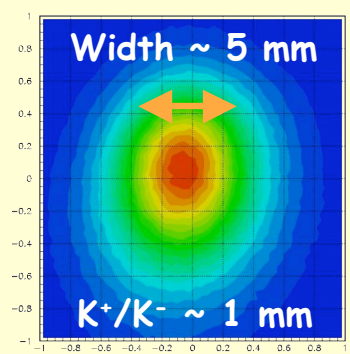
P_K = (60±3) GeV/c



Quadrupole,
Quadruplet:
Focusing
μ sweeping

Second achromat:
Cleaning
Beam spectrometer

$\delta P_K/P_K$ = 0.7%
$\delta_{x,y}$ ~ 100 μm



Detector

Magnetic spectrometer (4 DCHs):

- 4 view / DCH -> high efficiency
- $\sigma_P/P = 1.0\% + 0.044\% \cdot P$ [GeV/c]

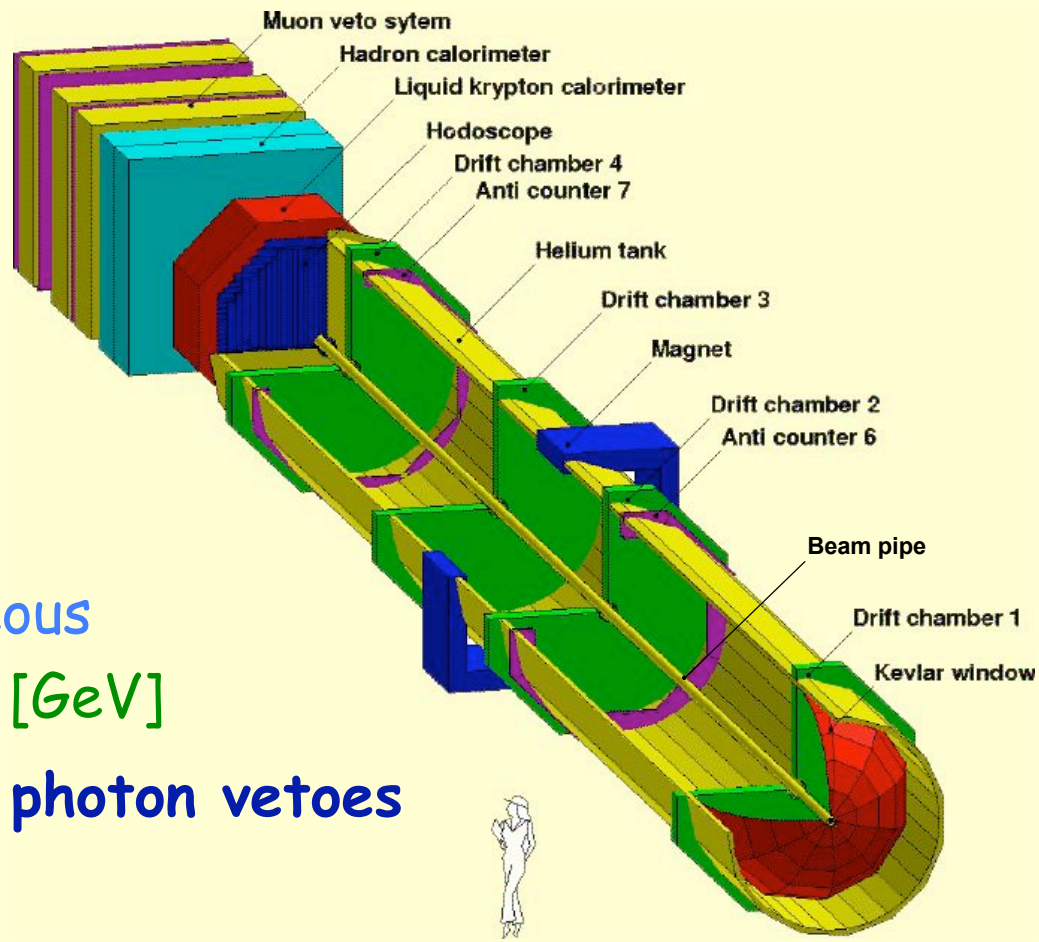
Hodoscope:

- Fast trigger
- $\sigma_t = 150$ps

Electromagnetic calorimeter (LKr):

- High granularity, quasi-homogeneous
- $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

Hadron calorimeter, **muon veto** and **photon vetoes**



Trigger:

- Fast hardware trigger (L1): hodoscope & DCHs multiplicity
- Level 2 trigger (L2): on-line processing of DCHs & LKr information

Data Taking

Run periods:

- 2003: ~ 50 days
- 2004: ~ 60 days

Total statistics in 2 years:

- $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: ~ $4 \cdot 10^{9}$
- $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$: ~ $1 \cdot 10^{8}$

-> >200 TB of data recorded

A view of the NA48/2 beam line

Rare $K^{\pm}$ decays can be measured down to BR ~ 10^{-9}

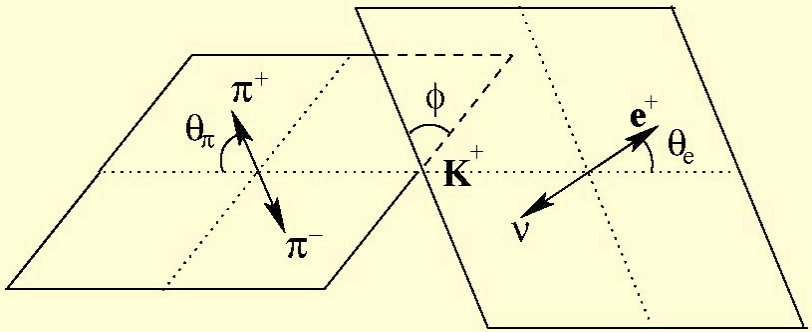
Low Energy QCD:

K_{e4} Decay

Formalism

The $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu$ (K_{e4}) dynamic is fully described by 5 variables (Cabibbo-Maksymovicz):

$M_{\pi\pi}^2$, $M_{e\nu}^2$, $\cos\theta_\pi$, $\cos\theta_e$ and ϕ



The transition amplitude can be written using 2 axial and 1 vector Form Factors that can be developed in a partial wave expansion:

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

$$G = G_p \cdot e^{i\delta_p} + \text{terms}_{\text{d-wave}}$$

$$H = H_p \cdot e^{i\delta_p} + \text{terms}_{\text{d-wave}}$$

The Form Factors can be expanded as a function of $q^2=(M_{\pi\pi}^2/4m_\pi^2-1)$ and $M_{e\nu}^2$:

$$F_s = f_s + f_s' \cdot q^2 + f_s'' \cdot q^4 + f_e' \cdot (M_{e\nu}^2/4m_\pi^2) + \ldots$$

$$F_p = f_p + f_p' \cdot q^2 + \ldots$$

$$G_p = g_p + g_p' \cdot q^2 + \ldots$$

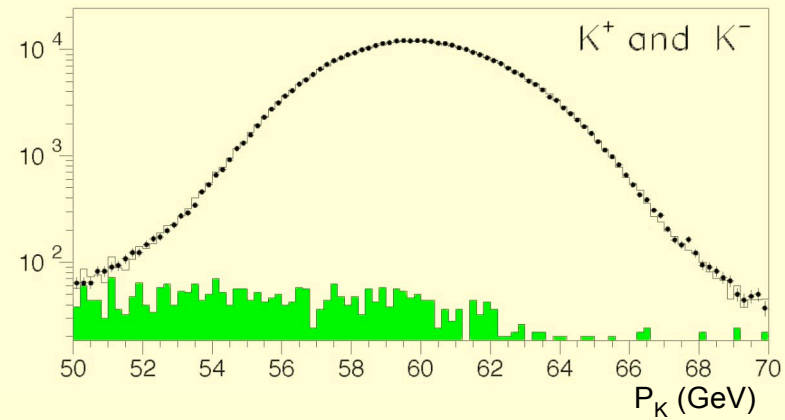
$$H_p = h_p + h_p' \cdot q^2 + \ldots$$

F_s, F_p, G_p, H_p and $\delta=\delta_s-\delta_p$ used as fit parameters

Selection and Background

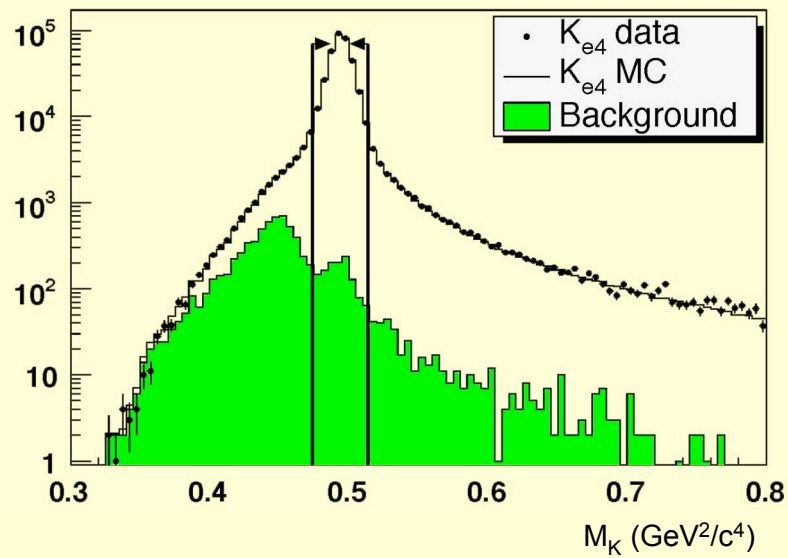
Signal selection:

- 3 charged tracks
- 2 opposite sign πs
- 1 e: LKr & DCH info E/P
- 1 ν: some missing energy & P_t



Main background sources:

- $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay with $\pi \to e\nu$ (dominant) or
- π mis-ID as e
- $K^{\pm} \to \pi^{\pm}\pi^{0}(\pi^{0})$ decay with $\pi^{0} \to e^{+}e^{-}\gamma$ and e
- mis-ID as $\pi + \gamma$s undetected
- Background is studied using the electron "wrong sign" events (assuming $\Delta Q=\Delta S$ and total charge ±1) and cross checked with MC



2003: 677500 events

Total background can be kept @ ~0.5% level

Fitting Procedure

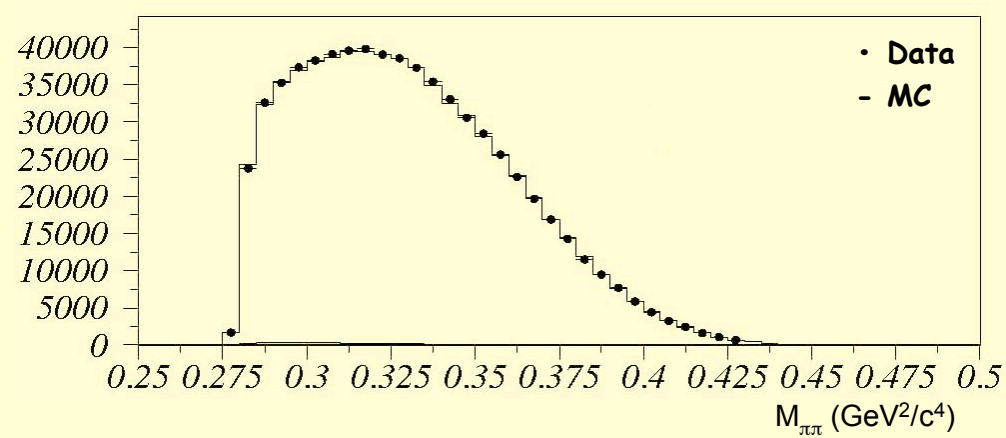
Using iso-populated bins in the 5-D space of the C.M. variables one defines a grid of:

$$10(M_{\pi\pi}) \times 5(M_{e\nu}) \times 5(\cos\theta_e) \times 5(\cos\theta_\pi) \times 12(\phi) = \mathbf{15000\ boxes}$$

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

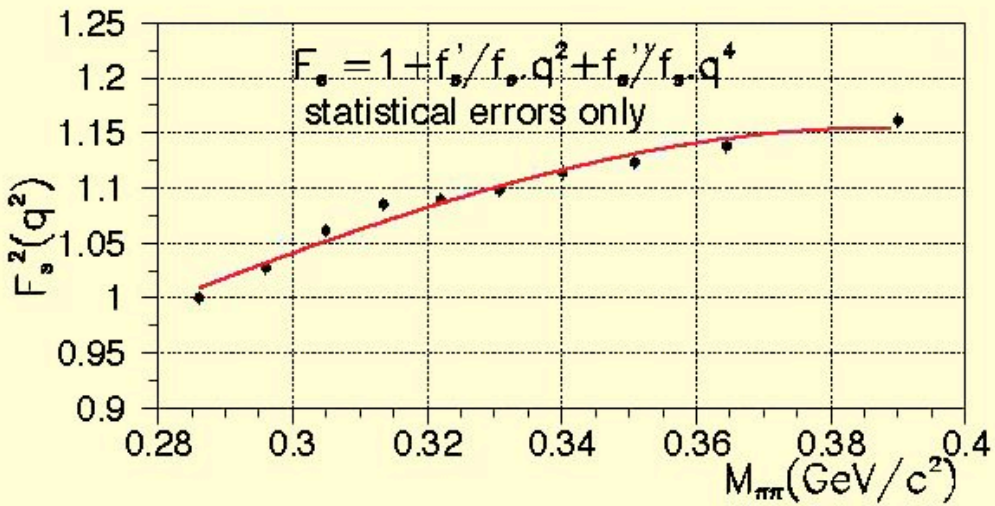
Assuming constant Form Factors over single boxes, ten independent fits in $M_{\pi\pi}$ bins have been performed to get model independent results

		Data	MC
K^+	Events	435654	10.0 M
	Events/bin	29	667
K^-	Events	241856	5.6 M
	Events/bin	16	373

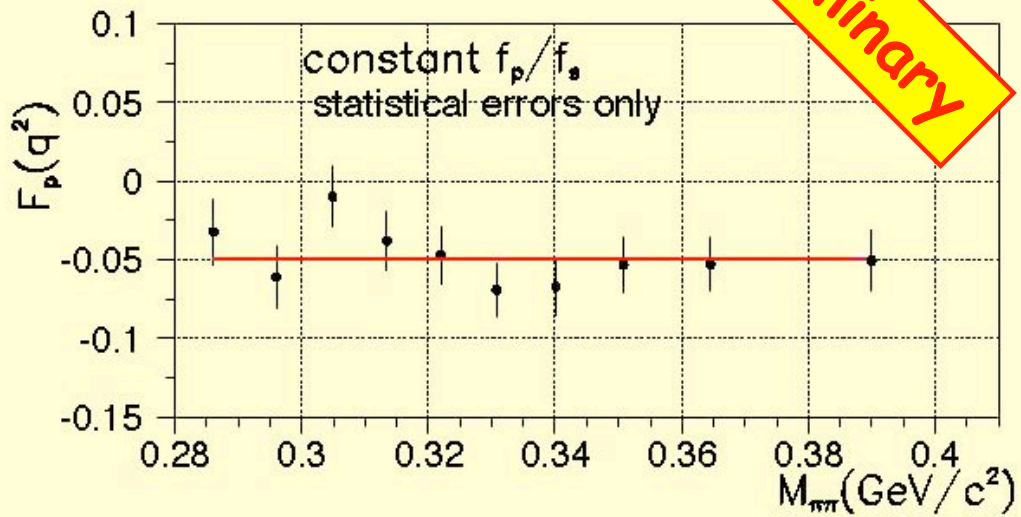


Results (I)

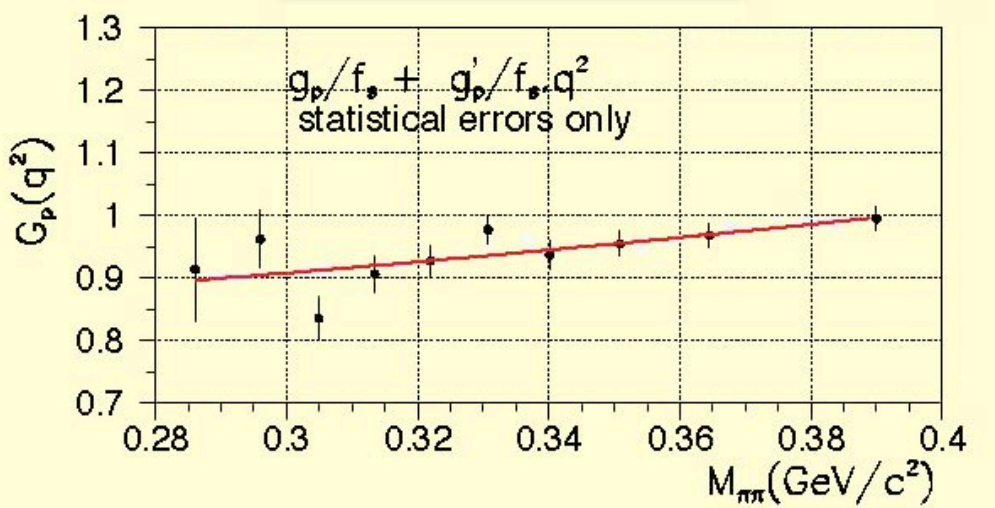
Preliminary



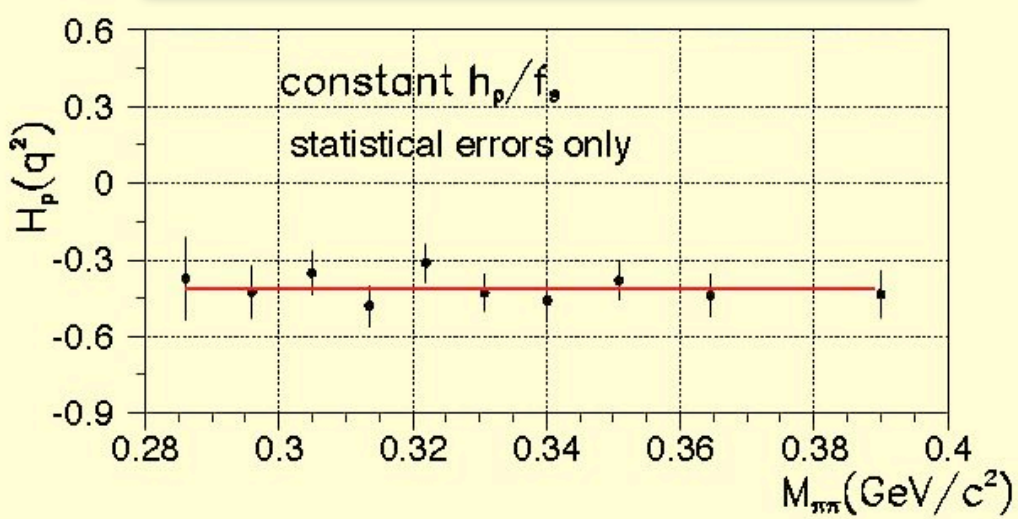
Quadratic in q^2



First measurement of $F_p \neq 0$



Linear in q^2



No linear term (h_p')

Results (II)

Preliminary

value ± stat ± syst

$f_s'/f_s = 0.165 \pm 0.011 \pm 0.006$

$f_s''/f_s = -0.092 \pm 0.011 \pm 0.007$

$f_e'/f_s = 0.081 \pm 0.011 \pm 0.008$

$f_p/f_s = -0.048 \pm 0.004 \pm 0.004$

$g_p/f_s = 0.873 \pm 0.013 \pm 0.012$

$g_p'/f_s = 0.081 \pm 0.022 \pm 0.014$

$h_p/f_s = -0.411 \pm 0.019 \pm 0.007$

Systematics checks:

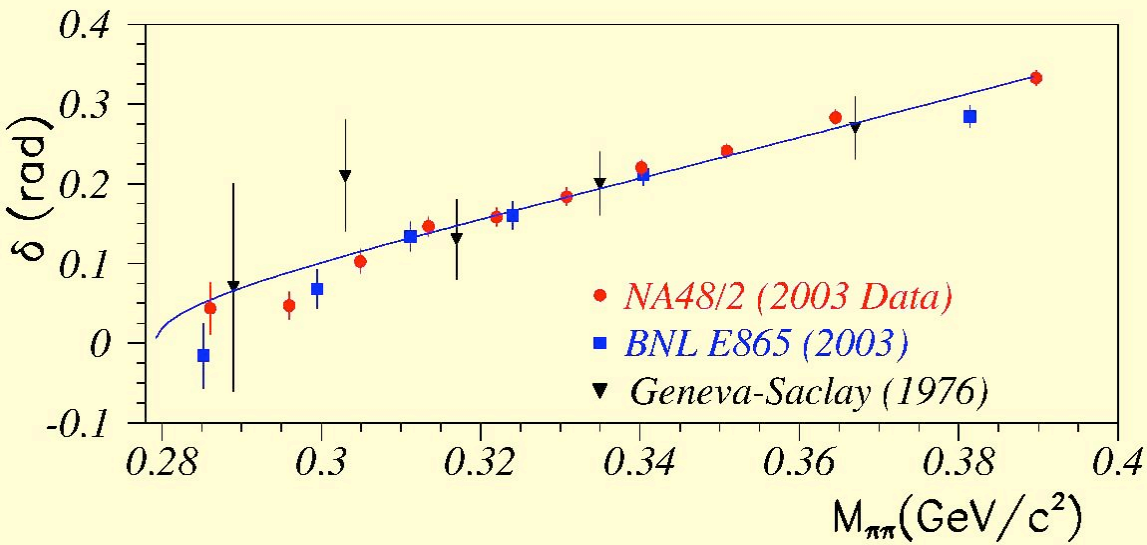
- Acceptance
- Background
- Particles ID
- Radiative corrections

- All the Form Factors are measured relatively to f_s (no BR measurement)
- Because of different beam geometries for K^+ and K^-, the event samples are fitted separately and the results combined according to their statistical precision ($K^+/K^- \sim 1.8$)
- First evidence of $f_p \neq 0$ and $f_e' \neq 0$
- Neglected $M_{e\nu}$ dependence of the normalization
- The Form Factors are measured at level of <5% of relative precision while the slopes at ~15% relative precision (factor 2÷3 improvement wrt. previous measurements)

δ Dependence

Preliminary

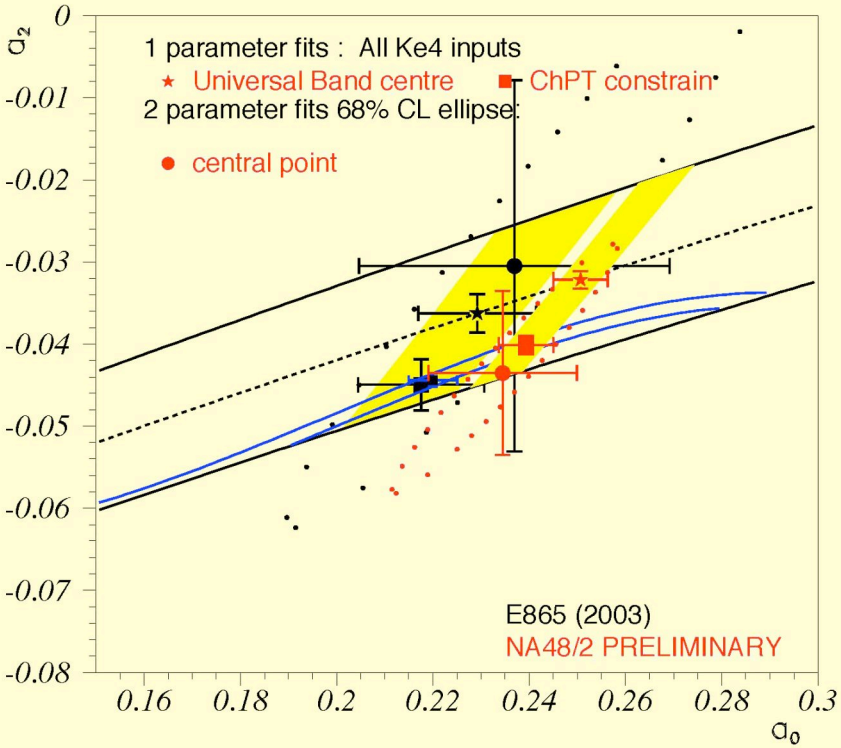
- The extraction of the $\pi\pi$ scattering lengths from the $\delta = \delta_s - \delta_p$ phase shift needs external theoretical and experimental data inputs
- The Roy equations provide this relation between δ and (a_0, a_2) near threshold, extrapolating from the $M_{\pi\pi} > 0.8$ GeV/c^2 region. The precision of these data defines the width of the Universal Band in the (a_0, a_2) plane
- The fit of the experimental points using the Roy equations in the Universal Band allows to extract the a_0 and a_2 values



(a_0, a_2) Plane (I)

Preliminary

Minimizing the χ^2 in the 2-D fit it's possible to identify the favoured solution (and the corresponding ellipse)



Single parameter fit (a_2 constrained to the center line of the UB):

$$a_0 \cdot m_{\pi^+} = 0.256 \pm 0.006_{stat} \pm 0.005_{syst}$$
$$(a_2 \cdot m_{\pi^+} = -0.031 \pm 0.001_{stat} \pm 0.001_{syst})$$

Two parameters fit:

$$a_0 \cdot m_{\pi^+} = 0.233 \pm 0.016_{stat} \pm 0.012_{syst}$$
$$a_2 \cdot m_{\pi^+} = -0.047 \pm 0.011_{stat} \pm 0.008_{syst}$$

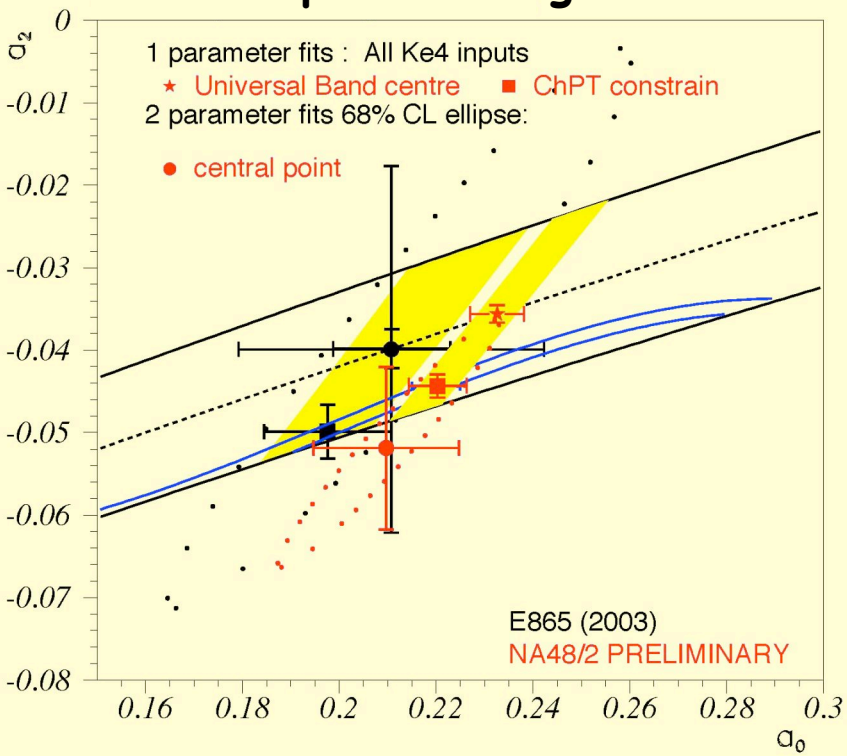
- The E865 and NA48/2 results agreement is marginal (manly due to the last δ point in E865)
- The correlation between a_0 and a_2 is ~96% (similar for both experiment)

(a_0, a_2) Plane (II)

Preliminary

Following recent developments one can correct the measured K_{e4} phases for isospin symmetry breaking effect before extracting a_0 (the correction is ~10÷12 mrad (negative))

With isospin breaking correction



- Using preliminary isospin corrections, both a_0 and a_2 values decrease (by ~0.02 and ~0.004 respectively) with statistical and systematic errors unchanged
- The new values would then be in very good agreement with the preferred ChPT prediction (a_0 = 0.220, a_2 = -0.0444) and the most recent lattice calculations (a_2 = -0.04330 ± 0.00042)

Both bands shift left and down in the (a_0, a_2) plane

K_{e4} "Neutral"

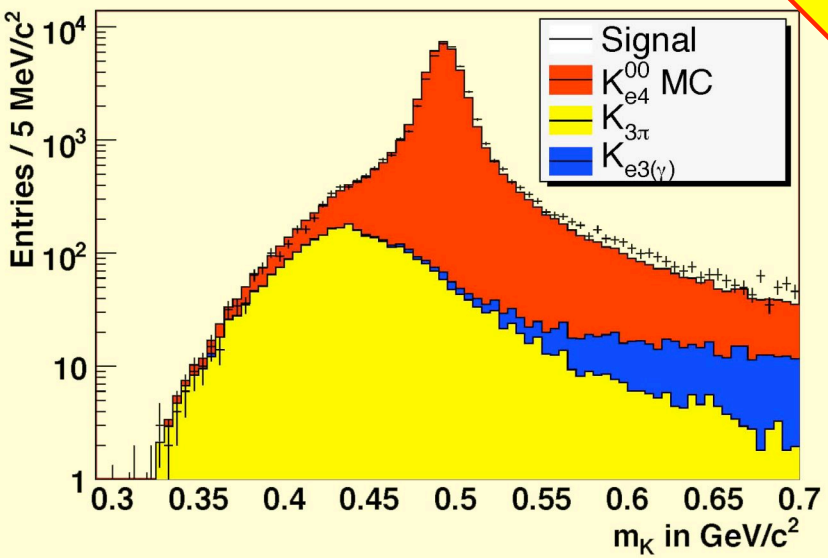
Preliminary

Signal selection:

- 1 e in the DCHs
- 4 γs in the LKr
- π^0 mass constraints
- 1 ν: missing P_t

Main background sources:

- $K^\pm \to \pi^\pm\pi^0\pi^0$ with a mis-ID $\pi^\pm$
- $K^\pm \to \pi^0 e^\pm \nu\gamma$ with 1 accidental γ and the 2 γs faking a π^0

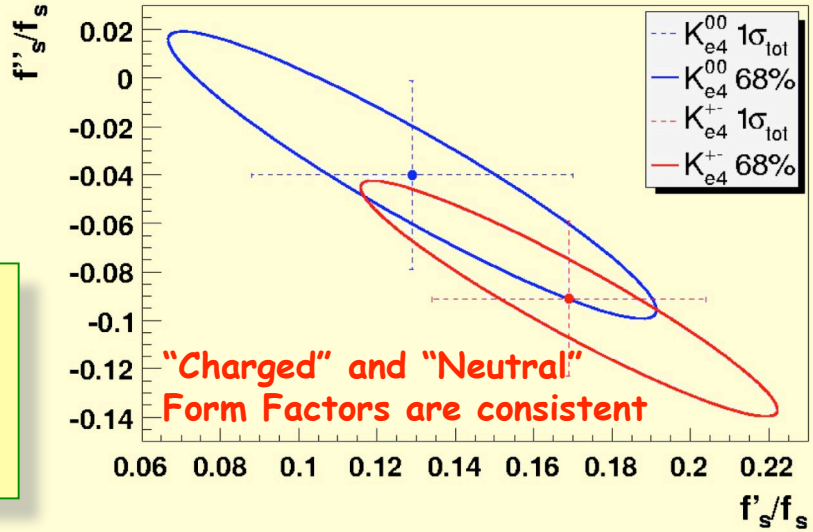


2003+2004: ~38000 events with ~2÷3% of residual background

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

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

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



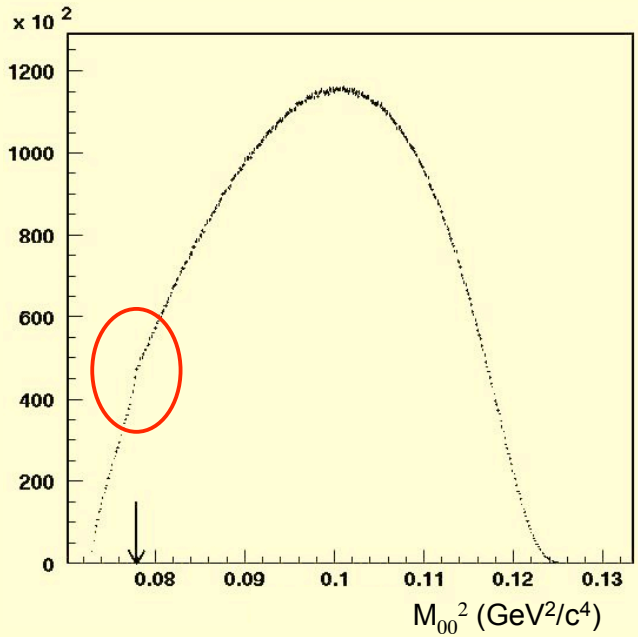
- BR 10 times better than current PDG value (KEK-E470 based on 216 signal events)
- f_e' consistent with 0 within the present statistics

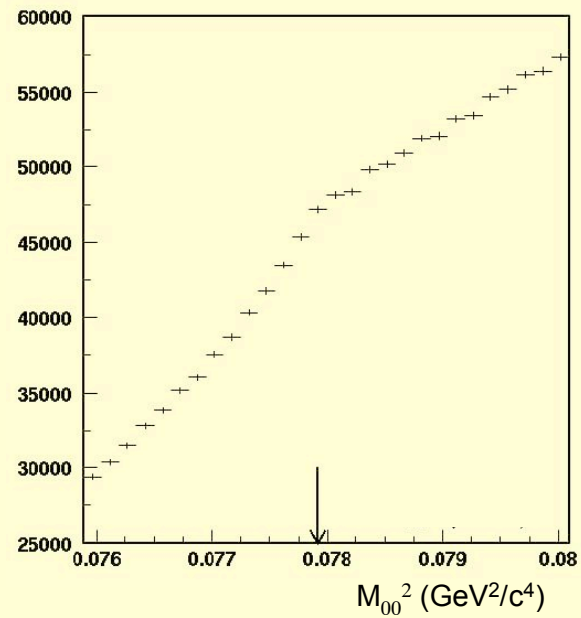
Low Energy QCD:

$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ Decay

A "Cusp"

- From $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decay (partial sample of 2003 data) we observed an anomaly in the M_{00}^2 invariant mass distribution in the region around $M_{00}^2 = (2m_{\pi^+})^2 = 0.07792\ (GeV^2/c^4)$





- This anomaly has been interpreted as a final state charge exchange scattering process of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ ($\pi^{+}\pi^{-} \to \pi^{0}\pi^{0}$)
- The parameter a_0-a_2 (difference between the S-wave $\pi\pi$ scattering lengths in the isospin I=0 and I=2 states) can be precisely measured using this sudden anomaly ("cusp")

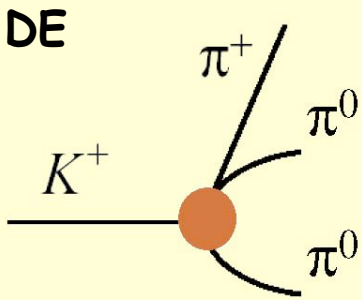
Interpretation (I)

Re-scattering model: two amplitudes contribute to $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

$$M(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = M_0 + M_1$$

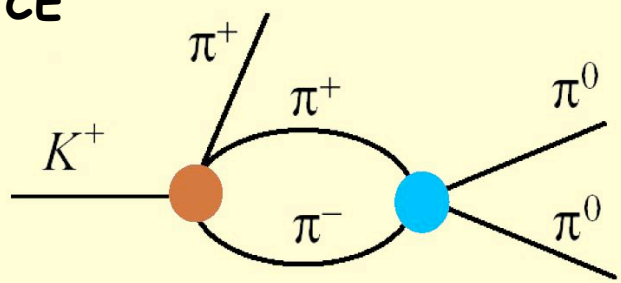
- M_0 : Direct emission
- M_1: Charge exchange in final state of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ ($\pi^{+}\pi^{-} \to \pi^{0}\pi^{0}$)

DE



$$M_0 \propto 1 + \frac{1}{2} g_0 u$$

CE



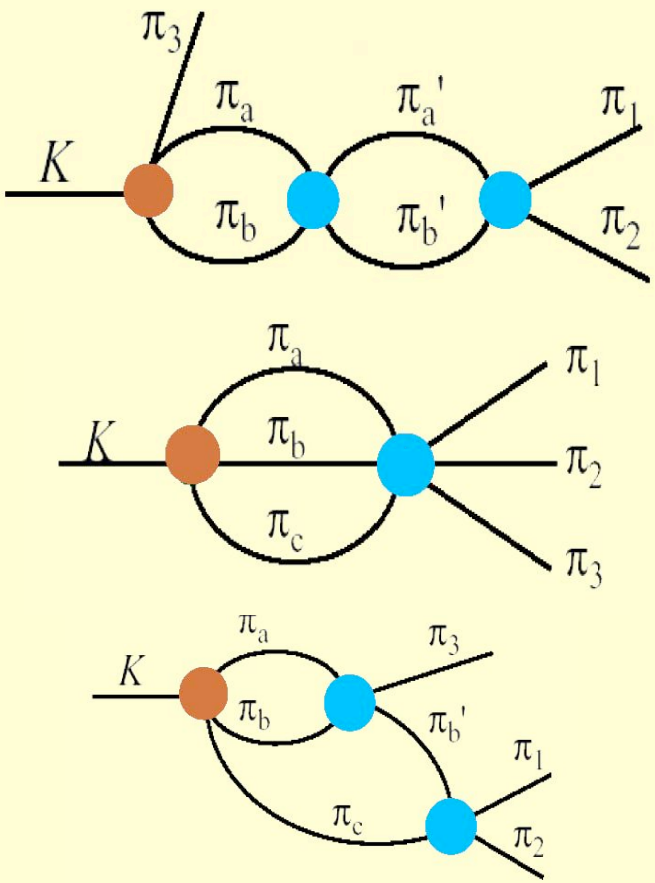
$$M_1 \propto (a_0 - a_2) \cdot m_{\pi^+}$$

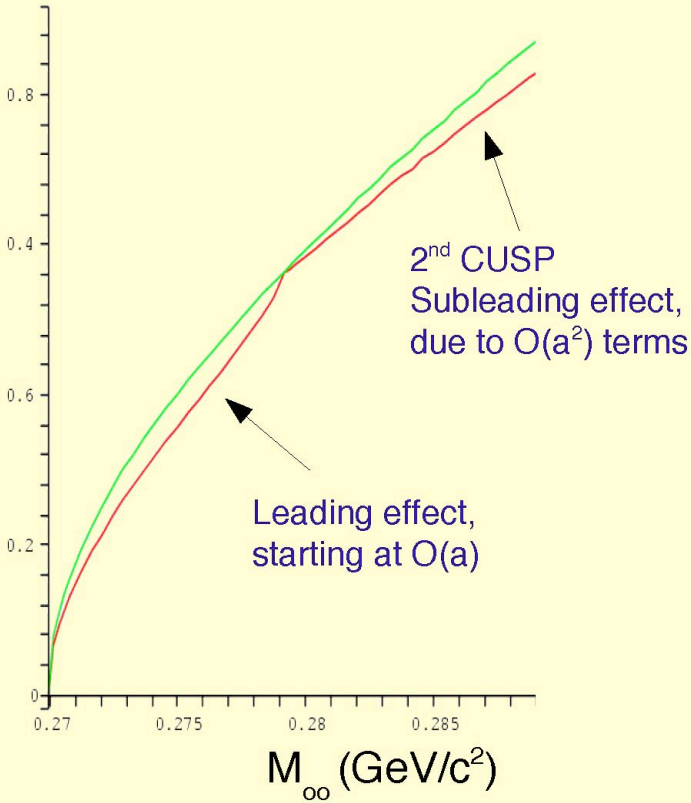
The singularity in the invariant mass spectrum at $\pi^{+}\pi^{-}$ threshold is mainly caused by the destructive interference of M_0 and M_1

The effect is present below the threshold and not above it (re-scattering model at one-loop (N. Cabibbo: PRL 93 (2004) 121801))

Interpretation (II)

More complete formulation of the model including all re-scattering processes at one-loop and two-loop level (N. Cabibbo and G. Isidori: JHEP 0503 (2005) 21) has been used to extract NA48/2 results





Results (I)

Systematic checks: acceptance determination, trigger efficiency and fitting interval

$$g_0 = 0.645 \pm 0.004_{stat} \pm 0.009_{syst}$$
$$h' = -0.047 \pm 0.012_{stat} \pm 0.011_{syst}$$

$$(a_0-a_2)\cdot m_{\pi^+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$
$$a_2\cdot m_{\pi^+} = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

Predictions in ChPT (PLB 488 (2000) 261):

- $(a_0-a_2)\cdot m_{\pi^+} = 0.265 \pm 0.004$
- $a_2\cdot m_{\pi^+} = -0.0444 \pm 0.0010$

Fit imposing ChPT constraint between a_0 and a_2 (PRL 86 (2001) 5008)

$$a_0\cdot m_{\pi^+} = 0.220 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.011_{ext}$$
$$(a_0-a_2)\cdot m_{\pi^+} = 0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

Published results (2003): PLB 633 (2006) 173-182

Results (II)

Preliminary

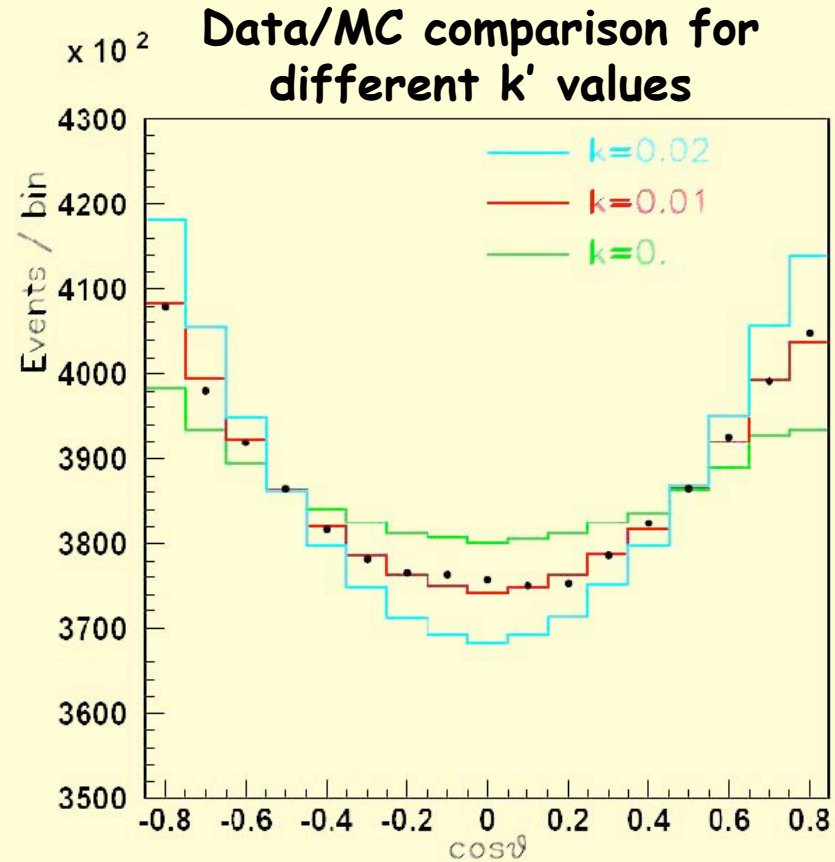
Fitting Dalitz plot above cusp finds evidence for k' > 0 term

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

Change of Dalitz variables, from (s_3, s_2-s_1) to (s_3, cosθ). Define θ as angle between $\pi^\pm$ and π^0 in $\pi^0\pi^0$ rest frame:

g_0 and h' change (2% and 25% respectively) but no change in $(a_0-a_2)\cdot m_{\pi^+}$ and $a_2 \cdot m_{\pi^+}$

Data/MC comparison for different k' values



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

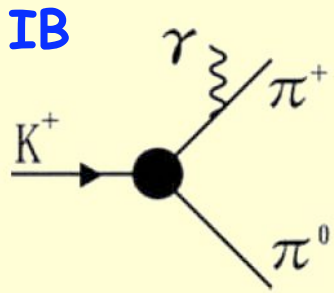
ChPT Tests:

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ Decay

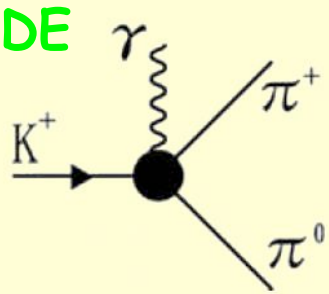
Introduction

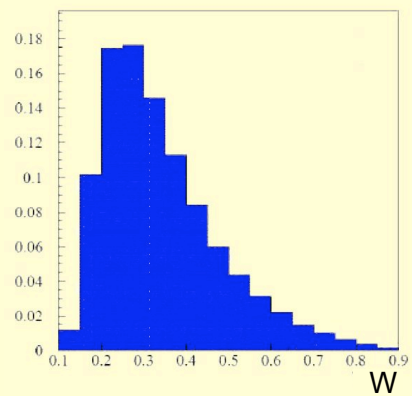
$$\frac{d\Gamma^{\pm}}{dW} \approx \underbrace{\left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB}\left[1\right.}_{\text{IB}} + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 \cdot W^2 \cdot |E|\cos\left((\delta_1-\delta_0)\pm\phi\right)}_{\text{INT}} + \left.\left(\frac{m_\pi}{m_K}\right)^4 \cdot \underbrace{W^4 \cdot \left(|E|^2+|M|^2\right)}_{\text{DE}}\right]$$

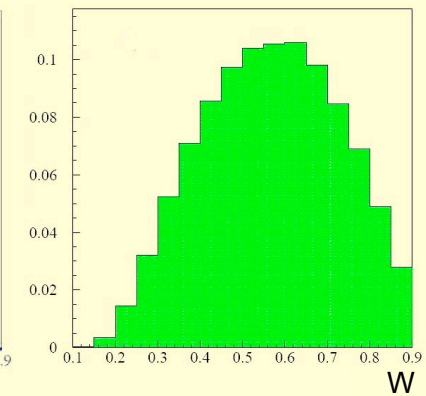
IB

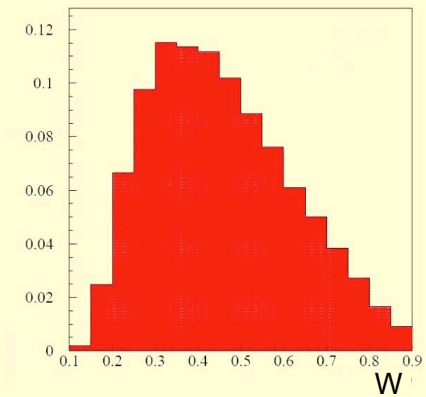


DE









$$W^2 = \frac{\left(P_K^* \cdot P_\gamma^*\right)\left(P_\pi^* \cdot P_\gamma^*\right)}{\left(m_K m_\pi\right)^2}$$

PDG (55 MeV < T^*_π < 90 MeV)

IB: $(2.75 \pm 0.15)\cdot 10^{-4}$

DE: $(4.4 \pm 0.8)\cdot 10^{-6}$

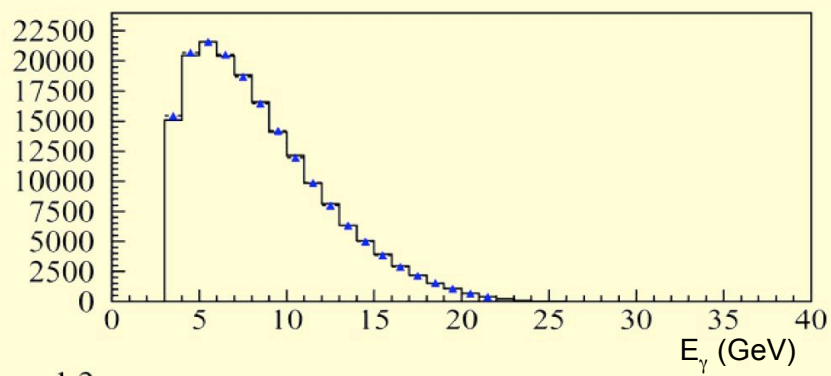
INT: not yet measured

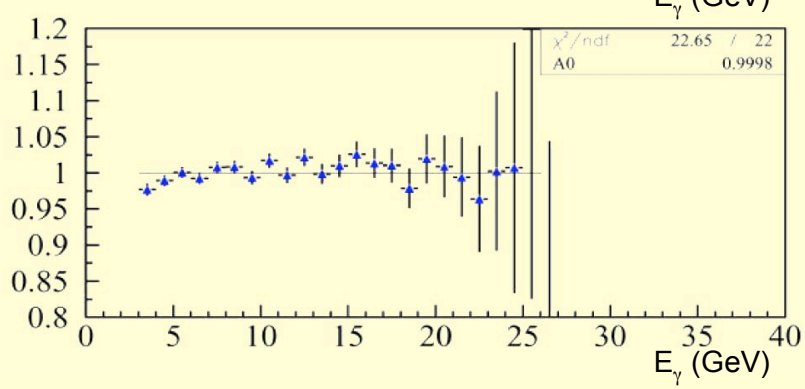
All previous measurements have been performed setting INT to zero

Data/MC Comparison

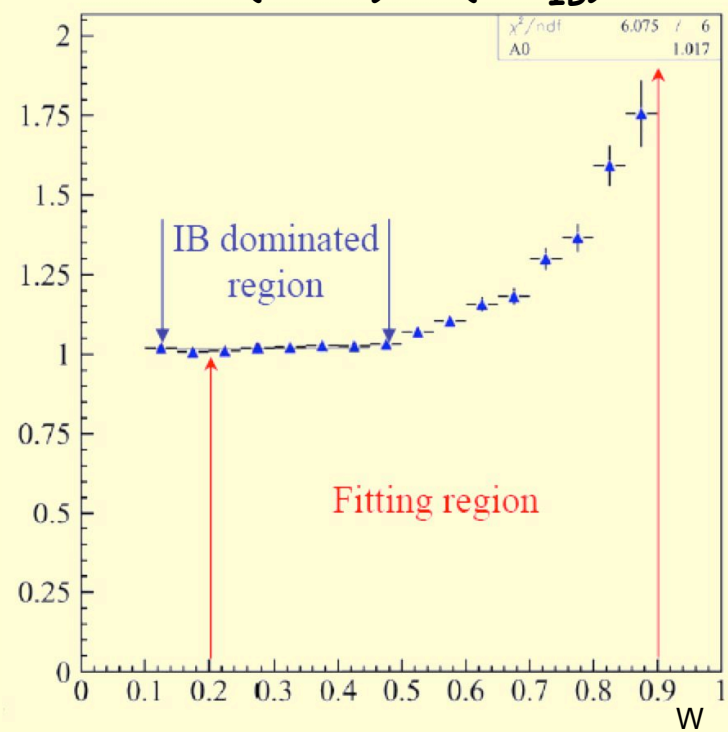
In the 2003 data sample (~30% of the whole statistics) ~$220 \cdot 10^3$ $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ have been selected:

- After trigger efficiency correction good agreement between Data and MC for E_γ, in particular for $E_\gamma > 5$ GeV (used for final result)
- The ratio $W(Data)/W(MC_{IB})$ is in good agreement for IB dominated region and clearly shows DE





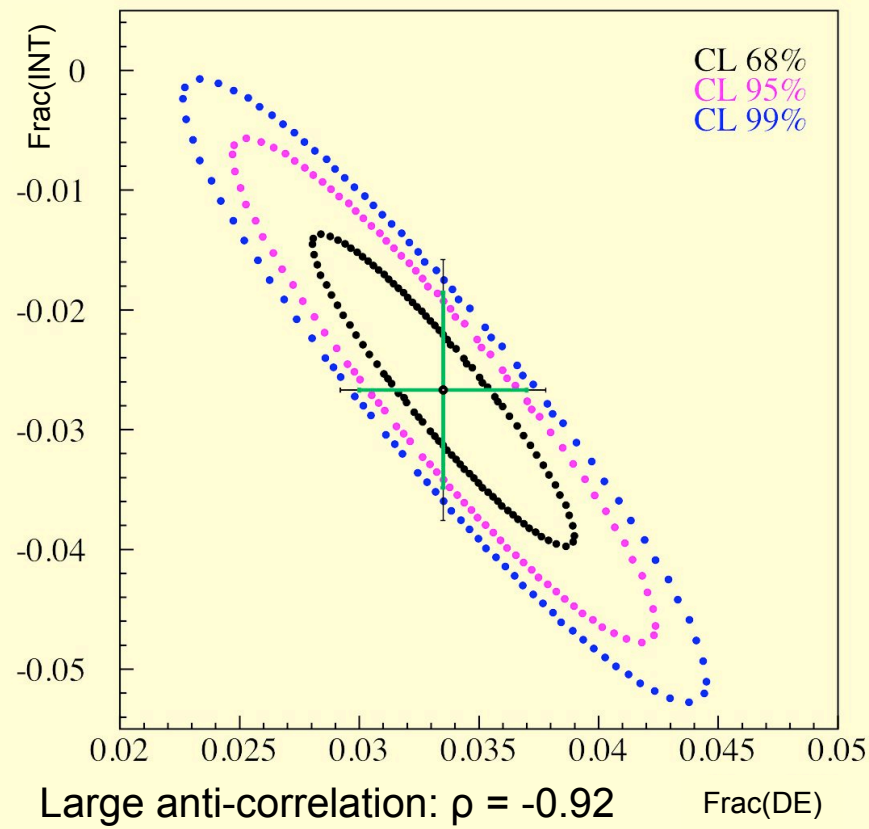
$W(Data)/W(MC_{IB})$



Results

Use extended Maximum Likelihood for 0.2 < W < 0.9 to fit in the region 0 MeV < T^*_π < 80 MeV (based on $124 \cdot 10^3$ events)

-> First evidence of Interference between Inner Bremsstrahlung and Direct Emission amplitudes



Large anti-correlation: ρ = -0.92

$$\text{Frac(DE)} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$$
$$\text{Frac(INT)} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$$

ChPT Tests:

$K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ Decay

BR Measurement

Preliminary

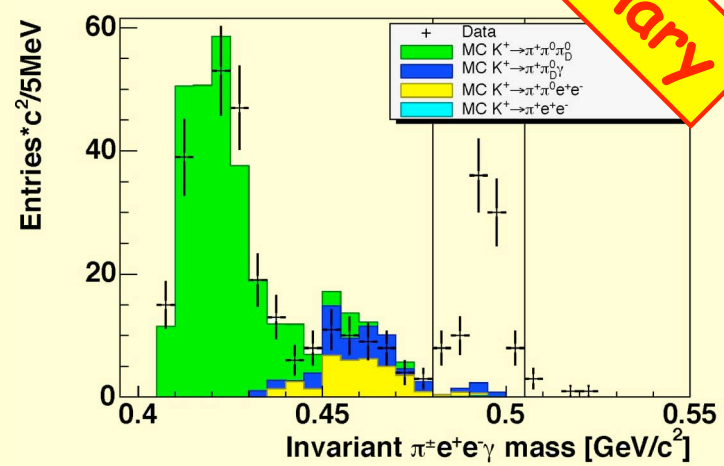
Never observed before. Naïve estimation of the BR:

$$BR(\pi^{\pm}e^{+}e^{-}\gamma) = BR(\pi^{\pm}\gamma\gamma) \cdot 2\alpha \sim 1.6 \cdot 10^{-8}$$

Theoretical expectation (ChPT, Gabbiani99):

$$BR(\pi^{\pm}e^{+}e^{-}\gamma) = (0.9 \div 1.6) \cdot 10^{-8}$$

depending on ĉ

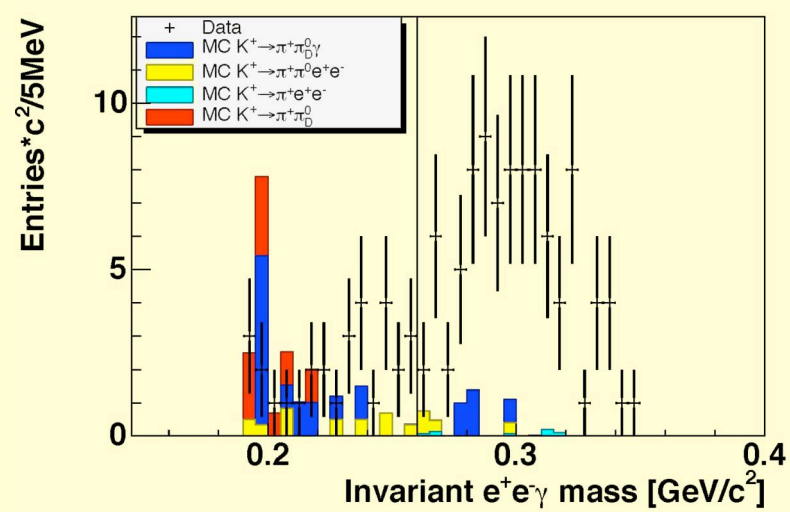


Event sample (2003+2004):

- 92 candidates events
- 1 ± 1 accidental background
- 5.1 ± 1.7 physical background

Normalization channel:

$K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$: $14 \cdot 10^{-6}$ events



$$BR(K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma) = (1.27 \pm 0.14_{stat} \pm 0.05_{syst}) \cdot 10^{-8}$$

Summary (I)

- NA48/2 has improved measurements of the K_{e4} Form Factors in the "charged" and "neutral" modes (5÷30% relative statistical precision)
- Using a conservative theoretical approach, preliminary values of a_0 and a_2 are obtained (2-D fit):

$$a_0 \cdot m_{\pi^+} = 0.233 \pm 0.016_{stat} \pm 0.012_{syst}$$
$$a_2 \cdot m_{\pi^+} = -0.047 \pm 0.011_{stat} \pm 0.008_{syst}$$

- More elaborated theoretical corrections would bring down those values in close agreement with ChPT predictions
- A new "cusp" structure in $K^\pm \to \pi^\pm\pi^0\pi^0$ was observed ($\pi\pi$ final state charge exchange process of $K^\pm \to \pi^\pm\pi^+\pi^-$) which provides a new method for the extraction of the $\pi\pi$ scattering lengths:

$$(a_0-a_2) \cdot m_{\pi^+} = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{theor}$$

- Parameter a_2 directly measured for the first time even though with low accuracy:

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

Summary (II)

- The first measurement of Direct Emission and Interference terms in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ has been performed in the region 0 MeV < T^{*}_{π} < 80 MeV:

$$Frac(DE) = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$$

$$Frac(INT) = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$$

- A first evidence of a negative Interference has been found and therefore a non negligible contribution of electric term to Direct Emission amplitude

- The $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay has been observed for the first time:

$$BR(K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma) = (1.27 \pm 0.14_{stat} \pm 0.05_{syst}) \cdot 10^{-8}$$