Title: Low energy QCD and ChPT tests at the NA48/2 experiment

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Abstract: In the last years, the NA48/2 experiment at the CERN SPS has recorded an unprecedented sample of charged kaon decays. From this, we report very precise measurements of fundamental parameters of Chiral Perturbation Theory (ChPT) and the study of low energy pi-pi scattering. Several rare and very rare decays have been studied. From more than 10^6 K+- -> pi+ pi0 gamma decays, a first measurement of the interference between Bremsstrahlung and Direct Emission amplitudes and a stringent limit on direct CP violation in this channel is presented. For K+- -> pi+ gamma gamma, about 1000 events have been selected, more than 30 times the existing statistics. Also, the first observation of K+- -> pi+ gamma e+ e- is reported with 120 events. For both decays, the branching fraction and the free parameter of O(p4) ChPT has been measured with high accuracy. Finally, we report on a new precise measurement of the branching fraction and form factors of K+- -> pi+- e+ e-, which is highly suppressed by the GIM mechanism. The measurement of the e+ e- spectrum is an important input for ChPT and probes the weak static interaction. The analyses of K+- -> pi+- pi0 pi0 (K3pi) and K+- -> pi+ pi- e+- nu (Ke4) decays give complementary approaches to the study of low energy pi-pi scattering. From data samples of ~90 Millions 3pi and ~1 Million Ke4 decays, precise values of a0 and a2, the Isospin 0 and 2 S-wave PI-PI scattering lengths, can be extracted with an unprecedented experimental precision, allowing accurate tests of Chiral Perturbation Theory predictions. The form factors of the Ke4 decays and their energy dependence are also measured with an improved precision, while the Dalitz plot parameters of the K3PI decays are determined including a new quadratic term.

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

Simone Bifani

University of Bern

on Behalf of the NA48/2 Collaboration

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

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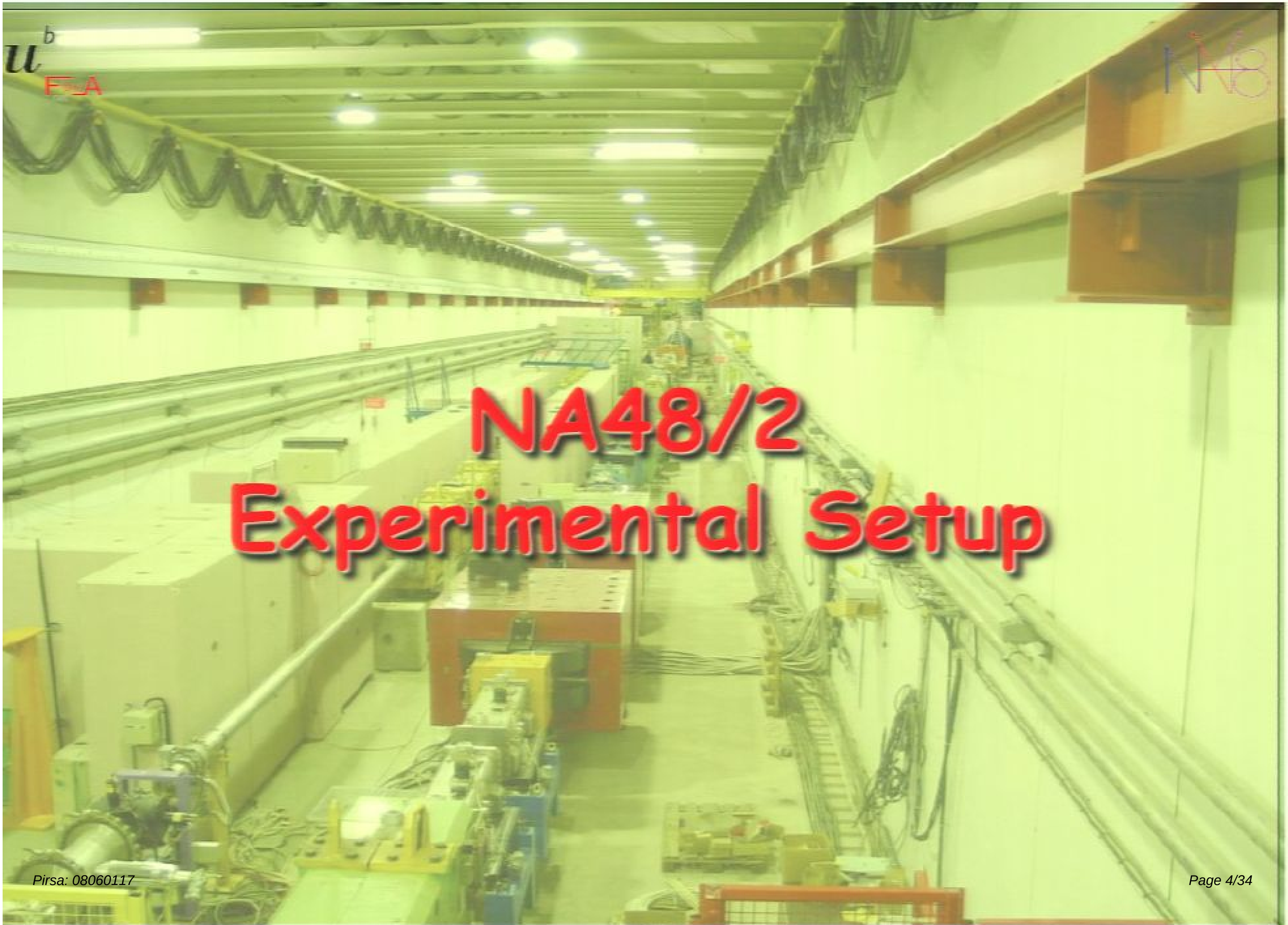
Outline

- NA48/2 Experimental Setup
- Low Energy QCD:
  - $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$: Form Factors and $\pi\pi$ Scattering Length
- Chiral Perturbation Theory Tests:
  - $K^{\pm} \to \pi^{\pm}\gamma\gamma$: Branching Ratio
  - $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$: Branching Ratio and Spectrum Shape
  - $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$: Branching Ratio and Form Factors



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

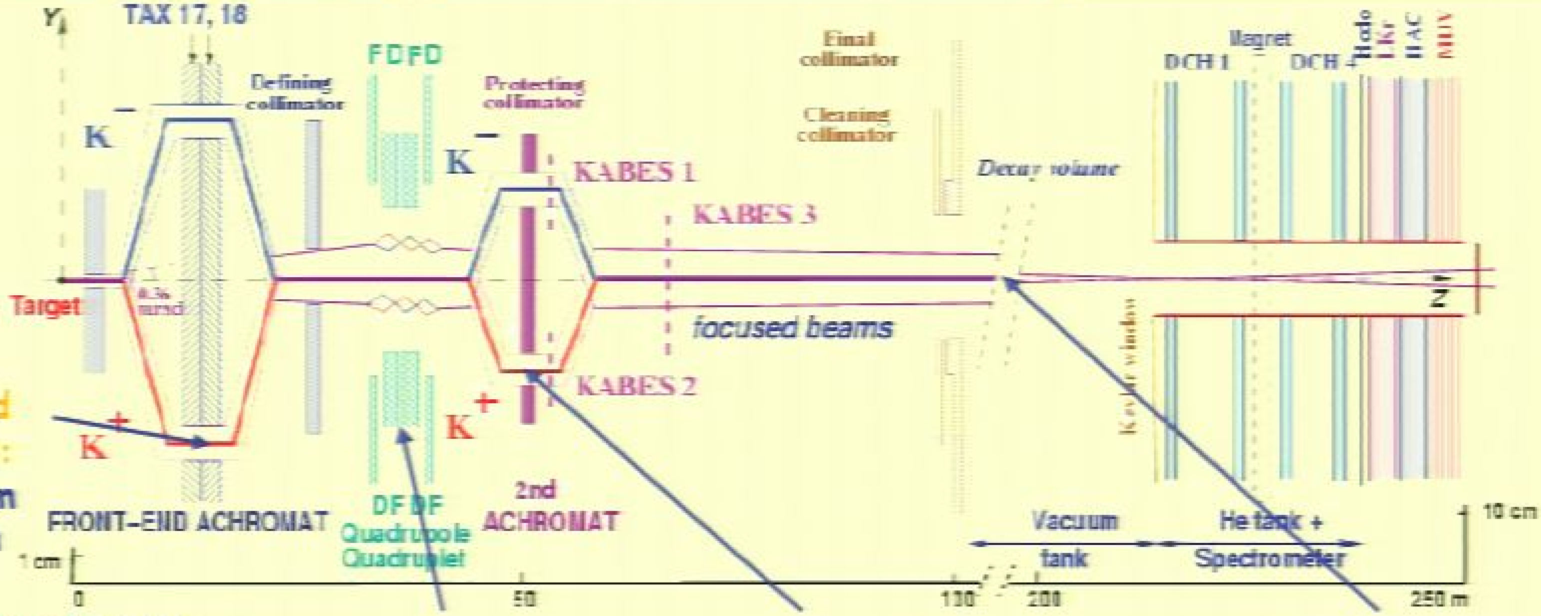
2-3M K/spill (π/K ~ 10)
π decay products stay in pipe
Flux ratio: K^+/K^- ~ 1.8

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

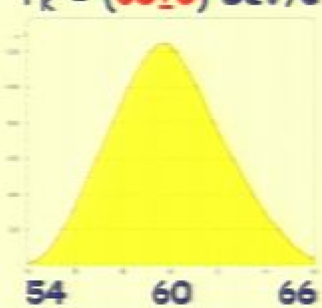
Beams coincide within ~1mm
all along 114m decay volume

~$7 \cdot 10^{11}$ p/spil
400 GeV/c

Front-end achromat:
Momentum selection



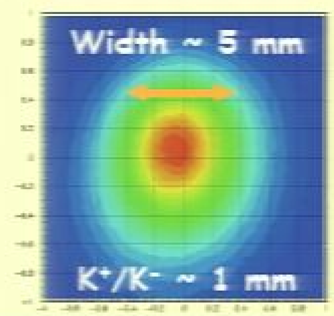
P_K = (60±3) GeV/c



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]

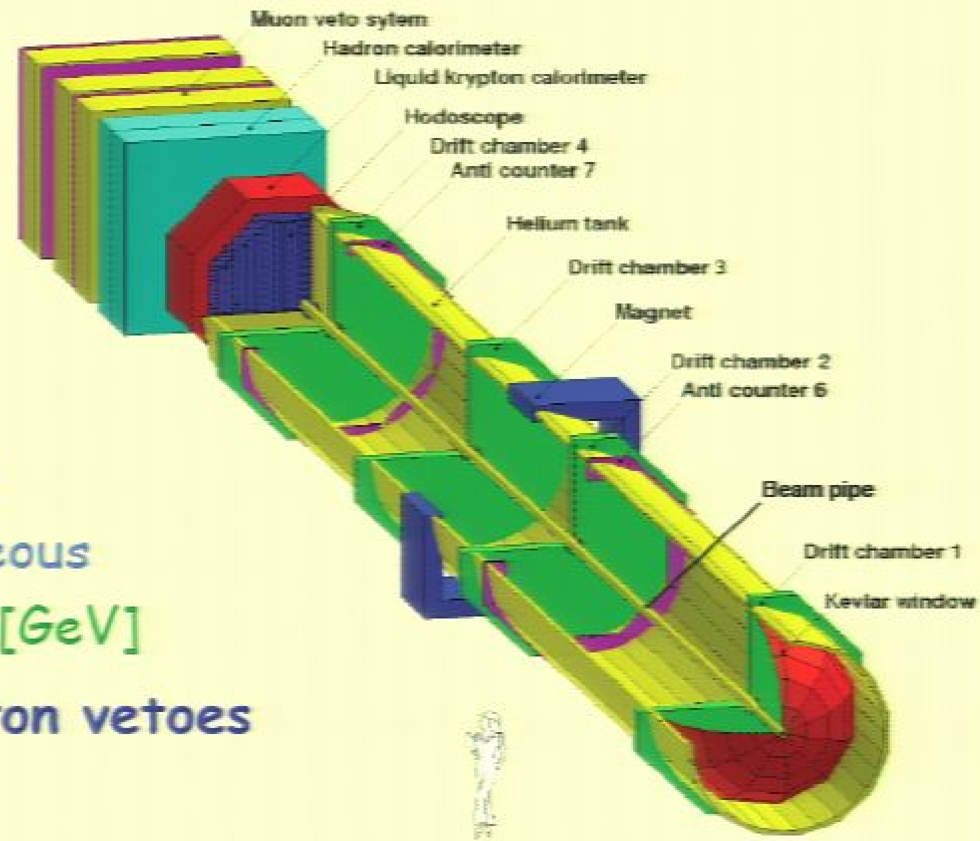
Hodoscope:

- 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 and **photon vetoes**



Trigger:

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

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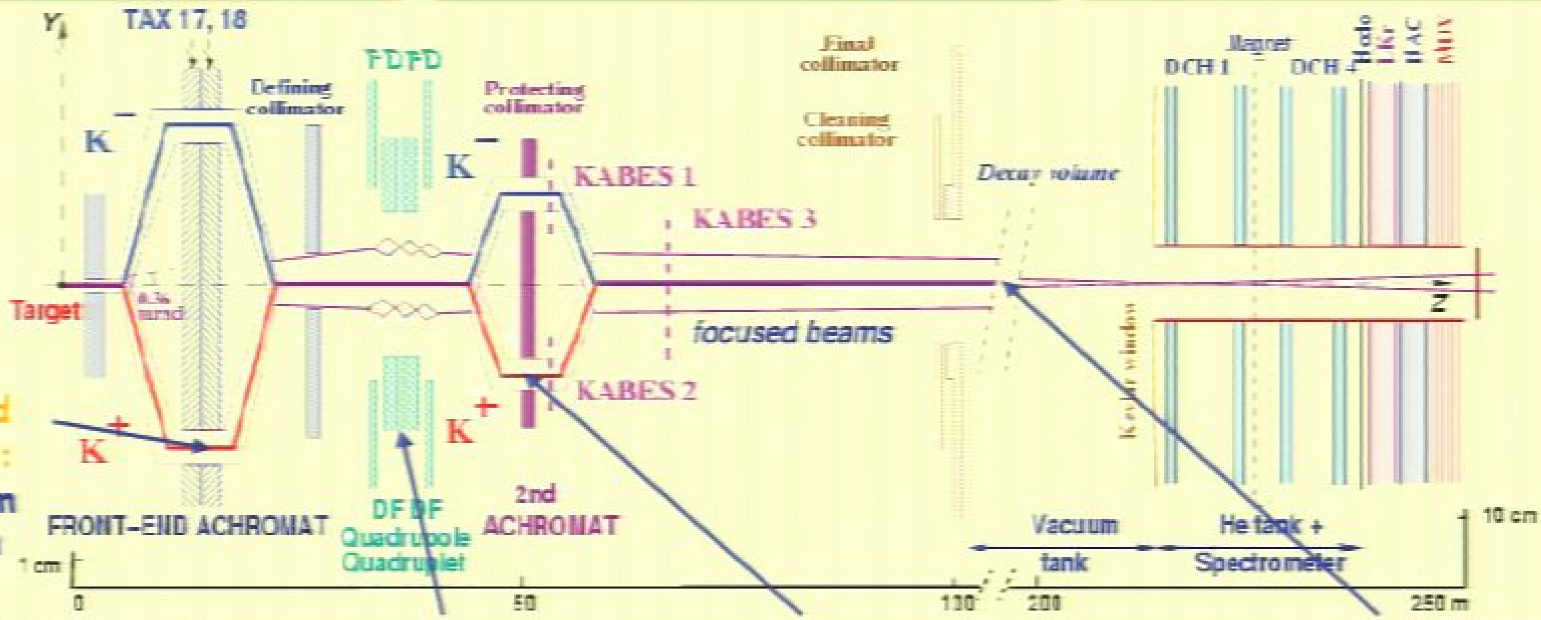

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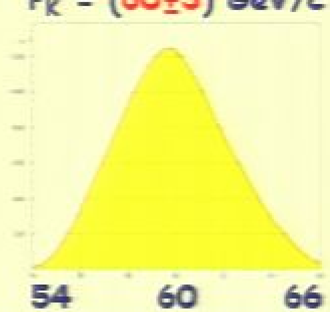

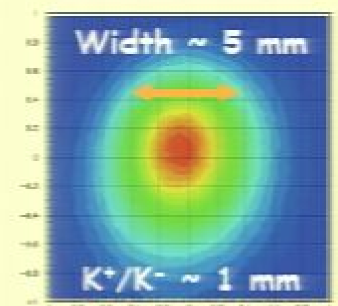

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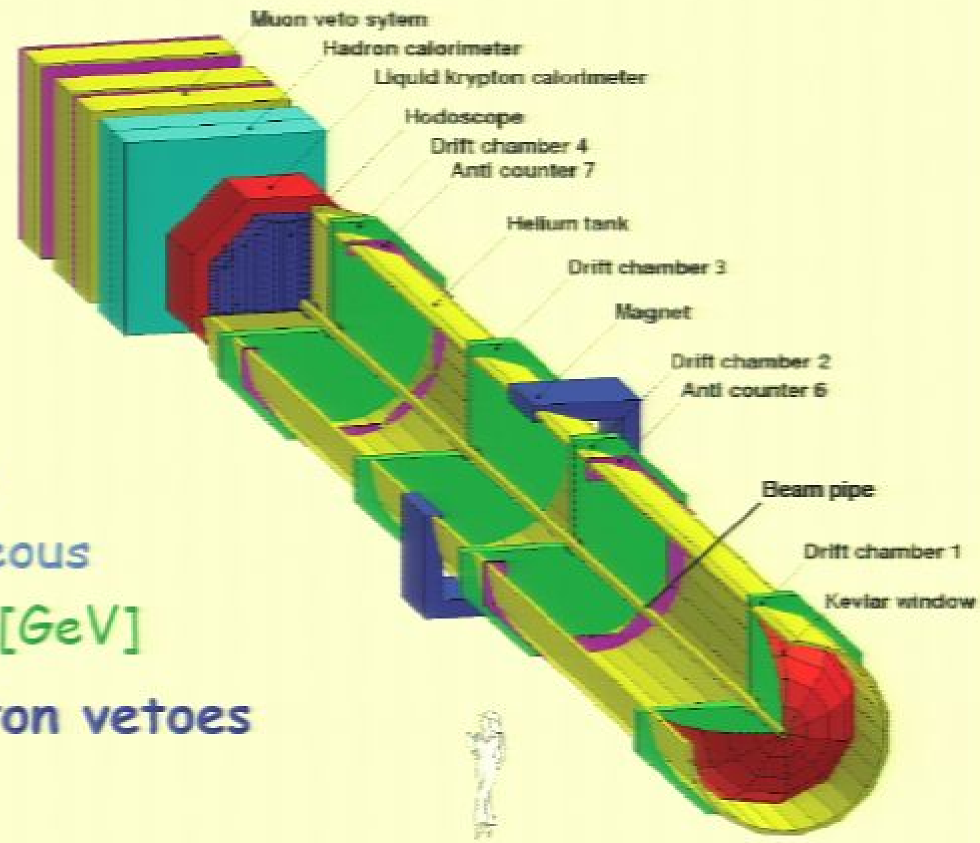

Trigger:
- Fast hardware trigger (L1): hodoscope & DCHs multiplicity
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Data Taking

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}

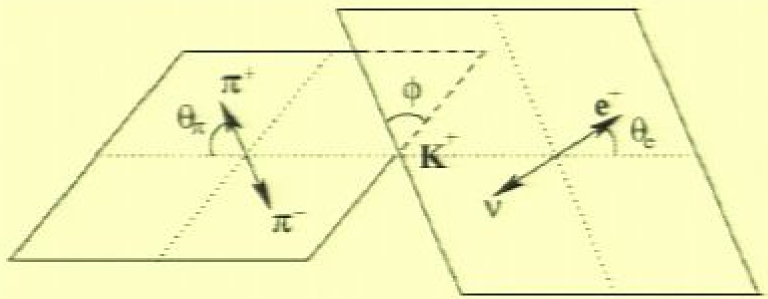
Low Energy QCD:

$K^{\pm}$ -> $\pi^+\pi^- e^{\pm}\nu$ Decay

Formalism

The $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ (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:

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

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

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

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

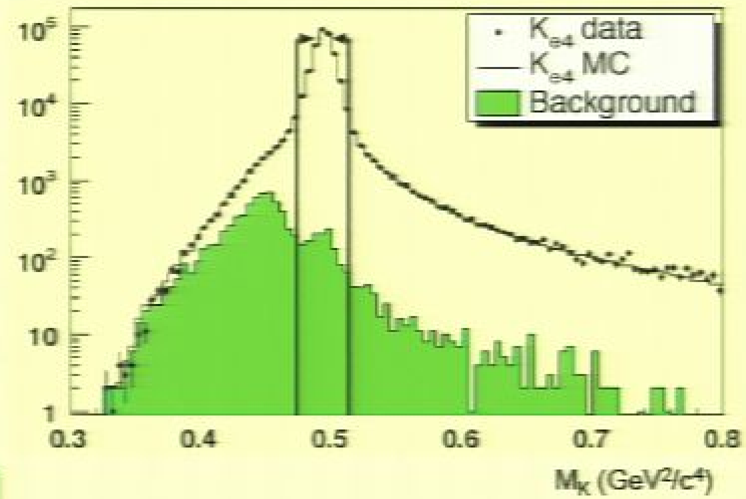
Selection and Background

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 π + γs undetected
- Background is studied using the electron "wrong sign" events (assuming ΔQ=ΔS and total charge ±1) and cross checked with MC



2003: 677500 events

Total background can be kept @ ~0.5% level

Fitting Procedure

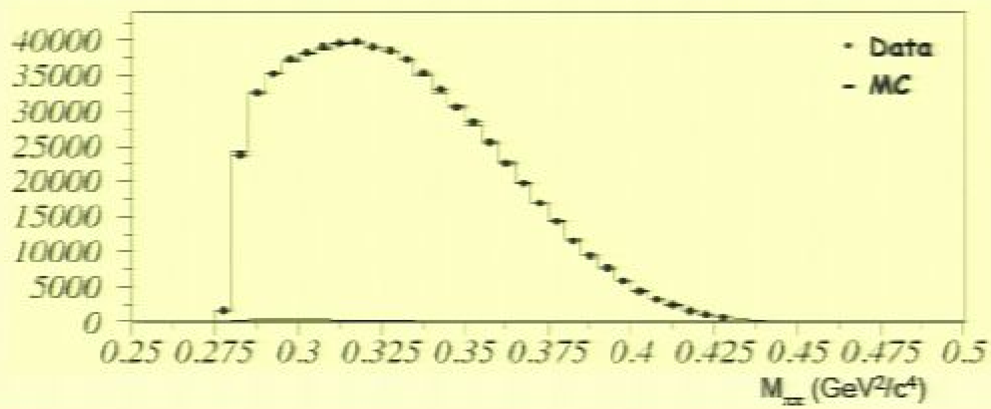
Using iso-populated bins in the 5-D space of the C.M. variables one defines a grid of:

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

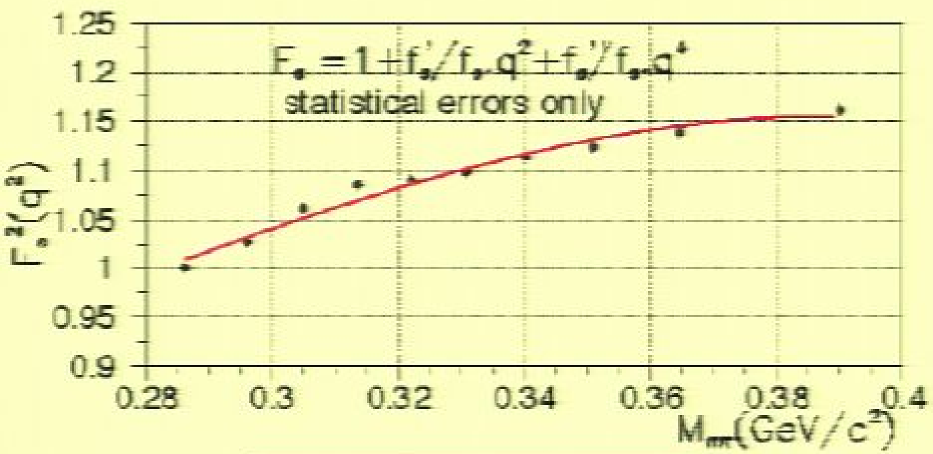
The set of Form Factor values is used to minimize a log-likelihood estimator well suited for small numbers of data event/bin and taking into account the statistics of the simulation (simulated and expected events/bin)

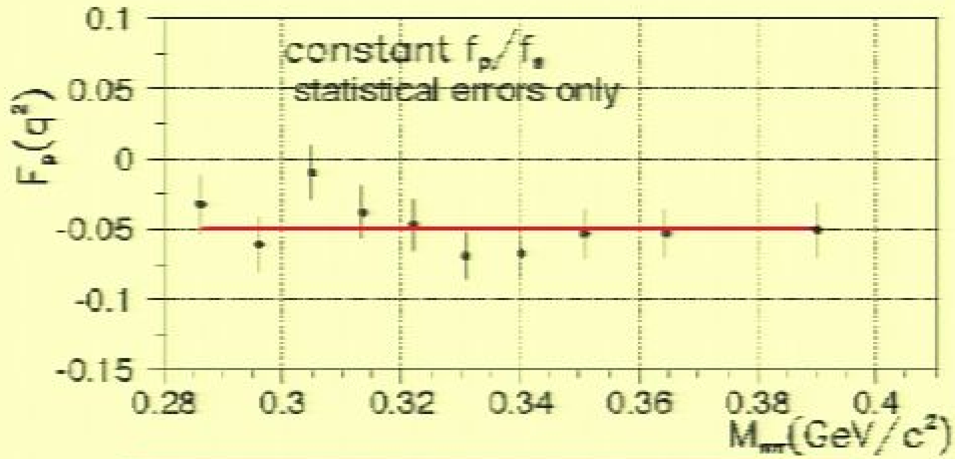
Assuming constant Form Factors over single boxes, ten independent fits in $M_{\pi\pi}$ bins have been performed to get model independent results

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



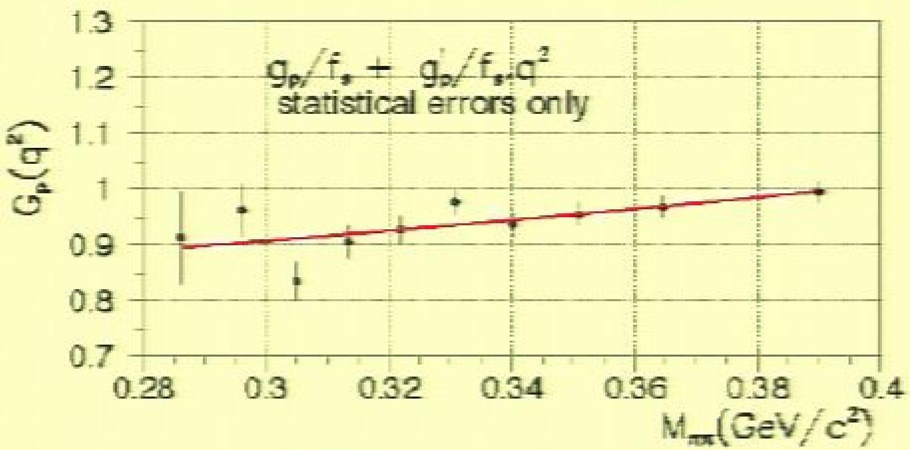
Results (I)

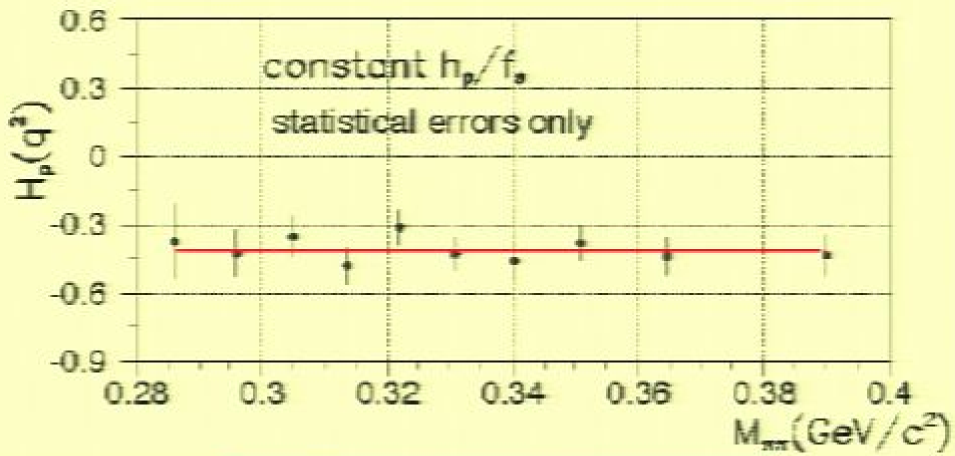




Quadratic in q^2

First measurement of $F_p \neq 0$





Linear in q^2

No linear term (h_p')

Results (II)

value ± stat ± syst

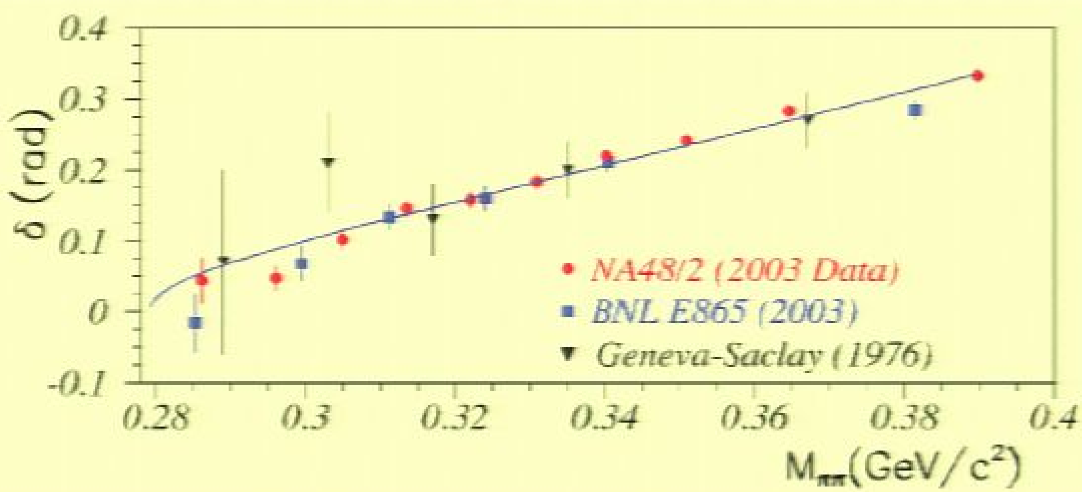
$f_s'/f_s = 0.165 \pm 0.011 \pm 0.006$
$f_s''/f_s = -0.092 \pm 0.011 \pm 0.007$
$f_e'/f_s = 0.081 \pm 0.011 \pm 0.008$
$f_p/f_s = -0.048 \pm 0.004 \pm 0.004$
$g_p/f_s = 0.873 \pm 0.013 \pm 0.012$
$g_p'/f_s = 0.081 \pm 0.022 \pm 0.014$
$h_p/f_s = -0.411 \pm 0.019 \pm 0.007$

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)

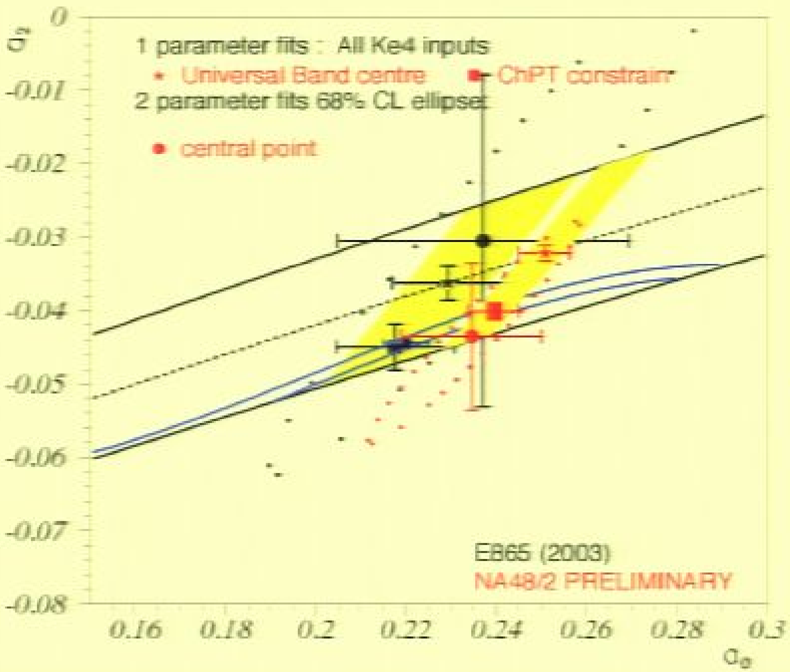
δ Dependence

- The extraction of the ππ 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)

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)

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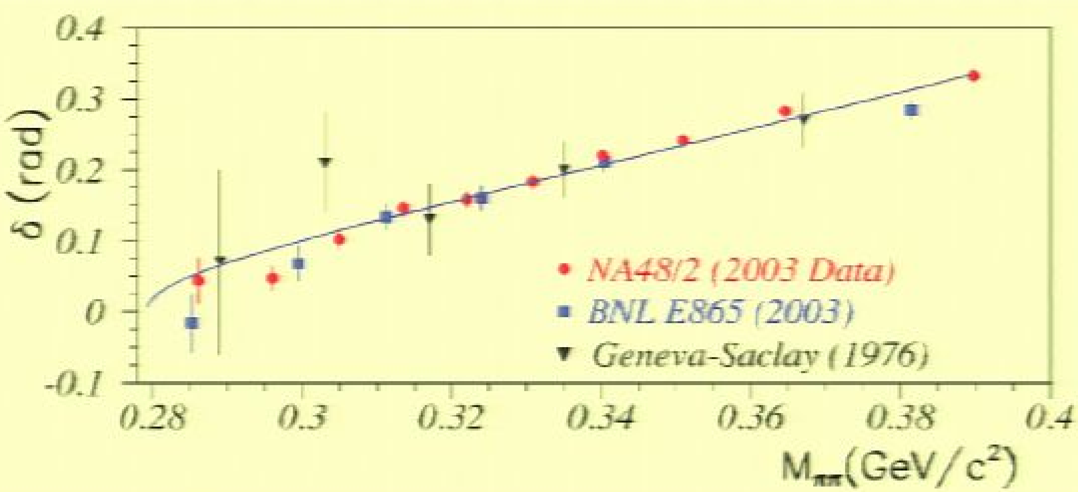

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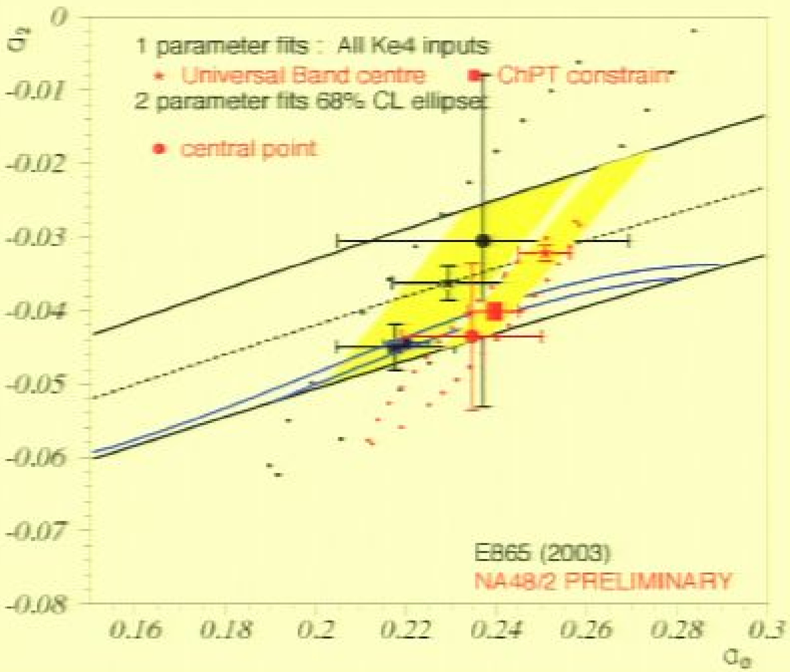

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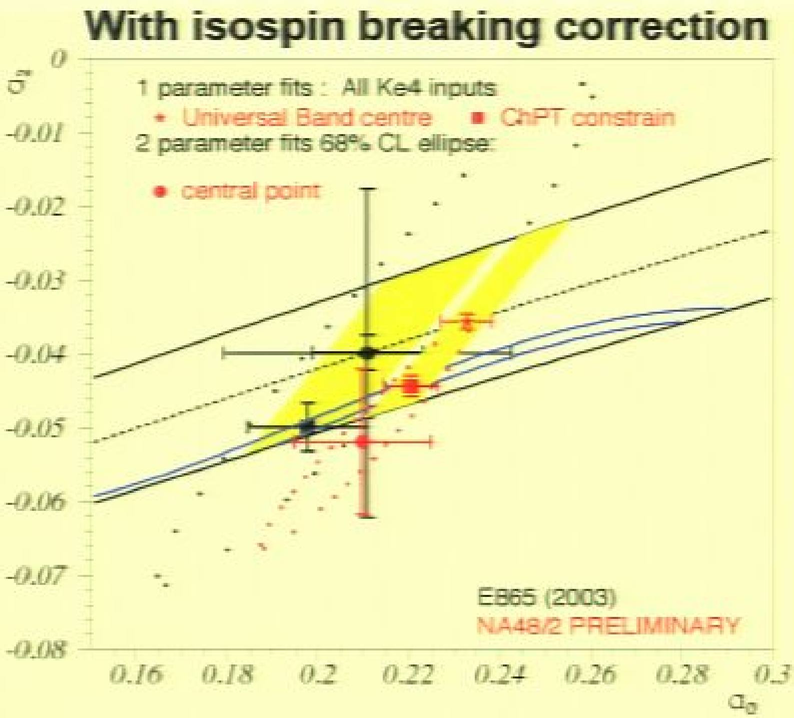
(a_0, a_2) Plane (II)

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))



- 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

ChPT Tests:

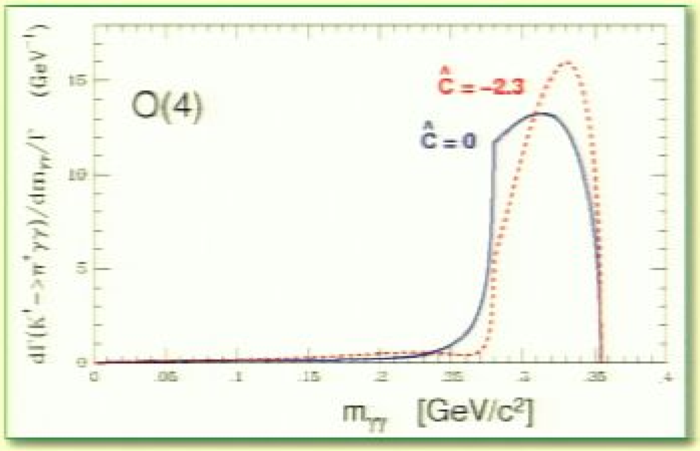
$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ & $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$ Decays

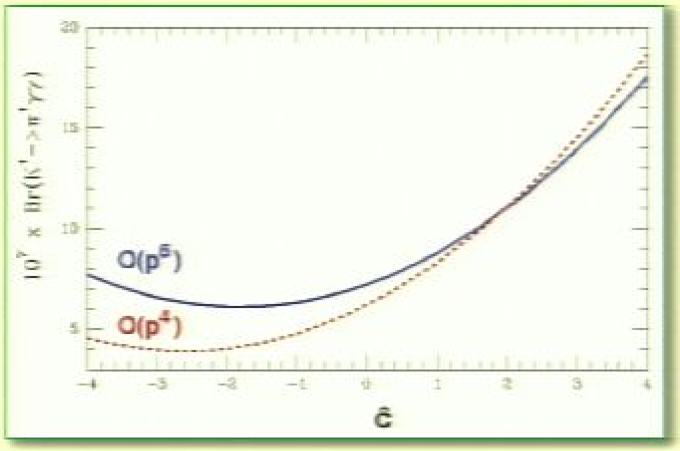
Motivation and Theory

Radiative non-leptonic decays $K^\pm \to \pi^\pm\gamma\gamma$ & $K^\pm \to \pi^\pm\gamma\gamma^* \to \pi^\pm\gamma e^+e^-$ represent a crucial test of the Chiral Perturbation Theory

$$d\Gamma/dz = f(\hat{c}, z) \qquad z = (m_{\gamma\gamma} / m_K)^2$$

- ChPT $O(p^4)$, $O(p^6)$ calculations [D'Ambrosio, Portolés, PLB386 (1996) 403 and Gabbiani, PRLD59 (1999) 094022]
- Both decay spectrum and rate strongly depend on the single $\hat{c}$ parameter
- The $m_{\gamma\gamma}$ spectrum has a pronounced cusp-like behaviour at 2π threshold





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

Previous measurement (E787):

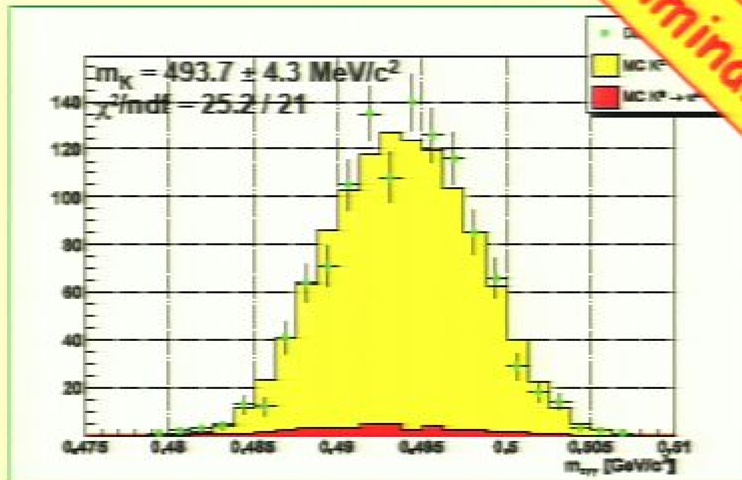
$BR(K^{+} \to \pi^{+}\gamma\gamma) = (1.10 \pm 0.32)\cdot 10^{-6}$

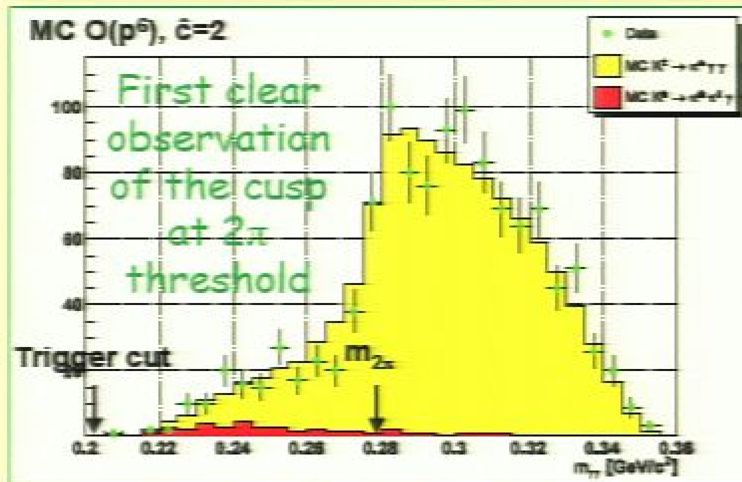
Event sample (~40% of the full statistics):

- 1164 candidate events
- 3.3% background (mainly $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events with overlapping γs @ the LKr)

Shape analysis:

- MC $O(p^6)$ and $\hat{c}=2$ for comparison
- Data shape follows ChPT prediction
- Possibility of precise $\hat{c}$ measurement but no quantitative result yet





$BR(K^{\pm} \to \pi^{\pm}\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{syst})\cdot 10^{-6}$

[assuming $O(p^6)$ distribution, $\hat{c}=2$]

ChPT Tests:

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

$K^\pm \to \pi^\pm e^+ e^- \gamma$

Never observed before. Naïve estimation of the BR:

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

Event sample (full statistics):

- 120 candidate events
- 7.3 ± 1.7 background (mainly $K^\pm \to \pi^\pm \pi^0_D \gamma$)

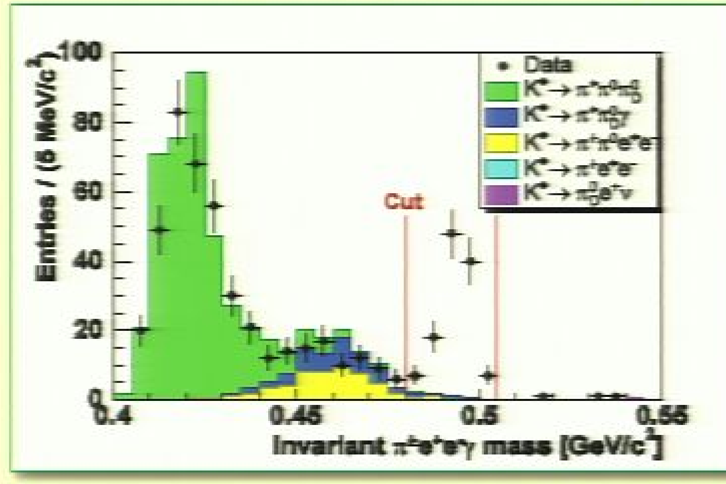
Shape analysis [using ChPT $O(p^4)$ model, F.Gabbiani, PRD59 (1999) 094022]:

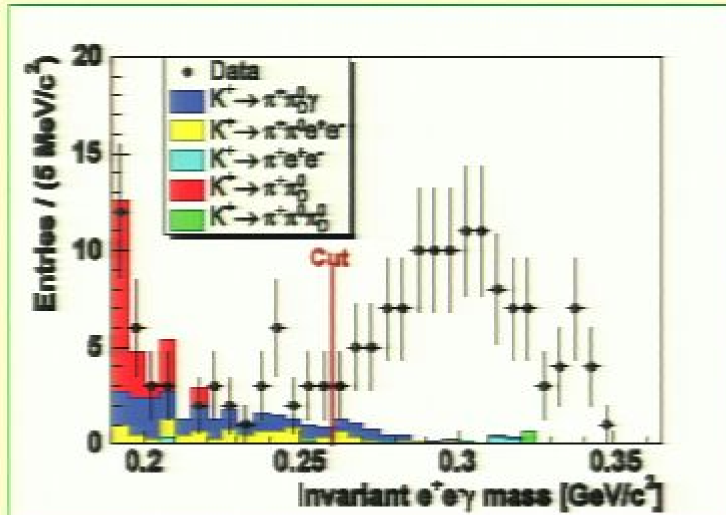
$$\hat{c} = (0.90 \pm 0.45)$$

[χ^2/ndf = 8.1 / 17 Prob 96.4%]

Model-Independent BR ($m_{ee\gamma}$ > 260 MeV/c^2):

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






ChPT Tests:
K± -> π±e+e- Decay

Motivation and Theory

$K^\pm \to \pi^\pm\gamma^* \to \pi^\pm l^+l^-$: suppressed FCNC process proceeding through one-photon exchange. Weak interactions at low energy, ChPT tests

$$d\Gamma/dz \sim P(z)\cdot|W(z)|^2$$

$z = (m_{ee} / m_K)^2$
$P(z)$ = phase space factor

Form Factors:

1) Polynomial: $W(z) = G_F \cdot m_K^2 \cdot f_0 \cdot (1 + \delta \cdot z)$
2) ChPT $O(p^6)$: $W(z) = G_F \cdot m_K^2 \cdot (a_+ + b_+ \cdot z) + W^{\pi\pi}(z)$ D'Ambrosio et al. JHEP 8 (1998) 4
3) Dubna ChPT: $W(z) = W(M_a, M_\rho, z)$ Dubnickova et al. hep-ph/0611175

(f_0, δ) or (a_+, b_+) or (M_a, M_ρ) fully determine a Model-Dependent BR

Goals:

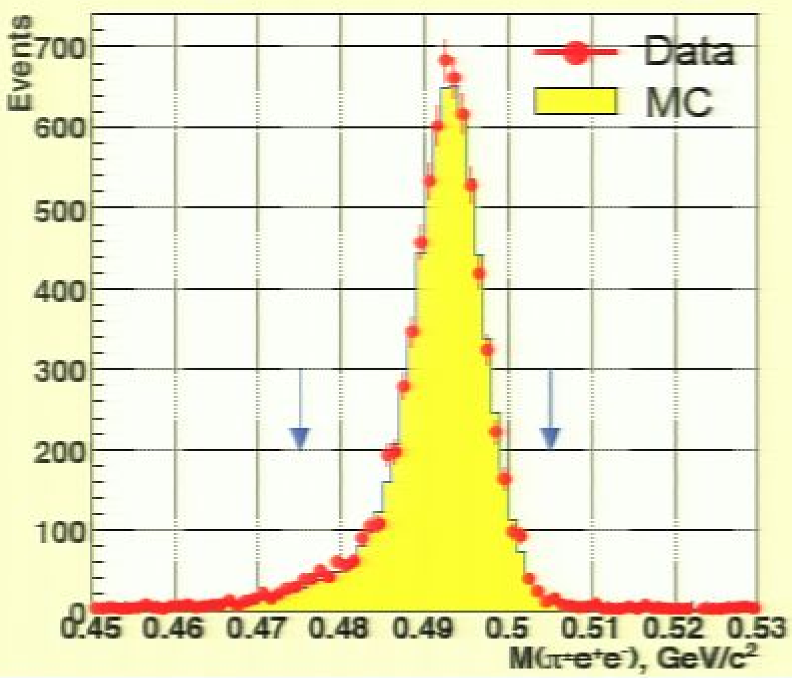
› Model-Independent BR($z > 0.08$) in visible kinematic range
› Parameters of models and BRs in the full kinematic range

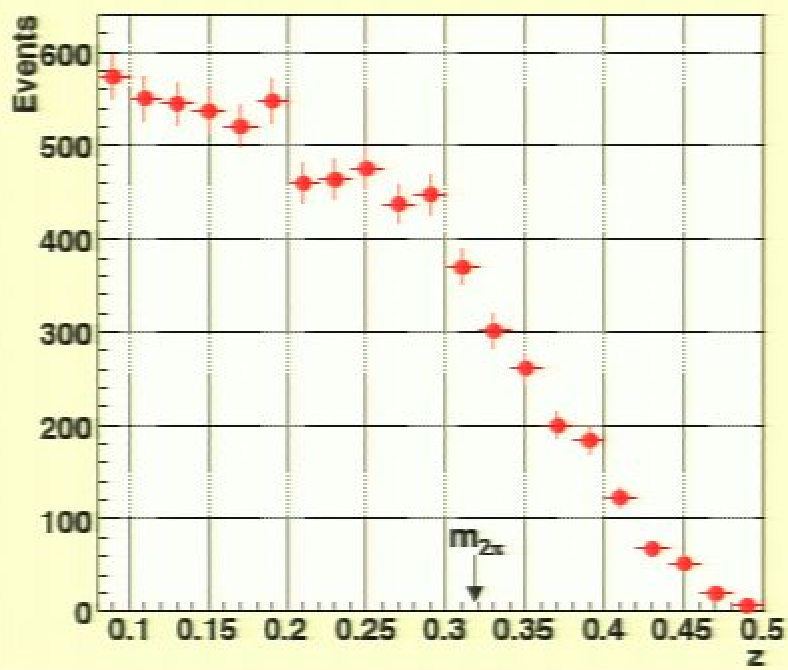
Selection and Background

Event sample (full statistics):

- 7146 candidate events
- 0.6% background/signal ($K^{\pm}\to\pi^{\pm}\pi^{0}_{D}$, $K^{\pm}\to\pi^{0}_{D}e^{\pm}\nu$ + particle mis-ID, subtracted with LFV same-sign candidates)

z distribution is sensitive to the Form Factors and contains all the dynamical information

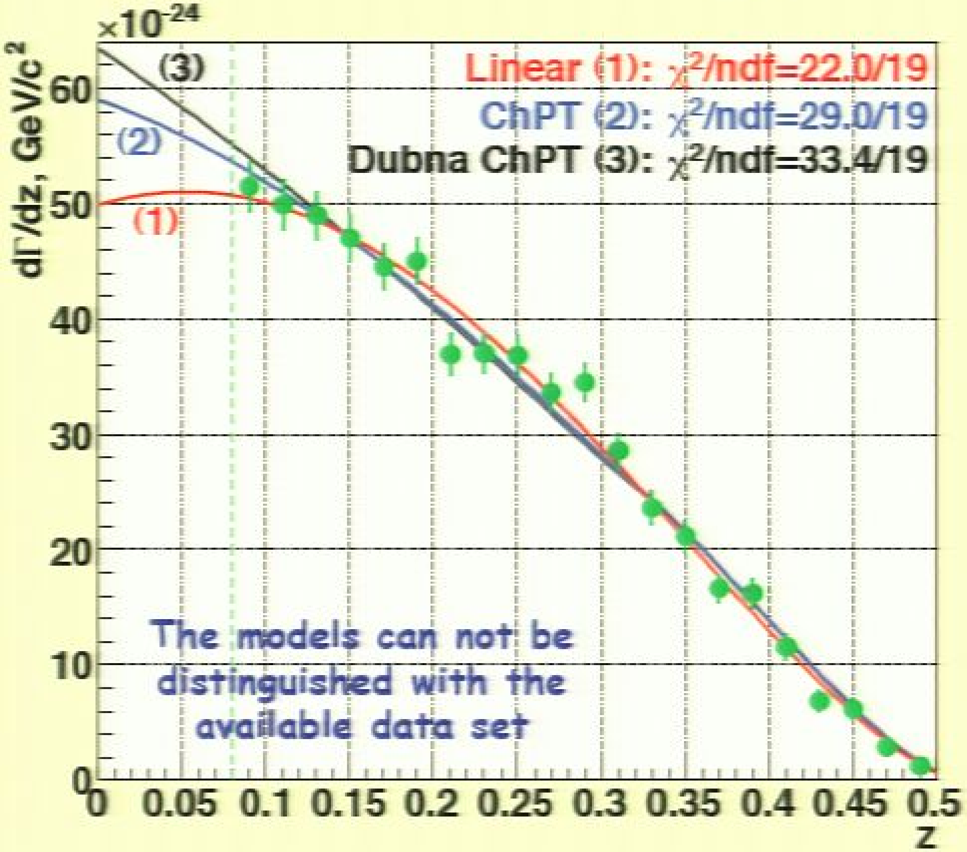




Results (I)

Preliminary

"Raw" values (no BKG/trigger correction, stat error only):



$\delta = 2.42 \pm 0.15$

$f_0 = 0.529 \pm 0.012$

$\rho(\delta, f_0) = -0.963$

$a_+ = -0.576 \pm 0.012$

$b_+ = -0.830 \pm 0.053$

$\rho(a_+, b_+) = -0.913$

$M_a = (0.951 \pm 0.028)$ [GeV]

$M_\rho = (0.705 \pm 0.010)$ [GeV]

$\rho(M_a, M_\rho) = 0.998$

Model-Independent $BR_{MI}(z > 0.08)$ computed by integrating $d\Gamma/dz$

Results (II)

Preliminary

$BR_{MI} \cdot 10^7 = 2.26 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.06_{ext} = 2.26 \pm 0.08$

$\delta = 2.35 \pm 0.15_{stat} \pm 0.09_{syst} = 2.35 \pm 0.18$

$f_0 = 0.532 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext} = 0.532 \pm 0.016$

$BR_1 \cdot 10^7 = 3.02 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.02 \pm 0.10$

$a_+ = -0.579 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext} = -0.579 \pm 0.016$

$b_+ = -0.798 \pm 0.053_{stat} \pm 0.037_{syst} \pm 0.017_{ext} = -0.798 \pm 0.067$

$BR_2 \cdot 10^7 = 3.11 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.11 \pm 0.10$

$M_a = 0.965 \pm 0.028_{stat} \pm 0.018_{syst} \pm 0.002_{ext} = 0.965 \pm 0.033$ [GeV/c]

$M_\rho = 0.711 \pm 0.010_{stat} \pm 0.007_{syst} \pm 0.002_{ext} = 0.711 \pm 0.013$ [GeV/c]

$BR_3 \cdot 10^7 = 3.15 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.15 \pm 0.10$

Including uncertainty due to the model dependence (full z range):

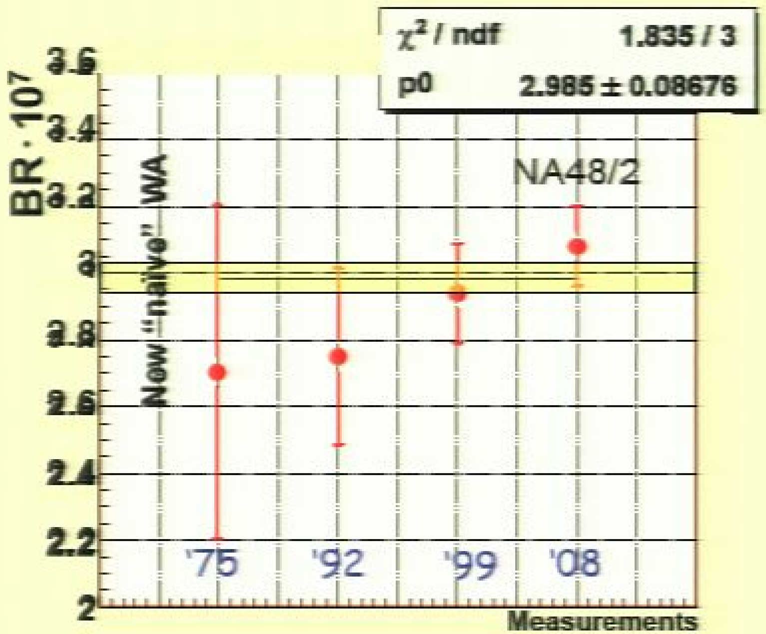
$BR(K^\pm \to \pi^\pm e^+e^-) = (3.08 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} \pm 0.07_{model}) \cdot 10^{-7}$

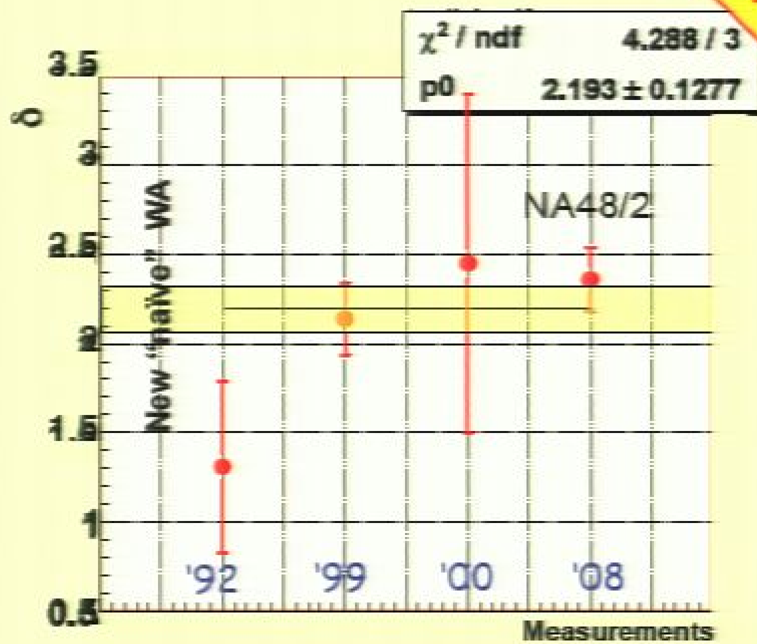
CPV parameter (first measurement):

$\Delta(K^\pm_{\pi ee}) = (BR^+ - BR^-) / (BR^+ + BR^-) = (-2.1 \pm 1.5_{stat} \pm 0.3_{syst})\%$

Results (III)

Preliminary





Measurement	$BR \cdot 10^7$
Bloch et al., PL 56 (1975) B201	2.70 ± 0.50
Alliegro et al., PRL 68 (1992) 278	2.75 ± 0.26
Appel et al. [E865], PRL 83 (1999) 4482	2.94 ± 0.15
NA48/2 preliminary	3.08 ± 0.12

Measurement	δ
Alliegro et al., PRL 68 (1992) 278	1.31 ± 0.48
Appel et al. [E865], PRL 83 (1999) 4482	2.14 ± 0.20
Ma et al. [E865], PRL 84 (2000) 2580	$2.45^{+1.30}_{-0.95}$
NA48/2 preliminary	2.35 ± 0.18

Summary

- ππ Scattering lengths from $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$
  - Improved measurements of Form Factors
  - A larger sample coming soon
- Precise study of the $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay (BR ~ 10^{-6})
  - Clear evidence for 2π cusp, first possibility for shape study
  - Measured BR in agreement with ChPT
  - Shape analysis and a larger sample coming soon
- First observation of the $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay (BR ~ 10^{-8})
  - An independent evidence for 2π cusp
  - Measurement of shape and the BR finalized
- Precise study of the $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ decay (BR ~ 10^{-7})
  - Sample & precision comparable to world's best ones
  - BR and Form Factors in agreement with ChPT and other measurements
  - First limit on the CP violating asymmetry obtained

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