Kaon Physics at CERN: recent results from the NA48/2 experiment

Cristina Biino * - INFN Torino

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*On behalf of the NA48/2 Collaboration

Outline

- Kaon physics at CERN
  - ★ the NA48/2 experiment
- The semileptonic Kl3 decays $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ and $K^{\pm} \rightarrow \pi^0 \mu^{\pm} \nu$
  - ★ Introduction & parametrization
  - ★ Preliminary Form Factors results

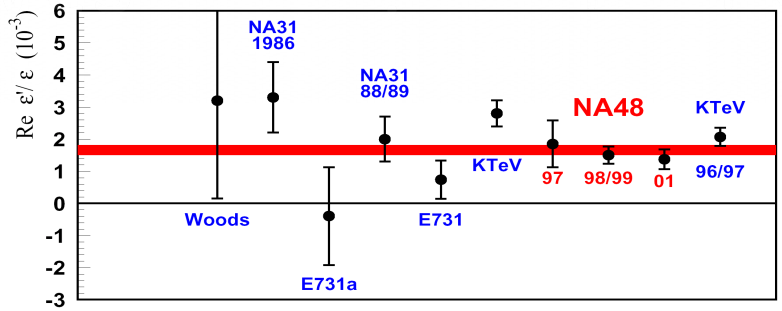
Preliminary

- The Ke4 decays $K^{\pm} \rightarrow e^{\pm} \nu \pi^{+} \pi^{-}$ and $K^{\pm} \rightarrow e^{\pm} \nu \pi^0 \pi^0$
  - ★ Interest of the decays in the ChPT framework
  - ★ Preliminary and New Branching Ratio and Form Factors measurements

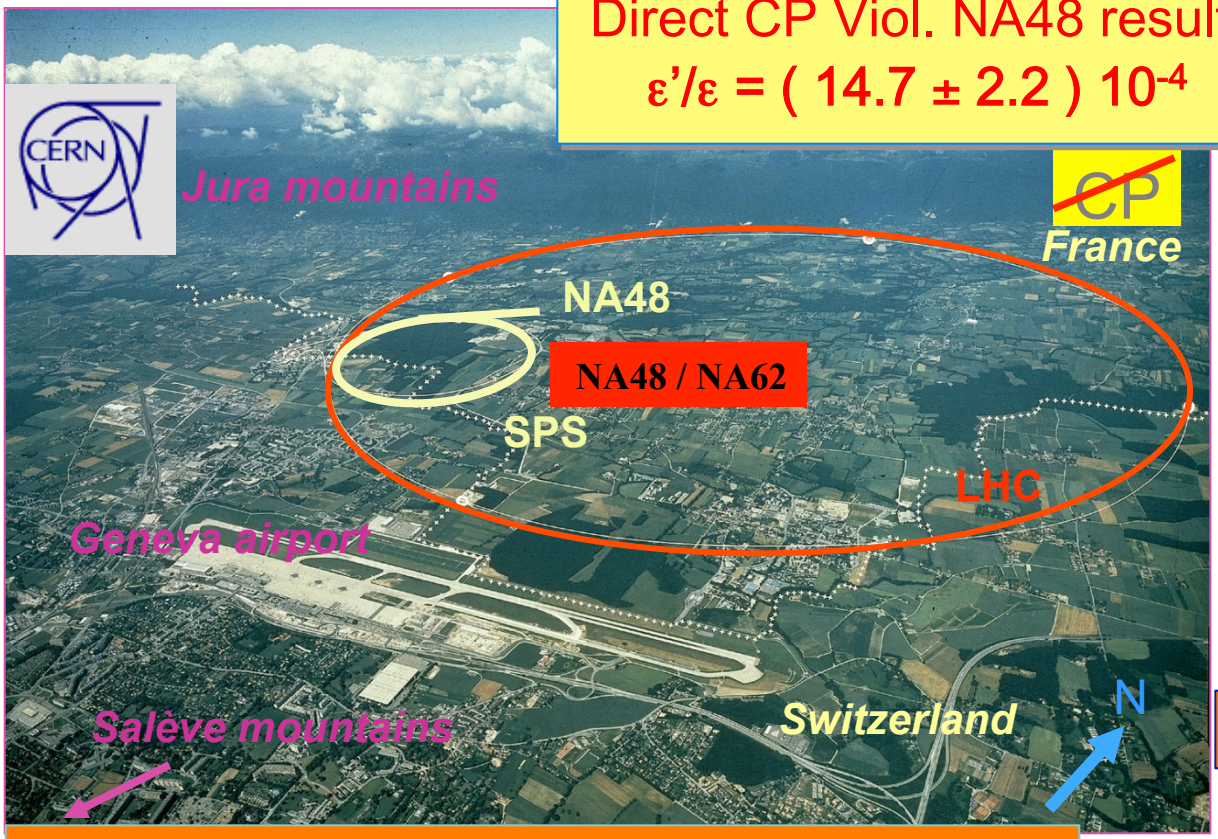
Preliminary & New

NA48 and NA62 experiments at CERN

A fixed target experiment at the CERN SPS dedicated to the study of CP violation and rare decays in the kaon sector



Direct CP Viol. NA48 result:
$\varepsilon'/\varepsilon = (14.7 \pm 2.2)\ 10^{-4}$

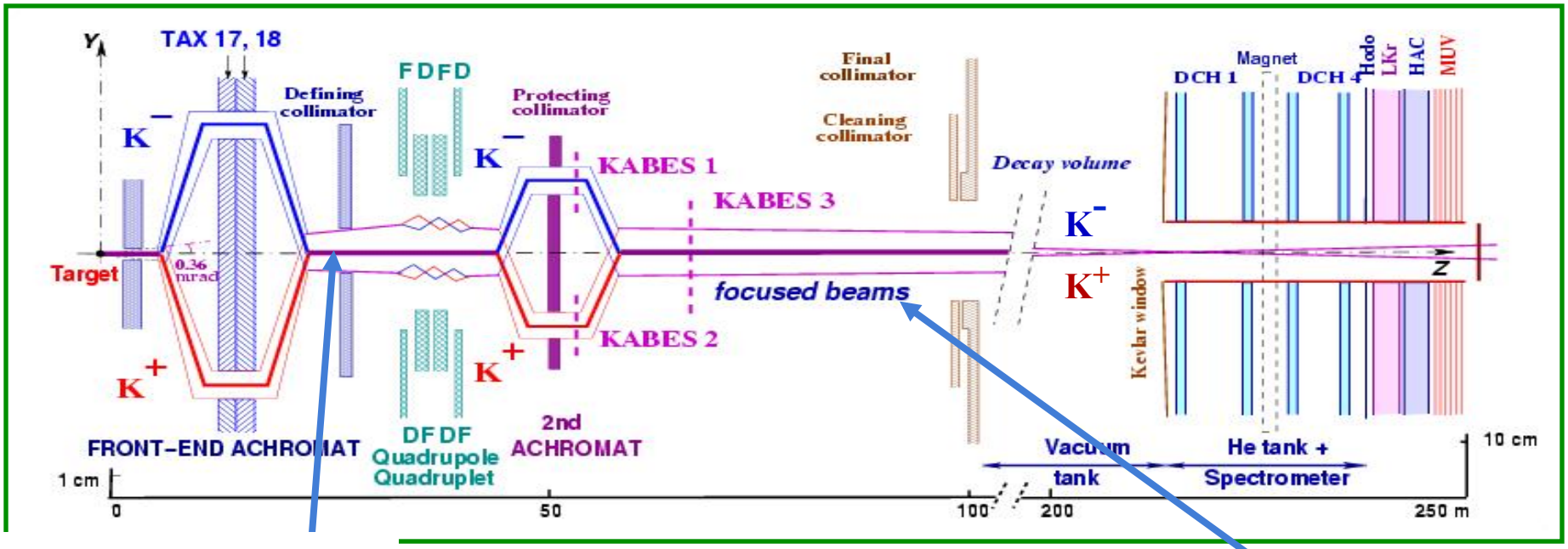


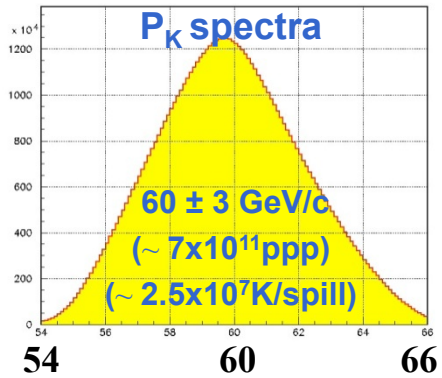
NA48	1997	ε'/ε run	$K_L + K_S$
	1998	ε'/ε run	$K_L + K_S$
	1999	ε'/ε run $K_L + K_S$	K_S Hi. Int
	2000	K_L only	K_S High Intensity; NO Spectrometer
	2001	ε'/ε run $K_L + K_S$	K_S High Int.
NA48/1	2002	K_S High Intensity	
NA48/2	2003	$K^\pm$ High Intensity	
	2004	$K^\pm$ High Intensity	
NA62(R_K)	2007/08:	$K^\pm_{e2}/K^\pm_{\mu 2}$ runs	
NA62	2007–2013:	R&D	
	2012:	Start $K^+ \to \pi^+ \nu\bar{\nu}$	

Also at this conference: ***Precision Measurements of Charged Kaon Decays with the NA48/2-NA62 Experiments*** **by V. Kekelidze**

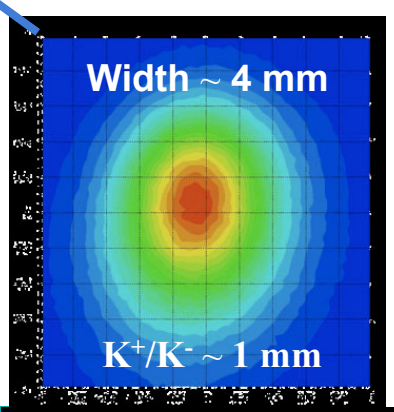
NA48/2 simultaneous $K^{\pm}$ beam

NA48/2 beams: simultaneous K^+/K^-, focused, high momentum, narrow band designed to precisely measure $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ ($\pi^0\ \pi^0\ \pi^{\pm}$) Dalitz-plot density to search for direct CPV.





- Simultaneous, unseparated, focused beams
- Kaon decays in the vacuum tank: 22%
- Flux ratio: K^+/K^- ~ 1.8
- Similar acceptance for K^+ and K^- decays
- Large charge symmetrization of experimental conditions



NA48 detector

- **Liquid Krypton EM calorimeter (LKr)**

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

$\sigma_x = \sigma_y = 4.2/E^{\frac{1}{2}} \oplus 0.6$ mm (E in GeV/)

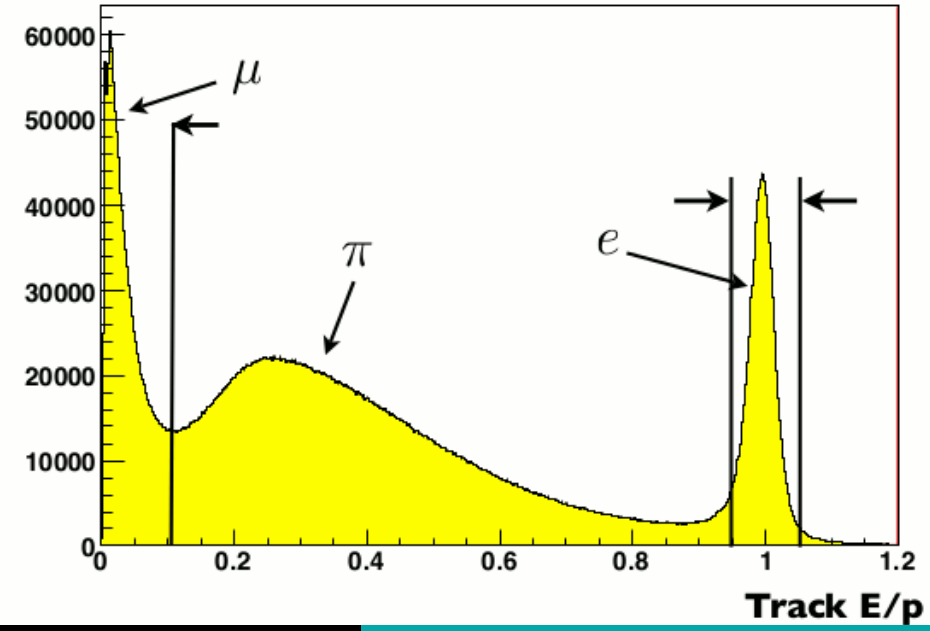
- **Magnetic spectrometer** (4 DCHs + dipole magnet)

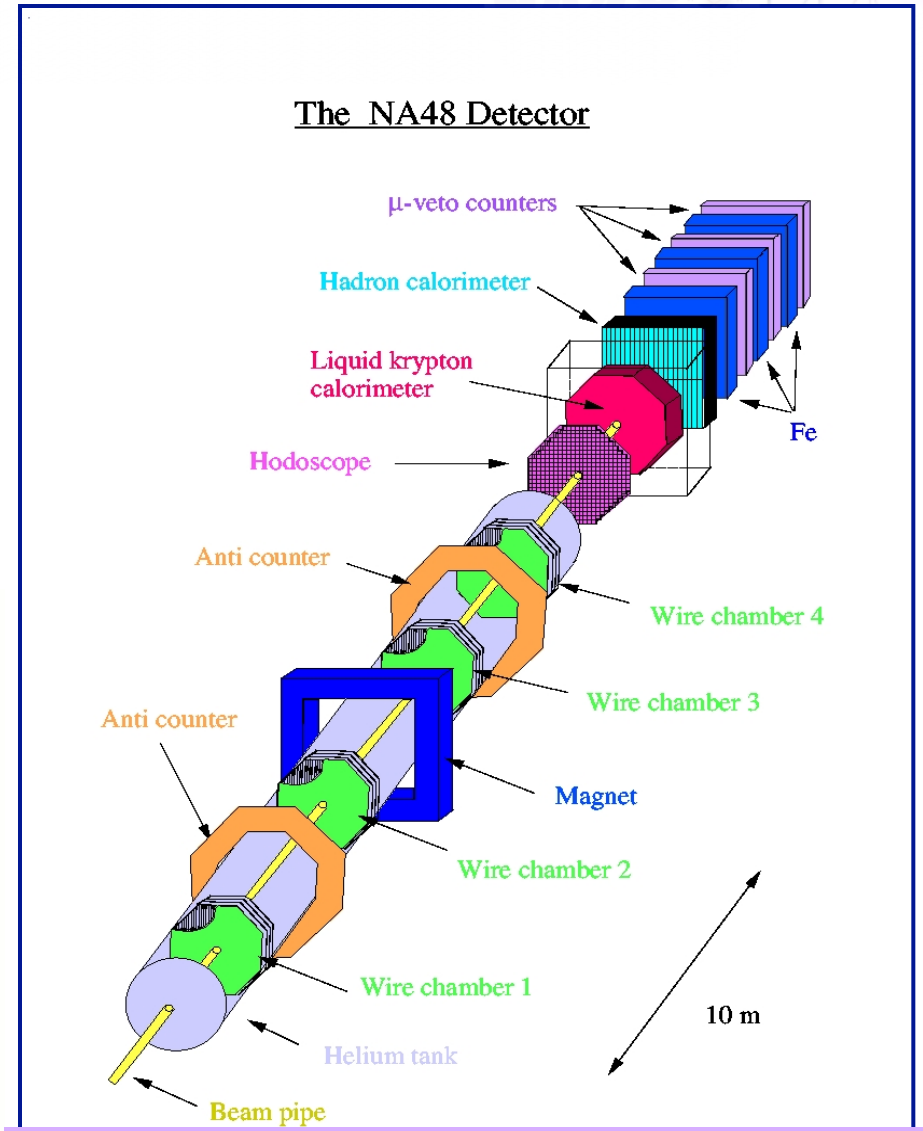
$\sigma_p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)

- **Charged Hodoscope** $\sigma_t = 150$ ps

- **Muon Veto counter**

E/p ratio used for e /π discrimination





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

$K^{\pm} \to \pi^0 l^{\pm} \nu$ (Kl3) Form Factors - Introduction

Precision measurement of $\mathbf{K^{\pm} \longrightarrow \pi^0 l^{\pm} \nu}$ (Kl3) provide the most accurate and theoretically cleanest way to access $|\mathbf{V_{us}}|$

K_{l3} decays are described by two **form factors $f_{\pm}(t)$** and the matrix element can be written as:

$$M=G_F/2\, V_{US} \left(f_+(t)(P_K + P_\pi)^\mu\, \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t)\, m_l\, \bar{u}_l (1+\gamma_5) u_\nu \right)$$

- $t=q^2$ is the squared 4-momentum transfer to the l-ν system
- $f_-(t)$ can only be measured in $K_{\mu 3}$ decays ($m_e \ll m_K$)
- $f_+(t)$ is the vector form factor and $f_0(t)$ the scalar form factor

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

$$\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)}$$

$$\bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}$$

$K^{\pm} \to \pi^0 l^{\pm} \nu$ Form Factors - Parametrization

- **Pole Parametrization:** assume the exchange of vector (1^-) and scalar (0^+) resonances K* and mass m_V/m_S. $f_+(t)$ can be described by K*(892), for $f_0(t)$ no obvious dominance is seen

$$\overline{f_{+,0}}(t) = \frac{m^2_{V,S}}{m^2_{V,S} - t}$$

- **Linear and quadratic parametrization:** expansion in the momentum transfer without a direct physical meaning

$$\overline{f_{+,0}}(t) = \left(1 + \lambda_{+,0} \frac{t}{m^2_\pi} \right)$$

linear

$$\overline{f_{+,0}}(t) = \left(1 + \lambda'_{+,0} \frac{t}{m^2_\pi} + \frac{1}{2} \lambda''_{+,0} \left(\frac{t}{m^2_\pi} \right)^2 \right)$$

quadratic

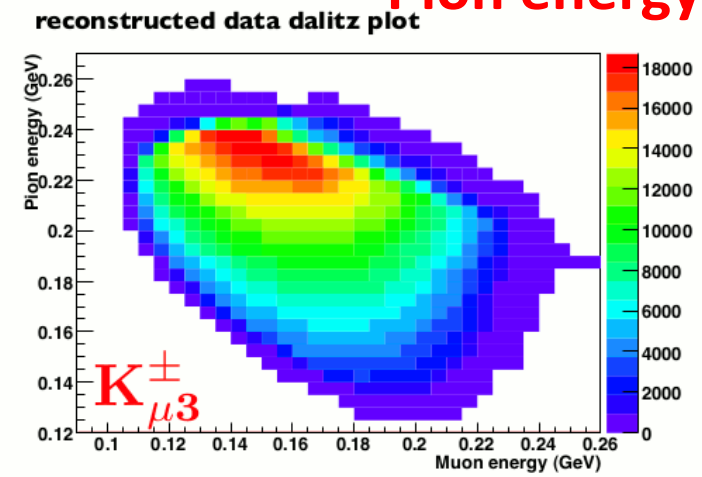
$K^{\pm} \to \pi^0 l^{\pm} \nu$ Form Factors – Dalitz plots

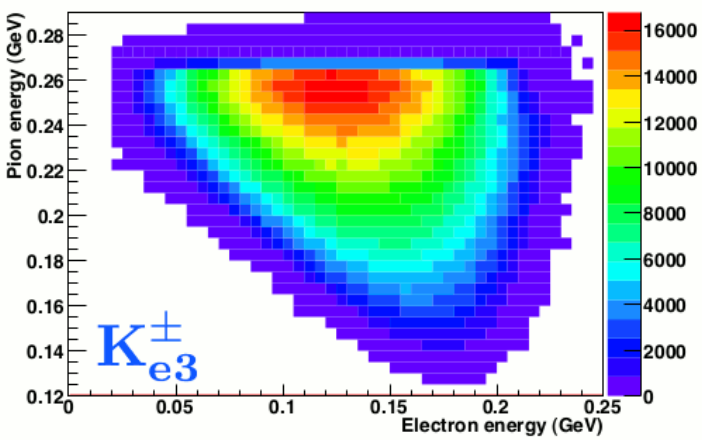
Data collected in 2004 in a 3 day run with a minimum bias trigger:

- 2.5 10^6 $K^{\pm}\mu 3$ candidates selected
- 4.0 10^6 $K^{\pm}e3$ candidates selected

Very low background, at per mill level

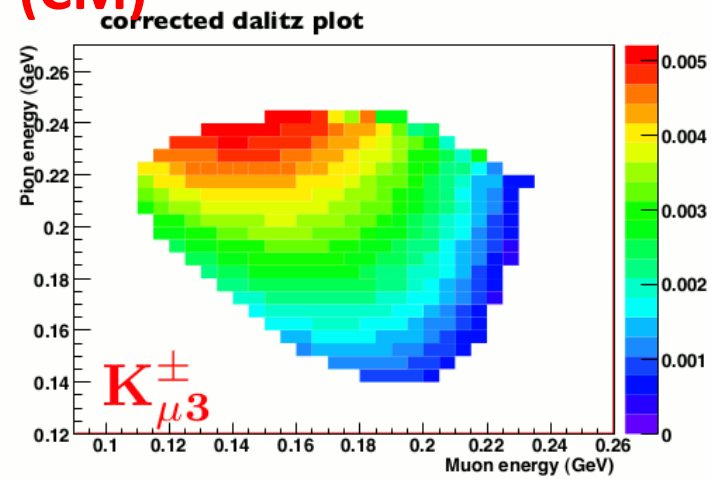
Pion energy vs Lepton energy (CM)

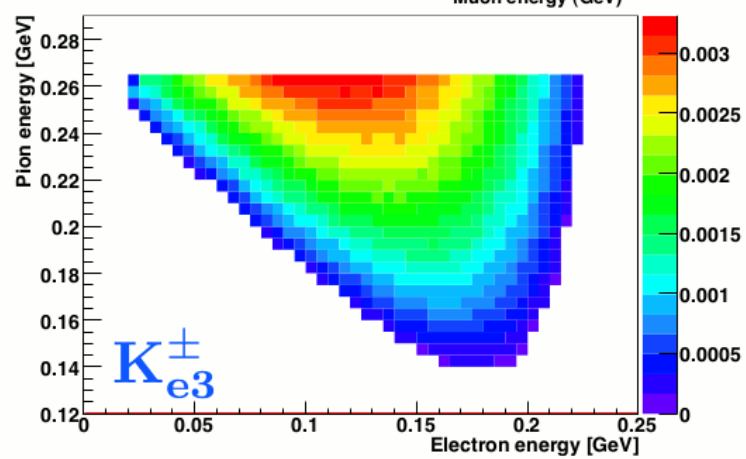




Applied corrections:

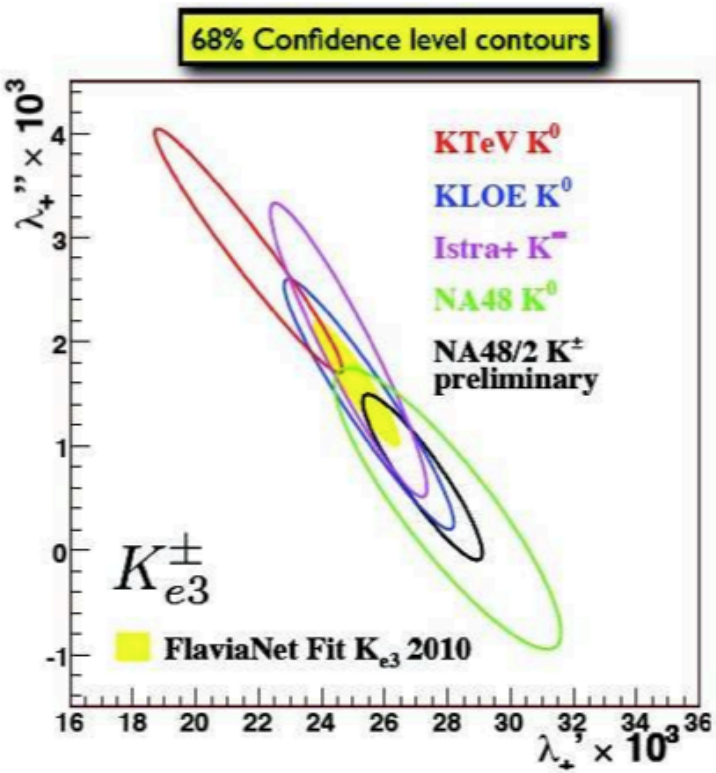
- Background subtraction.
- Acceptance.
- Radiative corrections.

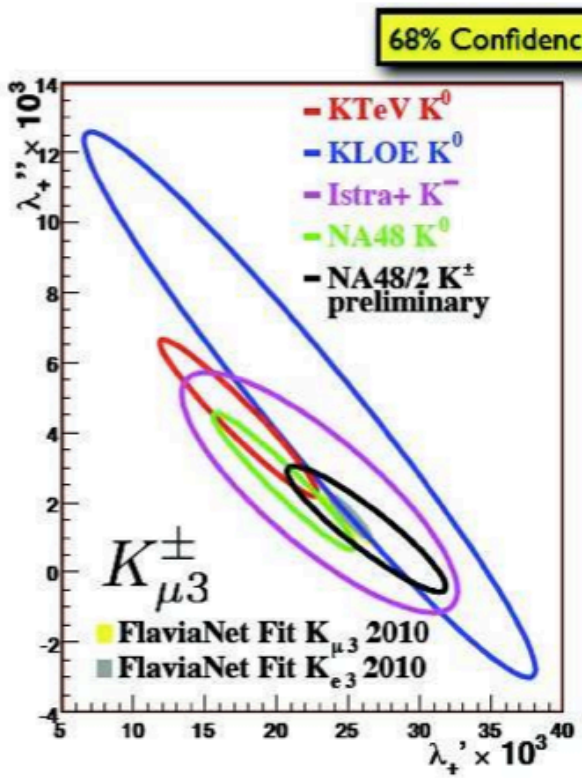


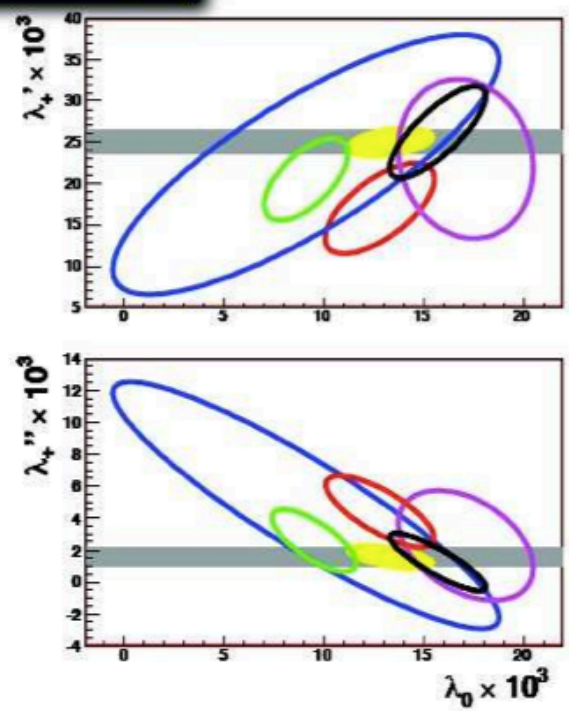


$K^{\pm} \to \pi^0 l^{\pm} \nu$ - Preliminary Results

Quadratic	λ'_+ (10^{-3})	λ''_+ (10^{-3})	λ_0 (10^{-3})
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0_{\rm stat} \pm 2.2_{\rm syst}$	$1.2 \pm 1.1_{\rm stat} \pm 1.1_{\rm syst}$	$15.7 \pm 1.4_{\rm stat} \pm 1.0_{\rm syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{\rm stat} \pm 1.1_{\rm syst}$	$0.7 \pm 0.3_{\rm stat} \pm 0.4_{\rm syst}$	
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu 3}$	$873 \pm 8_{\rm stat} \pm 9_{\rm syst}$		$1183 \pm 31_{\rm stat} \pm 16_{\rm syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{\rm stat} \pm 7_{\rm syst}$		



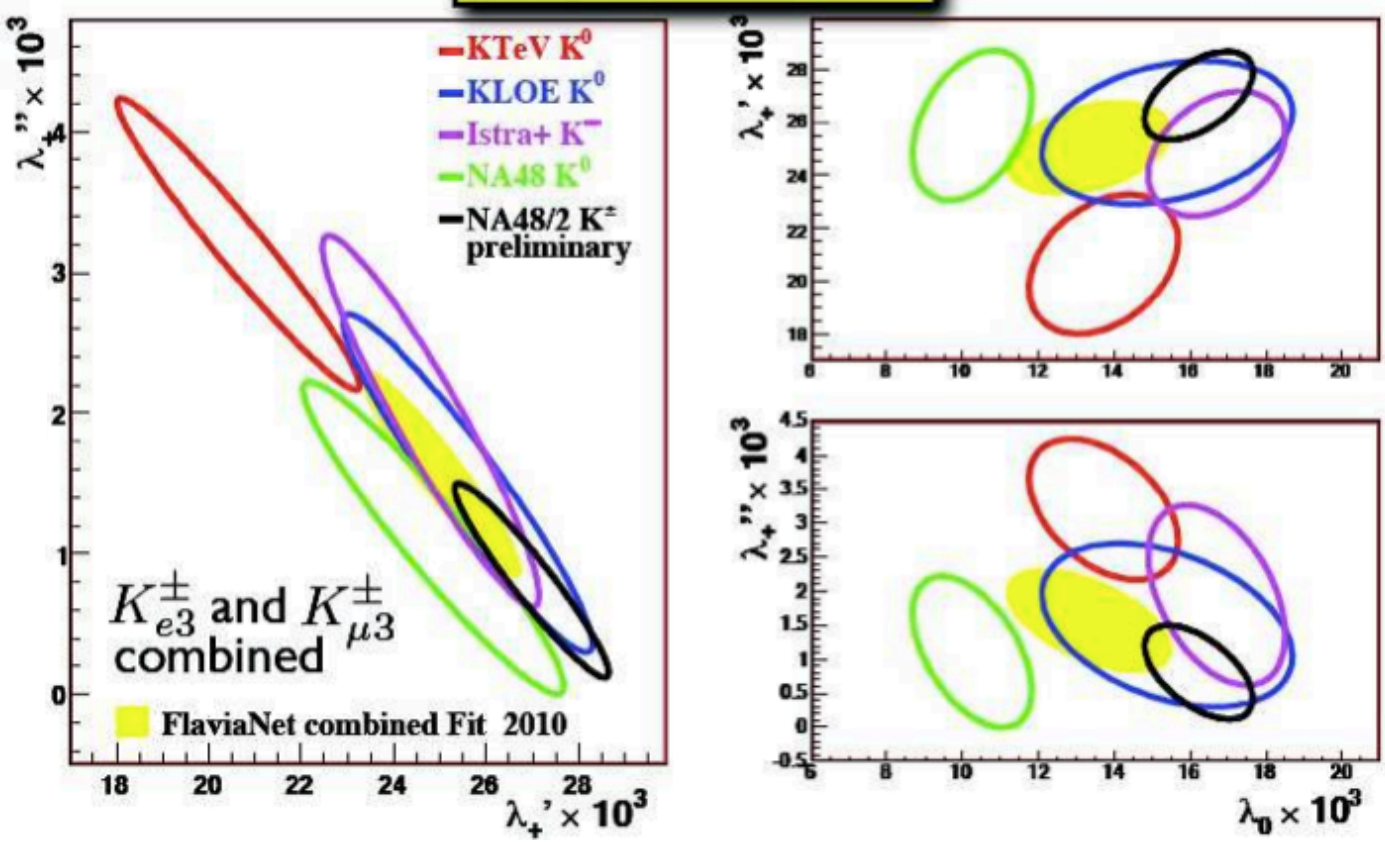




$K^{\pm} \to \pi^0 l^{\pm} \nu$ - Preliminary Combined Results

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	877 ± 6		1176 ± 31

68% Confidence level contours

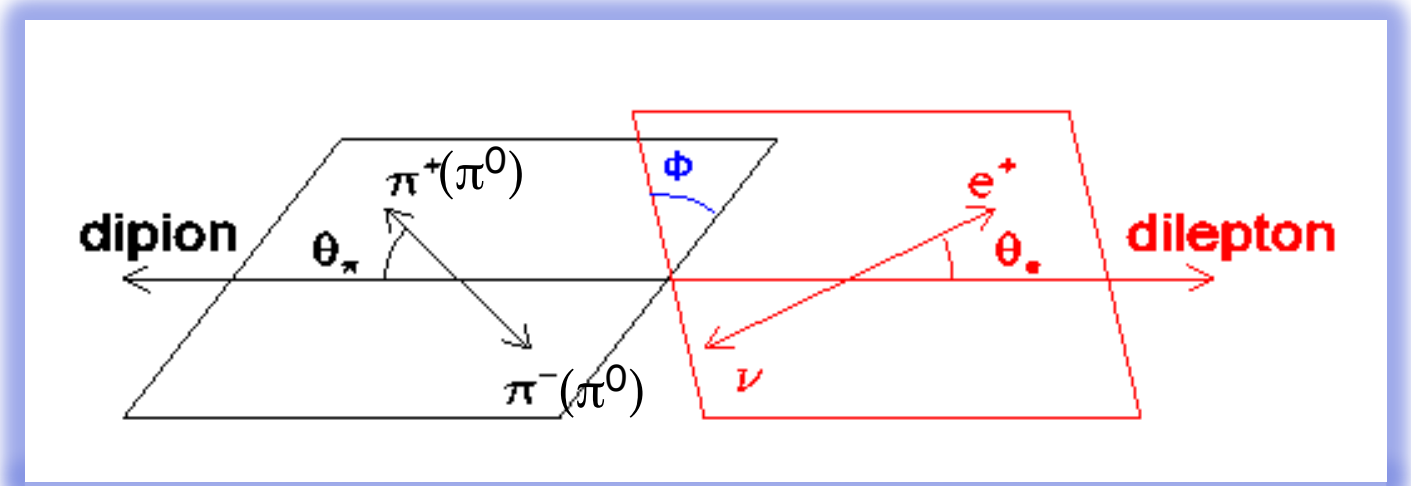


- NA48/2 is the first experiment which measures both $K^{\pm}e3$ and $K^{\pm}\mu 3$.
- Results for $K^{\pm}e3$ and $K^{\pm}\mu 3$ from NA48/2 in good agreement
- High precision preliminary results, competitive with other measurements. Smallest error in the combined result.
- More data soon from NA62.....

K_{e4} decays

Ke4 decay:

- $K^{\pm} \rightarrow e\, \nu\, \pi^{+}\, \pi^{-}$ called Ke4(+−) - charged mode
- $K^{\pm} \rightarrow e\, \nu\, \pi^{0}\, \pi^{0}$ called Ke4(00) - neutral mode



- Ke4 is a 4-body decay ⟹ **5 independent kinematic variables**

(Cabibbo-Maksymowicz variables, 1965)

$S_{\pi} = M^{2}_{\pi\pi}$; $S_{e} = M^{2}_{e\nu}$; $\cos \vartheta_{\pi}$; $\cos \vartheta_{e}$; Φ **for (+−)**

reduced to 3 indep. variables for (00)

Form factors: formalism of Ke4 decay

Ke4 hadronic current is described by form factors

→ partial wave expansion *[Pais Treiman and Watson Theorem (T invariance) PR168 (1968) 1858]*, limited to S and P wave.

- **Partial wave expansion of the amplitude** *[Pais-Treiman 1968 & Watson Theorem (T-invariance)]*

F,G are 2 Axial Form Factors:

- $F = F_S e^{i\delta_S} + F_P e^{i\delta_P} \cos\vartheta_\pi$
- $G = G_P e^{i\delta_P}$

H= 1 Vector Form Factor:

- $H = H_P e^{i\delta_P}$

The fit parameters (real) are:

(+-): F_S, F_P, G_P, H_P, $\delta=\delta_S-\delta_P$

(00): only F_S

Extract a0 and a2 from $\delta(q^2)$

- **q^2 dependence** can be studied expanding fitted form factors: *(Amoros-Bijens 1999)*

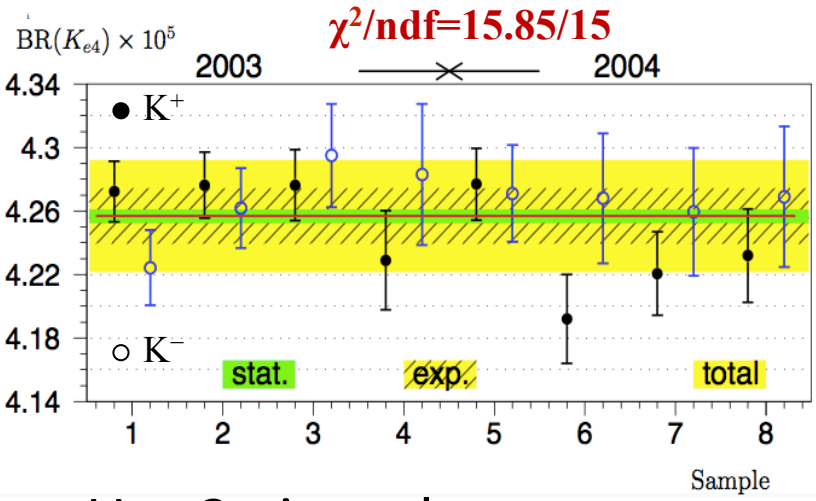
- $F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e' (m^2_{e\nu}/4\, m^2_\pi) + \ldots$
- $F_p = f_p + f_p' q^2 + \ldots$
- $G_p = g_p + g_p' q^2 + \ldots$
- $H_p = h_p + h_p' q^2 + \ldots$

with $q^2 = (M^2_{\pi\pi}/4\, m^2_\pi) - 1$

(these Taylor expansions are valid in the Isospin symmetry limit)

Ke4$^\pm$ form factors studied by NA48/2 with 1.1 million decays *[published in EPJ C70 (2010) 635]*

Ke4 decay - charged mode



$K^{\pm}_{e4}(+-)$

PDG : $(4.09 \pm 0.10)\times 10^{-5}$

$$BR(K^{\pm}_{e4}) = \frac{(N_s - N_b)}{N_n}\frac{A_n \varepsilon_n}{A_s \varepsilon_s} BR(K_{3\pi})$$

- Use 3 pions decays as normalization
- N_s, N_b, N_n : number of signal (1.11×10^6), background (0.95% of K_{e4}) and normalization (1.9×10^9) events
- A_S, A_n, ε_S, ε_n : signal and normalization acceptance (18.16% and 23.97%) and trigger efficiency (98.5% and 97.7%)
- BR($K^{\pm}\rightarrow\pi^+\pi^-\pi^{\pm}$) = (5.59±0.04)%

Systematic Uncertainty	%
Acceptance and beam geom.	0.18
Muon vetoing	0.16
Accidental activity	0.21
Background	0.07
Particle ID	0.09
Radiative effects	0.08

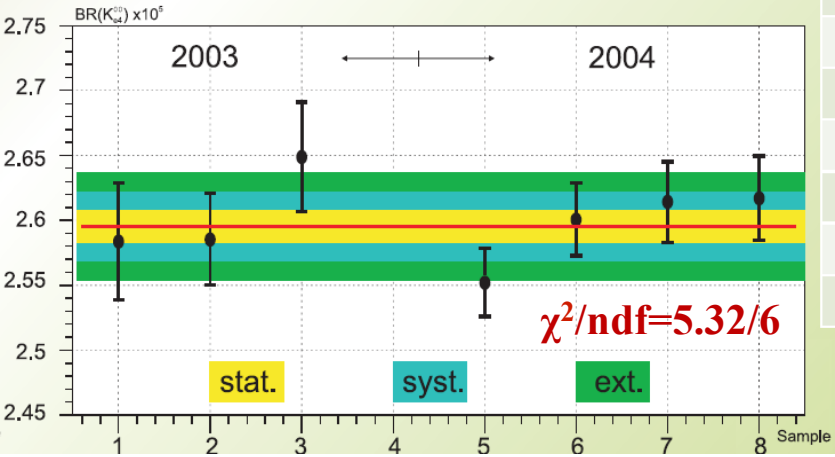
New Results

CERN-PH-EP-2012-185 *and* *http://arxiv.org/pdf/1206.7065.pdf*

$$BR(K^+_{e4}) = (4.255 \pm 0.008) \times 10^{-5};\ \ BR(K^-_{e4}) = (4.261 \pm 0.011) \times 10^{-5}$$

$$BR(K^{\pm}_{e4}(+-)) = (4.257 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext}) \times 10^{-5}$$

Ke4 decay - neutral mode



$K^{\pm}_{e4}(00)$

PDG : $(2.2 \pm 0.4) \times 10^{-5}$

$$BR(K^{\pm}_{e4}) = \frac{(N_s - N_b)}{N_n} \frac{A_n \varepsilon_n}{A_s \varepsilon_s} BR(K_{3\pi})$$

- Use 3 pions decays as normalization
- N_s, N_b, N_n : number of signal (44,909); background (1.3% of K_{e4}) and normalization (71×10^6) events
- A_S, A_n, ε_S, ε_n : signal and normalization acceptance (1.77% and 4.11%) and both trigger efficiencies in the range 92-98%
- BR($K^{\pm}\rightarrow\pi^0\pi^0\pi^{\pm}$) = (1.761±0.022)%

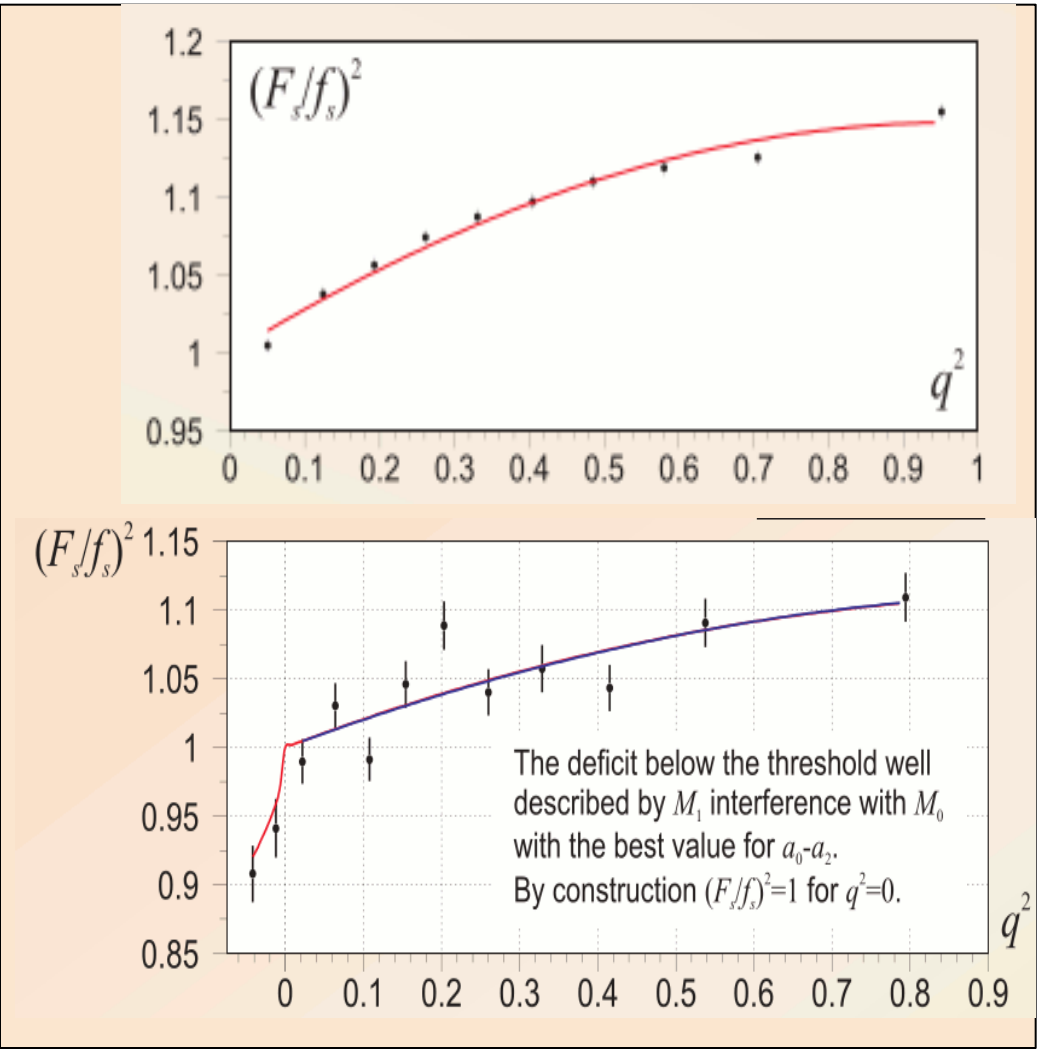
Systematic Uncertainty	%
Background	0.35
Simulation statistics	0.12
Form Factors dependence	0.20
Radiative effects	0.23
Trigger efficiency	0.80
Particle ID	0.10
Beam geometry	0.10

Preliminary Results

$$BR(K^{\pm}_{e4}(00)) = (2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext}) \times 10^{-5}$$

Ke4 decay – Form Factors variations

Relative form factor measurement as a function of $q^2=S_\pi/4(m_{\pi+})^2 - 1$



$K_{e4}(+-)$

"charged" mode

$K_{e4}(00)$

"neutral" mode: includes one-loop theoretical prescription with negative interference (charge exchange scattering $\pi^+\pi^- \rightarrow \pi^0\pi^0$)

Ke4(+−) Form Factors & Scattering Lengths

The overall form factor normalization:

$f_s = 5.705 \pm 0.003_{stat} \pm 0.017_{exp} \pm 0.031_{ext}$
$= 5.705 \pm 0.035_{norm}$

New

$f_s' = 0.867 \pm 0.040_{stat} \pm 0.029_{syst} \pm 0.005_{norm}$
$f_s'' = -0.416 \pm 0.040_{stat} \pm 0.034_{syst} \pm 0.003_{norm}$
$f_e' = 0.388 \pm 0.034_{stat} \pm 0.040_{syst} \pm 0.002_{norm}$
$f_p = -0.274 \pm 0.017_{stat} \pm 0.023_{syst} \pm 0.002_{norm}$
$g_p = 4.952 \pm 0.057_{stat} \pm 0.057_{syst} \pm 0.031_{norm}$
$g_p' = 0.508 \pm 0.097_{stat} \pm 0.074_{syst} \pm 0.003_{norm}$
$h_p = -2.271 \pm 0.086_{stat} \pm 0.046_{syst} \pm 0.014_{norm}$

Two statistically independent measurements by NA48: from Ke4 form factors and from $\pi^+\pi^- \to \pi^0\pi^0$ scattering length in $K^\pm \to \pi^\pm\pi^+\pi^-$ decays

✓Different systematics: calorimeter and trigger vs. electron misID and background

✓ Different theoretical inputs: rescattering in final state and ChPT expansion vs.Roy equation and Isospin breaking connection

✓ Large overlap in the (a_0, a_2) plane

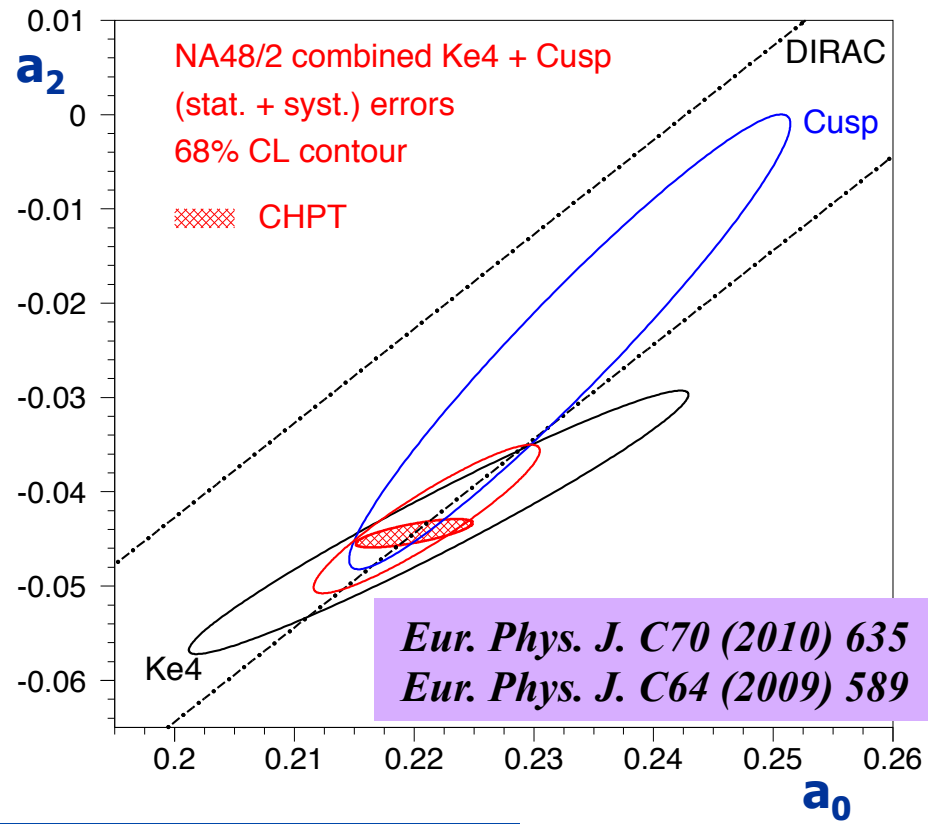
✓ Impressive agreement with ChPT

Precise ChPT prediction constraint:

[CGL NPB 603(2001), PRL86(2001)]

$a_0 = 0.2196 \pm 0.0028 \pm 0.0020$ and
$a_2 = -0.0444 \pm 0.0007 \pm 0.0005 \pm 0.0008$
or $(a0 - a2) = 0.2640 \pm 0.0021 \pm 0.0015$

Total error $\Delta a_2 = \pm 0.0009$ $\Delta a_0 = \pm 0.0034$
$\Delta(a_2 - a_2) = \pm 0.0026$



Eur. Phys. J. C70 (2010) 635
Eur. Phys. J. C64 (2009) 589