

RECENT RESULTS BY THE NA48/2 EXPERIMENT

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On behalf of the NA48/2 collaboration

Moriond QCD - 18/03/2010



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OUTLINE

- NA48/2 experiment: detectors and collected data;



- Form factor and phase shift estimation;

- Extraction of pion scattering lengths (a_0 and a_2);



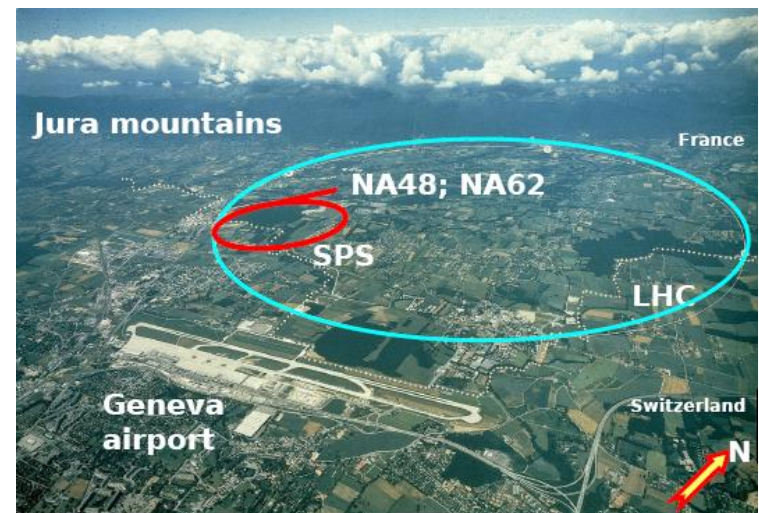
- DE and INT fraction estimation in the decay;

- CPV tests;

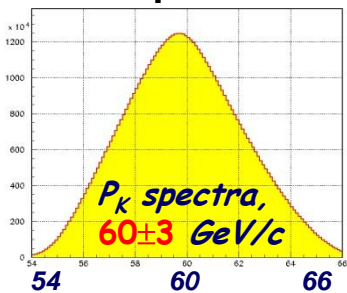
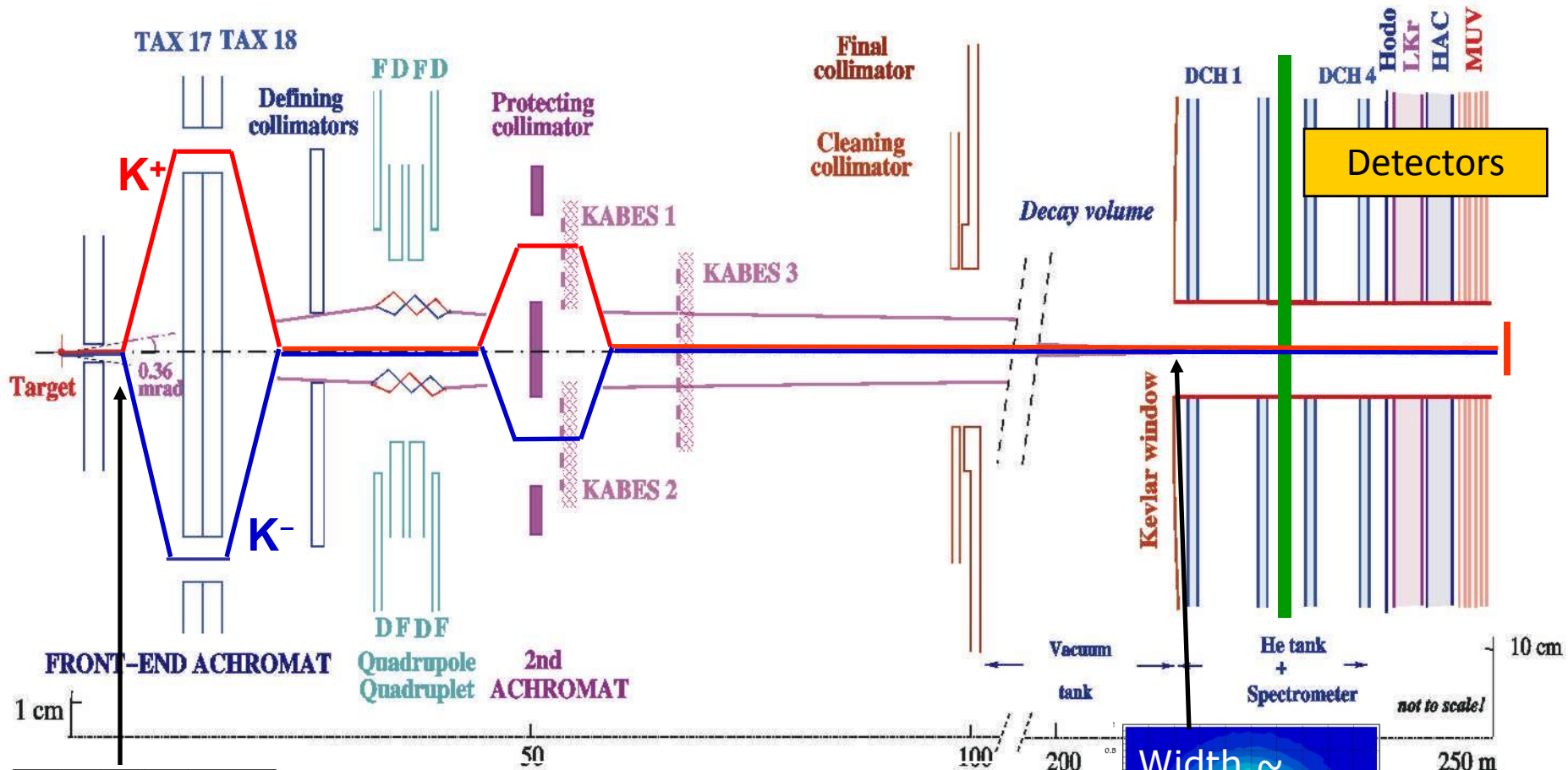


- BR estimation;
- Conclusions.

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 NO Spectrometer	K_S High Intensity
NA48/1	2001	ϵ'/ϵ run $K_L + K_S$	K_S High Int.
	2002	K_S High Intensity	
NA48/2	2003	K^\pm High Intensity	
	2004	K^\pm High Intensity	
NA62	2007	Ke2/K μ 2 measurement	
	2012/13	$K^+ \rightarrow \pi^+ \nu \nu$ measurement	

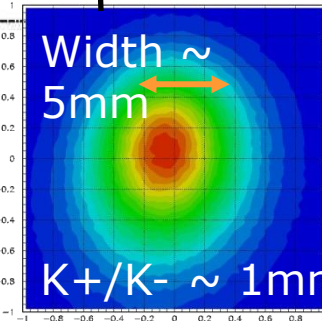


NA48/2 BEAM LINE



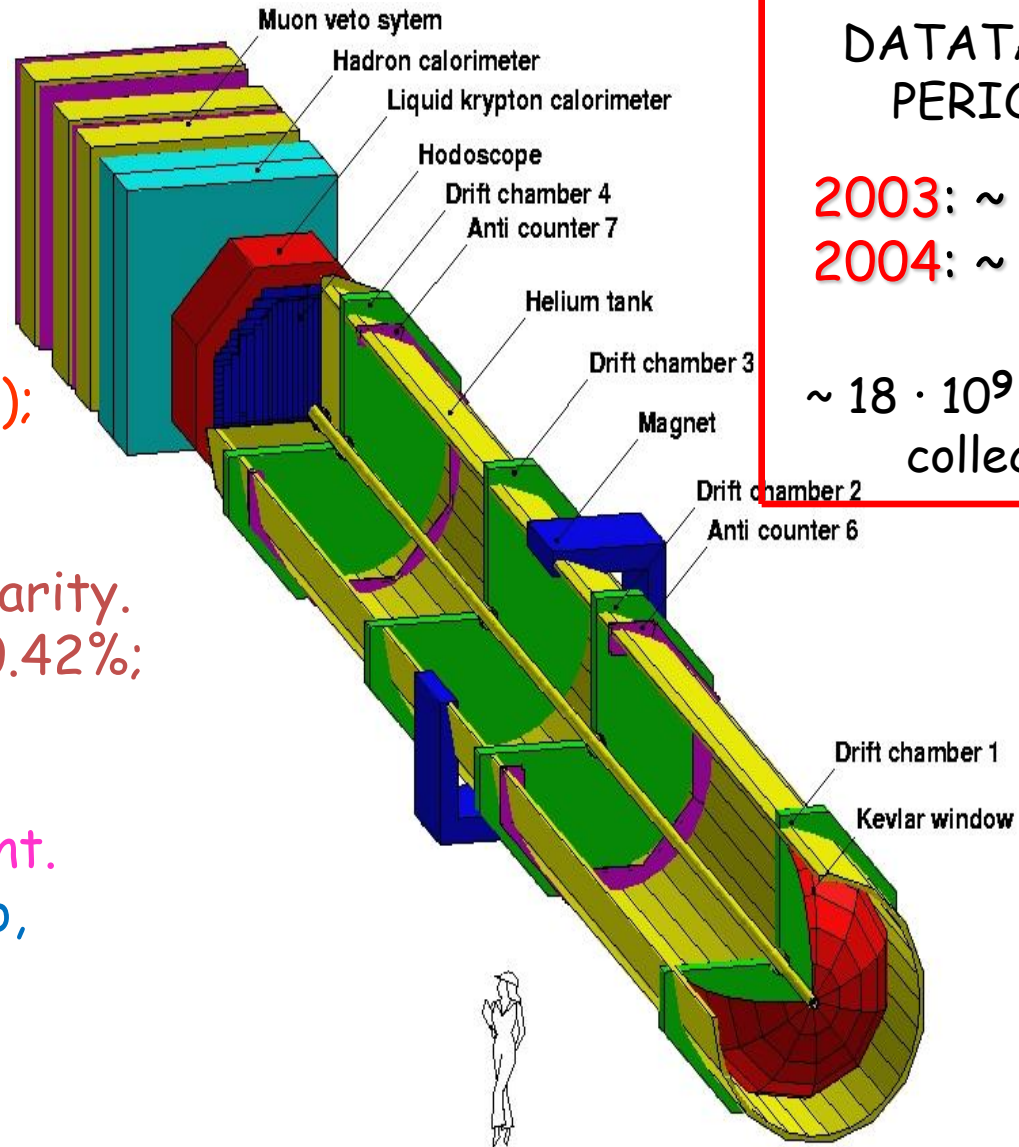
- 400 GeV protons from SPS
- K^+/K^- flux ~ 1.8
- 6.3×10^7 p.p.p.

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NA48/2 DETECTORS

- Spectrometer:
4 DCHs -> redundancy.
 $\sigma_p/p = 1.0\% + 0.044\% \times p(\text{GeV})$;
- Liquid Krypton EM calorimeter:
13000 cells -> high granularity.
 $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$;
- Hodoscopes (charged, neutral):
Trigger, time measurement.
- Muon veto, Hadronic calo, Kabes, photon vetoes.



DATA TAKING PERIODS:

2003: ~ 50 days

2004: ~ 60 days

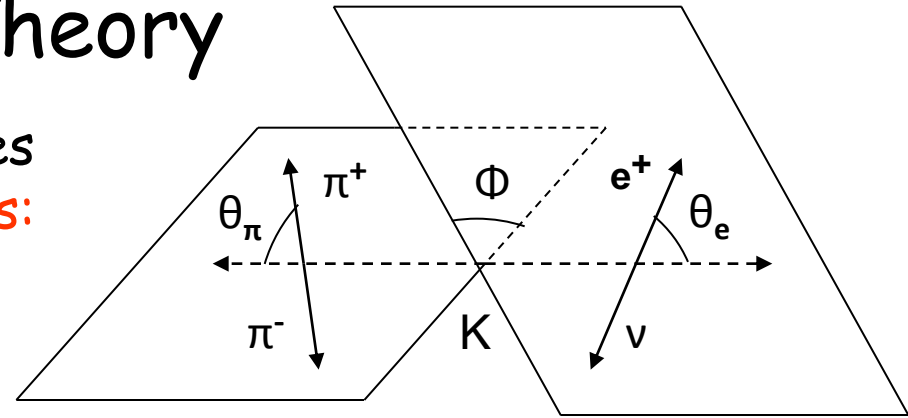
~ $18 \cdot 10^9$ triggers collected

Ke4: Theory

4 body decay \rightarrow 5 independent variables

Using Cabibbo-Maksymowicz variables:

$$S_\pi(M_{\pi\pi}^2), S_e(M_{e\nu}^2), \cos\theta_\pi, \cos\theta_e, \Phi$$



$$\text{Hadronic ME: } \langle \pi^+\pi^- | A_\lambda + V_\lambda | K \rangle = (1/M_K) [F P_\lambda + G Q_\lambda + R(K-P)_\lambda + (H/M^2) \epsilon_{\lambda\mu\nu\sigma} K_\mu P_\nu Q_\sigma]$$

(P_λ =dipion ; Q_λ =dilepton; K_λ =kaon 4 vectors)

F, G, R : axial form factors

H : vector form factor

R negligible since
proportional to m_e^2
(relevant in $K\mu 4$)

Partial wave expansion of amplitude:

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

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

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

f.f. expansion wrt S_e, q^2 :

$$F_s = f_s + f'_s q^2 + f''_s q^4 + f_e (S_e/4m_\pi^2) + \dots$$

$$F_p = f_p + f'_p q^2 + \dots$$

$$G_p = g_p + g'_p q^2 + \dots$$

$$H_p = h_p + h'_p q^2 + \dots$$

$$q^2 = (S_\pi/4m_\pi^2) - 1$$

Fit parameters: $F_s, F_p, G_p, H_p, \delta = \delta_s - \delta_p$

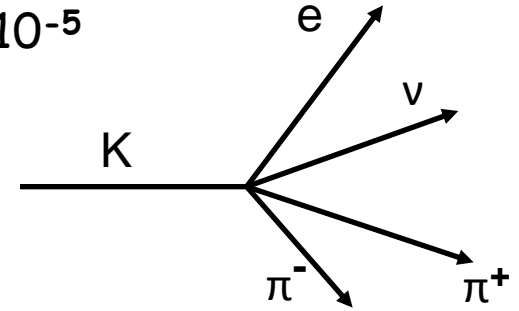
Ke4 Analysis: selection and BG rejection

Ke4 → 3 charged tracks (2 opposite sign pions), BR ~ $4 \cdot 10^{-5}$

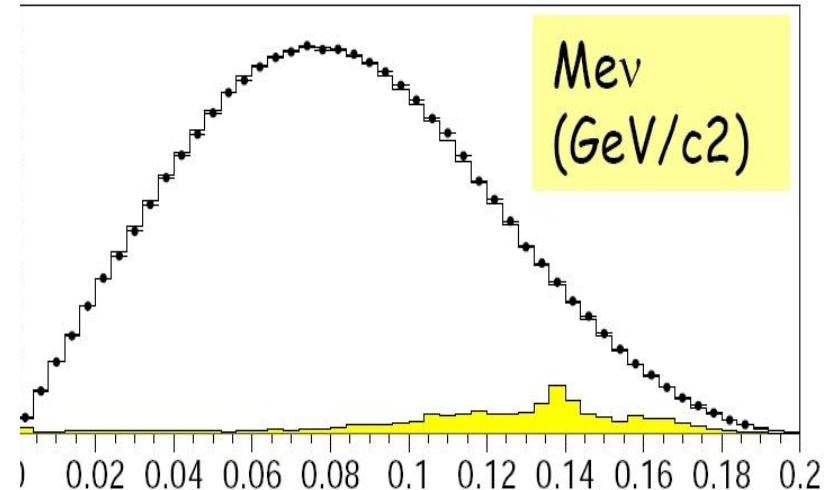
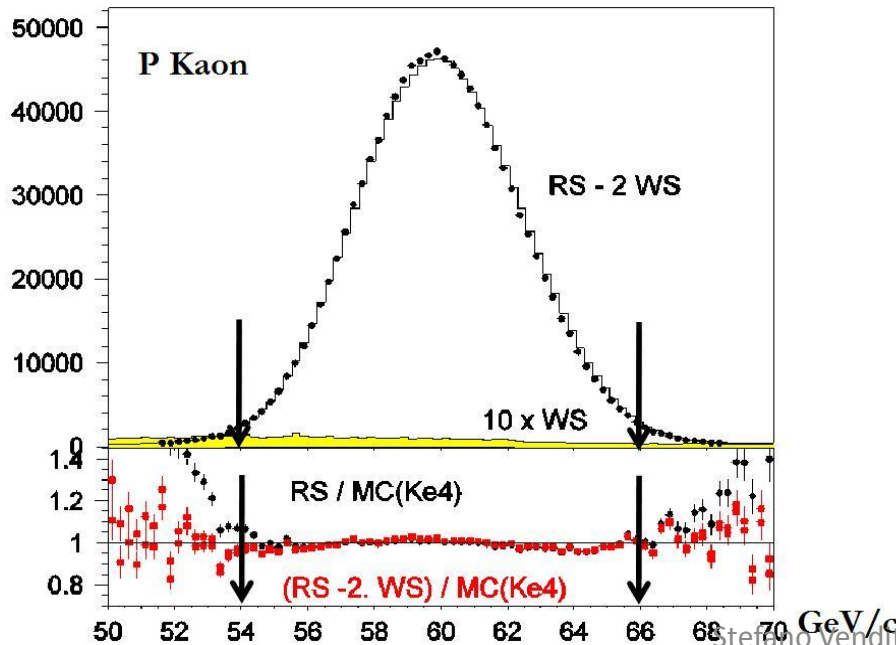
- Spectrometer for momenta measurement;
- LKR info used to tag electron and pions (E/p);
- Missing energy and Pt cuts.

Main BG sources:

- $\pi^\pm \pi^+ \pi^-$, with $\pi \rightarrow e \nu$ in-flight decay or π misidentified as e;
- $\pi^\pm \pi^0, \pi^\pm \pi^0 \pi^0$, with $\pi^0 \rightarrow e^+ e^- \gamma$ Dalitz decay, π^\pm / e^\pm misID and $\gamma(s)$ undetected.



Elliptic cut on $(M_{3\pi}, p_T)$ plane to reject BG, residual BG at the level of 0.5%, checked using wrong sign events (es: $K^- \rightarrow e^+ \pi^- \pi^- \nu, K^+ \rightarrow e^- \pi^+ \pi^+ \nu$)



Ke4: Fitting procedure

Iso-populated $10(M_{\pi\pi}) \times 5(\text{Mev}) \times 5(\cos\theta_e) \times 5(\cos\theta_\pi) \times 12(\Phi) = 15000$ bins used. Form factor values minimize a DATA-MC estimator well-suited for small numbers.

Ten independent fits in $M_{\pi\pi}$ bins, assuming constant f.f. over single bins.

K^+ : **Data**: 0.72M events, 48 evts/bin • No BR measurement → only relative f.f.

MC: 17.7 M events, ~1160 evts/bin (e.g. F_p/F_s) and their variation wrt

K^- : **Data**: 0.40 events, 27 evts/bin

MC: 9.8 M events, ~373 evts/bin

- Fits in 4-dim space for K^+/K^- separately;
- Residual variation (linear slope) observed wrt S_e for F_s ;
- $\langle \text{Relative normalization} \rangle = 1$ by F_s rescaling;
- f.f. values deconvoluted of F_s variation.

$K^+/K^- \sim 1.8$ (data & MC)

MC/Data ~ 23 (K^+ & K^-)

$$f'_s/f_s = 0.152 \pm 0.007 \pm 0.005$$

$$f''_s/f_s = -0.073 \pm 0.007 \pm 0.006$$

$$f'_e/f_s = 0.068 \pm 0.006 \pm 0.007$$

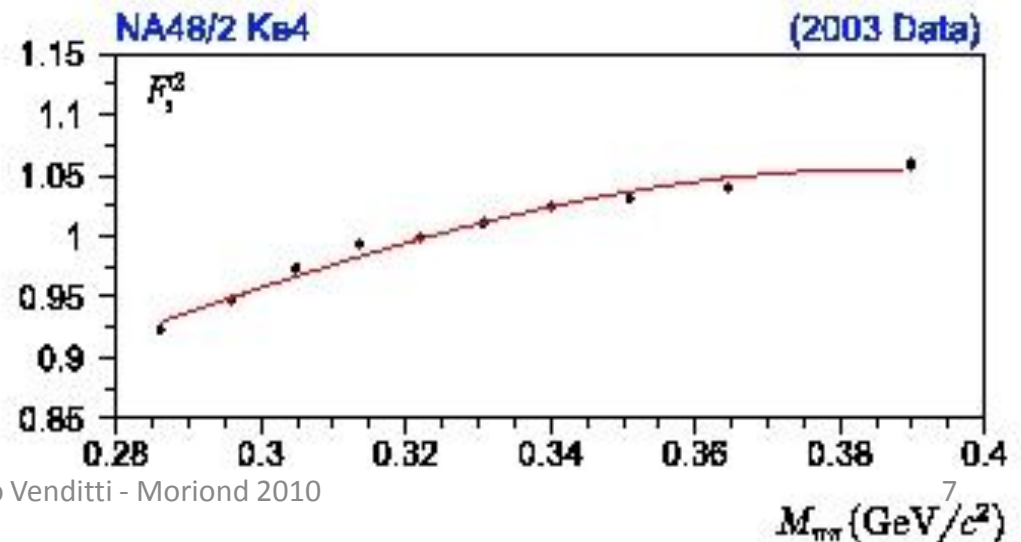
$$f_p/f_s = -0.048 \pm 0.003 \pm 0.004$$

$$g_p/f_s = 0.868 \pm 0.010 \pm 0.010$$

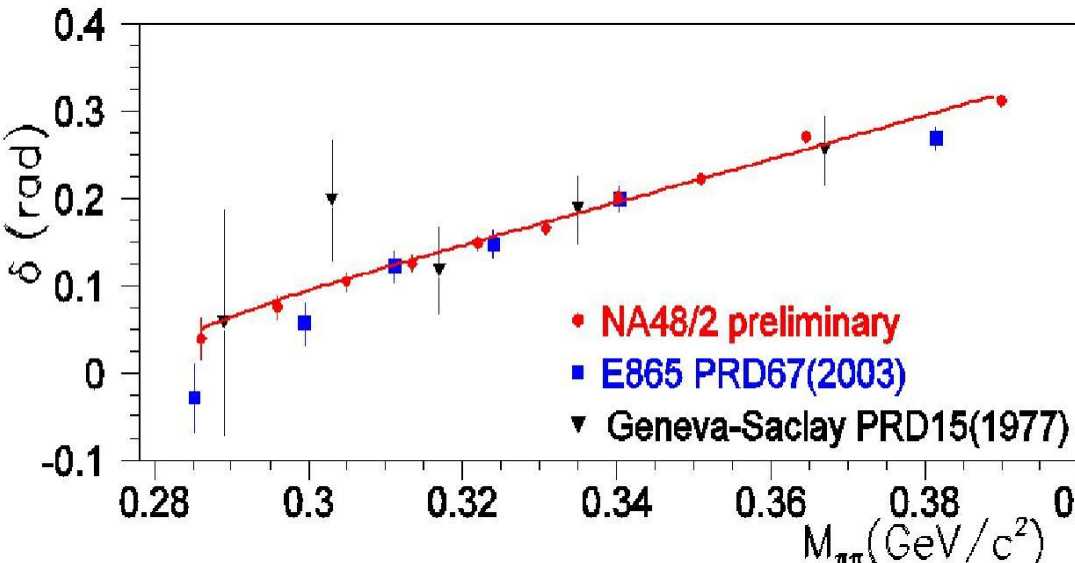
$$g'_p/f_s = 0.089 \pm 0.017 \pm 0.013$$

$$h_p/f_s = -0.398 \pm 0.015 \pm 0.008$$

$$F_s^2 \sim f_s^2 (1 + f'_s q^2 + f''_s q^4 + f'_e S_e / 4m_\pi^2) / (1 + f'_e S_e / 4m_\pi^2), \quad q^2 = (S_\pi / 4m_\pi^2) - 1$$



Ke4: δ phase shift and a_0, a_2 extraction



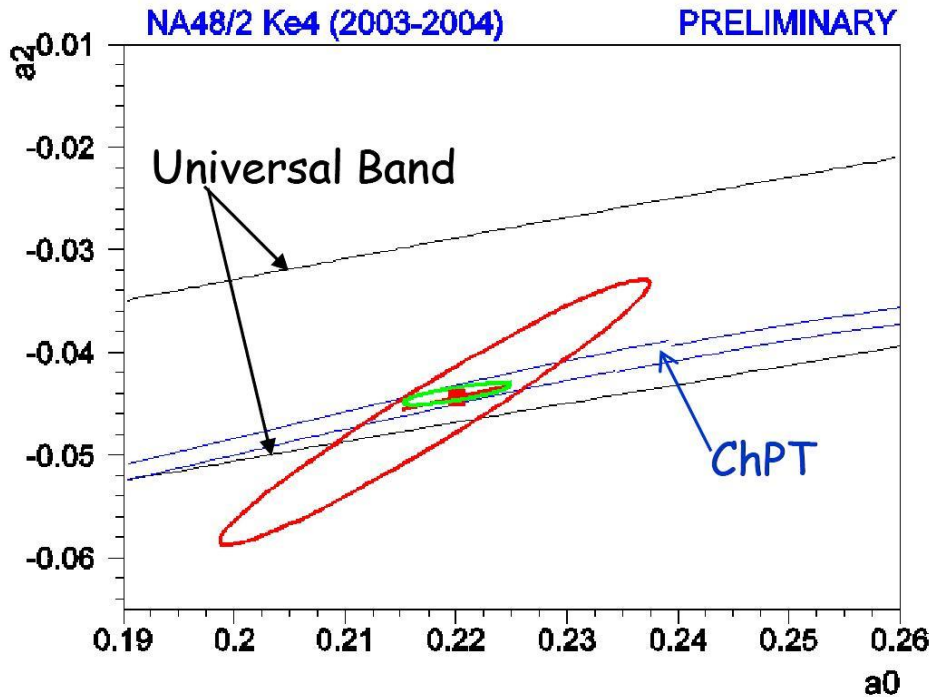
- Roy equations relate $\pi\pi$ phase difference $\delta = (\delta_0^0 - \delta_1^1)$ variation at threshold to $\pi\pi$ s-wave scattering lengths at $I=0$ (a_0) and 2 (a_2) using experimental data at $M_{\pi\pi} > 0.8$ GeV (1,2,3);
- The Universal Band parameterization is a constraint in the (a_0, a_2) plane, i.e. a 1-dim δ fit with a fixed relation between a_0 and a_2 ;
- An additional constraint in the (a_0, a_2) plane comes from ChPT:

$$a_2 = -0.0444 + 0.236(a_0 - 0.22) - 0.61(a_0 - 0.22)^2 - 9.9(a_0 - 0.22)^3 \pm 0.0008$$

- Effect of Coulomb correction (Gamow factor) and real photons included (PHOTOS);
- Isospin correction prescription given by Gasser (4) results in 10 to 15 mrad shift in fitted $M_{\pi\pi}$ range;
- 2 par. fit translates a 68% CL contour in the (a_0, a_2) plane;
- Isospin corrections \sim error in each point

- 1)[Ananthanarayan, Colangelo, Gasser, Leutwyler Phys.Rept.353:207-279 (2001)]
- 2)[Descotes-Genon, Fuchs, Girlanda, Stern Eur.Phys.J.C24:469-483,2002]
- 3)[Kaminski, Pelaez, Yndurain Phys.Rev.D77 (2008)]
- 4)[Gasser et al. Eur.Phys.J. C59:777,2009]

Ke4: a_0 and a_2 results



- Theory prediction from ChPT:
 [Colangelo, Gasser, Leutwyler
 Nucl.Phys.B603,2001]
 [Colangelo, Gasser, Leutwyler
 Phys.Rev.Lett.86,2001]:

$$a_0 = 0.220 \pm 0.005$$

$$a_2 = -0.0444 \pm 0.0008$$

ChPT constraint (1 par. fit): $a_0 = 0.2206 \pm 0.0049_{\text{stat}} \pm 0.0018_{\text{syst}} \pm 0.0064_{\text{th}}$

2 par. fit: $a_0 = 0.2220 \pm 0.0128_{\text{stat}} \pm 0.0050_{\text{syst}} \pm 0.0037_{\text{th}}$

(97% CORRELATION) $a_2 = -0.0432 \pm 0.0086_{\text{stat}} \pm 0.0034_{\text{syst}} \pm 0.0028_{\text{th}}$

Theoretical error computed from isospin corrections and Roy equation inputs
 [Gasser et al. Eur.Phys.J. C59:777,209]

Model independent procedure allows to use data from NA48/2 and past experiments:

$$a_0 = 0.2199 \pm 0.0125_{\text{exp}} \pm 0.0037_{\text{th}}$$

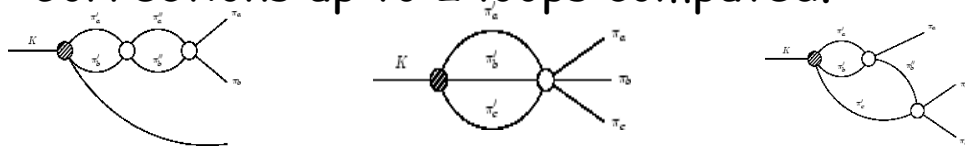
$$a_2 = -0.0430 \pm 0.0083_{\text{exp}} \pm 0.0028_{\text{th}}$$

Ke4 and cusp: Comparison

NA48/2 data provide an **ALTERNATIVE** way to estimate pion scattering lengths, to be compared with the result obtained in Ke4.

CUSP EFFECT: presence of a structure at the $M_{\pi^+\pi^-}$ threshold value in the $M^2_{\pi^0\pi^0}$ distribution of $K \rightarrow \pi \pi^0\pi^0$ decay

- Effect due to the strong $\pi^+\pi^- \rightarrow \pi^0\pi^0$ rescattering in the $K \rightarrow \pi \pi^+\pi^-$ decay;
- $(a_0 - a_2)$ and a_2 measured independently;
- Corrections up to 2 loops computed.



Cabibbo, Isidori JHEP 0503 (2005) 21

Bissegger, Fuhrer, Gasser, Kubis, Rusetsky, NPH B806:178 (2009)

2 DIFFERENT APPROACHES, THEY ARE IN GOOD AGREEMENT

FINAL RESULT:

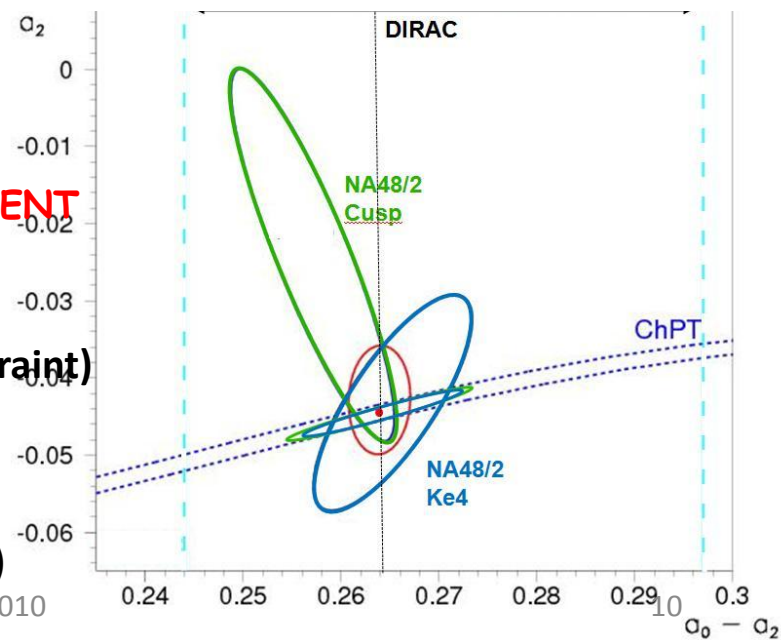
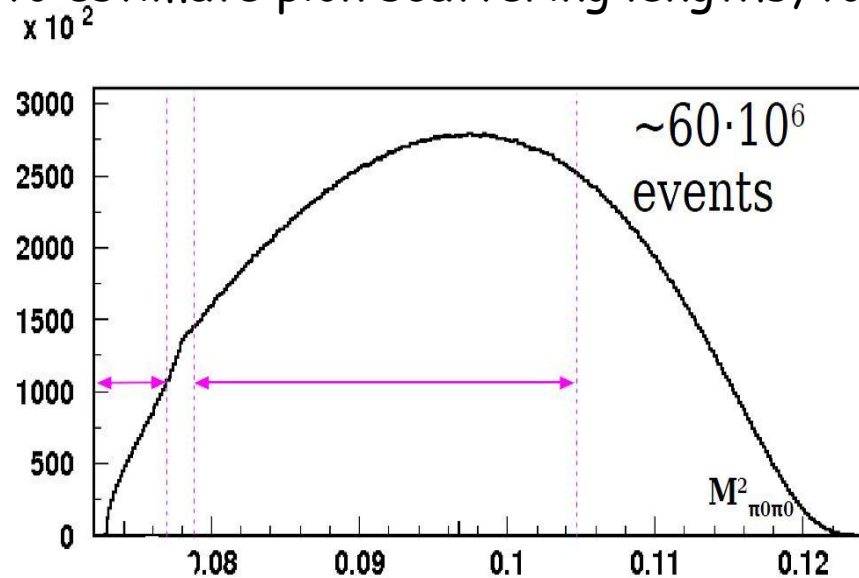
$(a_0 - a_2)_{m^+} = 0.2571 \pm 0.0048_{\text{stat.}} \pm 0.0025_{\text{syst.}} \pm 0.0014_{\text{ext.}}$

$a_2_{m^+} = -0.024 \pm 0.013_{\text{stat.}} \pm 0.009_{\text{syst.}} \pm 0.002_{\text{ext.}}$ (ChPT constraint)

COMBINED Ke4 AND CUSP RESULT:

$(a_0 - a_2)_{m^+} = 0.2639 \pm 0.0020 \pm 0.0004 \pm 0.0021$

$(a_0 - a_2)_{m^+} = 0.2640 \pm 0.0020 \pm 0.0017 \pm 0.0035$ (ChPT constraint)

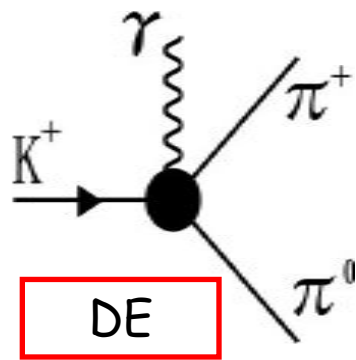
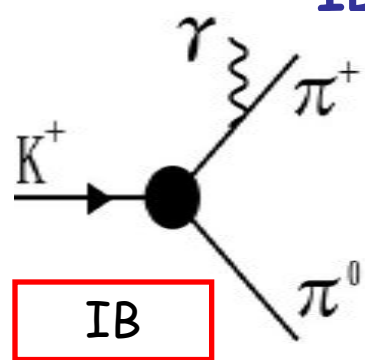


$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: Theory

3 terms (pure IB and DE, INT) in the decay width, can be disentangled using W variable (and integrating over $T^* \pi$):

N. Christ, Phys. Rev. 159, 1292 (1967)

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



$$W^2 = \frac{(P_K \cdot P_\gamma)(P_\pi \cdot P_\gamma)}{(M_K M_\pi)}$$

E = electric dipole
 M = magnetic dipole

T^*_π = Pion CM kin. energy

CURRENT PDG VALUES

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

$(55 \text{ MeV} < T^*_\pi < 90 \text{ MeV})$

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

$(55 \text{ MeV} < T^*_\pi < 90 \text{ MeV})$

INT term: not yet measured

- DE has magnetic (M) and electric (E) parts;
- DE electric part is non predictable;
- DE electric part interferes with IB amplitude, giving INT amplitude.
- A measure of IB and DE contribution allows to measure M and E

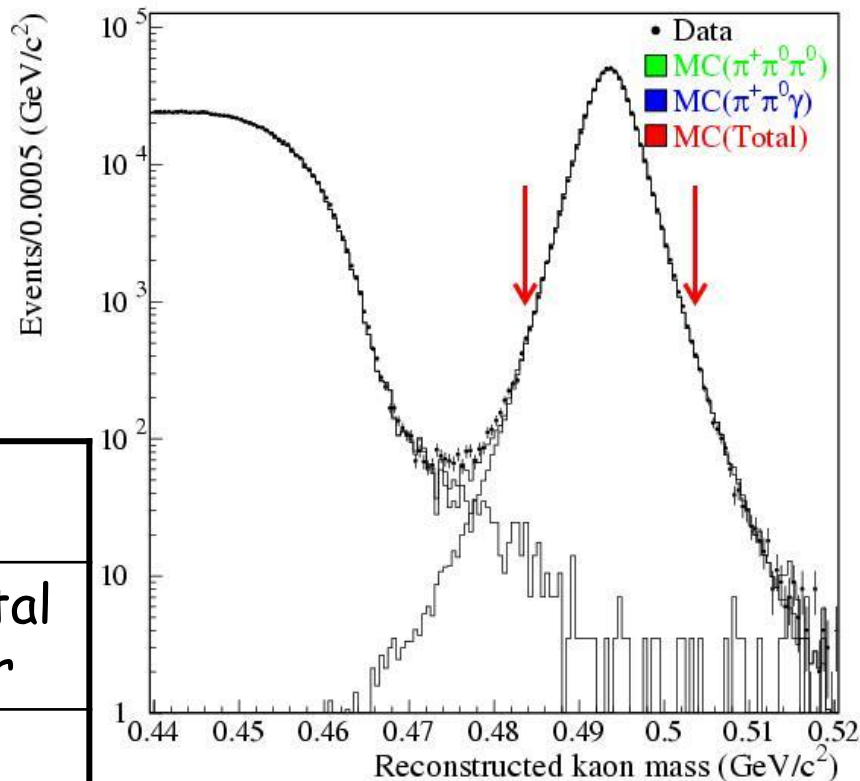
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: Event selection

EVENT SELECTION

- At least 1 track and 3 clusters;
- Acceptance and BG-rejection cuts (M_K , COG);
- Cut at $T_\pi < 80$ MeV

BG CHANNELS

BG channel	BR	BG mechanism
$K^\pm \rightarrow \pi^\pm \pi^0$	~21%	γ from accidental or hadr. shower
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$	~1.7%	missing or overlapping γ
$K^\pm \rightarrow e^\pm \pi^0 \nu$	~5%	e mistagged as π , accidental γ
$K^\pm \rightarrow \mu^\pm \pi^0 \nu$	~3.3%	μ mistagged as π , accidental γ

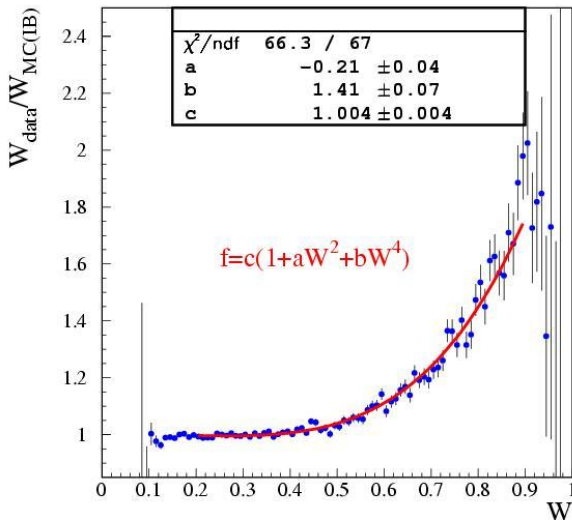
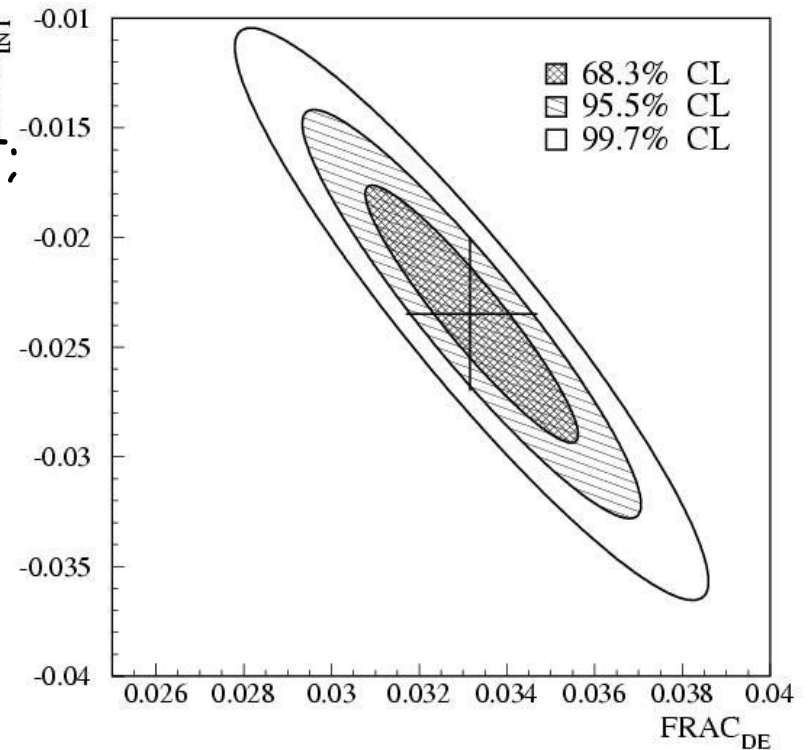


- Residual BG (due only to $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$) less than 1% of DE
- mistagging probability (self BG) at ‰ level

$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: DE & INT part

- IB, DE and INT MC sample produced separately;
- Fit in $0.2 < W < 0.9$, look for DE and INT weights (wrt IB) minimizing data/MC
- Fit Function used:

$$W_{\text{DATA}} = (1-A-B) \cdot W_{\text{IB}} + A \cdot W_{\text{DE}} + B \cdot W_{\text{INT}}$$
- A, B highly correlated (corr. = -0.92);
- systematics dominated by trigger efficiency;
- $B \neq 0$: first evidence of INT term



Final result on 2003+2004 data:

$$\text{FRAC}_{\text{DE}}(0 < W < 1) = (3.32 \pm 0.15_{\text{stat.}} \pm 0.14_{\text{syst.}})\%$$

$$\text{FRAC}_{\text{INT}}(0 < W < 1) = (-2.35 \pm 0.35_{\text{stat.}} \pm 0.39_{\text{syst.}})\%$$

$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: CPV tests

Two tests of CP violation can be performed using Kpi2g data:

DIFFERENCE IN K^+ AND K^- DECAY RATE: the variable A_N is computed, defined as:

$$A_N = \frac{N_+ - RN_-}{N_+ + RN_-}$$

- R (K^+/K^- ratio) computed using $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays (possible CPV effect on R negligible);
- Possible R dependencies on kaon momentum and T_π^* checked;
- L1 trigger asymmetry between K^+ and K^- cancels at first order because of a similar effect on R, residual difference ($\sim 10^{-5}$) comes from different π^\pm spectra;

RESULT: $A_N = (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3}$ ($R = 1.7998 \pm 0.0004$)

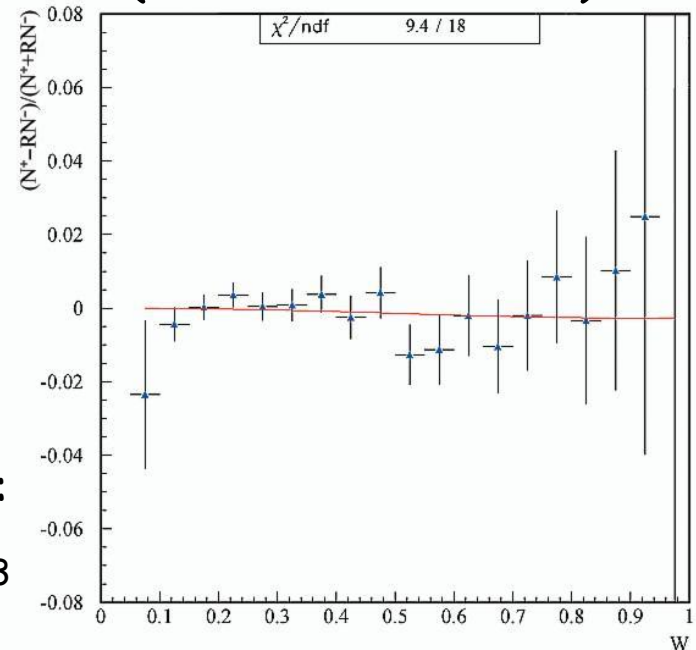
FIT TO THE W SPECTRUM: from the spectrum parameterization as a function of W, A_W can be defined as:

$$\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma_{IB}}{dW} (1 + (a \pm e)W^2 + bW^4)$$

$$\frac{dA_W}{dW} = \frac{eW^2}{1 + aW^2 + bW^4}$$

Where e is the only free parameter. Integrating:

RESULT: $(I_{INT}/I_{IB}) \times A_W = (-0.6 \pm 1.0_{\text{stat}}) \times 10^{-3}$



$K^\pm \rightarrow \pi^\pm \gamma\gamma$: Theory

$$\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^+}}{(8\pi)^3} \left[z^2 (|A+B|^2 + |C|^2) + \left(y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 (|B|^2 + |D|^2) \right]$$

$$y = \frac{P \cdot (q_1 - q_2)}{M_K^2} \quad z = \frac{(q_1 + q_2)^2}{M_K^2} = \frac{M_{\gamma\gamma}^2}{M_K^2}$$

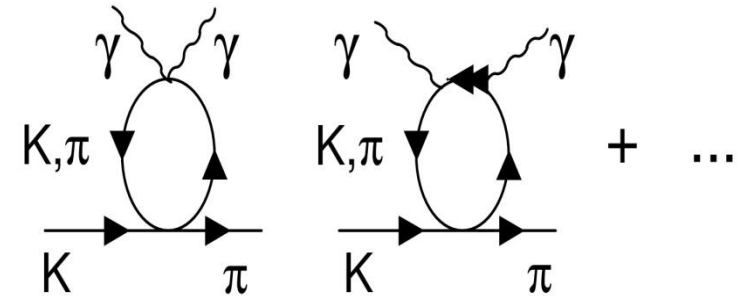
P =pion 4-momentum
 $q_{1,2}$ =photon 4-momenta

A, B, C, D depend on Z and on ChPT \hat{c} parameter

$\hat{c} = 0.90 \pm 0.45$ from $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$

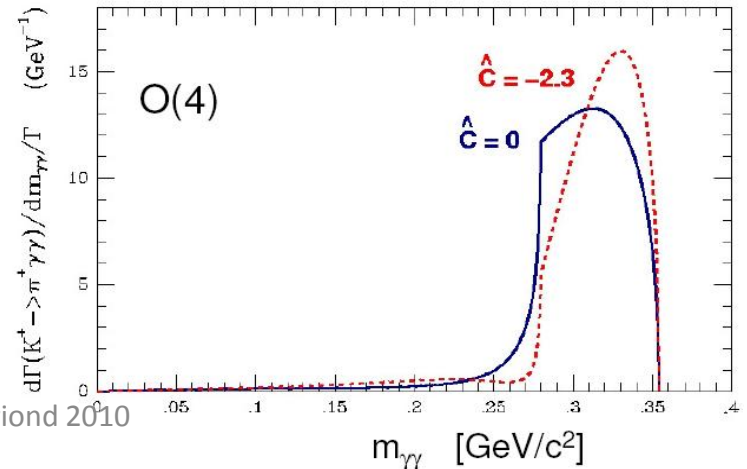
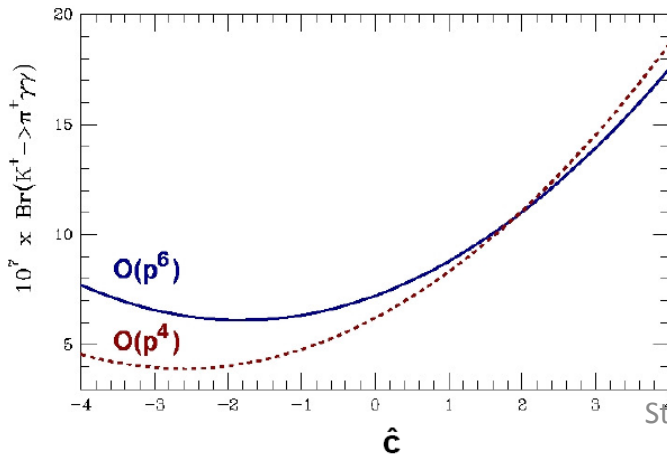
ChPT contributions to the amplitude:

$O(p^4)$: $A(z, \hat{c})$ responsible for cusp at $m_{\gamma\gamma} = 2m_\pi$
 $C \neq 0$ for WZW anomaly (poles & tadpoles), $B=D=0$



[D'Ambrosio, Portolés, PLB386 (1996) 403]

$O(p^6)$: unitarity corrections can increase BR by 30-40% (depending on \hat{c} value)



$K^\pm \rightarrow \pi^\pm \gamma \gamma$: BR measurement

EVENT SELECTION:

- at least 1 π track, 2 clusters
- COG, CDA, chd vertex cuts
- $0 < M_{\gamma\gamma} < M_K - M_\pi$ (kinematical limit)

1164 events selected

- 20% of full datasample
- 40 times larger than total world sample
- 3% BG (mainly from $\pi \pi^0 \gamma$)
- Good agreement with $\hat{c}=2$ generated MC sample

- Normalization: $K \rightarrow \pi^\pm \pi^0$ ($\sim 6M$ events)
- Main systs: $\pi\gamma$ distance cut, efficiency

PRELIMINARY RESULT

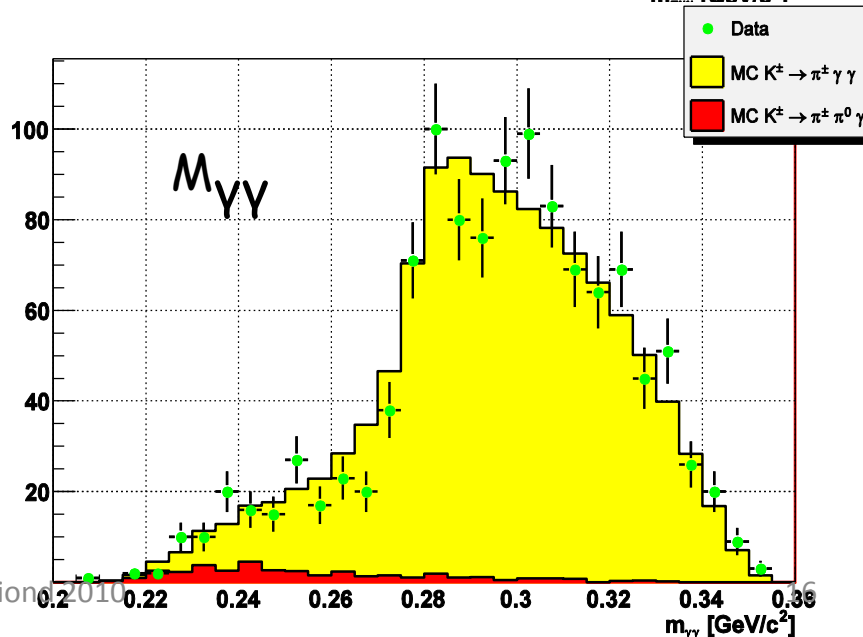
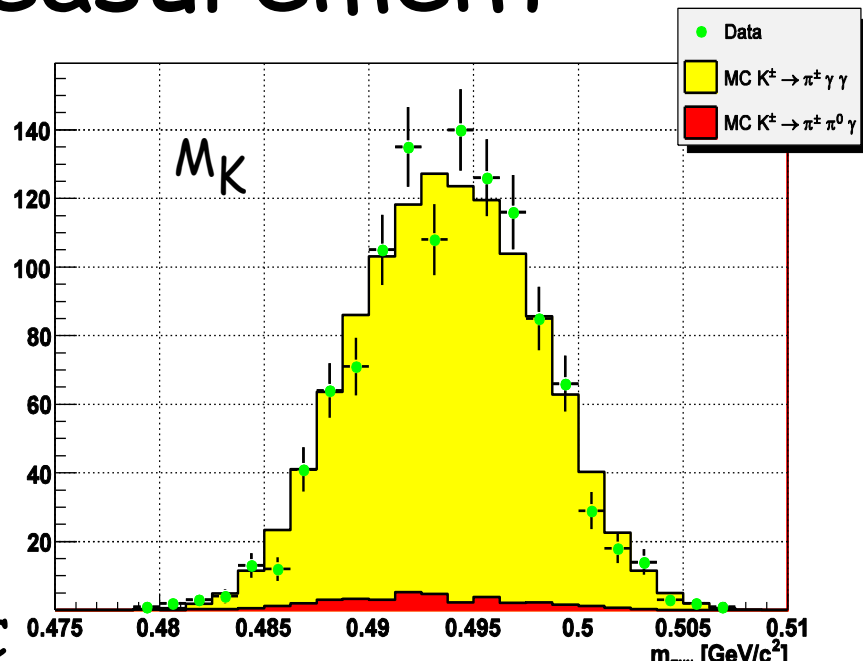
$$BR = (1.07 \pm 0.04_{\text{stat.}} \pm 0.08_{\text{syst.}}) \cdot 10^{-6}$$

Present measurement (on PDG):

BNL E787(1991):

31 candidates, 5 BG events

$$BR = (1.10 \pm 0.32) \cdot 10^{-6}$$



Conclusions

- Accurate study of low-energy hadronic interactions thanks to the unprecedented Ke4 statistics available in NA48/2;
- Good agreement between Ke4 and cusp result;
- First measurement of INT component in $K\pi 2\gamma$ decay, CPV tests;
- Relevant improvement in $K^\pm \rightarrow \pi^\pm \gamma\gamma$ statistics, $\sim 1\text{K}$ events selected.