"QCD tests at NA48/2"

EPS_09

Krakow 16.7.2009

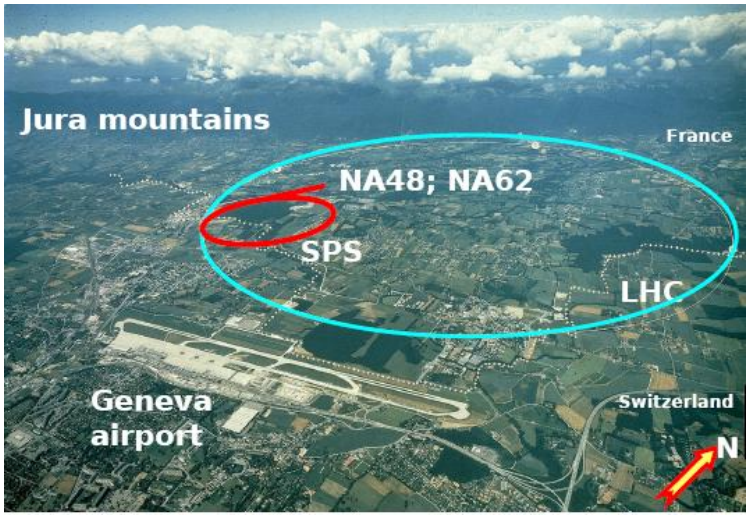
Gianluca Lamanna

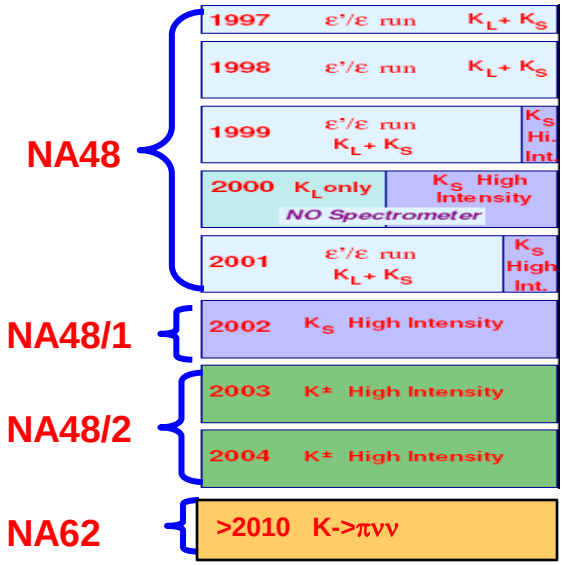
Scuola Normale Superiore and INFN Pisa

On behalf of the *NA48/2 collaboration*:
Cambridge, CERN, Chicago, Dubna, Edimburgh, Ferrara, Florence, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna

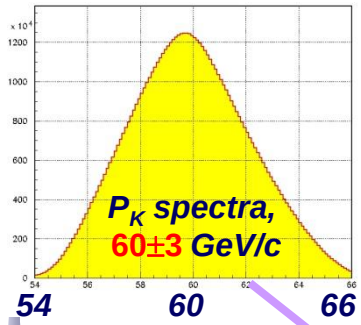
Outline

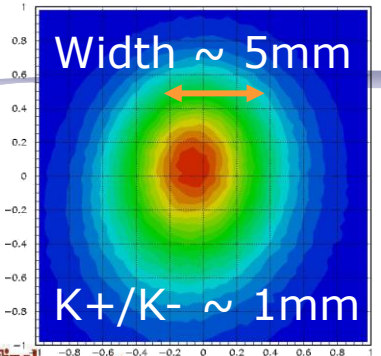
- NA48/2 experimental setup
- QCD tests
  - $\pi\pi$ scattering lengths (Ke4 and Cusp) (preliminary!)
  - $K^{\pm}\to\pi^{\pm}\gamma\gamma$: BR (preliminary!)
  - $K^{\pm}\to\pi^{\pm}\gamma e^{+}e^{-}$: BR and Shape (final!)
- Conclusions

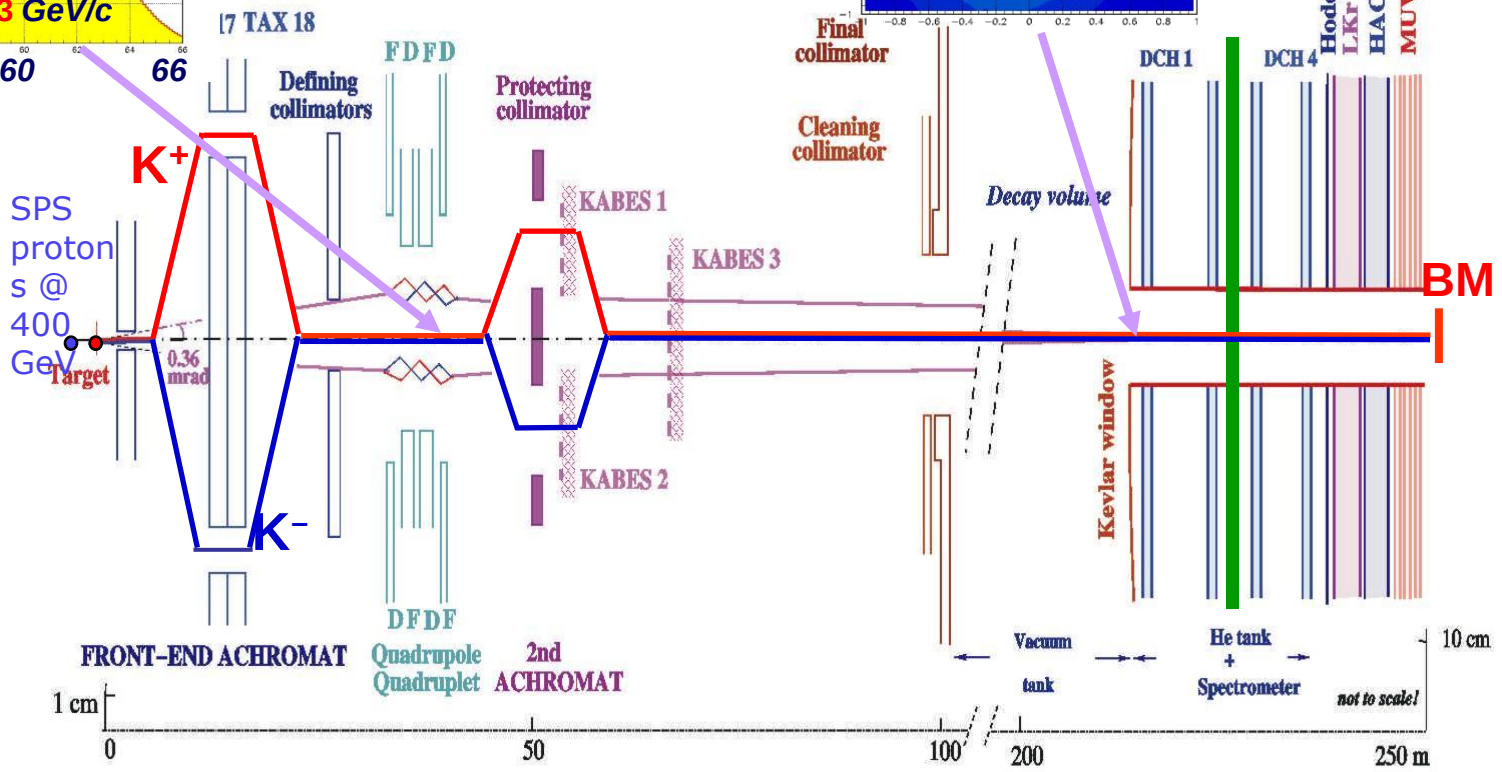




Beam Line

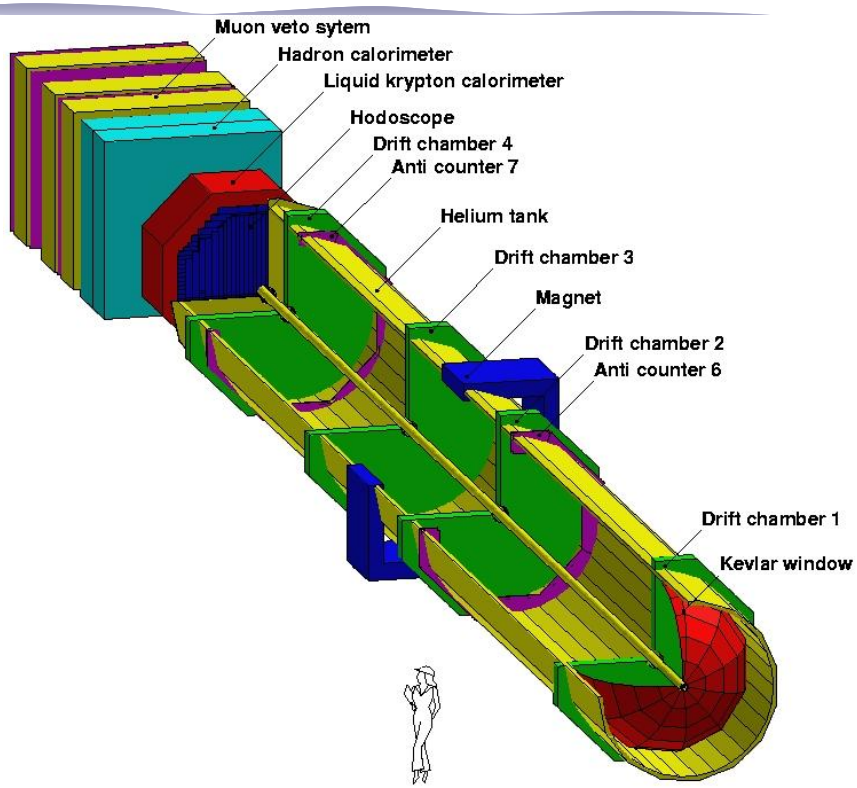






- fixed target experiment at CERN-SPS
- 60±3 GeV/c kaon momentum (~7x10^{11} ppp)
- 6.3 x 10^{7} particles per pulse in decay region
- Simultaneous, unseparated, focused beams
- Similar acceptance for K+ and K- decays
- K+/K- ~ 1.8

Detector



- ~100 m long decay region in vacuum
- Triggers based on LKr peaks, CHOD hits and DCH multiplicity
- Similar acceptance between K+ and K- beams checked reversing magnetics fields
- Pion decay products, from the hadronic beam, remain into the beam pipe

Spectrometer:

$\sigma_p/p = 1.0\% + 0.044\% \, p$ [p in GeV/*c*]

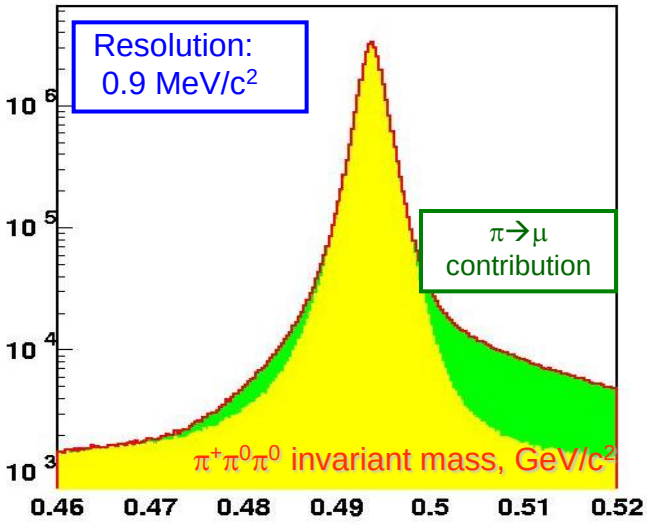
LKR calorimeter:

$\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [E in GeV]

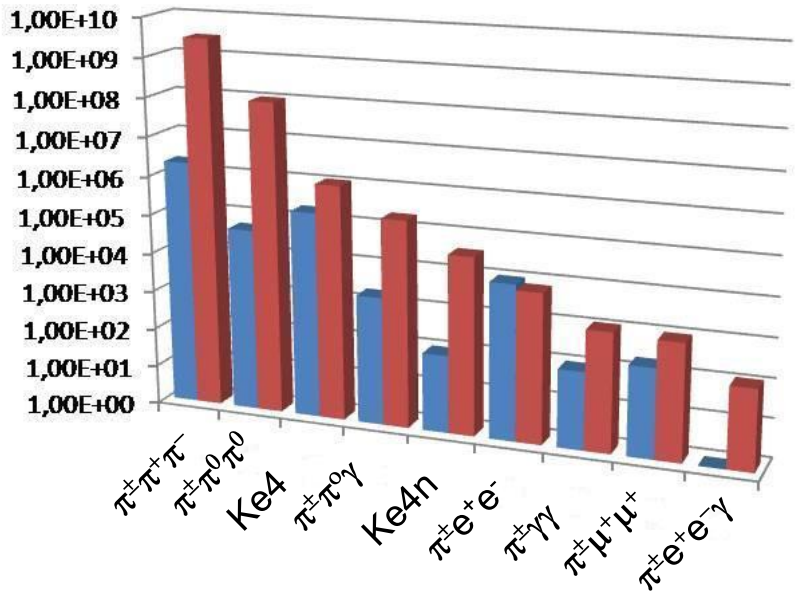
CHOD, HAC, MUV, vetos

Kabes

Beam Monitor



Data Taking



Detector and trigger optimized to collect 3 pions events

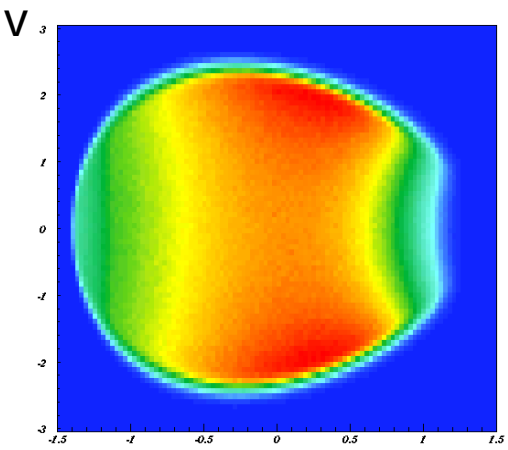
$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$: ~$1\cdot10^{8}$

$K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$: ~$3\cdot10^{9}$

- Unprecedented statistics in many channels
- Two years of data taking (2003+2004)
- Main purpose was to measure direct CP violation in charged Kaon decays, through asymmetry in Dalitz plot distribution.
- New limits on CP violation in charged kaon decays

$A_g=(-1.5+1.5_{stat}+0.9_{trig}+1.1_{syst})\cdot10^{-4}$

$A_g^0=(1.8+1.7_{stat}+0.5_{syst})\cdot10^{-4}$



Phys.Lett.B 634:474 482,2006
Phys.Lett.B 638:22-29,2006
Eur.Phys.J C52:875-891,2007

Ke4: Formalism

• The Ke4 ($K^{\pm}\to\pi^{+}\pi^{-}\,e^{\pm}\nu$) dynamics is fully described by 5 (*Cabibbo-Maksymovicz*) variables: $M_{\pi\pi}^2$, $M_{e\nu}^2$, $\cos\theta_\pi$, $\cos\theta_e$ and ϕ

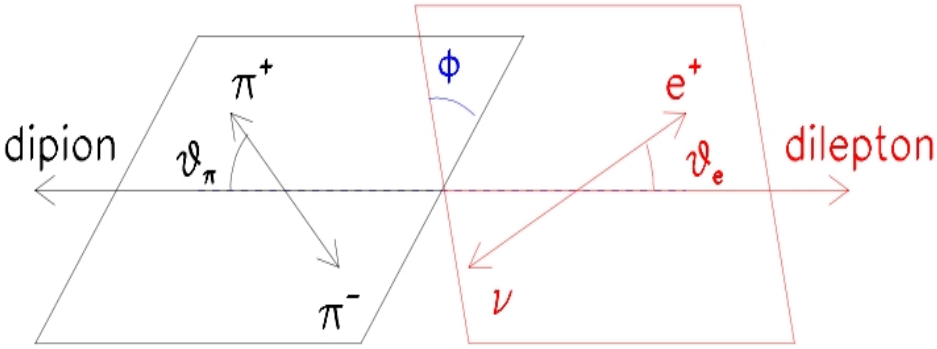
In the partial waves expansion the amplitude can be written using 2 axial and 1 vector form factors (the axial form factor R is suppressed in K_{e4} but accessible in $K_{\mu 4}$):

$$F=F_s e^{i\delta s}+F_p e^{i\delta p}\cos\theta_\pi$$

$$G=G_p e^{i\delta p}$$

$$H=H_p e^{i\delta p}$$

F (F_p,F_s), G, H and $\delta=\delta_p-\delta_s$ will be used as fit parameters



• The $q^2=(M_{\pi\pi}^2/4m_\pi^2)-1$ dependence can be studied expanding the fitted form factors assuming isospin symmetry:

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

$$F_p=f_p+f_p'q^2+...$$

$$G_p=g_p+g_p'q^2+...$$

$$H_p=h_p+h_p'q^2+...$$

Ke4: Selection

Signal selection:

- 3 tracks on spectrometer, total charge ±1
- Missing energy and missing Pt, compatible with ν
- LKr/DCH used for electron PID
- 2 opposite sign pions

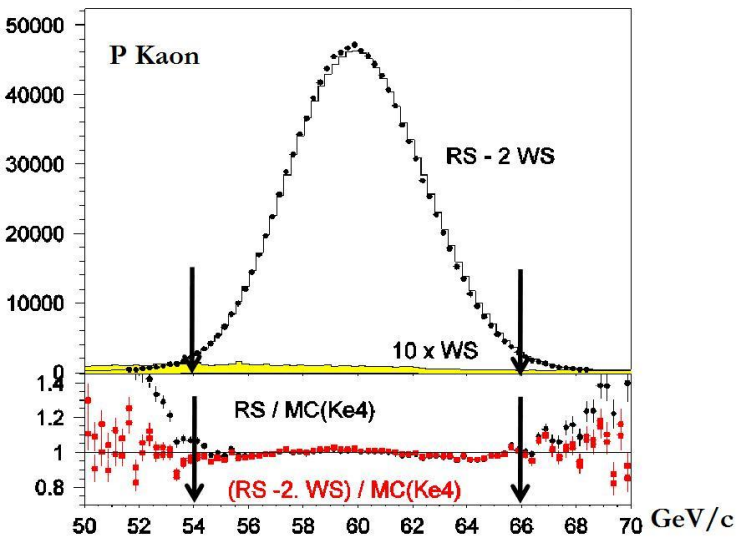
~1150000 decays

Main background sources:

$\pi\pi\pi + \pi \rightarrow e\nu$

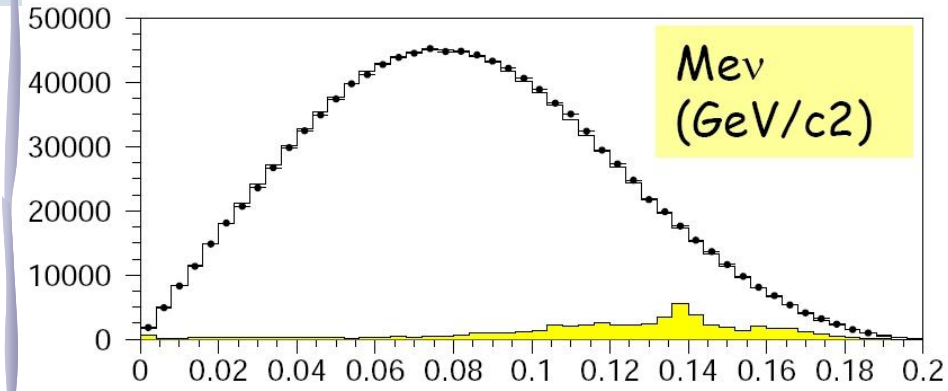
$\pi\pi\pi$ with π misidentified

$\pi\pi^0\pi^0$ or $\pi^0 + \pi^0$(Dalitz) +e misidentified and γs outside the LKr



The background is studied using the electron *"wrong"* sign (WS) events (we assume $\Delta Q=\Delta S$ and total charge ±1) and cross check with MC. The total bkg is at level of 0.5%.

Ke4: Fitting procedure



(2003+2004)		Data	MC
K+	evts	726400	17.7x10^6
	evts/bin	48	1160
K-	evts	404400	9.8x10^6
	evts/bin	27	650

- Define **10(Mππ)x5(Meν)x5(cosθe)x5(cosθπ)x12(ϕ)=15000** iso-populated boxes
- In each **Mππ** bin the F,G,H and δ form factors are extracted minimizing a log-likelihood estimator over the 1500 boxes
- All the form factors are measured relatively to fs (no overall BR measured)
- K+ and K- fitted separately, and then the fitted parameters are combined in each **Mππ** bin
- The form factors structure is studied in 10 bins of q^2 (or $M^2_{\pi\pi}$)
- Agreement with published results (based on 2003 data) [Batley et al. EPJC 54-3 (2008) 411]

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

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

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

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

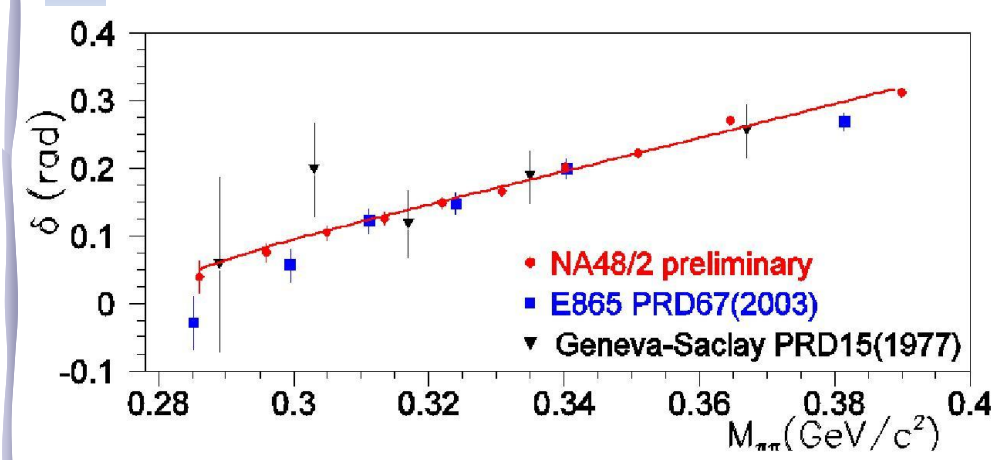
$g_p/f_s = 0.868 \pm 0.010 \pm 0.010$

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

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

(stat+syst error quoted)

Ke4: Phase shift and ππ scattering length



- Each point in the plot has been corrected for isospin effect: 10-15 mrad
- The total error in each point is different for each experiment:

Geneva-Saclay: 40-50 mrad

E865: 15-20 mrad

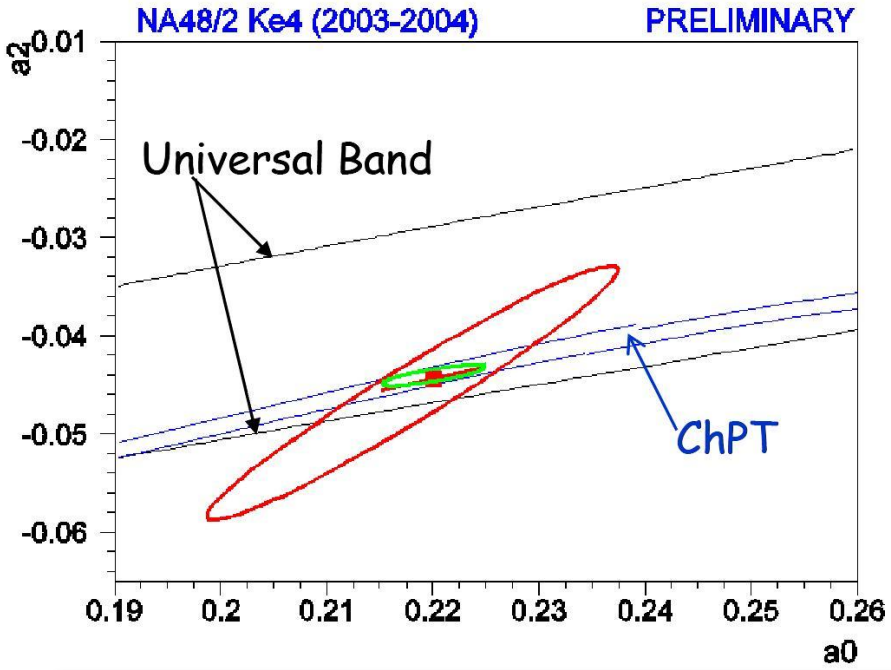
NA48/2: 7-8 mrad

- The extraction of pion scattering lengths from the fitted $\delta=\delta_s-\delta_p$ phase shift needs external theoretical and experimental inputs:
  - The *Roy equations* provide the relation between δ and a0 and a2 near threshold (1) (2) (3)
  - Extrapolating the data from the $M_{\pi\pi}>0.8$ GeV it's possible to fit the result in the threshold region (the uncertainty from the experimental data defines the *Universal Band*)

- Coulomb correction (Gamow factor) and real photons are included in simulation
- Isospin correction prescription given by Gasser (4) results in 11 to 15 mrad in the fitted Mππ range
- The isospin correction is slightly greater than the error on each point: can't be ignored!

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: a0 and a2 results



- Theory prediction

Assuming ChPt and low energy constants

[Colangelo,Gasser,Leutwyler Nucl.Phys.B603,2001]
[Colangelo,Gasser,Leytwyler Phys.Rew.Lett.86,2001]:

$a0 = 0.220 \pm 0.005$
$a2 = -0.0444 \pm 0.0008$

1 par. Fit (ChPt) : $a0 = 0.2206 \pm 0.0049_{stat} \pm 0.0018_{syst} \pm 0.0064_{th}$

2 par. Fit :
$a0 = 0.2220 \pm 0.0128_{stat} \pm 0.0050_{syst} \pm 0.0037_{th}$
$a2 = -0.0432 \pm 0.0086_{stat} \pm 0.0034_{syst} \pm 0.0028_{th}$

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

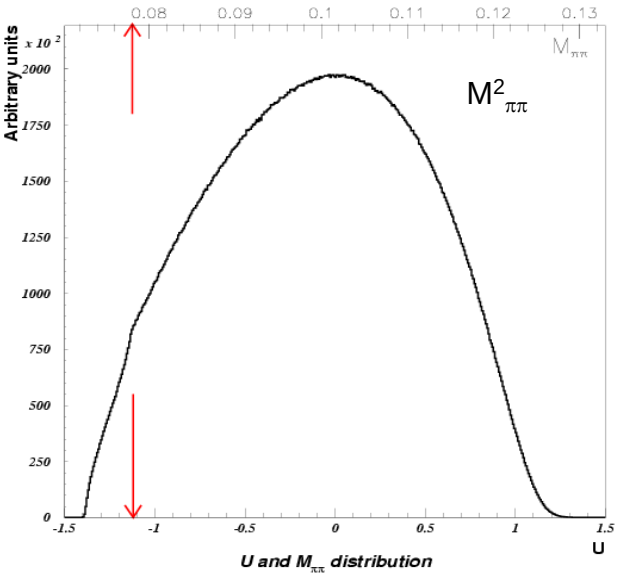
Using data (21 points) from the three experiments (dominated by NA48/2)

$a0 = 0.2199 \pm 0.0125_{exp} \pm 0.0037_{th}$
$a2 = -0.0430 \pm 0.0083_{exp} \pm 0.0028_{th}$

Cusp: Experimental evidence

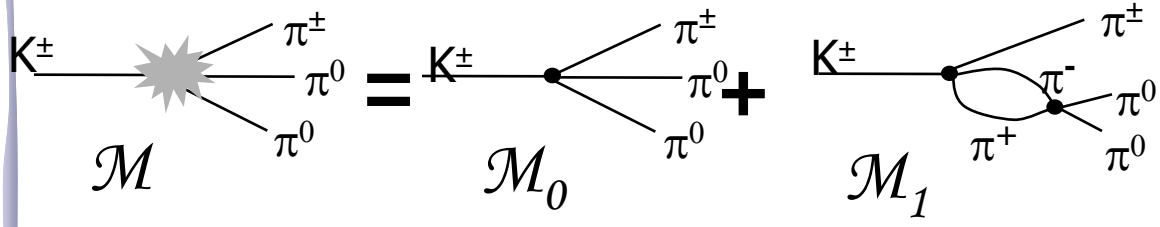
- In $K^{\pm}\to\pi^{\pm}\pi^0\pi^0$ decay the matrix element is usually given as polynominal expansion as a function of the Dalitz variables U and V

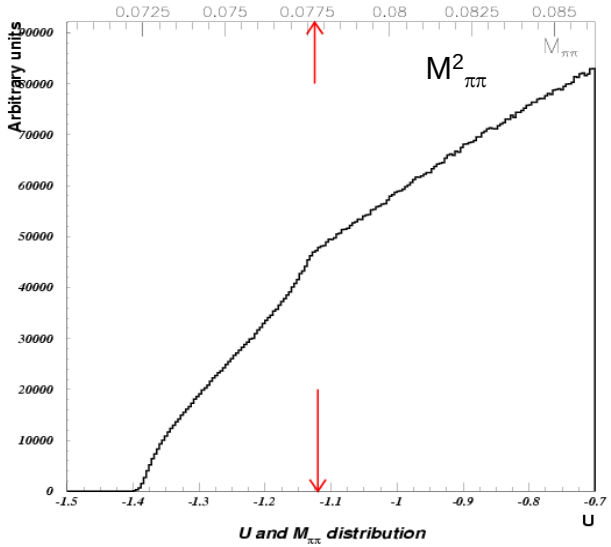
$$|M(u,v)|^2 \sim 1+gu+hu^2+kv^2+...$$
$$u=(s_3-s_0)/m_{\pi}^2 \qquad s_i=(P_K-P_{\pi,i})^2$$



- Thanks to the big statistics collected by NA48/2 and the good energy resolution, for the first time a structure has been observed at the $\pi\pi$ threshold value [Batley et al.,Phys.Lett. B633:173-283,2006]

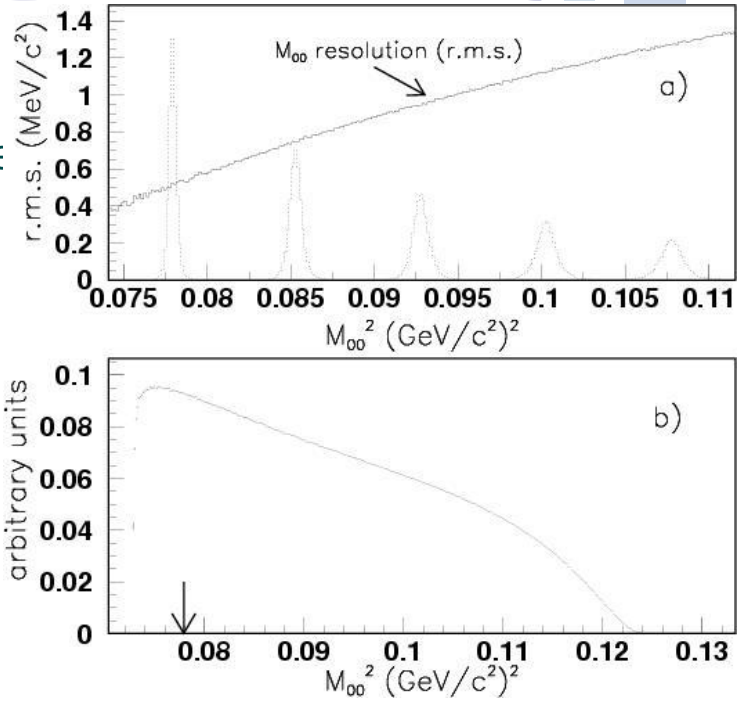
- This structure has been interpreted by Cabibbo [Cabibbo Phys. Rev. Lett. 93, 121801 (2004)] as due to the strong $\pi\pi$ rescattering in the $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ final state

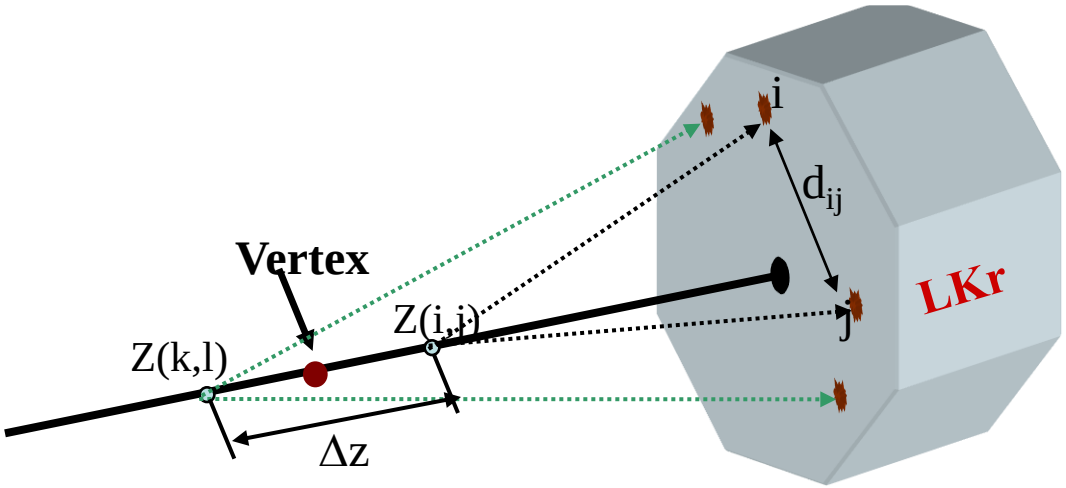




Cusp: K→3π selection

- Online selection:
  - (L1) one charged particle in CHOD and at least three peaks in at least one projection (x or y) of the LKr analog sum peak system.
  - (L2) The opposite mass with respect to the charged tracks have to be far from one π^0 mass.
- Offline selection: among all the possible γ pairings, the couple for which χ^2 is smallest is selected
  - the neutral vertex is obtained by imposing the π^0 mass. The final vertex is obtained as average between the 2 vertices.





- Very good acceptance and resolution in threshold region: high statistics and good opportunity to resolve tiny structures.

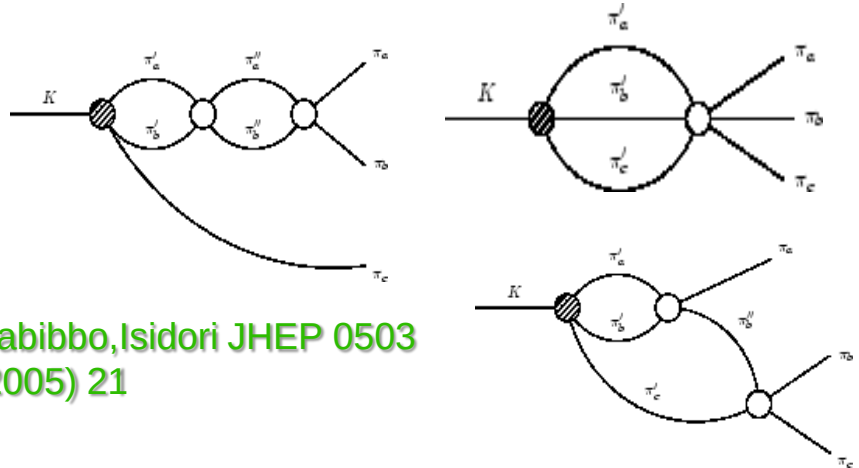
Cusp: Theoretical approach (Cabibbo-Isidori)

- Fenomenological approach
- The term M0 (no rescattering) is given by the standard PDG expansion
- the first rescattering terms is real below threshold and immaginary above. Interference below threshold.

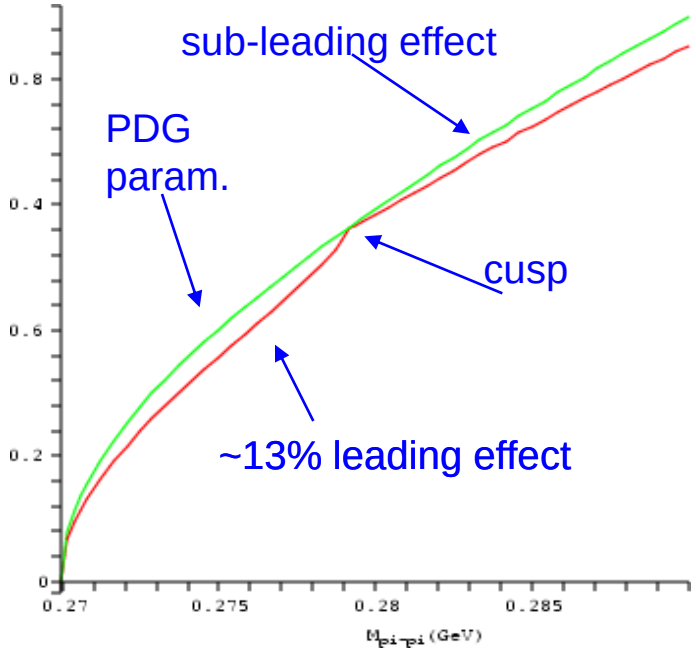
$s_{\pi\pi} > (2m_{\pi^+})^2$ $\quad M^2 = (M_0)^2 + |M_1|^2$

$s_{\pi\pi} < (2m_{\pi^+})^2$ $\quad M^2 = (M_0)^2 + (M_1)^2 + 2M_0M_1$

$$\mathcal{M}_1 = -2/3(a_0 - a_2) m_+ \mathcal{M}_+ \sqrt{1 - \frac{(M_{00})^2}{2m_+}}$$



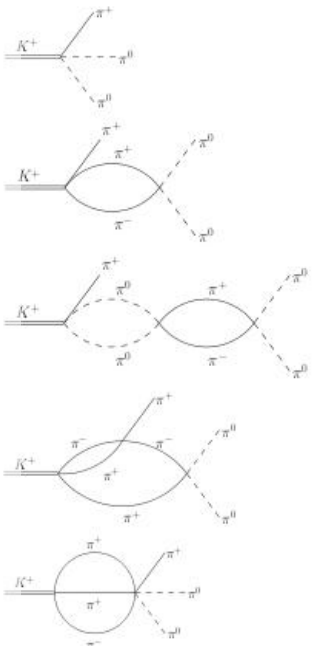
Cabibbo,Isidori JHEP 0503 (2005) 21



- The amplitude below threshold depends on (a0-a2)
- Other 5 terms rise from two loops calculation (proportional to scattering lengths): effects below and above threshold
- Theoretical error evaluated from the next level expansion (work in progress…)

Cusp: theoretical approach (Bern-Bonn)

- Different approach based on effective non-relativistic Lagrangian
- The electromagnetic effects are naturally included in this approach (explicitly omitted in the CI work)
- Different structure of the expansion (different correlation between the terms wrt the Cabibbo-Isidori expansion): kinetic energy and threshold parameter.
- Simultaneus fitting of charged and neutral amplitude to exctract M+ slope parameters (modified with respect to the PDG parametrization)
- Radiative correction, outside the cusp point, included in the BB model



$$\mathcal{M}^{\text{tree}} = G_0 + G_1(p_3^0 - M_\pi) + \dots$$

$$\mathcal{M}^{1-\text{loop}} = B_1 J_{+-}(s_3) + B_2 J_{00}(s_3) + \left[B_3 J_{+0}(s_1) + (s_1 \leftrightarrow s_2)\right]$$

$$\mathcal{M}^{2-\text{loop}} = 2G_0 C_x^2 \underbrace{J_{+-}(s_3) J_{00}(s_3)}_{\text{double loops}} + \dots$$

$$+ \; 4H_0 C_x C_{+-} \underbrace{F_+(\dots; s_3)}_{\text{overlapping loops}}$$

$$+ \; \mathcal{O}(i\,\epsilon^4) \quad [\not\propto \text{ scatt. lengths}]$$

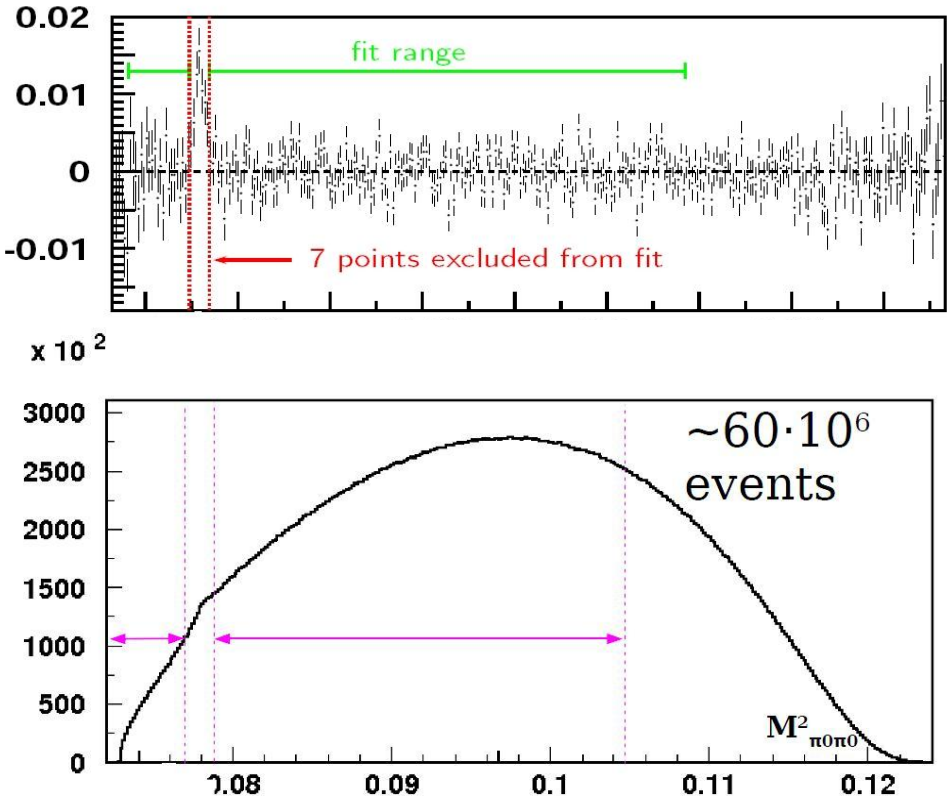
[Colangelo, Gasser, Kubis, Rusetsky in Phys.Lett.B638:187-194,2006]

[Bissenger, Fuhrer, Gasser, Kubis, Rusetsky in Phys.Lett.B659:576,2008]

[Bissegger, Fuhrer, Gasser, Kubis, Rusetsky in NPH B806:178, 2009]

Cusp: fitting procedure

- Resolution and detector response matrix obtained using accurate Geant3 based simulation
- Both theories can be fitted with the same procedure (fit parameters: g, h, a_0-a_2 , a_2 , N)
- The M+ terms appearing in the **CI** theory is fixed by the recent measured $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ slope parameters [Batley et al. Phys.Lett.B649:349-358,2007]
- In the **BB** the M+ term is obtained simultaneously fitting $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ and $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot
- Isospin effects included
- The excess of events in the cusp position, $R=(1.8\pm0.3)\cdot10^{-5}$, can be explain by:
  - pionium $0.8\cdot10^{-5}$ [Silagadze, JETP Lett. 60 (1994) 689]
  - unbound state with resonant structure [Gevorkian, Tarasov, Voskeresenskaya,Phys.Lett.B649:159,2007]

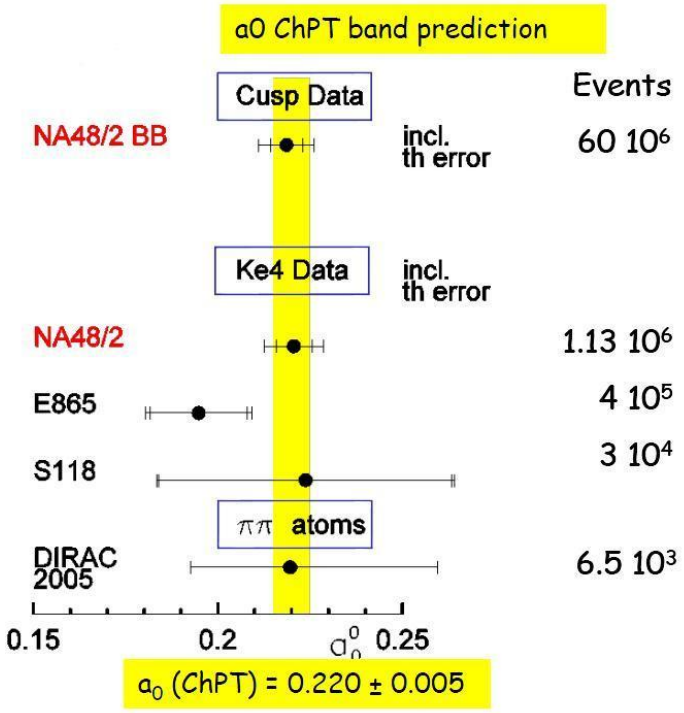


- The numbers of "atoms" is used as free parameter including the 7 bins around the cusp.

Cusp: Results

2 par. Fit : $(a_0-a_2)m_+ = 0.2571 \pm 0.0048_{stat.} \pm 0.0025_{syst.} \pm 0.0014_{ext.}$
$a_2 m_+ = -0.024 \pm 0.013_{stat.} \pm 0.009_{syst.} \pm 0.002_{ext.}$

1 par. Fit (ChPT): $(a_0-a_2)m_+ = 0.2633 \pm 0.0024_{stat.} \pm 0.0014_{syst.} \pm 0.0019_{ext.}$



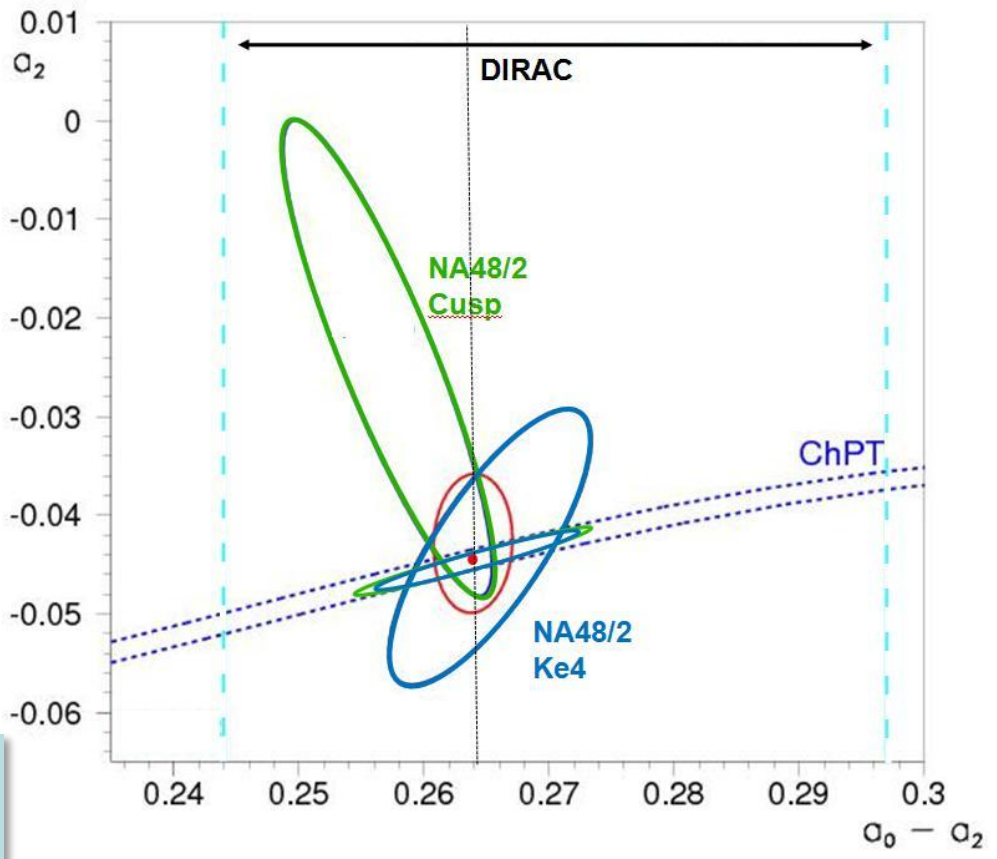
- Results based on BB model (better $\chi 2$, most complete theory)
- Very good agreement between the two approches
- Good agreement with ChPT prediction [Colangelo, Gasser, Leutwyler PRL 86 (2001) 5008]:

$(a0-a2)m_+ = 0.265 \pm 0.004$

- Similar theoretical and experimental precision
- Systematics error dominated by LKr non linearity and trigger efficiency

Cusp and Ke4: comparisons

- Two independent measurements
  - 60 M K3p
  - 1.13 M Ke4
- Different systematics
  - Cusp: Calorimeter and trigger
  - Ke4: electron misID and Background
- Different theoretical inputs
  - Cusp: rescattering in final state and ChPT expansion
  - Ke4: Roy equation and isospin breaking correction



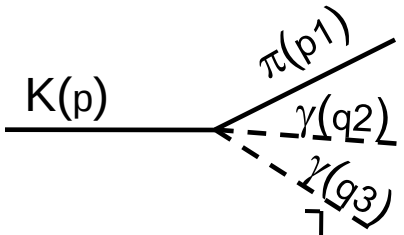
Very good agreement with ChPT prediction:
$(a0-a2)m_+=0.265 \pm 0.004$

Combined results
$(a0 -a2)m_+= 0.2639 \pm 0.0020 \pm 0.0004 \pm 0.0021$

Using ChPT constraints:
$(a0 -a2)m_+= 0.2640 \pm 0.0020 \pm 0.0017 \pm 0.0035$

K→πγγ: Theory

- At leading order, in the framework of ChPT, the K(p)→π(p1)γ(q2)γ(q3) differential rate is given by:

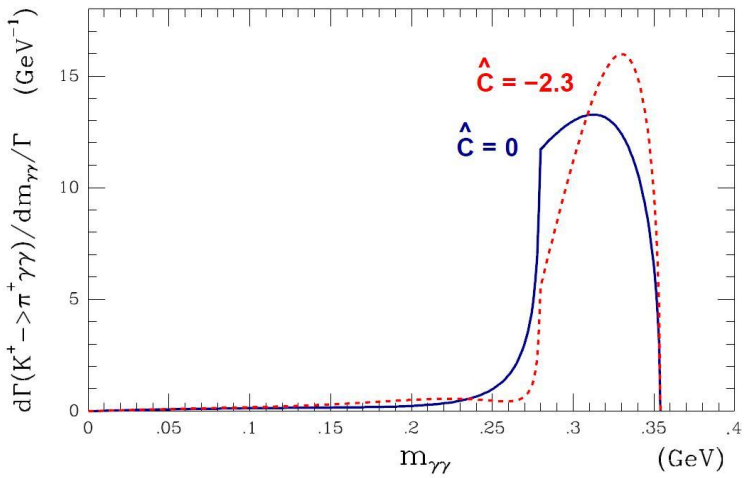


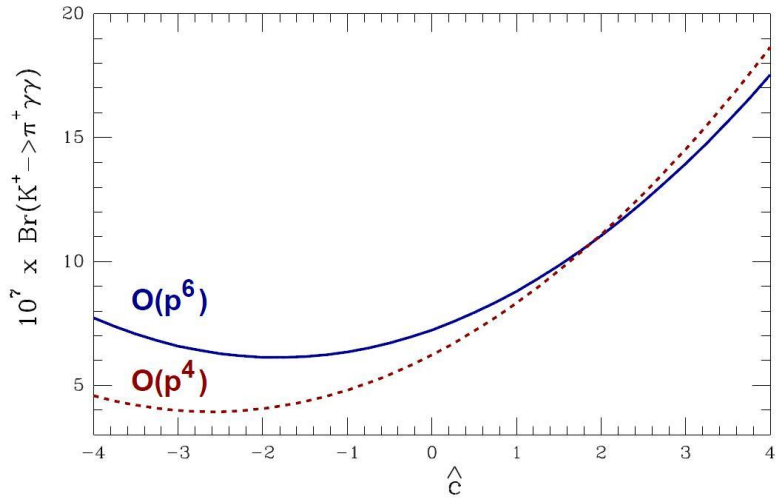
$y=p(q_2-q_3)/m_K^2$
$z=(q_2+q_3)/m_K^2$

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

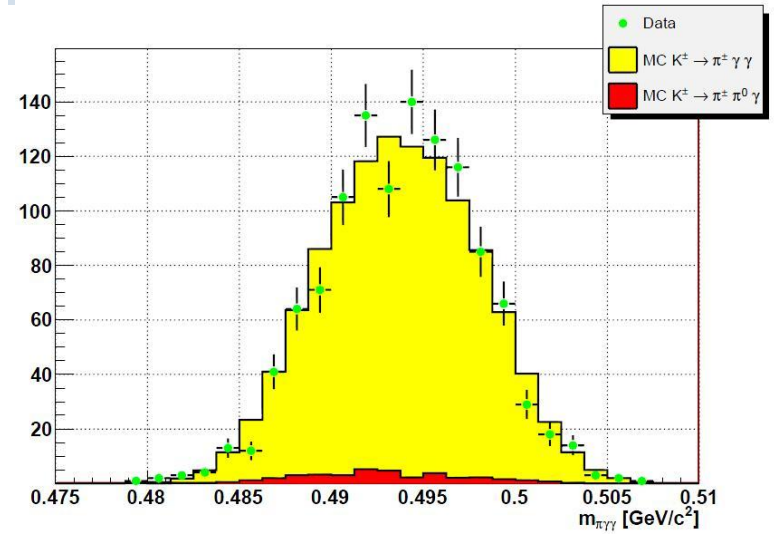
- At O(p4) the relevant contribution is given by A(z,ĉ) (loops) and C(z) (poles); B=D=0 at O(p4) and relevant at leading order only at low mγγ mass (1).
- **ĉ** is O(1) and have to be extracted from data
- Order O(p6) can be relevant (30%-40% enhanced in BR) (2).

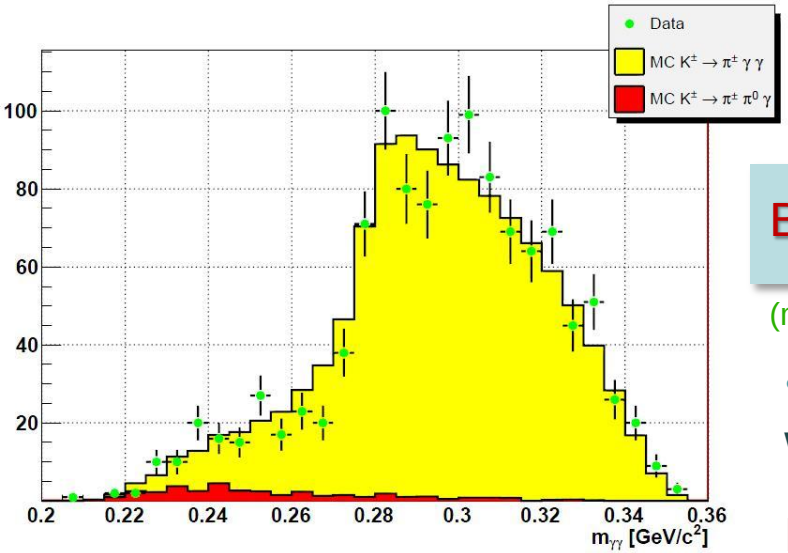
(1) [Ecker, Pich, De Rafael, in Nucl.Phys.B303:665,1988]
(2) [D'Ambrosio, Portoles, in Nucl.Phys.B386:403,1996]





K→πγγ: Results





- Analysis based on 40% of whole data set
- 1164 events found
- main background: $K^+ \to \pi^+\pi^0\gamma$ (3.3%)
- Main systematics from trigger efficency determination
- Data shape ($m_{\gamma\gamma}$) follows ChPT description ($\hat{c}=2$ shown for qualitative comparison)
- Assuming O(p6) and $\hat{c}=2$ the preliminary result on *model dependent* BR determination is

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

(model independent analysis on going)

- Overtaken the previous result from E787 with 31 events candidates:

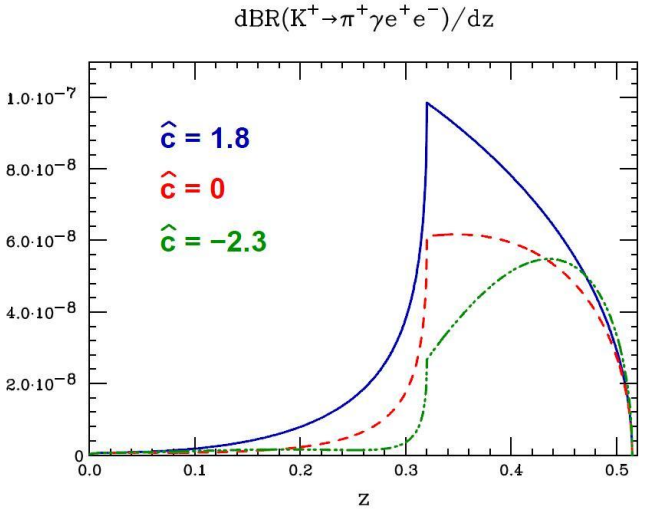
$$Br(K^+ \to \pi^+ \gamma\,\gamma) = (1.10 \pm 0.32) \cdot 10^{-6}$$

$K \to \pi\gamma ee$: Theory

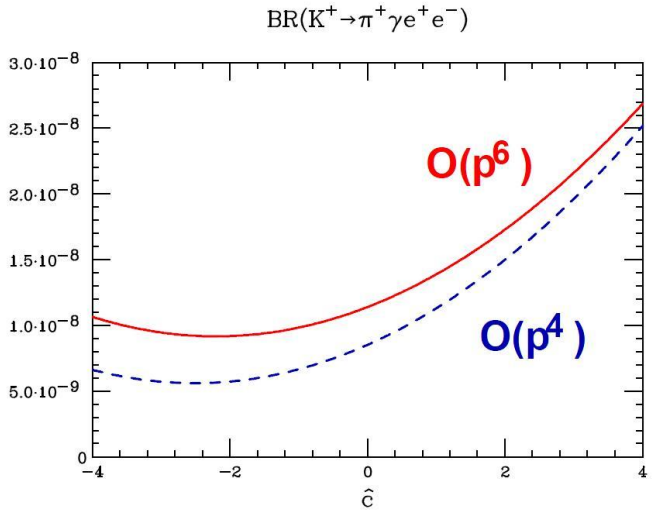
- Similar with respect to $K^+ \to \pi^+ \gamma\ \gamma$
- Br and $m_{ee\gamma}$ at order O(p4) determined by $\hat{c}$
- O(p6) could enhance the BR by 30%-40%
- Theoretical prediction at O(p6):

$$Br(K^+ \to \pi^+ \gamma\ e+e-) = (0.9 \div 1.6) \cdot 10^{-8}$$

[Gabbiani, in Phys.Rev.Lett.D59,1999]

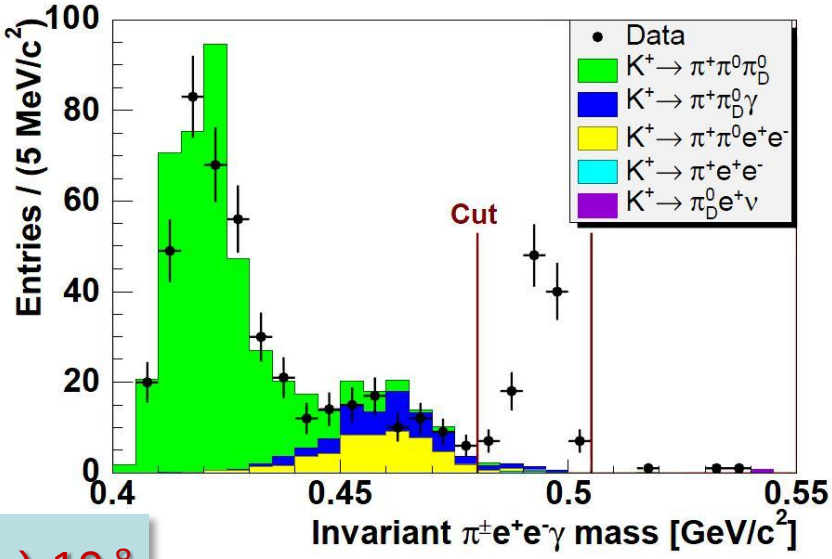


- Never observed before!



K→πγee : Results

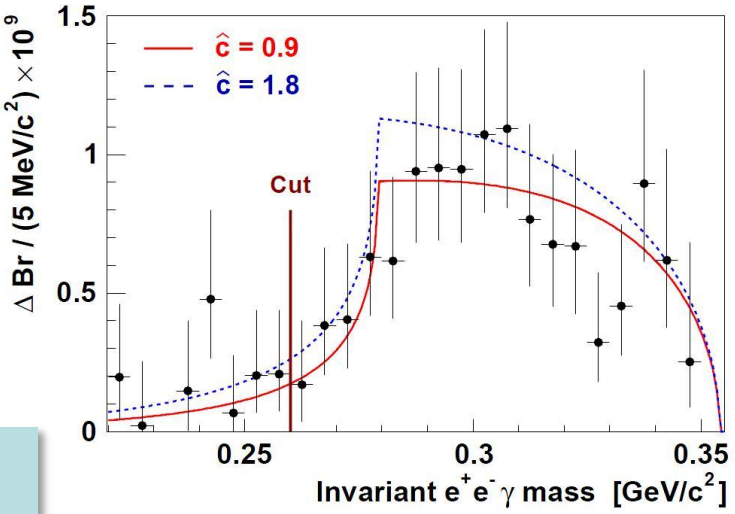
- 120 events candidates
- Background from $K^+ \to \pi^+\pi^0_D\gamma$ (6.1%)
- BR computed in bins of $m_{ee\gamma}$
- no assumption on $m_{ee\gamma}$ (model independent measurement)
- Cut on $m_{ee\gamma} > 260$ MeV/c^2



$$BR(K^\pm \to \pi^\pm e^+ e^- \gamma) = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \cdot 10^{-8}$$

- Assuming ChPT O(p6), the $\hat{c}$ value is extracted from $m_{ee\gamma}$ distribution

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



- From this the model dependent ChPT BR is:

$$BR(K^\pm \to \pi^\pm e^+ e^- \gamma) = (1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}}) \cdot 10^{-8}$$

[Batley et al. Phys.Lett.B659:493, 2008]

Conclusions

- The kaon decays give the possibility to study the low energy hadronic interaction with good precision
- Thanks to high statistics and high data quality, NA48/2 can check several ChPT predictions with very high accuracy
- Three significative *"examples"* have been presented in this talk:
  - $\pi\pi$ scattering lengths
  - $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$
  - $K^{\pm} \rightarrow \pi^{\pm}\gamma e^{+}e^{-}$
- The results obtained are compatible with the predictions
- In particular the measurement of the $\pi\pi$ scattering lengths obtained in two different ways, with an experimental error comparable with the theoretical uncertainty, is a very strong test of the theory.