# "QCD tests at NA48/2"

EPS_09
Krakow 16.7.2009

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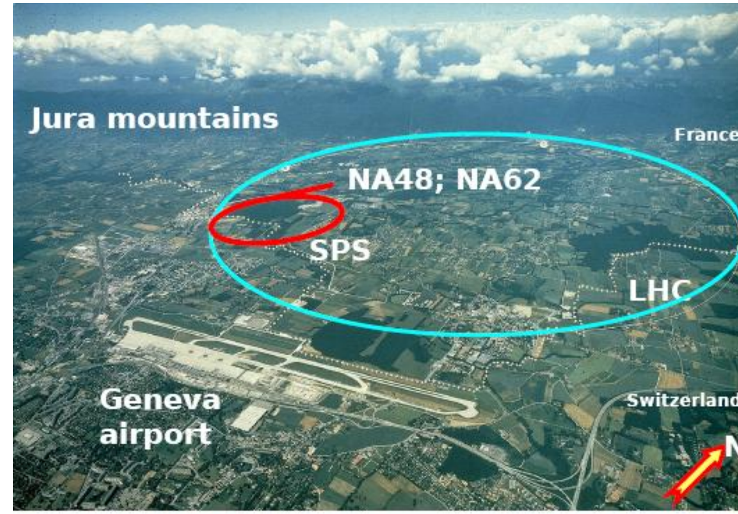
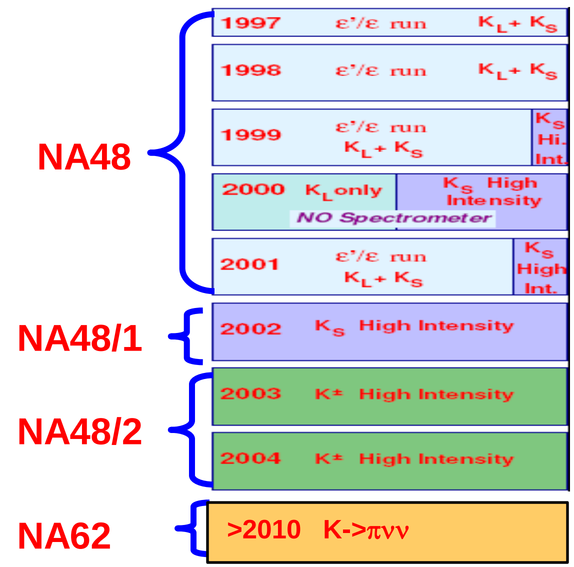
On behalf of the NA48/2 collaboration:
Cambridge, CERN, Chicago, Dubna, Edimburgh, Ferrara, Florence, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna

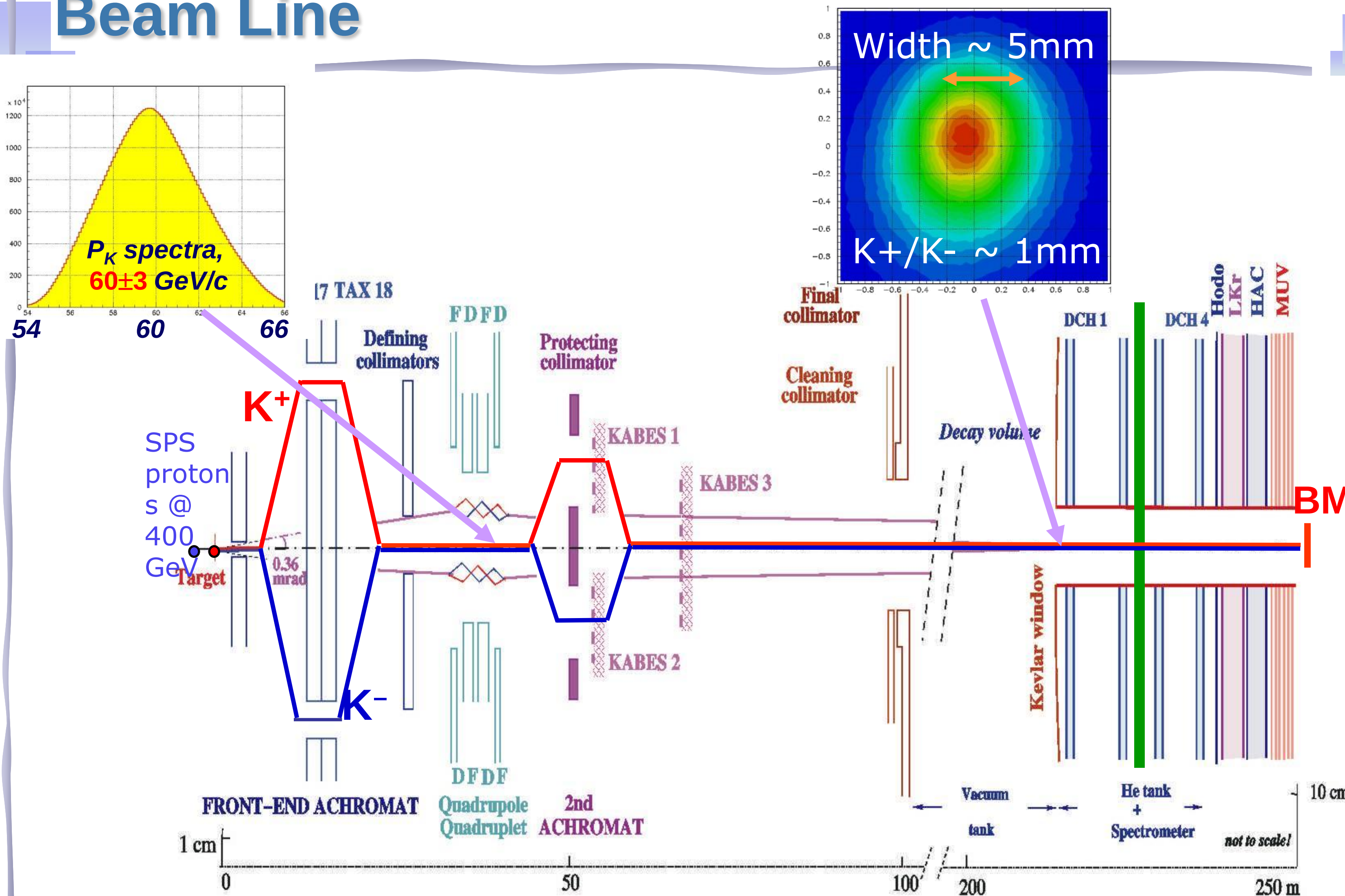
# Outline

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



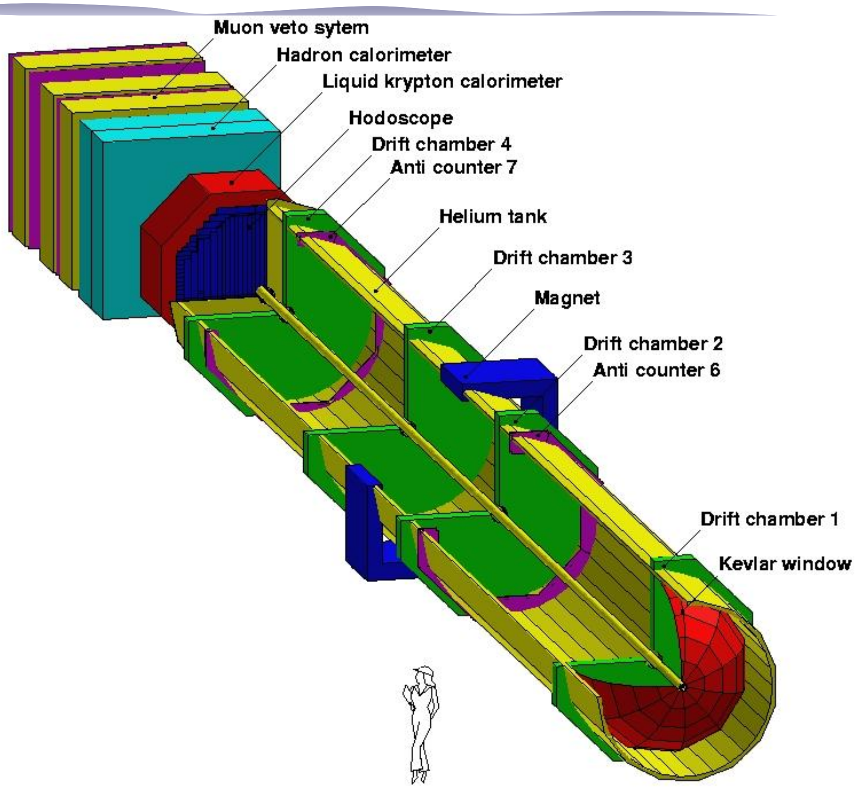



# Beam Line




- 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]

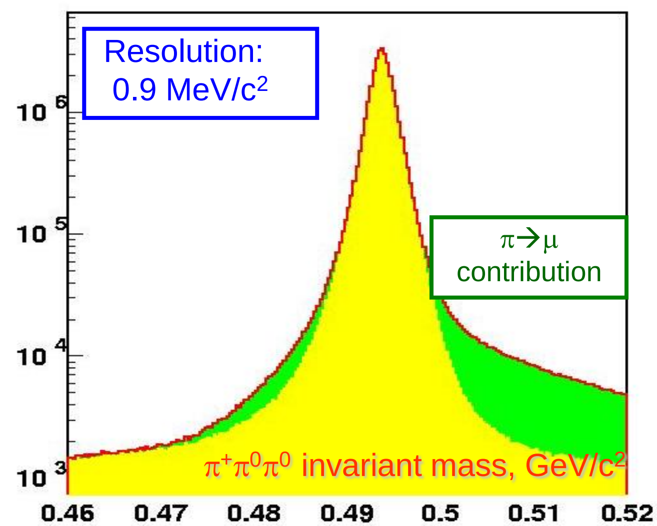
## LKR calorimeter:

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

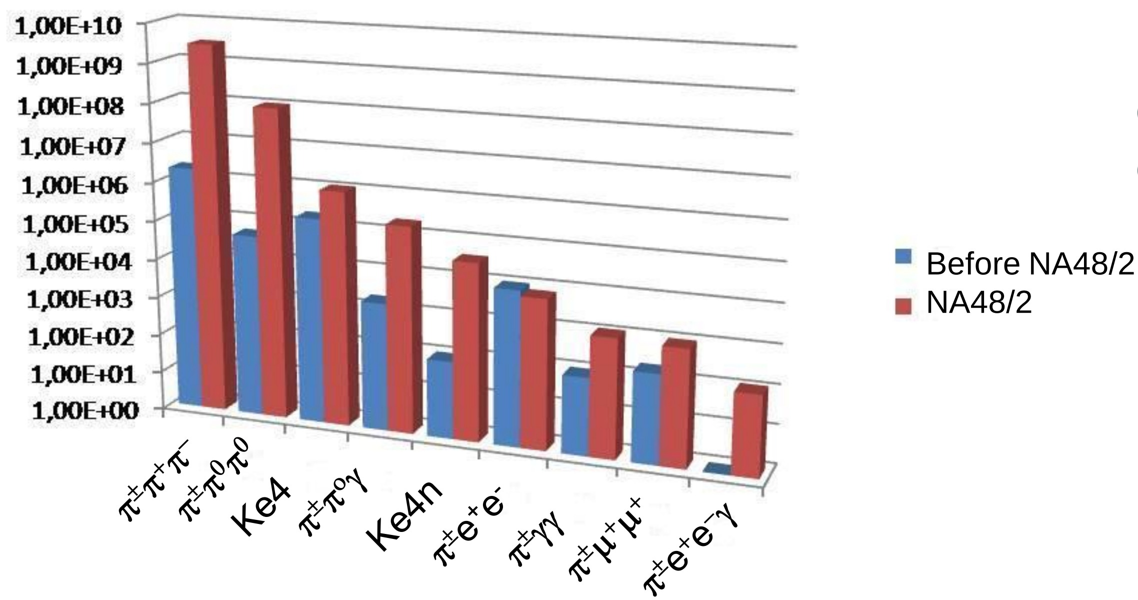
## CHOD, HAC, MUV, vetos

## Kabes

## Beam Monitor



# Data Taking




Detector and trigger optimized to collect 3 pions events

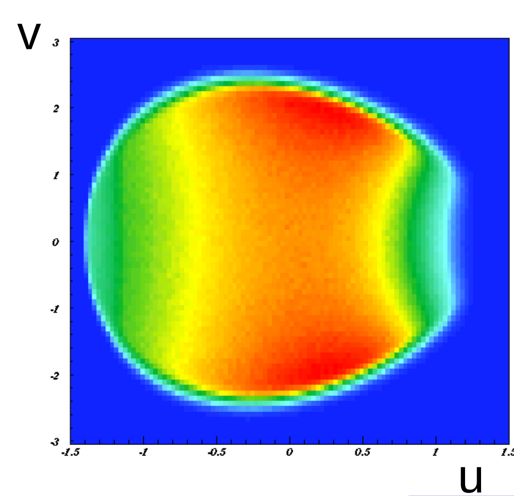
$K^\pm\to\pi^\pm\pi^0\pi^0$: ~$1\cdot10^8$

$K^\pm\to\pi^\pm\pi^+\pi^-$: ~$3\cdot10^9$

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

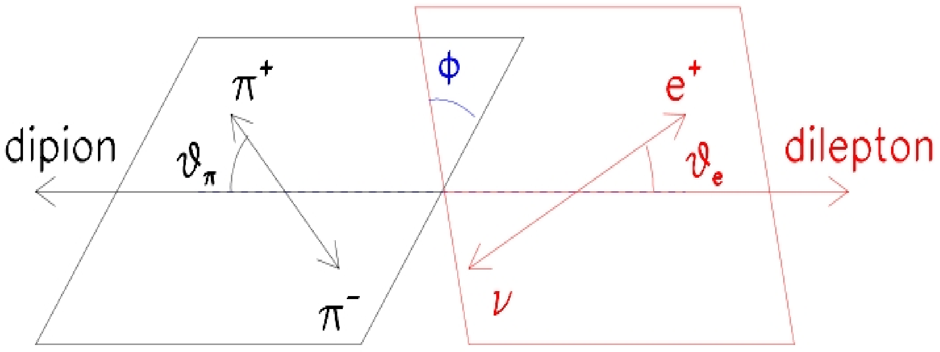
In the partial waves expansion the amplitude can be written using 2 axial and 1 vector form factors (the axial form factor R is suppressed in $K_{e4}$ but accessible in $K_{\mu4}$):

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

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

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

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

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## Signal selection:

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

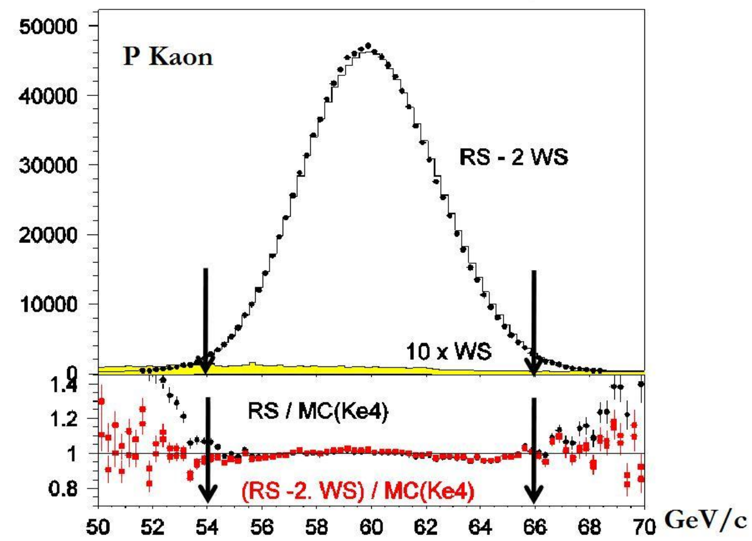
~1150000 decays

## Main background sources:

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

$\pi\pi\pi$ with $\pi$ misidentified

$\pi\pi^0\pi^0$ or $\pi^0 + \pi^0$(Dalitz) +e misidentified and $\gamma$s 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

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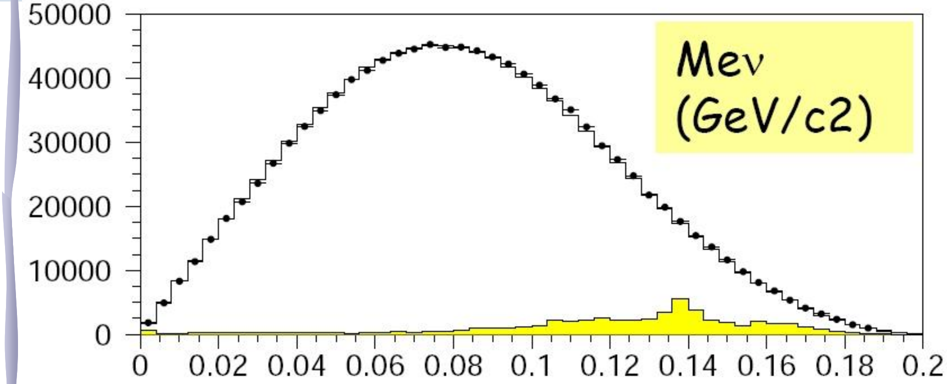



| (2003+2004) | | Data | MC |
|---|---|---|---|
| K+ | evts | 726400 | 17.7x10^6 |
| | evts/bin | 48 | 1160 |
| K- | evts | 404400 | 9.8x10^6 |
| | evts/bin | 27 | 650 |

- 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]

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

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

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

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

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

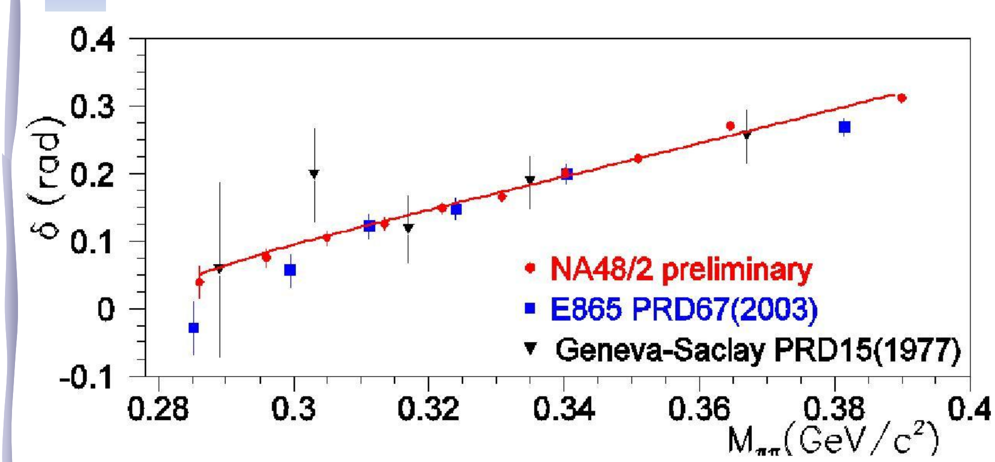
$g'p/f_s = 0.089 \pm 0.017 \pm 0.013$

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

(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

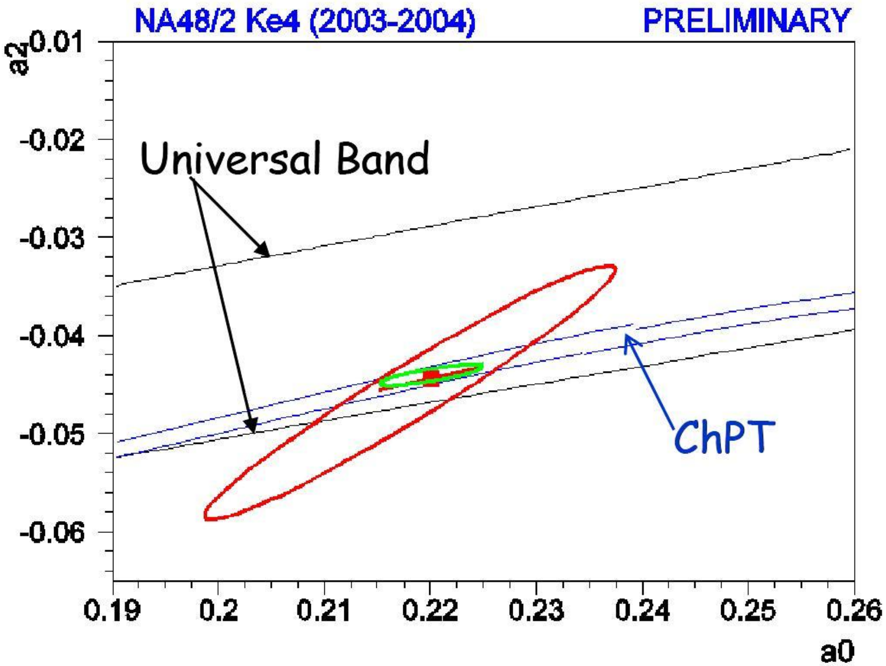
- The extraction of pion scattering lengths from the fitted $\delta=\delta_s-\delta_p$ phase shift needs external theoretical and experimental inputs:
  - The *Roy equations* provide the relation between δ and a0 and a2 near threshold (1) (2) (3)
  - Extrapolating the data from the $M_{\pi\pi}>0.8$ GeV 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 ±0.005
a2 = -0.0444 ±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

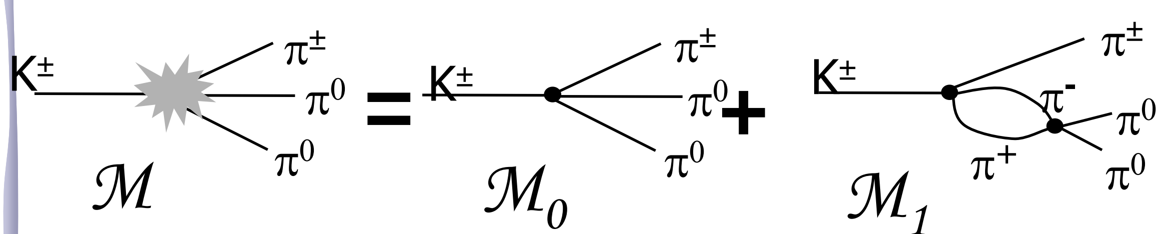
- In $K^\pm \to \pi^\pm \pi^0 \pi^0$ decay the matrix element is usually given as polynominal expansion as a function of the Dalitz variables U and V

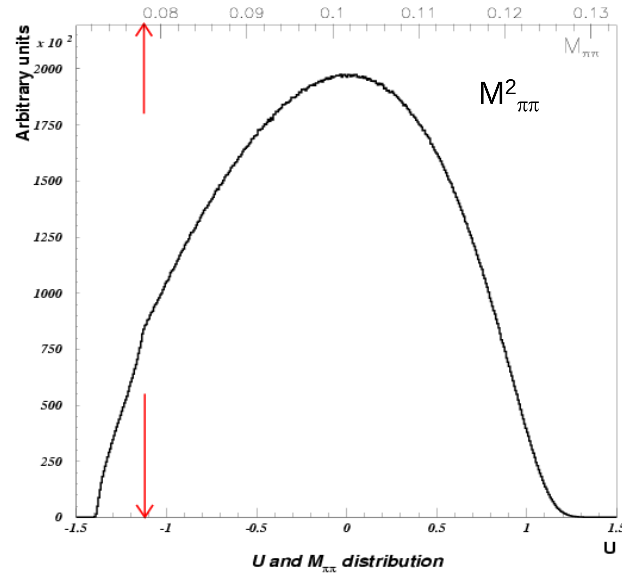
$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2 + \ldots$

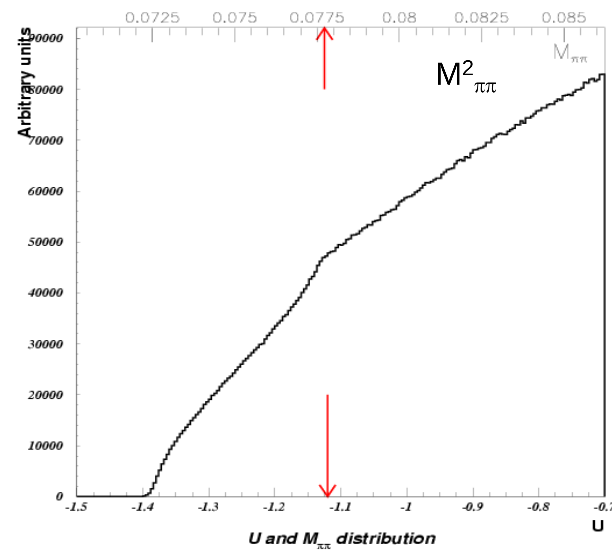
$u = (s_3 - s_0)/m_\pi^2 \qquad s_i = (P_K - P_{\pi,i})^2$

- 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

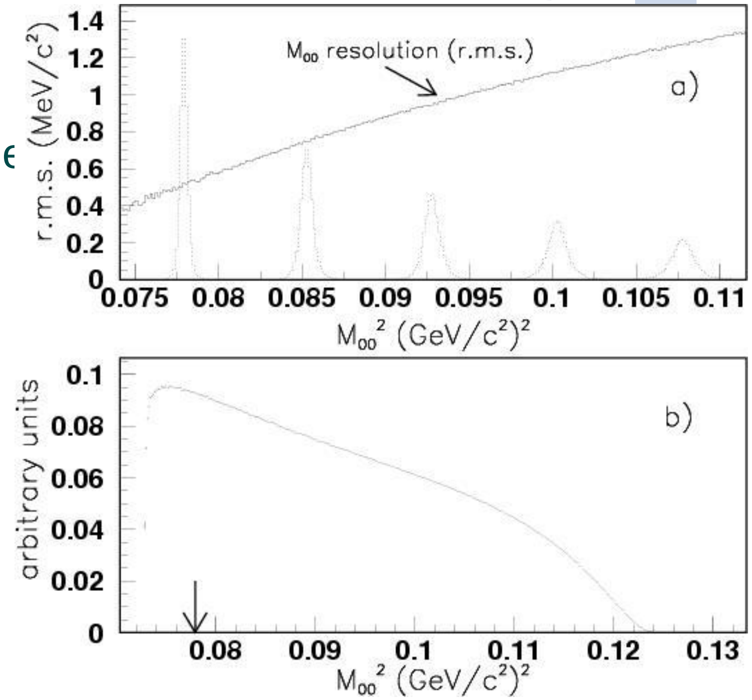


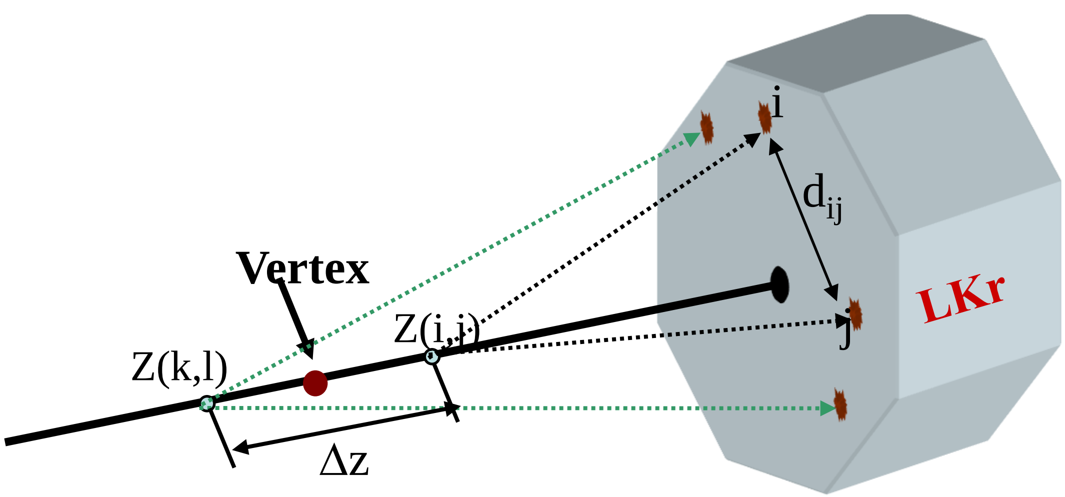



# Cusp: K→3π selection

- 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 $\pi^0$ mass.
- Offline selection: among all the possible $\gamma$ pairings, the couple for which $\chi^2$ is smallest is selected
  - the neutral vertex is obtained by imposing the $\pi^0$ 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)

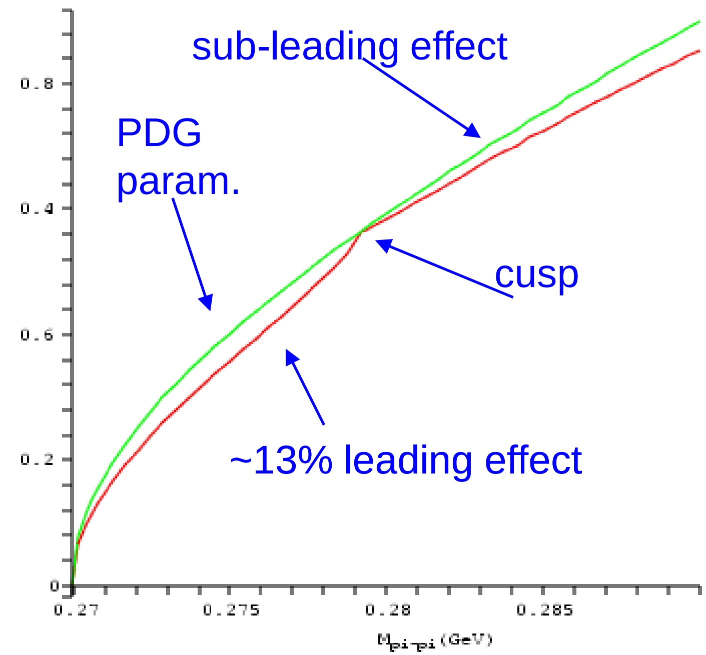


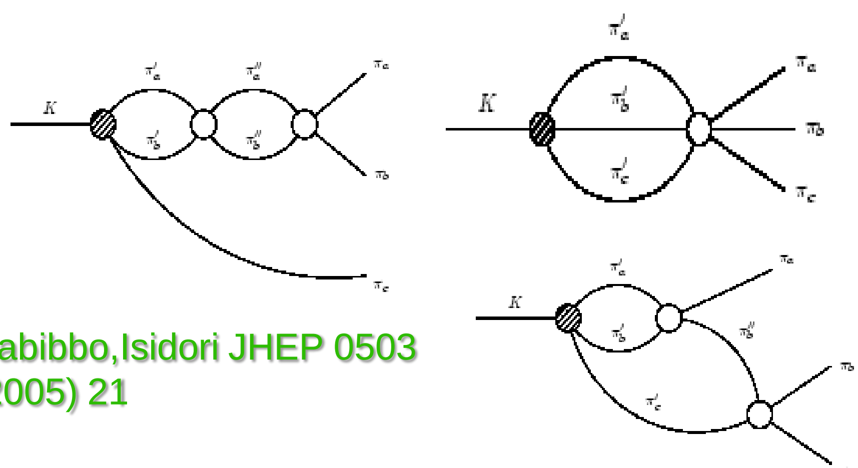
- Fenomenological approach
- The term M0 (no rescattering) is given by the standard PDG expansion
- the first rescattering terms is real below threshold and immaginary above. Interference below threshold.

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

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

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



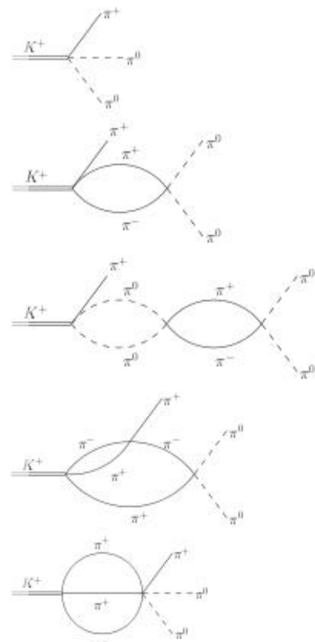
Cabibbo,Isidori JHEP 0503 (2005) 21

- 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]

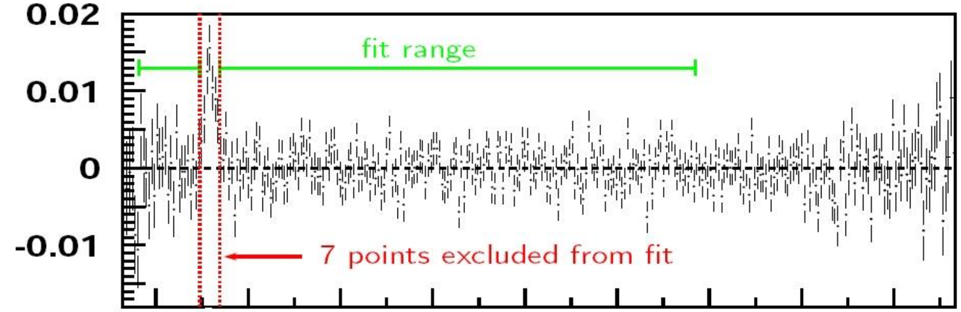
[Bissenger, Fuhrer, Gasser, Kubis, Rusetsky in Phys.Lett.B659:576,2008]

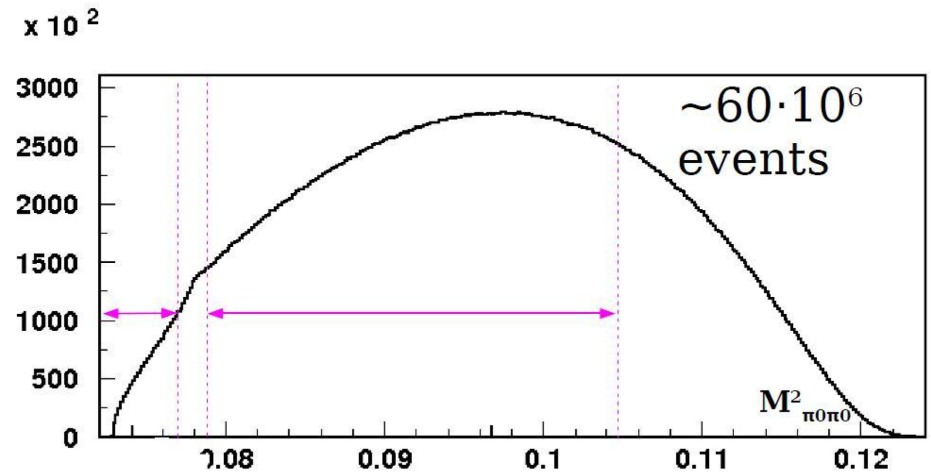
[Bissegger, Fuhrer, Gasser, Kubis, Rusetsky in NPH B806:178, 2009]

# 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 $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ slope parameters [Batley et al. Phys.Lett.B649:349-358,2007]
- In the **BB** the M+ term is obtained simultaneously fitting $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ and $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot
- Isospin effects included
- 7 bins around threshold excluded from the fit, upper limit to reduce the total error (226 bins)
- 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]



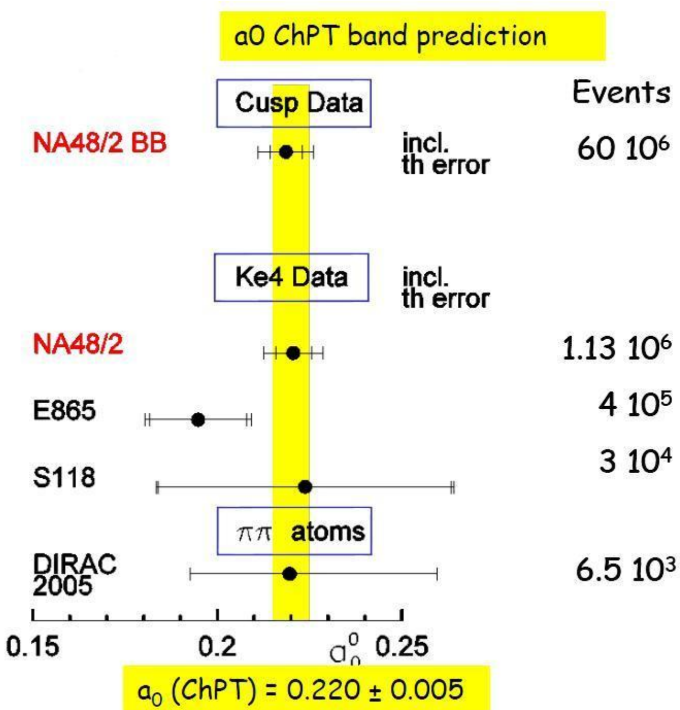




- The numbers of "atoms" is used as free parameter in the fits

# Cusp: Results

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

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




- 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]:

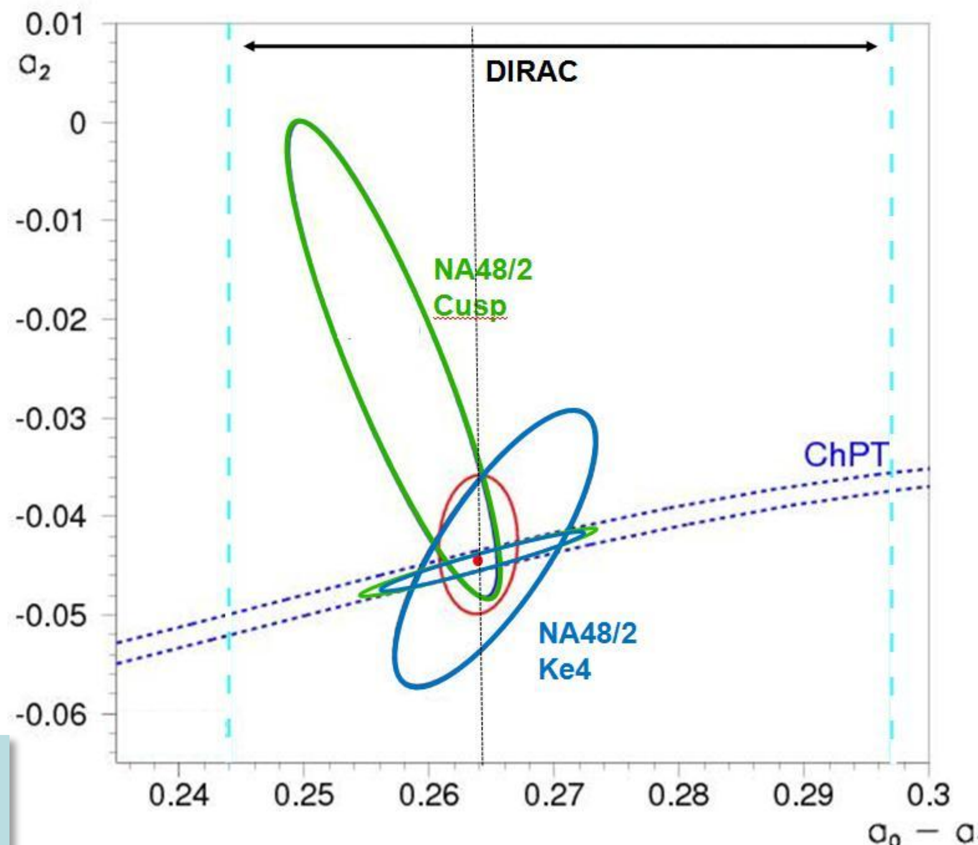
**$(a0\text{-}a2)m_+ = 0.265 \pm 0.004$**

- 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




Combined results

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

Using ChPT constraints:

$(a0 - a2)m_+ = 0.2640 \pm 0.0020 \pm 0.0017 \pm 0.0035$

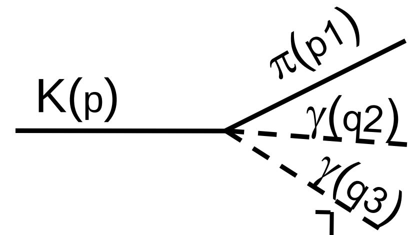
Very good agreement with ChPT prediction:

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

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



- At leading order, in the framework of ChPT, the $K(p)\to\pi(p1)\gamma(q2)\gamma(q3)$ differential rate is given by:

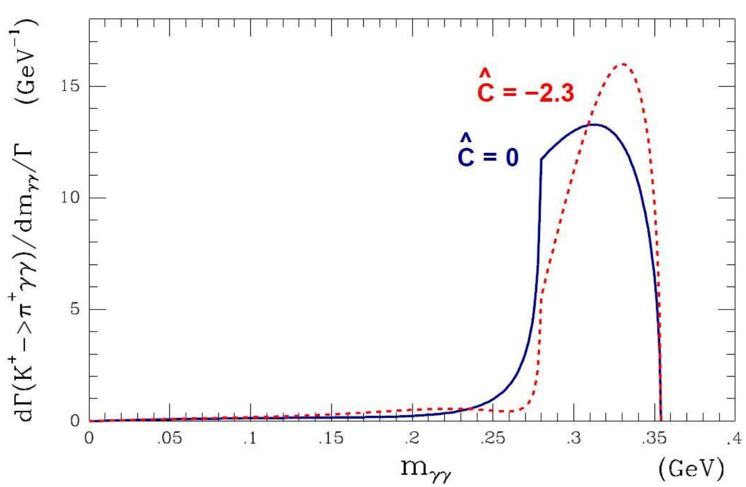


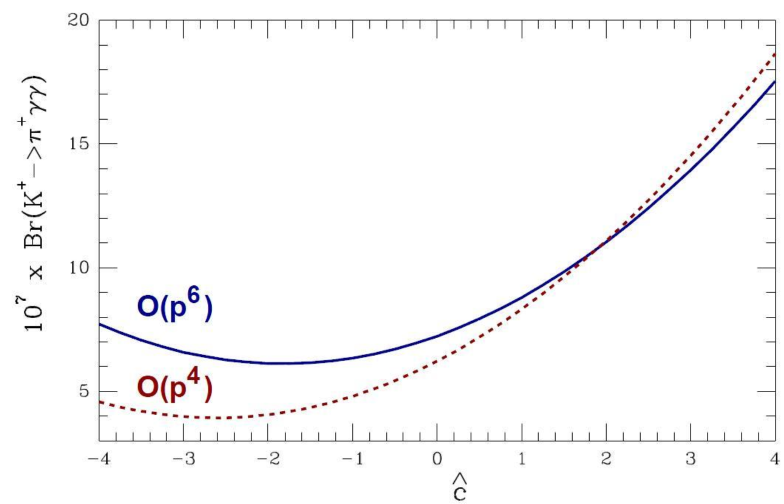

$y=p(q_2-q_3)/m_K^2$
$z=(q_2+q_3)/m_K^2$

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

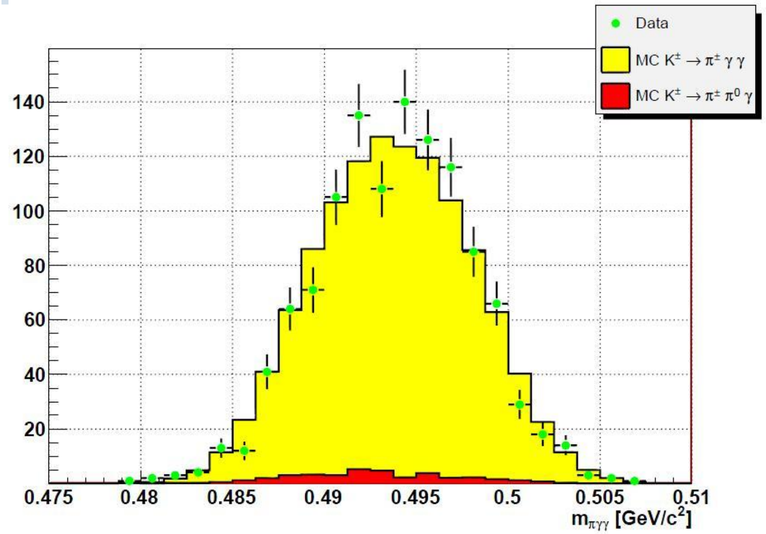
- At $O(p4)$ the relevant contribution is given by $A(z,\hat{c})$ (loops) and $C(z)$ (poles); $B=D=0$ at $O(p4)$ and relevant at leading order only at low $m\gamma\gamma$ mass (1).
- $\hat{c}$ is O(1) and have to be extracted from data
- Order $O(p6)$ can be relevant (30%-40% enhanced in BR) (2).

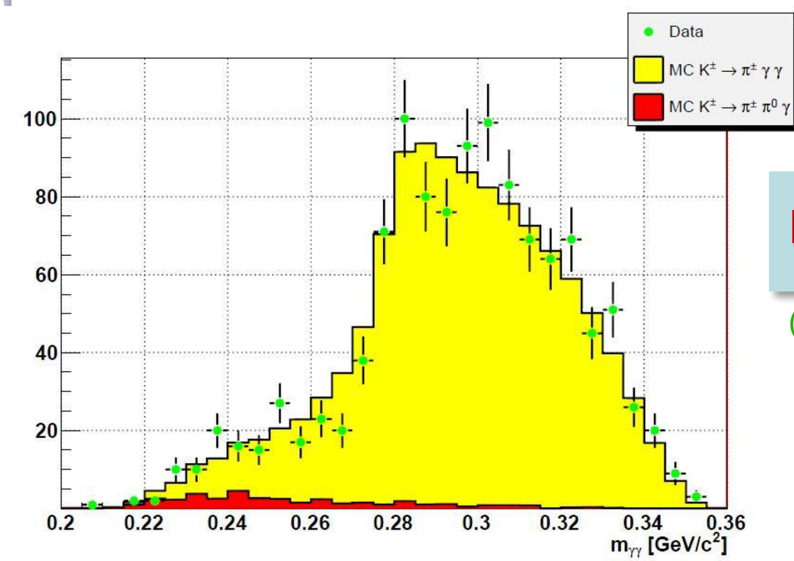
(1) [Ecker, Pich, De Rafael, in Nucl.Phys.B303:665,1988]
(2) [D'Ambrosio, Portoles, in Nucl.Phys.B386:403,1996]



# 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 (mγγ) follows ChPT description (ĉ=2 shown for qualitative comparison)
- Assuming O(p6) and ĉ=2 the preliminary result on *model dependent* BR determination is

$$Br(K^+\to\pi^+\gamma\,\gamma) = (1.07\pm0.04_{stat}\,\pm0.08_{syst})\cdot10^{-6}$$

(model independent analysis on going)

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

$$Br(K^+\to\pi^+\gamma\,\gamma) = (1.10\pm0.32)\cdot10^{-6}$$

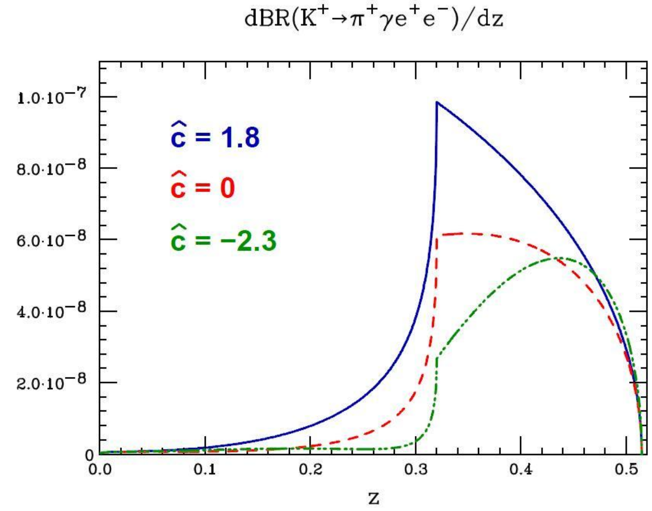
# $K \to \pi\gamma ee$: Theory



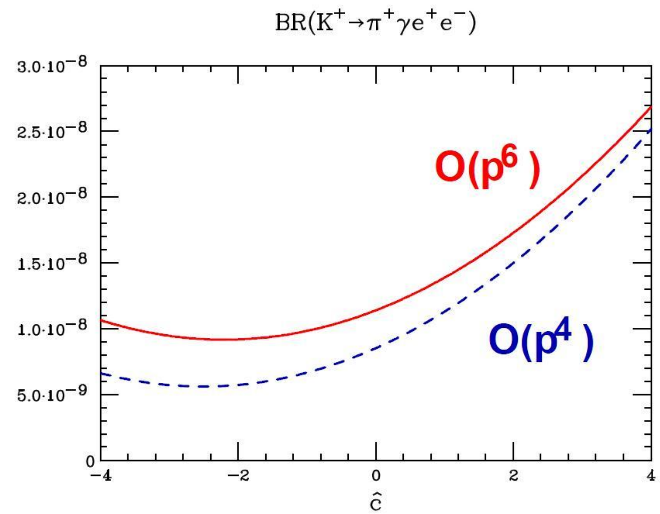
- Similar with respect to $K^+ \to \pi^+\gamma\,\gamma$
- Br and $m_{ee\gamma}$ at order O(p4) determined by $\hat{c}$
- O(p6) could enhance the BR by 30%-40%
- Theoretical prediction at O(p6):

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

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

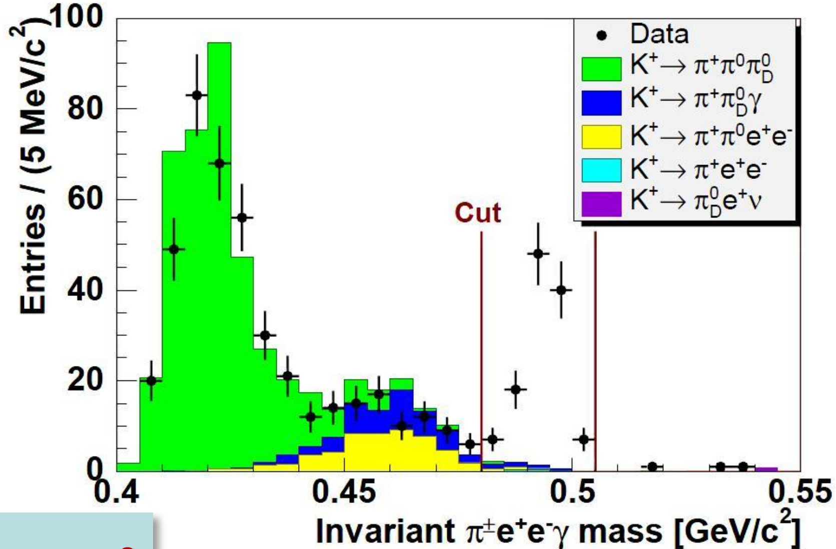



- Never observed before!



# K→πγee : Results

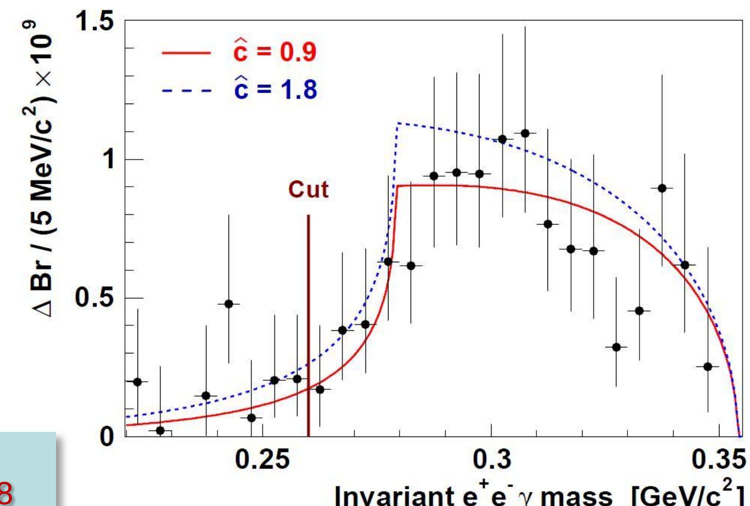
- $120$ events candidates
- Background from $K^+ \to \pi^+\pi^0_D\gamma$ (6.1%)
- BR computed in bins of $m_{ee\gamma}$
- no assumption on $m_{ee\gamma}$ (model independent measurement)
- Cut on $m_{ee\gamma} > 260$ MeV/c$^2$




$$BR(K^\pm \to \pi^\pm e^+e^-\gamma) = (1.19\pm0.12_{stat} \pm0.04_{syst})\cdot10^{-8}$$

- 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:

$$BR(K^\pm \to \pi^\pm e^+e^-\gamma) = (1.29\pm0.13_{exp} \pm0.03_{\hat{c}})\cdot10^{-8}$$

[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.