

Highlights on the NA48/2 experiment at CERN

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On behalf of the **NA48/2** collaboration

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

Overview

- The NA48/2 experiment
 - some history
 - experimental set-up description
- The most relevant cases of Physics
 - direct CP violation in $K^{\pm} \rightarrow \pi\pi\pi$
 - leptonic and semileptonic K^{\pm} decays
 - rare K^{\pm} decays
- Scattering lengths in $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$
 - observation of a structure
 - theoretical interpretation

NA48 physics through years

No spectrometer

Run	Beam	Physics goals
1997	K_L+K_S	D CPV in $K^0 \rightarrow \pi\pi$ (ϵ'/ϵ)
1998	K_L+K_S	ϵ'/ϵ Rare K_L decays
1999	K_L+K_S	ϵ'/ϵ Rare K_L decays
	HI K_S	K_S /hyperon decays
2000 NA48 and NA48/1	K_L	ϵ'/ϵ checks Neutral K_L decays
	HI K_S	Neutral K_S decays

Run	Beam	Physics goals
2001 NA48	K_L+K_S	ϵ'/ϵ
2002 NA48/1	HI K_S	Rare K_S decays Hyperon decays
2003 NA48/2	K^+/K^-	Direct CPV in $K^\pm \rightarrow (3\pi)^\pm$ Rare K decays
2004 NA48/2	K^+/K^-	Direct CPV in $K^\pm \rightarrow (3\pi)^\pm$ Rare K^+ decays
FUTURE(>2008) K very rare decays		

The most relevant cases of Physics

Main goal: study direct CP violation in $K^\pm \rightarrow \pi\pi\pi$

about 3.1×10^9 “good” events $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$

about 0.1×10^9 “good” events $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$

Rare K^\pm decays

$$K^\pm \rightarrow \pi\pi e\nu$$

form factors, a_0

$$K^\pm \rightarrow \pi^\pm e^+ e^-$$

form factors, BR

$$K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$$

form factors, BR

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

DE, IB, INT

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

form factors, BR

leptonic semileptonic K^\pm decays

$$Ke3$$

V_{us}

$$K\mu3$$

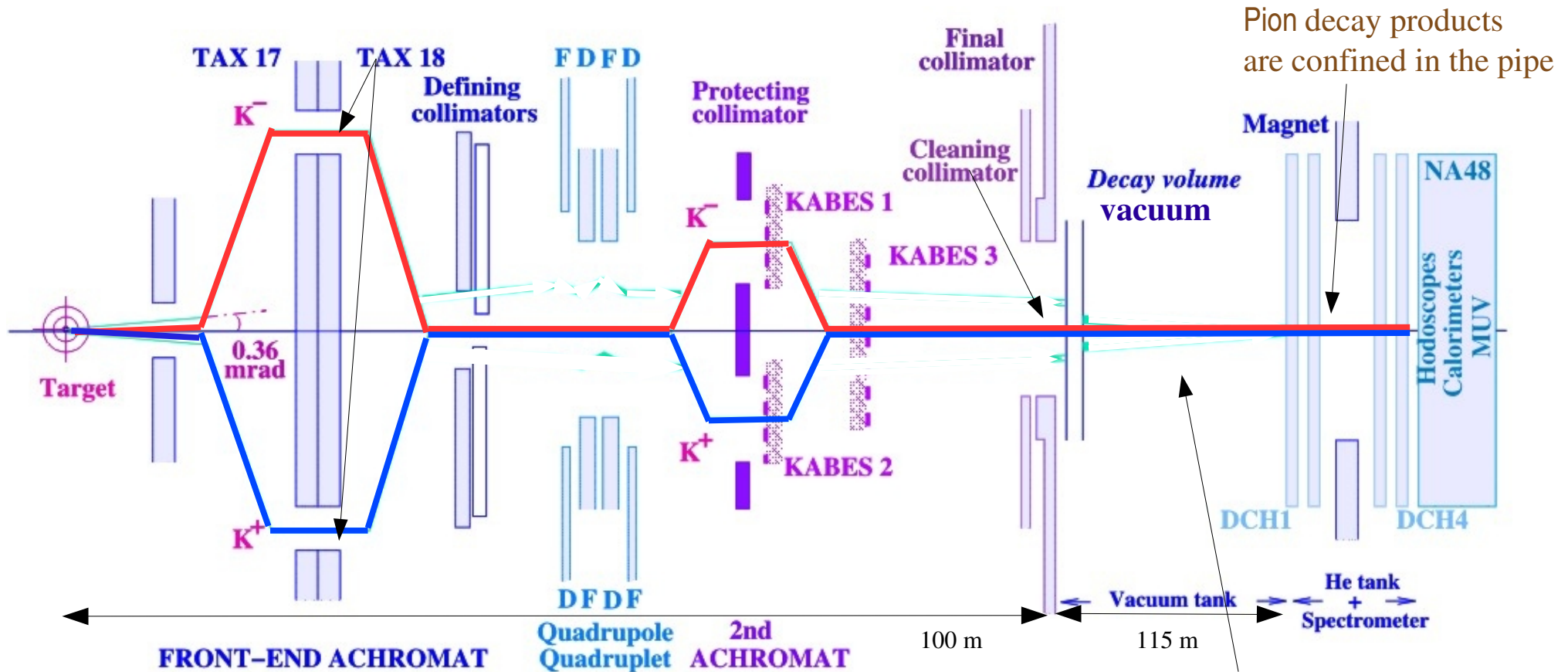
V_{us}

$$Ke2/K\mu2$$

test LFV

others

The NA48/2 beam line



Pion decay products are confined in the pipe

Decay volume vacuum

Beams overlap within $\sim 1 \text{ mm}$ through the 115m long decay volume (vacuum 10^{-5} mbar)

- Split +/-
- Select P (60 ± 3) GeV/c
- Recombine +/-

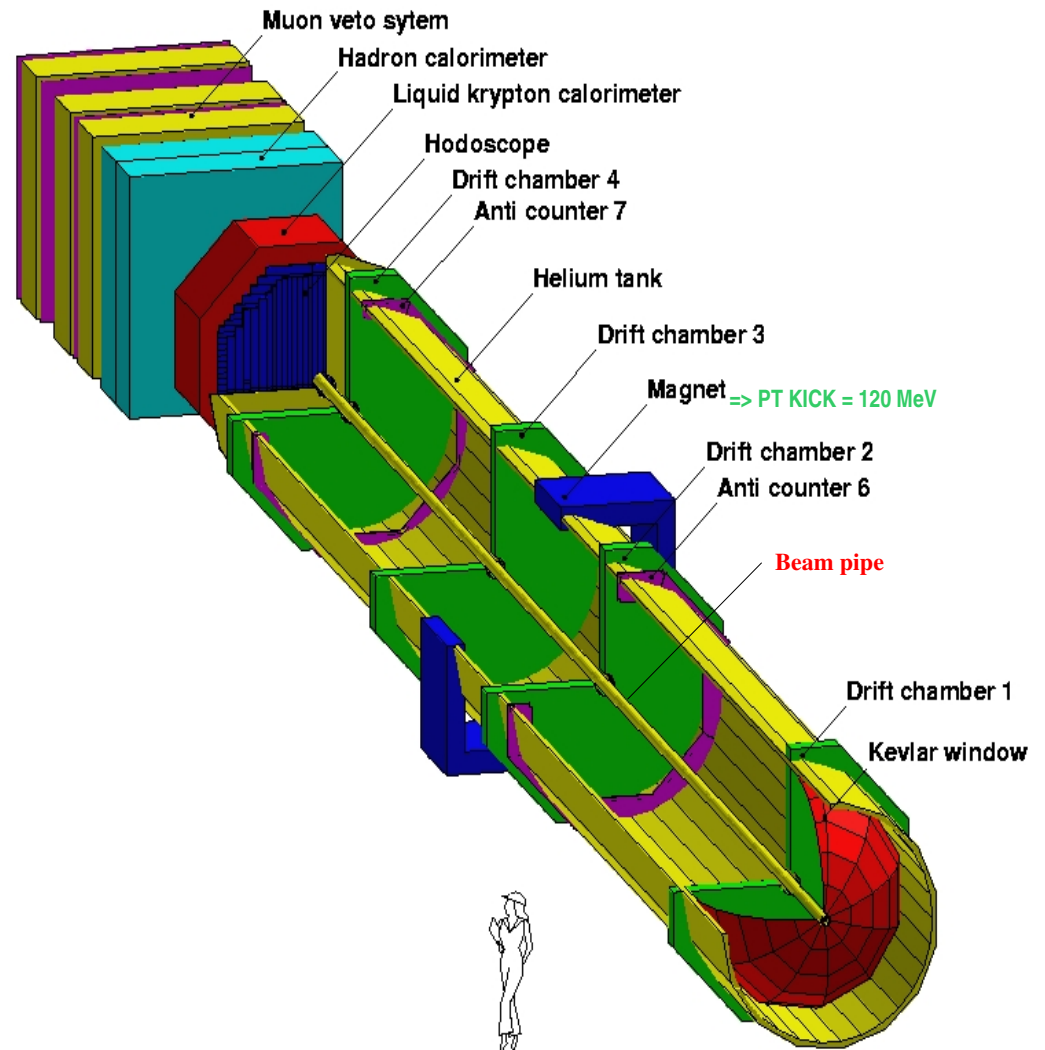
- Focusing
- Muon sweeping

- Cleaning
- Beam spectrometer (resolution 0.7 %)

NA48
Hodoscopes
Calorimeters
MUV

The NA48 detector

- Magnetic spectrometer (4 DCHs):
 $\Delta p/p = 1.0\% + 0.044\% \cdot p$ [GeV/c]
 $\pi^+ \pi^- \pi^\pm$ mass resolution about 1.7 MeV/c
- Liquid Krypton EM calorimeter (LKr)
High granularity, quasi-homogenous;
 $\Delta E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%[\text{GeV}]$
 $\sigma_x, \sigma_y \sim 1.5$ mm
 $\pi^0 \pi^0 \pi^\pm$ mass resolution about 1.4 MeV/c
- Hodoscope
fast trigger;
precise time measurement (150ps).
- Hadron calorimeter. muon veto counters.



The $K^\pm \rightarrow 3\pi$ decay

Kinematics:

$$s_i = (P_K - P_i)^2 \quad i=1,2,3 \quad (3=\text{odd})$$

$$s_0 = (s_1 + s_2 + s_3)/3$$

$$u = (s_3 - s_0)/m_\pi^2$$

$$v = (s_2 - s_1)/m_\pi^2$$

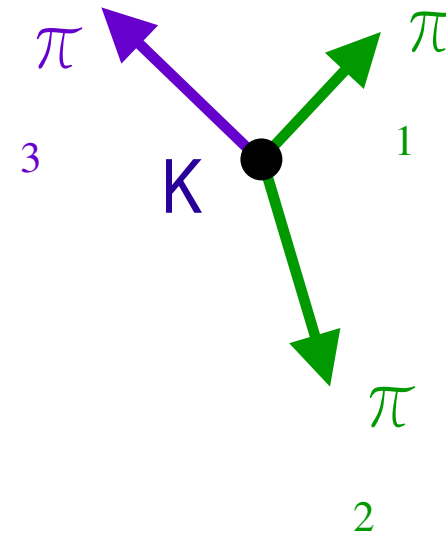
Matrix element:

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

$$A_g^{C,N} \stackrel{\text{def}}{=} \frac{(g_+ - g_-)}{(g_+ + g_-)} = \frac{(\Delta g)}{2g}$$

C : charged mode

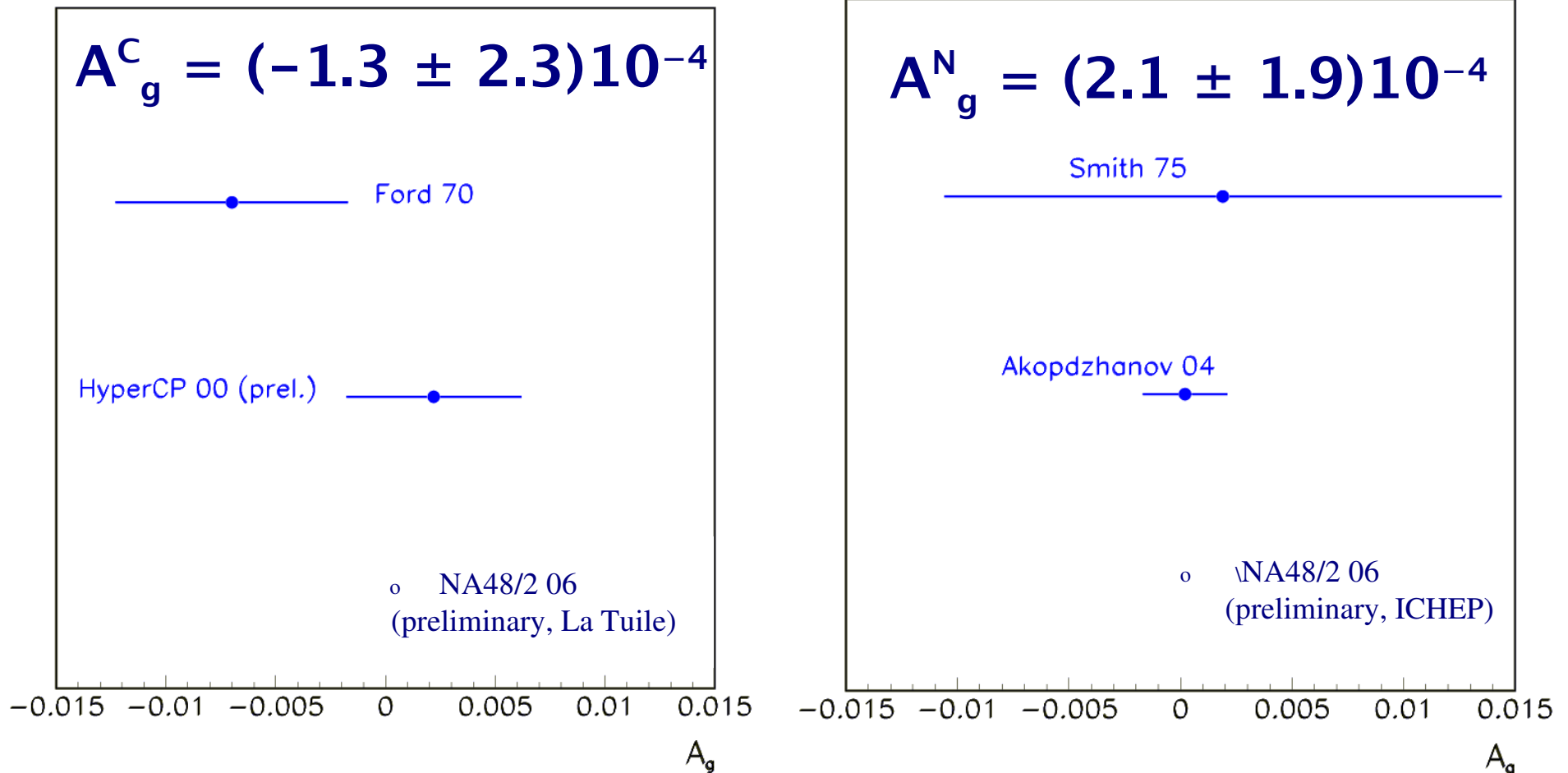
N: neutral mode



If asymmetries $A_g^{C,N} \neq 0$
→ direct CP violation

Asymmetry measurements

NO DCPV FOUND ... but with a sensitivity x10 better than previous experiments



Rare decay measurements

- $K^\pm \rightarrow \pi^+ \pi^- e^\pm \nu$

$$a_0 = 0.256 \pm 0.008_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.018_{\text{theo}}$$

- $K^\pm \rightarrow \pi^0 \pi^0 e^\pm \nu$

$$\text{BR} = (2.587 \pm 0.026_{\text{stat}} \pm 0.019_{\text{syst}} \pm 0.029_{\text{norm}}) \times 10^{-5}$$

$$f'_s / f_s = 0.129 \pm 0.036_{\text{stat}} \pm 0.020_{\text{syst}}$$

$$f''_s / f_s = -0.040 \pm 0.034_{\text{stat}} \pm 0.020_{\text{syst}}$$

- $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$

$$\text{Frac(DE)} = (3.35 \pm 0.35_{\text{stat}} \pm 0.25_{\text{syst}})\%$$

$$\text{Frac(INT)} = (-2.67 \pm 0.81_{\text{stat}} \pm 0.73_{\text{syst}})\%$$

Leptonic semi-leptonic measurements

- $K^\pm \rightarrow \pi^0 e^\pm \nu$

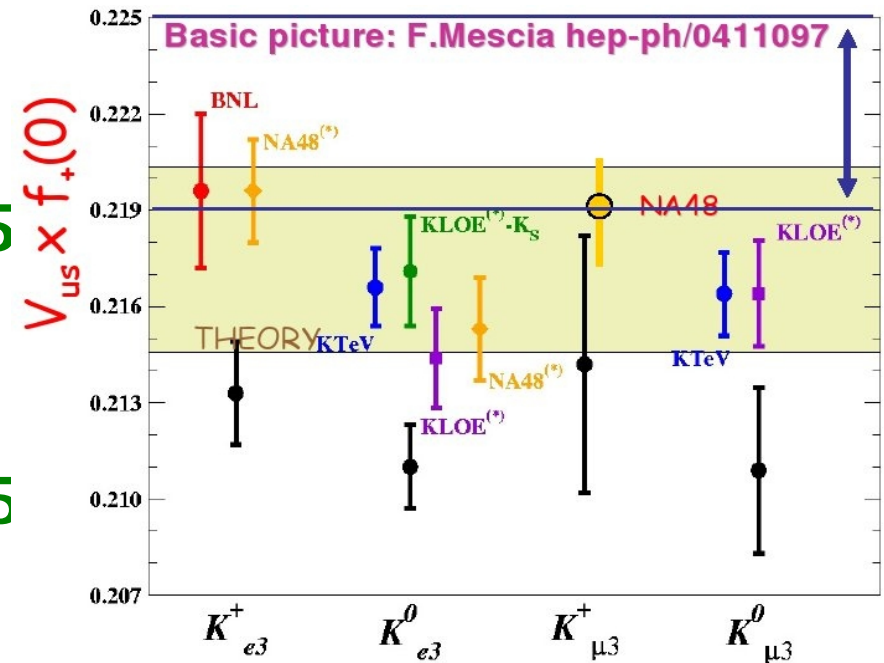
$$V_{us} \cdot f_+(0) = 0.2192 \pm 0.0015$$

- $K^\pm \rightarrow \pi^0 \mu^\pm \nu$

$$V_{us} \cdot f_+(0) = 0.2204 \pm 0.0015$$

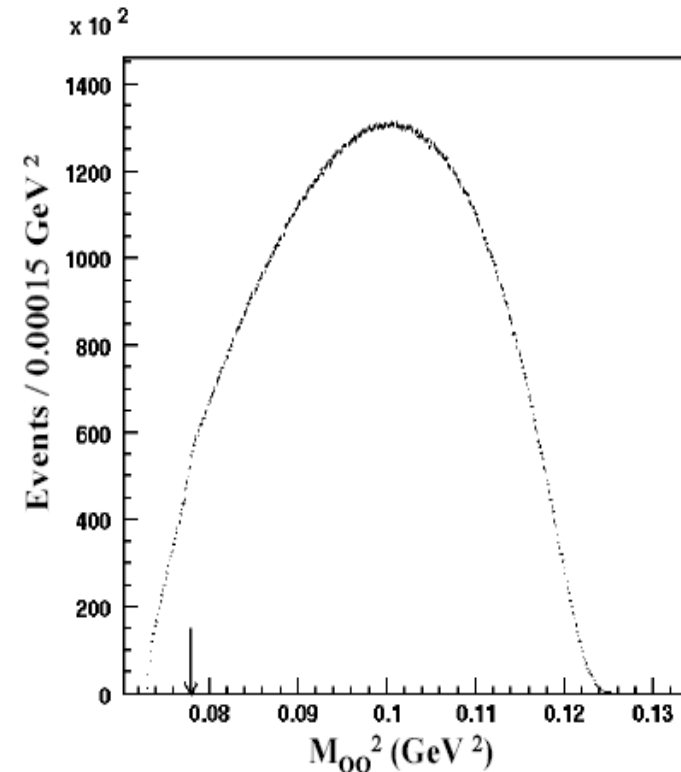
- $K^\pm \rightarrow e^\pm \nu$ and $K^\pm \rightarrow \mu^\pm \nu$

$$\Gamma(K^\pm \rightarrow e^\pm \nu) / \Gamma(K^\pm \rightarrow \mu^\pm \nu) = (2.416 \pm 0.026_{\text{stat}} \pm 0.043_{\text{syst}} \pm 0.024_{\text{norm}}) \times 10^{-5}$$



Observation of a “cusp” in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

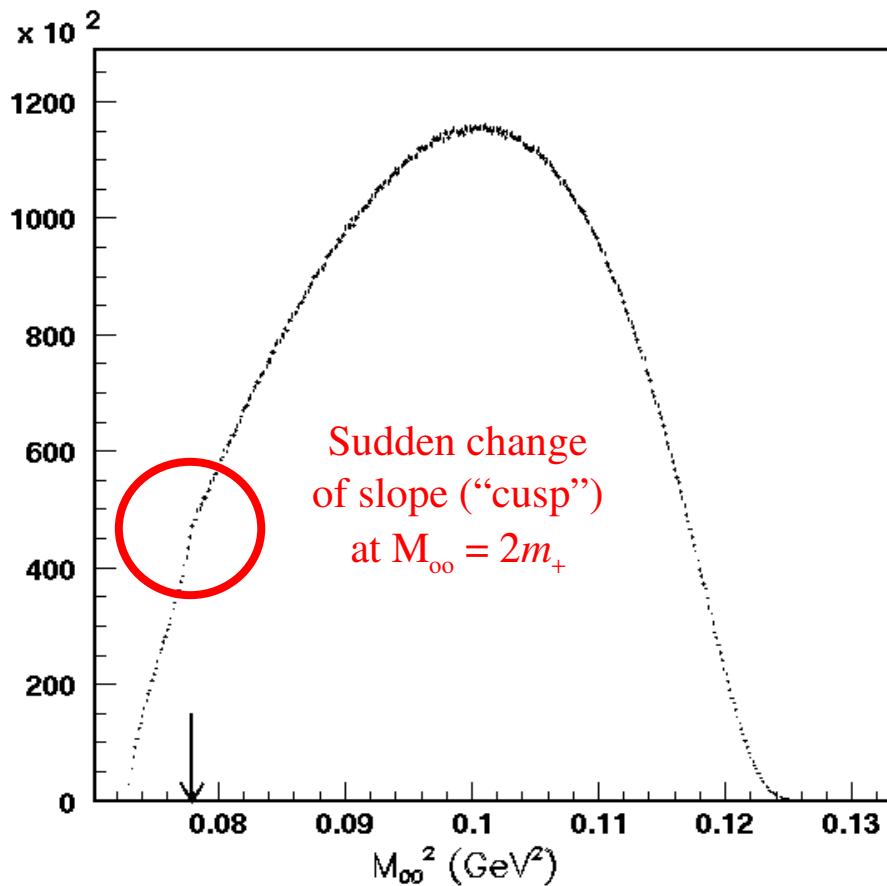
- Data reveal a structure in the $s_3 = M_{00}^2 = 4 m_+^2$ region. The structure has a physical origin: whatever torture is made to data it keeps sitting there
- **N.Cabibbo** realized that it was a “*clean and beautiful*” example of a general cusp-like behaviour of cross sections next to threshold for new channels
- He provided a method based on first principles (unitarity, analyticity) for extracting information on strong interaction at low energy.



Observation of a “cusp” in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

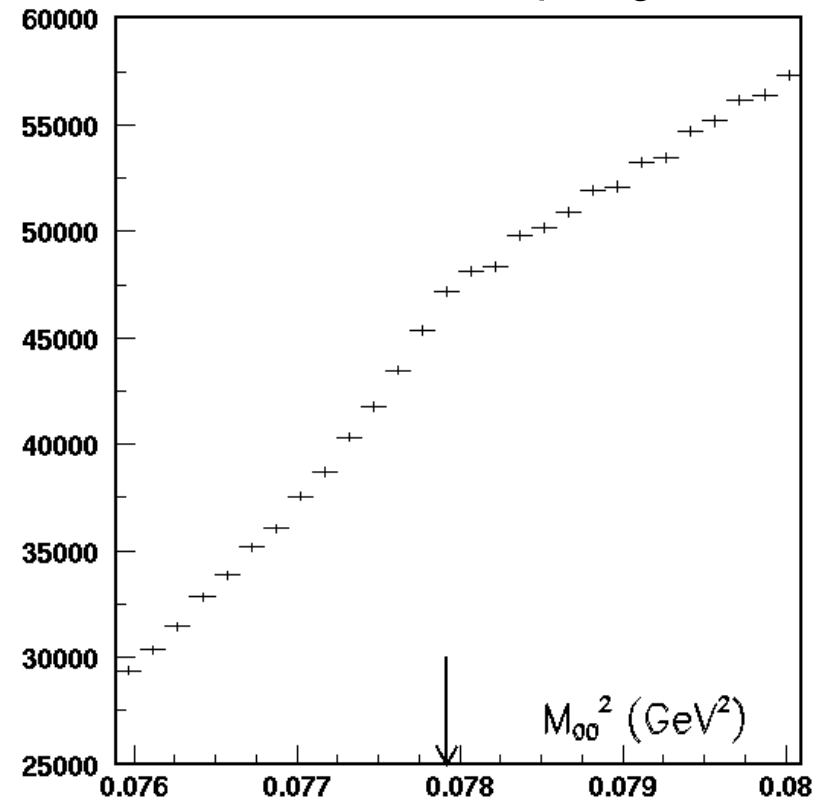
$\pi^0 \pi^0$ invariant mass squared ($M_{\pi^0 \pi^0}^2$)

23×10^6 $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ events



$M_{\pi^0 \pi^0}^2$ distribution

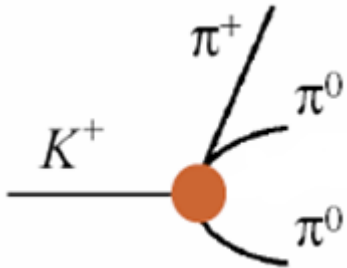
“Zoom” on the cusp region



The origin of the cusp

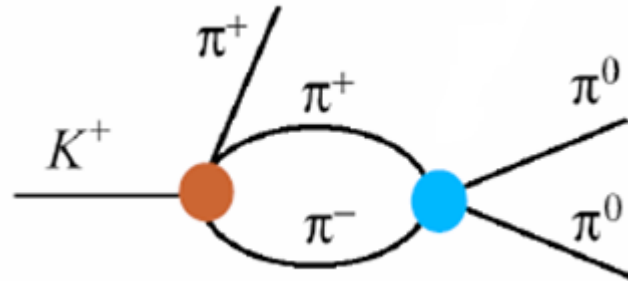
Interference (*destructive*) is the main cause of the singularity in the $\pi^0\pi^0$ invariant mass distribution. The effect of the interference is present (*first order*) below the threshold and not above.

Direct emission



Real
amplitude

Charge exchange $\pi^+\pi^- \rightarrow \pi^0\pi^0$



Amplitude $\sim i (M_{\pi^0\pi^0}^2 - 4m_{\pi^+}^2)^{1/2}$
Imaginary above threshold
Real amplitude below threshold

Cabibbo rescattering model (I)

$$\mathcal{M}(\mathcal{K}^\pm \rightarrow \pi^\pm \pi^0 \pi^0) = \mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1$$

“Unperturbed” amplitude



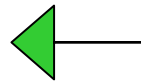
$$M_0 = A^0 \left(1 + g^0 (s_3 - s_0) / 2m_{\pi^+}^2 \right)$$

Above threshold (known)

Imaginary for

No interference

$$M_{00}^2 > 4m_{\pi^+}^2$$



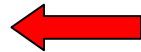
$$|M|^2 = (M_0)^2 + (iM_1)^2$$

Below threshold (analyticity)

Real < 0 for

Destructive interference

$$M_{00}^2 < 4m_{\pi^+}^2$$



$$|M|^2 = (M_0)^2 + (M_1)^2 + 2M_0 M_1$$

$$M_+ = A^+ \left(1 + g^+ (s_3 - s_0) / 2m_{\pi^+}^2 \right)$$

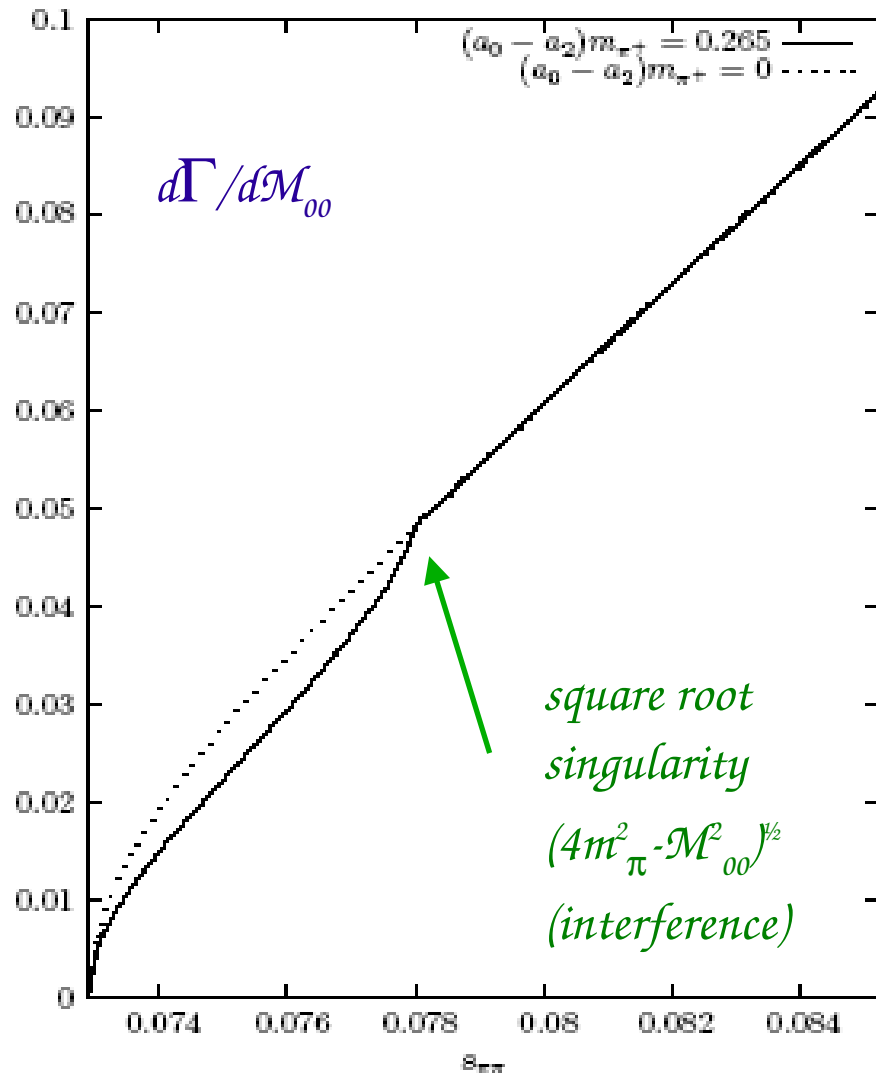
contributes to \mathcal{M}_1 at threshold



$$M_1 = i2 \frac{(a_0 - a_2) m_{\pi^+}}{3} M_+^{thr} \sqrt{\frac{s_3 - 4m_{\pi^+}^2}{s_3}}$$

$$M_1 = -2 \frac{(a_0 - a_2) m_{\pi^+}}{3} M_+^{thr} \sqrt{\frac{4m_{\pi^+}^2 - s_3}{s_3}}$$

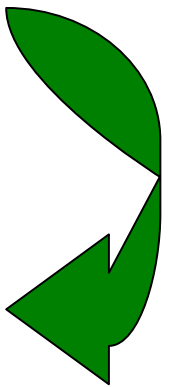
Cabibbo rescattering model (II)



The cusp is proportional to the S-wave $\pi^+\pi^-$ charge exchange scattering length $(a_0 - a_2)$ (in the limit of exact isospin).
 Extract $(a_0 - a_2)$ from the $\pi^0\pi^0$ spectrum

In order to deal with experimental measurement of $(a_0 - a_2)$ at few % by NA48, the theory has to be good to few 10^{-3} (cusp is a 10% effect)

Higher order rescattering effects + radiative corrections have to be included

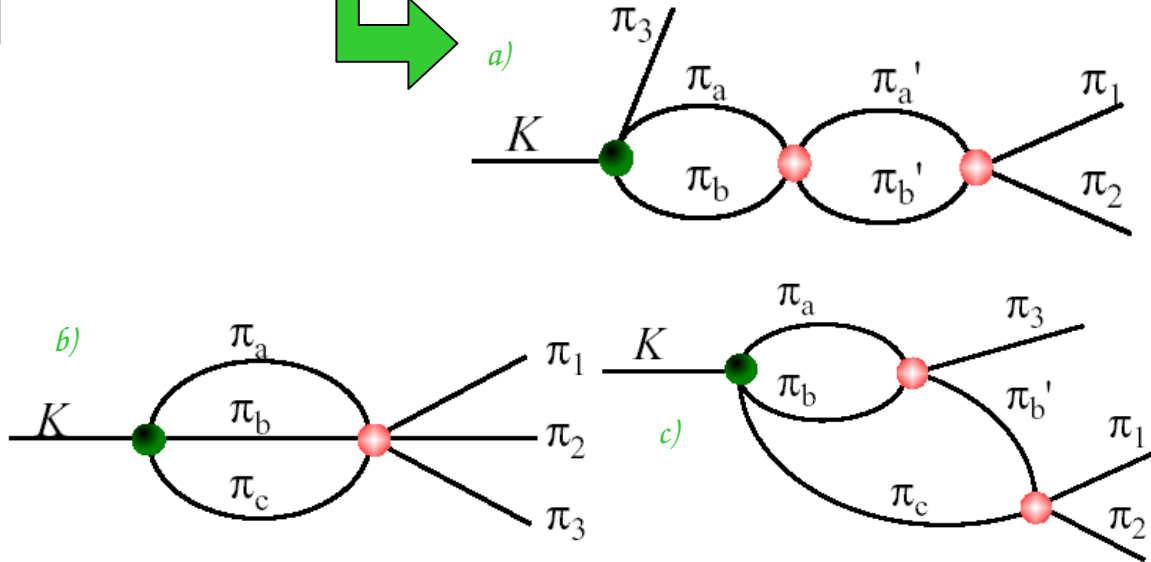
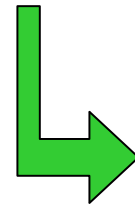
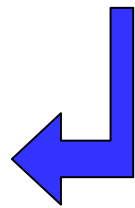
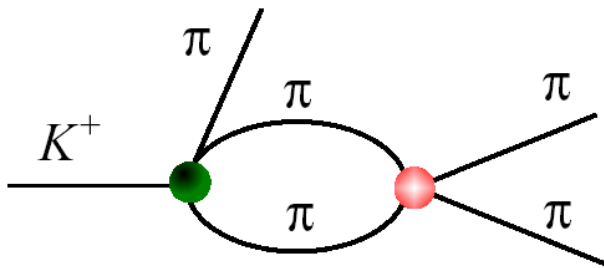


Cabibbo-Isidori model

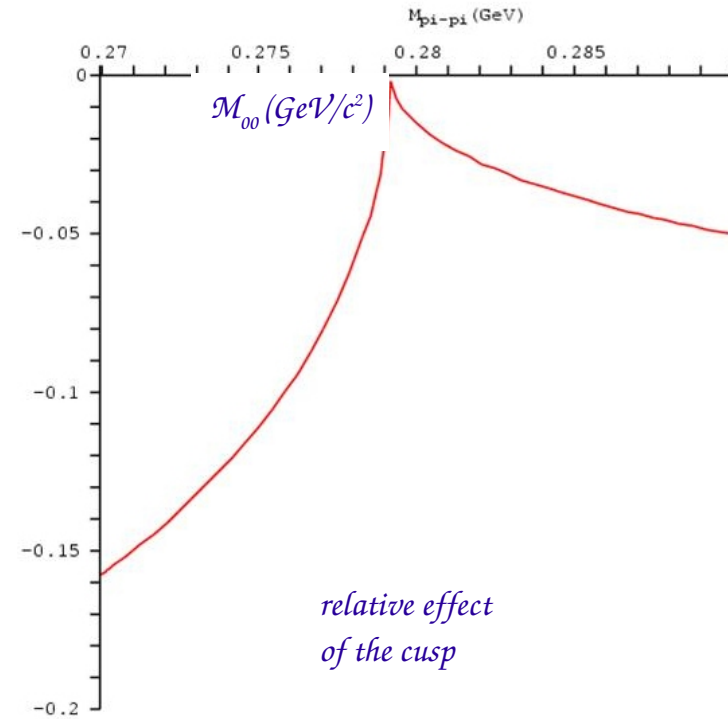
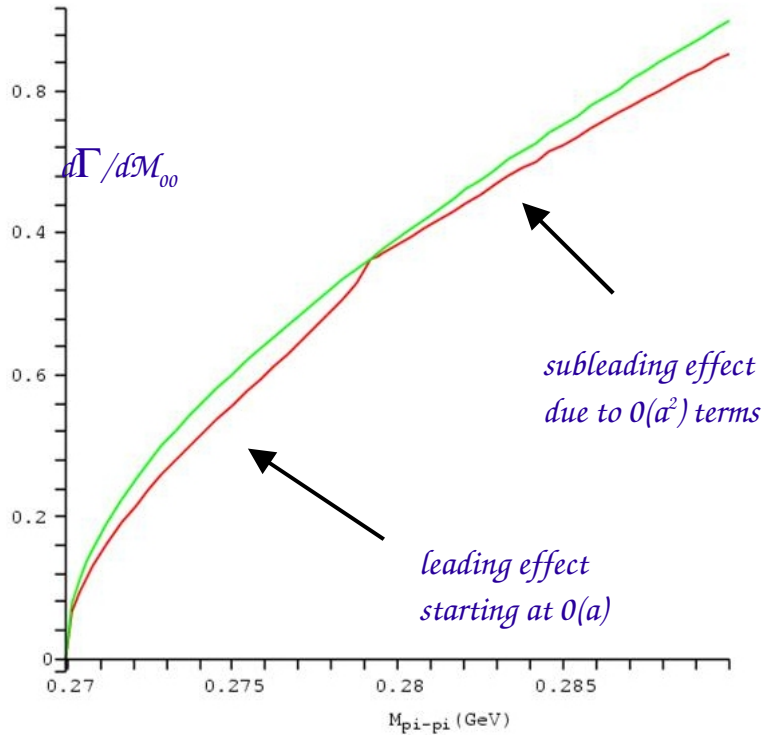
Computation of $O(a_i^2)$ corrections to $K \rightarrow 3\pi$ amplitudes

Including
One-loop and Two-loop
diagrams

- a) *Single channel $\pi\pi$ scattering*
- b) *Irreducible $3\pi \rightarrow 3\pi$*
- c) *Multi-channel $\pi\pi$ scattering*



Cabibbo-Isidori model (II)



$M_{00} (\text{GeV}/c^2)$

The development to the second order in powers of a_0 and a_2 produce a small square-root cusp behaviour also above the singularity

But $O(a_i^3)$ + radiative corrections can be computed. Theoretical uncertainty $\sim 1\%$

Electromagnetic effects

Radiative corrections

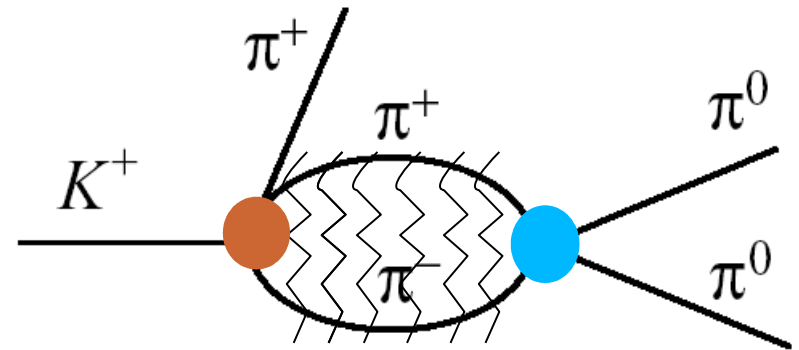
Corrections due to virtual and real photons are expected to be small (% level) except possibly next to the cusp (presence of bound state). Few bins around the cusp are excluded when fitting to extract (a_0 - a_2)

Bound state: pionium

A contribution from $\pi^+\pi^-$ bound state is expected (Silagadze, JETP Lett. 60 (1994) 689) with dominant decay mode $\pi^0\pi^0$ proportional to

$$\frac{\Gamma(K^+ \rightarrow \pi^+ + \text{pionium})}{\Gamma(K^+ \rightarrow \pi^+ \pi^0 \pi^0)} \approx 1.6 \cdot 10^{-5}$$

Expected contribution to the $(M_{00})^2$ bin centered at $(2m_+)^2$ is ~2.6%



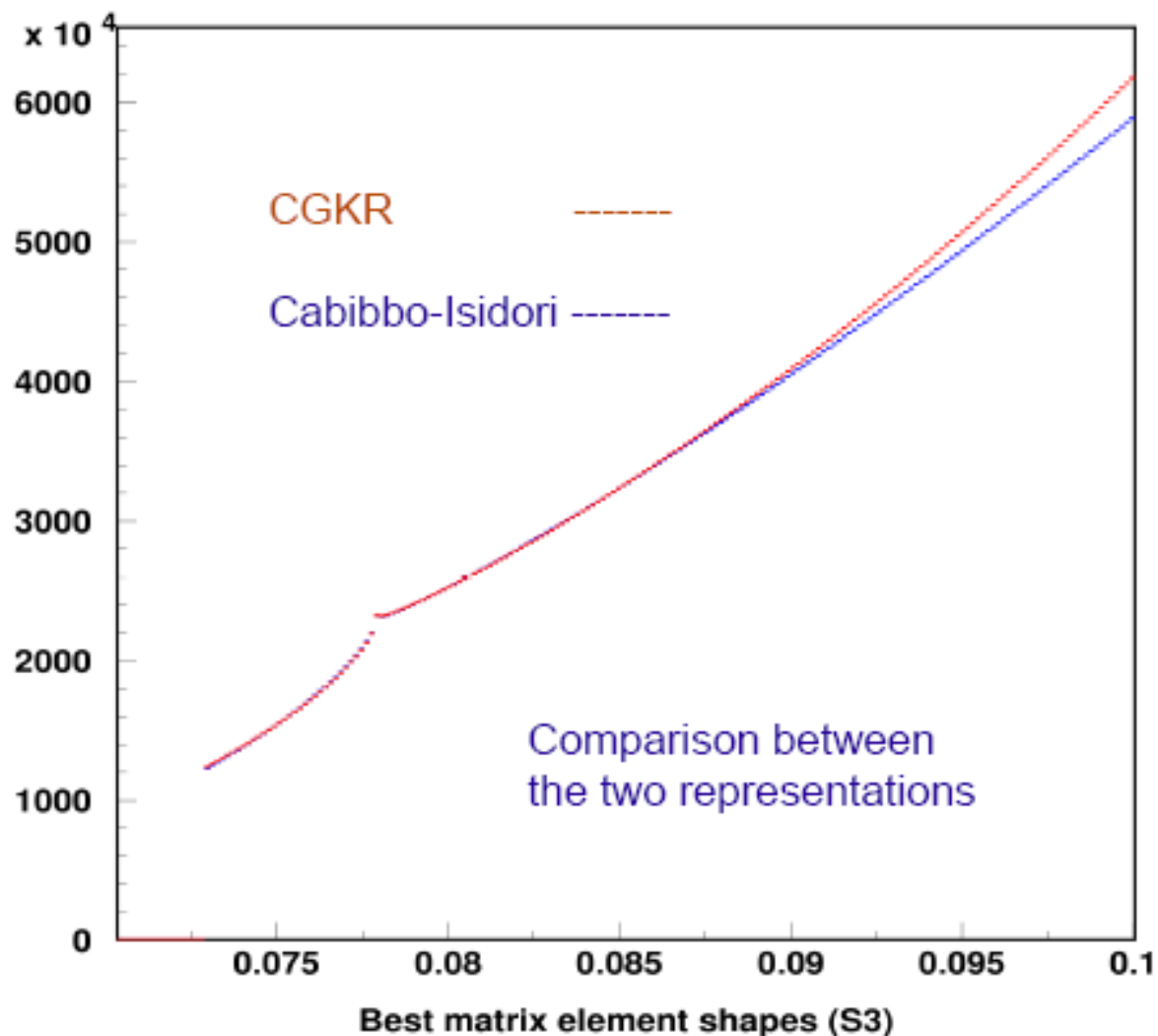
Effective field theory approach

Colangelo, Gasser, Kubis and Rusetsky hep-ph/0604084

Recently CGKR calculated the $K \rightarrow 3\pi$ amplitudes within a non-relativistic effective Lagrangian framework, by a double expansion in a (scattering lengths) and (kinetic energies) at order ε^2 , $a\varepsilon^3$, $a^2\varepsilon^2$.

CGKR representation is valid in the whole decay region.

Amplitudes agree with CI up to $a\varepsilon^3$, differ away from threshold at order a^2 .



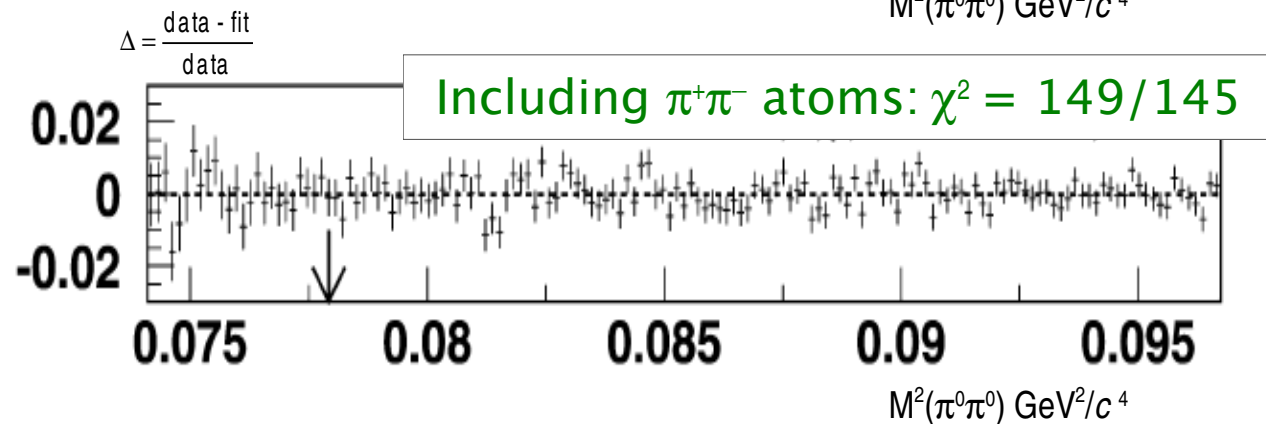
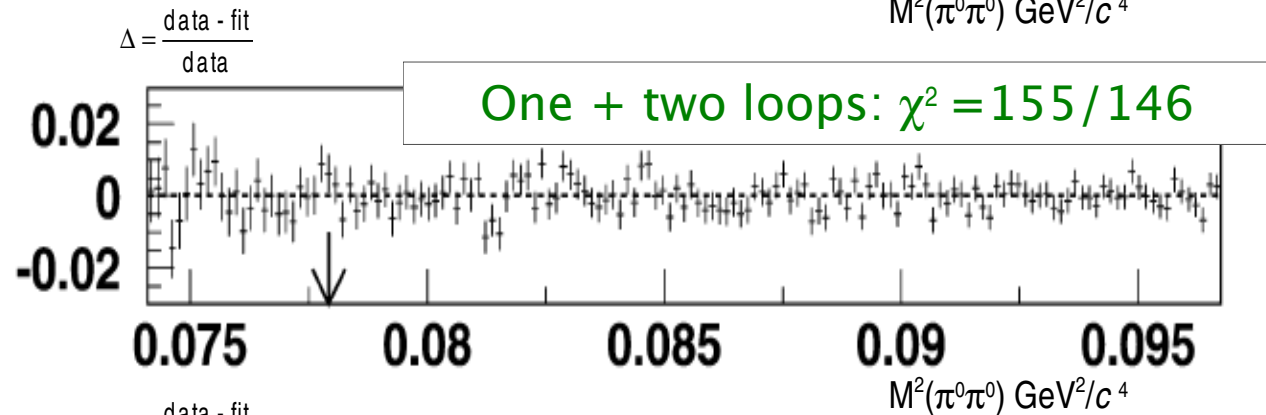
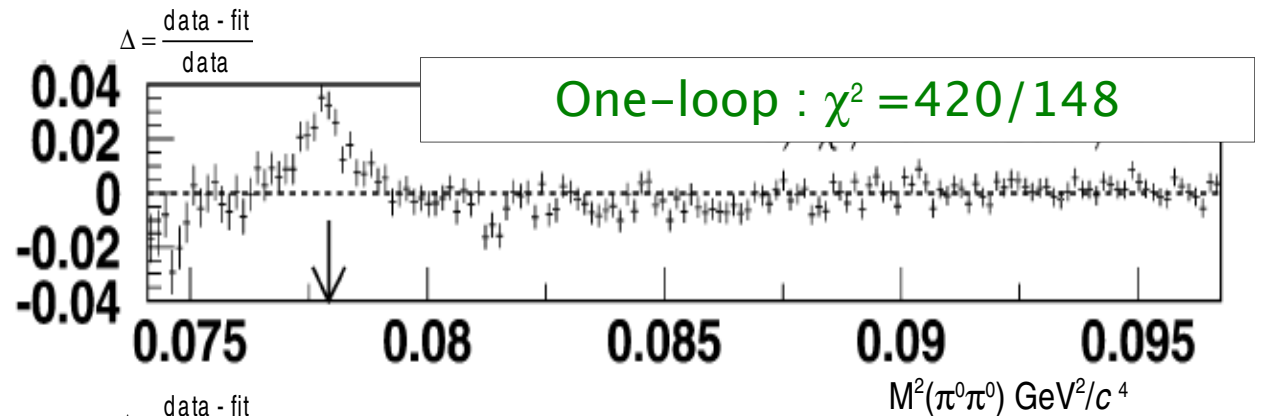
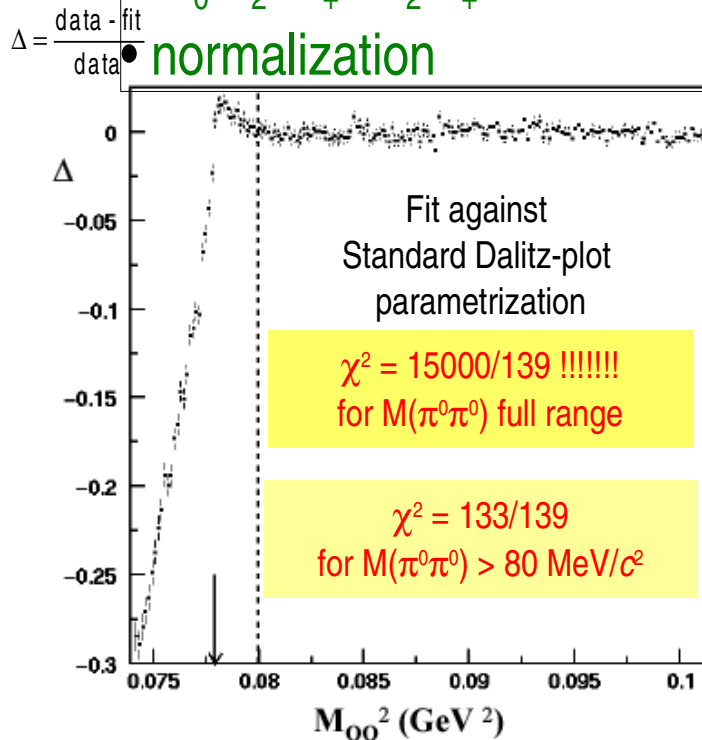
Fits to data

5 FIT PARAMETERS:

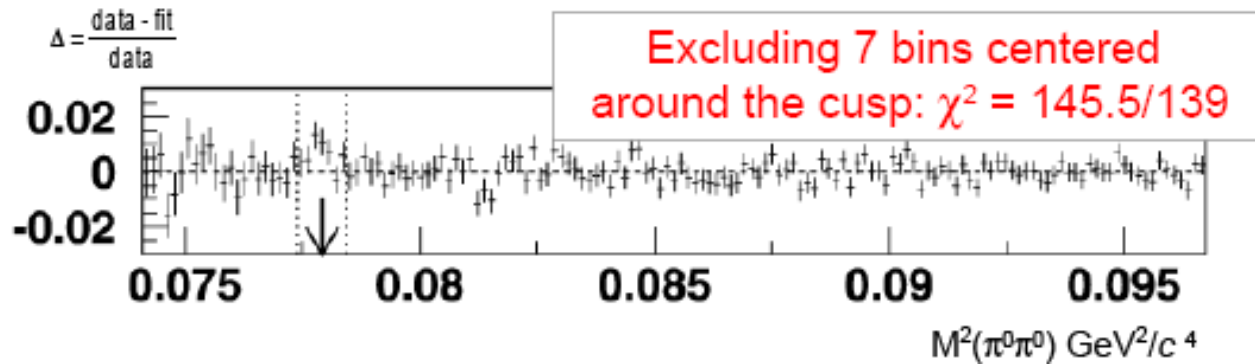
g, h: 1st 2nd order parameters linear and quadratic Dalitz plot param.s

• $(a_0 - a_2)m_+$, $a_2 m_+$

• normalization



Best fit parameters (I)



	<i>Stat.</i>	<i>Syst.</i>	<i>Ext. (*)</i>
$(a_0 - a_2)m_+$	0.268	± 0.010	$\pm 0.004 \pm 0.013$
$a_2 m_+$	-0.041	± 0.022	± 0.014
g	0.645	± 0.004	± 0.009
h	-0.047	± 0.012	± 0.011

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

By performing a 2D fit, also k extract:

$$k = \mathbf{0.0097} \pm \mathbf{0.0003}_{\text{stat}} \pm \mathbf{0.0008}_{\text{syst}}$$

$a_0 - a_2$ and a_0 don't move

g, h vary by 1-2%

(*) main component estimated by Cabibbo-Isidori as the result of neglecting higher order terms and radiative corrections in the rescattering model

Best fit parameters (II)

Performing the fit with constraints imposed by analyticity and chiral symmetry (after Colangelo et al. PRL 86 2001) leads to the following:

		Stat.	Syst.	Ext.
$(a_0 - a_2)m_+$	= 0.264	± 0.006	± 0.004	± 0.013
$a_0 m_+$	= 0.220	± 0.006	± 0.004	± 0.011

- This is in agreement with theory and other experiments
- This is in agreement with the NA48 result of a_0 from $K^\pm \rightarrow \pi^+ \pi^- e^\pm \nu$

Conclusion

- NA48/2 has studied many cases of Physics in the K charged system:
 - **direct CP violation in $K^{\pm} \rightarrow \pi\pi\pi$**
 - **leptonic and semileptonic K^{\pm} decays**
 - **Rare K^{\pm} decays**
- A new “cusp” structure has been found in $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$
 - **it has stimulated a theoretical effort**
 - **it provides a new precise method for measuring pion scattering lengths**
 - **results are in agreement with theory and experiments**