Rare and Radiative Kaon Decays from the NA48/2 Experiment

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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

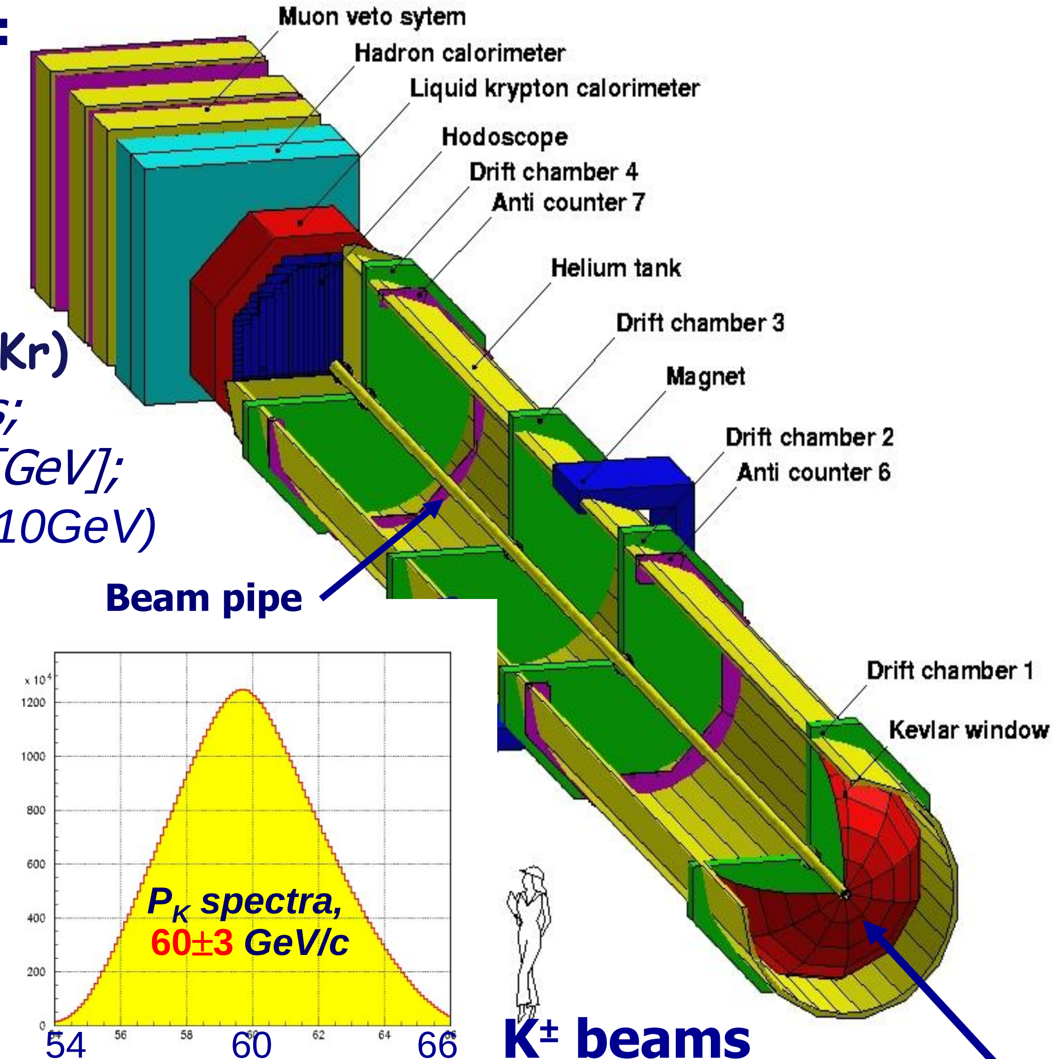
Content

- The NA48 detector
- $K^{\pm} \longrightarrow \pi^{+} \pi^{-} e^{\pm} \nu$ (Ke4)
- $K^{\pm} \longrightarrow \pi^{\pm} \pi^{0} \gamma$
- $K^{\pm} \longrightarrow \pi^{\pm} \gamma \gamma$
- Conclusions

The NA48 detector

Main detector components:

- **Magnetic spectrometer (4 DCHs):**
  4 views/DCH:
  $\Delta p/p = 1.0\% + 0.044\%*p$ [GeV/c].
- **Hodoscope**
  fast trigger (150ps).
- **Liquid Krypton EM calorimeter (LKr)**
  high granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$mm (1.5mm@10GeV)
- **Hadron calorimeter**
- **Muon veto counters**
- **Photon vetoes**



2-3M K/spill (π/K~10),
π decay products stay in pipe;
flux ratio: $K^+/K^- \approx 1.8$

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

1.13 M decays

The measurements of:

- **Form-Factors**
- **pion-pion scattering lengths:** a_0 *and* a_2

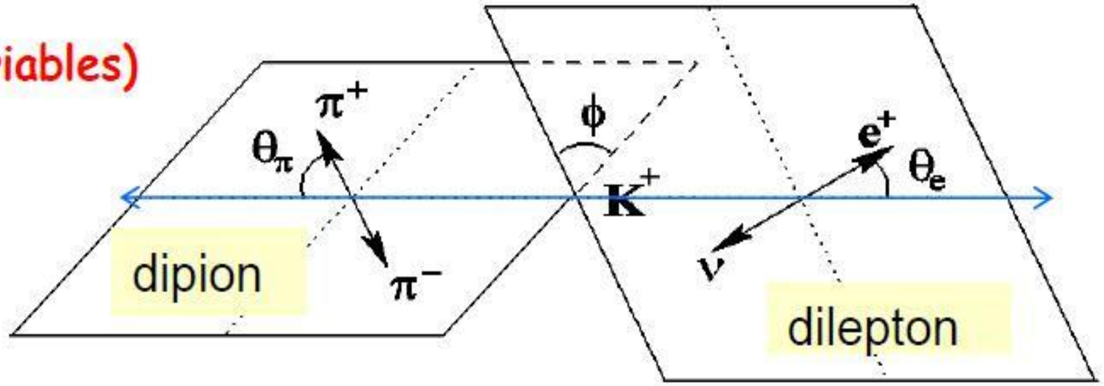
Ke4 decays : formalism

Five kinematic variables (Ca.Ma. variables)

(Cabibbo-Maksymowicz 1965)

S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$),

$\cos\theta_\pi$, $\cos\theta_e$ and ϕ.



Partial Wave expansion of the amplitude into s and p waves (Pais-Treiman 1968)
+ Watson theorem (T-invariance) for δ_ℓ^I

$$\delta_0^0 \equiv \delta_s \text{ and } \delta_1^1 \equiv \delta_p$$

F, G = 2 Axial Form Factors

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

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

H = 1 Vector Form Factor

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

F, G, H are complex and dimensionless

Map the distributions of the Ca.Ma. variables in the **five-dimensional space** with 4 Form factors and one phase shift , assuming identical phases for the p-wave Form Factors F_p, G_p, H_p:

The fit parameters are :

F_s F_p G_p H_p and $\delta = \delta_s - \delta_p$

(F_s , F_p , G_p , H_p are real)

Ke4 selection & background

Signal **($\pi^+ \pi^- e^\pm \nu$)** topology:

- 3 charged tracks, good vertex
- 2 opposite sign pions
- 1 electron ($E_{LKr}/P \sim 1$)

Main background sources:

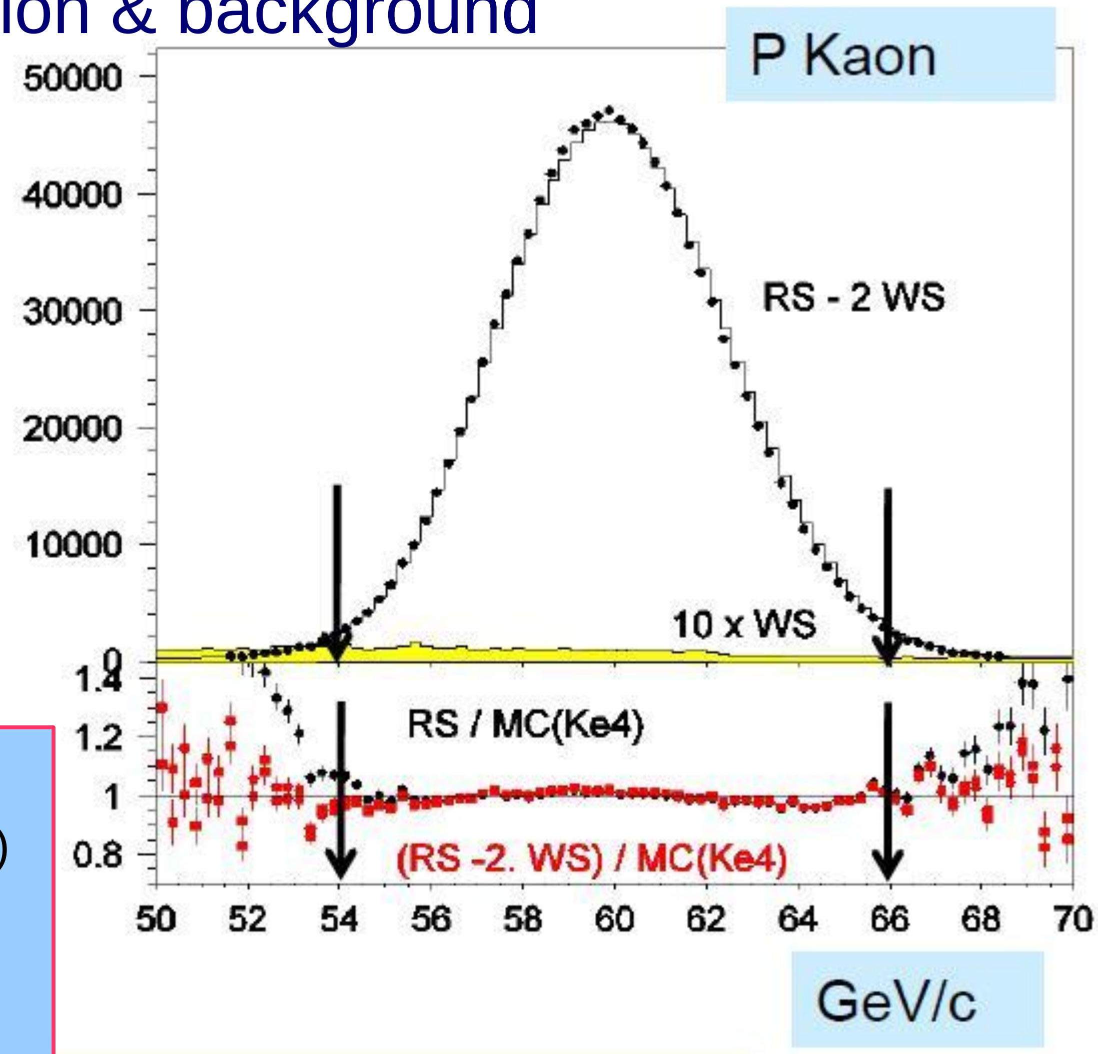
a) $K^+ \to [\pi^- \to \quad e^- \nu] \pi^+ \pi^+$

b) $K^+ \to [\pi^0 \to e^+ e^- (\gamma)] (\pi^0) \pi^+$

Background seen in «wrong sign» (WS) component (same sign pions)

a) 1(WS) **/ 2**(RS)

b) **1**(WS) **/ 1**(RS)



Total background is at the level of **2 x 0.3 %**

(estimated from WS events & checked by MC)

1.13 M of fully reconstructed **Ke4** *(2003+2004 data)*

Ke4 formfactor fit results

Series expansion with:

- $q^2 = S\pi/4m_\pi^2 - 1$
- $Se/4m_\pi^2$

$F_s^2 =$
$f_s^2(1+f'_s/f_s q^2+f''_s/f_s q^4+f'_e/f_s Se/4m_\pi^2)^2$

$G_p/f_s = g'_p/f_s + g'_p/f_s q^2$

Preliminary (2003+2004)

	value	stat	syst
f_s'/f_s	0.152	± 0.007	± 0.005
f_s''/f_s	-0.073	± 0.007	± 0.006
f_e'/f_s	0.068	± 0.006	± 0.007
f_p/f_s constant	-0.048	± 0.003	± 0.004
g_p/f_s	0.868	± 0.010	± 0.010
g_p'/f_s	0.089	± 0.017	± 0.013
h_p/f_s constant	-0.398	±0.015	± 0.008

From phase shifts to pion-pion scattering lengths: a_0 and a_2

- Roy equations (unitarity, analyticity & crossing symmetry)

  numerical solutions compute phases from data using a_0 and a_2, in *the isospin symmetry limit*

- Parameterization of Roy equations numerical solution:

$$\tan(\delta_l^I(s)) = \sigma_\pi\, q^2 (A_l^I + B_l^I q^2 + C_l^I q^4 + D_l^I q^6)(4m_\pi^2 - s_l^I)/(s - s_l^I)$$

δ_l^I –phases; A_l^I, B_l^I, C_l^I, D_l^I, s_l^I – coefficients, each is expressed as a 3-rd degree polynomial expansion of a_0 & a_2

ACGL PR 353(2001)207; DFGS EPJ C24(2002)469.

- Isospin corrections are evaluated as a correction to phase differences (*CGR EPJ C59(2009)777)*

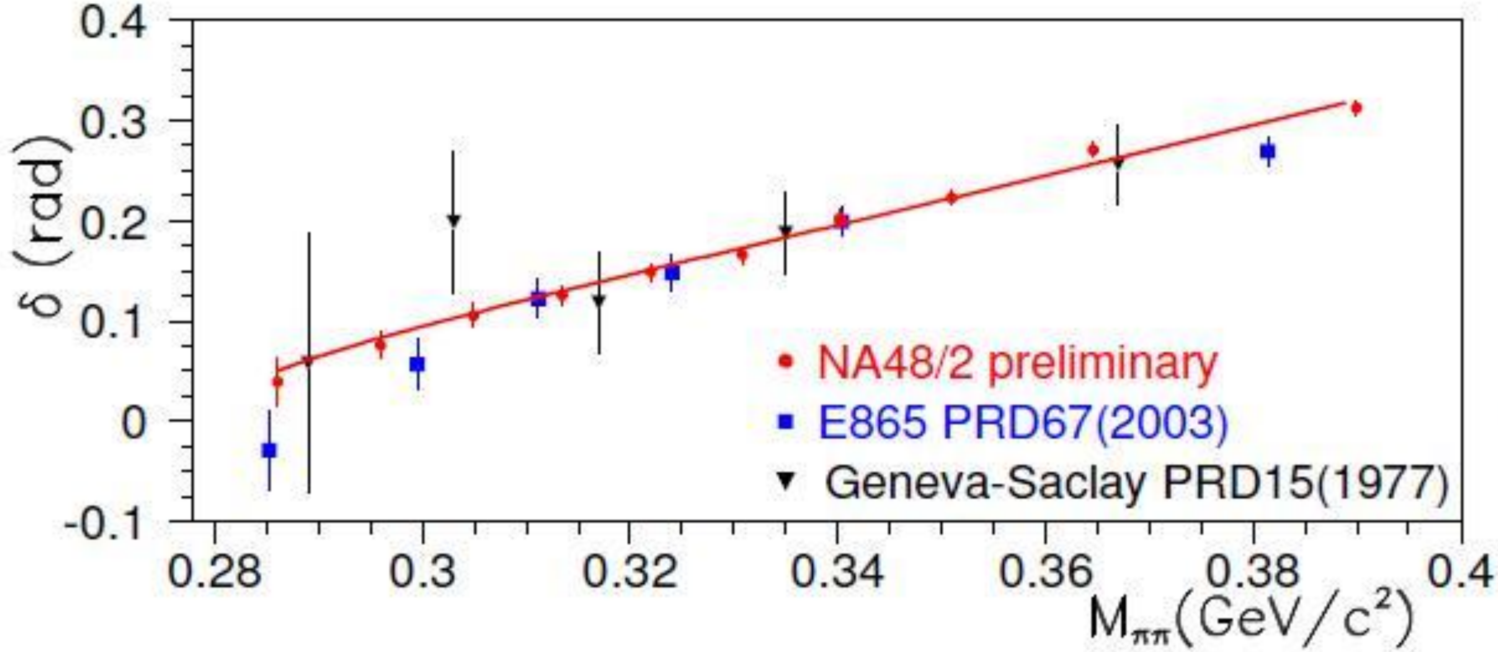
- Radiative effects are included in simulation

  — *Gamov factor ($\pi^+\pi^-$ Coloumb attraction) in matrix element & PHOTOS generator for real photons emission*

Ke4 phase shift measurement

isospin correction (10-15 mrad) to all published points — downward shift

errors — combined stat. and syst.; *fit to NA48/2 data alone*



Systematic errors:

-bin to bin correlated:

-*background level;*

-*isospin corrections*

- bin to bin uncorrelated:

-*fitting procedure;*

-*trigger efficiency;*

-*acceptance control;*

background shape;

electron identification;

radiative correction

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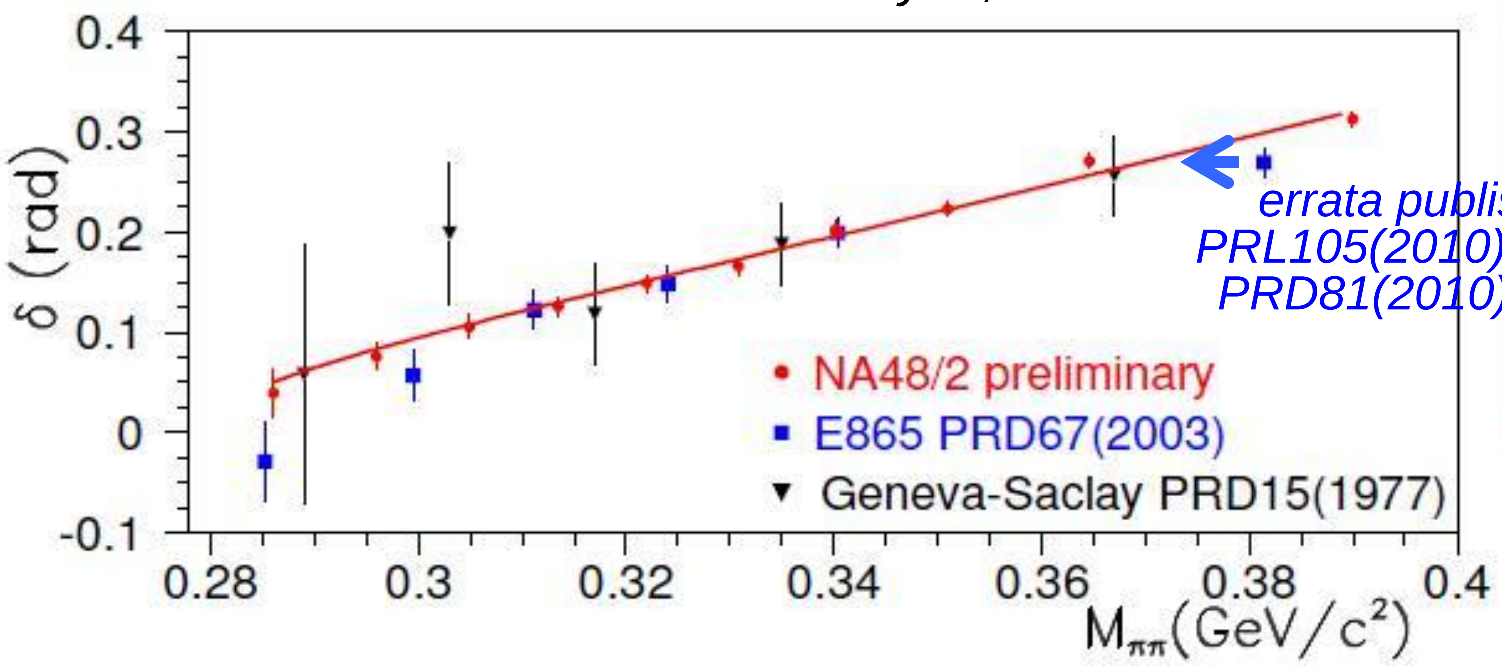

errata published in PRL105(2010)019901 PRD81(2010)119903

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radiative correction

Scattering lengths preliminary result

- *2 parameter fit (correlation 0.967)*

a_0 = **0.2220** ± **0.0128**(stat) ± **0.0050**(syst)± **0.0037**(th*)

a_2 = **- 0.0432** ± **0.0086**(stat) ± **0.0034**(syst)± **0.0028**(th*)

- *1 parameter fit using ChPT link between a_0 and a_2*

a_0 = **0.2206** ± **0.0049**(stat) ± **0.0018**(syst)± **0.0064**(th*)

** Theoretical errors evaluated from isospin corrections & inputs to Roy equations numerical solution*

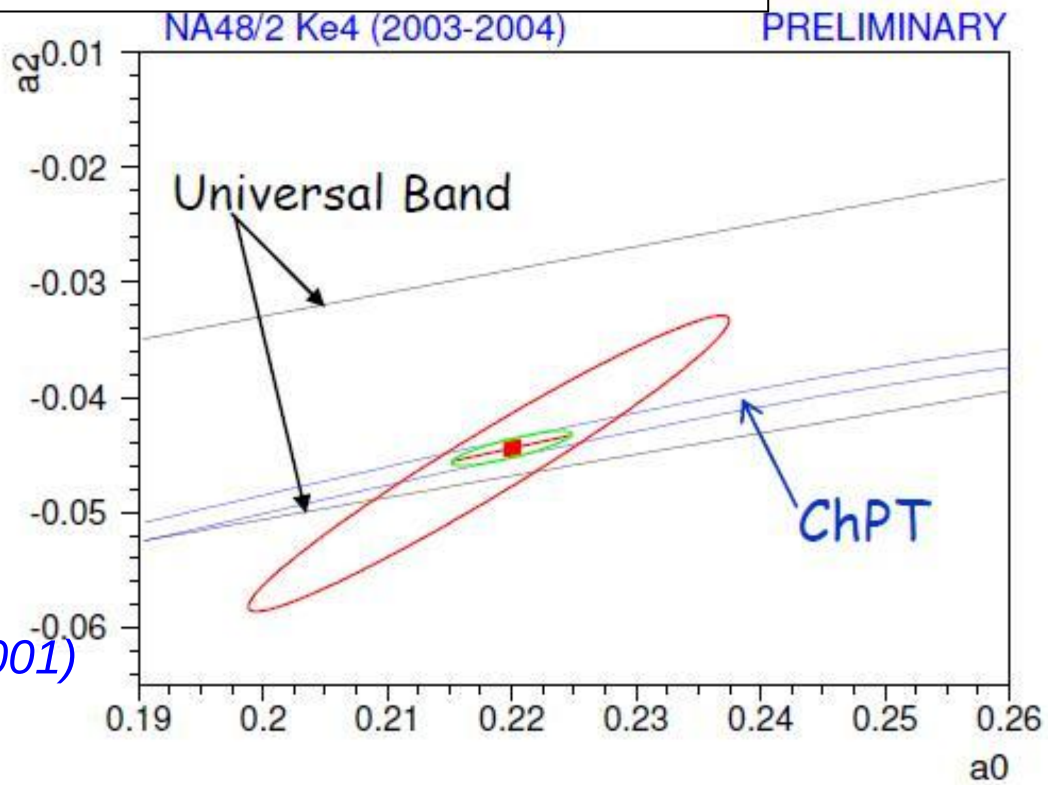
CGR EPJ C59 (2009) 777

Perfect agreement with theory prediction:

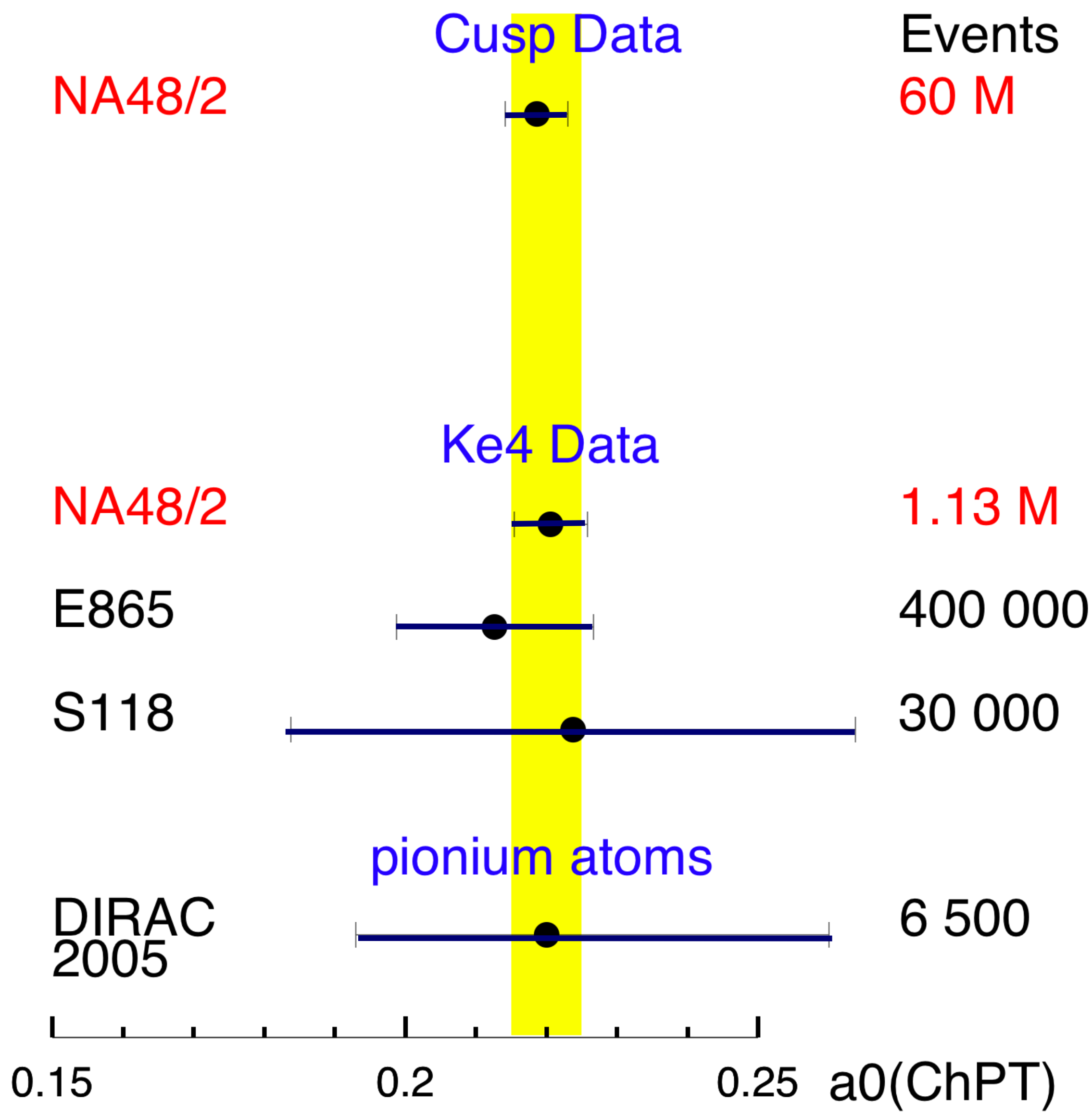
a_0 = 0.220 ± 0.005

a_2 = - 0.0444 ± 0.0010

CGL NP B603(2001), PRL 86 (2001)



Comparison with other measurements of a_0



ChPT prediction a0 = 0.220 +/- 0.005

EPJ C68 (2010)75

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

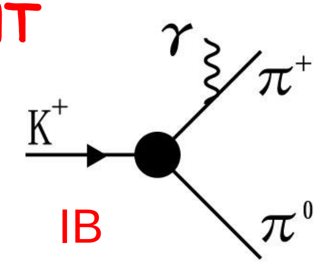
The measurements of:

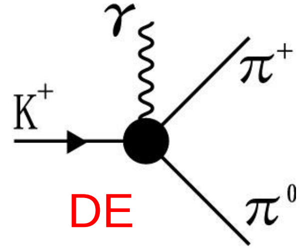
- DE & INT terms in decay **600k decays**
- CPV test **1M decays**

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

3 terms: IB, DE & INT

contributing to the decay could be disentangled in W spectra (integrated over T*π)





$$W^2 = \frac{(P_\pi^* \cdot P_\gamma^*)(P_K^* \cdot P_\gamma^*)}{(m_K m_\pi)^2}$$

$$\frac{\partial \Gamma^{\pm}}{\partial W} = \underbrace{\frac{\partial \Gamma^{\pm}_{IB}}{\partial W}}_{IB}\Big[1 + \underbrace{2\cos(\pm\phi + \delta_1^1 - \delta_0^2) m_\pi^2 m_K^2 |X_E| W^2}_{INT} + \underbrace{m_\pi^4 m_K^4 (|X_E|^2 + |X_M|^2) W^4}_{DE}\Big]$$

IB can be calculated as BR($\pi^+\pi^0$) + QED corrections

DE O(p^4) contribution has 2 terms:

- *X_M: magnetic part 2 contributions by chiral anomaly*
- *Reducible: calculated using WZW functional (X_M~270 GeV^{-4})*
- *Direct: cannot be calculated in model independent way*
- *X_E : no prediction in ChPT depends on unknown constants*

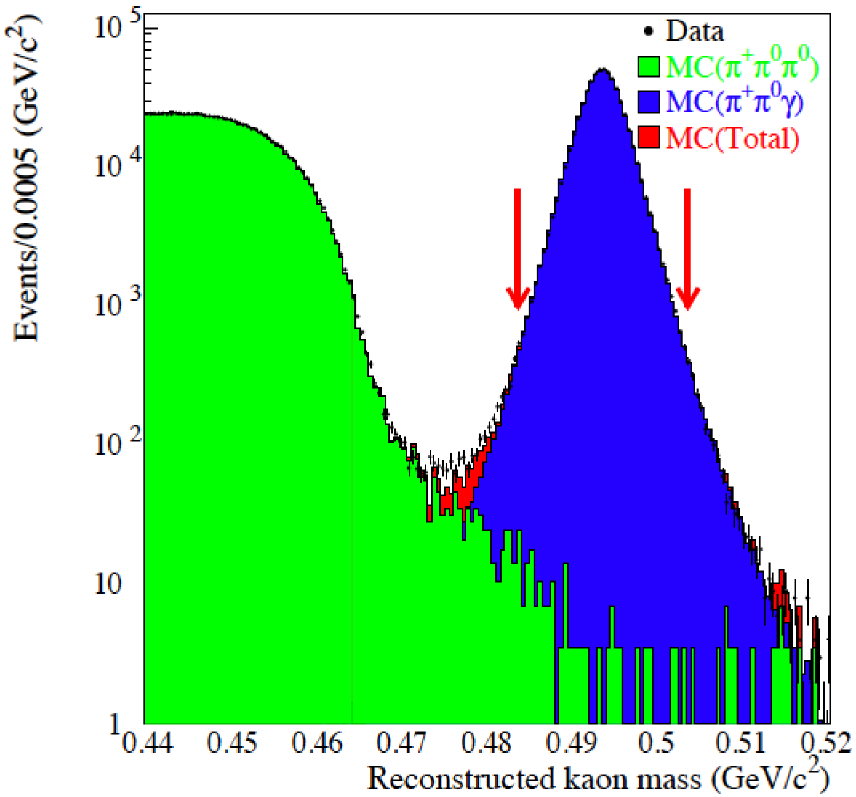
INT arises form interference of IB and X_E DE

- *no model independent prediction available in ChPT*

$K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \gamma$: event selection

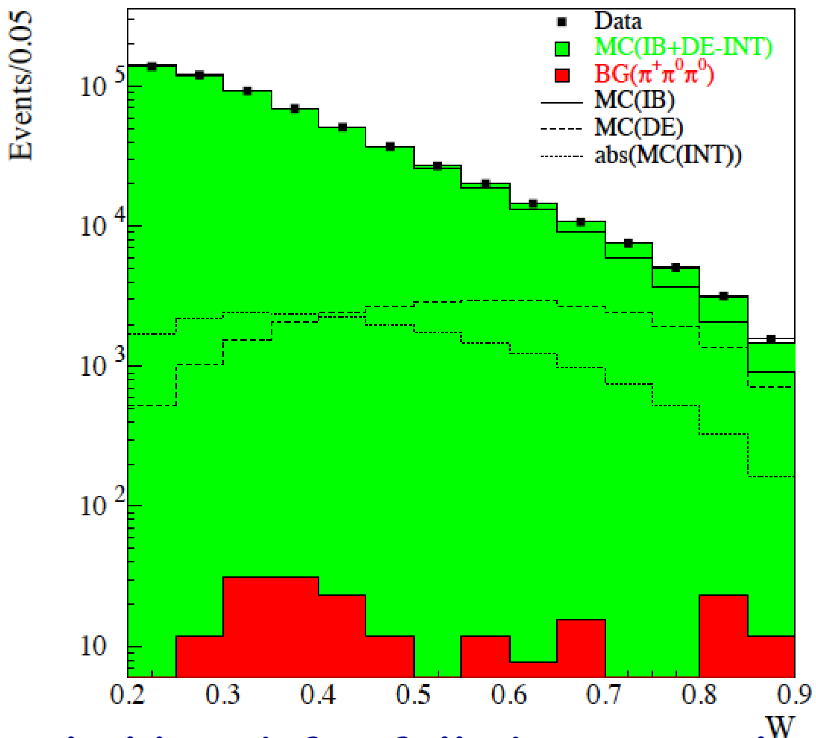
- At least 1 track + 3 clusters in LKr;
- Acceptance and BG-rejection cuts (M_K, COG etc...);
- T^*_{π} < 80 MeV.

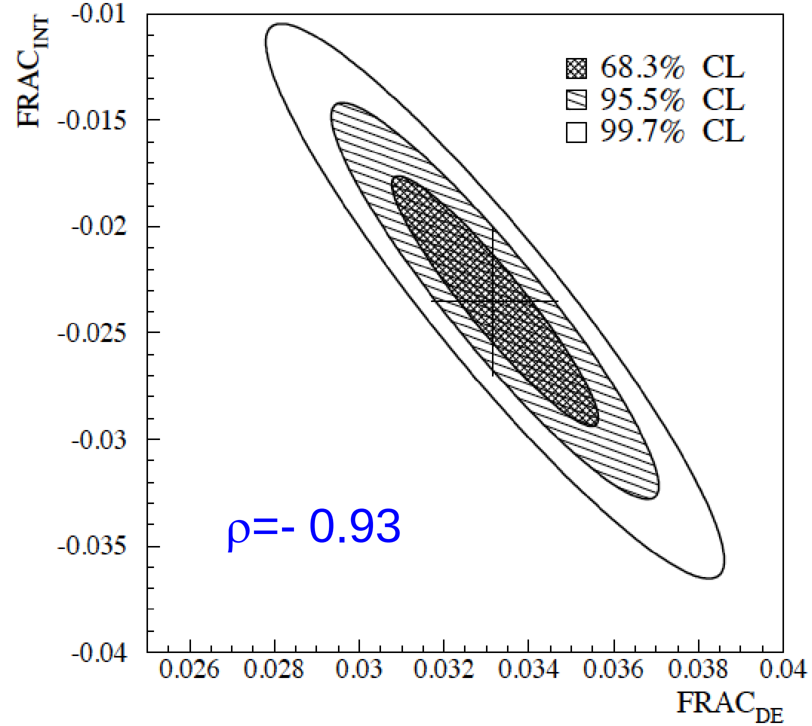
BG channel	BG mechanism
$K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$	missing or overlapping γ
$K^{\pm} \rightarrow \pi^{\pm} \pi^{0}$	γ from accidental or hadronic shower
$K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu$	e mistagged as π, accidental γ
$K^{\pm} \rightarrow \pi^{0} \mu^{\pm} \nu$	μ mistagged as π, accidental γ



Residual BG < 1%

Extended maximum likelihood fit





Likelihood fit full data sample

Frac(**DE**) = $(3.32 \pm 0.15_{stat} \pm 0.14_{syst}) \cdot 10^{-2}$

Frac(**INT**) = $(-2.35 \pm 0.35_{stat} \pm 0.39_{syst}) \cdot 10^{-2}$

First evidense of nonzero **INT** contribution

(systematics dominated by trigger efficiency)

PDG *($55 < T^*_\pi < 90$ MeV)*:

Br = $(2.75 \pm 0.15) \cdot 10^{-4}$, ***[DE / Br = $(1.56 \pm 0.27) \cdot 10^{-2}$];*** **INT** – no data

$K^{\pm} \rightarrow \pi^{\pm} \pi^0 \gamma$ CPV tests

1) Difference in K+ and K- decay rates:

$$A_N = (N^+ - RN^-)/(N^+ + RN^-) ,$$

where R(K⁺/K⁻) ratio = 1.7998 ± 0.0004 from K3π

Result :

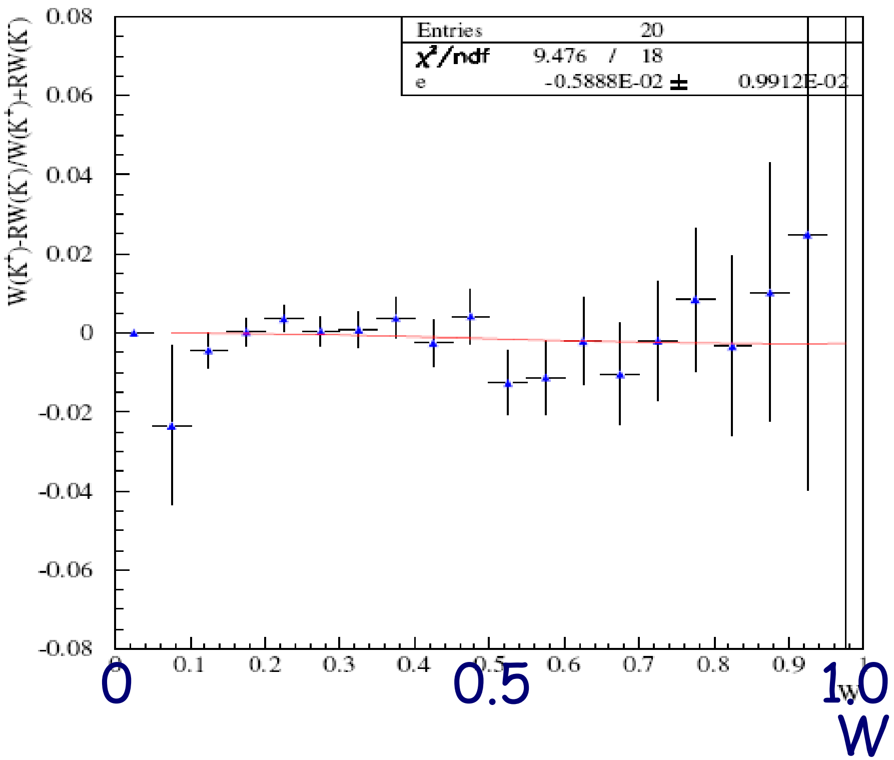
$$A_N = -0.0 \pm 0.001_{stat} \pm 0.0006_{syst}$$

systematics from trigger and kaon momentum distributions

2) Difference in W spectra shapes:

$$dA_W/dW = (\Gamma^+ - \Gamma^-)/(\Gamma^+ + \Gamma^-) = eW^2/(1+aW^2+bW^4),$$

e is a free parameter



Result (integrating):

$$(I_{INT}/I_{IB})A_W = -0.0006 \pm 0.0010_{stat}$$

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

1164 decays

The BR measurement

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

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

$$y = \frac{P\cdot(q1-q2)}{M^2_K} \qquad z = \frac{(q1+q2)^2}{M^2_K} = \frac{M^2_{\gamma\gamma}}{M^2_K}$$

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

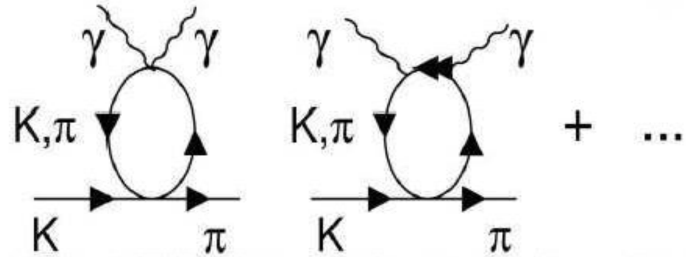
A,B,C,D depend on Z and on ChPT $\hat{c}$ parameter

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

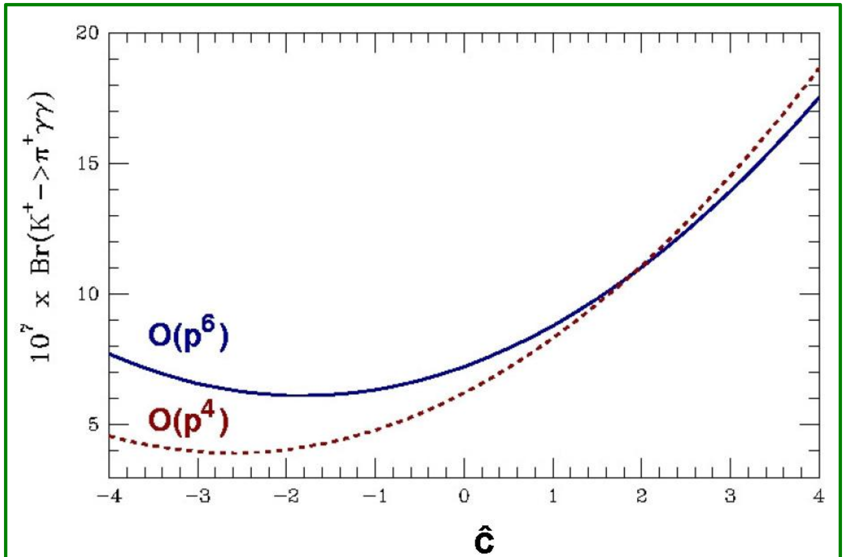
ChPT contributions to the amplitude:

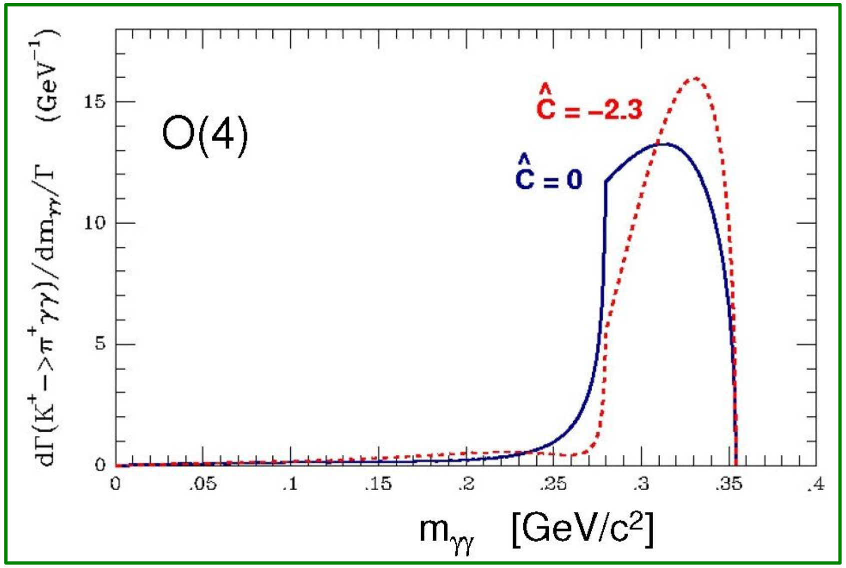
$O(p^4)$: $A(z,\hat{c})$ responsible for cusp at $m_{\gamma\gamma}=2m_\pi$
$C\neq0$ for WZW anomaly (poles & tadpoles), B=D=0

[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 track and 2 LKr clusters
- COG, CDA vertex cuts
- $M_{\gamma\gamma}$ in kinematical limits

1164 events selected

20% of full data sample

- **40 times** more than the world sample
- **3% Bkg** mainly from $\pi^{\pm}\pi^{0}\gamma$

[Br = $(2.75 \pm 0.15)\cdot 10^{-4}$]

- Normalization — **K2π (~6 M)**
- Main systematics : **acceptance**

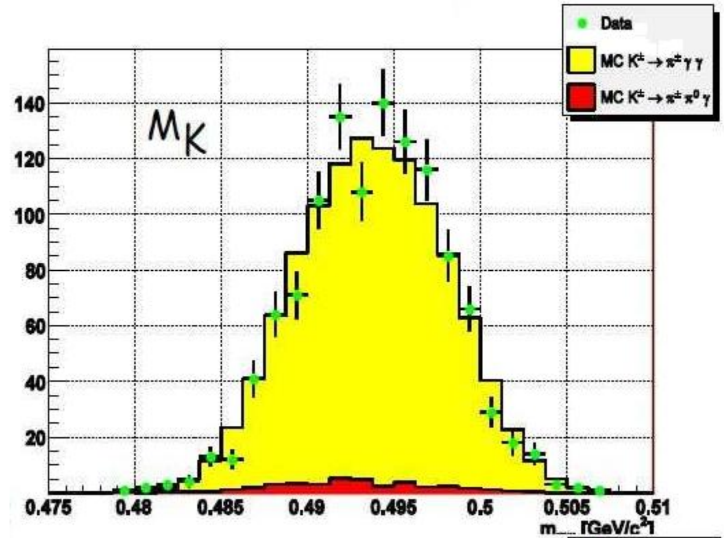
Preliminary:

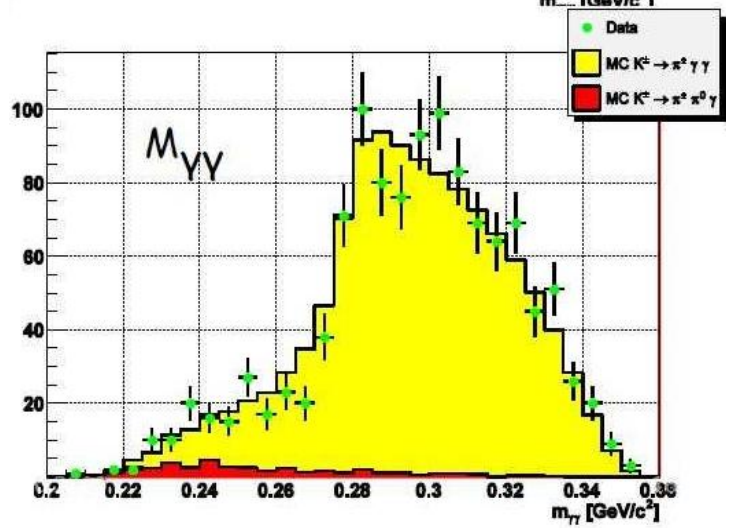
Br = $(1.07 \pm 0.04_{stat} \pm 0.08_{syst})\ 10^{-6}$

Last measurement: BNL E787(1991):

__31__ candidates, __5__ BG events:

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



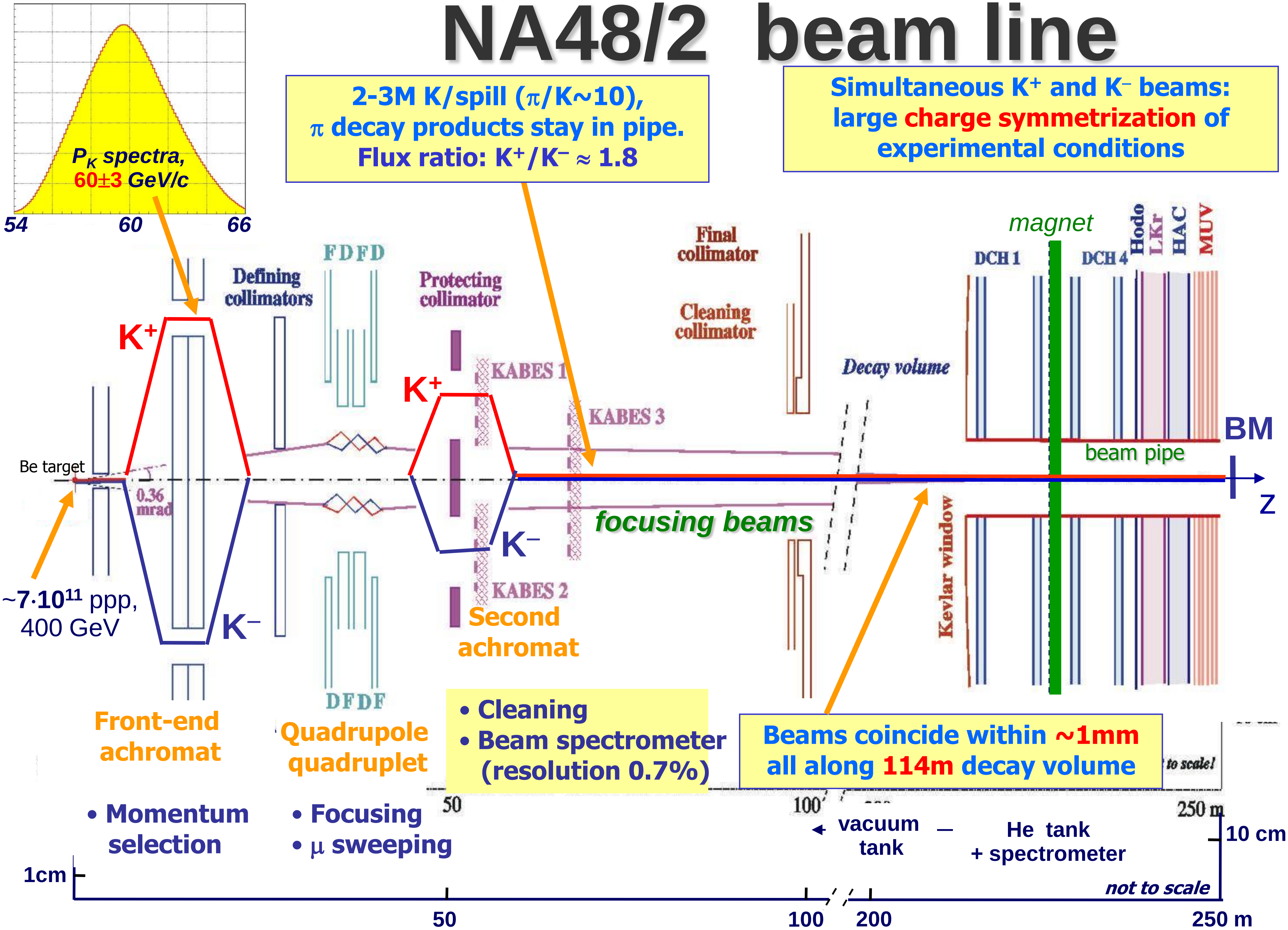


Conclusions

- an accurate study of low energy QCD based on highest statistics of Ke4 is achieved in the NA48/2 experiment:
  - 5 FF's are measured with high precision
  - the measured pi-pi scattering lengths are in very good agreement with the "cusp result" & ChPT prediction
- the first measurement of INT term in $\mathbf{K}^{\pm} \to \pi^{\pm} \pi^{0} \gamma$ decay & CPV test are performed
- the Br($\mathbf{K}^{\pm} \to \pi^{\pm} \gamma \gamma$) is measured with the highest precision

Spare

NA48/2 beam line



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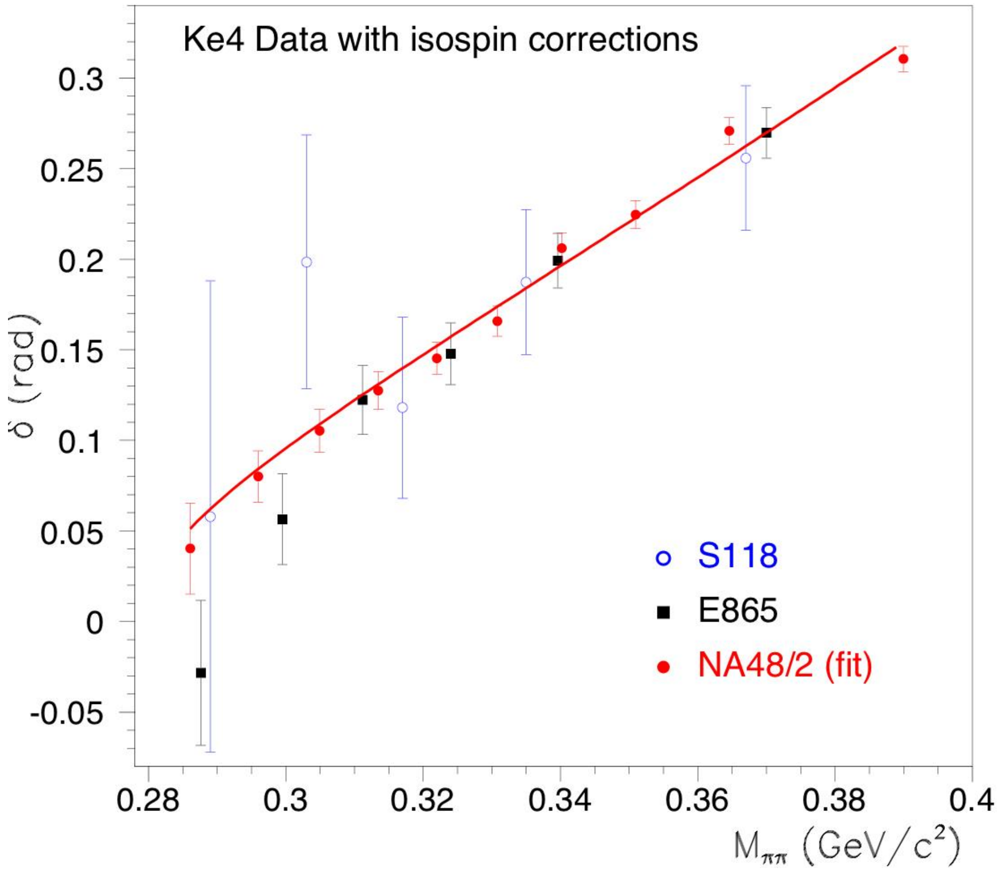
isospin correction (10-15 mrad) to all points are applied - downward shift

errors — combined stat. and syst.;   fit to NA48/2 data alone



Systematic errors:

- bin to bin uncorrelated:

fitting procedure
trigger efficiency
acceptance control
background shape
electron identification
radiative correction

-**bin to bin correlated:**

background level
isospin corrections

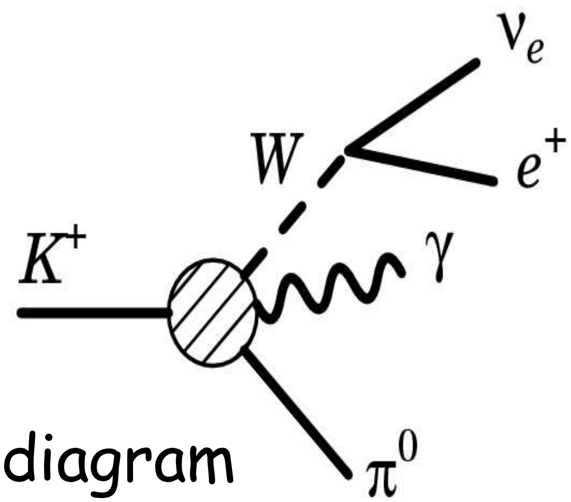
$$K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu \gamma$$

260k decays

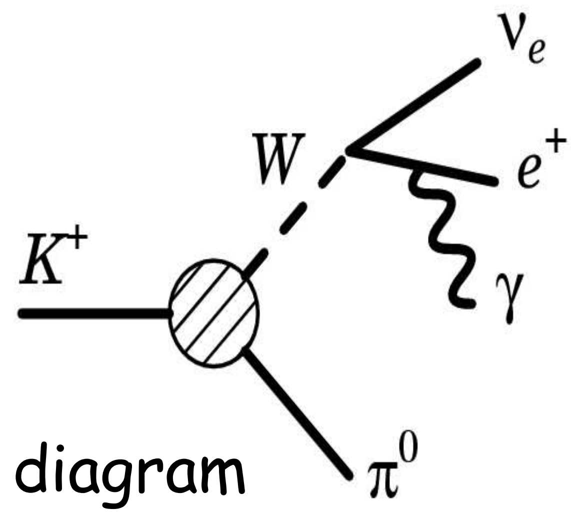
The measurements of:

- BR
- CPV test

Ke3γ: Theory (ChPT)



DE diagram



IB diagram

BR(Ke3γ/Ke3)=(6.40±0.08)·10^{-3} (E* > 30 MeV, θeγ* > 20°)

Computed in *Eur. Phys. Jour. C* 50 (2007)

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_\pi} \times \vec{p_e})}{{M_K}^3}$$

$N_{+(-)}$= number of events with positive (negative) ξ

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

(A_ξ^++A_ξ^-) directly probes CPV