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# Study of the Rare Decay $K^\pm \rightarrow \pi^\pm \gamma\gamma$ by the NA62 Experiment

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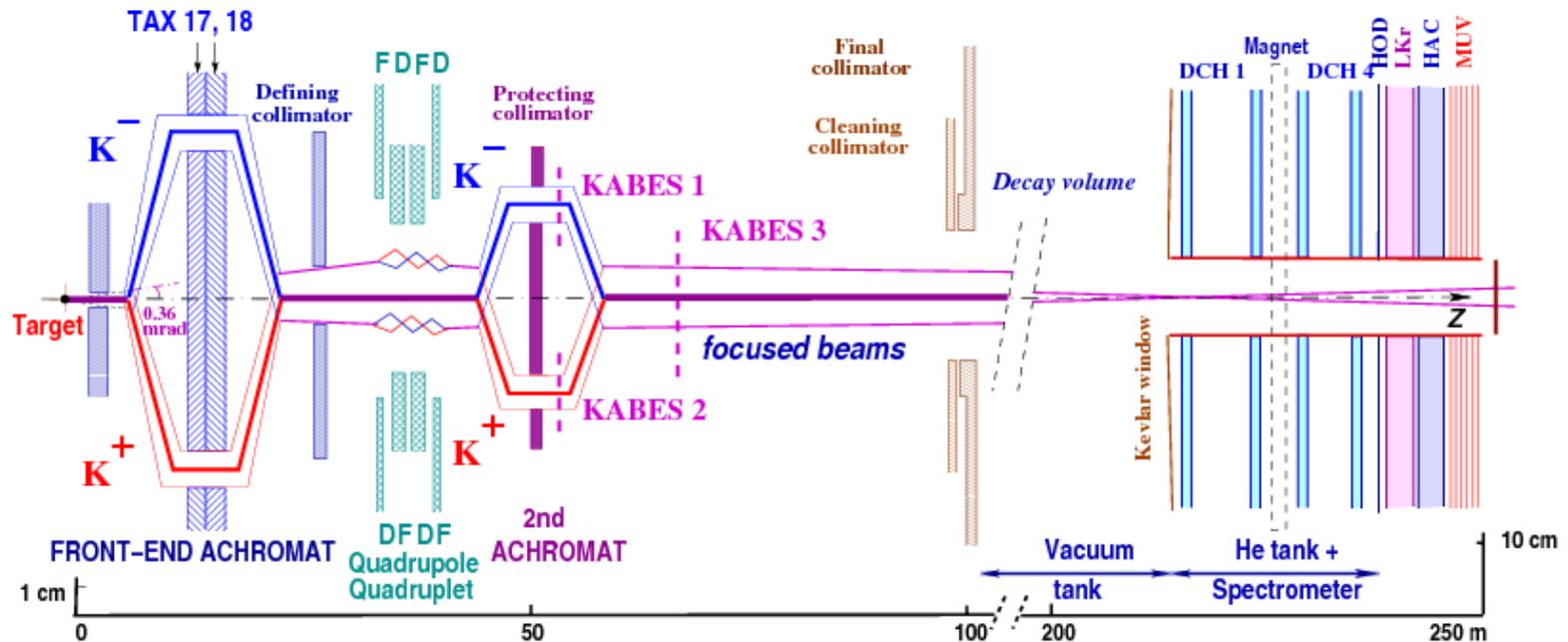
On behalf of the  collaboration



XXII International Workshop on Deep-Inelastic Scattering and Related Subjects  
28 April - 2 May 2014, Warsaw, Poland



## Beam line used by NA48/2 (2003-2004 runs) and NA62 $R_K$ -phase (2007 run)



- Fixed target experiment with 400 GeV/c proton beam from CERN-SPS
- NA62 (NA48/2) secondary beam:
  - Hadrons with central momentum 74 (60) GeV/c and spread of 1.4 (3) GeV/c
  - $\sim 6\%$   $K^\pm$  component
  - $K^+/K^- \sim 2$  (1.8)
  - $K^+$  and  $K^-$  delivered alternatively or simultaneously
  - $\sim 100 \text{ m}$  long decay region
  - Fraction of  $K^\pm$  decaying in the vacuum tank  $\sim 18\%$  (22%)

## ■ Magnetic spectrometer:

- 4 drift chambers and a dipole magnet between 2 and 3
- Resolution in 2003-2004:  
 $\sigma_p/p = (1.0 \oplus 0.044 \cdot p)\%$  ( $p$  in GeV/c)
- Resolution in 2007:  
 $\sigma_p/p = (0.48 \oplus 0.009 \cdot p)\%$

## ■ Charged hodoscope (CHOD):

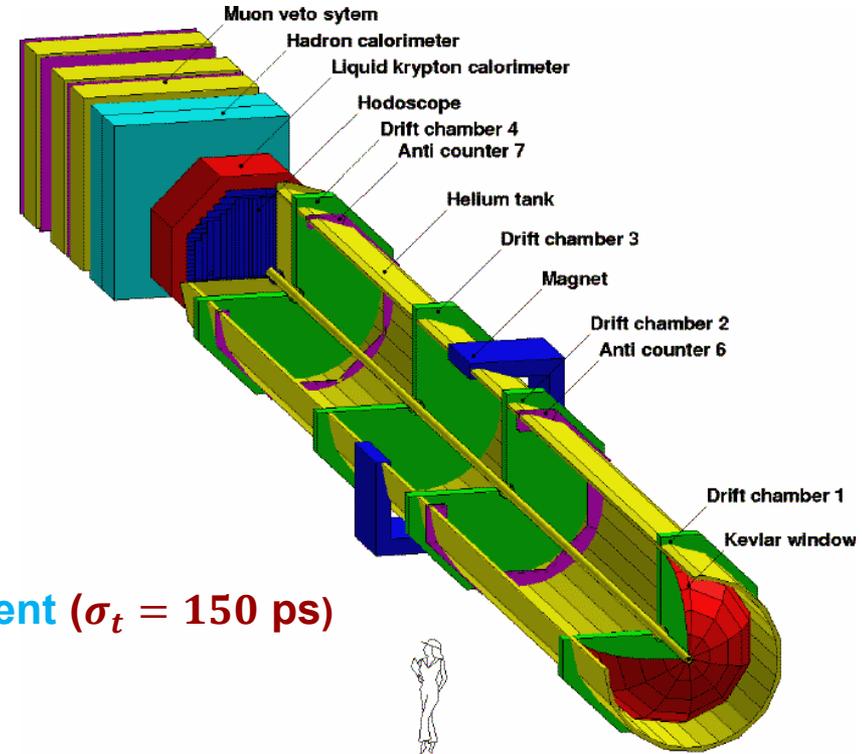
- 2 planes of plastic scintillator strips
- Fast trigger and precise time measurement ( $\sigma_t = 150$  ps)

## ■ LKr electromagnetic calorimeter:

- $\sim 27X_0$  deep
- $\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$  ( $E$  in GeV)
- $\sigma_x = \sigma_y = (4.2/\sqrt{E} \oplus 0.6)$  mm for  $E = 10$  GeV

## ■ Neutral hodoscope (NHOD):

- Inside the LKr at  $\sim 9.5X_0$
- Trigger signals



- **Model-independent measurement of  $B_{MI}(K_{\pi\gamma\gamma})$  in the kinematic range  $z > 2$**
- **$B_{ChPT}(K_{\pi\gamma\gamma})$  in the full-kinematic range assuming ChPT description**
- **In the ChPT framework the differential decay rate is:**

$$\frac{\partial \Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9 \pi^3} \left[ z^2 (|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2) + \left( y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 |B(z)|^2 \right]$$

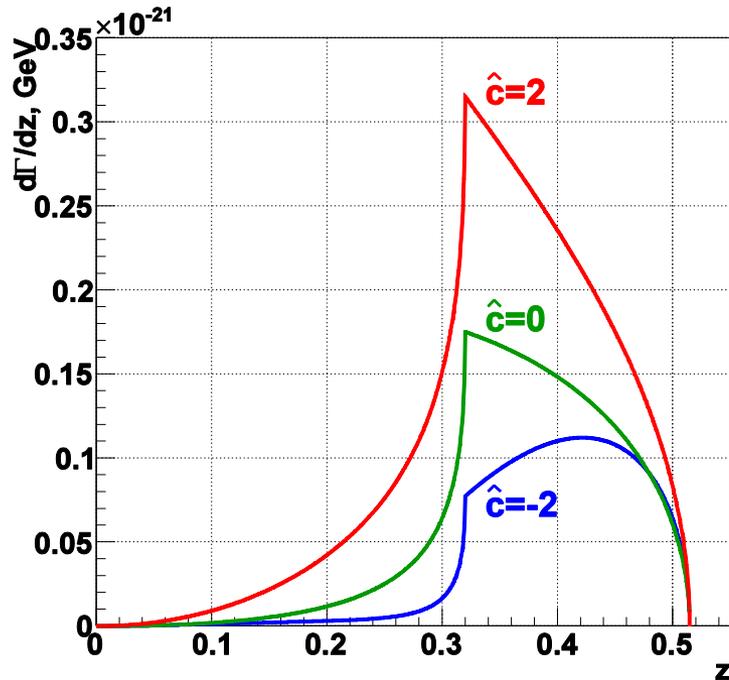
$$y = \frac{p(q_1 - q_2)}{m_K^2}, \quad z = \frac{(q_1 + q_2)^2}{m_K^2} = \left( \frac{m_{\gamma\gamma}}{m_K} \right)^2$$

- **A and B are the loop amplitudes, C is the pole amplitude**
- **A – leading  $O(p^4)$  order contribution responsible for a cusp at  $m_{\gamma\gamma} = m_{2\pi}$**
- **B – next-to-leading  $O(p^6)$  order, dominant at low  $z$**
- **Rate and spectrum depend on the unknown  $O(1)$  parameter  $\hat{c}$**
- **Amplitudes involve the external constant  $G_8$  – common to both  $O(p^4)$  and  $O(p^6)$**
- **$O(p^6)$  framework involve 10 additional parameters: 7 for the  $K_{3\pi}$  decay amplitude and 3 polynomial contributions  $\eta_i (i=1,2,3)$**

## $d\Gamma/dz$ distribution in the $O(p^4)$ and $O(p^6)$ models for different values of $\hat{c}$

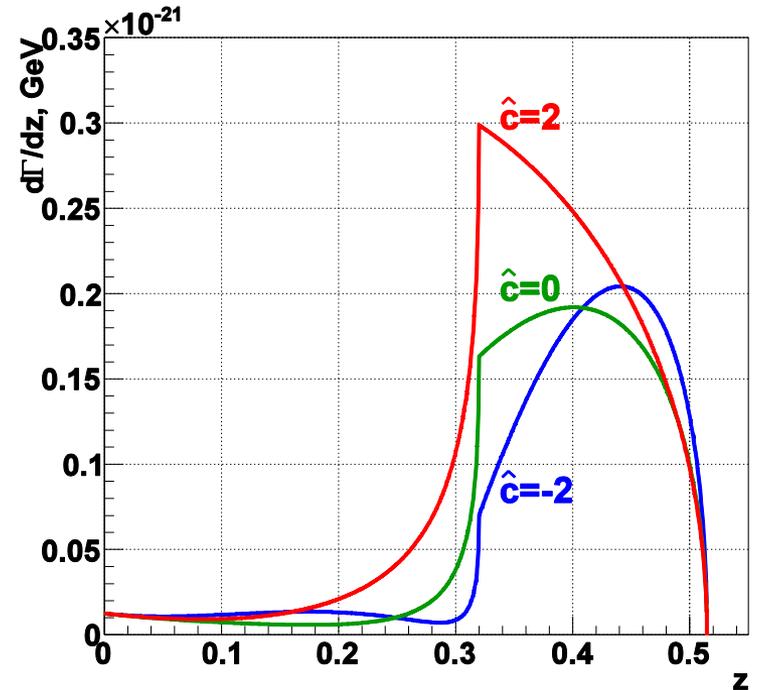
$O(p^4)$  loop

[Ecker, Pich, de Rafael, NPB303 (1988) 665]

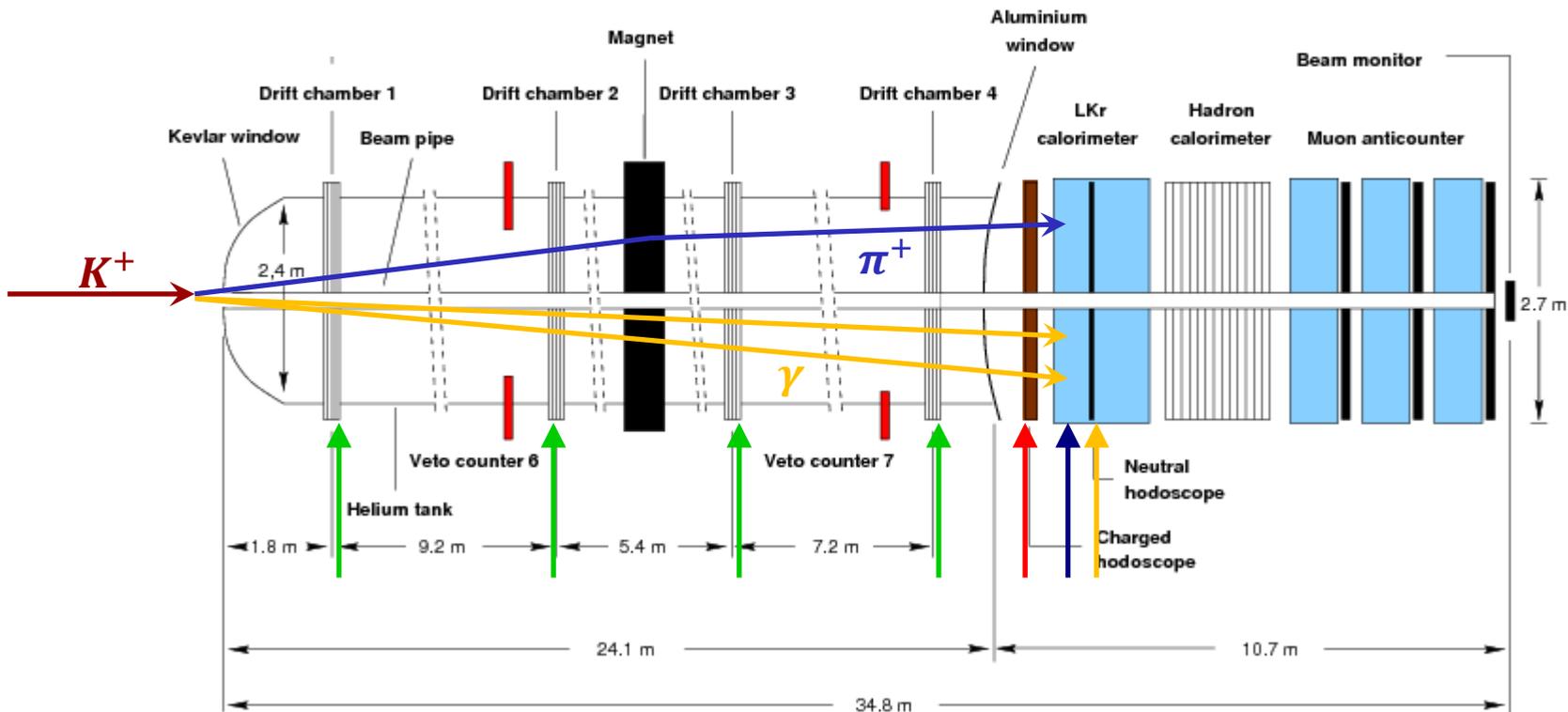


$O(p^6)$  unitary corrections

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



- A cusp visible at the  $2\pi$  threshold  $z = (2m_\pi/m_K)^2 = 0.320$
- Non-zero differential rate at  $z = 0$  generated by the B amplitude (for  $O(p^6)$ )
- $y^2$ -dependence of the differential rate arising at next-to-leading order  $O(p^6)$



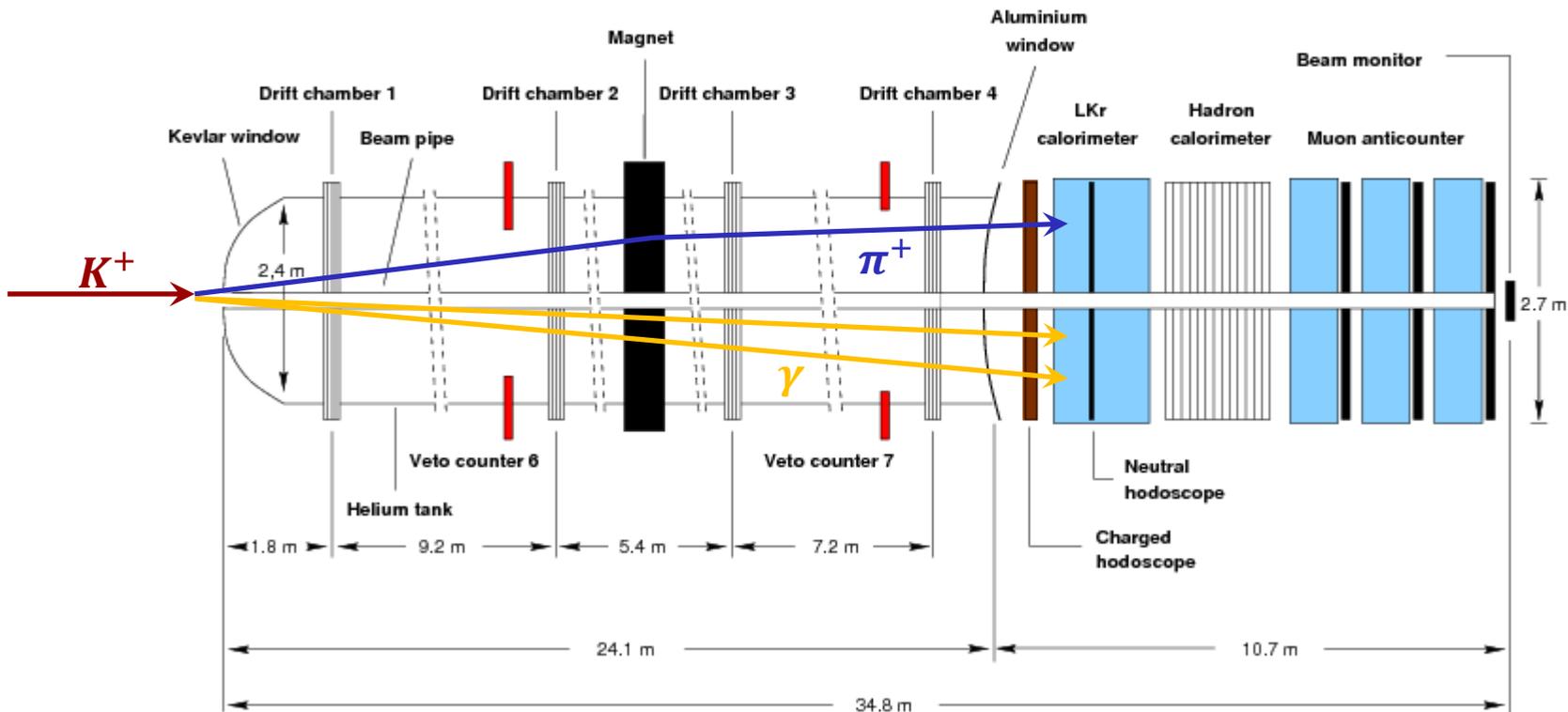
**NA48/2:** Special runs in 2003 and 2004 with a *minimum-bias* trigger:

- $Q_1$  & ( $E_{LKr} > 10$  GeV)

$Q_1$  – hit in the same quadrant of both CHOD planes

**NA62  $R_K$ -phase:** 90 days of running in 2007 with combination of downscaled *minimum-bias* conditions:

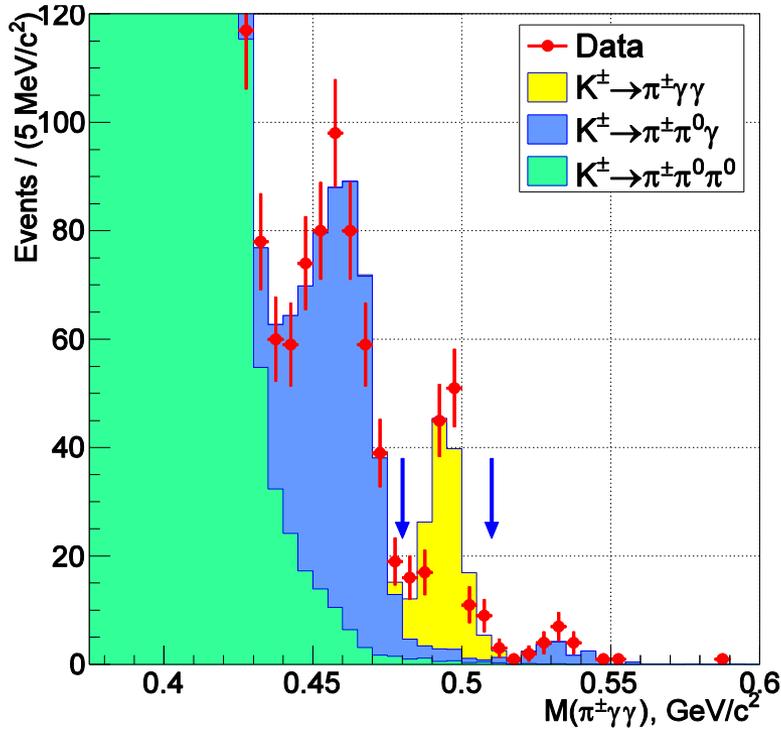
- $Q_1$  & (TRK) ~ 20% of the sample
- $Q_1$  & ( $E_{LKr} > 10$  GeV) & (TRK) ~60%
- NHOD signal ~20%



- Only one reconstructed track in detector acceptance ( $\pi^\pm$  candidate)
- Vertex: Closest Distance of Approach between  $\pi$  and  $K$  beam-axis (within the fiducial volume)
- Reconstructed track momentum:
  - $10 < p < 40 \text{ GeV}/c$  NA48/2 data (2003, 2004)
  - $8 < p < 50 \text{ GeV}/c$  NA62 data (2007)
- $E_{\text{LKr}} / p < 0.85$  for  $\pi^\pm$  identification
- 2 isolated clusters in LKr with  $E > 3 \text{ GeV}$ , in coincidence with a reconstructed track
- $0.48 < M(\pi^\pm \gamma \gamma) < 0.51 \text{ GeV}/c^2$
- $0.2 < z = (m_{\gamma\gamma}/m_K)^2 < 0.54$

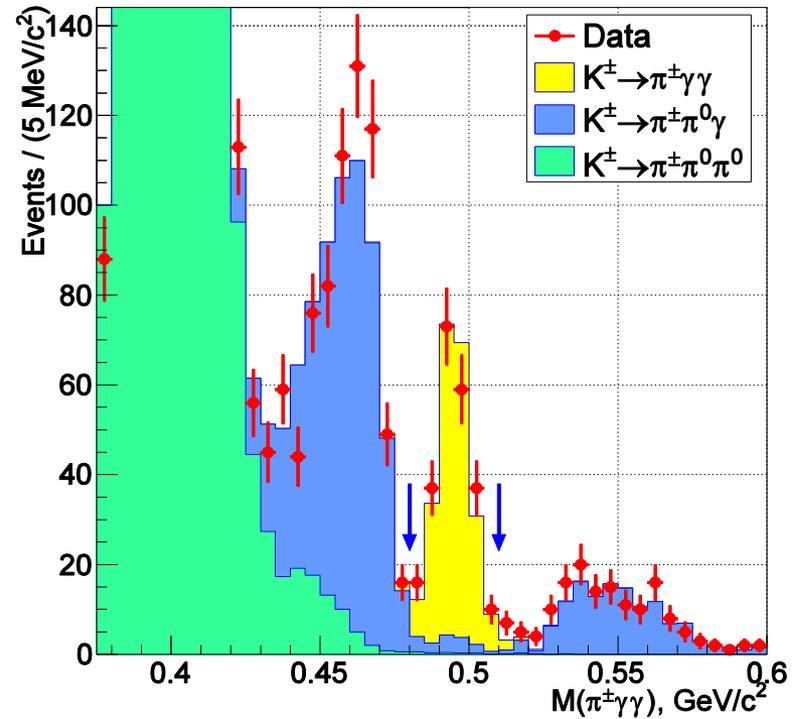
**NA48/2 (2003, 2004)**

[Phys. Lett. **B730** (2014) 141]



**NA62  $R_K$ -phase (2007)**

[Phys. Lett. **B732** (2014) 65]

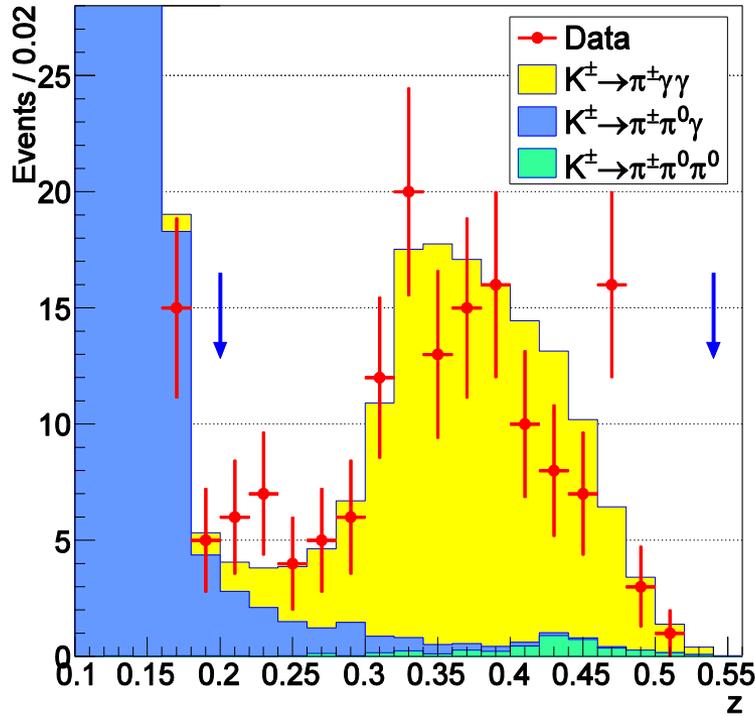


$K^\pm \rightarrow \pi^\pm\gamma\gamma$ candidates	149
$K^\pm \rightarrow \pi^\pm\pi^0(\gamma)$ background	$11.4 \pm 0.6$
$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ background	$4.1 \pm 0.4$
$K^\pm \rightarrow \pi^\pm\gamma\gamma$ signal	133

$K^\pm \rightarrow \pi^\pm\gamma\gamma$ candidates	232
$K^\pm \rightarrow \pi^\pm\pi^0(\gamma)$ background	$15.3 \pm 1.1$
$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ background	$2.1 \pm 0.3$
$K^\pm \rightarrow \pi^\pm\gamma\gamma$ signal	215

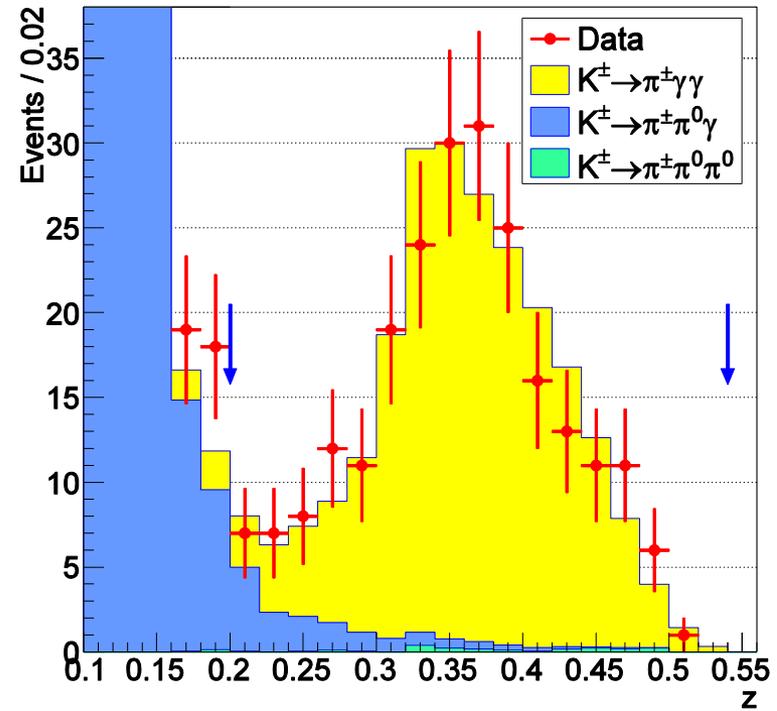
**NA48/2 (2003, 2004)**

[Phys. Lett. **B730** (2014) 141]



**NA62  $R_K$ -phase (2007)**

[Phys. Lett. **B732** (2014) 65]



- A cusp like behaviour at  $z = (2m_\pi/m_K)^2$
- Consider only the region above  $K^\pm \rightarrow \pi^\pm \pi^0$  peak ( $z > 0.2$ )

- $K_{\pi\gamma\gamma}$  decay rate measured with respect to normalisation decay chain  $K^\pm \rightarrow \pi^\pm \pi^0$  followed by  $\pi^0 \rightarrow \gamma\gamma$
- $K^\pm \rightarrow \pi^\pm \gamma \gamma$  and  $K^\pm \rightarrow \pi^\pm \pi^0$  collected with the same trigger
  - No dependence on: beam flux and composition, downscaling factors and variations throughout data-taking
  - Variations in geometrical acceptance must be considered
- Weak  $y$ -dependence of the signal acceptance
  - $B_{z>0.2}(K_{\pi\gamma\gamma})$  *model-independent* to good approximation
- Sum over  $z$  bins in the kinematic region

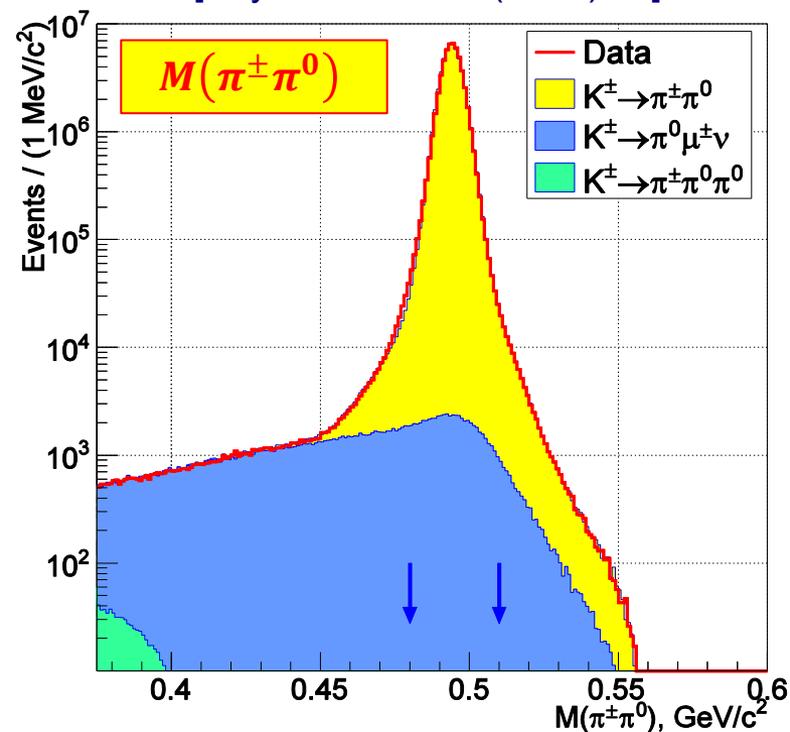
**NA48/2 (2003, 2004)** [Phys. Lett. **B730** (2014) 141]:

$$B_{MI}(z > 0.2) = (0.877 \pm 0.087 \text{ stat} \pm 0.017 \text{ syst}) \times 10^{-6}$$

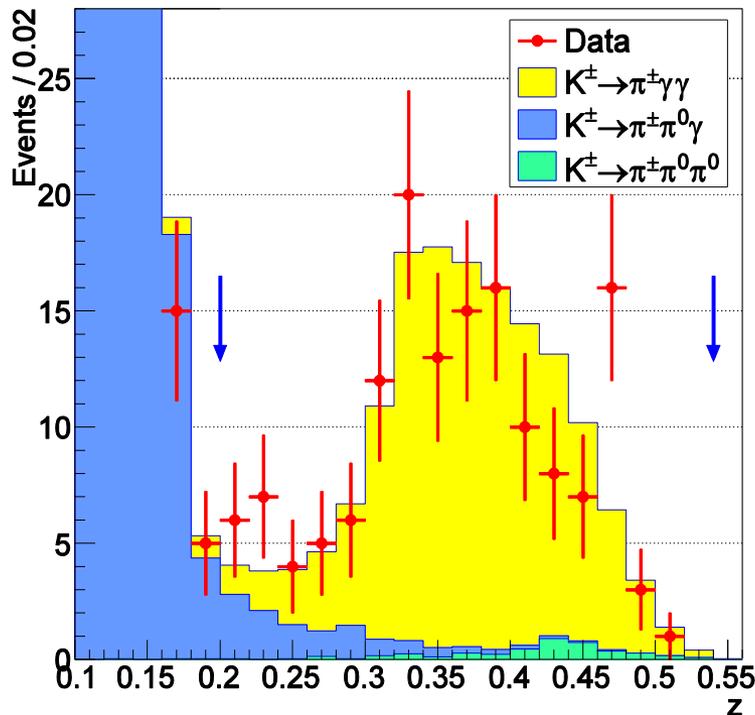
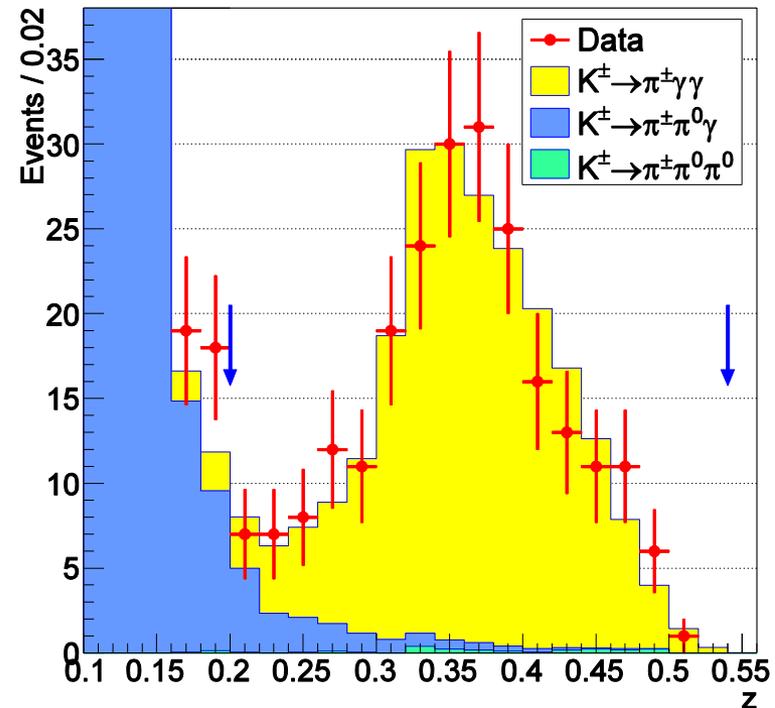
**NA62  $R_K$ -phase (2007)** [Phys. Lett. **B732** (2014) 65]:

$$B_{MI}(z > 0.2) = (1.088 \pm 0.093 \text{ stat} \pm 0.027 \text{ syst}) \times 10^{-6}$$

**NA62  $R_K$ -phase (2007)**  
[Phys. Lett. **B732** (2014) 65]



NA48/2 (2003, 2004)

[Phys. Lett. **B730** (2014) 141]NA62  $R_K$ -phase (2007)[Phys. Lett. **B732** (2014) 65]

ChPT  $O(p^4)$  and  $O(p^6)$  fits to reconstructed  $z$ -spectrum (*max. log-likelihood*)

ChPT  $O(p^4)$ :  $\hat{c}_4 = 1.37 \pm 0.33 \text{ stat} \pm 0.14 \text{ syst}$

ChPT  $O(p^6)$ :  $\hat{c}_6 = 1.41 \pm 0.38 \text{ stat} \pm 0.11 \text{ syst}$

ChPT  $O(p^4)$ :  $\hat{c}_4 = 1.93 \pm 0.26 \text{ stat} \pm 0.08 \text{ syst}$

ChPT  $O(p^6)$ :  $\hat{c}_6 = 2.10 \pm 0.28 \text{ stat} \pm 0.18 \text{ syst}$

- Data consistent with both ChPT descriptions
- Systematic uncertainty dominated by the precision of the background estimate

**NA48/2 (2003, 2004)**

[Phys. Lett. **B730** (2014) 141]

**ChPT  $O(p^4)$ :  $\hat{c}_4 = 1.37 \pm 0.33 \text{ stat} \pm 0.14 \text{ syst}$**

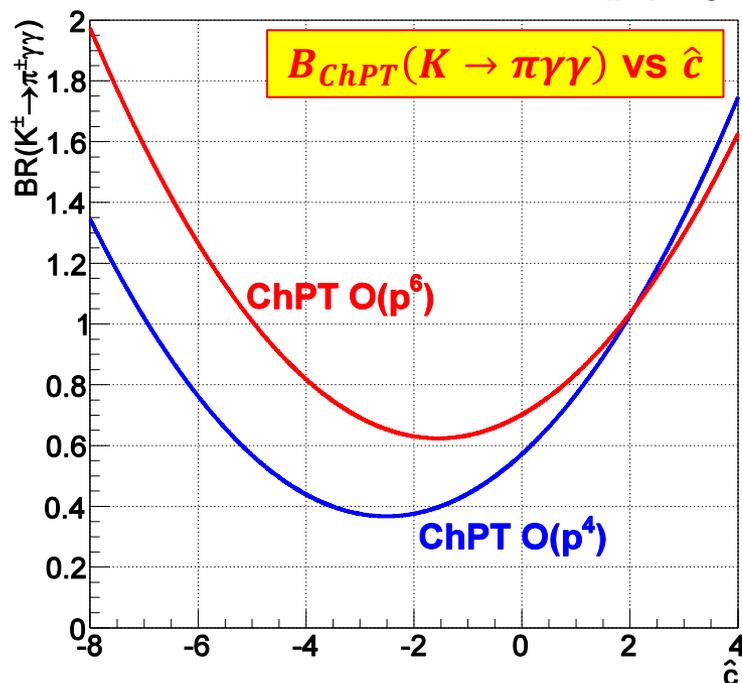
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[Phys. Lett. **B732** (2014) 65]

**ChPT  $O(p^4)$ :  $\hat{c}_4 = 1.93 \pm 0.26 \text{ stat} \pm 0.08 \text{ syst}$**

**ChPT  $O(p^6)$ :  $\hat{c}_6 = 2.10 \pm 0.28 \text{ stat} \pm 0.18 \text{ syst}$**



**Measured  $\hat{c}$  translates into model-dependent  $BR(K^\pm \rightarrow \pi^\pm \gamma\gamma)$  in the full kinematic range**

**Obtained by integration of the ChPT  $O(p^6)$  differential decay rate:**

**NA48/2 (2003,2004):  $B_{ChPT} = (0.910 \pm 0.072 \text{ stat} \pm 0.022 \text{ syst}) \times 10^{-6}$**

**NA62  $R_K$ -phase (2007):  $B_{ChPT} = (1.058 \pm 0.066 \text{ stat} \pm 0.044 \text{ syst}) \times 10^{-6}$**

*Under the assumed  $O(p^6)$  parametrisation!*

- Combination of the NA48/2 (2003,2004) and NA62  $R_K$ -phase (2007) results
- Same set of external parameters used in the measurement of  $\hat{c}$  parameter by NA48/2 and NA62  $R_K$ -phase
- Systematic uncertainty dominated by background subtraction

**Combined:**

[Phys. Lett. **B732** (2014) 65]

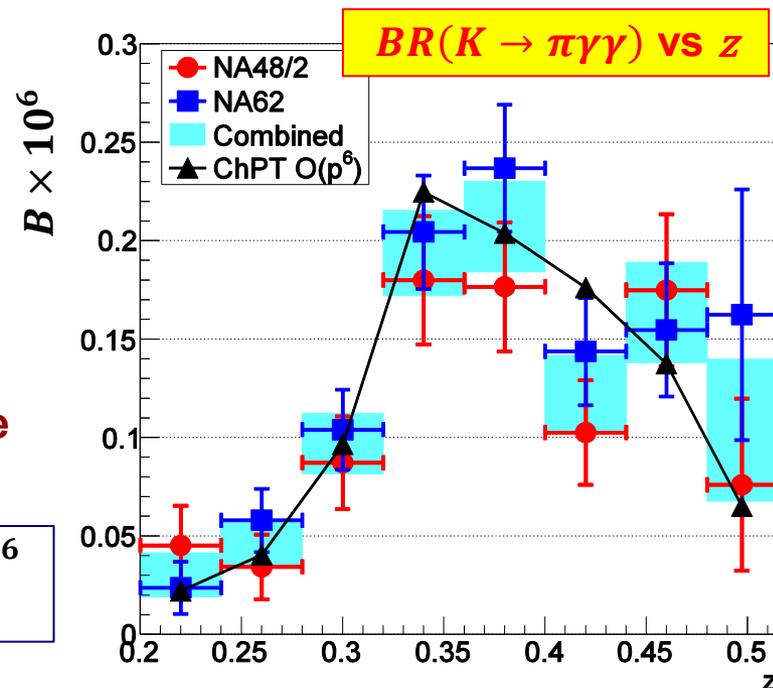
$$\hat{c}_4 = 1.72 \pm 0.20 \text{ stat} \pm 0.06 \text{ syst}$$

$$\hat{c}_6 = 1.86 \pm 0.23 \text{ stat} \pm 0.11 \text{ syst}$$

Integrating the  $O(p^6)$  differential decay rate for the combined value of  $\hat{c}_6$ :

$$B_{ChPT} = (1.003 \pm 0.051 \text{ stat} \pm 0.024 \text{ syst}) \times 10^{-6}$$

[Phys. Lett. **B732** (2014) 65]



- Previous measurements of the  $\hat{c}$  parameter published before this analysis
  - $\hat{c}_6$  and  $\hat{c}_6$  by the **BNL E787 experiment** [Phys.Rev.Lett. 79 (1997) 4079] and  $\hat{c}_6$  by the **NA48/2 experiment** [Phys.Lett. B 659 (2008) 493]

**E787: 31  $K_{\pi\gamma\gamma}^+$  candidates**

$$\hat{c}_4 = 1.6 \pm 0.6$$

$$\hat{c}_6 = 1.8 \pm 0.6$$

**NA48/2: 120  $K_{\pi\gamma ee}^\pm$  candidates**

$$\hat{c}_6 = 0.90 \pm 0.45$$

- Present study with 381 candidates ( $\sim 10$  times the *E787* sample)
- O(p<sup>6</sup>) parameterization involves external inputs**
  - G<sub>8</sub> parameter** – common to both O(p<sup>4</sup>) and O(p<sup>6</sup>) (in present study fixed according to [Rev.Mod.Phys. 84 (2012) 399])
  - polynomial contributions: 3 parameters** (set to 0 in present study)
  - K→3π amplitude: 7 parameters** (from fit to exp. data [Nucl. Phys. B648 (2003) 317])
- Different external parameters used by *E787* and the previous *NA48/2*
- The present  $\hat{c}$  measurement with the *E787* and *NA48/2* [Phys.Lett. B 659 (2008) 493] sets of external parameters:

**With *E787* parameters:**

$$\hat{c}_4 = 1.60 \pm 0.20 \text{ stat} \pm 0.06 \text{ syst}$$

$$\hat{c}_6 = 1.56 \pm 0.23 \text{ stat} \pm 0.11 \text{ syst}$$

**With *NA48/2* parameters:**

$$\hat{c}_6 = 1.59 \pm 0.23 \text{ stat} \pm 0.11 \text{ syst}$$

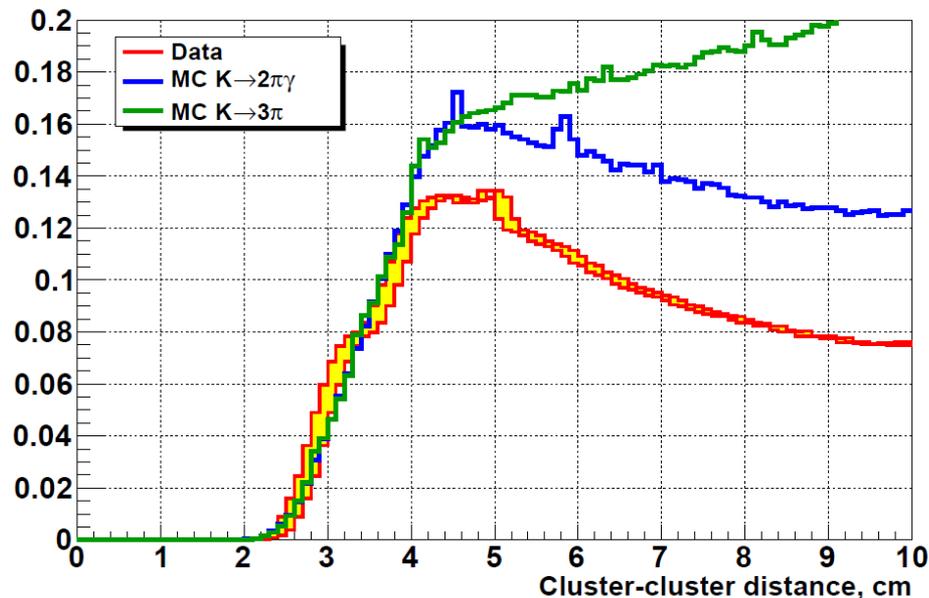
(comparison of  $K_{\pi\gamma ee}$  and  $K_{\pi\gamma\gamma}$  modes)

- Combined O(p<sup>6</sup>)  $B_{ChPT}$  has negligible sensitivity to difference of external parameters
  - Present value ( $B_{ChPT} = (1.003 \pm 0.051 \pm 0.024) \times 10^{-6}$ ) agrees with *E787* O(p<sup>6</sup>) result ( $B_{ChPT} = (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$ )

- **New published measurements of the  $K^\pm \rightarrow \pi^\pm \gamma \gamma$  decay using minimum-bias triggered data from NA48/2 (2004) and NA62  $R_K$ -phase (2007)**
  - **NA48/2** [Phys. Lett. B730 (2014) 141]
  - **NA62  $R_K$ -phase and combined results** [Phys. Lett. B732 (2014) 65]
- **Data agree to the ChPT prediction (observation of a cusp)**
- **ChPT parameter  $\hat{c}$  extracted from the measured z-spectrum**
- **Data consistent with both ChPT models  $O(p^4)$  and  $O(p^6)$**
- **Agreement with previous measurements of  $\hat{c}$  by NA48/2 and E787**
  - **present measurement obtained at improved precision!**



- $K^\pm \rightarrow \pi^\pm \pi^0(\gamma)$  and  $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$  background contamination dominate the systematic uncertainty
  - Merged LKr clusters



- Data/MC agreement studied by variation of the cluster lateral width cut
  - Maximum variations conservatively considered as systematic uncertainties
- Trigger inefficiencies systematics - negligible
- Pion mis-identification
  - Difference between data and MC cancels between signal and normalisation modes.
  - Residual bias - negligible