Chiral Perturbation Theory Tests at 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

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Outline

- NA48/2 Experimental Setup
- $K^{\pm} \to \pi^{\pm}\gamma\gamma$: Branching Ratio
- $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$: Branching Ratio and Spectrum Shape
- $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$: Branching Ratio and Form Factors

NA48/2 Experimental Setup

History

NA48 (1997-2001):
Direct CP-Violation in neutral K

- $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2)\cdot 10^{-4}$

NA48/1 (2002):
Rare K_S decays

- $BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8)\cdot 10^{-9}$
- $BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2)\cdot 10^{-9}$

NA48/2 (2003-2004):
Direct CP-Violation in charged K

- $A_g(K^\pm \to \pi^\pm \pi^+ \pi^-) = (-1.5 \pm 2.1)\cdot 10^{-4}$
- $A_g(K^\pm \to \pi^\pm \pi^0 \pi^0) = (1.8 \pm 1.8)\cdot 10^{-4}$

P326 / NA62 (2006-2012):
Very Rare K Decays

- $K^+ \to \pi^+ \nu\nu$

1997	ε'/ε	K_L & K_S
1998	K_L & K_S	
1999	K_L & K_S	K_S HI
2000	K_L Only	K_S HI
2001	K_L & K_S	K_S HI
2002	K_S & Hyperons HI	
2003-2004	K^+ & K^-	
2006-2010	Design & Construction	
2007-2008	$K_{e2}/K_{\mu 2}$	Tests
2011-2012	$K^+ \to \pi^+ \nu\nu$	

Simultaneous Beam

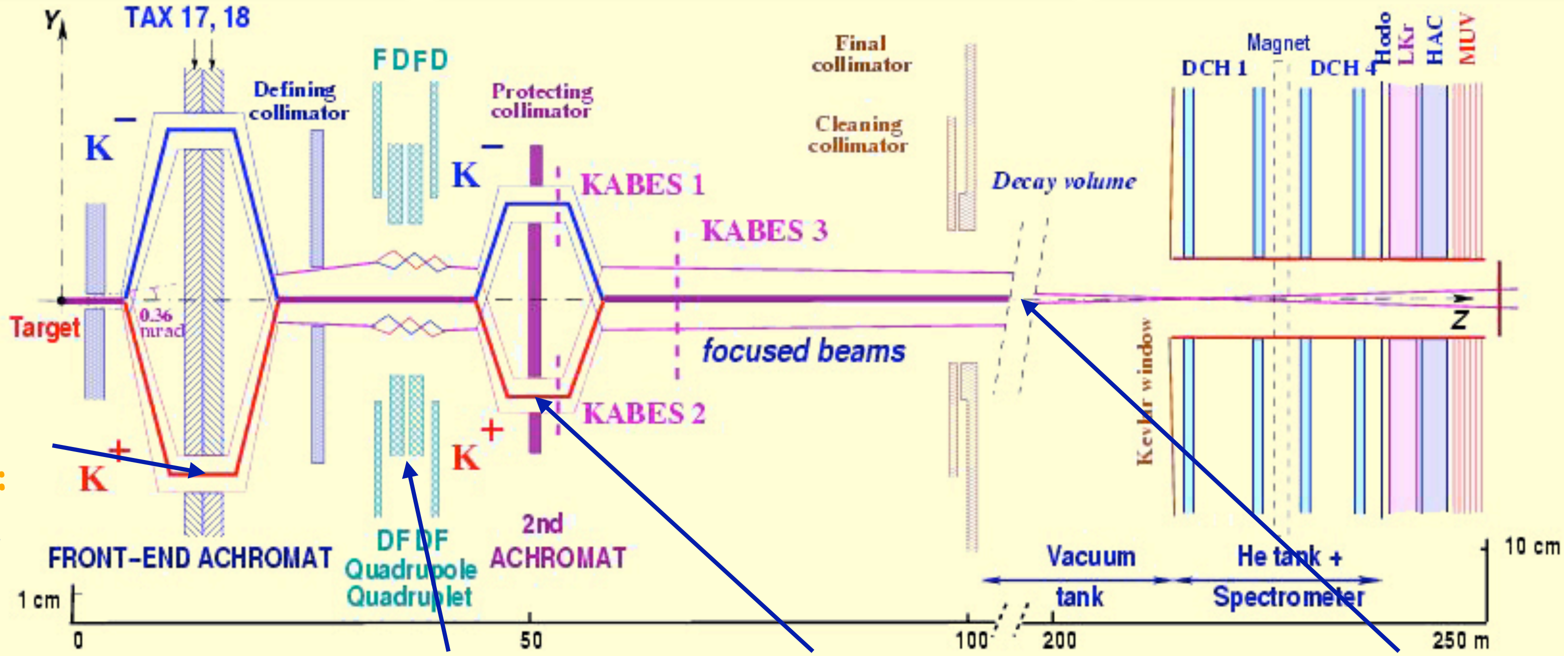
$2 \div 3$ M K/spill ($\pi/K \sim 10$)
π decay products stay in pipe
Flux ratio: $K^+/K^- \sim 1.8$

Simultaneous K^+ and K^- beams:
large charge symmetrization
of experimental conditions

Beams coincide within
~ 1 mm all along 114 m
decay volume

$\sim 7 \cdot 10^{11}$
p/spil
400 GeV/c

Front-End Achromat:
Momentum Selection

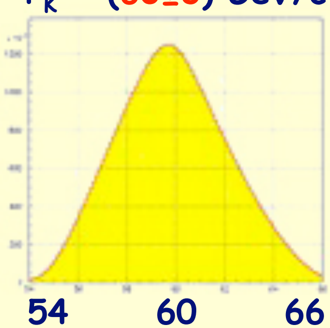


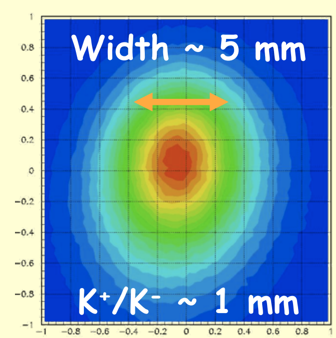
Quadrupole,
Quadruplet:
Focusing
μ Sweeping

Second chromat:
Cleaning
Beam Spectrometer

$\delta P_K/P_K = 0.7\%$
$\delta_{x,y} \sim 100\ \mu m$

$P_K = (60 \pm 3)$ GeV/c





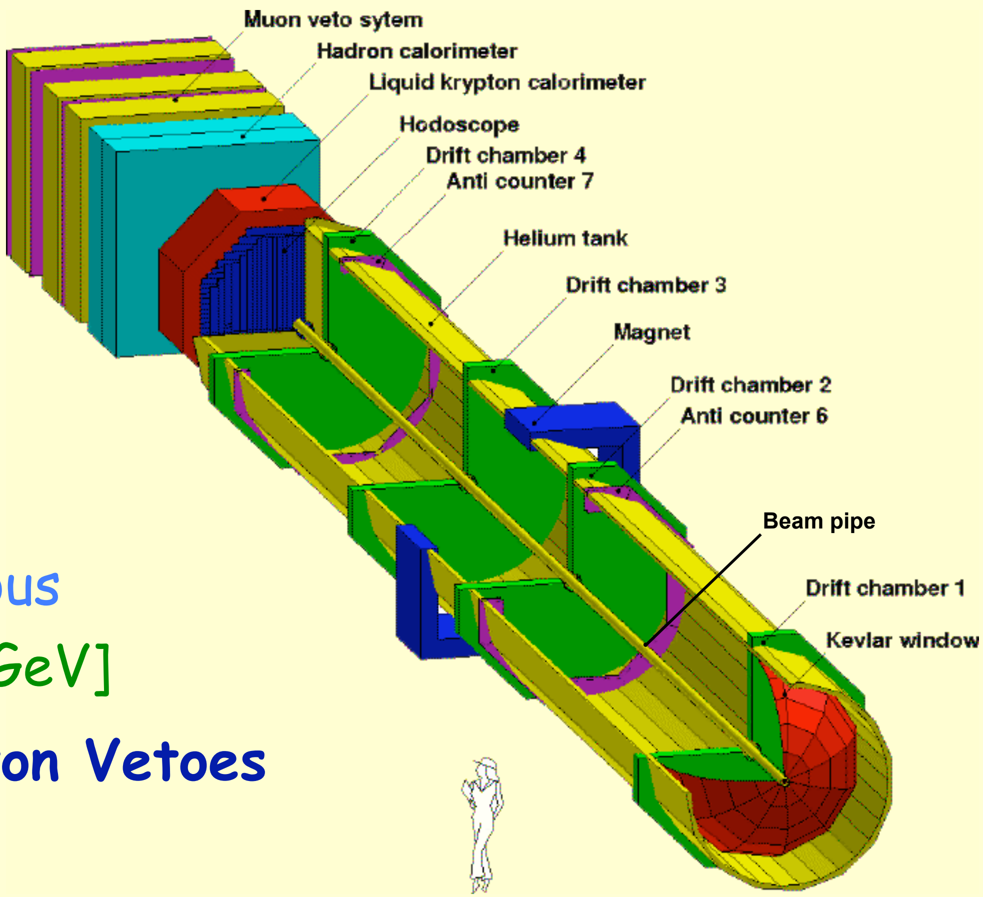
Detector

Magnetic Spectrometer (4 DCHs):
- 4 view / DCH -> high efficiency
- $\sigma_P/P = 1.0\% + 0.044\% \cdot P$ [GeV/c]

Hodoscope:
- Fast trigger
- σ_t = 150ps

Electromagnetic Calorimeter (LKr):
- High granularity, quasi-homogeneous
- $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

Hadron Calorimeter, **Muon** and **Photon Vetoes**



Trigger:
- Fast hardware trigger (L1): hodoscope & DCHs multiplicity
- Level 2 trigger (L2): on-line processing of DCHs & LKr information

Data Taking

Run periods:

- 2003: ~ 50 days
- 2004: ~ 60 days

Total collected statistics:

- $K^\pm \to \pi^\pm\pi^+\pi^-$: ~ $4\cdot10^9$
- $K^\pm \to \pi^\pm\pi^0\pi^0$: ~ $1\cdot10^8$

>200 TB of data recorded

A view of the NA48/2 beam line

Rare $K^\pm$ decays can be measured down to BR ~ 10^{-9}

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ & $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$ Decays

Motivation and Theory (I)

In the Chiral Perturbation Theory framework the differential rate of the $K^{\pm}(p) \to \pi^{\pm}(p_3)\,\gamma(q_1)\,\gamma(q_2)$ process (no $O(p^2)$ contribution) is:

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

$$y = \frac{p\cdot(q_1 - q_2)}{m_{K^\pm}^2} \qquad z = \frac{(q_1+q_2)^2}{m_{K^\pm}^2} = \frac{m_{\gamma\gamma}^2}{m_{K^\pm}^2}$$

relevant only @ low $m_{\gamma\gamma}$

- The leading contribution @ $O(p^4)$ is given by $A(z,\hat{c})$ (loops) which is responsible for a cusp at $m_{\gamma\gamma} = m_{2\pi}$
- C (WZW) corresponds to ~10% of A @ $O(p^4)$
- B, D = 0 @ $O(p^4)$

G. Ecker, A. Pich, E. de Rafael, Nucl. Phys. B303 (1988), 665

- $O(p^6)$ unitarity corrections can increase the BR by 30÷40%

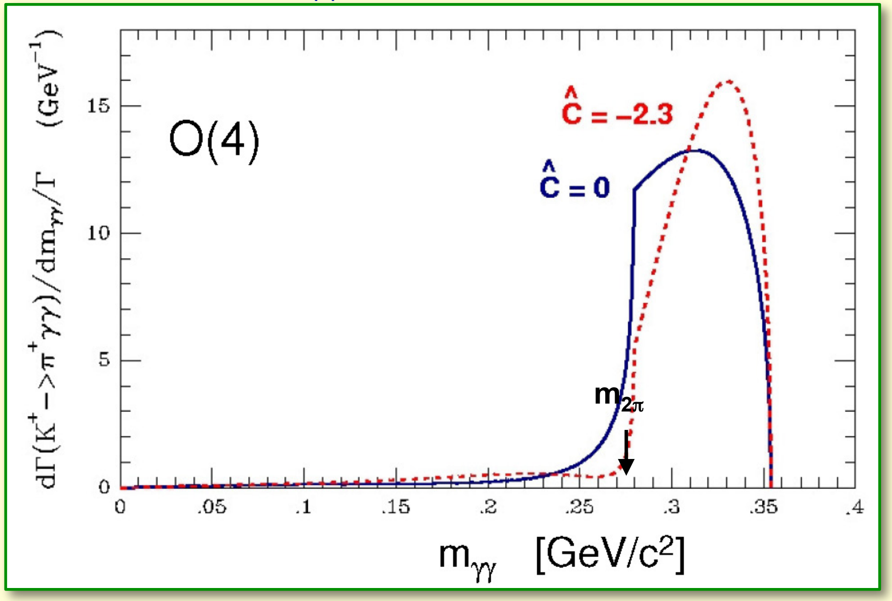
G. D'Ambrosio and J. Portoles, Nucl. Phys. B386 (1996), 403

Motivation and Theory (II)

Both decay spectrum and rate strongly depend on the single $\hat{c}$ parameter (O(1)):

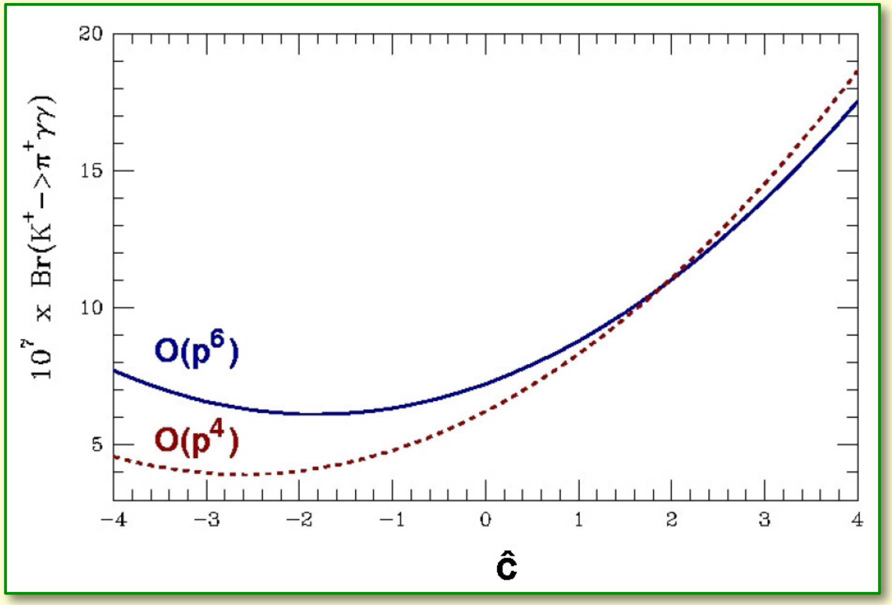
$$BR(K^+ \to \pi^+\gamma\gamma) = (5.26 + 1.64\cdot\hat{c} + 0.32\cdot\hat{c}^2 + 0.49)\cdot 10^{-7} \geq 4\cdot 10^{-7}$$

$m_{\gamma\gamma}$ spectrum



cusp-like behaviour at 2π threshold

unitarity corrections



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

Previous measurement by E787 (31 candidate, 5.1 ± 3.3 background events):

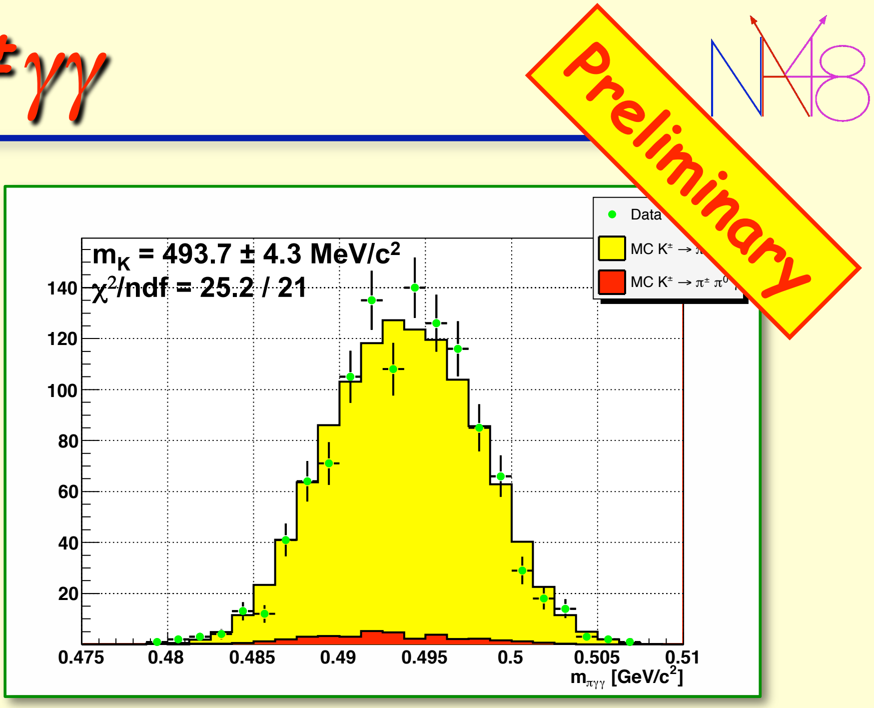
$$BR(\pi^{+}\gamma\gamma) = (1.10 \pm 0.32)\cdot 10^{-6}$$

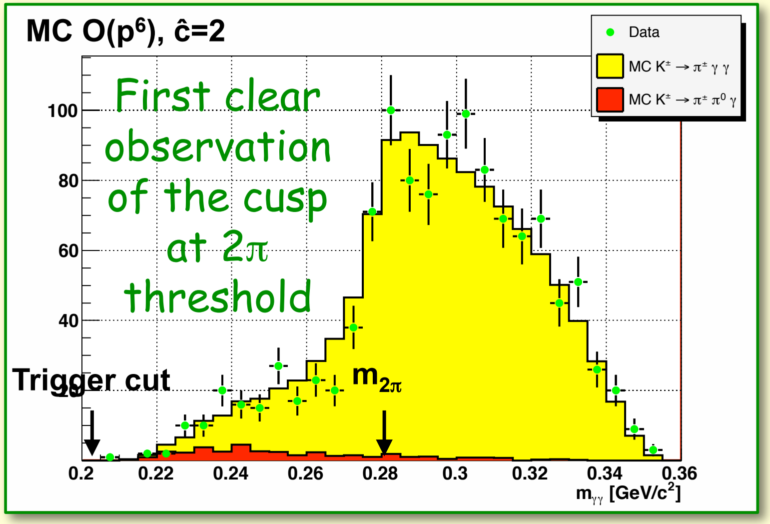
Event Sample (~40% of the full statistics):

- $K^{\pm} \to \pi^{\pm}\pi^{0}$ as normalization
- K flux: $\Phi_K = 2.06\cdot 10^{10}$
- 1164 candidate events
- 3.3% background ($K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$)

Shape Analysis:

- MC $O(p^6)$ and $\hat{c} = 2$ for comparison
- Data shape follows ChPT prediction
- Possibility of precise $\hat{c}$ measurement but no quantitative result yet

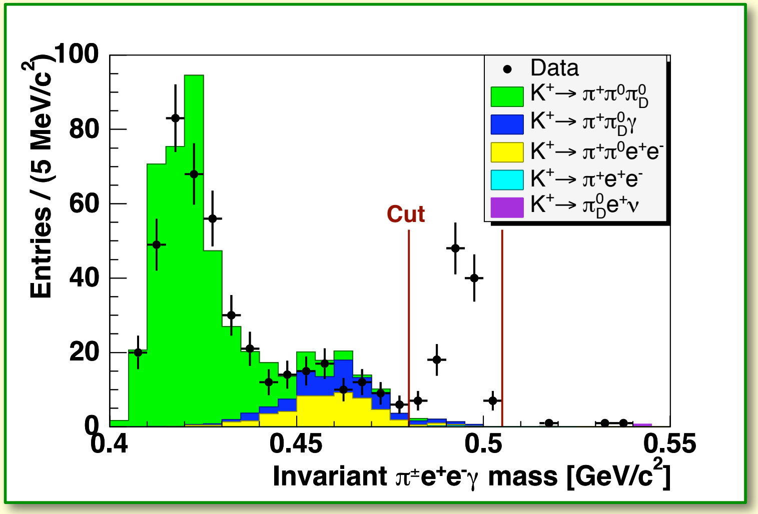


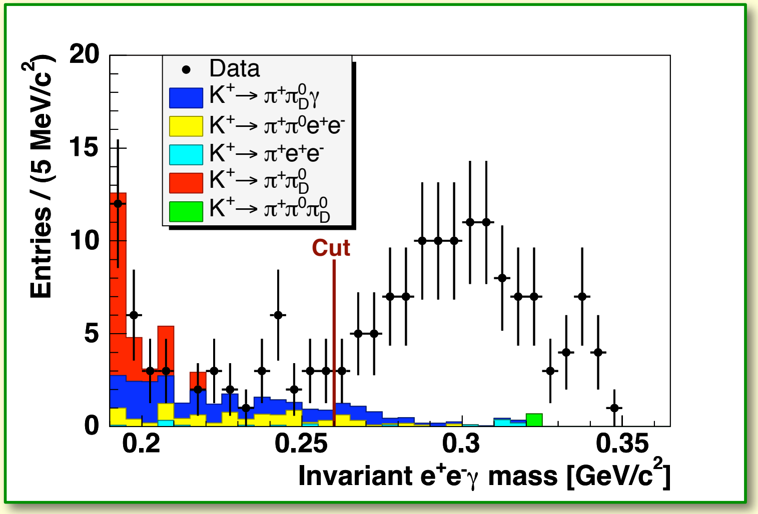


$$BR(K^{\pm} \to \pi^{\pm}\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{syst})\cdot 10^{-6}$$

assuming $O(p^6)$ distribution and $\hat{c} = 2$

$K^\pm \to \pi^\pm e^+ e^- \gamma$ (I)





Never observed before.

Naïve estimation of the BR:

$$K^\pm \to \pi^\pm \gamma^* \gamma \to \pi^\pm e^+ e^- \gamma$$

$$BR(\pi^\pm e^+ e^- \gamma) = BR(\pi^\pm \gamma\gamma) \cdot 2\alpha \sim 1.6 \cdot 10^{-8}$$

Theoretical expectation: *Gabbiani, PRL D59, 094022*

$$BR(\pi^\pm e^+ e^- \gamma) = (0.9 \div 1.6) \cdot 10^{-8}$$

Event Sample (full statistics):

- $K^\pm \to \pi^\pm \pi^0_D$ as normalization
- K flux: $\Phi_K = 1.48 \cdot 10^{11}$
- 120 candidate events
- 6.1% background ($K^\pm \to \pi^\pm \pi^0_D \gamma$)

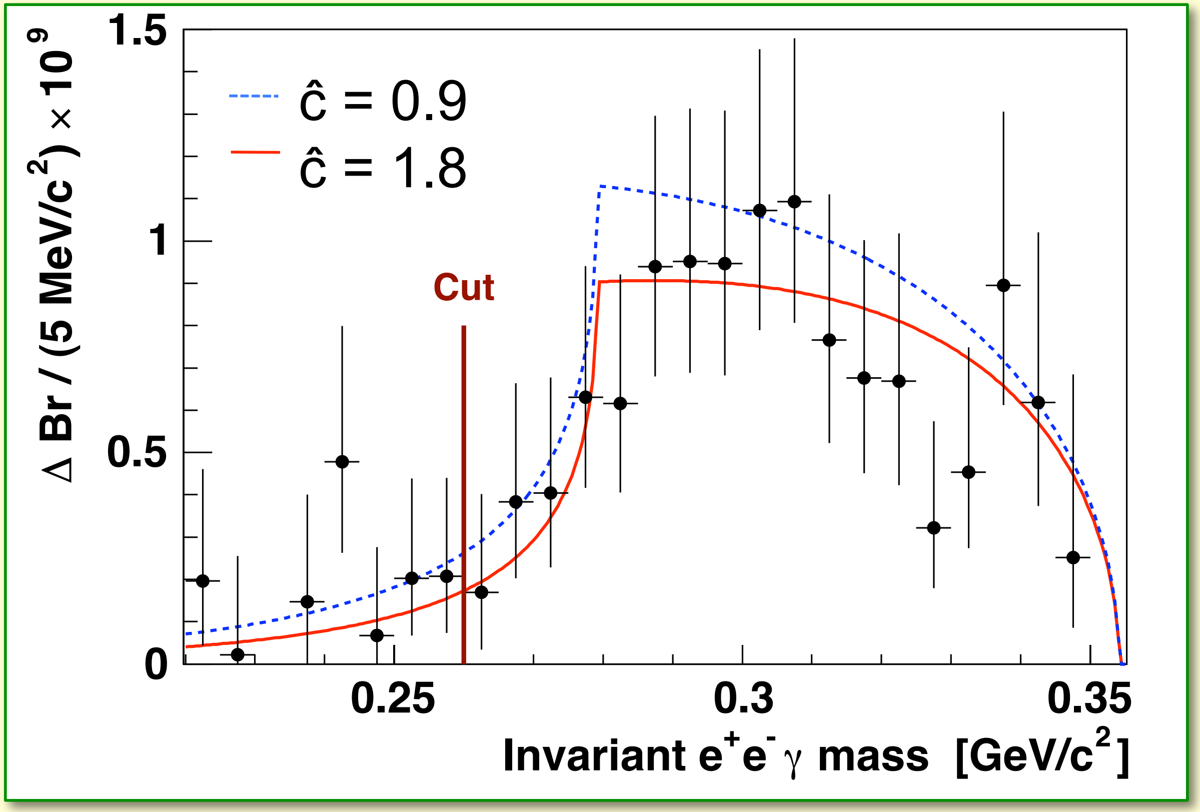
Model-Independent BR ($m_{ee\gamma}$ > 260 MeV/c²):

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

$K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ (II)

Shape Analysis: $\hat{c}$ has been extracted by fitting data to the absolute $O(p^4)$ ChPT prediction

Gabbiani, Phys. Rev. Lett. D59 (1999), 094022



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

χ^2/ndf = 8.1 / 17
Prob = 96.4%

1.2σ away from BNL E787 value in $K^{+} \to \pi^{+}\gamma\gamma$: $\hat{c} = 1.8 \pm 0.6$

Phys. Lett. B659 (2008), 493

$K^{\pm} \to \pi^{\pm} e^{+} e^{-}$ Decay

Motivation and Theory

$K^\pm \to \pi^\pm\gamma^* \to \pi^\pm l^+ l^-$: suppressed FCNC process proceeding through one-photon exchange. Weak interactions at low energy, ChPT tests

$$d\Gamma/dz \sim P(z)\cdot|W(z)|^2$$

$z = (m_{ee}/m_K)^2$

$P(z)$ = phase space factor

Form Factors:

1) Linear: $W(z) = G_F \cdot m_K^2 \cdot f_0 \cdot (1 + \delta \cdot z)$
2) ChPT $O(p^6)$: $W(z) = G_F \cdot m_K^2 \cdot (a_+ + b_+ \cdot z) + W^{\pi\pi}(z)$ *D'Ambrosio et al. JHEP 8 (1998), 4*
3) Dubna ChPT: $W(z) = W(M_a, M_\rho, z)$ *Dubnickova et al. hep-ph/0611175*

(f_0, δ) or (a_+, b_+) or (M_a, M_ρ) fully determine a Model-Dependent BR

Goals:

› Model-Independent BR($z > 0.08$) in visible kinematic range

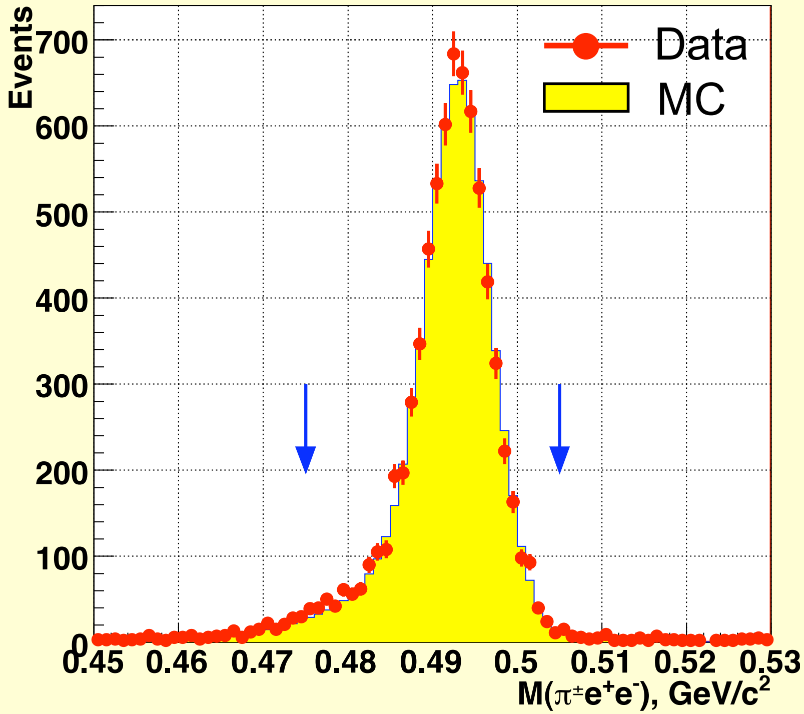
› Parameters of models and BRs in the full kinematic range

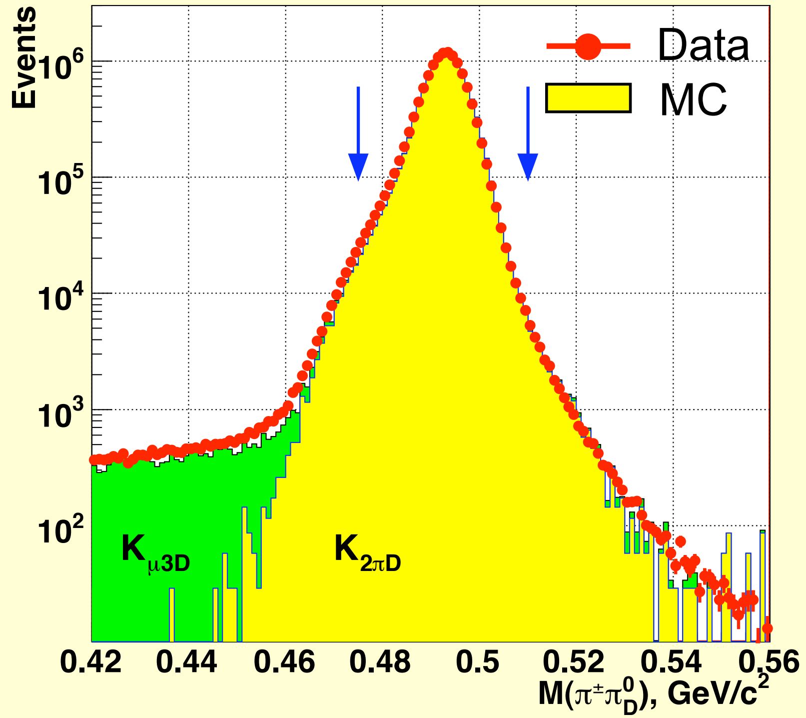
Signal and Normalization

Preliminary

Event Sample (full statistics):

- $K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$ as normalization
- K flux: $\Phi_K = 1.70 \cdot 10^{11}$
- 7146 candidate events
- 0.6% background/signal ($K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$, $K^{\pm} \to \pi^{0}_{D}e^{\pm}\nu$ + particle mis-ID)

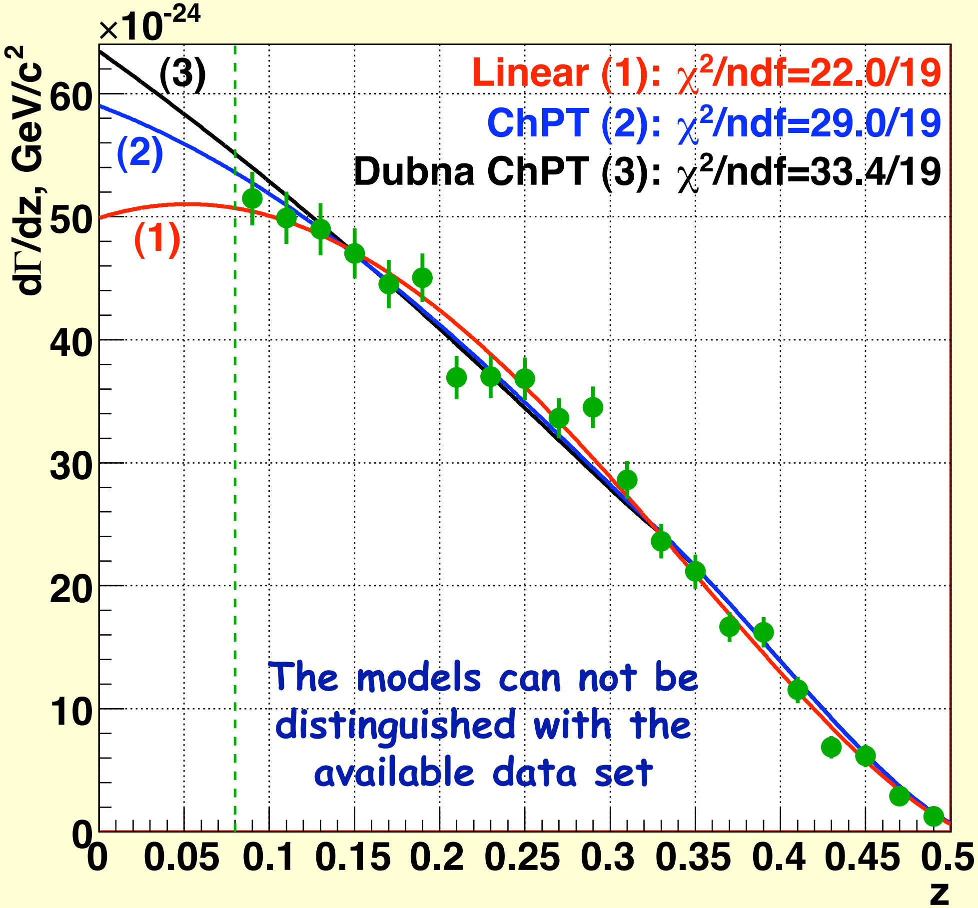




Results (I)

Preliminary

z distribution is sensitive to the Form Factors and contains all the dynamical information



"Raw" values

(no BKG/trigger correction, stat error only)

$\delta = 2.42 \pm 0.15$

$f_0 = 0.529 \pm 0.012$

$\rho(\delta, f_0) = -0.963$

$a_+ = -0.576 \pm 0.012$

$b_+ = -0.830 \pm 0.053$

$\rho(a_+, b_+) = -0.913$

$M_a = (0.951 \pm 0.028)$ [GeV]

$M_\rho = (0.705 \pm 0.010)$ [GeV]

$\rho(M_a, M_\rho) = 0.998$

Model-Independent $BR_{MI}(z > 0.08)$ computed by integrating $d\Gamma/dz$

Results (II)

Preliminary

$$BR_{MI}\cdot 10^7 = 2.26 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.06_{ext} = 2.26 \pm 0.08$$

$$\delta = 2.35 \pm 0.15_{stat} \pm 0.09_{syst} = 2.35 \pm 0.18$$

$$f_0 = 0.532 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext} = 0.532 \pm 0.016$$

$$BR_1\cdot 10^7 = 3.02 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.02 \pm 0.10$$

$$a_+ = -0.579 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext} = -0.579 \pm 0.016$$

$$b_+ = -0.798 \pm 0.053_{stat} \pm 0.037_{syst} \pm 0.017_{ext} = -0.798 \pm 0.067$$

$$BR_2\cdot 10^7 = 3.11 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.11 \pm 0.10$$

$$M_a = 0.965 \pm 0.028_{stat} \pm 0.018_{syst} \pm 0.002_{ext} = 0.965 \pm 0.033 \text{ [GeV/c]}$$

$$M_\rho = 0.711 \pm 0.010_{stat} \pm 0.007_{syst} \pm 0.002_{ext} = 0.711 \pm 0.013 \text{ [GeV/c]}$$

$$BR_3\cdot 10^7 = 3.15 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} = 3.15 \pm 0.10$$

Including uncertainty due to the model dependence (full z range):

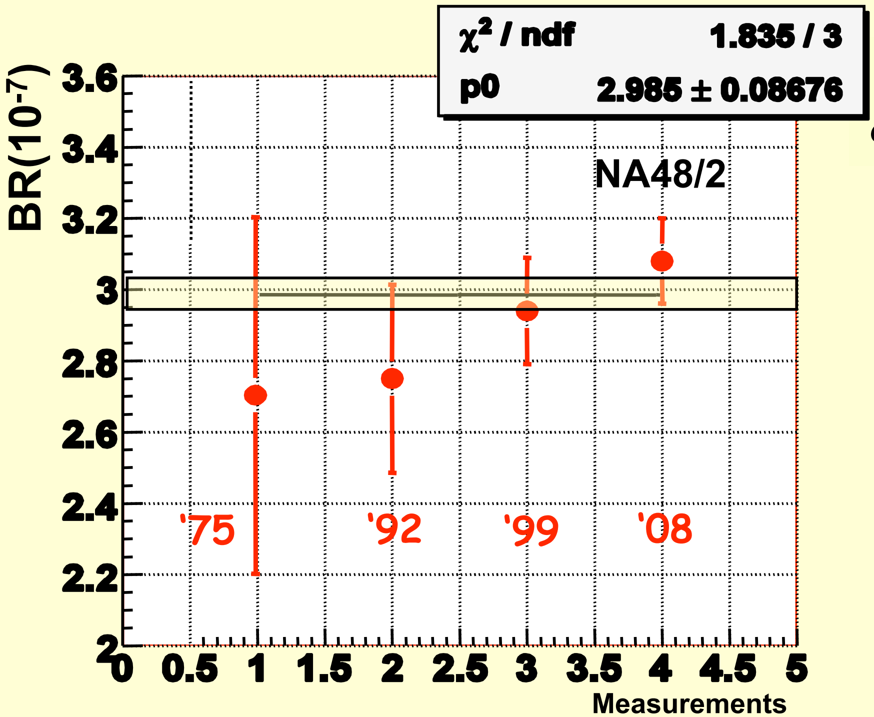
$$BR(K^\pm \to \pi^\pm e^+e^-) = (3.08 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} \pm 0.07_{model})\cdot 10^{-7}$$

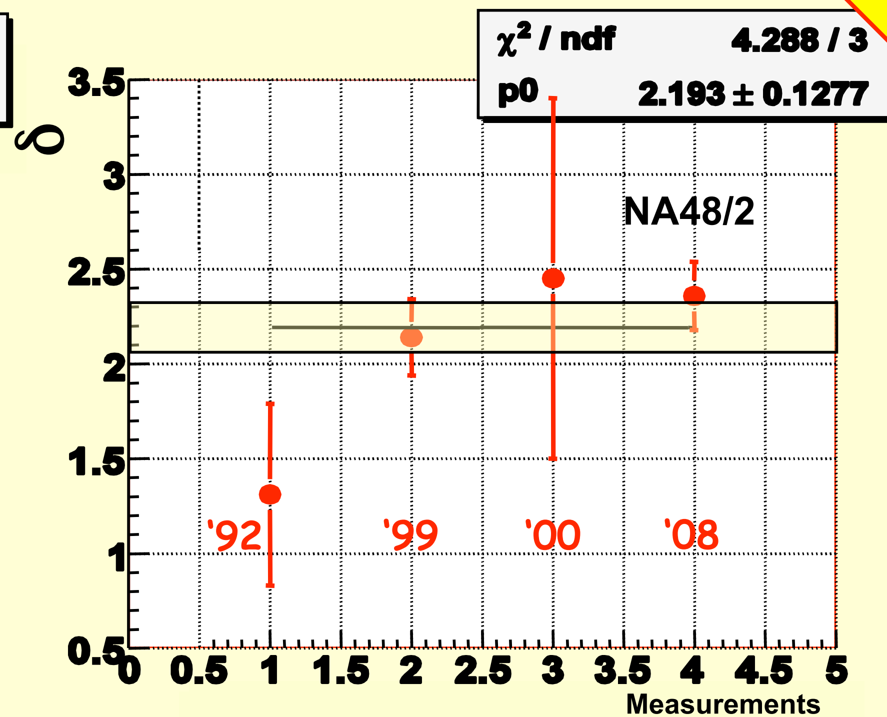
CPV parameter (first measurement):

$$\Delta(K^\pm \to \pi^\pm e^+e^-) = (BR^+ - BR^-) / (BR^+ + BR^-) = (-2.1 \pm 1.5_{stat} \pm 0.3_{syst})\%$$

Results (III)

Preliminary





Measurement	$BR\cdot 10^7$
Bloch et al., PL 56 (1975), B201	2.70 ± 0.50
Alliegro et al., PRL 68 (1992), 278	2.75 ± 0.26
Appel et al. [E865], PRL 83 (1999), 4482	2.94 ± 0.15
NA48/2 preliminary	3.08 ± 0.12

Measurement	δ
Alliegro et al., PRL 68 (1992), 278	1.31 ± 0.48
Appel et al. [E865], PRL 83 (1999), 4482	2.14 ± 0.20
Ma et al. [E865], PRL 84 (2000), 2580	$2.45^{+1.30}_{-0.95}$
NA48/2 preliminary	2.35 ± 0.18

Summary

- **Precise study of the $K^\pm \to \pi^\pm\gamma\gamma$ decay (BR ~ 10^{-6})**
  - Clear evidence for a cusp at $m_{\gamma\gamma} = m_{2\pi}$, first possibility for shape study
  - Measured ***BR*** in agreement with ChPT
  - Shape analysis and a larger sample coming soon
- **First observation of the $K^\pm \to \pi^\pm e^+e^-\gamma$ decay (BR ~ 10^{-8})**
  - An independent evidence for the cusp at $m_{\gamma\gamma} = m_{2\pi}$
  - Measurement of ***Shape*** and the ***BR*** finalized
- **Precise study of the $K^\pm \to \pi^\pm e^+e^-$ decay (BR ~ 10^{-7})**
  - Sample & precision comparable to world's best ones
  - ***BR*** and ***Form Factors*** in agreement with ChPT and other measurements
  - First limit on the ***CPV Asymmetry*** obtained

Spares

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ & $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$ Decays

Motivation and Theory

In the Chiral Perturbation Theory framework the differential rate of the $K^{\pm}(p) \to \pi^{\pm}(p_3)\ \gamma(q_1)\ \gamma(q_2)$ process (no $O(p^2)$ contribution) is:

$$\frac{d\Gamma}{dz} = \frac{m_{K^{\pm}}^5}{2(8\pi)^3} \cdot z^2 \cdot \lambda^{1/2}\left(1, z, r_\pi^2\right) \cdot \left[\left|A(z)\right|^2 + \left|C(z)\right|^2\right]$$

$$z = \frac{(q_1+q_2)^2}{m_{K^{\pm}}^2} = \frac{m_{\gamma\gamma}^2}{m_{K^{\pm}}^2}, \quad 0 < z < (1-r_\pi)^2, \quad r_\pi = \frac{m_{\pi^{\pm}}}{m_{K^{\pm}}}, \quad \lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$$

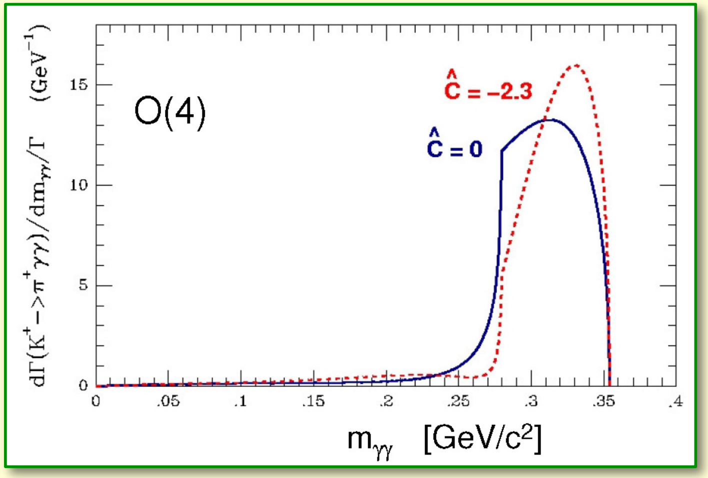
The leading contribution @ $O(p^4)$ is given by:

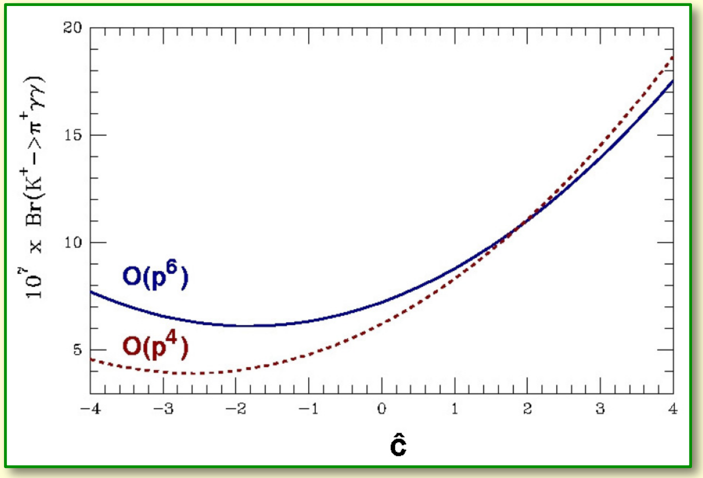
$$A(z,\hat{c}) = \frac{G_8 a_{em}}{2\pi \cdot z} \cdot \left[\left(r_\pi^2 - 1 - z\right) \cdot F\left(\frac{z}{r_\pi^2}\right) + \left(1 - z - r_\pi^2\right) \cdot F(z) + \hat{c} \cdot z\right]$$

π loop — K loop — tree level counterterm

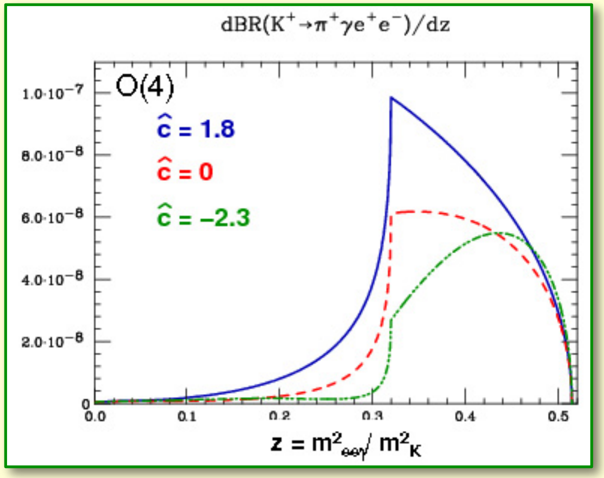
Motivation and Theory

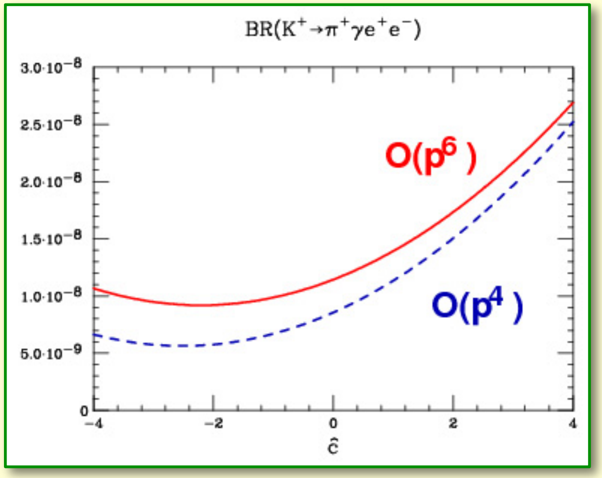
$K^{\pm} \to \pi^{\pm}\gamma\gamma$





$K^{\pm} \to \pi^{\pm}\gamma^{*}\gamma \to \pi^{\pm}e^{+}e^{-}\gamma$

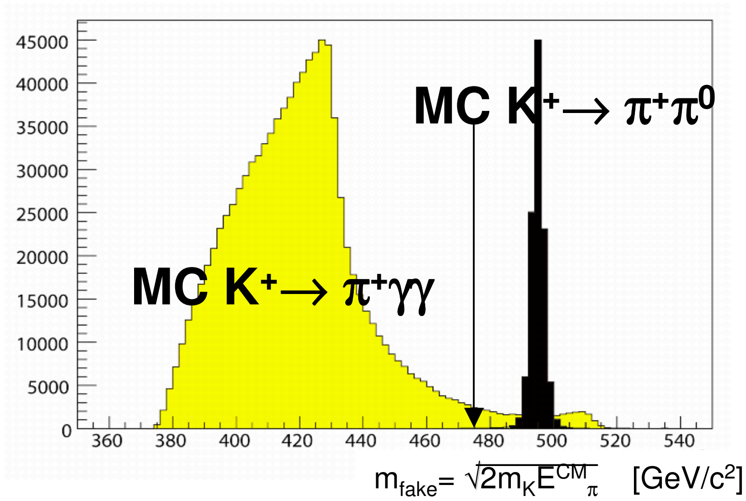




$K^{\pm} \to \pi^{\pm}\gamma\gamma$

$$BR(\pi^{\pm}\gamma\gamma) = \frac{1}{\Phi_{flux}} \times \frac{(\#\pi^{\pm}\gamma\gamma) - (\#bkg)}{Acc(\pi^{\pm}\gamma\gamma) \times Eff}$$

- Bad trigger conditions:
  - **Selected through neutral trigger:**
    L1 required more than 2 clusters in e.m. calorimeter ⇒ **50% efficiency.**
    L2 rejected $K^{\pm} \to \pi^{\pm}\pi^0$ decays (BR=20.92%!!) cutting on E^{CM}_{π}: **80%** efficient.



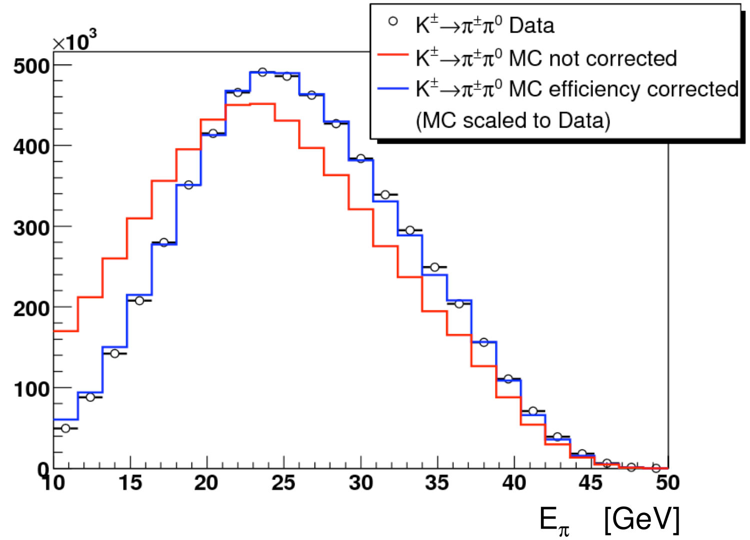
- Due to **low** amount of **statistics**, trigger efficiencies not measured with $K^{\pm} \to \pi^{\pm}\gamma\gamma$ data.
  - Solution: **use background** events

& study dependencies on kinematic variables:

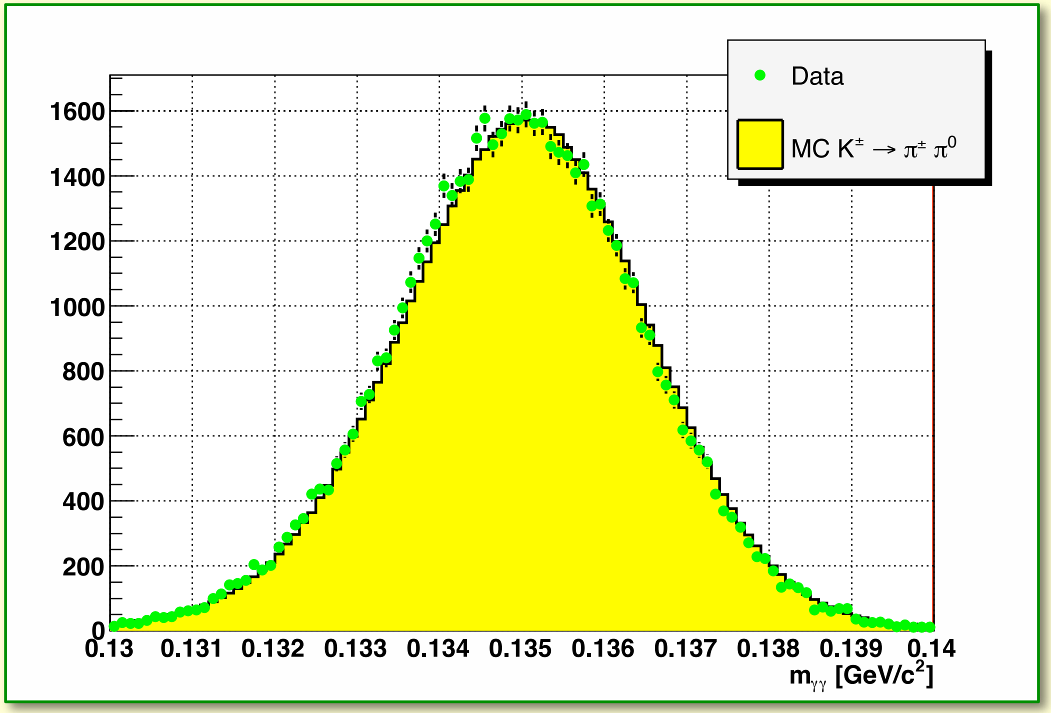
$$Eff^{L1}(p_{track}, d_{c1c2}),\ Eff^{L2}(p_{track}, z_{vertex}, r_{beampipe})$$

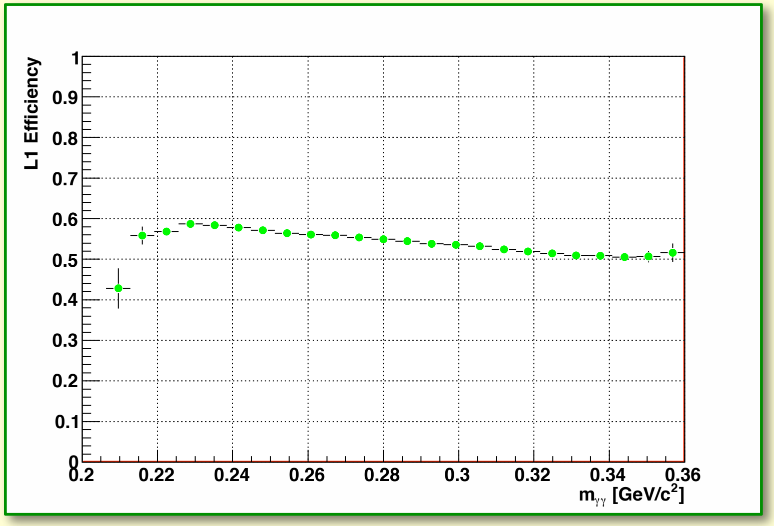
& use MC $K^{\pm} \to \pi^{\pm}\gamma\gamma$ to "reshape" variables and integrate

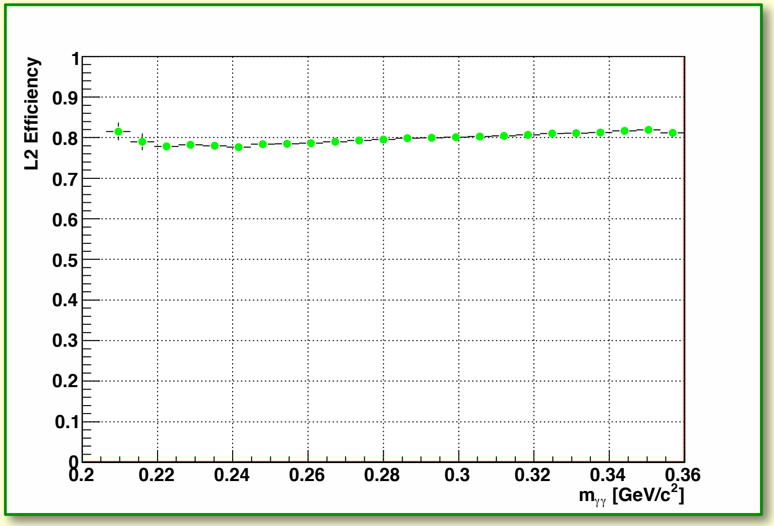
$$Eff^{L1,L2} = \frac{\Sigma_n\ (\#MC(v_1,\dots,v_n) \times Eff^{L1,L2}(v_1,\dots,v_n))}{\Sigma_n\ (\#MC(v_1,\dots,v_n))}$$



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







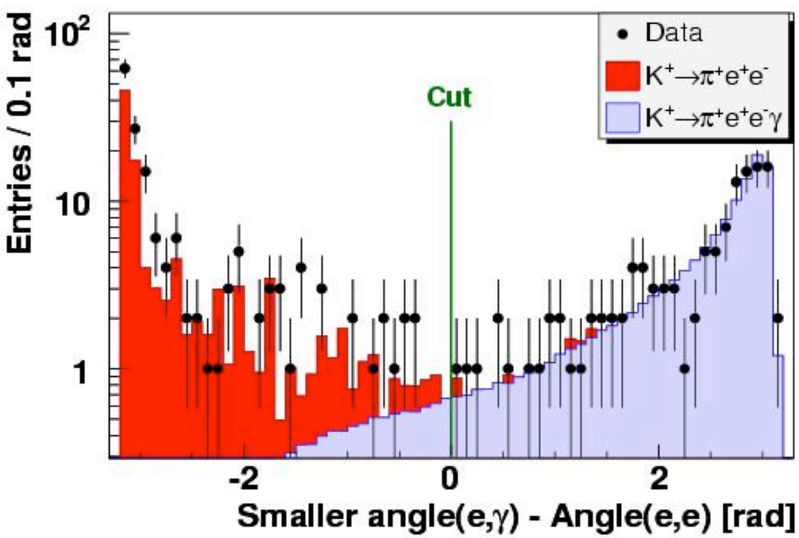
$K^\pm \to \pi^\pm e^+ e^- \gamma$

Event selection:

- at least 3 tracks with $Q_{tot}=\pm1$ and compatible decay vertex
- at least 1 cluster not associated to track
- $E/p > 0.94$ for $e^\pm$, $E/p < 0.8$ for $\pi^\pm$
- 54 GeV $< E_{tot} <$ 66 GeV

BG suppression:

- many BG sources considered and evaluated with MC
- $m_{ee\gamma} > 260$ MeV/c² (low BG area)
- cut on $\theta_{e\gamma}$ to reject $K^\pm \to \pi^\pm e^+ e^-$
- 480 MeV/c² $< m_{\pi ee\gamma} <$ 505 MeV/c² (K mass)



Background source	Branching ratio	Expected events
$K^\pm \to \pi^\pm \pi^0_D \gamma$ (IB)	3.3×10^{-6}	3.1 ± 0.5
$K^\pm \to \pi^\pm \pi^0_D \gamma$ (DE)	5.3×10^{-8}	0.12 ± 0.03
$K^\pm \to \pi^\pm \pi^0 e^+ e^-$ (IB)	$\sim 1.7 \times 10^{-6}$	1.6 ± 0.9
$K^\pm \to \pi^\pm \pi^0 e^+ e^-$ (DE)	$\sim 2.6 \times 10^{-8}$	0.02 ± 0.01
$K^\pm \to \pi^\pm e^+ e^-$	2.9×10^{-7}	0.8 ± 0.5
$K^\pm \to \pi^\pm \pi^0 \pi^0_D$	2.1×10^{-4}	0.7 ± 0.7
Accidentals	–	1.0 ± 1.0
Sum		7.3 ± 1.7

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

Selection Criteria

The $K^\pm \to \pi^\pm e^+ e^-$ is measured normalizing to $K^\pm \to \pi^\pm \pi^0_D \to \pi^\pm e^+ e^- \gamma$, thus particle ID efficiencies cancel in the first order

Common selection criteria:

3-track vertex [consistent in space/time]

1 π candidate, 2 opposite sign electron candidates

Electron (pion) ID based on E deposition : $E/p > 0.95$ ($E/p < 0.85$)

Signal selection:

Kinematic suppression of $\pi^\pm \pi^0_D$ background: $m_{ee} > 140$ MeV/c^2.

Limitations on reconstructed $\pi^\pm e^+ e^-$ invariant mass, total & transverse momentum

Normalization selection:

Selection of good γ candidate.

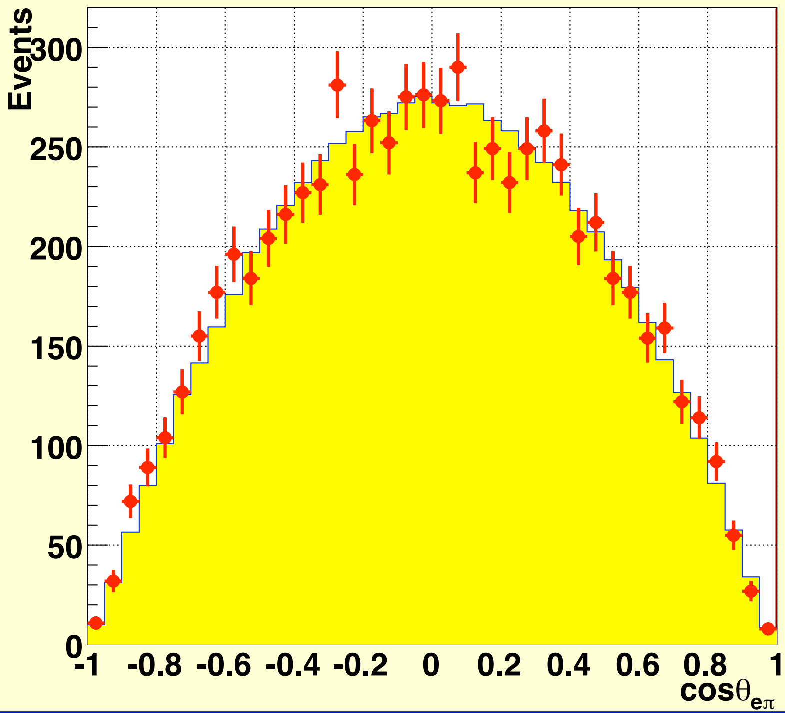
Limitations on reconstructed $e^+ e^- \gamma$ and $\pi^\pm e^+ e^- \gamma$ masses, total & transverse momentum

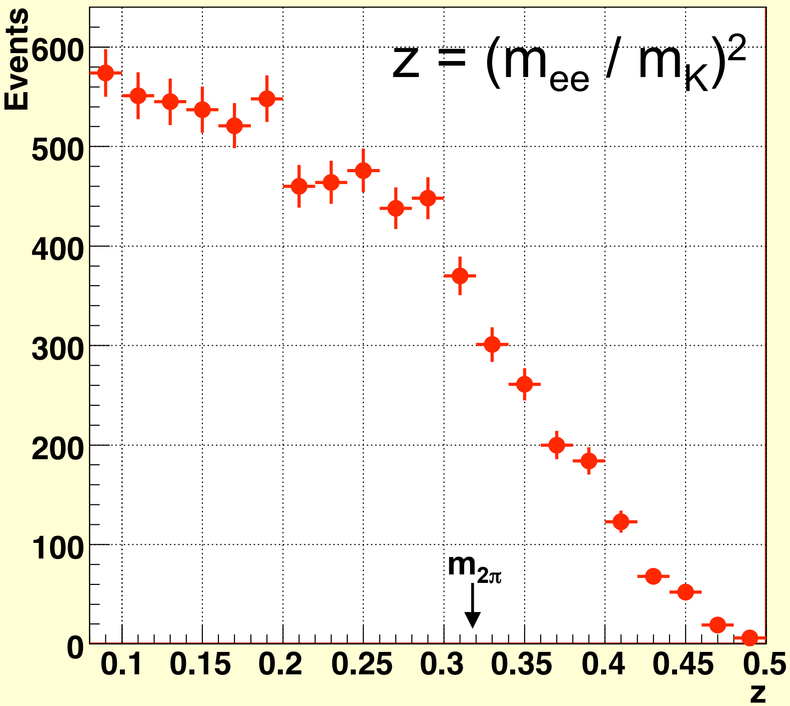
Kinematic Variables

No dynamical information from the angle between $(e^+, \pi^\pm)$ in (e^+, e^-) frame

$$\frac{d\Gamma}{d\vartheta} \sim \sin^2\vartheta = \left(1 - \cos^2\vartheta\right)$$

z distribution is sensitive to the Form Factors and contains all the dynamical information





Corrections and Uncertainties

Parameter	Electron ID	Beam Simulation	Radiative Corrections	Background to $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$	Trigger Inefficiency	Fitting Procedure	External (PDG)
$BR_{MI} \cdot 10^{7}$	0.02	0.01	0.01	-0.01±0.01	-0.01±0.01	-	0.06
Model (1): Linear							
δ	0.01	0.04	0.05	-0.04±0.04	-0.03±0.03	0.03	-
f_0	0.001	0.006	0.004	+0.002±0.002	+0.001±0.001	0.003	0.007
$BR_1 \cdot 10^{7}$	0.02	0.02	0.01	-0.01±0.01	-0.01±0.01	0.02	0.08
Model (2): $O(p^6)$ ChPT [D'Ambrosio, Ecker, Isidori, Portoles, hep-ph/9808289]							
a_+	0.001	0.005	0.004	-0.001±0.001	-0.002±0.002	0.004	0.007
b_+	0.009	0.015	0.022	+0.017±0.017	+0.015±0.015	0.010	0.017
$BR_2 \cdot 10^{7}$	0.02	0.02	0.01	-0.01±0.01	-0.01±0.01	0.02	0.08
Model (3): Dubna ChPT [Pervushin et al., hep-ph/0611175]							
M_a/GeV	0.004	0.009	0.009	+0.008±0.008	+0.006±0.006	0.006	0.002
M_ρ/GeV	0.002	0.003	0.004	+0.003±0.003	+0.003±0.003	0.002	0.002
$BR_3 \cdot 10^{7}$	0.02	0.02	0.01	-0.01±0.01	-0.01±0.01	0.02	0.08