Precision measurements of radiative charged Kaon decays at NA48/2

Andrea Bizzeti

University of Modena and Reggio Emilia
and INFN – Sezione di Firenze

on behalf of the NA48/2 Collaboration

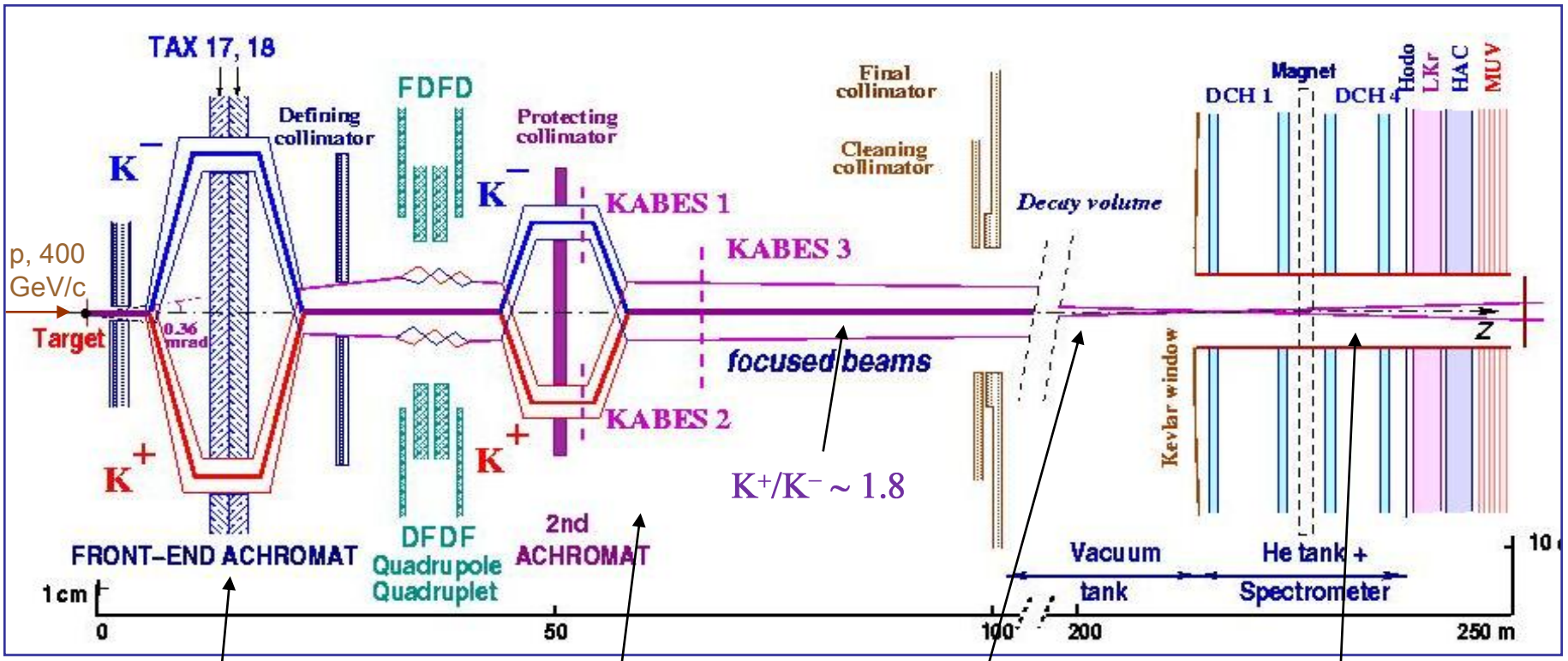
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

Excited QCD 09, Zakopane, february 11, 2009

Outline

- The NA48/2 experiment at CERN: beam and detector
- Study of the decays:
  - $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \gamma$ first observation of DE-IB interference
  - $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ high statistics
  - $K^{\pm} \rightarrow \pi^{\pm} e^+e^- \gamma$ first observation of the decay
  - $K^{\pm} \rightarrow \pi^{\pm} e^+e^-$ BR and Form Factor
- Conclusions

The NA48/2 beam line



Beam Spectrometer
(resolution 0.7 %)

Pion decay products are confined in the beam pipe

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

Decay volume (114m)

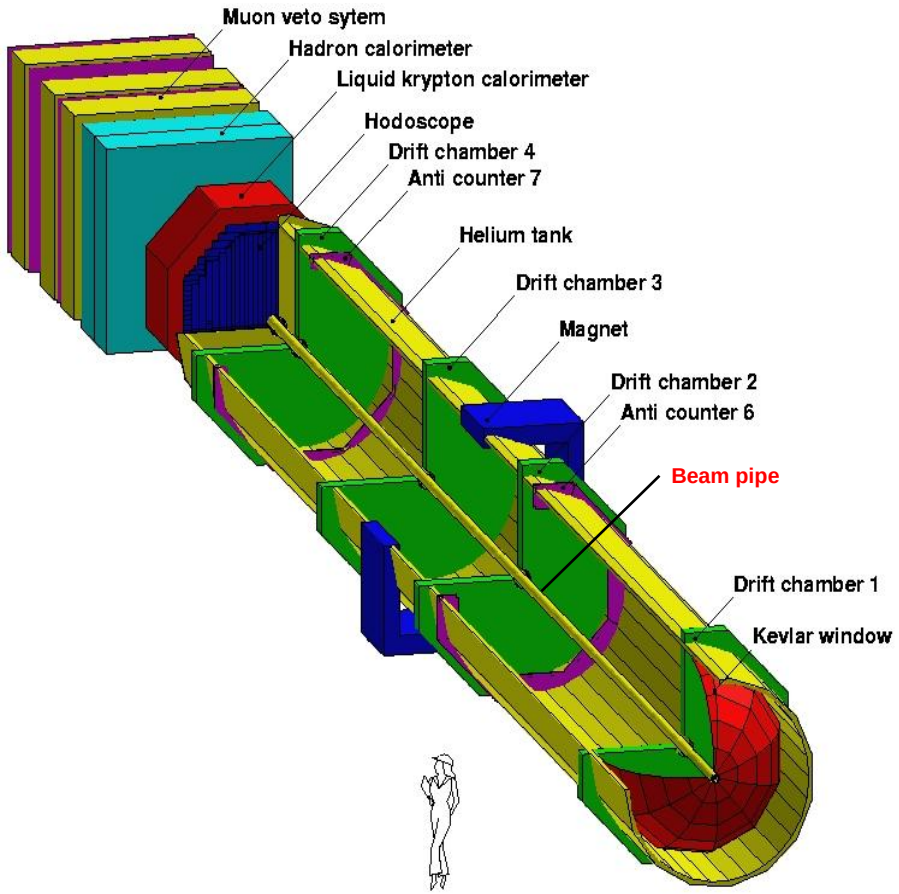
The NA48 detector

- Magnetic spectrometer :
  4 DCHs -> redundancy
  $\Delta p/p = 1.0\% + 0.044\% \cdot p$ [GeV/c]

- Liquid Krypton EM calorimeter (LKr) :
  High granularity, quasi-homogeneous
  $\Delta E/E = 3.2\%/\sqrt{E[GeV]} + 9\%/E[GeV] + 0.42\%$

- Scintillators hodoscope (2 planes) :
  fast trigger
  precise time measurement (150ps)

- hadron calorimeter
- muon veto counters
- photon vetoes



The NA48/2 data

2003 run: ~ 50 days
2004 run: ~ 60 days

$K_{3\pi}$ statistics in 2 years:

$K^{\pm} \rightarrow \pi^{\pm} \pi^{+}\pi^{-}$: ~ $4 \cdot 10^{9}$

$K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$: ~ $1 \cdot 10^{8}$

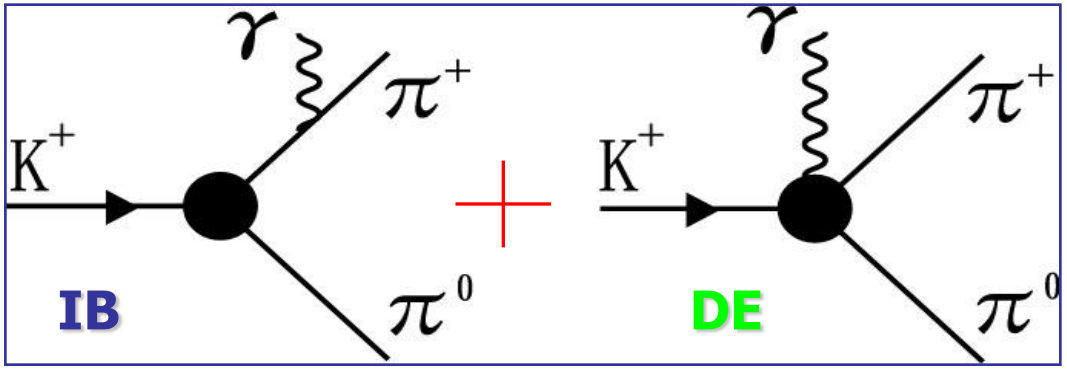
Rare $K^{\pm}$ decays:
Possibility to measure
BRs down to 10^{-9}

>200 TB of data recorded

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

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

Two amplitudes contribute to this decay:



IB : electric dipole, calculable (related to $K^{\pm} \rightarrow \pi^{\pm}\pi^0$ by Low's theorem)

DE : electric (E) and magnetic (M) amplitudes, both $O(p^4)$ in ChPT :

E : non predictable, interferes with IB amplitude

M : due to chiral anomaly (calculable) and direct contributions (non predictable)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: separating DE from IB

IB, DE amplitudes depend on 2 kinematical variables:

$T^*_\pi = \pi^{\pm}$ kinetic energy in the $K^{\pm}$ rest frame

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

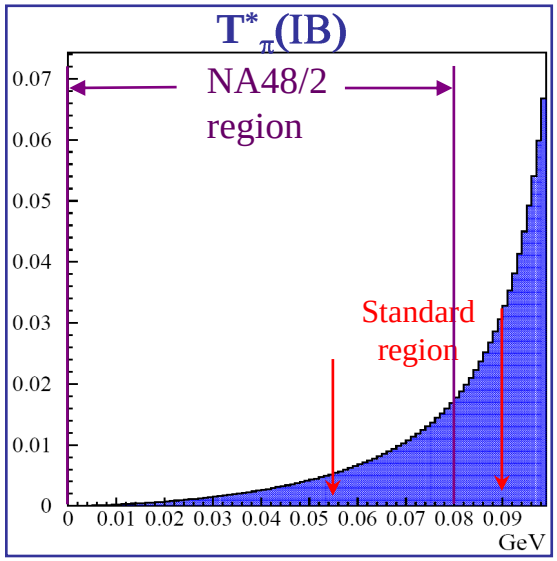
The decay width contains 3 terms (IB, DE and their interference INT), which can be disentangled using W variable (and integrating over T^*_π) :

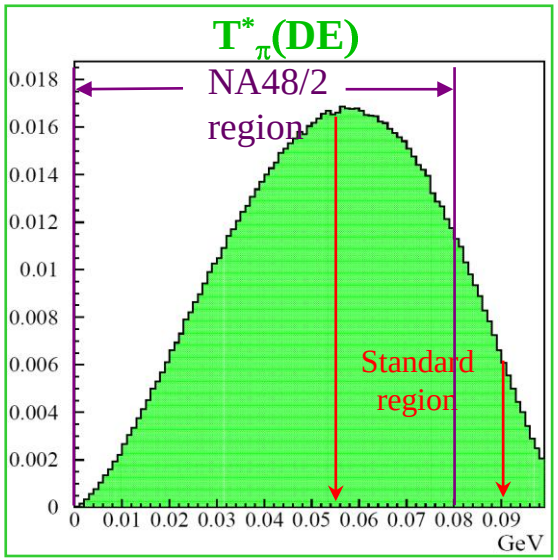
$$\frac{d\Gamma^{\pm}}{dW} \simeq \left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB} \left[\underbrace{1}_{\text{IB}} + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi)}_{\text{INT}} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)}_{\text{DE}} \right]$$

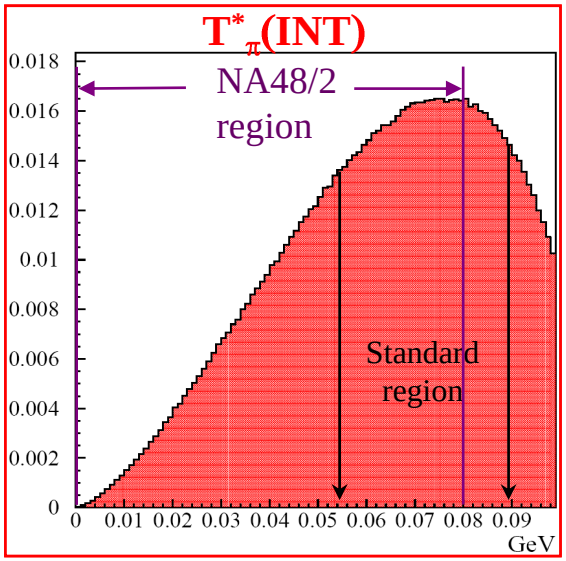
Current PDG values (55 MeV < T^*_π < 90 MeV)

Inner Bremsstrahlung (IB) :	BR = $(2.75 \pm 0.15) \cdot 10^{-4}$
Direct Emission (DE) :	BR = $(4.3 \pm 0.7) \cdot 10^{-6}$
Interference (INT) :	not yet measured

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: T^{*}_{π} region







55 MeV < T^{*}_{π} < 90 MeV region used in previous analyses to reject BG (mainly $\pi^{\pm}\pi^{0}$ and $\pi^{\pm}\pi^{0}\pi^{0}$). But…. this excludes most of the **DE** events

This measurement is performed in the region

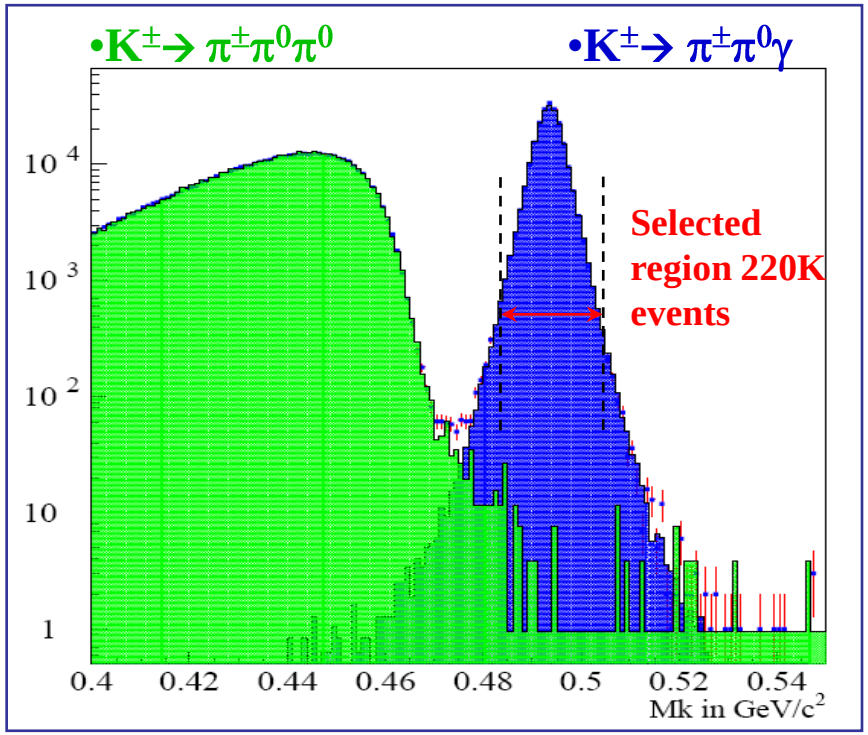
0 < T^{*}_{π} < 80 MeV

to improve statistics and sensitivity to **DE**

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

- Analysis of data taken in 2003
- Require at least 1 track and 3 photons
- Apply acceptance and BG-rejection cuts

  [$M_{inv}(\pi^{\pm}\pi^{0}\gamma)$, P_{tot} direction]



$M_{inv}(\pi^{\pm}\pi^{0}\gamma)$ [GeV/c^2]

- residual **BG** due only to $\pi^{\pm}\pi^{0}\pi^{0}$, <1% of DE
- γ mistagging probability (self BG) $\approx 10^{-3}$

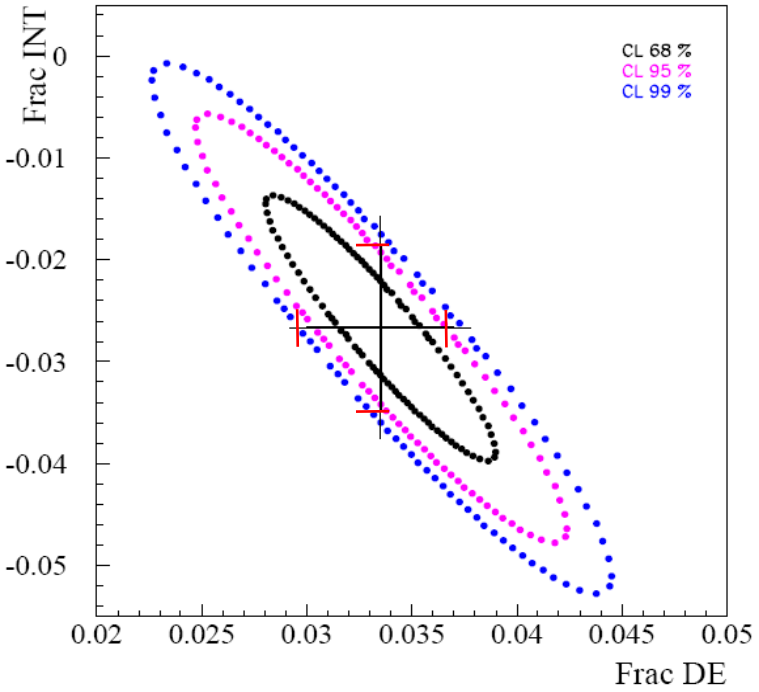
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: fit result

Fit the W data spectrum using MC shapes:

$$N(W)_{data}=(1-A-B)N(W)_{IB}+AN(W)_{DE}+BN(W)_{INT}$$

with **A** and **B** free parameters

- A and B highly correlated (corr. = -0.92)
- systematic dominated by trigger eff.
- B≠0 : first evidence of INT term



Preliminary results on 2003 data:

$$\text{Frac(DE)}_{0<T^*_\pi<80\ \text{MeV}} = (\ 3.35 \pm 0.35 \pm 0.25\ )\ \%$$

$$\text{Frac(INT)}_{0<T^*_\pi<80\ \text{MeV}} = (-2.67 \pm 0.81 \pm 0.73\ )\ \%$$

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

✓ complete NA48/2 data set (2003+2004) being analysed:

→ larger statistics (4x);

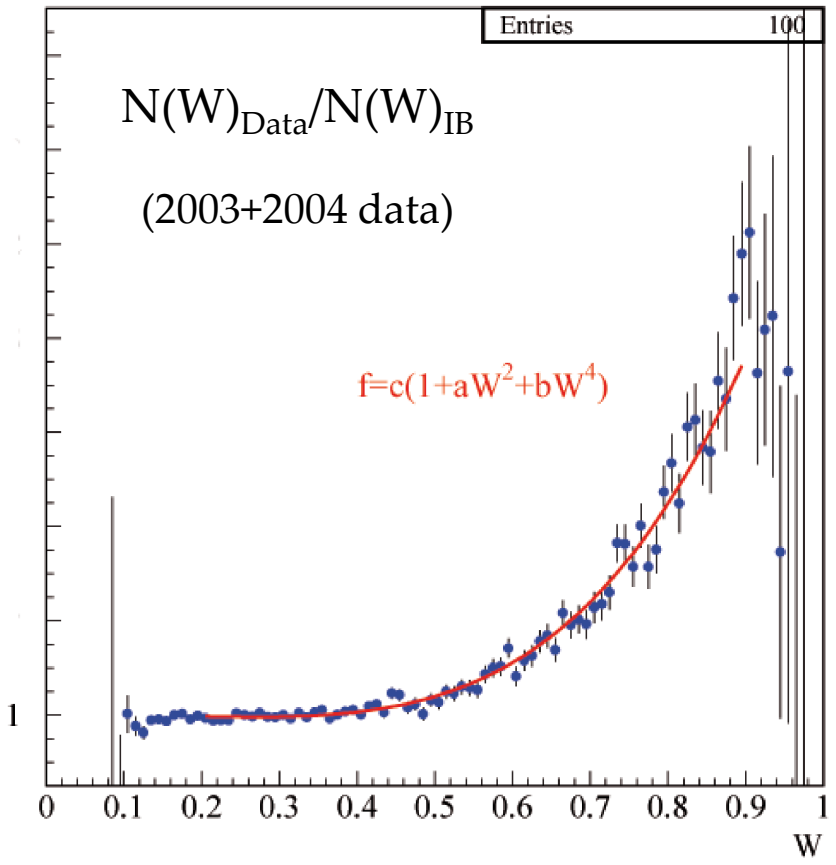
→ lower systematics (trigger)

→ also search for CP violating charge asymmetry

$$A_{CP} = \frac{B(K^+ \to \pi^+\pi^0\gamma) - B(K^- \to \pi^-\pi^0\gamma)}{B(K^+ \to \pi^+\pi^0\gamma) + B(K^- \to \pi^-\pi^0\gamma)}$$

with ≅ 10^{-3} sensitivity

→ final result will be ready soon

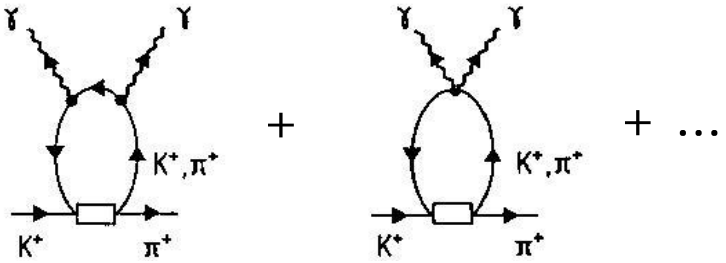


$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$

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

- Loop – induced decay:

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



- Decay rate $K^{\pm}(p) \to \pi^{\pm}(p)\,\gamma(q_1)\,\gamma(q_2)$:

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

- ChPT prediction:

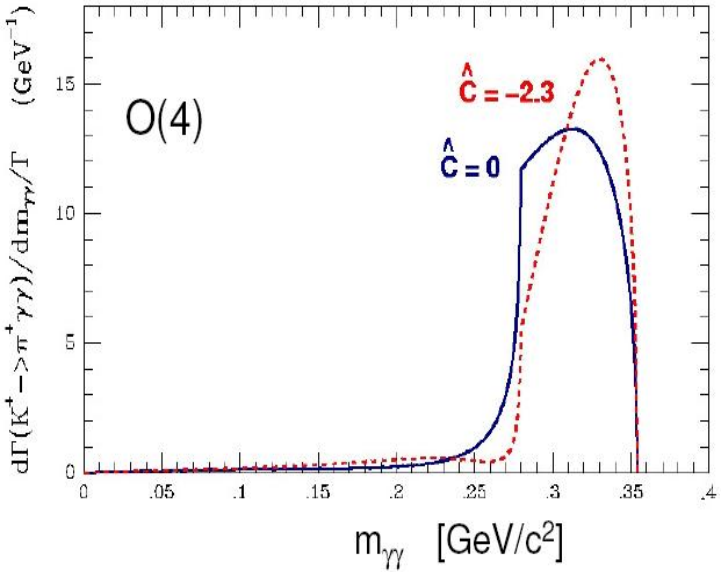
[D'Ambrosio, Portolés, PLB386 (1996) 403]

$O(p^4)$: $A = A(z;\hat{c}) \to$ cusp at $m_{\gamma\gamma} = 2m_\pi$;

$C = C(z)$ (~10% of A) ; $B=D=0$

$\hat{c}$ = unknown parameter ($\hat{c} \sim O(1)$)

$O(p^6)$: unitarity corrections can increase BR by 30-40% (depending on $\hat{c}$)

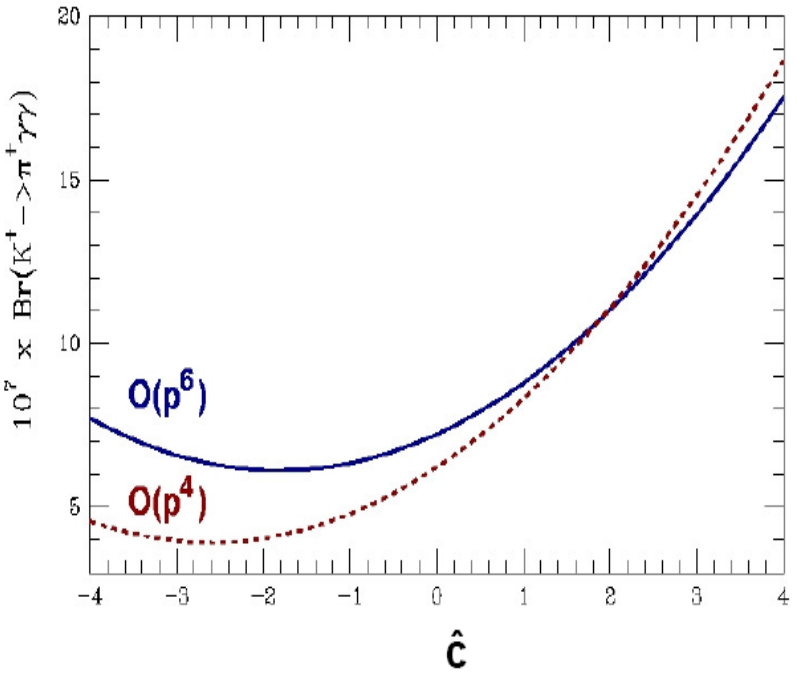


$K^{\pm} \to \pi^{\pm}\gamma\gamma$: Branching ratio

ChPT $O(p^4)$ predicts a dependence of the BR on the parameter $\hat{c}$:

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

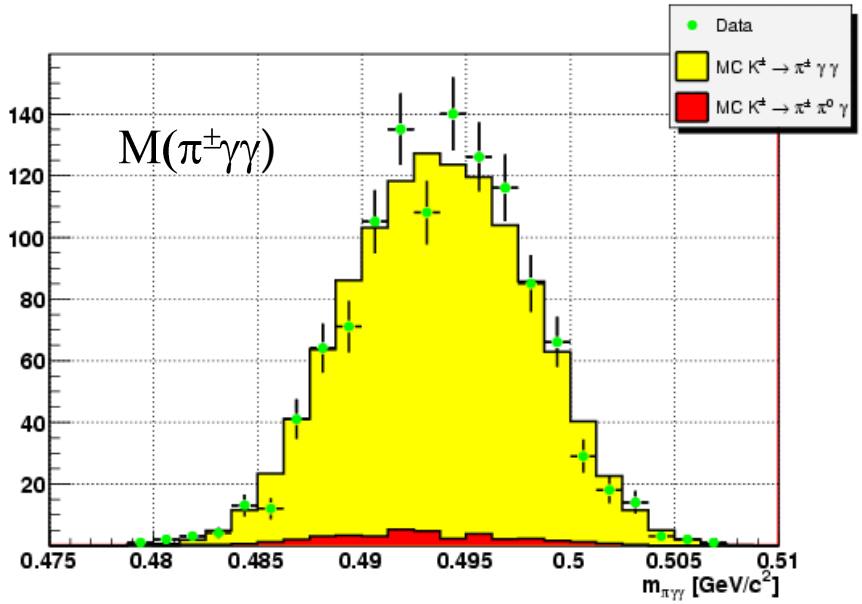
[Ecker, Pich, De Rafael, Nucl.Phys.B 303 (1998), 665]

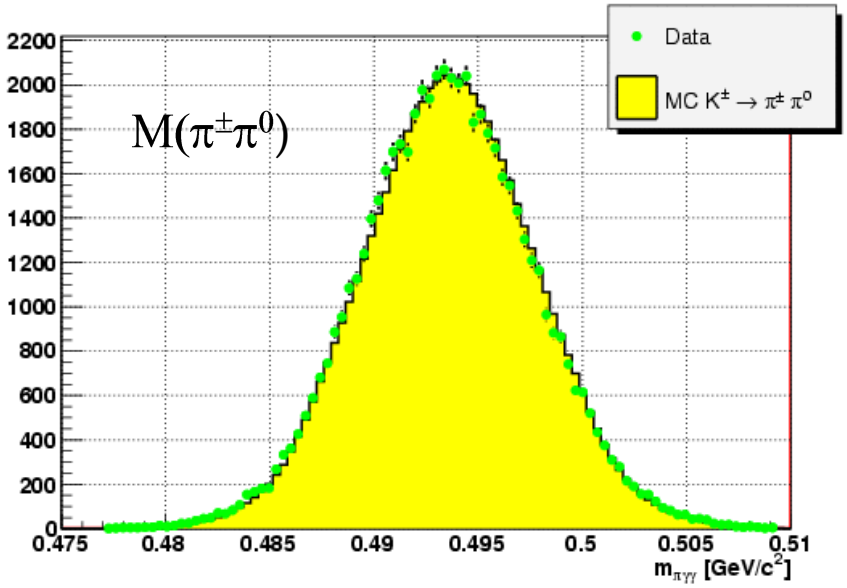


- Experimental goals:
  Measurement of BR and $\hat{c}$
- Existing measurement:
  $BR = (1.10 \pm 0.32) \times 10^{-6}$
  $\hat{c} = 1.8 \pm 0.6$
  [BNL E787 (1991), 31 evts.]

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

Data sample: 2003 data (40% of full statistics)





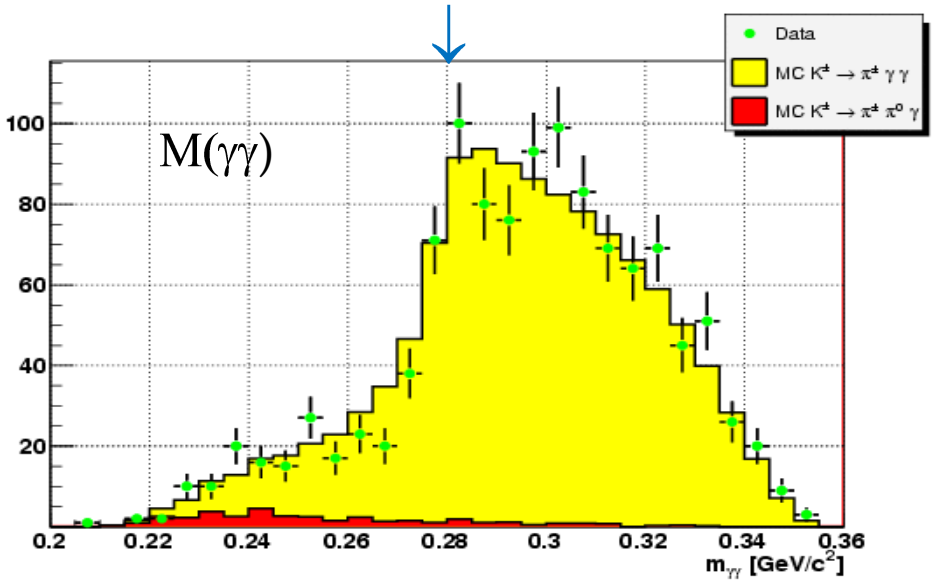
Signal :

- 1 track + 2 photons + kinematical cuts
- 1164 events (~40× world sample)
- Background: 3.3% (eval. from MC) from $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ (IB)

Normalization channel $K^{\pm} \to \pi^{\pm}\pi^{0}$:

- Same particles in final state → first order cancellation of systematics
- Very large sample (6M events) with known BR

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: preliminary results



- Clear evidence for the cusp at $m_{\gamma\gamma} = 0.28$ GeV/c^2
- Good agreement with $O(p^6)$ $\hat{c}$=2 generated MC sample

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

(preliminary, model dependent)

Next tasks:

- analysis of full data sample (~6000 events)
- $\hat{c}$ measurement

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

$K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-} \gamma$: Theory

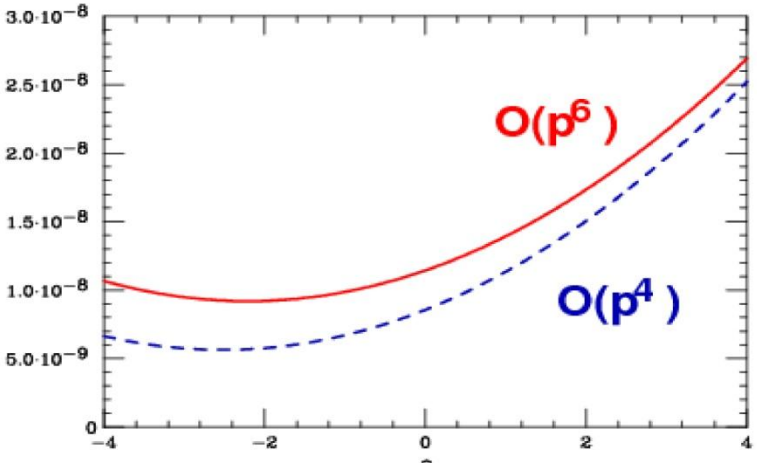
Theory is similar to $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ decay

[Gabbiani, Phys. Rev. D 59 (1999), 094022]

- Cusp $m_{\gamma\gamma}=2m_{\pi}$ expected by $O(p^4)$ ChPT
- Naïve expectation:
  $BR(K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma) \sim BR(K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma) \cdot 2\alpha \sim 1.6 \cdot 10^{-8}$
- ChPT uncertainty dominated by $\hat{c}$
- $O(p^6)$ increases BR of ~40% wrt $O(p^4)$

ChPT $O(p^6)$ predicts BR = $(0.9 \sim 1.7) \times 10^{-8}$

ChPT: predicted BR as a function of $\hat{c}$



Experimental goals

- Model-independent BR measurement (limited to visible kinematical range)
- Determination of $\hat{c}$ from the data
- Use $\hat{c}$ to compute model-dependent BR (in the full kinematical range)

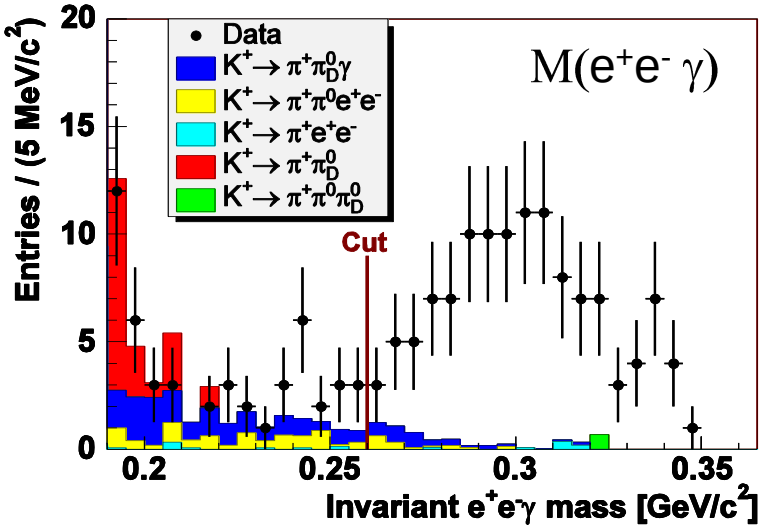
Existing measurement:

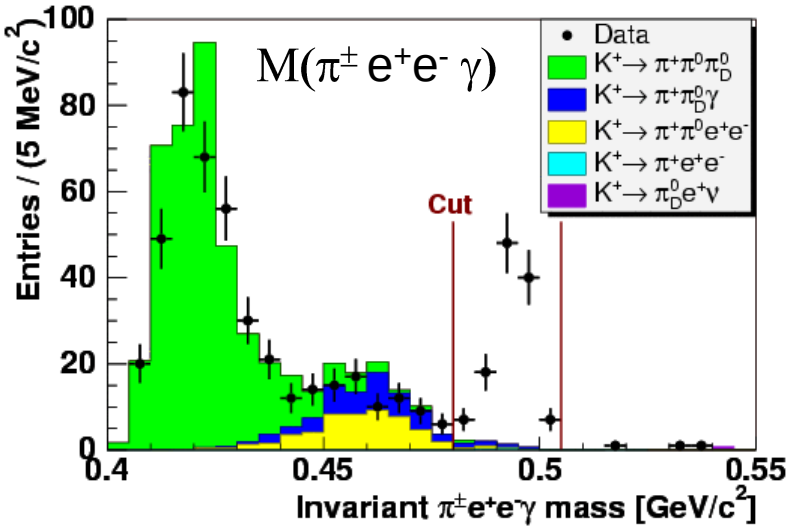
- Never observed

$K^{\pm} \rightarrow \pi^{\pm} e^+e^- \gamma$: event selection

Data sample: 2003 and 2004 NA48/2 $K^{\pm}$ runs.

Event selection: 3 tracks + 1 photon, $e^{\pm}$ ID(E/p), kin. cuts ($M_{ee\gamma}$, $M_{\pi ee\gamma}$, $\vartheta_{e\gamma}$)





Signal region: $M_{ee\gamma} > 260$ MeV/c^2

Signal: 120 events

Background: 6% (MC estimate)

FIRST OBSERVATION of this decay

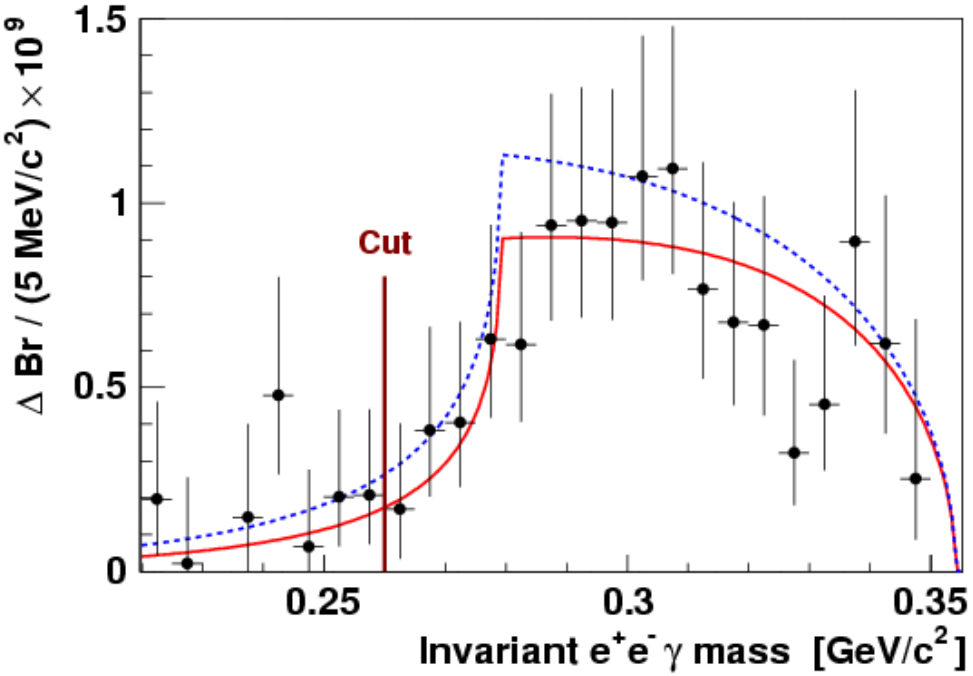
Normalization channel $K^{\pm} \rightarrow \pi^{\pm}\pi^0_D$

- Same particles in final state
- First order cancellation of systematics

Normalization: 14M events

$K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-} \gamma$: results

- Model independent BR measured in bins of $M_{ee\gamma}$ (each bin 5 MeV/c^2 wide)
- Least squares fit on $M_{ee\gamma}$ to extract $\hat{c}$
- Main systematics:
  - BG subtraction
  - normalization
  - MC statistics



NA48/2 final results:

$BR_{MI} = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \times 10^{-8}$ ($M_{ee\gamma} > 0.260$ MeV/c^2, model independent)

$\hat{c} = 0.90 \pm 0.45$ (1.2σ from BNL E787 result in $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$: $\hat{c} = 1.8 \pm 0.6$)

$BR = (1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}}) \times 10^{-8}$ (model dependent, assuming $\hat{c} = 0.9 \pm 0.45$)

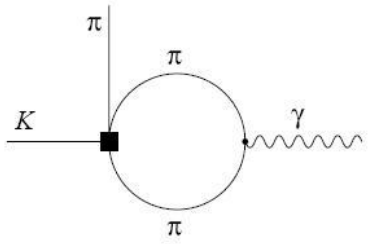
Errors dominated by statistics

Phys. Lett. B 695 (2008) 493

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

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

- Suppressed FCNC process
- Loop -induced decay ($K^{\pm} \rightarrow \pi^{\pm}\gamma^{*}$)



$$d\Gamma/dz = P(z)\,|W(z)|^2$$

P(z) = phase space factor

$z = (M_{ee}/M_K)^2$

- Different models tested for W(z):
  - Polynomial: $W(z) = G_F M_K^2 f_0 \cdot (1 + \delta \cdot z)$
  - ChPT O(p^6): $W(z) = G_F M_K^2 \cdot (a_+ + b_+ z) + W^{\pi\pi}(z)$ [JHEP 8 (1998) 4]
  - "Dubna" ChPT: $W(z) = W(M_a, M_\rho, z)$ [hep-ph/0611175]

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

- Experimental goals:
  - model-independent BR(z>0.8) in accepted kinematical range
  - for each model: parameters and BR in the full kinematical range

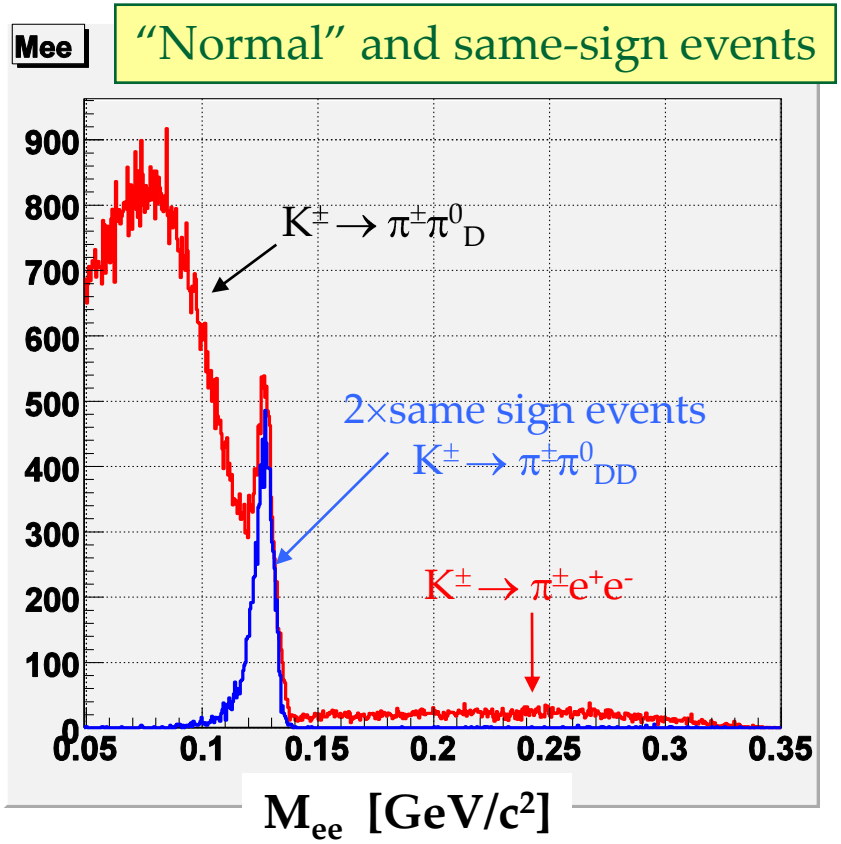
- Previous measurements: $BR = (2.94 \pm 0.15) \cdot 10^{-7}$ [BNL E865 (1999), 10300 evts]

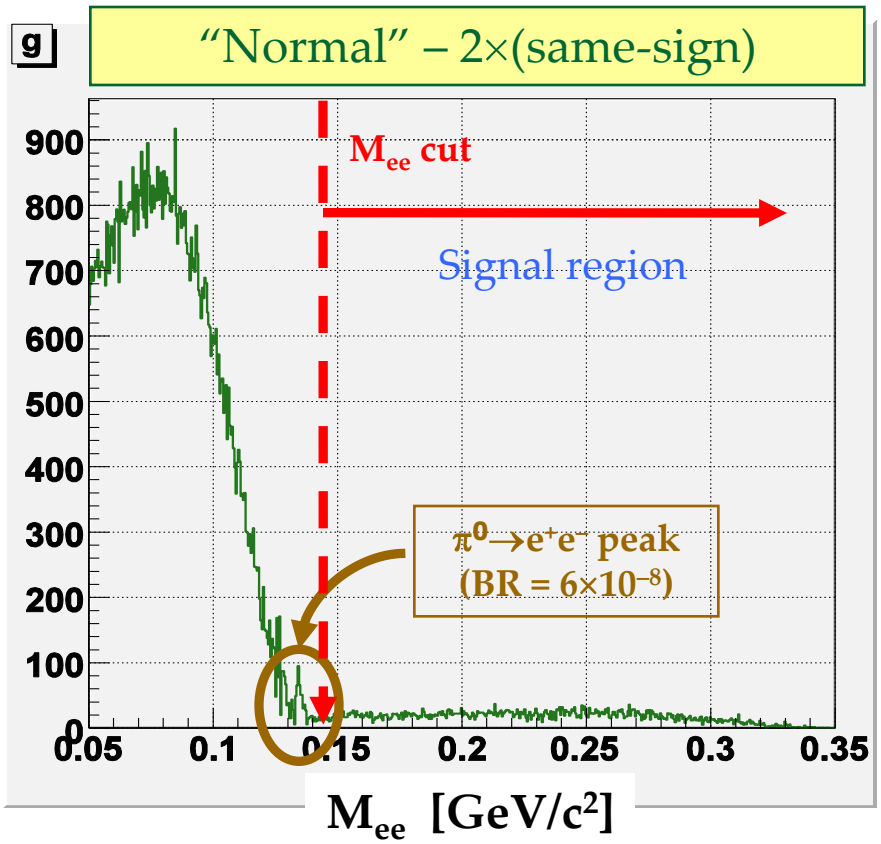
$K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-}$: event selection

- Data sample: 2003 + 2004 runs
- Event selection: 3 tracks, particle ID (E/p), invariant mass cut
- Background subtraction:
  - MC used only to identify BG
  - BG by particle misID ($\pi^{\pm} \leftrightarrow e^{\pm}$) in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$ and $K^{\pm} \rightarrow e^{\pm}\nu\pi^{0}_{D}$) estimated directly on data using "same sign" ($\pi^{+}e^{-}e^{-}$) events

- Normalization channel: $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D} \rightarrow \pi^{+} e^{+}e^{-} \gamma$
  - Same final state as the signal, plus one photon
  - Same charged particles → first order cancellation of systematics (trigger and PID inefficiency) in the BR ratio
  - Large sample with known BR.

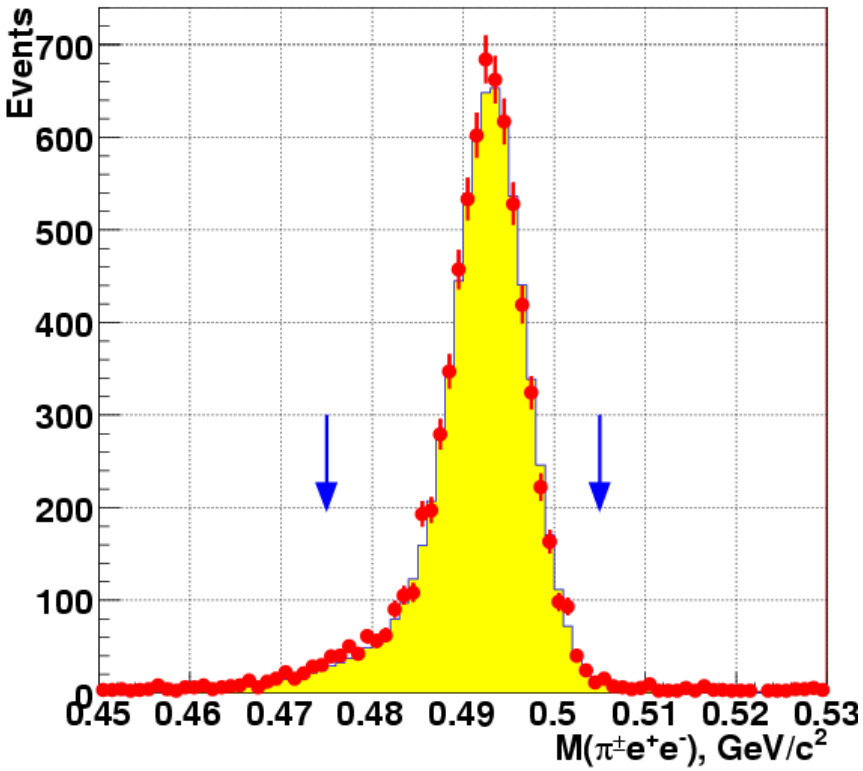
$K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-}$: Signal region

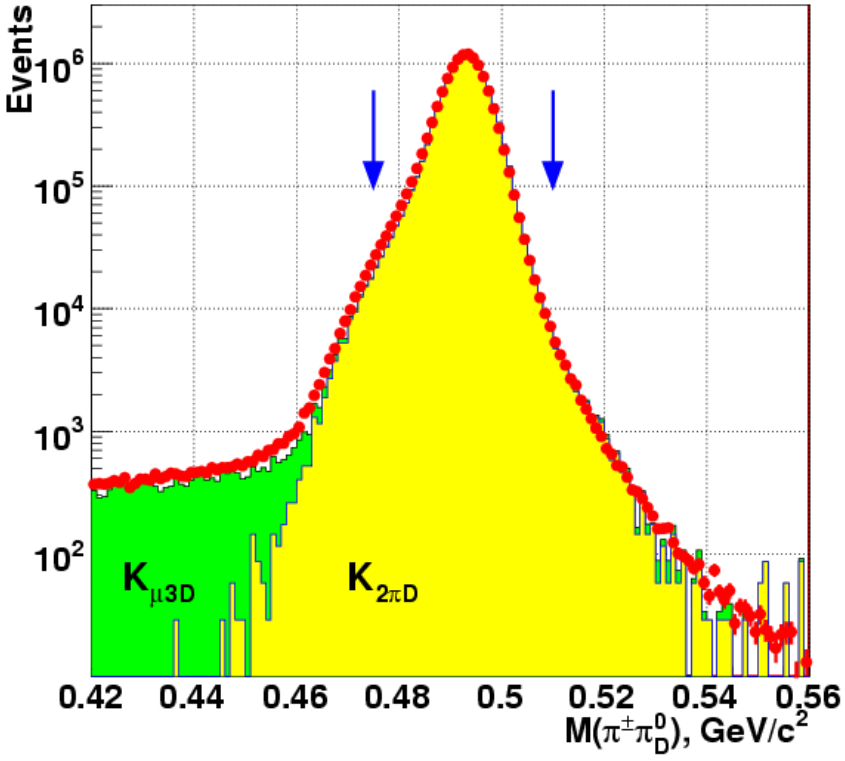




- $M_{ee} > 140$ MeV/c^2 ($z > 0.08$) : signal region
  - $M_{ee} < 140$MeV/c^2 dominated by background ($K^{\pm} \rightarrow \pi^{+}\pi^{0}_{D}$, $K^{\pm} \rightarrow \pi^{+}\pi^{0}_{DD}$)
  - After BG subtraction, the $\pi^0 \rightarrow e^+e^-$ peak (~500 events) can be seen

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





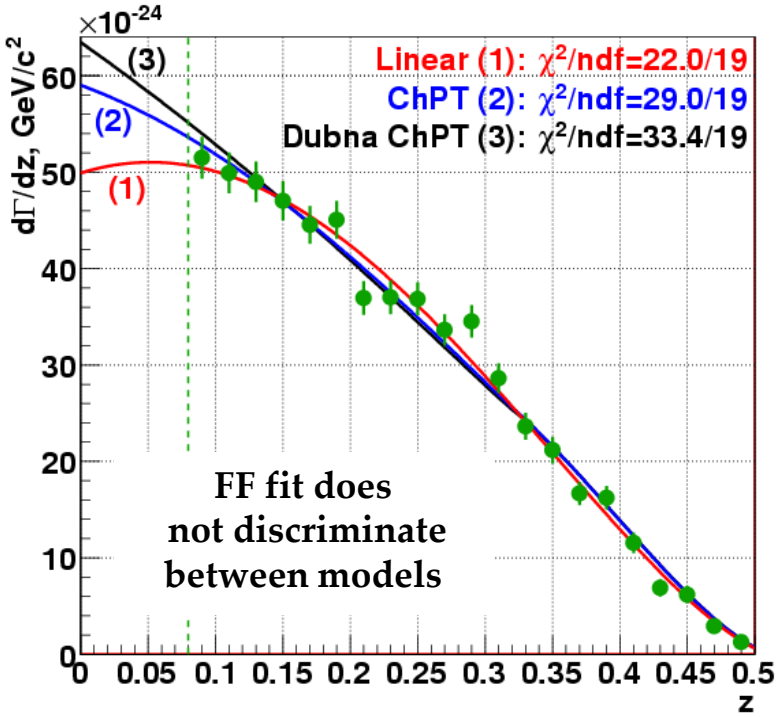
- Signal: 7146 candidates

Background: 0.6% (from same sign events), due to particle misID($\pi^{\pm} \leftrightarrow e^{\pm}$) in $K^{\pm} \rightarrow \pi^{\pm} \pi^{0}_{D}$, $\pi^{0}_{D} e^{\pm} \nu$

- Normalization: 12.2×10^{6} events
  - Background: ~0.15% ($K^{\pm} \rightarrow \pi^{0}_{D} \mu^{\pm} \nu$)
  - BR($\pi^{\pm}\pi^{0}$) from PDG

$K^{\pm} \rightarrow \pi^{\pm} e^{+}e^{-}$: Preliminary Results

Measured dΓ/dz
(corrected for acceptance)



Model independent BR ($z > 0.08$):

$$BR = (2.26 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.06_{ext}) \times 10^{-7}$$

Form factors (fit to dΓ/dz):

- Polynomial

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

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

- ChPT

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

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

- "Dubna" ChPT (GeV/c^2)

$$M_a = 0.965 \pm 0.028_{stat} \pm 0.018_{syst} \pm 0.002_{ext}$$

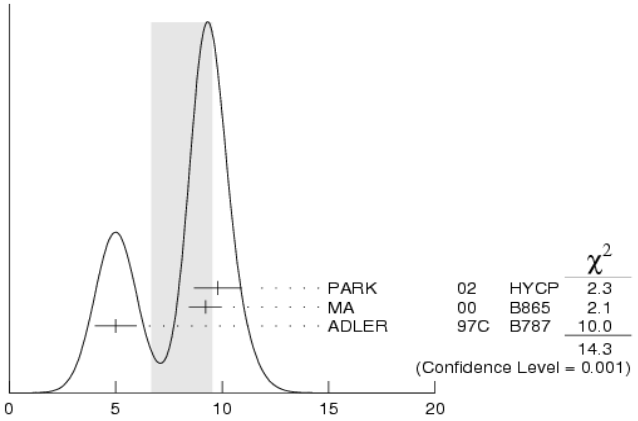
$$M_\rho = 0.711 \pm 0.010_{stat} \pm 0.007_{syst} \pm 0.002_{ext}$$

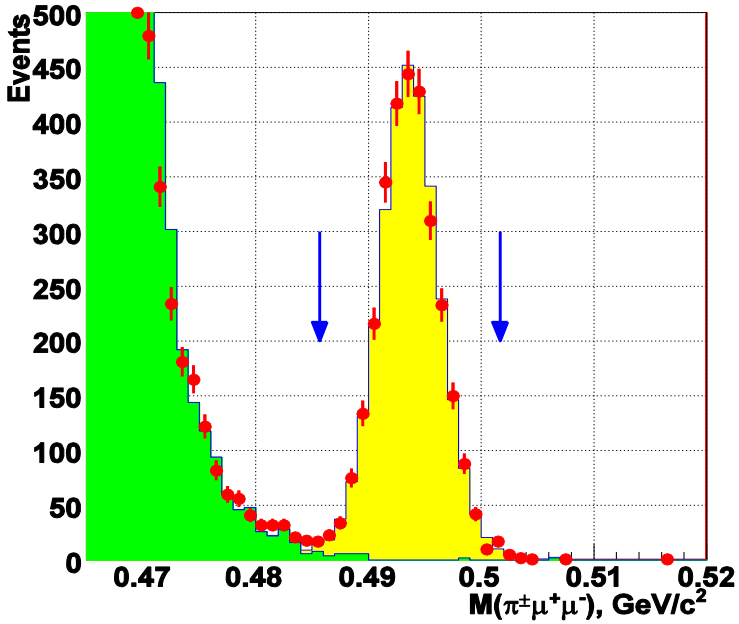
$BR = (3.08 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext} \pm 0.07_{model}) \times 10^{-7}$
(including uncertainty due to model dependence), in agreement with BNL E865 result

CPV asymm.: $(BR^+ - BR^-)/(BR^+ + BR^-) = (-2.1 \pm 1.5_{stat} \pm 0.3_{syst})\%$ (first measurement)

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

- Previous experiments:
  - <800 world sample (BNL E865 ~400, HyperCP@FNAL ~110 in 20% of data)
  - Poor PDG agreement on BR
  - Linear form factor agrees with πee
- Experimental difficulty
  - Large BG from $K \rightarrow 3\pi$ (E865: 6.5%)
- NA48/2 analysis on going
  - 2003 + 2004 data
  - Few thousands of events
  - Background O(1%)





Conclusions

- $K^{\pm} \to \pi^{\pm} \pi^0 \gamma$: first evidence of DE-IB interference in the decay
  - Measurement of DE/IB and INT/IB branching ratios
- $K^{\pm} \to \pi^{\pm} \gamma \gamma$: statistics improved 40x wrt previous measurements
  - Clear evidence for the 2π cusp
  - Measured BR in agreement with ChPT
- $K^{\pm} \to \pi^{\pm} e^+e^- \gamma$: first observation
  - Independent evidence for the 2π cusp
  - Final results on BR and shape analysis (ChPT parameter $\hat{c}$)
- $K^{\pm} \to \pi^{\pm} e^+e^-$: Sample and precision comparable to world's best ones
  - BR and FF in agreement with ChPT and other measurements
  - First limit on the CP violating charge asymmetry
- Large sample of $K^{\pm} \to \pi^{\pm}\mu^+\mu^-$ with small background (analysis on-going)