



Precision measurements of radiative charged Kaon decays at NA48/2

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on behalf of the NA48/2 Collaboration

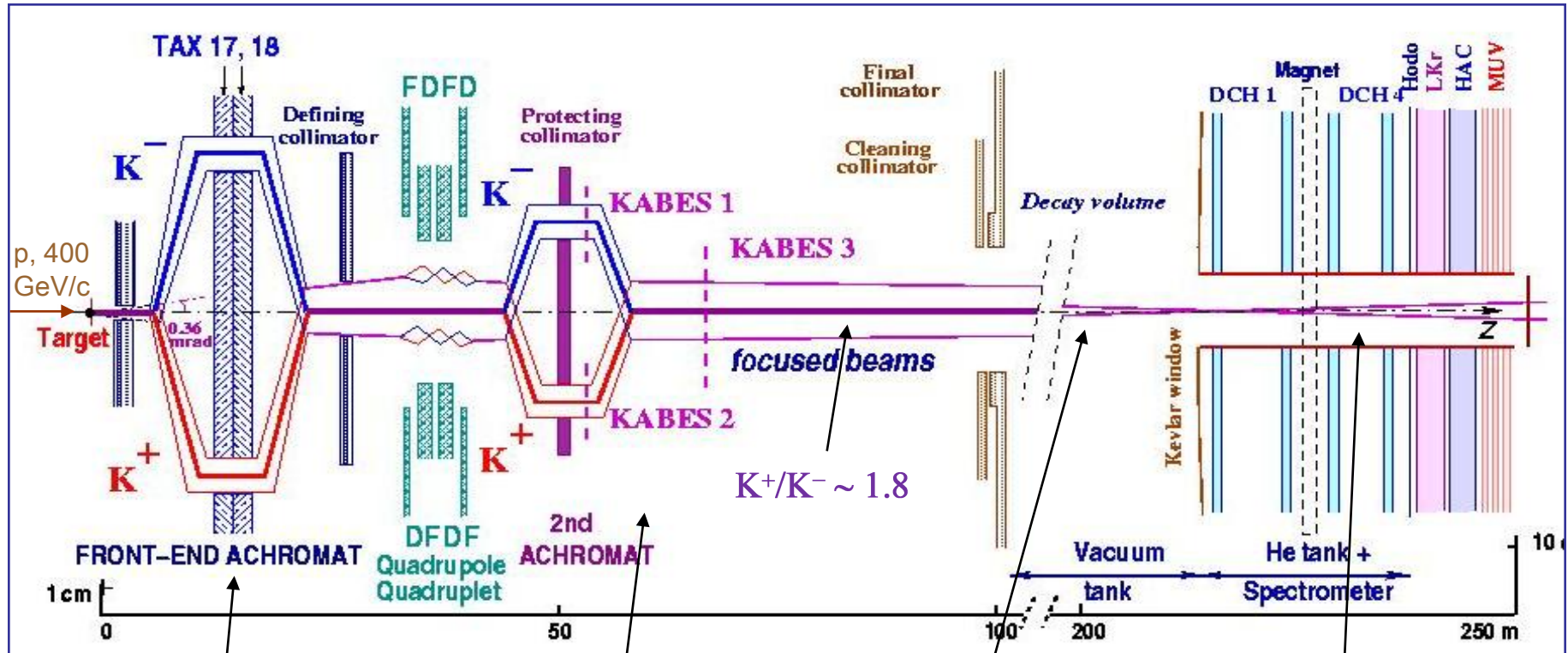
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz,
Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

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 %)

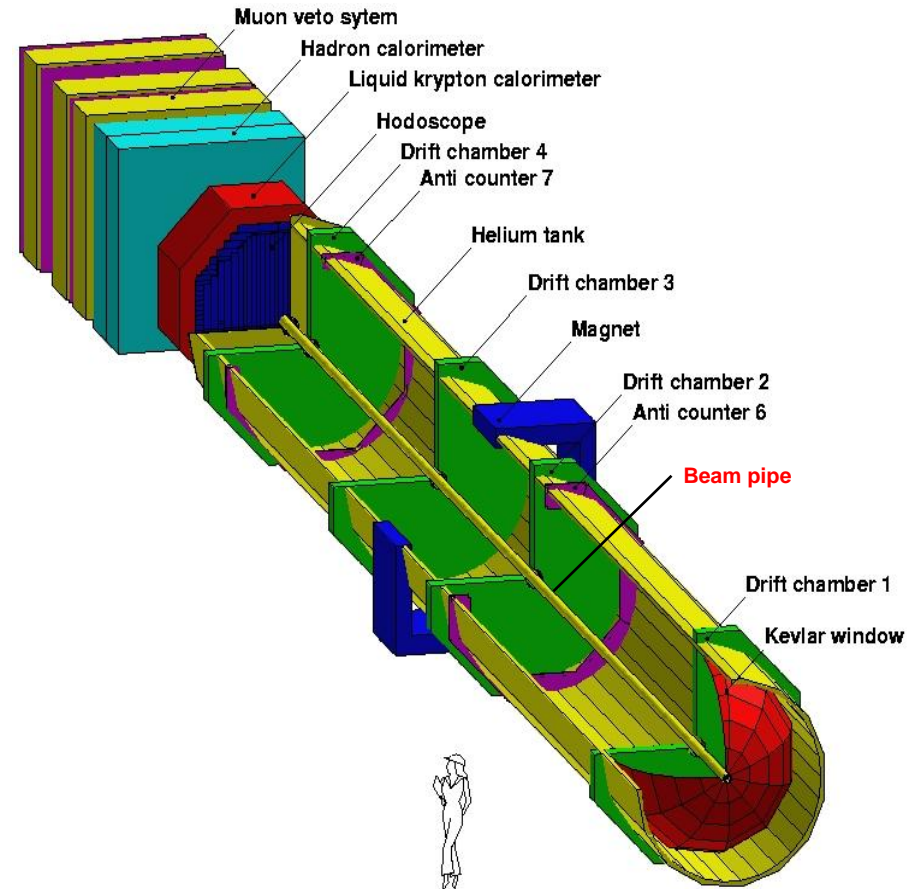
Decay volume (114m)

Pion decay products are confined in the beam pipe

- Split +/-
- Select $P=(60\pm 3)\text{GeV/c}$
- Recombine +/-

The NA48 detector

- Magnetic spectrometer :
4 DCHs -> redundancy
 $\Delta p/p = 1.0\% + 0.044\% \cdot p \text{ [GeV/c]}$
- Liquid Krypton EM calorimeter (LKr) :
High granularity, quasi-homogeneous
 $\Delta E/E = 3.2\%/\sqrt{E[\text{GeV}]} + 9\%/E[\text{GeV}] + 0.42\%$
- 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:

$K^\pm \rightarrow \pi^\pm \pi^+ \pi^- : \sim 4 \cdot 10^9$

$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 : \sim 1 \cdot 10^8$

Rare K^\pm decays:

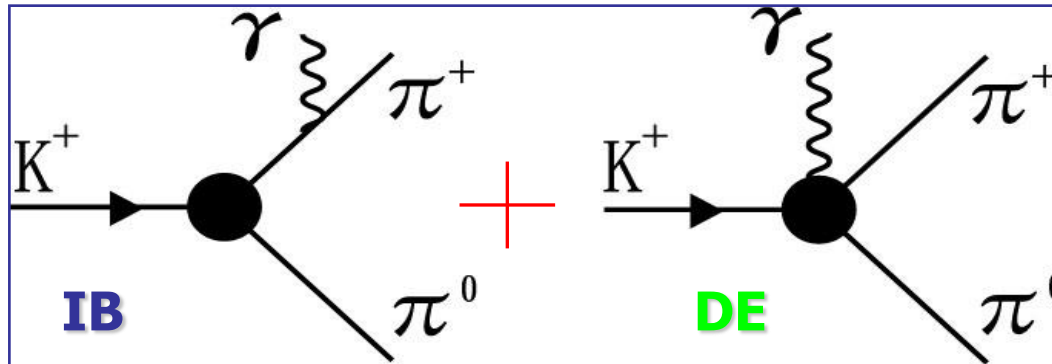
Possibility to measure
BRs down to 10^{-9}

>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^*):

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

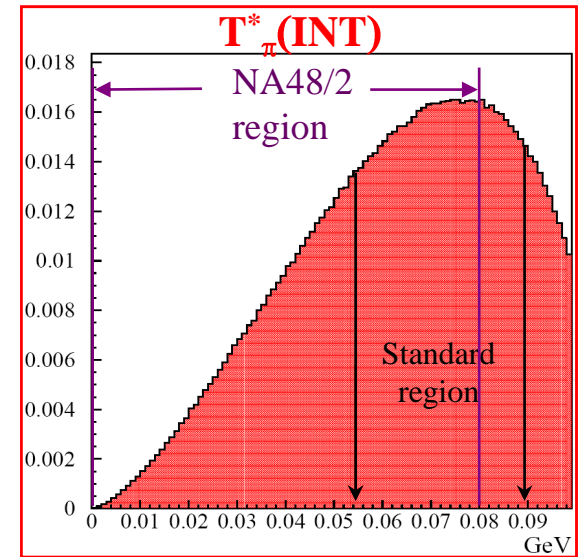
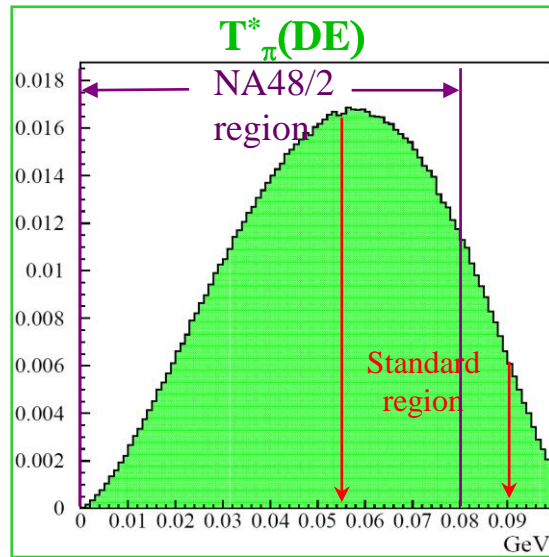
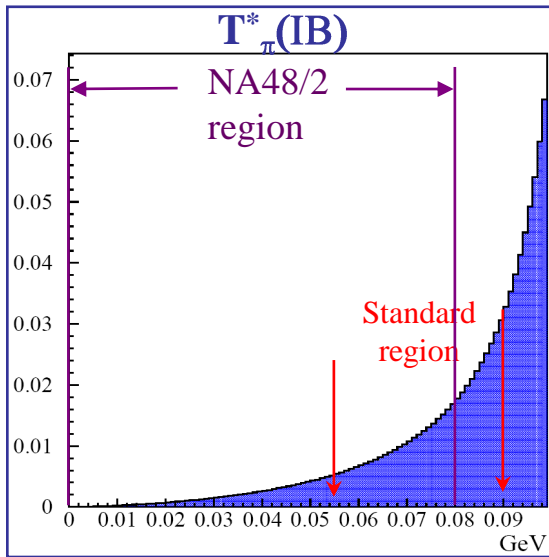
Current PDG values ($55 \text{ MeV} < T_\pi^* < 90 \text{ MeV}$)

Inner Bremsstrahlung (IB) : $\text{BR} = (2.75 \pm 0.15) \cdot 10^{-4}$

Direct Emission (DE) : $\text{BR} = (4.3 \pm 0.7) \cdot 10^{-6}$

Interference (INT) : not yet measured

$K^\pm \rightarrow \pi^\pm \pi^0 \gamma : T_\pi^*$ region



$55 \text{ MeV} < T_\pi^* < 90 \text{ MeV}$ 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

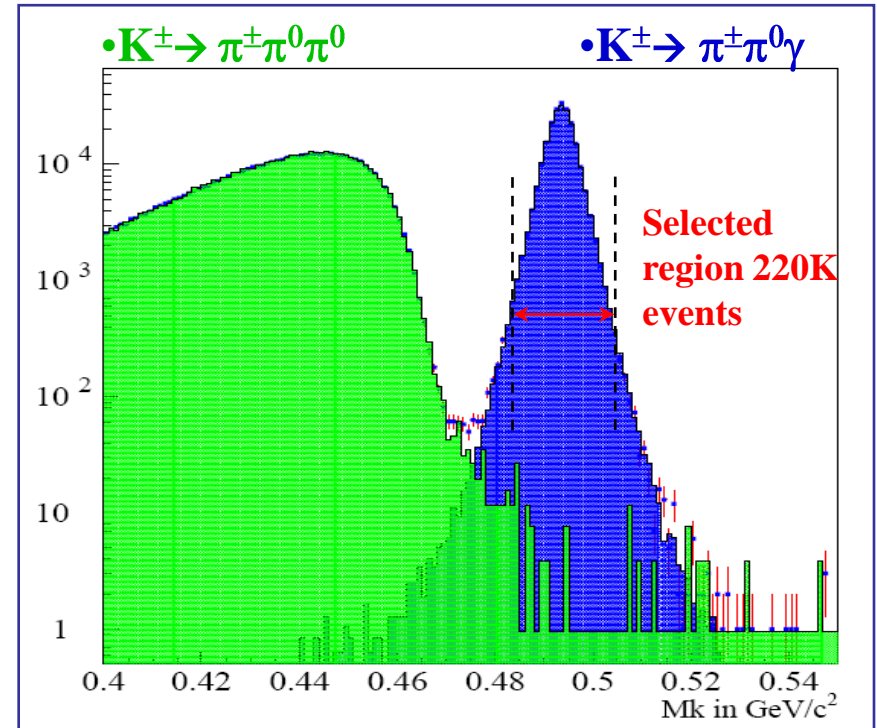
$$0 < T_\pi^* < 80 \text{ MeV}$$

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

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



$M_{\text{inv}}(\pi^\pm \pi^0 \gamma)$ [GeV/c²]

- 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:

$$N(W)_{\text{data}} = (1 - \mathbf{A} - \mathbf{B})N(W)_{\text{IB}} + \mathbf{A}N(W)_{\text{DE}} + \mathbf{B}N(W)_{\text{INT}}$$

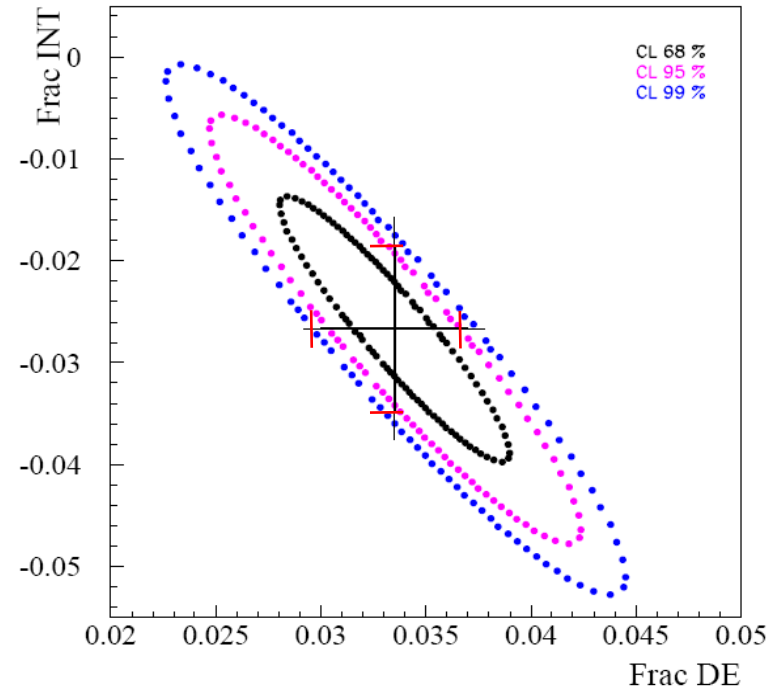
with \mathbf{A} and \mathbf{B} free parameters

- \mathbf{A} and \mathbf{B} highly correlated (corr. = -0.92)
- systematic dominated by trigger eff.
- $\mathbf{B} \neq 0$: first evidence of INT term

Preliminary results on 2003 data:

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

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



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

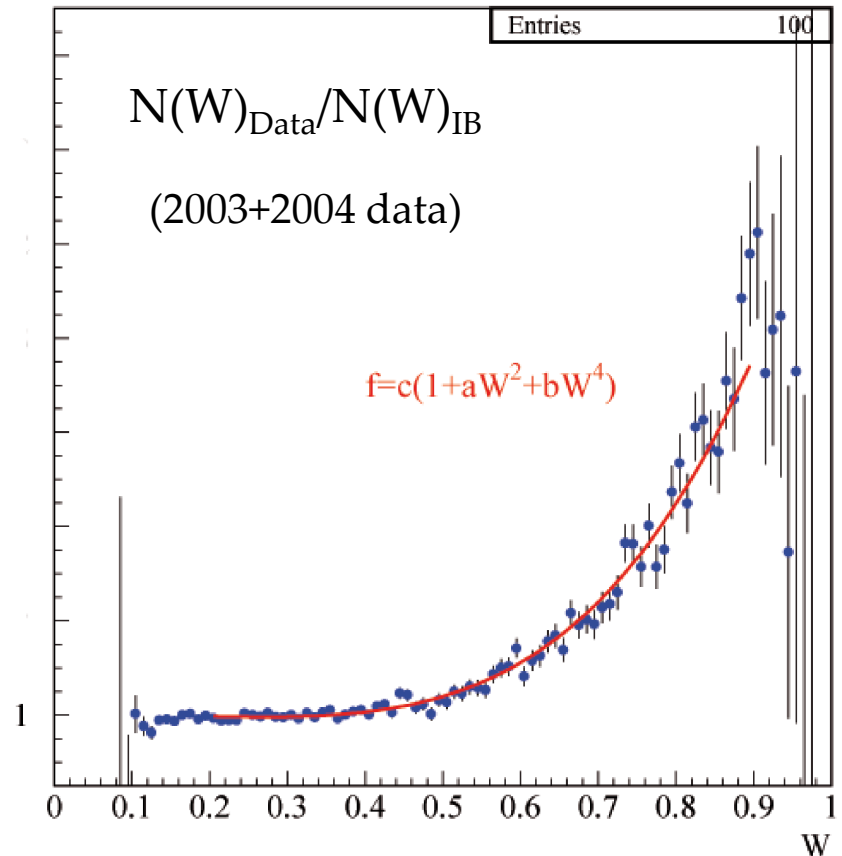
✓ complete NA48/2 data set (2003+2004) being analysed:

- larger statistics (4x);
- lower systematics (trigger)
- also search for CP violating charge asymmetry

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

with $\cong 10^{-3}$ sensitivity

- final result will be ready soon

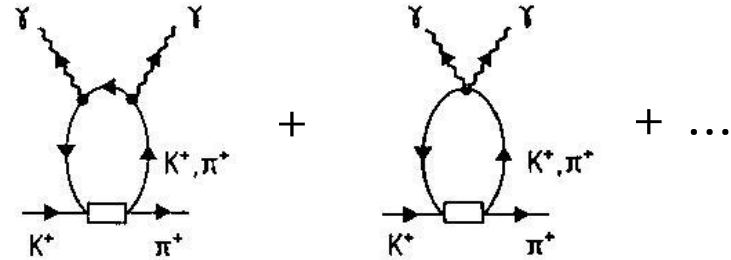


$$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$$

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

- Loop – induced decay:

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



- Decay rate $K^\pm(p) \rightarrow \pi^\pm(p) \gamma(q_1) \gamma(q_2)$:

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

- ChPT prediction:

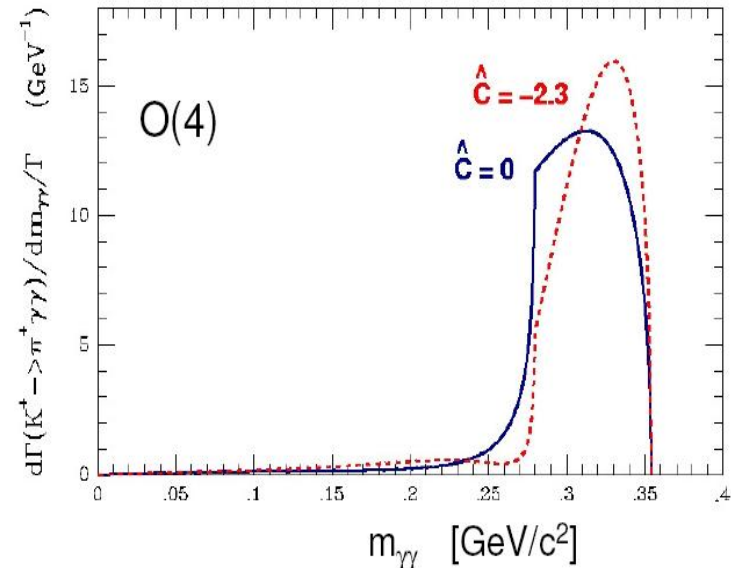
[D'Ambrosio, Portolés, PLB386 (1996) 403]

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

$C = C(z)$ ($\sim 10\%$ 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})

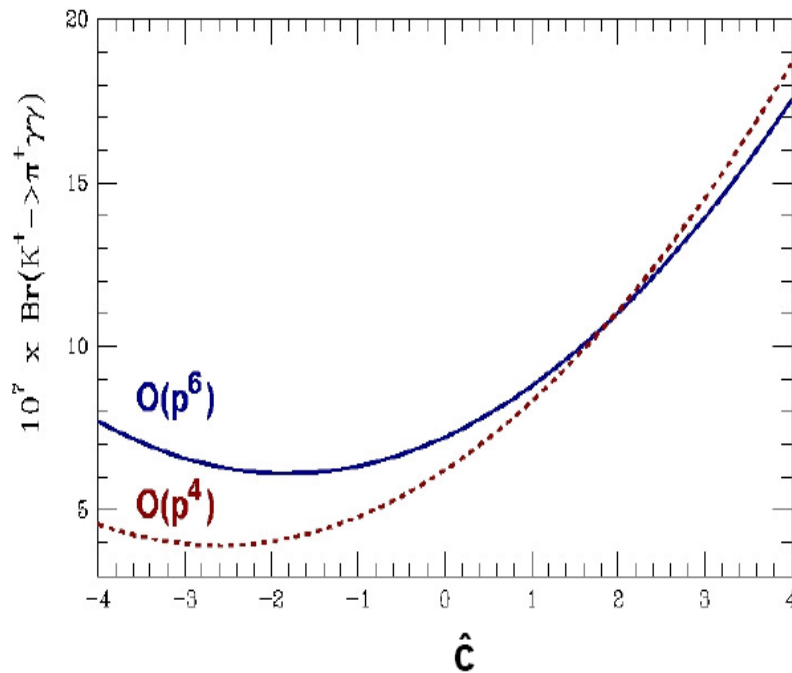


$K^\pm \rightarrow \pi^\pm \gamma\gamma$: Branching ratio

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

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

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



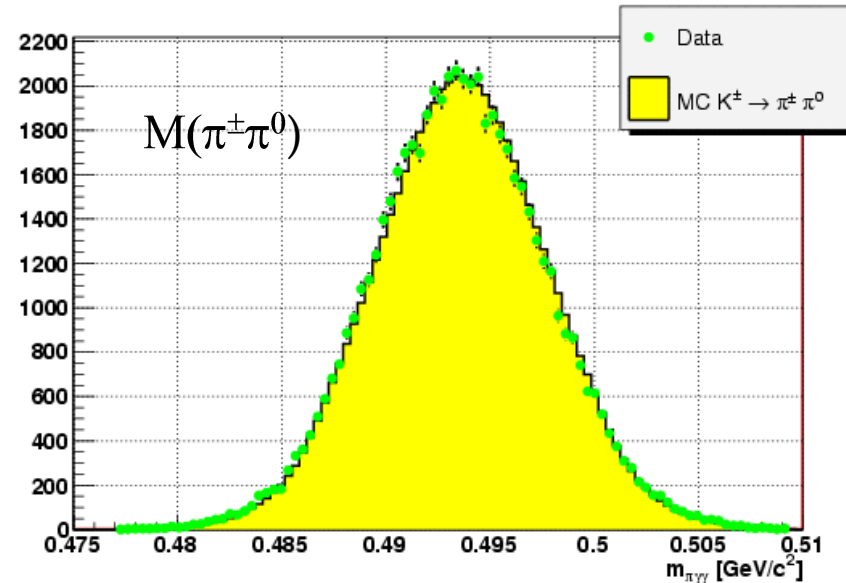
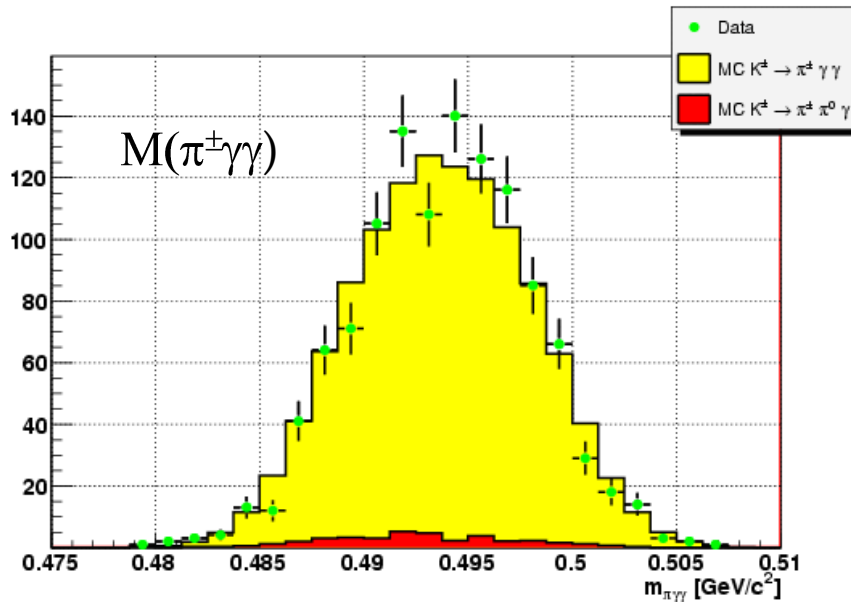
- Experimental goals:
Measurement of BR and \hat{c}

- Existing measurement:
 $\text{BR} = (1.10 \pm 0.32) \times 10^{-6}$
 $\hat{c} = 1.8 \pm 0.6$

[BNL E787 (1991), 31 evts.]

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

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



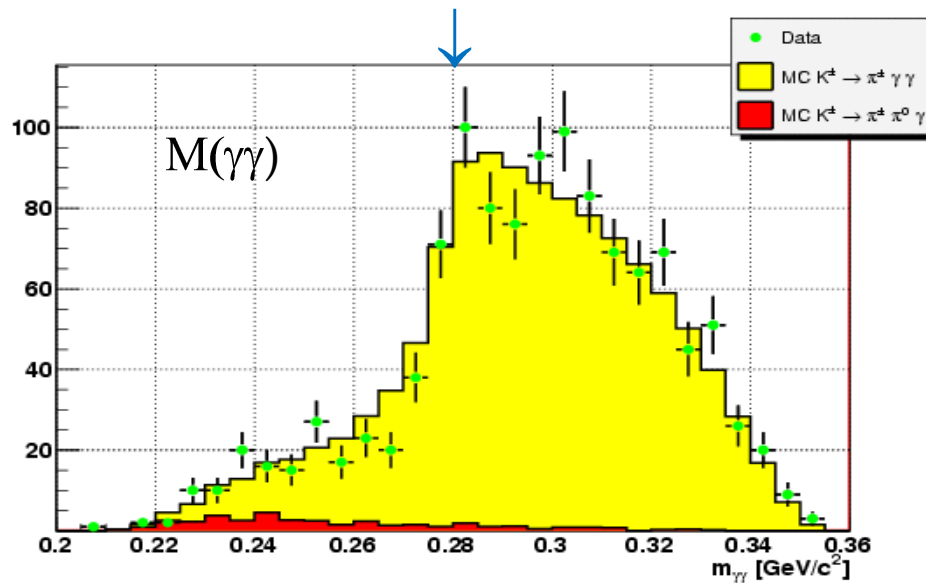
Signal :

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

Normalization channel $K^\pm \rightarrow \pi^\pm \pi^0$:

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

$K^\pm \rightarrow \pi^\pm \gamma\gamma$: preliminary results



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

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

(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 $\sim 40\%$ wrt $O(p^4)$

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

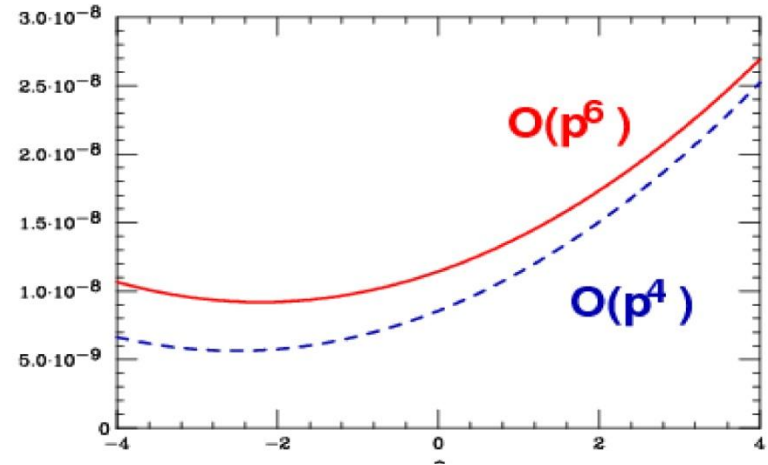
Experimental goals

- 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

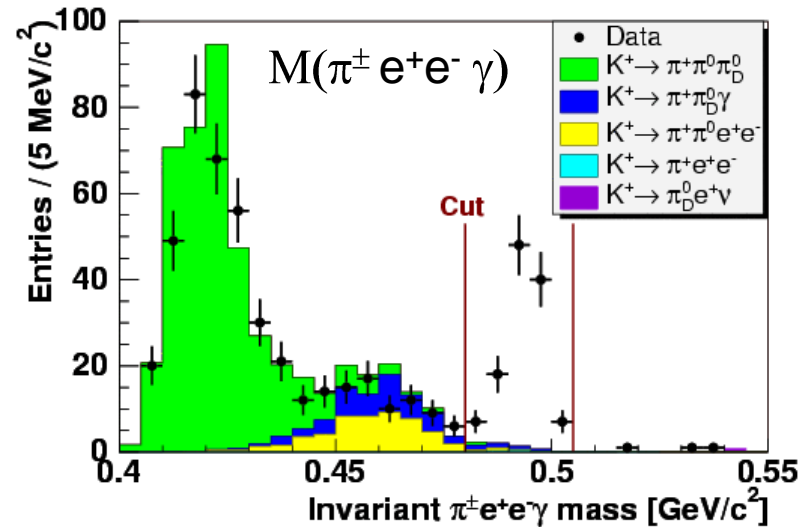
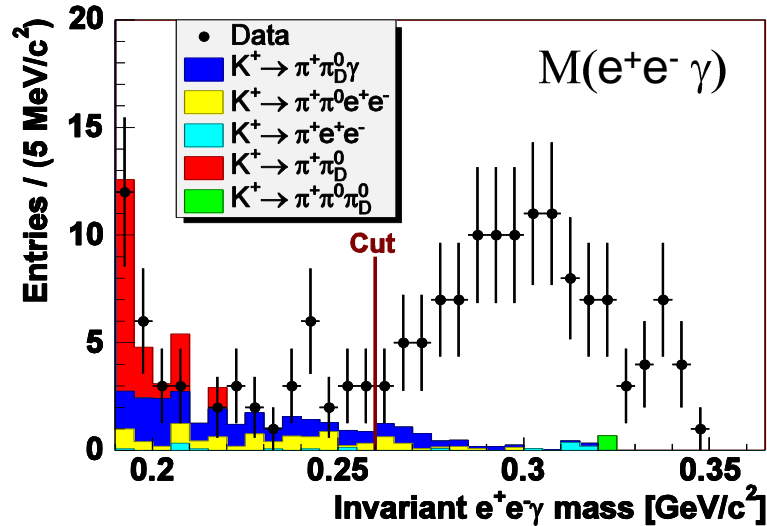
ChPT: predicted BR as a function of \hat{c}



$K^\pm \rightarrow \pi^\pm e^+e^- \gamma$: 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 ($M_{ee\gamma}$, $M_{\pi ee\gamma}$, $\mathcal{G}_{e\gamma}$)



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



Signal: **120 events**

Background: 6% (MC estimate)

FIRST OBSERVATION of this decay

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

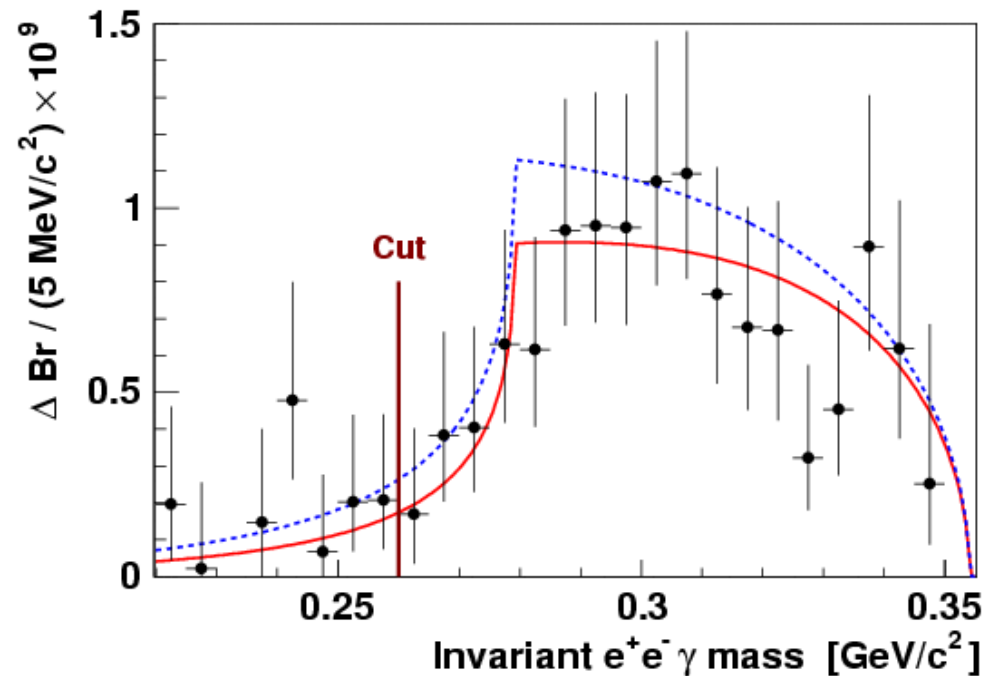
- Same particles in final state
- First order cancellation of systematics



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/c² wide)
- Least squares fit on $M_{ee\gamma}$ to extract \hat{c}
- Main systematics:
 - BG subtraction
 - normalization
 - MC statistics



NA48/2 final results:

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

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

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

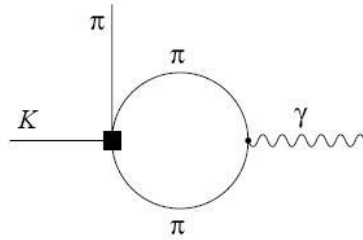
Errors dominated by statistics

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: $W(z) = G_F M_K^2 \mathbf{f}_0 \cdot (1 + \delta \cdot z)$
 - ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (\mathbf{a}_+ + \mathbf{b}_+ z) + W^{\pi\pi}(z)$ [JHEP 8 (1998) 4]
 - “Dubna” ChPT: $W(z) = W(\mathbf{M}_a, \mathbf{M}_\rho, z)$ [hep-ph/0611175]
- (\mathbf{f}_0, δ) or $(\mathbf{a}_+, \mathbf{b}_+)$ or $(\mathbf{M}_a, \mathbf{M}_\rho)$ fully determine a model-dependent **BR**

■ Experimental goals:

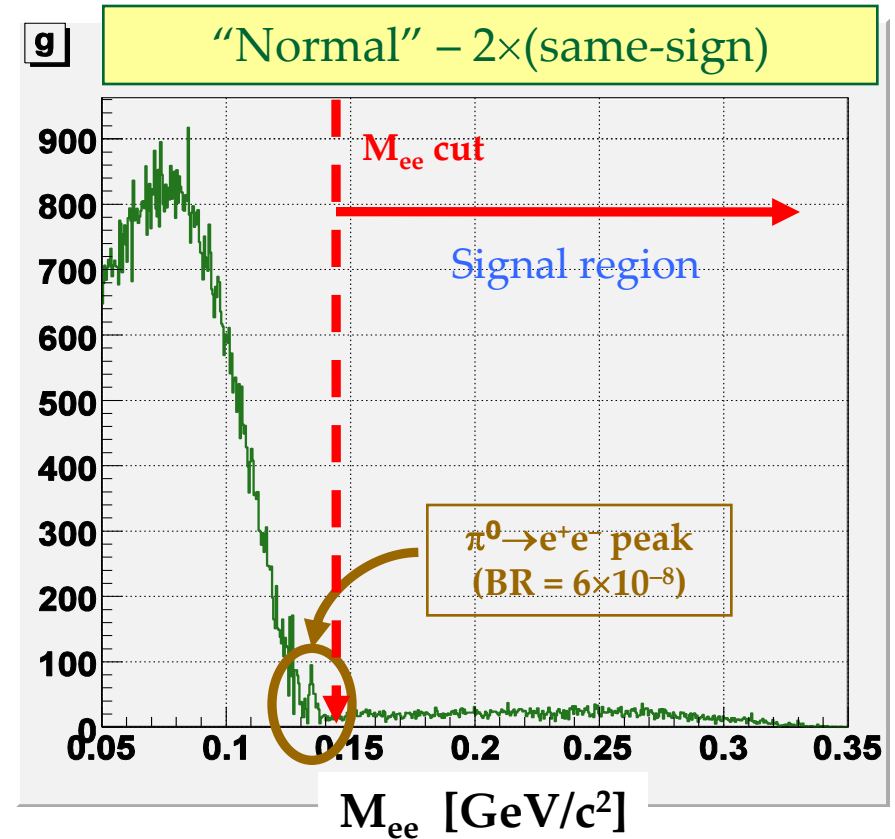
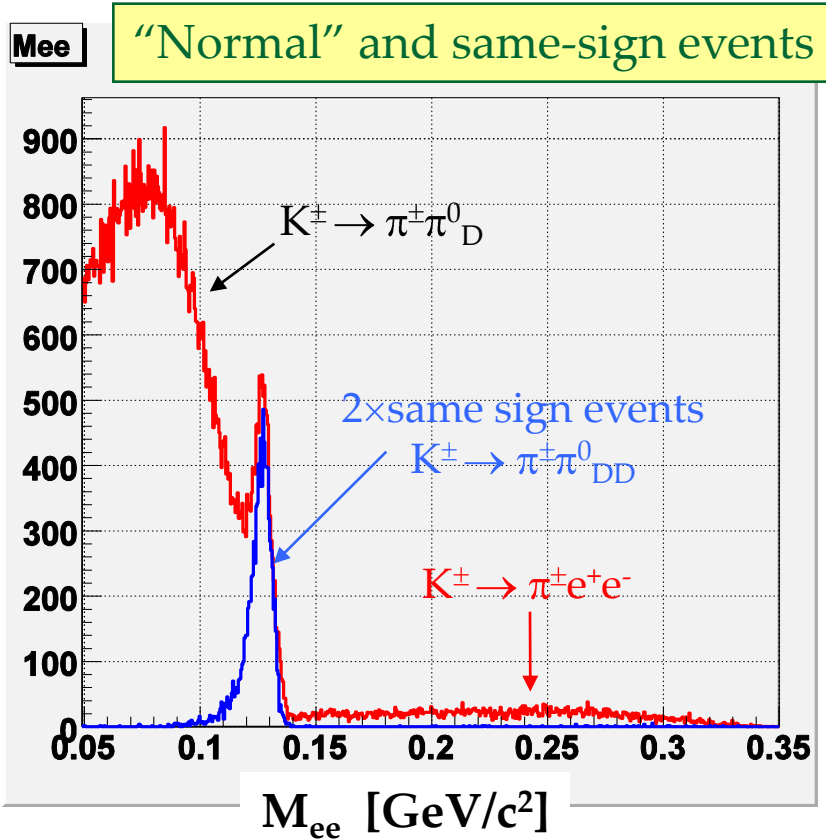
- model-independent **BR**($z > 0.8$) in accepted kinematical range
- for each model: **parameters** and **BR** in the full kinematical range

■ 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

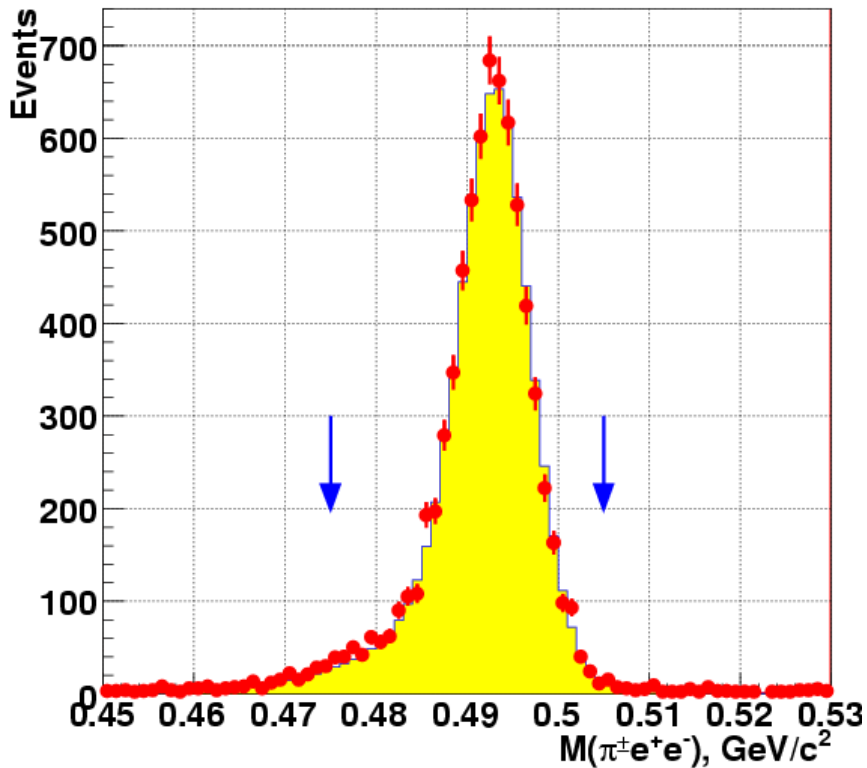
- Data sample: 2003 + 2004 runs
- Event selection: 3 tracks, particle ID (E/p), invariant mass cut
- Background subtraction:
 - MC used only to identify BG
 - BG by particle misID ($\pi^\pm \leftrightarrow e^\pm$) in $K^\pm \rightarrow \pi^\pm \pi_D^0$ and $K^\pm \rightarrow e^\pm \nu \pi_D^0$) estimated **directly on data** using “same sign” ($\pi^+e^-e^-$) events
- Normalization channel: $K^\pm \rightarrow \pi^\pm \pi_D^0 \rightarrow \pi^\pm e^+e^- \gamma$
 - Same final state as the signal, plus one photon
 - Same charged particles \rightarrow 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



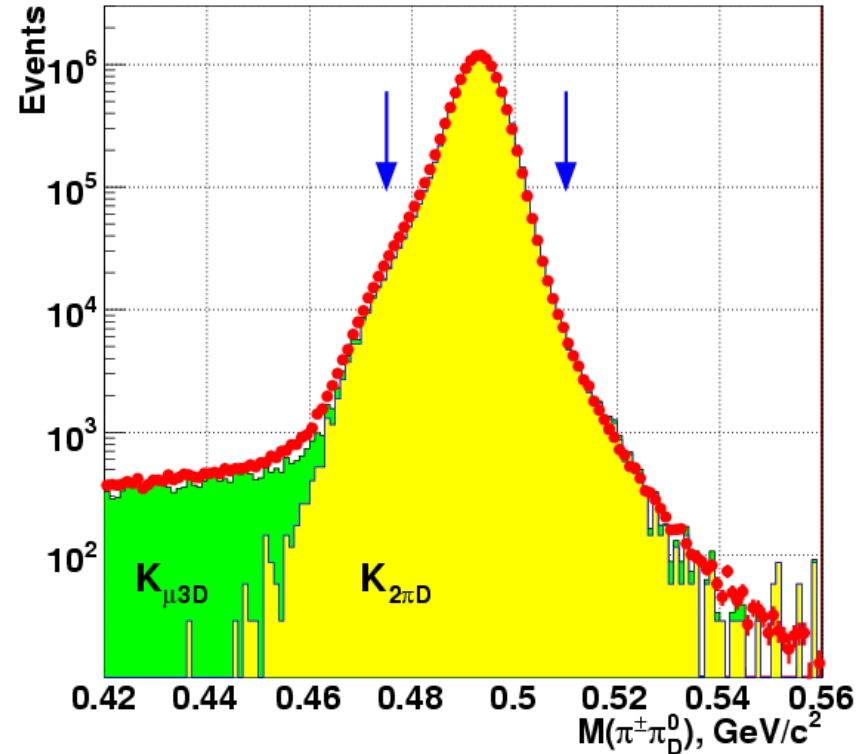
- $M_{ee} > 140 \text{ MeV}/c^2$ ($z > 0.08$) : signal region
 - $M_{ee} < 140 \text{ MeV}/c^2$ dominated by background ($K^\pm \rightarrow \pi^\pm \pi_D^0$, $K^\pm \rightarrow \pi^\pm \pi_{DD}^0$)
 - After BG subtraction, the $\pi^0 \rightarrow e^+e^-$ peak (~ 500 events) can be seen

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



■ Signal: 7146 candidates

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



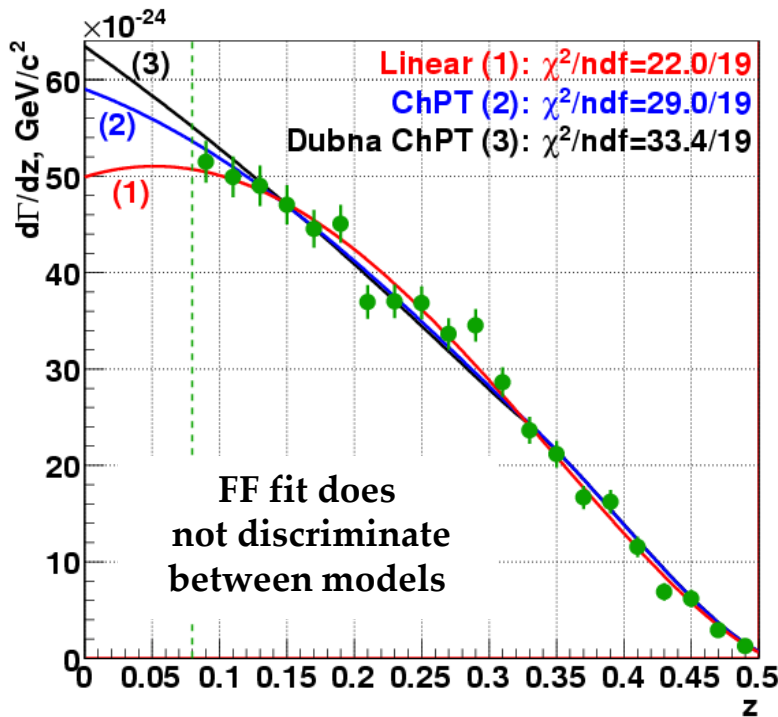
■ Normalization: 12.2×10^6 events

□ Background: $\sim 0.15\%$ ($K^\pm \rightarrow \pi_D^0 \mu^\pm \nu$)

□ BR($\pi^\pm \pi^0$) from PDG

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

Measured $d\Gamma/dz$
(corrected for acceptance)



Model independent BR ($z > 0.08$):

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

Form factors (fit to $d\Gamma/dz$):

■ Polynomial

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

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

□ ChPT

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

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

□ "Dubna" ChPT (GeV/c^2)

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

$$M_p = 0.711 \pm 0.010_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.002_{\text{ext}}$$

$$\text{BR} = (3.08 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} \pm 0.07_{\text{model}}) \times 10^{-7}$$

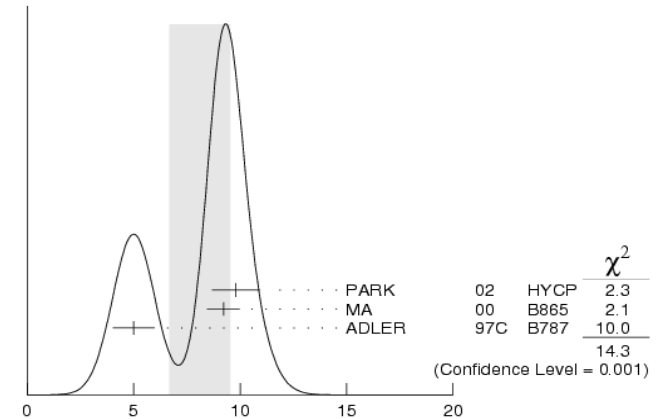
(including uncertainty due to model dependence), in agreement with BNL E865 result

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

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

- 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 $\pi e e$

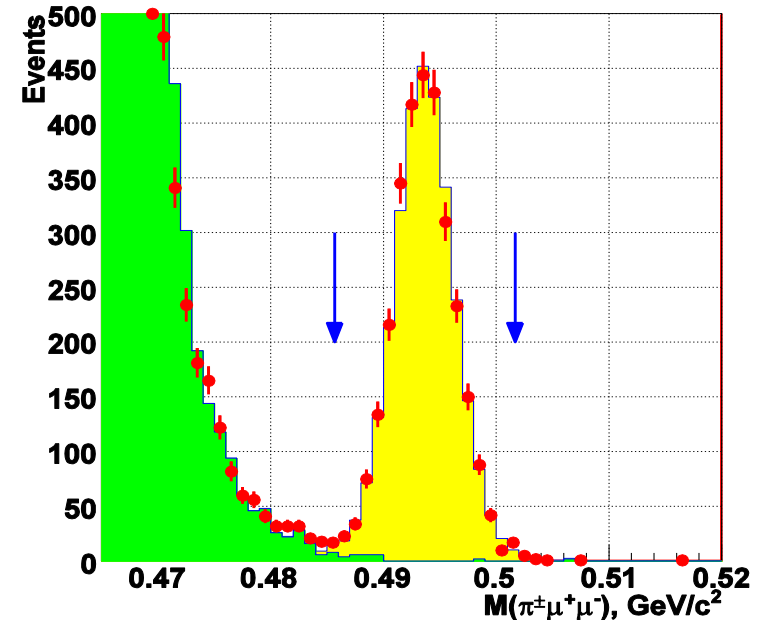


- Experimental difficulty

- 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

- $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: first evidence of DE-IB interference in the decay
 - Measurement of DE/IB and INT/IB branching ratios
- $K^\pm \rightarrow \pi^\pm \gamma \gamma$: statistics improved 40x wrt previous measurements
 - Clear evidence for the 2π cusp
 - Measured BR in agreement with ChPT
- $K^\pm \rightarrow \pi^\pm e^+e^- \gamma$: first observation
 - Independent evidence for the 2π cusp
 - Final results on BR and shape analysis (ChPT parameter \hat{c})
- $K^\pm \rightarrow \pi^\pm e^+e^-$: 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 $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ with small background (analysis on-going)