First observation and study of the rare decay $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ by the NA48/2 experiment

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on behalf of the NA48/2 Collaboration

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

Rencontres de Moriond
QCD and High Energy Interactions

21st-28th March 2015, La Thuile, Italy

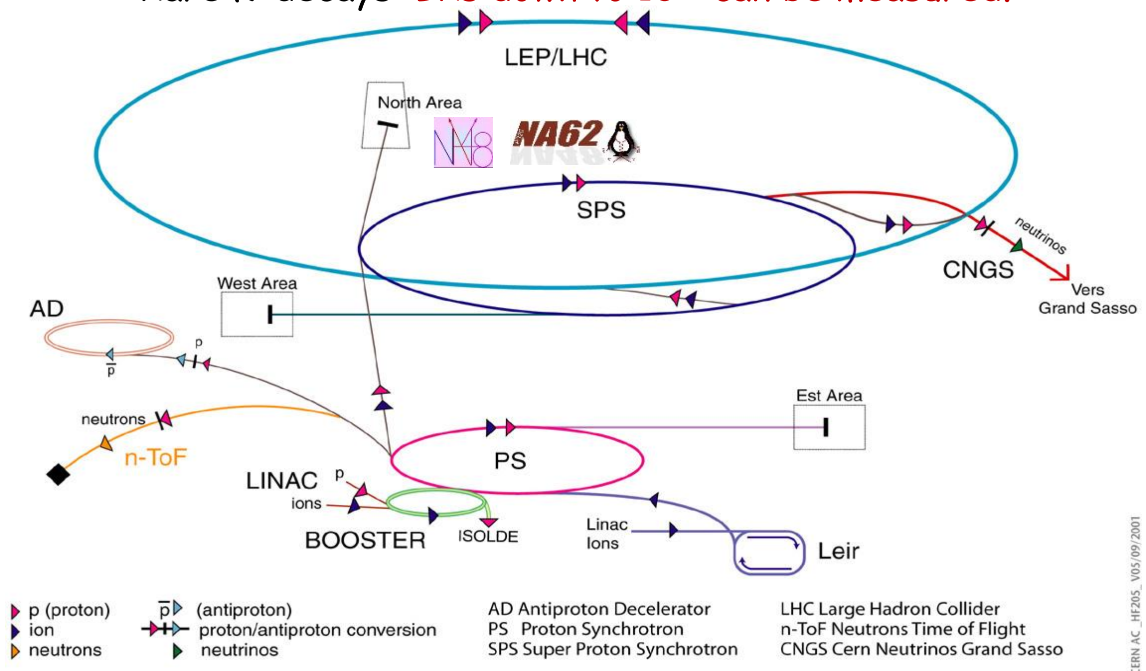
Outline

- Introduction to the NA48/2: beam line and detector
- ChPT and NA48/2 chiral tests via charged kaon decays
- Motivation of searching and study $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$
- Selection and MC simulation
- Data samples and background estimates
- BR($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$) – preliminary !
- Conclusion

NA48/2 - fixed target experiment at the North Area of the CERN SPS

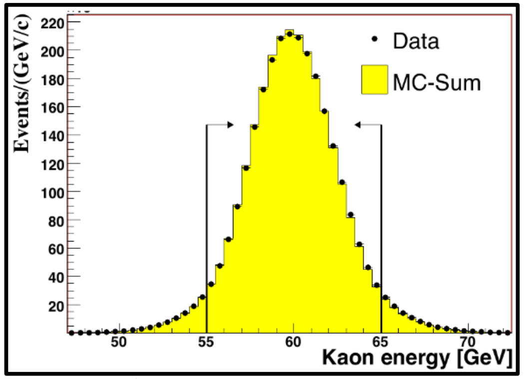
- Specifically designed for precision measurement of direct CP violation in $K_{3\pi}$ decays.
- Other goals: tests of CKM unitarity, $\pi\pi$ scattering lengths, ChPT tests, lepton universality.

- NA48/2 data taking has been completed: 2003 run (~50 days) and 2004 run (~60 days) .
  - $K_{3\pi}$ statistics: ~ 4×10^9 $K^\pm \to \pi^-\pi^+\pi^\pm$ & : ~1×10^8 $K^\pm \to \pi^0\pi^0\pi^\pm$.
  - Rare $K^\pm$ decays: BRs down to 10^{-9} can be measured.



Experimental hall of NA48/2 … now *NA62*

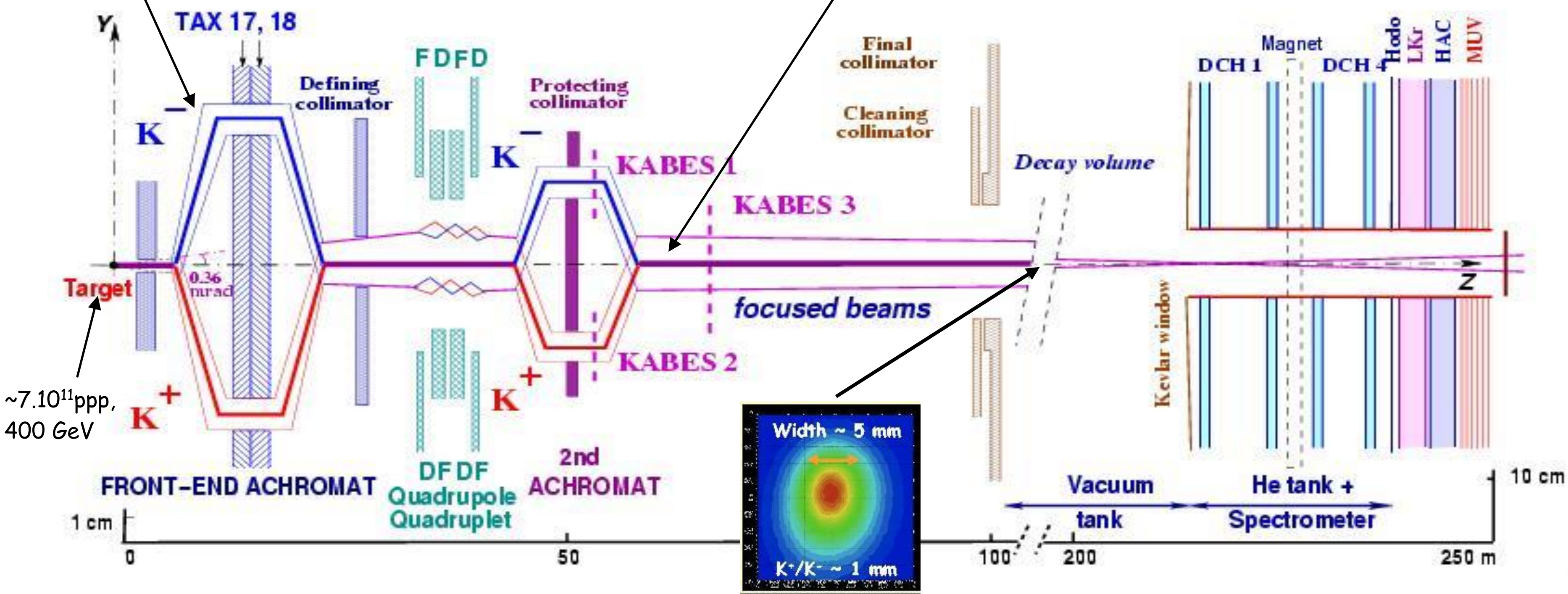
NA48/2 beam line - simultaneous K^+ & K^- beams



P_K= 60±3 GeV/c

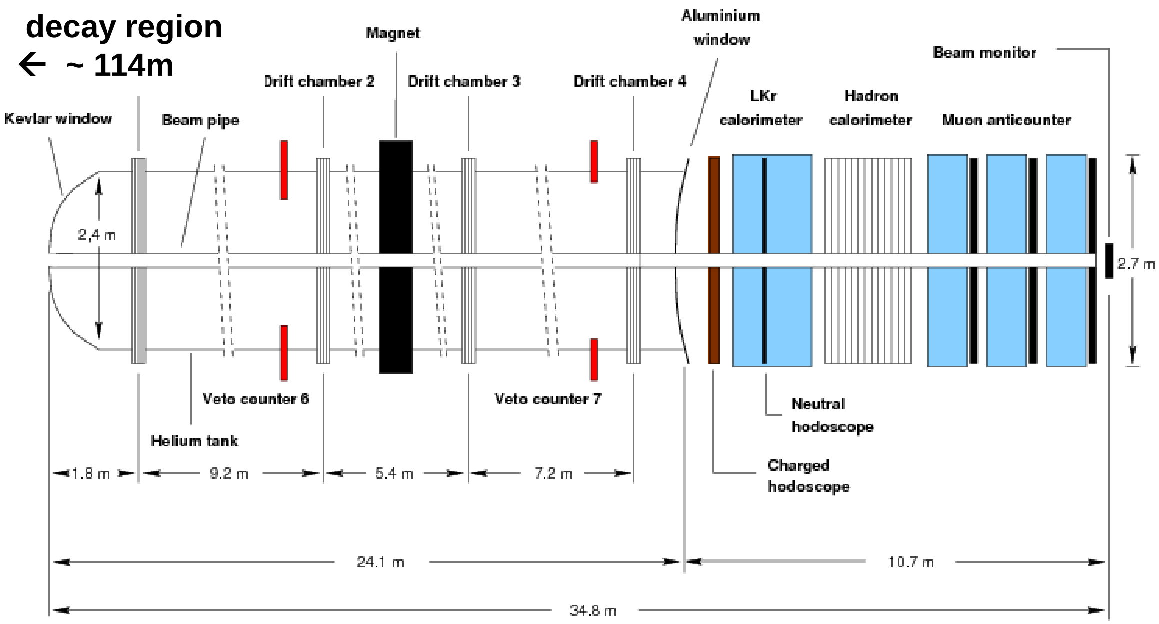
2-3M K/spill (π/K~10),π-decay products stay in the beam pipe.
Flux ratio K+/K- ≈1.8

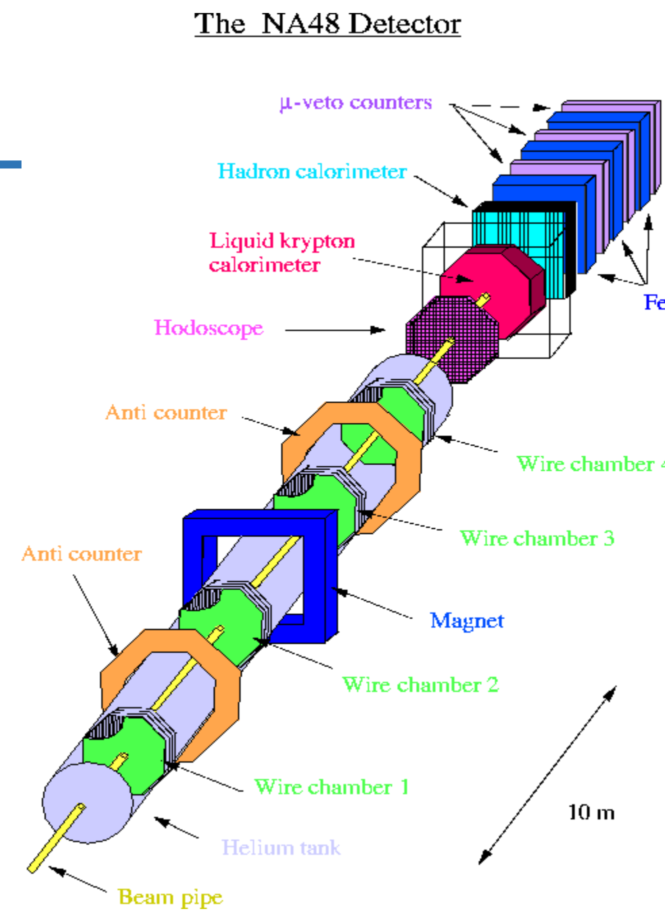
Beams coincide within ~1mm all along 114m decay volume



NA48/2 detector

Target
← ~ 200m
decay region
← ~ 114m





- ❑ Magnetic spectrometer
  - 4 drift chambers and dipole magnit
  - σ(p)/p=1.02% + 0.044*p% [p in GeV/c]
- ❑ Hodoscope
  - Fast trigger
  - Precise track time measurement (150ps)
- ❑ Liquid Krypton calorimeter (LKr)
  - High granularity (13248 cells 2x2cm^2)
  - Quasi-homogeneous(7m^3 liquid Kr,28X$_0$)
  - σ(E)/E=3.2%/√E + 9%/E+0.42% [E in GeV]
  - Particle ID and γ detection
- ❑ Hadron calorimeter, muon veto counters,photon counters

K-mesons and Chiral Perturbation Theory

Chiral Perturbation Theory:

- Effective field theory for the analysis of the low energy properties of the strong interaction.
  - Treat the lightest particles as relevant degrees of freedom
  - QCD Lagrangian written in terms of u,d,s –quarks in chiral limit ($m_u=m_d=m_s=0$)
  - Chiral symmetry $SU_L(3)\times SU_R(3)$
  - The chiral Lagrangian is a function of Goldstone boson fields (π, $K^{\pm}$, K^0, η) collected in the matrix-value field $U=\exp(i\varphi^a\lambda^a)$

K-meson:

- Decays into pions (pseudo-scalar mesons) /photons, leptons/
- Characteristic momenta is smaller than the natural scale of chiral symmetry breaking.
- ChPT is an ideal framework to describe kaon decays.
- Kaon decays give a great opportunity to test the weak part of ChPT Lagrangian

$\Delta S=1$ chiral Lagrangian $O(p^4)$ $$L_{\Delta S=1} = L^2_{\Delta S=1} + L^4_{\Delta S=1} \simeq G_8 F^4 < \lambda_6 D_\mu U^\dagger D^\mu U > + G_8 F^2 \sum N_i W^i$$

- The coefficients N_i and the operators W_i are poorly known
- Combinations of the couplings can be determined by measuring branching ratios and form factors of different kaon decay channels.

NA48/2 ChPT tests

NA48/2 have access to the following charged kaon decays with high precision:

- $K^{\pm} \to \pi^{+} \pi^{-} e^{\pm} \nu$ / EPJC70 (2010) 635-657, PLB 715 (2012) 105-115, EPJC 54 (2008) 411-423 /

  -- Determination of the s-wave $\pi\pi$ scattering length

  -- BR and form-factors measurement

- $K^{\pm} \to \pi^{\pm} \pi^{0} \pi^{0}$ / EPJ C64 (2009) 589 /

  -- $\pi^{0}\pi^{0}$ invariant mass distribution shows a cusp-like anomaly in the region around $M_{\pi 0\, \pi 0} = 2m_{\pi+}$

  -- Determination of the s-wave $\pi\pi$ scattering length

- $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ / EPJC 68 (2010) 75-87 /

  -- the first measurement of the DE and INT terms

  -- access to the chiral parameters (N_{14}-N_{15}-N_{16}-N_{17})

- $K^{\pm} \to \pi^{\pm}\gamma\,\gamma$ /NA62: Phys. Lett. B 732C (2014) 65-74; NA48/2: Phys. Lett.B 730 (2014) 141-148 /

  -- BR measurement and access to the chiral parameters (N_{14}-N_{15}-N_{16}-N_{17})

- $K^{\pm} \to \pi^{\pm}\gamma\, e^{-}e^{+}$ / PLB659 (2008) 493-499/

  -- the first BR measurement & the first determination of $\hat{c}$ (N_{14}-N_{15}-$2N_{18}$)

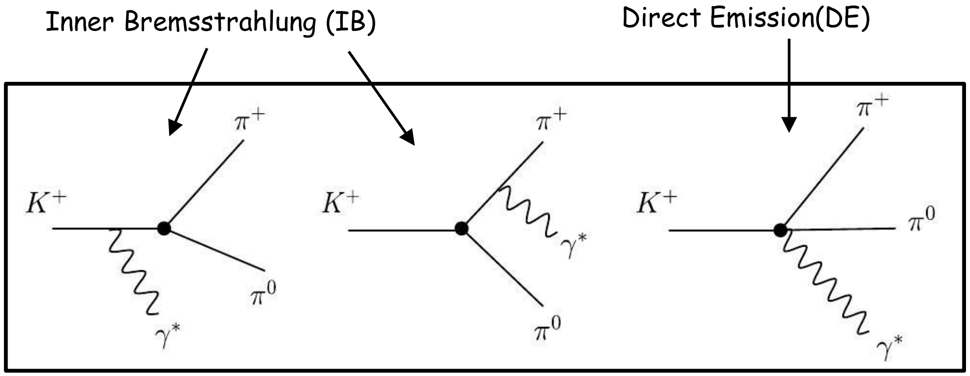
- $K^{\pm} \to \pi^{\pm} e^{-} e^{+}$, $K^{\pm} \to \pi^{\pm} \mu^{+}\mu^{-}$ /PLB 677 (2009) 246-254, PLB 697 (2011) 107-115/

  -- access to the chiral parameters (N_{14}-N_{15})

- $K^{\pm} \to \pi^{\pm} \pi^{0} e^{-} e^{+}$ /unobserved!/

  -- access to the chiral parameters (N_{14}^{r}-N_{15}^{r}-3(N_{16}^{r}-N_{17}))

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma^{*} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$: Motivation and Theory



Decay width $\Gamma_{total} = \int |A|^2 d\Phi$

$$|A|^2 = const.*(A_{IB} + A_{DE(E)} + A_{DE(M)})^2/q^4$$

$$\frac{d^3\Gamma}{dE^*_\gamma dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{E}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{M}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{int}}{dE^*_\gamma dT_c dq^2}$$

$q^2 = M^2_{e+e-}$ Tc = kinetic energy $\pi^{\pm}$

L. Cappiello, O.Cata, G. D'Ambrosio, Dao Neng-Gao, Eur. Phys. J. C 72:1872

- Never observed …
- Experimental goals:
  - Experimental measurement of BR($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$) /for the 1st time!/
  - Electric interference ($\Gamma_{IB}\Gamma_{E}$) extraction can be used to check the discrepancy in sign with the theoretical estimation observed by the NA48/2 in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ analysis /EPJC 68 (2010) 75-87/
  - Magnetic interference (genuine for $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$) can be used to determine the sign of the magnetic term Γ_M
  - Non-vanishing charge asymmetry is an indication of direct CP violation.
- Theoretical papers:

(2001) H.Pichl, Eur. Phys. J. C 20, 371
(2012) L.Cappiello, O.Cata, G. D'Ambrosio, Dao Neng-Gao, Eur. Phys. J. C 72:1872
(2014) S.Gevorkyan, M.Misheva, Eur. Phys. J. C (2014) 74: 2860

$K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ candidates

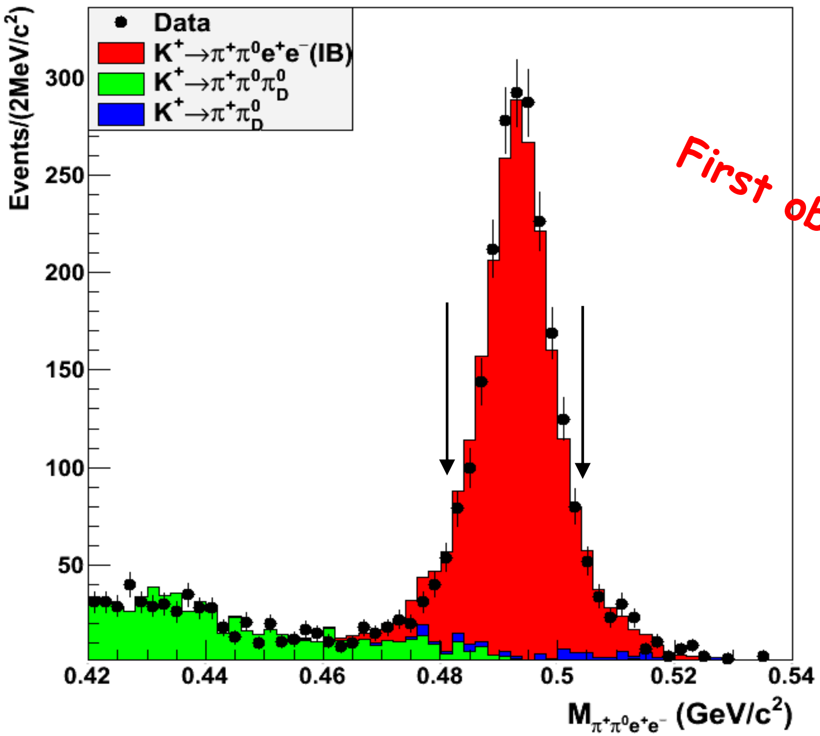
- Data samples
  - 2003 data sample has been analyzed.

- Monte Carlo simulation
  - Tree-level description:
    Inner Bremsstrahlung, Direct Emission and Electric Interference generators (no magnetic interference)
    based on the paper **L. Cappiello, O. Cata, G. D'Ambrosio, Dao Neng-Gao, Eur. Phys. J. C 72:1872 (2012)**
  - Coulomb correction and real photon simulation (PHOTOS package) are additionally implemented in the MC simulation as far as there is no theoretical calculations for the exact radiative corrections.

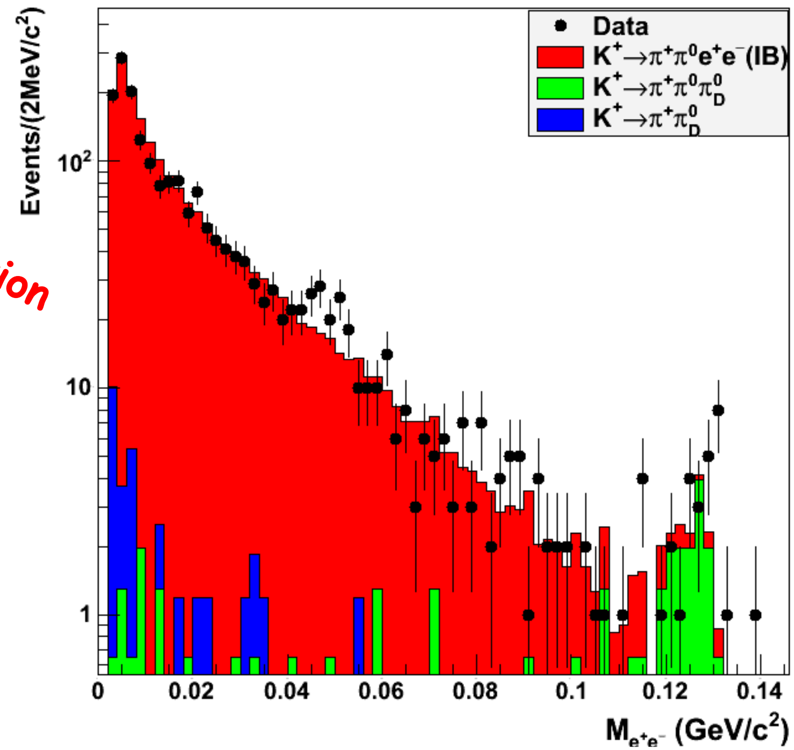
- Selection
  - 3 reconstructed tracks coming from one decay vertex
  - Particle ID (E_{LKr}/p_{DCHs} ratio is used for $e^{\pm}/\pi^{\pm}$ separation)
  - 2 reconstructed γ-clusters compatible with π^0 mass
  - $P_{electrons} > 2$ GeV
  - $E_{\pi^{\pm}\pi^{0}e^{+}e^{-}}$ to be within (54 – 66) GeV
  - 483.677 MeV < $M_{\pi^{\pm}\pi^{0}e^{+}e^{-}}$ < 503.677 MeV

- Background sources
  - $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{Dalitz} \to \pi^{\pm}\pi^{0}e^{-}e^{+}\gamma$ with a lost or merged photon
    Mass ($\pi^{\pm}\pi^{0}$) is much smaller than in the signal
  - $K^{\pm} \to \pi^{\pm}\pi^{0}_{Dalitz}(\gamma) \to \pi^{\pm}e^{-}e^{+}\gamma$ + extra or radiated photon
    at least one ($e^{-}e^{+}\gamma$) is compatible with π^0 mass

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ Data samples and background estimates



First observation

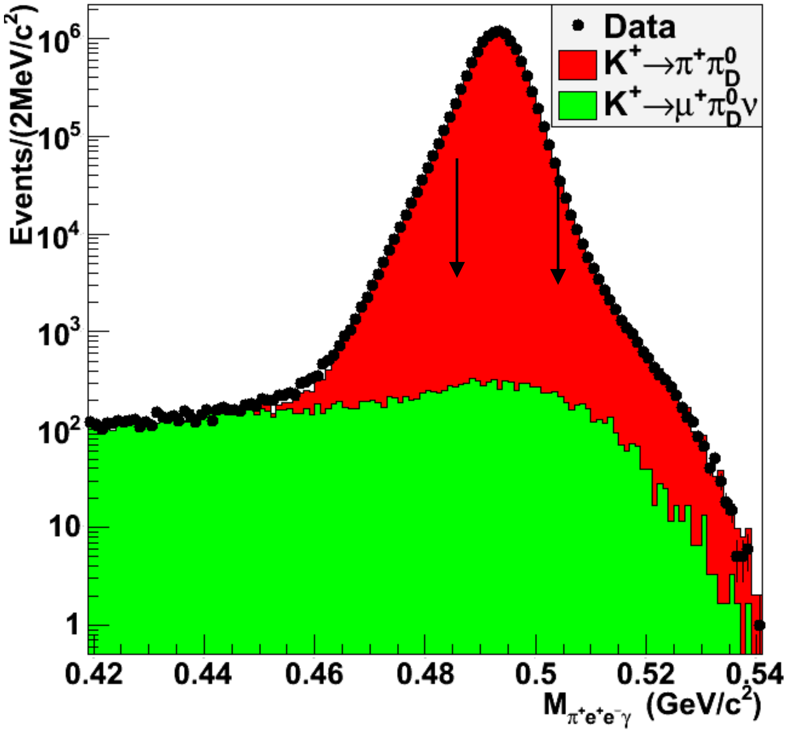


- 1916 -total number of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ candidates
- Total background (~3%)
  - $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}_{e-e+\gamma}$ (30 ± 5.5)events
  - $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{e-e+\gamma}(\gamma)$ (26 ± 5.1)events

- Background suppression
  - $K^{\pm} \rightarrow \pi^{\pm}\pi^{0} e^{-}e^{+}\gamma$ ($M^{2}_{\pi\pi} > 0.120$ (GeV/c²)²)
  - $K^{\pm} \rightarrow \pi^{\pm} e^{-}e^{+}\gamma$ (γ) ($|M_{ee\gamma} - M_{\pi 0}$ PDG$| > 7$ MeV)
- 1860 genuine $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ events

Kaon flux calculation

The number of $K^{\pm}$ decays (kaon flux) is measured by using reference channel $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}(\gamma)$.



- 2003 data only
- Very large sample with known BR (PDG)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$ events	6714917±2591	
Statistical error		**0.04%**
Acceptance	(3.555±0.002)%	0.002%
Trigger efficiency	(97.64± 0.04)%	0.04%
Background	3365±58	8×10^{-4} %
Rad. corr.	0.78%	0.78%
Systematic error		**0.78%**
BR($\pi^+\pi^0_D(\gamma)$)	$(2.425\pm0.073)\times10^{-3}$	3.01%
External error		**3.01%**

- Mass $K^{\pm}$ to be within $|M_{\pi\pm e-e+\gamma} - \text{PDG } M_K| < 10$ MeV
- Background < 0.1% $K^{\pm} \rightarrow \mu^{\pm}\nu\,\pi^{0}_{D}$

Kaon flux = $(7.97\pm0.03_{Stat}\pm0.06_{Sys}\pm0.24_{Ext})\times10^{10} = (7.97 \pm 0.25)\times10^{10}$

Table of errors

Error type	Value [%]
Number of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ events (1916)	
Total Statistical	**2.35%**
Radiative correction on IB	0.5%
Signal total acceptance	0.34% (statistical error)
	1% systematic (fraction mixture)
Background subtraction	0.4% (statistical error)
	0.05% (systematic due to rad. corr. $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$)
Trigger efficiency	0.65% (statistical error)
Total systematics	**1.4%**
Kaon flux measurement	3.1% (from BR of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$)
Total external	**3.1%**

- ❑ Systematic error dominated by model dependent acceptance
- ❑ External error from BR($\pi^{0}_{D} \rightarrow e^{+}e^{-}\gamma$) dominates the total error

Measurement of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$ branching ratio

Model dependent BR measurement

We are not able to measure the DE and the El.Int. contributions with the present data.

We computed a model dependent branching ratio by using the theoretical calculations of the DE and El.Int. fractions (D'Ambrosio et al., Eur. Phys. J. C (2012) 72:1872)

$$Acc(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}) = \frac{Acc(IB) + Acc(DE)*Frac(DE)_{TH} + Acc(El.Int.)*Frac(El.Int.)_{TH}}{1+Frac(DE)_{TH} + Frac(El.Int.)_{TH}}$$

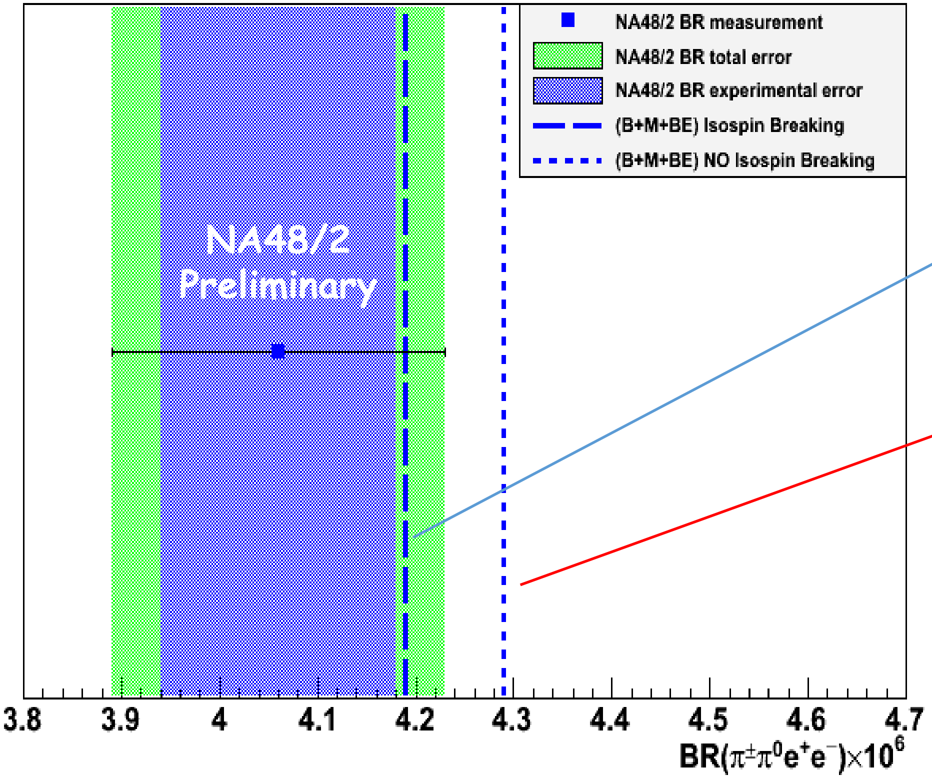
$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+})^{\text{Theory}} = BR^{IB}\,(1+ 1/71 +1/128) = 4.0995\times10^{-6} \times (1+ 1/71 +1/128) = 4.19\times10^{-6}$

/D'Ambrosio et al. --- isospin breaking, private communication/

$$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}) = \frac{N^{data}_{\pi^{\pm}\pi^{0}e^{+}e^{-}} - N^{BGR}}{\varepsilon(\pi^{\pm}\pi^{0}e^{+}e^{-}) * Acc(\pi^{\pm}\pi^{0}e^{+}e^{-}) * Kaon\ flux}$$

$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}) = (4.06 \pm 0.10_{stat.} \pm 0.06_{syst.} \pm 0.13_{ext})\times10^{-6}$

Preliminary result of BR($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$)



L. Cappiello, O. Cata, G. D'Ambrosio, Dao Neng-Gao,

Eur. Phys. J. C 72:1872 (2012) :

Isospin breaking (private communication)

BR($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$)^{Theory} = $4.19 \cdot 10^{-6}$

No isospin breaking (published)

BR($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$)^{Theory} = $4.29 \cdot 10^{-6}$

No radiative corrections in the theoretical predictions!

Rad. corr. is taken into account in the experimental result via Photos implementation in the MC simulaton.

NA48/2 2003 data

BR ($K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{-}e^{+}$)$_{total}$ = $(4.06 \pm 0.12_{exp} \pm 0.13_{ext}) \times 10^{-6}$

Conclusion

- First observation of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ by the NA48/2 Collaboration.

- Preliminary BR ($K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$) measurement /model dependent/ is obtained on the basis of 1860 selected $K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$ events /2003 NA48/2 data samples/:

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+})^{NA48/2} = (4.06 \pm 0.10_{stat.} \pm 0.06_{syst.} \pm 0.13_{ext}) \cdot 10^{-6}$$

- The BR ($K^{\pm} \to \pi^{\pm}\pi^{0}e^{-}e^{+}$) is compatible with the theoretical expectation within one standard deviation (isospin breaking).

- DE and Int. contributions requires radiative correction in the theoretical model.

- Final result is expected by the end of the 2015!