The $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} e^{+} e^{-}$ decay: First observation and study with the NA48/2 experiment at CERN

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- The NA48/2 experiment at CERN
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Kaon physics at CERN

NA48

NA31 (1984-1990)
First evidence of direct CPV
Beams: K_L / K_S

NA48
Main goal: Search for direct CPV
Measurement of ε'/ε
Beams: K_L / K_S

NA48/1
Main goal: Rare K_S decays and hyperon decays, CPV tests
Beam: K_S

NA48/2
Main goal: Search for direct CPV
Charge asymmetry measurement
Beams: K^+ / K^-

1997 ↓
2001
2002
2003
2004
2007
2008
2014 ↓
2018
2021 ↓

NA62

NA62 - R_K
Main goal: Test of μ-e universality R_K measurement
Beams: K^+ / K^-

NA62
Main goal: Rare kaon decays, measurement of $K^+ \to \pi^+ \nu\nu$
Beam: K^+

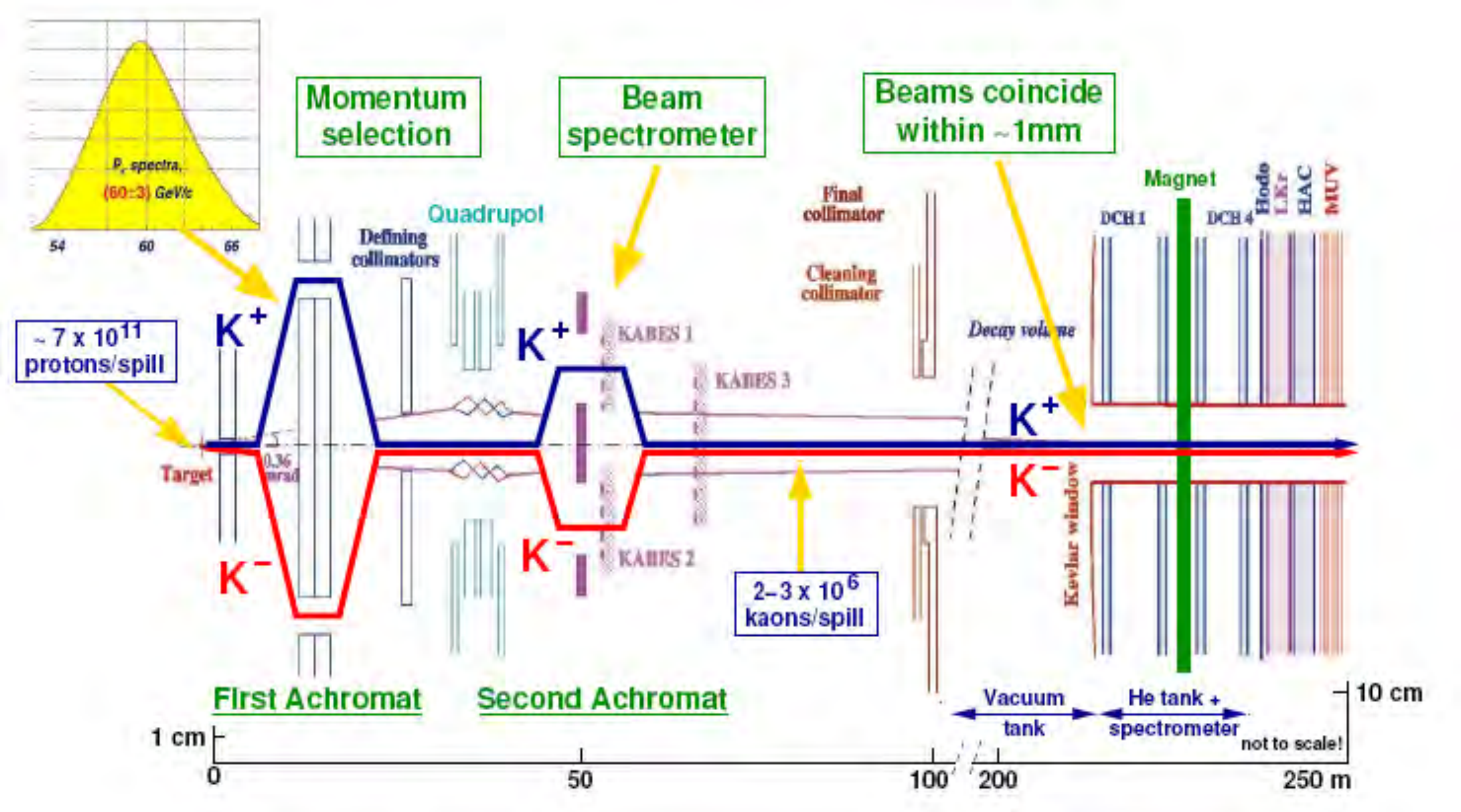
The NA48/2 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of CP violation and rare decays in the kaon sector

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

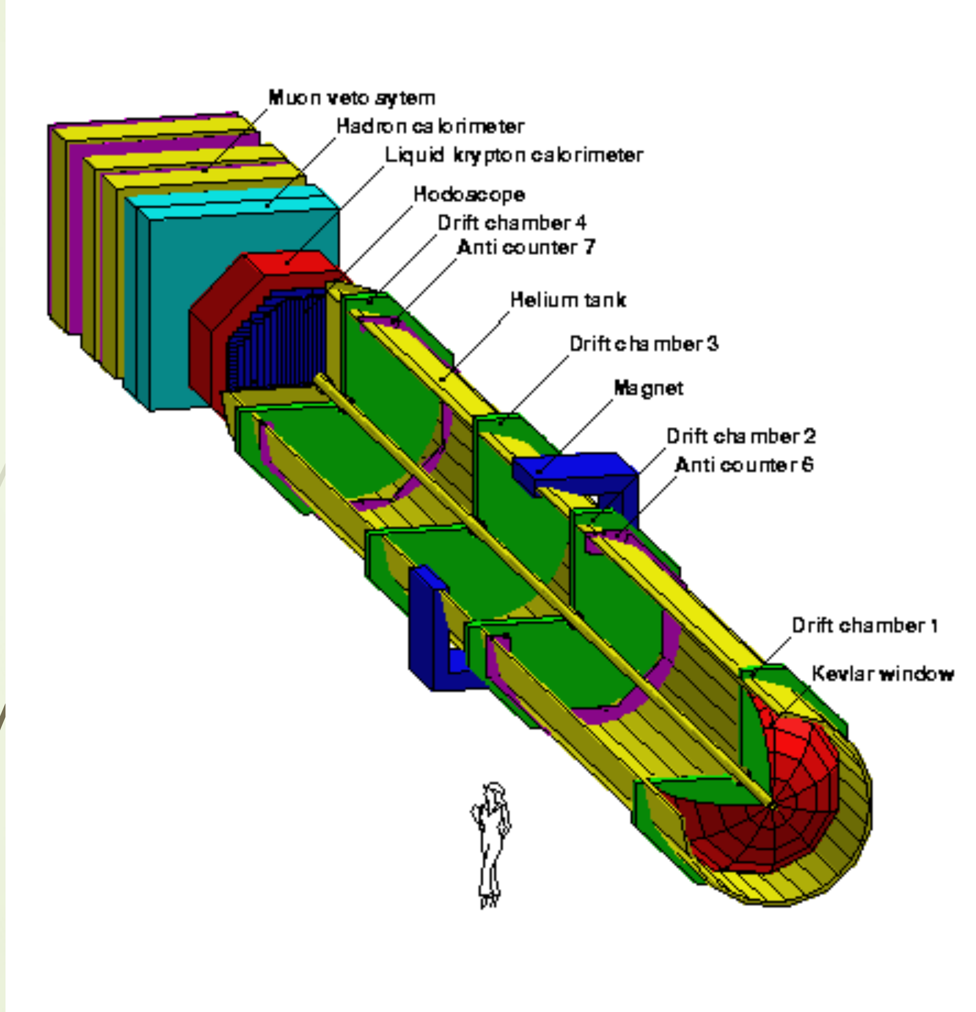
➡ ~ 120 participants, 15 institutions, 8 countries

NA48/2 – the Kaon beam



- 400 GeV proton beam on a beryllium target
- (60 ± 3) GeV Kaon momentum (~7x10^{11} ppp)
- Simultaneous, unseparated focused beams
- Similar acceptance for K^+ and K^- decays
- flux ratio K^+/K^- = 1.8
- Data collected in 2003-2004, ~ 6 months
- ~ 2 x 10^{11} $K^{\pm}$ decays in flight

NA48/2 – the detector



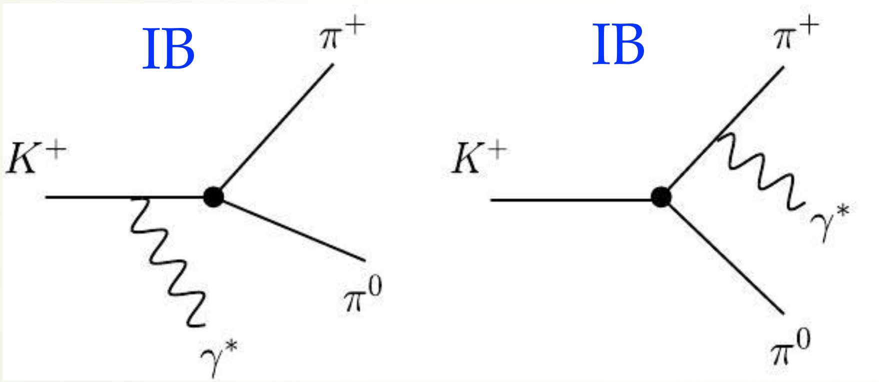
Main detector components

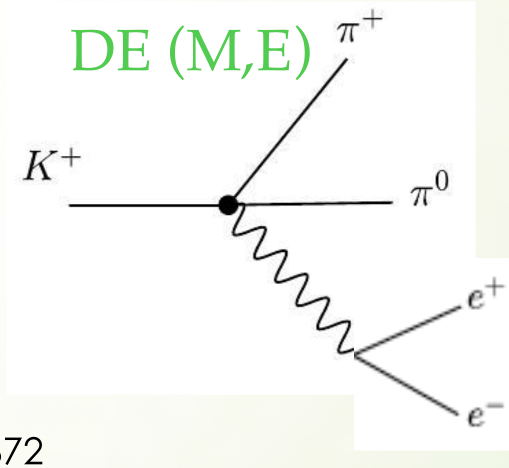
- Magnetic spectrometer (4 DCHs + dipole magnet)
  - 4 views: redudancy efficiency
  - $\sigma(p)/p = (1.02 \oplus 0.044 \cdot p)\%$ (p in GeV/c)
- Hodoscope
  - fast trigger, precise time measurement (150 ps)
- Liquid Kryptron e.m. calorimeter
  - high granularity, quasi-homogeneous, 10 m^3 (~22 t), 1.27 m (27 X_0)
  - $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)
- Hadron calorimeter, photon vetos, muon counters

First observation of the $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ rare decay

Motivation

- Test of Chiral Perturbation Theory
- Long distance dominated decay, proceeds through virtual photon exchange $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{*} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$
- The differential decay rate is described in terms of three components:
- Inner Bremsstrahlung (IB), Direct Emission (DE (M,E)) and Interference
- Never observed so far





+ interference

H.Pichl, EPJ C20 (2001) 371
L. Cappiello, O. Catà, G. D'Ambrosio, D.N. Gao, EPJ C72 (2012) 1872
L. Cappiello, O. Catà, G. D'Ambrosio, EPJ C78 (2018) 265

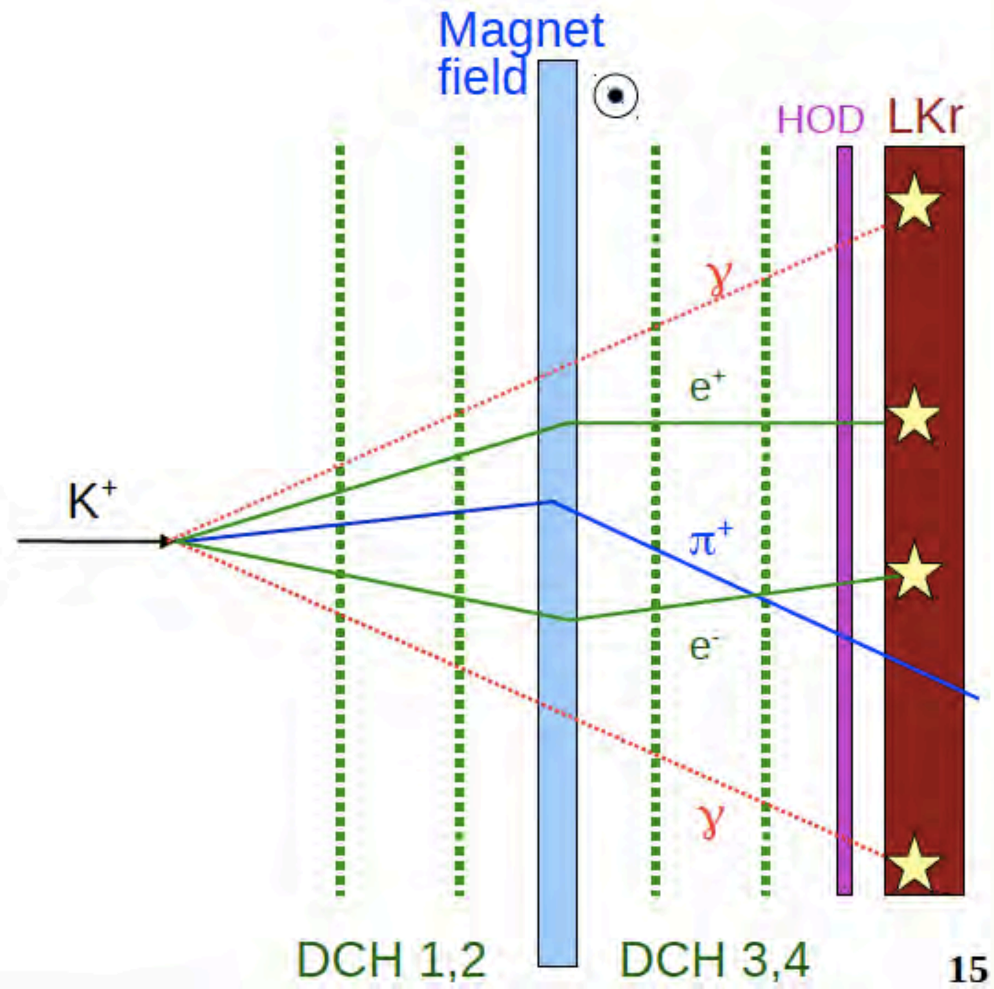
Motivation

- Cappiello et al. predicted, on the basis of the NA48/2 measurement of the magnetic and electric terms involved in the $K^\pm \rightarrow \pi^\pm\pi^0\gamma$ decay, the BR of IB, DE and INT components of the $K^\pm \rightarrow \pi^\pm\pi^0 e^+e^-$ decay
- A recent revised paper by the same authors re-evaluates the INT term, using more experimental results and fewer theoretical assumption
- The square amplitude of the decay, including the various contributions, can be written

$$\sum_{spins} |M|^2 = \frac{2e^2}{q^4}\left[\sum_{i=1}^{3} |F_i|^2 T_{ii} + 2Re \sum_{i<j}^{3} (F_i^* F_j) T_{ij}\right]$$

- where F_i are complex Form Factors and T_{ij} are kinematic expressions which depend on the four-momenta of the decay products in the kaon rest frame
- The FF's that correspond to the electric part of DE make use of the ChPT counterterms $N_E^{(0,1,2)}$, whilst the one corresponding to the magnetic part of DE makes use of the counterterm $N_M^{(0)}$

Event signature: signal and normalization



Signal: $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-} \to \pi^{\pm}\gamma\gamma e^{+}e^{-}$

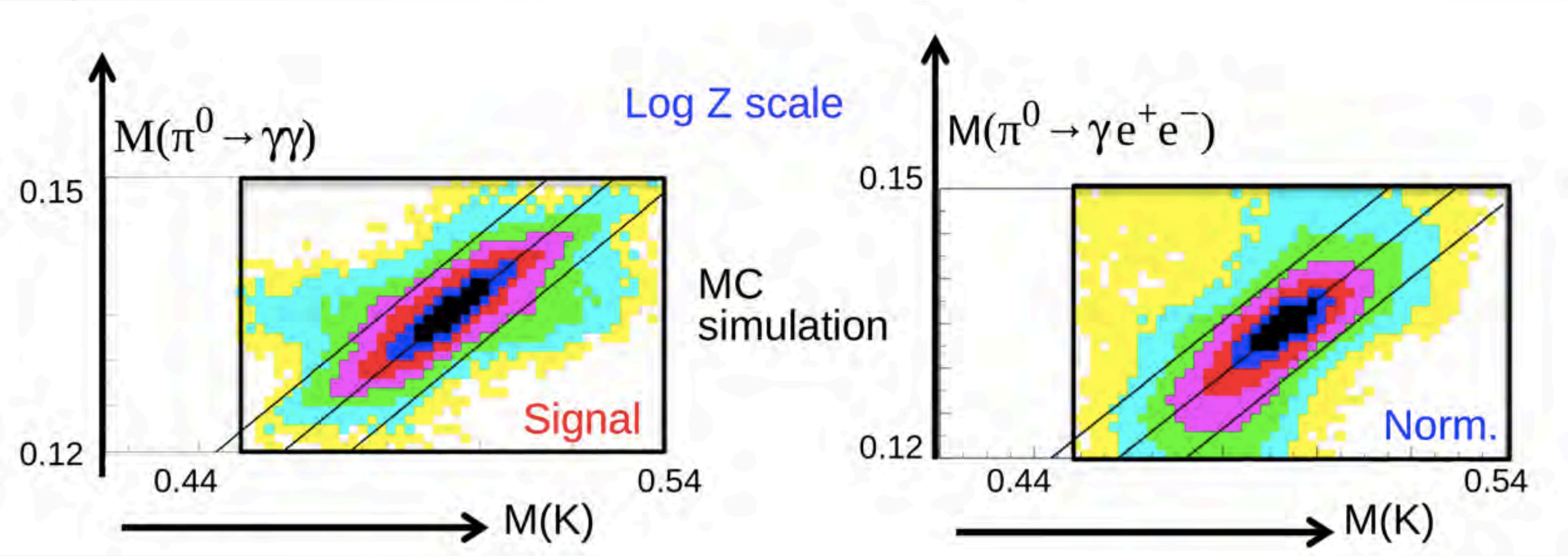
- 3 charged tracks (2 "same sign" + 1 "opposite sign"), forming a vertex
- 2 photon clusters in LKr forming a π^{0} pointing to the same decay vertex
- No PID from LKr, only kinematics → no LKr acceptance cuts on tracks

Normalization: $K^{\pm} \to \pi^{\pm}\pi^{0}_{D} \to \pi^{\pm}e^{+}e^{-}\gamma$

- Very abundant: $BR(\pi^{\pm}\pi^{0})$ = 22.66 % and $\Gamma(\pi^{0}_{D})/\Gamma(\pi^{0}_{\gamma\gamma})=(1.188 \pm 0.035)\%$
- similar topology, only 1 photon
- similar cuts as for the signal

Event selection

- Assign electron mass to the «opposite-sign» track
- For both (m_e, m_π) assignments to same-sign charged tracks, compute reconstructed masses $M(\pi^0)$ and $M(K^\pm)$ and apply cuts



$$|M_{\pi^0} - M_{\pi^0}^{PDG}| < 15\ MeV/c^2$$

$$|M_{K^+} - M_{K^+}^{PDG}| < 45\ MeV/c^2$$

$$|M_{\pi^0} - 0.42\ M_{K^+} + 73.2\ MeV/c^2| < 6\ MeV/c^2$$

Background evaluation

Main backgrounds to signal:
use specific cuts to suppress

$$K_{3\pi D}\left(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{D}\right)$$ 1 γ lost

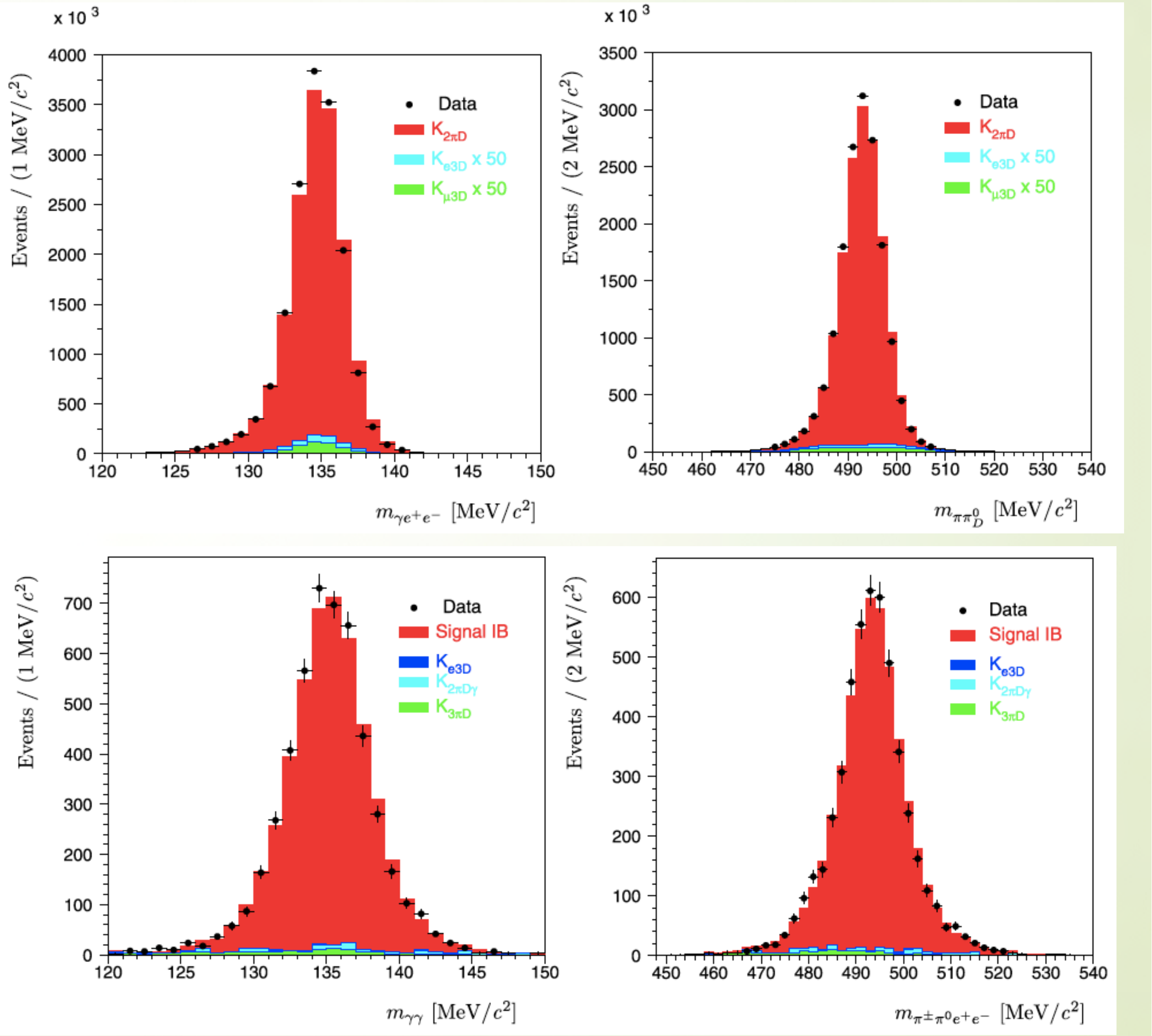
$$K_{2\pi D}\left(K^{\pm} \to \pi^{\pm}\pi^{0}_{D}\right)$$ 1 extra γ

$$M^{2}\left(\pi^{+}\pi^{0}\right) > 0.12\ GeV^{2}/c^{4}$$

$$\left|M\left(e^{+}e^{-}\gamma\right) - M_{PDG}\left(\pi^{0}\right)\right| > 7\ MeV/c^{2}$$

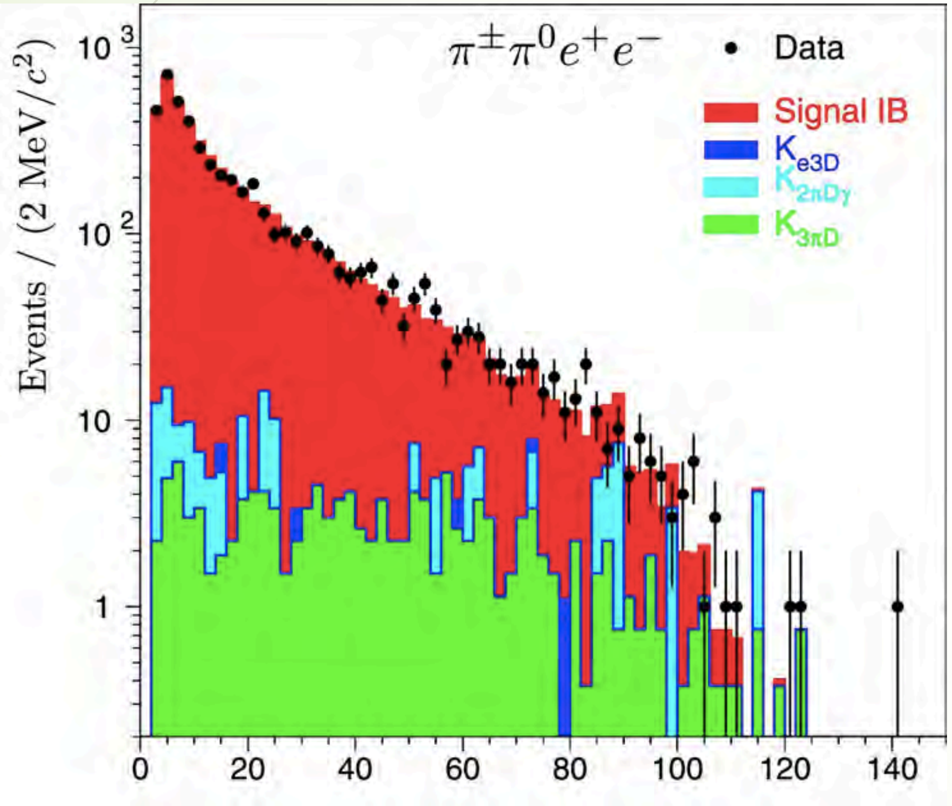
normalization candidates

signal candidates

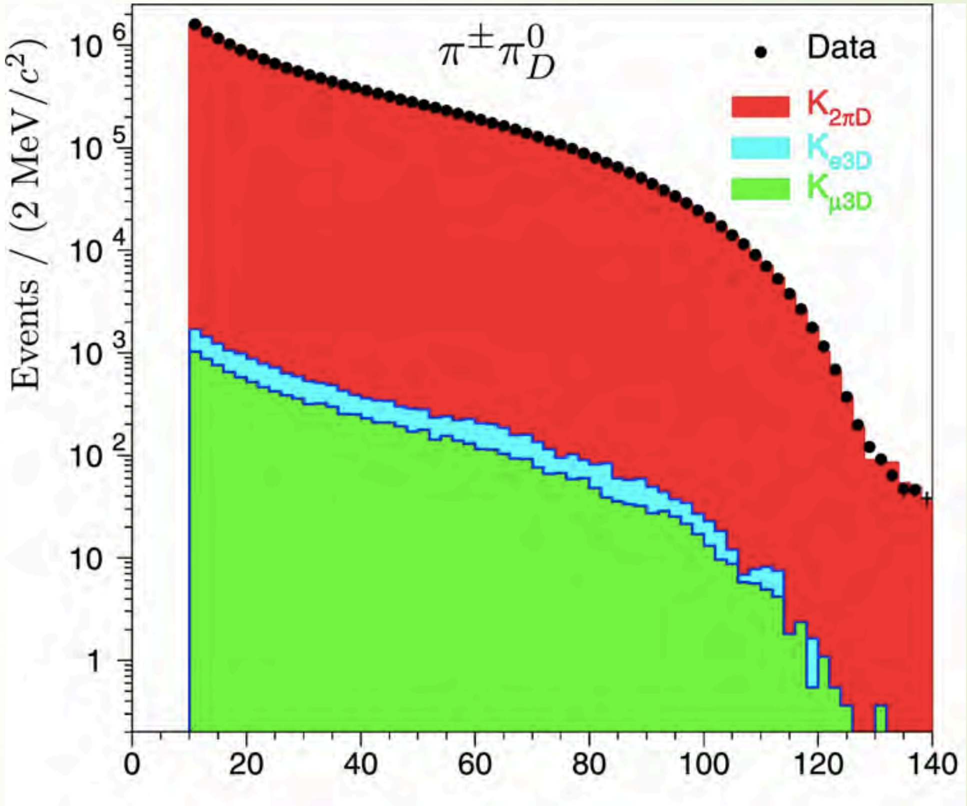


M_{ee} spectra

Data sample: ~ 1.7 x 10^{11} kaon decays (K^+ and K^-), collected in 2003-2004



M_{ee}(MeV/c^2)



M_{ee}(MeV/c^2)

Branching Ratio measurement

$$BR(K^\pm \to \pi^\pm \pi^0 e^+ e^-) = \frac{N_S - N_{BS}}{N_N - N_{BN}} \cdot \frac{A_N}{A_S} \cdot \frac{\varepsilon_N}{\varepsilon_S} \cdot \frac{\Gamma(\pi^0_D)}{\Gamma(\pi^0_{\gamma\gamma})} \cdot BR(K^\pm \to \pi^\pm \pi^0)$$

Signal		Normalization	
Candidates N_S	4919	Candidates N_N	16.3 x 10^6
Background N_{BS}	241± 21	Background N_{BN}	17288 ± 159
Acceptance A_S	0.662 (1) %	Acceptance A_N	3.981(2) %
L1 trigger eff. (S)	(99.729 ± 0.009)%	L1 trigger eff. (N)	(99.767 ± 0.003)%
L2 trigger eff. (S)	(98.604 ± 0.021)%	L2 trigger eff. (N)	(98.495 ± 0.006)%

- A_S is the weighted average of IB, DE, INT acceptances using expected relative contributions to the total rate
- A_N is computed using the simulation of $K^\pm \to \pi^\pm \pi^0$ (1) followed by the π^0_D decay according to (2)
- radiative correction to the signal taken into account using PHOTOS

1) C. Gatti, Eur. Phys. J. C45 (2006) 417
2) T. Husek et al.,Phys. Rev. D92 (2015) 054027

Uncertainties evaluation

Several sources of uncertainties have been considered

statistical uncertainties

Source	$\delta BR/BR \times 10^2$
N_s	1.426
N_{bs}	0.416
N_n	0.025
N_{bn}	negligible
TOTAL STATISTICS	1.486

external uncertainties

Source	$\delta BR/BR \times 10^2$
BR ($K2\pi$)	0.387
$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$	2.946
TOTAL EXTERNAL	2.971

systematic uncertainties

Source	$\delta BR/BR \times 10^2$
A_s (MC statistics)	0.171
A_n (MC statistics)	0.051
ε ($L1_s \times L2_s$) (MC statistics)	0.023
ε ($L1_n \times L2_n$) (MC statistics)	0.007
Acceptance geometry control	0.083
Acceptance time variation control	0.064
Backgound control	0.280
Trigger efficiency (systematics)	0.400
Model dependence	0.285
Radiative effects	0.490
TOTAL SYSTEMATICS	*0.777*

Branching ratio result

$$BR(K^{\pm} \rightarrow \pi^{\pm}\,\pi^{0} e^{+} e^{-}) = \left(4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}\right) \text{ x } 10^{-6}$$

- ✓ The statistical error is dominated by the signal statistics, the systematic error by the radiative effects and external error by the BR (π^{0}_{D}) uncertainty
- ✓ Result is in agreement with ChPT [EPJ C72 (2012), EPJ C 78 (2018) 265]
- ✓ Prediction for Inner Bremsstrahlung only
  - ✓ BR(IB) = 4.183×10^{-6}
- ✓ Prediction including Direct Emission and Interference
  - ✓ BR(IB) = 4.229×10^{-6}

First observation!

NEW

Phys.Lett. B788 (2019) 552

Kinematic space study/1

- The contribution of the DE magnetic term (M) to the total decay rate cannot be quantified within the collected statistics
- In [Eur. Phys. J. C 72 (2012) 1872, Eur. Phys. J. C 78 (2018) 265] the authors pointed out that the contributions of IB, M, and IB-E terms have different distributions in the Dalitz plot (T_π^*,E_γ^*) for different ranges of q^2 values (T_π^*, E_γ^* and q^2 are the charged pion kinetic energy, the virtual photon energy in the kaon rest frame, and the e^+e^- mass squared, respectively)

→ A detailed study of the kinematic space has been performed

- 3d-boxes in the kinematic space (q^2, T_π^*, E_γ^*) are used to determine the relative fraction of each component
- The data 3d-space is split first into N1slices along q^2, then into N2 slices along T_π^* and, finally, into N3 E_γ^* slices
- N1 x N2 x N3 exclusive boxes of variable size, but equal population, are formed

Kinematic space study/2

- To obtain the fractions (M)/IB and (IB-E)/IB reproducing the data, a χ^2 estimator is minimized:

$$\chi^2 = \sum_{i=1}^{N1\,x\,N2\,x\,N3} (N_i - M_i)/(\delta N_i^2 + \delta M_i^2)$$

- where N_i (δN_i) is the data population (error) and M_i (δM_i) is the expected population (error) in box *i*
- The expected number of events in box i is computed as (N is a global scale factor)

$$M_i = \mathrm{N\,x}\left(N_i^{IB} + a \cdot N_i^{M} + b \cdot N_i^{IB-E}\right) + N_i^{Bkg}$$

- At the end of minimization, the obtained values of *a* and *b* can be related to the relative contributions (M)/IB and (IB-E)/IB

Kinematic space study/3

- The obtained values for the two fractions (M)/IB and (IB-E)/IB are

	DATA	THEORY
M/IB	$0.0114 \pm 0.0043_{stat}$	$0.0141 \pm 0.0014_{ext}$
(IB-E)/IB	$-0.0014 \pm 0.0036_{stat}$	$0.0039 \pm 0.0028_{ext}$
χ^2	98.2/87	
Probability	19%	
Correlation	C(a,b) = 0.06	

consistent with the predicted value obtained using the experimental measurement of $N_M^{(0)}$

no sensitivity to this contribution within the current data statistics

agrees with the predicted value obtained using the experimental measurement of $N_E^{(0,1,2)}$

Asymmetry investigations/1

- The simplest CP-violating asymmetry is the charge asymmetry between K^+ and K^- partial rates integrated over the whole phase space:

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

- The value of A_{CP} can be related to the IB-E interference term
- The asymmetry is obtained from the statistically independent measurements of K^+ and K^- Branching Ratios
- The value obtained, $A_{CP} = -0.0284 \pm 0.0155$ (the error is statistical only, as the systematic and external errors cancel in the ratio) is consistent with zero and is translated to a single-sided limit:

$$BR\ (K^+) = (4.151 \pm 0.078_{stat})\ \mathrm{x}\ 10^{-6}$$
$$BR\ (K^-) = (4.394 \pm 0.108_{stat})\ \mathrm{x}\ 10^{-6}$$

$$\Rightarrow \quad |A_{CP}| < 4.82\ \mathrm{x}\ 10^{-2}\ at\ 90\%\ CL$$

Asymmetry investigations/2

- Other angular/charge asymmetries (defined in [EPJ C 72 (2012) 1872]) can be extracted selecting particular integration regions of the ϕ angular variable: $A_{CP}^{\varphi^*}$ and $A_{CP}^{\tilde{\varphi}}$
- Both asymmetries are consistent with zero. The single-sided limits are

$A_{CP}^{\varphi^*} = 0.0119 \pm 0.0150_{stat}$	⇒	$\left\|A_{CP}^{\varphi^*}\right\| < 3.11\ x\ 10^{-2}$ (90% CL)
$A_{CP}^{\tilde{\varphi}} = 0.0058 \pm 0.0150_{stat}$	⇒	$\left\|A_{CP}^{\tilde{\varphi}}\right\| < 2.50\ x\ 10^{-2}$ (90% CL)

- The long distance P-violating asymmetry $A_P^{(L)}$ also has been found to be consistent with zero

Summary and perspectives

- The decay $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} e^{+} e^{-}$ has been observed for the first time
- Using 4919 signal events, with 4.9% background, the Branching Ratio has been measured

$$BR(K^{\pm} \rightarrow \pi^{\pm} \pi^{0} e^{+} e^{-}) = \left(4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}\right) \text{ x } 10^{-6}$$

- The result is in agreement with the ChPT prediction
- The relative contributions, (M)/IB = $(1.14 \pm 0.43_{stat})$ x 10^{-2} and (IB-E)/IB = $(-0.14 \pm 0.36_{stat})$ x 10^{-2}, are also found consistent with the theoretical expectation
- Several CP-violating asymmetries and a long-distance P-violating asymmetry have been evaluated and found to be consistent with zero
- If larger data statistics becomes available (e.g. at the NA62 experiment), improved evaluation of DE term contribution can be achieved

NA48/2 still alive with new physics results!!

Thank you for your attention