Rare Kaon decays at NA48 and NA62

Andrea Bizzeti

University of Modena e Reggio Emilia
and I.N.F.N. Sezione di Firenze, Italy

on behalf of the NA48/2 and NA62 collaborations

Outline:

1. The NA48 and NA62 experiments at CERN
2. Study of the rare decay $K^{\pm} \to \pi^{\pm}\gamma\gamma$
3. Precision measurements on $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ and $K^{\pm} \to \pi^{0}\pi^{0}e^{\pm}\nu$
4. Summary

16th Lomonosov Conference – August 27 , 2013

NA48/NA62 experiments at CERN SPS

High statistics for rare Kaon decays

NA48: direct CPV (ε'/ε)
- 1997 – 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

NA48/1
- 2002 : K_S / hyperons

NA48/2
- 2003 – 2004 :
- $K^+ + K^-$ CPV$(K_{3\pi})$

NA62-R_K
- 2007 – 2008 :
- $K^+ + K^-$ $(K_{e2}/K_{\mu 2})$

NA62
- 2007 – 2013 : design & construction
- 2014 – 2016 : $K^+ \to \pi^+ \nu \bar{\nu}$

see talk by Viacheslav Duk on August 23rd ⟵ NA62

Beam and detector

2003 – 2008 : charged kaon beams
+ the NA48 detector

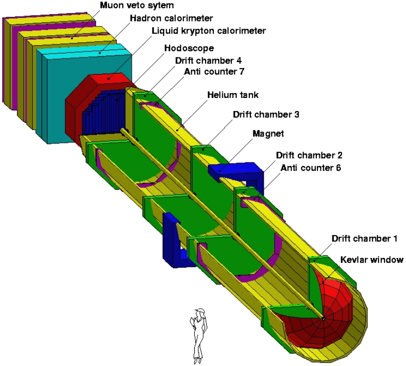
Narrow momentum band $K^{\pm}$ beams

- NA48/2: 6 months in 2003-04
- NA62-R_K: 4 months in 2007

Main subdetectors:

- magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy ⇒ efficiency
  $\delta p/p = 1.02\% \oplus 0.044\%\, p$ (NA48/2)
  $\delta p/p = 0.48\% \oplus 0.009\%\, p$ (NA62-R_K)
- scintillator hodoscope
  fast trigger, time measurements (150 ps)
- Liquid Krypton EM cal. (LKr)
  high granularity, quasi-homogeneous
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$

⇒ $e/\mu/\pi$ discrimination (E/p)



$K^{\pm}$ data samples

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	NA62 (K^{+}, planned)
Data taking period	2003-2004	2007-2008	2014-2017
Beam momentum [GeV/c]	60	74	75
Beam momentum RMS [GeV/c]	2.2	1.4	0.8
Spectrometer thickness [X_0]	2.8%	2.8%	1.8%
Spectrometer P_T kick [MeV/c]	120	265	270
$M(K^{\pm}\to 3\pi^{\pm})$ resolution [MeV/c^2]	1.7	1.2	0.8
$K^{\pm}$ decays in fiducial volume	1.9×10^{11}	2.5×10^{10}	1.2×10^{13}
Main trigger	multi-track, $K^{\pm}\to\pi^{\pm}\pi^0\pi^0$	$e^{\pm}$	$K_{\pi\nu\bar{\nu}} + \ldots$

Same detector (NA48) [NA48/2 and NA62-R_K]

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

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

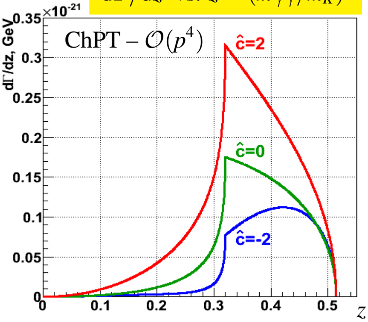
ChPT description:

- Rate and spectrum depend on a single unknown parameter $\hat{c}$
- Leading contribution at $\mathcal{O}(p^4)$ loop:

  cusp at $2\,m_\pi$ threshold

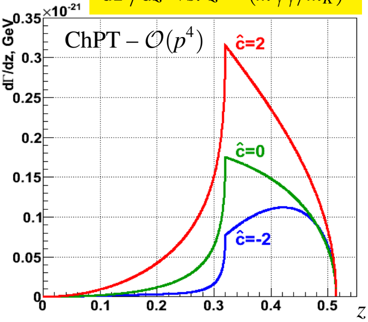
  [Ecker, Pich, de Rafael, NPB303 (1988) 665]

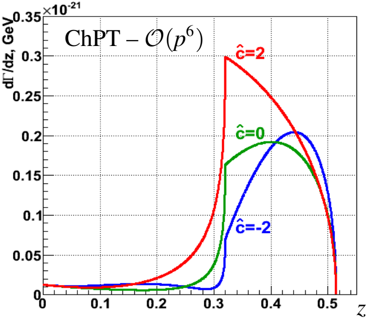
$d\Gamma/dz$ vs. $z = (m_{\gamma\gamma}/m_K)^2$



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

$\mathrm{d}\Gamma/\mathrm{d}z$ vs. $z = (m_{\gamma\gamma}/m_K)^2$





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  [Ecker, Pich, de Rafael, NPB303 (1988) 665]
- $\mathcal{O}(p^6)$ "unitarity corrections" increase BR at low $\hat{c}$ and result in a non-zero rate at $m_{\gamma\gamma} \to 0$
  [D'Ambrosio, Portolés, PLB386 (1996) 403]
  [Gérard, Smith, Trine, NPB730 (2005) 1]

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

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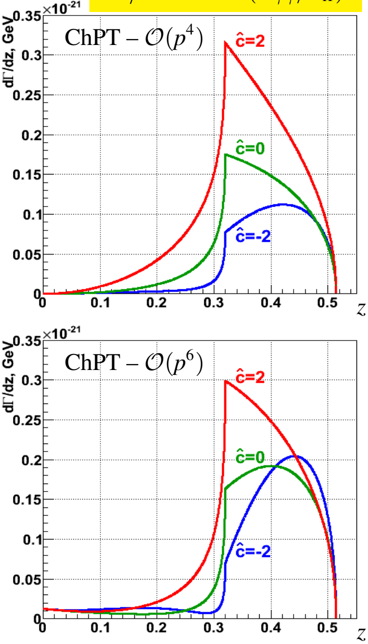
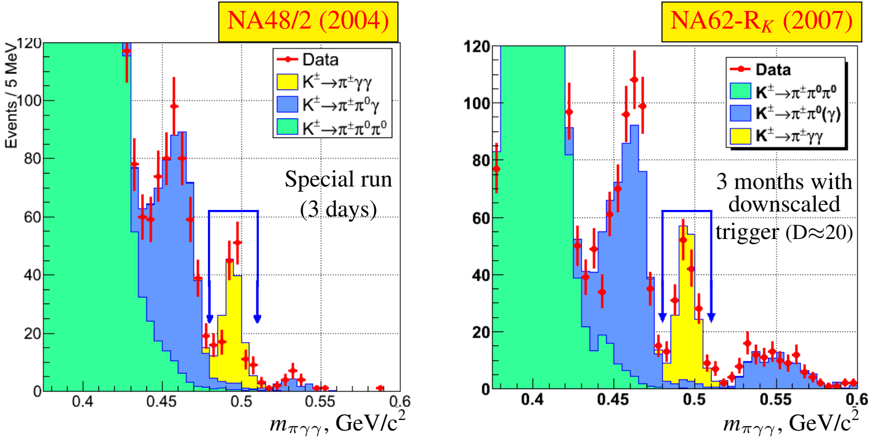
Experimental status:

- BNL E787: 31 candidates
  BR$= (1.10 \pm 0.32) \times 10^{-6}$
  [PRL79 (1997) 4079]
- NA48/2, NA62-R_K :
  using "minimum bias" samples

$\mathrm{d}\Gamma/\mathrm{d}z$ vs. $z = (m_{\gamma\gamma}/m_K)^2$



$K^{\pm} \to \pi^{\pm}\gamma\gamma$: data samples



		NA48/2	NA62-R_K
$K_{\pi\gamma\gamma}$	candidates	149	175
$K_{2\pi(\gamma)}$	background	11.4 ± 0.6	11.1 ± 1.0
$K_{3\pi}$	background	4.1 ± 0.4	1.3 ± 0.3
$K_{\pi\gamma\gamma}$	signal	134 ± 12	163 ± 13

$K^\pm \to \pi^\pm\gamma\gamma$: NA48/2 model-independent BR

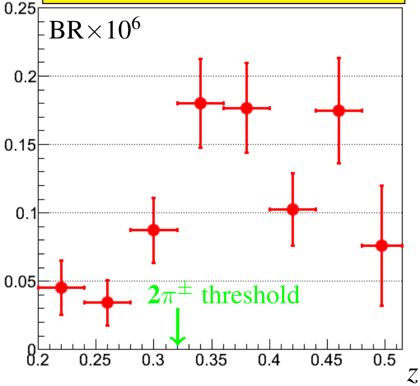
NEW: July 2013

THE FINAL NA48/2 RESULT

Sufficiently small bins:
acceptance almost independent
of kinematical distribution

z range	N_j	N_j^B	A_j	$\mathcal{B}_j \times 10^6$
0.20–0.24	13	4.89	0.194	0.045 ± 0.020
0.24–0.28	9	2.73	0.198	0.034 ± 0.016
0.28–0.32	18	2.33	0.194	0.087 ± 0.024
0.32–0.36	33	1.30	0.190	0.180 ± 0.033
0.36–0.40	31	0.98	0.184	0.177 ± 0.033
0.40–0.44	18	1.61	0.173	0.103 ± 0.027
0.44–0.48	23	1.21	0.135	0.175 ± 0.038
$z > 0.48$	4	0.52	0.049	0.076 ± 0.044

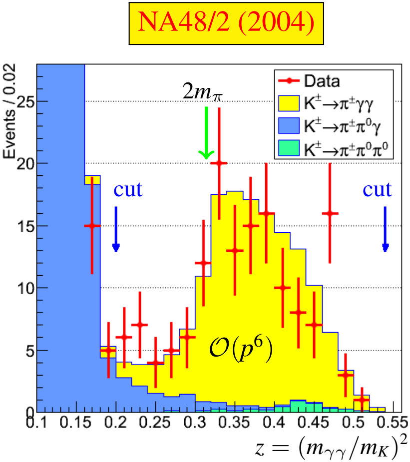
Model-independent BR in z bins

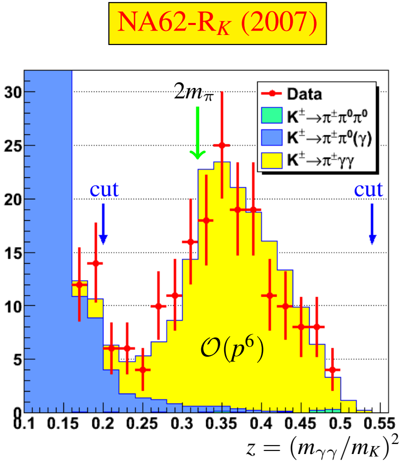


$$\mathrm{BR_{MI}}(z > 0.2) = (0.877 \pm 0.087_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}}) \times 10^{-6}$$

$K^\pm \to \pi^\pm\gamma\gamma$: fits to ChPT description

preliminary





- Data support the ChPT prediction of a cusp at the $2\,m_{\pi^+}$ threshold
- ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ predictions cannot be distinguished

$K^\pm \to \pi^\pm\gamma\gamma$ fits to ChPT: results

preliminary

ChPT formulation: D'Ambrosio, Portolés, PLB 386 (1996) 403

NA48/2 (2004)

ChPT $\mathcal{O}(p^4)$:

$\hat{c} = 1.36 \pm 0.33_{\text{stat}} \pm 0.07_{\text{syst}} = 1.36 \pm 0.34$

ChPT $\mathcal{O}(p^6)$:

$\hat{c} = 1.67 \pm 0.39_{\text{stat}} \pm 0.09_{\text{syst}} = 1.67 \pm 0.40$

NA62-R$_K$ (2007)

ChPT $\mathcal{O}(p^4)$:

$\hat{c} = 1.71 \pm 0.29_{\text{stat}} \pm 0.06_{\text{syst}} = 1.71 \pm 0.30$

ChPT $\mathcal{O}(p^6)$:

$\hat{c} = 2.21 \pm 0.31_{\text{stat}} \pm 0.08_{\text{syst}} = 2.21 \pm 0.32$

$\Downarrow$

COMBINED

ChPT $\mathcal{O}(p^4)$:

$\hat{c} = 1.56 \pm 0.22_{\text{stat}} \pm 0.07_{\text{syst}} = 1.56 \pm 0.23$

ChPT $\mathcal{O}(p^6)$:

$\hat{c} = 2.00 \pm 0.24_{\text{stat}} \pm 0.09_{\text{syst}} = 2.00 \pm 0.26$

$\text{BR}_6 = (1.01 \pm 0.06) \times 10^{-6}$

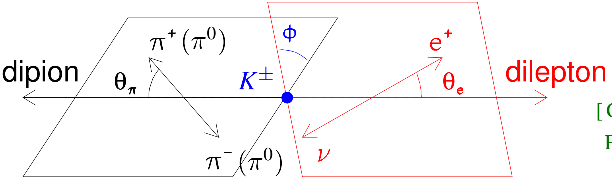
(model-dependent BR in full phase space)

cf. PDG(=E787): $\text{BR}_6 = (1.10 \pm 0.32) \times 10^{-6}$

K_{e4} decays

K_{e4} decays: kinematics and formalism

Five kinematic variables: $s_\pi = M^2_{\pi\pi}$, $s_e = M^2_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$, ϕ



[Cabibbo, Maksymowicz, PR 137 (1965) B438]

Partial wave expansion and form factors

Pais, Treiman, PR 168 (1968) 1858

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

$$F = F_s\, e^{i\delta_s} + F_p\, e^{i\delta_p} \cos\theta_\pi + \ldots$$
$$G = G_p\, e^{i\delta_p} + \ldots; \quad H = H_p\, e^{i\delta_p} + \ldots$$

$$F_s = f_s + f_s' \cdot q^2 + f_s'' \cdot q^4 + f_e' S_e/4m_\pi^2 + \ldots$$
$$F_p = f_p + f_p' \cdot q^2 + \ldots$$
$$G_p = g_p + g_p' \cdot q^2 + \ldots \qquad [\,F,\ G = \text{axial FF}]$$
$$H_p = h_p + h_p' \cdot q^2 + \ldots \qquad [\,H = \text{vector FF}]$$
$$\delta(q^2) = \delta_s - \delta_p$$

$K^\pm \to \pi^0\pi^0 e^\pm \nu$

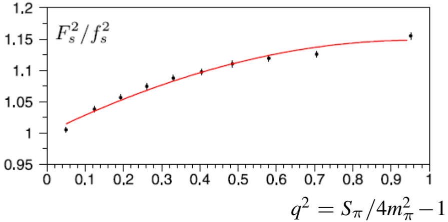
$$F = F_s\, e^{i\delta_s}$$

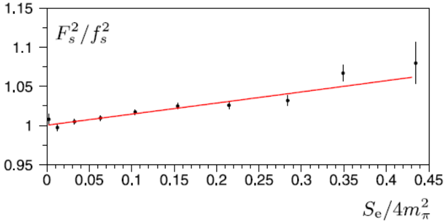
$\pi\pi$ S-wave scattering lengths can be extracted from variation of δ with $q^2 = (S_\pi/4m_\pi^2 - 1)$

[Ananthanarayan et al., Phys. Rep. 353 (2001) 207; Colangelo, Gasser, Rusetsky, EPJ C59 (2009) 777]

$K^{\pm} \to \pi^+\pi^-e^{\pm}\nu$: form factors

Final NA48/2 results [EPJ C70 (2010) 635]





$K^{\pm} \to \pi^+\pi^-e^{\pm}\nu$ data sample:

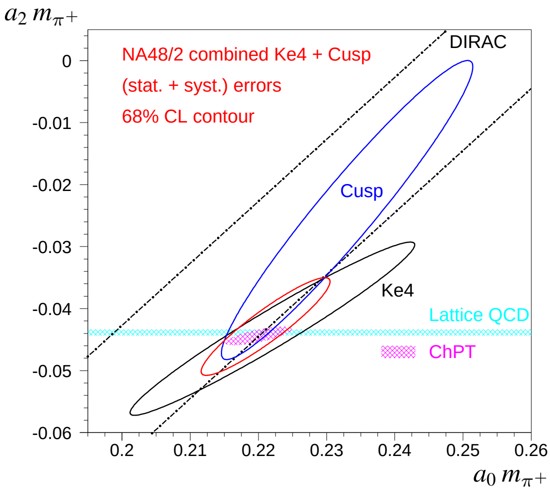
- 1.13×10^6 candidates
- 0.6% background

Relative Form Factors

f_s'/f_s	$=$	0.152	$\pm 0.007_{\text{stat}}$	$\pm 0.005_{\text{syst}}$
f_s''/f_s	$=$	-0.073	$\pm 0.007_{\text{stat}}$	$\pm 0.006_{\text{syst}}$
f_e'/f_s	$=$	0.068	$\pm 0.006_{\text{stat}}$	$\pm 0.007_{\text{syst}}$
f_p/f_s	$=$	-0.048	$\pm 0.003_{\text{stat}}$	$\pm 0.004_{\text{syst}}$
g_p/f_s	$=$	0.868	$\pm 0.010_{\text{stat}}$	$\pm 0.010_{\text{syst}}$
g_p'/f_s	$=$	0.089	$\pm 0.017_{\text{stat}}$	$\pm 0.013_{\text{syst}}$
h_p/f_s	$=$	-0.398	$\pm 0.015_{\text{stat}}$	$\pm 0.008_{\text{syst}}$

$K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$: $\pi\pi$ scattering lengths

s-wave $\pi\pi$ scattering lenghts a_I $(I = 0, 2)$



NA48/2 $K_{3\pi}$ cusp
[EPJ C64 (2009) 589]

NA48/2 K_{e4} phase shift
+ NA48/2 combination
[EPJ C70 (2010) 635]

DIRAC $\pi\pi$ atoms
[PLB 704 (2011) 24]

Lattice QCD
[PLB 684 (2010) 268,
PRD 77 (2008) 014505]

ChPT
[PLB 488 (2000) 261]

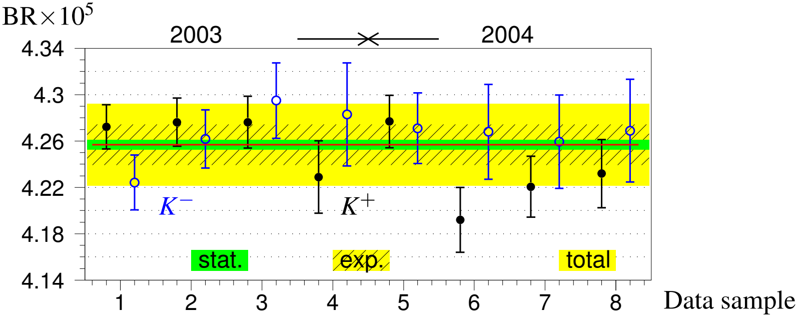
$K^{\pm} \to \pi^+\pi^-e^{\pm}\nu$: BR and f_s

BR measured w.r.t. normalization mode $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$

Final result: [PLB 715 (2012) 105]

$\mathrm{BR}(K^{\pm} \to \pi^+\pi^-e^{\pm}\nu) = (4.257 \pm 0.004_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}}) \times 10^{-5}$

cf. PDG: $\mathrm{BR} = (4.09 \pm 0.10) \times 10^{-5}$



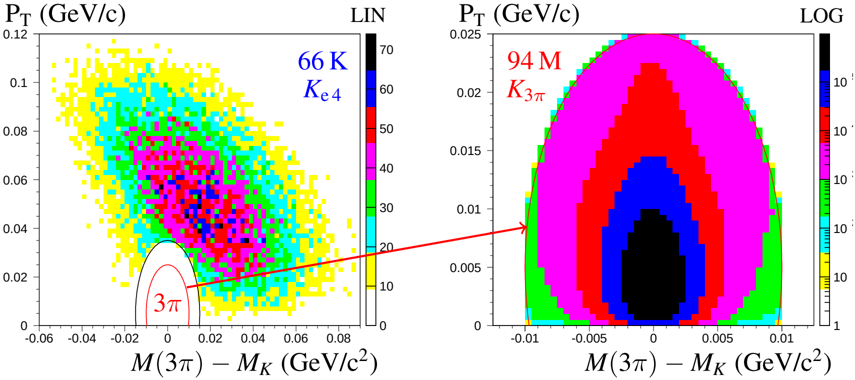
$\mathrm{BR}(K^{\pm} \to \pi^+\pi^-e^{\pm}\nu) = \tau_K(|V_{us}|f_s)^2\mathcal{I} \to$ absolute f_s measurement.

Results: $|V_{us}|f_s = 1.285 \pm 0.001_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.005_{\mathrm{ext}}$

$f_s = 5.705 \pm 0.003_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}}$

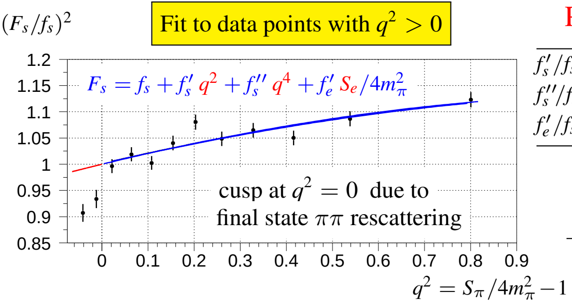
$K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu$: signal selection

- Plot P_T vs reconstructed $\pi^{\pm}\pi^0\pi^0$ mass (assuming charged track = pion)
- K_{e4} candidates well separated from $K_{3\pi}$ events



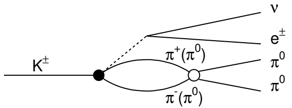
- electron identification: E/p and shower properties
- 66×10^3 K_{e4}candidates, 1.07% background

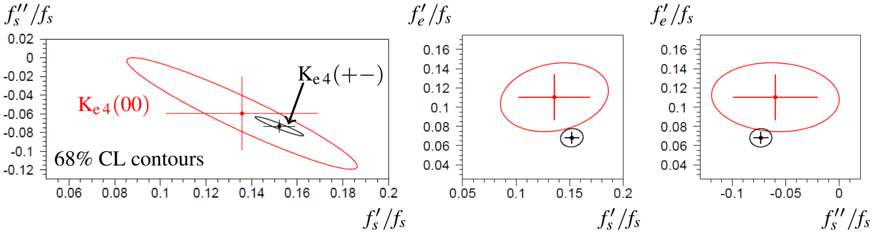
$K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu$: form factor



Preliminary results:

$$f_s'/f_s = 0.136 \pm 0.033_{stat} \pm 0.015_{syst}$$
$$f_s''/f_s = -0.060 \pm 0.039_{stat} \pm 0.015_{syst}$$
$$f_e'/f_s = 0.110 \pm 0.024_{stat} \pm 0.022_{syst}$$





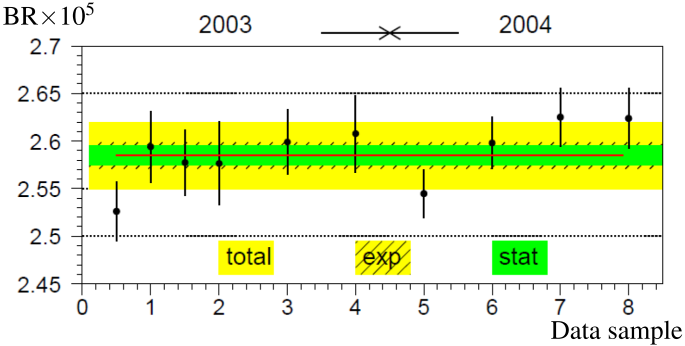
$K^\pm \to \pi^0\pi^0 e^\pm \nu$: BR and f_s

BR measured w.r.t. normalization mode $K^\pm \to \pi^0\pi^0\pi^\pm$

Preliminary result:

$$\mathrm{BR}(K^\pm \to \pi^0\pi^0 e^\pm \nu) = (2.585 \pm 0.010_{\mathrm{stat}} \pm 0.010_{\mathrm{syst}} \pm 0.032_{\mathrm{ext}}) \times 10^{-5}$$

cf. PDG: $\mathrm{BR} = (2.2 \pm 0.14) \times 10^{-5}$



$\mathrm{BR}(K^\pm \to \pi^0\pi^0 e^\pm \nu) = \tau_K (|V_{us}| f_s)^2 \mathcal{I}$ $\to$ absolute f_s measurement.

Results: $|V_{us}| f_s = 1.372 \pm 0.003_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.008_{\mathrm{ext}}$

$f_s = 6.092 \pm 0.012_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.045_{\mathrm{ext}}$

Summary

- $K^{\pm} \to \pi^{\pm}\gamma\gamma$ rare decay (NA48/2 + NA62-R_K) [preliminary]
  - data agree with ChPT description
  - cannot distinguish between $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ predictions
  - new NA48/2 model-independent measurement of BR($z > 0.2$)
  - final results and publications are in preparation

- $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ decay (NA48/2) [PLB 715 (2012) 105]
  - precision measurements of form factors and BR
  - determination of $\pi\pi$ scattering lengths

- $K^{\pm} \to \pi^{0}\pi^{0}e^{\pm}\nu$ decay (NA48/2) [work in progress]
  - first measurement of form factor
  - evidence of $\pi\pi$ rescattering in final state
  - most precise BR measurement (1.3% relative uncertainty)

BACKUP SLIDES

$K^\pm \to \pi^0\pi^0 e^\pm \nu$: event reconstruction

$K^\pm \to \pi^0\pi^0 e^\pm \nu$ relative to $K^\pm \to \pi^0\pi^0\pi^\pm$, BR=$(1.761 \pm 0.022)\%$

Common event reconstruction for ($\pi^0\pi^0$ + charged track):

Find γ cluster pairs 1(ab) and 2(cd) and:

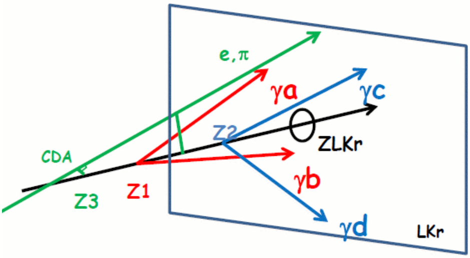
1) derive vertex positions $Z_1,\ Z_2$ using π^0 mass constraint:

- $Z_1 = Z(LKr) - \frac{1}{m(\pi^0)} D(ab)\sqrt{E_a E_b}$
- $Z_2 = Z(LKr) - \frac{1}{m(\pi^0)} D(cd)\sqrt{E_c E_d}$

2) require:

- $|Z_1 - Z_2| < 5\,\text{m}$
- $Z_n = \frac{1}{2}(Z_1 + Z_2)$ within fiducial volume

3) combine with a charged track if Z_3 (CDA to beam line) satisfies $|Z_3 - Z_n| < 8\,\text{m}$



up to now: no PID

Ke4(+-) decay: Event selection and background rejection

Signal ($\pi^+\pi^-e^\pm\nu$) topology:

- 3 charged tracks, forming a good vertex
- 2 opposite sign pions, 1 electron [$E_{LKr}/p \simeq 1$]
- some missing energy and p_T (ν)
- good reconstructed P_K (missing ν hypothesis)

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Background main sources (suppressed by specific cuts):

- $K^+ \to \pi^+\pi^-\pi^+$ ($\pi^+ \to e^+\nu$ or π^+ mis-ID)
- $K^+ \to \pi^+\pi^0$ ($\pi^0 \to e^+e^-\gamma$ and e^- mis-ID)

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Background control sample from data (assuming $\Delta S = \Delta Q$):

- $\pi^\pm\pi^\pm e^\mp\nu$ ("Wrong-Sign" events)

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- Ratio "Right-Sign" : "Wrong-Sign" =

  2 : 1 if coming from $K_{3\pi}$ (dominant)

  1 : 1 if coming from $K_{2\pi}$

Ke4(+-) decay: Event selection and background rejection

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Background control sample from data (assuming $\Delta S = \Delta Q$):

- $\pi^\pm\pi^\pm e^\mp\nu$ ("Wrong-Sign" events)
- Ratio "Right-Sign" : "Wrong-Sign" =

  2 : 1 if coming from $K_{3\pi}$ (dominant)

  1 : 1 if coming from $K_{2\pi}$

Data sample: 1.13×10^6 events. Total background is less than 1%

Ke4(+-) decay: background rejection

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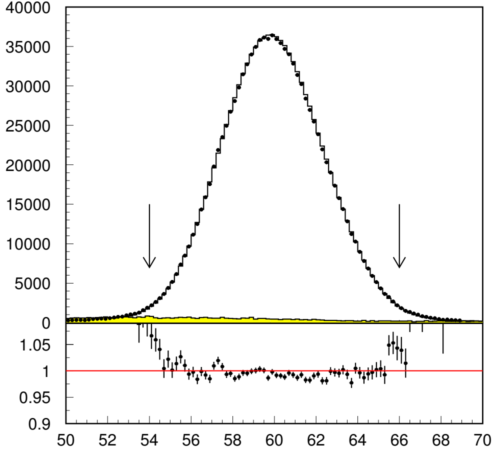

Reconstructed Kaon momentum (GeV/c)

Background

- estimated from $\pi^{\pm}\pi^{\pm}e^{\mp}\nu$ "Wrong-Sign" events in Data
- checked with MC simulation of background processes

Points = Data
Hisogram = MC simulation
Yellow hist. = background ($\times$5 to be visible)

← Data/MC ratio

Ke4(+-) decay and $\pi\pi$ scattering lengths

The S-wave $\pi\pi$ scattering lengths a_0 and a_2 ($I = 0$ and $I = 2$)

are precisely predicted by ChPT

Two statistically independent measurements by NA48/2:

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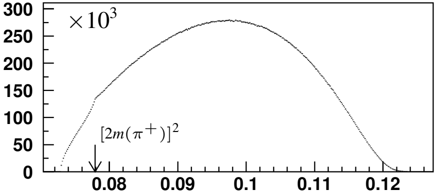
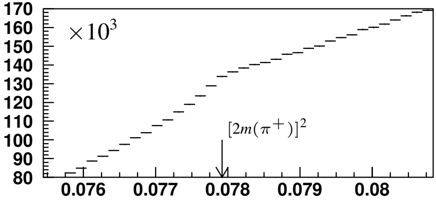


$M^2(\pi^0\pi^0)$ [(GeV/c^2)^2]

Interference between

$K^\pm \to \pi^\pm\pi^0\pi^0$ and

$K^\pm \to \pi^\pm\pi^+\pi^-$, $\pi^+\pi^- \to \pi^0\pi^0$



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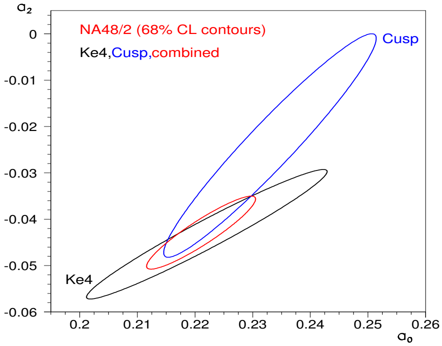

[a_0, a_2 values in units of $1/m(\pi^+)$]

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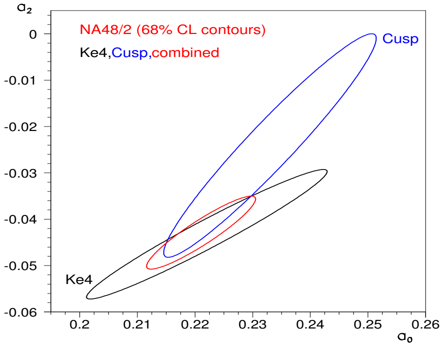
- Different systematics: electron misID and background vs. calorimeter and trigger
- Different theoretical inputs: Roy equations and isospin breaking correction vs. rescattering in final state and ChPT expansion



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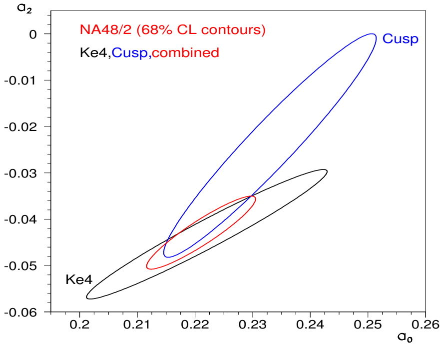
▶ Large overlap in the a_0, a_2 plane



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Ke4(+-): absolute Form Factors

BR $\rightarrow$ overall form factor normalization: $K^{\pm}_{e4}(+-)$

$$
\begin{aligned}
f_s &= 5.705 \pm 0.003_{\rm stat} \pm 0.017_{\rm syst} \pm 0.031_{\rm ext} \\
&= 5.705 \pm 0.035_{\rm norm}
\end{aligned}
$$

$$
\begin{aligned}
f_s' &= 0.867 \pm 0.040_{\rm stat} \pm 0.029_{\rm syst} \pm 0.005_{\rm norm} \\
f_s'' &= -0.416 \pm 0.040_{\rm stat} \pm 0.034_{\rm syst} \pm 0.003_{\rm norm} \\
f_e' &= 0.388 \pm 0.034_{\rm stat} \pm 0.040_{\rm syst} \pm 0.002_{\rm norm} \\
f_p &= -0.274 \pm 0.017_{\rm stat} \pm 0.023_{\rm syst} \pm 0.002_{\rm norm} \\
g_p &= 4.952 \pm 0.057_{\rm stat} \pm 0.057_{\rm syst} \pm 0.031_{\rm norm} \\
g_p' &= 0.508 \pm 0.097_{\rm stat} \pm 0.074_{\rm syst} \pm 0.003_{\rm norm} \\
h_p &= -2.271 \pm 0.086_{\rm stat} \pm 0.046_{\rm syst} \pm 0.014_{\rm norm}
\end{aligned}
$$

$\rightarrow$ Published in Phys. Lett. B 715, 105-115 (2012)