Kaon decays at NA48: recent results and perspectives

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on behalf of the NA48/2 collaboration

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Outline

The NA48 experiment at CERN SPS

$K^{\pm} \to \pi\pi e^{\pm}\nu$ (K_{e4}), $\pi\pi$ scattering lengths, $K_{\mu 4}$

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: new result (NA48/2 +NA62)

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{(*)}$: first observation of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$

$K^{\pm} \to \pi^{\pm}l^{+}l^{-}$: recent results on $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

Conclusions

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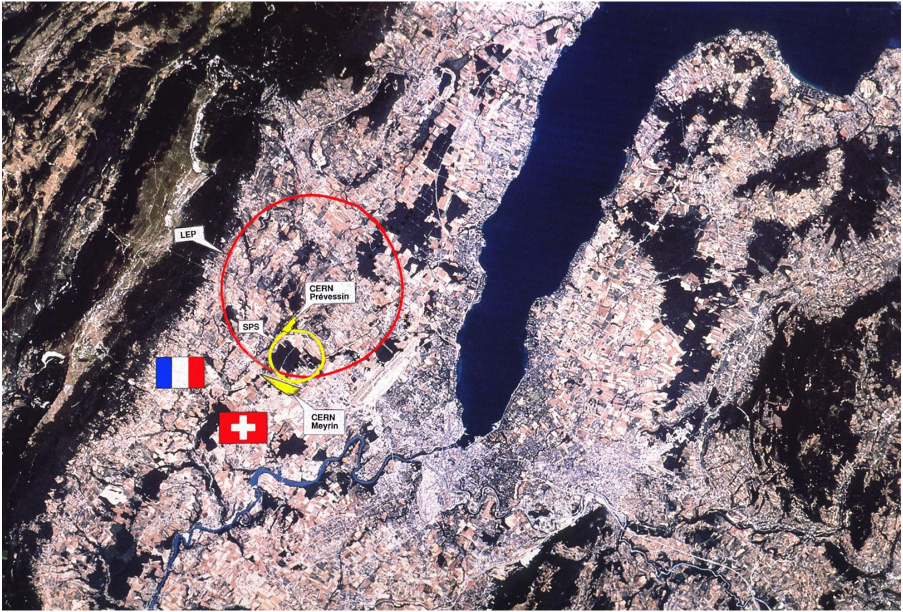


The NA48 experiment

NA48/2: Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

NA62: Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-La-Neuve, Mainz, Merced, Napoli, Perugia, Pisa, Prague, Roma I, Roma II, Saclay, San Luis Potosì, Stanford, Sofia, Torino, TRIUMF

NA48: direct CPV (ε'/ε)
- 1997 : $K_L + K_S$
- 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

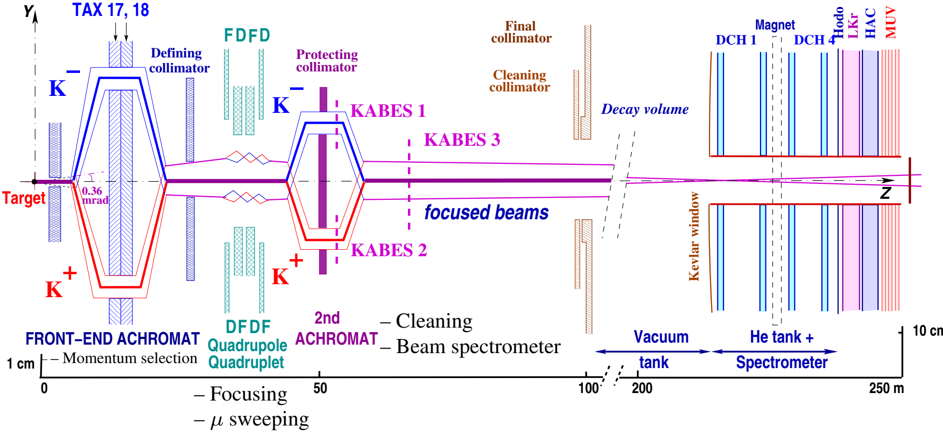
NA48/2 ($K_{3\pi}$)
- 2003 : $K^+ + K^-$
- 2004 : $K^+ + K^-$

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

NA62
- 2014 : K^+ ($\to \pi^+ \nu \bar{\nu}$)
- $\cdots$

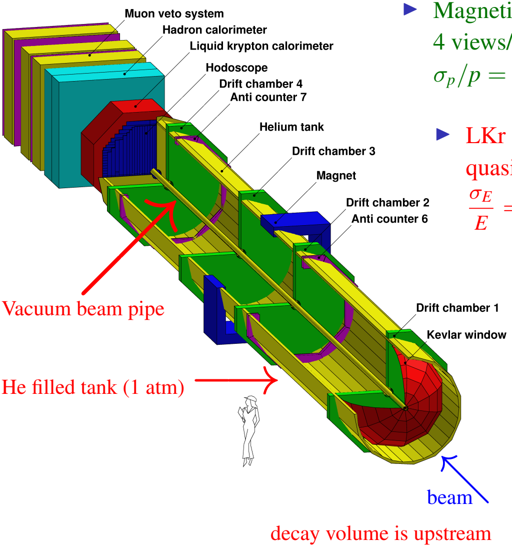
High statistics for rare Kaon decays

The NA48/2 beams (2003–2004)



- 400 GeV/c SPS protons ⇒ unseparated secondary charged beam (≈ 5% kaons)
- 60 GeV/c (± 3.8% rms) simultaneous K^+ and K^- beams ($K^+/K^- \simeq 1.8$)
  ⇒ large charge symmetrization of experimental conditions
- $\sim 4\,\mathrm{mm} \times 4\,\mathrm{mm}$, $\sim 10\,\mu\mathrm{rad} \times 10\,\mu\mathrm{rad}$ (rms)
- 22% of kaons decay in the 114 m long vacuum tank.

The NA48/2 detectors



<u>Detectors:</u>

- Magnetic spectrometer (4 DCH)
  4 views/DCH: redundancy ⇒ efficiency
  $\sigma_p/p = 1.02\% \oplus 0.044\% * p$ [GeV/c]

- LKr electromagnetic calorimeter:
  quasi-homogeneous, high granularity
  $\frac{\sigma_E}{E} = \frac{3.2\%}{E^{1/2}} \oplus \frac{9\%}{E} \oplus 0.42\%$ [GeV]

  ⇒ e/π discrimination (E/p)

- Scintillator hodoscope
  for charged fast trigger:
  $\sigma(t) = 150$ ps

- hadron calorimeter

- muon counters

- photon vetos

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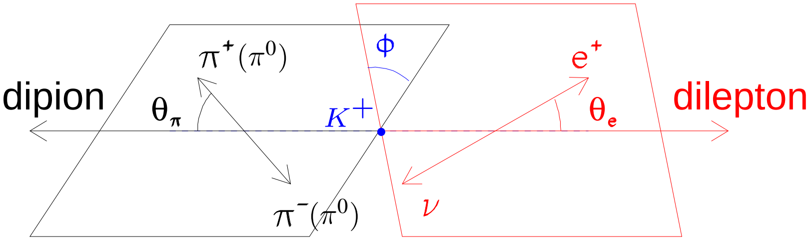
Ke4 decays

- $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$, called $K_{e4}(+-)$ - charged mode
- $K^{\pm} \to \pi^{0}\,\pi^{0}\,e^{\pm}\nu$, called $K_{e4}(00)$ - neutral mode



Five kinematic variables (Cabibbo-Maksymowicz 1965):

$$s_{\pi} = M^2_{\pi\pi}, \qquad s_e = M^2_{e\nu}, \qquad \cos\theta_{\pi}, \qquad \cos\theta_e, \qquad \phi$$

Form factors: formalism of K_{e4} decay

K_{e4} hadronic current is described by form factors

$\to$ Partial Wave expansion, limited to S and P waves

[Pais-Treiman (1968) + Watson theorem (T invariance)]

Partial Wave expansion:

2 Axial Form Factors (F and G):

$F = F_s\, e^{i\delta_s} + F_p\, e^{i\delta_p} \cos\theta_\pi$

$G = G_p\, e^{i\delta_p}$

1 Vector Form Factor (H):

$H = H_p\, e^{i\delta_p}$

The fit parameters (real) are:

(+-) F_s , F_p , G_p , H_p , $\delta = \delta_s - \delta_p$

(00) F_s only (no P-wave)

q^2 dependence can be studied from FF fitted in q^2 bins [J.Phys. G **26**, 1607 (1999)]

$$F_s^2 = f_s^2 \left[1 + \frac{f_s'}{f_s}\, q^2 + \frac{f_s''}{f_s}\, q^4 + \frac{f_e'}{f_s}\, \frac{M_{e\nu}^2}{4m_\pi^2} \right]^2$$

$$\frac{G_p}{f_s} = \frac{g_p}{f_s} + \frac{g_p'}{f_s}\, q^2 \,, \quad F_p = f_p \,, \quad H_p = h_p$$

$$q^2 = \left[\frac{M_{\pi\pi}^2}{4\, m_\pi^2} - 1 \right] \qquad m_\pi = m(\pi^\pm)$$

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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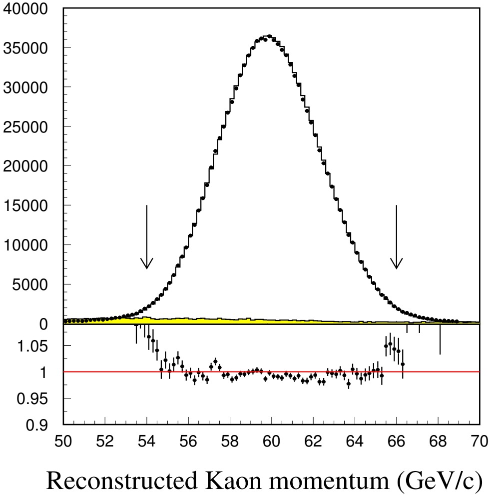
- $\pi^{\pm}\pi^{\pm}e^{\mp}\nu$ (“Wrong-Sign” events)
- Ratio “Right-Sign” : “Wrong-Sign” =

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

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

Ke4(+-) decay: background rejection

Data sample: 1.1×10^6 events. Total background is less than 1%



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(+-) relative Form Factors: fit results

$$F_s^2 = f_s^2 \left[1 + \frac{f_s'}{f_s} q^2 + \frac{f_s''}{f_s} q^4 + \frac{f_e'}{f_s} \frac{M_{e\nu}^2}{4\, m_\pi^2}\right]^2 \quad ; \quad \frac{G_p}{f_s} = \frac{g_p}{f_s} + \frac{g_p'}{f_s} q^2$$

$$\frac{F_p}{f_s} = \frac{f_p}{f_s} \quad ; \quad \frac{H_p}{f_s} = \frac{h_p}{f_s}$$

Total statistics (2003+2004)

	value	stat	syst
f_s'/f_s	0.152	± 0.007	± 0.005
f_s''/f_s	-0.073	± 0.007	± 0.006
f_e'/f_s	0.068	± 0.006	± 0.007
f_p/f_s	-0.048	± 0.003	± 0.004
g_p/f_s	0.868	± 0.010	± 0.010
g_p'/f_s	0.089	± 0.017	± 0.013
h_p/f_s	-0.398	± 0.015	± 0.008

Systematics:

- mostly from background + acceptance control
- comparable or smaller than statistical error

$\rightarrow$ Published in Eur. Phys J. C70 (2010) 635

Ke4(+-) decay: branching fraction

$K^{\pm}_{e4}$(+-) PDG: $(4.09 \pm 0.10) \times 10^{-5}$

$$\mathrm{BR}(K^{\pm}_{e4}) = \frac{(N_s - N_b)}{N_n}\frac{A_n \varepsilon_n}{A_s \varepsilon_s}\mathrm{BR}(K^{\pm}_{3\pi})$$

- Use $\pi^{\pm}\pi^{+}\pi^{-}$ decays as normalization
- N_s, N_b, N_n : number of signal (1.11×10^6), background (0.95% of K_{e4}) and normalization (1.9×10^9) events
- A_s, A_n, ε_s ε_n : signal and normalization acceptance (18.16% and 23.97%) and trigger efficiency (98.5% and 97.7%)
- $\mathrm{BR}(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = (5.59 \pm 0.04)\%$

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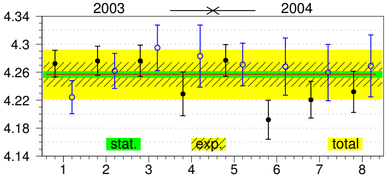

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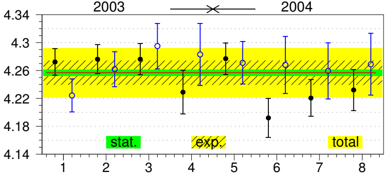

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Relative Systematic Uncertainty	(%)
Acceptance, beam geom.	0.18
Muon vetoing	0.16
Accidental activity	0.21
Particle ID	0.09
Background	0.07
Radiative effects	0.08
Trigger efficiency	0.11
Simulation statistics	0.05
Total systematics	0.37
External error [BR($K_{3\pi}$)]	0.72

New result

arxiv:1206.7065[hep-ex] ; PLB (2012), in the press
http://dx.doi.org/10.1016/j.physletb.2012.07.048

$$\mathrm{BR}(K^{+}_{e4}) = (4.255 \pm 0.008) \times 10^{-5}; \quad \mathrm{BR}(K^{-}_{e4}) = (4.261 \pm 0.011) \times 10^{-5}$$

$$\mathrm{BR}[K^{\pm}_{e4}(+-)] = (4.257 \pm 0.004_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}}) \times 10^{-5}$$

Ke4(00) BR measurement: event reconstruction

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

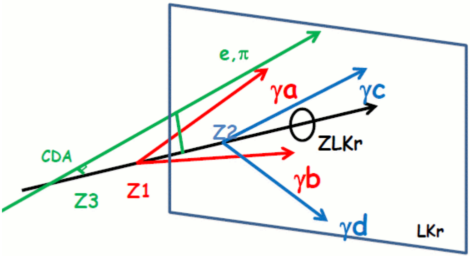
Common event reconstruction for ($\pi^0\pi^0$ + charged track):

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

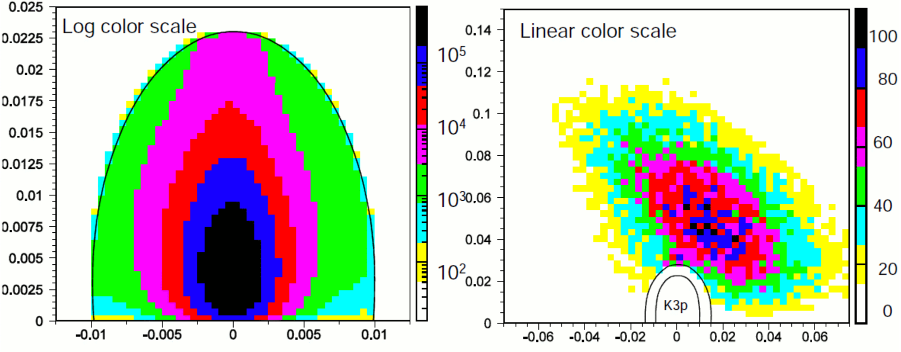
3) combine with a charged track if Z_3 (CDA to beam line) satisfies $|Z_3 - Z_n| < 8\,\text{m}$



up to now: no PID

Ke4(00) BR measurement: signal selection

- Assign m_π to the charged track, plot P_t(to beam axis) vs invariant mass
- elliptic cut separates $\sim$ 70 000 000 $K_{3\pi}$ from $\sim$ 45 000 K_{e4} candidates



P_T (GeV/c) vs $M(3\pi) - M_K$ (GeV/c^2)

- electron identification: E/p and shower properties

Ke4(00) decay: branching fraction

$K^{\pm}_{e4}(00)$

PDG: $(2.2 \pm 0.4) \times 10^{-5}$

$$\mathrm{BR}(K^{\pm}_{e4}) = \frac{(N_s - N_b)}{N_n}\frac{A_n\varepsilon_n}{A_s\varepsilon_s}\mathrm{BR}(K^{\pm}_{3\pi})$$

- Use $\pi^{\pm}\pi^{0}\pi^{0}$ decays as normalization
- N_s , N_b , N_n : number of signal (44 909), background (1.3% of K_{e4}) and normalization (71×10^{6}) events
- A_s , A_n , ε_s ε_n : signal and normalization acceptance (1.77% and 4.11%) and both trigger efficiencies in the range 92-98%
- $\mathrm{BR}(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = (1.761 \pm 0.022)\%$

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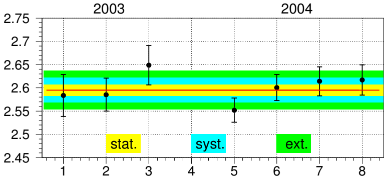

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- $\mathrm{BR}(K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0) = (1.761 \pm 0.022)\%$

Relative Systematic Uncertainty	(%)
Background	0.35
Simulation statistics	0.12
Form factor dependence	0.20
Radiative effects	0.23
Trigger efficiency	0.80
Particle ID	0.10
Beam geometry	0.10
Total systematics	0.94
External error [BR($K_{3\pi}$)]	1.25

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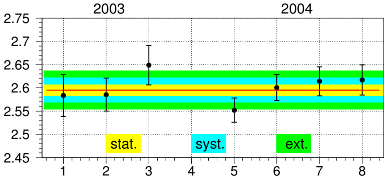

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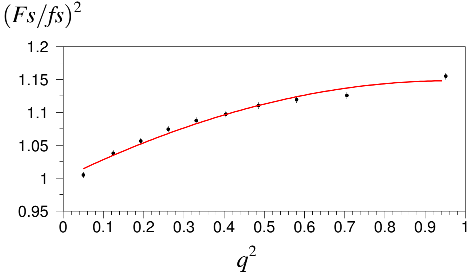
Preliminary result – analysis in progress

$$\mathrm{BR}[K^{\pm}_{e4}(00)] = (2.595 \pm 0.012_{\mathrm{stat}} \pm 0.024_{\mathrm{syst}} \pm 0.032_{\mathrm{ext}}) \times 10^{-5}$$

Ke4 decay: Form Factors variation



$K^{\pm}_{e4}(+-)$ "charged" mode

$$q^2 = \frac{M^2_{\pi\pi}}{4\,m^2_{\pi}} - 1 \quad , \qquad m_{\pi} = m(\pi^+)$$

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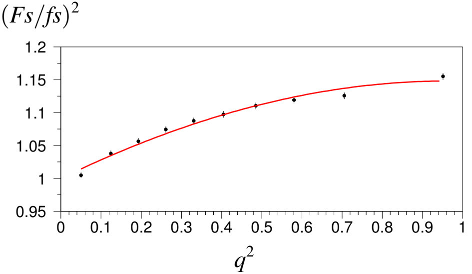

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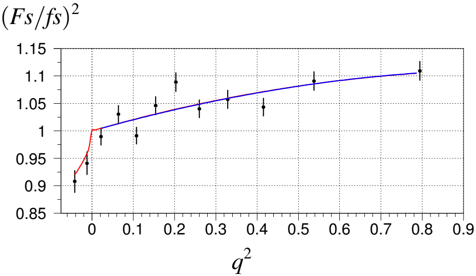
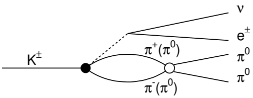


$K^{\pm}_{e4}(0\,0)$ "neutral" mode

blue line = polynomial fit ($q^2 > 0$)

red line = extrapolation from fit + negative interference with $\pi\pi$ rescattering

New! using known values of a_0 and a_2



Ke4(+-): absolute Form Factors

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

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

New!

$$f_s' = 0.867 \pm 0.040_{\rm stat} \pm 0.029_{\rm syst} \pm 0.005_{\rm norm}$$
$$f_s'' = -0.416 \pm 0.040_{\rm stat} \pm 0.034_{\rm syst} \pm 0.003_{\rm norm}$$
$$f_e' = 0.388 \pm 0.034_{\rm stat} \pm 0.040_{\rm syst} \pm 0.002_{\rm norm}$$

$$f_p = -0.274 \pm 0.017_{\rm stat} \pm 0.023_{\rm syst} \pm 0.002_{\rm norm}$$

$$g_p = 4.952 \pm 0.057_{\rm stat} \pm 0.057_{\rm syst} \pm 0.031_{\rm norm}$$
$$g_p' = 0.508 \pm 0.097_{\rm stat} \pm 0.074_{\rm syst} \pm 0.003_{\rm norm}$$

$$h_p = -2.271 \pm 0.086_{\rm stat} \pm 0.046_{\rm syst} \pm 0.014_{\rm norm}$$

PLB (2012), in the press
`http://dx.doi.org/10.1016/j.physletb.2012.07.048`

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 :

$$a_0 = (\ \ 0.220 \ \pm 0.005\ \ ) \times (1/m_\pi)$$
$$a_2 = (-0.0444 \pm 0.0010) \times (1/m_\pi)$$

[Colangelo, Gasser, Leutwyler, Nucl. Phys. B 603, 125 (2001); Phys. Rev. Lett. 86, 5008 (2001)]

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Two statistically independent measurements by NA48/2:

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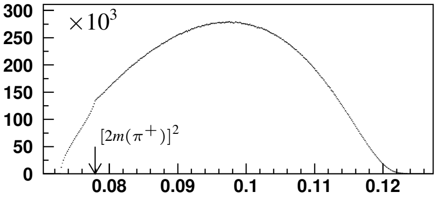
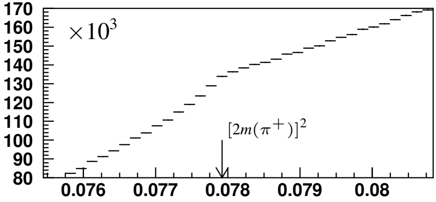


Interference between

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

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

$M^2(\pi^0\pi^0)$ $[\,(\mathrm{GeV/c^2})^2\,]$



$M^2(\pi^0\pi^0)$ $[\,(\mathrm{GeV/c^2})^2\,]$

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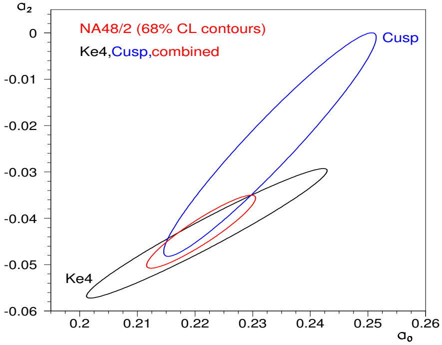

[a_0, a_2 values in units of 1/m(π^+)]

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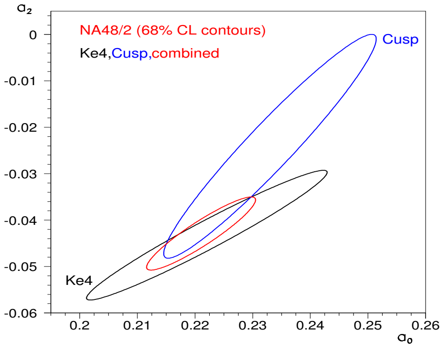
- Different systematics:
  eletron misID and background
  vs. calorimeter and trigger
- Different theoretical inputs:
  Roy equations and isospin breaking correction vs. rescattering in final state and ChPT expansion



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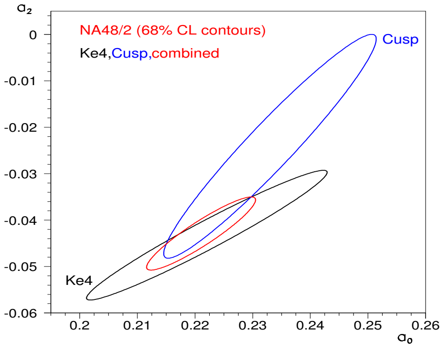
► Large overlap in the a_0, a_2 plane



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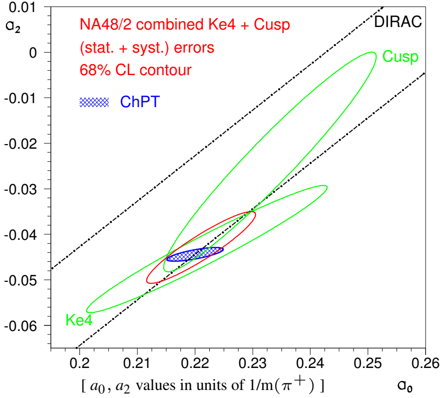


- ▶ Large overlap in the a_0, a_2 plane
- ▶ Impressive agreement with ChPT

Kμ4 decays: status and perspectives

- Poor experimental knowledge
- Similar to K_{e4}, with one more vector form factor (R)
- FF and BR predicted by ChPT [NPB427 (1994) 427]

$K^{\pm}_{\mu 4}(0\,0)$:

- Never observed so far
- few 10^3 events expected in NA48/2 data
- Goal: first observation, measure BR

$K^{\pm}_{\mu 4}(+-)$:

- Measured BR = $(1.4 \pm 0.9) \times 10^{-5}$ from 9 events [PDG]
- Predicted BR = $(0.412 \pm 0.018) \times 10^{-5}$ [NPB427 (1994) 427]
- several 10^3 events expected in NA48/2 data
- Goal: measure BR + first attempt to measure R form factor

The NA48 experiment at CERN SPS

$K^{\pm} \to \pi\pi e^{\pm}\nu$ (K_{e4}), $\pi\pi$ scattering lengths, $K_{\mu 4}$

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: new result (NA48/2 +NA62)

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{(*)}$: first observation of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$

$K^{\pm} \to \pi^{\pm}l^{+}l^{-}$: recent results on $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

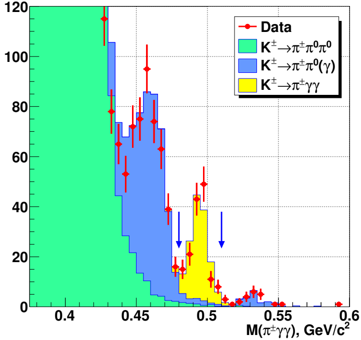
Conclusions

The $K^{\pm} \to \pi^{\pm}\gamma\gamma$ rare decay

Detailed ChPT predictions:

- leading contribution at $\mathcal{O}(p^4)$, important corrections at $\mathcal{O}(p^6)$
  [D'Ambrosio, Portoles, PLB 386 (1996) 403]
- spectrum and rate predicted as a function of an unknown parameter $\hat{c}$

NA48/2 (2004) data



Total $\sim$ 300 events from 2 data samples:

- NA48/2 (2004): 3 days of dedicated run
- NA62-R_K (2007): 3 months with downscaled minimum bias trigger

Combined analysis: see NA62 talk by T. Spadaro

Preliminary results:

- model dependent BR $= (1.01 \pm 0.06) \times 10^{-6}$
  [PDG: BR $= (1.10 \pm 0.32) \times 10^{-6}$]
- $\hat{c}\ [\mathcal{O}(p^4)] = 1.56 \pm 0.23$
- $\hat{c}\ [\mathcal{O}(p^6)] = 2.00 \pm 0.26$

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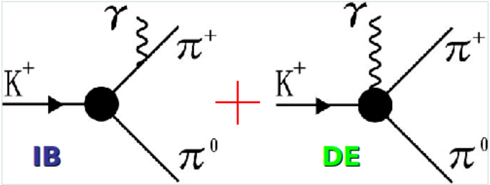
Conclusions

$K^\pm \to \pi^\pm\pi^0\gamma$: Theory

Two sources of γ radiation:

Inner Bremsstrahlung (IB) and Direct Emission (DE)



Two kinematic variables:

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

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

After integrating on T^*_π:

$$\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma^\pm_{IB}}{dW}\Big[\, 1 \qquad \Leftarrow \text{(IB)}$$
$$+\, 2m_K^2 m_\pi^2 \cos(\pm\phi + \delta_1^1 - \delta_0^2)\; X_E\; W^2 \qquad \Leftarrow \text{(INT)}$$
$$+\, m_K^4 m_\pi^4 \left(|X_E|^2 + |X_M|^2\right) W^4 \,\Big] \qquad \Leftarrow \text{(DE)}$$

$K^\pm \to \pi^\pm\pi^0\gamma$: NA48/2 results

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IB	is known from $K^\pm \to \pi^\pm\pi^0$ (Low theorem) + QED corrections
DE	amplitude contains electric X_E and magnetic X_M dipole terms
INT	is interference between IB and electric DE (X_E) amplitudes

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NA48/2 ($0 < T^*_\pi < 80\,\text{MeV}$): $> 10^6$ events, $< 0.01\%$ background

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Final NA48/2 results: [EPJC68 (2010) 75]

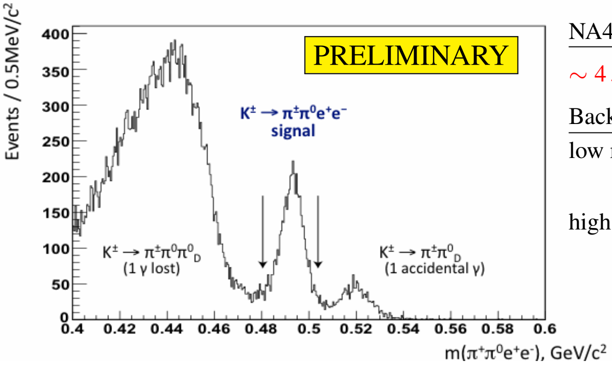
- Frac(DE) $= (3.19 \pm 0.16) \cdot 10^{-2}$
- Frac(INT) $= (-2.21 \pm 0.41) \cdot 10^{-2}$ ← first evidence
- $A_{CP} = \left|\frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}\right| < 1.5 \cdot 10^{-3}$ (90% CL) ← first measurement

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

- Mainly from $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{*} \to \pi^{\pm}\pi^{\pm}e^{+}e^{-}$ [EPJC **72**, 187 (2012)]
- DE and INT depend on X_E and X_M form factors
- Short distance contributions, sensitive to New physics

NA48/2: first observation of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$

$\pi^{\pm}\pi^{0}e^{+}e^{-}$ invariant mass



NA48/2 (2003+2004 data):

$\sim$ 4 500 events in signal region

Backgrounds

low m: $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{D}$
$(\pi^{0}_{D} \to e^{+}e^{-}\gamma_{\mathrm{LOST}})$

high m: $K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$
$(\pi^{0}_{D} \to e^{+}e^{-}\gamma) + \gamma_{\mathrm{ACC}}$

Analysis in progress

The NA48 experiment at CERN SPS

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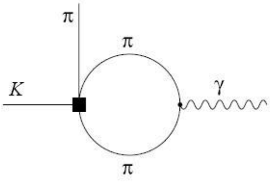
Conclusions

$K^{\pm} \to \pi^{\pm} l^{+} l^{-}$: theory

$K^{\pm} \to \pi^{\pm} e^{+} e^{-}$, $K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-}$

- Suppressed ($BR \approx 10^{-7}$) FCNC processes
- Loop-induced decays ($K^{\pm} \to \pi^{\pm} \gamma^{*}$)



$$\frac{d\Gamma}{dz} = P(z) \cdot |W(z)|^2 \quad ; \quad z = \left(\frac{m_{ll}}{m_K}\right)^2 \quad ; \quad P(z) = \text{ phase space factor}$$

Several models exist for $W(z)$ form factor

- Linear: $W(z) = G_F\, m_K^2\, f_0\, (1 + \delta \cdot z)$
- ChPT $\mathcal{O}(p^6)$: $W(z) = G_F\, m_K^2\, (a_+ + b_+ z) + W^{\pi\pi}(z)$ [JHEP 8, 4 (1998)]
- ChPT + large-N_C QCD: $W(z) = W(\tilde{w}, \beta, z)$ [PLB 595, 301 (2004)]
- "Dubna" ChPT: $W(z) = W(M_a, M_\rho, z)$ [hep-ph/0611175]

$K^{\pm} \to \pi^{\pm} l^+ l^-$: NA48/2 data analysis

Event selection (2003+2004 data)

- 3 tracks, 1 vertex, total charge $= \pm 1$
- $|\vec{p}|$, p_T consistent with $K^{\pm} \to$ 3 charged particles
- Use E_{LKr}/p for Particle ID ($e^{\pm}$ vs $\mu^{\pm}, \pi^{\pm}$)
- $K_{\pi ee}$: $z > 0.08$ ($m_{ee} > m_{\pi^0}$) kinematical cut against $\pi^{\pm}\pi^0_D$ background
- $K_{\pi\mu\mu}$: signals in MUV counters for positive muon identification
- $\pi^{\pm} l^+ l^-$ invariant mass cut (Kaon mass peak)

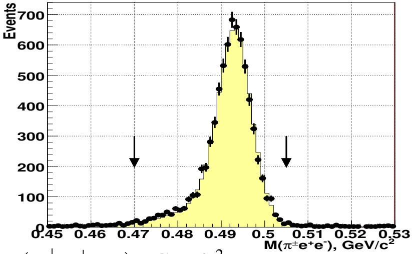
Efficiencies and background measured from data.

Normalization channels ($\pi^{\pm}\pi^0_{\mathrm{Dalitz}}$; $\pi^{\pm}\pi^+\pi^-$) : 3 tracks, similar topology
$\Rightarrow$ first-order cancellation of most systematics

Observation of both K^+ and K^- decays
$\Rightarrow$ first measurement of CP-violating charge asymmetry $A_{\mathrm{CP}} \equiv \frac{BR^+ - BR^-}{BR^+ + BR^-}$

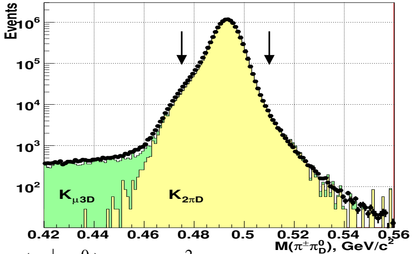
$K^\pm \to \pi^\pm e^+ e^-$: NA48/2 results [PLB 677, 246 (2009)]

Signal ($\pi^\pm e^+ e^-$)



$m(\pi^\pm e^+ e^-)$ [GeV/c^2]

Normalization channel ($\pi^\pm \pi^0_D$)



$m(\pi^\pm \pi^0_D)$ [GeV/c^2]

- 7253 $K^\pm \to \pi^\pm e^+ e^-$ events, with 1.0% background

  $BR(K^\pm \to \pi^\pm e^+ e^-) = (3.11 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}} \pm 0.07_{\text{model}}) \cdot 10^{-7}$

  $BR(K^\pm \to \pi^\pm e^+ e^-) = (3.11 \pm 0.12) \cdot 10^{-7}$

  First observation of $K^-_{\pi ee}$

- $A_{\text{CP}} = (-2.2 \pm 1.5_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-2} \Rightarrow$ $|A_{\text{CP}}| < 2.1 \cdot 10^{-2}$ (90% CL)

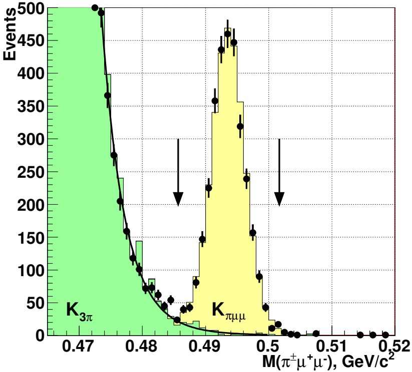
  Theoretical predictions: $A^{\text{SM}}_{\text{CP}} \sim 10^{-5}$ [JHEP **9808** (1998) 4]

  $A^{\text{SUSY}}_{\text{CP}} \sim 10^{-3}$ [EPJC **53** (2008) 567]

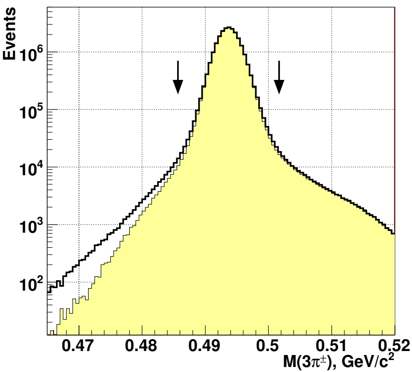
- Measured $W(z)$ agrees with theoretical models

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

Signal ($\pi^{\pm}\mu^{+}\mu^{-}$)



Normalization channel ($\pi^{\pm}\pi^{+}\pi^{-}$)



- 3120 $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ event candidates [>4× total world statistics]
- $(3.3 \pm 0.7)\%$ background ($K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ with $\pi \to \mu\nu$)

$K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: NA48/2 results [PLB 697, 107 (2011)]

- $BR(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = (9.62 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.07_{\text{ext}}) \cdot 10^{-8}$

  $BR(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = (9.62 \pm 0.25) \cdot 10^{-8}$

  Error improved (x 1/3) w.r.t. BNL E865 [PRL84,2580(2000)]

- CPV asymmetry: $BR^{+} = (9.70 \pm 0.26) \cdot 10^{-8}$; $BR^{-} = (9.49 \pm 0.35) \cdot 10^{-8}$

  $A_{\text{CP}}(K^{\pm}_{\pi\mu\mu}) \equiv \frac{BR^{+} - BR^{-}}{BR^{+} + BR^{-}} = (1.1 \pm 2.3)10^{-2} \Rightarrow$ $|A_{\text{CP}}| < 2.9 \cdot 10^{-2}$ (90% CL)

  Factor 4 improvement w.r.t. HyperCP [PRL **88**, 111801 (2002)]

  Theoretical predictions: $A_{\text{CP}}^{\text{SM}} \sim 10^{-4}$ [JHEP **9808**, 4 (1998)]

  $A_{\text{CP}}^{\text{SUSY}} \sim 10^{-3}$ [PLB **538**, 130 (2002); JHEP **0207**, 068 (2002)]

- Forward-backward asymmetry in $\theta_{K\mu}$:

  ($\theta_{K\mu}$ = angle between the kaon and the opposite-sign lepton in the dilepton rest frame)

  $A_{\text{FB}} = (-2.4 \pm 1.8) \cdot 10^{-2}$ $\Rightarrow$ $|A_{\text{FB}}| < 2.3 \cdot 10^{-2}$ (90% CL)

  Theoretical predictions: $A_{\text{FB}} \sim 10^{-3}$ [PRD **69**, 094030 (2004); PRD **67**, 074029 (2003)]

- Measured $W(z)$ agrees with theoretical models and is consistent with $K_{\pi ee}$

- Search for Lepton Number Violating decays $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$

$K^\pm \to \pi^\pm l^+ l^-$ form factors

Models tested for $W(z)$ $\qquad \frac{d\Gamma}{dz} = P(z) \cdot |W(z)|^2 \quad ; \qquad z = \left(\frac{m_{ll}}{m_K}\right)^2$

- Linear: $W(z) = G_F m_K^2 \, f_0 \, (1 + \delta \cdot z)$
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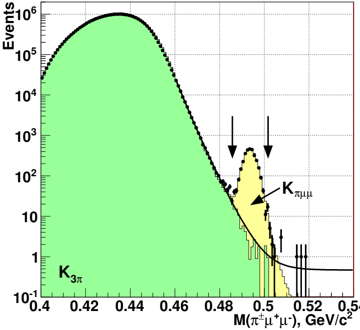
Measurements of *BR* and form factor parameters

Decay Experiment Reference Year	$K^+_{\pi ee}$ BNL E777 PRL**68**,278 (1992)	$K^+_{\pi ee}$ BNL E865 PRL**83**,4482 (1999)	$K^\pm_{\pi ee}$ CERN NA48/2 PLB**677**,246 (2009)	$K^+_{\pi\mu\mu}$ BNL E865 PRL**84**,2580 (2000)	$K^\pm_{\pi\mu\mu}$ CERN NA48/2 PLB**697**,107 (2011)
Nr. of events	$\sim$ 500	10 300	7 253	430	3 120
$BR \cdot 10^8$	27.5 ± 2.6	29.4 ± 1.5	31.1 ± 1.2	9.22 ± 0.77	9.62 ± 0.25
$\lvert f_0 \rvert$		0.533 ± 0.012	0.531 ± 0.016		0.470 ± 0.040
δ	1.31 ± 0.48	2.14 ± 0.20	2.32 ± 0.18	$2.45^{+1.30}_{-0.95}$	3.11 ± 0.57
a_+		-0.587 ± 0.010	-0.578 ± 0.016		-0.575 ± 0.039
b_+		-0.655 ± 0.044	-0.779 ± 0.066		-0.813 ± 0.145
$\tilde{w}$		0.045 ± 0.003	0.057 ± 0.007		0.064 ± 0.014
β		2.8 ± 0.1	3.45 ± 0.30		3.77 ± 0.62
M_a [GeV/c^2]			0.974 ± 0.035		0.993 ± 0.085
M_ρ [GeV/c^2]			0.716 ± 0.014		0.721 ± 0.028

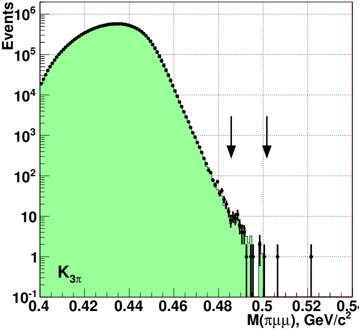
Search for $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decays

- Lepton Number Violating ($|\Delta L| = 2$) decays
- Look for "wrong-sign" events in $\pi\mu\mu$ data

$K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ FCNC candidates



$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ LNV candidates



$N_{\text{data}} = 52$
$N_{\text{bkg}} = 52.6 \pm 19.8_{\text{syst}}$

$\Rightarrow$ $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \cdot 10^{-9}$ (90% CL)

factor 3 improvement w.r.t. E865 [PRL **85**, 2877 (2000)]

The NA48 experiment at CERN SPS

$K^{\pm} \to \pi\pi e^{\pm}\nu$ (K_{e4}), $\pi\pi$ scattering lengths, $K_{\mu 4}$

$K^{\pm} \to \pi^{\pm}\gamma\gamma$: new result (NA48/2 +NA62)

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{(*)}$: first observation of $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$

$K^{\pm} \to \pi^{\pm}l^{+}l^{-}$: recent results on $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

Conclusions

Summary

- $K^{\pm} \rightarrow \pi\pi e^{\pm}\nu$ [PLB, in the press (2012)]
  - 1.1M K_{e4}(+-) and 45 000 K_{e4}(00) events analized
  - Precise determination of $\pi\pi$ scattering lengths from K_{e4} and $K_{3\pi}$, in excellent agreement with ChPT prediction
  - New improved measurements of K_{e4} BR and form factors
  - Future studies on $K_{\mu 4}$ decays, very little known

- $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ [preliminary]
  - $\sim$ 300 events from NA48/2 + NA62
  - Preliminary results on $M_{\gamma\gamma}$ spectrum, BR and ChPT parameter $\hat{c}$

- $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma^{(*)}$ [preliminary]
  - First observation of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$

- $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ [PLB 697, 107 (2011)]
  - Four times larger sample than existing world statistics
  - Unprecedented precision achieved on BR and form factor
  - Improved limits on: CPV and FB asymmetries, LNV decay