$K^{\pm}_{\mu 3}$ Form Factors Measurement at NA48/2

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On behalf of the NA48/2 Collaboration

Outline

- Physics motivations
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- $K^{\pm}_{\mu 3}$ analysis
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- $K^{\pm}_{e3}$ Analysis
- $K_{\ell 3}$ Form Factors @ NA62
- Summary

$K_{\ell 3}$ Form Factors: Physics Motivations

The $K_{\ell 3}$ decay is described by two form factors, $f_{\pm}(t)$

$$\mathfrak{M} = G_F/\sqrt{2}\ V_{us}\ [f_+(t)\,(P_K + P_\pi)^\mu\ \bar{u}_\ell \gamma_\mu (1+\gamma_5) u_\nu + f_-(t)\ m_\ell \bar{u}_\ell (1+\gamma_5) u_\nu]$$

t is the square of the four–momentum transfer to the lepton system

$f_- \Rightarrow m_\ell^2/m_K^2$ Can be measured only in $K_{\mu 3}$ decays

$f_0(t)$, which is a combination of the two, is used:

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

$f_+(0) = f_0(0)$ by construction

$f_+(0)$ is not directly measurable

$\Rightarrow$ factor out $f_+^{K^0\pi^-}(0)$ and normalize the ff of all channels

$\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)}$ $\bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}$ $\bar{f}_+(0) = \bar{f}_0(0)$

$K_{\ell 3}$ Form Factors Parametrizations

Class I: Make use of physical constraints - Only one parameter required

$$\bar{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t} \qquad \text{POLE}$$

Exchange of K^* resonances with spin–parity $1^-/0^+$ and mass m_V/m_S

For f_+ dominance of $K^*(892)$, no obvious dominance for f_0

$$\bar{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ + \mathrm{H(t)})\right] \qquad \text{DISPERSIVE}$$

$$\bar{f}_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}(\mathrm{lnC} - \mathrm{G(t)})\right]$$

This parametrization is based on a dispersive approach with a relation subtracted twice ($t = 0,\ t = \Delta_{K\pi}$) [PLB 638(2006) 480, PRD 80(2009) 034034]

Accurate polynomial approximations for the dispersive integrals $\mathrm{G(t)}$ and $\mathrm{H(t)}$

$K_{\ell 3}$ Form Factors Parametrizations

Class II: No Physics input - Power series expansion

Well known and widely used are the linear and quadratic:

$$\bar{f}_{+,0}(t) = \left(1 + \lambda_{+,0}\ t/m_\pi^2\right) \qquad \text{LINEAR}$$

$$\bar{f}_{+,0}(t) = \left[1 + \lambda'_{+,0}\ t/m_\pi^2 + \frac{1}{2}\ \lambda''_{+,0}\ (t/m_\pi^2)^2\right] \qquad \text{QUADRATIC}$$

- More parameters to be determined by fit $\Rightarrow$ Correlations
- Not possible to determine λ''_0 experimentally
  $\Rightarrow$ $\bar{f}_+$ quadratic / $\bar{f}_0$ linear

z-fit parametrization (PRD74(2006) 096006) belongs to this class

$K_{\ell 3}$ Form Factors and $|V_{us}|$ Determination

$K_{\ell 3}$ decays $\Rightarrow$ most accurate and theoretically clean way to access $|V_{us}|$

The master formula for $K_{\ell 3}$ decay rates:

$$\Gamma_{K\ell 3(\gamma)} = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} \, |V_{us}|^2 \, |f_+(0)|^2 \, I_K^\ell(\lambda_{+0}) \, (1 + \delta^\ell_{SU(2)} + \delta^\ell_{EM})^2$$

$K = K^0, \ K^\pm; \quad C^2_{K^0} = 1 \quad C^2_{K^\pm} = 1/2$

Experimental Inputs

$\Gamma(K_{\ell 3(\gamma)})$	Branching Ratios
	Kaon lifetimes
$I_K^\ell \, [f_{+,0}(t)]$	Phase space integral
	Depends on ff

Theory Inputs

$\mathbf{S}_{EW}$	Universal short distance
	EW correction (1.0232±0.0003)
$\mathbf{f}_+(0)$	Calculated ff at t=0
	2^{nd} order SU(3)
$\delta^K_{SU(2)}$	Form factor correction for
	isospin breaking ($K^\pm$ only)
	$f_+^{K^\pm \pi^0}(0)/f_+^{K^0\pi^-}(0) - 1 = \ 0.029 \pm 0.0004$
$\delta^{K_\ell}_{EM}$	Long distance EM effects
	$\delta^{K_\ell}_{EM} \approx 0$ for $K^\pm$

$K_{\ell 3}$ Form Factors and SM Test

- The Callan–Treiman theorem gives the value of $f_0(t)$ at the unphysical point $t = \Delta_{K\pi} = (m_K^2 - m_\pi^2)$
- The dispersive parametrization provides the link from the experimentally accessible t region to $\Delta_{K\pi}$:

$$C = \bar{f}_0(\Delta_{K\pi}) = \frac{f_{K+}}{f_{\pi+}\ f_+(0)} + \Delta_{CT}$$

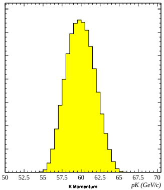
- Δ_{CT} evaluated at NLO in ChPT [Gasser and Leutwyler (85)] $\Delta_{CT} = (-3.5 \pm 8)10^{-3}$
- For $K^\pm$ the effect of isospin breaking is larger: $\Delta_{CT} \sim 1.5\ 10^{-2}$

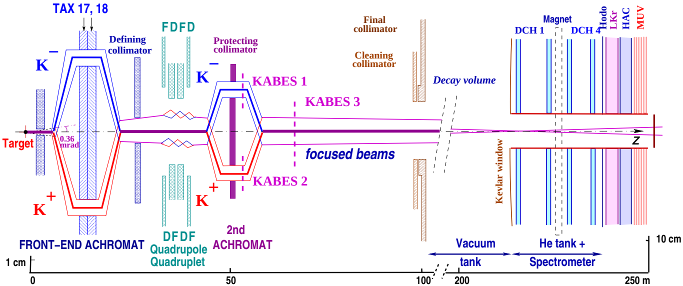
Physics beyond SM can lead to small modifications of the fundamental QCD quantities $f_{K^+},\ f_{\pi^+},\ f_+(0)$

- Compare the C values obtained by BR measurements/Lattice calculations with those obtained by $K_{\mu 3}$ dispersive analysis
- If the standard values of decay constants are used lattice calculations of $f_+(0)$ can be cross-checked

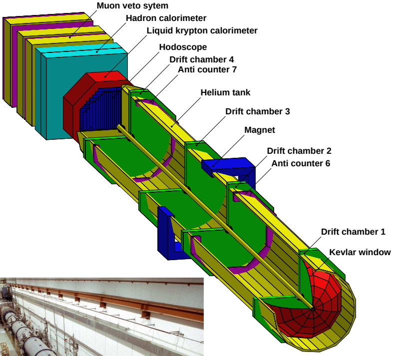
$K^{\pm}_{\ell 3}$ Form Factors @ NA48/2 Experiment

- $K^{\pm}$ collected during 2004 data taking: NA48/2 experiment
  (Main purpose search for direct CP violation in $K^{\pm} \to 3\pi$ decays)
- Simultaneous K^{+} and K^{-} beams
- K^{+} flux $\simeq 3.2 \times 10^{6}$; $K^{+}/K^{-} \simeq 1.78$ (production rate @target)
- Dedicated run with minimum bias trigger and low intensity ($\times 1/4\ I_0$)
- Reduced momentum spread: (60 ± 1.8) GeV/c
- K^{+} and K^{-} beams coincide within 1 mm all along 114 m decay volume





The NA48 Detector



Min Bias trigger: $Q1 \times E_{LKR} > 10$

Magnetic Spectrometer

4 drift chambers

$\frac{\sigma_p}{p}(\%) = 1 \oplus 0.044\ p\ (\mathrm{GeV/c})$

Hodoscope

Two $\perp$ planes of scintillator

Fast trigger

Precise track time measurement

$\sigma_t \simeq 150$ ps

Liquid Krypton EM Calorimeter

Quasi-homogeneous - High granularity

13248 cells of 2×2 cm^2

$\frac{\sigma_E}{E}(\%) = \frac{3.2}{\sqrt{E}} \oplus \frac{9.0}{E} \oplus 0.42\ (\mathrm{GeV})$

Muon Counter

3 planes of scintillator

Each shielded by 80 cm of iron

25×25 cm^2 cells

$\sigma_t \simeq 350$ ps

$K^{\pm}_{\mu 3}$ Event Selection

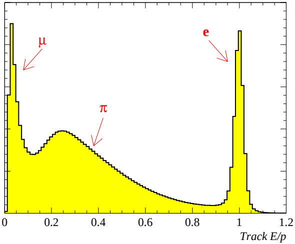
- 1 "good" track and 1 π^0
  - Geometrical detector acceptance
  - Vertex - dCA track and K nominal axis
  - Track P>10 GeV/c for MUC efficiency
  - Timing
  - $|m_{\gamma\gamma} - m^{PDG}_{\pi 0}| < 10$ MeV
- E/p < 0.2
- 1 MUC Hit matched to the track
- $|t_{MUC} - t_{HOD}| < 3$ ns
- $|\,\mathrm{MM}(\mu)|^2 < 10\ \mathrm{MeV}^2$

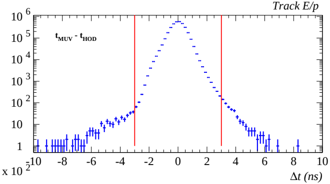
  Missing Mass: $\mathrm{MM}^2 = (P_K - P_\mu - P_{\pi^0})^2$
- P $\pi^0 > 15$ GeV

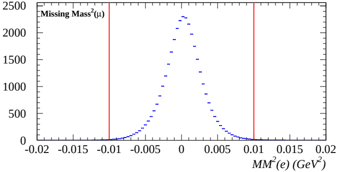
  (Trigger efficiency)
- Cut to remove $\pi^{\pm}\pi^0$ BKG

  (see following slide)

$3.4 \times 10^6 K^{\pm}_{\mu 3}$ events selected



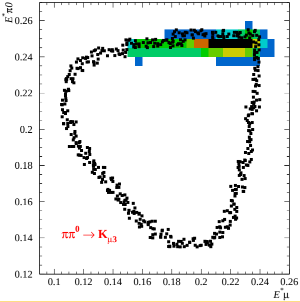


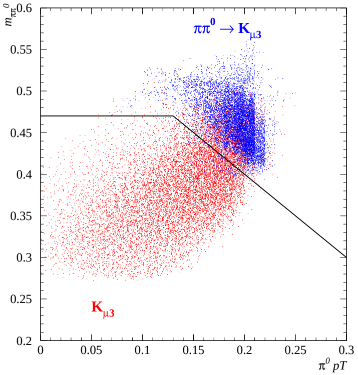


$\pi^{\pm}\pi^{0}$ Background

Decay	BR(%)	$\mathcal{P}(\pi^{\pm}\pi^{0} \rightarrow K_{\mu 3})(\%)$
$\pi^{\pm}\pi^{0}$	20.66 ± 0.08	19.8

- $\pi^{\pm}\pi^{0}$ events with $\pi \rightarrow \mu$ can fake a $K^{\pm}_{\mu 3}$ decay
- This BKG is well localized on the Dalitz plot !!
- Apply cut on $m_{\pi\pi^0}$ vs $\pi^0 pT$ plane
- The loss of $K_{\mu 3}$ signal is about 24%
- $\pi^{\pm}\pi^{0}$ contamination reduced to 0.6%

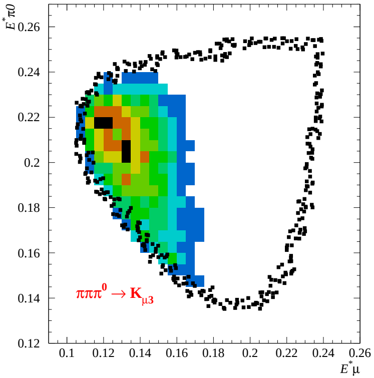




$\pi^{\pm}\pi^{0}\pi^{0}$ Background

Decay	BR(%)	$\mathcal{P}(\pi^{\pm}\pi^{0}\pi^{0} \to K_{\mu 3})(\%)$
$\pi^{\pm}\pi^{0}\pi^{0}$	1.761 ± 0.022	0.14

- Need to correct also for $\pi^{\pm}\pi^{0}\pi^{0}$ BKG
- Small contamination but localized on the Dalitz plot
- Shift of $\simeq 0.5\ \sigma_{stat}$ if the correction is not applied



Fitting Procedure

Dalitz Plot analysis: to extract the form factors perform a fit to the DP density

$$\rho(E^*_\mu, E^*_\pi) = \frac{d^2N(E^*_\mu, E^*_\pi)}{dE^*_\mu \; dE^*_\pi} \propto Af_+^2 + Bf_+\left(f_0 - f_+\right)\frac{m_K^2 - m_\pi^2}{t} + C\left[\left(f_0 - f_+\right)\frac{m_K^2 - m_\pi^2}{t}\right]^2$$

E^*_μ, E^*_π are the energies of μ and π in the kaon CMS
A, B and C are kinematical terms

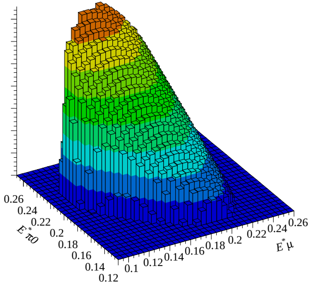
5×5 MeV^2 cells - Cells crossed by the Dalitz border are not used in the fit

Need to correct for:

- Acceptance

$$\epsilon = \frac{\rho(E^*_\mu, E^*_{\pi 0})^{MC \;\; Rec}}{\rho(E^*_\mu, E^*_{\pi 0})^{MC \;\; Gen}}$$

- Background subtraction
- Radiative corrections
    - Tree level parametrization
    - Need to cancel the distortion induced by radiative effects



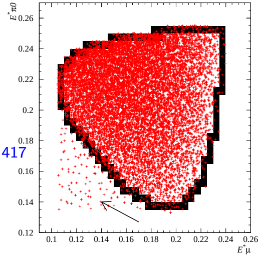
Including first order radiative corrections the $K_{\ell 3}$ decay rate is:

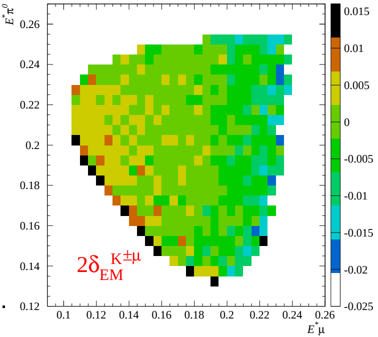
$$\Gamma_{K_{\ell 3}} = \Gamma^0_{K_{\ell 3}} + \Gamma^1_{K_{\ell 3}} = \Gamma^0_{K_{\ell 3}}(1 + 2\delta^{K\ell}_{EM})$$

- Simulation with C. Gatti code: EPJ C45 (2006) 417
- For the normalization use: JHEP 11 (2008) 006

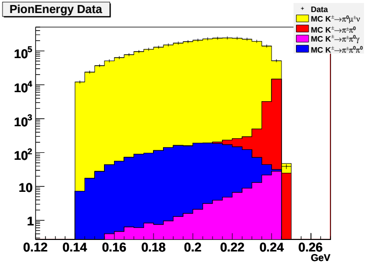
Mode	$\delta^{K\ell}_{EM}(\%)$
K^0_{e3}	0.495±0.110
$K^{\pm}_{e3}$	0.050±0.125
$K^0_{\mu 3}$	0.700±0.110
$K^{\pm}_{\mu 3}$	0.008±0.125

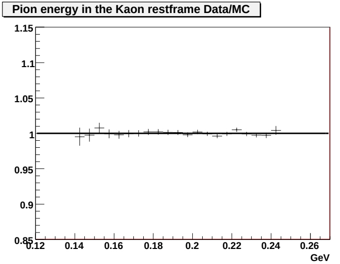
- Small effect on the acceptance
- Sign changes - Integral can be 0 even in presence of large corrections
- Smaller distortion w.r.t. the $K^0_{\mu 3}$ case
  $\rightarrow$ Only one charged particle in the f. s.

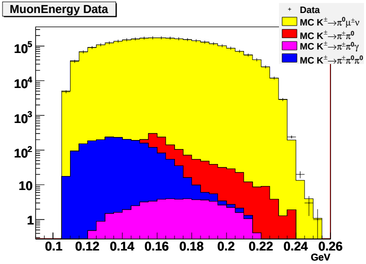


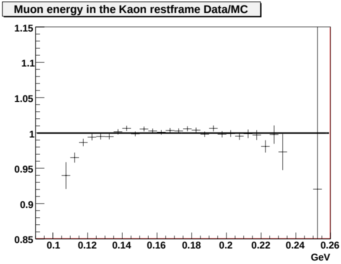


DATA–MC Comparison









$K^{\pm}_{\mu 3}$ Form Factors - PRELIMINARY NA48/2 Results

QUADRATIC ($\times 10^3$)		
λ'_+	λ''_+	λ_0
30.3±2.7±1.4	1.0±1.0±0.7	15.6±1.2±0.9

POLE (MeV/c^2)	
m_V	m_S
836±7±9	1210±25±10

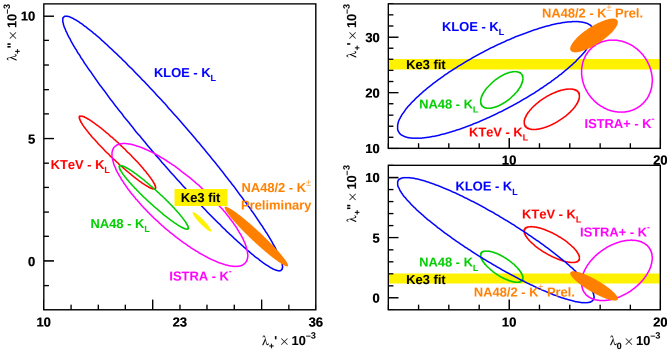
DISPERSIVE ($\times 10^3$)	
Λ_+	$\ln C$
28.5±0.6±0.7±0.5	188.8±7.1±3.7±5.0

- First error is stat, second is syst
- To the dispersive results theo uncertainty has been added

V. Bernard et al., PRD80 (2009) 034034

z-fit in progress...

$K^{\pm}_{\mu 3}$ Form Factors - Quadratic Fits



K_{e3} averages from FlaviA net WG1

1 σ contours

- Experimental situation on quadratic fit for $K_{\mu 3}$ decay
- $K^0_{\mu 3}$ results from KLOE, KTeV and NA48, ISTRA measures $K^-_{\mu 3}$
- First measurement which uses also $K^+_{\mu 3}$
- High precision - Very competitive with other results
- Small quadratic term - Larger λ_0 with respect to NA48 case
- Size and dispersion of ellipses indicate the difficulty of this measurement

Preliminary Survey of Systematics

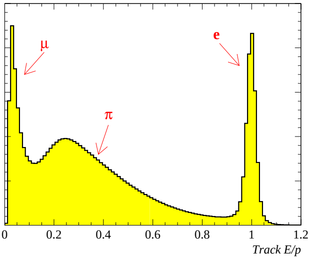
	$\Delta\lambda_+'$	$\Delta\lambda_+''$	$\Delta\lambda_0$	Δm_V	Δm_S	$\Delta\Lambda_+$	$\Delta \ln C$
		$\times 10^{-3}$		MeV/c^2		$\times 10^{-3}$	
$K^\pm$ Energy	± 0.7	± 0.5	± 0.6	± 7	± 2	± 0.5	± 2.6
Vertexing	± 1.0	± 0.4	± 0.6	± 2	± 4	± 0.1	± 1.1
Acceptance	± 0.3	± 0.1	± 0.2	± 2	± 7	± 0.1	± 1.8
$\pi \rightarrow \mu$ scale	± 0.4	± 0.2	± 0.2	± 1	± 1	± 0.0	± 0.0
2^{nd} analysis	± 0.4	± 0.1	± 0.2	± 6	± 6	± 0.5	± 1.5
Total Systematic	± 1.4	± 0.7	± 0.9	± 10	± 10	± 0.7	± 3.7
Statistical	± 2.7	± 1.0	± 1.3	± 7	± 26	± 0.6	± 7.1
Theory						± 0.5	± 5.0
Total Error	± 3.0	± 1.2	± 1.6	± 12	± 28	± 1.0	± 10.1

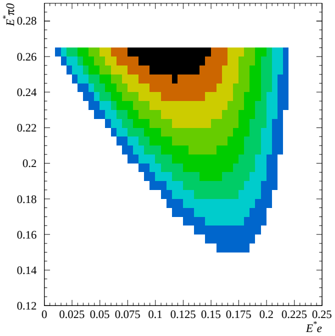
- $K^\pm$ Energy - Calculate two energy solutions (as in K_L case) instead of using the nominal beam energy of 60 GeV
  $\Rightarrow$ Better resolution on CMS variables
- KType2 (2 sol) - KType1 (1 sol) - KType0 (sol outside allowed range)
- $\pi \rightarrow \mu$ scale - Accounts for not perfect modeling of π decay in the region from LKR onwards

$K_{e3}^{\pm}$ Form Factors

- Event selection is similar to $K_{\mu3}^{\pm}$
- Require 1 "good" track and 1 π^0
- electron ID with $0.95 < E/p < 1.05$
- Event pT cut to remove $\pi^{\pm}\pi^0$ BKG
- "Easier" measurement
  - Only one form factor
    $\longrightarrow$ Reduced correlations
  - BKG issues less critical
    $\longrightarrow$ Need a π with $E/p > 0.95$
- Expected more precise results
- Analysis is in progress
- Results for the winter conferences

4.2×10^6 $K_{e3}^{\pm}$ events selected





$K_{\ell 3}$ Form Factors at NA62

NA62, during the 2007 run, collected data for a dedicated measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ and tests for the future $K^+ \to \pi^+ \nu \overline{\nu}$ experiment

- 4 months data taking with minimum bias trigger
  $\to$ 1 track+ 10 GeV deposition in EM calorimeter
- Simultaneous K^+ and K^- beams of P=(74 ± 1.6) GeV/c
- Better track momentum resolution ($\to p_T$ kick doubled)
- Collected $\sim$ 150000 K_{e2} events
- First results for 40% of stat presented at BEACH2010 and ICHEP2010
- Expected precision on the full data sample: $\sigma(R_K)/R_K \simeq \pm 0.4\%$

$K_{\ell 3}$ from NA62 2007 data

- Huge $K^+_{e3}/K^+_{\mu 3}$ statistics of $\approx 40/20 \times 10^6$
- Special K_L run (15 h) to measure electron ID efficiency
  K^0_{e3} and $K^0_{\mu 3}$ statistics $\approx 4 \times 10^6$

NA48 analyses of $K^0_{\ell 3}$ and $K^{\pm}_{\ell 3}$ can be repeated with different/larger data sets

Summary

- NA48/2 has provided a new contribution to $|V_{us}|$ quest
- Preliminary results on $K^{\pm}_{\mu 3}$ form factors
- For the first time both K^{+} and K^{-} decays have been studied
- High precision measurement very competitive with other results
- Soon also new results on $K^{\pm}_{e3}$ will appear
- NA62 is ready to give its contribution with high statistics data samples of $K^{\pm}_{\ell 3}$ and $K^{0}_{\ell 3}$