Study of leptonic and semileptonic kaon decays at CERN

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on behalf of the NA48 and NA62 Collaborations

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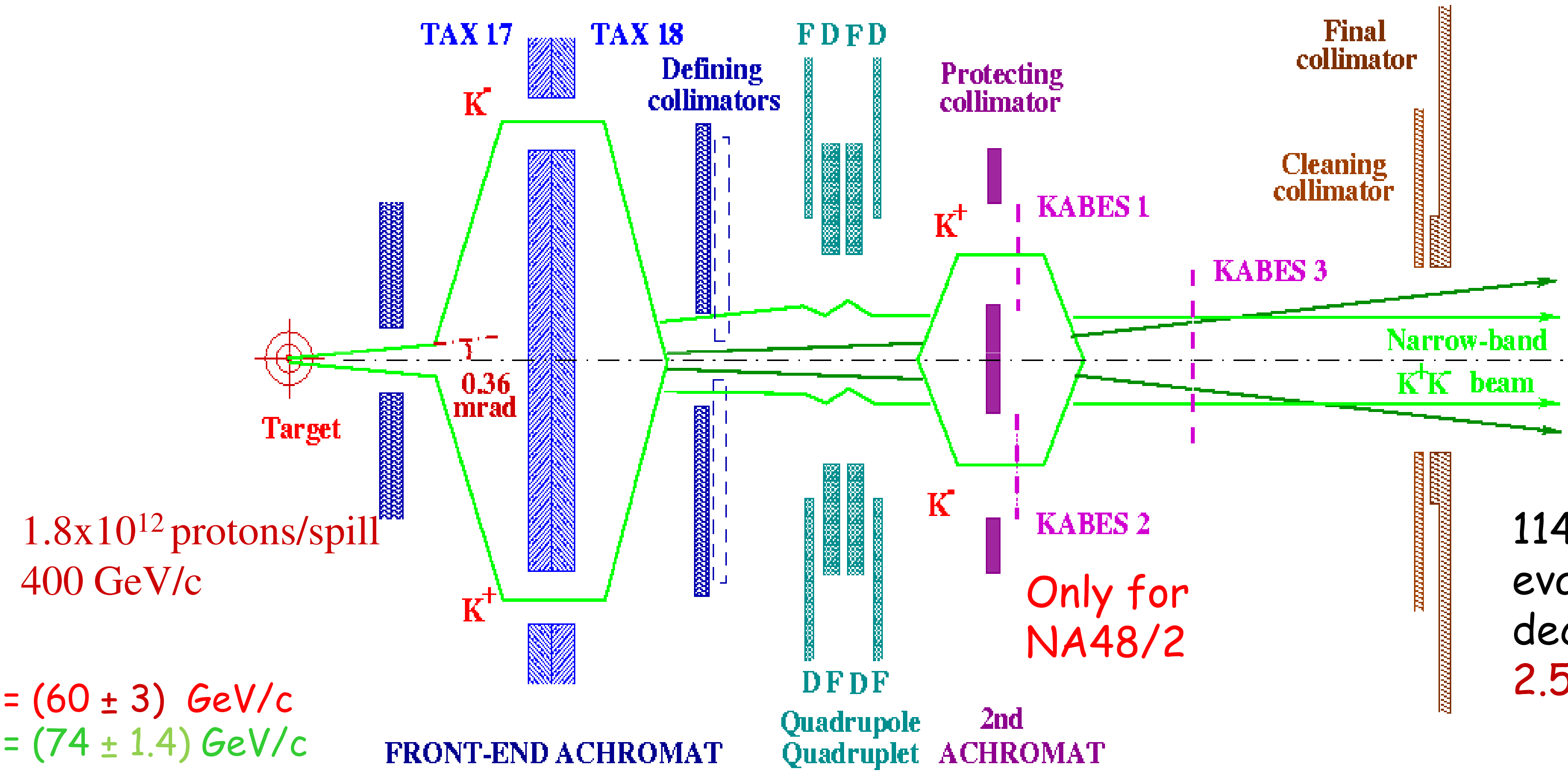
Outline

- The NA48/2-NA62 beams and detector
- NA62 measurement of $R_K = \frac{\Gamma(K \to e\nu(\gamma))}{\Gamma(K \to \mu\nu(\gamma))}$
- NA48/2 results on $K^{\pm} \to \pi^0 e^{\pm} \nu$ and $K^{\pm} \to \pi^0 \mu^{\pm} \nu$

The NA48/2-NA62 Beam

NA48/2 beam (2003-2004): simultaneous K^+/K^-

NA62 beam (2007-2008): simultaneous or single K^+/K^-



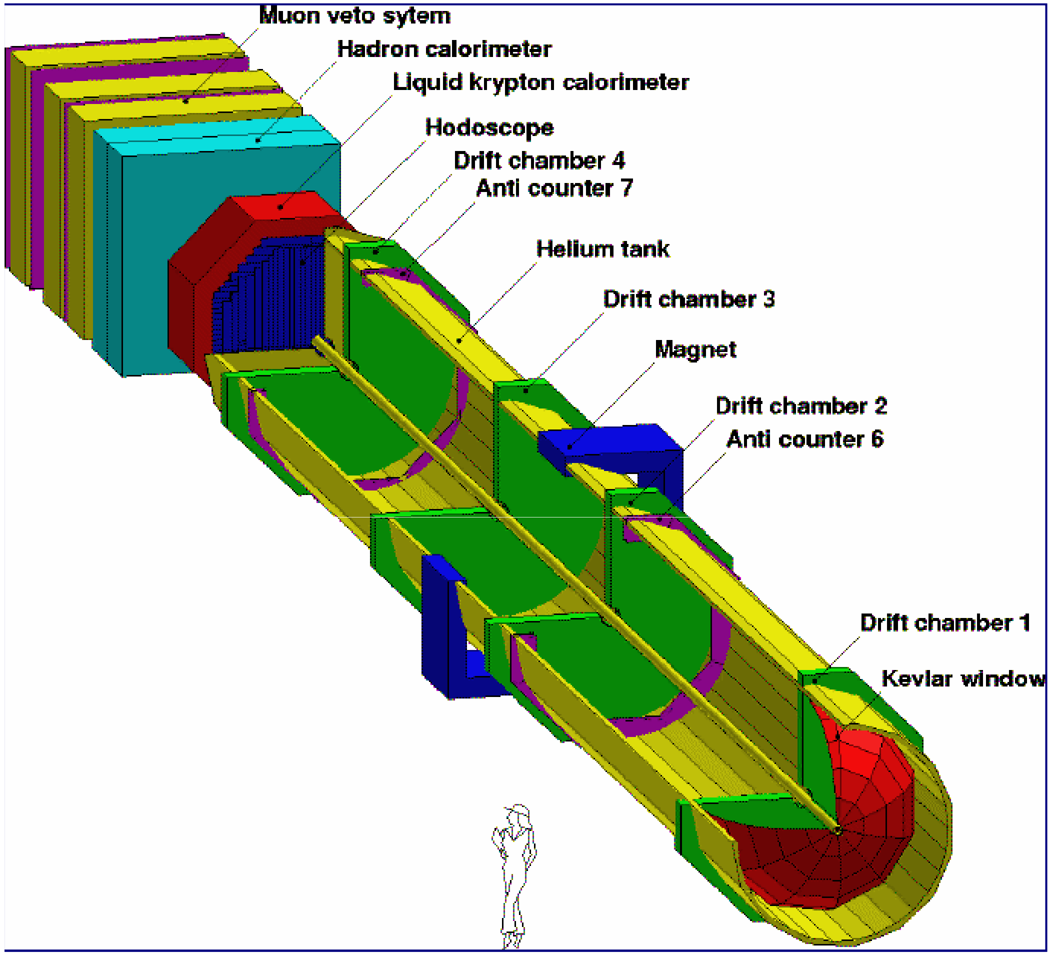
Only for NA48/2

114 m long evacuated decay volume
2.5×10^7 K/spill

$P_K = (60 \pm 3)$ GeV/c
$P_K = (74 \pm 1.4)$ GeV/c

K+ decays in the decay volume: 22% (18%)

The Detector



Used by NA48 and NA62

Spectrometer P_T kick:

120 MeV/c in 2003-2004

265 MeV/c in 2007-2008

Spectrometer:

$\sigma(P)/P \cong 1.02\% \oplus 0.044\, P[GeV/c]\%$ NA48
$\sigma(P)/P \cong .48\% \oplus 0.009\, P[GeV/c]\%$ NA62

Scintillator hodoscope: fast trigger and good time resolution (150 ps)

LKr Calorimeter:

$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

Minimum bias trigger for both decay modes:
1 track in the hodoscope and E_{LKr} > 10 Gev

R_K measurement

Physics motivations

$$R_K = \frac{\Gamma(K \to e\nu(\gamma))}{\Gamma(K \to \mu\nu(\gamma))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K)$$

Test of lepton universality

- Excellent accuracy due to cancellation of hadronic uncertainties in the ratio
- Helicity suppression of electronic mode, enhancement of sensitivity to non-SM effects

$R_K(SM) = (2.477 \pm 0.001) \cdot 10^{-5}$ 0.04% precision!!

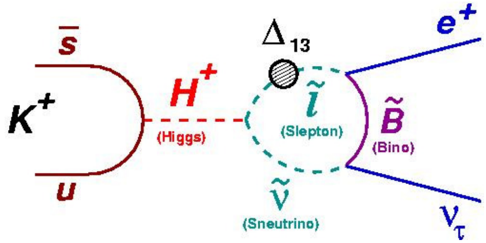
(V. Cirigliano, I. Rosell PRL 99 (2007) 231801)

- δR_K due to IB part of the radiative $K \to e\nu\gamma$ process
- $K \to e\nu\gamma$(IB) included by default in R_K

R_K beyond the Standard Model

- The value of R_K could be different in case of SUSY LFV
  - Masiero, Paradisi, Petronzio, Phys. Rev. D74 (2006) 011701
    - "Charged Higgs mediated SUSY LFV contributions can be strongly enhanced in kaon decays into an electron or a muon and a tau neutrino"

$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)\left|\Delta_{13}\right|^2 \tan^6\beta\right]$$



- Sensitive to slepton mixing. R_K enhancement experimentally accessible
- MSSM: 1% effect possible
  - Girrbach and Nierste, arXiv:1202:4096
  - However limited by recent $B_S \to \mu^+\mu^-$ measurement
- Sensitive to SM extensions with 4th generation, sterile ν

The experimental situation

- Three esperiments from the 70's
  - $R_K = (2.45 \pm 0.11) \cdot 10^{-5}$
  - $\delta R_K / R_K = 4.5\%$

- 2009: KLOE (LNF) – 2001-2005 data
  - ~13800 K_{e2} candidates, 16% bckg
  - $R_K = (2.493 \pm 0.025 \pm 0.019) \cdot 10^{-5}$
  - $\delta R_K / R_K = 1.3\%$

- NA62 2013, full statistics, this talk

•NA62 goals from the proposal
  - ~150000 K_{e2} events
  - ~0.4% accuracy

• Data collected in the 2007-2008 run

NA62 R_K measurement strategy

- K_{e2} and $K_{\mu 2}$ decays collected simultaneously
  - Do not rely on the kaon flux measurement
  - Many systematic effects cancel to first order in the ratio
    - E.g. reconstruction/trigger efficiencies, time dependent effects
- Limited use of MC simulations
  - Geometric acceptance correction
  - PID, trigger, readout efficiencies measured directly on data
- Perform analysis in 10 lepton momentum bins
  - Background composition varies strongly with momentum

Selected signal events

PID efficiencies

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \bullet \frac{A(K_{\mu 2}) \times f_\mu \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \bullet \frac{1}{f_{LKr}} \bullet \frac{1}{D}$$

Bckg events

Main syst source

Acceptances

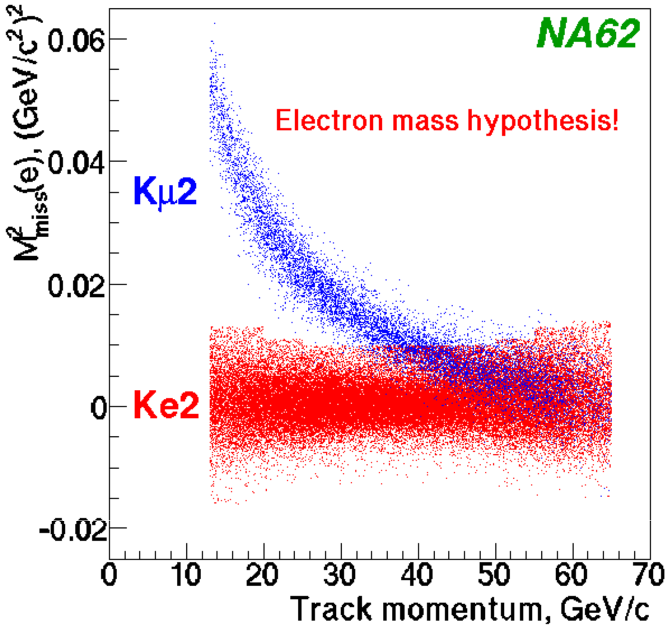
Trigger efficiencies

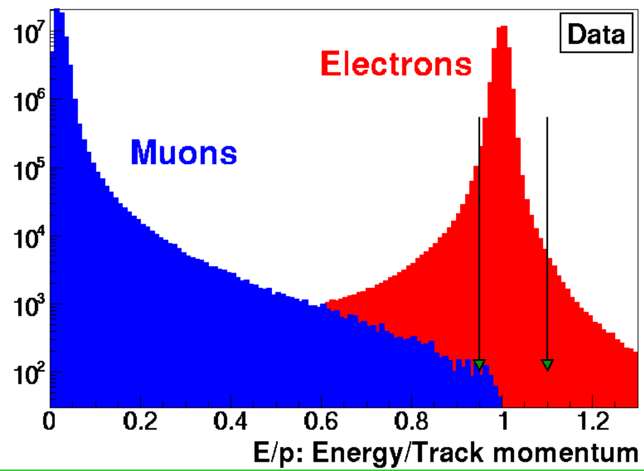
LKR readout efficiency

$K_{\mu 2}$ trigger downscaling factor

K_{e2} and $K_{\mu 2}$ selection

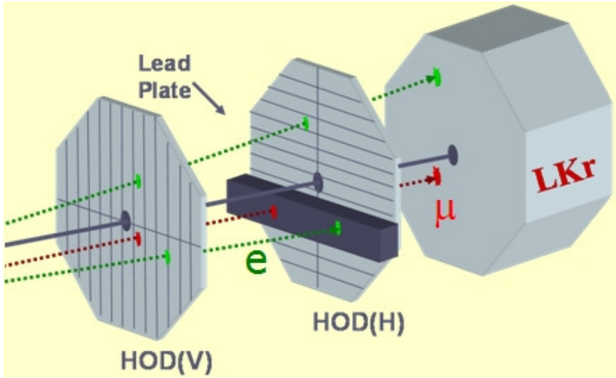
- Common selection
  - One reconstructed track, $13 < P < 65$ GeV/c
  - Common geometrical cuts
  - Decay vertex defined as closest distance of approach track-nominal K axis
  - Veto extra LKr energy deposition clusters
- Kinematical identification
  - Use missing mass squared $M^2_{miss}=(P_K-P_\ell)^2$
  - P_K (average) is monitored from the data with $K \to 3\pi$
    - Enough $K_{e2}/K_{\mu 2}$ separation for $P_{track} < 25$ GeV/c
- Lepton identification
  - $E_{LKr}/P_{track} < 0.85$ for muons, between 0.95 (0.90 below 25 GeV/c) and 1.10 for electrons



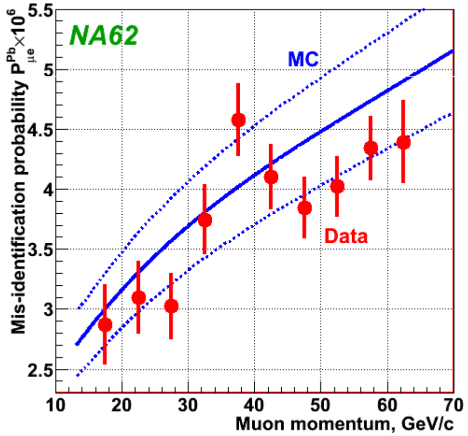


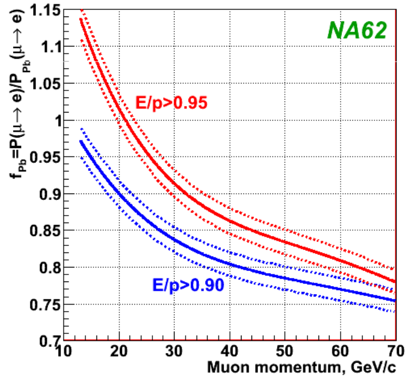
The major background to K_{e2}

- Catastrophic bremsstrahlung of muons in the LKr
  - Gives $E/p > 0.95 \rightarrow$ tag the event as K_{e2}
  - Probability $P_{\mu e} \sim 3 \cdot 10^{-6}$ (momentum dependent)
    - $K_{\mu 2}/K_{e2} \sim 40000 \rightarrow$ background $O(10\%)$
  - Need a direct measurement to validate the muon bremsstrahlung cross section in this region



- Measure it putting 9.2 X_0 of lead in front of the calorimeter
  - For about 50% of the run time, 18% acceptance reduction
  - Suppress 10^{-4} contamination of $\mu \rightarrow e$ decays
  - Tracks traversing the lead are pure muons
  - $P_{\mu e}$ is modified by the Pb wall
    - Ionization losses in the Pb (at low p)
    - Bremsstrahlung in Pb (at high p)
  - The correction is evaluated with a dedicated Geant4 simulation

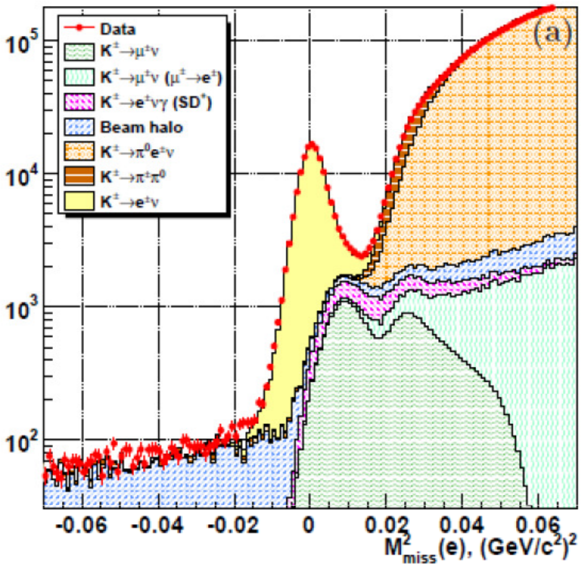




Contribution to background: B/(S+B) = 5~6 %

Uncertainty ~3 times smaller than simulation alone

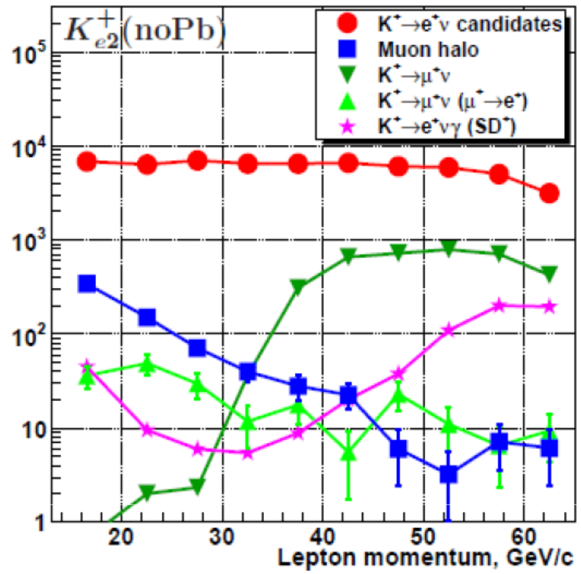
K_{e2} candidates



145958 K_{e2} candidates

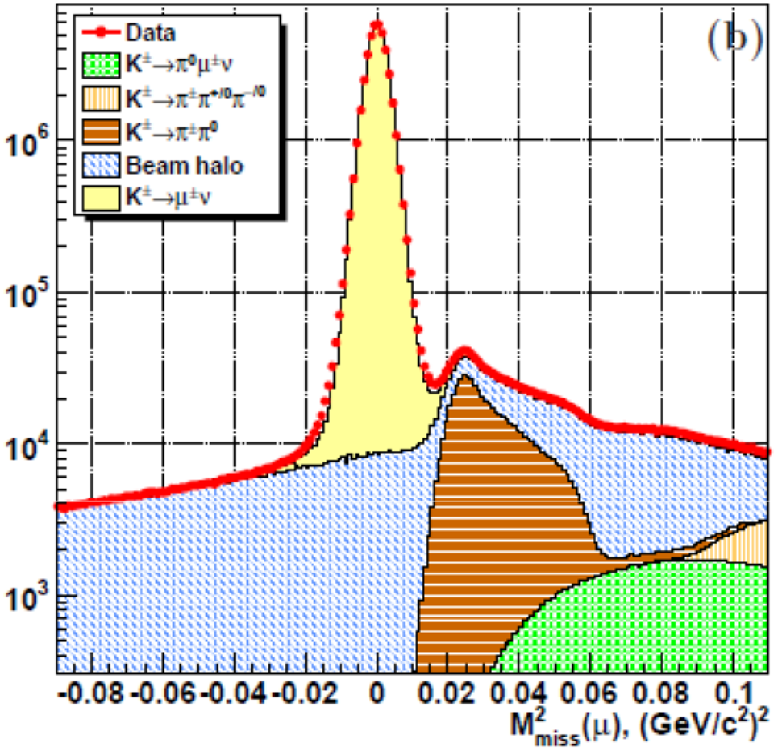
B/(S+B) = (10.95 ±0.27)%

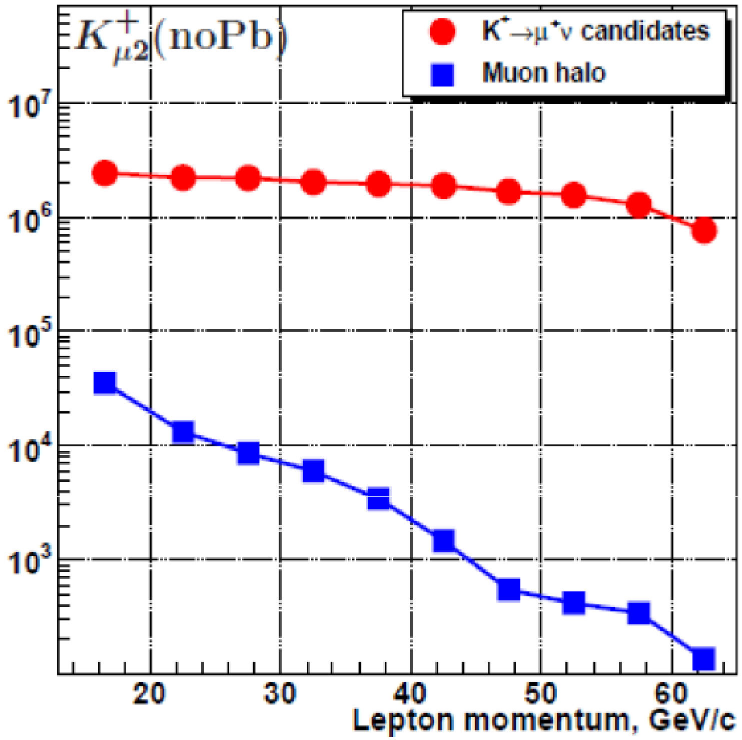
e± ID eff= 99.28 ± 0.05%



Data sample	K^+(noPb)	K^+(Pb)	K^-(noPb)	K^-(Pb)
K_{e2} candidates	59813	63282	10530	12333
Muon halo	$(1.11 \pm 0.09)\%$	$(1.51 \pm 0.10)\%$	$(4.61 \pm 0.18)\%$	$(7.86 \pm 0.23)\%$
$K_{\mu 2}$	$(6.11 \pm 0.22)\%$	$(5.33 \pm 0.19)\%$	$(5.76 \pm 0.20)\%$	$(4.87 \pm 0.17)\%$
$K_{\mu 2}$ ($\mu \to e$ decay)	$(0.26 \pm 0.04)\%$	$(0.27 \pm 0.04)\%$	$(0.31 \pm 0.09)\%$	$(0.19 \pm 0.07)\%$
$K^\pm \to e^\pm \nu\gamma$ (SD$^+$)	$(1.07 \pm 0.05)\%$	$(4.01 \pm 0.18)\%$	$(1.25 \pm 0.06)\%$	$(3.95 \pm 0.17)\%$
$K^\pm \to \pi^0 e^\pm \nu$	$(0.05 \pm 0.03)\%$	$(0.28 \pm 0.14)\%$	$(0.09 \pm 0.05)\%$	$(0.37 \pm 0.17)\%$
$K^\pm \to \pi^\pm \pi^0$	$(0.05 \pm 0.03)\%$	$(0.18 \pm 0.09)\%$	$(0.06 \pm 0.03)\%$	$(0.18 \pm 0.09)\%$
Opposite sign K	–	$(0.04 \pm 0.01)\%$	–	$(0.25 \pm 0.03)\%$
Total background	$(8.65 \pm 0.25)\%$	$(11.62 \pm 0.33)\%$	$(12.08 \pm 0.29)\%$	$(17.67 \pm 0.39)\%$

$K_{\mu 2}$ candidates





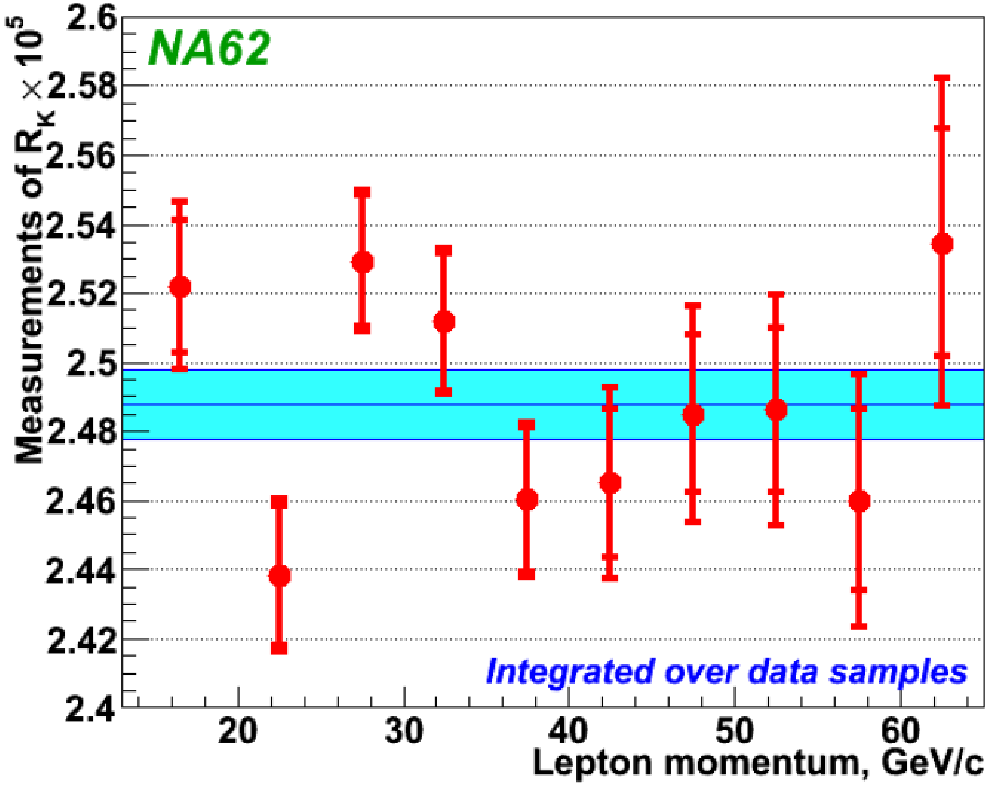
42.8 10^6 candidates with low background

	K^+(noPb)	K^+(Pb)	K^-(noPb)	K^-(Pb)
$K_{\mu 2}$ candidates $/10^6$	18.027	18.433	3.069	3.288
Muon halo	0.39%	0.44%	0.77%	1.22%

NA62 final result

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}$ (χ^2/ndf = 47/39)

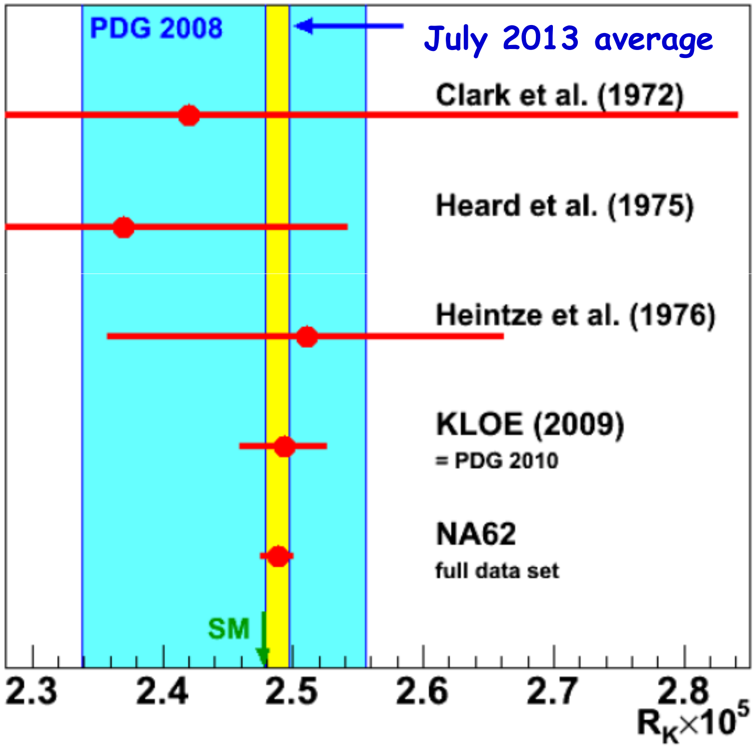
PLB 719 (2013) 326



Uncertainties

Source	δR_K*10^5
Statistical	0.007
Systematic	0.007
$K_{\mu 2}$	0.004
BR($K_{e2\gamma}$ SD+)	0.002
$K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^+ \pi^0$ bkg	0.003
Beam halo	0.002
Material in the spectrometer	0.002
Acceptance	0.002
DCH alignment	0.001
Electron ID eff.	0.001
1-track trigger eff.	0.001
LKr readout ineff.	0.001
Total	0.010

Result summary



World average	R_K*10^5	Precision
PDG 2008	2.447±0.109	4.5%
Today	2.488±0.009	0.36%

Consistency with older measurements and with the Standard Model

Experimental uncertainty is still an order of magnitude larger then the one in the SM prediction

Motivation for improved precision measurement

Measurement of the $K^{\pm}_{\ell 3}$ decay form factors

Motivation

Master formula to access V_{us}

$$\Gamma(K_{l3(\gamma)}) = \frac{G_f^2 m_K^5}{192\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta_{SU(2)}^l + 2\delta_{EM}^l)$$

The phase space integral (I^l_K), including the form factor variation over the phase space, is an important ingredient to be measured accurately

Determined by the theory:

$f_+(0)$: Hadronic form factor at $q^2=0$ (different for $K^\pm$ and K^0)

δ^l_{SU2}, δ^l_{EM} : Corrections for SU(2) breaking and long-distance EM interactions

Two form factors in K_{l3} decays: $f_+(t)$, $f_-(t)$

$$M = \frac{G_F}{2} V_{us}\left(f_+(t)(P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \bar{u}_l (1+\gamma_5) u_\nu\right)$$

f_+ = vector form factor

f_0 = scalar form factor

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

$f_+(0)$ cannot be measured directly

- Given by theory
- Only relative form factors experimentally accessible

Form factor parametrizations

- Parameters with physical meaning
  - Pole parametrization

    Assumes exchange of vector (1^-) or scalar (0^+) resonances with masses mv and ms

    $f_+(t) \rightarrow K^*(892)$

    $f_0(t) \rightarrow$ no dominating resonances
  - Dispersive parametrization

    Free parameters Λ_+ and lnC

    Polynomial approximation for the dispersive integrals G(t) and H(t) available

    PLB638 (2006) 480, PRD 80 (2009) 034034
- Parameters without a physical meaning
  - Expansion in the momentum transfer

    Linear/Quadratic as a Taylor series

    Widely used in the past

    Large correlations between parameters (for quadratic expansion)

$$f_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$$

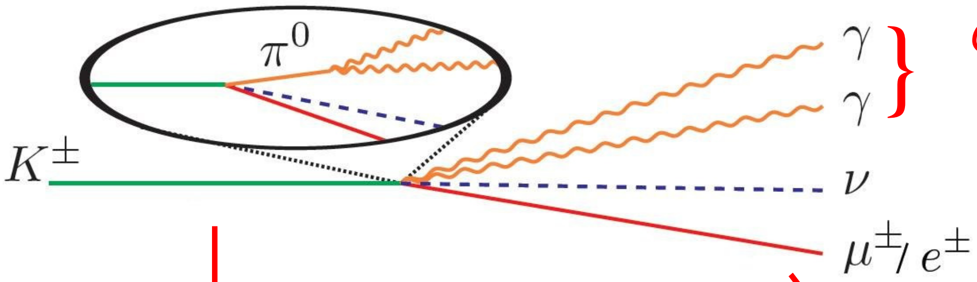
$$\bar{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ + H(t))\right]$$

$$\bar{f}_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}(\ln C + G(t))\right]$$

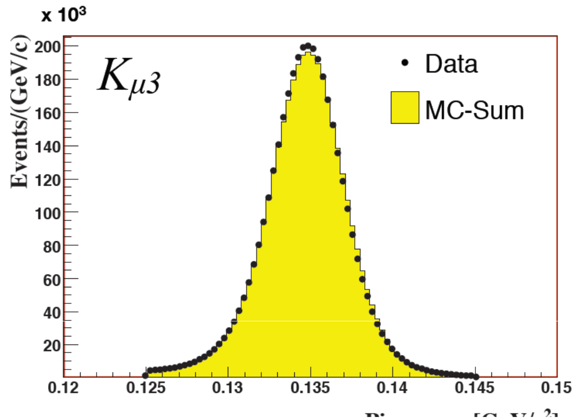
$$f_{+,0}(t) = \left[1 + \lambda_{+,0}\frac{t}{m_\pi^2}\right]$$

$$f_{+,0}(t) = \left[1 + \lambda'_{+,0}\frac{t}{m_\pi^2} + \frac{1}{2}\lambda''_{+,0}\left(\frac{t}{m_\pi^2}\right)^2\right]$$

$K^{\pm}_{l3}$ selection

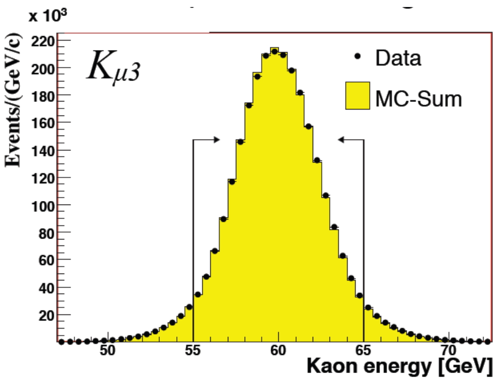


One good $\pi^0 \to \gamma\gamma$
$|m_{\gamma\gamma}-m_{\pi^0}| < 10$ MeV/c^2

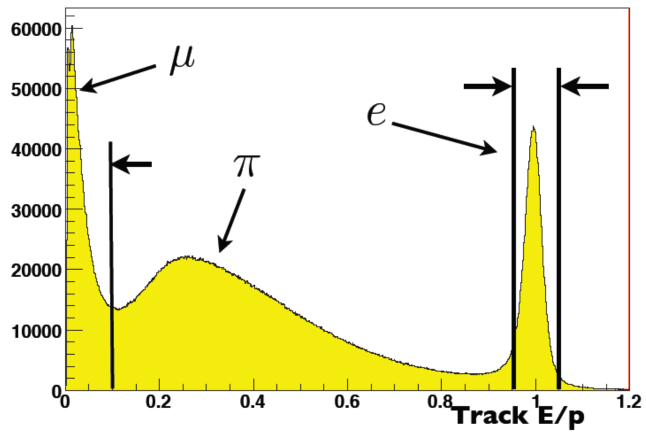


One good event
Photons and track in-time
(missing mass)^2 < 0.01(GeV/c^2)^2
Reconstructed kaon energy:
55 < E_K < 65 GeV (missing ν hyp)

One good track
μ: μ veto and E/p
e: E/p



2.5 10^6 $K_{\mu 3}$ events
4.0 10^6 K_{e3} events
Collected in the 2004 run
Minimum bias trigger + reduced K momentum & momentum byte

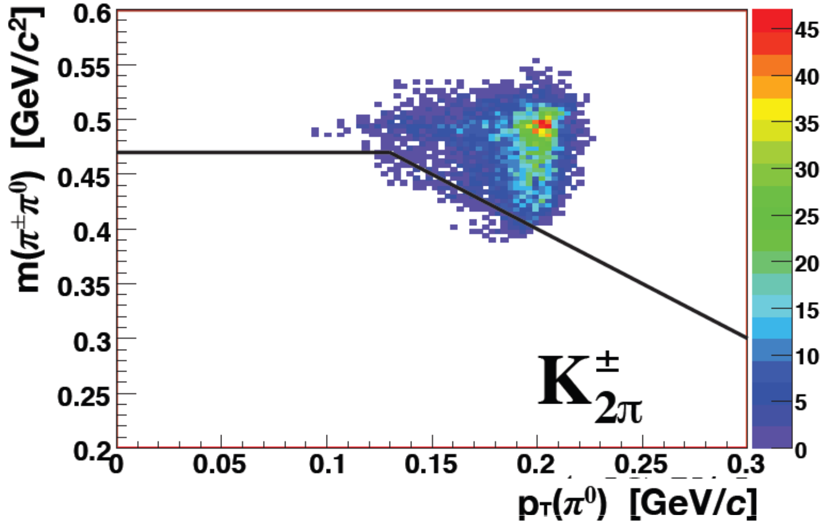


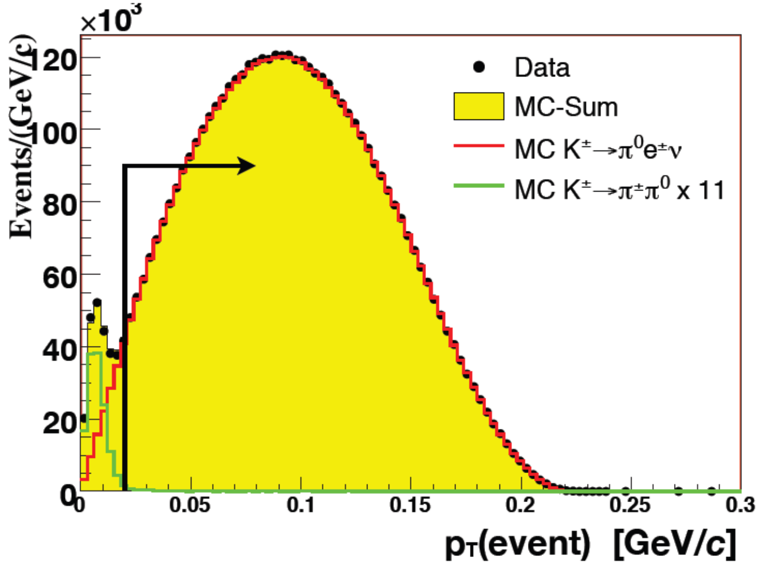
Backgrounds

$K_{\mu 3}$: $\pi^+\pi^0$ with $\pi \to \mu$ mis-ID or decay
Without suppression: 20% background

Cut in the invariant $\pi^+\pi^0$ mass and pion p_T

Background reduced to 0.5%
24% acceptance loss





K_{e3}: $\pi^+\pi^0$ with $\pi \to e$ mis-ID if E/p >0.95

Cut on transverse momentum of the event

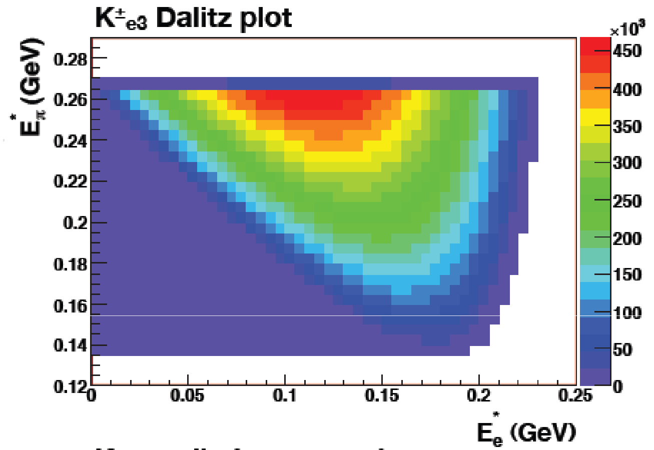
Background contamination < 0.1%
Acceptance loss ~ 3%

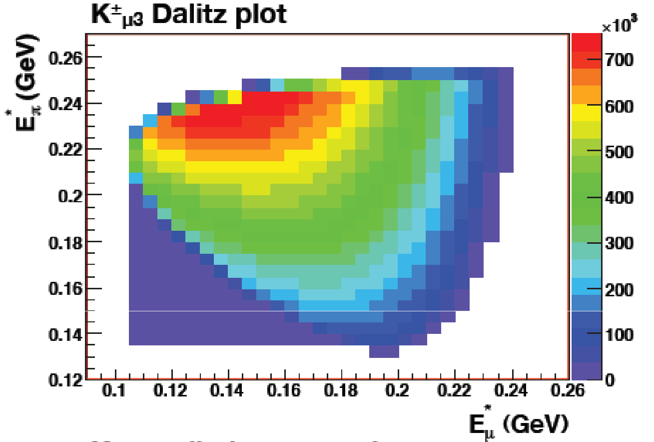
Radiative effects

Include first order radiative corrections to the decay rate

Use KLOE simulation code (EPJ C45 (2006) 417)

$$\Gamma_{K_{l3}} = \Gamma^{0}_{K_{l3}} + \Gamma^{1}_{K_{l3}} = \Gamma^{0}_{K_{l3}}\left(1+2\delta^{Kl}_{EM}\right)$$





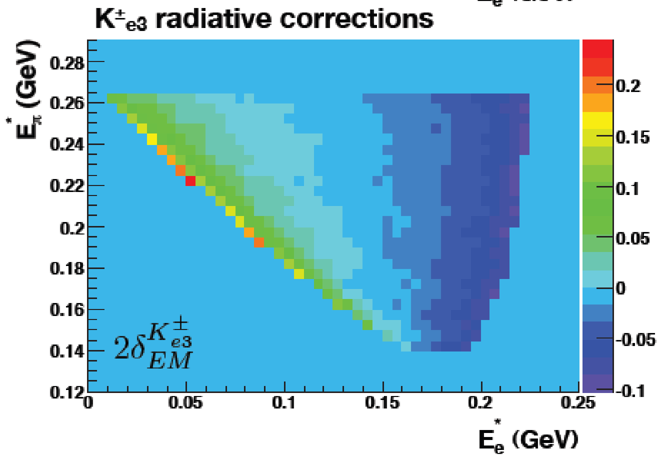
Overall correction δ_{EM}

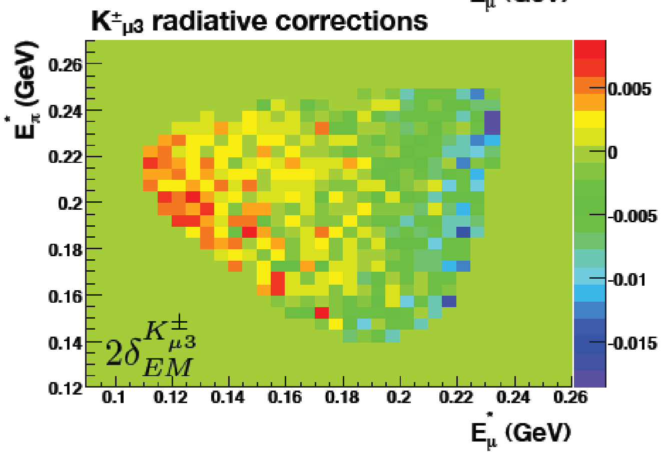
$K_{\mu 3}$	(0.008±0.125)%
K_{e3}	(0.050 ±0.125)%

Small, but:

Effect on Dalitz plot slope:

$K_{\mu 3}$	~1%
K_{e3}	~10%





Fit to the Dalitz Plot Density

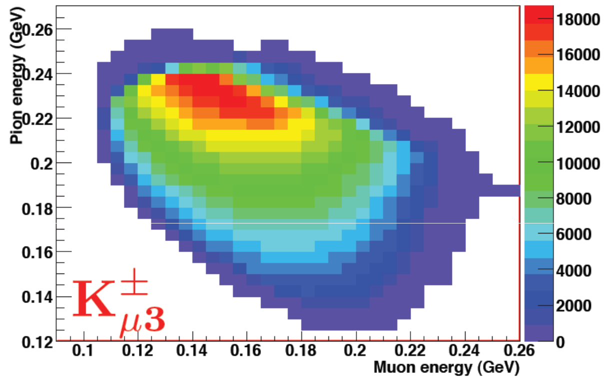
$$\rho\left(E_l^*, E_\pi^*\right) = \frac{d^2N\left(E_l^*, E_\pi^*\right)}{dE_l^* dE_\pi^*} \propto Af_+^2(t) + Bf_+(t)(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t} + C\left[(f_0 - f_+)\frac{m_K^2 - m_\pi^2}{t}\right]^2$$

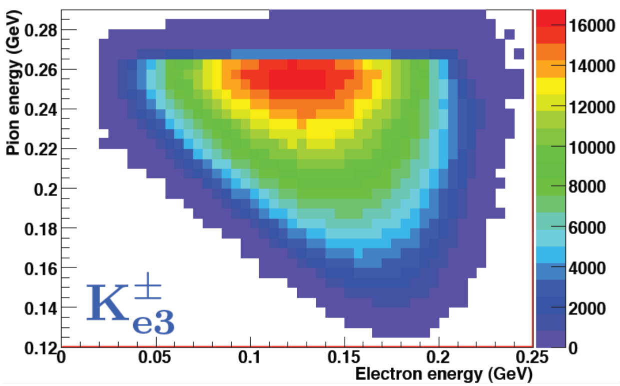
E_l, E_π = Energies of the lepton and of the pion in the kaon rest frame

A,B,C known kinematical terms

Fit performed in 5*5 MeV^2 bins

Cells outside or crossing the border of the physical region of the Dalitz plot are not used in the fit



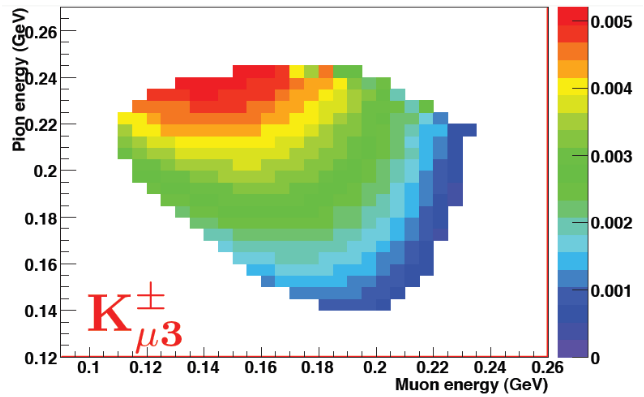


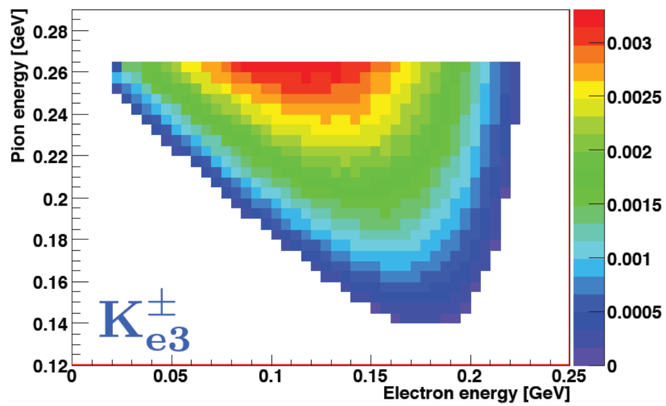
Background subtraction

Acceptance

Radiative effects

→





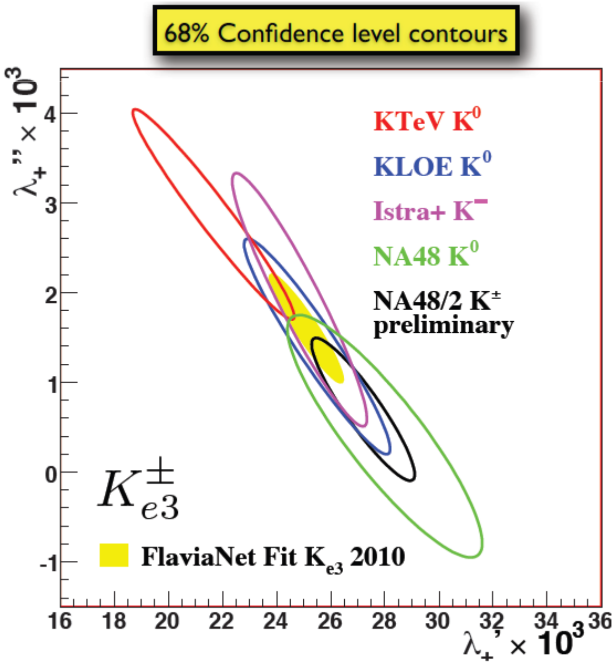
Systematics

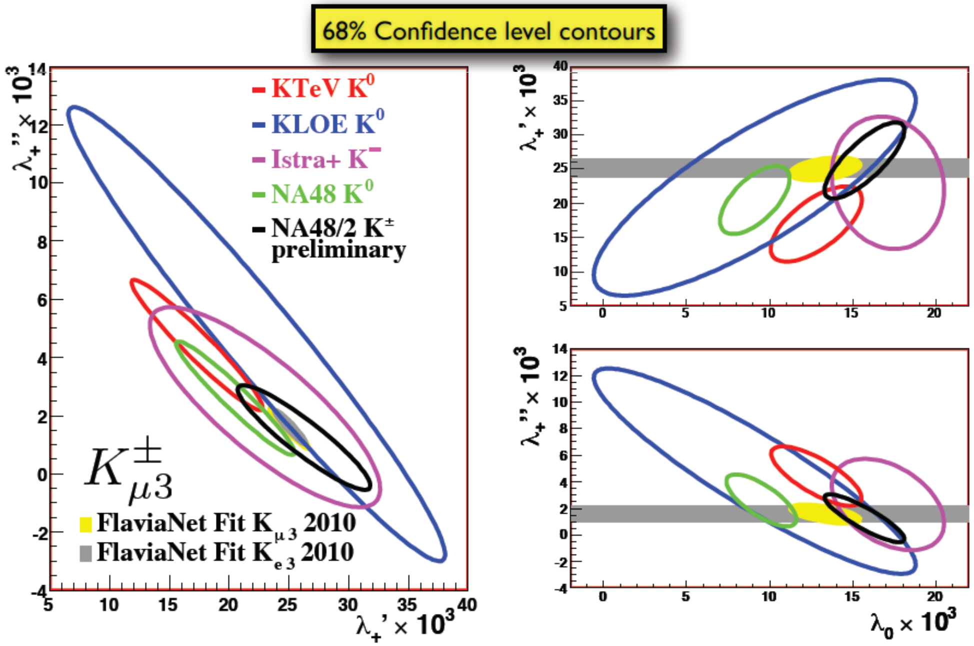
$K^{\pm}_{\mu 3}$	$\Delta\lambda'_{+}$	$\Delta\lambda''_{+}$ $\times 10^{-3}$	$\Delta\lambda_0$	Δm_V MeV/c^2	Δm_S
Kaon Energy	±0.1	±0.0	±0.3	±1	±8
Vertex	±1.0	±0.5	±0.1	±2	±7
Bin size	±0.8	±0.4	±0.7	±3	±10
Energy scale	±0.3	±0.1	±0.1	±0	±1
Acceptance	±0.2	±0.1	±0.3	±2	±5
$K_{2\pi}$ background	±1.7	±0.5	±0.6	±3	±0
2nd Analysis	±0.1	±0.1	±0.2	±2	±5
FF input	±0.3	±0.8	±0.1	±7	±3
Systematic	±2.2	±1.1	±1.0	±9	±16
Statistical	±3.0	±1.1	±1.4	±8	±31

$K^{\pm}_{e3}$	$\Delta\lambda'_{+}$	$\Delta\lambda''_{+}$ $\times 10^{-3}$	Δm_V MeV/c^2
Kaon Energy	±0.3	±0.1	±6
Vertex	±0.2	±0.1	±0
Bin size	±0.0	±0.1	±2
Energy scale	±0.1	±0.0	±0
Acceptance	±0.2	±0.0	±3
2nd Analysis	±0.9	±0.4	±1
FF input	±0.4	±0.0	±1
Systematic	±1.1	±0.4	±7
Statistical	±0.7	±0.3	±3

Results

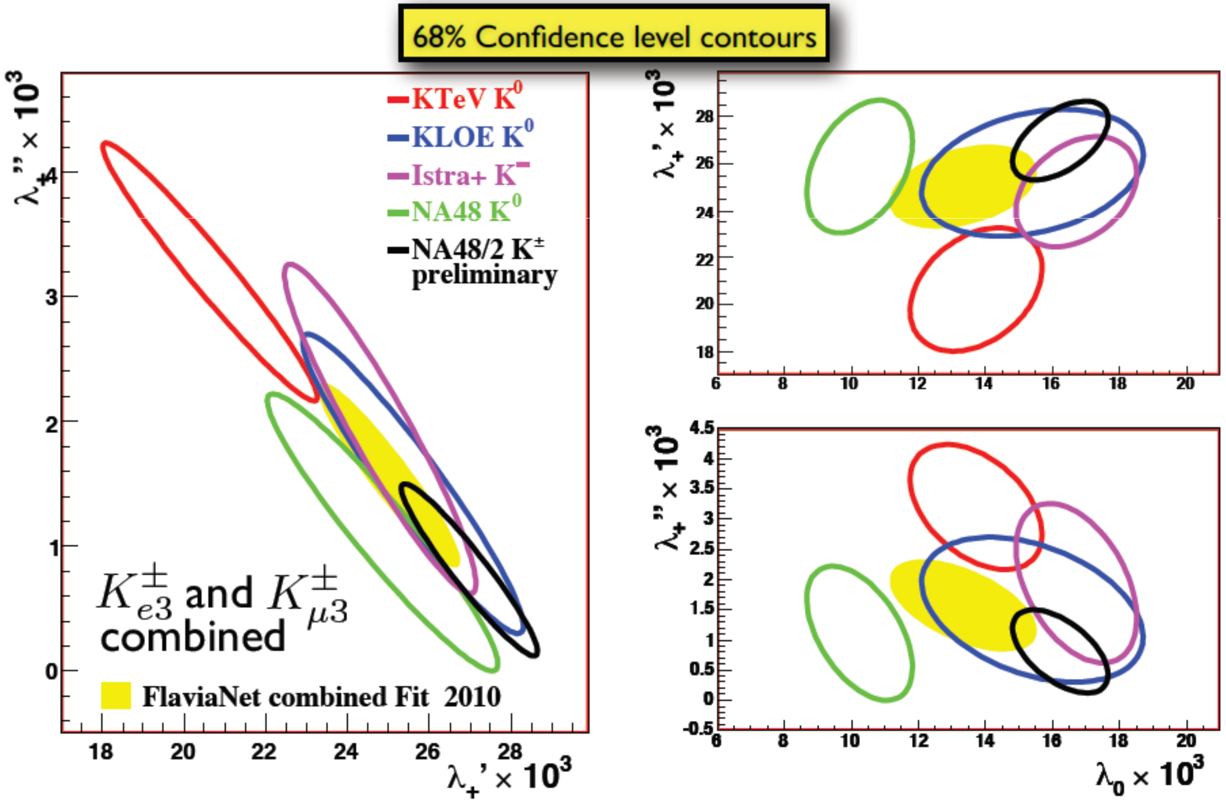
Quadratic (x10^{-3})	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Pole (MeV/c^2)	**m_V**		**m_S**
$K^{\pm}_{\mu 3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{stat} \pm 7_{syst}$		





Combined results

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
	26.98±1.11	0.81±0.46	16.23±0.95
Pole (MeV/c^2)	m_V		m_S
	877±6		1176±31



Summary and outlook

- NA62 has taken data in 2007-2008 to reach 0.4% precision on R_K
- The analysis of the full data sethas been completed
- The measured value is $R_K = (2.488 \pm 0.010) * 10^{-5}$
- The precision achieved is 0.4%

- With data collected in 2004, NA48/2 has studied the semileptonic decays $K^\pm \to \pi^0 \mu^\pm \nu$ and $K^\pm \to \pi^0 e^\pm \nu$
- Preliminary results on the form factor parametrization have been presented
- More $K^\pm$ and K^0 data collected by NA62 in 2007 are ready to be analyzed

Expected to have $O(10^7)$ $K^\pm_{l3}$ and $O(10^6)$ K^0_{l3} decays