Precision measurement of the charged kaon semileptonic decays $K^{\pm}_{l3}$

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Outline

The NA48/2 experiment at CERN SPS

The $K^{\pm} \to \pi^0 l^{\pm} \nu$ decay

Summary

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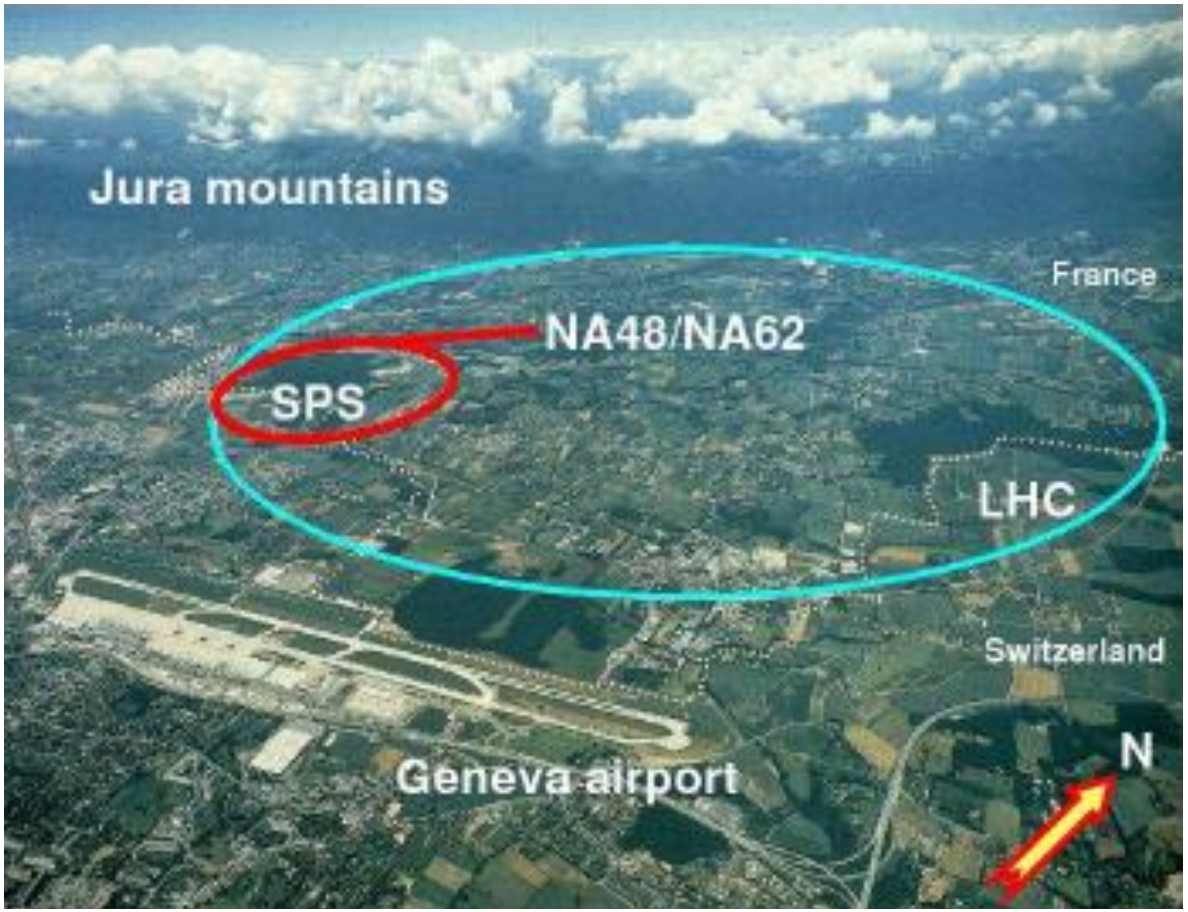
Summary

The NA48/NA62 experiments at CERN SPS



NA48 direct CPV ε'/ε	1997	$K_L + K_S$
	1998	$K_L + K_S$
	1999	$K_L + K_S$
	2000	K_L only
	2001	$K_L + K_S$
NA48/1	2002	K_S / hyperons
NA48/2	2003	$K^+ + K^-$
	2004	Ag (CPV)
NA62 (R_K)	2007:	$K^+ + K^-$
	2008:	R_K + tests
NA62	2007	design &
	2008	construction
	2012	technical run
	2013	long shutdown
	2014	commissioning
	2015	&
	2016	data
	2017	taking
	2018	

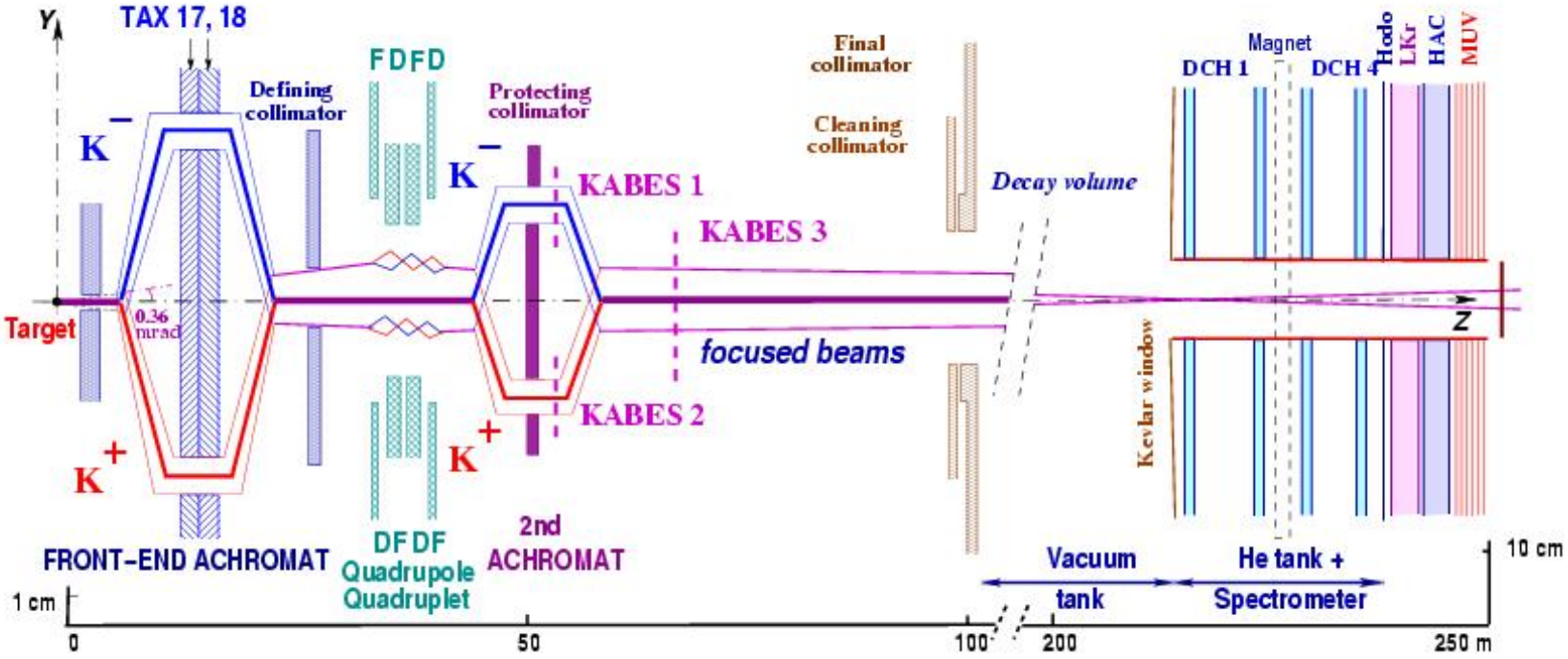
The NA48/2 collaboration:

$\sim$ 100 physicists from 15 institutes in 8 countries

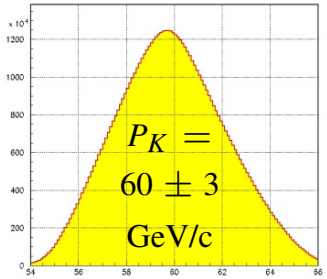
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

The NA48/2 Kaon beam

2003 + 2004 run: $\sim$ 6 months, $\sim 2 \times 10^{11}$ $K^{\pm}$ decays in flight

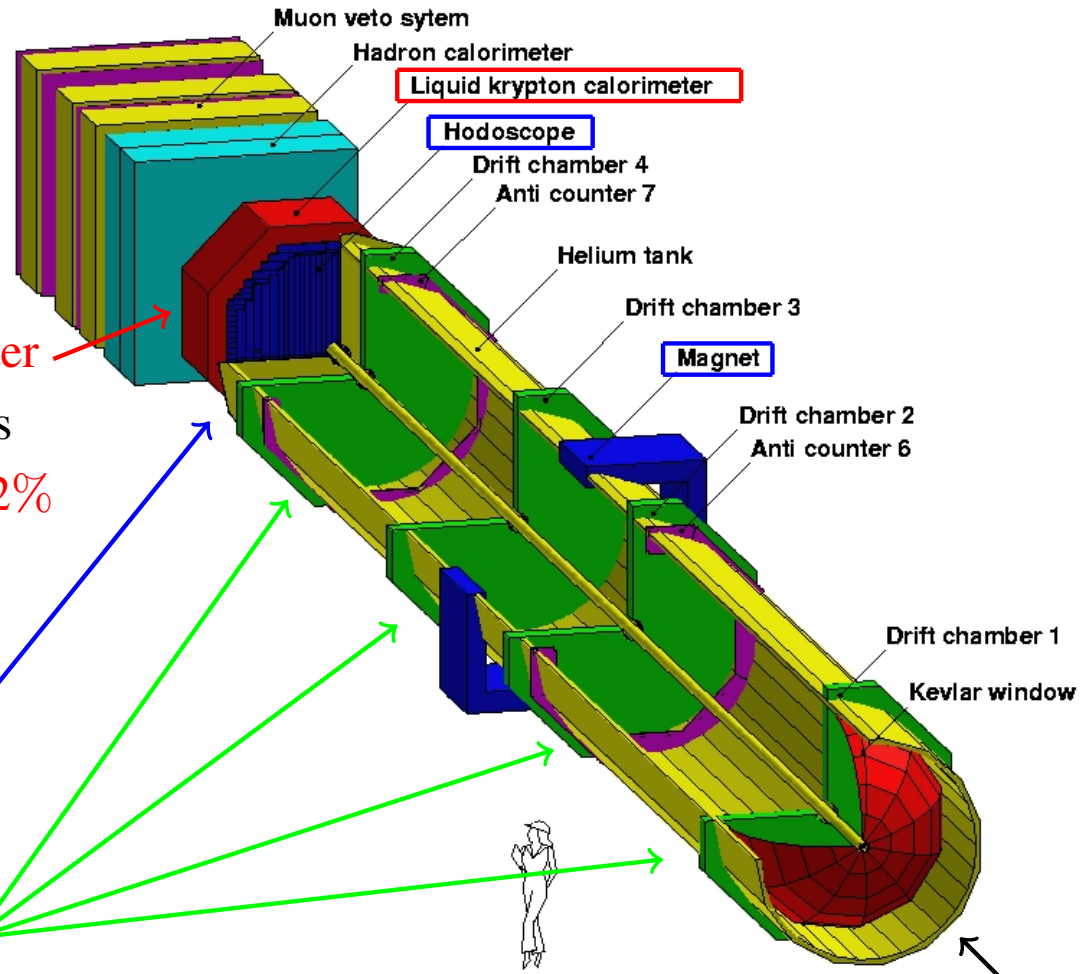


Simultaneous K^+ and K^- beams: large charge symmetrization of experimental conditions



Beams coincide within $\sim$ 1 mm all along the 114 m decay volume
Flux ratio K^+/K^- ~ 1.8

The NA48/2 detectors



Main detectors:

- Liquid Krypton (LKr) EM calorimeter
  high granularity, quasi-homogeneous
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  (E in GeV)
  $\sigma_x = \sigma_y \sim 1.5$ mm at 10 GeV
- Scintillator hodoscope (2 planes)
  fast trigger, $\sigma_t = 150$ ps
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency
  $\sigma_p/p = 1.02\% \oplus 0.044\%\, p$ (p in GeV/c)

Decay region $\sim$ 114 m long
Detector region $\sim$ 50 m long

Other detectors: hadron calorimeter (HCAL), muon vetos (MUV)

The NA48/2 experiment at CERN SPS

The $K^{\pm} \to \pi^0 l^{\pm} \nu$ decay

Summary

The $K^{\pm} \to \pi^0 l^{\pm} \nu$ ($K^{\pm}_{l3}$) decay form factors

$$\boxed{\frac{d^2\Gamma}{dE_l\, dE_\pi} \propto A\, f_+^2(t) + B\, f_+(t) f_-(t) + C\, f_-^2(t)}$$ (neglecting radiative effects), where:

$t = M^2_{l\nu} \quad = (P_K - P_\pi)^2 = m_K^2 + m_\pi^2 - 2 m_K E_\pi$

E_π, E_l, E_ν = energies in the $K^{\pm}$ rest frame

$f_-(t) \quad = (f_+(t) - f_0(t))\,(m_K^2 - m_\pi^2)\,/\,t$

$f_0(t), f_+(t)$ = "scalar" and "vector" FF

$A = M_K[2E_l E_\nu - m_K(E_\pi^{\max} - E_\pi)] + M_l^2\,[\frac{1}{4}(E_\pi^{\max} - E_\pi) - E_\nu]$

$B = M_l^2[E_\nu - \frac{1}{2}(E_\pi^{\max} - E_\pi)]$ negligible for K_{e3}

$C = \frac{1}{4} M_l^2 (E_\pi^{\max} - E_\pi) 4$ negligible for K_{e3}

FF parametrization	$f_+(t, \text{parameters})$	$f_0(t, \text{parameters})$
Quadratic (linear for $f_0(t)$)	$1 + \lambda'_+ t/m_\pi^2 + \lambda''_+ (t/m_\pi)^2$	$1 + \lambda'_0 t/m_\pi^2$
Pole	${M_V}^2/({M_V}^2 - t)$	${M_S}^2/({M_S}^2 - t)$
Dispersive *	$\exp\left((\Lambda_+ + H(t))t/m_\pi^2\right)$	$\exp\left((\ln[C] - G(t))t/(m_K^2 - m_\pi^2)\right)$

* B. Bernard, M. Oertel, E. Passemar, J. Stern, Phys.Rev.D80(2009) 034034

We use MC radiative decay generator of C. Gatti [Eur.Phys.J. C45(2006) 417-420] provided by the KLOE collaboration. It includes $f_0 = f_+ = 1 + \lambda' t/m_\pi^2$

Event reconstruction

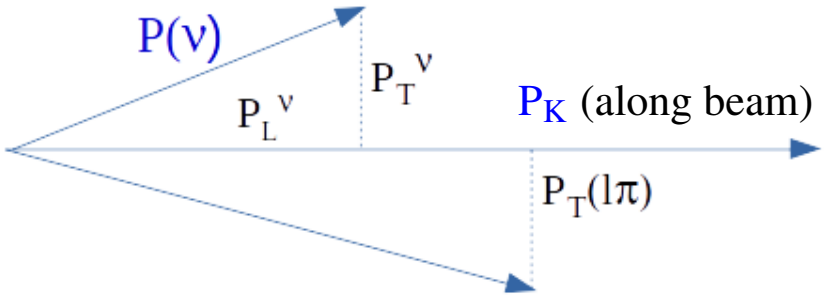
- Data sample: 3 days of NA48/2 special run taken in 2004
- Trigger: 1 charged track and $E_{\mathrm{LKr}} > 10$ GeV
- Beam geometry and average momentum P_{beam} are measured from $K_{3\pi^{\pm}}$
- K_{e3} $(K_{\mu 3})$ event selection:
  - 1 track with $P > 5$ (10) GeV$/c$
  - 2 energy clusters in LKr, > 15 cm from closest track
  - Kaon momentum reconstruction (assuming $\vec{P}_T^{\nu} = -\vec{P}_T(l\pi)$): two solutions for P_K

    $P_{1,2} = (\Phi P_{\mathrm{zb}} \pm \sqrt{d})/(E^2 - P_{\mathrm{zb}}^2)$, where

    $\Phi = 0.5(m_K^2 + E^2 - P_T^2 - P_{\mathrm{zb}}^2)$,

    $d = \Phi^2 P_{\mathrm{zb}}^2 - (E^2 - P_{\mathrm{zb}}^2)(M_K^2 E^2 - \Phi^2)$

    When $d < 0$ we assume $d = 0$



  - choose solution with smallest $\Delta P = |P_K - P_{\mathrm{beam}}|$
  - require $\Delta P < 7.5$ GeV$/c$

Event selection

π^0 :

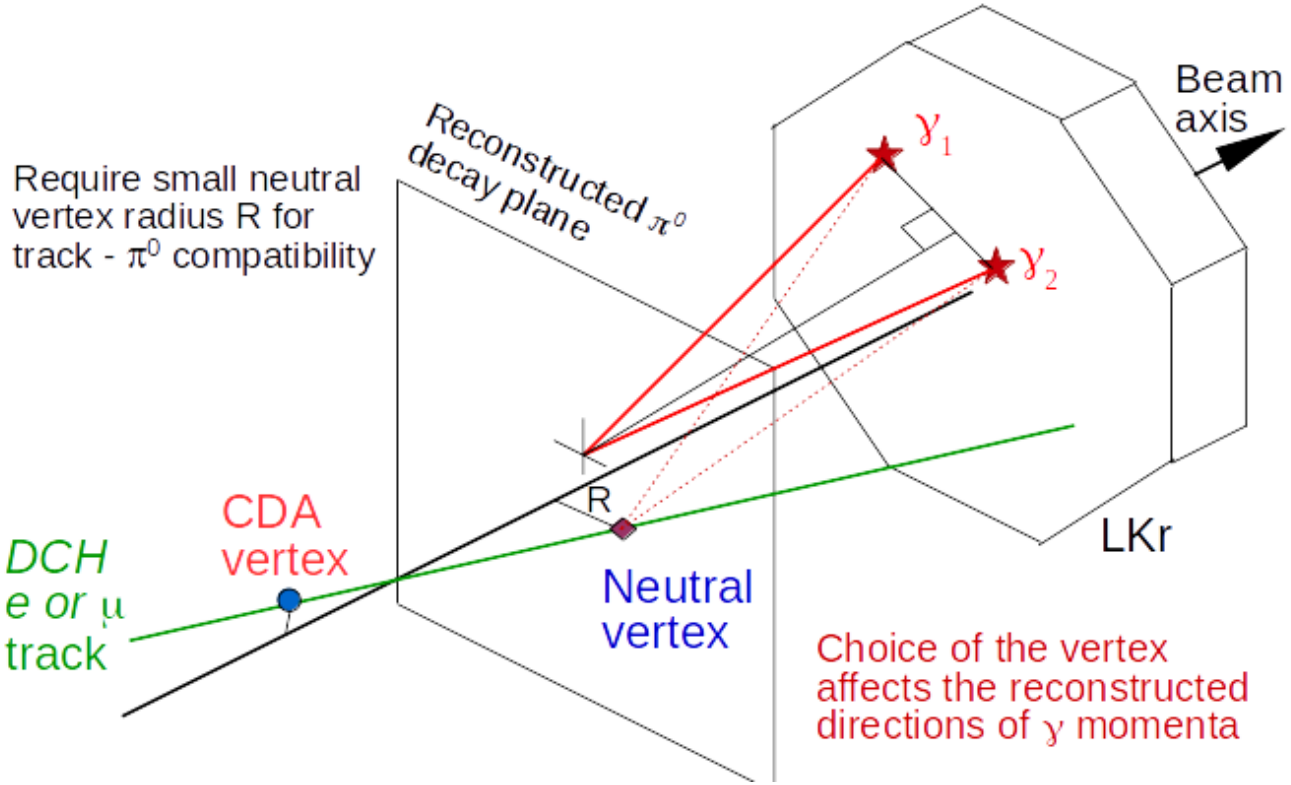
- 2 γ in LKr, separated by > 20 cm
- $E(\pi^0) > 15$ GeV
- Z(decay) derived assuming π^0 mass

e / μ :

- 1-track event
- K_{e3} electron if $E/P > 0.9$
- $K_{\mu 3}$ muon if signal in MUV and $E/P < 0.9$

Loose E/P cuts $\Rightarrow$ negligible related systematics

Decay vertex reconstruction



- CDA vertex: track point closest to beam axis (used in previous analysis)
  - systematic shift of the vertex closer to the beam
  - high sensitivity to exact beam shape simulation
- "neutral" vertex: Z_n from π^0 reconstruction (π^0 mass constraint)
  - X_n, Y_n = impact point of charged track on $Z = Z_n$ plane
  - no transverse bias chosen for this analysis

Final cuts

For K_{e3}

- P_T^{ν} (w.r.t. beam axis) > 0.03 GeV$/c$
- $(P_L^{\nu})^2 = (E^{\nu})^2/c^2 - (P_T^{\nu})^2 > 0.0014$ (GeV$/c)^2$
  (negative tail and zero region sensitive to beam shape)

For $K_{\mu 3}$

- cuts against $K^{\pm} \to \pi^{\pm}(\to \mu^{\pm}\nu)\pi^0$ background:
  - $M(\pi^{\pm}\pi^0) < 0.47$ GeV$/c^2$ (assuming pion mass for the charged particle)
  - $M(\pi^{\pm}\pi^0) < 0.6$ GeV$/c^2 - P_T(\pi^0)/c$
  - $M(\mu^{\pm}\nu) > 0.18$ GeV$/c^2$ (to exclude $\pi^{\pm}$ mass region)
- cut against $\pi^{\pm}\pi^0\pi^0$: $|P_2 - P_1| < 60$ GeV
  (difference between two P solutions is large when one π^0 is missing)

For both K_{l3}

- compatibility of neutral vertex (X_n, Y_n, Z_n) with beam axis $(X_n^0(Z), Y_n^0(Z))$

$$\sqrt{\left(\frac{X_n - X_n^0(Z_n)}{\sigma_{X_n^0}(Z_n)}\right)^2 + \left(\frac{Y_n - Y_n^0(Z_n)}{\sigma_{Y_n^0}(Z_n)}\right)^2} < 11$$

Background

Contamination from other $K^{\pm}$ decay modes is estimated by MC simulation.

Decay	Notation	BR [%]	$N_{\text{gen.}}$ $[10^6]$	F_e $[10^{-3}]$	F_μ $[10^{-3}]$
$K^{\pm} \to \pi^{\pm}(\pi^0 \to 2\gamma)$	2π	20.66	393.2	0.270	0.264
$K^{\pm} \to \pi^{\pm}2(\pi^0 \to 2\gamma)$	3π	1.761	62.5	0.286	1.833
$K^{\pm} \to \pi^{\pm}(\pi^0 \to e^+e^-\gamma)$	2πD	1.174	1.5	0.049	0.000
$K^{\pm} \to \pi^{\pm}\gamma(\pi^0 \to 2\gamma)$	$2\pi\gamma$	0.0275	35.3	0.004	0.044
$K^{\pm} \to \pi^0(\mu^{\pm} \to e^{\pm}\nu\nu)\nu$	$K^e_{\mu 3}$	0.03353	174.3	0.004	0.000

$N_{\text{gen.}}$ = number of MC generated events

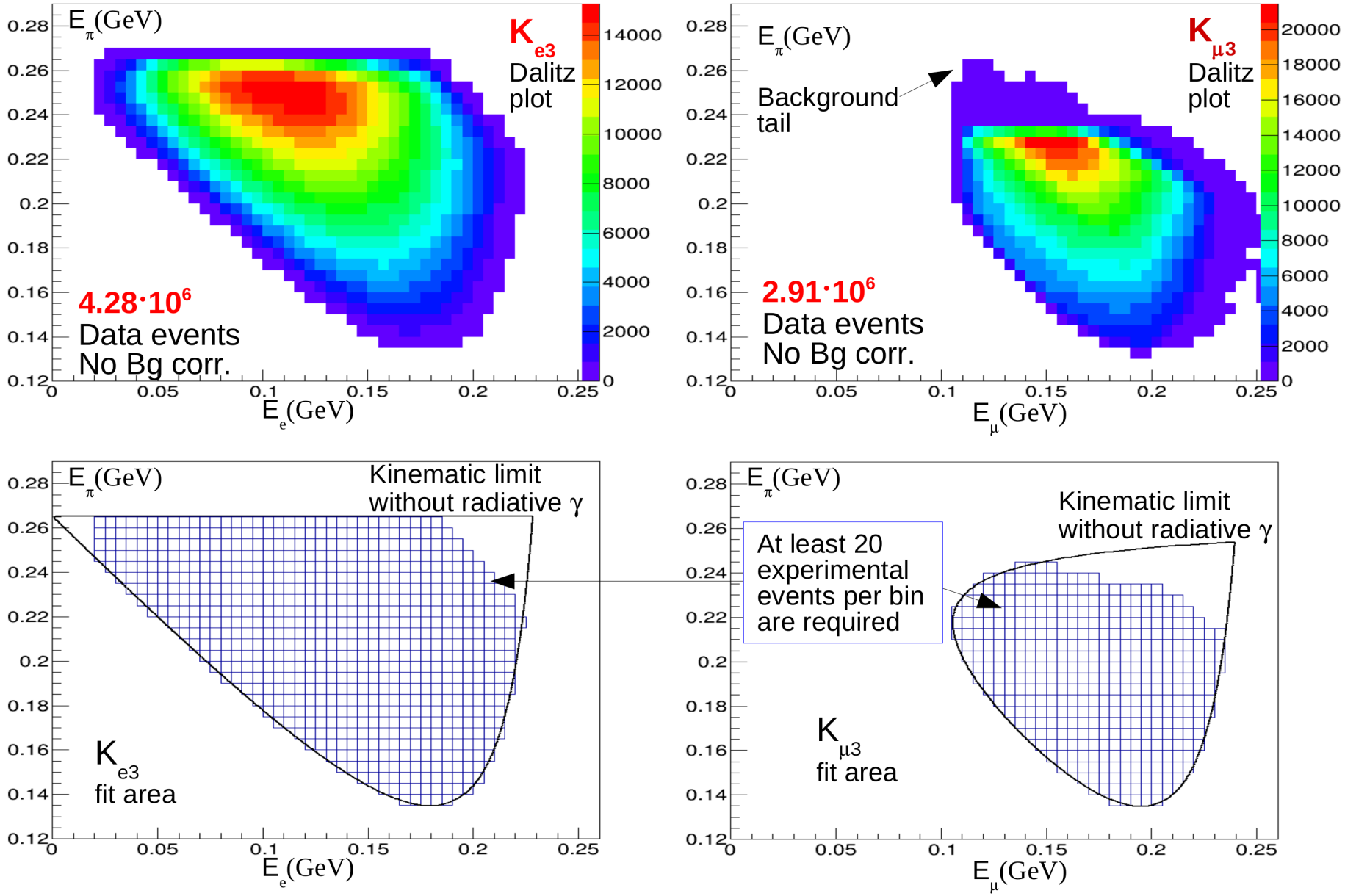
F_e, F_μ = estimated background contamination in $K_{e3}, K_{\mu 3}$ data

- BG contamination from 2π and 3π: very small, $O(10^{-4} - 10^{-3})$
- BG contamination from other channels: negligible

Data are corrected by subtracting the (small) MC-estimated background

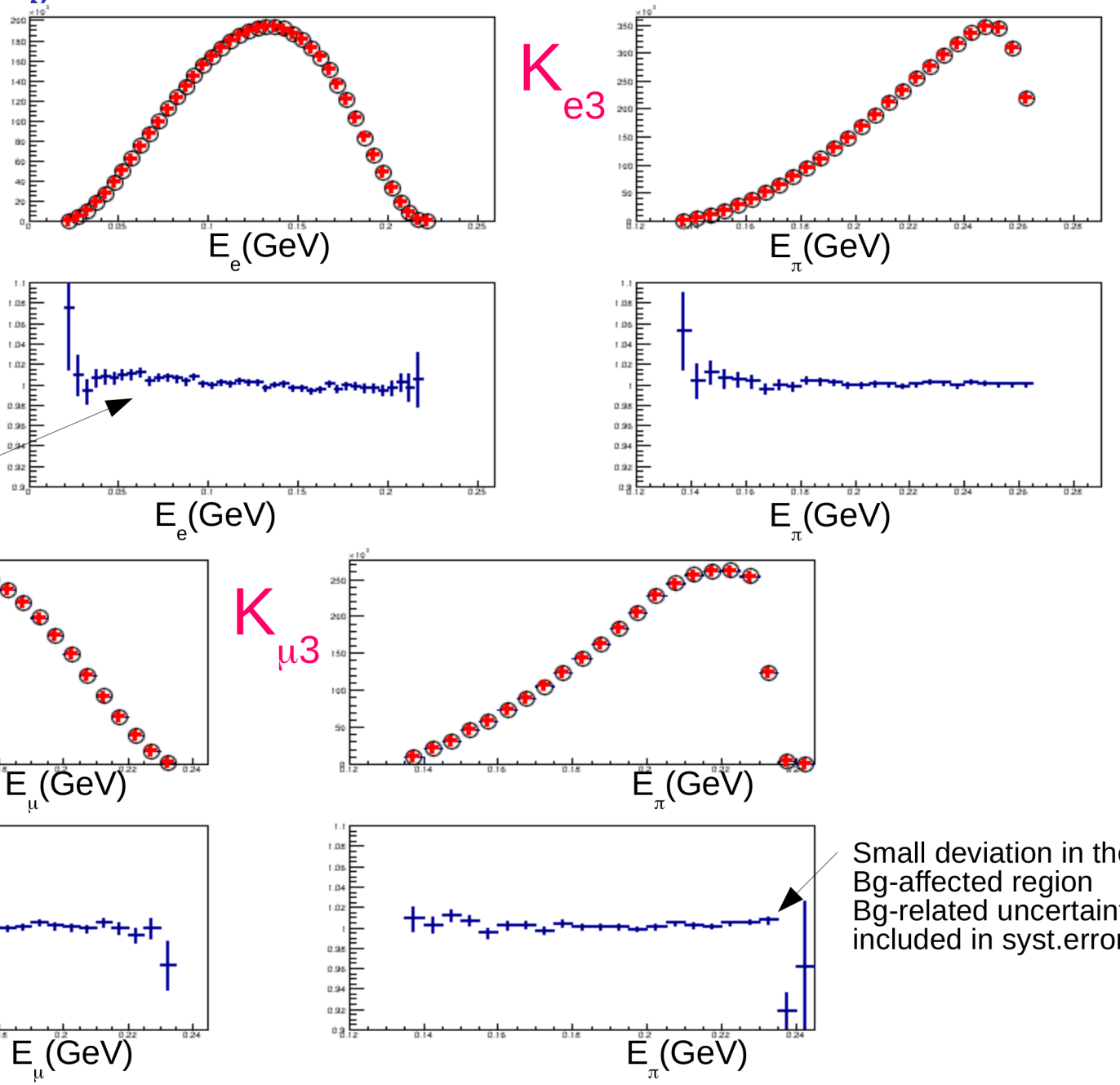
Measured Dalitz plots and fit areas

(5x5 MeV cells)



Dalitz plots projections

- ○ Data-Bg
- + MC fit result (quadr.)
- + (Data-Bg)/MC



Marginally significant slope, within the radiative correction precision. Radiative effect uncertainty is included in the systematic error.

Small deviation in the Bg-affected region Bg-related uncertainty is included in syst.error.

Fit results

Analysis has been performed:

- for K_{e3}
- for $K_{\mu 3}$
- for the combined K_{l3} result (joint fit)

Results of the combined K_{l3} analysis

K_{l3} – Quadratic parametrization

	λ'_+	λ''_+	λ'_0
Central values	23.55	1.73	14.90
Stat. error	0.75	0.29	0.55
Syst. error	1.23	0.41	0.80
Total error	1.44	0.50	0.97

Correlation coefficients

	λ''_+	λ_0
λ'_+	-0.954	-0.076
λ''_+		0.035

K_{l3} – Pole parametrization
(parameters in MeV)

	M_V	M_S
Central values	894.3	1185.5
Stat. error	3.2	16.6
Syst. error	5.4	35.5
Total error	6.3	39.2

(correlation = -0.278)

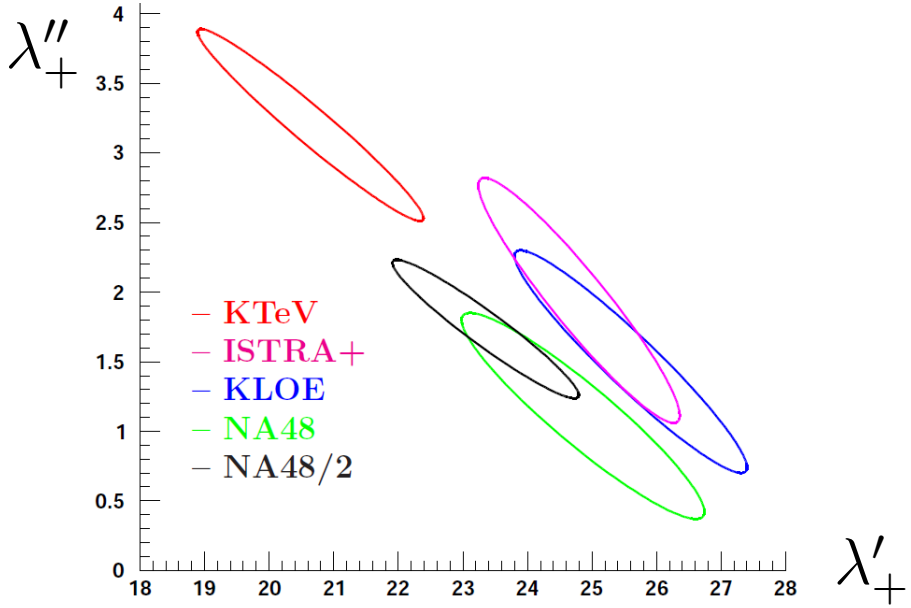
K_{l3} – Dispersion parametrization

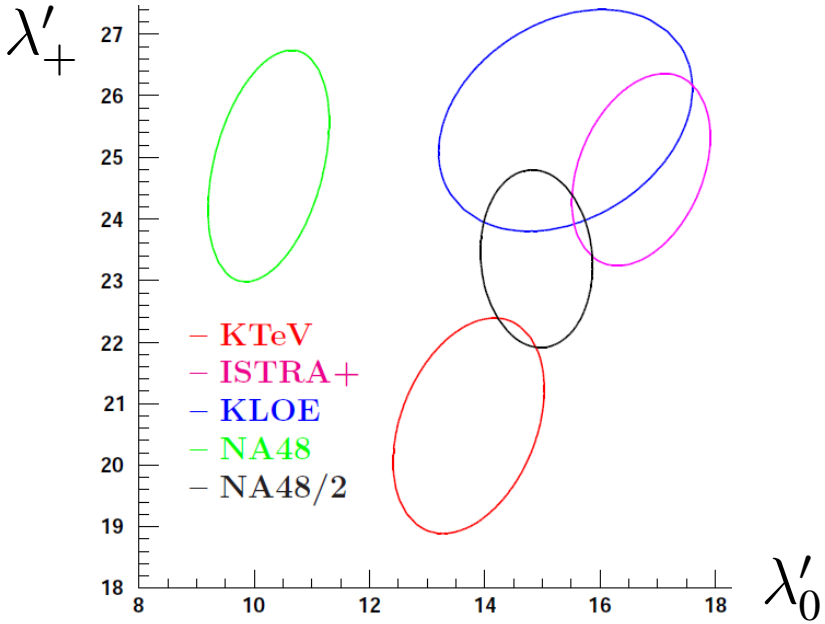
(units of 10^{-3})	Λ_+	$\ln[C]$
Central values	22.76	180.1
Stat. error	0.18	4.9
Syst. error	0.55	11.1
Total error	0.58	12.1

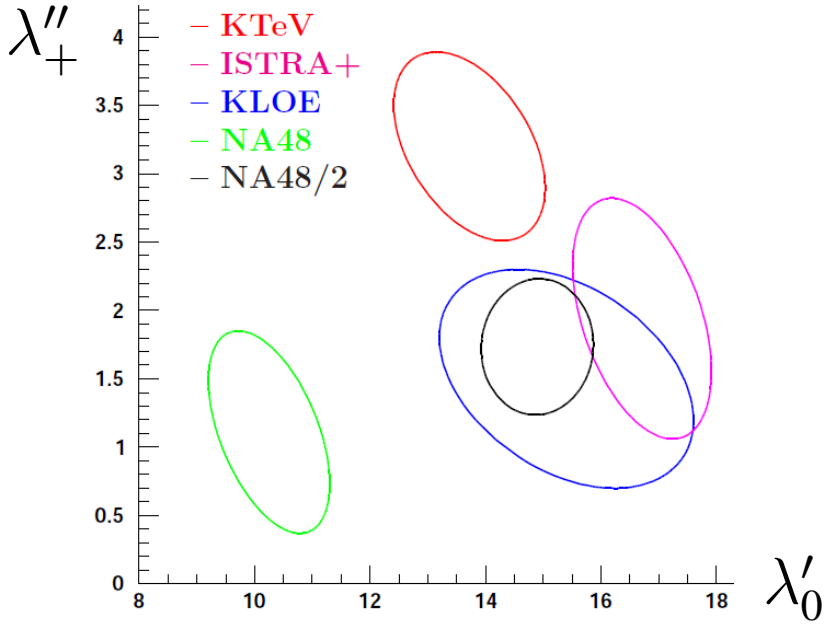
(correlation = -0.035)

Results for the joint K_{l3} analysis

- Quadratic fit: $\to \lambda'_+ \,,\ \lambda''_+ \,,\ \lambda'_0$
- Parameter correlation (1σ ellipses)
- black ellipse = NA48/2
- comparison to other experiments







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- Form factors of $K_{l3}^{\pm}$ decays have been measured by NA48/2 from 4.3 million K_{e3} and 2.9 million $K_{\mu 3}$ events collected in 2004
- An improved vertex definition makes this analysis almost insensitive to the beam shape
- The NA48/2 combined analysis of K_{e3} and $K_{\mu 3}$ decays provides the most precise measurement of $K_{l3}^{\pm}$ form factors