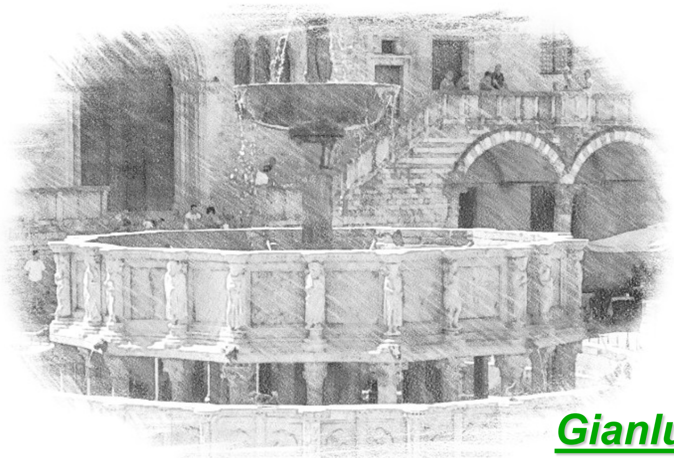
"Charged Kaon Semi-Leptonic Form Factors from NA48/2"



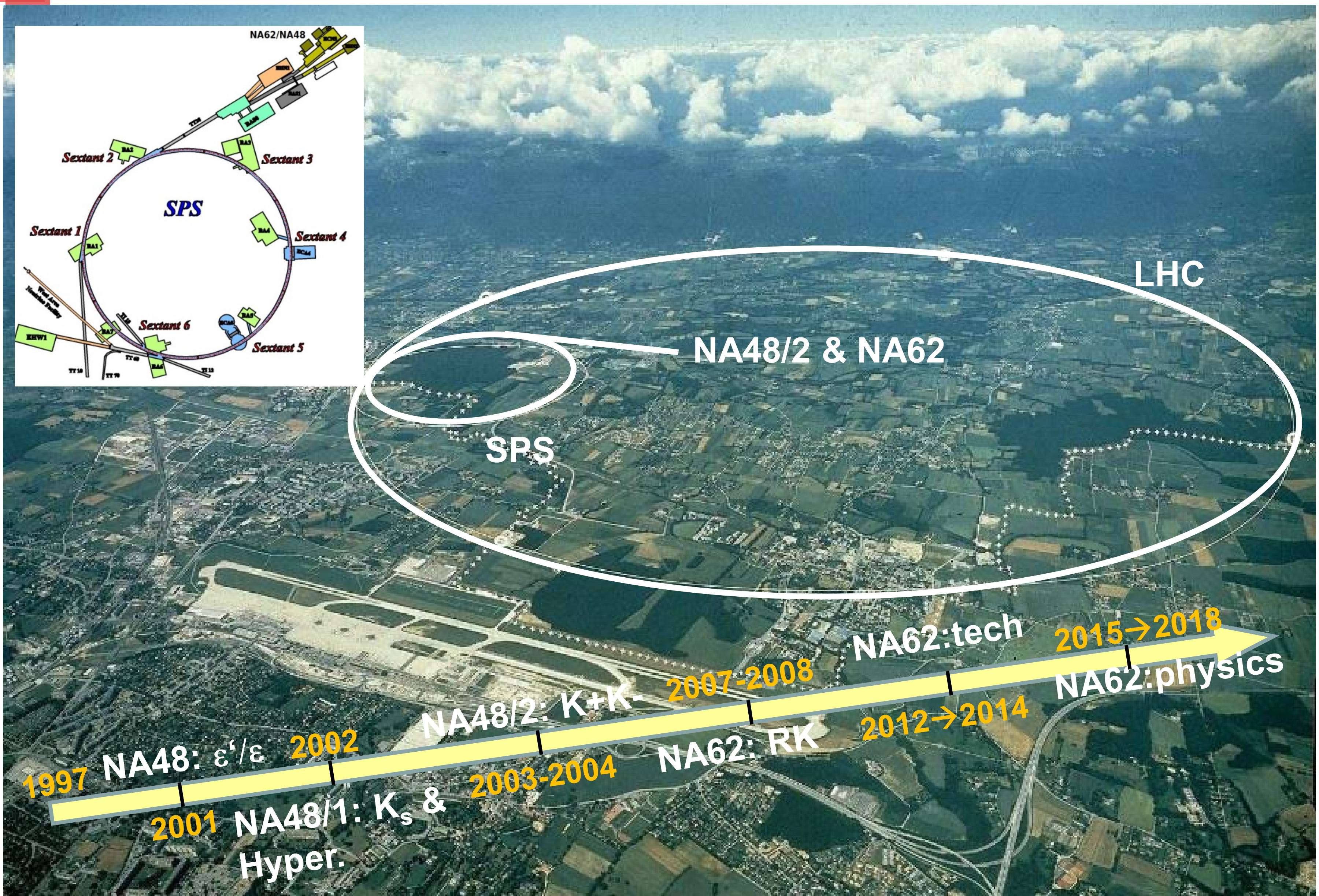
KAON2019
10.9.2019
Perugia

Gianluca Lamanna (Univ. & INFN Pisa)
On behalf of the NA48/2 collaboration

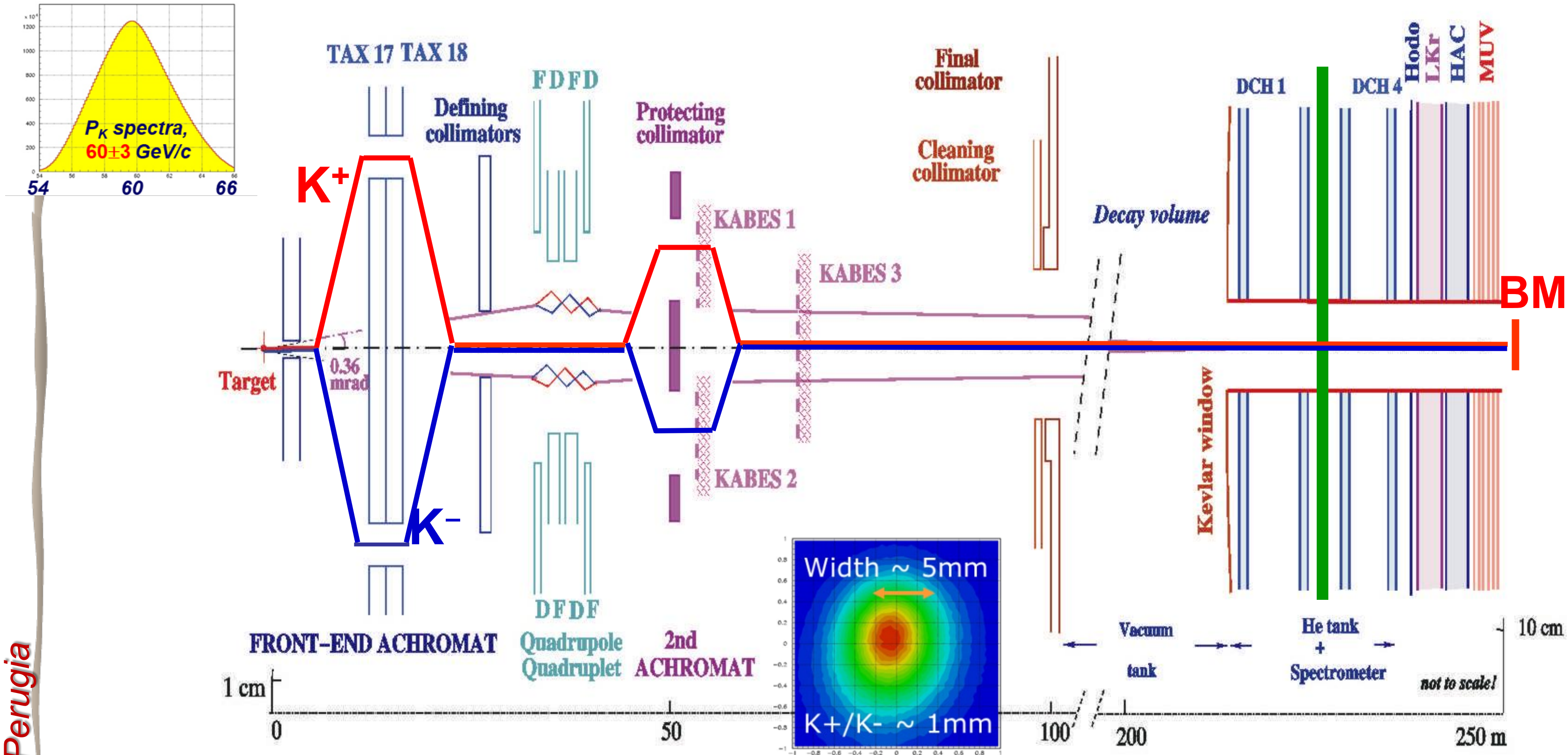
Outline

- NA48/2 experiment
  - Beam line
  - Detector
- Precise measurement of K_{l3} form factors (FF).
- Conclusions

Kaon physics @ CERN



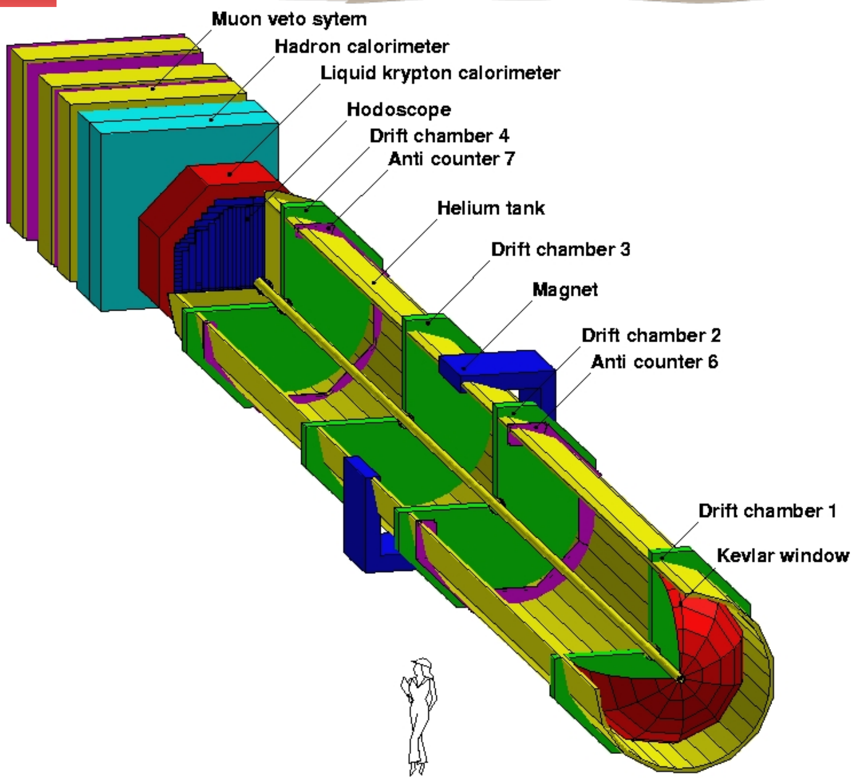
NA48/2 beam line



- fixed target experiment at CERN-SPS
- 60±3 GeV/c kaon momentum (~7x10^{11} ppp)
- 6.3x10^{7} particles per pulse in decay region

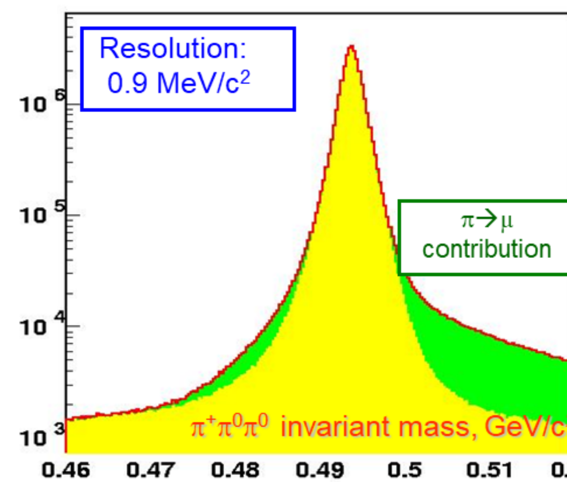
- Simultaneous, unseparated, focused beams
- Similar acceptance for K^+ and K^- decays
- Beams superimposed with 1mm for the whole decay region
- K^+/K^- ~ 1.8

NA48/2 Detectors



- ~100 m long decay region in vacuum
- Triggers based on LKr peaks, CHOD hits and DCH multiplicity
- Similar acceptance between K+ and K- beams checked reversing magnetics fields
- Pion decay products, from the hadronic beam, remain into the beam pipe

- Spectrometer:
  - $\sigma_p/p = 1.02\% + 0.044\%\, p$ [p in GeV/c]
- LKR calorimeter:
  - $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [E in GeV]
  - $\sigma_x = \sigma_y = 0.42/\sqrt{E} + 0.06\text{cm}$ [E in GeV]
- CHOD, HAC,MUV, vetos, Kabes, Beam Monitor



$K^{\pm} \to \pi^0 e^{\pm} \nu$ (K_{e3}) and $K^{\pm} \to \pi^0 \mu^{\pm} \nu$ ($K_{\mu3}$) form factors

[Batley et al. (NA48/2 Collaboration) JHEP 1810 (2018) 150]

Semileptonic Form Factors

$$A = M_K\left(2E_l E_\nu - M_K(E_\pi^{max} - E_\pi)\right) + M_l^2\left(\frac{E_\pi^{max} - E_\pi}{4} - E_\nu\right)$$

$$\frac{d^2\Gamma}{dE_l dE_\pi} \propto A f_+^2(t) + B f_-(t) f_+(t) + C f_-^2(t)$$

$$\begin{cases} l = e, \mu \\ t = (P_K - P_\pi)^2 = M_{l\nu}^2 \\ E_\pi^{max} = \dfrac{M_K^2 + M_\pi^2 - M_l^2}{2M_K} \end{cases}$$

$$B = M_l^2\left(E_\nu - \frac{E_\pi^{max} - E_\pi}{2}\right) \qquad C = \frac{M_l^2(E_\pi^{max} - E_\pi)}{4}$$

- f^+ and f^- are the Form Factors (FF)

$$f^-(t) = \left(f^+(t) - f^0(t)\right)\frac{(m_K^2 - m_\pi^2)}{t}$$

f^0 : «scalar» FF
$f^{+,-}$: «vector» FF

- The FF can be parametrized in several ways

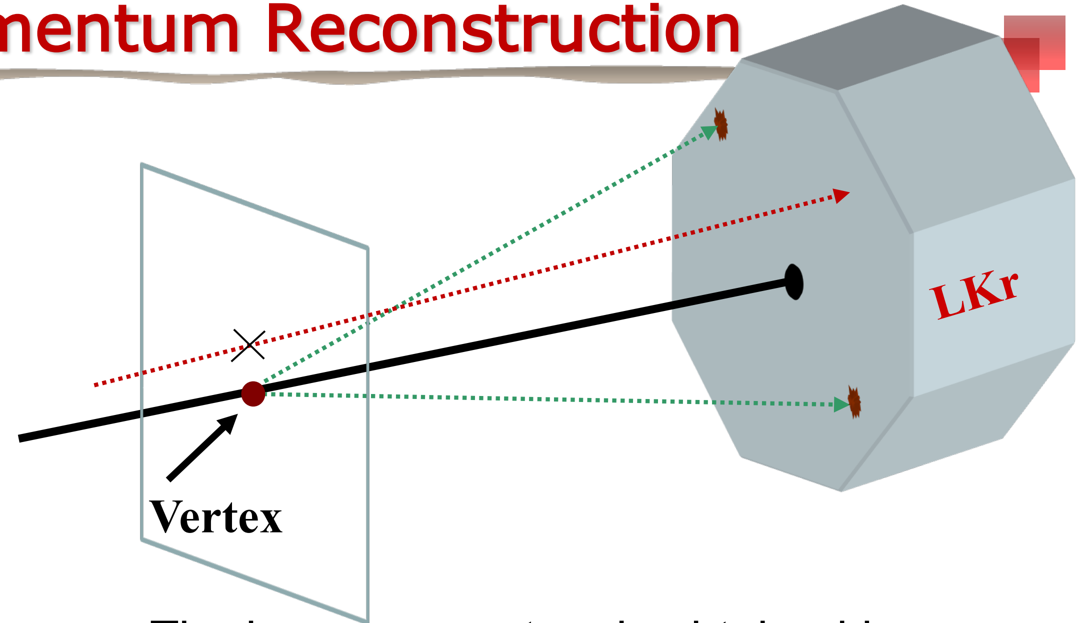
FF Parametrization	$f^+(t)$	$f^0(t)$
Quadratic	$1 + \lambda'_+\left(\frac{t}{m_\pi^2}\right) + \frac{1}{2}\lambda''_+\left(\frac{t}{m_\pi^2}\right)^2$	$1 + \lambda'_0\left(\frac{t}{m_\pi^2}\right)$
Pole	$\frac{M_V^2}{M_V^2 - t}$	$\frac{M_S^2}{M_S^2 - t}$
Dispersive	$e^{(\Lambda_+ + H(t))\left(\frac{t}{m_\pi^2}\right)}$	$e^{(\ln(C) - G(t))\left(\frac{t}{M_K^2 - M_\pi^2}\right)}$

Data Selection

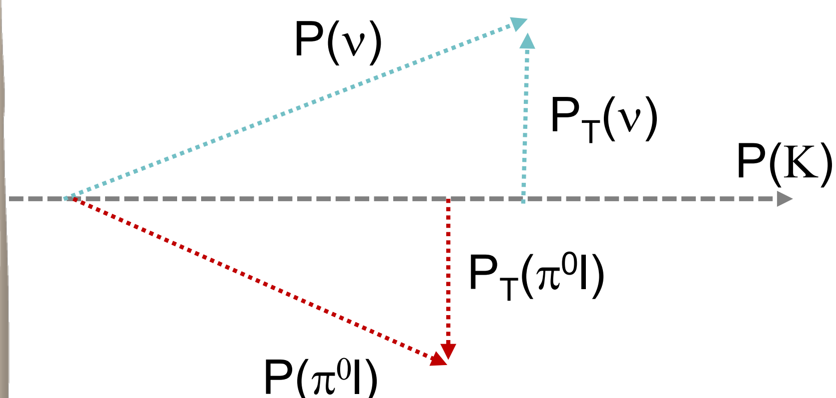
- Generic cuts
  - γ isolation: distance > 15 cm from charged tracks extrapolation
  - π^0 candidate: 2 gammas on LKr with distance > 20 cm and total energy > 15 GeV
  - Neutral vertex: obtained only with γs; compatibility with beam axis and decay region.
  - 1 good track in time with the π^0 (<10 ns), no extra charged tracks in 8 ns
  - Reconstructed kaon momentum compatible (in ±7.5 GeV) with nominal beam momentum (measured on run by run basis with $K\rightarrow\pi\pi\pi$)
- K_{e3} dedicated cuts
  - Track Momentum > 5 GeV/c
  - E/P > 0.9
  - Cut to remove $\pi^{\pm}\pi^0$ with mis-identified pion ($P_{t,\nu} > 0.03\ GeV/c$)
- $K_{\mu3}$ dedicated cuts
  - Track Momentum > 10 GeV/c
  - E/P < 0.2
  - Signal in MUV
  - Cuts to remove $\pi^{\pm}\pi^0\pi^0$ and $\pi^{\pm}\pi^0$ with $\pi^{\pm}\rightarrow\mu^{\pm}\nu$ decay in flight ($m(K-\pi^0) > 0.16\frac{GeV}{c^2}$ and $m(\pi^{\pm}\pi^0) + P_{t,\pi^0}/c < 0.6\ GeV/c^2$)

Vertex and Kaon Momentum Reconstruction

- The vertex position is defined by the two π^0's gammas (assuming π^0 mass).
- The transverse position is determined by the charged tracks at the neutral vertex position.



- The kaon momentum is obtained by kinematic as solution of a quadratic equation (assuming m_ν=0 and $P_T(\nu)=-P_T$ and with P_L, P_T and E as momentum and energy of the π^0l system):



$$P_K = \frac{\Phi P_L}{E^2 - P_L^2} \pm \sqrt{D}$$

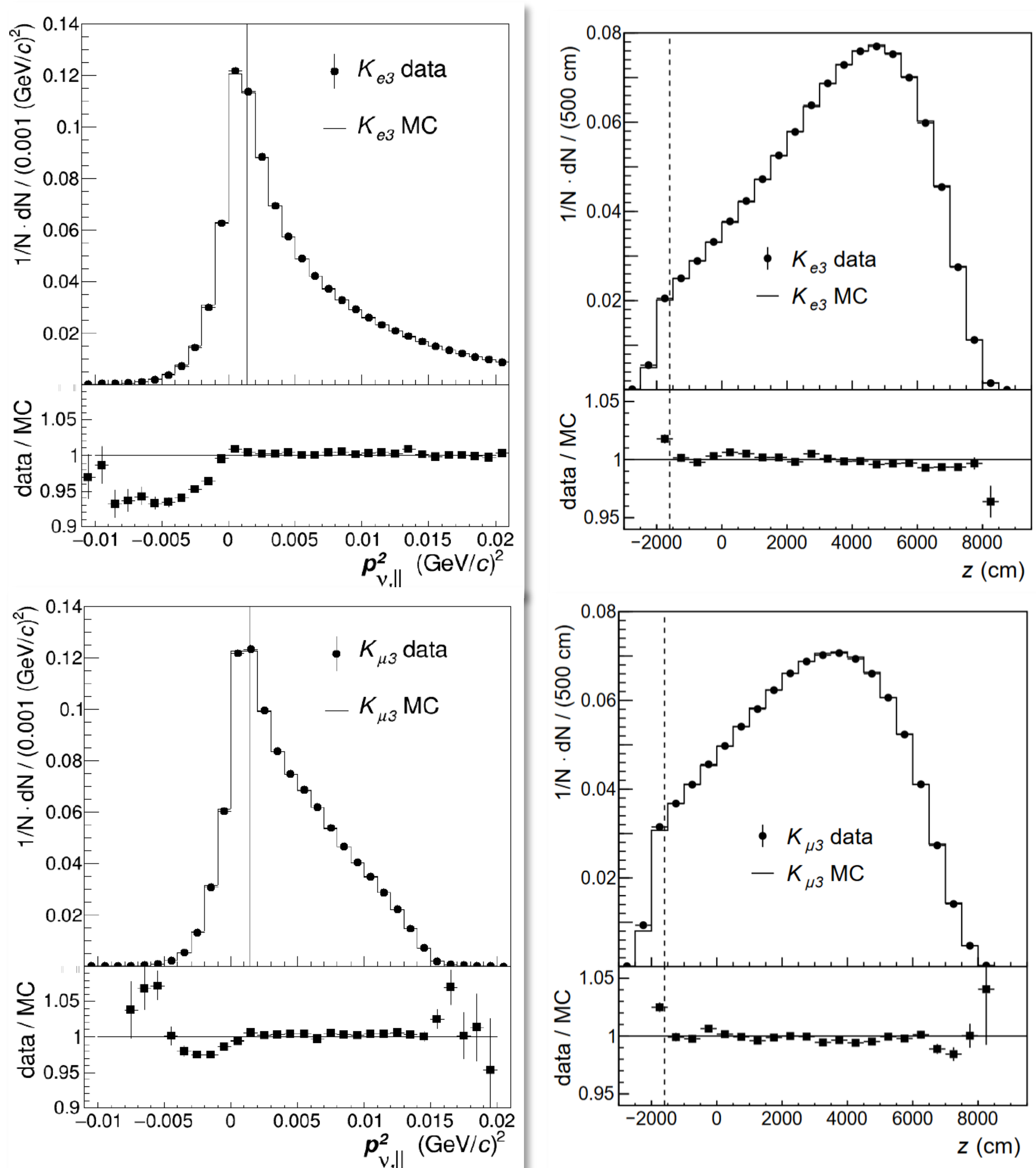
Where:

$$\Phi = \frac{1}{2}\left(m_K^2 + E^2 - P_L^2 - P_T^2\right)$$

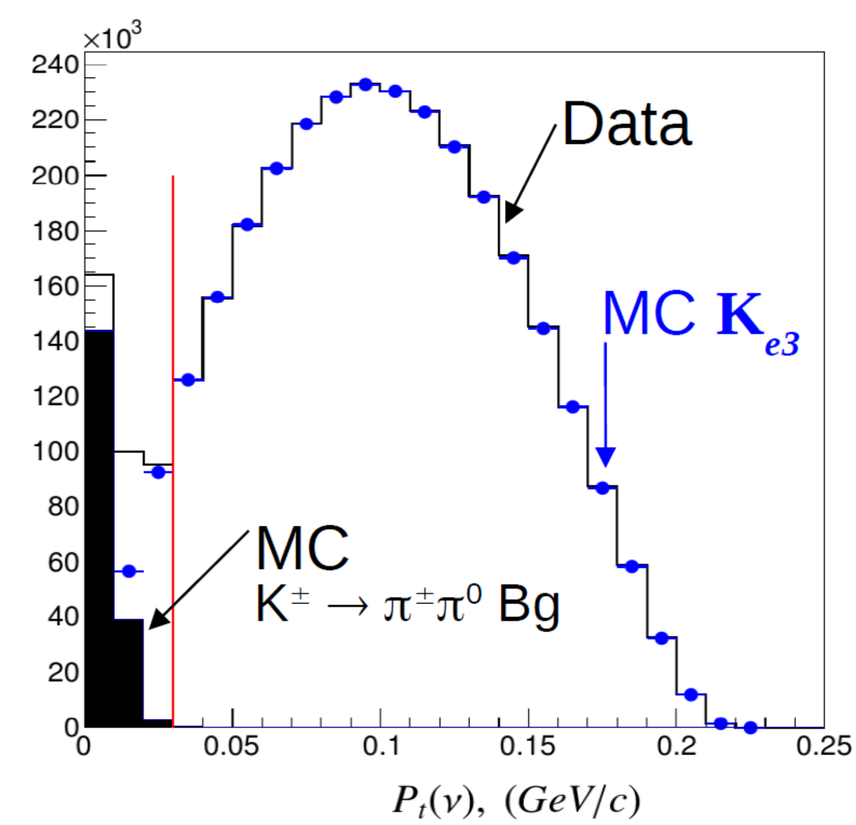
$$D = \Phi^2 \frac{P_L^2}{\left(E^2 - P_L^2\right)^2} - \frac{m_K^2 E^2 - \Phi^2}{E^2 - P_L^2}$$

Selection Cuts

- Difficult to simulate the negative tails of the longitudinal neutrino momentum (>0.014 GeV²/c²)
- Cut on the vertex position (>-1600 cm) to avoid background from last collimator.



K_{e3} Dedicated cuts



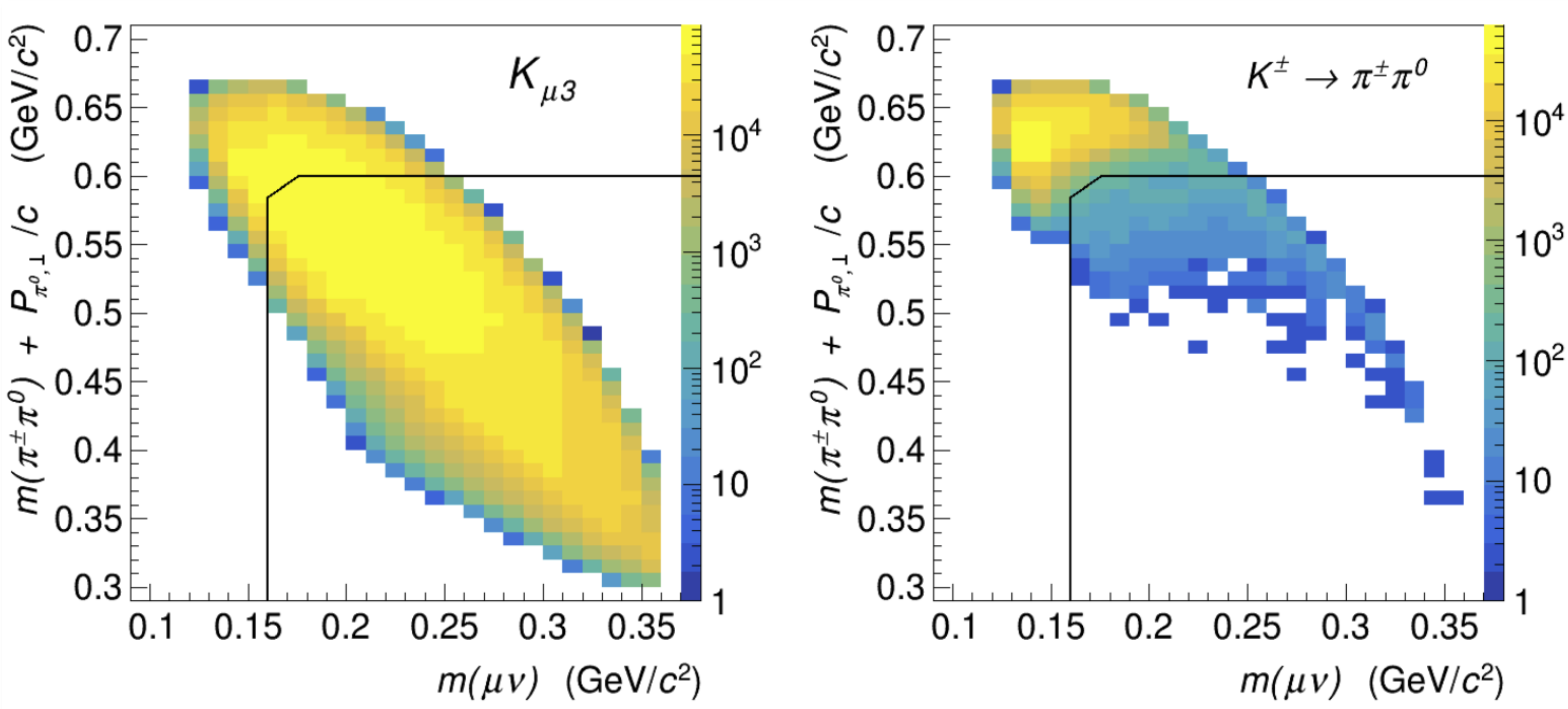
- $P_T(\nu)>0.03$ GeV/c
- To reduce the contamination of the $\pi^+\pi^0$

$K_{\mu3}$ dedicated cuts

- 2D Cut to avoid $\pi^{\pm}\pi^{0}$ background:

$m(\mu\nu) > 0.16$ GeV/c^2

$m(\pi\pi^0) + P_{\pi0,T}/c < 0.6$ GeV/c^2

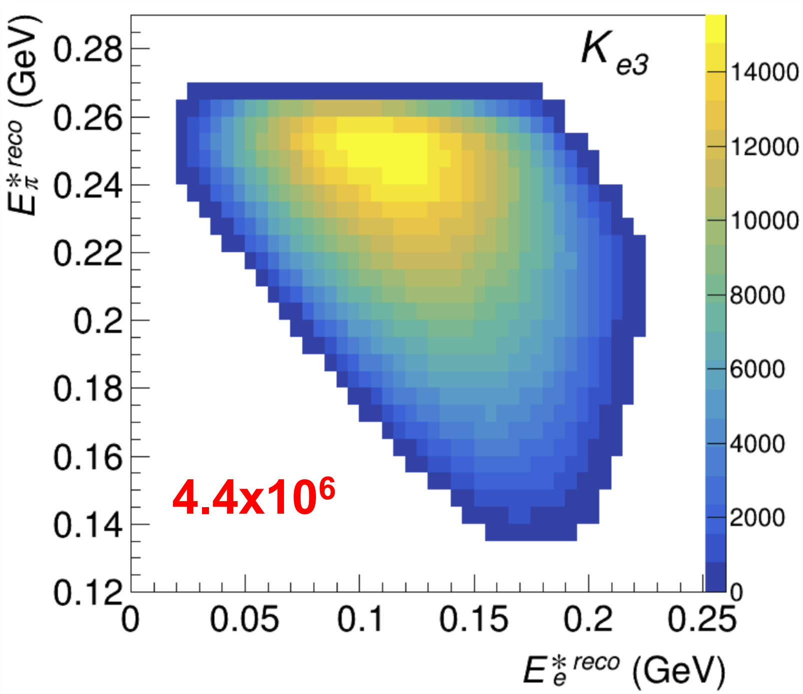


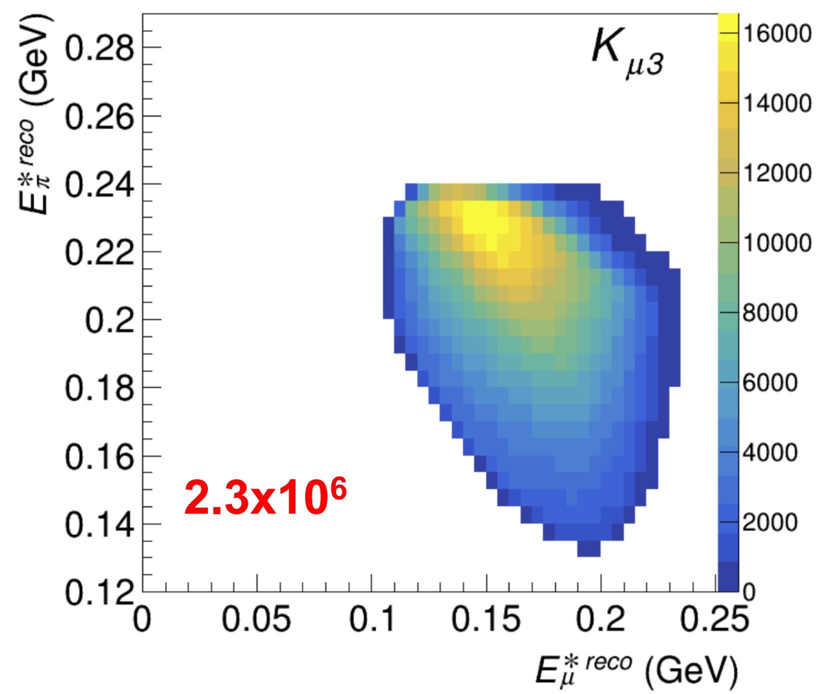
Data Selection

- Special run with dedicated trigger configuration
  - 16 runs, 4 days in 2004
  - Trigger : 1 track (2 hod hits) + LKr(E>10 GeV)
- Events selected:
  - 4.4×10^6 K_{e3}
  - 2.3×10^6 $K_{\mu 3}$
- Small or negligible background contamination

Decay	BR (%)	F_e (10^{-3})	F_μ (10^{-3})
$K^\pm \to \pi^\pm \pi^0$ (2π)	20.66	0.272	0.392
$K^\pm \to \pi^\pm \pi^0 \pi^0$(3π)	1.761	0.287	2.192
$K^\pm \to \pi^\pm \pi^0_D$ (2πD)	1.174	0.049	0.000
$K^\pm \to \pi^\pm \pi^0 \gamma$ (2πγ)	0.0275	0.004	0.044
$K^\pm \to \mu^\pm \pi^0 \nu$ (Kμ3)	0.03353	0.004	0.000

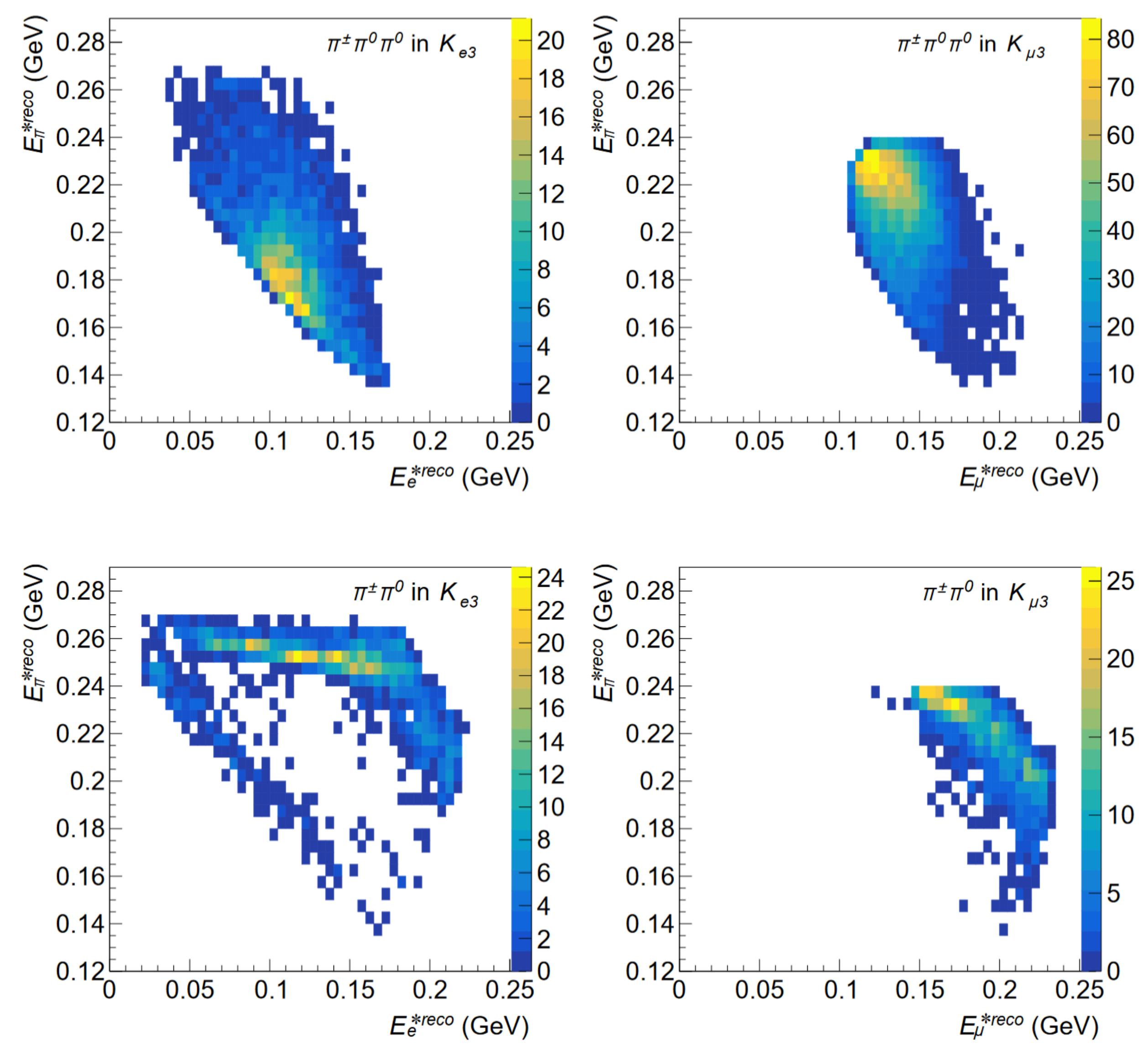
Dalitz Plot





- Dalitz plot: Pion and leptons energy in the K rest frame
- Bin size chosen to have at least 20 events per bin in the whole allowed region: 5x5 MeV^2
- Background tails and radiative corrections outside the kinematic limits are not considered in the fit

Dalitz plot for Backgrounds



- Backgrounds surviving to K_{e3} and $K_{\mu3}$ selection
- The simulated backgrounds are normalized to the kaon flux

Fit Procedure

- The MC generated Dalitz Plot (with form factors $\overrightarrow{\lambda_{gen}}$) is reweighted using a different set of form factors parameters $\vec{L}$:

$$w\left(\vec{L}\right) = w_R(E_l, E_\pi)\,\frac{\rho\left(\vec{L}, E_l, E_\pi\right)}{\rho\left(\overrightarrow{\lambda_{gen}}, E_l, E_\pi\right)}$$

  - ρ is the non radiative density Dalitz formula
  - w_R is used for K_{e3} to apply radiative correction in the corresponding Dalitz Plot bin *[V. Cirigliano et al. Eur. Phys. J. C23 (2002) 121–133]*

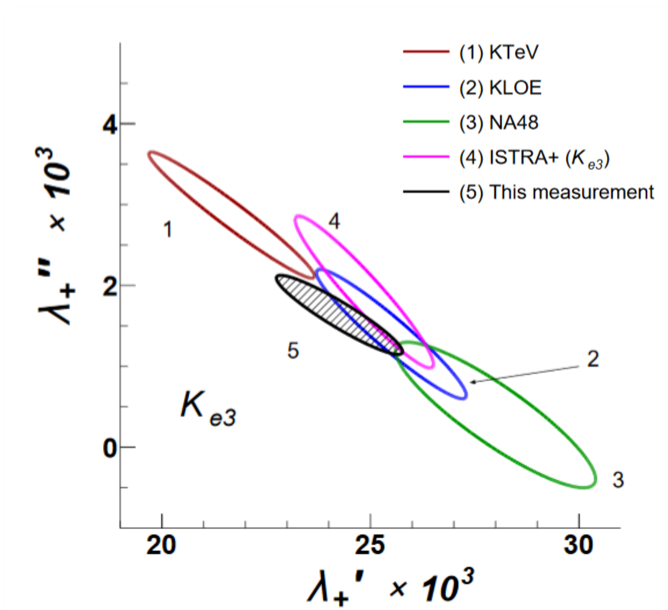
- The most probable FF ($\vec{L}$) are obtained minimizing

$$\chi^2 = \sum_{bins} \frac{\left(\omega_i^{data} - N \cdot \omega_i^{MC} - \omega_i^{bkg}\right)^2}{\sigma_{i,data}^2 + N^2 \cdot \sigma_{i,MC}^2 + \sigma_{i,bkg}^2}$$

  - $\omega_{i,data}$ and $\omega_{i,MC}$ are the contents of experimental data in the i-th bin and the reweighted bin contents from MC, $\omega_{i,bkg}$ is the background contribution in the i-th bin.

Results K_{e3}

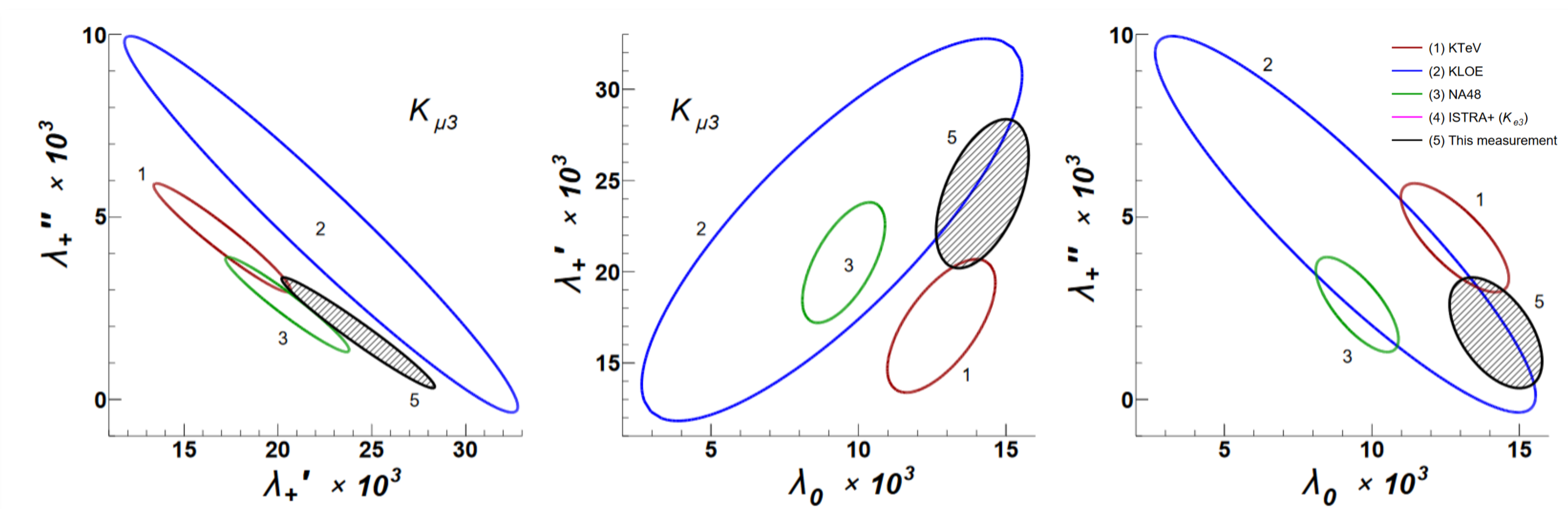
	Quadratic (10^{-3})		Pole (MeV)	Dispersive (10^{-3})
	λ'_+	λ''_+	M_V	Λ_+
Central value	*24.26*	*1.64*	*885.2*	*24.94*
σ_{stat}	0.78	0.30	3.3	0.21
σ_{syst}	1.30	0.39	7.2	0.64
Total error	*1.51*	*0.49*	*7.9*	*0.67*
χ^2**/ndf**	569.1/687		568.9/688	569.0/688
Correlation	-0.929		-	-



Only results validated by FLAVIANET are quoted, OKA (2018) results not yet included. **See next talk by E.Passemar.**

Results $K_{\mu3}$

	Quadratic (10^{-3})			Pole (MeV)		Dispersive (10^{-3})	
	λ'_+	λ''_+	λ'_0	M_V	M_S	Λ_+	ln(C)
Central value	*24.27*	*1.83*	*14.20*	*878.4*	*1214.8*	*25.36*	*182.17*
σ_{stat}	2.88	1.05	1.14	8.8	23.5	0.58	6.31
σ_{syst}	2.89	1.09	1.07	8.3	49.2	0.72	14.45
Total error	*4.08*	*1.52*	*1.57*	*12.1*	*54.5*	*0.92*	*15.76*
χ^2/ndf	409.9/381			409.9/382		410.3/382	
Correlation	-0.974 (λ'_+/λ''_+); 0.551(λ'_+/λ'_0); -0.513(λ''_+/λ'_0)			0.029		0.104	

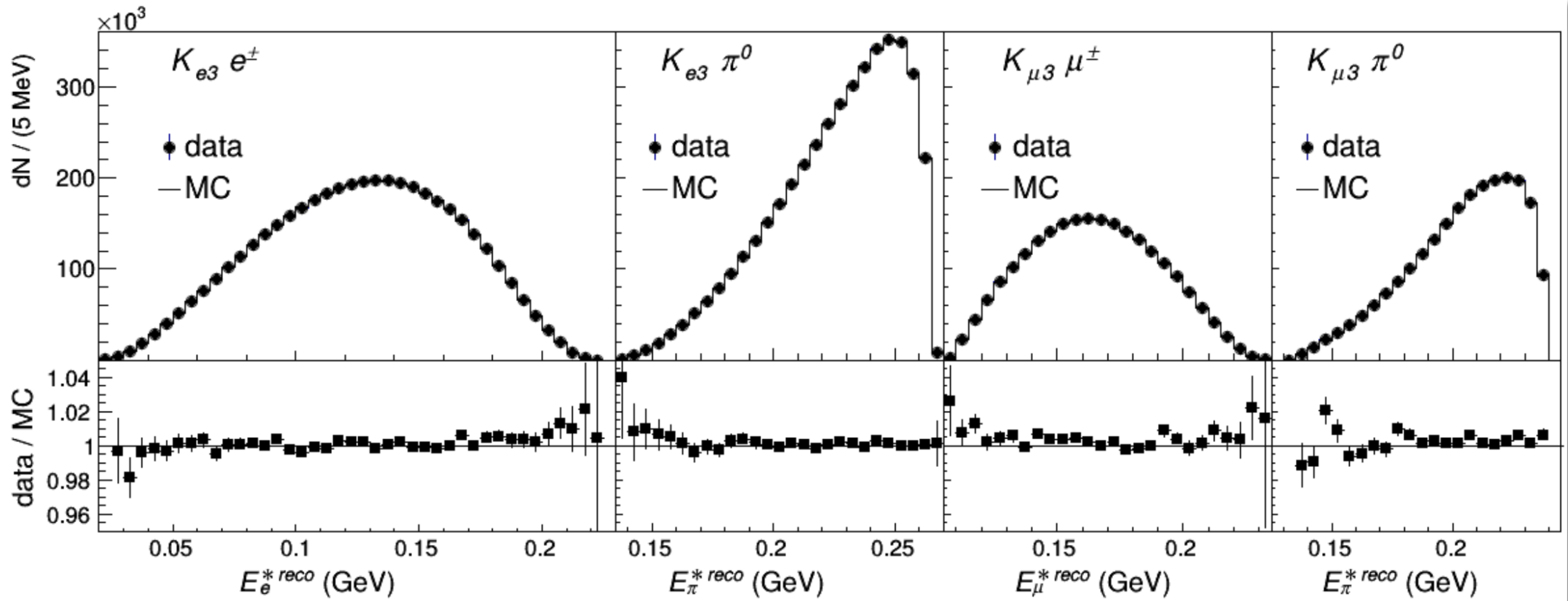


Combined results

	Quadratic (10^{-3})			Pole (MeV)		Dispersive (10^{-3})	
	λ'_+	λ''_+	λ'_0	M_V	M_S	Λ_+	ln(C)
Central value	*24.24*	*1.67*	*14.47*	*884.4*	*1208.3*	*24.99*	*183.65*
σ_{stat}	0.75	0.29	0.63	3.1	21.2	0.20	5.92
σ_{syst}	1.30	0.41	1.17	6.7	47.5	0.62	14.25
Total error	*1.50*	*0.50*	*1.32*	*7.4*	*52.1*	*0.65*	*15.43*
χ^2/ndf	979.6/1070			979.3/1071		979.7/1071	

- Joint fits obtained minimizing $\chi^2_{(Ke3)}+\chi^2_{(K\mu3)}$ with a common set of parameters

Dalitz Plot: data-MC



- Dalitz plot projections assuming the result of the fit (Taylor expansion)
- Good data-mc agreement

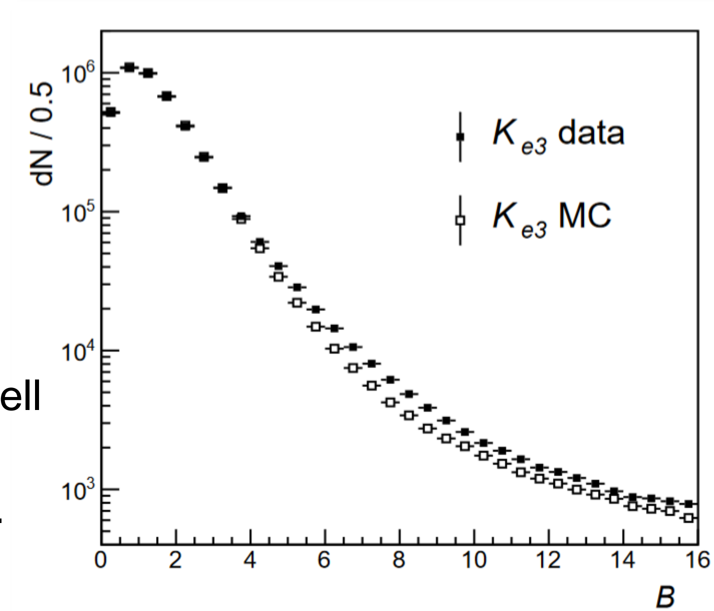
Combined results: systematics

	Quadratic (10^{-3})			Pole (MeV)		Dispersive (10^{-3})	
	λ'_+	λ''_+	λ'_0	M_V	M_S	Λ_+	$\ln(C)$
Diverging beam	0.97	0.35	0.55	1.1	32.2	0.08	9.43
Kaon mom. spectrum	0.00	0.00	0.02	0.1	0.7	0.00	0.19
Kaon mean momentum	0.04	0.01	0.04	0.2	1.7	0.01	0.47
LKr energy scale	0.66	0.12	0.61	4.9	17.4	0.32	5.16
LKr non-linearity	0.20	0.01	0.55	3.1	19.6	0.20	5.77
Residual Bacground	0.08	0.03	0.04	0.1	0.7	0.01	0.05
Electron ID	0.01	0.01	0.01	0.2	0.2	0.01	0.05
Event pileup	0.23	0.08	0.08	0.4	0.2	0.03	0.07
Acceptance	0.23	0.07	0.03	0.7	4.3	0.05	1.11
Neutrino mom. Resolution	0.16	0.04	0.04	0.9	3.3	0.06	0.88
Trigger eff.	0.29	0.13	0.20	1.1	9.9	0.07	2.82
Dalitz plot bin.	0.05	0.04	0.06	0.9	1.1	0.06	0.29
Dalitz plot res.	0.02	0.01	0.03	0.0	1.3	0.00	0.39
Radiative	0.17	0.01	0.57	2.5	20.1	0.16	5.92
External inputs	---	---	---	---	---	0.44	2.94
Syst.error	***1.30***	***0.41***	***1.17***	***6.7***	***47.5***	***0.62***	***14.25***

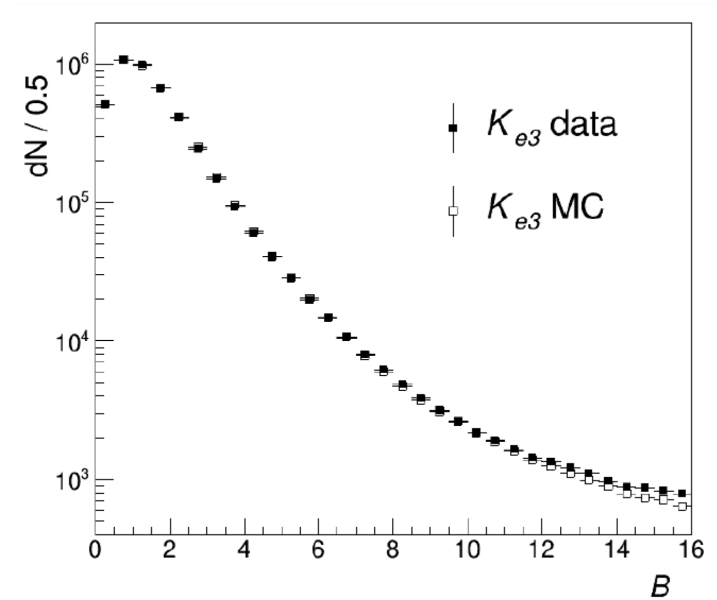
Beam Profile

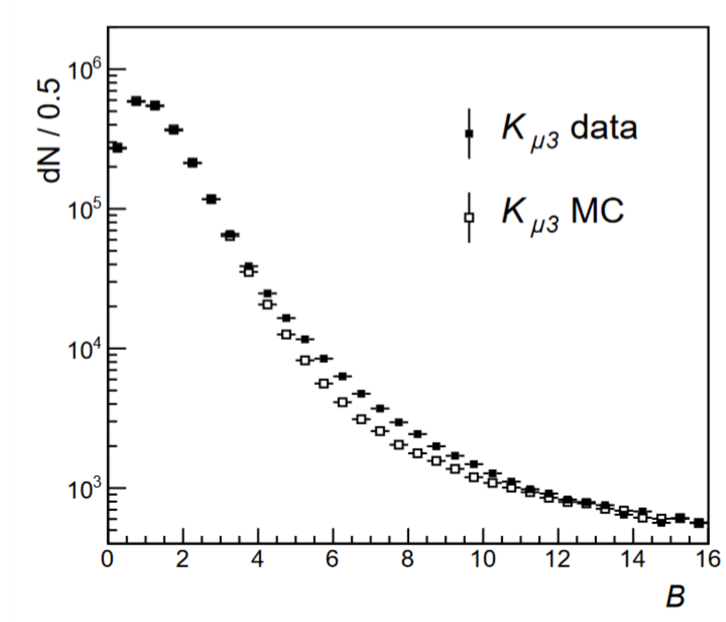
- Main systematics: beam diverging component.
- Decays can happen few cm off the beam axis
- This is measured with:

$$B = \sqrt{\left(\frac{x - x_0}{\sigma_x}\right)^2 + \left(\frac{y - y_0}{\sigma_y}\right)^2}$$

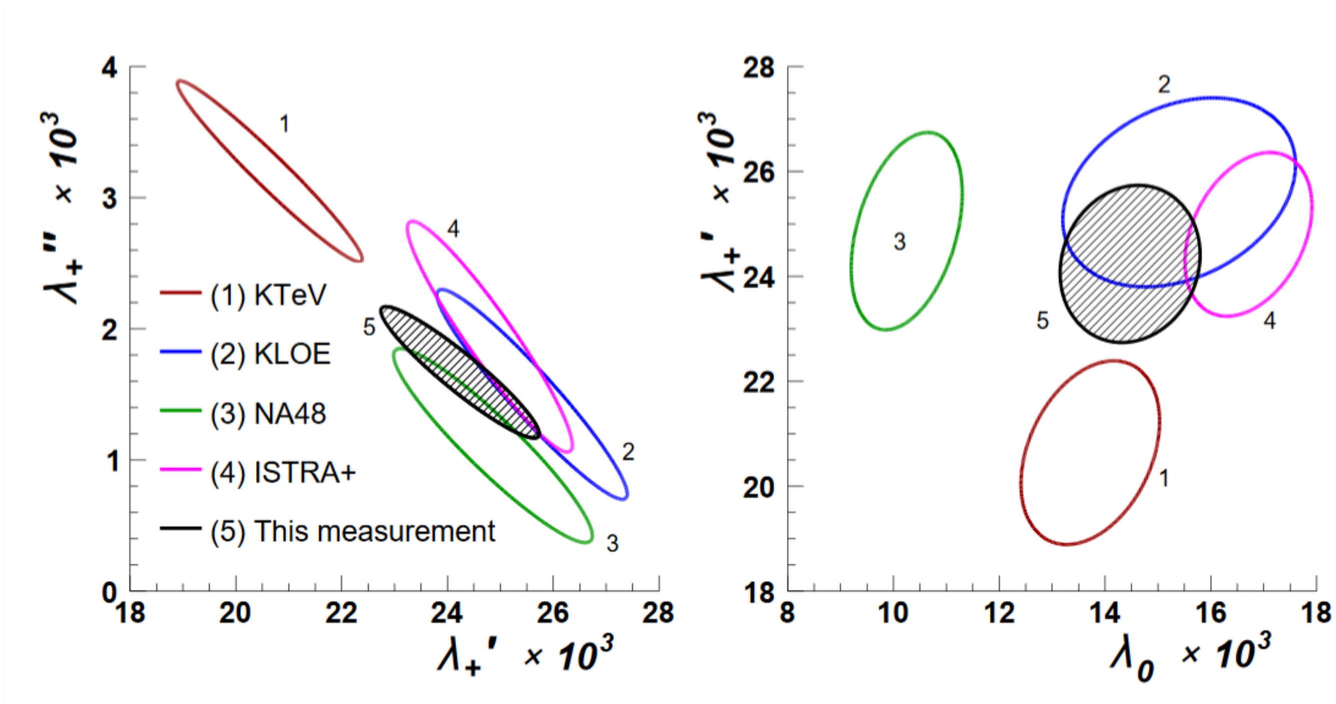


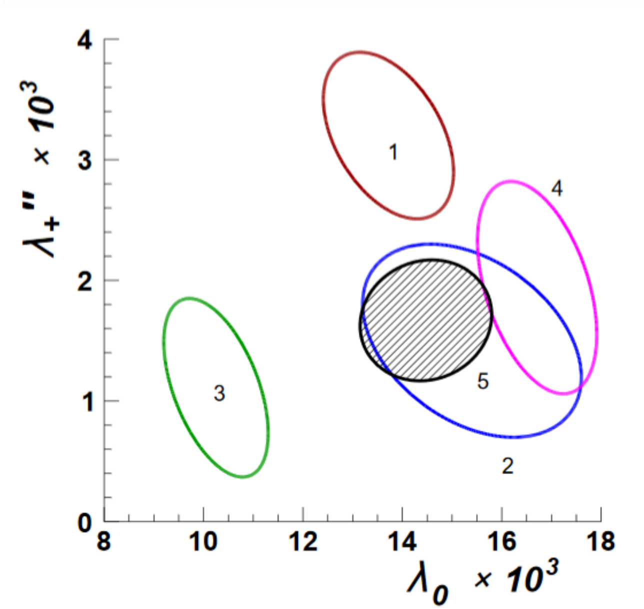
- Main systematics: beam diverging component.
- Only the core of the beam distribution (B<3) is well simulated.
- Beam divergence added for systematics studies.
- B<11 to minimize correlation beetwen beam direction and momentum





Combined results





- 1σ ellipse (39.4% CL): to improve visibility
- Compatible with previous results
- Better precision

Only results validated by FLAVIANET are quoted, OKA (2018) results not yet included.
See next talk by E.Passemar

Conclusions

- K_{l3} form factors are measured with **~4.4·10^6 K_{e3}** and **~2.3·10^6 $K_{\mu 3}$** events, from the 2004 NA48/2 data taking in a special minimum bias run (3 days).
- For the first time the measurement is done simultaneously in K+ and K-.
- Improved vertex definition with respect to the preliminary result → result less sensitive to beam shape.
- Similar level of precision with other experiments in the Kμ3 mode and the smallest error in Ke3 has been reached.
- The combined result is fully compatible with previous measurement with improved precision.

- NA62 will collect order of 10^7-10^8 semileptonic decays, with better vertex definition (Gigatracker); no dedicated trigger, minimium bias trigger with large downscaling.

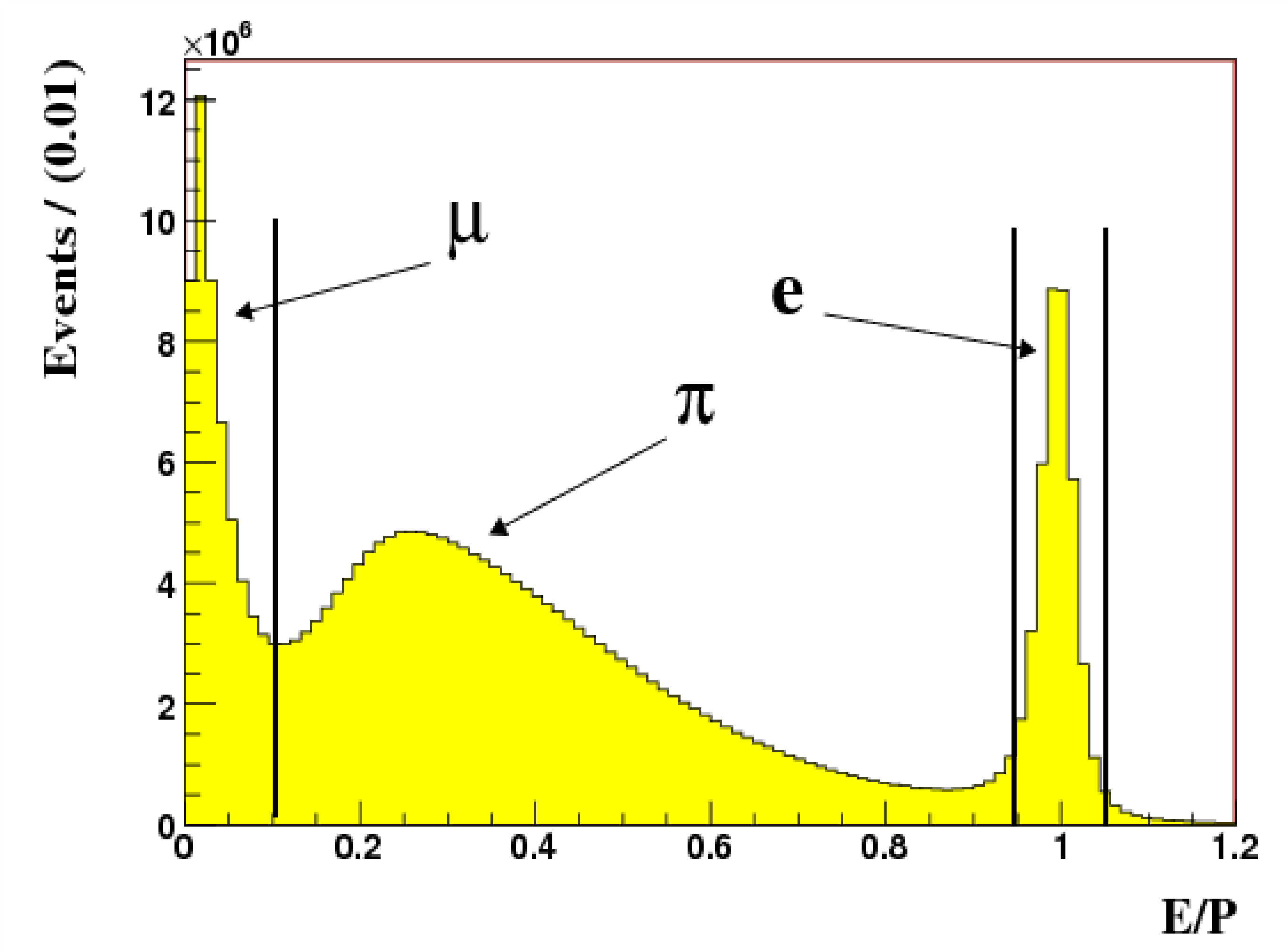
Spares

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

- Theory:
  - S_{EW} = Universal short distance EW correction
  - $f_+(0)$ = form factor at 0 momentum transfer
  - $\delta^l_{SU(2)}$ = Isospin breaking correction
  - δ^l_{EM} = Long distance EM effects

- Experiment:
  - Γ = Branching ratios and Lifetime
  - I_K = Phase space integral

E/P



Neutral Kl3

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0_{\rm stat} \pm 2.2_{\rm syst}$	$1.2 \pm 1.1_{\rm stat} \pm 1.1_{\rm syst}$	$15.7 \pm 1.4_{\rm stat} \pm 1.0_{\rm syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{\rm stat} \pm 1.1_{\rm syst}$	$0.7 \pm 0.3_{\rm stat} \pm 0.4_{\rm syst}$	
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu 3}$	$873 \pm 8_{\rm stat} \pm 9_{\rm syst}$		$1183 \pm 31_{\rm stat} \pm 16_{\rm syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{\rm stat} \pm 7_{\rm syst}$		

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	877 ± 6		1176 ± 31

- 4 milions K_{e3} and 2.5 millions $K_{\mu 3}$ analyzed