Measurements of $\mathrm{K_{l3}}$ decays by NA48

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for the

NA48 Collaboration

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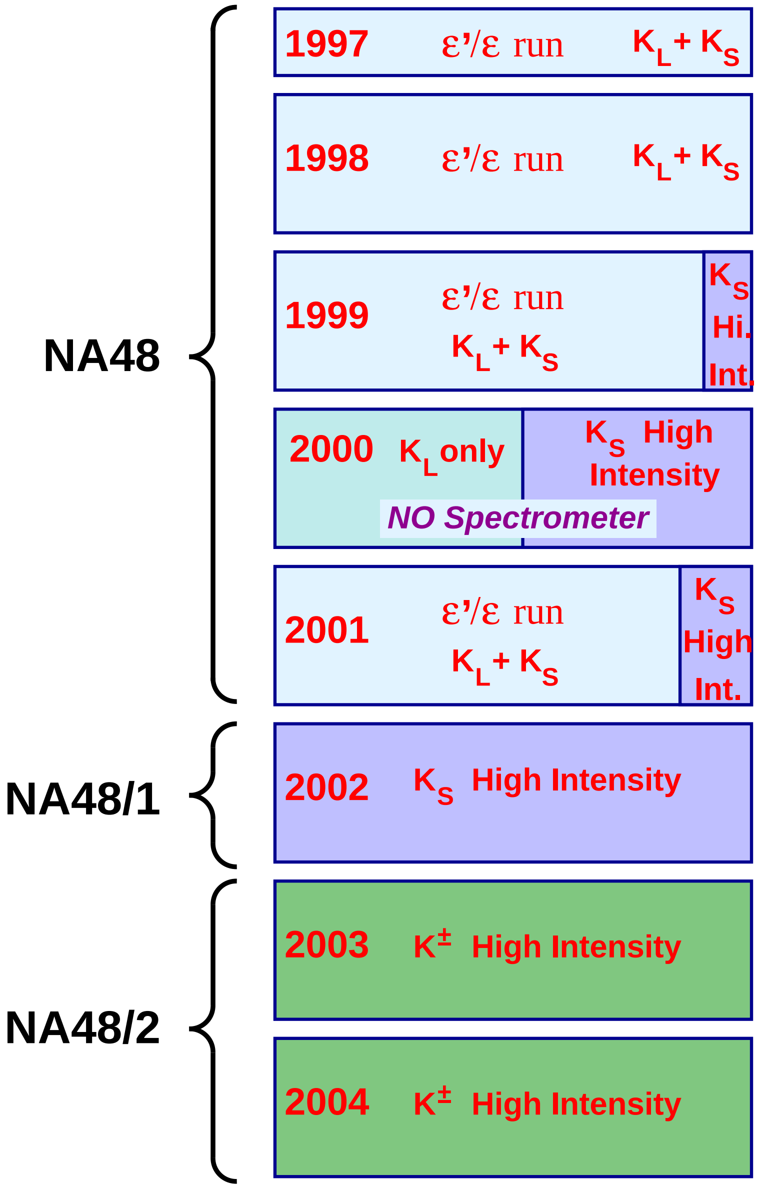
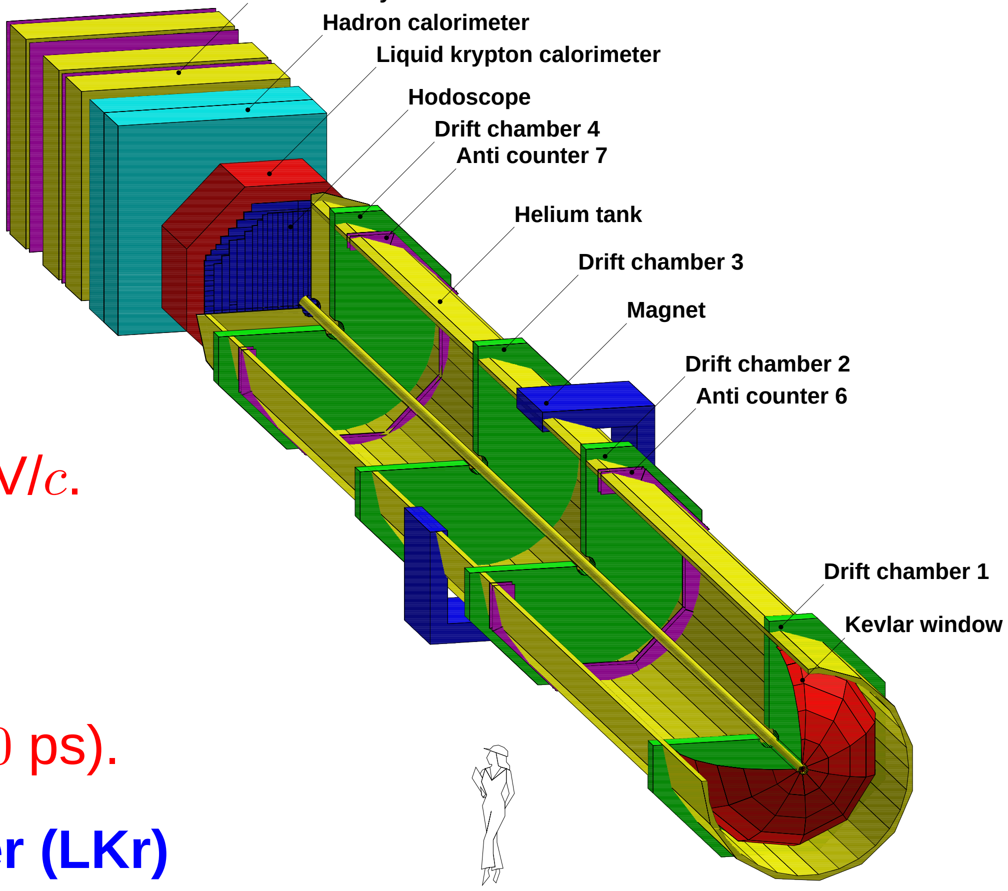
K_{l3} Decays from NA48

- NA48: ϵ'/ϵ and $\mathrm{K_L}$ Decays
  - Measurement of $K_{L\,\mu3}$ Form Factors
- NA48/2: $\mathrm{K}^\pm$ Decays
  - Precise Measurement of $K^\pm_{e3}/K^\pm_{2\pi}$ and $K^\pm_{\mu3}/K^\pm_{2\pi}$
- NA48/1: $\mathrm{K_S}$ and Ξ^0 Decays
  - Measurement of $\mathrm{K_{S\,e3}}/\mathrm{K_{L\,e3}}$



The NA48 Detector



Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\Delta p/p \leq 1\%$ for $p = 20$ GeV/c.

- **Hodoscopes:**

  Fast trigger, precise time measurement ($\sigma_t = 150$ ps).

- **Liquid Krypton Calorimeter (LKr)**

  $\Delta E/E \approx 1.0\%$ for $E_{e,\gamma} = 20$ GeV/c.

- **Hadron calorimeter, photon vetos, muon counters**

Measurement of $K^0_{\mu 3}$ Form Factors

Measurement of $K_{\mu 3}$ Form Factors

$K_{\mu 3}$ matrix element:

$$\mathcal{M} = \frac{G}{\sqrt{2}} V_{us} [\mathbf{f_+(t)} (p_K + p_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + \mathbf{f_-(t)} m_l \bar{u}_l (1+\gamma_5) u_\nu]$$

- Vector form factor: $\mathbf{f_+(t)}$
- Scalar form factor: $\mathbf{f_0(t)} = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$

Several different parametrizations on the market:

- Linear Expansion: $f_{+,0}(t) = f_{+,0}(0)(1 + \lambda_{+,\mathbf{0}} \frac{t}{m_\pi^2})$
- Quadratic Expansion: $f_{+,0}(t) = f_{+,0}(0)(1 + \lambda'_{+,\mathbf{0}} \frac{t}{m_\pi^2}) + \frac{1}{2} \lambda''_{+,\mathbf{0}} \frac{t^2}{m_\pi^4})$
- Pole Model: $f_+(t) = f_+(0) \frac{\mathbf{m_V^2}}{\mathbf{m_V^2} - t}, \quad f_0(t) = f_0(0) \frac{\mathbf{m_S^2}}{\mathbf{m_S^2} - t}$
- Dispersive Parametrization: (Bernard, Oertel, Passemar, Stern, 2006)

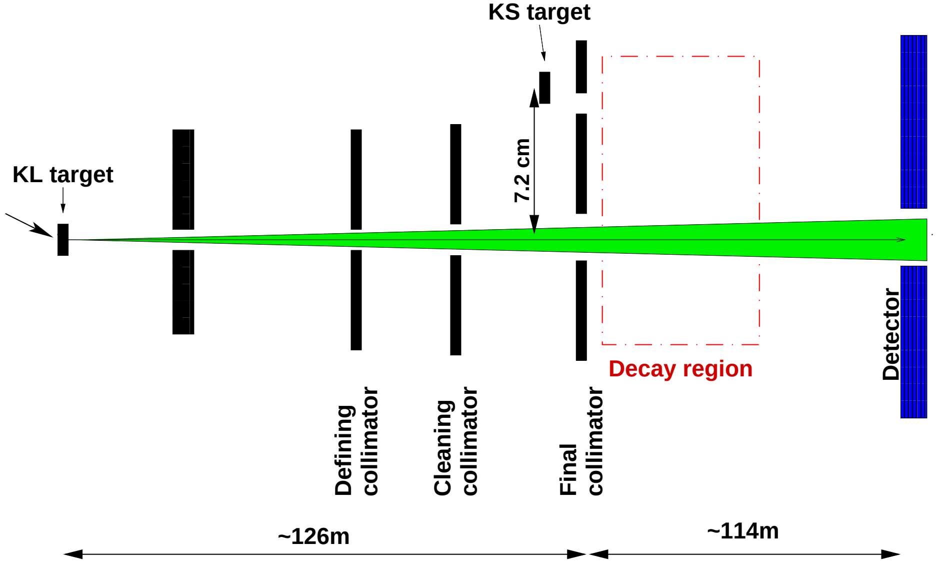
$$f_+(t) = f_+(0) \exp[\frac{t}{m_\pi^2}(\mathbf{\Lambda_+} + H(t))],$$

$$f_0(t) = f_0(0) \exp[\frac{t}{m_K^2 - m_\pi^2}(\ln \mathbf{C} - G(t))]$$

Measurement of $K_{\mu 3}$ Form Factors

Special run September 1999:

- Around 2 days of low intensity data taking with beam from K_L target only and minimum bias trigger.
- Trigger on just two charged particles.
  $\Longrightarrow$ ~ 80 million events.



$\mathrm{K}_{\mu 3}$ data selection:

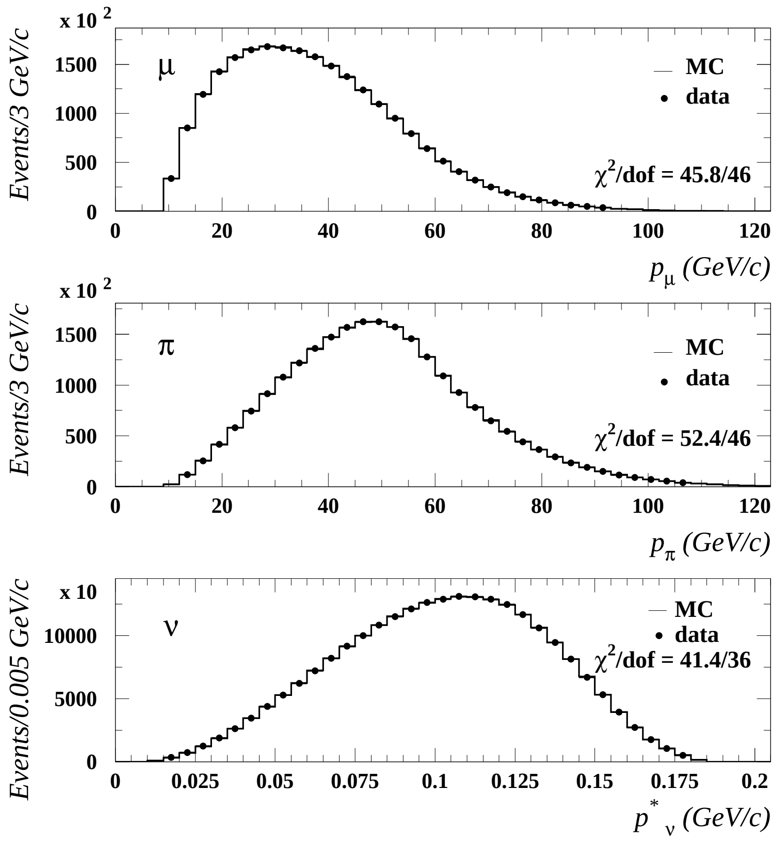
- Two tracks including one muon (muon counter efficiency $> 99\%$).
- Rejection of $K_{3\pi}$ by kinematics.
- Rejection of K_{e3} by E/p in the LKr calorimeter.

$\Longrightarrow$ **2.34 million $\mathrm{K}_{\mu 3}$ events** (Bkgd contamination $\sim 2 \times 10^{-3}$)

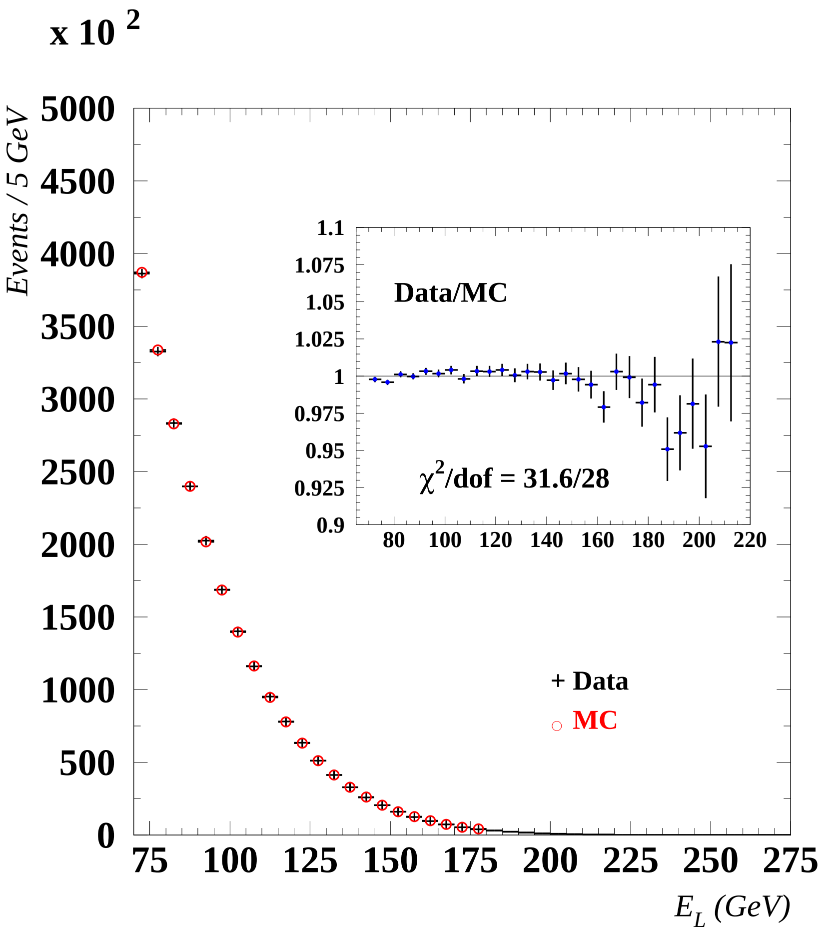
Measurement of $K_{\mu 3}$ Form Factors

Important: Good Monte Carlo description of the data:

Momenta of μ, π, ν_μ:



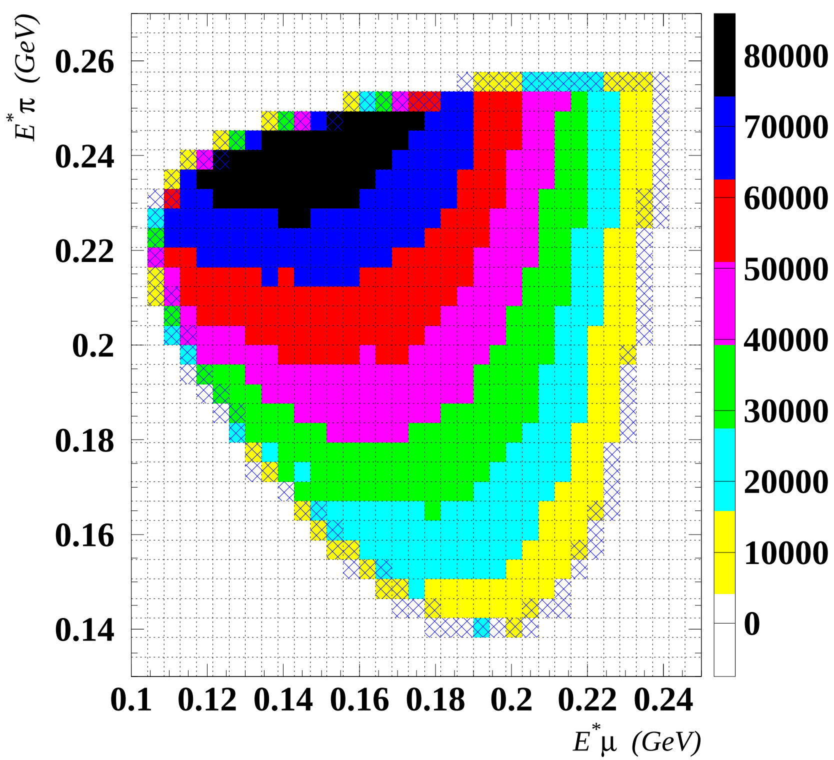
Low-energy solution:

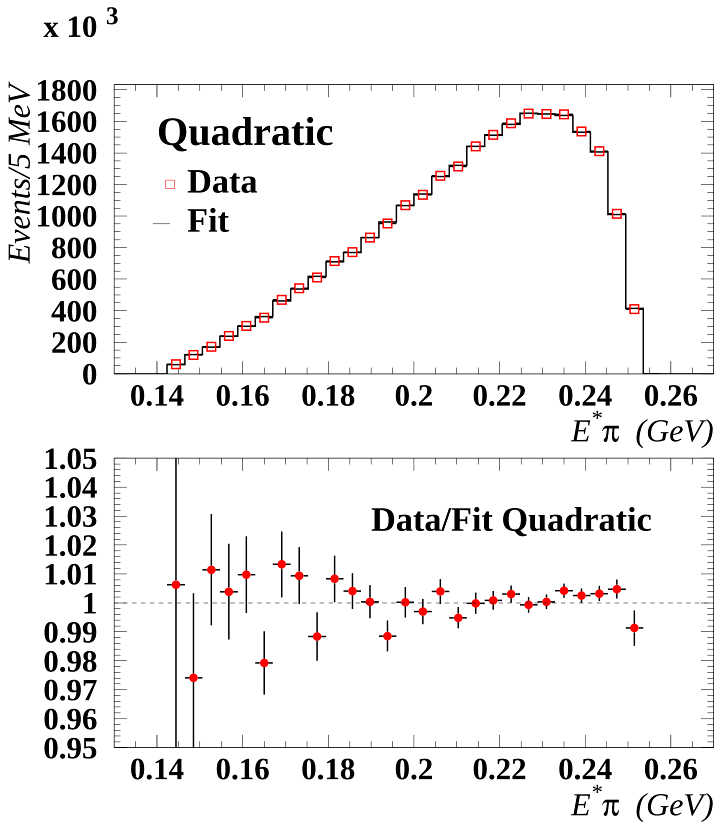


Measurement of $K_{\mu 3}$ Form Factors

Fit to the Dalitz plot: (using solution with lower energy)

- Boundary excluded from fit
- Four different parametrizations *(linear, quadratic, pole, dispersive)*





Measurement of $K_{\mu 3}$ Form Factors

Many results for many models:

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Linear Parametrization:

$$\lambda_+ = 0.0267(6)(8)$$
$$\lambda_0 = 0.0117(7)(10)$$

Correlation: $\rho = -0.40$

Pole Parametrization:

$$m_V = 905(9)(17) \text{ MeV}/c^2$$
$$m_S = 1400(46)(153) \text{ MeV}/c^2$$

Correlation: $\rho = -0.47$

Quadratic Parametrization:

$$\lambda'_+ = 0.0205(22)(24)$$
$$\lambda''_+ = 0.0026(9)(10)$$
$$\lambda_0 = 0.0095(11)(8)$$

Correlations: $\rho_{\lambda'_+,\lambda''_+} = -0.96$

$\rho_{\lambda'_+,\lambda_0} = 0.63$

$\rho_{\lambda''_+,\lambda_0} = -0.73$

Dispersive Parametrization:

$$\Lambda_+ = 0.0233(5)(8)$$
$$\ln C = 0.1438(80)(112)$$

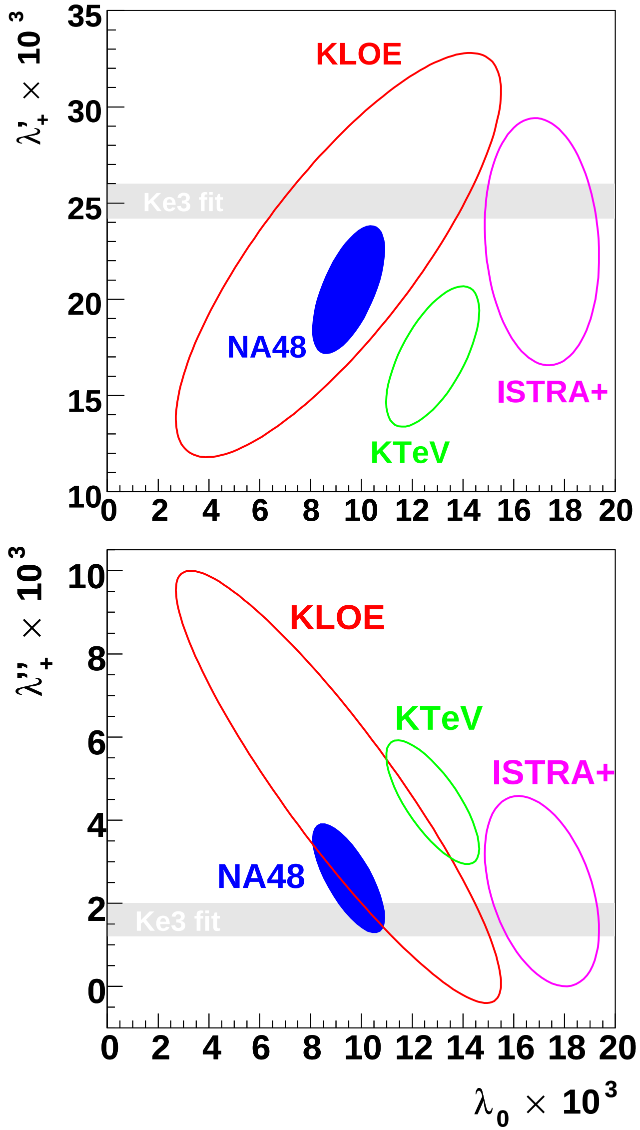
Correlation: $\rho = -0.44$

Measurement of $K_{\mu3}$ Form Factors

Comparison with other experiments:

- **Vector form factor:**
  - Good agreement with both other $K_{\mu3}$ and K_{e3} measurements.
- **Scalar form factor:**
  - Disagreement with measurements from KTeV and ISTRA+
  - Would indicate right-handed currents
    (Bernard, Oertel, Passemar, Stern, 2006)

$K_{\mu3}$ data only (1σ cont's)**:**

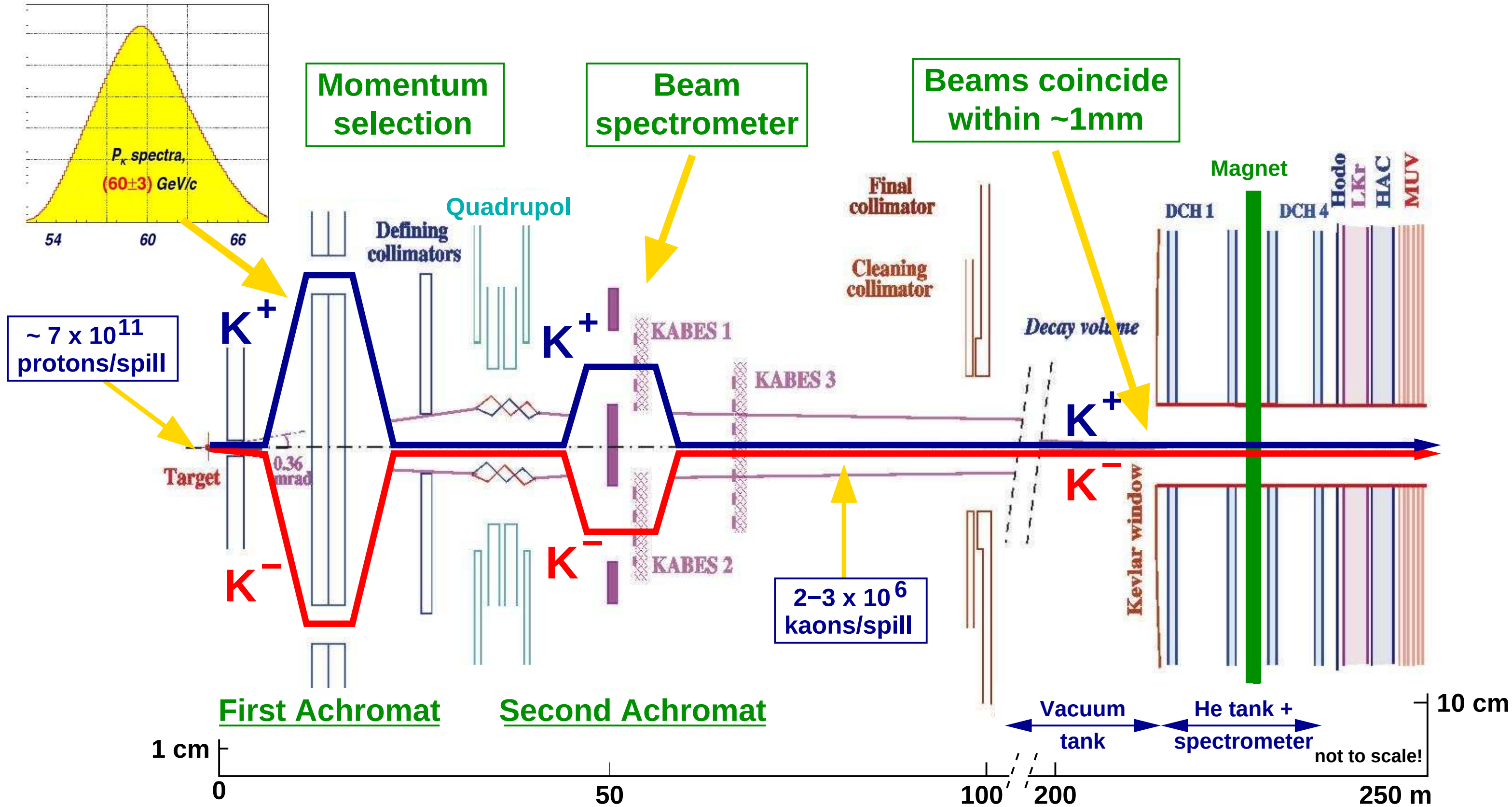


$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

NA48/2 experiment in 2003/2004:

- **Simultaneous K^+ and K^- beams** with $p_{K^\pm} = (60 \pm 3)$ GeV/c.



$|V_{us}|$ Measurement from $K_{l3}^{\pm}$

Minimum bias data taking in 2003:

- 8 hours low intensity K^+/K^- with min. bias trigger.

  $\Longrightarrow$ Measurement of leptonic and semileptonic decays.

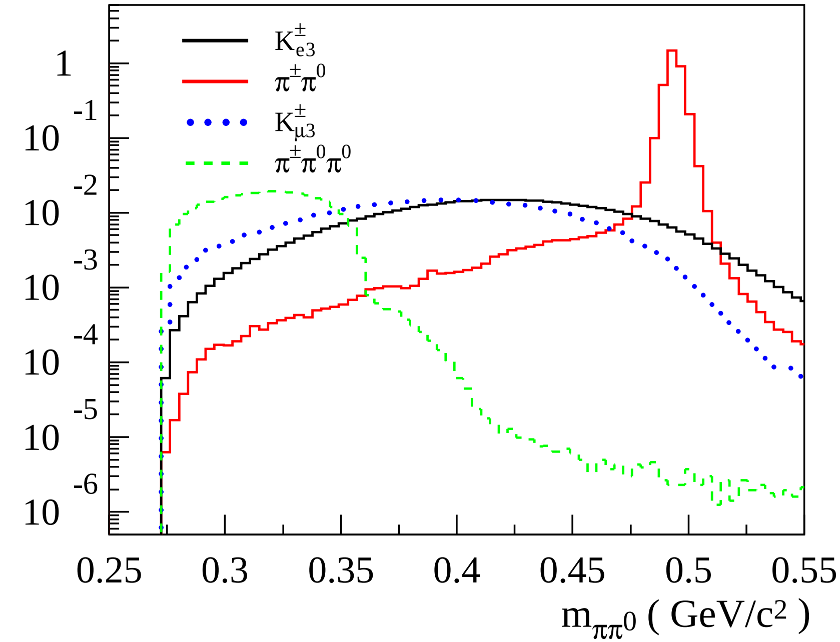
Method of the Measurement:

- Normalize K_{e3} and $K_{\mu 3}$ to $K_{2\pi}$

  $\Longrightarrow$ very similar topologies and selection criteria.

- Select one track + two photons, consistent with a π^0 from a common decay vertex.

- Distinction of K_{l3} and $K_{2\pi}$ mainly through kinematics.



$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

Particle identification:

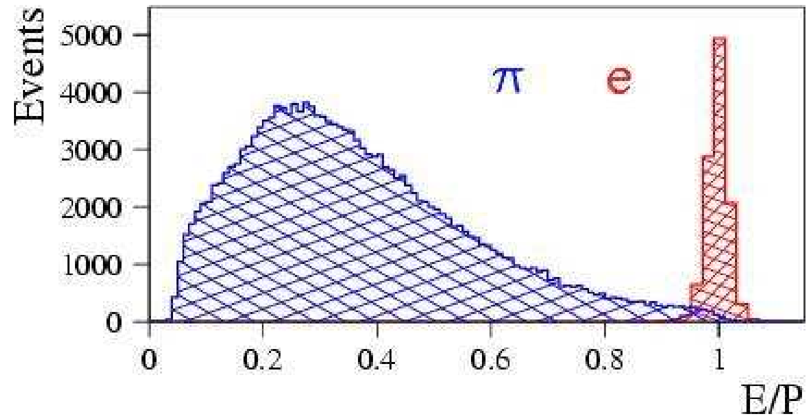
- **Electrons:** $\mathbf{E/p > 0.95}$

  $\Longrightarrow$ Efficiency $\approx \mathbf{98.6\%}$

- **Pions:** $\mathbf{E/p < 0.95}$

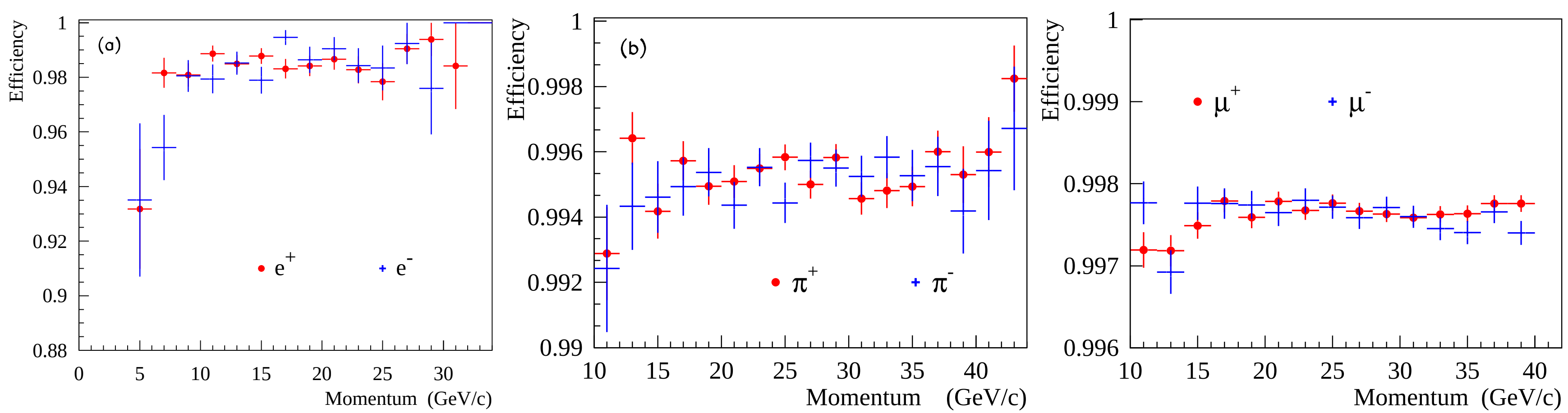
  $\Longrightarrow$ Efficiency $\approx \mathbf{99.5\%}$

Illustration from data



- **Muons:** In-time hits in first two muon counters.

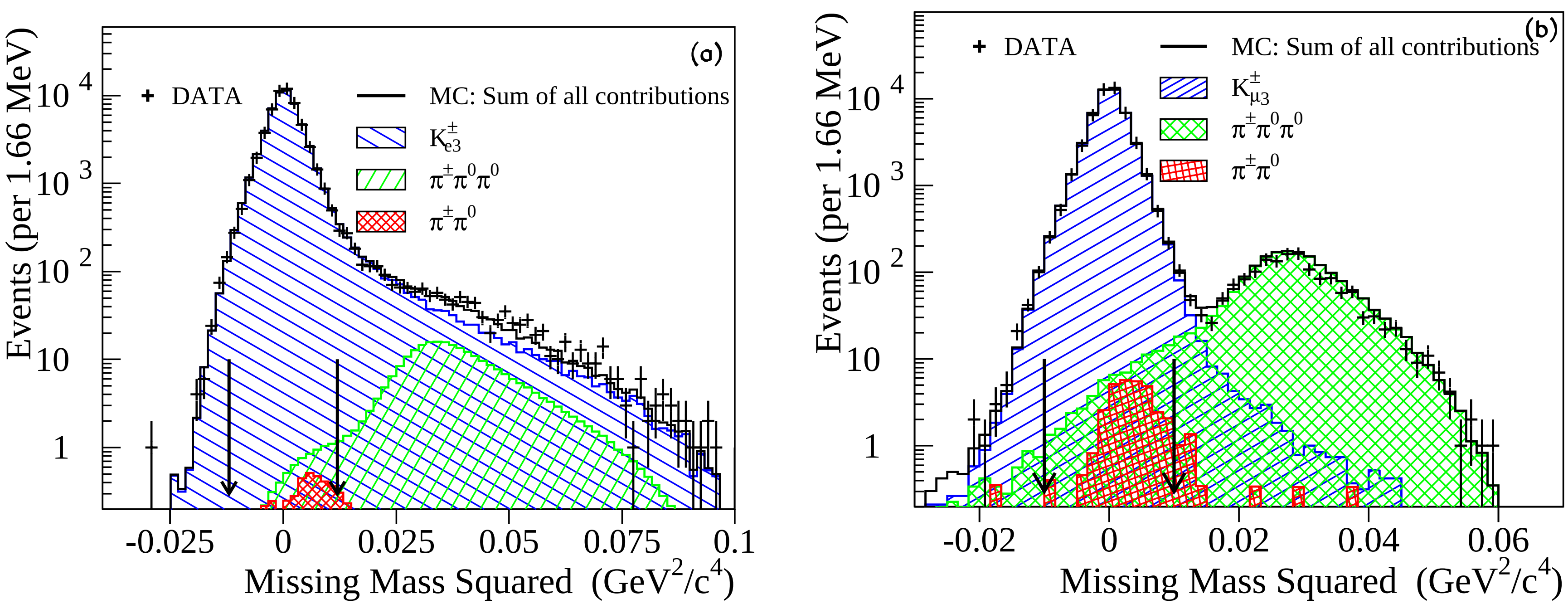
  $\Longrightarrow$ Efficiency $\approx \mathbf{99.8\%}$



$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

Yields after all selection criteria applied:

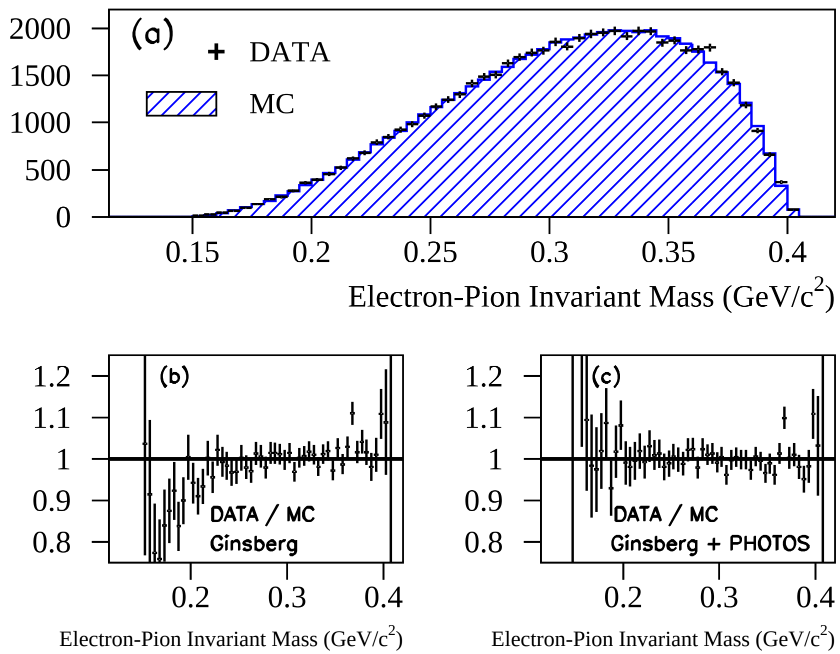
Channel	Acc × P-ID	K^+	K^-	Background
Ke3	$\sim 7.0\%$	**56 195**	**30 898**	$< 0.1\%$
Kμ3	$\sim 9.3\%$	**49 364**	**27 525**	$\sim 0.2\%$
K2π	$\sim 14.2\%$	**461 837**	**256 619**	$\sim 0.3\%$

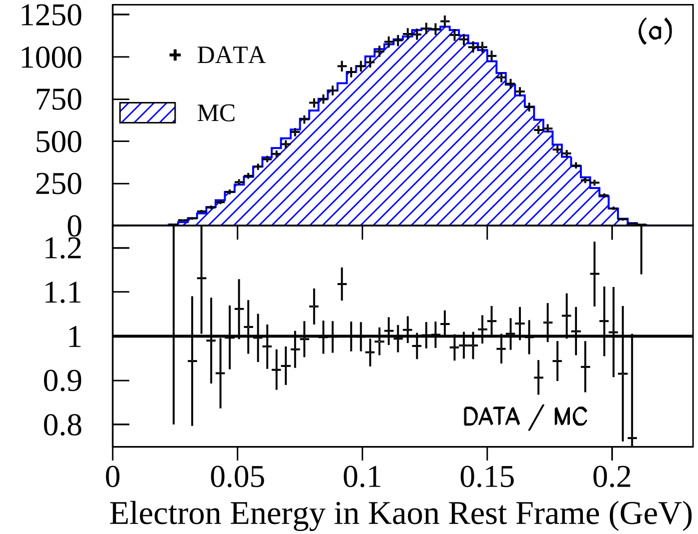


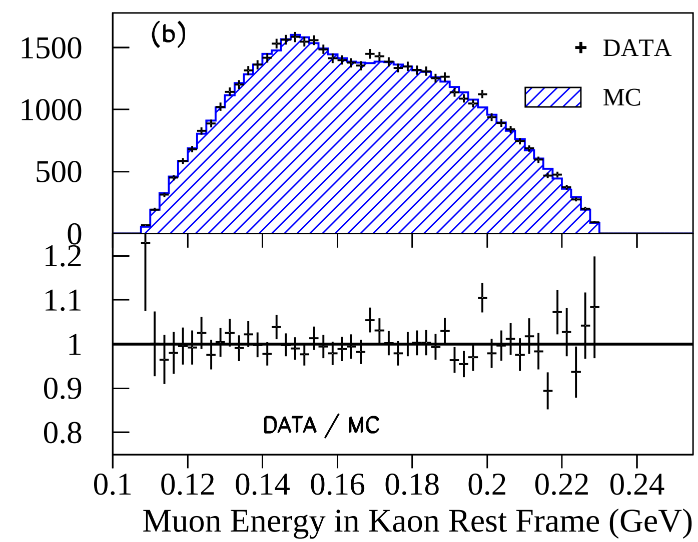
$|V_{us}|$ Measurement from $K_{l3}^{\pm}$

Radiative corrections:

- Using **Ginsberg** prescription for real and virtual photons.
- Real bremsstrahlung photons added with **PHOTOS.**







$\Longrightarrow$ **Very good description of data!**

$|V_{us}|$ *Measurement from* $K^{\pm}_{l3}$

Form factors:

- Quadratic expansion for $f_+(t)$ ($\lambda'_+ = 0.02485(163)$, $\lambda''_+ = 0.00192(62)$) and linear expansion for $f_0(t)$ ($\lambda_0 = 0.00196(34)$) from PDG'06.
- Form factor variations within their errors and difference to pole model parametrization taken as systematic uncertainties.

Results:

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$$\mathcal{R}_{\mathbf{Ke3/K2\pi}} = \mathbf{0.2470} \pm \mathbf{0.0009}_{\text{stat}} \pm \mathbf{0.0004}_{\text{sys}}$$

$$\mathcal{R}_{\mathbf{K\mu3/K2\pi}} = \mathbf{0.1636} \pm \mathbf{0.0006}_{\text{stat}} \pm \mathbf{0.0003}_{\text{sys}}$$

Accuracy of 0.4%!

Systematics:

- $\mathbf{Ke3/K2\pi}$: Mainly $Ke3$, $K2\pi$ acceptance, trigger efficiency.
- $\mathbf{K\mu3/K2\pi}$: Mainly $K\mu3$ form factors and $Ke3$, $K2\pi$ acceptance.

Statistical uncertainties dominate

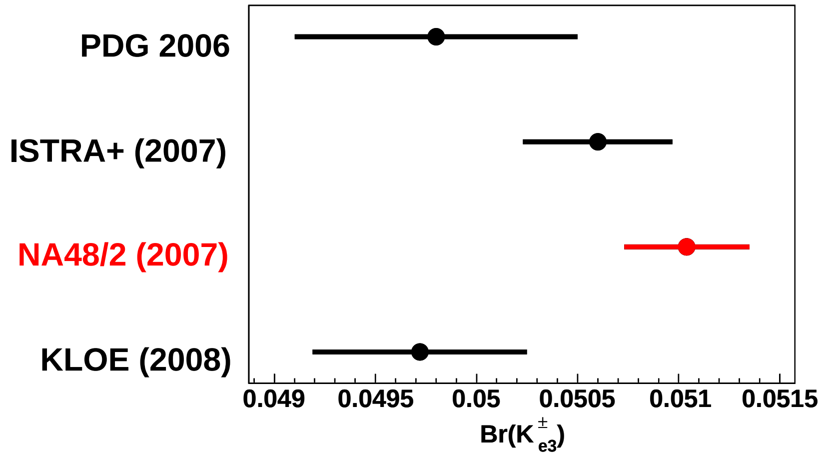
$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

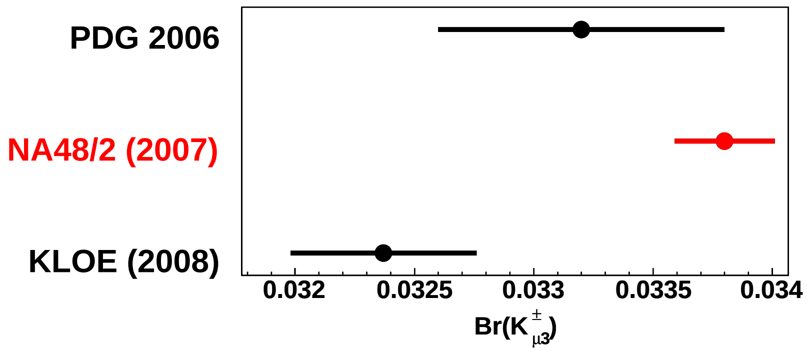
Absolute BR's: *(Update w.r.t. publication)*

Use new KLOE measurement of Br$(K_{2\pi(\gamma)}) = 0.2065(5)(8)$,
shifted ($+0.06\%$) to $\tau_{K^\pm} = 12.370(19)$ ns (average PDG'06 & KLOE'08):

$$\mathrm{Br}(\mathbf{K}^{\pm}_{\mathbf{e3}}) = \mathbf{0.05104} \pm \mathbf{0.00019}_{\mathrm{stat}} \pm \mathbf{0.00008}_{\mathrm{sys}} \pm \mathbf{0.00023}_{\mathrm{norm}}$$
$$\mathrm{Br}(\mathbf{K}^{\pm}_{\mu\mathbf{3}}) = \mathbf{0.03380} \pm \mathbf{0.00013}_{\mathrm{stat}} \pm \mathbf{0.00006}_{\mathrm{sys}} \pm \mathbf{0.00015}_{\mathrm{norm}}$$

Most precise single measurements!





(ISTRA+ scaled to new Br$(K_{2\pi}.)$)

$|V_{us}|$ *Measurement from* $K^{\pm}_{l3}$

Determination of $|\mathbf{V_{us}}|$:

Use $\tau_{K^{\pm}} = 12.370(19)$ ns (average PDG'06 & KLOE'08)

and $\delta^{e/\mu}_{\text{em}}$, $\delta^{e/\mu}_{SU(2)}$, $I^{e/\mu}_{K}$ from Flavianet note:

$$\mathbf{Ke3}: |\mathbf{V_{us}}|\mathbf{f_+(0)} = \mathbf{0.21794\,(43)_{\text{exp}}\,(52)_{\text{norm},\tau}\,(61)_{\text{ext}} = 0.2179(9)}$$

$$\mathbf{K\mu3}: |\mathbf{V_{us}}|\mathbf{f_+(0)} = \mathbf{0.21818\,(46)_{\text{exp}}\,(52)_{\text{norm},\tau}\,(66)_{\text{ext}} = 0.2182(10)}$$

$\Longrightarrow$ **Very good agreement between $\mathbf{K_{e3}}$ and $\mathbf{K_{\mu3}}$**

Combination of $\mathbf{K_{e3}}$ and $\mathbf{K_{\mu3}}$ (correlations taken into account):

$$|\mathbf{V_{us}}|\,\mathbf{f_+(0)} = \mathbf{0.2180 \pm 0.0008}$$

Finally: Use $\mathbf{f_+(0)} = \mathbf{0.964 \pm 0.005}$ (RBC-UKQCD'07):

$$|\mathbf{V_{us}}| = \mathbf{0.2261 \pm 0.0014}$$

Test of Lepton Universality:

Build ratio $\mathbf{Ke3/K\mu3}$:

$$\mathcal{R}_{\mathbf{K\mu3/Ke3}} = \mathbf{0.663} \pm \mathbf{0.003}_{\text{stat}} \pm \mathbf{0.001}_{\text{sys}}$$

Most precise measurement so far and consistent with lepton universality (SM prediction: $\mathcal{R}_{K\mu3/Ke3} = 0.661(3)$ with $\delta^{e/\mu}_{\text{em}}$, $\delta^{e/\mu}_{SU(2)}$, $I_K^{e/\mu}$ from Flavianet note).

Turn it around: Assume lepton universality and determine f.f. slope λ_0:

(Bijnens, Colangelo, Ecker, Gasser, hep-ph/9411311)

$$\mathcal{R}_{K\mu3/Ke3} = \frac{0.645 + 2.087\,\lambda_+ + 1.464\,\lambda_0 + 3.375\,\lambda_+^2 + 2.573\,\lambda_0^2}{1 + 3.457\,\lambda_+ + 4.783\,\lambda_+^2}$$

Use $\lambda_+ = 0.0296 \pm 0.0008$ (PDG'06):

$$\Longrightarrow \quad \lambda_0 = \mathbf{0.0155} \pm \mathbf{0.0020}$$

Measurement of $\mathrm{K_S e3 / K_L e3}$

Measurement of $K_S e3/K_L e3$

NA48/1: High-intensity K_S beam.
Equal production rates of K_S and K_L at the target.

$\Longrightarrow$ Can measure $K_S e3$ decays with respect to $K_L e3$:

$$\frac{dN}{dt}(\pi e \nu) \;\propto\; |\eta|^2 e^{-t/\tau_S} + e^{-t/\tau_L} \quad \text{with} \quad \eta \equiv \frac{A(K_S e3)}{A(K_L e3)}$$

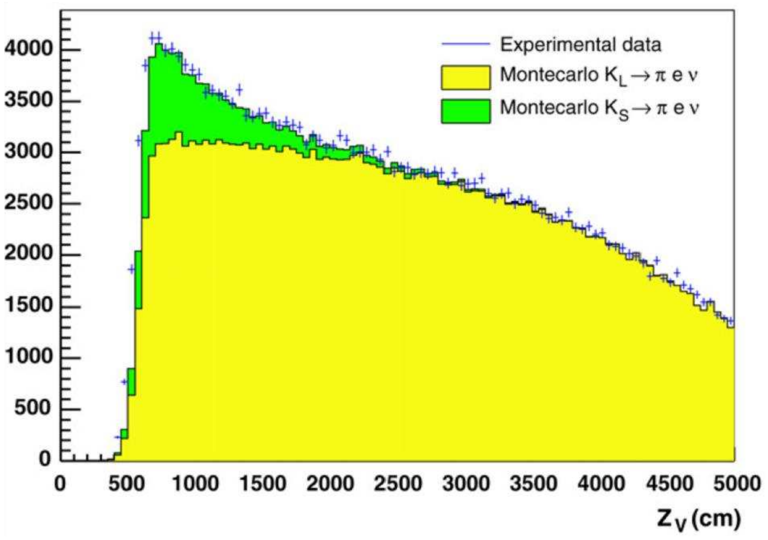
Select $\pi^{\pm} e^{\mp} \nu$ regardless of K_S, K_L.
Backgrounds are negligible.

In total: $\sim$ **400 000 events**

(about 4% are $K_S e3$)

Fit to the shape: (PLB 653 (2007) 145)

$$|\eta|^2 = 0.993 \pm 0.026_{\text{stat}} \pm 0.022_{\text{sys}}$$



Use PDG'06 (Br$(K_L e3) = 0.4053(15)$, $\tau_L = 51.14(21)$ ns, $\tau_S = 89.58(6)$ ps)

$$\Longrightarrow \quad \text{Br}(K_S e3) = (7.05 \pm 0.18_{\text{stat}} \pm 0.16_{\text{sys}}) \times 10^{-4}$$

In good agreement with KLOE 2006, but larger error.

Conclusions

- **Form Factor Measurement in $\mathbf{K_{L\,\mu3}}$:**
  - **More than 2 million events** analyzed.
  - Disagreement with other experiments in scalar form factor.

- **$|\mathbf{V_{us}}|$ from $\mathbf{K^{\pm}_{l3}}$ Decays:**
  - Very precise measurements of $\mathbf{\Gamma(K^{\pm}_{e3})/\Gamma(K^{\pm}_{2\pi})}$ and $\mathbf{\Gamma(K^{\pm}_{\mu3})/\Gamma(K^{\pm}_{2\pi})}$.
  - $|\mathbf{V_{us}}|$ determined from these data: $|\mathbf{V_{us}}| = \mathbf{0.2261 \pm 0.0014}$

- **Ratio $\mathbf{K_S e3/K_L e3}$:**
  - $\mathbf{Br(K_S e3) = (7.05 \pm 0.18_{stat} \pm 0.16_{sys}) \times 10^{-4}}$