NA48 Results on Kaon and Hyperon Decays Relevant to $|V_{us}|$

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CKM
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On behalf of the NA48 Collaboration

Outline

The NA48 detector

Charged Kaons

- $BR(K^{\pm} \to \pi^0 e^{\pm} \nu)$
- $BR(K^{\pm} \to \pi^0 \mu^{\pm} \nu)$

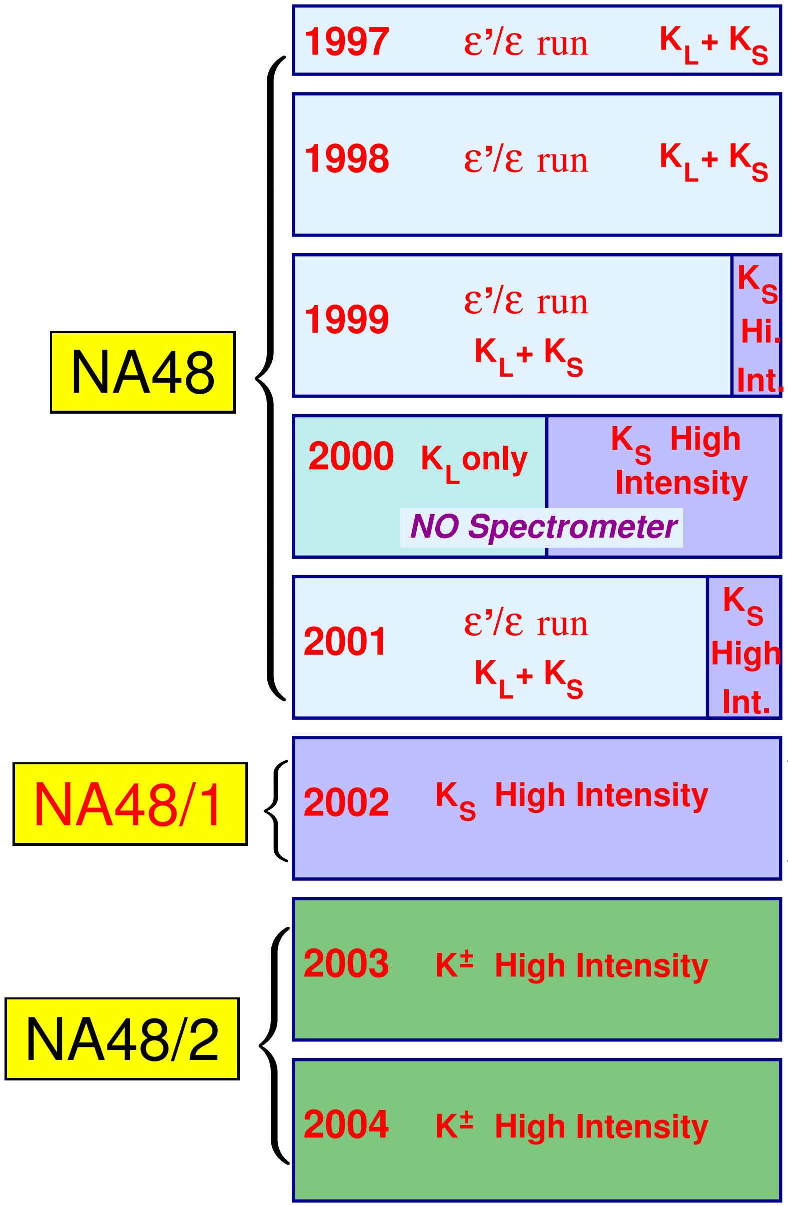
Neutral Kaons

- BR$(K_L \to \pi^+ \pi^-)$
- $K_L \to \pi^{\pm} \mu^{\mp} \nu$ Form Factors

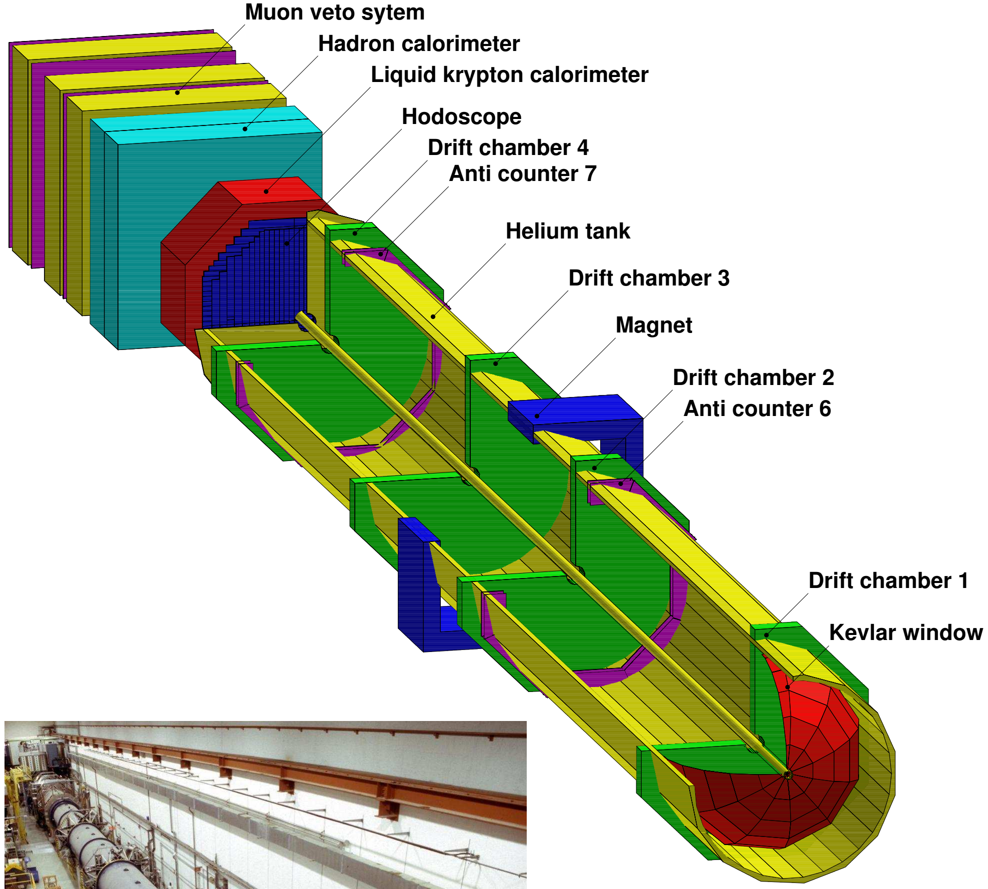
Hyperons

- Ξ_0 Beta Decay

Summary



The NA48 Detector



Magnetic Spectrometer

4 drift chambers

$\frac{\sigma_p}{p}(\%) = 0.48 \oplus 0.009\, p$ (GeV/c)

Dipole magnet with 265(120) MeV/c

p_T kick

Hodoscope

Fast trigger

Precise time measurement

$\sigma_t \simeq 150$ ps

Liquid Krypton EM Calorimeter

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

Muon Counter

$25cm \times 25cm$ cells

$\sigma_t \simeq 350$ ps

$|V_{us}|$ and $K_{\ell 3}$

$K_{\ell 3}$ decays $\Rightarrow$ the most accurate and theoretically cleanest way to extract $|V_{us}|$

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

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

Short Distance Corrections

Calculated f.f. @ t=0
2^{nd} order SU(3)

$\delta^\ell_{SU(2)}$ = 0 for K^0

$\delta^\ell_{EM} \approx 0$ for $K^\pm$
larger for K^0

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

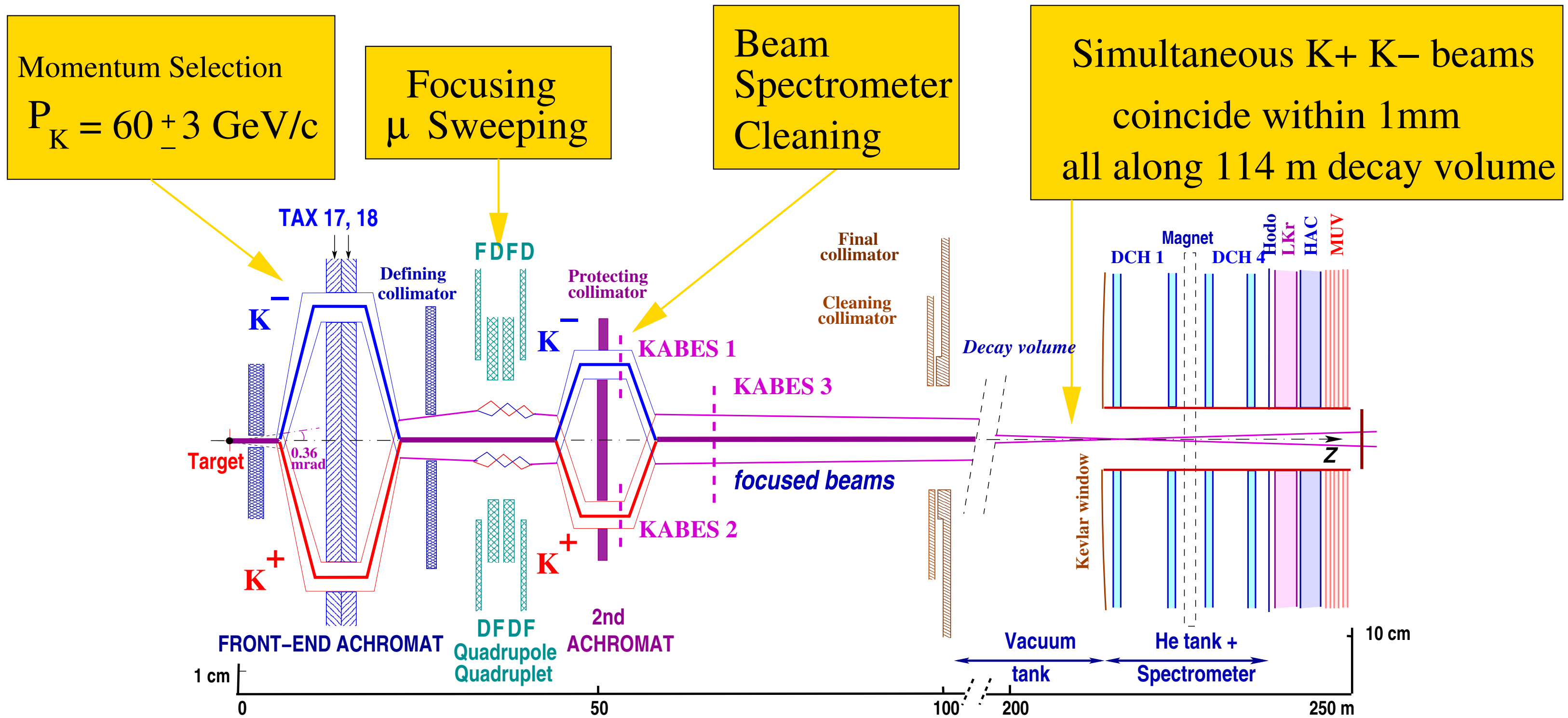
Measured BR and Lifetime

Phase Space integral
depends on f.f.

Experiments supply BR, τ and Form Factor measurements

BR($K^{\pm}_{e3}$) and BR($K^{\pm}_{\mu 3}$)

- $K^{\pm}$ collected during 2003 data taking **NA48/2 Experiment**
  (Main purpose search for direct CP violation in $K^{\pm} \to 3\pi$ decays)
- Special low intensity ($\times$1/8) minimum bias run
- Simultaneous K^{+} and K^{-} beams
- K^{+} flux $\simeq 3.2 \times 10^{6}$; $K^{+}/K^{-} \simeq 1.78$ (production rate @target)



BR($K^{\pm}_{e3}$) and BR($K^{\pm}_{\mu3}$)

We measured the ratios of these decay rates:

$$R_{K3e/K2\pi} = \frac{\Gamma(K^{\pm}\rightarrow\pi^{0}e^{\pm}\nu)}{\Gamma(K^{\pm}\rightarrow\pi^{\pm}\pi^{0})} \quad R_{K\mu3/K2\pi} = \frac{\Gamma(K^{\pm}\rightarrow\pi^{0}\mu^{\pm}\nu)}{\Gamma(K^{\pm}\rightarrow\pi^{\pm}\pi^{0})} \quad R_{K\mu3/Ke3} = \frac{\Gamma(K^{\pm}\rightarrow\pi^{0}\mu^{\pm}\nu)}{\Gamma(K^{\pm}\rightarrow\pi^{0}e^{\pm}\nu)}$$

Same event signature in the ratio: 1 charged track and 2 γ from a π^0 decay

↳ Cancellation of uncertainties

E/p > 0.95	e id
E/p < 0.95	π id
Hit in time in MUC	μ id

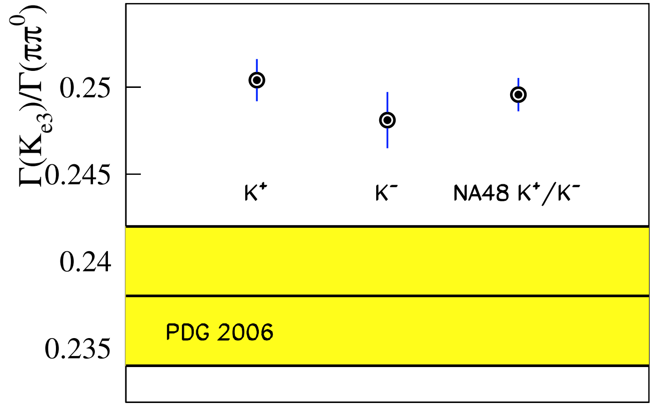
Selected Events

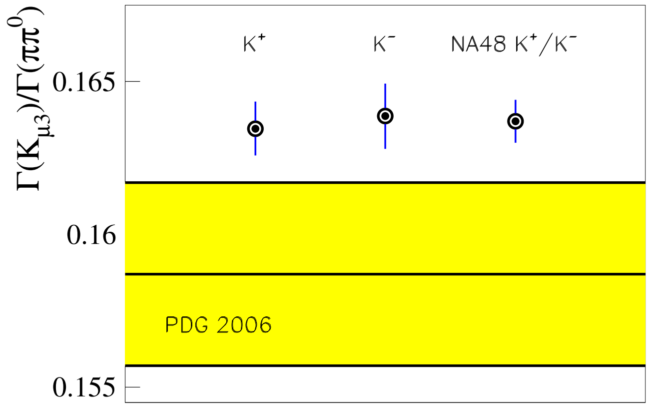
K^{+}_{e3}	K^{-}_{e3}	$K^{+}_{\mu3}$	$K^{-}_{\mu3}$	$K^{+}_{2\pi}$	$K^{+}_{2\pi}$
56196	30898	49364	27525	461837	256619

Background < 1%

BR($K^{\pm}_{e3}$) and BR($K^{\pm}_{\mu3}$)

$$R_{Ke3/K2\pi} = 0.2496 \pm 0.0009_{stat} \pm 0.0004_{syst}$$
$$R_{K\mu3/K2\pi} = 0.1637 \pm 0.0006_{stat} \pm 0.0003_{syst}$$
$$R_{K\mu3/Ke3} = 0.656 \pm 0.003_{stat} \pm 0.001_{syst}$$





Systematics

- Detector Acceptance
  Account for Radiative Corrections
- Trigger Efficiency
- Form Factors
  Input values and Model

Taking BR($K_{2\pi}$) from PDG we evaluate:

$$\text{BR}(K^{\pm}_{e3}) = 0.05221 \pm 0.00019_{stat} \pm 0.00008_{syst} \pm 0.00030_{norm}$$
$$\text{BR}(K^{\pm}_{\mu3}) = 0.03425 \pm 0.00013_{stat} \pm 0.0006_{syst} \pm 0.00020_{norm}$$

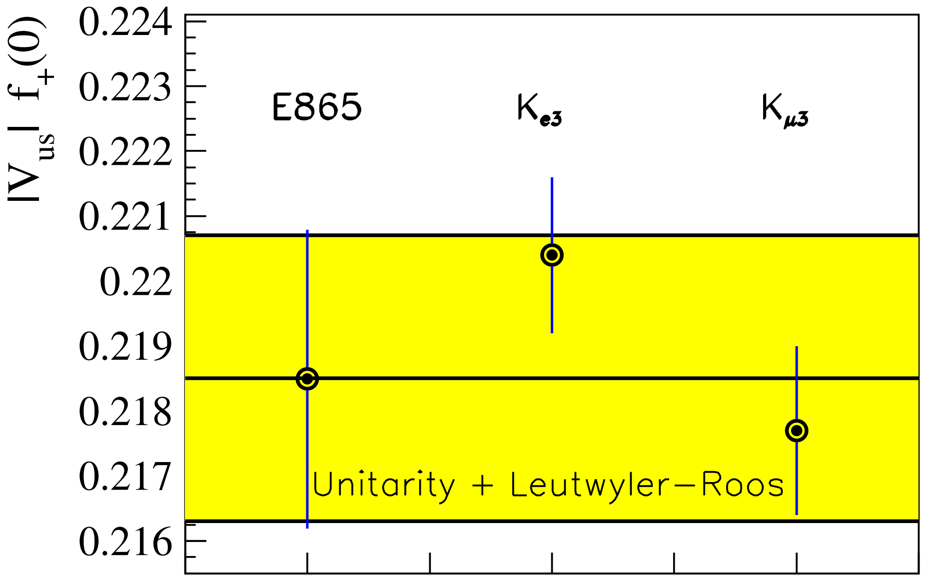
Error dominated by BR($K_{2\pi}$) uncertainty

BNL–E865 result is confirmed

Results for $f_+(0)\,|V_{us}|$ from $K^{\pm}_{e3}$ and $K^{\pm}_{\mu 3}$

With the BR($K^{\pm}_{e3}$) and BR($K^{\pm}_{\mu 3}$) we can derive $f_+(0)\,|V_{us}|$

$$f_+(0)\,|V_{us}| = 0.2204 \pm 0.0012 \quad K^{\pm}_{e3}$$
$$f_+(0)\,|V_{us}| = 0.2177 \pm 0.0013 \quad K^{\pm}_{\mu 3}$$
$$f_+(0)\,|V_{us}| = 0.2197 \pm 0.0012 \quad K^{\pm}_{\ell 3}$$



External Input Used

M_{K+} and τ_{K+} from PDG

$G_F = (1.16637 \pm 0.00001) \times 10^{-5}$ GeV^{-2}

$S_{EW} = (1.0230 \pm 0.0003)$

$\delta^{e,\mu}_{SU2} = (2.31 \pm 0.22)\%$

$\delta^{e}_{EM} = (0.03 \pm 0.10)\%$

$\delta^{\mu}_{EM} = (0.20 \pm 0.20)\%$

$I^{e}_{K} = 0.1591 \pm 0.0012$

$I^{\mu}_{K} = 0.1066 \pm 0.0008$

In good agreement with CKM unitarity

$\mathbf{BR}(K_L \to \pi^+\pi^-)$

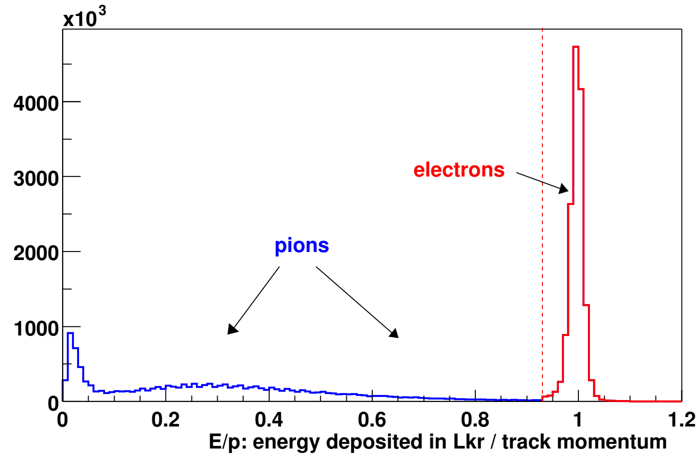
- K_L collected during 1999 ϵ'/ϵ data taking
- Special minimum bias run, K_L beam only

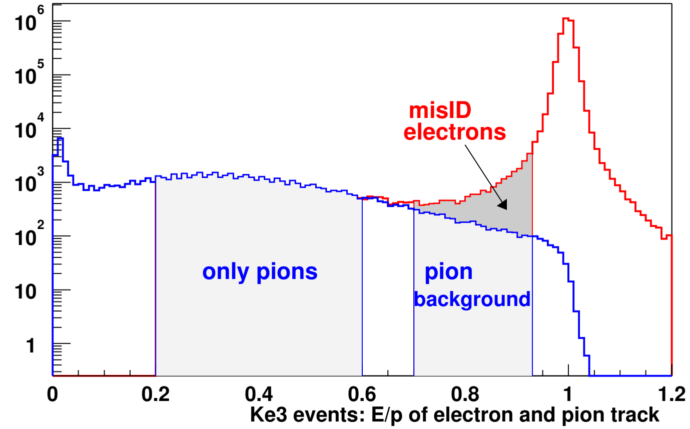
NA48 Experiment

We measured the following ratio:

$$R_{K2\pi/Ke3} = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e\nu)}$$

<u>Event Selection</u>	$\pi^+\pi^-$	K_{e3}
2 tracks $\pm$	E/p < 0.93	E/p > 0.93
good vertex	no μ	
	$m_{\pi\pi}$	
Selected events	47k	5×10^6



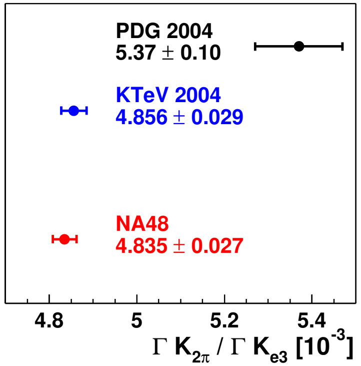


Determine from data $W(\pi \to e) = (0.592 \pm 0.006_{stat})\%$ and $W(e \to \pi) = (0.478 \pm 0.004_{stat})\%$

BR($K_L \to \pi^+\pi^-$)

$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)} = (4.835 \pm 0.022_{stat} \pm 0.020_{syst}) \times 10^-3$$

(hep–ex/0611052)

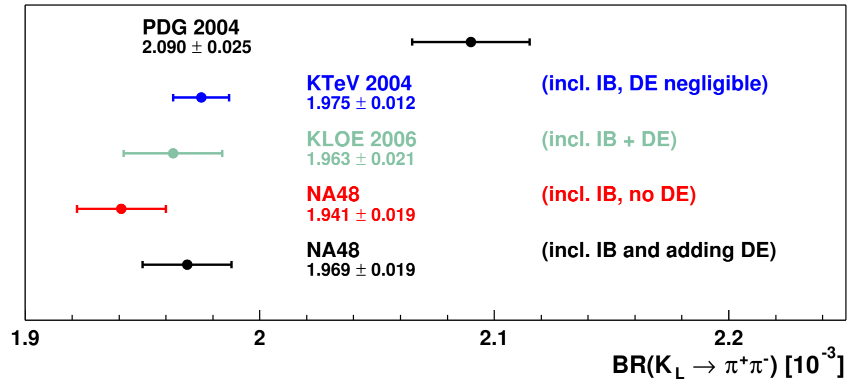


Corrections (%)	
Background in $K_{2\pi}$	-0.49
μ cut	+0.48
E/p cut	+1.34
Trigger Efficiencies	-1.29
Total Correction	+0.04

Using updated NA48 measurement
BR(K_{e3}) $= 0.4022 \pm 0031$

$$\text{BR}(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3} \text{ (no DE)}$$

In agreement with KTeV and KLOE and contradicting former PDG averages



$K^0_{\mu 3}$ Form Factors: Physics Motivations

$I_K^\ell\left(f_+(t), f_0(t)\right)$ **is needed for the extraction of** $|V_{us}|$

Two form factors, $f_\pm(t)$, describe the $K_{\ell 3}$ decay

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

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

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

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

$f_{+,0}(t)$ are the vector and scalar form factor and are related to the angular momentum of the lepton pair

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

Well known parametrizations of the form factors are: **Linear, Quadratic and Pole**

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

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

$$f_+(t) = f_+(0)\ \frac{m_V^2}{m_V^2 - t} \qquad \text{POLE}$$

$$f_0(t) = f_+(0)\ \frac{m_S^2}{m_S^2 - t}$$

In the pole model the f.f. acquire a physical meaning: they are related to the exchange of K^* resonaces with spin–parity $1^-/0^+$ and mass m_V/m_S

Experiments measure the normalized f.f.: $\tilde{f}(t) = f_{+,0}(t)/f_+(0)$

New Parametrizations of the $K^0_{\mu 3}$ Form Factors

Recently new parametrizations of the $K^0_{\mu 3}$ Form Factors have been proposed

[Phys. Lett. B 638(2006) 480] (hep–ph/0603202)

$$f_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ + H(t))\right] \qquad f_0(t) = \exp\left[\frac{t}{(m_K^2 - m_\pi^2)}(\ln C - G(t))\right]$$

- Based on dispersion techniques
- Describe simultaneously the slope and the curvature of the f.f.
- For the dispersive integrals $H(t)$ and $G(t)$ accurate polynomial approximations have been derived
- Key parameter is $\ln C = \ln[f_0(m_K^2 - m_\pi^2)]$ the value of the scalar f.f. at the Callan–Treiman point
- The value of $\ln C$ can provide a test of Right Handed quark Currents coupled to the standard W boson

$$\ln C = 0.2151 \pm 0.0045 + \tilde{\Delta}_{CT} + \Delta(\epsilon)$$

$\Delta(\epsilon)$ is the RHC contribution and $\tilde{\Delta}_{CT} \approx 10^{-3}$ is the Callan–Treiman discrepancy

$K_L \to \pi^{\pm}\mu^{\mp}\nu_{\mu}$ Form Factors Analysis

- K_L collected during 1999 ϵ'/ϵ data taking

NA48 Experiment

- Special minimum bias run, K_L beam only
- Dalitz Plot analysis: to extract the f.f. fit the DP density

$$\rho(E^*_\mu, E^*_\pi) = \frac{dN^2(E^*_\mu, E^*_\pi)}{dE^*_\mu\, dE^*_\pi} \propto A f_+^2(t) + B f_+(t) f_-(t) + C f_-^2(t)$$

Event Selection

μ id. (Hit in time in MUC)

π id. ($E/p < 0.9$)

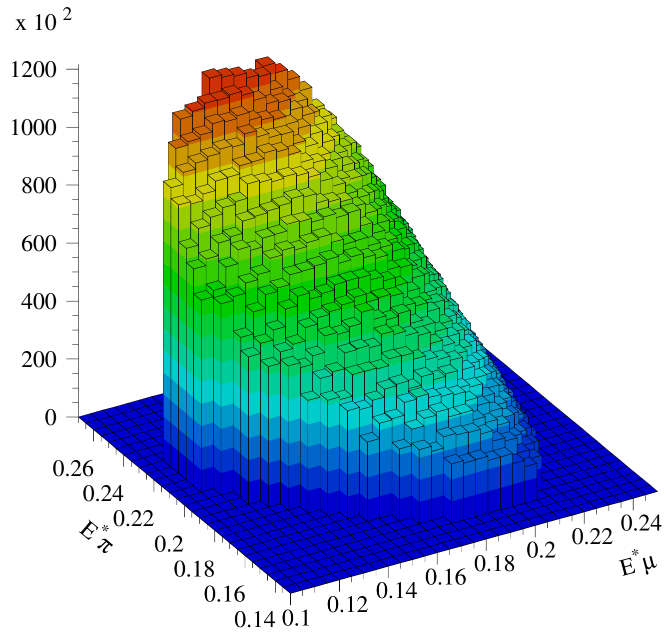
no e (against K_{e3})

no $K_{3\pi}$ ($P_0'^2 < -0.004$ (GeV/c)^2)

Radiative Corrections with KLOR

use the LOW energy solution (true 61%)

Selected 2.3×10^6 events



$K_L \to \pi^{\pm}\mu^{\mp}\nu_{\mu}$ Form Factors Preliminary Results

Linear ($\times 10^{-3}$)	
λ_+ =	26.1$\pm$0.6$\pm$0.8
λ_0 =	12.6$\pm$0.7$\pm$1.0
χ^2/ndf =	405.0/406

Quadratic λ_+ ($\times 10^{-3}$)	
λ'_+ =	16.8$\pm$2.3$\pm$2.4
λ''_+ =	4.0$\pm$1.0$\pm$1.0
λ_0 =	9.1$\pm$1.1$\pm$0.8
χ^2/ndf =	388.4/405

Pole (MeV/c^2)	
m_V =	915$\pm$10$\pm$17
m_S =	1348$\pm$43$\pm$53
χ^2/ndf =	395.3/406

Dispersive ($\times 10^{-3}$)	
Λ_+ =	22.7$\pm$0.6$\pm$0.8
$\ln\ C$ =	153.3$\pm$8.4$\pm$11.0
χ^2/ndf =	394.1/406

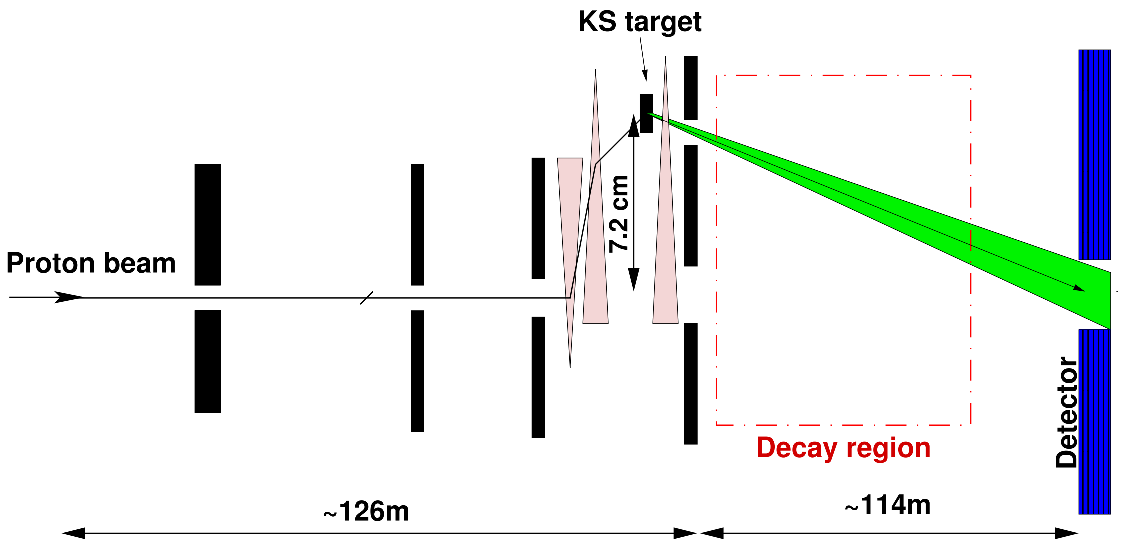
- Like other exp. we observe a quadratic term in the expansion of $f_+(t)$
- λ_0 is smaller than what recently reported
- According to the model of Stern and Coll. the value of $\ln\ C$ from the dispersive fit gives: $\Delta(\epsilon) + \tilde{\Delta}_{CT} = -0.062 \pm 0.014_{NA48} \pm 0.002_{theo} \pm 0.005_{ext}$

Ξ^0 BR and Lifetime

- Ξ^0 collected during 2002 data taking **NA48/1 experiment**
- Purpose: Measurement of very rare K_S decays and neutral hyperon decays
- Neutral beam with target close to the decay region
- Same K_S target from $\epsilon^{'}/\epsilon$ measurement but $200\times$ intensity

Ξ^0 , Λ lifetime $\approx K_S$ lifetime

➜ Kaon experiments can provide large samples of neutral hyperons



Flux in the decay region

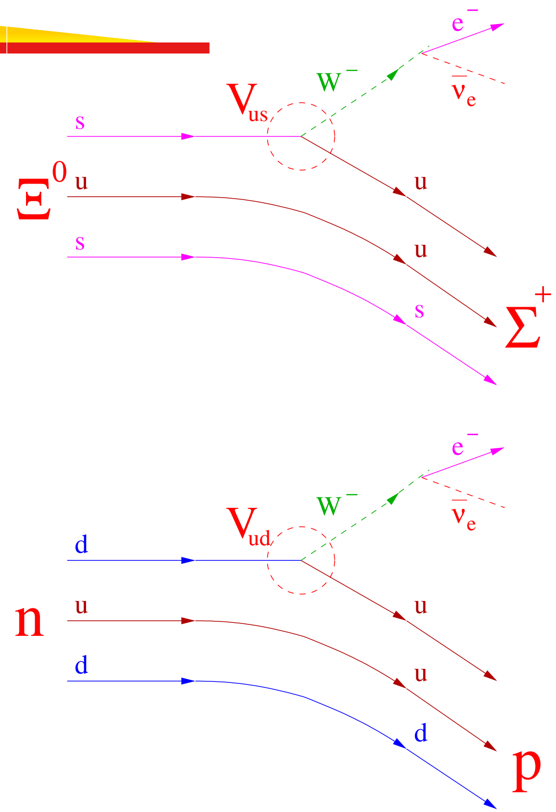
$K_S \quad \sim 3.5 \times 10^{10}$

$\Xi^0 \quad \sim 2.4 \times 10^{9}$

Ξ^0 Beta Decay

Ξ^0 (uss): strange partner of the n(uud)

- Under interchange of d and s quark the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ decay is analog to neutron β–decay



Test of $SU(3)$ simmetry

- In exact $SU(3)$ the ratio between g_1/f_1 is equal to the neutron β–decay

Possible measurement of $|V_{us}|$ complementary to the one obtained with K decays

$$\Gamma = \frac{BR_{\Xi^0 \to \Sigma e \nu}}{\tau_{\Xi^0}} \approx G_F^2 |V_{us}|^2 \frac{\Delta m^5}{60\pi^3}(1 - \tfrac{3}{2}\beta)(|f_1^2| + 3|g_1^2|)$$

$\Delta m = m_{\Xi^0} - m_{\Sigma^+} = 0.12546 \pm 0.00021$ GeV/c^2 and $\beta = \frac{\Delta m}{m_{\Xi^0}} = 0.09542 \pm 0.00011$

So far only one BR measurement by KTeV with 176 events

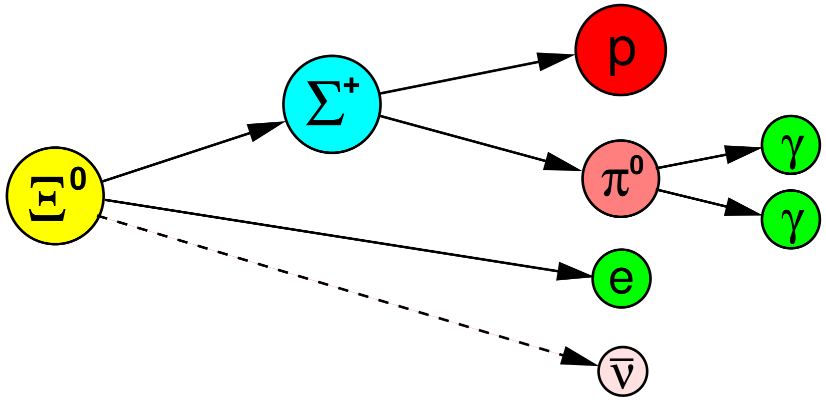
Ξ^0 Beta Decay: Event Selection

Σ^+ is a unique signature of Ξ^0 β–decay

Two body mode forbidden by energy conservation

Reconstruct the Σ^+ by its decay to $p\ \pi^0$

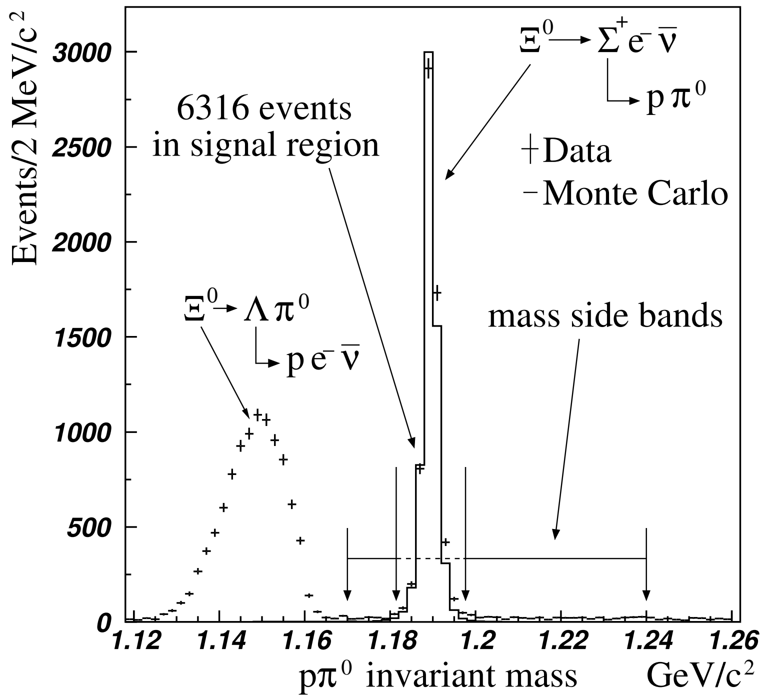
Require the presence of an electron



NA48/1 has 6316 candidates

Background $\approx$ 215 events (3.4%)
Estimated from mass side bands

Use $\Xi^0 \to \Lambda\pi^0$ as normalization channel (59K events)



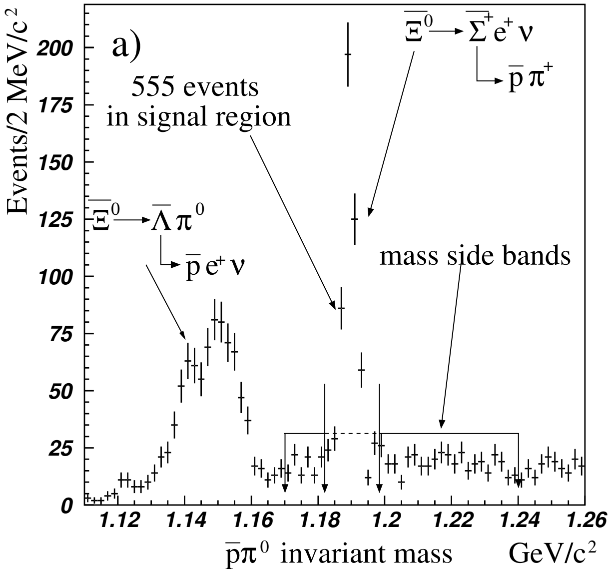
BR($\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$)

The NA48/1 result is: (CERN–PH–EP/2006–032)

$$\text{BR}(\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e) = (2.51 \pm 0.03_{stat} \pm 0.09_{syst}) \times 10^{-4}$$

Systematics	
Trigger efficiency	$\pm 2.2\%$
Form factors	$\pm 1.6\%$
Acceptance	$\pm 1.0\%$
Ξ^0 polarization	$\pm 1.0\%$
Normalization	$\pm 1.0\%$
Others (bkg, τ_{Ξ^0})	$\pm 1.0\%$
Total	$\pm 3.4\%$

Apply charge inversion to get $\overline{\Xi^0}$



Measured also: BR($\overline{\Xi^0} \to \overline{\Sigma^+} e^+ \nu_e$) (555 events)

$$\text{BR}(\overline{\Xi^0} \to \overline{\Sigma^+} e^+ \nu_e) = (2.55 \pm 0.14_{stat} \pm 0.10_{syst}) \times 10^{-4}$$

$|V_{us}|$ from Ξ^0 Beta Decay

- Use Ξ^0 lifetime from PDG06 and the combined result of Ξ^0 and $\overline{\Xi}^0$ branching ratios to evaluate the decay rate:

$$\Gamma(\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e) = (8.66 \pm 0.31_{exp} \pm 0.27_{\Xi^0_{lifetime}}) \times 10^5 s^{-1}$$

- With KTeV form factors and neglecting SU(3) breaking for f_1 we obtain

$$|V_{us}| = 0.209 \pm 0.005_{exp}{}^{+0.022}_{-0.028\ \mathrm{form\ factors}}$$

Good agreement with $|V_{us}|$ from K decay but large uncertainty from form factors

Use $|V_{us}|$ from Kaon decay to determine g_1/f_1 instead

$$g_1/f_1 = 1.20 \pm 0.04_{BR} \pm 0.03_{ext}$$

➜ To be compared with $g_1/f_1 = 1.267$ of neutron decay

Summary

New results relevant for $|V_{us}|$ from the NA48 experiment:

BR$(K^{\pm} \to \pi^0 e^{\pm} \nu) = 0.05221 \pm 0.00019_{stat} \pm 0.00008_{syst} \pm 0.00030_{norm}$

BR$(K^{\pm} \to \pi^0 \mu^{\pm} \nu) = 0.03425 \pm 0.00013_{stat} \pm 0.0006_{syst} \pm 0.00020_{norm}$

PRELIMINARY $K_L \to \pi^{\pm} \mu^{\mp} \nu_{\mu}$ Form Factors

BR$(\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e) = (2.51 \pm 0.03_{stat} \pm 0.09_{syst}) \times 10^{-4}$

And others not shown:

Ξ^0 **Lifetime** $\tau_{\Xi^0} = (3.082 \pm 0.013 \pm 0.012) \times 10^{-10}$ s

About 2σ above PDG2004 average and 5 times more precise PRELIMINARY

Using the new lifetime value:

$$|V_{us}| = 0.203 \pm 0.004_{exp}{}^{+0.022}_{-0.027\ \mathrm{form\ factors}}$$

Semi–muonic Ξ^0 decay (from 99 events) PRELIMINARY

BR$(\Xi^0 \to \Sigma^+ \mu^- \overline{\nu}_{\mu}) = (2.2 \pm 0.3_{stat} \pm 0.2_{syst}) \times 10^{-6}$