Measurement of Vus. Recent NA48 results on semileptonic and rare Kaon decays

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Introduction

- CKM Unitarity
- NA48 Experimental setup
- Measurement of Br(K^0_Le3)/Br(2tr)
- Br(K^0_Le3)
- Measurement of Br($K^0_L \rightarrow 3\pi^0$)
- Measurement of Br($K^{\pm}$e3)
- Extraction of Vus
- K^0_Le3 form factors
- Radiative decay Br(K^0_Le3γ)
- Rare decays
  - $K^0_L \rightarrow e^+e^-\gamma$ form factor
  - Br($K^0_L \rightarrow e^+e^- e^+e^-$)
  - K^0_{e4} decay
  - Search for $K^0_s \rightarrow 3\pi^0$
  - Observation of $K^0s \rightarrow \pi^0\mu^+\mu$
- Conclusions

CKM Unitarity

Unitarity of CKM matrix requires for the first row

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

PDG 2004 data

$|V_{ud}| = 0.9738 \pm 0.0005$ - well measured

$|V_{ub}| = (3.67 \pm 0.47).10^{-3}$ - ($|V_{ub}|^2 \approx 10^{-5}$ negligible)

SM prediction

$|V_{us}| = 0.2274 \pm 0.0021$

Experimental value

$|V_{us}| = 0.2200 \pm 0.0026$

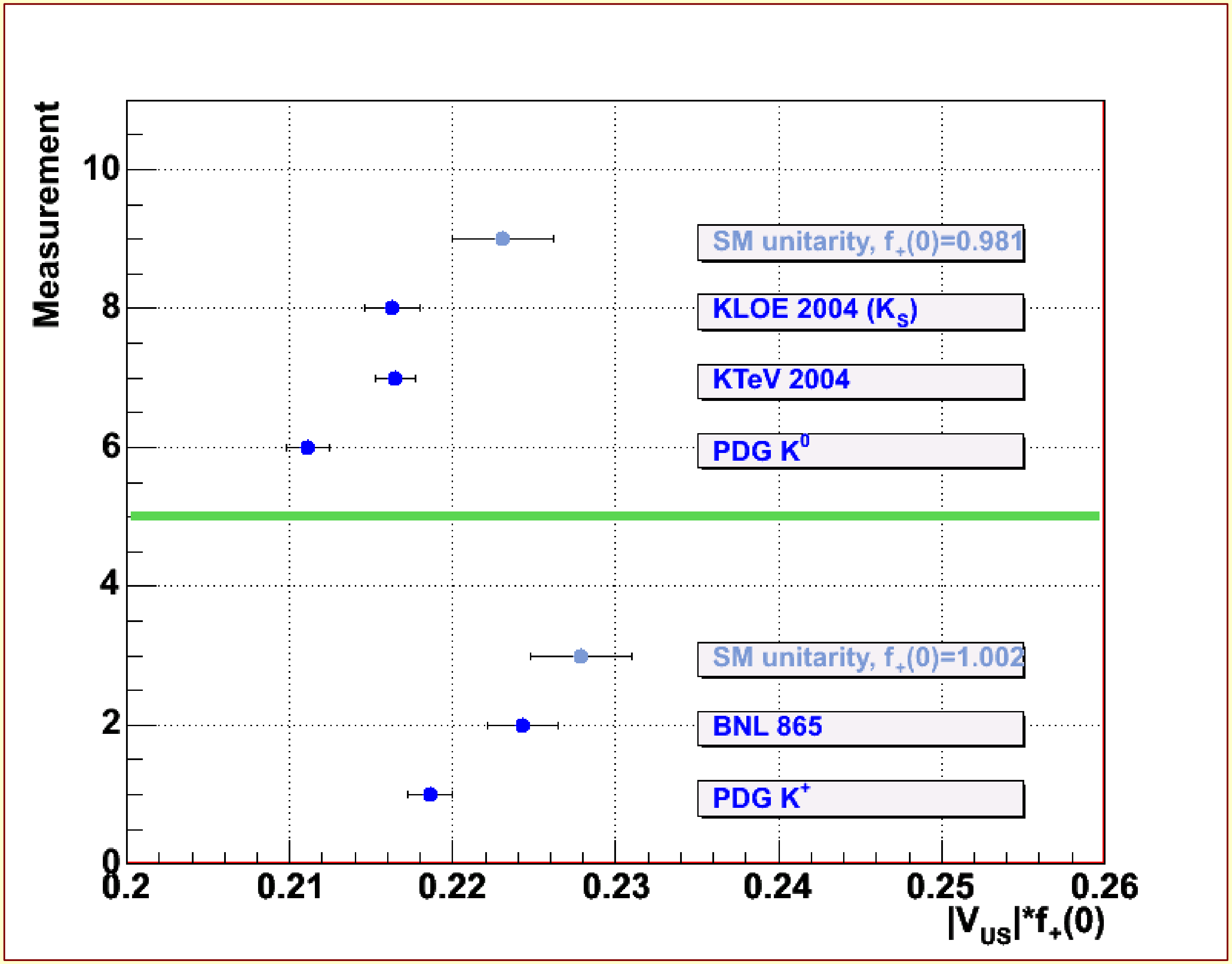
$\Delta|V_{us}| = 0.0074 \pm 0.0033$ ~2.2 σ discrepancy

To solve the problem – measurement with precision ~ 1% (limited by theory)

Semileptonic decays $K \to \pi e \nu$ best for determination of $|V_{us}|$

Recent measurements from K^+e3 (BNL2003) and K^0e3 (KTeV) and KLOE,prel, 2004) are significantly above previous results.

$V_{us}f_+(0)$

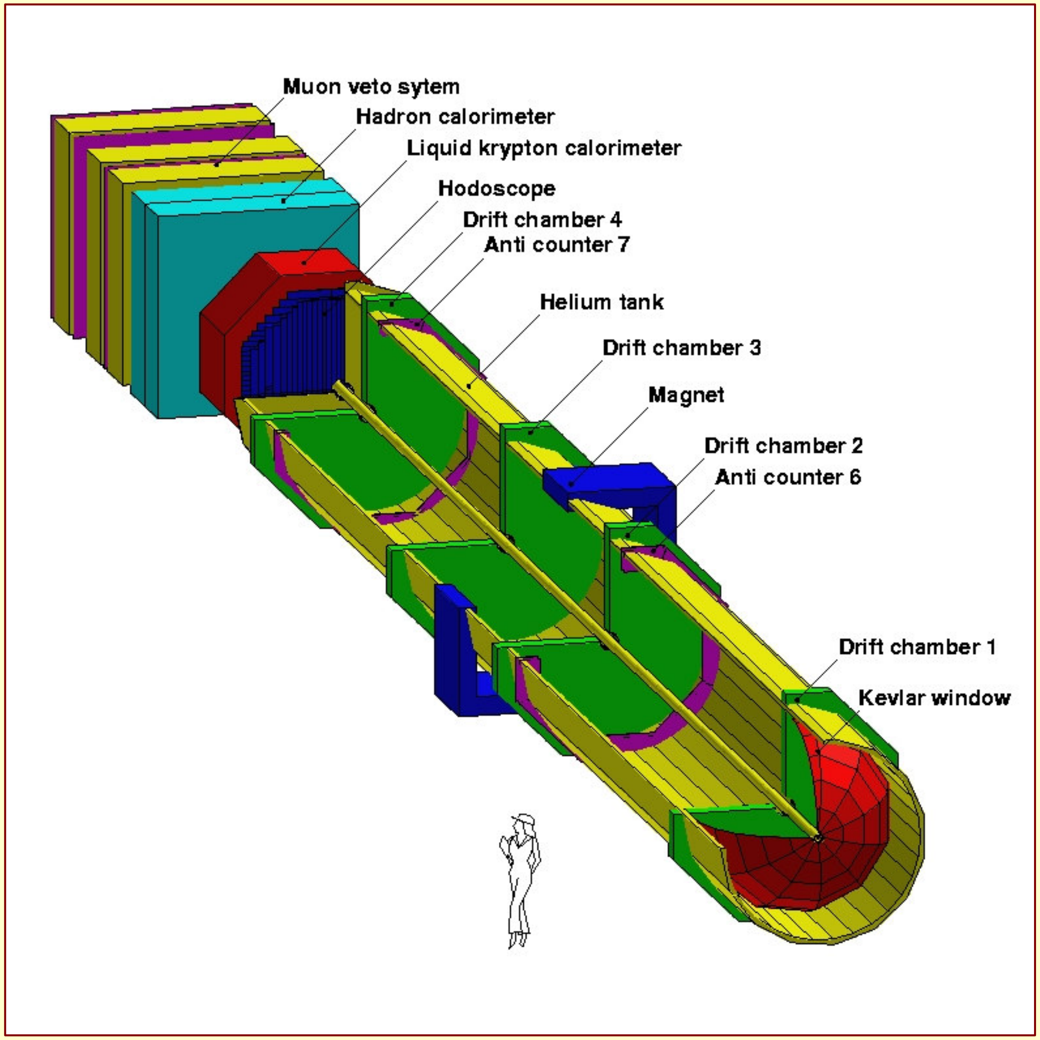


Measurement
10
8
6
4
2
0
0.2
0.21
0.22
0.23
0.24
0.25
0.26
$|V_{us}|*f_+(0)$
SM unitarity, $f_+(0)$=0.981
KLOE 2004 (K_S)
KTeV 2004
PDG K^0
SM unitarity, $f_+(0)$=1.002
BNL 865
PDG K^+

NA48 experiment

- Main detector components
- ❖Magnet spectrometer
  - ➢Two drift chambers before and two after spectrometer magnet
  - ➢Momentum resolution < 1% for 20 GeV/c momentum

$$\frac{\delta E}{E} = \frac{3.2\%}{\sqrt{E[GeV]}} \oplus \frac{90MeV}{E} \oplus 0.42\%$$



- ❖Hadron Calorimeter
- ❖Muon Veto system
- ❖Beams – K^0_L,K^0_s,$K^{\pm}$

Vus measurement

$K^0_L \rightarrow \pi e \nu$

- Semileptonic K_L decays $K^0_L \rightarrow \pi l \nu$
  - Data from special minimum bias run 1999 with pure K^0_L beam
  - Very high statistics available – 80 million triggers taken
- General idea
  - Normalize to as many as possible channels
  - Data selection and analysis - as simple as possible
- Measure the ratio $Br(K^0_L\ e3)/Br(2tr)$ 2tr = all K^0_L decays with two charged particles in the spectrometer
  - Normalization on

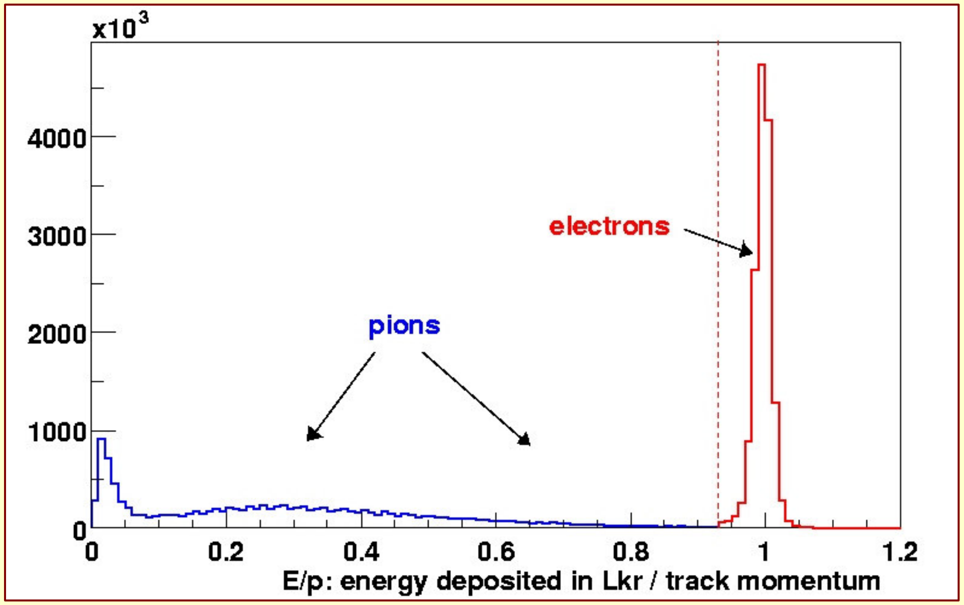
$$Br(2tr) = 1.0048 - Br(K^0_L \rightarrow 3\pi^0)$$

$K^0_L \rightarrow \pi e \nu$

❖Main selection criteria for 2 track sample

- ➢Decay vertex within 8 m and 33 m from final collimator
- ➢Track separation in LKr > 25 cm
- ➢Track momenta > 10 GeV
- ➢Psum = P1 + P2 > 60 GeV

12.6 million 2 track events



❖$K^0_L \rightarrow \pi e \nu$ selection – the same but

- ➢E(LKr)/p > 0.93

$K^0_L \rightarrow \pi e \nu$

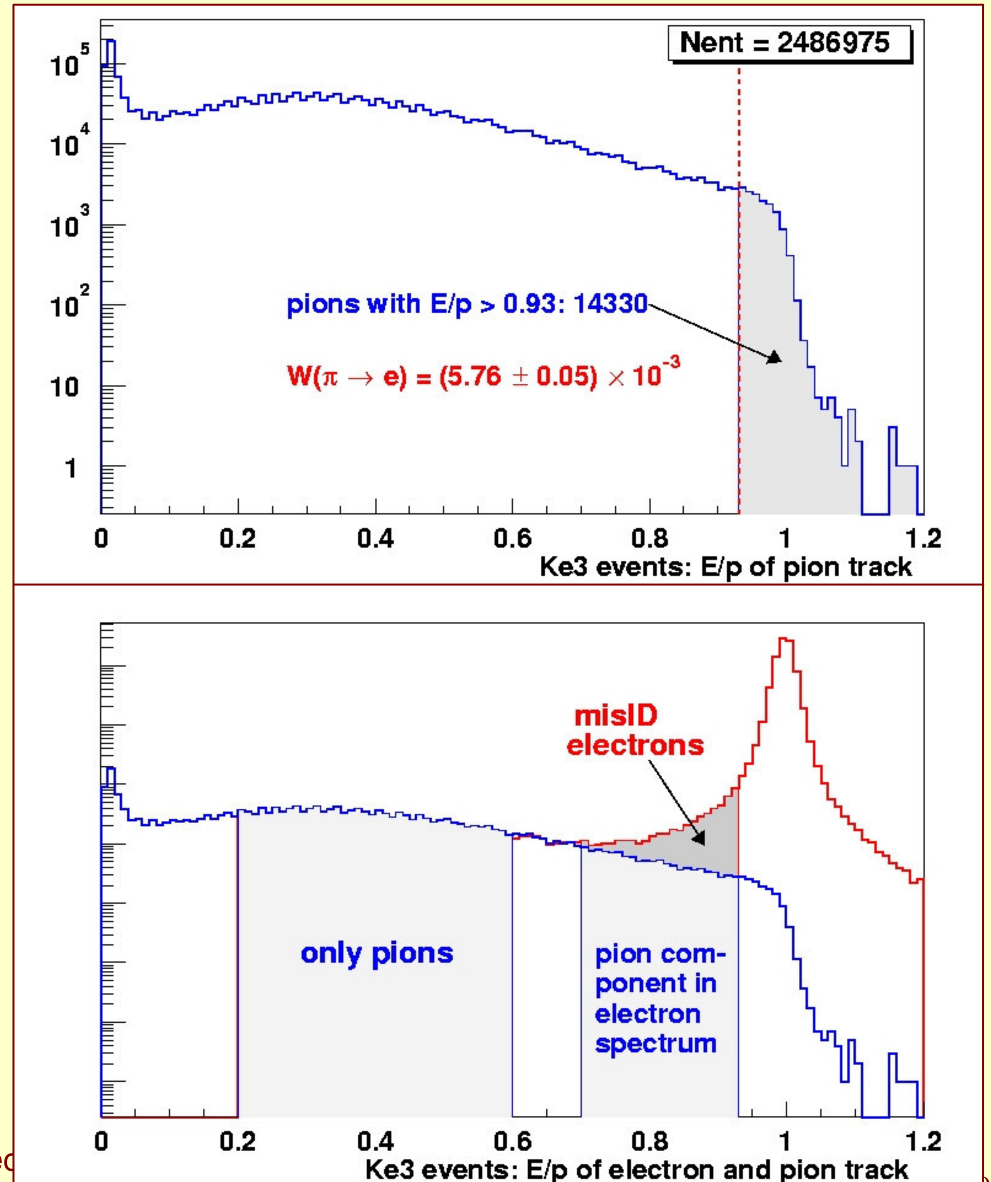
- Background to K_{e3} sample
  - BG from $K\mu3$ and $K3\pi$ with $\pi^{\pm}$ misidentified as $e^{\pm}$
  - Estimate the BG from K_{e3} data with identified $e^{\pm}$ ($E/p > 1$)

    $P(\pi \rightarrow e) = 5.8.10^{-3}$

- Inefficiency of electron ID
  - Estimate $e^{\pm}$ inefficiency from K_{e3} data with identified $\pi^{\pm}$ ($0.3 < E/p < 0.7$)

    $P(e \rightarrow \pi) = 4.9.10^{-3}$

Selected 6.7 million K_{e3}



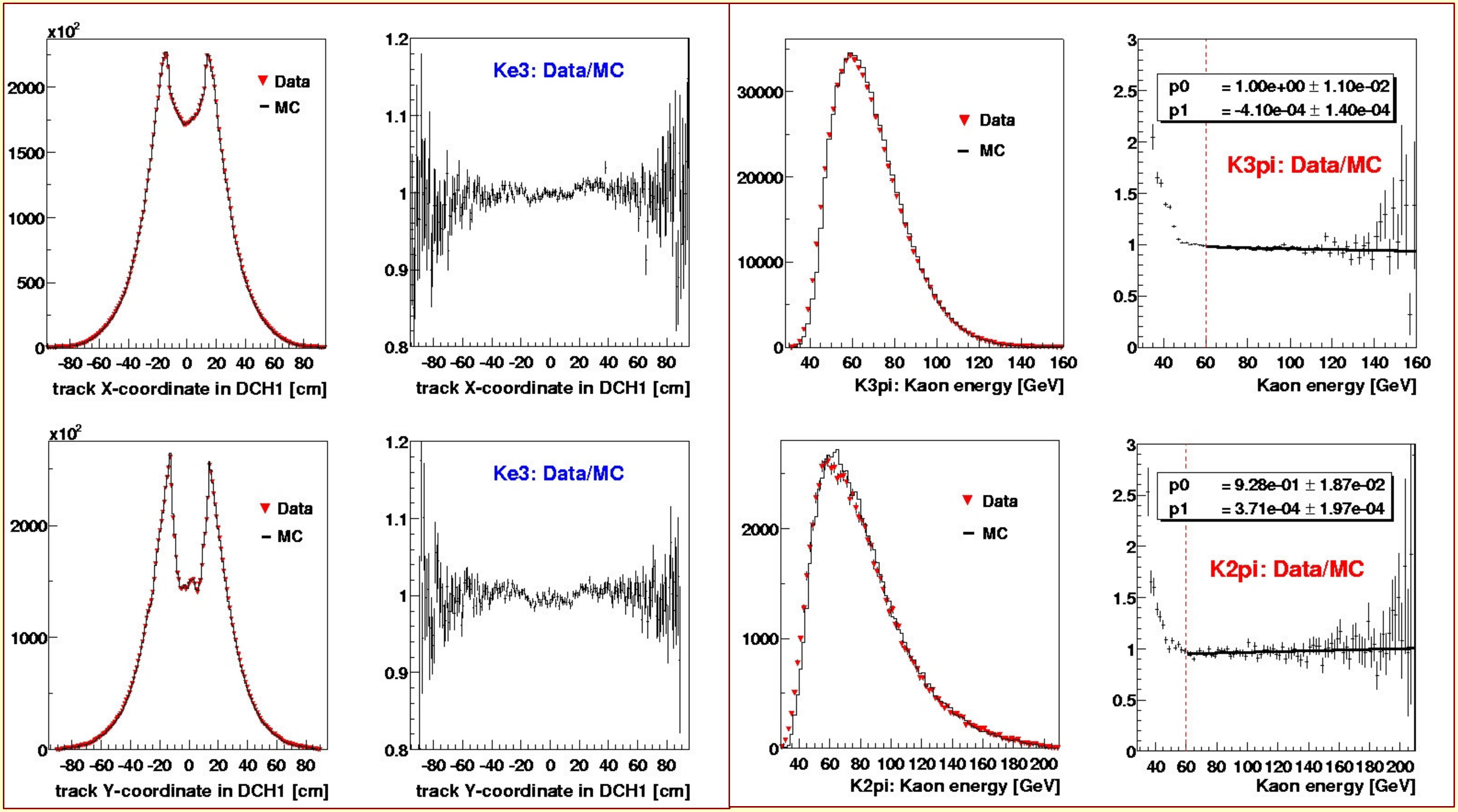
$K^0_L \rightarrow \pi e \nu$

- Monte Carlo simulation of detector acceptance
  - All two track channels involved – (Ke3, Kμ3, K3π,K2π,K3π^0_D)
  - For average 2-track acceptance use Br fractions
  - Average from PDG and KTeV (Bμ3/Be3, B3π/Be3,….)

$$A_{2tr} = 0.2412 \pm 0.0004$$

- Ke3 simulation includes radiative corrections and Ke3γ with real photons Ginsberg (Phys.Rev. 171, 1675(1968)+ errata)
- Good agreement between MC and data except for high momentum K^0_L
- Systematic errors
  - Main contribution comes from inexact knowledge of beam momentum (can be reconstructed only up to quadratic ambiguity)
  - For measurement of beam momentum distribution – K2pi and K3pi decays
  - Experimental uncertainty of 0.7% on measured ratio
- Statistical errors are negligible

$K^0_L \rightarrow \pi e \nu$



$K^0_L \rightarrow \pi e \nu$

Experimental result

$Br(K^0_L\ e3)/Br(2tr) = 0.498 \pm 0.004$

Preliminary

To determine $Br(K^0_L \rightarrow \pi e \nu)$ we need $Br(K^0_L \rightarrow 3\pi^0)$

PDG04: $Br(K^0_L \rightarrow 3\pi^0) = 0.2105 \pm 0.0028$

KTeV $Br(K^0_L \rightarrow 3\pi^0) = 0.1945 \pm 0.0018$?

Average according PDG prescription

$Br(K^0_L \rightarrow 3\pi^0) = 0.1992 \pm 0.0070$

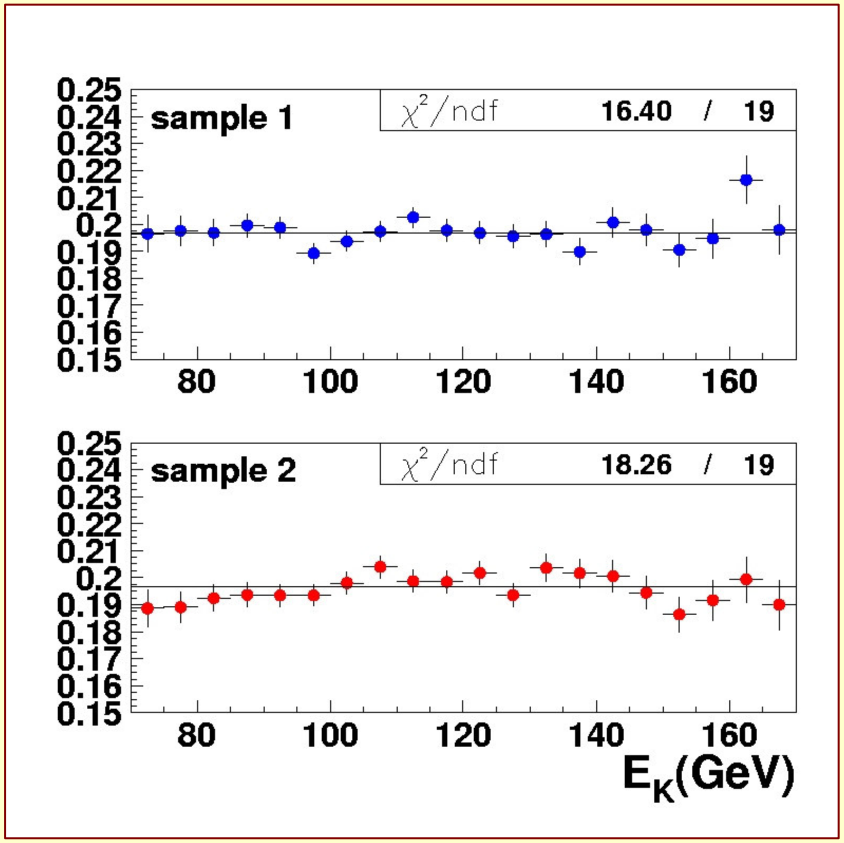
$Br(K^0_L\ e3) = 0.4010 \pm 0.0028_{exp} \pm 0.0035_{norm}$

Preliminary

Measurement of Br($K^0_L \to 3\pi^0$)

- Br($K^0_L \to 3\pi^0$) is the main experimental uncertainty on Br(K^0_L e3)
  - PDG (Kreutz et al 1995) inconsistent with new KTeV result by $\approx 5\ \sigma$
  - Measure Br($K_L \to \pi^0\pi^0\pi^0$)/ Br($Ks \to \pi^0\pi^0$)
  - Br($Ks \to \pi^0\pi^0$) $= 0.3104 \pm 0.0014$ well measured
- NA48/1 data, 2000:
  - High intensity Ks beam
  - No material (DCH etc) between collimator and LKr calorimeter
  - Ideal for measurement of neutral Kaon decays
- We used only small amount of 2000 data
  - ~200 000 $K_L \to \pi^0\pi^0\pi^0$
  - ~600 000 $Ks \to \pi^0\pi^0$
  - Two independent samples
  - Same number of K_L and K_s is produced on the target

Measurement of Br($K^0_L \to 3\pi^0$)



❖Main systematic

- ➢LKr energy scale ±0.0020
- ➢Effective target position ±0.0017
- ➢K_L life time: ±0.0015

$$Br(K_L \to \pi^0\pi^0\pi^0) = 0.1966 \pm 0.0006_{stat} \pm 0.0033_{syst}$$

Preliminary

In a good agreement with KTeV result

Measurement of Br($K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$)

- NA48/2 data from 2003
  - Low intensity K^+/K^- run (8 hours) with minimum bias trigger
- Normalize $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ decays to $K^{\pm} \rightarrow \pi^{\pm} \pi^0$

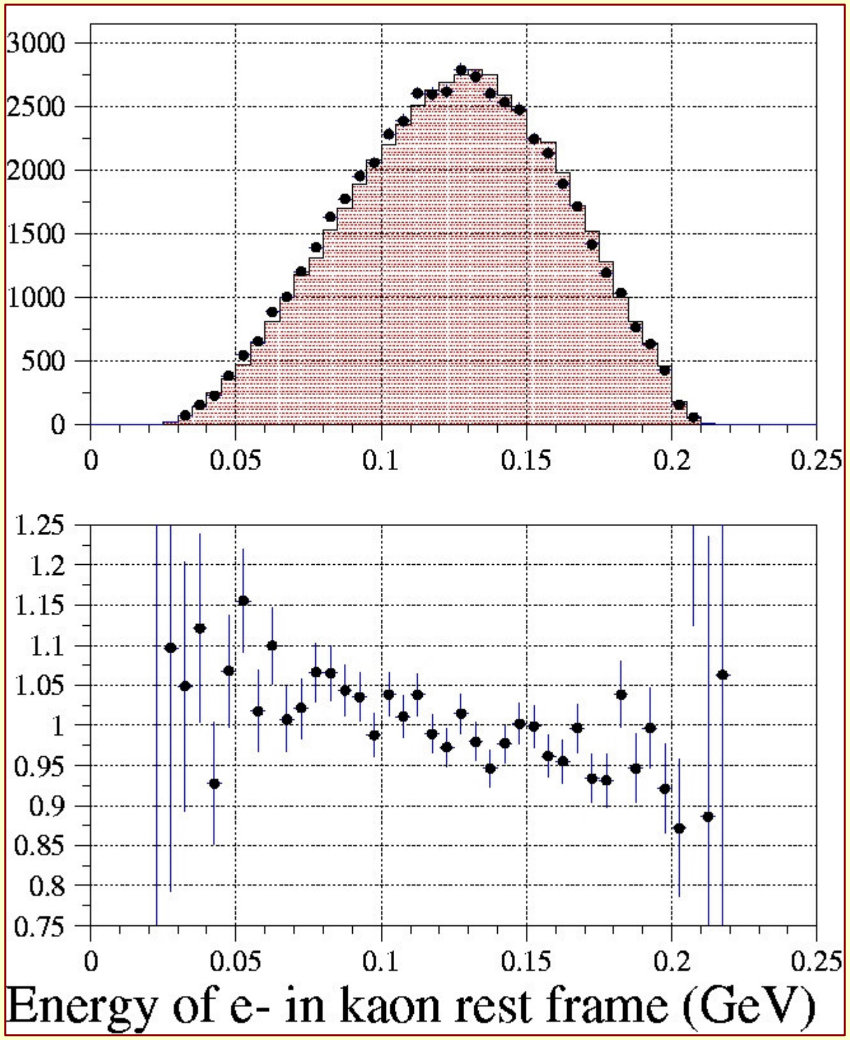
$$Br(K^{\pm} \rightarrow \pi^{\pm} \pi^0) = 0.2113 \pm 0.0014$$

- Selected events

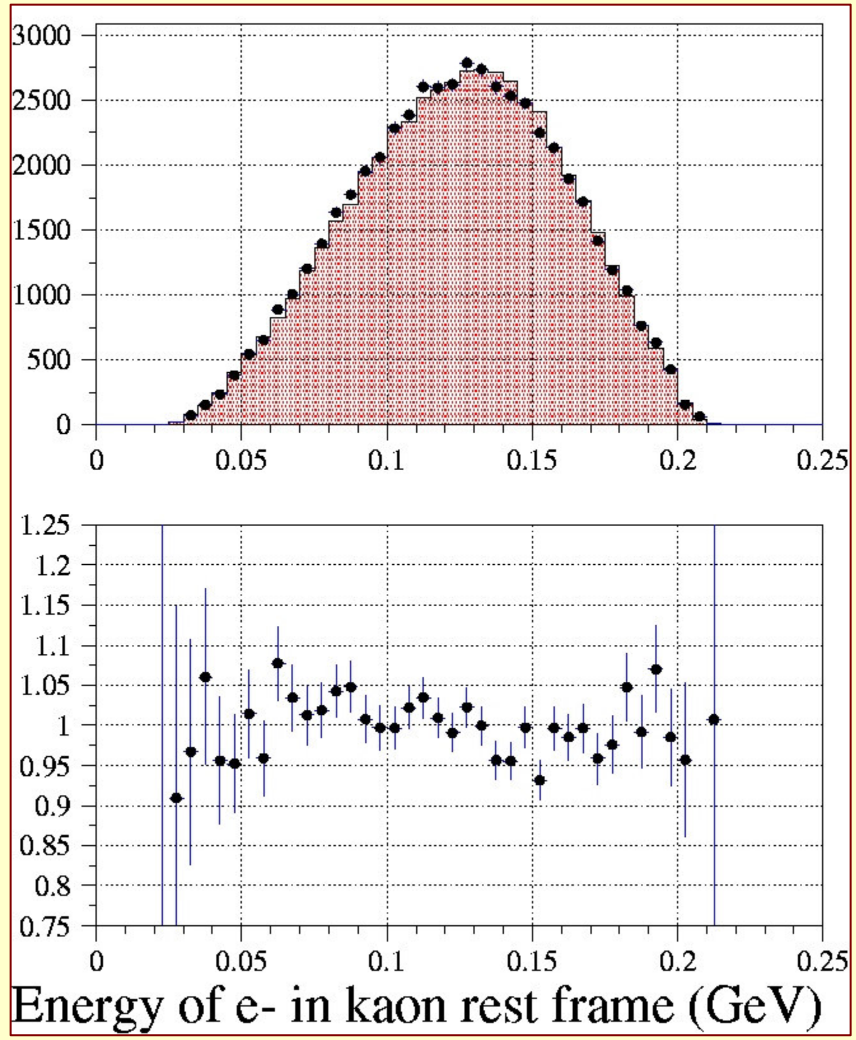
$K^+ \rightarrow \pi^0 e^+ \nu$	59 000 ev.
$K^- \rightarrow \pi^0 e^- \nu$	33 000 ev.
$K^+ \rightarrow \pi^+ \pi^0$	468 000 ev.
$K^- \rightarrow \pi^- \pi^0$	260 000 ev.

- Practically background free
- Systematic
  - Main sources – Detector acceptance, Br($K^{\pm} \rightarrow \pi^{\pm} \pi^0$), MC statistic

Measurement of Br($K^{\pm} \rightarrow \pi^{\pm} e\nu$)



Without radiative corrections



With radiative corrections

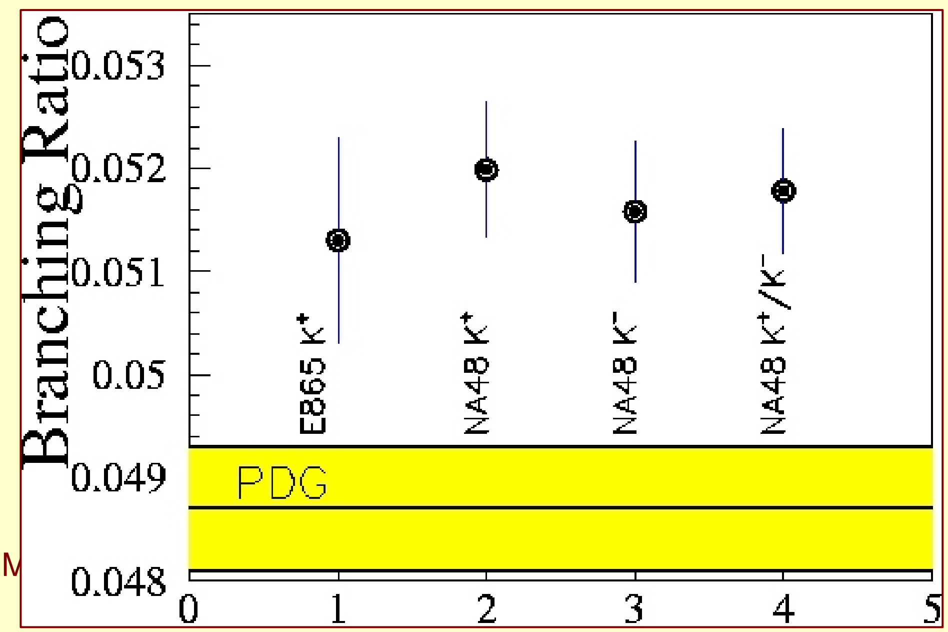
Measurement of Br($K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu$)

Preliminary NA48/2 result on Br($K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu$)

Br($K^{+} \rightarrow \pi^{0} e^{+} \nu$) = ($5.163 \pm 0.021_{stat} \pm 0.056_{syst}$) %

Br($K^{-} \rightarrow \pi^{0} e^{-} \nu$) = ($5.093 \pm 0.028_{stat} \pm 0.056_{syst}$) %

Br($K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu$) = ($5.14 \pm 0.02_{stat} \pm 0.06_{syst}$) %



Determination of Vus

|Vus| can be extracted from K → πeν via

$$|V_{us}|.f_{+}^{K\pi}(0)=\sqrt{\frac{128\pi^{3}\Gamma(Ke3(\gamma))}{C^{2}G_{F}^{2}M_{K}^{5}S_{EW}I_{K}}}$$

Where:

Sew = 1.0232 – short distance enhancement factor,

I_k - phase space integral,

$$C=\begin{Bmatrix} 1 & K_{e3}^{0} \\ 1/\sqrt{2} & K_{e3}^{+} \end{Bmatrix}$$

$$f_{+}^{K^{0}\pi^{+}}(0)=0.981\pm0.010$$

$$f_{+}^{K^{+}\pi^{0}}(0)=1.002\pm0.010$$

We used the values obtained by Cirigliano,Neufeld,Pichl (EPJ C35, 53,2004) Isospin violation effects, e.m. corrections, $O(p^6)$ terms are taken into account

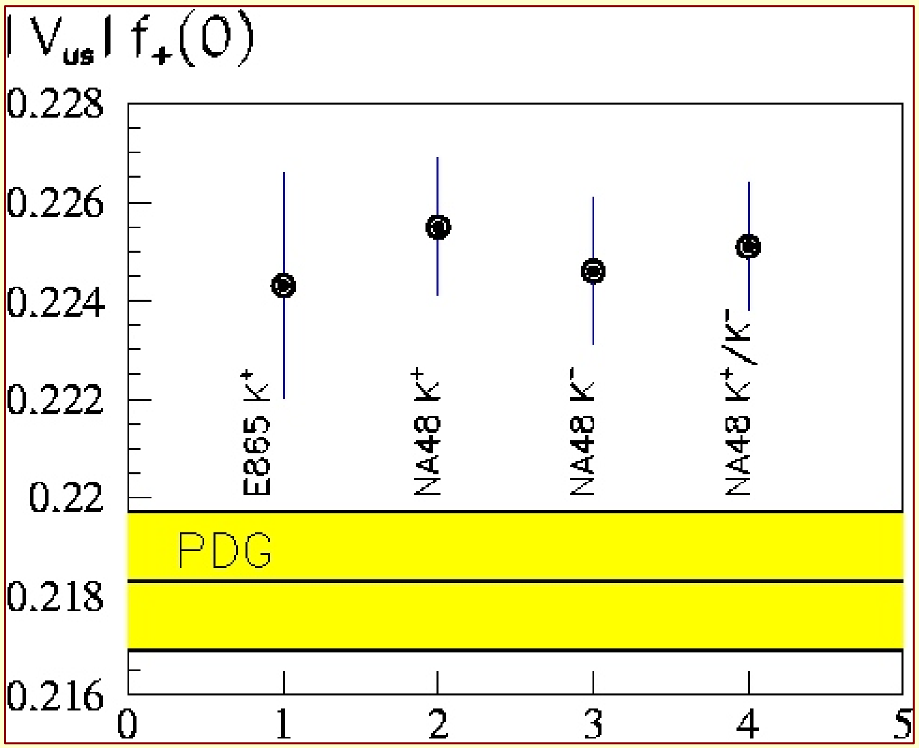
Determination of $V_{us}f_+(0)$

$$|V_{us}|.f_+^{K^0\pi^+}(0) = 0.2146 \pm 0.0016$$

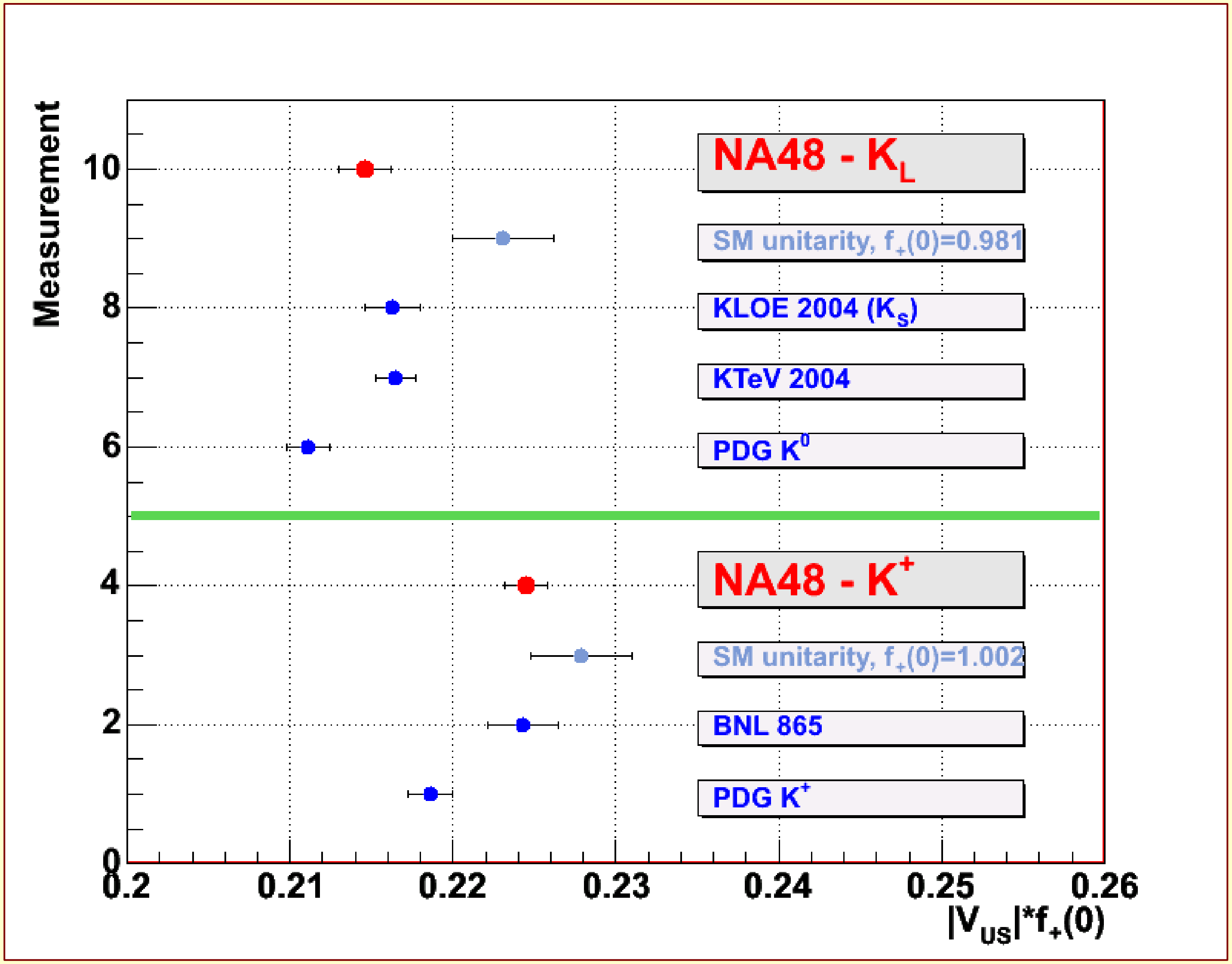
$$|V_{us}|.f_+^{K^+\pi^0}(0) = 0.2250 \pm 0.0013$$

$$|V_{us}|.f_+^{K^-\pi^0}(0) = 0.2235 \pm 0.0014$$

$$|V_{us}|.f_+^{K^\pm\pi^0}(0) = 0.2245 \pm 0.0013$$



Determination of $V_{us}f_+(0)$



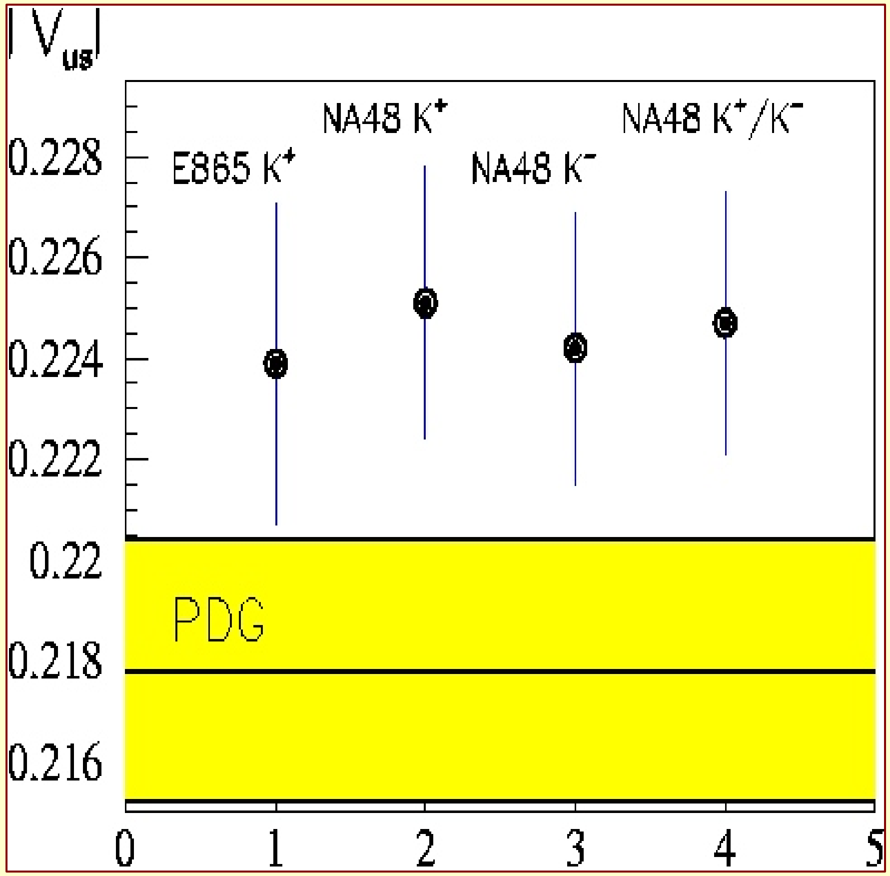
Determination of V_{us}

$$|V_{us}|^{K^0\pi^+}(0) = 0.2187 \pm 0.0016_{\exp} \pm 0.0023_{theor}$$

$$|V_{us}|^{K^+\pi^0}(0) = 0.2246 \pm 0.0013_{\exp} \pm 0.0023_{theor}$$

$$|V_{us}|^{K^-\pi^0}(0) = 0.2231 \pm 0.0014_{\exp} \pm 0.0023_{theor}$$

$$|V_{us}|^{K^\pm\pi^0}(0) = 0.2241 \pm 0.0013_{\exp} \pm 0.0023_{theor}$$



Determination of V_{us}

Conclusions

Experimental determination of Vus from

- $K^{\pm}$
  - in disagreement with old measurements (PDG)
  - in agreement with BNL result and SM prediction
- K^0_L
  - in disagreement with old measurements (PDG)
  - In agreement with new KTeV and KLOE measurements
  - Still in disagreement with SM prediction ~ 2.5 σ
- Main uncertainty comes from theoretical calculations of $f_+(0)$
  - More accurate calculation of O(p6) contribution required

Other results

Ke3 form factors

❖ $K_L \to \pi e \nu$ form factors the same 1999 data

- 5.6 million reconstructed events
- Preliminary result for pure vector interaction

$$\lambda_+ = 0.0288 \pm 0.0005_{stat} \pm 0.0011_{syst}$$

- Preliminary result for 3-parameter fit:

$$\lambda_+ = 0.0284 \pm 0.0007 \pm 0.0013$$

$$\left|\frac{f_S}{f_+(0)}\right| = 0.015^{+0.007}_{-0.010} \pm 0.0012$$

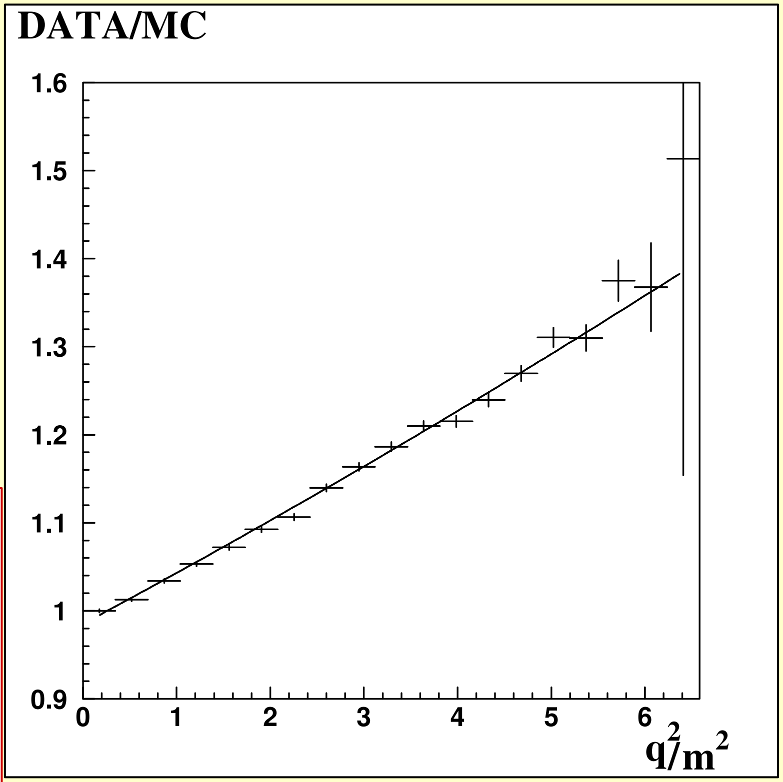
$$\left|\frac{f_T}{f_+(0)}\right| = 0.05^{+0.03}_{-0.04} \pm 0.03$$

$PDG(2004)$:

$$\lambda_+ = 0.0291 \pm 0.0018$$

$$\left|\frac{f_S}{f_+(0)}\right| < 0.04$$

$$\left|\frac{f_T}{f_+(0)}\right| < 0.23$$

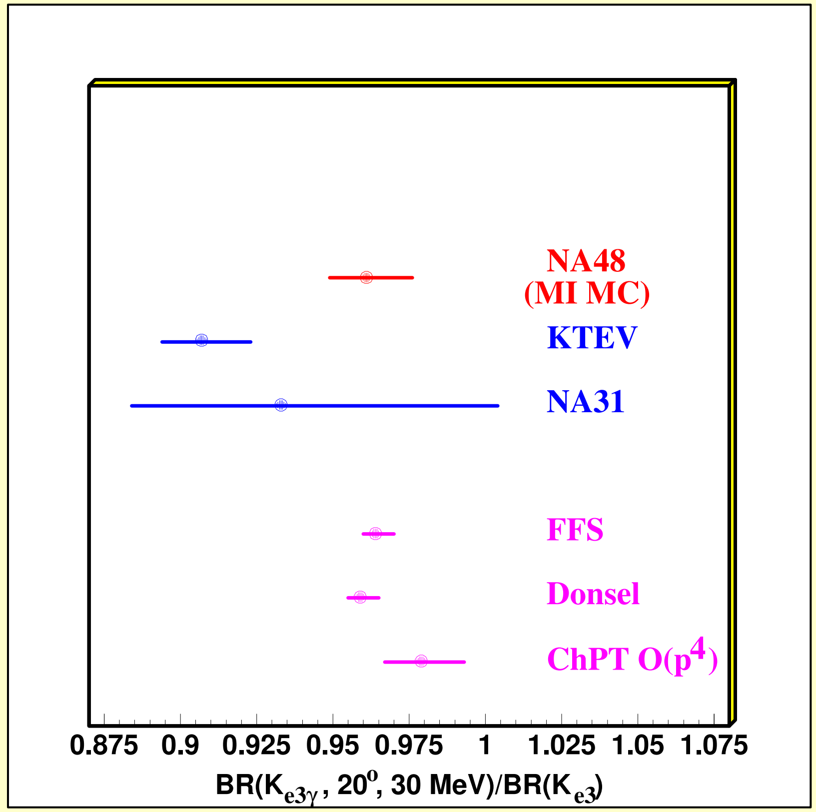


❖ No evidence for scalar and tensor couplings!

$K^0_L \rightarrow \pi e \nu \gamma$

❖Data analysis

- ➢Tight selection in order to suppress background from $K_{3\pi}$, K_{e4} and K_{e3} + accidental photon
- ➢Selected events:
  - 19000 : $K_{e3\gamma}$
  - 5.6 million : K_{e3}



Preliminary result:

$$\frac{\Gamma(K_{e3\gamma}, E^*_\gamma > 30 MeV, \theta^*_{e\gamma} > 20^\circ)}{\Gamma(K_{e3})} = (0.964 \pm 0.008^{+0.012}_{-0.011})\%$$

❖Good agreement with theory predictions!

Rare decays

- $K^0_L \rightarrow e^+e^-\gamma$ form factor

Measures structure of γ^* vertex

NA48 98-2001 data ~ 60 000 ev.

Preliminary result for BMS form factor

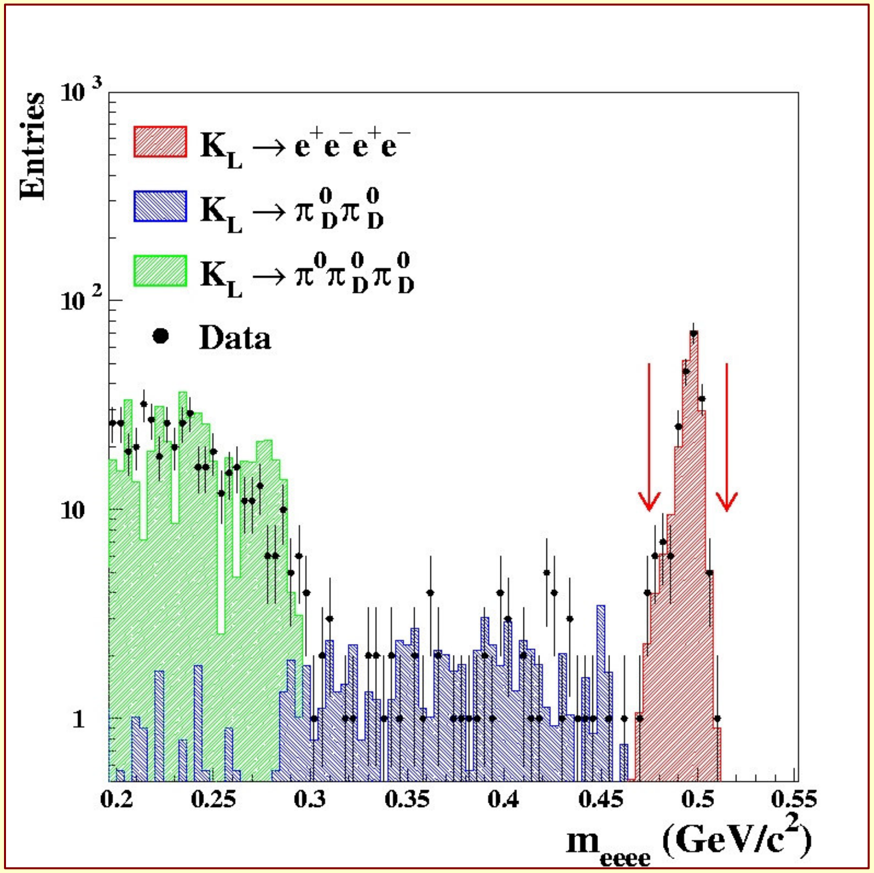
$\alpha_K^* = -0.207 \pm 0.019 \pm 0.017$

In good agreement with KTeV

- $Br(K^0_L \rightarrow e^+e^- e^+e^-)$

200 events from 98/99 data

$Br(K^\pm \rightarrow e^+e^- e^+e^-) =$
$(3.30 \pm 0.24_{stat} \pm 0.14_{syst} \pm 0.24_{norm})\times10^{-8}$



Rare decays

- K^0e4 decay

$Br(K_L \rightarrow \pi^{\pm} \pi^{0} e^{\pm} \nu) = (5.21 \pm 0.07_{stat} \pm 0.09_{syst}) \times 10^{-5}$

Precise measurement of the form factors   Phys.Lett B 595,75,2004

- Search for $K_s \rightarrow \pi^0\pi^0\pi^0$. Final result on CPV parameter η^{000}

$Re(\eta^{000}) = -0.002 \pm 0.011_{stat} \pm 0.015_{syst}$
$Im(\eta^{000}) = -0.003 \pm 0.013_{stat} \pm 0.017_{syst}$

hep-ex/0408053

$Br(K_s \rightarrow \pi^0\pi^0\pi^0) < 7.4 \times 10^{-7}$ 90% CL

- Observation of 6 $K_s \rightarrow \pi^+\mu^+\mu^-$ events

$Br(K_s \rightarrow \pi^+ \mu^+ \mu^-) = (2.8 +0.15_{stat} - 0.12_{stat} \pm 0.2_{syst}) \times 10^{-9}$

Conclusions

- PDG values on |Vus| are in poor agreement with unitarity of the CKM matrix
- NA48 has performed |Vus| measurements in K^0_Le3 and $K^\pm$e3 decays
- K_L and $K^\pm$ results are
  - in disagreement with previous PDG values
  - In good agreement with recent results from KTeV and BNL
  - In fair agreement with SM predictions (better for $K^\pm$, worse for K_L)
- More precise values for $f_+(0)$ are needed to solve the unitarity dilemma
- Semileptonic K_L decays
  - $K^0_L \rightarrow \pi e \nu$ form factors
  - Radiative decays $K^0_L \rightarrow \pi e \nu \gamma$
- Kl $\rightarrow \gamma^* \gamma^{(*)}$ decays
  - $K^0_L \rightarrow e^+ e^- \gamma$ form factor and $K^0_L \rightarrow e^+ e^- e^+ e^-$
- Rare Ks decays
  - First observation of Ks $\rightarrow \pi^+ \mu^+ \mu^-$
  - Search for $K_s \rightarrow \pi^0 \pi^0 \pi^0$