V_{us} measurement and CKM unitarity

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Neutral Kaons discovered in
Cosmic rays in 1947.

Unitarity test of CKM

Unitarity (or lack thereof) of CKM matrix tests existence of further quark generations and possible new physics (eg. Supersymmetry)

Most precise test of unitarity possible at present comes from 1st row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$$

Can test if $\Delta = 0$ at 10^{-3} level:

from super-allowed nuclear β -decays: $2|V_{ud}|\delta V_{ud} = 0.0010$

from semileptonic kaon decays: $2|V_{us}|\delta V_{us} = 0.0010$

$V_{ud}^2 = 0.9483 \pm 0.0010$ (nuclear decays)

$V_{us}^2 = 0.0482 \pm 0.0010$ (from e.g. $K^+ \to \pi^0 e^+ \nu_e$)

$V_{ub}^2 = 0.000011 \pm 0.000003$ (B meson decays)

PDG 2004

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0\ 9965 \pm 0.0015$$

(~ 2.3 σ deviation)

V_{us} from Kl3 decays

$|V_{us}|$ can be determined from K_{l3} partial decay widths

$$|V_{us}|\cdot f_+^{K^0\pi^-}(0)=\frac{1}{C_i}\left[\frac{192\pi^3\Gamma_i}{G_\mu^2 M_{K_i}^5 S_{ew} I_i(\lambda_+,\lambda_0)}\right]^{1/2}\frac{1}{1+\delta^i_{SU(2)}+\delta^i_{e^2p^2}+1/2\,\Delta I_i(\lambda_+,\lambda_0)}$$

where *i* runs over the four modes $K^{\pm,0}_{e3}$, $K^{\pm,0}_{\mu 3}$
[C_i=1($2^{-1/2}$) for neutral (charged kaon decays)]

Experimental inputs: $\Gamma(Br,\tau)$, λ, M_K

- $f_+^{K^0\pi^-}(0)$ form factor at zero momentum transfer: pure theory calculation (χPT, lattice)
- $I_i(\lambda_+,\lambda_0)$ phase space integral
- S_{ew} short distance corrections (1.0232)
- $\Delta I_i(\lambda_+,\lambda_0)$ phase space electromagnetic correction
- $\delta^i_{SU(2)}$, $\delta^i_{e^2p^2}$ ff correction due to isospin breaking (strong and e.m.)

Recent measurements

	K^0	$K^{\pm}$
E865		$BR(K^{\pm}_{e3})$
KTeV	K_L dominant BR's K_L semileptonic ff slopes	
NA48	$BR(K_{Le3})$ K_L vec. & scal. ff slopes	$BR(K^{\pm}_{\ell 3})$
KLOE	$BR(K_{Se3})$ K_L dominant BR's K_L lifetime K_L vec. ff slopes	$K^{\pm}$ semileptonic BR's $BR(K^{+}_{\mu 2})$ $K^{\pm}$ lifetime
ISTRA+		$BR(K^{-}_{e3})$ K^{-} vec. & scal. ff slopes

2003: A new value for BR(K^+_{e3})

BNL E865

BR($K^+ \rightarrow \pi^0 e^+ \nu(\gamma)$) = ($5.13 \pm 0.02_{stat} \pm 0.10_{sys}$)%

PDG(<2004): (4.87±0.06)%

Gives value for V_{us} consistent with unitarity but BR is 2.7σ above previous value.

Correct treatment of radiative process done for the first time

Using 70,000 K^+_{e3} decays normalized to $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \pi^0\mu^+\nu$, $K^+ \rightarrow \pi^+\pi^0\pi^0$,

- Key issue is systematic control of the Branching Ratio.
- Detector not optimized for photons (designed for $\pi^+\mu^- e^+$)
- ***Require:*** $\pi^0 \rightarrow e^+e^-\gamma$ in signal and normalization

K_L BRs from KTeV

KTeV measures 5 K_L decay ratios **$K_{L\mu3}/K_{Le3}$; $3\pi^0/K_{Le3}$; $\pi^+\pi^-\pi^0/K_{Le3}$; $\pi^+\pi^-/K_{Le3}$; $\pi^0\pi^0/3\pi^0$**

(sample sizes 10^5-10^6)

These 6 decay modes account for 99.93% of K_L decays and the ratio can be combined to extract BR,i.e

$$B_{K_{e3}} = \frac{1-B_{rare}}{1-\frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}+\frac{\Gamma_{000}}{\Gamma_{Ke3}}+\frac{\Gamma_{+-0}}{\Gamma_{Ke3}}+\frac{\Gamma_{+-.}}{\Gamma_{Ke3}}+\frac{\Gamma_{00}}{\Gamma_{Ke3}}}$$

$$BR(K_L\to\pi e\nu(\gamma)) = 0.4067 \pm 0.0011$$

$$BR(K_L\to\pi\mu\nu(\gamma)) = 0.2701 \pm 0.0009$$

$$BR(K_L\to\pi^+\pi^-\pi^0(\gamma)) = 0.1252 \pm 0.0007$$

[PRD 70 (2004)]

$$BR(K_L\to\pi^0\pi^0\pi^0) = 0.1945 \pm 0.0018$$

$$BR(K_L\to\pi^+\pi^-(\gamma)) = (1.975 \pm 0.012)\times10^{-3}$$

$$BR(K_L\to\pi^0\pi^0) = (0.865 \pm 0.010)\times10^{-3}$$

$BR(K_{L\,e3})$ from NA48

measures ratio of BR: (~6 million reconstructed K_{e3})

- $$R = \frac{BR(K_L \to \pi e \nu)}{BR(2\ \text{track})} = 0.4978 \pm 0.0035 \approx \frac{BR(K_L \to \pi e \nu)}{1 - BR(K_L \to 3\pi^0)}$$

Using PDG-KTeV average for $BR(K_L \to 3\pi^0) = 0.1992 \pm 0.0070$

[PLB, 602 (2004)]

$$BR(K_L \to \pi e \nu(\gamma)) = 0.4010 \pm 0.0028_{exp} \pm 0.0035_{norm}$$

- They also have a **preliminary** measurement of $BR(K_L \to 3\pi^0)$ extracted from $BR(K_L \to 3\pi^0)/BR(K_S \to 2\pi^0)$

$$BR(K_L \to 3\pi^0) = 0.1966 \pm 0.0006 \pm 0.0033$$ (PDG value for $BR(K_L \to 2\pi^0)$)

Compare $BR(K_L \to 3\pi^0) = 0.1969 \pm 0.0026$ from KLOE-KTeV average

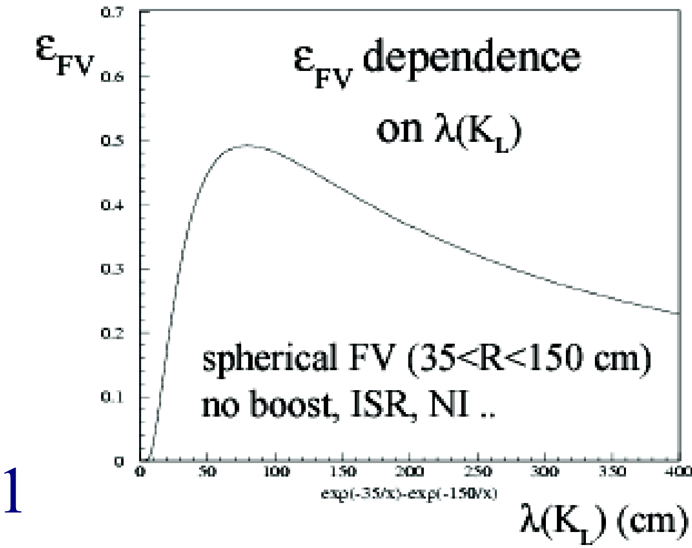
K_L BRs and τ_L from KLOE

KLOE measures 4 dominant τ_L dependent absolote BRs by K_S tagging

Setting Σ BR($K_L \rightarrow$ X) =1 **(sample sizes 10^7)**
independent measurement of τ_L

K_L FV acceptance depends on the lifetime :

$\tau_L = 50.72 \pm 0.17 \pm 0.33$ ns [PLB, 632 (2006)]



$BR(K_L \rightarrow \pi e \nu(\gamma)) = 0.4007 \pm 0.0006 \pm 0.0014$

$BR(K_L \rightarrow \pi \mu \nu(\gamma)) = 0.2698 \pm 0.0006 \pm 0.0014$

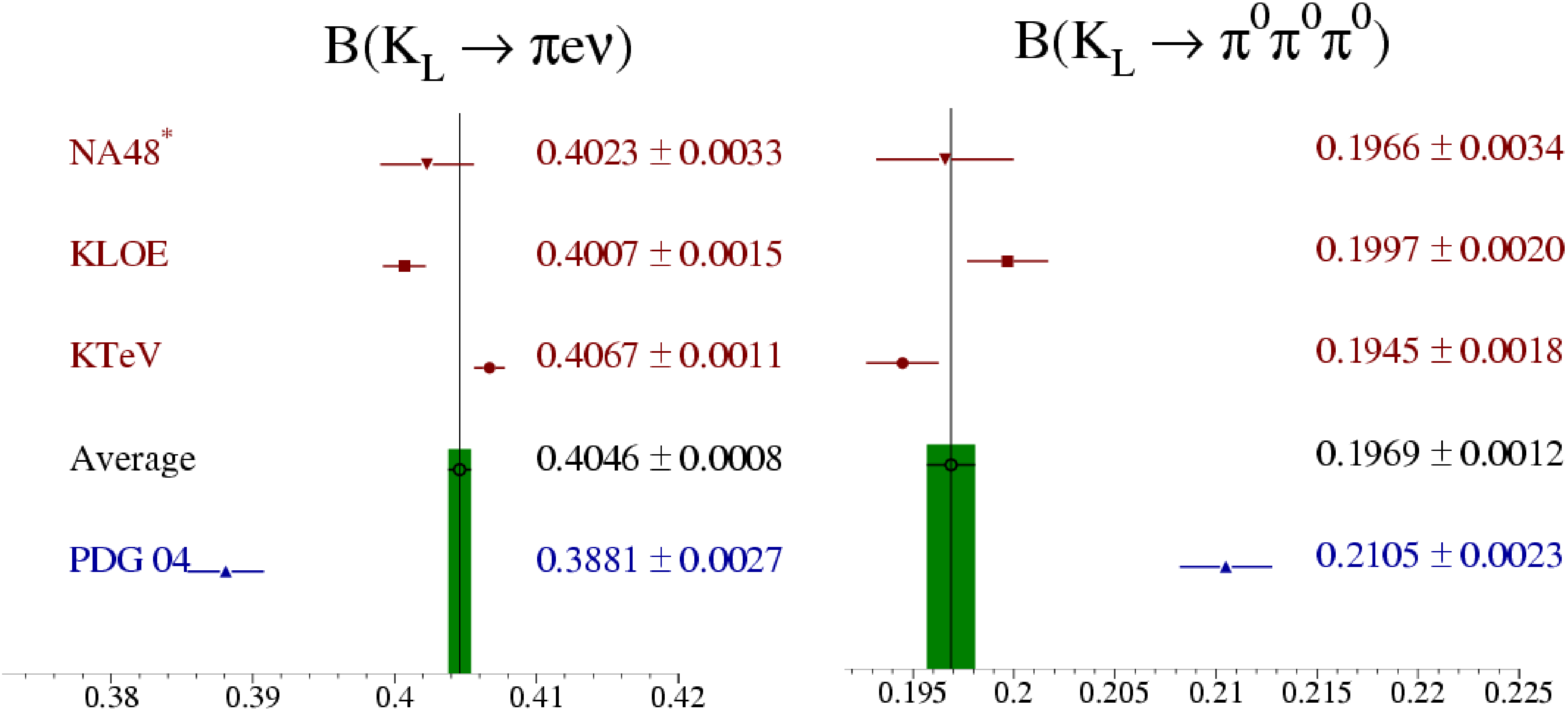
$BR(K_L \rightarrow 3\pi^0) = 0.1997 \pm 0.0005 \pm 0.0019$

$BR(K_L \rightarrow \pi^+\pi^-\pi^0(\gamma)) = 0.1263 \pm 0.0005 \pm 0.0011$

KLOE measures τ_L from K_L decay time distribution [PLB, 626 (2005)]

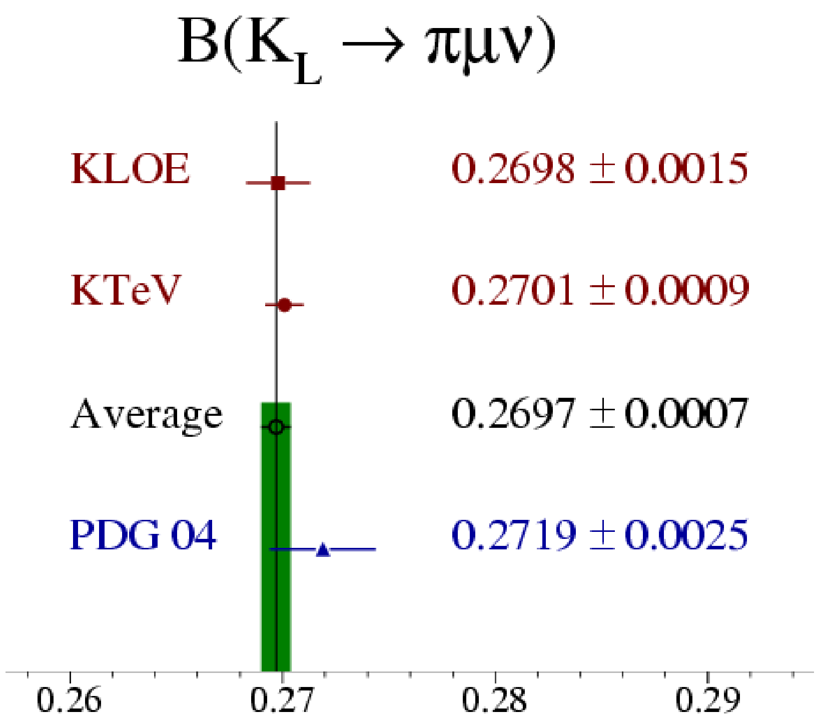
$\tau_L = 50.92 \pm 0.17 \pm 0.25$ ns 14.5×10^6 $K_L \rightarrow 3\pi^0$ events

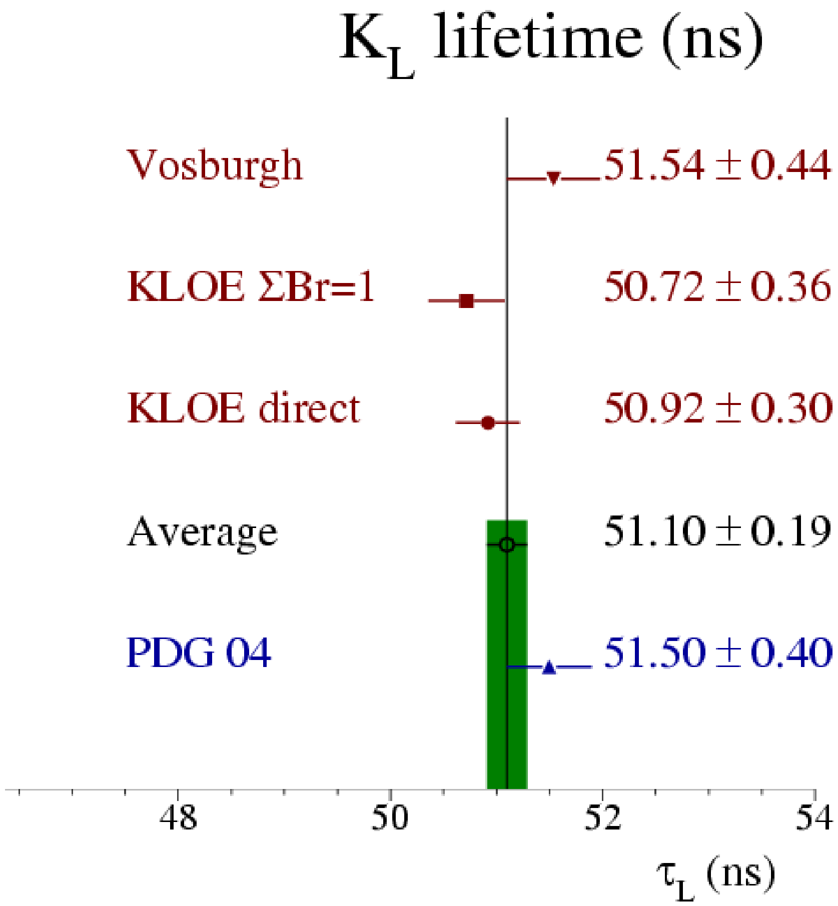
Comparison of recent measurement



*using NA48 measurement for $3\pi^0$

Comparision of recent measurement





A Fit to recent measurement

**Preliminary

$B(K_{L000})$** = 0.1966 ±0.0034

$B(K_{Le3})/B(K_{L2T})$ = 0.4978 ±0.0035

$B(K_{+-0})/B(K_{Le3})$ = 0.3078 ±0.0017

$B(K_{000})/B(K_{Le3})$ = 0.4782 ±0.0053

$B(K_{L\mu3})/B(K_{Le3})$ = 0.6640 ±0.0026

τ_L = 51.54 ±0.44 ns

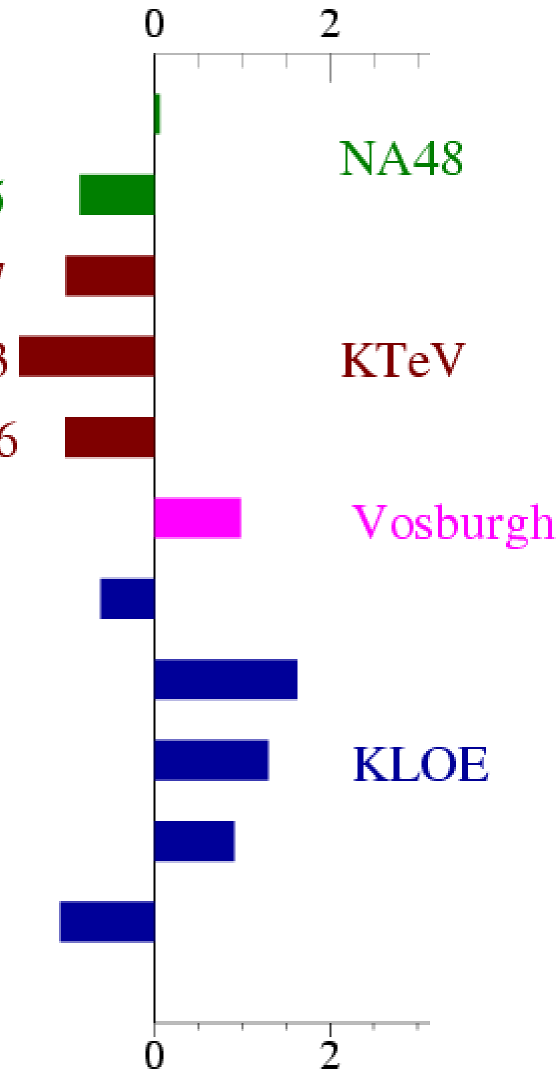
τ_L = 50.92 ±0.30 ns

$B(K_{L000})$ = 0.2018 $f(\tau_L)$ ±0.0023

$B(K_{L+-0})$ = 0.1276 $f(\tau_L)$ ±0.0015

$B(K_{L\mu3})$ = 0.2726 $f(\tau_L)$ ±0.0016

$B(K_{Le3})$ = 0.4049 $f(\tau_L)$ ±0.0021



$P(\chi^2)$=7.5%

$f(\tau_L)=1/(1+1.5(\tau_v-\tau_L)/\tau_v)$; τ_v=51.54 ns

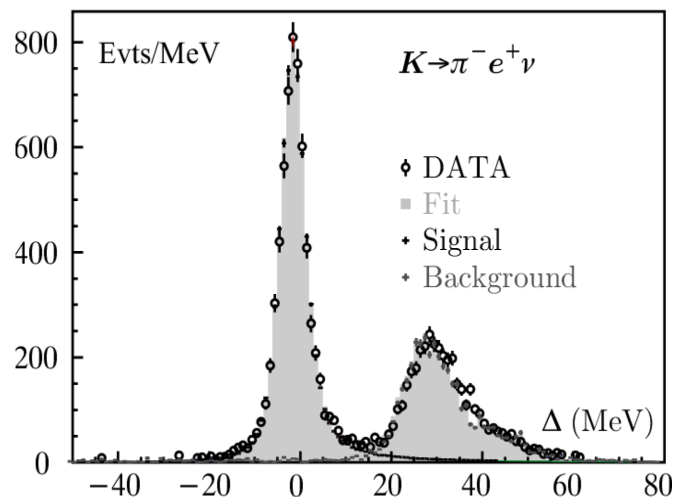
KLOE: $K_S \to \pi e \nu$ decays

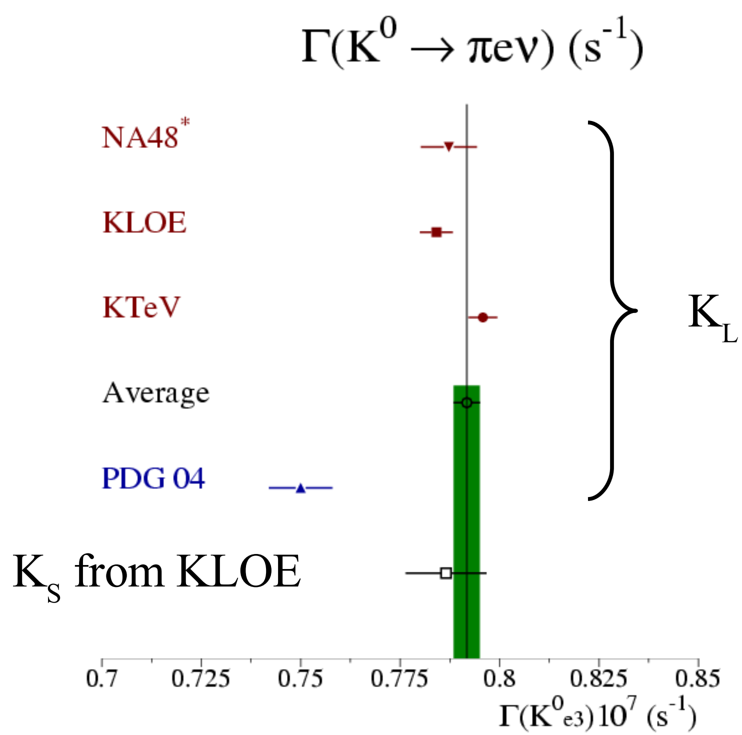
unique to KLOE

$BR(K_S \to \pi^- e^+ \nu) = (3.528 \pm 0.057_{stat} \pm 0.027_{syst})\ 10^{-4}$

$BR(K_S \to \pi^+ e^- \nu) = (3.517 \pm 0.051_{stat} \pm 0.029_{syst})\ 10^{-4}$ [PLB 636(2006)]

$BR(K_S \to \pi e \nu) = (7.046 \pm 0.077_{stat} \pm 0.049_{syst})\ 10^{-4}$





linear form factor slope

$\lambda_+ = (33.9 \pm 4.1) \times 10^{-3}$

$K^{\pm}_{e3}$ from KLOE, NA48 and ISTRA

KLOE preliminary:

$BR(K^{\pm}_{e3}) = (5.047 \pm 0.019_{Stat} \pm 0.039_{Syst})\%$

$BR(K^{\pm}_{\mu 3}) = (3.310 \pm 0.016_{Stat} \pm 0.045_{Syst-})\%$

NA48 preliminary:

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

Using PDG04 value for $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0})$

$BR(K^{\pm}\rightarrow\pi^{0}e\nu) = (5.14\pm0.02_{stat} \pm0.06_{syst})\%$

Measurement of $R_{\mu e} = BR(K^{\pm}\rightarrow\pi^{0}\mu\nu)/BR(K^{\pm}\rightarrow\pi^{0}e\nu)$

$R_{\mu e} = 0.6749 \pm 0.0035 \pm 0.0011 \pm 0.0021$

ISTRA+ preliminary:

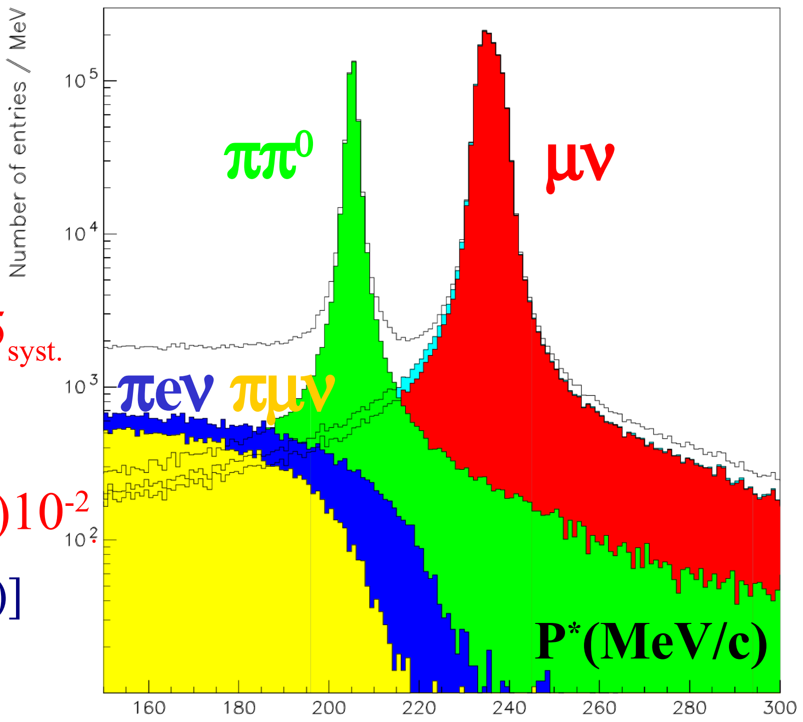
Measurement of $BR(K^{-}\rightarrow\pi^{0}e\nu)/BR(K^{-}\rightarrow\pi^{-}\pi^{0})$

$BR(K^{-}\rightarrow\pi^{0}e\nu) = (5.22\pm0.11)\%$

Others recent dominant $K^{\pm}$ BRs

Kμ2 from KLOE

- **Tag from $K^- \rightarrow \mu^- \nu$** [PLB 632 (2006)]
- **2002 data ~ 175 pb^{-1}**
- **Event counting performed by fitting the P^* distribution**



$BR(K^+ \rightarrow \mu^+\nu(\gamma)) = 0.6366 \pm 0.0009_{stat.} \pm 0.0015_{syst.}$

$K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ from KLOE [PLB 597 (2004)]

$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0) = (1.763 \pm 0.013_{stat.} \pm 0.022_{syst})10^{-2}$

$K^{\pm}\mu3/K^{\pm}e3$ from E246 (KEK) [PLB 513 (2001)]

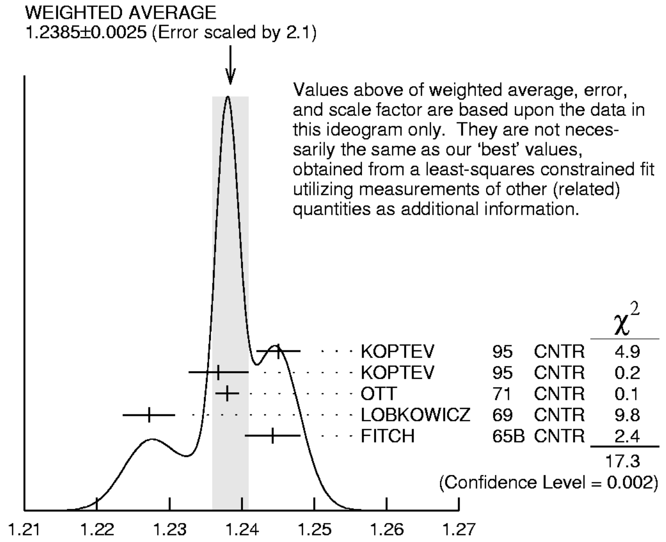
$R_{\mu e} = (0.671 \pm 0.007_{stat.} \pm 0.008_{syst})10^{-2}$.

Kμ2/Kπ2 from part of PS183 [PRD 45 (1992)]

$BR(K^+ \rightarrow \mu^+\nu(\gamma))/BR(K^+ \rightarrow \pi^+\pi^0) = 0.3329 \pm 0.0047_{stat.} \pm 0.0010_{syst.}$

For $K^+ \rightarrow \pi^+\pi^+\pi^-$ need to go back to the '60s (use PDG average)

KLOE: $K^{\pm}$ lifetime

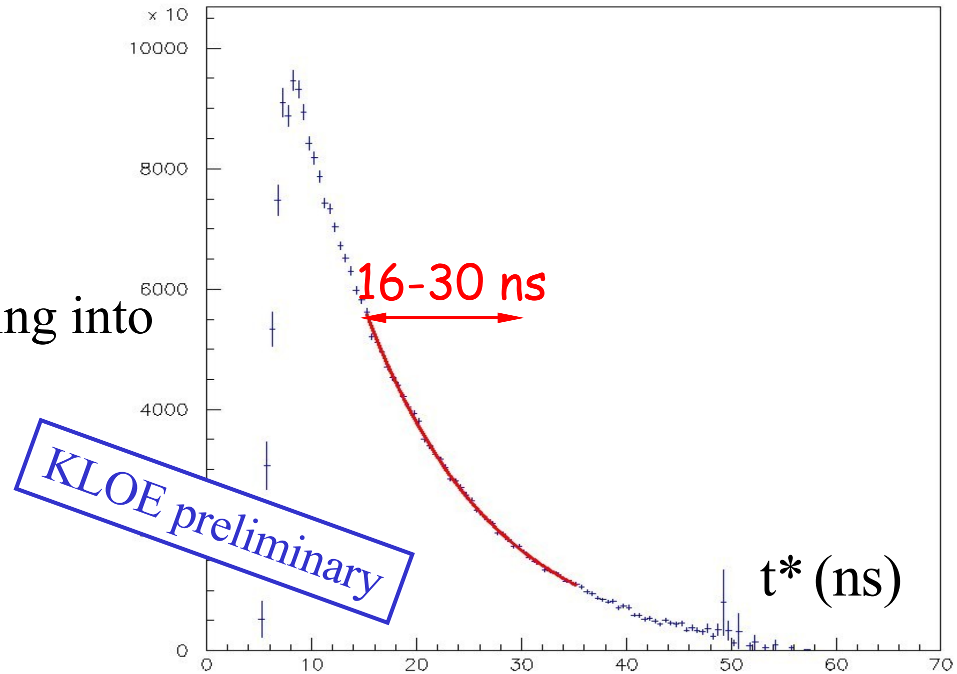


- Very good accuracy
- Poor consistency among measurements
- Needs for cross checks

$\tau_{\pm}$ from the K decay length at KLOE

Fit the kaon decay length distribution, taking into account the energy loss: $t^* = \sum_i L_i/(\beta_i\gamma_i c)$

$\tau_{\pm}$= 12.367 ± 0.044_{Stat} ± 0.065_{Syst} ns



A fit to the recent measurements

$BR(K^+ \to \mu^+\nu) = 0.6356 \pm 0.0013$

$BR(K^+ \to \pi^+\pi^0) = 0.2077 \pm 0.0012$

$BR(K^+ \to \pi^+\pi^+\pi^-) = (5.48 \pm 0.10)\%$

$BR(K^+ \to \pi^+\pi^0\pi^0) = (1.77 \pm 0.03)\%$

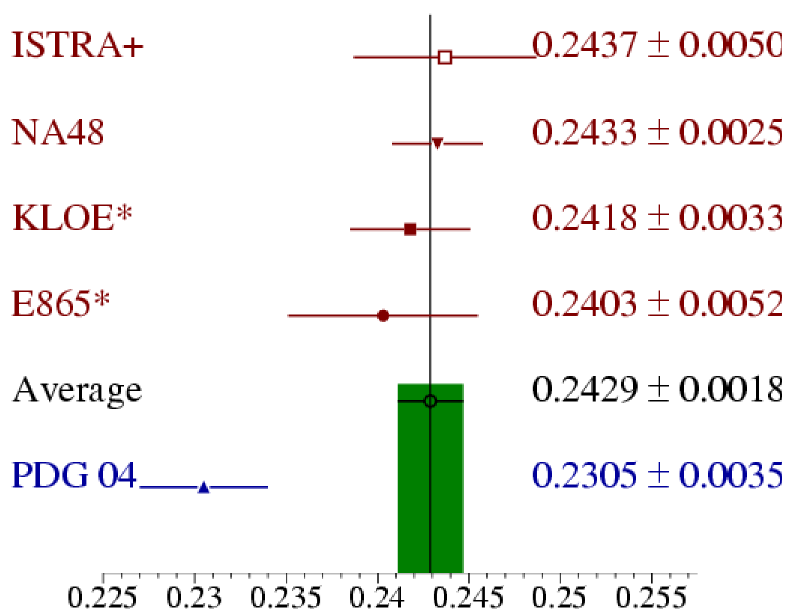
$BR(K^+ \to \pi^+ e\nu) = (5.048 \pm 0.031)\%$

$BR(K^+ \to \pi^+\mu\nu) = (3.383 \pm 0.027)\%$

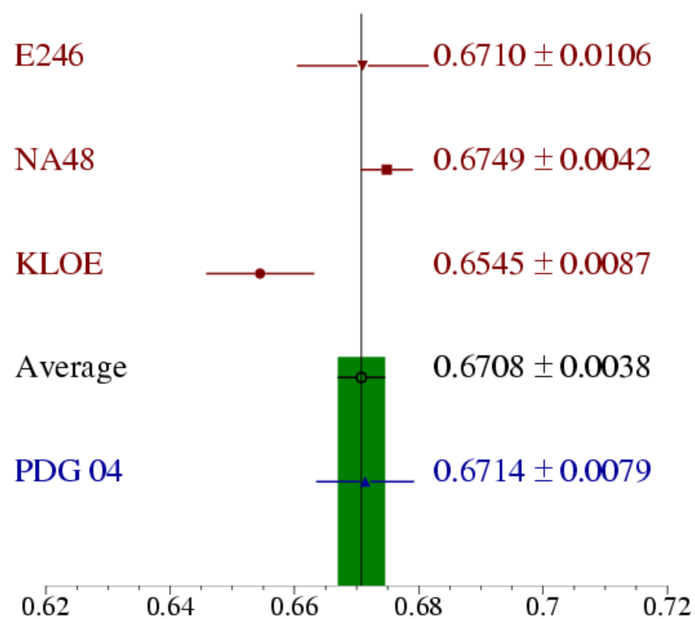
$\tau^+ = 12.384 \pm 0.022$ ns

$\chi^2/ndf=6.7/7$

$B(K^\pm \to \pi e\nu)/B(K^\pm \to \pi^\pm\pi^0)$



$B(K^\pm \to \pi\mu\nu)/B(K^\pm \to \pi e\nu)$



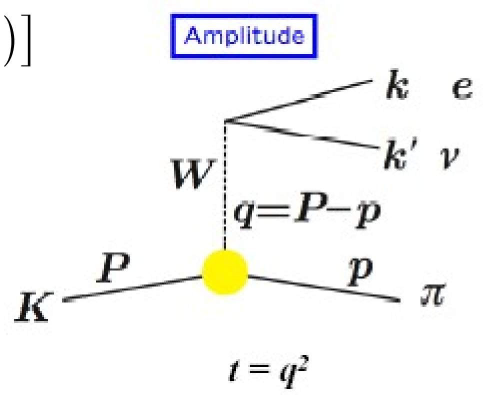
* $K\pi2$ from fit excluding ISTRA and NA48

Form Factor

$$\langle \pi | J^\alpha | K \rangle = f_{+.}(0)\left[(P+p)^\alpha \tilde{f}_{+.}(t) + (P-p)^\alpha \tilde{f}_{-.}(t) \right]$$

$$\tilde{f}_0(t) = \tilde{f}_{+.}(t) + \frac{t}{m_\pi^2 + M_K^2}$$

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\frac{t}{m_\pi^2} + \frac{1}{2}\lambda''_{+,0}\frac{t^2}{m_\pi^4} + ...$$



$I(\lambda_+, \lambda_0)$ phase space integral needed for extracting Vus is a function of ff slopes

e.g. for Ke3,

$$I_{e3} = 0.56340158 + 1.9470583\lambda' + 2.6907652(\lambda'^2 + \lambda'') + 9.2753527\lambda''\lambda' + 9.10997871\lambda''^2$$

Fit of ***t*-spectrum** with different hypotheses on form factor $f(t)/f(0)$:

Quadratic

$$1 + \lambda'\frac{t}{m_\pi^2} + \frac{1}{2}\lambda''\frac{t^2}{m_\pi^4}$$

or

Polar

$$\frac{M^2}{M^2 - t}$$

, implying $\lambda' = \frac{m_\pi^2}{M^2}; \lambda'' = 2\lambda'^2$

Form Factor comparison

KTeV [PRD 70(2004)]

K^0_{e3} quadratic fit: $\lambda''_+ \neq 0$ @ 4σ level

$K^0_{\mu 3}$ quadraqtic fit: $\lambda_0 = (13.72 \pm 1.31)\ 10^{-3}$

Slopes consistent for K^0_{e3} and $K^0_{\mu 3}$

ISTRA+ [PLB 581(2004), PLB589(2004)]

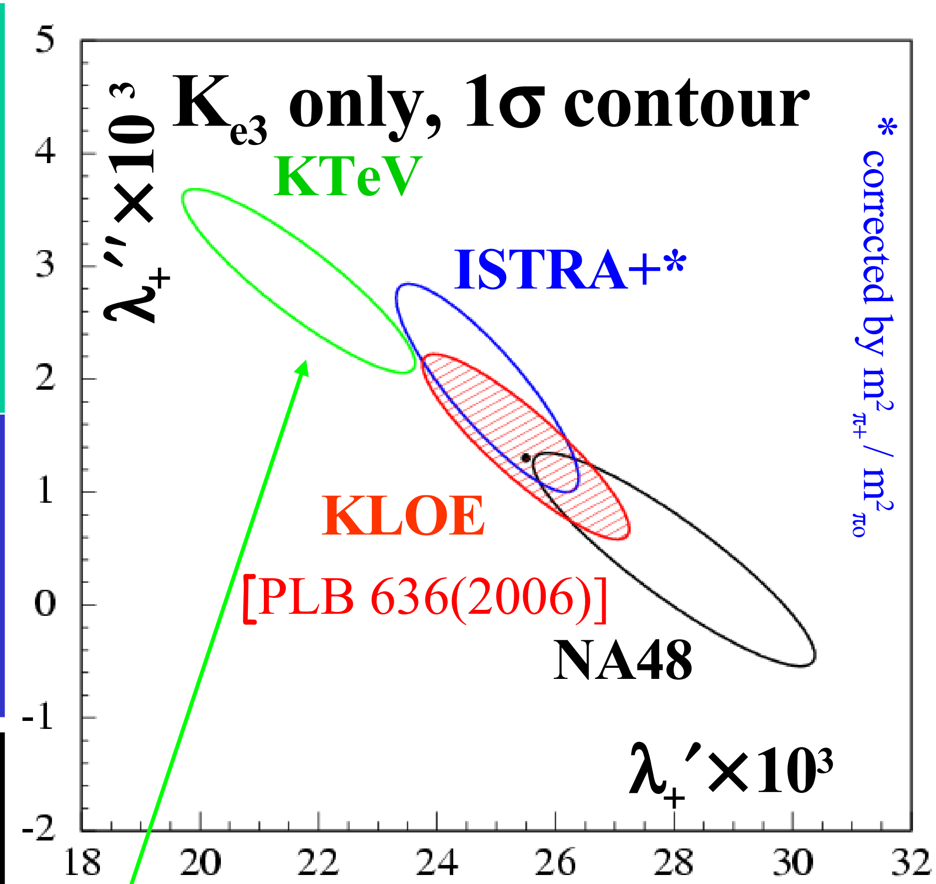
K^-_{e3} quadratic fit: $\lambda''_+ \neq 0$ @ 2σ level

$K^-_{\mu 3}$ quadratic fit: $\lambda_0 = (17.11 \pm 2.31)\ 10^{-3}$

NA48 [PLB 604(2004), HEP2005 289]

K^0_{e3}: No evidence for quadratic term

$K^0_{\mu 3}$ linear fit: $\lambda_0 = (12.0 \pm 1.7)\ 10^{-3}$



$\lambda''_+ \rightarrow -1\%$ phase space integral

$\rightarrow +0.5\%$ for V_{us}

Form Factor comparison

Pole model $\lambda' = (m/M_V)^2,\ \lambda'' = 2\lambda'^2$

KLOE

$M_V = (870 \pm 7)$ MeV /c²

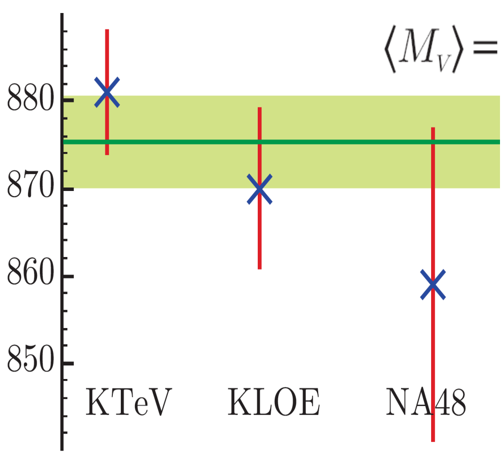
KTeV

$M_V = (882.32 \pm 6.54)$ MeV /c²

$M_s = (1173.80 \pm 39.47)$ MeV/c²

NA48

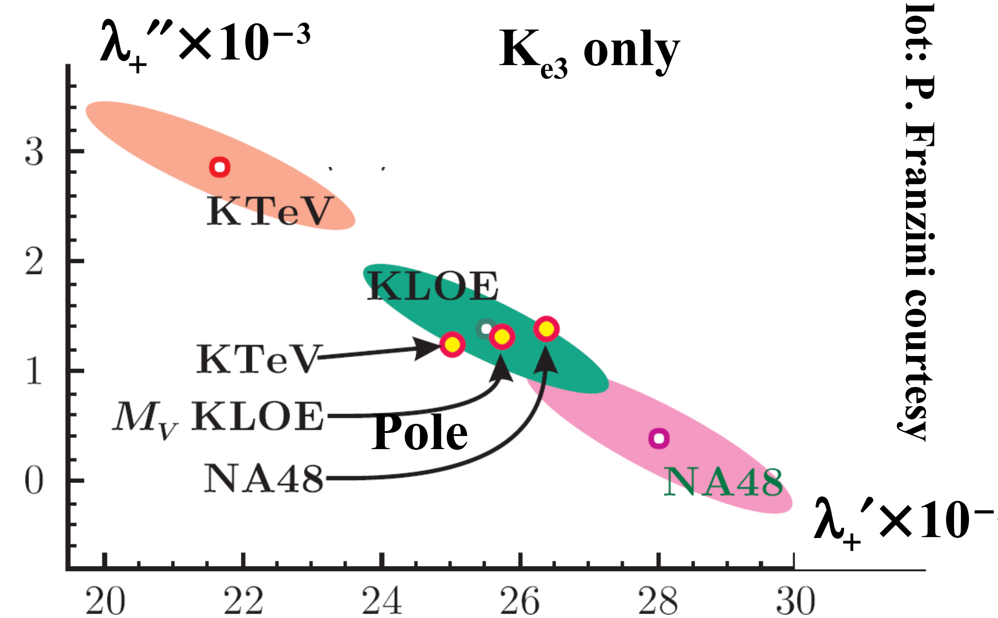
$M_V = (859 \pm 18)$ MeV /c²



$\langle M_V \rangle = 875.3 \pm 5.4,\quad \chi^2 = 1.8$

$\lambda' = 25.42 \pm 0.31$

$\lambda'' = 1.29 \pm 0.032$



plot: P. Franzini courtesy

Phase space integral, **Pole model** versus **Quadratic parameterization**:

- KLOE: 0.5 per mil difference
- KTeV: 6 per mil difference.

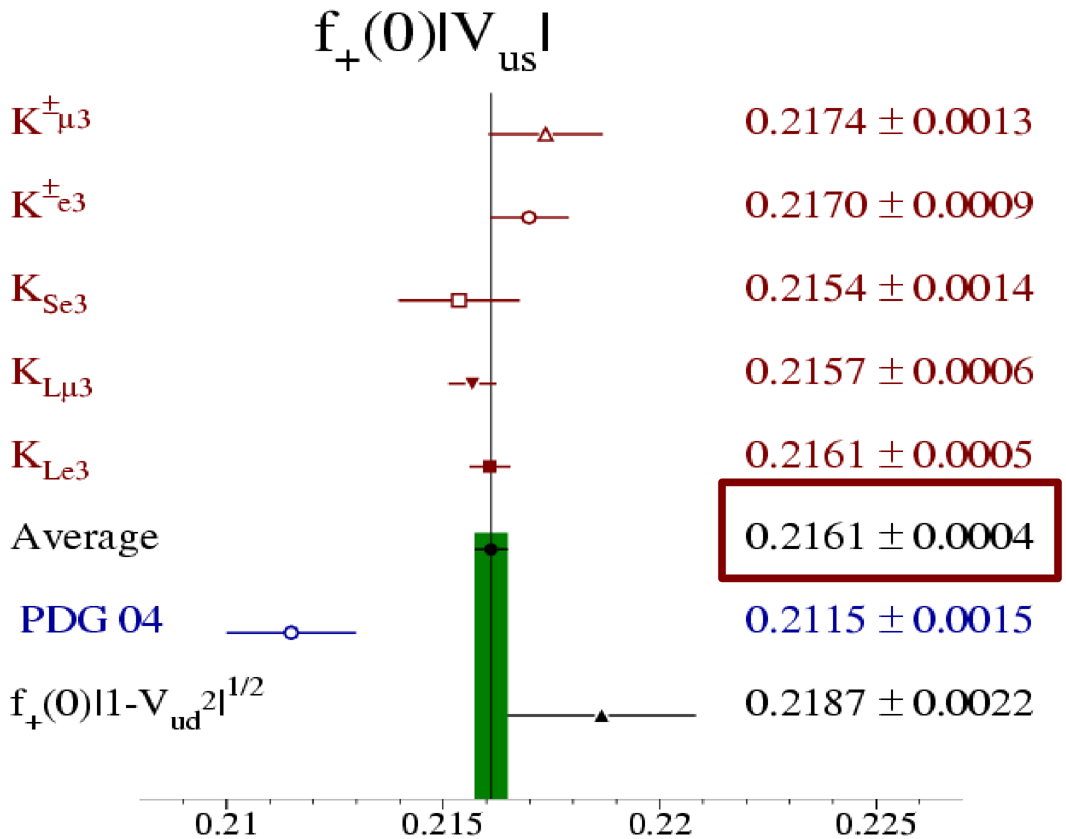
V_{us} determination from Kl3

	$K_L\,e3$	$K_L\,\mu3$	$K_S\,e3$	$K^{\pm}e3$	$K^{\pm}\mu3$
BR	0.4046(8)	0.2697(7)	7.046(91)×10^{-4}	0.05043(31)	0.03383(27)
τ	51.10(19) ns		89.58(6) ps	12.386(22) ns	

$\lambda'_+ = 0.02496(79)$

$\lambda''_+ = 0.0016(3)$

$\lambda_0 = 0.01587(95)$



- $f_+(0)=0.961(8)$
  Leutwyler and Roos Z. [Phys. **C25**, 91, 1984]
- $V_{ud}=0.97377(27)$
  Marciano and Sirlin [Phys.Rev.Lett.96 032002,2006]

$$V_{us} = 0.2249 \pm 0.0019$$

From $R_{e\mu}$:

$$\frac{g_e}{g_\mu} = 1.0014 \pm 0.0037$$

$V_{us} - V_{ud}$ plane

Combining the experimental value of $\Gamma(K\to\mu\nu(\gamma))/\Gamma(\pi\to\mu\nu(\gamma))$ with the ratio f_K/f_π obtained from lattice calculations we can extract $|V_{us}|/|V_{ud}|$

(Marciano hep-ph/0406324) $\Gamma(K\to\mu\nu(\gamma))/\Gamma(\pi\to\mu\nu(\gamma)) \propto |V_{us}|^2/|V_{ud}|^2 f_K^2/f_\pi^2$

Using f_K/f_π =1.198(3)($^{+16}_{-5}$) from MILC

and **KLOE BR($K^+ \to \mu^+\nu$)**

we get **V_{us}/V_{ud} = 0.2294 ± 0.0026**

Fit of the above results:

V_{us} = 0.2244 ± 0.0015

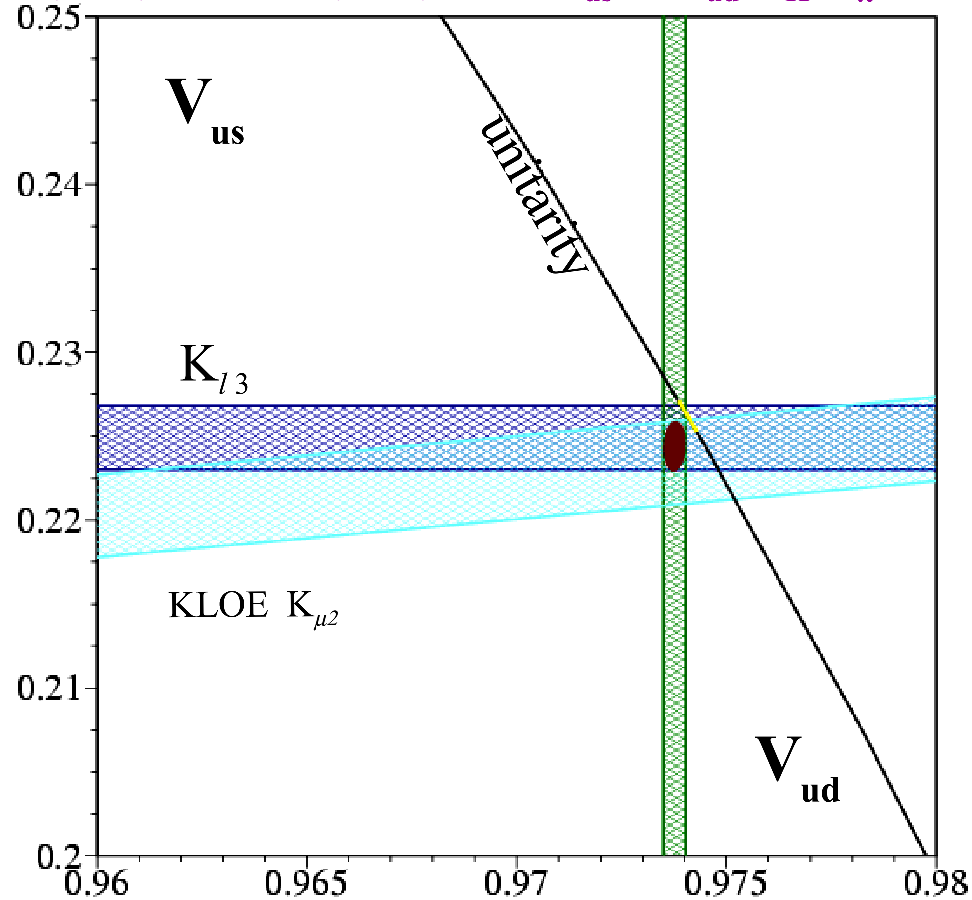
V_{ud} = 0.97377 ± 0.00027

$P(\chi^2)$ = 0.63

Fit assuming unitarity:

$\sin(\theta_c)$= 0.2263 ± 0.0009

$P(\chi^2)$ = 0.22



Conclusions and Perspectives

- the CKM matrix appears to be unitary within $\sim 1\sigma$
- V_{us} still only known to about 1%

• improvement for $f_+(0)$ expected from lattice calculations

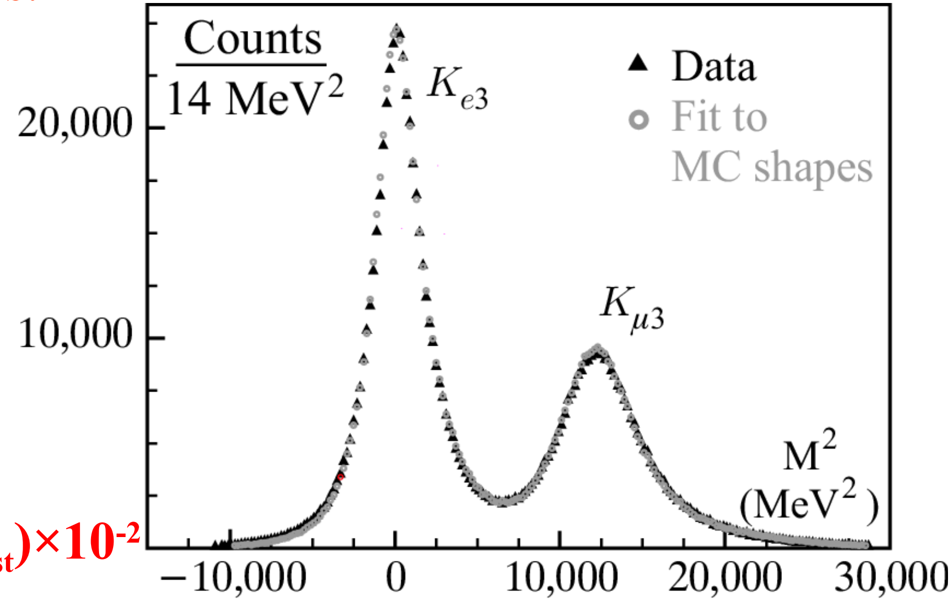
• KLOE and NA48 will have soon final results on charged kaon Branching Ratios and slopes

• Almost all dominant charged kaons BR's needs new measurements

• Using the full data sample (2.4 fb^{-1}) KLOE will update the BR measurement and will refine the slopes measurements improving by a factor 2 the statistical accuracy

KLOE: $K^{\pm}_{e3,\mu3}$ semileptonic BR

- **4 independent tag: $K^{\pm}\mu2$, $K^{\pm}\pi2$**; keep the systematic effects due to the tag selection under control.
- kinematical cuts to reject non-semileptonic decays, residual background is about 1.5% of the selected Kl3 sample
- Obtain number of signal events from a constrained likelihood fit of a **m^2 data distributions from ToF measurements**.



- Perform the **BR measurement on each tag sample** separately normalizing to tag counts in the same data set.

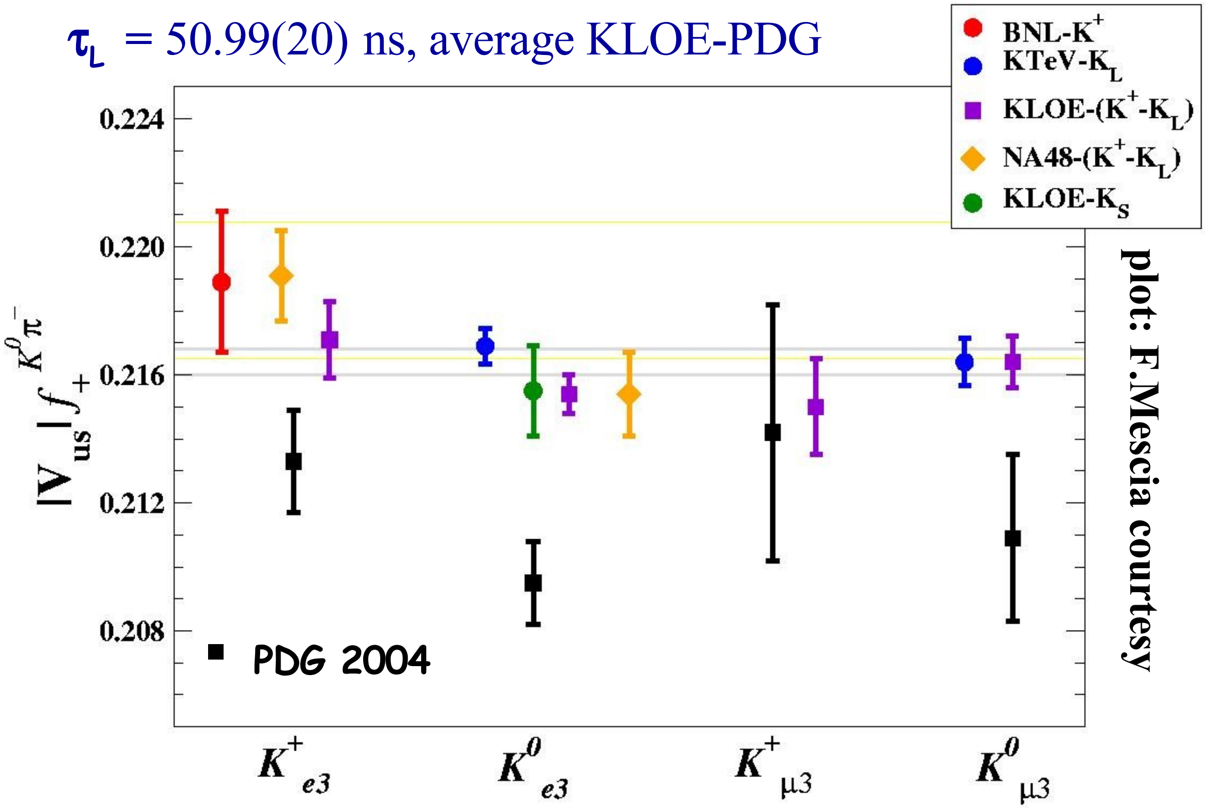
KLOE 2005 **preliminary**:

$$\mathbf{BR(K^{\pm}_{e3}) = (5.047 \pm 0.019_{Stat} \pm 0.039_{Syst})\times 10^{-2}}$$

$$\mathbf{BR(K^{\pm}_{\mu3}) = (3.310 \pm 0.016_{Stat} \pm 0.045_{Syst-})\times 10^{-2}}$$

V_{us} from all experiments

τ_L = 50.99(20) ns, average KLOE-PDG



plot: F.Mescia courtesy

$<V_{us} \times f_+(0)>_{\text{WORD AV.}} = 0.2164(4)$

CKM unitarity within $\sim 1\sigma$

Slopes

$\lambda'_+ = 0.02542(31)$

$\lambda''_+ = 0.00129(3)$

(Pole model: KLOE, KTeV, and NA48 ave.)

$\lambda_0 = 0.01587(95)$

(KTeV and Istra+ ave.)

From unitarity

- $f_+(0)=0.961(8)$

  Leutwyler and Roos Z. [Phys. **C25**, 91, 1984]
- $V_{ud}=0.97377(27)$

  Marciano and Sirlin [Phys.Rev.Lett.96 032002,2006]

$V_{us} \times f_+(0) = 0.2187(22)$

$V_{us} - V_{ud}$ plane

- Using $f_K / f_\pi = 1.198(3)(^{+16}_{-5})$ from MILC Coll. (2005) and **KLOE BR($K^+ \to \mu^+\nu$)** we get **$V_{us}/V_{ud} = 0.2294 \pm 0.0026$**
- $V_{us} = 0.2248 \pm 0.0020$

  K_{l3} KLOE, using $f_+(0)=0.961(8)$
- $V_{ud} = 0.97377 \pm 0.00027$

  Marciano and Sirlin
  Phys.Rev.Lett.96 032002,2006

Fit of the above results:

$V_{us} = 0.2242 \pm 0.0016$

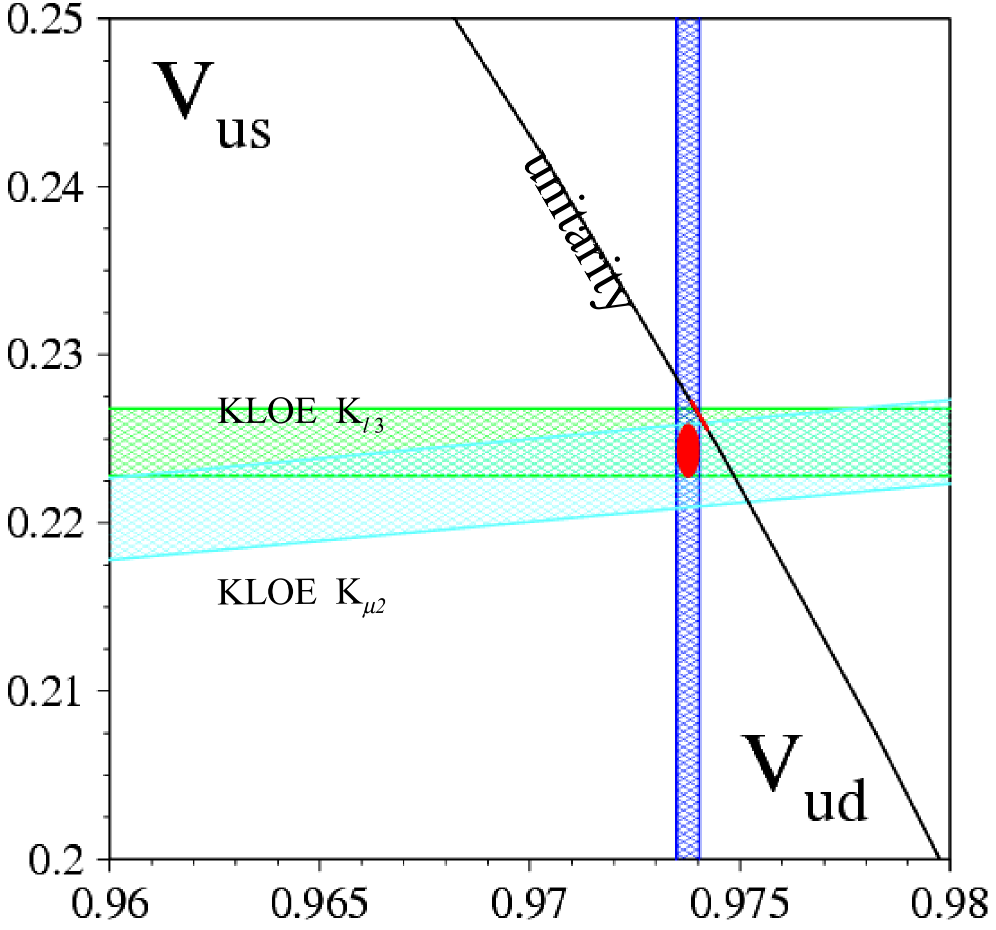
$V_{ud} = 0.97377 \pm 0.00027$

$P(\chi^2) = 0.8$

Fit assuming unitarity:

$V_{us} = 0.2264 \pm 0.0009$

$P(\chi^2) = 0.1$



NA48, KTEV, ISTRA: Form Factor

KTeV [PRD 70 (2004)]

$f_+(t)$ is consistent for the two decay modes ⬋ $\lambda' = (20.64 \pm 1.75) \times 10^{-3}$

$\lambda''_+ = (3.20 \pm 0.69) \times 10^{-3}$ 4σ

λ_0 ~ 5 times more precise than PDG ⬋ $\lambda_0 = (13.72 \pm 1.31) \times 10^{-3}$

Pole model

$M_V = (882.32 \pm 6.54)$ MeV /c²

$M_s = (1173.80 \pm 39.47)$ MeV/c²

λ''_+ ⬋ results in a 1% reduction of the phase space integral corresponding to an increase of 0.5% for V_{us}

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K^0_{e3} $\lambda'_+ = (28.8 \pm 1.2) \times 10^{-3}$ no evidence for quadratic term

Pole model $M_V = (859 \pm 18)$ MeV /c²

$K^0_{\mu3}$ $\lambda'_+ = (26.0 \pm 1.2) \times 10^{-3}$

$\lambda_0 = (12.0 \pm 1.7) \times 10^{-3}$

ISTRA +[PLB 581 (2004), PLB 589 (2004)]

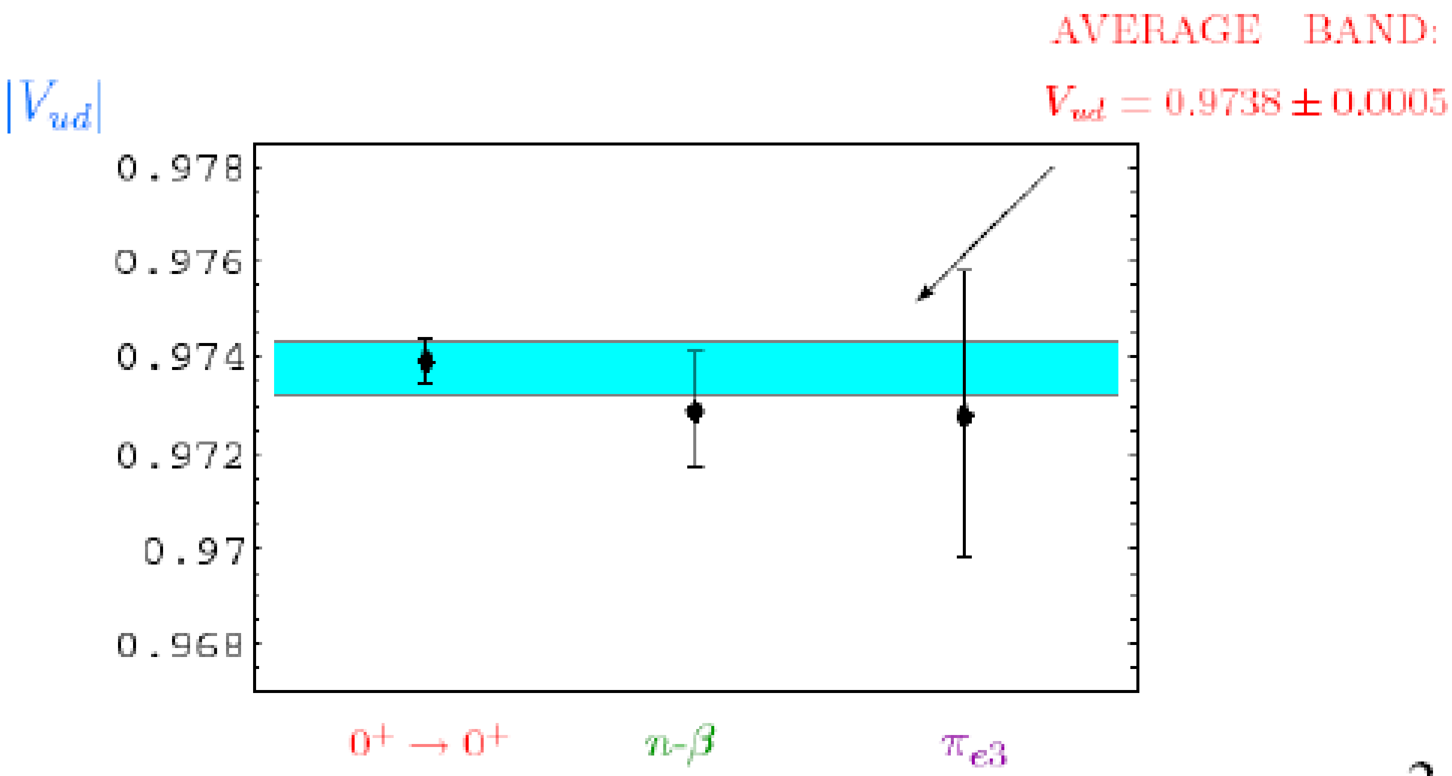
K^0_{e3} $\lambda'_+ = (24.85 \pm 1.66) \times 10^{-3}$ $K^0_{\mu3}$ $\lambda'_+ = (22.99 \pm 6.46) \times 10^{-3}$

$\lambda''_+ = (2.99 \pm 2.29) \times 10^{-3}$

$\lambda''_+ = (1.92 \pm 0.94) \times 10^{-3}$ $\lambda_0 = (17.11 \pm 2.31) \times 10^{-3}$

SU(2) and em corrections

	$\delta^{K}_{SU(2)}(\%)$	$\delta^{K\ell}_{em}(\%)$	
		3-body	full
K^{+}_{e3}	2.31 ± 0.22	-0.35 ± 0.16	-0.10 ± 0.16
K^{0}_{e3}	0	$+0.30 \pm 0.10$	$+0.55 \pm 0.10$
$K^{+}_{\mu3}$	2.31 ± 0.22	-0.05 ± 0.20	$+0.20 \pm 0.20$
$K^{0}_{\mu3}$	0	$+0.55 \pm 0.20$	$+0.80 \pm 0.20$

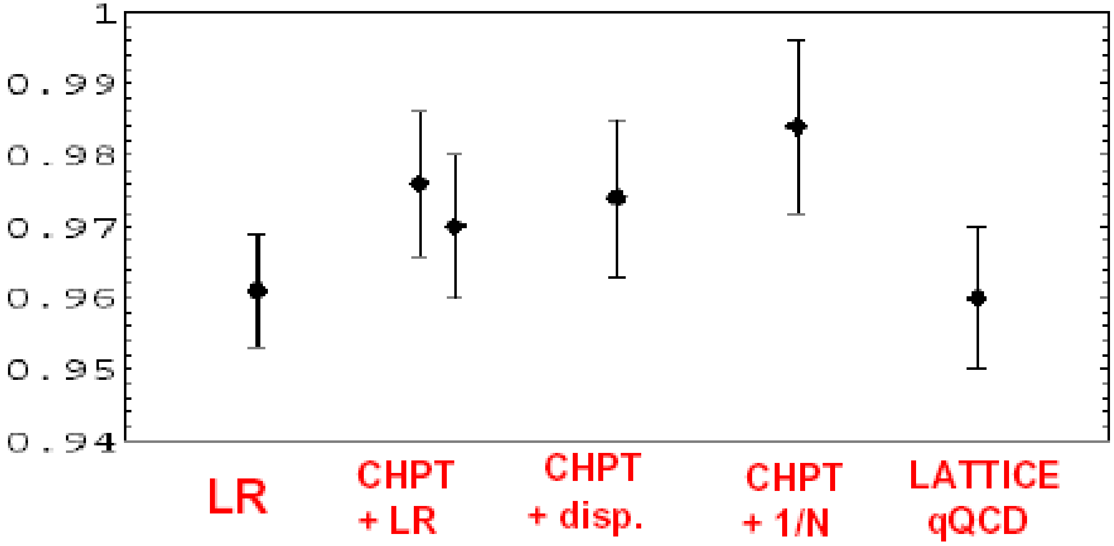


AVERAGE BAND:
$V_{ud} = 0.9738 \pm 0.0005$
$|V_{ud}|$
0.978
0.976
0.974
0.972
0.97
0.968
$0^+ \to 0^+$
n-β
π_{e3}

3

Form factor summary

$f_+^{K^0\pi^-}(0)$



KLOE: Absolute BR's results

- **Absolute BR results with (τ_{KL}= 51.54 ± 0.44 ns):**

¾ of 2001-2002 data has been used for efficiency evaluation and ¼ for BR measurement corresponding to 13×10^6 tagged K_L.

330 pb^{-1}

2001-2002

$BR(K_L \to \pi e \nu(\gamma)) = 0.4049 \pm 0.0010 \pm 0.0031$ ~8×10^5 events

$BR(K_L \to \pi \mu \nu(\gamma)) = 0.2726 \pm 0.0008 \pm 0.0022$ ~ 5×10^5 events

$BR(K_L \to 3\pi^0) = 0.2018 \pm 0.0004 \pm 0.0026$ ~ 7×10^5 events

$BR(K_L \to \pi^+\pi^-\pi^0(\gamma)) = 0.1276 \pm 0.0006 \pm 0.0016$ ~ 2×10^5 events

KLOE: Measurement of K_L BR's

Tagging → Precisely measure absolute branching ratios

$$BR(K_L \to i) = \frac{N_i}{N_{tag}} \times \frac{1}{\varepsilon(i)_{rec} \times \varepsilon_{FV}(\tau_L) \times \varepsilon_{tag}(i)/\varepsilon_{tag}(all)}$$

Reconstruction efficiencies:

$K_L \to \pi\mu\nu, \pi e\nu$	ε (rec) ≅ 55%
$K_L \to \pi^+\pi^-\pi^0$	ε (rec) ≅ 40%
$K_L \to 3\pi^0$	ε (rec) ≅ 100%

Integral over the fiducial volume:
ε (FV, τ_L) ≅ 26%, depends on τ_L

Tag bias

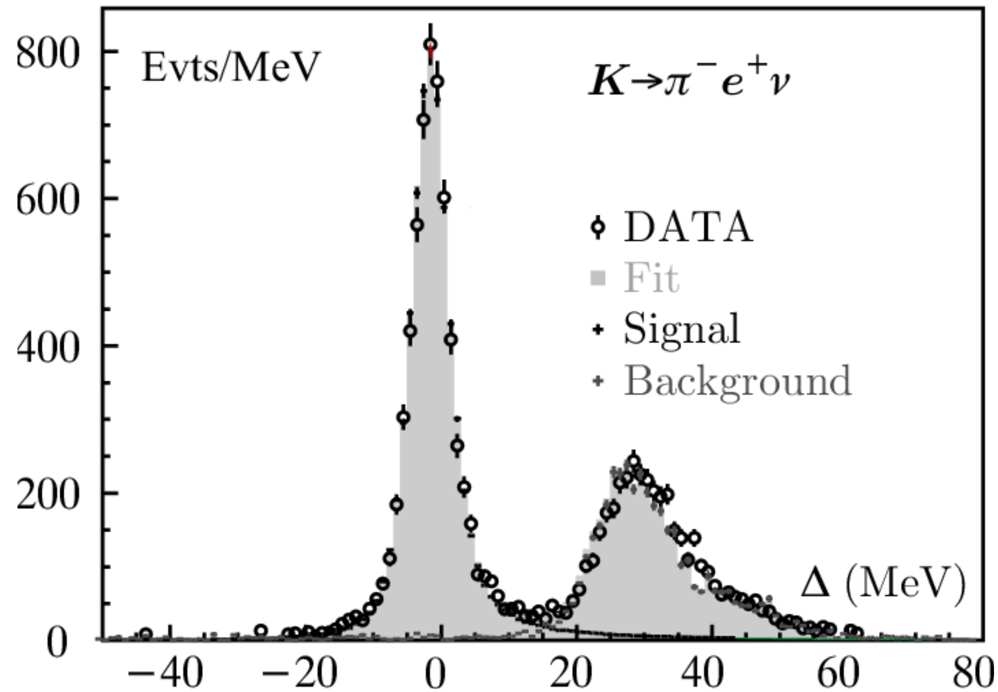
Trigger required on the K_S side

KLOE $K_S \to \pi e \nu$ decays

- Kinematic closure: use K_L to obtain K_S momentum $\mathbf{P_K}$ and test for presence of neutrino:

$$E_{miss} = \sqrt{M_K^2 + P_K^2} - E_\pi - E_e$$

$$P_{miss} = |\mathbf{P_K} - \mathbf{P_\pi} - \mathbf{P_e}|$$



- Further rejection of $K_S \to \pi\pi$ background from TOF identification
- Obtain number of signal events from a constrained likelihood fit to multiple data distributions
- Use BR($K_S \to \pi\pi$) to calculate BR($K_S \to \pi e \nu$)

Dominant K_L branching ratios

Absolute BR mmts to 0.5-1% using K_L beam tagged by $K_S \to \pi^+\pi^-$

328 pb^{-1} '01 + '02 data

13×10^6 K_L's for counting (25%)

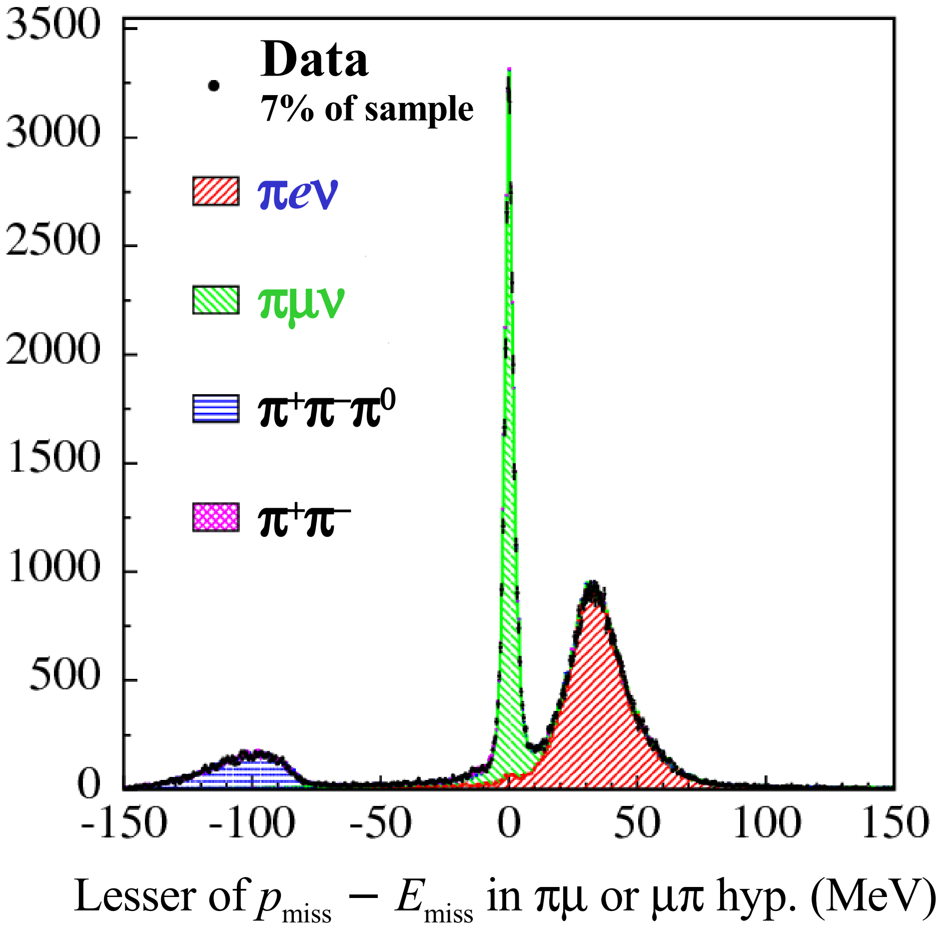
75% used to evaluate efficiencies

BR's to $\pi e\nu$, $\pi\mu\nu$, and $\pi^+\pi^-\pi^0$:

- K_L vertex reconstructed in DC
- PID using decay kinematics
- Fit with MC spectra including radiative processes and optimized EmC response to $\mu/\pi/K_L$

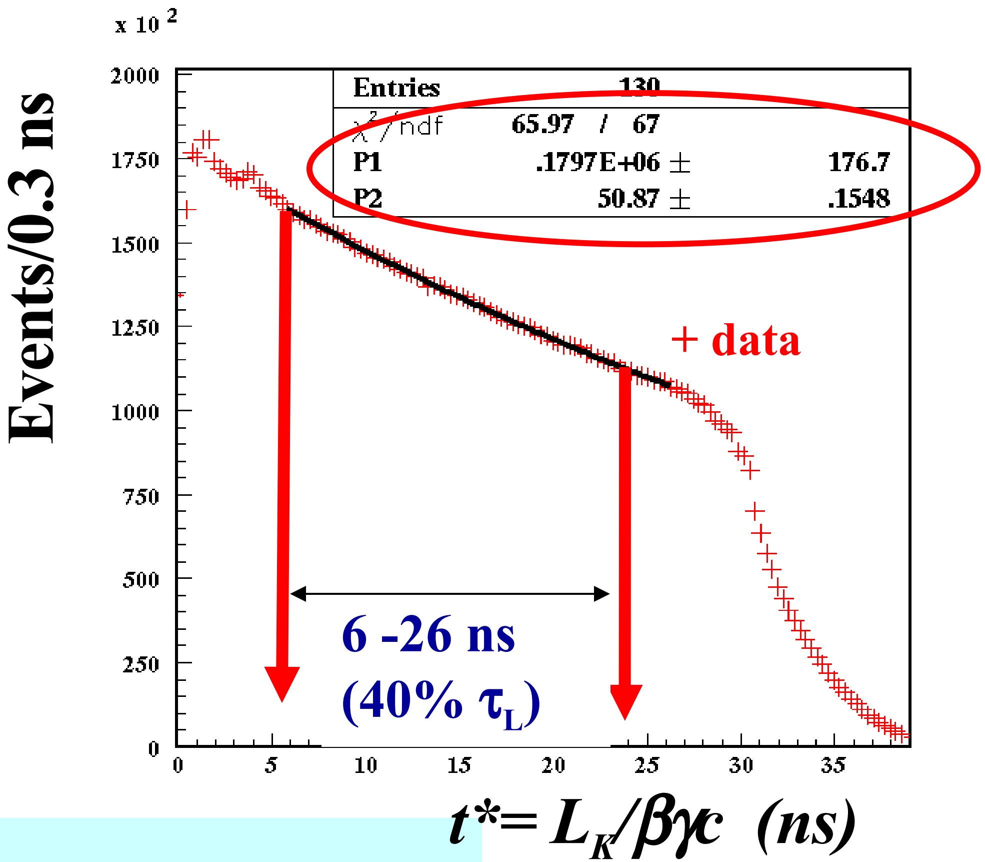
BR to $\pi^0\pi^0\pi^0$:

- Photon vertex reconstructed by TOF using EmC (≥ 3 clusters)
- ε_{rec} = 99%, background < 1%



KLOE: K_L lifetime from $K_L \to 3\pi^0$

- Large acceptance for K_L decays ~0.4 $\lambda \Rightarrow$ high statistical accuracy
- K_L momentum measured from $K_S \to \pi^+\pi^-$
- $K_L \to 3\pi^0$ efficiency >99% little variation along the K_L path
- $K_L \to \pi^+\pi^-\pi^0$ as a control sample for the estimate of efficiency, resolution and time scale



τ (PDG) (fit) = (51.7 ± 0.4) ns

τ (Vosburg, 1972) = (51.54 ± 0.44) ns - 0.4 Mevents

τ_L (KLOE) = $(50.92 \pm 0.17 \pm 0.25)$ ns - 14.5 Mevents – 440 pb^{-1}

Average with result from K_L BR's: $\tau_L = 50.84 \pm 0.23$ ns

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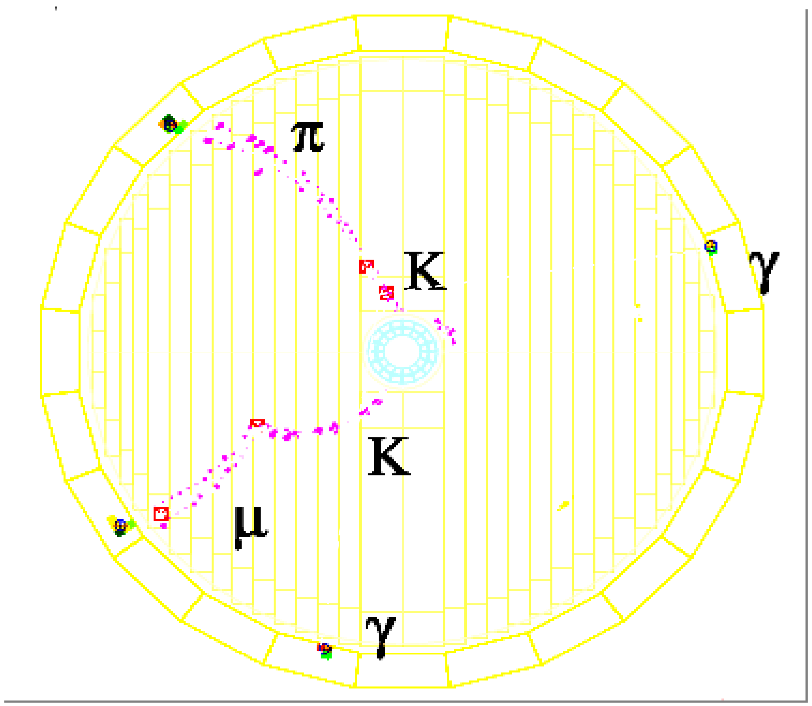
KLOE: Charged Kaon

$K^{\pm}$ beam tagged from

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}, \ \mu^{\pm}\nu$ (85% of $K^{\pm}$ decays)

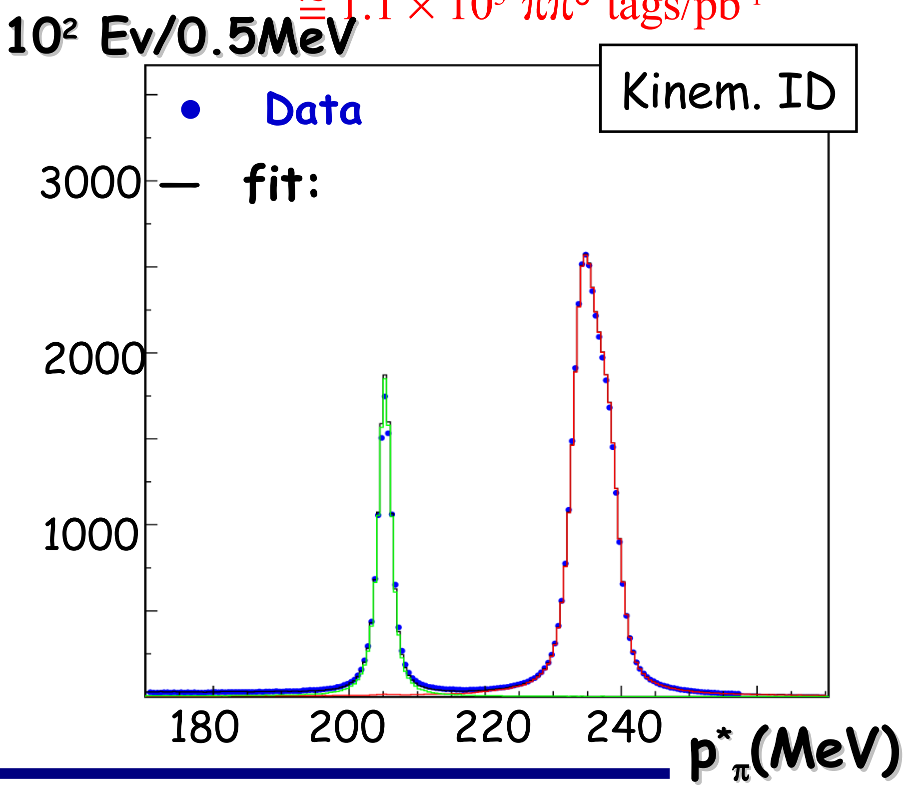
$\cong 1.5 \times 10^{6}\ K^{+}K^{-}$ evts/pb^{-1}



two-body decays identified as peaks in the momentum spectrum of secondary tracks in the kaon rest frame ↙ $P^{*}(m_{\pi})$

$\varepsilon_{tag} \cong 36\ \% \Rightarrow \cong 3.4 \times 10^{5}\ \mu\nu$ tags/pb^{-1}

$\cong 1.1 \times 10^{5}\ \pi\pi^{0}$ tags/pb^{-1}



KLOE: Form Factor

- **328 pb^{-1}, 2×10^6 K_{Le3} decays**
- Kinematic cuts + TOF PID to reduce background (~ 0.7% final contamination)
- Momentum transfer **t** measured from π and K_L momenta: σ_t/m_π^2 ~0.3
- separate measurement for each charge state ($e^+\pi^-$, π^+e^-) to check systematics

Linear: $1 + \lambda_+ t$

$\lambda_+ = (28.6 \pm 0.5 \pm 0.4) \times 10^{-3}$ P(χ^2) =89%

Quadratic: $1 + \lambda'_+ t/m_{\pi+} + 1/2\, \lambda''_+ (t/m_{\pi+})^2$

$\lambda'_+ = (25.5 \pm 1.5 \pm 1.0) \times 10^{-3}$

$\lambda''_+ = (1.4 \pm 0.7 \pm 0.4) \times 10^{-3}$

$\rho(\lambda'_+, \lambda''_+) = -0.95$ P(χ^2) =92%

Pole model: $M_V^2/(M_V^2-t)$,

Taylor exp.⇒ $\lambda'_+=(m_\pi/M_V)^2$, $\lambda''_+=2\,\lambda'^2_+$

$m_V = (870 \pm 7)$ MeV P(χ^2) =92.4%

[PLB 636(2006)]