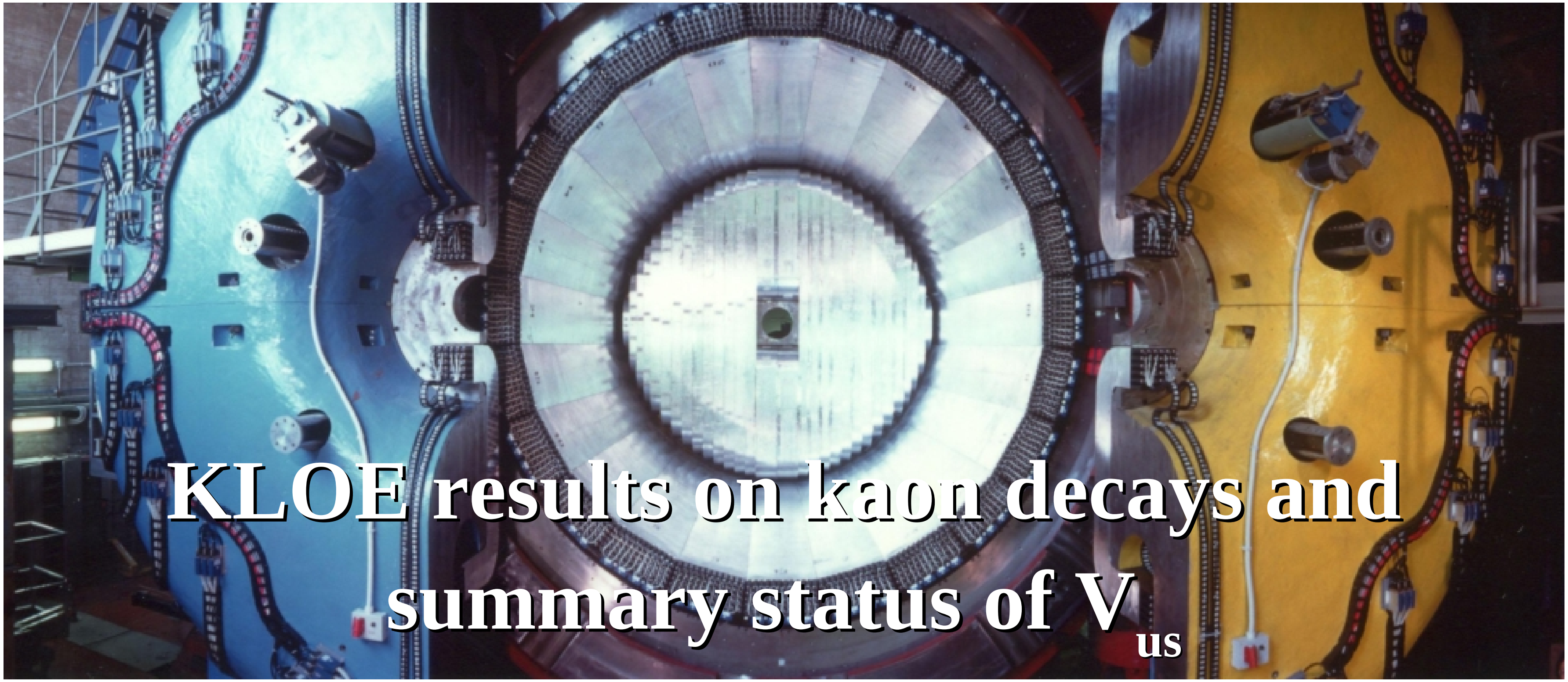

KLOE results on kaon decays and summary status of V_{us}

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for the KLOE collaboration

CKM 06 Workshop
Nagoya, 13th December, 2006

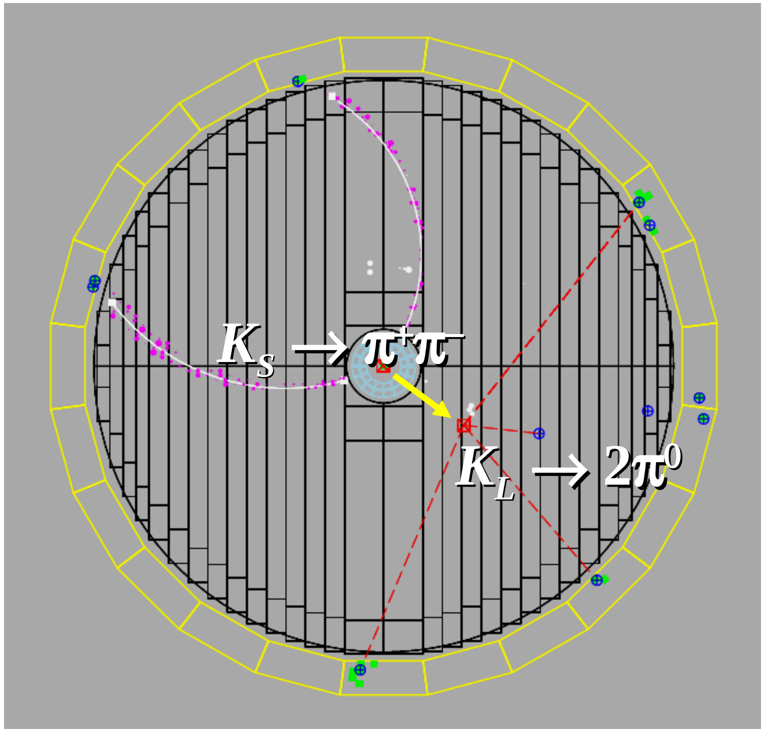
Kaon physics at KLOE

$K_S K_L$ pairs emitted ~back to back, p ~ 110 MeV

Identification of $K_S(K_L)$ decay (interaction) tags presence of $K_L(K_S)$

Almost pure $K_{L,S}$ and $K^{+,-}$ beams of known momentum + PID (kinematics & TOF):

- **Access to absolute BR's**
- **Precise measurements of K_{Le3} from factors and K_L, K^+ lifetimes (acceptance ~0.5 τ_L, τ_+)**



Above points crucial for V_{us} determination

V_{us} from semileptonic kaon decays

Master formula: $\Gamma(K_{l3(\gamma)}) = |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \, \frac{G_F^2 \, m_K^5}{128\pi^3} S_{\rm EW} \, C_K^2 \, I_{K\ell} \, (1 + \delta_K^\ell)$

Theoretical inputs:

- **$f_+(0)$**, form factor at zero momentum transfer: purely theoretical calculation
- **δ^ℓ_K**, e.m.- and (for $K^\pm$) isospin-breaking effects, presently known @ few per mil level
- [S_{EW}, short distance corrections (1.0232), $C_K = 1$ ($2^{-½}$) for K^0 (K^+) decays]

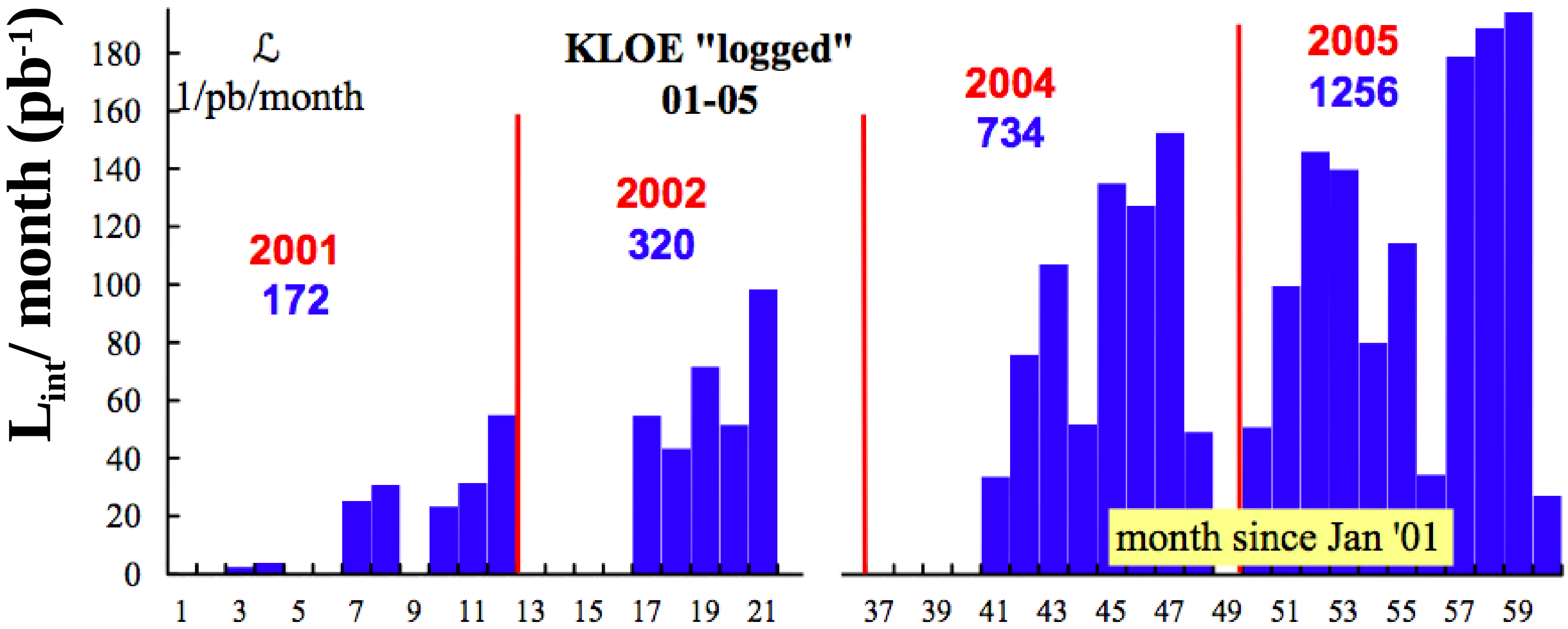
Experimental inputs:

- **$I^\ell_K = I(\{\lambda_+\},\{\lambda_0\},0)$**, phase space integral, **λ_+, λ_0** denote the t-dependence of vector and scalar form factors
- **$\Gamma_{K\ell 3(\gamma)}$**, semileptonic decay width, evaluated from γ-inclusive BR and lifetime
- **m_K**, appropriate kaon mass

KLOE is able to measure all relevant inputs: BR's, lifetimes, ff's

Overview of KLOE data

Data taking for KLOE experiment, years 2001-2005, now run completed



~2.5 fb^{-1} integrated @ $\sqrt{s}$=M(ϕ), corresponding to 2.5 10^{9} K_SK_L pairs

Results presented here based on first 400 pb^{-1} collected

Recent KLOE results

Results from kaon decays analyses published by KLOE in 2006:

Absolute BR's for 4 main K_L channels and τ_L	**PLB 632 (2006) 43**
Form factor slopes for K_{Le3} decays	**PLB 636 (2006) 166**
BR's and charge asymmetry for K_{se3}	**PLB 636 (2006) 173**
Precise measurement of $\Gamma(\pi^+\pi^-(\gamma))/\Gamma(\pi^0\pi^0)$	**EPJ C48 (2006) 767**
Absolute BR for $K^+ \to \mu\nu(\gamma)$ decay	**PLB 632 (2006) 76**
Absolute BR for $K_L \to \pi^+\pi^-(\gamma)$ decay	**PLB 638 (2006) 140**
Determination of CP, CPT parameters of K^0 system via BSR and data from KLOE	**JHEP 122006011 (2006)**

A couple of preliminary measurements have also been announced:

Absolute BR's for K^+_{l3} decays, K^+ lifetime

Precise measurement of K_L BR's

Results are therefore a function of $\Delta\tau = \tau_L^{PDG} - \tau_L$ ($k = 0.0128\ \mathrm{ns}^{-1}$):

$BR(K_L \to \pi e \nu)\,[\%] = 40.49(10)(18)/[1 + k\,\Delta\tau]$

$BR(K_L \to \pi \mu \nu)\,[\%] = 27.26(9)(14)/[1 + k\,\Delta\tau_L]$

$BR(K_L \to 3\pi^0)\,[\%] = 20.18(5)(23)/[1 + k\,\Delta\tau]$

$BR(K_L \to \pi\pi\pi)\,[\%] = 12.76(6)(14)/[1 + k\,\Delta\tau]$

$$\begin{pmatrix} 1 & 0.09 & 0.07 & 0.49 \\ & 1 & -0.03 & 0.27 \\ & & 1 & 0.07 \\ & & & 1 \end{pmatrix}$$

For evaluation of world average V_{us}, those above are the KLOE inputs

Imposing $\Sigma_{i=1,4} BR_i = 1 - BR_{\pi\pi} - BR_{\gamma\gamma} = 1 - 0.36\%$, extract BR's and τ_L:

$BR(K_L \to \pi e \nu)\,[\%] = 40.08(6)(14)$

$BR(K_L \to \pi \mu \nu)\,[\%] = 26.99(6)(13)$

$BR(K_L \to 3\pi^0)\,[\%] = 19.96(5)(19)$

$BR(K_L \to \pi\pi\pi)\,[\%] = 12.61(5)(10)$

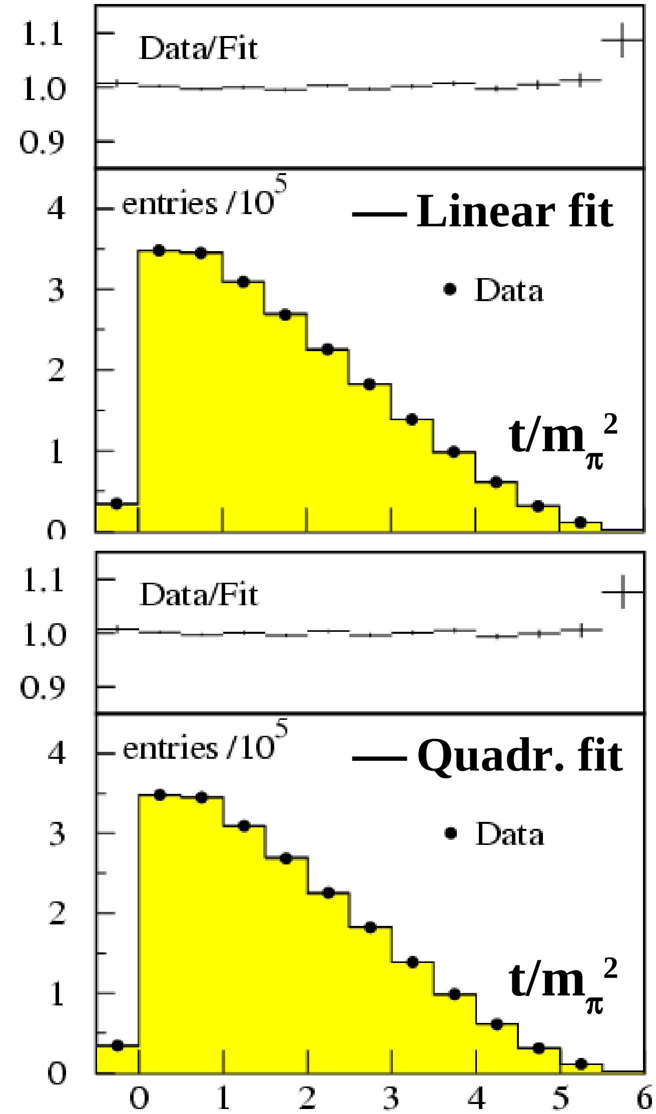
$\tau(K_L) = 50.84(14)(18)\ \mathrm{ns}$

$$\begin{pmatrix} 1 & -0.31 & -0.55 & -0.01 & 0.16 \\ & 1 & -0.41 & -0.14 & 0.22 \\ & & 1 & -0.47 & -0.14 \\ & & & 1 & -0.26 \\ & & & & 1 \end{pmatrix}$$

[include fit with KLOE direct mmt PLB 626 (2005) 15: $\tau(K_L) = 50.92(17)(25)$ ns]

Measurement of K_{Le3} form factor slopes

- Same sample used for K_L BR's + loose kinematics & TOF PID cuts:
  - **Select 2×10^6 events**
  - **Contamination of ~0.7% from** $K_L \rightarrow$ **$\pi\mu\nu$**
- **Analysis by charge,** giving robustness to efficiency correction. Without TOF correction:
  - 20% variation on λ_+
  - 15% difference in results from π^+e^- and π^-e^+
- **Binned log-L fit,** include statistical fluctuatio in the efficiency correction
- **Compare linear, quadratic, pole ff's fits**



Measurement of K_{Le3} form factor slopes

Both linear and quadratic fits show good χ^2 probabilities, 89% and 92%

Linear fit	$\lambda_+ \times 10^3$	χ^2/ndf
$K_L \to \pi^- e^+ \nu$	28.7 ± 0.7	$156/181$
$K_L \to \pi^+ e^- \overline{\nu}$	28.5 ± 0.6	$174/181$
Combined	28.6 ± 0.5	$330/363$

Quadratic fit	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	χ^2/ndf
$K_L \to \pi^- e^+ \nu$	24.6 ± 2.1	1.9 ± 1.0	$152/180$
$K_L \to \pi^+ e^- \overline{\nu}$	26.4 ± 2.1	1.0 ± 1.0	$173/180$
Combined	25.5 ± 1.5	1.4 ± 0.7	$325/362$

$$\lambda_+ = (28.6 \pm 0.5_{\mathrm{stat.}} \pm 0.4_{\mathrm{syst.}}) \times 10^{-3}$$

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

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

$\rho(\lambda', \lambda'') \sim -0.95$

Pole fit result (92% χ^2 probability) indicates dominance of the K*(892)-exchange in the Kπ transition:

$$M_V = (870 \pm 6_{\mathrm{stat.}} \pm 7_{\mathrm{syst.}})\ \mathrm{MeV}$$

Systematic errors dominated by uncertainties in TOF efficiency correction

Measurement of K_{Le3} form factor slopes

- **KLOE measurements of K_{Le3} BR and ff slopes determine:**

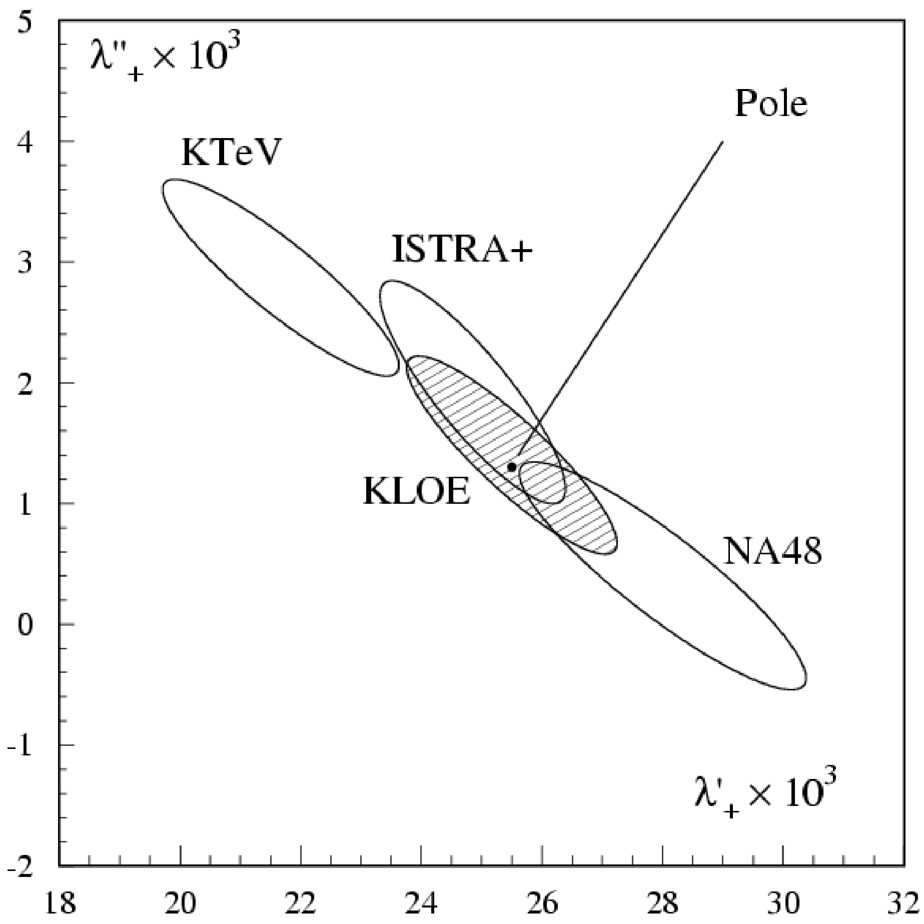
$f_+(0) \times |V_{us}| = 0.21561(69)$

Inputs only from KLOE, error 0.32%

- **In comparing with results from other experiments, have to take correlations into account** (for averaging methods and state-of-the-art results, see **M. Moulson** talk, friday)

- **For BR($K_{L\mu3}$), use average slopes of $KLOE_{e3}$, $NA48_{e3}$, $KTeV_{e3,\mu3}$ $ISTRA+_{e3,\mu3}$:**

$f_+(0) \times |V_{us}| = 0.21633(78)$



Measurement of $K_{L\mu3}$ form factor slopes

Measuring scalar form factor slopes is relevant:

- **V_{us} from $K_{\mu3}$, test e/μ universality with KLOE only**
- **Probe scalar-current, V+A amplitudes**

In progress, **will reach $\delta\lambda_0/\lambda_0$ ~ 5-10% with 2.5 fb^{-1}**

π/μ separation at low energies is difficult:

1) improve PID, by kinem. + TOF + cluster shapes, or

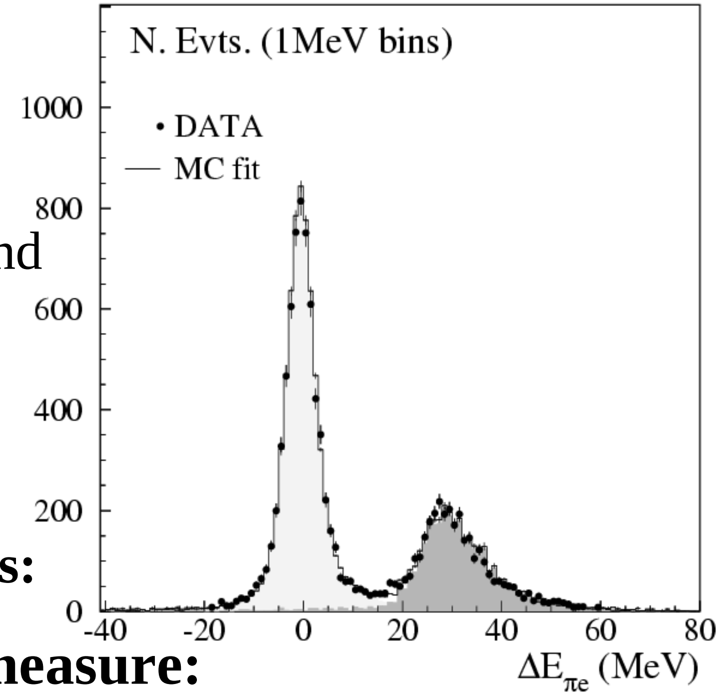
2) fit E_ν spectrum, losing sensitivity by ×0.5 (λ_+), ×0.8 (λ_0)

Problems in keeping low systematics on λ_0:

- **Contamination from wrong-charge $K_{\mu3}$**
- **High sensitivity to efficiency correction/resolution effects around E_{max}: +1% in signal counts → +15% in λ_0**

Unique to KLOE: K_{Se3} BR's

- **Events with K_L's interacting in the EmC:**
  - **$K_S \to \pi^- e^+ \nu, \pi^+ e^- \nu$:** extrapolate tracks from IP to the EmC, discriminate $e^{+,-}$ from π^{-+} using TOF, and fit distribution of multiple kinematic variables
  - **$K_S \to \pi^+ \pi^-$:** extrapolate tracks to the IP, accept events with one track pair



- **Normalize $K_S \to \pi^- e^+ \nu, \pi^+ e^- \nu$ to $K_S \to \pi^+ \pi^-$ counts:**
- **Correct for selection efficiencies by charge, measure:**

$$R_{e+} \equiv \frac{\Gamma(K_S \to \pi^- e^+ \nu)}{\Gamma(K_S \to \pi^+ \pi^-)} = (5.099 \pm 0.082_{\rm stat} \pm 0.039_{\rm syst}) \times 10^{-4}$$

$$R_{e-} \equiv \frac{\Gamma(K_S \to \pi^+ e^- \bar{\nu})}{\Gamma(K_S \to \pi^+ \pi^-)} = (5.083 \pm 0.073_{\rm stat} \pm 0.042_{\rm syst}) \times 10^{-4}$$

- **Total error dominated by statistics, O(1%)**

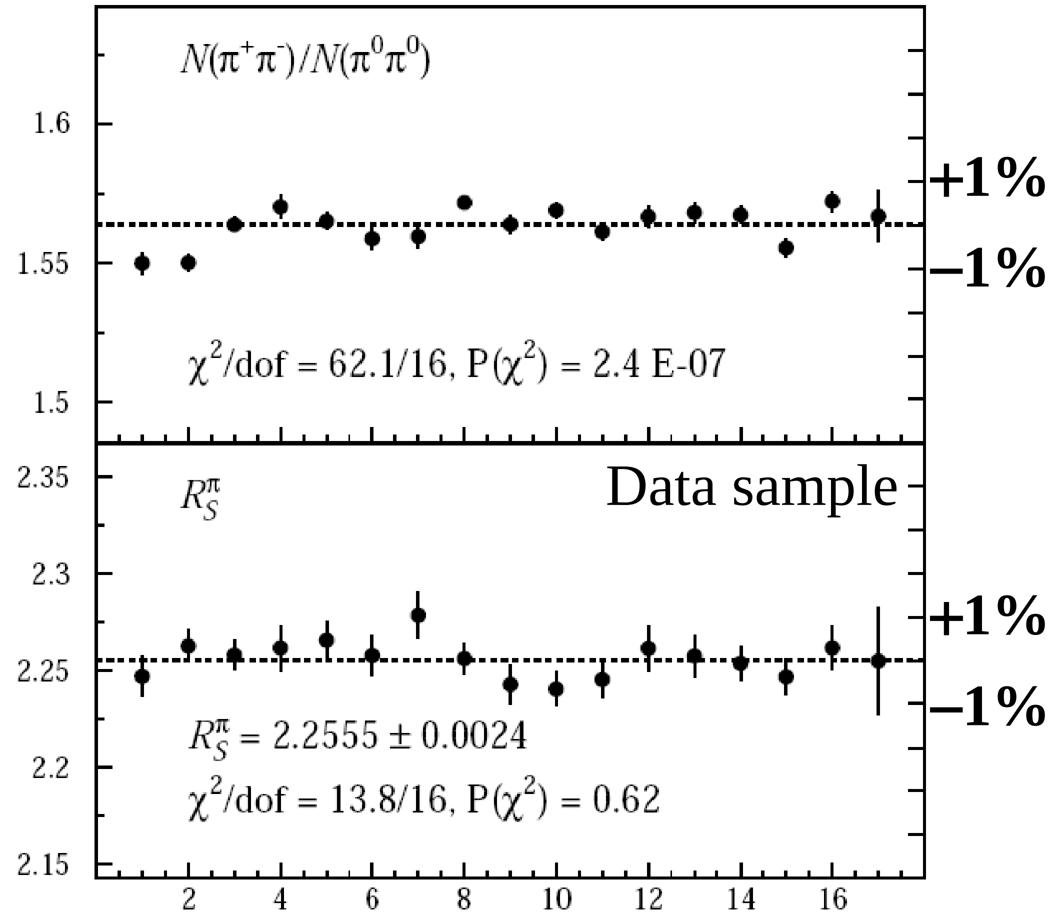
Close K_S BR's to unity: two-pion ratio

Precise measurement of $R = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)} = 2.2549 \pm 0.0054$

Measurement inclusive with respect to photon radiation

Careful check of systematic uncertainties:

- Ratio of selection efficiencies for $\pi^+\pi^-(\gamma)$ and $\pi^0\pi^0$
- Dependence of tagging efficiency on decay mode
- Dependence of R on level of machine background, stability studies



Unique to KLOE: Vus from K_{Se3}

Combine ratio of Ke3 BR's with R, impose e/μ universality, and obtain:

$$\begin{cases} BR(K_S \to \pi^+\pi^-) = (69.196 \pm 0.051) \times 10^{-2} \\ BR(K_S \to \pi^0\pi^0) = (30.687 \pm 0.051) \times 10^{-2} \\ BR(K_S \to \pi^- e^+ \nu) = (3.528 \pm 0.062) \times 10^{-4} \\ BR(K_S \to \pi^+ e^- \bar{\nu}) = (3.517 \pm 0.058) \times 10^{-4} \end{cases}$$

and:

$$\boxed{BR(K_S \to \pi e \nu) = (7.046 \pm 0.091) \times 10^{-4}}$$

Tightening the cuts, select 15,000 πeν events with 0.7% contamination

From linear fit of t distribution (not enough sensitivity for quadratic term):

First measurement from K_S: $\lambda_+ = (33.9 \pm 4.1) \times 10^{-3}$

From the above BR, benefiting of precise measurement of τ_S, can extract:

$f_+(0) \times |V_{us}| = 0.2154 \pm 0.0014$, error 0.67% (96% from BR itself)

Other impacts from K_{se3} (1)

Comparing $\Gamma(K_S \to \pi e\nu)$ to $\Gamma(K_L \to \pi e\nu)$, test $\Delta S = \Delta Q$:

×2 improvement in precision on $\mathrm{Re}\, x_+ = (-0.5 \pm 3.6) \times 10^{-3}$

Sensitivity to CPT violating effects through charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} \quad \begin{cases} A_S - A_L = 4\,[\mathrm{Re}\,(\delta) + \mathrm{Re}\,(x\_)] \\ A_S + A_L = 4\,[\mathrm{Re}\,(\varepsilon) - \mathrm{Re}\,(y)] \end{cases}$$

Evaluate A_S from: $A_S = \dfrac{N(\pi^- e^+ \nu)/\epsilon^+_{\mathrm{tot}} - N(\pi^+ e^- \bar{\nu})/\epsilon^-_{\mathrm{tot}}}{N(\pi^- e^+ \nu)/\epsilon^+_{\mathrm{tot}} + N(\pi^+ e^- \bar{\nu})/\epsilon^-_{\mathrm{tot}}}$

A_S measured for the first time: $A_S = (1.5 \pm 9.6_{\mathrm{stat}} \pm 2.9_{\mathrm{syst}}) \times 10^{-3}$

Error dominated by statistics, ×3 improvement after analysis of 2.5 fb^{-1}

Other impacts from K_{se3} (2)

From $A_S - A_L$, using $A_L = 3.34(7)\ 10^{-3}$ from KTeV, Re (δ) from CPLEAR:

×5 improvement for error on $\mathrm{Re}\,x_- = (-0.8 \pm 2.5) \times 10^{-3}$

From $A_S + A_L$, determine for the first time $\mathrm{Re}\,y = (0.4 \pm 2.5) \times 10^{-3}$

From Re(y) and two recent KLOE measurements,

$\mathrm{BR}(K_L \to \pi^+\pi^-) = 1.963(12)(17) \times 10^{-3}$ and

$\mathrm{BR}(K_S \to 3\pi^0) \leq 1.2\times10^{-7}$ @ 90% CL,

improve CPT violation test via Bell-Steinberger relation:

×2.5 improvement for error on Re(ε) and Im(δ)

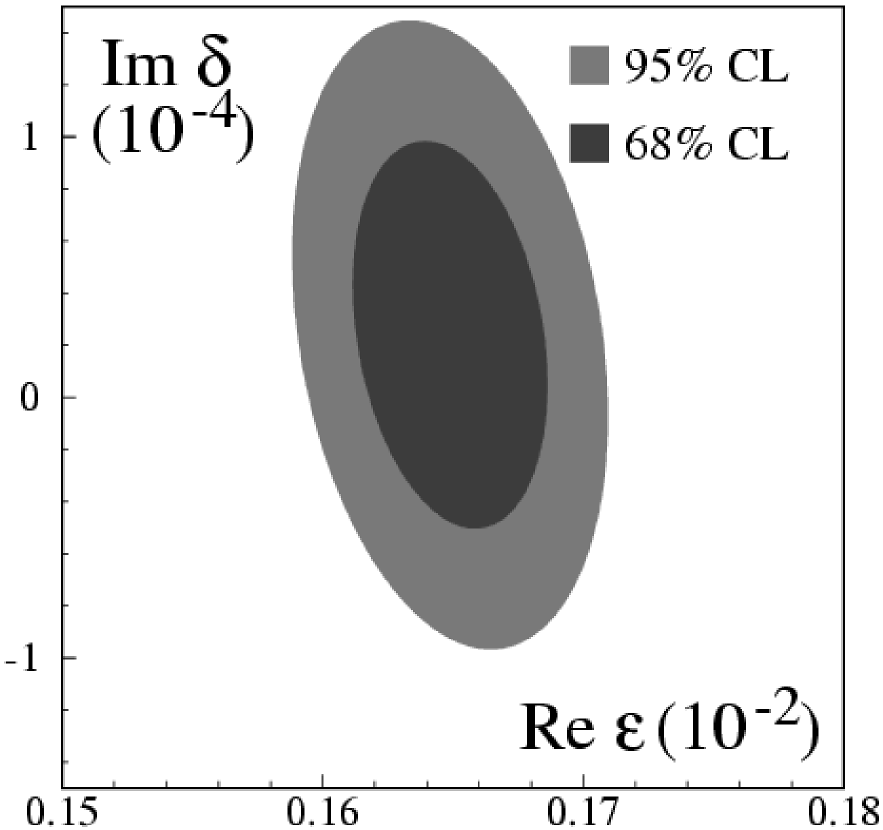
Shift central value of Re(ε) by 2σ, no impact on UT because of δB_K

Impact of KLOE: results from BSR

After CPLEAR measurements (2001)

$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$

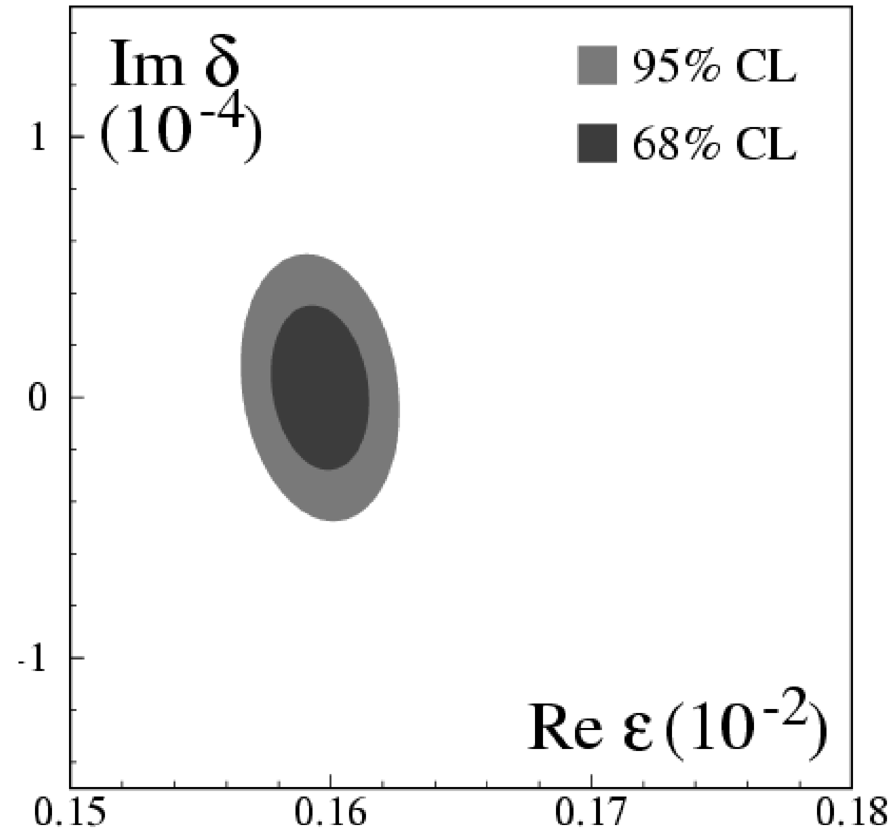
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$



After KLOE measurements (2006)

$$\mathrm{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5}$$

$$\mathrm{Im}(\delta) = (\ 0.4 \pm 2.1) \times 10^{-5}$$



Unique to KLOE: $K_{S\mu3}$ decays

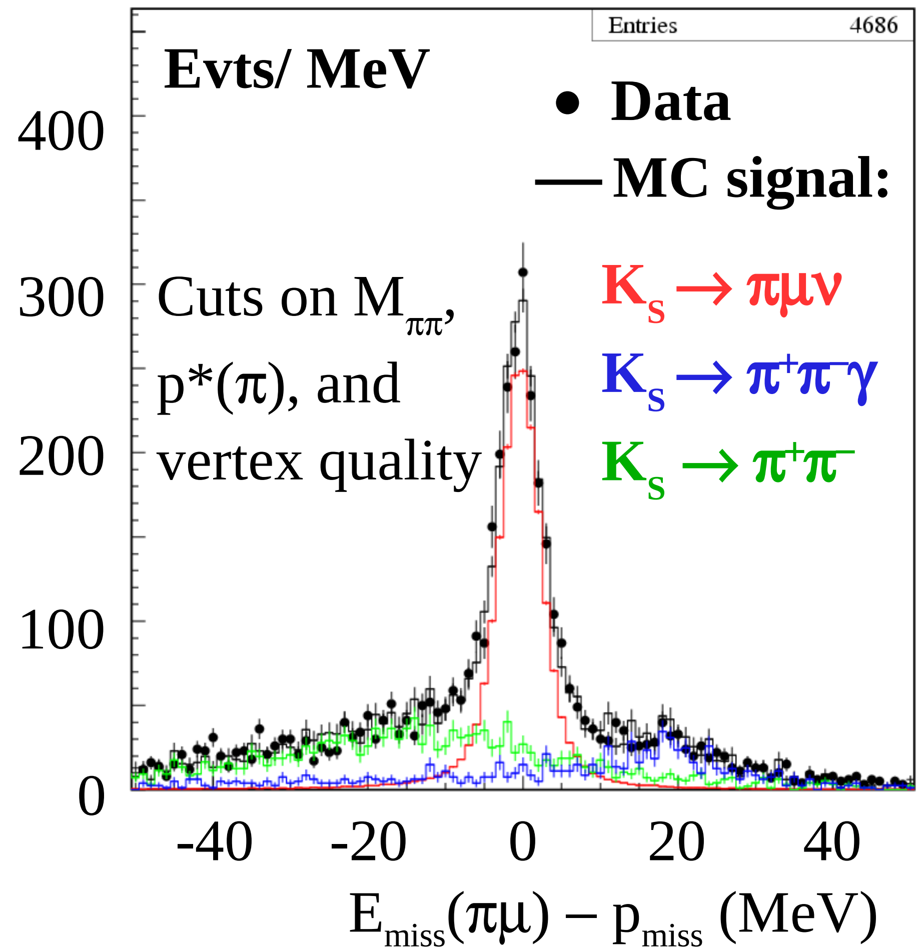
Decay mode has never been observed

Compare width with $K_L \to \pi\mu\nu$: test of validity of $\Delta S = \Delta Q$ rule

Compare with $K_S \to \pi e\nu$: test universality of lepton couplings

Measure charge asymmetry: test of CPT, CP violation

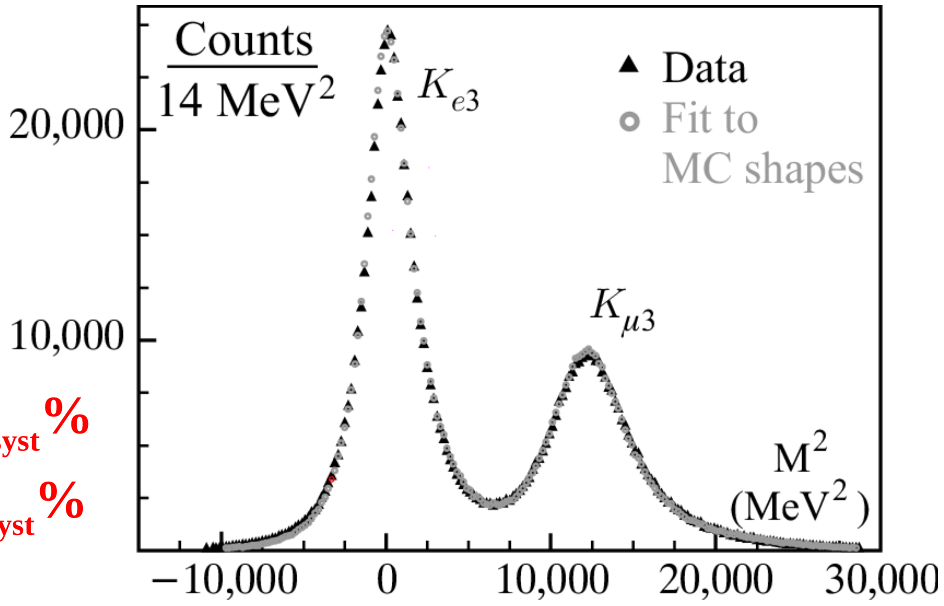
Total error dominated by statistics, expect 3% @ the end of analysis



V_{us} from K^+ decays: absolute BR for K^+_{l3}

- **4 independent tagging decays: $K^\pm\mu2$, $K^\pm\pi2$**; keep systematic effects due to the tag selection under control
- Kinematical cuts to reject non-semileptonic decays, residual background ~1.5%
- Obtain number of signal events from a constrained likelihood fit of **data distribution of lepton mass squared (M^2) known from TOF**

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



- KLOE 2005 **preliminary**:

  $BR(K^\pm_{e3}) = 5.047(19)_{stat}(39)_{corr\text{-}stat}(81)_{syst}\%$

  $BR(K^\pm_{\mu3}) = 3.310(16)_{stat}(45)_{corr\text{-}stat}(65)_{syst}\%$

  $\rho(K_{e3},K_{\mu3}) = 0.42$

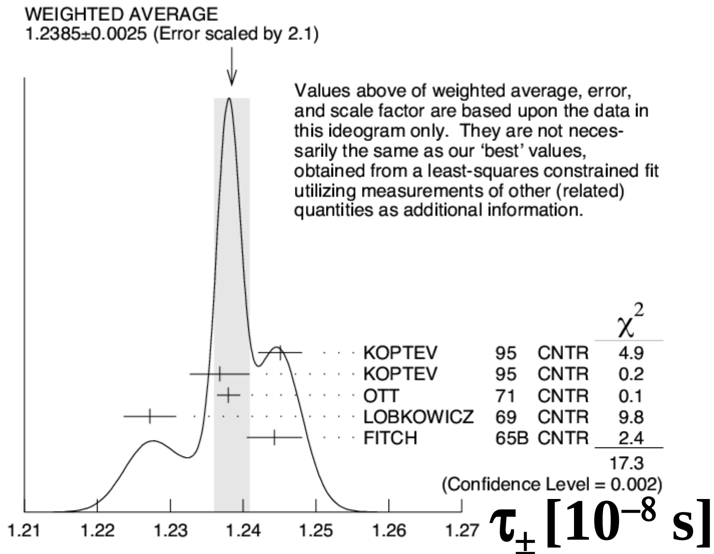
- **Systematic dominated by uncertainty on tracking efficiency correction**

V_{us} from K^+ decays: measurement of τ_+

- **Experimental status unclear:**
  - PDG average $\delta\tau/\tau \sim 0.2\% \rightarrow \delta V_{us}/V_{us} \sim 0.1\%$
  - Mmts spread $\delta\tau/\tau \sim 0.8\% \rightarrow \delta V_{us}/V_{us} \sim 0.4\%$
- **Two methods to measure $\tau_\pm$ at KLOE:**

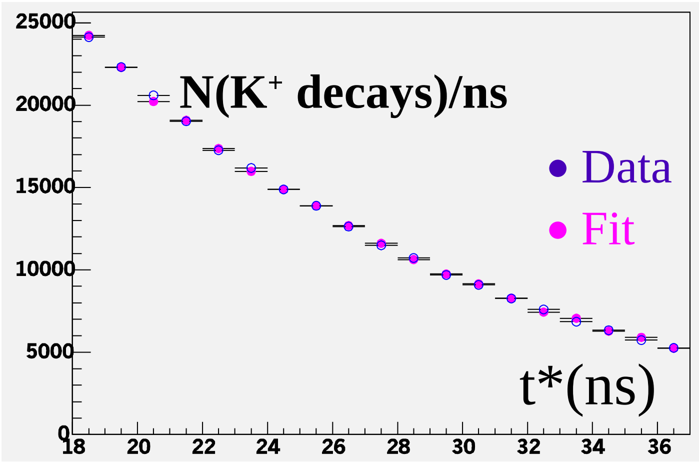
  1) From $\mathbf{K^+ \rightarrow 1track}$ decay-length, proper time accounting for energy losses: $t^* = \sum_i L_i/(\beta_i\gamma_i c)$

  2) From $\mathbf{K^+ \rightarrow X\pi^0}$, t* from photon TOF's



- **Allow systematic checks, only features common to both methods are:**
  - Tag is done with $K_{\mu 2}$ decay identification
  - Kaon decay vertex is in the DC
- **KLOE preliminary** (1st method, ~175 pb^{-1}):

  $\tau_\pm = 12.367(44)(65)$ ns



After analysis of entire data set, KLOE can clarify τ_+ landscape

KLOE summary of $f_0 \times V_{us}$

For K_{e3} modes, use ff slopes from KLOE

For $K_{\mu3}$ modes, use average of $KLOE_{e3}$, $NA48_{e3}$, $KteV_{e3,\mu3}$, $ISTRA+_{e3,\mu3}$:

$$\lambda_+' = 24.92(83) \times 10^{-3},\ \lambda_+'' = 1.59(36) \times 10^{-3},\ \text{with}\ \rho(\lambda_+', \lambda_+'') = -0.94$$

$$\lambda_0 = 16.07(82) \times 10^{-3},\ \text{with}\ \rho(\lambda_+', \lambda_0) = +0.24,\ \rho(\lambda_+'', \lambda_0) = -0.34$$

Mode	$f_+(0) \times \lvert V_{us} \rvert$	Error,%	KLOE input	External input
K_{Le3}	**0.21561(69)**	**0.32**	**ff,** BR, τ_L	
$K_{L\mu3}$	**0.21633(78)**	**0.36**	BR, τ_L	ff [KLOE,NA48,ISTRA,KTeV]
K_{Se3}	**0.2154(14)**	**0.67**	**ff**, BR	τ_S [PDG]
K^+_{e3}	**0.2170(21)**	**0.96**	ff, BR*	τ^+ [PDG]
$K^+_{\mu3}$	**0.2150(28)**	**1.3**	BR*	ff [KLOE,NA48,ISTRA,KTeV], τ_+ [PDG]

Best accuracy is achieved for K_L's, with errors dominated by τ_L

Intermediate accuracy for K_S, with error dominated by BR

*Preliminary measurement

KLOE summary of $f_0 \times V_{us}$ (2)

For simplicity, use ff slopes average of KLOE$_{e3}$, NA48$_{e3}$, KteV$_{e3,\mu3}$, ISTRA+$_{e3,\mu3}$

Mode	$f_+(0) \times \lvert V_{us}\rvert$	Error,%	KLOE input	External input
K_{Le3}	**0.21572(64)**	**0.30**	**ff,** BR, τ_L	
$K_{L\mu3}$	**0.21633(78)**	**0.36**	BR, τ_L	ff [KLOE,NA48,ISTRA,KTeV]
K_{Se3}	**0.2155(14)**	**0.66**	**ff**, BR	τ_S [PDG]
K^+_{e3}	**0.2171(21)**	**0.96**	ff, BR*	τ^+ [PDG]
$K^+_{\mu3}$	**0.2150(28)**	**1.3**	BR*	ff [KLOE,NA48,ISTRA,KTeV], τ_+ [PDG]
Avg™	**0.21595(50)**	**0.23**		

Unitarity, use V_{ud} = 0.97377(27), $f_+(0)$ = 0.961(8): $\mathbf{\Delta = 1 - V_{ud}^2 - V_{us}^2 = (-13 \pm 10) \times 10^{-4}}$

e/μ universality satisfied:

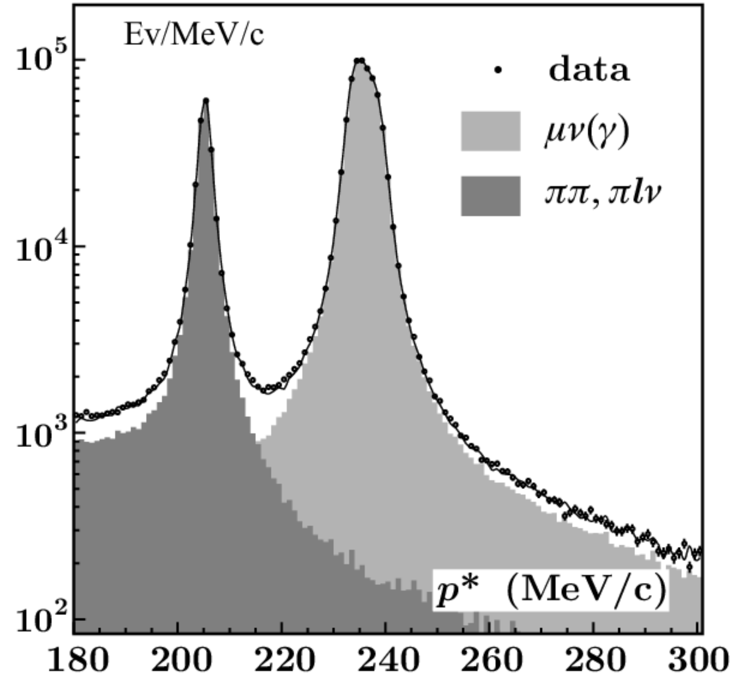
K_L $[G_F(\mu)/G_F(e)]^2$ = 1.0059(83) cfr with $G_F(\mu)/G_F(e)$ = 1.047(14) [PDG04]

K^+ $[G_F(\mu)/G_F(e)]^2$ = 0.981(25) cfr with $G_F(\mu)/G_F(e)$ = 1.004(16) [PDG04]

™ takes correlations into account (see M. Moulson talk), $P(\chi^2/ndf = 1.3/4)$ = 86%

Vus from $K_{\mu 2}$

- Get $|V_{us}/V_{ud}|$ **from K,π → μν widths:** $$\frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}=\frac{m_K\left(1-\frac{m_\mu^2}{m_K^2}\right)^2}{m_\pi\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2}\frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{1+\frac{\alpha}{\pi}C_K}{1+\frac{\alpha}{\pi}C_\pi}$$
  [Marciano PRL93 231803,2004]
  - **Theoretical inputs:** f_K/f_π, radiative correction C_K and C_π for K and π decays
  - **Experimental inputs:** $m_{K,\pi,\mu}$, $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$
- **KLOE measurement of BR($K^+\to\mu^+\nu$):**
  - Tag events from $K^-\to\mu^-\nu$
  - Select K^+ decays to a charged track in FV
  - Event count from fit of **p*** distribution of secondary



- **From analysis of ~ 175 pb^{-1} of 2002 data,**

  BR($K^+\to\mu^+\nu(\gamma)$) = 63.66(9)(15)%

Vus from $K_{\mu 2}$ vs Vus from Kl3 (1)

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

- $f_K/f_\pi = 1.208(2)(^{+7}_{-14})$ [MILC Coll. 2006]
- C_K, C_π [Marciano PRL93 231803,2004]
- $M_{K,\pi,\mu}$, τ_+, $\Gamma(\pi^+ \to \mu^+\nu)$ [PDG]

get $|V_{us}/V_{ud}| = 0.2286(^{+27}_{-15})$

Can fit:

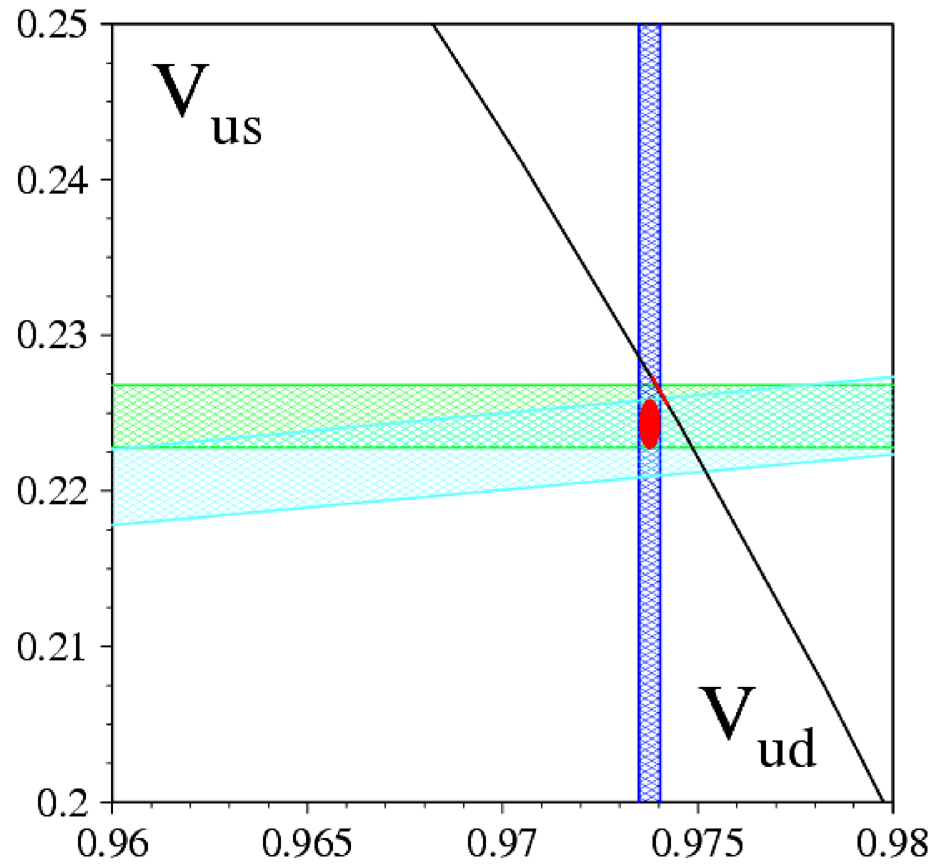
1) $|V_{us}/V_{ud}| = 0.2286(^{+27}_{-15})$

2) $|V_{us}| = 0.2247(19)$

[KLOE K_{l3}, Leutwyler-Roos, $f_+(0) = 0.961(8)$]

3) $|V_{ud}| = 0.97377(27)$

[Marciano & Sirlin PRL96 032002,2006]



get $|V_{us}| = 0.2240(16)$, with $P(\chi^2) = 53\%$ and $\Delta = 1.60(89) \times 10^{-3}$

[With $f_+(0) = 0.9680(16)$ [RBC/UKQCD], get $\Delta = 2.02(59)\times10^{-3}$, > 3σ from 0]

Conclusions

Recent KLOE measurements greatly improve knowledge of $V_{us} \times f_+(0)$

- **Absolute K_L BR's for four main channels**
- **BR and charge asymmetry for K_{Se3} decays, unique to KLOE**
- **Absolute BR for $K^+_{\mu 2}$, input for $|V_{us}/V_{ud}|$ determination**

From these results:

- **Improved test of 1st row CKM matrix unitarity**
- **Consistent picture of K^0 decays from Bell-Steinberger relation**
  - **Improved test of CPT violation via BSR**
  - **accuracy on Re (ε) improved by a factor ~2.5, central value moved**

Future developments:

- **Completion of analyses for K^+_{l3}, τ_+, and $K^+ \rightarrow \pi^+\pi^0$**
- **Analyses of whole data set for $K_S \rightarrow \pi\mu\nu$, ff slopes for $K_L \rightarrow \pi\mu\nu$**