Precision test of the SM with \( K_{\ell 2} \) and \( K_{\ell 3} \) decays at the KLOE experiment

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KLOE measurements of $K \rightarrow \pi \nu$, $\nu$ decays can shed light on NP BSM

**Precise determination of $V_{us}$** from BR’s for $K \rightarrow \pi \nu$, ff slopes, etc.:
- allows most precise test of unitarity of the CKM matrix
- translates into a severe constraint for many NP models

**Test of SM** from $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$:
- probes NP RH contributions to charged weak currents
- probes $H^+$ exchange in every SM extension with 2 Higgs doublets

**LF violation test** from $\Gamma(K_{e 2})/\Gamma(K_{\mu 2})$:
- sensitive to NP effects, which might be at % level wrt SM prediction

CPT test from BR’s and charge asymmetry in $K_{L,S} \rightarrow \pi \nu$ decays:
- dramatically improve precision of CPT test via unitarity relation
In SM, universality of weak coupling dictates:

\[ G_F^2 (|V_{ud}|^2 + |V_{us}|^2) = G^2 \text{(from } \mu \text{ lifetime)} = (g_w/M_w)^2 \] [V_{ub} negligible]

One can test for possible breaking of one of the two conditions:

CKM unitarity: is \(|V_{ud}|^2 + |V_{us}|^2) = 1\?

coupling universality: is \(G_F^2 (|V_{ud}|^2 + |V_{us}|^2) = G^2 \text{(from } \mu \text{ lifetime)}\? 

New physics extensions of the SM can indeed break coupling universality:

\[ \text{SM + NP } \propto G_F^2 |V_{uq}|^2 (1 + a \frac{M_{NP}^2}{M_W^2})^2, \text{ naively } a_{\text{tree}} \sim 1, \ a_{\text{loop}} \sim g_w^2/16\pi^2 \]
Kaon decay observables

Kl2 and Kl3 decay observables linked to the wanted short distance physics with independent theoretical uncertainty

For Kl3 decays, Ademollo-Gatto theorem dictates SU(3) terms appear at 2\textsuperscript{nd} order in f_{K\pi}^+(0)

K_{\mu_2}/\pi_{\mu_2}: f_K/f_\pi uncertainty reduced from latest lattice results
Interest in $V_{us}$ measurement with kaons

A measurement of $G_{\text{CKM}} = G_F (|V_{ud}|^2 + |V_{us}|^2)$ with error @ 0.5%

- is sensitive to tree masses $M_{NP} \sim 10$ TeV and to loop masses $M_{NP} \sim 1$ TeV
- is competitive with ew precision tests:

$G_F = 1.166371(6) \times 10^{-5}$ GeV$^{-2}$

$G_\tau = 1.1678(26) \times 10^{-5}$ GeV$^{-2}$

$G_{\text{ew}} = 1.1655(12) \times 10^{-5}$ GeV$^{-2}$

$G_{\text{CKM}} = 1.16xx(04) \times 10^{-5}$ GeV$^{-2}$
$V_{us}$ from semileptonic kaon decays

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

Theoretical inputs:
- $f_{+}(0)$, form factor at zero momentum transfer: purely theoretical calculation
  
  Recent result from UKQCD/RBC, 07 prel.: $f_{+}(0) = 0.964(5)$
- $\delta_{K}^\ell = 2(\Delta_{K}^{SU(2)} + \Delta_{K}^{em})$, I-breaking and e.m. effects:
  
  Recent $\chi$Pt results: $\Delta_{K+}^{SU(2)} = +2.36(22)\%$, $\Delta_{K}^{em} = +0.57(15)\% +0.08(15)\% \ell = e$
  $+0.80(15)\% -0.12(15)\% \ell = \mu$
- $S_{EW}$, short distance corrections (1.0232), $C_K = 1 / (2^{1/2})$ for $K^0$ ($K^+$) decays

Experimental inputs:
- $I_{K}^\ell = I(\{\lambda_+\},\{\lambda_0\},0)$, phase space integral, $\lambda_+,$ $\lambda_0 \rightarrow t$-dependence of vector, scalar ffs
- $\Gamma_{Kl3(\gamma)}$, semileptonic decay width evaluated from $\gamma$-inclusive BR and lifetime
- $m_{K}$, appropriate kaon mass

KLOE measurements for all relevant inputs: BR's, $\tau$'s, ff's

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Can also get $|V_{us}/V_{ud}|$ from $K,\pi \rightarrow \mu\nu$ widths [Marciano PRL93 231803, 2004]:

$$\frac{\Gamma(K \rightarrow \mu\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} = \frac{m_K \left(1 - \frac{m_{\mu}^2}{m_K^2}\right)^2}{m_\pi \left(1 - \frac{m_{\mu}^2}{m_\pi^2}\right)^2} \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{1 + \frac{e}{\pi} C_K}{1 + \frac{e}{\pi} C_\pi}$$

Theoretical inputs:
- radiative correction $C_K, C_\pi$
- form factor ratio $f_K/f_\pi$

Experimental inputs:
- $m_{K,\pi,\mu}, \Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$
Collisions at cm energy around $m_\phi$: $\sqrt{s} \sim 1019.4$ MeV

Angle between the beams @ IP: $\alpha \sim 12.5$ mrad

Residual laboratory momentum of $\phi$: $p_\phi \sim 13$ MeV

Cross section for $\phi$ production @ peak: $\sigma_\phi \sim 3.1$ $\mu$b
The KLOE detector

Large cylindrical drift chamber + lead/scintillating-fiber calorimeter + superconducting coil providing a 0.52 T field

\[ \sigma_{p/p} = 0.4 \% \text{ (tracks with } \theta > 45^\circ) \]
\[ \sigma_{x_{\text{hit}}} = 150 \mu m \text{ (xy), 2 mm (z)} \]
\[ \sigma_{x_{\text{vertex}}} \approx 1 \text{ mm} \]

\[ \sigma_{E/E} = 5.7\% \text{ } /\sqrt{E} \text{ (GeV)} \]
\[ \sigma_{t} = 54 \text{ ps } /\sqrt{E} \text{ (GeV)} \oplus 50 \text{ ps} \text{ (relative time between clusters)} \]
\[ \sigma_{L(\gamma\gamma)} \approx 2 \text{ cm (} \pi^0 \text{ from } K_L \rightarrow \pi^+\pi^-\pi^0) \]
Kaon physics at KLOE

KK pairs emitted ~back to back, p ~ 110 MeV

Identification of $K_{S,L}(K^{+/-})$ decay (interaction) tags presence of $K_{L,S}(K^{-+})$

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

• Access to absolute BR's

• Precise measurements of $K_{L3}$ from factors and $K_L$, $K^+$ lifetimes (acceptance ~0.5 $\tau_L$, $\tau_+$)

Above points crucial for $V_{us}$ determination
Overview of KLOE data

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

2001–5: \( \sim 2.5 \text{ fb}^{-1} \) integrated @ \( \sqrt{s} = M(\phi) \), yielding \( \sim 2.5 \times 10^9 \) \( K_S K_L \) pairs

Maximum peak luminosity, \( 2.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
Recent KLOE results in kaon physics

Focus on $V_{us}$ determination, LFV violation, and CPT and $\chi_{Pt}$ tests

KLOE results from kaon decays in last year:

- Neutral Kaon mass
- Scalar form factor slope from $K_{L_{\mu 3}}$
- Absolute BR for $K^{+}\rightarrow\pi^{+}\pi^{0}$ decay
- Absolute BR's for $K^{+,-}\rightarrow\pi l\nu$
- $K^{+,-}$ lifetime
- Combined $V_{us}$ determination
- CP, CPT parameters of $K^0$ system via BSR
- $d\Gamma(K_L \rightarrow \pi e\nu\gamma)/dE_{\gamma}$
- $BR(K_S \rightarrow \gamma\gamma)$

Preliminary mmts have also been announced:

- Updated form factor slopes from $K_{L_{\mu 3}}$
- UL[$BR(K_S \rightarrow e^+e^-)$]
- $\Gamma(K^+ \rightarrow ev)/\Gamma(K^+ \rightarrow \mu\nu)$

### Vus from Kl3 decays: results

Only use KLOE inputs, except $\tau_S$ from PDG:

| Decay          | $f_+(0) \times |V_{us}|$     | Error, % |
|----------------|---------------------|----------|
| $K_{Le3}$      | 0.2155(7)           | 0.3      |
| $K_{L\mu3}$    | 0.2167(9)           | 0.4      |
| $K_{Se3}$      | 0.2153(14)          | 0.7      |
| $K^+_{e3}$     | 0.2152(13)          | 0.6      |
| $K^+_{\mu3}$   | 0.2132(15)          | 0.7      |
| **Avg**        | **0.2157(6)**       | **0.28** |

Compare with world average including KLOE: 0.2166(5)

Use $f_+(0) = 0.9644(49)$ from UKQCD/RBC: $|V_{us}| = 0.2237(13)$

Use $|V_{ud}| = 0.97418(26)$ from $0^+ \rightarrow 0^+ \beta$ decays: $1 - |V_{ud}|^2 - |V_{us}|^2 = 9(8) \times 10^{-4}$
\[ \frac{V_{us}}{V_{ud}} \text{ from } K_{\mu 2} \text{ vs } V_{us} \text{ from } Kl3 \]

From the following inputs:

- \( BR(K^+ \rightarrow \mu^+\nu) \), \( \tau(K^+) \) [KLOE]
- \( f_K/f_\pi = 1.189(7) \) [HP/UKQCD 07]
- \( C_K, C_\pi \) [Marciano PRL93, 2004]
- \( M_{K,\pi,\mu}, \Gamma(\pi^+ \rightarrow \mu^+\nu) \) [PDG]

Result: \( |\frac{V_{us}}{V_{ud}}| = 0.2323(15) \)

Now can fit:

1) \( |\frac{V_{us}}{V_{ud}}| = 0.2323(15) \)
2) \( |V_{us}| = 0.2237(13) \) [KLOE Kl3]
3) \( |V_{ud}| = 0.97418(26) \) [Towner & Hardy arXiv:0710.3181]

Obtain: \( |V_{ud}| = 0.97417(26), |V_{us}| = 0.2249(10), P(\chi^2=2.34/1) = 13\% \)

CKM unitarity satisfied: \( 1 - |V_{ud}|^2 - |V_{us}|^2 = 4(7) \times 10^{-4} \)
Weak coupling universality test

Agreement between weak couplings from K decays and from μ lifetime:

\[ G_F = 1.166371(6) \times 10^{-5} \text{ GeV}^{-2} \leftarrow \]

\[ G_{\text{CKM}} = 1.16604(40) \times 10^{-5} \text{ GeV}^{-2} \leftarrow \]

Agreement at this level of accuracy implies observation of short distance radiative corrections at \( \sim 40 \)  σ level [Marciano]:

\[ 2 \frac{\alpha}{\pi} \log \frac{M_Z}{M} + \ldots \sim 2.5\% \]

Agreement of \( f_+(0) \times V_{us} \) for \( K^+ \) and \( K^0 \), brilliant success of the calculation of isospin breaking and e.m. corrections at few per mils
Agreement between weak couplings from K and from $\mu$ constraints NP

In SO(10) $Z_\chi$ boson [Marciano]:

$$G_F = G_{\text{CKM}} \left[ 1 - 0.007 \times \frac{8}{3} \times \ln \left( \frac{M_{Z'}}{M_W} \right) / \left( \frac{M_{Z'}^2}{M_W^2} - 1 \right) \right]$$

Implies: $M_{Z'} > 750$ GeV @ 95% CL
In non-universal gauge interaction model, a tree level contribution from a *Z'* boson breaking unitarity might be present [K. Y. Lee PRD 76, 117702 2007]

Assume different couplings of 1\textsuperscript{st}-2\textsuperscript{nd} lepton generation ($g_\text{l}$) and 3\textsuperscript{rd} ($g_\text{h}$):

\begin{align*}
  g_\text{l} &= e / \sin \theta_w \cos \phi \\
  g_\text{h} &= e / \sin \theta_w \sin \phi \\
  g' &= e / \cos \theta_w 
\end{align*}

$\theta_w$ is the weak mixing angle

$\phi$ is the mixing angle between SU(2)\text{l} and SU(2)\text{h}

Gauge structure appears in extended technicolor
Weak coupling universality test: MSSM

Scanning over MSSM parameter space, unitarity is sensitive to the squark-slepton mass difference [R. Barbieri 85, K. Hagiwara et al. 95, A Kurylov 00]

\[ [1 - (V_{ud}^2 + V_{us}^2)^{1/2}] \times 10^4 \]

Present error 0.35%

Need to improve it by \( \times 2 \) to really enter this game

Excluded by LEP

[Code by Mescia and Paradisi]
Weak coupling universality test: MSSM

Chance of improving? Lattice seems very solid:

Other tools are available to validate lattice results

Precision SM test with KI2 & KI3 at KLOE – T. Spadaro – Rencontres de Moriond, 11/03/2009
Weak coupling universality test: MSSM

Dispersive parametrization of $f_0(t)$ from $K \mu 3 + K \pi$ scattering data
relate value in the Callan-Treiman point to $f_K/f_\pi$ [Stern et al., Pich et al.]
The correction $\Delta_{CT}$ is evaluated in p-QCD

Perspectives: info from $\tau$ decay + theory improvements possible
In two Higgs doublet models (MSSM, too), exchange of $H^+$ provides an additional scalar current, which might contribute sizeably wrt to SM:

$$\frac{\Gamma(K \rightarrow \ell \nu)}{\Gamma_{SM}(K \rightarrow \ell \nu)} \approx \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left(1 - \frac{m_d}{m_s}\right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta} \right|$$

[Hou PRD48 (1992) 2342, Isidori-Paradisi]

NP effect is suppressed for $\pi_\ell^2$ wrt $K_\ell^2$, so NP might appear in $K_l2 / \pi_l2$, predicted in the SM to be:

$$\frac{\Gamma(K^{\pm}_{\ell2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell2(\gamma)})} = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(1 - \frac{m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2}\right)^2 \times (1 + \delta_{em})$$

NP test from comparing $V_{us}/V_{ud}$ from $M \rightarrow l\nu$ with $V_{us}(K_{l3})/V_{ud}(0^+ \rightarrow 0^+)$:

$$\left| \frac{V_{us}(K_{\ell2})}{V_{us}(K_{\ell3})} \times \frac{V_{ud}(0^+ \rightarrow 0^+)}{V_{ud}(\pi_{\ell2})} \right| ? \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left(1 - \frac{m_d}{m_s}\right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta} \right|$$
$K_{\mu 2} - Sensitivity\ to\ NP$

Result is:
\[
\left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \rightarrow 0^+)}{V_{ud}(\pi \ell 2)} \right| = 1.008(8)
\]

NP sensitivity from $K \rightarrow \mu \nu \sim$ as that from $BR(B \rightarrow \tau \nu) = 1.73(35) \times 10^{-4}$

For Belle update see A. Bozek and E. Baracchini talks. For a combined fit in 2-Higgs doublet models, see M. Goebel talk in this conference

Error dominated by theoretical uncertainties in form factors

NP induced by weak right-handed currents can be also tested (there, complement lattice information with Callan-Treiman scalar ff constraint)

[FlaviaNet arXiv:0801.1817]
**NP potential of** $R_K = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu2})}$

SM prediction with 0.04% precision, benefits of cancellation of hadronic uncertainties (no $f_K$): $R_K = 2.477(1) \times 10^{-5}$ [Cirigliano Rosell JHEP 710:005, 2007]

Helicity suppression can boost NP [Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

In R-parity MSSM, LFV can give 1% deviations from SM:

$$R_K^{LFV} \approx R_K^{SM} \left[ 1 + \left( \frac{m_K^4}{M_H^4} \right) \left( \frac{m_\tau^2}{m_e^2} \right) \left| \Delta_{13}^R \right|^2 \tan^6 \beta \right]$$

NP dominated by contribution of $e\nu_\tau$ final state, with effective coupling

$lH^\pm\nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_{13}$, from loop

Present exp. accuracy on $R_K$ @ 6%

New measurement of $R_K$ can be very interesting, if error is pushed @1% or better
Main actors (experiments) in the challenge to push down precision on $R_K$:

**KLOE**

- preliminary result with 2001—5 data: $R_K = 2.55 (5)_{\text{stat}} (5)_{\text{syst}} \times 10^{-5}$, from $\sim 8000$ $K\pi$ candidates (3% accuracy)

**NA48/2**

- preliminary result with 2003 data: $R_K = 2.416 (43)_{\text{stat}} (24)_{\text{syst}} \times 10^{-5}$, from $\sim 4000$ $K\pi$ candidates, statistical error dominating (2% accuracy)
- preliminary result with 2004 data: $R_K = 2.455 (45)_{\text{stat}} (41)_{\text{syst}} \times 10^{-5}$, from $\sim 4000$ $K\pi$ candidates from special minimum bias run (3% accuracy)

**NA62 (ex NA48), see talk by A. Winhart in this conference**

- collected $\sim 150,000$ $K\pi$ events in dedicated 2007 run, aims at breaking the 1% precision wall, possibly reaching $< \sim 0.5%$
Analysis of $K_{e2}/K_{\mu2}$ – basic principles

KLOE integrated $\sim 2.5$ fb$^{-1}$ of data & BR($K_{e2}$)$\sim 10^{-5}$: expect $< \sim 4 \times 10^4$ events

Perform direct search for $K_{e2}$ and $K_{\mu2}$, no tag: gain $\times 4$ of statistics

Select 1-prong kinks in DC, K track from IP & secondary $P > 180$ MeV

Exploit tracking of K and secondary: assuming $m_{\nu} = 0$ get $M^2_{lep}$

$K^- \rightarrow \mu^+ \nu$

$K^+ \rightarrow \pi^+ \pi^0$

$K^+ \rightarrow \pi^+ \pi^0$

$\gamma \rightarrow K^+ K^-$

$MC K_{\mu2}$

$MC K_{e2}$

$M^2_{lep}$ (MeV$^2$)
**$R_K$ analysis, kinematic selection**

Rule of the game: reject $K\mu_2$ by $10^4$, with $K\varepsilon_2$ efficiency of $O(50\%)$…

Background composition: $K\mu_2$ events with bad $P_K$, bad $P_l$ reconstruction

Apply quality cuts for $K$ and exploit $\Phi \rightarrow KK$ two-body kinematics
**In doing extrapolation for K, material budget is a key issue:** $\beta_K \sim 0.2$

For the Carbon-fiber DC inner wall, sensitivity on thickness difference $\Delta_{DC}$ wrt nominal value of 0.9 mm is order of 10 $\mu$m

Get rid of bad-P_i’s using fit quality + asymmetry of DC hits in L & R views
**$R_K$ analysis, quality criteria**

$M_{lep}^2 = f(P_K, P_l, \cos\theta)$ → a-priori error $\delta M_{lep}^2$ is scaled by opening angle

Achieve cancellation in Ke2/Kμ2 efficiencies, applying $\cos\theta$ trailing cuts

Efficiency ~ 33% at this level
**Analysis of $R_K$, electron identification**

Apply quality cuts, enough to count $K_{\mu 2}$, not for $K_{e 2}$ (still Bkg $\sim 10 \times$ Sig)

**Further rejection for $K_{e 2}$**: extrapolate track to EmC, select closest cluster

PID exploits EmC granularity: energy deposits $E_k$ into 5 layers in depth

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**After quality cuts**

- MC $K_{\mu 2}$
- MC $K_{e 2}$

**EmC, fiber direction view**

- Cluster depth
- Impact position
- Cluster energy centroid

$M^2_{lep}$ (MeV$^2$)
**Analysis of $R_K$, electron identification**

**Improve bkg rejection, PID refined**

Combine 12 variables using NN
- $E/P$
- Cluster depth
- Asymmetry of energy lost in first two innermost (outermost) planes
- $T2p$, $Aet$ (curvature of the fit)
- Energy deposit in first 15 cm
- Skewness of cell-depth distribution
- RMS of plane energies ($E_{RMS}$)
- Plane releases: $E1$, $N_{max}$, $E_{max}$
- TOF

Parametrize with $P_{lep}$, impact angle

Use $K_{Le3}$ to correct MC response at cell level and use MC to train NN

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**Precision SM test with K12 & K13 at KLOE** – T. Spadaro – Rencontres de Moriond, 11/03/2009
**$R_K$ analysis, fitting for Ke2 counting**

Two-dimensional binned likelihood fit in the NN- $M^2_{lep}$ plane

Count in entire statistics: $N_{Ke2(e^+)} = 7060(98)$, $N_{Ke2(e^-)} = 6750(97)$

Precision SM test with Ki2 & Ki3 at KLOE – T. Spadaro – Rencontres de Moriond, 11/03/2009
$R_K$ analysis, fitting for Ke2 counting

Two-dimensional binned likelihood fit in the NN- $M^2_{lep}$ plane

Vary significantly contamination + lever arm to assess fit systematics

Precision SM test with KI2 & KI3 at KLOE – T. Spadaro – Rencontres de Moriond, 11/03/2009
Analysis of $R_K$ – Radiative corrections

To match theory, has to count IB only
Expect $DE \sim IB$, but we poorly know
$\delta DE/DE \sim 15\%$

- Fit using IB+DE, count IB by considering as “signal” events those with $E_\gamma^* < 20$ MeV
- Correct for IB tail, $\varepsilon_{IB} = 95.28(5)$
- Repeat fit varying DE by its 15% uncertainty, get 0.45% error…

…too bad. Perform a dedicated analysis to measure DE:

- Explicitly detect radiated photon
- Compare DE/IB ratio with expectation from theory
Analysis of $R_K$ – Radiative corrections

Pass from IB/DE ~ 9 to IB/DE ~ 0.6 by explicitly detecting radiated $\gamma$

Count 752(36) + 692(36) events

Obtain: $\frac{IB}{IB+DE} = 0.5153(96)$

• Agrees with expectation, $\frac{IB_{SM}}{IB_{SM}+DE_{mmt}} = 0.509(38)$

• Allow systematics from DE to IB measurement to be pushed down at 0.1%
Reconstruction efficiency from MC, corrections from control samples
Select $K^{+,-}_\mu \mu_2$ and $K^{+,-}_e e_3$ in events tagged by identification of a $K^{-,+}_\mu \mu_2$ decay
Fit $P_\mu(P_e)$ using $\mu(e)$ cluster r,t (& E), kinematics: no K, $\mu(e)$ trks required.

![Graphs showing data and MC distributions for $P_\mu(P_e)$](image-url)
### $R_K$ systematic error budget

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Further systematic check: use same algorithms to measure $R_3 = Ke3/K\mu3$

- $R_3 = 1.507 \pm 0.005$ for $K^+$
- $R_3 = 1.510 \pm 0.006$ for $K^-$

World avg $R_3 = 1.506 \pm 0.003$ (FlaviaNet)
$R_K$ result

$R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

Stat error is 1.1% (0.85% from 14K Ke2 events $\oplus$ bkg subtraction)

Syst error is dominated by statistics again (0.015)

Measurement do not depend on K charge (good systematic check)

$K^+: 2.496(37)$ vs $K^-: 2.490(38)$, (uncorrelated errors only)

Measurement agrees with SM prediction, $R_K = 2.477(1)$
$R_K – Sensitivity to NP$

Sensitivity shown as 95%-CL excluded regions in the tan$\beta$ - $M_H$ plane, for fixed values of the 1-3 slepton-mass matrix element, $\Delta_{13} = 10^{-3}, 0.5 \times 10^{-3}, 10^{-4}$

WA w new KLOE result: $R_K = 2.468(25) \times 10^{-5}$

Precision SM test with K12 & K13 at KLOE – T. Spadaro – Rencontres de Moriond, 11/03/2009
Conclusions – kaon physics

Recent KLOE mmts greatly improve knowledge of gauge coupling:

- Comprehensive set of observables for K decays: BR's, τ's, FF's
- Improved unitarity test of 1st row of CKM matrix: \(1 - V_{ud}^2 - V_{us}^2 = 4(7) \times 10^{-4}\)
- Sensitivity to NP contribution from test of universality of gauge coupling
  - Lepton universality test from \(K_{\ell3}\) decays satisfied at < 0.5%

New and interesting tests of NP effects from two-body decay studies

- Sensitivity to NP effects from \(K_{\mu2}/\pi_{\mu2}\): comparable to \(B \rightarrow \tau\nu\)

Golden observable: \(R_K\), final result \(R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}\)

Future developments:

- Focus on FF slopes from \(K_{\ell3}^\pm\) decays + \(BR(K_S \rightarrow \pi\mu\nu)\), still missing
Spare slides
Status of $V_{ud}$ in 2008

1) $G_v$ constant

$$\varphi_t = \frac{K}{2G_v^2 (1 + \Delta_R)}$$

✓ verified to $\pm 0.013\%$

2) Scalar current zero

✓ limit, $C_s/C_v = 0.0011$ (14)

3) Precise value determined for $V_{ud}$

$$V_{ud} = \frac{G_v}{G_\mu}$$

$V_{ud} = 0.97425 \pm 0.00023$

Compare:

- neutron $V_{ud} = 0.9746 \pm 0.0019$
- pion $V_{ud} = 0.9749 \pm 0.0026$

I. S. Towner
@ CKM08

Precision SM test with K12 & K13 at KLOE – T. Spadaro – Le rencontres de Moriond, 11/03/2009
Possible improvements in $V_{ud}$

- Goal remains to tighten the window for new physics by reducing the uncertainty on $V_{ud}$.

- Uncertainty on calculated radiative correction $\Delta_R$ is the dominant contribution to the error budget.

- Nuclear-structure-dependent corrections, $\delta_c$ and $\delta_{NS}$, can be tested by experiment; this has already led to improvements, but more are still possible.

Data on “well known” transitions can be made more precise, and new cases can be measured.

I. S. Towner @ CKM08
Beyond the quadratic $ff$ parametrization

[Stern et al]

Dispersion relation for $\ln f_0(t)$ subtracted at $t = 0$ and $t = m_K^2 - m_\pi^2$, giving:

\[ \tilde{f}_0(t) = \exp \left[ \frac{t}{m_K^2 - m_\pi^2} (\ln C - G(t)) \right] \]

$G(t)$ evaluated using $K\pi$ scattering data

1 fit parameter: $\log C$

$\log C = 0.204 \pm 0.023$

Very precise relation between $f_0(0)^*$ and $f_K/f_\pi$:

\[ f_0(\Delta_{K\pi}) = f_K/f_\pi + \Delta_{CT} \]

\[ f_+(0) \, f_0(\Delta_{K\pi}) = f_K/f_\pi + \Delta_{CT} \]

$\Delta_{K\pi} = m_K^2 - m_\pi^2$; $\Delta_{CT} = 3.5 \times 10^{-3}$ $SU(2)$

![Graph showing the relationship between $f_0(t)$, $f_K/f_\pi + \Delta_{CT}$, and $f_+(0)$ with $\Delta_{K\pi}$ and $\Delta_{CT}$ indicated.]
In SM, electron and muon differs only by mass and coupling to Higgs

New physics extensions of the SM with LFV not ruled out, so:

- Can search for processes forbidden/ultra-rare in SM, e.g. $K \to \mu e$

- Can measure ratio of coupling constants, seeking deviations from 1 in processes well known in SM, like:

$$R_{e\mu} = \frac{\Gamma(K_{e3})}{\Gamma(K_{\mu3})} \to \frac{G_F^e}{G_F^\mu}$$

Testing $H^+$ effects or right-handed currents in:

$$R_{K\pi} = \frac{\Gamma(K \to \mu \nu)}{\Gamma(\pi \to \mu \nu)}$$

Testing LFV violation NP amplitudes contributing to:

$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu \nu)}$$
For each kaon charge state of $K_{l3}$ decays can evaluate:

\[
\frac{(R_{\mu e})_{\text{obs}}}{(R_{\mu e})_{\text{SM}}} = \frac{\Gamma_{\mu}}{\Gamma_{e}} \cdot \frac{I_{e3}(1 + \delta_{e3})}{I_{\mu3}(1 + \delta_{\mu3})} = \frac{\left| V_{us} \right|^2 f^+(0)}{\left| V_{us} \right|^2 f^+(0)}_{e3, \text{obs}} \frac{g_{\mu}^2}{g_{e}^2}
\]

e/\mu universality satisfied, using only KLOE results get accuracy < 0.01:

- $K_L$ \( g_{\mu}^2/g_{e}^2 = 1.011(9) \) cfr with \( g_{\mu}^2/g_{e}^2 = 1.0232(68) \) [PDG04]
- $K^+$ \( g_{\mu}^2/g_{e}^2 = 0.99(1) \) cfr with \( g_{\mu}^2/g_{e}^2 = 1.0020(80) \) [PDG04]
- Avg \( g_{\mu}^2/g_{e}^2 = 1.000(8) \)

Compare with

- $\tau \rightarrow l\nu\nu$ \( g_{\mu}^2/g_{e}^2 = 1.000(4) \) [Davier, Höcker, Zhang ‘06]
- $\pi \rightarrow l\nu$ \( g_{\mu}^2/g_{e}^2 = 1.004(3) \) [Erler, Ramsey-Musolf ‘06]
**$K_{\mu 2} – Sensitivity to NP$**

Experimental inputs are known at few per-mil level:

- $m_{K,\pi,\mu}, \Gamma(\pi_{\mu 2})$ [PDG]
- $\tau^+ = 12.347(30)$ [KLOE]
- $\text{BR}(K^+ \rightarrow \mu^+\nu(\gamma)) = 63.66(17)\%$ [KLOE]
- $|f_+(0)V_{us}| = 0.2157(6)$ [KLOE]
- $V_{ud} = 0.97418(26)$ [world average $0^+ \rightarrow 0^+$]

Theoretical inputs dominate the uncertainty, through the form factors:

- $f_K/f_\pi = 1.189(7)$ [MILC-HPQCD arXiv:0706.1726]
- $f_+(0) = 0.964(5)$ [UKQCD-RBC hep-lat/0702026]
- $\delta_{em} = -0.0070(35)$ [Marciano PRL 93 (2004) 231803, Cirigliano Rosell JHEP 0710, 005 (2007)]
$R_K$ analysis, quality criteria

$M_{lep}^2 = f(P_K, P_l, \cos\theta)$ → a-priori error $\delta M_{lep}^2$ is scaled by opening angle

Achieve cancellation in $K\mu2/K_e2$ efficiencies, applying $\cos\theta$ trailing cuts

![Graph showing data and MC comparison after quality cuts](image)
**$R_K$ analysis, fitting for Ke2 counting**

Two-dimensional binned likelihood fit in the NN- $M^2_{lep}$ plane

Count in entire statistics: $N_{Ke2}(e^+) = 7060(98)$, $N_{Ke2}(e^-) = 6750(97)$
**$R_K$ analysis, fitting for Ke2 counting**

Two-dimensional binned likelihood fit in the NN- $M_{lep}^2$ plane

**0.94 < NN < 0.96**

**0.96 < NN < 0.98**

**0.98 < NN < 1.00**

**1.00 < NN < 1.02**

**Count in entire statistics:** $N_{Ke2(e^+)} = 7060(98)$, $N_{Ke2(e^-)} = 6750(97)$

Precision SM test with K12 & K13 at KLOE – T. Spadaro – Le rencontres de Moriond, 11/03/2009
$R_K$ analysis, counting $Km2$ events

$M^2_{lep} (\text{MeV}^2)$

Precision SM test with K12 & K13 at KLOE – T. Spadaro – Le rencontres de Moriond, 11/03/2009
Check NN output using $K^{\pm}_{e3}$, $K^{\pm}_{\mu3}$ (can check TOF, not possible with $K_L$)

Require $\pi^0$ detection

Cut against $\pi\pi^0$ bkg

Use $\pi^0\gamma$’s to evaluate $E_{\text{miss}}$, $P_{\text{miss}}$

Log z scale

$E_{\text{miss}} - P_{\text{miss}}$ (MeV)
Can select pure $K_{e3}^\pm$ sample above 0.2
Can select $K_{\mu3}^\pm$ sample below 0.4
Perform 2d fit in entire plane
Analysis of $R_K$ – PID using EmC

e’s: initiate shower @ EmC entrance, $E_{cl}/P \sim 1$
\mu’s: MIP-like in layers 1-2, Bragg peak @ end

Cut on $A_F = \frac{(E_2-E_1)}{(E_2+E_1)}$, $E_{\text{max}} = \max\{E_k\}$

Cut on $A_L = \frac{(E_n-E_{n-1})}{(E_n+E_{n-1})}$, $E_{\text{RMS}} = \text{RMS}\{E_k\}$ left for signal counting
Rejection from PID now $> 1000 \rightarrow$ loosen kinematic criteria

Compare OLD selection with NEW selection
$R_K - \text{experimental status as of yesterday}$

$$R_K = \frac{N_{Ke2}}{N_{K\mu2}} \left[ \frac{\varepsilon^{TRG}_{K\mu2}}{\varepsilon_{Ke2}} \right] \left[ C^{TRK}_{TRK} \varepsilon^{TRK}_{K\mu2} \varepsilon^{-1}_{Ke2} \right] \left[ \frac{1}{C^{PID} \varepsilon^{PID}_{Ke2}} \right] \frac{1}{\varepsilon^{IB}} = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}$$

Recent (preliminary) results improved greatly with respect to 2006 PDG World average, $R_K = 2.457(32) \times 10^{-5}$, agrees with SM
Measurement of $K_{L_{e3}}$ form factor slopes

Both linear and quadratic fits show good $\chi^2$ probabilities, 89% and 92%.

<table>
<thead>
<tr>
<th>Linear fit</th>
<th>$\lambda_+ \times 10^3$</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \pi^- e^+ \nu$</td>
<td>$28.7 \pm 0.7$</td>
<td>156/181</td>
</tr>
<tr>
<td>$K_L \to \pi^+ e^- \bar{\nu}$</td>
<td>$28.5 \pm 0.6$</td>
<td>174/181</td>
</tr>
<tr>
<td>Combined</td>
<td>$28.6 \pm 0.5$</td>
<td>330/363</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quadratic fit</th>
<th>$\lambda'_+ \times 10^3$</th>
<th>$\lambda''_+ \times 10^3$</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \pi^- e^+ \nu$</td>
<td>$24.6 \pm 2.1$</td>
<td>$1.9 \pm 1.0$</td>
<td>152/180</td>
</tr>
<tr>
<td>$K_L \to \pi^+ e^- \bar{\nu}$</td>
<td>$26.4 \pm 2.1$</td>
<td>$1.0 \pm 1.0$</td>
<td>173/180</td>
</tr>
<tr>
<td>Combined</td>
<td>$25.5 \pm 1.5$</td>
<td>$1.4 \pm 0.7$</td>
<td>325/362</td>
</tr>
</tbody>
</table>

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

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

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

\[ \rho(\lambda', \lambda'') \sim -0.95 \]

Pole fit result (92% $\chi^2$ probability) indicates dominance of $K^*(892)$-exchange in the $K\pi$ transition:

\[ M_V = (870 \pm 6_{\text{stat.}} \pm 7_{\text{syst.}}) \text{ MeV} \]

Systematic errors dominated by uncertainties in TOF efficiency correction.
Measurement of $K_{Le3}$ form factor slopes

- KLOE measurements of $K_{Le3}$ and $K_{l\mu3}$ BR and ff slopes determine:
  \[ f_+(0) \times |V_{us}| = 0.21561(69) \]
  \[ f_+(0) \times |V_{us}| = 0.21633(78) \]

Inputs only from KLOE, errors of 0.32% and 0.40%

- In comparing with results from other experiments, have to take correlations into account, especially for ff's
Other impacts from $K_{s e 3}$ (1)

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

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

Sensitivity to CPT violating effects through charge asymmetry:

$A_{S,L} = \frac{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) - \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) + \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})}$

\[
\begin{align*}
A_S - A_L &= 4 \left[ \Re (\delta) + \Re (x_\nu) \right] \\
A_S + A_L &= 4 \left[ \Re (\varepsilon) - \Re (y) \right]
\end{align*}
\]

Evaluate $A_S$ from:

$A_S = \frac{N(\pi^- e^+ \nu)/\epsilon_+^{\pm} - N(\pi^+ e^- \bar{\nu})/\epsilon_-^{\pm}}{N(\pi^- e^+ \nu)/\epsilon_+^{\pm} + N(\pi^+ e^- \bar{\nu})/\epsilon_-^{\pm}}$

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

Error dominated by statistics, $\times 3$ improvement after analysis of 2.5 fb$^{-1}$
Impact of new data on $K^0$ decays: BSR

With KLOE data improved CPT test via Bell-Steinberger (unitarity) relation:

$$\left( \frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left( \frac{\Re \epsilon - i \Im \delta}{1 + \epsilon^2} \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f A_L(f) A_S^*(f)$$

After CPLEAR measurements (2001)

$$\begin{align*}
\Re(\epsilon) &= (164.9 \pm 2.5) \times 10^{-5} \\
\Im(\delta) &= (2.4 \pm 5.0) \times 10^{-5}
\end{align*}$$

After KLOE measurements (2006)

$$\begin{align*}
\Re(\epsilon) &= (159.6 \pm 1.3) \times 10^{-5} \\
\Im(\delta) &= (0.4 \pm 2.1) \times 10^{-5}
\end{align*}$$
Impact of new data on K0 decays: UT

From BSR, shift central value of $\Re \varepsilon$ by 3.6 $\sigma$ with respect to PDG04

$|\varepsilon|$ is related to the $\eta$ and $\rho$ parameters of the CKM matrix:

$$|\varepsilon| = C_1 B_K V_{cb}^2 \eta [C_2 + C_3 V_{cb}^2 (1-\rho)]$$

Compare input values for $B_K$:

- Standard, $B_K = 0.79(2)(9)$
- RBC/UKQCD, $B_K = 0.770(15)(22)$

Impact on UT fit now limited by $\delta V_{cb}$
Measurements of $K^+,−$ BR’s

Tagging starts from one-prong decay reconstruction in drift chamber
Cut on $p^*_\pi$ to identify two-body decays, $K \rightarrow \pi\pi^0$ and $K \rightarrow \mu\nu$

4 independent taggings: $K^{\pm}\pi^{\pm}$ & $K^{\pm}\mu^{\pm}$:

• Can measure absolute BR’s for each tag sample separately: keep tag-bias effects under control

• Compare results by charge: keep systematics from $K^-$ nuclear interactions in traversed material under control
Measurements of $K^{+,-}$ semileptonic BR's

- Detect photons from $\pi^0$
- Kinematical cuts to reject non-Kl3 decays: not-Kl3 background $\sim 1.5$
- Signal counts: log-$L$ fit of distribution of lepton mass squared ($M^2$) from TOF

$\text{BR}(K_{e3}^\pm) = 4.965(19)_{\text{stat}}^{(33)}_{\text{corr-stat}}(37)_{\text{syst}} \%$

Result: $\text{BR}(K_{\mu3}^\pm) = 3.233(16)_{\text{stat}}^{(24)}_{\text{corr-stat}}(26)_{\text{syst}} \%$

$\rho(K_{e3}^\pm,K_{\mu3}^\pm) = 0.63$

Above mmt @ $\tau^+=12.384$ ns, for $V_{us}$ use dependency $d\text{BR}/\text{BR} = -0.45d\tau/\tau$

Systematics dominated by uncertainty on tracking efficiency correction
Measurements of $K^+\,\text{and}\,K^-$ lifetime

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 $K^+ \rightarrow X\pi^0$, proper time $t^*$ from $\gamma$ TOF's

2) From $K^+ \rightarrow 1\text{track}$ decay-length, $t^* = \sum_i L_i/(\beta_i\gamma_i c)$

Allow systematic checks, only features in common to both methods are:

Tag is done with $K_{\mu 2}$ decay identification

Kaon decay vertex is in the DC

4 results are compatible, thus can average:

$\tau_{\pm} = 12.347(30)$ ns

$\tau(K^+)/\tau(K^-) = 1.004(4)$
Unique to KLOE: $K_{S\mu3}$ decays

Decay mode has never been observed

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

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

Measure charge asymmetry: test of CPT, CP violation

Total error dominated by statistics, expect 3% @ the end of analysis
Generators for radiative $K$ decays

Generators for kaon decays include radiation, no cutoff energy

- Full $O(\alpha)$ amplitudes (real and virtual contributions) summed to all orders in $\alpha$ by exponentiation (soft-photon approximation)
- Carefully checked against all available data and calculations, e.g:

$$BR(K_L \rightarrow \pi e \nu\gamma, E_{\gamma} > 30\,MeV, \theta_{e\gamma} > 20^\circ) = \frac{BR(K_L \rightarrow \pi e \nu)}{BR(K_L \rightarrow \pi e \nu)}$$

$kTeV$

(0.908 ± 0.015)×10^{-2}

$Bijnens et al$

0.93×10^{-2}

$MC$

0.93×10^{-2}

$$BR(K_S \rightarrow \pi\pi\gamma, E_{\gamma} > 50\,MeV) = \frac{E731}{BR(K_S \rightarrow \pi\pi)} (2.56±0.09)×10^{-3}$$

$MC$

2.6×10^{-3}

[C. Gatti, EPJC 45 (2006)]