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for the KLOE Collaboration

Vus and lepton universality
with kaons at KLOE
Kaon Physics

- Precise determination of $V_{us}$
- Test of **Lepton universality** $K_{e3}$ vs $K_{\mu 3}$
- Most precise test of **CKM unitarity**
  
  $|V_{ud}|^2 + |V_{us}|^2 = 1, \quad |V_{ub}|^2$ negligible

- **Lepton-Quark universality** of weak int.
  
  $G_F^2 \equiv G_{\text{CKM}}^2 = (|V_{ud}|^2 + |V_{us}|^2)G_F^2$

- **Lepton Flavor Violation** test with $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

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- Vector transition: only 2\textsuperscript{nd} order SU(3) breaking [Ademollo-Gatto]

- Helicity suppressed: Sensitivity to NP enhanced
Set bounds on New Physics from Lepton-Quark Universality

New Physics extensions of the SM can break gauge universality in the form of tree or loop level contributions to muon decays and/or semileptonic processes.

i. **Exotic Muon Decays** would contribute to the muon lifetime

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - BR(\text{exotic muon decays}) \]

*Provides best limit on* \( BR(\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu) \) *better than direct search*

ii. **Additional Z’ Gauge Bosons** contributing at loop level to muons and semileptonic decays differently (*Competitive with direct search*) [PRD 35 (1987)]

iii. SUSY particle loops affecting muon and semileptonic decays differently: constraints on slepton-squark mass difference (*x2-3 precision needed*) [PRL 75 (1995), PRL 88 (2002)]

Present accuracy set bounds on the scale of New Physics \( \Lambda_{NP} \) at 1-2 TeV

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \varepsilon_{NP} \quad \varepsilon_{NP} \approx \frac{M_W^2}{\Lambda_{NP}^2} \]
$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f^+_{K^0\pi^-}(0)|^2 \times I_{Kl}(\{\lambda\}_{KL}) (1 + 2\Delta_K^{SU(2)} + 2\Delta_{KL}^{EM})$

with $K \in \{K^+, K^0\}$; $l \in \{e, \mu\}$, and:
$C_K^2 = 1/2$ for $K^+$, $1$ for $K^0$

**Inputs from theory:**

$S_{EW}$ Universal short distance EW correction ($1.0232$)

$f^+_{K^0\pi^-}(0)$ Hadronic matrix element at zero momentum transfer ($t=0$)

$\Delta_K^{SU(2)}$ Form factor correction for strong SU(2) breaking

$\Delta_{KL}^{EM}$ Long distance EM effects

**Inputs from experiment:**

$\Gamma(K_{l3(\gamma)})$ Branching ratios with well determined treatment of radiative decays; lifetimes

$I_{Kl}(\lambda)$ Phase space integral: $\lambda$s parameterize form factor dependence on $t$:
- $K_{e3}$: only $\lambda_+$ (or $\lambda_+’, \lambda_+''$)
- $K_{\mu3}$: need $\lambda_+$ and $\lambda_0$

**KLOE has measured all relevant inputs for charged and neutral kaons:** BR’s, lifetimes ($K_L, K^0$), form factors (FFs)
To extract $\nu_{us}$ from neutral kaons

**PLB 632 (2006)**

$\text{BR}(K_{e3}) = 0.4008(15)$  \hspace{1cm} 0.37%
$\text{BR}(K_{\mu3}) = 0.2699(14)$  \hspace{1cm} 0.52%

Based on $13\times10^6 K_L$ decays tagged by $K_S \rightarrow \pi^+\pi^-$

**PLB 626 (2005)**

$\tau_L = 50.92(30) \text{ ns}$  \hspace{1cm} 0.58%

Fit the time dependence over $0.4\tau_L$ of $8.5\times10^6$ $K_L \rightarrow \pi^0\pi^0\pi^0$ decays tagged by $K_S \rightarrow \pi^+\pi^-$

*(P. de Simone talk)*

**PLB 636 (2006)**

$\text{BR}(K_S \rightarrow \pi e\nu) = 7.046(91) \times 10^{-4}$  \hspace{1cm} 1.3%

From tagged $K_S$ beam $1.2\times10^8$ events

**JHEP12(2007)**

$\lambda' = (25.6 \pm 1.5_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-3}$
$\lambda'' = (1.5 \pm 0.7_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$
$\lambda_0 = (15.4 \pm 1.8_{\text{stat}} \pm 1.3_{\text{syst}}) \times 10^{-3}$

Based on $1.8\times10^6 K_L \mu3$ decays tagged by $K_S \rightarrow \pi^+\pi^-$ and from combined fit with $K_L e3$ data

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To extract $\nu_{us}$ from charged kaons

**PLB 632 (2006)**

$\text{BR}(K^+ \rightarrow \mu^+ \nu) = 0.6366(17)$  
0.27%

**JHEP 01 (2008)**

$\tau^\pm = 12.347(30)$  
0.24%

**JHEP 02 (2008)**

$\text{BR}(K^\pm \rightarrow \pi^0 e^\pm \nu) = 0.04965(53)$  
1%

$\text{BR}(K^\pm \rightarrow \pi^0 \mu^\pm \nu) = 0.03233(39)$  
1.2%

**PLB 666 (2008)**

$\text{BR}(K^+ \rightarrow \pi^+ \pi^0 (\gamma)) = 0.2065(9)$  
0.43%

From $4.2 \times 10^6 \phi \rightarrow K^+ K^-$ tagged by $K^- \mu_2$ decays

From $15 \times 10^6 \phi \rightarrow K^+ K^-$ tagged by $K_\mu_2$ decays

From $6 \times 10^7 \phi \rightarrow K^+ K^-$ decays tagged by both $K_\mu_2$ and $K_\pi_2$ decays

From $20 \times 10^6 \phi \rightarrow K^+ K^-$ decays tagged by both $K^- \mu_2$ and $K^- \pi_2$ decays
$|V_{us}|f_{+}(0)$ at KLOE

All KLOE exp. inputs but $K_s$ lifetime (M. Dreucci talk)

Lepton universality

$r_{\mu e} \equiv \frac{|f_{+}(0) V_{us}|^2_{\mu 3, \text{exp}}}{|f_{+}(0) V_{us}|^2_{e 3, \text{exp}}} = \frac{g_{\mu}^2}{g_{e}^2}$

$r_{\mu e} = 1.000(8)$

$\tau$ decays: $(r_{\mu e})_\tau = 1.0005(41)$ (PDG06)

$\pi$ decays: $(r_{\mu e})_\pi = 1.0042(33)$

KLOE average $|V_{us}|f_{+}(0) = 0.2157(6)$ $\chi^2/\text{ndf}=7/4$ (13%)

World Average 0.2166(5)

$|V_{us}| = 0.2237(13)$

$1 - |V_{ud}|^2 - |V_{us}|^2 = 9(8) \times 10^{-4}$

$f_{+}(0) = 0.964(5)$

$|V_{ud}| = 0.97418(26)$

PRL 100 (2008)

PRC 77 (2008)

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$|V_{us}/V_{ud}| = 0.2323(15)$

$|V_{us}| = 0.2237(13)$ from Kl3 decays

- Fit to $|V_{ud}|^2$, $|V_{us}|^2$ and $|V_{us}/V_{ud}|^2$

- Agreement with unitarity

$1 - V_{ud}^2 - V_{us}^2 = 4(7) \times 10^{-4} \ @ 0.6 \sigma$

- Universality of lepton and quark weak coupling to W

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

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

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

$G_F^2 \equiv G_{CKM}^2 = (|V_{ud}|^2 + |V_{us}|^2)G_F^2$

from ew precision tests

$\text{BR}(K^\pm \to \mu^\pm \nu) = 0.6366(17)$

$f_K/f_\pi = 1.189(7)$

$|V_{us}/V_{ud}|^2 = 0.9490(5)$

$|V_{us}|^2 = 0.0506(4)$

$\chi^2 = 2.3/1 (13\%)$
Lepton Flavor Violation:

\[ R_K = \frac{\Gamma(Ke2(\gamma_{IB}))}{\Gamma(K\mu2(\gamma_{IB}))} \]

- \( R_K = \frac{\Gamma(Ke2(\gamma_{IB}))}{\Gamma(K\mu2(\gamma_{IB}))} \) inclusive of IB only
- DE (or SD) \( \approx \) IB presently known with 15% accuracy

To achieve \( \sim 1\% \) accuracy on \( R_K \) improve knowledge of DE

- In the SM \( R_K \) calculated at 0.04% (no hadronic uncertainties)
  \( R_K^{SM} = 2.477(1) \times 10^{-5} \) [Cirigliano, Rossell JHEP10(2007)005]

- Lepton Flavor Violation in the MSSM would enhance \( R_K \) up to 1%
  LFV appears at 1-loop level via an effective \( H^+ \ell \nu_\tau \) Yukawa interaction
  dominated by \( e \nu_\tau \)

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

$R_K$: analysis strategy

- 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

  Signal events with $E_\gamma < 10$ MeV (no explicit photon detection)
- Exploit tracking of K and secondary: assuming $m_\nu = 0$ get $M_{lep}^2$ ($S/B \sim 1/10$)
- Particle Identification by Neural Network based on EMC information (training with KLe3)

**Signal count from fit in NN- $M_{lep}^2$**

*Free parameters:*
  - normalization factors for $K_{\mu2}$ and $K_{e2}(\gamma)$ including only IB with $E_\gamma < 10$ MeV (to $O(\alpha_{em})$ and resummation of leading logs)

*Fixed parameter:*
  - $f_{DE} = 10.2\%$ (Ke2 contamination from $K_{e2}(\gamma)$ with $E_\gamma > 10$ MeV)

*But* 0.5% systematics on $R_K$ from $f_{DE}$ ($\delta(DE)/DE = 15\%$)

$\Rightarrow$ dedicated measurement of $K_{e2}(\gamma)$ with $E_\gamma > 10$ MeV
$R_K$: fitting for $K_{e2}$ and $K_{\mu2}$ counting

- $K_{e2}$ counts from two-dimensional binned likelihood fit in the NN- $M^2_{lep}$ plane with $0.86 < NN < 1.02$ and $-3700 < M^2_{lep} < 6100$.

Using the whole statistics: $N_{Ke2}(e^+) = 7064(102)$, $N_{Ke2}(e^-) = 6750(101)$

- $K_{\mu2}$ counting from 1-dimensional fit of $M^2_{lep}$ distribution without PID.
Key amplitudes

\[
\frac{d\Gamma(K \rightarrow e\nu\gamma)}{dx \, dy} = \rho_{IB}(x, y) + \rho_{SD}(x, y) + \rho_{INT}(x, y)
\]

\[
\rho_{SD}(x, y) = \frac{G_F^2 \left| V_{us} \right|^2 \alpha}{64\pi^2} m_K^5 \left( (V + A)^2 f_{SD+}(x, y) + (V - A)^2 f_{SD-}(x, y) \right)
\]

\[
x = \frac{2E_{\gamma}^*}{m_K}
\]

\[
y = \frac{2E_e^*}{m_K}
\]

\(V, A:\) effective vector and axial couplings

\[
P_e^*\ [\text{MeV}]
\]

\[
E_{\gamma}^*\ [\text{MeV}]
\]

\[
SD^+ \quad V + A
\]

\[
SD^- \quad V - A
\]

endpoint of \(K_{e3}\) decays
Ke2\(\gamma\): signal selection

- 1-prong selection -- NN > 0.98 -- 1 photon cluster with \(E_\gamma > 20\) MeV in time with K
- Cluster times for photon and electron must be compatible

With this selection we measure Ke2\(\gamma\) with:

\[ E_\gamma > 10\ \text{MeV} \]
\[ \cos \theta_{e\gamma} * > 0.9 \]
\[ p_e * > 200\ \text{MeV} \]

No sensitivity for Ke2\(\gamma\) with \(p_e < 200\) MeV (SD-)

Acceptance for SD+ events \(\sim 90\%\)

SD- events \(\sim 2\%\)

Residual IB events \(\sim 1\%\)

Dominant backgrounds:

\(K\mu2\) for \(M^2_{\text{lep}} < 20000\ \text{MeV}^2\) and Ke3 for \(M^2_{\text{lep}} > 20000\ \text{MeV}^2\)

- Further reject Ke3 decays with \(\Delta E_\gamma = E_\gamma^{\text{LAB}} - E_\gamma^{\text{CAL}}\) (\(\sigma_{E^{\text{LAB}}} \approx 12\ \text{MeV}\ \sigma_{E^{\text{CAL}}} \approx 30\ \text{MeV}\) )

Signal count from 2-dimensional binned likelihood fit in \(M^2_{\text{lep}}, \Delta E_\gamma / \sigma\) in 5 bins of \(E_\gamma^*\)
Ke2γ spectrum vs $O(p^4)$ ChPT

We measure

$$\frac{1}{\Gamma(K_{\mu2(\gamma)})} \frac{d\Gamma_{SD+}(K_{e2\gamma})}{dE_\gamma}$$

where “SD+” means:

- $E_\gamma^* > 10$ MeV
- $\cos \theta_{e\gamma}^* < 0.9$
- $p_e^* > 200$ MeV

Summed over all bins in $E_\gamma^*$:

$$N_{SD+}(K_{e2\gamma}) = 1378 \pm 63$$

$$\frac{\Gamma_{SD+}(K_{e2\gamma})}{\Gamma(K_{\mu2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$$

in agreement with ChPT $O(p^4)$ prediction, $1.447 \times 10^{-5}$ [Bijnens, Ecker, Gasser '93]

KLOE MC implements $O(p^4)$ ChPT for SD – used in analysis of $R_\kappa$

Validated to within 4.6% - systematic error on $R_\kappa$ from SD = 0.2%
**$R_K$: the final result**

Using the complete KLOE data set (2.2 fb$^{-1}$) we obtain:

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

$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

<table>
<thead>
<tr>
<th>Systematic errors %</th>
<th>stat</th>
<th>syst</th>
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<tbody>
<tr>
<td>Reconstruction</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Trigger efficiency</td>
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<td>-</td>
</tr>
<tr>
<td>Background sub</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Ke2(DE) comp.</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Clustering</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Main contribution to systematic uncertainty from control-sample statistics (0.6%)

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, $\Delta_{13} = 10^{-3}, 0.5 \times 10^{-3}, 10^{-4}$

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**Draft paper under Collaboration’s revision**

**Erika De Lucia -- EPS2009 -- Krakow 16-22 July 2009**
**$R_K$: World Average**

**World average:** $R_K = 2.498(14) \times 10^{-5}$ (0.56%)

Includes NA62 preliminary (40% data set):

$R_K = 2.500(16) \times 10^{-5}$ (0.64%)

$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$

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, $\Delta_{13} = 10^{-3}, 0.5\times10^{-3}, 10^{-4}$

![Graph showing $\tan\beta$ vs. $M_H$ with excluded regions and sensitivity values.](image-url)
Summary & conclusions

Precision physics with Kaon decays to test the Standard Model

- Today \(|V_{us}| f_+ (0) @ 0.3\%\) with KLOE (0.2\% from World Average Fit)
- Lepton universality satisfied to better than 0.5\%
- Unitarity of CKM matrix satisfied to better than 0.1\% (\(|V_{us}|\) at 0.4\%)
- Universality of lepton and quark weak coupling from unitarity and set constraints on New Physics models

- with \(Z'\) and \(H^\pm\) boson, with Lepton Flavor Violation
- \(R_K\) at 1.3\% from \(1.4 \times 10^4\) \(K\gamma\) decays with 2.2 \(fb^{-1}\) data sample
- \(\Gamma(K\gamma; 10 < E_\gamma < 250\ \text{MeV} \text{ and } p_\gamma > 200\ \text{MeV}) / \Gamma(K\mu2)\) at 4.6\% reduces from 0.5\% to 0.2\% the systematic uncertainty on \(R_K\) from DE which is also very important for NA62 \(R_K\) measurement
SPARE SLIDES
Today with $f_+(0)@ 0.5\%$ the accuracy on the unitarity relation of the first row is

$$\sigma (1-V_{ud}^2-V_{us}^2) = 6 \times 10^{-4}$$

- $f_+(0)@ 0.1\%$ accuracy from lattice within few years

<table>
<thead>
<tr>
<th></th>
<th>$f_+(0)$</th>
<th>$V_{us}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KLOE today</strong></td>
<td>0.28%</td>
<td>0.30%</td>
</tr>
<tr>
<td>(World Average)</td>
<td>(0.23%)</td>
<td>(0.25%)</td>
</tr>
<tr>
<td><strong>KLOE + Step0 (5 fb^{-1}) + World Average</strong></td>
<td>0.14%</td>
<td>0.17%</td>
</tr>
</tbody>
</table>

- $f_K/f_\pi @ 0.1\%$ within few years and $|V_{us}/V_{ud}| @ 0.28\%$ from $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$

- With $|V_{ud}| @ 0.02\%$ and $|V_{us}| @ 0.17\%$ the accuracy on the unitarity relation of the first row would improve by a factor of $\sim 2$

$$\sigma (1-V_{ud}^2-V_{us}^2) = (3\div 4) \times 10^{-4}$$

Improve constraints on New Physics and interplay with other sectors