Charged kaons at KLOE

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on behalf of the KLOE collaboration
I get it!

СПАСИБО!!!
Outline

• Vus with charged kaons
• **TAG mechanism**
• $K^+ \to \mu^+ \nu (\gamma)$
• **Semileptonic decays**
• **Charged kaon lifetime**
• Conclusions
**V_{us} form charged kaons**

- From **semileptonic decays**

\[ \Gamma (K^\pm \to \pi^0 l^\pm \nu_l) = \frac{BR (K^\pm \to \pi^0 l^\pm \nu_l)}{\tau (K^\pm)} \propto \left| V_{us} f_+ (0) \right|^2 S_{EW} (1 + \delta^e_K) I^e_K \]


\[ \frac{\Gamma (K \to \mu \nu (\gamma))}{\Gamma (K \to \pi \nu (\gamma))} \propto \left| \frac{V_{us}}{V_{ud}} \right|^2 \times \left( \frac{f_K}{f_\pi} \right)^2 \]

*Form factor*  \*Radiative corrections*  \*Phase space* \( (\lambda_+, \lambda_0) \)

*Lattice QCD*
Kaon pair production

The \( \phi \) decays at rest producing a kaon pair: \( K_L K_S \) or \( K^+ K^- \).

The detection of a \( K \) \textit{guarantees the presence} of the \( \bar{K} \) with known momentum \( \Rightarrow \) \textbf{Tag mechanism}.

\textbf{Normalization} to the number of tags allows a precise measurement of \textit{absolute} BRs.

\[ \sigma(e^+ e^- \to \phi) \approx 3 \mu b \quad P_{LAB} = 127 \text{ MeV}/c \]

\[ BR(\phi \to K^+ K^-) \approx 49\% \quad \lambda(K^+) = 95 \text{ cm} \]
Tag mechanism

$K^\pm$ events tagged using two body decays (about 85%): $K^\pm \rightarrow \mu^\pm \nu, \pi^\pm \pi^0 \approx 1.5 \times 10^6 K^+K^- \text{ ev/pb}^{-1}$

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

To minimize the impact of the trigger efficiency tags must provide themselves the Emc trigger of the event: **self-triggering tags**

$N_{\text{self-trg Tag}} \approx 2 \times 10^5 \text{ pb}^{-1}$
Measurement of the absolute branching ratio

\[ K^+ \rightarrow \mu^+ \nu(\gamma) \]

Overview \( K^+ \rightarrow \mu^+ \nu(\gamma) \)

- Normalization \( N_{\text{TAG}} \) given by 175 pb\(^{-1}\) from self-triggering \( K^- \rightarrow \mu^- \bar{\nu} \)
- Counting events in the distribution of secondary track momentum in the kaon rest frame \( p^* \)
- Background subtraction

- Efficiency related to DC reconstruction only (tracking plus vertexing), evaluated on data
**Signal**  \( K^+ \rightarrow \mu^+ \nu(\gamma) \)

- Signal given by \( K^+ \) decay in the DC FV (40 cm < \( \rho \) < 150 cm)
  
  Using \( \sim 60 \text{ pb}^{-1} \)

- Background given by events with \( \pi^0 \) in the final state:
  
  \[
  K^+ \rightarrow \pi^+ \pi^0 \\
  K^+ \rightarrow \pi^0 e^+ \nu_e \\
  K^+ \rightarrow \pi^0 \mu^+ \nu_\mu
  \]

\[
BR = \frac{N_{K\mu\nu(\gamma)}}{N_{TAG}} \cdot \frac{1}{\epsilon_{DC}}
\]
\textbf{Epsilon (\(\varepsilon\)) evaluation}

- Efficiency has been evaluated on a second \textit{uncorrelated sample} of \(\sim 115\, pb^{-1}\) using \textit{only calorimeter} information.

- Double K\(\mu\nu\) events have a typical signature in the EMC, i.e., 2 isolated clusters with energy in the range \(80 < E_{\text{CLU}} < 320\) MeV.

- A correction \(O(10^{-4})\) to the efficiency has been evaluated from MC:

\[
\varepsilon_{\text{DC}} = \varepsilon_{\text{DATA}} \times C_{\text{MC}} \quad \quad C_{\text{MC}} = \frac{\varepsilon_{\text{MC True}}}{\varepsilon_{\text{MC recon}}}.
\]
Result

\[ BR = 0.6366 \pm 0.0009_{\text{stat.}} \pm 0.0015_{\text{syst.}} \]

Summary table of systematic and statistical uncertainties

<table>
<thead>
<tr>
<th>Source of syst. uncert.</th>
<th>Value</th>
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<tbody>
<tr>
<td>( \delta_{\text{Low Energy Cut}} )</td>
<td>( 5 \times 10^{-4} )</td>
<td>First estimate</td>
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<td>( \delta_{\text{High Energy radiative } \gamma} )</td>
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<td>Data efficiency</td>
<td>( 4 \times 10^{-4} )</td>
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<td>( \delta_{\text{High Energy Cut}} )</td>
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<td>MC efficiency</td>
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<td>( \delta_{\text{Fiducial Volume}} )</td>
<td>( 5 \times 10^{-4} )</td>
<td>True MC efficiency</td>
<td>( 3 \times 10^{-4} )</td>
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<tr>
<td>( \delta_{\text{Background}} )</td>
<td>( 3 \times 10^{-4} )</td>
<td>Tag bias</td>
<td>( 1 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \delta_{\text{p}^\star \text{ range}} )</td>
<td>( 3 \times 10^{-4} )</td>
<td>Total stat. uncert.</td>
<td>( 9 \times 10^{-4} )</td>
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<tr>
<td>( \delta_{\text{Tag}} )</td>
<td>( 1 \times 10^{-4} )</td>
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<tr>
<td>( \delta_{\text{MC Lifetime}} )</td>
<td>&lt; ( 10^{-6} )</td>
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<tr>
<td>( \delta_{\text{Nuclear interactions}} )</td>
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<tr>
<td>( \delta_{\text{FILFO}} )</td>
<td>&lt; ( 3 \times 10^{-4} )</td>
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<td>( \delta_{\text{T3 filter}} )</td>
<td>( \mathcal{O}(10^{-6}) )</td>
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<td>( \delta_{\text{Trigger}} )</td>
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<tr>
<td>Total syst. uncert.</td>
<td>( 15 \times 10^{-4} )</td>
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</table>

Total number of events: 865283

Total accuracy: 0.27%
Result

$$BR = 0.6366 \pm 0.0009_{\text{stat.}} \pm 0.0015_{\text{syst.}}$$

$$\frac{BR(K \to \mu \nu(\gamma))}{BR(K \to \pi \nu(\gamma))} \propto \left| \frac{V_{us}}{V_{ud}} \right|^2 \times \left| \frac{f_K}{f_\pi} \right|^2$$

Using the updated result from MILC: $f_K/f_\pi = 1.198 \pm 0.003^{+0.016}_{-0.005}$

we obtain:

$$\left| \frac{V_{us}}{V_{ud}} \right| = 0.2294 \pm 0.0026$$
\( V_{us} - V_{ud} \) plane

**Inputs:**

\[
\begin{align*}
V_{us} &= 0.2248 \pm 0.0020 \quad (K_\pi KLOE) \\
V_{ud} &= 0.97377 \pm 0.00027 \quad (Marciano) \\
V_{us}/V_{ud} &= 0.2294 \pm 0.0026 \quad (K_\mu^2 KLOE)
\end{align*}
\]

**Fit results:**

\[
\begin{align*}
V_{us} &= 0.2243 \pm 0.0016 \\
V_{ud} &= 0.97377 \pm 0.00027
\end{align*}
\]

**Fit results assuming unitarity:**

\[
\begin{align*}
V_{us} &= 0.2264 \pm 0.0009 \\
P(\chi^2) &= 0.43
\end{align*}
\]
Measurement of the $K^\pm$ semileptonic decays

absolute branching ratios

\[ K^\pm \rightarrow \pi^0 e^\pm \nu_e \quad \& \quad K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu \]
Semileptonic overview

- 4 independent normalization samples (2 tag x 2 charges)
- 410 pb$^{-1}$ self-triggering tags from 2001 and 2002 data
- Fit of the charged secondary square mass spectrum $m_{\text{lept}}^2$
- $K^\pm \rightarrow \mu^\pm \nu$ and $K^\pm \rightarrow \pi^\pm \pi^0$ rejected cutting on $p^*(m_\pi)$
- Efficiency evaluated from MC and corrected for Data/MC ratio
**Signal selection**

- Two tracks **vertex in the FV:**
  40 cm < ρ < 150 cm
- Track of charged secondary extrapolated to EMC
- Two body decays cut:
  p*(m_π) < 195 MeV/c
- π⁰ reconstruction:
  2 neutral clusters in EMC with TOF matching the kaon decay vertex
- Mass of charged secondary from TOF measurement

\[ t_{\pi^0}^{\text{decay}} = \frac{(t_1 - L_1/c) + (t_2 - L_2/c)}{2} \]

\[ m_{\text{lept}}^2 = p_{\text{lept}}^2 \cdot \frac{c^2}{L_{\text{lept}}^2} \left( t_{\text{lept}} - t_{\pi^0}^{\text{decay}} \right)^2 - 1 \]
Background (I)

$K^\pm \to \pi^\pm \pi^0 \pi^0$ with a $\pi^0$ undergoing a Dalitz decay, or with a wrong cluster associated to $\pi^\pm$, give a $m_1^2$ under the Ke3 peak

$\Rightarrow$ cut requiring

$(E_{\text{miss}} - P_{\text{miss}}) < 90$ MeV

$K^\pm \to \pi^\pm \pi^0$ with early $\pi^\pm \to \mu^\pm \nu$, give $m_1^2$ under the K$\mu$3 peak

$\Rightarrow$ rejected using the missing momentum of the secondary track in the pion rest frame ($P^*_{\text{sec}} < 90$ MeV)
**Background (II)**

The cuts reject \( \approx 96\% \) of the background events.

The efficiency on the signal is \( \approx 50\% \) for both \( K_{e3} \) and \( K_{\mu3} \).

The residual background is \( \approx 1.5\% \) of the selected \( K_{\pm3} \) sample.

It has \( m_{\text{lept}}^2 \approx m_\pi^2 \).
**Event counting**

Fit $m_{\text{lept}}^2$ spectrum with linear combination of $K_{e3}$, $K_{\mu3}$ shapes, and bck contribution.

Average of the four data samples.

- **Fractional accuracy:**
  - $0.9\%$ for $K_{e3}$ and $1.2\%$ for $K_{\mu3}$

- **Systematic error studies** to be completed

- Dominated by the **knowledge of selection efficiency**

\[
\begin{align*}
BR(K^\pm \rightarrow \pi^0 e^\pm \nu_e) &= (5.047 \pm 0.046)\% \\
BR(K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu) &= (3.310 \pm 0.040)\%
\end{align*}
\]
$V_{us}$ from semileptonic decays

$\tau(K_L) = 50.84 \pm 0.23$ ns

$\langle V_{us} \times f_+(0) \rangle_{\text{KLOE}} = 0.2160 \pm 0.0005$

$\chi^2/\text{dof} = 1.9/4$

$V_{us}(0.961)$

from $V_{ud}$ and unitarity: $V_{us} \times f_+(0) = 0.2187 \pm 0.0022$
Measurement of the charged kaon lifetime
Two different methods to measure $\tau$:

- **#1: using K decay length**
- **#2: using K decay time**

Allow cross check of systematics.

### Method #1: using K decay length

- $K^\pm \rightarrow \mu^\pm \nu$ self-triggering tag
- Signal K decay vertex (using DC only)
- Signal K track extrapolated backwards to the IP
- $\text{d}e/\text{d}x$ taken into account $\Rightarrow$ 2mm step

\[ \Delta T = \sum_i \Delta T_i = \sum_i \frac{\sqrt{1-\beta^2}}{\beta} \Delta l_i \]

- Efficiency evaluated directly on data
Efficiency has been evaluated directly on data.

Look for a charged vertex on a sample selected requiring a neutral vertex.

Neutral vertex from timing of the neutral clusters fired by the γs from the π⁰ decay.

\[
\epsilon_{\text{DATA}} = \frac{DC\text{ vtx } (K \to X) \in FV}{\pi^0 \text{ vtx } (K \to X\pi^0) \in FV}
\]
The proper time is fitted together with the efficiency and taking into account resolution effects too.

Fit between 16 and 30 ns

\[ \chi^2 = 1.18 \]

Preliminary

\[ \tau^+ = (12.377 \pm 0.044 \pm 0.065) \text{ ns} \]

\[ \chi^2 = 17.7/15 \quad P(\chi^2) = 28.4\% \]
Two different methods to measure $\tau$:

**#1: using K decay length**

**#2: using K decay time**

Allow cross check of systematics.

---

**Method #2: using K decay time**

- $K^\pm \rightarrow \mu^\pm \nu$ self-triggering tag
- Tag K track extrapolated backwards to the IP
- Second kaon helix extrapolated forwards
- Step along the helix looking for a $\pi^0$ decay vertex
- For each photon:

$$\tau = \left| t_y - \frac{r_y}{C} - t_\phi \right| \cdot \sqrt{1 - \beta_K^2}$$
**K± at KLOE - summary**

Absolute BR($K^+ \rightarrow \mu^+\nu(\gamma)$) with 0.27% accuracy


$K^\pm \rightarrow \pi^0\pi^\pm\nu_\nu$ absolute branching ratios and lifetime: preliminary results

BR($K^\pm \rightarrow \pi^\pm\pi^0$) finalizing

Using 2 fb$^{-1}$ collected KLOE will be able to measure:

$K^\pm \rightarrow \pi^0\pi^\pm\nu_\nu$ form factors, BR($K^\pm \rightarrow \pi^0\pi^0\pi^\pm\nu_\nu$)

and the ratio BR($K \rightarrow e\nu$)/BR($K \rightarrow \mu\nu$) for e-$\mu$ universality

About 5 x $10^4$ Ke2 events produced with 2fb$^{-1}$
Spare slides
The KLOE design was driven by the measurement of direct CP parameter $\varepsilon'/\varepsilon$

Beam pipe (spherical, 10 cm $\varnothing$, 0.5 mm thick) + instrumented permanent magnet quadrupoles (32 PMT’s)

Drift chamber (4 m $\varnothing \times$ 3.75 m, CF frame)
- Gas mixture: 90% He + 10% C$_4$H$_{10}$
- 12582 stereo–stereo sense wires
- almost squared cells

Electromagnetic calorimeter
- lead/scintillating fibers (1 mm $\varnothing$), 15 $X_0$
- 4880 PMT’s
- 98% solid angle coverage

Superconducting coil ($B = 0.52$ T)
\[ \sigma_{E/E} = 5.7\% \sqrt{E(\text{GeV})} \]

\[ \sigma_t = 54 \text{ ps} \sqrt{E(\text{GeV})} \oplus 50 \text{ ps} \]

\[ \sigma_{vtx}(\gamma\gamma) \sim 1.5 \text{ cm} \]

\[ \sigma_p/p = 0.4\% \]

(\text{tracks with } \theta > 45^\circ)

\[ \sigma^\text{hit}_x = 150 \mu\text{m (xy), 2 mm (z)} \]

\[ \sigma^\text{vertex}_x \sim 1 \text{ mm} \]
Tag mechanism (I)

K± events tagged using two body decays (about 85%):

\[ K^\pm \rightarrow \mu^\pm \nu, \pi^\pm \pi^0 \approx 1.5 \times 10^6 \text{ K}^+\text{K}^- \text{ ev/pb}^{-1} \]

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

\[ \epsilon_{TAG} \approx 36\% \Rightarrow \approx 3.4 \times 10^5 \mu \nu \text{ tags/}pb^{-1} \]

\[ \approx 1.1 \times 10^5 \pi \pi^0 \text{ tags/}pb^{-1} \]
To minimize the impact of the trigger efficiency on the signal side we restrict our normalization sample $N_{\text{TAG}}$ to 2-body decays which provide themselves the Emc trigger of the event:

**self-triggering tags**

Emc trigger: 2 trigger sectors over threshold $\sim 50$ MeV

The $\mu$ fires two sectors:

$\varepsilon_{\text{Trigger}} \sim 35\%$

The photons from the $\pi^0$ fire two sectors

$\varepsilon_{\text{Trigger}} \sim 75\%$
Tag bias

Measuring the BRs we must take into account a correction due to the bias on the signal sample induced by the tag selection. **Tag bias**

The correction $C_{TB}$ is evaluated from MC and is given by:

$$C_{TB} = \frac{BR_{MC}(\text{with tag})}{BR_{MC}(\text{without tag})}$$
$K^+ \rightarrow \mu^+ \nu(\gamma)$

- Signal given by $K^+$ decay in the DC FV ($40 \text{ cm} < \rho < 150 \text{ cm}$)
  Using $\sim 60 \text{ pb}^{-1}$
- Background given by events with $\pi^0$ in the final state:

  $K^+ \rightarrow \pi^+ \pi^0 \quad K^+ \rightarrow \pi^0 e^+ \nu_e$

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

$$BR = \frac{N_{K\mu\nu(\gamma)}}{N_{TAG}} \cdot \frac{1}{\epsilon_{DC}} \cdot \frac{1}{C_{TB}}$$

Tag bias estimated from MC:

$C_{TB} = 1.0164 +/- 0.0002$
Efficiency evaluated on $\sim 115 \, pb^{-1}$ sample

Double $K\mu\nu$ events selected using Emc

1) Self-triggering $K^- \to \mu^- \nu$ tag
2) Ask for:
   - 1 cluster with $80 < E_{CLU} < 320$ MeV
   - no cluster with $20 < E_{CLU} < 80$ MeV
3) No requirements for $E_{CLU} < 20$ MeV

Low E radiative $\gamma$

$$\epsilon_{DC} = \epsilon_{DATA} \times C_{MC}$$

$$C_{MC} = \frac{\epsilon_{MC \ True}}{\epsilon_{MC \ recon.}}$$
$K^\pm \rightarrow \pi^\pm \pi^0$

- Normalization $N_{\text{TAG}}$ given by $175 \text{ pb}^{-1}$ from 2002's data

  - self-triggering $K^- \rightarrow \mu^- \bar{\nu}$

- Counting events in the distribution of secondary track momentum in the kaon rest frame $p^*$

- Fit together signal and backgrounds $Km2$ and 3-bodies

- Efficiency related to DC reconstruction only

  (tracking plus vertexing), evaluated on data
$K^\pm \rightarrow \pi^\pm \pi^0$

Status: finalizing

Efficency evaluated on a sample selected requiring a neutral vertex $p^*$ fit cut at 180 MeV/c

fitting the $p^*$ distribution with $\mu\nu$ peak from EMC sample $\pi\pi^0$ peak requiring the $\pi^0$ 3-body decays from MC

$N_{\mu\nu}$
$2562920 \pm 2309$ ('02 data)

$N_{\pi\pi}$
$818562 \pm 1383$

Status: finalizing
KI3 preliminary results

- Averages accounting for correlations:

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<td>BR(Ke3)</td>
<td>5.047 ± 0.046</td>
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<td>BR(Kμ3)</td>
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- $\chi^2$/dof for the 4 measurements:

  $Ke3$: $\chi^2$/dof = 3.20/3 → $P(\chi^2) \approx 36\%$

  $K\mu3$: $\chi^2$/dof = 5.32/3 → $P(\chi^2) \approx 15\%$

- The **error accounts for** the data and Monte Carlo statistics used in the fit, the MC statistics for the efficiency evaluation, the Data/MC efficiency corrections, and the systematics on the tag selection. It is dominated by the error on Data/MC efficiency correction.

- Still to be evaluated the systematics due to the signal selection efficiency, to the nuclear interaction, and to the momentum dependency of the tracking efficiency.
$V_{us}$ from semileptonic decays

Quad. Parametrisation

$\lambda'_+ = 0.02496(80)$, $\lambda''_+ = 0.00162(35)$, $\lambda_0 = 0.01587(95)$

Plot by F. Mescia
**$V_{us}$ from semileptonic decays**

- KLOE $\tau_L = 50.84(23)$ ns
  - Five KLOE BR(KL3)
  - Form factors quad. param.
    - $\lambda_0 = 0.01587(95)$
    - $\lambda_+ = 0.02496(80)$
    - $\lambda'_+ = 0.00162(35)$
    - $V_{us} \times f_+(0) = 0.2169(5)$

- KLOE + PDG $\tau_L = 50.99(20)$ ns
  - All available BRs
  - Form factors quad. param.
    - $V_{us} \times f_+(0) = 0.2164(4)$

- Imposing unitarity
  - $f+(0) = 0.961(8)$ (Leutwyler, Roos)
  - $V_{ud} = 0.97377(27)$ (Marciano)
    - $V_{us} \times f_+(0) = 0.2187(22)$
The K track on the tagging side is extrapolated backwards to the signal hemisphere.

Step along the extrapolated kaon looking for the best neutral vertex.

Using timing of the neutral clusters fired by the $\gamma$s from the $\pi^0$ decay.

$$\epsilon_{DATA} = \frac{DC \ vtx \ (K \rightarrow X) \in FV}{\pi^0 \ vtx \ (K \rightarrow X \pi^0) \in FV}$$

$FV \equiv 40 \text{ cm} \leq \rho \leq 150 \text{ cm}$
\[ BR(K \to e\nu) / BR(K \to \mu\nu) \]

- Extremely well known within SM:
  \[ R_K^{\text{SM}} = (2.472 \pm 0.001) \times 10^{-5} \]

- Probe \( \mu\)-e universality:
  
  non-universal terms from LFV sources in SUSY extensions

- At KLOE the measurement is extremely challenging,
  especially the PID due to huge \( K\mu2 \) background \( O(4 \times 10^4) \)

- Produced about \( 5 \times 10^4 \) events with \( 2 \text{fb}^{-1} \)