A new $K_S \rightarrow \pi e \nu$ branching fraction measurement from KLOE-2

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on behalf of the KLOE-2 Collaboration

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DAΦNE and KLOE

DAΦNE is a e+e- collider @ $\sqrt{s} = 1020$ MeV, located in Frascati National Laboratories.

Worked for KLOE (2000-2006):
- Max peak lumi: $1.5 \times 10^{32}$ cm$^{-1}$s$^{-1}$
- Best daily int. lumi: $8.5$ pb$^{-1}$

Upgraded in 2008 with crab-waist scheme

- Max peak lumi: $2.4 \times 10^{32}$ cm$^{-1}$s$^{-1}$
- Best daily int. lumi: $11$ pb$^{-1}$

KLOE collected 2.5 fb$^{-1}$ at the $\phi$ resonance peak and 250 pb$^{-1}$ at $\sqrt{s} = 1000$ MeV.

Integrals luminosity (pb$^{-1}$)

- 2005: 1256 pb$^{-1}$
- 2004: 734 pb$^{-1}$
- 2002: 320 pb$^{-1}$
- 2001: 172 pb$^{-1}$

KLOE-2 collected 5.5 fb$^{-1}$ at the $\phi$ resonance peak

Goals:
- Run I: $L = 0.8$ fb$^{-1}$ eff. = 77%
- Run II: $L = 1.6$ fb$^{-1}$ eff. = 82%
- Run III: $L = 1.7$ fb$^{-1}$ eff. = 82%
- Run IV: $L = 1.4$ fb$^{-1}$ eff. = 81%

Total delivery: 6584.0
Total Acquired: 5488.6
The KLOE detector

Large volume Drift Chamber
(13K cells, He gas mixt.) :

4m-ø, 3.75m-length, all-stereo
\[ \sigma_p/p = 0.4\% \] (tracks with \( \theta > 45^\circ \))
\[ \sigma_x^{\text{hit}} = 150\ \mu\text{m (xy), 2 mm (z)} \]
\[ \sigma_x^{\text{vertex}} \sim 1\ \text{mm} \quad \sigma_{\text{M}_{\pi}} \sim 1\ \text{MeV} \]

Pb-SciFi Calorimeter
( barrel + endcap, 15 X_0 depth,
98% solid angle coverage) :

\[ \sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})} \]
\[ \sigma_T = 54\ \text{ps} / \sqrt{E(\text{GeV})} \oplus 100\ \text{ps} \]

- PID capabilities mostly from TOF

Interaction region:
Instrument quadrupoles,
Al-Be spherical beam pipe
The $\phi$-factory advantage

- The final KK state has the same quantum numbers as the $\phi$ i.e. is a pure $J^{PC} = 1^{--}$ quantum state

\[ |i\rangle \propto \frac{1}{\sqrt{2}} \left( |K_L,p\rangle |K_S,-p\rangle - |K_L,-p\rangle |K_S,p\rangle \right) \]

- $P_K = -P_{\bar{K}} \sim 110$ MeV/c

- $\lambda(K_S) = 6$ mm ($\tau = 90$ ps), $\lambda(K_L) = 3.5$ m ($\tau = 51.7$ ns)

The presence of one kaon tags the other opposite one. All $K_S$ decay near the i.p.

KLOE has the unique capability of selecting pure $KS$ and $KL$ beams

Moreover: interference pattern and entanglement of $K_S K_L$ state allows to study fundamental symmetries and quantum mechanics: see talk by E. Czerwinski at this Conference.
Neutral kaon tagging at KLOE

\( K_S \) tagged by \( K_L \) interaction in EmC

- \( K_L \) velocity in \( \phi \) rest frame \( \beta^* = 0.218 \)
- Efficiency \( \sim 30\% \) (largely geometrical)
- \( K_S \) angular resolution: \( \sim 1^\circ \) (0.3° in \( \phi \))
- \( K_S \) momentum resolution: \( \sim 2 \text{ MeV} \)

\( K_L \) tagged by \( K_S \rightarrow \pi^+\pi^- \) vertex at IP

- Efficiency \( \sim 70\% \) (mainly geometrical)
- \( K_L \) angular resolution: \( \sim 1^\circ \)
- \( K_L \) momentum resolution: \( \sim 2 \text{ MeV} \)
The KSe3 decay and the Cabibbo angle

In the SM:

\[
\mathcal{B}(K_S \rightarrow \pi \ell \nu) = \frac{G^2(f_+(0)|V_{us}|^2)}{192\pi^3} \tau_{SM} \frac{m_K^5 I_K^E S_{EW}(1 + \delta_{EM})}{f_+}
\]

The KSe3 determination of $|V_{us}|f_+(0)$ is the less accurate (apart from the recently measured and rarer KS\(\mu\)3 mode Phys.Lett.B 804 (2020) 135378).

The presently available BR(KSe3) value is dominated by the KLOE measurement based on 0.4 fb\(^{-1}\) data sample:

\[
\text{BR}(K_S \rightarrow \pi e \nu) = (7.046 \pm 0.078 \pm 0.049) \times 10^{-4}
\]

PLB 636 (2006) 173

1.4\% total uncertainty (1.1\% stat \pm 0.7\% syst)

We present here a new measurement based on 1.63 fb\(^{-1}\) independent KLOE data sample.

M.Moulson and E.Passemar, CKM 2021
What we measure

\[ \mathcal{B}(K_S \rightarrow \pi e \nu) = \frac{N_{\pi e \nu}}{\varepsilon_{\pi e \nu}} \times \frac{\varepsilon_{\pi \pi}}{N_{\pi \pi}} \times R_\varepsilon \times \mathcal{B}(K_S \rightarrow \pi^+ \pi^-) \]

- \( N_{\pi e \nu}, N_{\pi \pi} \): number of selected events for \( K_S \rightarrow \pi e \nu \) and \( K_S \rightarrow \pi^+ \pi^- \)
- \( \varepsilon_{\pi e \nu}, \varepsilon_{\pi \pi} \): selection efficiencies
- \( R_\varepsilon \): ratio of common efficiencies for trigger, online filter, event classification and preselection

\[ BR( K_S \rightarrow \pi^+ \pi^- ) = 0.69196 \pm 0.00051 \text{ measured by KLOE} \quad \text{Eur. Phys. J. C 48 (2006) 767} \]
**Preselection and normalization sample**

**$K_L$-crash:**
- one neutral cluster with $E > 100$ MeV and polar angle $15^\circ < \theta < 165^\circ$
- velocity $0.17 < \beta^* < 0.28$ in the $\phi$ c.m.s. (in the lab: $\beta=r_{clu}/ct_{clu}$)

**$K_S$ side selection:**
- two charged tracks of opposite curvature forming a vertex inside the cylinder ($\rho < 5$ cm; $z < 10$ cm)

The normalization sample of $K_S \to \pi^+ \pi^-$ decays is selected at this stage by requiring each of the two charged tracks momentum to be $140$ MeV < $p$ < $280$ MeV. We obtain:

$$N_{\pi\pi} = (282.314 \pm 0.017) \times 10^6 \text{ events}$$

Efficiency 97.4% and purity 99.9% determined by simulation.
**Sample composition after preselection**

<table>
<thead>
<tr>
<th>Event</th>
<th>n. events</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>301 645 500</td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>312 018 500</td>
<td></td>
</tr>
<tr>
<td>$K_S \rightarrow \pi e\nu$</td>
<td>259 264</td>
<td>0.08</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+\pi^-$</td>
<td>301 976 400</td>
<td>96.78</td>
</tr>
<tr>
<td>$\varphi \rightarrow K^+K^-$</td>
<td>9 565 465</td>
<td>3.07</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^0\pi^0$</td>
<td>30 353</td>
<td>0.01</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi\mu\nu$</td>
<td>139 585</td>
<td>0.04</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+\pi^-e^+e^-$</td>
<td>18 397</td>
<td>$6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\varphi \rightarrow \pi^+\pi^-\pi^0$</td>
<td>24 153</td>
<td>$8 \times 10^{-3}$</td>
</tr>
<tr>
<td>others</td>
<td>4 852</td>
<td>$2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Signal selection is then performed in two steps based on uncorrelated information:

1) the event kinematics using only DC tracking variables

2) the time-of-flight measured with the calorimeter
5 discriminatting variables are selected. In the signal region they show satisfactory data-MC agreement

1. the tracks momenta: $\vec{p}_1, \vec{p}_2$
2. $\alpha_{1,2}$ angle formed by tracks momenta in the $K_S$ reference system
3. $\alpha_{LS}$ angle between the total momentum and the $K_L$ crash direction
4. $\Delta p$ difference between total momentum and $|p_{KS}|$ (determined from $p_{KL}$ and $p_\phi$)
5. $m_{\pi\pi}$ the 2 tracks invariant mass in 2 pion hypothesis
Multivariate selection based on tracking variables/2

BDT classifier trained on 5000 signal events and 50000 background simulated events. Tested on same size samples and run over both full data and MC samples.

Events with BDT output > 0.15 are retained to reduce main backgrounds from charged kaons and $K_S \rightarrow \pi\pi$. 

07/07/2022
Time of flight selection/1

Track-to-cluster association (TCA) is required for both tracks:
clusters must have $E_{\text{clu}} > 20$ MeV, $\theta_{\text{clu}} > 15^\circ$, centroid within 30 cm of the track extrapolation.

For each track:

$$\delta t_i = t_{\text{clu},i} - L_i/c\beta_i(m_i)$$

$L_i$ track length, $m_i$ mass hypothesis

Correct mass hypothesis yields null $\delta t_i$
$\delta t = \delta t_1 - \delta t_2$ minimize event $T_0$ uncertainty

Test of the $\pi\pi$ hypothesis:

$$\delta t_{\pi\pi} = \delta t_{1,\pi} - \delta t_{2,\pi}$$

Selection applied: $2.5$ ns $<$ $|\delta t_{\pi\pi}|$ $<$ $10$ ns
Time of flight selection/2

Test of $\pi e$ vs $e\pi$ hypotheses:

$$\delta t_{\pi e} = \delta t_{1,\pi} - \delta t_{2,e} \quad \text{vs} \quad \delta t_{e\pi} = \delta t_{1,e} - \delta t_{2,\pi}$$

(random track ordering)

Lowest $|\delta t|$ is chosen as the correct hypothesis $\delta t_e$

$|\delta t_e| < 1 \text{ ns}$ is required
Signal extraction

Selected sample is now signal dominated. $m_e^2$ distribution is used to fit number of events:

$$m_e^2 = (E_{KS} - E_{\pi} - p_{miss})^2 - p_e^2$$

($E_{KS}$ and $p_{KS}$ from KL-crash)

Fit with 3 components ($\pi\nu$, $\pi\pi$, others) yields:

$$N_{\pi\nu} = 49647 \pm 316 \quad \chi^2/\text{ndf} = 76/96$$
Evaluation of efficiencies

The KL \rightarrow \pi e \nu control sample (CS) allows to determine efficiencies from data:

\[ \epsilon_{\pi e\nu} = \epsilon_{CS} \times \frac{MC_{\pi e\nu}}{MC_{CS}} \]

CS Selected by K_S tag, requiring K_L decay radius in the range (1 cm, 5 cm). Missing mass cut discards \(\pi^+\pi^0\) component.

Two high purity (>95%) CS are built by cutting on TOF variables (for \(\epsilon_{kine}\) evaluation) or kine variables (for \(\epsilon_{tof}\) evaluation).

Good comparison of CS and signal samples observed in MC

We obtain:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection (from MC)</td>
<td>0.9961 ± 0.0002</td>
</tr>
<tr>
<td>Kin. variables selection</td>
<td>0.9720 ± 0.0007</td>
</tr>
<tr>
<td>BDT selection</td>
<td>0.6534 ± 0.0013</td>
</tr>
<tr>
<td>TCA selection</td>
<td>0.4639 ± 0.0009</td>
</tr>
<tr>
<td>TOF selection</td>
<td>0.6605 ± 0.0012</td>
</tr>
<tr>
<td>Total</td>
<td>0.1938 ± 0.0006</td>
</tr>
</tbody>
</table>

The K_S \rightarrow \pi^+\pi^- data sample sample is corrected for signal contamination after the momentum cut obtained by a dedicated CS. We then get:

\[ \epsilon_{\pi\pi} = (96.657 \pm 0.002) \% \]

From simulation: \( R_\epsilon = 1.1882 \pm 0.0012 \)
Systematic uncertainty

BDT cut is varied in the range (0.135,0.17) and good $N_{\pi e\nu}$ stability is observed. Spread is used as uncertainty.

TCA checked in CS. $\delta t$ resolution checked to be identical in signal and control samples.

Lower $\delta t_{\pi\pi}$ cut varied in (2-3ns) range, $|\delta t_e|$ cut varied in (0.8-1.2 ns) range.

$m_e^2$ fit repeated varying range and bin width. Separate components for KS$\mu 3$ and $\phi \rightarrow K^+K^-$ backgrounds are tested.

<table>
<thead>
<tr>
<th>Selection</th>
<th>$\delta e_{\pi e\nu}^{syst} [10^{-4}]$</th>
<th>$\delta e_{\pi+\pi-}^{syst} [10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT selection</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>TCA &amp; TOF selection</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Fit parameters</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+\pi^-$ efficiency</td>
<td></td>
<td>8.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8.5</strong></td>
<td><strong>8.8</strong></td>
</tr>
</tbody>
</table>

$R_e$ systematics evaluated by comparing data and MC for each of the included common selections
\[ N_{\pi e\nu} = 49647 \pm 316 \]
\[ N_{\pi\pi} = (282.314 \pm 0.017) \times 10^6 \]
\[ \epsilon_{\pi^+\pi^-} = (96.657 \pm 0.088)\% \]
\[ \epsilon_{\pi e\nu} = (19.38 \pm 0.10)\% \]
\[ R_\epsilon = 1.1882 \pm 0.0059 \]

**Including systematics**

**New KLOE result:**

\[ \mathcal{B}(K_S \rightarrow \pi e\nu) = \frac{N_{\pi e\nu}}{\epsilon_{\pi e\nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon \times \mathcal{B}(K_S \rightarrow \pi^+\pi^-) \]

\[ \mathcal{B}(K_S \rightarrow \pi^+\pi^-) = 0.69196 \pm 0.00051 \]

**Previous KLOE result:** 0.4 fb\(^{-1}\) independent data sample. Phys.Lett. B \textbf{636} (2006) 173

\[ \mathcal{B}(K_S \rightarrow \pi e\nu) = (7.046 \pm 0.076)_{\text{stat}} \pm 0.049_{\text{syst}} \times 10^{-4} = (7.046 \pm 0.091) \times 10^{-4} \]

**Combination taking into account correlated systematics:**

\[ \mathcal{B}(K_S \rightarrow \pi e\nu) = (7.153 \pm 0.037)_{\text{stat}} \pm 0.043_{\text{syst}} \times 10^{-4} = (7.153 \pm 0.057) \times 10^{-4} \]
Conclusions

The KLOE experiment has performed a new measurement of the $K_S \to \pi e \nu$ branching ratio based on a 1.63 fb-1 data sample collected in 2004-05, with a $< 1\%$ overall uncertainty.

Combination with the previous KLOE measurement yields a new determination of $\text{BR}(K_S \to \pi e \nu)$ with 0.8% precision.

Using the SM formula

$$B(K_S \to \pi \ell \nu) = \frac{G^2 (f_+(0)|V_{us}|)^2}{192\pi^3} \tau_S m_K^5 I_K S_{\text{EW}} (1 + \delta_{\text{EM}}^\ell)$$

and taking the PDG values for $\tau_S$ and $m_K$ and the most recent calculations of the other parameters (Phys.Rev.D 105, (2022) 013005) we obtain:

$$f_+(0)|V_{us}| = 0.2170 \pm 0.0009$$

with a sizeable uncertainty reduction with respect to the previous BR(Kse3) measurement.

The sum of the four main $K_S$ branching ratios measured by KLOE yields:

$$B_{\pi^+\pi^-} + B_{\pi^0\pi^0} + B_{\pi e \nu} + B_{\pi \mu \nu} > 0.9983 \text{ @95\% CL}$$
SPARES
Systematic uncertainties estimation

- BDT cut vs. Events/efficiency
- \(\delta t_{\text{cut}}\) vs. Events/efficiency
- \(\delta t_{\text{cut}}\) vs. Events/efficiency
- \(m_e^2\) vs. fit type
Combination of the 2 KLOE measurements of BR(KSe3)

<table>
<thead>
<tr>
<th></th>
<th>old stat $[10^{-3}]$</th>
<th>old syst $[10^{-3}]$</th>
<th>new stat $[10^{-3}]$</th>
<th>new syst $[10^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td></td>
<td>0.9</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Efficiencies</td>
<td></td>
<td>3.7</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>TOF</td>
<td></td>
<td>2.3</td>
<td></td>
<td>3.1</td>
</tr>
<tr>
<td>Ratio $\frac{\pi\pi}{\pi\nu}$</td>
<td></td>
<td>5.1</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>Fit</td>
<td></td>
<td>6.2</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>$B_{KS^{-}\rightarrow\pi^{+}\pi^{-}}$</td>
<td></td>
<td>0.7</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Total</td>
<td>9.1</td>
<td>9.2</td>
<td>6.4</td>
<td>7.0</td>
</tr>
</tbody>
</table>
The $f_+(0)|V_{us}|$ estimate from new BR(KSe3) is now more accurate than those from $K^\pm$ semileptonic decays.