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on behalf of the KLOE Collaboration

KAON09 Tsukuba June 9th 2009

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Outline

- DAΦNE and KLOE experiment

- study of the $K_S$ lifetime

- $K_L$ lifetime: preliminary update with new data

- study of the $\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+)$
The DAΦNE e⁺e⁻ collider

Frascati Φ–Factory complex

\[ W = m_\phi \ (1019.4 \text{ MeV}) \]
\[ L_{\text{peak}} = 1.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

- Collisions at cm energy around \( \sqrt{s} \sim 1019.4 \text{ MeV} \) (\( m_\phi \))

- Angle between the beams @ IP: \( \alpha \sim \pi-2*12.5 \text{ mrad} \)

- Residual laboratory momentum of \( \phi \): \( p_\phi \sim 13 \text{ MeV} \)

- Cross section for \( \phi \) production @ peak: \( \sigma_\phi \sim 3.1 \mu\text{b} \)
Summary of KLOE data taking

Integrated luminosity $L = 2.5 \text{ fb}^{-1}$
about $2.5 \times 10^9 \ K_S K_L$; $3.6 \times 10^9 \ K^+ K^-$
**Kaon Physics at the \( \phi \) resonance**

The \( \phi \) decay at rest provides monochromatic and pure kaon beams

They are produced in a pure \( J^{PC} = 1^{--} \) state

\[
\sigma(e^+e^- \rightarrow \phi) \approx 3 \text{ \(\mu\)b}
\]

\[ \phi \rightarrow K_S, K^+ \quad K_L, K^- \]

detection of a \( K_S (K_L) \) guarantees the presence of a \( K_L (K_S) \) with known momentum and direction (the same for \( K^+K^- \)) \( \Rightarrow \) **tagging**

Pure kaon beam obtained \( \Rightarrow \) normalization (\( N_{tag} \)) sample

\( \Rightarrow \) allows precision measurements of absolute BRs

**\( K^+K^- \)**
- BR \( \approx 49\% \)
- \( p_{\text{lab}} = 127 \text{ MeV}/c \)
- \( \lambda_\pm = 95 \text{ cm} \)

**\( K_LK_S \)**
- BR \( \approx 34\% \); \( p_{\text{lab}} = 110 \text{ MeV}/c \)
- \( \lambda_S = 0.6 \text{ cm} \) \( K_S \) decays near interaction point
- \( \lambda_L = 340 \text{ cm} \) Large detector to keep reasonable acceptance for \( K_L \) decays (\( \approx 0.5 \lambda_L \))
The KLOE experiment

Be beam pipe (0.5 mm thick), r =10 cm (Ks fiducial volume)
Instrumented permanent magnet quadrupoles (32 PMT's)

Drift chamber (4 m Ø x 3.3 m)
90% He + 10% IsoB, CF frame
12582 stereo sense wires

Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMT's, cover 98% of the solid angle

Superconducting coil
B = 0.52 T (∫ B dl = 2 T·m)
KLOE detector performance

$\sigma_E/E \equiv 5.7\% / \sqrt{E} (\text{GeV})$

$\sigma_+ \equiv 57 \text{ ps} / \sqrt{E} (\text{GeV}) \oplus 140 \text{ ps}$

$\sigma_{\gamma\gamma} \sim 2 \text{ cm} (\pi^0 \text{ from } K_L \rightarrow \pi^+\pi^-\pi^0)$

$\sigma_p/p \equiv 0.4 \% \ (\text{tracks with } \theta > 45^\circ)$

$\sigma_x^{\text{hit}} \equiv 150 \mu\text{m (xy), } 2 \text{ mm (z)}$

$\sigma_x^{\text{vertex}} \sim 3 \text{ mm}$
Reconstruction of $K_S \to \pi^+ \pi^-$

$K_S \to \pi^+ \pi^-$ decay selection:
- 2 tracks of opposite sign
- invariant mass consistent with $M_K$

$\sigma = 1$ MeV

$\varepsilon \sim 70\%$ (mainly geometrical)
$K_S$ angular resolution $\sim 1^\circ$
$K_S$ momentum resolution of 1 MeV
from track momenta $p_{KS} = p_{\pi^+} + p_{\pi^-}$
At a $\phi$-factory, we have a redundant $p_{KS}$ measurement. For each event we measure:

1) $p_{KS}$ from $\sqrt{s}$ and from kinematics of $\phi \to KK$ two-body decay resolution $\sim 1$ MeV dominated by beam energy spread.

2) $p_{KS}$ from pion momenta measurements in the drift chamber $\sigma \sim 1$ MeV.

Requiring consistency between momentum measurements guarantees good track quality.
Average $\phi$ decay point determined with Bhabha events on a run by run basis.

Resolution = beam spot size $(\sigma_x \sim 1\,\text{mm}, \sigma_y = \mathcal{O}(10\,\mu\text{m}), \sigma_z \sim 1.5\,\text{cm})$

A better determination of decay point along the beam line ($z$) is evaluated event by event by using the point of closest approach of $K_S^0$ line of flight to the beam axis line.
$K_S$ lifetime
Measurement of the $K_S$ lifetime

Motivation:

- first measurement with pure $K_S$ beam and with an event-by-event knowledge of $K_S$ momentum
- KLOE is well suited to perform $\tau_S$ measurement as a function of sidereal time which is interesting to test QM, CPT and Lorentz invariance
- $V_{us}$ from $K_S$ with KLOE data
  (we measured BR($K_S e3$) at 1.3%, we can reach 0.5% on the whole data set)

Method:

lifetime obtained from fit to proper time $t^*$ distribution of $K_S \rightarrow \pi^+ \pi^-$ decay

$$t^* = \frac{L}{\beta \gamma c} = \frac{LM_K}{pc}$$
Raw Time resolution

\[ t^* = \frac{L}{\beta \gamma c} = \frac{LM_K}{pc} \]

This first attempt produces a resolution function \textit{not centered around zero}\n
\[ \text{not appropriate for a } < 0.1\% \text{ measurement!} \]

So see next transparency...
Improvement of $K_S$ decay length resolution

1) Further improve reconstruction of IP event-by-event using full geometrical fit

2) Optimize the selection criteria, requiring pions to decay at large angle with respect to the $K_S$ line of flight

3) Use only well measured tracks: cut on the $\chi^2$ value from the track fit

20 million events selected in 600 pb$^{-1}$

Path length resolution improved by factor of 3
Fit to the lifetime

Since resolution depends on K beam direction, fit is done for each of 270 bins in $\cos\theta_K$ and $\phi_K$.

This is also necessary to measure $\tau_s$ as a function of sidereal coordinates.

Fit range: from -2 to 7 $t^*/\tau_s$

Fit function: exponential convoluted with two gaussians

(5 parameters: lifetime, 2 normalizations, 2 widths)
## Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Value ((\tau/\tau_s \times 10^{-4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection cuts</td>
<td>3.3</td>
</tr>
<tr>
<td>(\cos \theta_K) cut</td>
<td>5.7</td>
</tr>
<tr>
<td>Momentum calibration</td>
<td>0.4</td>
</tr>
<tr>
<td>Fit range</td>
<td>5.0</td>
</tr>
</tbody>
</table>

We expect a total error competitive with the precise measurements from KTeV and NA48
$K_L$ lifetime

with $K_L \rightarrow \pi^0 \pi^0 \pi^0$

decay channel
**$K_L$ lifetime measurement**

**direct measurement:** \( \frac{d\tau}{\tau} \approx 0.6\% \) \[ \tau_L = (50.92 \pm 0.17 \pm 0.25) \text{ ns} \]

uses 10 M $K_L \rightarrow \pi^0\pi^0\pi^0$ events from 2001-2002 data

**indirect measurement:** \[ \tau_L = (50.72 \pm 0.11 \pm 0.35) \text{ ns} \]

uses constraint $\sum \text{BR}(K_L) = 1$

The error on $\tau_L$ is now the main limiting factor on $V_{us}$ accuracy from $K_L$ decay rates:

\[ \text{BR}/\tau = \Gamma(K \rightarrow \pi \ell \nu(\gamma)) = \frac{G_F^2 m_K^5}{768\pi^3} C_K^2 |V_{us}|^2 |f_+^{K}\pi(0)|^2 I_K^{\ell} S_{ew} \left[ 1 + \delta_{SU(2)} + \delta_{em} \right] \]

$\tau_L$ direct measurement can be improved both in statistical and systematic accuracy using the 2004-05 data sample

\[ \delta(V_{us} f+(0))/(V_{us} f+(0)) = 0.1\% \oplus 0.2\% \oplus 0.1\% \oplus 0.1\% \]

**Phases in space integral**

**Radiative corrections**

**BR** \hspace{1cm} $\tau_L$ \hspace{1cm} Integral
$K_L \rightarrow \pi^0\pi^0\pi^0$ decay vertex

Reconstruction of $K_S \rightarrow \pi^+\pi^-$ determines $K_L$ momentum within 1 MeV and 1 degree

Vertex reconstruction from the neutral clusters on the calorimeter

Can extract $L_K$, $L_\gamma$
Neutral vertex reconstruction efficiency

Multiphoton vertex evaluated from vertices given by the neutral clusters on the EmC

To reconstruct the $K_L$ vertex, we require at least 3 photons from the $\pi^0\pi^0\pi^0$ decay

Reconstruction efficiency for $K_L \rightarrow \pi^0\pi^0\pi^0$ with $N_\gamma \geq 3$ is high and uniform over a broad interval in $L_K$
Photon multiplicities

Only retain $N \geq 3$ for the analysis
Neutral vertex calibration

Use of a control sample of $K_L \rightarrow \pi^+\pi^-\pi^0$ decays allows comparison between the vertex given by the reconstructed pion tracks and the neutral vertex, which is fundamental to:

1) calibrate the time scale
2) study the neutral vertex resolution

$\Delta R = R_{cha} - R_{neu}$

Spatial resolution $\sim 2$ cm
**Single $\gamma$ reconstruction efficiency**

Use of the control sample $K_L \rightarrow \pi^+\pi^-\pi^0$ allow to measure the vertex reconstruction efficiency from the single photon

$$\varepsilon_\gamma = \frac{N_{\gamma\text{ rec}}}{N_{\gamma\text{ tag}}}$$

- Number of events in which a second photon is detected where we expect to find from kinematics
- Number of events in which at least one photon is detected

We correct the MC efficiency with the ratio $\varepsilon_{\text{data}} / \varepsilon_{\text{MC}}$
Fit result

Fit performed with

$$f(t^*) = \varepsilon_{sel}(t^*) N \cdot e^{-t^*/\tau} + f_{bck} B(t^*)$$

$$\chi^2/\text{dof} = 50/54$$

Fit range: 8-26 ns

In the fit region:

data events: 46 millions
background after cuts: 1.81% 1.1pb$^{-1}$

Residuals

$K_L \rightarrow \pi^\pm \pi^\mp \pi^0$

$K_L \rightarrow K_S \rightarrow \pi^0 \pi^0$ regen
Fit result

Fit performed with

$$ f(t^*) = \epsilon_{sel}(t^*) N_0 e^{-t^*/\tau} + f_{bck} B(t^*) $$

$$ \chi^2/\text{dof} = 50/54 $$

Fit range: 8-26 ns

**Fit result:**

$$ \tau_L = (50.56 \pm 0.14) \text{ ns} $$

Statistical error can be improved by decreasing the lower limit of the fit region (taking into account of the $K_L$ beam losses on the regenerating surfaces)
## Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta\tau/\tau$</th>
<th>$\Delta\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tag efficiency</td>
<td>0.34%</td>
<td>0.17 ns</td>
</tr>
<tr>
<td>Preselection efficiency</td>
<td>0.16%</td>
<td>0.08 ns</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Time scale</td>
<td>0.12%</td>
<td>0.06 ns</td>
</tr>
<tr>
<td>Nuclear interaction</td>
<td>0.16%</td>
<td>0.08 ns</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.21 ns</td>
</tr>
</tbody>
</table>

$\tau_L = (50.56 \pm 0.14_{\text{stat}} \pm 0.21_{\text{syst}}) \text{ ns}$
**$K_L$ lifetimes**

Comparison with previous KLOE measurements:

$$\tau_L = (50.92 \pm 0.17_{\text{stat}} \pm 0.13_{\text{syst uncorr}} \pm 0.27_{\text{syst corr}}) \text{ ns}$$

$\Delta=1.4\sigma$, taking into account the correlation between syst. errors

$$\tau_L = (50.72 \pm 0.11_{\text{stat}} \pm 0.35_{\text{syst}}) \text{ ns} \quad \sum_i BR_i = 1$$

$\Delta=0.4\sigma$

For final result:

1) add 2004 data set $\sigma_{\text{stat}} \rightarrow 0.11 \text{ ns}$

2) reduce systematic error on the tagging efficiency

KLOE PLB 626 (2005)

KLOE PLB 635 (2006)
Absolute $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$

branching ratio
Tagging $K^+K^-$ beams

$K^\pm$ beam tagged from $K^\pm \to \pi^\pm \pi^0, \mu^\pm \nu$ (85% of $K^\pm$ decays)

$\approx 1.5 \times 10^6 K^+K^- \text{ evts/pb}^{-1}$

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

$\epsilon_{\text{tag}} \approx 25\% \Rightarrow \approx 3.4 \times 10^5 \mu\nu \text{ tags/pb}^{-1}$

$\approx 1.1 \times 10^5 \pi\pi^0 \text{ tags/pb}^{-1}$
**Absolute BR( K^+ → π^+π^-π^+(γ) )**

- this measurement completes the KLOE program of precise and fully inclusive K^± dominant BR's

<table>
<thead>
<tr>
<th>Reaction</th>
<th>BR</th>
<th>Error</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>K^+ → µν</td>
<td>0.6366(18)</td>
<td>0.3%</td>
<td>PLB 632(2006)</td>
</tr>
<tr>
<td>K^+ → π^+π^0</td>
<td>0.2065(9)</td>
<td>0.5%</td>
<td>PLB 666(2008)</td>
</tr>
<tr>
<td>K^± → π^0e^±ν</td>
<td>0.0497(5)</td>
<td>1.0%</td>
<td>JHEP 02(2008)</td>
</tr>
<tr>
<td>K^± → π^0µ^±ν</td>
<td>0.0324(4)</td>
<td>1.2%</td>
<td>JHEP 02(2008)</td>
</tr>
<tr>
<td>K^± → π^±π^0π^0</td>
<td>0.0176(3)</td>
<td>1.7%</td>
<td>PLB 597(2004)</td>
</tr>
<tr>
<td>τ^±</td>
<td>12.347(30) ns</td>
<td>0.24%</td>
<td>JHEP 01 (2008)</td>
</tr>
</tbody>
</table>

- needed to perform a global fit to K^± BR's
- available measurement dates back to ’72 (no information on radiation cut-off)

**CHIANG** (2330 evts)  \[ \text{BR}(K \rightarrow π^+π^-π^+) = (5.56 \pm 0.20)\% \quad \Delta \text{BR}/\text{BR} = 3.6 \times 10^{-2} \]

2002 KLOE data set enough to reach **statistical relative error at few permil level**
Signal selection

2 independent normalization samples given by the $\mu\nu$ and $\pi\pi^0$ tags

the track of the tagging $K$ is backward extrapolated to the IP

the known kinematic of $\phi \rightarrow K^+K^-$ defines the signal $K$ path (direction and momentum)

we require two reconstructed tracks making a vertex along the $K$ path before the inner wall of the DC ($\alpha_{geo} \approx 26\%$)

we count the signal decays in the missing mass spectrum
The selected sample

\[ \sim 60000 \text{ } K^+ \rightarrow 3\pi \text{ events} \]

(Background subtracted)

\[ \text{tag } \mu\nu \]

\[ \sim 25000 \text{ } K^+ \rightarrow 3\pi \text{ events} \]

(Background subtracted)
Signal selection efficiency measured on MC and folded with \( \frac{\varepsilon_{\text{single trk}}(\text{data})}{\varepsilon_{\text{single trk}}(\text{MC})} \)

\( K \rightarrow \pi^0\pi^0 \) control sample to measure \( \varepsilon_{\text{single trk}} \)

**control sample selection**

- K path from the tagged K track and \( \phi \) kinematic
- reconstruct neutral vertex \( K \rightarrow \pi^0\pi^0 X \) decays looking for 4 \( \gamma \)'s with time measurements

\[ \Delta p\pi = pK^\pm - p\pi^0 - p\pi^0 \]

\( \sigma p_\pi \approx 14 \text{ MeV} \)

the purity of the sample is \( \approx 99\% \)
Conclusions

KLOE will soon have a competitive result on the measurement of $\tau_S$ taking advantage of pure sample of $K_s \rightarrow \pi^+\pi^-$ and precise determination of event kinematics.

KLOE has a new preliminary measurement of $\tau_L$ based on 2005 data. The final measurement will include 2004 data and will have a significantly reduced systematic error.

We are finalizing the measurement of the absolute $\text{BR}(K^+ \rightarrow \pi^+\pi^-\pi^+)$; this will allow to constrain the sum of the dominant $K^+$ decay modes.
Spare slides
Tagging of $K_S K_L$ beams

$K_L$ tagged by $K_S \to \pi^+\pi^-$ vertex at IP

$K_S$ tagged by $K_L$ interaction in EmC

$\varepsilon \sim 70\%$ (mainly geometrical)

$K_L$ angular resolution: $\sim 1^\circ$

$K_L$ momentum resolution: $\sim 1$ MeV

$\varepsilon \sim 30\%$ (largely geometrical)

$K_S$ angular resolution: $\sim 1^\circ$ (0.3$^\circ$ in $\phi$)

$K_S$ momentum resolution: $\sim 1$ MeV
Tagging of $K^+K^-$ beams (II)

to minimize the impact of the trigger efficiency on the signal side we restrict our normalization sample $N_{\text{tag}}$ to 2-body decays that provide themselves the Emc trigger of the event **self-triggering tags**

Emc trigger given by 2 trigger sectors over threshold $\sim 50$ MeV

$$\tag{π π^0}$$

$\pi^0$ clusters must satisfy the Emc trigger

the sample $N_{\text{tag}}$ is reduced by $\approx 75\%$

$$\tag{µ ν}$$

the µ cluster fires 2 trigger sectors

the sample $N_{\text{tag}}$ is reduced by $\approx 35\%$
resolutions: neutral VTX vs DC reconstructed quantities

- Bin $p_\pi = 30$ MeV
  - Data
  - MC
  - $\sigma p_\pi \approx 14$ MeV

- Bin $\rho_{vtx} = 5$ cm
  - Data
  - MC
  - $\sigma \rho_{vtx} \approx 2.2$ cm

- Bin $\theta_\pi = 30$
  - Data
  - MC
  - $\Delta \rho_{vtx}$ (cm)
$BR(K^+ \rightarrow \pi^+ \pi^- \pi^+)$

- **PDG 04 average:** $\Delta \text{BR}/\text{BR} = 1.8\%$  
  **CHIANG ’72:** $\Delta \text{BR}/\text{BR} = 3.6\%$

$\Sigma_f \text{BR}(K^\pm \rightarrow f) = 1$ and no info on rad. cut-off

**Signal selection**

- 2-tracks vertex before DC inner wall and along the K path obtained from backward extrapolation of the tagging kaon track to the I.P.
- Signal peak in the missing mass spectrum ($\sim m_{\pi}^2$)

- Correct MC efficiency with single track efficiency $\frac{\text{DATA/MC}}{}$ from $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ control sample

$\varepsilon_{\text{single trk}} (K \rightarrow 3\pi) p_{\pi} (\text{MeV})$

$\varepsilon_{\text{single trk}} (K \rightarrow \pi^\pm \pi^0 \pi^0)$