$K_s$ lifetime and $Ke2g$

g from KLOE

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DAΦNE $e^+e^-$ collider at LNF

- $\sqrt{s} \sim 1019.46$ MeV = $m_\phi$
- $\sigma_\phi \sim 3.1$ µb at peak
- crossing angle $\sim 12.5$ mrad

- today, $L_{\text{peak}} = 4.5 \times 10^{32}$ cm$^2$ s$^{-1}$
Kaon physics at KLOE

The $\phi$ decay at rest provides \textit{monochromatic} and \textit{pure} beam of kaons

$$K^+ K_S \xleftrightarrow{\phi} K_L K^-$$

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

<table>
<thead>
<tr>
<th>$\phi$ decay mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^-$</td>
<td>49.1%</td>
</tr>
<tr>
<td>$K_SK_L$</td>
<td>34.1%</td>
</tr>
</tbody>
</table>

$\Rightarrow K_S$ beam unique!!

$\Rightarrow$ kaon momentum is measured with 1 MeV resolution

$K^+K^- \quad p^* = 127 \text{ MeV/c}$

$K_SK_L \quad p^* = 110 \text{ MeV/c}$

$\lambda_\pm = 95 \text{ cm}$

$\lambda_S = 6 \text{ mm}; \quad \lambda_L = 3.4 \text{ m}$
The KLOE Experiment

- Magnet SC coil, $B = 0.6$ T
- EM Calorimeter Pb-scint fiber 4880 PMs, 2440 cells
- Drift chamber 12582 sense wires 52140 tot wires Carbon fiber walls
- Al-Be beam pipe $r = 10$ cm, 0.5 cm thick
Detector performances

\[ \frac{\sigma_{E}}{E} = 5.7 \sqrt{E \text{ (GeV)}} \]
\[ \sigma_{t} = 54 \sqrt{E \text{ (GeV)}} + 140 \text{ ps} \]

EM Calorimeter

Drift Chamber

\[ \sigma \left( \frac{p_{\perp}}{p_{\perp}} \right) = 4 \% , \sigma \left( m_{K^{0}} \right) \leq 1 \text{ MeV} \]
\[ \sigma_{x,y} = 150 \text{ mm} ; \sigma_{z} = 2 \text{ mm} \]
Summary of KLOE data taking

\[ \int L = 2.2 \text{ fb}^{-1} \]

at \( \phi \) peak

yielding \( 3 \times 10^9 \) \( K^+K^- \) and \( 2 \times 10^9 \) \( K_SK_L \) pairs
$K_s$ lifetime
Introduction

Fit to proper time distribution of 
\[ K_S \rightarrow \pi^+\pi^- \]

\[ t^* = \frac{d}{\beta \gamma c} = \frac{dM_k}{c p_k} \]

Needs for \( O(10^4) \)* measurement:

\( O(10^7) \) \( K_S \rightarrow \pi^+\pi^- \), not a problem with the KLOE data set, 0.4 fb\(^{-1} \) (2004)
Calibration of \( K_S \) momentum at \( 10^{-4} \): determination from \( \sqrt{s} \) and kinematic
Decay length \( \sim \) resolution: improve resolution as much as possible
Calibration of decay point: use redundant \( K_S \) momentum determination
Resolution from negative tail of proper time distribution

* \( \sim \) accuracy of WA (NA48 + KTeV)
- 2 tracks from ~ IP
- standard cut on invariant mass (10 MeV)

Very bad resolution!
- use events with:
  well measured tracks
  passing topological cuts
- additional improvement
  with geometrical fit

\[ \Delta t / \tau_s \]

\[ \text{RMS} = 0.3 \tau_s \]
decay length & momentum calibration

\[ \Delta d \quad (cm) \]

MC

\[ p_{\pi\pi} - p_{K_{MCtrue}} \quad (\text{MeV}) \]

Decay point correction using 2\textsuperscript{nd} determination of kaon momenta

\[ \frac{\tau}{\tau_S} \]

without

\[ \chi^2/\text{ndf} \quad 99.75 / 4 \]

P1 \quad 1.000 \pm 0.2524E-03

with

\[ \chi^2/\text{ndf} \quad 7.953 / 4 \]

P1 \quad 1.000 \pm 0.2401E-03
FIT METHOD

Detector divided in : $18 \times 10 \left[ \phi_K, \cos \theta_K \right]$ \hspace{1em} (-0.5<\cos \theta_K<0.5)

Account for resolution dependence
Check result stability

Fit range : 15 bins from -1 to +6.5 ($\tau_s$)

Fit parameters:

\[ \tau, \sigma_1(\phi, \theta), \sigma_2(\phi, \theta), \alpha(\phi, \theta), \delta(\phi, \theta) \]

Resolution:

\[ R = \alpha g_1 + (1 - \alpha) g_2 \]

- Fit function derived from :

\[ f(t) = A \int_{-\infty}^{\infty} \theta(x) \frac{1}{\tau} \exp(x/\tau) \varepsilon(x) g(t + \delta - x) \, dx \]

- We perform 180 fits $\rightarrow$ weighted average
FIT results

Fit example

$N_i$

$\tau^*/\tau_{MC}$

$\chi^2$

$\chi^2/\text{ndf} \quad 5.946 / 11$

Constant $\quad 33.333 \pm 3.371$

Mean $\quad -0.36980 \pm 0.7976E-01$

Sigma $\quad 1.0430 \pm 0.6953E-01$

pull
Systematics

• Fit stability: study results with different fit ranges (+-2 $\tau_s$)
  fractional uncertainty $13 \times 10^{-5}$

• Decay length calibration
  uncertainty on residual calibration
  study result stability by changing selection cuts
  affecting d resolution and calibration (+/- 60% in $\varepsilon$)

  fractional uncertainty $27 \times 10^{-5}$

  comparable results form knowledge of
  momentum calibration + dp vs $\Delta d$ correlation from MC ($\sim 3 \times 10^{-4}$)
Systematics

- kaon momentum calibration and kaon mass
  use momentum from boost with the appropriate kaon mass (KLOE determination) reduce detector zone momentum calibration effects (impact on result stability) $p_k \sim \sqrt{e_{\text{beam}}^2 - m_k^2}$
  Residual effects:
  absolute P scale + knowledge of ISR effects
  Fractional uncertainty $37 \times 10^{-5}$
  knowledge of kaon mass
  Fractional uncertainty $4 \times 10^{-5}$
- Knowledge of efficiency variation:
  very uniform efficiency over 10's of $\tau$s:
  check result with exactly uniform efficiency
  Fractional uncertainty $5 \times 10^{-5}$
- additional checks, result stability verified over data taking period, detector region, decay topology ...
Result

<table>
<thead>
<tr>
<th>Source</th>
<th>value ( (\text{ps}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>fit range</td>
<td>0.012</td>
</tr>
<tr>
<td>d calibration</td>
<td>0.024</td>
</tr>
<tr>
<td>pk calibration</td>
<td>0.033</td>
</tr>
<tr>
<td>Kaon mass</td>
<td>0.004</td>
</tr>
<tr>
<td>efficiency</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>0.043</td>
</tr>
</tbody>
</table>

\[ \tau_s = (89.562 \pm 0.029_{\text{stat}} \pm 0.043_{\text{syst}}) \text{ ps} \]
Results on the market and WA

\[ \tau_{S}(WA) = 89.567 \pm 0.039 \]
isotropy of $K_S$ lifetime measurement!

- The CMB dipole anisotropy, if interpreted as a Doppler effect, is due to Local Group motion (~570 km/s) in the direction $(l,b) = (263.86^\circ, 48.24^\circ)$

- A test of the isotropy of $K_S$ lifetime measurement is done by comparing the result parallel and antiparallel w.r.t. an assigned direction

\[ A = \frac{\tau_{S,\text{up}} - \tau_{S,\text{down}}}{\tau_{S,\text{up}} + \tau_{S,\text{down}}} \]

- retain decay events with $p_{K_{\text{GC}}}$ within a $30^\circ$ cone around:
  - $(263.86^\circ, 48.24^\circ)$ (CMB) $\quad A = -0.0002 \pm 0.0010 \pm 0.0003$
  - $(173.86^\circ, 0^\circ)$ $\quad A = 0.0002 \pm 0.0009 \pm 0.0004$
  - $(263.86^\circ, -41.76^\circ)$ $\quad A = 0.0000 \pm 0.0008 \pm 0.0003$
$K_{e2\gamma}$
Ke2(γ): introduction

SM prediction made in terms of IB process only: unobservable!

From theory (ChPT) expect SD ≈ IB for Ke2, but experimental knowledge is poor

δSD/SD≈15%

1) Consider as “signal” events with $E_γ < 10$ MeV (SD negligible)
2) Correct for IB tail, 0.0625(5)
Analysis basic principles

1) Select kinks in DC (≈ fiducial volume)
   - K track from IP
   - secondary with $p_{lep} > 180$ MeV

   for decays occurring in the FV, the reconstruction efficiency is $\approx 51\%$

2) No tag required on the opposite hemisphere
   (as we usually do!)

   $\rightarrow$ gain $\times 4$ of statistics
Analysis basic principles

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

\[
M_{lep}^2 = (E_K - p_{miss})^2 - p_{lep}^2
\]

around \( M^2_{lep} = \)0 we get \( S/B = 10^{-3} \)
Background rejection (track quality)

we accept $\approx 35\%$ of decays in the FV

most of Ke2 events lost have bad resolution

$S/B = 1/20$

*not enough!*
Background rejection (PID)

1) Particle ID exploits EMC granularity: energy deposits into 5 layers in depth
   - cluster depth
   - RMS of plane energies
   - asymmetry of first (last) two energy releases
   - skewness of cell-depth distribution
   - E1, Emax, Nmax
   - $\Delta E/\Delta x$

2) Add E/P and TOF
Combine PID variables using a NN.

Use a pure sample of $K_{Le3}$ to correct cell response in MC and for NN training.
Ke2 fit: radiative corrections

The analysis above is inclusive of photons in the final state

- in our fit region we expect
  \[ \frac{\text{Ke2 (E}_\gamma\text{>10MeV)}}{\text{Ke2(E}_\gamma\text{<10MeV)}} \approx 10\% \]

- repeat fit by varying
  \[ \text{Ke2 (E}_\gamma\text{>10MeV)} \]
  by 15\% (SD uncertainty): get 0.5\% error…too large

- Need a dedicated study of the Ke2 (E_\gamma>10MeV) component
Ke\_2\gamma \ text{process}

Dalitz density

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

helicity suppressed

negligible

\[
x = 2 \frac{E_g}{M_K} \quad y = 2 \frac{E_e}{M_K}
\]

E\_\gamma, E\_e \text{ in the K rest frame}

Structure Dependent

\[
\rho_{SD}(x,y) = \frac{G_F^2 |V_{us}|^2}{64 \rho^2} M_K^5 \left( f_V + f_A \right)^2 f_{SD+}(x,y) + \left( f_V - f_A \right)^2 f_{SD-}(x,y)
\]

f\_V, f\_A : \text{effective vector and axial couplings}

SD\_+ = V+A : \gamma \text{ polarization +}

SD\_− = V−A : \gamma \text{ polarization −}
Dalitz plots for SD+ and SD−

electron peaks at 250 MeV, e-γ antiparallel

Broad electron peak at 100 MeV: very bad, since Ke3 endpoint is 230 MeV
Ke2γ: theory predictions

1) ChPT at O(p^4):
   \[ f_V \approx 0.0945 \]
   \[ f_A \approx 0.0425 \]
   no dependence on photon energy
   Bijnens, Ecker, Gasser 93

2) ChPT at O(p^6):
   \[ f_V \approx 0.082(1+\lambda(1-x)) \]
   \[ f_A \approx 0.034 \]
   V linear x dependence (\(\lambda \approx 0.4\))
   Ametller, Bijnens, Bramon, Cornet 93
   Geng, Ho, Wu 04
   Chen, Geng, Lih 08

3) LFQM:
   non trivial x dependence
   \[ f_V = f_A = 0 \] at x=0
   Chen, Geng, Lih 08
Ke$2\gamma$ selection: photon detection

- A photon is required with energy $E_{\gamma} > 20$ MeV to reject bkg (we lose $Ke_{2B}$, too)
- Time of arrival compatible with that of the event (electron):
  \[
  \Delta t_{\gamma e} = \left| t_\gamma - r_\gamma/c \right| - \left| t_e - r_e/c \right| < 2\sigma
  \]
  $(r = \text{distance from K decay vtx})$

\[\gamma\text{ from } \pi^0\]
\[\beta(\pi^+) \approx 0.8 \text{ instead of } 1\]

Fake $\gamma$ from accidental bkg
Ke2γ selection

After photon detection bkg is dominated by
- Kµ2 in the low $M^2_{kp}$ region
- Ke3 for $M^2_{kp} > 20000$

No sensitivity for Ke2γ with $p_e < 200$ MeV (SD− amplitude)

We measure Ke2γ ($E_γ > 10$ MeV, $p_e < 200$ MeV) → SD+ amplitude
Ke2\gamma selection: photon matching

1) best evaluation of $E_{\gamma}^{lab}$ from the kinematics of Ke2\gamma, using measured $p_K$, $p_e$ and photon direction $n_\gamma$

$$E_{\gamma}^{lab} = \frac{M_K^2 + m_e^2 - 2E_K E_e + 2 \overrightarrow{p}_K \cdot \overrightarrow{p}_e}{2 \left| E_K - E_e - \overrightarrow{p}_K \cdot \overrightarrow{n}_\gamma + \overrightarrow{p}_e \cdot \overrightarrow{n}_\gamma \right|}$$

$\rightarrow$ 12 MeV resolution

$\sigma_{\text{calo}} \approx 30$ MeV)

2) $\Delta E_{\gamma} = E_{\gamma}^{lab} - E_{\gamma}^{calo}$ is also useful as a discriminating variable against background
**Ke2\(\gamma\) event counting**

- Two-dimensional binned likelihood fit in the \(M_{\text{lep}}^2 - \Delta E_\gamma/\sigma\) plane

5 bins of \(E_\gamma\) (from \(E_{\gamma}^{\text{lab}}\) pass in K rest frame):

(10, 50) (50,100) (100,150) (150,200) (200,250)

- Most populated bins

100< \(E_\gamma<150\) MeV: \(N = 463 \pm 32\), \(\chi^2 = 87/106\)

150< \(E_\gamma<200\) MeV: \(N = 494 \pm 38\), \(\chi^2 = 100/106\)
Ke$2\gamma$ event counting

Fit projections on $\Delta E_\gamma/\sigma$ (all $E_\gamma$ bins together) according to $M_\gamma^2$, we show separately regions dominated by signal and bkg data fit $K\mu_2$ $K\mu_3$

In total, we count $N_{e2\gamma} = 1484 \pm 63$
We measure:

\[
\frac{1}{\Gamma(K_{\mu 2})} \frac{d \Gamma(K_{e 2}, E_\gamma > 10 \text{MeV}, p_e^i > 200 \text{MeV})}{d E_\gamma}
\]

Data are compared with ChPT O(p^4) calculation

Integrating we obtain:

\[
\frac{\Gamma(K_{e 2}, E_\gamma > 10 \text{MeV}, p_e^i > 200 \text{MeV})}{G(K_{\mu 2})} = 1.483(68) \times 10^{-5}
\]

in agreement with $1.447 \times 10^{-5}$ of ChPT O(p^4)

This confirm the SD content of our MC, evaluated with ChPT O(p^4), within an accuracy of 4.6% and allows a 0.2% systematic error on Ke2\$_B$ to be assessed.
Ke$_2\gamma$ spectrum: fit to ChPT O(p$^6$)

- We fit our data to extract $f_V + f_A$ (SD+), allowing for a slope of the vector $f_V$
  \[ f_V = f_{V0} \left(1 + \lambda \left(1 - x\right)\right) \]
- Since we are not sensitive to the SD amplitude (acceptance≈2%) we keep $f_V - f_A$ fixed to the ChPT O(p$^6$) prediction

We obtain:

\[ f_{V0} + f_A = (0.125\pm0.007) \]
\[ \lambda = 0.38 \pm 0.21 \]

Compare to ChPT O(p$^6$): $f_{V0} + f_A \approx 0.116, \quad \lambda \approx 0.4$

The spectrum predicted by the Light Front Quark Model is excluded by our data, $\chi^2 = 127/5$. 

**Ke$^2\gamma$ spectrum vs LFQM**

![Graph showing Ke$^2\gamma$ spectrum vs LFQM](image)
CONCLUSION

We have performed the most accurate measurement of the $K_S$ lifetime:

$$\tau_S = (89.562 \pm 0.029^{\text{stat}} \pm 0.043^{\text{syst}}) \text{ ps}$$

.. and a funny test of isotropy (the most accurate with lifetime to my knowledge)

We also presented today the first measurement of the decay spectrum in a region dominated by SD

$$\frac{1}{\Gamma(K_{\mu2})} \frac{d \Gamma(K_{e2}, E_\gamma > 10\text{MeV}, p_e^i > 200\text{MeV})}{d E_\gamma}$$

Results are in good agreement with expectations from ChPT
Reconstruction efficiencies

We use MC, with corrections from data control samples

1) kink reconstruction (tracking): $K^+e3$ and $K^+\mu2$ data control samples selected with tagging and additional criteria based on EMC info’s only (next slide)

2) cluster efficiency ($e, \mu$): $K_L$ control samples, selected with tagging and kinematic criteria based on DC info’s only

3) trigger: exploit the OR combination of EMC and DC triggers (almost uncorrelated); downscaled samples are used to measure efficiencies for cosmic-ray and machine background vetoes

we obtain:

$$\varepsilon(Ke2)/\varepsilon(K\mu2) = 0.946 \pm 0.007$$
Control samples for tracking efficiencies

Just an example: selection of $K^+e3$ control sample to measure tracking efficiency for electrons

0) Tagging decay ($K\mu2$ or $K\pi2$) coming from IP
Control samples for tracking efficiencies

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1) Tagging decay ($K\mu2$ or $K\pi2$): reconstruction of the opposite charge kaon flight path
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2) A $\pi^0 \rightarrow \gamma\gamma$ decay vertex is reconstructed along the $K$ decay path, using TOF
Control samples for tracking efficiencies

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0) Tagging decay ($K\mu2$ or $K\pi2$) coming from IP

1) Tagging decay ($K\mu2$ or $K\pi2$): reconstruction of the opposite charge kaon flight path

2) A $\pi^0\rightarrow\gamma\gamma$ decay vertex is reconstructed along the K decay path, using TOF

3) Electron cluster required; $p_e$ estimated from a kinematic fit with constraints on $E/p$, TOF, $r_e$ and $E_{miss} - P_{miss}$

We evaluate the $K^+e^-$ electron kink reconstruction efficiency
Decay point correction using 2\textsuperscript{nd} determination of kaon momenta
Stability with/out corrections

\[ \chi^2/\text{ndf} \]

without

\[ \chi^2/\text{ndf} \]

with
Control samples for tracking efficiencies

\[ \sigma \approx 19 \text{ MeV} \]

with a similar method, we get \( \sigma \approx 7 \text{ MeV} \) for muon tracks
Systematics and checks

Cross-check on efficiencies: use same algorithms to measure $R_{l3} = \Gamma(Ke3)/\Gamma(K\mu3)$

$R_{l3} = 1.507 \pm 0.005$ for $K^+$

$R_{l3} = 1.510 \pm 0.006$ for $K^-$

SM expectation (FlaviaNet) $R_{l3} = 1.506 \pm 0.003$

Summary of systematics:

<table>
<thead>
<tr>
<th>Source of Systematics</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>0.6%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.4%</td>
</tr>
<tr>
<td>syst on Ke2 counts</td>
<td>0.3%</td>
</tr>
<tr>
<td>Ke2$\gamma$ SD component</td>
<td>0.2%</td>
</tr>
<tr>
<td>Clustering for e, $\mu$</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total Syst</strong></td>
<td><strong>0.8%</strong></td>
</tr>
</tbody>
</table>

0.6% from statistics of control samples
$R_K : \text{KLOE result}$

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

Total error $1.3\% = 1.0\%_{\text{stat}} + 0.8\%_{\text{syst}}$

0.9\% from 14k Ke2 + bkg subtraction dominated by statistics

• The result does not depend upon the kaon charge:

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

• Our measurement agrees with SM prediction,

  $R_K = 2.477(1) \times 10^{-5}$
\[ R_K : \text{world average} \]

**PDG 2008:**

\[ R_K = (2.45 \pm 0.11) \times 10^{-5} \]

4.5% accuracy

**New world average:**

\[ R_K = (2.468 \pm 0.025) \times 10^{-5} \]

1% accuracy

\[ R_K^{\text{SM}} = 2.477(1) \times 10^{-5} \]
$R_K$ : sensitivity to new physics

Sensitivity shown as 95% CL excluded regions in the $M_H - \tan \beta$ plane, for different values of the LFV effective coupling, $\Delta_{13} = 10^{-3}, 5 \times 10^{-4}, 10^{-4}$

$R_K = (2.493 \pm 0.032) \times 10^{-5}$

$R_K = (2.468 \pm 0.025) \times 10^{-5}$
\( K_{\mu\bar{\nu}} \) : sensitivity to new physics

Scalar currents, e.g. due to Higgs exchange, affect \( K \to \mu \nu \) width

\[
R_{123} = \left| \frac{V_{us}(K m_2)}{V_{us}(K l_3)} \cdot \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(p m_2)} \right|
\]

\[
= \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left( 1 - \frac{m_{p^+}^2}{m_{K^+}^2} \right) \frac{\tan^2 \beta}{1 - e_0 \tan \beta} \right|
\]

[Hou, Isidori-Paradisi]

\( R_{123} = 1 \) in SM

we find

\( R_{123} = 1.008 \pm 0.008 \)

limited by lattice uncertainty on \( f_+(0) \) and \( f_K/f_\pi \)

From direct searches (LEP), \( M_{H^+} > 80 \) GeV, \( \tan \beta > 2 \)