Physics with the KLOE2 experiment at DAΦNE

• Machine and detector upgrade

• CKM precision measurements

• Interferometry

• Dark matter search
KLOE-2 at upgraded DAΦNE

Upgrade of DAΦNE in luminosity:
Crabbed waist scheme at DAΦNE (proposal by P. Raimondi)
- increase L by a factor $O(5)$
- requires minor modifications
- relatively low cost
- Successful experimental test at DAΦNE

KLOE-2 Plan:
- phase 0: KLOE restart taking data end 2009 with a minimal upgrade ($L \sim 5 \text{ fb}^{-1}$)
- phase 1: full KLOE upgrade (KLOE-2) > 2011 ($L > 20 \text{ fb}^{-1}$)

Physics issues:
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare $K_S$ decays
- Dark matter
- η, η’ physics
- Light scalars, γγ physics
- Hadron cross section at low energy, muon anomaly

Detector upgrade issues:
- Inner tracker R&D
- γγ tagging system
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, ...)


DAΦNE Beam distributions @ IP

<table>
<thead>
<tr>
<th></th>
<th>DAΦNE KLOE</th>
<th>DAΦNE Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{bunch}}$ (mA)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>$N_{\text{bunch}}$</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>$\beta_y^*$ (cm)</td>
<td>1.7</td>
<td>0.65</td>
</tr>
<tr>
<td>$\beta_x^*$ (cm)</td>
<td>170</td>
<td>20</td>
</tr>
<tr>
<td>$\sigma_y^*$ ($\mu$m)</td>
<td>7</td>
<td>2.6</td>
</tr>
<tr>
<td>$\sigma_x^*$ (mm)</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>$\theta_{\text{cross/2}}$ (mrad)</td>
<td>12.5</td>
<td>25</td>
</tr>
<tr>
<td>$\Phi_{\text{Piwinski}}$</td>
<td>0.45</td>
<td>2.5</td>
</tr>
<tr>
<td>$L$ (cm$^{-2}$s$^{-1}$) x10$^{32}$</td>
<td>1.5</td>
<td>&gt;5</td>
</tr>
</tbody>
</table>
Luminosity vs tunes scan

Crab On $\rightarrow 0.6/\theta$

$L_{\text{max}} = 2.97 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
$L_{\text{min}} = 2.52 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

Crab Off

$L_{\text{max}} = 1.74 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
$L_{\text{min}} = 2.78 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
DAΦNE Luminosity versus colliding currents

NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs
The HET detector consists in a position detector with a pitch of few millimeter ($\frac{\% E}{\%}$ ~ 0.6 MeV/mm). The characteristics of this detector are the following:

- Good time resolution to disentangle each bunch (~2.7 ns bunch spacing);
- Capability to acquire data at a frequency of 368 MHz in order to permit event

The LET detector consists of a calorimeter capable of detecting electrons and positrons within a wide energy range peaked around 200 MeV. The environmental conditions require radiation-tolerant devices, insensitive to magnetic fields. The physical requirements are the following:

- Good energy resolution to improve the reconstruction of the $\gamma\gamma$ invariant mass from the decay products;
- Good time resolution to associate detected events with the proper bunch crossing;
- Small size.
Inner tracker at KLOE

- 5 independent tracking layers for a fine vertex reconstruction of \( K_S \) and \( \eta \)
- 200 \( \mu m \) \( \sigma_{r\phi} \) and 500 \( \mu m \) \( \sigma_z \) spatial resolutions with XV readout
- 700 mm active length
- from 150 to 250 mm radii
- 1.8% \( X_0 \) total radiation length in the active region
- Realized with Cylindrical-GEM detectors
Kaon physics

- Set bounds on New Physics from Lepton-Quark Universality
- Precise determination of $V_{us}$
- Test of Lepton universality $K_{e3} \text{ vs } K_{\mu3}$
- Most precise test of CKM unitarity

New Physics extensions of the SM can break gauge universality in the form of tree or loop level

i. **Exotic Muon Decays**: would contribute to the muon lifetime contributions to muon decays and/or semileptonic processes.

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

*Provides best limit on* $BR(\mu^+ \to e^+ \bar{\nu}_e \nu_\mu) \sim 10$ *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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \varepsilon_{NP}$$

$\varepsilon_{NP} \approx M_W^2/\Lambda_{NP}^2$
Vus, lepton universality and CKM unitarity at KLOE

\[ \Gamma(K \rightarrow \pi \ell \nu(\gamma)) \propto |V_{us}|^2 |f_+^{K\pi}(0)|^2 \]
\[ I'_K(\lambda_+,\lambda_0,0) (1 + \delta'_K) \]

All KLOE exp. inputs but K\(_S\) lifetime

KLOE average @ 0.28%

| \[ |V_{us}| = 0.2237(13) \] 0.6% |

\[ r_{\mu e} = \frac{|f_+(0) V_{us}|^2}{|f_+(0) V_{us}|^2_{e3, \text{exp}}} \]

World Average: 6x10\(^{-4}\) accuracy
\[ \Gamma(K_{l3}(\gamma)) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{K\ell}(\lambda_{+,0}) (1+\delta_{SU(2)}^{K}+\delta_{em}^{K\ell})^2 \]

<table>
<thead>
<tr>
<th>% err</th>
<th>BR</th>
<th>(\tau)</th>
<th>(\delta)</th>
<th>I_{Ke}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21652(56)</td>
<td>0.25</td>
<td>0.11</td>
<td>0.20</td>
<td>0.11</td>
</tr>
<tr>
<td>0.21746(69)</td>
<td>0.32</td>
<td>0.17</td>
<td>0.19</td>
<td>0.11</td>
</tr>
<tr>
<td>0.21572(132)</td>
<td>0.61</td>
<td>0.60</td>
<td>0.03</td>
<td>0.11</td>
</tr>
<tr>
<td>0.21624(113)</td>
<td>0.52</td>
<td>0.31</td>
<td>0.06</td>
<td>0.41</td>
</tr>
<tr>
<td>0.21676(141)</td>
<td>0.65</td>
<td>0.48</td>
<td>0.06</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Average: \(|V_{us}|f(0) = 0.21660(47)\)  \(\chi^2/\text{ndf} = 3.03/4\) (55%)
$|V_{us}| f_+(0): \text{KLOE+Step0+WA}$

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K_0\pi}(0)|^2 I_{K\ell}(\lambda_{+,0}) (1+\delta_{SU(2)}^K + \delta_{em}^{K\ell})^2$$

Approx. contr. to % err from:

<table>
<thead>
<tr>
<th>% err</th>
<th>BR</th>
<th>$\tau$</th>
<th>$\delta$</th>
<th>$I_{K\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L e_3$</td>
<td>0.2155(4)</td>
<td>0.21</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>$K_L \mu_3$</td>
<td>0.2167(5)</td>
<td>0.25</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>$K_S e_3$</td>
<td>0.2153(7)</td>
<td>0.33</td>
<td>0.30</td>
<td>0.03</td>
</tr>
<tr>
<td>$K^{\pm} e_3$</td>
<td>0.2152(8)</td>
<td>0.38</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>$K^{\pm} \mu_3$</td>
<td>0.2132(9)</td>
<td>0.42</td>
<td>0.27</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Fractional error on $|V_{us}| f_+(0)$ is 0.14%  
World Average is 0.23%
Universality: KLOE+Step0+WA

- Today with $f_+(0)@0.5\%$ the accuracy on the unitarity relation of the first row is

\[ \sigma \left( 1 - V_{ud}^2 - V_{us}^2 \right) = 6 \times 10^{-4} \]

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

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

- 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 $\sim2$

\[ \sigma \left( 1 - V_{ud}^2 - V_{us}^2 \right) = (3/4) \times 10^{-4} \]
Neutral kaon interferometry

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right] \]

Most precise test of quantum coherence in an entangled system:

\[ \zeta_{00} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}) \times 10^{-7} \]

\( \zeta \) decoherence parameter (QM predicts \( \zeta=0 \))

Quantum gravity effects might induce:
1) decoherence and CPT violation
   (at most \( \gamma=O(m_K^2/M_{\text{Planck}}) \sim 2 \times 10^{-20} \) GeV)

2) modification of the initial correlation of the kaon pair
   (at most \( \omega=O(m_K^2/M_{\text{Planck}}/\Delta \Gamma) \sim 1 \times 10^{-3} \))

\[ |i\rangle \propto \left( K^0 \bar{K}^0 - K^0 \bar{K}^0 \right) + \omega \left( K^0 \bar{K}^0 + K^0 \bar{K}^0 \right) \]

EPR correlation: no simultaneous decays (\( \Delta t=0 \)) in the same final state due to the destructive QM interference

\[ \gamma = (0.7 \pm 1.2_{\text{STAT}} \pm 0.3_{\text{SYST}}) \times 10^{-21} \text{ GeV} \]

\[ \Re \omega = (-1.6^{+3.0}_{-2.1\text{STAT}} \pm 0.4_{\text{SYST}}) \times 10^{-4} \]

\[ \Im \omega = (-1.7^{+3.3}_{-3.0\text{STAT}} \pm 1.2_{\text{SYST}}) \times 10^{-4} \]
Interferometry at KLOE-2: $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

Possible signal of decoherence concentrated at very small $\Delta t$

$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t)$ (a.u.)

\[ \zeta_{00} = 4 \times 10^{-6} \]

\[ \zeta_{00} = 0 \]

Theoretical distribution

Reconstructed distribution (MC)

Black hist.: $\sigma(\Delta t) \sim 1/\tau_S \Rightarrow 6\text{mm} \ (\text{KLOE})$

Red hist: $\sigma(\Delta t) \sim 1/4 \tau_S \Rightarrow 1.5\text{mm} \ (\text{KLOE + inner tracker})$

Blue curve: ideal
## Perspectives with KLOE-2 at upgraded DAΦNE

<table>
<thead>
<tr>
<th>Mode</th>
<th>Test of</th>
<th>Param.</th>
<th>Present best published measurement</th>
<th>KLOE-2 L=50 fb⁻¹</th>
</tr>
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<tbody>
<tr>
<td>$K_S \to \pi \nu e$</td>
<td>CP, CPT</td>
<td>$A_S$</td>
<td>$(1.5 \pm 11) \times 10^{-3}$</td>
<td>$\pm 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^+\pi^- \pi^\nu e$</td>
<td>CP, CPT</td>
<td>$A_L$</td>
<td>$(3322 \pm 58 \pm 47) \times 10^{-6}$</td>
<td>$\pm 25 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\pi^+\pi^- \pi^0\pi^0$</td>
<td>CP</td>
<td>Re($\varepsilon'/\varepsilon$)</td>
<td>$(1.65 \pm 0.26) \times 10^{-3}$ (*)</td>
<td>$\pm 0.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^+\pi^- \pi^0\pi^0$</td>
<td>CP, CPT</td>
<td>Im($\varepsilon'/\varepsilon$)</td>
<td>$(-1.2 \pm 2.3) \times 10^{-3}$ (*)</td>
<td>$\pm 3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^\nu e \pi^\nu e$</td>
<td>CPT</td>
<td>Re($\delta$)+Re($x_-$)</td>
<td>Re($\delta$) = $(0.25 \pm 0.23) \times 10^{-3}$ (*)</td>
<td>$\pm 0.2 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Re($x_-$) = $(-4.2 \pm 1.7) \times 10^{-3}$ (*)</td>
<td></td>
</tr>
<tr>
<td>$\pi^\nu e \pi^\nu e$</td>
<td>CPT</td>
<td>Im($\delta$)+Im($x_+$)</td>
<td>Im($\delta$) = $(-0.6 \pm 1.9) \times 10^{-5}$ (*)</td>
<td>$\pm 3 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Im($x_+$) = $(0.2 \pm 2.2) \times 10^{-3}$ (*)</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^- \pi^+\pi^-$</td>
<td></td>
<td>$\Delta m$</td>
<td>$(5.288 \pm 0.043) \times 10^9 \text{ s}^{-1}$</td>
<td>$\pm 0.03 \times 10^9 \text{ s}^{-1}$</td>
</tr>
</tbody>
</table>

(*) = PDG 2008 fit
# Perspectives with KLOE-2 at upgraded DAΦNE

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</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>QM</td>
<td>$\zeta_{00}$</td>
<td>$(1.0 \pm 2.1) \times 10^{-6}$</td>
<td>$\pm 0.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>QM</td>
<td>$\zeta_{SL}$</td>
<td>$(1.8 \pm 4.1) \times 10^{-2}$</td>
<td>$\pm 0.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; QM</td>
<td>$\alpha$</td>
<td>$(-0.5 \pm 2.8) \times 10^{-17}$ GeV</td>
<td>$\pm 2 \times 10^{-17}$ GeV</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; QM</td>
<td>$\beta$</td>
<td>$(2.5 \pm 2.3) \times 10^{-19}$ GeV</td>
<td>$\pm 0.1 \times 10^{-19}$ GeV</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; QM</td>
<td>$\gamma$</td>
<td>$(1.1 \pm 2.5) \times 10^{-21}$ GeV</td>
<td>$\pm 0.2 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.1 \times 10^{-21}$ GeV</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; EPR corr.</td>
<td>Re($\omega$)</td>
<td>$(1.1 \pm 7.0) \times 10^{-4}$</td>
<td>$\pm 2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; EPR corr.</td>
<td>Im($\omega$)</td>
<td>$(3.4 \pm 4.9) \times 10^{-4}$</td>
<td>$\pm 2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K_{S,L}\to\pi\nu$</td>
<td>CPT &amp; Lorentz</td>
<td>$\Delta a_0$</td>
<td>$[(0.4 \pm 1.8) \times 10^{-17}$ GeV]</td>
<td>$\pm 2 \times 10^{-18}$ GeV</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>CPT &amp; Lorentz</td>
<td>$\Delta a_Z$</td>
<td>$[(2.4 \pm 9.7) \times 10^{-18}$ GeV]</td>
<td>$\pm 7 \times 10^{-19}$ GeV</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^{+}\pi^{-}$</td>
<td>CPT &amp; Lorentz</td>
<td>$\Delta a_{X,Y}$</td>
<td>$[&lt;10^{-21}$ GeV]</td>
<td>$\pm 4 \times 10^{-19}$ GeV</td>
</tr>
</tbody>
</table>
Several recent puzzling astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA) can be interpreted by postulating the existence of some secluded gauge sector with a rich phenomenology at low ($O(1 \text{ GeV})$) energies. Some basic papers on the issue are:

**Hidden valley model**

These models postulate a hidden valley, well separated from the world with which they only occasionally get in touch.

Here, the secluded particles mix with the Standard Model ones through some mechanism with mixing parameter $k$ of order up to $10^{-2} - 10^{-3}$. Interestingly enough much lower values for $k$ are disfavoured by cosmological consideration.

(from reference 6)
The U boson can be observed through the radiative process:

\[ e^+e^- \rightarrow U \gamma \rightarrow l^+l^- (l=e,m) \]

The cross section for this process is suppressed wrt the QED continuum by a factor \( k^2 \), so it can be at most \( \approx 1 \) pb.

The two leptons however resonate about the U mass, while the QED continuum events do not.
**S channel production**

Probably the most interesting mechanism for secluded particles production is the higgs’-strahlung: \( e^+ e^- \rightarrow U h' \), which can have a cross section of order 1 pb at DAFNE energies.

\[ e^- \quad U^* \quad h' \]

\[ e^+ \quad U \]

If \( m_{h'} < m_u \) then the higgs’ is relatively long-lived, \( O(10^{-9} \text{ s}) \) thus escaping detection inside KLOE.

The resulting signal (again assuming that the U decays only to SM particles) would then be a pair of leptons + missing energy.
Experimental detection

The two produced leptons have energies high enough to trigger the events with efficiencies > 90% for almost all possible combinations of $m_U$ and $m_{h'}$, at least for the electron channel.

A possible background specific to DAFNE is $K_S \rightarrow \pi^+\pi^-$, with the parent $K_L$ flying through the apparatus.

This should be a problem only for the muon channel and for masses of the $U$ boson close to $m_K$. It can however be well calibrated by using $K$ crash events.

If it turns out to be still a problem one can always think to run at $\sqrt{s} < 2m_K$. 
If $m_{h'} > 2 m_U$ then the higgs’ decays mainly into two $U$ bosons giving rise to spectacular 4 leptons+g or 6 leptons final states.

**Spectacular final states**

- $e^- \rightarrow U^*$
- $e^- \rightarrow U$
- $e^- \rightarrow \gamma$
- $e^- \rightarrow h'$
- $e^- \rightarrow U$
- $e^- \rightarrow U$
- $e^- \rightarrow U$
Conclusions

- $| V_{us} | f_+(0) @ 0.14\%$ (5 fb$^{-1}$ are enough to do the job).
- Unitarity test at few $10^{-4}$, with lattice improvements on form factors.
- Improve constraints on New Physics and interplay with other sectors.
- at the moment all KLOE results are compatible with no CPT violation.
- Neutral kaon interferometry, CPT symmetry and QM tests are among the main issues of the KLOE-2 physics program. Measurements will benefit from both a huge data sample (20-50 fb$^{-1}$) and a better detector.
- moreover.... KLOE-2 can cover an interesting region of the dark matter parameter space in terms of the mixing parameter with the “standard sector” and mass.