Physics at DAΦNE and KLOE-2

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DAΦNE accelerator complex

- $e^+e^-$ collider at $\phi$-meson peak (1020 MeV)
- 2 interaction regions
- Trajectory length: 97.69 m
- Number of stored bunches: up to 120
- $\phi$ - momentum: $\sim$ 13 MeV/c

First data taking period: 1999 – 2006
Best result:

$$L = 1.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$
$$\int L dt = 8.5 \text{ pb}^{-1}/ \text{ per day}$$
In 2008 DAΦNE has implemented a new interaction scheme based of a large Piwinski angle ($\psi$) and crab-waist compensation induced by properly designed sextupoles

$$\psi \approx \frac{\sigma_z}{\sigma_x} \times \frac{\theta}{2} \quad \beta_y \approx \frac{\sigma_x}{\theta} \ll \sigma_z$$

New collision scheme (tested with the SIDDHARTA experiment)
Large angle and crab-waist compensation $\psi = 1.9$, $\beta_y^* = 9$ mm

Old collision scheme
KLOE 2005 $\psi = 0.6$, $\beta_y^* = 18$ mm
KLOE 2002 $\psi = 0.3$, $\beta_y^* = 25$ mm

Peak luminosity $L_{\text{new}} \sim 3 \times L_{\text{old}}$
Recent time (2009 – 2011 years) AD had too much problem to start upgraded collider

Now the planned time to begin KLOE–2 operations is November 2001

Time reserved for KLOE–2 data –taking is around 2 or 3 years

As SuperB construction begins, DAΦNE running should be winding down.

SuperB will be funded separately from INFN base budget

Now (April 2011) the site of new project was chosen: campus of the Tor Vergata University (Roma 2)
In SuperB is inserted in April 2010 among the Italian National Research Program (PNR) as a flagship project.

In April 2011 PNR approved 250M for next four years.

Special Russian–Italian agreement for SuperB and funding – managed through "Kurchatov Institute" (70M).
SuperB project

- $e^+e^-$ asymmetrical collider
- Max. energy up to 4 and 7 GeV
- Flexible running energy
- Starting luminosity at large Piwinski angle
  \[ L = 1 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \]
- Luminosity upgrade to \( 2.5 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \) after 5 years of running
- Two distinct modes of operation:
  - 4S region $\Upsilon(1S) - \Upsilon(6S)$
  - Charm threshold region: $\psi(3770)$ and nearby thresholds
- Super Flavour Factory at large data sample
- Alternative way to search for new physics beyond the LHC scale

Year 0 = 2016
KLOE – detector

Drift chamber

- Large volume: $\varnothing = 4\text{m}$, $L = 3.3\text{ m}$
- Gas mixture: $90\% \text{ He} + 10\% \text{ C}_4\text{H}_{10}$
- Resolutions: $\sigma_{xy} = 0.15\text{ mm}, \sigma_z = 2\text{ mm}$
  $\delta p/p = 0.4\%, \sigma_{\text{vertex}} \approx 1\text{ mm}$

Calorimeter

- Construction: lead / scintillating fibers
- Solid angle coverage: 98%
- Resolutions: $\sigma E/E = 5.7\%/\sqrt{E(\text{GeV})}$
  $\sigma t = 55\text{ ps}/\sqrt{E(\text{GeV})} \oplus 100\text{ ps}$
- PID capabilities
From 2001 to 2005 KLOE collected ~ 2.5 fb\(^{-1}\) (8×10\(^9\) \(\phi–\) meson decays)

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Events (2.5 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+K^-)</td>
<td>3.7×10(^9)</td>
</tr>
<tr>
<td>(K_SK_L)</td>
<td>2.5×10(^9)</td>
</tr>
<tr>
<td>(\rho\pi^+\pi^+\pi^-\pi^0)</td>
<td>1.1×10(^9)</td>
</tr>
<tr>
<td>(\eta\gamma)</td>
<td>9.7×10(^7)</td>
</tr>
<tr>
<td>(\pi^0\gamma)</td>
<td>9.4×10(^6)</td>
</tr>
<tr>
<td>(\eta'\gamma)</td>
<td>4.6×10(^5)</td>
</tr>
<tr>
<td>(\pi\pi\gamma)</td>
<td>2.2×10(^6)</td>
</tr>
<tr>
<td>(\eta\pi^0\gamma)</td>
<td>5.2×10(^5)</td>
</tr>
</tbody>
</table>

Tagging Kaon beams

\(K_L\rightarrow\text{crash}\)
Minimal detector upgrade for the first KLOE–2 run (~ 5 fb\(^{-1}\) for one year data taking): taggers to detect electron and positrons from

\[ e^+e^- \rightarrow e^+e^- \gamma^*\gamma^* \rightarrow e^+e^-X \]

Two type of taggers are installed:

**Low Energy Tagger (LET)**
- 1.5 m from IP
- 160 < E < 230 MeV

**High Energy Tagger (HET)**
- 11 m from IP
- E > 400 MeV

LNF Note 10/17(P), 2010
- **LET** – calorimeter detector
- It installed inside **KLOE–2**
- Size: 6 cm × 7.5 cm × 12 cm
- **LET** constructed from 20 LYSO crystals ($X_0 \sim 1$ cm) and coupled to the SiPM
- Good energy resolution was obtained on small prototype:
  \[ \sigma_E/E < 10\% \text{ at } E < 100 \text{ MeV} \]
- **HET** – position detector (hodoscope) and provides a measurement of the scattered leptons with respect to nominal orbit
- There is a strong correlation between energies and displacement in the horizontal plane
- Detector position can be moved between 30 – 50 mm from beam
- Hodoscope made by two rows of 15 scintillators (3×5×6 mm³)
- Spatial resolution: 5mm; time resolution: ~200 ps
- Active part of the detector has been assembled with their mechanical structure. Installation is planned to be within September 2011
- **IT** (Inner Tracker) installation (between beam pipe and drift chamber) to improve tracking and vertex reconstruction of the charged particles decaying near IP

- **QCALT** (Quadrupole tile calorimeter): detection of the $\gamma$’s coming from $K_L$ – decays in the drift chamber

- **CCALT** (Crystal calorimeter): increase acceptance for $\gamma$’s from IP (polar angle from $21^0$ down to $10^0$)
Main physics goals:
- Vertex reconstruction in the $K_S$, $\eta$, $\eta'$ – decays and in $K_S - K_L$ interference measurement
- Cylindrical GEM (CGEM) detector was proposed and built for the first time ever
- XV strips – pads readout
- 4 CGEM layers with radii from 13 to 23 cm from IP and before DC wall
- Spatial resolution:
  - $\sigma_{r\phi} \sim 200$ μm, $\sigma_z \sim 500$ μm
- 700 mm active length
- Radiation length in the active volume is 1.5% $X_0$

CGEM design requirements, performance and XV readout scheme validated with exhaustive R&D phase

The construction of the Inner Tracker was started and planned to be completed next summer

LNF Note 10/3(P), 2010
QCALT and CCALT – calorimeters

✓ QCALT located along beam–line
✓ Two dodecagonal structures (1 m length)
✓ 5 layers with tungsten (thick = 3.5 mm) + tiles (5mm) + air gap (1mm) for a total 5.5 X0
✓ 20 cells / row for a total of 2400 readout channels
✓ Fast timing resolution < 1ns
✓ Readout was performed with 400 pixels SiPM (MPPC)

➢ CCALT composed of two small barrels of 24 LYSO crystals each
➢ Each crystal has a length of 10 – 13 cm and transverse area from 1.5×1.5 cm² to 2 ×2 cm²
➢ Time resolution : 300–500 ps for 20 MeV photons
➢ Readout was done with SiPM
KLOE – 2 physics program

Main purpose: collect 20 fb\(^{-1}\) at the DAΦNE upgraded luminosity using the crab–waist scheme

✓ Kaon physics
  • Test of CPT in correlated kaon decays and Ks – semileptonic decays
  • Test of SM (CKM unitarity and lepton universality)
  • Test of ChPT in Ks – decays

✓ Spectroscopy of the light mesons
  • $\eta$, $\eta'$, $a_0$, $f_0$, $\sigma$ from $\phi$ – radiative decays

✓ $\gamma\gamma$ - physics
  • Scalar resonances in two photon collisions ($e^+e^- \rightarrow e^+e^- \pi^+\pi^-$)
  • Single pseudoscalar final state

✓ Dark matter searches
  • Light U – boson (low energy region)

CPT–symmetry test in $K\pi\pi$ decays

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

CPT invariance: $A_S = A_L = 2\text{Re} \epsilon \sim 3 \times 10^{-3}$

KLOE result: $A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3}$

KTEV(02): $A_L = (3.32 \pm 0.06_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-3}$

✓ Result based on $L_{\text{int}} = 410 \text{ pb}^{-1}$ sample and statistical error gives a main contribution

✓ With IT installation and KLOE (KLOE–2) statistics it’s expected $0.3\%$ on $BR(K_s \to \pi e \nu)$

Quantum decoherence

Interference between two kaons in the entangled state has been observed in \( \phi \to K_S K_L \to \pi^+ \pi^- \pi^+ \pi^- \) by the KLOE (2005).

\[
I(\pi^+ \pi^−, \pi^+ \pi^-; \Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL})e^{-\left(\Gamma_S + \Gamma_L\right)/2\Delta t} \cos(\Delta m \Delta t)
\]

\( \zeta_{SL} \) – decoherence parameter (in the \( \{K^0 \bar{K}^0\} \) basic defined as \( \zeta_{00} \))

KLOE result based on 1.5 fb\(^{-1}\)

\( \zeta_{SL} = (0.3 \pm 1.8_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-2} \)

\( \zeta_{00} = (1.4 \pm 9.5_{\text{stat}} \pm 3.8_{\text{syst}}) \times 10^{-7} \)

Compatible with the prediction: \( \zeta_{SL} = \zeta_{00} = 0 \)

(no decoherence effect and good test of CPT coservation)

CP–violation in $K_S \rightarrow 3\pi^0$

✓ $K_S \rightarrow 3\pi^0$ is a pure CP – violating process

✓ CP – violation is parameterized as:

$$\eta_{000} = \frac{A(K_S \rightarrow \pi^0 \pi^0 \pi^0)}{A(K_L \rightarrow \pi^0 \pi^0 \pi^0)} = \varepsilon + \varepsilon'_\eta$$

where $\varepsilon$ and $\varepsilon'_\eta$ quantify indirect and direct CP – violation. Assuming that $\eta_{000} \sim \varepsilon$ one can estimate $\text{BR}(K_S \rightarrow 3\pi^0) \sim 1.9 \times 10^{-9}$

✓ Search of the decay was performed by KLOE with a pure $K_S$ beam obtained by $K_L$ interaction in the calorimeter ($K_L$ – crash) and detecting six photons for $L_{\text{int}} = 450 \text{ pb}^{-1}$

$$\text{BR}(K_S \rightarrow 3\pi^0) < 1.2 \times 10^{-7} \text{ and } |\eta_{000}| < 0.018$$


➢ New procedure to refine cluster reconstruction has been obtained

➢ KLOE–2 expectation: an upper limit lower than $10^{-8}$
## KLOE–2 sensitivity to CP/CPT

<table>
<thead>
<tr>
<th>Mode</th>
<th>Parameter</th>
<th>Present best measurement</th>
<th>KLOE–2 (25 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S \rightarrow \pi e \nu$</td>
<td>$A_S$</td>
<td>$(1.5 \pm 11) \times 10^{-3}$</td>
<td>$\pm 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \nu$</td>
<td>$A_L$</td>
<td>$(332.2 \pm 5.8 \pm 4.7) \times 10^{-5}$</td>
<td>$\pm 4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \pi^0$</td>
<td>$Re(\varepsilon'/\varepsilon)$</td>
<td>$(1.65 \pm 0.26) \times 10^{-3}$</td>
<td>$\pm 0.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \pi^0$</td>
<td>$Im(\varepsilon'/\varepsilon)$</td>
<td>$(-1.2 \pm 2.3) \times 10^{-3}$</td>
<td>$\pm 4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$\Delta m$</td>
<td>$(5.288 \pm 0.043) \times 10^9$ s⁻¹</td>
<td>$\pm 0.05 \times 10^9$ s⁻¹</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$\zeta_{SL}$</td>
<td>$(0.3 \pm 1.9) \times 10^{-2}$</td>
<td>$\pm 0.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$\zeta_{00}$</td>
<td>$(0.1 \pm 1.0) \times 10^{-6}$</td>
<td>$\pm 0.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</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>$\beta$</td>
<td>$(2.5 \pm 2.3) \times 10^{-19}$ GeV</td>
<td>$\pm 0.2 \times 10^{-19}$ GeV</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$\gamma$</td>
<td>$(1.1 \pm 2.5) \times 10^{-21}$ GeV</td>
<td>$\pm 0.3 \times 10^{-21}$ GeV</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$Re(\omega)$</td>
<td>$(-1.6^{+3.0}_{-2.1} \pm 0.4) \times 10^{-4}$</td>
<td>$\pm 3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

**KLOE current resolution**: $\sigma(\Delta t) \sim \tau_S$, IT installation gives $\sigma(\Delta t) \sim 0.3 \tau_S$
\[ e^+e^- \rightarrow e^+e^- \gamma^*\gamma^* \rightarrow e^+e^- X \]

\[ N_{eeX} = L_{ee} \int \frac{dF}{dW_{\gamma\gamma}} \sigma_{\gamma\gamma \rightarrow X}(W_{\gamma\gamma})dW_{\gamma\gamma} \]

- \( L_{ee} \) — integrated luminosity
- \( W_{\gamma\gamma} \) — invariant mass of 2 \( \gamma \)'s

\[ L_{ee} = 1 \text{ fb}^{-1} \]

Taggers are essential to reduce background from \( \phi \)-decays and close kinematics.
IInd region (450–850 MeV) contains peak of scalar resonance $\sigma$, or $f_0(600)$

- Structure of $\sigma$ (q$q$ or q$q\bar{q}\bar{q}$) is under discussion
- Values of mass and width are known with large uncertainties

- Best way to search: $\pi^0\pi^0$
- $\pi^+\pi^-$ channel has a large $\mu^+\mu^-$ bckg.
- Analysis was started on the KLOE data
Single pseudoscalar mesons

Final states: \( X = P = \pi^0, \eta, \eta' \)

- Measurement of two-photons decay width \( \Gamma(P \rightarrow \gamma\gamma) \) which can be extracted from cross sections \( \sigma(e^+e^- \rightarrow e^+e^- P) \)

- Measurement of the form factors \( \gamma^*\gamma^* \rightarrow \pi^0, \eta \) at low \( Q^2 \)

\[
0.02 \text{ GeV}^2 < Q^2 < 0.4 \text{ GeV}^2
\]

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (GeV)</th>
<th>1.02</th>
<th>1.2</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(e^+e^- \rightarrow e^+e^- \pi^0) ) nb</td>
<td>271</td>
<td>371</td>
<td>364</td>
</tr>
<tr>
<td>( \sigma(e^+e^- \rightarrow e^+e^- \eta) ) nb</td>
<td>45</td>
<td>66</td>
<td>90</td>
</tr>
<tr>
<td>( \sigma(e^+e^- \rightarrow e^+e^- \eta') ) nb</td>
<td>4.9</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>
$\eta - \eta'$ mixing and $\eta'$ gluonium content

$\eta'$ meson is considered a good candidate to host a gluon condensate. This question has been extensively investigated but it’s still without a definite conclusion

$$|\eta'\rangle = \cos \phi_G \sin \varphi_p \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}\rangle + \cos \phi_G \cos \varphi_p |s\bar{s}\rangle + \sin \phi_G |\text{gluonium}\rangle$$

$$|\eta\rangle = \cos \varphi_p \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}\rangle - \sin \varphi_p |s\bar{s}\rangle$$

$\varphi_p$ : $\eta - \eta'$ mixing angle

$Z_G^2 = \sin^2 \phi_G$ gluonium content

KLOE measurement: $$R_\phi = \frac{BR(\phi \rightarrow \eta'\gamma)}{BR(\phi \rightarrow \eta\gamma)} = (4.77 \pm 0.09_{\text{STAT.}} \pm 0.19_{\text{Syst.}}) \times 10^{-3}$$

related to the mixing angle and gluonium content.

$$\varphi_p = (40.4 \pm 0.6)^0 \quad Z_G^2 = 0.12 \pm 0.04$$

at

$$\chi^2/\text{ndf} = 4.6/3 \quad \text{P}(\chi^2) = 20\%$$

F. Ambrosino et al., JHEP 0907, 105(2009)
$\eta - \eta'$ mixing: from KLOE to KLOE–2

**KLOE**: global fit with 6 free parameters to various relation between hadronic widths

**KLOE–2** expectation measuring of $\eta'$ branching ratio with 1% accuracy
Dark matter searches

Recent observations from independent experiments (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA) can be explained by a secluded gauge sector ($U$ – boson with mass near the GeV scale). $U$ – boson couples the secluded sector to SM through its kinetic mixing (mixing parameter $\varepsilon \leq 10^{-3}$)


Possible scenarios:

- $\phi \rightarrow \eta U$, $U \rightarrow e^+e^-$
- $e^+e^- \rightarrow Uh'$ (Higgs’ strahlung):
  - $(m_{h'} < m_U): U \rightarrow l^+l^-$, $h'$ – undetected; process can be defined only by two detected leptons + missing mass
  - $(m_{h'} > m_U): h' \rightarrow UU \rightarrow 4l$ (multi-lepton events)
Search of the $U$–boson in $\phi \rightarrow \eta U$

- KLOE search $\phi \rightarrow \eta U$, $U \rightarrow e^+e^-$
  - $\eta \rightarrow \pi^+\pi^-\pi^0$ (preliminary result available), $\eta \rightarrow \gamma\gamma$ (in progress)
- Main irreducible background from $\phi \rightarrow \eta e^+e^-$ (BR measured in CMD–2, SND)
- KLOE obtained result (systematics not included) on 739 pb$^{-1} \sim 20$ events and $\varepsilon < 3 \times 10^{-3}$ in the region $25 < M_{ee} < 425$ MeV
- KLOE–2 data taking can improve result to $10^{-3}$

Fit of $\phi \rightarrow \eta e^+e^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$

Exclusion plots

$\sim 20$ events

$\varepsilon \sim 3 \times 10^{-3}$
Search of the $U$–boson in $e^+e^- \rightarrow Uh'$

- KLOE–data ($L_{int.} = 1.65$ fb$^{-1}$ at $\phi$ – peak and $L_{int.} = 0.2$ fb$^{-1}$ $\sqrt{S} = 1$ GeV)
- Crucial background from $\phi \rightarrow K^+ K^- / \pi^+ \pi^- \pi^0$
- Possible decision to suppress background: using off–peak sample
- Next step: improvement of the vertex reconstruction (IT installation)
Conclusions

✓ New DAΦNE interaction scheme (crab-waist) is successfully implemented. It increased the old luminosity by factor 3 (instantaneous luminosity $\sim 4 \times 10^{32} \, cm^{-2} \, s^{-1}$)

✓ DAΦNE is in commissioning phase

✓ KLOE–2 collaboration proposed a wide physics program

✓ KLOE–2 is ready to start a long period of data-taking

✓ Installation of the taggers (HET and LET) gives a way to search $\gamma\gamma$ – physics processes

✓ New detector upgrades (calorimeters and inner tracker) are planned to install next year
Thank You
SPARES
Tagging strategy for $\gamma\gamma$ – physics

- Studied $\gamma^* \gamma^* \rightarrow \pi^0 \pi^0$ (BDSIM/GEANT4)
- Single acceptance (only 1 tagger) = 54%
- Single arm acceptance:
  
  $\text{HET} = 14\%, \text{LET} = 17\%$

$$\int L dt = 1 \text{ fb}^{-1}$$

$$t_i = (p_e^- - p_{e^-'})^2$$

$\pi^0 \rightarrow \gamma\gamma$

- HET $\times$ HET is enough for measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ (EKHARA Monte Carlo generator)
- HET $\times$ HET + LET $\times$ KLOE is trigger for the form factors of $\gamma\gamma \rightarrow \pi^0, \eta$