Hadron Physics with KLOE-2 data at the $\phi$-factory

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on behalf of the KLOE-2 Collaboration
Physics with KLOE-2

### Recent Published Results

<table>
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<tr>
<th>Publication</th>
<th>Title</th>
<th>Details</th>
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<tr>
<td>PLB 784 (2018) 336</td>
<td>Combined limit on the production of a light gauge boson decaying into $\mu \mu$ and $\pi \pi$</td>
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<tr>
<td>JHEP 1809 (2018)021</td>
<td>Measurement of the charge asymmetry in $K_s$ semileptonic decays and test of CPT</td>
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<tr>
<td>JHEP 1803 (2018) 173</td>
<td>Combination of KLOE hadronic cross section measurements and determination of $a_\mu$ in the energy range from 0.1-0.95 GeV$^2$</td>
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<tr>
<td>PLB 767 (2017) 485</td>
<td>Measurement of the running of the fine structure constant below 1 GeV</td>
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### Ongoing analyses

- Unique data sample of 5.5+2.5 fb$^{-1}$ recorded
- Entagled kaon pairs: $\sim 8(16) \times 10^9$
- Low-mass hadrons produced in $\phi$-decays and with processes in the continuum: $e^+e^-$ and $\gamma-\gamma$ scattering
- CP and CPT tests, $K_s$ rare decays, searches in the dark sector, analysis of $\pi^0$ production in $\gamma-\gamma$ scattering are being pursued

- $e^+ e^- \rightarrow \gamma^* \gamma^* \rightarrow \pi^0 e^+ e^-$
- $K_s \rightarrow \pi \mu \nu \quad [K_s \rightarrow \pi e \nu] \quad K_L$ interaction in emc
- $K_s \rightarrow \pi^0 \pi^0 \pi^0$
- $K_s \rightarrow \pi^+ \pi^- \quad K_L \rightarrow \pi^+ \pi^-$
- $K_s K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^\pm \pi^\mp \pi^\mp$ (T/CPT tests)
- $K_s \rightarrow \pi^+ \pi^- \pi^0$
- $\phi \rightarrow \eta \pi^0 \gamma$ (B-boson search)
- $\eta \rightarrow \pi^0 \gamma \gamma$
- $\eta \rightarrow \pi^+ \pi^-$
- $e^+ e^- \rightarrow \omega \gamma_{\text{ISR}}$
KLOE-2 Data

- 5.5 fb\(^{-1}\) recorded, Nov14 - Mar18
- Data quality studies and data reconstruction with first release of reconstruction completed
- Feedback from current reconstruction to finalize data selection and tracking
- In July-December final reconstruction campaign
- Data preservation planned
Data quality

- **Drift Chamber**
  - Low-Z gas mixture (90% He), all-stereo wires, C-fiber end-plates
  - 0.4% $p_T$ resolution

- **Calorimeter**
  - Lead-Scint.Fiber fine sampling calorimeter
  - C-shaped endcaps : 98% hermeticity
  - Excellent time resolution O(200) ps
Data quality (cont’d)

- Stable Calorimeter time/energy resolution achieved

![Graph showing energy resolution](image1.png)

- Stable DC resolution and efficiency

![Graph showing efficiency](image2.png)
CCALT – LYSO Crystal w/ SiPM - Low polar angle

QCALT – Tungsten / Scintillating Tiles w/ SiPM
Quadrupole Instrumentation

Inner Tracker – 4 layers of Cylindrical GEM detectors

HET: Scintillator hodoscope + PMTs
pitch: 5 mm; placed at 11 m from IP
Inner Tracker

First cylindrical (triple)-GEM detector ever

4 layers of cylindrical triple GEMs
\( \sigma_{r\phi} \sim 250 \, \mu m \) and \( \sigma_z \sim 400 \, \mu m \)
XV strips/pads readout (20° ÷ 30° stereo angle)
2% of radiation length in the active region

CAEN HV board (A1515)
designed specifically for GEM detectors
read-out currents with 0.1 nA resolution
Data reconstruction and computing power

- Reconstruction completed in February 2019
  - Average reconstruction rate \(\sim 20 \text{ pb}^{-1}/\text{day}\)
    (4 \(\text{ fb}^{-1}\) in 10 months)

- Data Quality performed
- Feedback to a new release
- Final reconstruction campaign start: July 2019

- Data preservation
  - Test & official code implementation ongoing

- Monte Carlo production rate \(\approx 15 \text{ pb}^{-1}/\text{day}\)
- All \(\phi\) decays produced along with Bhabha’s sample
- MC data for 2.3 \(\text{ fb}^{-1}\) available
- MC update in progress:
  - Data/MC crosscheck
  - Fine tuning of the detector performance

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Run II</th>
<th>Run III</th>
<th>Run IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Lum</td>
<td>0.7 fb-1</td>
<td>1.4 fb-1</td>
<td>1.6 fb-1</td>
<td>1.3 fb-1</td>
</tr>
<tr>
<td>Recon Lum</td>
<td>0.03 fb-1</td>
<td>1.2 fb-1</td>
<td>1.6 fb-1</td>
<td>1.3 fb-1</td>
</tr>
</tbody>
</table>
Kaons at a $\phi$-factory

- Kaon pairs are produced in an antisymmetric quantum state with $J^{PC} = 1^{- -}$

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

$$= \frac{N}{\sqrt{2}} \left[ | K_S(\bar{p})\rangle | K_L(\bar{p})\rangle - | K_L(\bar{p})\rangle | K_S(\bar{p})\rangle \right]$$

- The presence of one kaon tags the other one on the opposite side
- Unique possibility at a $\phi$-factory to select a pure $K_S$ beam (not possible at fixed target experiments)
- Interference pattern and entanglement allow to study fundamental symmetries and quantum mechanics

$p = 100$ MeV

$\lambda(K_S) = 6$ mm

$\lambda(K_L) = 3.5$ m
Ks branching fraction: $\rightarrow \pi^0\pi^0\pi^0$

- Rare CP-violating decay $\rightarrow$ Expected BR $2 \times 10^{-9}$
- Tagged at the $\phi$-factory by Klong (interactions in the calorimeter): $K_L$-crash: $E>150$ MeV, $0.2<\beta<0.225$
- $K$s $\rightarrow \pi^0\pi^0$ used as normalization
- Previous measurement from KLOE on 1.7 fb$^{-1}$ has reached a sensitivity of $\text{Br}(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% C.L. [PLB723(2013)54]
- Current analysis is based on 1.5 fb$^{-1}$ recorded in 2016
- On-time photons selected: $E_{\text{cl}}>20$ MeV; $|\cos \theta_{\text{cl}}| \leq 0.915$ and $|\Delta T_{\text{cl}}| \leq \text{Min}(3\cdot\sigma_T(E_{\text{cl}}),2 \text{ ns})$
- Major limitation from background from $K_s \rightarrow \pi^0\pi^0$ with additional clusters of different origin, overlapping in time
- Cut-based analysis: Track Veto, Kinematic fit on $K_S$, consistency between $K_L/K_S$ kinematics, Photon-pairing in both, 3 $\pi^0$ and 2 $\pi^0$ hypotheses, Distance btw clusters
- Zero candidates obtained from MC. Cut-based analysis efficiency obtained is 29% (was 36%)
- Recently a mva analysis on clusters has shown to kept the rejection while improving efficiency by a factor of 2
- New limit expected a factor of 2 better than previous UL
Ks branching fraction: semileptonic decays

- Charge asymmetry in semileptonic decays measures CP-violation in weak interactions
- CPT symmetry imposes same charge asymmetry in Ks and Kl systems

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

- \( A_{S,L} \neq 0 \Rightarrow \) CP violation
- \( A_S \neq A_L \Rightarrow \) CPT violation
- 1.7 fb\(^{-1}\) analyzed

\[ \delta A_S (\text{stat}) \rightarrow \sim 3 \times 10^{-3} \]
**K_S** semileptonic decays

- Precision measurement of $V_{us}$
- From $K_{Se3}$ the largest contribution to the uncertainty [old KLOE meas. $\text{Br}(K_{Se3}) = (7.046 \pm 0.091) \times 10^{-4}$]
- 49647 events in 1.6 fb$^{-1}$
- Systematics are being studied

<table>
<thead>
<tr>
<th>$V_{us}$</th>
<th>$f_+(0)$</th>
<th>% err</th>
<th>Approx. contrib. to % err from:</th>
<th>BR</th>
<th>$\tau$</th>
<th>$\Delta$</th>
<th>Int</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{Le3}$</td>
<td>0.2163(6)</td>
<td>0.26</td>
<td></td>
<td>0.09</td>
<td>0.20</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>$K_{Lu3}$</td>
<td>0.2166(6)</td>
<td>0.28</td>
<td></td>
<td>0.15</td>
<td>0.18</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>$K_{Se3}$</td>
<td>0.2155(13)</td>
<td>0.61</td>
<td></td>
<td>0.60</td>
<td>0.02</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>$K^{±}e3$</td>
<td>0.2172(8)</td>
<td>0.36</td>
<td></td>
<td>0.27</td>
<td>0.06</td>
<td>0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>$K^{±}\mu3$</td>
<td>0.2170(11)</td>
<td>0.51</td>
<td></td>
<td>0.45</td>
<td>0.06</td>
<td>0.23</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Ks branching fraction: -> πμν

- KLOE has obtained the first evidence ever of Ks-> π μ ν
- First measurement of Br(Ks →πμν)
- 7223 events in 1.6 fb⁻¹
- Expected Br(KSμ3) = (4.69 ± 0.05)×10⁻⁴
- Uncertainty of the preliminary measurement
  - 2.5 % stat ± 3.1 % sys
- Control of the systematics being finalized
- Lepton universality test and improvement of Vus precision
\( \eta \rightarrow \pi^+\pi^- \)

- P and CP violating, Br expected of order \( 10^{-27} \) in the SM
- Detection at any accessible level would be signal of CP viol. beyond the SM

Best limit \( Br < 1.3 \times 10^{-5} \) @ 90% C.L. (350 pb\(^{-1}\)) [KLOE, PLB606(2005)276]

LHCb recent measurement: \( Br < 1.6 \times 10^{-5} \) @ 90% C.L. [PLB764(2017)233]

After cut: \( 129 < M_{tr} < 149 \text{ MeV} \)

- \( L = 1.6 \text{ fb}^{-1} \Rightarrow \) Preliminary U.L.: \( Br < 5.8 \times 10^{-6} \) @ 90% C.L.
- With 8 fb\(^{-1}\) \( \Rightarrow \) U.L. expected \( \sim 3 \times 10^{-6} \)
\( \eta \rightarrow \pi^0 \gamma \gamma \)

- \( \eta \rightarrow \pi^0 \gamma \gamma \) (from \( \phi \rightarrow \eta \gamma \)): \( \chiPT \) golden mode, \( O(p^2) \) null, \( O(p^4) \) suppressed
  \( \Rightarrow \) sensitive to \( O(p^6) \)

\[ Br = (22.1 \pm 2.4 \pm 4.7) \times 10^{-5} \text{ CB@AGS(2008)} \]

\[ Br = (25.2 \pm 2.5) \times 10^{-5} \text{ CB@MAMI (2014)} \]

5 photon sample:
- Current analysis based on 0.5 fb \(^{-1}\)
- Main bckg is \( \phi \rightarrow \eta \gamma \), with \( \eta \rightarrow 3\pi^0 \) and lost or merged photons
- Multivariate Analysis with cluster shape to separate single photon from merged photon clusters
- Signal evidence in data distribution
- Efficiency studies ongoing
Searches in the dark sector

- Dark photon as mediator of a dark sector coupled to the EW sector via kinetic mixing
- Dark photon decays in electron- muon and pion pairs were searched
- Combination of $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\gamma$ final states [PLB784(2018)336]
- Analysis based on 1.93 fb$^{-1}$

\[ \varepsilon < (6 - 1.94) \times 10^{-7} \text{ above 650 MeV} \]
Dark photon coupled to hadrons

- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the $\omega(782) \Rightarrow I^G = 0^-$

$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu \quad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\text{MeV})$$

- Dominant decay channel ($m_B < 600$ MeV): $B \rightarrow \pi^0 \gamma$
B-boson search

- Current study based on ~0.8 fb\(^{-1}\)
- Analysis of the whole sample in progress, 1.7 fb\(^{-1}\) ready to be included
- \(\phi \rightarrow \eta B\), signal efficiency ~12.5%
- Main background from \(\phi \rightarrow a_0 \gamma \rightarrow \eta \pi^0 \gamma\) and \(\phi \rightarrow \eta \gamma \rightarrow 3\pi^0 \gamma\) with lost or merged photons
HET taggers for $\gamma$-$\gamma$ physics

- Main goal is the precision measurement of the $\pi^0$ width
  Bernstein, Rev.Mod.Phys. 85 (2013) 49

- The HET stations are installed at the end of the bending dipoles, 11 m from the IR
- 28+1 scintillators
- Operational since the very beginning of the KLOE-2 data taking
High Energy Tagger

- Bending dipoles of DAΦNE closer to IP act as spectrometer for scattered $e^+/e^-$ (420 < E < 495 MeV)
- Strong correlation between E and trajectory
- HET and KLOE-2 DAQ are asynchronous
- HET-DAQ based on Xilinx Virtex 5 - FPGA
- HET-DAQ on a Time Window of ~2.5 DAfNE turns (2.5x120x2.7 ns)
- Synchronization by RF signal from DAΦNE (and KLOE-Trigger)
Forward-Lepton HET taggers at the $\phi$-factory

- Time measurements in the HET stations from leptons with energy 425-490 MeV
- Mostly from Bhabha scattering
- Operational stability has been studied
- Rate per scintillator, per bunch and on different run periods studied
- Comparison with the luminosity measured by KLOE (large angle Bhabha’s) is used to measure the raw Bhabha’s cross section (\(\sigma \times \text{Acceptance} \times \varepsilon\))
- Rate stability proved for 18(11) channels/28 on the electron (positron) side on a time scale of months
- Validation of Bbbrem code (small-angle Bhabha generator) interfaced with a GEANT4 simulation of the lepton transport in Daφne is being finalized

![Graph](image-url)
Accidental-pure and Accidental+signal samples

- Effective cross sections of Radiative Bhabha’s detected by the HET are of $O(10)$ mbarn ~2 mbarn for the selected plastics
- The analysis cannot be based only on time-coincidences
- It is necessary to subtract pure-accidentals, whose rate and kind depend on data taking conditions

- Pure-accidentals are given by time-coincidences from independent interactions
- We continuously measured the time-dependent sample of pure-accidentals because the HET DAQ time window is ~2.5 larger than the KLOE one and the sub-sample in the out-of-time window can be used to get information on pure-accidentals
Analysis Criteria

- KLOE trigger conditions (50 vs >100 MeV trigger threshold) and background levels in the calorimeter suggest to search $\pi^0$’s with decay photons in the barrel
- Photon reconstruction and trigger efficiency have been measured by the analysis of radiative Bhabha’s in the barrel
- Selection in KLOE is based on a sample of 2-clusters associated to the same bunch crossing
- Selected in a time-window of ~30 ns centered on the KLOE trigger

Best time resolution to establish HET-tagged candidates is from the comparison of hit delays from the trigger as measured by KLOE and HET

Comparison of accidental-pure with accidental+signal samples
Tagged sample established with the analysis of 18/28 channels in the electron-side station, on 500 pb$^{-1}$

- The sample includes radiative Bhabha’s with photons in KLOE and $\pi^0’s$ from $\gamma$-$\gamma$ scattering (Ekhara-like events)

- Multivariate analysis helpful to separate Ekhara-like from radiative Bhabha’s

- Dependence of the results on HET-multiplicity (possibly related to the Virtex Firmware) is being investigated

- Simulation of Bhabha’s sample in different conditions in progress to obtain AcceptanceXefficiency and associated systematics
Conclusions

• KLOE-2 data-taking successfully completed on March 30, 2018
  \[\Rightarrow 5.5 \text{ fb}^{-1} \text{ recorded}\]

• KLOE + KLOE-2 sample \[\Rightarrow \sim 8 \text{ fb}^{-1}\]

• Unique sample of \(2.4 \times 10^{10}\) \(\phi\)’s decays

• Good Data quality – high-efficiency/high-resolution DC&EMC operation
  \[\Rightarrow \text{Data Preservation is being pursued}\]

• Recent results include the charge asymmetry measurement of Ks semileptonic decay, the experimental evidence for \(K_s \rightarrow \pi \mu \nu\), and upper limits on dark photon production at the \(\phi\)-factory

• T and CPT Tests on neutral kaons, studies on Ks and \(\eta\) mesons, precision measurement of the \(\pi^0\) width, searches in the Dark sector are in progress
Measurement of $\alpha_{em}(s)$

$$\frac{\alpha(s)}{\alpha(0)} = \frac{d\sigma_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))/d\sqrt{s}}{d\sigma_{MC}^0(e^+e^- \to \mu^+\mu^-\gamma(\gamma))/d\sqrt{s}}$$

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

$$\text{Re } \Delta\alpha = \sqrt{|\alpha(0)/\alpha(s)|^2 - (\text{Im } \Delta\alpha)^2}$$

$$\text{Im } \Delta\alpha = -\frac{\alpha}{3}R(s) \quad \text{from KLOE data on had. cross-section}$$

$$\text{Br}(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4 \pm 1.7) \times 10^{-5}$$

(PDG: $(9.0 \pm 3.1) \times 10^{-5}$)
T/CPT test with $\phi \to K_S K_L \to 3\pi^0 \nu e, \pi\pi\nu e$

Direct tests of the T and CPT symmetry by comparison of rates of the following processes:
- $\phi \to K_S K_L \to \pi^+\nu, 3\pi^0$
- $\phi \to K_S K_L \to \pi^+\pi^-, \pi\nu e$

Observables (Focusing on the asymptotic region $\Delta \tau \gg \tau_s$):

**T-violation sensitive:**

\[
R_T^2 = \frac{I(\pi^+ e^-, 3\pi^0)}{I(\pi^+ \pi^-, \pi^- e^+)}
\]
\[
R_T^4 = \frac{I(\pi^- e^+, 3\pi^0)}{I(\pi^- \pi^-, \pi^+ e^-)}
\]

**Double ratios:**

\[
\frac{R_T^2}{R_T^4} = \frac{I(3\pi^0, e^-) I(\pi^+ \pi^-, e^-)}{I(3\pi^0, e^+) I(\pi^+ \pi^-, e^+)}
\]
\[
\frac{R_T^{CPT}}{R_T^{CPT}} = \frac{I(3\pi^0, e^-) I(\pi^+ \pi^-, e^+)}{I(3\pi^0, e^+) I(\pi^+ \pi^-, e^-)}
\]

**CPT-violation sensitive:**

\[
R_{CPT}^{exp}(\Delta t) = \frac{I(\pi^+ e^-\bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^- e^-\bar{\nu}; \Delta t)}
\]
\[
R_{CPT}^{exp}(\Delta t) = \frac{I(\pi^- e^+\nu, 3\pi^0; \Delta t)}{I(\pi^- \pi^-, \pi^+ e^+\nu; \Delta t)}
\]

**CP-violation sensitive (auxilliary):**

\[
R_{CPT}^{CP}(\Delta t) = \frac{I(\pi^+ e^-\bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+\nu, 3\pi^0; \Delta t)}
\]
\[
R_{CPT}^{CP}(\Delta t) = \frac{I(\pi^- \pi^-, \pi^- e^+\nu; \Delta t)}{I(\pi^- \pi^-, \pi^+ e^-\bar{\nu}; \Delta t)}
\]

---

T/CPT test with $\phi \rightarrow K_S K_L \rightarrow 3\pi^0 \pi^\pm \nu_e, \pi^+ \pi^- \pi^0 \nu_e$ (cont’d)

Event subsample selection:

- Division of each process in 2 subsamples by lepton charge
- Estimation of the selection efficiency using control samples

$K_S K_L \rightarrow \pi^\pm \pi^\mp \nu_e$:
- Events selection efficiency $\sim 10.5\%$
- $S/B = 28$

$K_S K_L \rightarrow \pi^0 \pi^0 \nu_e$:
- Events selection efficiency $\sim 14\%$
- $S/B = 64$

- Calculation of single and double T and CPT asymmetry ratios
- Constant fit of the ratios to the region $\Delta t \gg t_S$
T/CPT test with $\phi \rightarrow K_S K_L \rightarrow 3\pi^0 \pi^+ \pi^- \nu_e, \pi^0 \pi^- \nu_e$ (cont’d)

\[
\text{T asymmetric } R_2^T / R_4^T
\]

\[
\frac{R_2^T}{R_4^T} = \frac{I(3\pi^0, e^-) I(\pi^+\pi^-, e^-)}{I(\pi^0, e^+) I(\pi^+\pi^-, e^+)}
\]

\[
\text{CPT asymmetric } R_2^{CPT} / R_4^{CPT}
\]

\[
\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{I(3\pi^0, e^-) I(\pi^+\pi^-, e^+)}{I(3\pi^0, e^+) I(\pi^+\pi^-, e^-)}
\]
Single Photon Trigger

- Implemented in Nov. 2016 ⇒ 2.7 fb\(^{-1}\) collected
- 350 MeV threshold (on the barrel calorimeter)
- Search for invisible decay of Dark Photon
- Signature: monochromatic photon ⇒ \(M_U < 570\) MeV
  \(\sigma \sim 1/s, \sim 100\) times higher than at B-factories
- Also search for long living ALPs