Hadron Physics at KLOE-2

C. Bloise

on behalf of the KLOE-2 Collaboration

INFN Frascati Laboratory, Italy
Outline

• Status Report on KLOE-2 at Daφne
• Precision measurements in hadron physics
• Form factor of $\phi \to \eta e^+e^-$ transitions
• Form factor of $\phi \to \pi^0 e^+e^-$ transitions
• Analysis of the $\phi \to \pi^+\pi^-\pi^0$ Dalitz plot
• $\gamma\gamma$ physics
• Conclusions
The KLOE experiment


2.5 fb⁻¹ integrated at 1.02 GeV; 250 pb⁻¹ at 1 GeV

Excellent-quality data set for precision measurements of

CKM unitarity
QM, and CPT invariance;
CP in kaons;
QCD models based on ChPT;
isospin-violating decays for the measurement of the light quark masses ratio;
hadronic cross section for the calculation of HVP
γγ physics

New data taking to integrate 5 fb⁻¹ during 2014-17
G. Amelino-Camelia et al., EPJ C68, 619 (2010)

KLOE-2 Run follows
the upgrade of Daφne interaction region with crab-waist
the KLOE upgrade with the installation of IT, calorimeters at low angle, taggers for γγ physics
consolidation works on Daφne
Detector upgrades

Installation of the upgrades and the IR in Dafne completed on 12 July 2013
Tagging system for $\gamma \gamma$ physics

Two stations have been installed:
- **HET station** (scintillator strips) @ 11 m from the IP
- **LET station** (LYSO crystals) @ 2 m from the IP, in one of the QCALT wedges

*HET station* is used as a spectrometer.

Energy acceptance for final-state particles expected in the range 410-490 MeV.

LET station should detect final-state particles of about 200 MeV.

With taggers, on-peak data could be used for $\gamma - \gamma$ study.
Daφne operation

The accelerator complex was consolidate in 2013-14 to substantially improve the uptime.

It is able to routinely deliver $12 \text{ pb}^{-1}$ per day.

Electron and positron beam currents in excess of $1.4 (e^-)$ and $1 (e^+) \text{ A}$ in 105 bunches stored.

Continuous alternate injections of electron and positron beams on a time basis of 10 min.

Average luminosity exceeds $1.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.
The KLOE-2 Run

From Nov 2014 KLOE-2 recorded 2.4 out of 3 fb\(^{-1}\) delivered by Da\(φ\)ne closely following data taking plans

Performance and operation stability still improving

The goal is to achieve 5 fb\(^{-1}\) by the end of 2017
Transition form factors

Mesons to photon coupling and the transition form factors, TFF, are fundamental measurements in hadron physics, relevant to

- ChPT and its low-$q^2$ extensions
- The analytic extrapolations of ChPT Lagrangian to resonances region
- The treatment of the transition regime from soft, non-perturbative QCD, to hard processes (pQCD)

They are measured from

i) **Meson decays**, with $P \to V \gamma \ (*)$ transitions, as $\eta \to \pi^0 \ e^+ \ e^-$

$\frac{d}{dq^2} \Gamma(\phi \to \eta e^+ e^-) = \frac{\alpha}{3\pi} \Gamma(\phi \to \eta \gamma) \left| F_{\mu\nu}(q^2) \right|^2 \sqrt{1 - \frac{4m^2}{q^2}} \left( 1 + \frac{2m^2}{q^2} \right) \left[ \left( 1 + \frac{q^2}{m^2 - m_{\eta}^2} \right)^2 - \frac{4m^2 q^2}{(m^2 - m_{\eta}^2)^2} \right]^{3/2}$

ii) **Radiative meson production in $e^+ e^-$ interactions**, as $\phi \to \pi^0 \ e^+ \ e^-$ or $\phi \to \eta \ e^+ \ e^-$

iii) **Meson production in $\gamma-\gamma$ interactions**
\[ \Phi \rightarrow \eta e^+ e^- \]


\[ \eta \rightarrow \pi^0 \pi^0 \pi^0 \] decays have been selected for the purity of the sample obtained

3x10^4 events selected

15.5% global efficiency

3% residual background
The TFF $\Phi \to \eta$

The results are in agreement with VMD predictions and with previous measurements from SND and CMD-2

The transition form factor slope is a factor of five more precise than previous measurement

$\text{BR}(\phi \to \eta e^+ e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$

$b_{\phi \to \eta} = (1.17 \pm 0.10^{+0.07}_{-0.11}) \text{ GeV}^{-2}$
$\Phi \rightarrow \pi^0 e^+ e^-$


It is the first analysis of the transition form factor

Background from radiative Bhabha and $\phi \rightarrow \pi^0 \gamma$ is relevant

Background subtraction has been obtained separately in different $q^2$ windows

Global efficiency from 15% at low $M_{ee}$ to 2% at 0.6 GeV

9500 events selected (background-subtracted)
The systematic error receive equal contribution from the control of the analysis cuts and from the procedure of background subtraction.

\[
\text{BR}(\phi \to \pi e^+ e^-) = (1.35 \pm 0.05 ^{+0.05}_{-0.07}) \times 10^{-5}
\]

\[
b_{\phi \to \pi} = (2.02 \pm 0.11) \text{ GeV}^{-2}
\]
The results on TFFs

Comparison with different models

One-pole approximation with KLOE data
One-pole approximation - VMD

S. P. Schneider, B. Kubis, F. Niecknig, Phys. Rev. D 86 (2012) 054013
One-pole approximation - VMD
The interest to improve on the precision of the measurement of the density of the Dalitz plot is related to the development of dispersive techniques to derive more powerful constraints on the light quark masses.

H. Leutwyler 0911.1416

The Dalitz plot density has been obtained with an high-purity sample (15% global efficiency) and corrected to take into account the residual background.
Results on $\eta \rightarrow \pi \pi^+\pi^-$

The decay amplitude has been parametrised by a polynomial expansion around the Dalitz plot centre. The results improve the precision on the parameters by a factor of 2. Systematics also improved using control data sample for the efficiency measurement.
Main goal at present is the precision measurement of the $\pi^0$ width [Bernstein, Rev.Mod.Phys. 85 (2013) 49] using meson production $\gamma\gamma$ from scattering $O(10^4) \pi^0$ expected with 5 fb$^{-1}$

HET stations installed after bending dipoles, 11 m from the IP
28+1 scintillators of different length
Operational since the very beginning of the KLOE-2 data taking
Energy acceptance from 425-490 MeV. MC validation needed
Time resolution

Time difference between electron and positron stations in agreement with uncorrelated events

Time resolution of 550 ps measured

Bunch structure in Daφne measured separately by both, HET and KLOE
HET rates are dominated by single-arm Bhabha’s. Particles from intra-bunch scattering give a 24% (4%) contribution to the e⁻ (e⁺) rates (average, Jan 2016).

It is the ideal device to provide fast, reliable feedbacks on the machine operation.

Timeline of the rates

Timeline of the T/(B+T) ratio
Tagger data analysis

HET stations are completely noiseless

The timeline of the counting rate for electron AND positron stations shows only 2 visible contributions: from luminosity and from Touschek particles. Machine background reaches a maximal relative contribution of 30% for electron and 6% for positron beams.

The total rate dominated by Bhabha scattering is at the level of 500-600 kHz.

The rate of uncorrelated time-coincidences between KLOE and HET requires full reconstruction of a large fraction of the KLOE triggers.

We have pre-filtered candidates of single-$\pi^0$ production from $\gamma\gamma$ scattering. A total of 450 pb$^{-1}$ are being analysed.
Conclusions

The large data sample of light mesons recorded at the $\phi$ factory and the sensitivity of the KLOE detector provide a unique opportunity for precision measurements in hadron physics.

Precision measurements of $V\to P\gamma^*$ transitions from $\Phi \to \eta e^+e^-$ and $\Phi \to \pi^0 e^+e^-$ have been obtained.

The Dalitz plot density of the isospin-violating $\eta \to \pi\pi\pi$ decays, sensitive to the light quark mass ratio, has been studied at KLOE and both statistical and systematic accuracy have been improved.

Da$\phi$ne is currently operating with a novel beam crossing scheme and good operational stability providing stable beams in continuous injection mode. More than 12 pb$^{-1}$ per day are routinely delivered.

The upgraded detector, KLOE-2, has already collected 2.4 fb-1 demonstrating the feasibility of the goal to record 5 fb$^{-1}$ by the end of 2017.

The KLOE-2 physics program is mainly focused on the study of low energy hadrons and on neutral kaon interferometry.

The analysis of meson production from $\gamma\gamma$ exploiting the KLOE-2 tagging system has been started. The goal is to improve to the percent level the precision of the $p0$ radiative width and obtain the first measurement of the TFF at low momentum transfer.
$\eta \rightarrow \pi^0 \pi^+ \pi^- :$ data-MC comparison
\[ \eta \rightarrow \pi^0 \pi^+ \pi^- : \text{theory} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(-a)</th>
<th>(b)</th>
<th>(d)</th>
<th>(f)</th>
<th>(-g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gormley(70) [16]</td>
<td>1.17 ± 0.02</td>
<td>0.21 ± 0.03</td>
<td>0.06 ± 0.04</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Layter(73) [17]</td>
<td>1.080 ± 0.014</td>
<td>0.03 ± 0.03</td>
<td>0.05 ± 0.03</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CBarrel(98) [18]</td>
<td>1.22 ± 0.07</td>
<td>0.22 ± 0.11</td>
<td>0.06(fixed)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>KLOE(08) [19]</td>
<td>1.090 ± 0.005 ± 0.019 ± 0.005</td>
<td>0.124 ± 0.006 ± 0.010</td>
<td>0.057 ± 0.006 ± 0.007</td>
<td>0.14 ± 0.01 ± 0.02</td>
<td>–</td>
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<tr>
<td>WASA(14) [20]</td>
<td>1.144 ± 0.018</td>
<td>0.219 ± 0.019 ± 0.047</td>
<td>0.086 ± 0.018 ± 0.015</td>
<td>0.115 ± 0.037</td>
<td>–</td>
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<tr>
<td>BESIII(15) [21]</td>
<td>1.128 ± 0.015 ± 0.008</td>
<td>0.153 ± 0.017 ± 0.004</td>
<td>0.085 ± 0.016 ± 0.009</td>
<td>0.173 ± 0.028 ± 0.021</td>
<td>–</td>
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<table>
<thead>
<tr>
<th>Calculations</th>
<th>(-a)</th>
<th>(b)</th>
<th>(d)</th>
<th>(f)</th>
<th>(-g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChPT LO [10]</td>
<td>1.039</td>
<td>0.27</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>ChPT NLO [10]</td>
<td>1.371</td>
<td>0.452</td>
<td>0.053</td>
<td>0.027</td>
<td>–</td>
</tr>
<tr>
<td>ChPT NNLO[10]</td>
<td>1.271 ± 0.075</td>
<td>0.394 ± 0.102</td>
<td>0.055 ± 0.057</td>
<td>0.025 ± 0.160</td>
<td>–</td>
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<tr>
<td>dispersive [22]</td>
<td>1.16</td>
<td>0.26</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>simplified disp [5]</td>
<td>1.21</td>
<td>0.33</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>NREFT [12]</td>
<td>1.213 ± 0.014</td>
<td>0.308 ± 0.023</td>
<td>0.050 ± 0.003</td>
<td>0.083 ± 0.019</td>
<td>0.039 ± 0.002</td>
</tr>
<tr>
<td>UChPT [11]</td>
<td>1.054 ± 0.025</td>
<td>0.185 ± 0.015</td>
<td>0.079 ± 0.026</td>
<td>0.064 ± 0.012</td>
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π⁰ radiative width
KLOE trigger thresholds

\[\chi^2/\text{ndf} = 27.96 \quad / \quad 12\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Error</th>
</tr>
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<tbody>
<tr>
<td>P1</td>
<td>0.9782 ±</td>
<td>0.1787E-01</td>
</tr>
<tr>
<td>P2</td>
<td>0.5999E-01 ±</td>
<td>0.9235E-03</td>
</tr>
<tr>
<td>P3</td>
<td>1.021 ±</td>
<td>0.1809E-01</td>
</tr>
<tr>
<td>P4</td>
<td>51.81 ±</td>
<td>0.1653</td>
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![Graph showing trigger efficiency against energy (MeV)]
$\pi^0$ candidates