Latest KLOE results on hadron physics

Dario Moricciani
INFN Roma “Tor Vergata”

On behalf KLOE Collaboration
Outline

Status Report on KLOE at DAΦNE precision measurements in hadron physics:

• Form factor of $\phi \rightarrow \eta \, e^+e^-$ transition
• Form factor of $\phi \rightarrow \pi^0e^+e^-$ transition
• Analysis of the $\phi \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot

Conclusions
KLOE@DAΦNE

- Frascati φ-factory: e⁺e⁻ collider
  @ √s = M_φ ≈ 1020 MeV

- KLOE: 2.5 fb⁻¹ @ √s=M_φ and
  + 250 pb⁻¹ off-peak @ √s=1 GeV

- Best performances in 2005:
  • L_{peak} = 1.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}
  • ∫ L dt = 8.5 pb⁻¹/day

Excellent-quality data set for precision measurements of:
CKM unitarity
QM, and CPT invariance;
CP in kaons;
QCD models based on χPT;
Isospin-violating decays for the measurement of the light quark masses ratio;
Hadronic cross section for the calculation of HVP
Transition Form Factor (TFF)

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

- $\chi^P$PT and its low-$q^2$ extensions
- the analytic extrapolations of $\chi^P$PT 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 $P \rightarrow V\gamma^*$ transitions, as $\eta \rightarrow \pi^0 e^+e^-$
- ii) radiative meson production in $e^+e^-$ interactions, as $e^+e^- \rightarrow \{\pi^0,\eta\}\gamma$

\[
\frac{d}{dq^2} \Gamma(\phi \rightarrow \eta e^+e^-) = \frac{\alpha}{3\pi} \Gamma(\phi \rightarrow \eta\gamma) \left| \frac{F_{\phi\eta}(q^2)}{q^2} \right|^2 \sqrt{1 - \frac{4m^2}{q^2}} \left(1 + \frac{2m^2}{q^2} \right) \left(1 + \frac{q^2}{m^2_{\phi} - m^2_{\eta}} \right)^2 - \frac{4m^2_{\phi}q^2}{(m^2_{\phi} - m^2_{\eta})^2}
\]
V→Pγ* and NA60 VMD puzzle

NA60 Collaboration / Physics Letters B 677 (2009) 260–266

NA60 found discrepancy between data and VMD prediction. Some models try to explain this puzzle (modifying VMD). These models need experimental verification also from different reactions. KLOE data could contribute measuring the reactions: φ→ηe+e− and φ→π0e+e−.

KLOE $\phi \rightarrow \eta e^+ e^-$ results

Previous Results ....

SND : 213 events

CMD : 1860 events

Using the total data sample of 15.1 pb$^{-1}$ collected by CMD-2 in the c.m. energy range 985–1060 MeV, the following results were obtained for various conversion decays of the $\phi$ and $\eta$ mesons:

$B(\phi \rightarrow \eta^0 e^+ e^-) = (1.14 \pm 0.10 \pm 0.06) \times 10^{-4}$,

$B(\eta \rightarrow \eta^0 e^+ e^-) = (7.10 \pm 0.64 \pm 0.46) \times 10^{-5}$,

$B(\eta \rightarrow \pi^+ \pi^- e^+ e^-) = (3.7 \pm 2.5 \pm 0.3) \times 10^{-4}$,

$B(\phi \rightarrow \eta^0 \mu^+ \mu^-) < 9.4 \times 10^{-6}$ at 90% CL,

$B(\eta \rightarrow e^+ e^+ e^-) < 6.9 \times 10^{-5}$ at 90% CL.

KLOE Events selection

~ 31000 events in 1.7 fb$^{-1}$

15.5 % Global efficiency

3 % Residual Background

\begin{itemize}
  \item The KLOE results are in agreement with VMD predictions and with previous measurements from SND and CMD-2
  \item The TFF slope is a factor of twenty more precise than previous measurement
\end{itemize}

BR($\phi \rightarrow \eta^0 e^+ e^-$) = (1.075 ± 0.007 ± 0.038) × 10$^{-4}$
KLOE $\phi \to \pi^0 e^+ e^-$ results

Previous Results ....

\[ \text{Br}(\phi \to \pi^0 e^+ e^-) = (1.01 \pm 0.28 \pm 0.29) \times 10^{-5}. \]

\[ N_{\text{exp}} = 89 \pm 12 \]

\[ \sigma_{\text{tot}} = 0.01 \]

\[ \sigma_{\text{el}} = 0.005 \]

\[ E_{\text{tot}}, \text{MeV} \]

\[ M_{\pi^0}, \text{MeV} \]

KLOE event selection

- It is the first analysis of the TFF
- Background from radiative Bhabha and $\phi \to \pi^0 \gamma$ 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
- BR is factor of five more precise wrt previous experiments

\[ \text{BR}(\phi \to \pi^0 e^+ e^-) = (1.35 \pm 0.05^{+0.10}_{-0.10}) \times 10^{-5}. \]

S. P. Schneider, B. Kubis, F. Niecknig, Phys. Rev. D 86 (2012) 054013

One-pole approximation - VMD

05/08/16
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.
\[ \eta \rightarrow \pi^+ \pi^- \pi^0 \]

The isospin violating \( \eta \rightarrow \pi^+ \pi^- \pi^0 \) decay can proceed via electromagnetic interactions or via strong interactions due to the difference between the masses of u and d quarks. The electromagnetic part of the decay amplitude is long known to be strongly suppressed. The recent calculations performed at next-to-leading order (NLO) of the chiral perturbation theory (\( \chi \)PT) reaffirm that the decay amplitude is dominated by the isospin violating part of the strong interaction.

\[
A(\eta \rightarrow \pi^+ \pi^- \pi^0) \overset{\text{LO}}{=} -\frac{\sqrt{3}}{4} \cdot \frac{m_d - m_u}{m_s - m_{ud}} \cdot \frac{s - \frac{4}{3}M_\pi^2}{F_\pi^2} \quad Q^2 \equiv \frac{m_d^2 - m_u^2}{m_s^2 - m_{ud}^2}
\]

\[
A(\eta \rightarrow \pi^+ \pi^- \pi^0) \overset{\text{NLO}}{=} -\frac{1}{Q^2} \cdot \frac{M_K^2(M_K^2 - M_\pi^2)}{3\sqrt{3}M_\pi^2F_\pi^2} \cdot M(s, t, u), \quad m_{ud} = \frac{m_u + m_d}{2}
\]

\[
|A(X, Y)|^2 \simeq N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots).
\]

\[
X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta}
\]

\[
Y = \frac{3T_{\pi^0}}{Q_\eta} - 1 \quad Q_\eta = T_{\pi^+} + T_{\pi^-} + T_{\pi^0} = m_\eta - 2m_{\pi^+} - m_{\pi^0}.
\]
**KLOE data : φ→ηγ, η→π⁺π⁻π⁰**

- The decay amplitude has been parametrized by a polynomial expansion around the Dalitz plot center
- The results improve the precision on the parameters by a factor of 2
- Systematics also improved using control data sample for the efficiency measurement

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**Figure 4.** (Color online) Missing mass squared, $P_{\eta^0}^2$, with the MC contributions scaled. The cut $||P_{\eta^0}| - m_{\eta^0}| < 15$ MeV is represented by the two vertical lines.

- The decay amplitude has been parametrized by a polynomial expansion around the Dalitz plot center
- The results improve the precision on the parameters by a factor of 2
- Systematics also improved using control data sample for the efficiency measurement
Previous data ...

\[ |A(X,Y)|^2 \simeq N(1+aY+bY^2+cX+dX^2+eXY+fY^3+gX^2Y+hXY^2+lX^3+\ldots). \]

<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)</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)</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>CBarell(98)</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)</td>
<td>1.090 ± 0.005(\pm 0.019)(\pm 0.008)</td>
<td>0.124 ± 0.006 ± 0.010</td>
<td>0.057 ± 0.006(\pm 0.007)(\pm 0.016)</td>
<td>0.14 ± 0.01 ± 0.02</td>
<td>–</td>
</tr>
<tr>
<td>WASA(14)</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>
</tr>
<tr>
<td>BESII(15)</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>
</tr>
<tr>
<td><strong>Calculations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ChPT LO</td>
<td>1.039</td>
<td>0.27</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>ChPT NLO</td>
<td>1.371</td>
<td>0.452</td>
<td>0.053</td>
<td>0.027</td>
<td>–</td>
</tr>
<tr>
<td>ChPT NNLO</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>
</tr>
<tr>
<td>dispersive</td>
<td>1.16</td>
<td>0.26</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>simplified disp</td>
<td>1.21</td>
<td>0.33</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>NREFT</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</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>
<td>–</td>
</tr>
</tbody>
</table>

*Table 1.* Summary of Dalitz plot parameters from experiments and theoretical predictions.
KLOE Results: JHEP 1605 (2016) 019

\[ |A(X,Y)|^2 \simeq N(1+aY+bY^2+cX+dX^2+eXY+fY^3+gX^2Y+hXY^2+lX^3+\ldots). \]

<table>
<thead>
<tr>
<th>Fit/set#</th>
<th>( a )</th>
<th>( b \cdot 10 )</th>
<th>( d \cdot 10^2 )</th>
<th>( f \cdot 10 )</th>
<th>( g \cdot 10^2 )</th>
<th>( \chi^2/\text{dof} )</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>-1.095 ± 0.003</td>
<td>1.454 ± 0.030</td>
<td>8.11 ± 0.32</td>
<td>1.41 ± 0.07</td>
<td>-4.4 ± 0.9</td>
<td>free</td>
<td>354/361</td>
</tr>
<tr>
<td>(2)</td>
<td>-1.104 ± 0.002</td>
<td>1.533 ± 0.028</td>
<td>6.75 ± 0.27</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1007/367</td>
</tr>
<tr>
<td>(3)</td>
<td>-1.104 ± 0.003</td>
<td>1.420 ± 0.029</td>
<td>7.26 ± 0.27</td>
<td>1.54 ± 0.06</td>
<td>0</td>
<td>0</td>
<td>385/366</td>
</tr>
<tr>
<td>(4)</td>
<td>-1.035 ± 0.002</td>
<td>1.598 ± 0.029</td>
<td>9.14 ± 0.33</td>
<td>0</td>
<td>-11.7 ± 0.9</td>
<td>free</td>
<td>792/362</td>
</tr>
<tr>
<td>(5)</td>
<td>-1.095 ± 0.003</td>
<td>1.454 ± 0.030</td>
<td>8.11 ± 0.33</td>
<td>1.41 ± 0.07</td>
<td>-4.4 ± 0.9</td>
<td>0</td>
<td>360/365</td>
</tr>
<tr>
<td>(6)</td>
<td>-1.092 ± 0.003</td>
<td>1.45 ± 0.03</td>
<td>8.1 ± 0.3</td>
<td>1.37 ± 0.06</td>
<td>-4.4 ± 0.9</td>
<td>0</td>
<td>369/365</td>
</tr>
<tr>
<td>(7)</td>
<td>-1.101 ± 0.003</td>
<td>1.41 ± 0.03</td>
<td>7.2 ± 0.3</td>
<td>1.50 ± 0.06</td>
<td>0</td>
<td>0</td>
<td>397/366</td>
</tr>
</tbody>
</table>

Table 2. Results for the Dalitz plot parameter fits. The main result corresponds to fit #5 which includes both cubic parameters \( g \) and \( f \), while fit #3, with \( g = 0 \), can be directly compared to previous results. The fits #6 and #7 use the acceptance corrected data (see appendix A).

The statistical uncertainty of all parameters is improved by a factor two with respect to earlier measurements.

\[ a = -1.095 \pm 0.003^{+0.003}_{-0.002} \]
\[ b = +0.145 \pm 0.003 \pm 0.005 \]
\[ d = +0.081 \pm 0.003^{+0.006}_{-0.005} \]
\[ f = +0.141 \pm 0.007^{+0.007}_{-0.008} \]
\[ g = -0.044 \pm 0.009^{+0.012}_{-0.013} \]
What Next?

- The accelerator complex was consolidate in 2013-14 to substantially improve the uptime: it is able to routinely deliver 12 pb\(^{-1}\) per day.
- Average luminosity exceeds \(1.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\).
- From Nov 2014 KLOE-2 recorded 2.4 out of 3 fb\(^{-1}\) delivered by Da\(\phi\)ne closely following data taking plans.
- The goal is to achieve 5 fb\(^{-1}\) by the end of 2017.
- KLOE install new detectors: IT, QCAL, CCALT and \(\gamma\gamma\) taggers: HET and LET.
I would like to invite everybody interested ...

KLOE-2 Workshop on e+e- collision physics at 1 GeV

26-28 October 2016  INFN - Laboratori Nazionali di Frascati
Europe/Rome timezone

https://agenda.infn.it/conferenceDisplay.py?confId=11722
Conclusion

• 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 $\eta \to \pi^+\pi^-\pi^0$ 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 $\pi^0$ radiative width and obtain the first measurement of the TFF at low momentum transfer.