“Precision measurements of the $\eta \to \pi^+\pi^-\pi^0$
Dalitz Plot and the TFF in $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$
with the KLOE detector”

Matteo Mascolo
(on behalf of the KLOE-2 coll.)

49th Rencontres de Moriond - La Thuile, March 22-29, 2014
Talk Outline

✔ DAΦNE and KLOE @LNF
✔ The Dalitz Plot analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$
✔ Recent results on $\phi \rightarrow \eta e^+e^-$ analyses
✔ Recent results on $\phi \rightarrow \pi^0 e^+e^-$ analysis
✔ Conclusions
The DAΦNE \(e^+e^-\) collider @LNF

Double Anular \(\Phi\) Factory for Nice Experiments

Main features:
- \(e^+e^-\) collider @ \(\sqrt{s} = 1.02\) GeV
- 97m separate rings for \(e^+e^-\)
- Up to 120+120 bunches
- Max collision freq. \(\rightarrow 356\) MHz
- \(T_{\text{bunch}} = 2.7\) ns

Best performance:
- \(L_{\text{peak}} = 1.4 \times 10^{32}\) cm\(^2\) s\(^{-1}\)
- \(L_{\text{int}} = 8\) pb\(^{-1}\) /day

Data Sample:
- \(L_{\text{int}} = 2.5\) fb\(^{-1}\) (until March 2006)
- \(L_{\text{int}} = 300\) pb\(^{-1}\) (collected off the \(\Phi\) peak)
- KLOE-2 upgrade completed (expected 5 fb\(^{-1}\) in next 3 years [Eur. Phys. J. C 68 (2010), 619])
The KLOE detector
The KLOE detector

Drift chamber
- Gas mixture (90% He + 10% C$_4$H$_{10}$)
- $\delta p_t/p_t < 0.4\%$ ($\theta > 45^\circ$)
- $\sigma_{xy} \sim 150 \mu m$ $\sigma_z \sim 2$ mm
The KLOE detector

EmC Calorimeter
- Lead/scintillating fibers
- 98% coverage of $4\pi$
- $\frac{\delta E}{E} = 5.7\% / \sqrt{E} \text{(GeV)}$
- $\delta t = 57 \text{ ps} / \sqrt{E} \text{(GeV)} + 100 \text{ ps}$
The KLOE detector

- Magnetic field \(~0.5\) T
The $\eta \to \pi^+\pi^-\pi^0$ Dalitz Plot analysis
New analysis of $\eta \to \pi^+\pi^-\pi^0$ (1/3)

- Experimental decay width of $\eta \to \pi^+\pi^-\pi^0$ ($\Gamma_{\text{exp}} = 296 \pm 16$ eV) not well described by LO ($\Gamma_{\text{LO}} \sim 70$ eV) and NLO ($\Gamma_{\text{NLO}} = 170 \pm 50$ eV) ChPT

- Sensitive to $Q$, which gives constraints to the light quark masses [Leutwyler, Mod. Ph. Lett. A28 (2013) 1360014]

- Exp. Dalitz Plot tests the dynamics of the decay

$$\Gamma(\eta \to \pi^+\pi^-\pi^0) \propto Q^{-4}$$

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \hat{m} = \frac{1}{2}(m_d + m_u)$$

- KLOE08: [Ambrosino et al. JHEP 5, 006 (2008)]
  $1.3 \times 10^6$ evts from $\phi \to \gamma \eta$ with $\eta \to \pi^+\pi^-\pi^0$
  (based on $L_{\text{int}} = 450$ pb$^{-1}$ data sample)

- Dispersive analysis based on KLOE measurement provided $Q = (21.3 \pm 0.6)$ [Colangelo et al. PoS(EPS-HEP2011) 304]
New analysis of $\eta \to \pi^+\pi^-\pi^0$ (2/3)

- The new analysis of KLOE data on a larger (factor ~ 4, being $L_{\text{int}} = 1.7 \text{ fb}^{-1}$), independent data set

  i) New selection scheme with improved systematics
     (in progress: dominant contribution from pre-selection efficiency directly measured from a minimum bias sample)
  ii) Improved MC simulation

- Analysis steps:

  $e^+e^- \to \phi \to \eta \gamma_{\text{mon}} \to \pi^+\pi^-\pi^0 \gamma_{\text{mon}} \to \pi^+\pi^-\gamma\gamma\gamma_{\text{mon}}$

- 2 tracks (from PCA assumed pions) and $\geq 3$ $\gamma$s
- Most energetic photon ($E > 250$ MeV) assumed from $\phi$ decay
- $\gamma$s from $\pi^0$ selected by opening-angle ($>165^\circ$ in $\pi^0$ r.f.)
- Bhabha scattering rejected by kinematics + TOF
- $| M_{\text{miss}}(\phi - \gamma_{\text{mon}} - \pi^+ - \pi^-) - m(\pi^0) | < 15$ MeV

- Signal efficiency $\sim 38\%$ with a residual background contamination of about $1\%$ (bkg contributions from fit to data with MC-simulated shapes)
New analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$ (3/3)

- The Dalitz Plot of $X$ and $Y$ is fit with a polynomial expansion around $(X=0, Y=0)$, folded with smearing matrix and analysis efficiency.

![Dalitz Plot Diagram]

\[
\begin{align*}
\ln\eta\text{-rest frame} \\
X &= \sqrt{3} \frac{T_+ - T_-}{Q_\eta} \\
Y &= \frac{3T_0}{Q_\eta} - 1 = \frac{\sqrt{3}}{2m_\eta Q_\eta}
\end{align*}
\]

\[
(Q_\eta = T_+ + T_- + T_0)
\]

\[
\chi^2 / \text{dof} = 1.15 \quad \text{P}(\chi^2) = 27\%
\]

\[
|A(X,Y)|^2 = N \left( 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 \right)
\]

- Coefficients $e = c$ and $e$ consistent with 0 (C-invariance condition) → both fixed to 0.

Results are in agreement with KLOE08. The systematics evaluation is in progress...

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$-a$</th>
<th>$b$</th>
<th>$d$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLOE 08[4]</td>
<td>1.090(5)$^{+8}_{-19}$</td>
<td>0.124(6)(10)</td>
<td>0.057(6)$^{+7}_{-16}$</td>
<td>0.14(1)(2)</td>
</tr>
<tr>
<td>New KLOE, prel.</td>
<td>1.104(3)</td>
<td>0.144(3)</td>
<td>0.073(3)</td>
<td>0.155(6)</td>
</tr>
</tbody>
</table>

Preliminary!!
The $\phi \rightarrow \eta \ e^{+}e^{-}$ and $\phi \rightarrow \pi^{0} \ e^{+}e^{-}$ analyses
 Physics motivation (1/2)

✔ Test the modelings of the TFF: the naïve VMD approach is satisfactory in the description of \( \eta \rightarrow \gamma \mu^+\mu^- \) but dramatically fails in \( \omega \rightarrow \pi^0 \mu^+\mu^- \) (enhancement of 10\(\sigma \) w.r.t. VMD!)

**Data**
- NA60 [In-In] [Phys. Lett. B 677 260-266 (2009)]
- NA60 [p-A] [Nucl. Phys. A 855 189-196 (2011)]

**Theory**
- Schneider, Kubis, Nieking [Phys. Rev. D86 054013 (2012)]

![Graphs showing \( \eta \rightarrow \gamma \mu^+\mu^- \) and \( \omega \rightarrow \pi^0 \mu^+\mu^- \) with data points and model curves.]
Physics motivation (2/2)

✓ $F_{\phi \eta \gamma^*}$ slope is needed, $b_{\phi \eta} = \Lambda^2 = \left. dF(q^2)/dq^2 \right|_{q^2 = 0}$

✓ NO DATA available for $F_{\phi \pi^0 \gamma^*}$ TFF (an enhancement due to $\rho$ resonance is expected)

✓ TFFs enters the $(g-2)_\mu$ calculation, experimental constraints to the hadronic $LbL$ contribution are needed (space-like region from $\gamma\gamma$-physics with KLOE-2 [EPJC C72 (2012) 1917])

✓ Improve the measurement of the BRs ($\phi \rightarrow \pi^0 e^+e^-$ is OZI suppressed)

<table>
<thead>
<tr>
<th>BR decay</th>
<th>SND</th>
<th>CMD-2</th>
<th>PDG av.</th>
<th>Tot err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \rightarrow \eta e^+e^- (10^{-4})$</td>
<td>$(1.19 \pm 0.19 \pm 0.07)$</td>
<td>$(1.14 \pm 0.10 \pm 0.06)$</td>
<td>$(1.15 \pm 0.10)$</td>
<td>$\sim 8.7 %$</td>
</tr>
<tr>
<td>$\phi \rightarrow \pi^0 e^+e^- (10^{-5})$</td>
<td>$(1.01 \pm 0.28 \pm 0.29)$</td>
<td>$(1.22 \pm 0.34 \pm 0.21)$</td>
<td>$(1.12 \pm 0.28)$</td>
<td>$\sim 25 %$</td>
</tr>
</tbody>
</table>


$b_{exp} = (3.8 \pm 1.8) \text{ GeV}^{-2}$

$b_{VMD} \approx 1.0 \text{ GeV}^{-2}$

SND @ VEPP-2M [Phys. Lett. B 504 275-281 (2001)]
The $\phi \rightarrow \eta e^+e^-$ analysis
The analysis of $\phi \rightarrow \eta \; e^+e^-$ ($\eta \rightarrow \pi^0\pi^0\pi^0$)

- The analysis is performed on 1.7 fb$^{-1}$ collected at $\sqrt{s} = M_\phi \approx 1.02$ GeV

- Pre-selection:
  - 2 tracks of opposite charge from IP
  - 6 photon-clusters candidates from IP

- Selection:
  - $(400 < M_{6\gamma} < 700)$ MeV
  - $(536.5 < M_{\text{miss-ee}} < 554.5)$ MeV
  - Cut to reject $\gamma$ conversion on BP and DC walls
  - TOF cut for $e^+e^-$ selection

- $\sim 3 \times 10^4$ events selected, $\sim 15\%$ global efficiency
  - $< 3\%$ residual background contamination
TFF $\phi \rightarrow \eta e^+e^- (\eta \rightarrow \pi^0\pi^0\pi^0)$

- Good MC-Data agreement after bkg subtraction
- $F_{\phi \eta \gamma^*}$ is extracted by a fit of the invariant-mass spectrum of the $e^+e^-$ pair to the Landsberg formula
  
  $d\Gamma(\phi \rightarrow \eta e^+e^-) \quad \frac{d\Gamma(\phi \rightarrow \eta \gamma)}{d\Gamma(\phi \rightarrow \eta \gamma)} = \frac{\alpha}{3\pi} \frac{|F_{\eta\gamma}(q^2)|^2}{q^2} \sqrt{1-\frac{4m^2}{q^2} \left(1+\frac{2m^2}{q^2}\right)\left[1+\frac{q^2}{m^2_{\phi}-m^2_{\eta}}-\frac{4m^2_{\phi}q^2}{(m^2_{\phi}-m^2_{\eta})^2}\right]^{3/2}}$

folded with analysis efficiency and smearing effects

<table>
<thead>
<tr>
<th>Previous exp.</th>
<th>KLOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{\phi\eta} = \Lambda_{\phi\eta}$ [GeV$^{-2}$]</td>
<td>(3.8 ± 1.8)</td>
</tr>
<tr>
<td>CMD-2</td>
<td>---</td>
</tr>
<tr>
<td>BR ($\phi \rightarrow \eta e^+e^-$) ($10^{-4}$)</td>
<td>SND (1.19 ± 0.22)</td>
</tr>
<tr>
<td>CMD-2</td>
<td>(1.14 ± 0.12)</td>
</tr>
</tbody>
</table>
The analysis of $\phi \rightarrow \eta \, e^+e^-$ ($\eta \rightarrow \pi^+\pi^-\pi^0$)

- The analysis is performed on 1.5 fb\(^{-1}\) collected at $\sqrt{s} = M_\phi \approx 1.02$ GeV

- Pre-selection:
  - 4 tracks from IP
  - 2 photon-clusters candidates from IP

- Selection:
  - $495 < M_{\gamma\gamma\pi\pi} < 600$ MeV / $70 < M_{\gamma\gamma} < 200$ MeV
  - $70 < M_{\text{miss-ee}} < 200$ MeV
  - Cut to reject $\gamma$ conversion on BP and DC walls
  - TOF cut for $e^+e^-$ selection

- $\sim 1.3 \times 10^4$ evts $\rightarrow$ fit checks and systematics evaluation in progress

The $\phi \rightarrow \pi^0 e^+e^-$ analysis
Status of $\phi \rightarrow \pi^0 e^+ e^-$

✓ NO DATA available for $F_{\phi \pi^0 \gamma^*}$ TFF → needed to test the theoretical models ($\omega$ decay)

![Graph showing $|F_{\omega \pi^0 \gamma^*}|^2$ versus $m_{\pi^0 \mu^+ \mu^-}$]

**Theoretical uncertainty in the $\phi \pi^0 \gamma^*$ form factor**

![Graphs illustrating the theoretical uncertainty in $\phi \pi^0 \gamma^*$ form factor]

S. Ivashyn ("KIPT", Kharkiv)  V.P. GAMMA FORM FACTORS  17.06.2013  13 / 30
The analysis of $\phi \rightarrow \pi^0 e^+e^-$

- The signal is searched in $2 \, e^+e^- + 2 \, \gamma$ events (ECL algorithm tag)

- Main bkgs: $e^+e^- \rightarrow e^+e^- \gamma\gamma$ and $\phi \rightarrow \pi^0\gamma$
  (with $\gamma$ conversion and $\pi^0$ Dalitz decay)
  Several orders of magnitude larger!

- Selection (main):
  - $E_e < 460$ MeV
  - $470 < E_{e^+} + E_{e^-} < 750$ MeV
  - $300 < E_{\gamma_1} + E_{\gamma_2} < 670$ MeV
  - $\theta_{\text{open}} (ee) < 145^\circ$ and $27^\circ < \theta_{\text{open}} (\gamma\gamma) < 57^\circ$
  - $90 < M_{2\gamma} < 190$ MeV and $80 < M_{\text{miss}}^{ee} < 180$ MeV
  - Cut to reject $\gamma$ conv. on BP and DC walls
The analysis of $\phi \rightarrow \pi^0 e^+e^-$

- The signal is searched in 2 $e^+e^-$ + 2 $\gamma$ events (ECL algorithm tag)

- Main bkgs: $e^+e^- \rightarrow e^+e^-\gamma\gamma$ and $\phi \rightarrow \pi^0\gamma$ (with $\gamma$ conversion and $\pi^0$ Dalitz decay) Several orders of magnitude larger!

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  - Cut to reject $\gamma$ conv. on BP and DC walls
$\phi \rightarrow \pi^0 e^+e^-$: Data-MC agreement
\( \phi \to \pi^0 e^+e^- : \) preliminary VMD comparison

- Bkg is subtracted by means of a bin-by-bin fit of \( m(\text{miss-ee}) \) → systematics are limited by the statistics of the Bhabha MC sample

- \( \sim 9000 \) events after background subtraction!!

**DATA**

MC FF = 1

**Very Preliminary!!**
Conclusions

✔ New Dalitz Plot analysis of the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay, on a larger independent data set ($L_{\text{int}} = 1.7$ fb$^{-1}$) was performed. Evaluation of the improvement on the light-quarks mass ratio using dispersive relations ([Leutwyler, Mod. Ph. Lett. A28 (2013) 1360014]) in progress.

✔ $\phi \rightarrow \eta e^+e^-$ decay under study (test of VMD):

$$TFF \text{ slope } b_{\phi\eta} = (1.17 \pm 0.11^{+0.09}_{-0.08}) \ [\text{GeV}^{-2}] \quad \text{(in agreement with VMD)}$$

$$B.R.(\phi \rightarrow \eta e^+e^-) = (1.131 \pm 0.032^{+0.011}_{-0.06}) \times 10^{-4} \quad \text{(in agreement with VMD)}$$

- Combining results of neutral ($\eta \rightarrow \pi^0\pi^0\pi^0$) and charged channel ($\eta \rightarrow \pi^+\pi^-\pi^0$)

✔ The $\phi \rightarrow \pi^0 e^+e^-$ analysis is ongoing: events selected for the first measurement of the transition form factor $F_{\phi\pi^0}$
Thank you for your attention
SPARES
U boson searches in $\phi \rightarrow \eta \ e^+e^-$

- Associated decay of $\phi$ into a PS and a U suggested by M. Reece and L.T. Wang [JHEP 0907:051 (2009)]
  
  $\text{BR}(X \rightarrow YU) \sim \varepsilon^2 \times |\text{FF}_{XY\gamma}|^2 \times \text{BR}(X \rightarrow Y\gamma)$

- Investigated decay chains:
  
  - **OLD:** $\phi \rightarrow U\eta$ ($\eta \rightarrow \pi^+\pi^-\pi^0$ $U \rightarrow e^+e^-$)  

  - **NEW:** $\phi \rightarrow U\eta$ ($\eta \rightarrow \pi^+\pi^-\pi^0/\pi^0\pi^0\pi^0$ $U \rightarrow e^+e^-$)  

- Upper limit for $\alpha'/\alpha$ (90% C.L.)

  $\alpha'/\alpha < 1.7 \times 10^{-5}$ for $30 < M_U < 400$ MeV

  ($\alpha'/\alpha < 8.0 \times 10^{-6}$ for $50 < M_U < 210$ MeV)
DAΦNE

- Frascati $\phi$-factory: $e^+e^-$ collider
  @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$ ; $\sigma_{\text{peak}} \approx 3.1$ μb

- Best performance in 2005:
  $L_{\text{peak}} = 1.4 \times 10^{32}$ cm$^{-1}$s$^{-1}$ \(\int Ldt = 8.5\) pb$^{-1}$/day

- KLOE: $2.5$ fb$^{-1}$ @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9$ $\phi$ produced)
  + 250 pb$^{-1}$ off-peak @ $\sqrt{s}=1000$ MeV

- DAΦNE upgrade (2008): new interaction scheme;
  large beam crossing angle + crabbed waist sextupoles
- 2010: DAΦNE commissioning for KLOE-2 start
  several hardware failures $\Rightarrow$ long shutdown
- End 2011: commissioning resumed
- Nov-Dec. 2012: 100 pb$^{-1}$ collected with carbon target for
  the study of deeply bound kaonic states (AMADEUS)
- Dec.2012-July 2013: shutdown for installation
  of new detectors

- DAΦNE operations restarted in July 2013
- KLOE-2 goal: collect $\sim 5$ fb$^{-1}$ in the next 2-3 years
Transition Form Factors

- \( a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (31.25 \pm 8.54) \times 10^{-10} \Rightarrow 3.7 \sigma \text{ discrepancy} \)

- \( a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}} \)

- Main contribution to the uncertainty on \( a_\mu^{\text{SM}} \)

- An important part of \( a_\mu^{\text{had}} \) is the Light-by-Light scattering

- \( (a_\mu^{\text{Lbl}} = (11.6 \pm 3.9) \times 10^{-10}) \) [Jegerlehner-Nyffeler P.Rep.477(2009)]

The leading contribution comes from the exchange of single pseudoscalar mesons

- TFFs for off-shell mesons \( \Rightarrow \) model dependent

- \( \Rightarrow \) measurements of TFFs of on-shell mesons can help to constrain models to get a precise evaluation of the Lbl contribution
Transition Form Factors

Information on the structure of mesons comes from their coupling to photons, described by the TFFs

$$F_{P\gamma\gamma}(q_1^2, q_2^2)$$

$$\gamma^* \rightarrow P\gamma$$
$$P \rightarrow \gamma\gamma^* \rightarrow \gamma\ell^+\ell^-$$
$$\gamma^*\gamma^* \rightarrow P$$

\[ \Rightarrow \text{space-like } q^2 \]

\[ \Rightarrow \text{time-like } q^2 \]
\[ \eta \rightarrow \pi^+ \pi^- \pi^0 \]

- Dispersive analyses of \( \eta \rightarrow 3\pi \): subtraction constants fixed from a fit to KLOE measurements of \( \eta \rightarrow \pi^+ \pi^- \pi^0 \)

\[ \Rightarrow Q = 21.3 \pm 0.6 \]

and by using \( \hat{m} \) and \( m_S \) from lattice QCD

\[ \Rightarrow R = \frac{m_S - \hat{m}}{m_d - m_u} = 37.7 \pm 3.3 \]

[Colangelo et al. PoS(EPS-HEP2011)304]

\[ m_u = (2.02 \pm 0.14) \text{MeV} \]

\[ m_d = (4.91 \pm 0.11) \text{MeV} \]

[Zdrahal NPB(Proc.Suppl)219(2011)]

\[ m_u = (2.23 \pm 0.14) \text{MeV} \]

\[ m_d = (4.63 \pm 0.14) \text{MeV} \]

Kampf et al., PRD84(2011)114015

P.Gauzzi

Excited QCD 2014
$\eta \rightarrow \pi^+ \pi^- \pi^0$: fit result

Dalitz plot slices in $Y$

| Dalitz plot slices in $X$ |

| $a$ | $-1.090 \pm 0.005^{+0.008}_{-0.019}$ | $-1.103 \pm 0.003$ |
| $b$ | $0.124 \pm 0.006 \pm 0.010$ | $0.1419 \pm 0.0029$ |
| $d$ | $0.057 \pm 0.006^{+0.007}_{-0.016}$ | $0.0725 \pm 0.0027$ |
| $f$ | $0.14 \pm 0.01 \pm 0.02$ | $0.154 \pm 0.006$ |

$P(\chi^2) = 27\%$

- Agreement with previous result
- $c$ and $e$ consistent with zero (C-violating parameters)
- Evaluation of systematics in progress
Transition FFs from Dalitz decays

- VMD well describes $\eta \rightarrow \gamma \ell^+\ell^-$, but fails for $\omega \rightarrow \pi^0 \ell^+\ell^-$

\[ F'(q^2) = \frac{1}{1 - q^2/\Lambda^2} \]


- $\phi \rightarrow \eta e^+e^- : \Lambda^2 = (3.8 \pm 1.8) \text{ GeV}^{-2}$ ($\sim$ 50% error) SND @ VEPP-2M VMD $\Rightarrow \Lambda^2 \approx M_{\phi}^{-2} \approx 1 \text{ GeV}^{-2}$

- $\phi \rightarrow \pi^0 e^+e^- : \text{no data available on FF} ; \text{VMD} \Rightarrow \Lambda^2 \approx 1.6 \text{ GeV}^{-2}$
Transition FF

- FF extracted from a fit of the $e^+e^-$ invariant mass to:

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

\[
F(q^2) = \frac{1}{1 - q^2/\Lambda^2}
\]

\[
\Rightarrow \frac{dF}{dq^2} \bigg|_{q^2=0} = \Lambda^{-2}
\]

\[
\Lambda^{-2} = (1.17 \pm 0.11 \pm 0.09) GeV^{-2}
\]

(SND: (3.8 \pm 1.8) GeV^{-2})

In agreement with VMD ($\Lambda^{-2} \approx M_{\phi}^{-2} \approx 1 GeV^{-2}$)

P.Gauzzi

Excited QCD 2014 - Feb
\[ e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X \]

\[ [C(X) = +1] \]

\[ \frac{dN}{dW_{\gamma\gamma}} = L_{int} \frac{dF}{dW_{\gamma\gamma}} \sigma(\gamma\gamma \rightarrow X) \]

- \( X = \pi^0, \eta \Rightarrow \sigma_{\gamma\gamma \rightarrow X}(q_1, q_2) = \frac{8\pi^2}{M_X} \Gamma_{X \rightarrow \gamma\gamma} \delta[((q_1 + q_2)^2 - M_X^2) |F(q_1^2, q_2^2)|^2 \]

  - Two-photon width \( \Gamma(X \rightarrow \gamma\gamma) \)
  - Transition form factors \( F_{X\gamma^*\gamma^*}(q_1^2, q_2^2) \) at space-like \( q^2 \)

- \( X = \pi^0\pi^0 \Rightarrow \) study of \( f_0(500) \)

- KLÖE data: no \( e^* \) tagging \( \Rightarrow \) analysis of off-peak data (\( \sqrt{s} = 1 \text{ GeV} \))
Detector upgrade

- LET + HET: taggers for scattered $e^\pm$ in $\gamma\gamma$ processes
- Inner Tracker: to improve acceptance for low momentum tracks and to achieve a better vertex reconstruction
- QCALT: W + scint. tiles + SiPM quadrupole coverage for $K_L$ decays
- CCALT: LYSO + APD to increase acceptance for $\gamma$’s from the IP (21° to 10°)
Low Energy Tagger

- To detect $e^\pm$ of $E \approx 150 - 350$ MeV escaping from the beam-pipe
- Weak correlation between $E$ and scattering angle

$\Rightarrow$ calorimeters: $20 \times 2$ LYSO crystals read-out by SiPM, placed at $\sim 1.5$ m from the IP
$\sigma_E/E < 10\%$ for $E > 150$ MeV
Low Energy Tagger

- To detect $e^+$ of $E \approx 150 - 350$ MeV escaping from the beam-pipe

- Weak correlation between $E$ and scattering angle

$\Rightarrow$ calorimeters: $20 \times 2$ LYSO crystals read-out by SiPM, placed at $\sim 1.5$ m from the IP

$\sigma_{E/E} < 10\%$ for $E > 150$ MeV
Inner Tracker

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

Cylindrical Triple GEM
\[ \gamma^*\gamma^* \rightarrow \pi^0 \text{ @KLOE-2} \]

- \( \Gamma(\pi^0 \rightarrow \gamma\gamma) = (8.09 \pm 0.11) \text{ eV (theory)} \Rightarrow 1.4\% \text{ uncert.} \)

- PrimEx Coll. @JLAB \( \Rightarrow \Gamma(\pi^0 \rightarrow \gamma\gamma) = (7.82 \pm 0.14 \pm 0.17) \text{ eV} \Rightarrow 2.8\% \text{ uncert.} \)

- KLOE-2: \( \sqrt{s} = M_\phi \)
  - 2\(\gamma\) in the EMC + \(e^+\) and \(e^-\) in the HETs
  - \(|q^2| < 10^{-3} \text{ GeV}^2 \Rightarrow \text{quasi-real photons}\)

- \( \sigma_{\text{tot}}(e^+e^- \rightarrow e^+e^-\pi^0) \approx 0.28 \text{ nb} \)
- 1.2\% acceptance
  \( \Rightarrow 2000 \text{ evts/fb}^{-1} \text{ expected} \)

with \(L = 5 \text{ fb}^{-1} \Rightarrow \delta\Gamma(\pi^0 \rightarrow \gamma\gamma) \approx 1\% \text{ achievable} \)

[EPJC72(2012)1917]
$\gamma^* \gamma^* \rightarrow \pi^0$ @ KLOE-2

- $\pi^0 \gamma^* \gamma$ Transition FF $\mathcal{F}_{\pi^0 \gamma \gamma^*}(q^2, 0)$

lepton in the HET $\Rightarrow |q^2| \approx 0$ quasi-real photon

lepton in the DCH/EMC $\Rightarrow |q^2| < 0.1 \text{ GeV}^2$

- unexplored $q^2$ region
- check TFF parametrizations
- reduce the model dependence of the LbL scattering contribution to $(g-2)_\mu$
- with $L = 5 \text{ fb}^{-1} \Rightarrow 6\%$ error on each point
Search for dark forces @ KLOE

Several unexpected astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA, CoGent...) could be explained with the existence of a hidden gauge sector weakly coupled with SM through a mixing mechanism of a new gauge boson (U, A’, V...) with the photon:

\[ \varepsilon^2 = \frac{\alpha'}{\alpha_{em}} \]

- U mass range: 1 MeV – few GeV
- Coupling constant of electric charge to U: \( \varepsilon \leq 10^{-3} \)
- U production/decay through photon mixing

Observable @ KLOE:
- \( \phi \) Dalitz decays
- \( e^+e^- \rightarrow U\gamma \rightarrow \ell^+\ell^-\gamma \)
- \( e^+e^- \rightarrow Uh' \rightarrow \ell^+\ell^-+ \) missing energy

[Arkani-Hamed et al. PRD79 015014 (2009)]
[Essig et al., PRD80 015003 (2009)]
\( \phi \rightarrow \eta e^+ e^- : \) search for dark forces \( @ \) KLOE

Meson having radiative decay to one photon can decay to a U boson with 
\[
\text{BR}(X \rightarrow YU) \sim \varepsilon^2 \times |F_{XY\gamma}|^2 \times \text{BR}(X \rightarrow Y\gamma) \quad [M.\text{Reece and L.T.}\text{Wang, JHEP 0907:051 (2009)}]
\]

Selected decay chain: \( \phi \rightarrow \eta U, \; U \rightarrow e^+ e^- + \eta \rightarrow \pi \pi \pi \)

Irreducible background:
\( \phi \) Dalitz decay \( \phi \rightarrow \eta \gamma^* \rightarrow \eta l^+ l^- \)

Same analysis of TFF. Bckg shape fitting sidebands of the \( M_{ee} \) distribution

\[ \begin{array}{c}
\text{Events / 5MeV} \\
\hline
0 & 10^4 \\
100 & 10^3 \\
200 & 10^2 \\
300 & 10^1 \\
400 & 10^0 \\
500 & 10^{-1} \\
\end{array} \]

\[ \begin{array}{c}
M_{ee} (\text{MeV}) \\
\hline
0 & 50 & 100 & 150 & 200 & 250 & 300 & 350 & 400 & 450 & 500 \\
\end{array} \]

\[ \begin{array}{c}
BR(\phi \rightarrow \eta U \rightarrow e^+ e^-) \\
\hline
0 & 10^{-8} \\
50 & 10^{-7} \\
100 & 10^{-6} \\
150 & 10^{-5} \\
200 & 10^{-4} \\
250 & 10^{-3} \\
300 & 10^{-2} \\
350 & 10^{-1} \\
400 & 10^0 \\
450 & 10^1 \\
\end{array} \]

\[ \begin{array}{c}
M_U (\text{MeV}) \\
\hline
0 & 50 & 100 & 150 & 200 & 250 & 300 & 350 & 400 & 450 \\
\end{array} \]

Limit from \( \phi \rightarrow \eta e^+ e^- \) 
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Limit from \( e^+ e^- \rightarrow \mu^+ \mu^\gamma \)