Perspectives on $\eta-\eta'$ physics

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Expected data sample

Working hypothesis: 20 fb$^{-1}$ of integrated luminosity (a factor 10 more w.r.t. the expected KLOE final data sample)

\[ \sigma_{\phi} = 3.3 \ \mu b \]
\[ \text{BR}(\phi \rightarrow \eta \gamma) = (1.295 \pm 0.025)\% \]
\[ N_{\eta}(20 \ \text{fb}^{-1}) \approx 8.6 \times 10^8 \]

\[ \sigma_{\phi} = 3.3 \ \mu b \]
\[ \text{BR}(\phi \rightarrow \eta' \gamma) = (6.2 \pm 0.7) \times 10^{-5} \]
\[ N_{\eta'}(20 \ \text{fb}^{-1}) \approx 4 \times 10^6 \]
η identification

η produced through $\phi \rightarrow \eta \gamma$  

Identified by the monochromatic recoil photon 
$E_{\text{recoil}(\eta)} = 363 \text{ MeV}$

Very clean and tagged η sample

$\phi \rightarrow \eta \gamma \rightarrow \pi^0 \pi^0 \pi^0 \gamma$

$\gamma$ from $\pi^0$
$\gamma$ rad

$\phi \rightarrow \eta \gamma \rightarrow \pi^+ \pi^- \pi^0 \gamma$

$\gamma$ from $\pi^0$
Rad.$\gamma$

$E_\gamma (\text{MeV})$
Main $\eta$ decay channels

<table>
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- PDG fit needs to scale BRs of main $\eta$ decay modes from 1.2 to 1.3
- Main BRs known with $O(\%)$ precision. Further improvement requires a complete measurement of all main decay channels
- All these decays already studied @ KLOE
  By tagging the recoil photon, it is possible to overcome the normalization problem
Main $\eta$ decay channels

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- Main BRs known with $O(\%)$ precision. Further improvement requires a complete measurement of all main decay channels.
- All these decays already studied @ KLOE.
- By tagging the recoil photon, it is possible to overcome the normalization problem.

Probably not too much to say on main decay channels after the analysis of the final KLOE data sample (2.5 fb$^{-1}$).
At the moment just poor experimental data from the 70’s

1. **Dalit plot: left–right asymmetry parameter**

2. Shape of the $E_γ$ spectrum to test ChPT predictions

- **Resonant contribution:**
  1. $\rho$ production with its subsequent decay to a pion pair (VDM)
  2. existence of a small non-VDM contribution

- **Anomalous contribution:**
  box anomaly (similar to the classical triangle anomaly),
  responsible for $\eta/\eta' \rightarrow \pi^+\pi^-\gamma$ decays predicted by PCAC and by
  the Wess-Zumino-Witten chiral lagrangian
$\eta \to \pi^+ \pi^- \gamma$: box anomaly

### Anomalies in QCD

$$L_{WZW} = L_{AVV} + L_{AAAV} + \ldots$$

**Triangle anomaly**

**Box anomaly**

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*S. L. Adler, Phys. Rev. 117 (1969) 2426*

*J. S. Bell, R. Jackiw, Nuovo Cim. A 60 (1969) 47*


*M. S. Chanowitz, Phys. Rev. Lett. 33 (1975) 977*


\[ \eta \rightarrow \pi^+\pi^-\gamma: M_{\pi\pi} \text{ spectrum} \]

Box Anomaly and \( \eta/\eta' \rightarrow \pi^+\pi^-\gamma \)

\[ BW(\rho) = \frac{1}{(m_{\pi\pi}^2 - m_\rho^2) - i m_{\pi\pi} \Gamma_\rho} + \frac{\xi}{m_{\eta'\eta}^2} e^{i\phi} \]

**EChPT, HLS model**


Unfortunately \( \eta \rightarrow \pi^+\pi^-\gamma \) not sensitive to the box anomaly contribution
$\eta \rightarrow \pi^+\pi^-\gamma$ @ KLOE

Preliminary KLOE analysis looks promising…

First sample analyzed: 29 pb$^{-1}$ of 2001 data

Analysis scheme:

- 1 vtx with 2 tracks
- 2 prompt neutral clusters
- Kin fit: $P(\chi^2) > 10^{-4}$
- $357.8 < E_{\gamma\text{ recoil}} < 368.2$ MeV
- $M_{\text{miss}}(\pi^+\pi^-) > 160$ MeV

S/B $\sim 460$
$\eta \rightarrow \pi^0 \gamma \gamma$

Interesting from the theoretical point of view because the bigger contribution comes from $p^6$ in $\chi_{PT}$

- $\pi^- + p \rightarrow \eta + n$
  (CERN, Brookhaven, GAMS, Crystal Ball)
- $\pi^+ + d \rightarrow p + p + \eta$ (67)
- $\pi^+ + p \rightarrow \pi^+ + p + \eta$ (67, 69)
- $K^- + p \rightarrow \Lambda + \eta$ (70 AGS)
- $\pi^+ + n \rightarrow \eta + p$ (71)
- $\pi^- + n \rightarrow \pi^- + n + \eta$ (80)
- $\phi \rightarrow \eta \gamma$ (SND 01)

Prel. KLOE measurement
η→π⁰γγ: mass spectrum measurement

A further improvement on BR is expected with 20 fb⁻¹, but more interesting is the shape of the γγ mass spectrum


Rescaling KLOE results:
3500 events expected
at the end of the analysis
The study of the e.m. structure of neutral mesons can be done through the $\eta \rightarrow \gamma l^+ l^-$ transition form factor $f(q^2)$ arising in the vertex provides information on the meson structure.

A transition form factor $f(q^2)$ arising in the vertex provides information on the meson structure.

- Observable: $l^+ l^-$ invariant mass
- $F(q^2)$ calculations: (1) VMD (2) Quark triangle loop (3) ChPT

**Dalitz decays**
Dalitz and double Dalitz decay can be easily reached with $20 \text{ fb}^{-1}$

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<td>$\eta \rightarrow e^+e^-\gamma$</td>
<td>$(6.0 \pm 0.8) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \mu^+\mu^-\gamma$</td>
<td>$(3.1 \pm 0.4) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta \rightarrow e^+e^-e^+e^-$</td>
<td>$&lt; 6.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+\pi^-e^+e^-$</td>
<td>$(4.0^{+14.0}_{-2.7}) \times 10^{-4}$</td>
</tr>
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Bckgs: $\phi \rightarrow \pi^+\pi^0\pi^0$

$\eta \rightarrow \pi^+\pi^-\gamma$

$\approx 60,000$ produced

All these measurements can be significantly improved and a first observation of $e^+e^-e^+e^-$ can be achieved (theoretical expectations: $\text{BR}(\eta \rightarrow e^+e^-e^+e^-) = 6.5 \times 10^{-5}$ [PR 98 (1955) 1355])
η → π⁺π⁻e⁺e⁻: test of CP violation beyond CKM

- Standard model: source of CP violation is a single phase in CKM mixing matrix describing quark flavor changing weak interaction couplings

- Test CP symmetry in flavour conserving process, where Standard Model predictions are vanishingly small

TEST OF NEW PHYSICS BEHOND THE STANDARD MODEL
CP violation in $K_L \rightarrow \pi^+\pi^- e^+e^-$

**dominant amplitudes**

- CP violating bremsstrahlung
  - $K_L \rightarrow \pi^+\pi^-\gamma$ (not shown)
  - $K_L \rightarrow \pi^+\pi^- e^+e^-$ (not shown)

- CP conserving M1 $\gamma$ emission
  - $K_L \rightarrow \pi^+\pi^-\gamma$ (not shown)
  - $K_L \rightarrow \pi^+\pi^- e^+e^-$ (not shown)

**interference of amplitudes**

$\Rightarrow$ CP violating circular photon polarisation

$\Rightarrow$ CP violating asymmetry in $\sin\varphi \cos\varphi$

L. M. Sehgal, M. Wasminger, PR D-46 (1992) 1035,
P. Heiliger, L. M. Sehgal, PR D-48 (1993) 4146

$\varphi = \angle (\pi^+\pi^-), (e^+e^-) \text{ planes in } K_L \text{ cms}$

$$A_\varphi = \frac{N_{\sin\varphi \cos\varphi > 0} - N_{\sin\varphi \cos\varphi < 0}}{N_{\sin\varphi \cos\varphi > 0} + N_{\sin\varphi \cos\varphi < 0}}$$

**NA48 result**

(A. Lai et al., EPJC 30 (2003) 33)

$K_L \rightarrow \pi^+\pi^- e^+e^-$

Acceptance corrected

$A_\varphi = (14.2 \pm 3.0_{\text{stat}})\%$
CP violation in $\eta \rightarrow \pi^+ \pi^- e^+ e^-$

**amplitudes**

$\Rightarrow$ CP violating bremsstrahlung

$\Rightarrow$ CP conserving $M1$ $\gamma$ emission

**interference of amplitudes**

$\Rightarrow$ CP violating asymmetry in $\sin \phi \cos \phi$

$\phi = \angle (\pi^+ \pi^-), (e^+ e^-)$ planes in $\eta$ cms

$\Rightarrow$ construct operators, that do not contribute directly to $\eta \rightarrow \pi^+ \pi^-$ and $K^0$ decays

$\Rightarrow$ flavor conserving CP violating four-fermion operators involving two $s$-quarks

C.Q. Geng, J.N. Ng, T.H. Wu, MPLA 17 (2002) 1489,
D.N. Gao, MPLA 17 (2002) 1583

$A_4$ up to 2%
\[ \eta \rightarrow e^+e^- / \mu^+\mu^- \]

<table>
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<tr>
<th>Decay</th>
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<th>Prediction</th>
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<tr>
<td>( \eta \rightarrow e^+e^- )</td>
<td>( &lt; 7.7 \times 10^{-5} )</td>
<td>( 6 \times 10^{-9} )</td>
</tr>
<tr>
<td>( \eta \rightarrow \mu^+\mu^- )</td>
<td>( (5.8 \pm 0.8) \times 10^{-6} )</td>
<td>( 4 \times 10^{-6} )</td>
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A large improvement on U.L. expected from the statistical point of view for \( \eta \rightarrow e^+e^- \)

However… large background from \( e^+e^- \rightarrow e^+e^- (\gamma) \) expected

1. Kinematic fit imposing \( \eta \) mass
2. Study of angular and momentum distributions of the decay products
C, P, CP, LF violating \( \eta \) decays

Already measured with KLOE 2001/2002 data:

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<tr>
<td>( \eta \to \pi^+\pi^- )</td>
<td>&lt; 1.3\times10^{-5}</td>
<td>P, CP</td>
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<tr>
<td>( \eta \to \gamma\gamma\gamma )</td>
<td>&lt; 1.6\times10^{-5}</td>
<td>C</td>
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Upper limits on \( \pi^+\pi^-/\gamma\gamma\gamma \), background limited, will improve with \( \sqrt{(L_{\text{NEW}}/L_{\text{OLD}})} \)

Other decays:

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<td>( \eta \to \pi^0\pi^0\pi^0\pi^0 )</td>
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<td>( \eta \to \pi^0 \mu^+\mu^- )</td>
<td>&lt; 5\times10^{-6}</td>
<td>C</td>
</tr>
<tr>
<td>( \eta \to \mu^+e^-, \mu^-e^+ )</td>
<td>&lt; 6\times10^{-6}</td>
<td>LF</td>
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Too much bckg: \( \phi \to S\gamma \)
\( \phi \to K_SK_L \)
\( \pi^+\pi^-\pi^0 \) bckg to be removed
Similar search of \( \phi \to \eta\gamma \) with \( \eta \to \mu^+\mu^- \)
Competitors: Crystall Ball @ MAMI

- $\sigma_E/E = 2\%/\sqrt{E(\text{GeV})}$
- $\sigma_0 = 2-3$ degrees

✓ 30M $\eta$ acquired @ AGS (BNL) [$\pi^- (720 \text{ MeV/c})p \rightarrow \eta\eta$]
✓ 30M $\eta$ acquired @ MAMI (MAINZ) in 2004, 300 hours run
  [$\gamma (180-820 \text{ MeV})p \rightarrow p\eta$]
✓ MAMI upgrade in progress: next run $E_\gamma$ up to 1.5 GeV
  300M $\eta$ expected + $\eta'$ sample
Competitors: WASA @ COSY

- Production mechanism: pp→ppη(η')
- Expected rate: 2500 η/s  30 η'/s
- Expected start-up: January 2007
η’ decays

\[ N_{\eta'}(20 \text{ fb}^{-1}) \approx 4 \cdot 10^6 \]

DAFNE2 is an η’ factory!
But beware: WASA@ COSY claims \(2 \cdot 10^6\) η’/day ....

- η’ main BRs known with an error of 3–10%
- We can probably improve the situation on the less frequent decay by measuring ratio of BRs (sth already @ KLOE/DAFNE)
- For the others, we need tagged measurement of all the decay chains Hard, but this could reduce the systematic error in the measurement of \(R = \frac{\text{BR}(\phi \rightarrow \eta'\gamma)}{\text{BR}(\phi \rightarrow \eta\gamma)}\) which dominates already its error

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<td>(\eta' \rightarrow \pi^+\pi^-\eta)</td>
<td>(44.3 ± 1.5)%</td>
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<td>(\eta' \rightarrow \pi^+\pi^-\gamma)</td>
<td>(29.5 ± 1.0)%</td>
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<td>(\eta' \rightarrow \pi^0\pi^0\eta)</td>
<td>(20.0 ± 1.2)%</td>
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<td>(\eta' \rightarrow \omega\gamma)</td>
<td>(3.03 ± 0.31)%</td>
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<td>(\eta' \rightarrow \gamma\gamma)</td>
<td>(2.12 ± 0.14)%</td>
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BR currently known at 7%.

BR is the main uncertainty in the extraction of the $\eta'$ full width

$8 \cdot 10^4$ events produced. With 10% efficiency can improve BR accuracy to about 4%. But hard from the exp. point of view (QED bkg).

$\Gamma_{\gamma\gamma}$ is already known to 3% thus no improvement for $\eta$–$\eta'$ mixing parameters.

…not a big issue….
η′ \rightarrow ηππ : Dalitz plot analysis

- Interesting to study scalar mesons (no tree contributions from VMD)
- Sensitive to σ(600) (PRD 60, 034002)
- Expect 200,000 evts in Dalitz plot with realistic efficiency.
$\eta' \rightarrow \pi^+\pi^-\pi^0$: first observation?

- Interesting, because it is sensitive to isospin violating part of strong Lagrangian, and proportional to $m_d - m_u$

- Currently only upper limit @ 5% (!)

- Expected at $O(10^{-3})$ i.e. 4000 evts produced

- With realistic efficiency can expect to measure BR @ some % level
Interesting, because $\gamma$ energy spectrum is sensitive to the “box anomaly” term of the WZW chiral Lagrangian

- Asymmetry related to possible C violation in strong interactions

- Difficult background from $\rho \pi$ (but we know we can deal with it reasonably for the $\eta$)

- More than 1 million events produced
Other $\eta'$ decays

- With an expected BR of $2 \cdot 10^{-4}$ the Dalitz decay could be observed with order 10% accuracy or less (transition form factor, light by light scattering etc.)

- $4\pi$ decays could possibly be observed... but we could not find theoretical prediction for that....

- Reasonably one could slightly improve limits on C, CP violating decays down to $10^{-4}$ level.