What Can be Learned from Decay of Light Mesons?

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Outline

- Introduction
- Dalitz Decays
- Radiative Decays
- Hadronic Decays
- Summary
Light (u,d,s) Mesons (not all)

Pseudoscalar \( J^P=0^- \)

- \( K^0 \), \( \pi^- \), \( \eta \), \( \pi^0 \), \( \pi^+ \), \( \eta' \), \( K^- \), \( \bar{K}^0 \)

Parity \( P=(-1)^{L+1} \)
C-parity \( C=(-1)^{L+S} \)
G-parity \( G=C(-1)^I = (-1)^{L+S+I} \)

Vector \( J^P=1^- \)

- \( K^{*0} \), \( K^{*+} \), \( K^{*-} \), \( K^{*0} \), \( \rho^- \), \( \omega \), \( \rho^0 \), \( \phi \), \( \rho^+ \)

Gell-Mann-Nishidjima:
\( Q=I_3 + Y/2 \)
\( Y=B+S \)
<table>
<thead>
<tr>
<th>$\pi^0$</th>
<th>$e^+e^-\gamma$</th>
<th>$\pi^+\pi^-\gamma$</th>
<th>$\pi^+\pi^-\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>$e^+e^-\gamma$</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$\pi^+\pi^-\pi^0$</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>$e^+e^-\gamma$</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$\pi^+\pi^-\pi^0$</td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td>$\pi^+\pi^-\gamma$</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>$e^+e^-\pi^0$</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$\pi^+\pi^-\pi^0$</td>
</tr>
<tr>
<td>$\varphi$</td>
<td></td>
<td></td>
<td>$\pi^+\pi^-\pi^0$</td>
</tr>
</tbody>
</table>
In this paper we consider only the data in the space-like region of photon virtuality, thus the modeling of the vertex couplings: $V_{\pi\gamma\gamma}(\nu)$ driven by $Q^2(\nu)$.

From Eqs. (2), (3) and (4) we see that $F^{\nu t}_{\pi\gamma\gamma}(Q^2)$ have information only about the region of photon virtuality, thus the modeling of the vertex couplings: $V_{\pi\gamma\gamma}(\nu)$ driven by $Q^2(\nu)$.

We evaluate the parameters in (2), (3) and (4) as a function of $Q^2$ with the photon virtuality $Q^2>0.5\text{GeV}^2$.

The two-photon form factors $F^{\nu t}_{\pi\gamma\gamma}(Q^2)$ are given by $F^{\nu t}_{\pi\gamma\gamma}(Q^2)\approx 1+a_\pi Q^2$.

One of the main objectives of this paper was to define the two-photon form factors $F^{\nu t}_{\pi\gamma\gamma}(Q^2)$.

The Brodsky-Lepage [23] high-energy model predicts the transition form factor the model agrees with CELLO [45] and CLEO [46], and disagrees with the BaBar data [1].

The overall agreement of this simple model is not good. In total, for the pion transition form factor the model is in a perfect agreement with CELLO, however for CLEO and BaBar the model is not in agreement.

The values $a_\pi=0.0309\pm0.0008\pm0.0009$ (CLEO) well measured at $Q^2>0.5\text{GeV}^2$.
Time-Like Form Factor $\pi^0 \rightarrow e^+e^-\gamma$

The slope is measured with very large errors:

$$a_\pi = -0.11 \pm 0.03 \pm 0.08 \quad [2]$$
$$a_\pi = +0.026 \pm 0.024 \pm 0.0048 \quad [3]$$
$$a_\pi = +0.025 \pm 0.014 \pm 0.026 \quad [4]$$

Here $a_\pi$ is defined from the following expression for the decay rate $[5]$

$$\frac{d\Gamma(\pi^0 \rightarrow e^+e^-\gamma)}{d\Gamma(\pi^0 \rightarrow \gamma\gamma)} = \left(\frac{d\Gamma}{dx}\right)_{QED} \times |F(x)|^2$$

(Kroll-Wada)

$$\left(\frac{d\Gamma}{dx}\right)_{QED} = \frac{2\alpha}{3\pi} \frac{1}{x} \frac{1}{(1-x)^3} \left(1 + \frac{r}{2x}\right) \left(1 - \frac{r}{x}\right)^{1/2}$$

$$F(x) = 1 + a_\pi x$$

where $x = m_{e^+e^-}^2/m_{\pi^0}^2$, $r = 4m_e^2/m_{\pi^0}^2$, and $F(x)$ is $\pi^0$ transition form factor.

CLAS g12 Data

Mean: $0.1349 \pm 0.0001$ GeV

$\sigma$: $0.0097 \pm 0.0001$ GeV

Range: $\pm 2.0 \sigma$

Yield: 16048

Background: 558

$\frac{S}{B} = 28.8$
The accuracy of eq. (4) is negligible. Our simulation shows that in Fig. 3. Thus, for the KLOE-2 case the possible $e^4$ expected to be less than 0 to the form factor parametrization in the generator is $\theta$.

By requiring one lepton inside the KLOE detector (20 diamonds) with small virtuality of the photons. The lepton double tagging (HET-HET) selects the events (red diamonds) with small virtuality of the photons.

The distribution of the photon virtuality in Fig. 4 shows the expected experimental distribution compared to the theoretical predictions.
CLAS g12 Data

Mean: $0.5477 \pm 0.0002$ GeV

$\sigma: 0.0126 \pm 0.0003$ GeV

Range: $\pm 2.0 \sigma$

Yield: 2998

Background: 156

$\frac{S}{B} = 19.2$
Time-Like Form Factor of $\eta$

\[
\frac{d\Gamma(\eta \rightarrow l^+ l^- \gamma)}{dm \Gamma(\eta \rightarrow \gamma \gamma)} = [QED] \cdot |F_\eta(m^2)|^2
\]

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

\[
b = \left| \frac{dF}{dm^2} \right|_{m^2=0} = \Lambda^{-2}
\]

\[
b = \langle r^2 \rangle / 6 \text{ (size of } \eta \text{)}
\]
6. Results

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

\[
\Lambda^2 = 1.950 \pm 0.002 \text{(stat.) \ GeV}^{-2}
\]

CB/TAPS: \( \Lambda^2 = 1.92 \pm 0.35 \text{(stat.)} \pm 0.13 \text{(syst.) GeV}^{-2} \)

NA60: \( \Lambda^2 = 1.95 \pm 0.17 \text{(stat.)} \pm 0.05 \text{(syst.) GeV}^{-2} \)

CLAS syst. err. \( \sim 0.05 \) (preliminary)
Photon Conversion in CLAS (MC Simulation)

Photon conversion contribution is <1% (except for first bin for $\pi^0$)

\[ R = \frac{N(\gamma \rightarrow e^+e^-)}{N(\pi^0 \rightarrow e^+e^-)} \frac{Br[\pi^0(\gamma\gamma)\rightarrow\eta]}{Br[\pi^0(\gamma\gamma)\rightarrow\pi^0(\gamma\gamma)\rightarrow\eta]} \]

\[ R = \frac{N(\gamma \rightarrow e^+e^-)}{N(\eta \rightarrow e^+e^-)} \frac{Br[\eta(\gamma\gamma)\rightarrow\pi^0]}{Br[\eta(\gamma\gamma)\rightarrow\pi^0]} \]
First measurement of Dalitz Decay of eta’ from CLAS

Mean: \(0.9578 \pm 0.0015\) GeV
\(\sigma: 0.0103 \pm 0.0011\) GeV
Range: \(\pm 2.0\) \(\sigma\)
Yield: 106
Background: 63

\(S/B = 1.7\)
Chapter 3

Anomalous decays

In the following Chapter we will discuss the decays of the neutral pseudoscalar mesons \( P \in \{ \pi^0, \eta, \eta' \} \) that are induced by the chiral anomaly. We differentiate between those which are governed by the triangle anomaly and the ones resulting from the box anomaly, because the structure of the pertinent form factors will be quite similar in the respective cases.

\[ P \gamma(\ast) \gamma(\ast) \]

Figure 3.1: triangle anomaly

\[ P \rightarrow \pi^+ \pi^- \gamma \]

Figure 3.2: box anomaly

The leading decays induced by the triangle anomaly are discussed next. We add here the qualifier 'leading' in order to discriminate these decays from those which involve sub-leading sequential decays as, e.g., Bremsstrahlung corrections etc. The discussed decays are

\[ P \rightarrow \gamma \gamma, \quad P \rightarrow l^+ l^- \gamma \]

where \( l^+ l^- \) are lepton-antilepton pairs. Obviously only electrons and muons are involved.

Why is it interesting?

It gives an access to the box anomaly term of Wess-Zumino-Witten Lagrangian

Also via Primakoff effect in COMPASS experiment (long standing problem)

\[ \pi^- \gamma \rightarrow \pi^- \pi^0 \]
Box Anomaly \[ \gamma \pi^- \rightarrow \pi^- \pi^0 \]

Y.M. Antipov et al., PRD 36(1987), 21

\[ A^{2\gamma}_{\pi} = \frac{e^2 N_c}{12 \pi^2 f_\pi} \]

Constrained by \( \gamma \gamma \) width of \( \pi^0 \)

\[ A^{2\gamma}_{\pi} = e f_\pi^2 A^{3\pi}_\gamma \]

(Theory prediction)

\[ A^{3\pi}_\gamma = \lim_{m \rightarrow 0} F^{3\pi}_\gamma(p_1, p_2, p_3 = 0) = \frac{e N_c}{12 \pi^2 f_\pi^3} \]

Very poorly measured
Radiative Decay $\eta, \eta' \rightarrow \pi^+\pi^-\gamma$

$M_X^2(p)$ versus $M_X^2(p\pi^+\pi^-)$

$ME > 0.01\text{GeV}$

$ME - E_{\gamma} < 0.03\text{GeV}$
Mx(p)=0.55±0.01 GeV  
0.76±0.06 GeV  
0.96±0.01 GeV
Invariant Mass vs Missing Mass

\[ \gamma + p = p\pi^+\pi^-\gamma \]

Missing Mass Resolution is much better as expected
Fig. 2. Experimental data and error weighted fits for $\eta \rightarrow \pi^+\pi^-\gamma$ (left, data are from Ref. [17] (filled squares) and Ref. [18] (open circles)) and $\eta' \rightarrow \pi^+\pi^-\gamma$ (right, data are from Ref. [20]).

Concerning the former decay, Gormley et al. [18] provides $\alpha = (1.7 \pm 0.4)$ GeV$^{-2}$ while Layter et al. [19] gives $\alpha = (-1.0 \pm 0.1)$ GeV$^{-2}$. The acceptance correction of these old experiments was derived from the specified $d\Gamma/dE$ distributions, respectively, under the assumption that the pertinent matrix element is the simplest gauge in variant and $F_{\pi\pi}(s) = \pi\pi$.

The Layter et al. result seems to be inconsistent both with WASA [17] and Gormley et al. [18]. However, from the information provided in those old experiment al papers it is impossible to evaluate systematic uncertainties. In case of the $\eta'$, we obtain $\alpha' = (3 \pm 1)$ GeV$^{-2}$ from the data of the GAMS-200 collaboration [21], which is larger, but within error bars consistent with the value listed above. Hence, in the following, we use the values given in Eq. (8).

Instead of looking at the data themselves it is illustrative to extract from data directly the polynomials $P_{\pi\pi}(s)$. These are shown for both radiative $\eta$ and $\eta'$ decay in the left and right panel of Fig. 3, respectively. Here one clearly sees that the residual $s_{\pi\pi}$ dependence for both transition amplitudes — once the pion form factor and the phase space are divided out — has a linear behavior to a very good approximation. The statement is further corroborated by the fact that any additional quadratic term to the linear polynomial with coefficients as specified in Eq. (8) is compatible with zero: $\beta = (0.07 \pm 0.65)$ GeV$^{-4}$ and $\beta' = (0.10 \pm 0.38)$ GeV$^{-4}$. This appears reassuring, although it came as a surprise that even for the $\eta'$ a first-order polynomial is sufficient. The origin of this might be in the current quality of the data which is best in the region of large values of $E_\gamma$ which corresponds to moderate values of $s_{\pi\pi}$ — this is the region where the chiral expansion is expected to converge (on resonance effects are taken out). This can also be seen in Fig. 3, right panel: clearly the fit is dominated by values of $s_{\pi\pi} \leq 0.6$ GeV$^2$ (this corresponds to pion 6 cm).
CLAS Hadronic decays: g11 Data
The internal dynamics of the decay $\eta \rightarrow \pi^+ \pi^- \pi^0$ or $\eta \rightarrow \pi^+ \pi^- \eta$. To see the hadronic decays $\pi^0$ or $\pi^+ \pi^-$. Experimental data are from CLAS g11 experiment. Largest statistics in the world is $17M \omega$'s. Not corrected for acceptance.

\[ X = \frac{\sqrt{3}}{Q} (T_{\pi^+} - T_{\pi^-}), \quad Y = \frac{3T_{\pi^0}}{Q} - 1 \]

\[ Q = T_{\pi^+} + T_{\pi^-} + T_{\pi^0} \]
Branching ratio is known to osb precision only an upper bound for the $\omega$ is quoted in the PDG. This channel may also yield new results in particular a measurement of $\omega \rightarrow \pi^+ \pi^- \gamma$ branching ratio.

Hadronic decays

In this section we present experimental data for the reaction $\gamma h p \rightarrow p \pi^+ \pi^- \pi^0$. The $\pi^0$ or $\eta$ is identified via missing mass of the He$^1\gamma, p \pi^+ \pi^- f X$ reaction.

In Fig. I left panel a distribution of missing mass of the proton in the $\gamma h p \rightarrow p \pi^+ \pi^- \pi^0$ reaction is presented showing clear peaks for the $\eta$ and $\omega$ mesons with $\sim nM$ and $\sim pM$ events in the peaks respectively. Our Dalitz plot distribution for the decay $\eta \rightarrow \pi^+ \pi^- \pi^0$ is seen in Fig. II. There are also hints of $\eta'$ and $\phi$ mesons. To see the $\eta'$ and $\phi$ signals in Fig. II we plot a zoom of the same distribution in the mass range above the $\omega$ meson. We clearly observe one of the rare decays $\eta' \rightarrow \pi^+ \pi^- \pi^0 eBr = q \pm n o \times q - 3 f$ and the OZI violating decay $\phi \rightarrow \pi^+ \pi^- \pi^0 eBr = q b f l$ This is the first observation of these decays in photoproduction. According to Grossi Treimani and Wilczek, the decay width ratio $\Gamma e \eta' \rightarrow \pi^+ \pi^- f \pi^0 \Gamma e \eta \rightarrow \pi^+ \pi^- f \eta \pi f$ $\propto m m d - m m u m s$ is sensitive to the quark mass difference $m d - m u$ where $m d$, $m u$ and $m s$ are masses of $u$, $d$ and $s$ quarks respectively.

FIG. 9: Left panel: distribution of missing mass of the proton in the reaction $\gamma h p \rightarrow p \pi^+ \pi^- \eta f$ where $\eta$ is reconstructed in the missing mass of the $p \pi^+ \pi^- f$ system. As one can see there is a clear peak of $\eta'$ with $\sim nM K$ events which is almost an order of magnitude higher than the recent BES data. In Fig. II we show our Dalitz plot distribution for the decay $\eta' \rightarrow \pi^+ \pi^- \eta$. The internal dynamics of the decay $\eta \rightarrow \pi^+ \pi^- \pi^0$ and $\eta' \rightarrow \pi^+ \pi^- \eta$ can be described by two degrees of freedom since all particles involved have spin zero. The Dalitz plot distribution for the decay $\eta \rightarrow \pi^+ \pi^- \pi^0$ is described by the following two variables $X = \sqrt{3} (T \pi^+ - T \pi^-) Q e f, Y = \frac{3 T \pi^0}{Q} - 1$. $\sim 2 M$ events.
Dalitz plot projections \( \eta \to \pi^+ \pi^- \pi^0 \)

\[
M^2 = A(1 + aY + bY^2 + cX + dX^2)
\]

\[
A \propto \frac{1}{Q^2} = \frac{m_d^2 - m_u^2}{m_s^2 - \hat{m}^2}; \quad \hat{m} = \frac{m_u + m_d}{2}
\]

\( g11 \) Data
A New Dispersive Analysis of $\eta \rightarrow \pi^+ \pi^- \pi^0$

Stefan Lanz

Figure 2: The Dalitz plot for $\eta \rightarrow \pi^+ \pi^- \pi^0$, normalized to $-\pi^0$. The dimensionless Dalitz plot variables $X$ and $Y$ are defined in the text.

Figure 3: A selection of results for $Q_0$. Our result is $[0.8 \pm 0.0]$ and is indicated by the grey band. The error is only due to the experimental uncertainty on the decay width. The other results are taken from Leutwyler's talk at this conference, from a dispersive analysis in ref. [9], from a two-loop calculation in $\chi$PT, from Weinberg's quark mass ratios, and from an analysis including Dashen violation. The last value we calculated from the MILC quark mass ratios presented by Heller at this conference.

G. Colangelo et al., arXiv:0910.0765

[Graph showing a plot of Quark mass ratio with various results and error bands.

- Our preliminary result
- Leutwyler's talk
- Kambor, Wiesendanger & Wyler'95
- Bijnens & Ghorbani'07
- Kaon mass splitting
  - Weinberg'77
  - Kastner & Neufeld'08
- Lattice
  - MILC'09]
From Particle Data Group:

\[
\eta
\]

\[I^G(J^{PC}) = 0^+(0^-+)\]

Mass \(m = 547.853 \pm 0.024\) MeV
Full width \(\Gamma = 1.30 \pm 0.07\) keV

\textbf{C-nonconserving decay parameters}

\begin{align*}
\pi^+ \pi^- \pi^0 & \quad \text{left-right asymmetry} = (0.09^{+0.11}_{-0.12}) \times 10^{-2} \\
\pi^+ \pi^- \pi^0 & \quad \text{sextant asymmetry} = (0.12^{+0.10}_{-0.11}) \times 10^{-2} \\
\pi^+ \pi^- \pi^0 & \quad \text{quadrant asymmetry} = (-0.09 \pm 0.09) \times 10^{-2} \\
\pi^+ \pi^- \gamma & \quad \text{left-right asymmetry} = (0.9 \pm 0.4) \times 10^{-2} \\
\pi^+ \pi^- \gamma & \quad \beta (D\text{-wave}) = -0.02 \pm 0.07 \quad (S = 1.3)
\end{align*}
Test of C-Parity Violation

**Fig. 1.** Comparison of obtained values of asymmetries [7] with results determined by previous experiments [3,4,5], and a value given by PDG [6].

- **Left-Right Asymmetry**
  - This work
  - PRELIMINARY
  - LAYTER 1972
  - JANE 1974
  - KLOE 2008
  - PDG average

- **Quadrant Asymmetry**
  - This work
  - PRELIMINARY
  - LAYTER 1972
  - JANE 1974
  - KLOE 2008
  - PDG average

- **Sextant Asymmetry**
  - This work
  - PRELIMINARY
  - GORMLEY 1968
  - LAYTER 1972
  - JANE 1974
  - KLOE 2008
  - PDG average

**CLAS expected stat. error. δ ≤ 0.001**
**Hadronic decay**

\[ \eta' \rightarrow \pi\pi\eta \]

- **Mean:** 0.958 GeV
- **σ:** 0.005 GeV

**G-Parity violation**

\[ \Phi \rightarrow \pi\pi\eta \]

- **PDG Exp. limit**
  - **Br:** \( < 1.8 \times 10^{-5} \)
  - **M:** 1.021 GeV
  - **σ:** 0.005 GeV

---

**CLAS g11 Data** *(7 times more \( \eta' \) than in BESIII)*

- Another 3 times more on tape *(from CLASg12 run)*
Dalitz plot $\eta' \rightarrow \pi\pi\eta$
Dalitz plot projections $\eta' \rightarrow \pi\pi\eta$

CLAS Preliminary uncorrected

<table>
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<th>Par.</th>
<th>VES</th>
<th>Theory</th>
<th>BES</th>
<th>Stat err. in BES</th>
<th>Stat. err. in CLAS</th>
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</thead>
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<td>a</td>
<td>-0.127+0.018</td>
<td>-0.116+0.011</td>
<td>-0.047+0.012</td>
<td>-0.011</td>
<td>-0.004</td>
</tr>
<tr>
<td>b</td>
<td>-0.106+0.032</td>
<td>-0.042+0.034</td>
<td>-0.069+0.021</td>
<td>-0.019</td>
<td>-0.006</td>
</tr>
<tr>
<td>c</td>
<td>+0.015+0.018</td>
<td></td>
<td>+0.019+0.012</td>
<td>-0.011</td>
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</tr>
<tr>
<td>d</td>
<td>-0.082+0.019</td>
<td>+0.010+0.019</td>
<td>-0.073+0.013</td>
<td>-0.012</td>
<td>-0.004</td>
</tr>
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</table>
Testing Scalar Mesons in $\pi^+\pi^-$ from $\eta'$

Fig. 18: The $m_{\pi^+\pi^-}$ distribution in the $\eta' \rightarrow \eta\pi^+\pi^-$ decay with the $\sigma$ meson (right–centered distribution) and without (left–centered distribution) contribution.

Based on Fariborz and Schechter model
PRD 67,054001,2003

arXiv:1003.3868
Dalitz decay $\omega \rightarrow e^+e^-\pi^0$

CLAS g12 Data
We expect significant improvement in stat. error with CLAS Data
Photoproduction and Decay of Light Mesons in CLAS

CLAS Analysis Proposal


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3 INFN, Sezione di Genova, 16146 Genova, Italy
4 The George Washington University, Washington, DC 20052
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(Dated: September 30, 2012)
Summary

We expect to release at least the following results:

1. Transition form factor of $\pi^0$ in the time-like region from Dalitz decay $e^+e^-\gamma$
2. Transition form factor of $\eta$ in the time-like region from Dalitz decay $e^+e^-\gamma$
3. Branching ratio $\eta' \to e^+e^-\gamma$ for the first time
4. Measurement of $E_\gamma$ distribution in radiative decay $\eta \to \pi^+\pi^-\gamma$
5. Measurement of $E_\gamma$ distribution in radiative decay $\eta' \to \pi^+\pi^-\gamma$
6. Transition form factor of $\omega$ in time-like region from Dalitz decay $\omega \to e^+e^-\pi^0$
7. Dalitz plot analysis of hadronic decay $\eta \to \pi^+\pi^-\pi^0$
8. Dalitz plot analysis of hadronic decay $\eta' \to \pi^+\pi^-\eta$
9. First observation of G-parity violating decay $\phi \to \pi^+\pi^-\eta$