Workshop on Meson Transition Form Factors

Recent results and perspectives on pseudo-scalar mesons and form factors at BES III

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on behalf of the BES III collaboration

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Outline

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- BES III detector
- Analysis $\eta' \rightarrow \eta \pi^+ \pi^-$
- Analysis $\eta' \rightarrow \pi^+ \pi^- l^+ l^-$
- Analysis $\gamma\gamma \rightarrow \pi^0/\eta/\eta'$
- Conclusion
Introduction

- Since its discovery (PRL 12, 527 (1964)), \( \eta' \) decays inspired interest in both, theory and experiments

- \( \eta - \eta' \) mixing probes strange quark content of light pseudo-scalar mesons and gluon dynamics of QCD

- Hadronic decays of \( \eta' \), in particular the ones to 3 pions, have garnered attention because of their large experimental limit and because they can probe isospin symmetry breaking

\[
\begin{align*}
    r_0 &\equiv \frac{\mathcal{B}(\eta' \to 3\pi^0)}{\mathcal{B}(\eta' \to \pi^0\pi^0\eta)} = (75 \pm 13) \times 10^{-4} \quad \text{PLB 667, 1 (2008)} \\
    r_\pm &\equiv \frac{\mathcal{B}(\eta' \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\eta' \to \pi^+\pi^-\eta)}
\end{align*}
\]

- Under the 2 assumptions that the decay \( \pi^+\pi^-\pi^0 \) appears only through \( \eta' \to \eta\pi^+\pi^- \) followed by \( \eta - \pi^0 \) mixing and such decays populate uniformly the available phsp, \( r_\pm \) is found to be proportional to the mass difference \( u-d \) quark and \( r_\pm/r_0 \approx 0.37 \)

- A suggestion to use \( U(3) \) chiral effective field theory to examine \( \eta' \) decays is given (PLB 643, 41 (2006)): \( \eta' \to \eta\pi\pi \) Dalitz slope parameters can give large contribution to \( \eta' \to \pi^+\pi^-\pi^0 \); prediction: \( r_\pm/r_0 \approx 5 \)
The BES III experiment

B = 1T
resolution(MDC): $\sigma_p / P = 0.58\%$
resolution(MDC): $\sigma_E / E = 6.0\%$
resolution(TOF): $\sigma_\tau = 100\text{ps}$
resolution(EMC): $\sigma / E = 2.5\%$
Muon detected: $p > 400\text{ MeV/c}$

Very good separation $e/\pi$

<table>
<thead>
<tr>
<th>BESIII collected by the end of 2011</th>
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<tr>
<td>$J/\psi$: 225 Million</td>
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<td>$\Psi'$: 106 Million</td>
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<tr>
<td>$\psi(3770)$: 2.9fb$^{-1}$</td>
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<tr>
<td>$\psi(4010)$: 0.5fb$^{-1}$</td>
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BES III detector at BepC (Beijing, China) offers a unique opportunity to perform light hadron physics analyses and transition form factor measurements.
Measurement of the matrix element of the decay

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

*PRD 83, 012003 (2011)*
The hadronic decay of $\eta'$ is extremely valuable in studies devoted to the effect of the gluon component in chiral perturbation theory and the possible nonet of light scalars.

Dalitz plot parameters of some hadronic $\eta'$ decay were already studied:

- VES P.L.B 651, 22(2007) $\eta' \to \eta \pi^+ \pi^-$
- GAMS-4$\pi$ P.N. 72, 231 (2009) $\eta' \to \eta \pi^0 \pi^0$

In the isospin limit the values of the Dalitz plot parameters should be the same; however, the experimental results show some discrepancy.
Analysis $\eta' \rightarrow \eta \pi^+ \pi^-$: strategy

- Energy c.m. = $J/\psi$ mass production 225 millions $J/\psi$

- Reconstruction:
  $\eta' \rightarrow \eta \pi^+ \pi^-$
  $\eta \rightarrow \gamma \gamma$ (J/$\psi$ radiative decays)

- Selection:
  the candidate events with topology $\gamma \gamma \pi^+ \pi^-$ with minimum $\chi^2$(4C fit)

- Background:
  $J/\psi \rightarrow \gamma \eta' \rightarrow \gamma \gamma \rho^0 \rightarrow \gamma \gamma \pi^+ \pi^-$
  $J/\psi \rightarrow \gamma \eta' \rightarrow \gamma \omega \rightarrow \gamma \gamma \pi^+ \pi^- \pi^0$
  No additional peaking background come from $f1(1285), \eta(1405), \eta(1475), f1(1510)$
  $\rightarrow \gamma \eta \pi^+ \pi^-$

$$\mathcal{B}(J/\psi \rightarrow \gamma \eta') = \frac{N_{\text{obs}}}{N_{J/\psi} \times \varepsilon \times \mathcal{B}(\eta' \rightarrow \eta \pi^+ \pi^-) \times \mathcal{B}(\eta \rightarrow \gamma \gamma)} = (4.84 \pm 0.03(\text{stat}) \pm 0.24(\text{sys})) \times 10^{-3}$$

PRD 83, 012003 (2011)
Analysis $\eta' \rightarrow \eta \pi^+ \pi^-$: Dalitz plot parameters

The dynamic of this decay can be described by 2 degrees of freedom, as all particles of this decay have spin = 0.

The Dalitz plot distribution is described by 2 variables and in different parametrization:

- $X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-})$
- $Y = \frac{m_\eta + 2m_\pi T_\eta}{m_\pi Q} - 1$

1) $M^2 = A(1 + aY + bY^2 + cX + dX^2)$

is the decay amplitude (general decomposition) expanded in terms of Dalitz parameters to be evaluated.

- Odd term in $X$ are forbidden in this decay.

The parameter $c = \begin{cases} 0, & \eta' \rightarrow \eta \pi^0 \pi^0 \\ 
\text{not necessarily 0,} & \eta' \rightarrow \eta \pi^+ \pi^- \end{cases}$
A second parametrization is the linear parametrization:

\[ M^2 = A(|1 + \alpha Y|^2 + cX + dX^2) \]

linear function of the kinetic energy of the \( \eta \).
\( \alpha \) is a complex parameter

A non zero value of \( \alpha \) may represent the contribution of a gluon component in the wave function of the \( \eta' \) in the dynamics of the decay

For comparison with the parametrization 1):

\[ a = 2 \text{Re}(\alpha) \]
\[ b = \text{Re}^2(\alpha) + \text{Im}^2(\alpha) \]
Analysis $\eta' \rightarrow \eta \pi^+ \pi^-$: results

The parameter c is consistent with 0 within 1.8σ

1) general decomposition parametrization:

$$M_i = \sum_{j=1}^{N_{ev}} (1 + aY_j + bY_j^2 + cX_j + dX_j^2)$$

$$a = -0.047 \pm 0.011 \begin{pmatrix} 1.000 & -0.442 & -0.010 & -0.239 \\ b = -0.069 \pm 0.019 & 1.000 & 0.025 & 0.282 \\ c = +0.019 \pm 0.011 & 1.000 & 0.030 & \end{pmatrix}$$

$$d = -0.073 \pm 0.012$$

2) linear parametrization

$$M_i = \sum_{j=1}^{N_{ev}} (|1 + \alpha Y_j|^2 + cX_j + dX_j^2)$$

$$\text{Re}(\alpha) = -0.033 \pm 0.005$$

$$\text{Im}(\alpha) = 0.000 \pm 0.049$$

$$c = +0.018 \pm 0.009$$

$$d = -0.059 \pm 0.012$$

The parameter c is consistent with 0 within 2.1σ
Analysis $\eta' \to \eta \pi^+ \pi^-$: comparison

The negative value of $b$ indicates that the 2 parametrizations are not equivalent.
The parameters $a$ and $b$ are consistent with the ones from GAMS-4$\pi$.

$X^2 Y^2$ value are different from 0.

The 2 parametrizations do not look equivalent because of the estimated value of $b$.

The value $b$ shows to be different from the expected chiral Lagrangian model (zero); however, it can be accommodated in a U(3) chiral unitarized model by including final state interactions [N.P. A716, 186 (2003)].

The value $c$, which test C-parity violation in the strong interaction, is consistent with 0.

The BR is found consistent with previous BESII measurement and improves the statistical errors [PRD 73, 052008 (2006)].
Measurement of BF

\[ \eta' \rightarrow \pi^+ \pi^- \pi^+ \pi^- \]

PRELIMINARY RESULTS
The BR for $\eta' \rightarrow \pi^+ \pi^- X$ ($X=e,\mu$) are expected to scale with those for $\eta' \rightarrow \gamma X$.

The most copious decay should be $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ (experimental limit: 0.6%) expected: 0.3%

Different theoretical approaches provide explanation for $\rho^0$-dominance for the $\pi^+ \pi^-$ invariant mass, $e^+ e^-$ mass distribution peaking just above $2m_e$, with long tail extended to ~300 MeV.

The BR limit on $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ is expected to be $\sim 2 \times 10^{-5}$

The analysis from CLEO has been shown the following results:

$BR(\eta' \rightarrow \pi^+ \pi^- e^+ e^-) = (2.5^{+1.2}_{-0.9} \pm 0.5) \times 10^{-3}$

$BR(\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-) < 2.4 \times 10^{-4}$

CLEO PRL 102, 061801 (2009)
Analysis $\eta'\to\pi^+\pi^-l^+l^-$: strategy

- Energy c.m. = J/$\psi$ mass production 225 millions J/$\psi$

- Reconstruction:

$$\eta' \to \pi^+\pi^-\mu^+\mu^- \quad \eta' \to \pi^+\pi^-e^+e^-$$

The topology of the event studied is $J/\psi \to \gamma\eta'$, $\eta' \to \pi^+\pi^-l^+l^-$

- Selection:

$$\chi^2\text{ cut (4C fit)}$$

- Background:

The events $J/\psi \to \gamma\eta'$, $\eta'\to\gamma\pi^+\pi^-$ are under exam; other possible sources of background are:

$$J/\psi \to \gamma\eta', \eta' \to \gamma\rho^0, \rho^0 \to \pi^+\pi^-$$
$$J/\psi \to \gamma\eta', \eta' \to \gamma\rho^0, \rho^0 \to \pi^+\pi^-\gamma_{FSR}$$
$$J/\psi \to \pi^+\pi^-\rho^0\gamma_{FSR}$$
$$J/\psi \to \gamma\eta', \eta' \to \gamma\omega, \omega \to \pi^+\pi^-$$
$$J/\psi \to h_1(1170)\pi^0, h_1(1170) \to \rho^0\pi^0, \rho^0 \to \pi^+\pi^-$$
$$J/\psi \to \pi^+\pi^-\rho^0$$

This is the main background source
Analysis $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$: invariant mass

$\eta' \rightarrow \gamma \rho^0, \rho^0 \rightarrow \pi^+ \pi^-$ via $\gamma$ conversion

As from prediction, a long tail up to $\sim 300$ MeV is observed

As from prediction, the di-lepton ($e^+ e^-$) mass peaks about $\sim 2m_e$

As from prediction, a huge signal is observed in $e^+ e^- \pi^+ \pi^-$

As from prediction, the $\rho^0$-dominance is observed in $\pi^+ \pi^-$ mass
Analysis $\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-$: invariant mass

- No signal observed on data

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29th May 2012
Analysis $\eta' \rightarrow \pi^+ \pi^- l^+ l^-$: results

- A specific MC generator was used to simulate events $\eta' \rightarrow \pi^+ \pi^- l^+ l^-$, where the form factor (FF) assumption is done (DIY) with $Q^2$ dependence.

- To estimate the uncertainty introduced from the form factor model, a constant value was introduced, to eliminate the dependence of FF from $Q^2$.

- Other sources of uncertainty in this analysis are conventional.

\[
BR(\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-) < \frac{N_{\eta' \rightarrow \pi \pi \mu \mu}^{U,L}}{N_{\eta' \rightarrow \gamma \rho^0}} \times \epsilon_{\eta' \rightarrow \gamma \rho^0} \times BR(\eta' \rightarrow \gamma \rho^0) \times 2.62 \times 10^{-5}
\]

Good agreement with predictions.

\[
BR(\eta' \rightarrow \pi^+ \pi^- e^+ e^-) = \frac{N_{\eta' \rightarrow \pi e e}}{N_{\eta' \rightarrow \gamma \rho^0}} \times \epsilon_{\eta' \rightarrow \gamma \rho^0} \times BR(\eta' \rightarrow \gamma \rho^0) =
\]

\[
= (2.13 \pm 0.13\,(stat.) \pm 0.19\,(syst.)) \times 10^{-3}
\]
Transition meson form factor of

\[ \gamma\gamma \rightarrow e^+e^-\pi^0/\eta/\eta' \]

*FEASIBILITY study: analysis ongoing*

Only feasibility studies are presented here today
Anomalous magnetic momentum of the muon $a_{\mu} = (g-2)_{\mu}/2$ is a very important observable providing test at the precision frontier of the Standard Model.

Presently **3.6\sigma deviation observed** for $(g-2)_{\mu}$ and Standard Model prediction.

$$a_{\mu}(\text{SM}) = (116\ 591\ 594.7 \pm 70) \times 10^{-11}$$

$$a_{\mu}(\text{SM}) = a_{\mu} (\text{QED}) + a_{\mu} (\text{hadronic}) + a_{\mu} (\text{weak})$$

$$a_{\mu} (\text{New Physics}) = a_{\mu} (\text{Measured}) - a_{\mu} (\text{SM})$$

**Contribution from strong interactions not calculable within perturbative QCD**
Contribution to the measurement of a $\mu$

**QED contribution** = $(11\,658\,471.810 \pm 0.016) \times 10^{-10}$

**Weak contribution** = $(15.4 \pm 0.2) \times 10^{-10}$

**Hadronic vacuum polarization** = $(695.5 \pm 4.1) \times 10^{-10}$

**Hadronic Light-by-light scattering** = $(10.5 \pm 2.6) \times 10^{-10}$

Hadronic vacuum polarization

Standard Model precision limited by strong contribution

**Hadronic LBL contribution** still smaller compared to **Hadronic vacuum polarization**, but its uncertainty is calculated of the same order

Measurement of **meson transition form factor** of utmost importance to validate hadronic models
To solve beyond QED-effects more precision in theory and experiments needs
Need to study the transition form factor of $\pi^0, \eta, \eta'$ to give new input to the theory
Due to the upcoming experiment at Fermilab, the hadronic $LBL$ correction will become the main uncertainty to evaluate for the precision measurement of $(g-2)_\mu$

**Hadronic Light-by-Light Scattering**

$$a_{\mu}^{(had),LbL} = (10.5 \pm 2.6) \cdot 10^{-10} \quad \text{Prades et al.}$$

$$\quad (11.6 \pm 4.0) \cdot 10^{-10} \quad \text{Nyffeler}$$

$$\quad (21.6 \pm 9.1) \cdot 10^{-10} \quad \text{Fischer et al.}$$
How the form factor can be measured

- **Two-photon production** of the meson
  - \(- S + M^2 < q_1^2 < 0, \ q_2^2 \approx 0, \ Q^2 \equiv -q_1^2\)
  - \(d\sigma/dQ^2\) falls as \(1/Q^6\)
  - At \(\sqrt{s} = 10.6\ \text{GeV}\) for \(e^+e^- \rightarrow e^+e^- \pi^0\)
    \(d\sigma/dQ^2(10\ \text{GeV}^2) \approx 10\ \text{fb/GeV}^2\)

- **Annihilation process** \(e^+e^- \rightarrow P\gamma\)
  - \(Q^2 = S > M^2\)
  - \(\sigma \propto 1/S^2\)
  - \(\sigma(e^+e^- \rightarrow \eta\gamma) \approx 5\ \text{fb at}\ \sqrt{s} = 10.6\ \text{GeV}\)

- **Dalitz decay** \(P \rightarrow \gamma e^+e^-\)
  - \(0 < Q^2 < M^2\)
  - \(M^2d\Gamma/dQ^2 \approx (2\alpha/\pi)\Gamma(P \rightarrow \gamma\gamma)\) at \(Q^2/M^2 \approx 1/4\)
Analysis $\gamma \gamma \rightarrow e^+e^-\pi^0/\eta/\eta'$: strategy

- Electrons are scattered predominantly at small angles

- **Single-tag mode technique:**
  - one electron is detected
  - $Q^2 = -q_1^2 = 2EE'(1-\cos \theta)$
  - $q_2^2 \approx 0$
  - electron is detected and identified
  - the meson is detected and fully reconstructed
  - electron + meson system has low $p_{T}$
  - missing mass in an event is close to 0

$$dN/dQ^2 \quad \rightarrow \quad d\sigma/dQ^2 \quad \rightarrow \quad |F(Q^2)|$$
Analysis $\gamma\gamma \rightarrow e^+e^−\pi^0/\eta/\eta'$: feasibility study

- Errors definitively reduced: high precision!
- Possibility to check very low $Q^2$
- Cross check the BaBar/Belle data up to 10GeV$^2$
- Cross check CLEO data from $Q^2=1.5$ up to 7GeV$^2$

All simulation are performed with EKHARA 2.0: no detector simulation included.
Analysis $\gamma\gamma \rightarrow e^+e^-\pi^0/\eta/\eta'$: cross section

- **E c.m. = 3.77 GeV;** it reduces the background due to $e^+e^-$ from $J/\psi$

<table>
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<tr>
<th>EKHARA simulation</th>
<th>$e^+e^- \rightarrow e^+e^-\gamma \rightarrow e^+e^-\pi^0$ (nb)</th>
<th>$e^+e^- \rightarrow e^+e^-\gamma \rightarrow e^+e^-\eta$ (nb)</th>
<th>$e^+e^- \rightarrow e^+e^-\gamma \rightarrow e^+e^-\eta'$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non tagged</td>
<td>$(832.2 \pm 2.9)x10^{-3}$</td>
<td>$(297.2 \pm 1.0)x10^{-3}$</td>
<td>$(212.2 \pm 1.1)x10^{-3}$</td>
</tr>
<tr>
<td>Tagged $e^+$</td>
<td>$(6.672 \pm 0.059)x10^{-3}$</td>
<td>$(5.240 \pm 0.019)x10^{-3}$</td>
<td>$(6.776 \pm 0.039)x10^{-3}$</td>
</tr>
<tr>
<td>$21.6&lt;\theta&lt;158.4$</td>
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- @BESIII we can perform the analysis $\gamma^* \rightarrow P$ tagging one lepton
Analysis $\gamma \gamma \rightarrow e^+e^-\pi^0/\eta/\eta'$: acceptance

After the detector acceptance is included, a loss of events is seen at the threshold. It is due to the photon acceptance.

This analysis is ongoing....
BaBar could not check very low $Q^2$ values due to the trigger.

Simulations show that in BESIII it is possible

$Q^2 \in [1/3] \text{ GeV}^2$ is theoretically the best range to test hadronic \textit{LBL} correction to $(g-2)\mu$

\textbf{INPUT TO THE THEORY!}
Conclusion

- The BES III detector collected high quality data, that allow us to do precise and competitive measurements compared to other experiments.

- Interesting analysis are going on pseudo-scalar mesons and light hadron physics: BES III can give an important contribution in this sector.

- The study of the Dalitz plot matrix elements of $\eta' \rightarrow \eta \pi \pi$ allow us to conclude that BES III is in agreement with VES (parameters $c$ and $d$) and GAMs-4$\pi$ (parameters $a$ and $b$). As expected, the parameter $c$ related to C-parity violation is consistent with 0 (as expected for strong interactions).

- High precision measurement of BF($\eta' \rightarrow \pi^+ \pi^- \pi^0 \pi^0$) has been performed: it confirms the theoretical prediction and it will be published very soon.

- The analysis of transition form factor of $\pi^0, \eta, \eta'$ is ongoing at BES III:
  - **Range observable: $Q^2 [0.3;10.0] \text{ GeV}^2$**
    - improved efficiency compared to other experiments
    - never tested the area $Q^2$ in $[0.5;1.5] \text{ GeV}^2$ from other experiments
    - possibility to cross check CLEO data at low $Q^2 [1.5;3]\text{GeV}^2$
    - complementary measurement to BaBar/Belle experiment (e.g. $Q^2$ in $[4;40]\text{GeV}^2$)
Thank you!