Meson Transition Form Factors at BES-III

April 9, 2014  |  Christoph Florian Redmer
for the BES-III Collaboration

“(g-2)µ : Quo vadis?”

SFB1044 Workshop

Institut für Kernphysik, Mainz
Outline

- The BES-III Experiment
- Measurement of Meson Transition Form Factors
  - Time - like
  - Space - like
- Summary
Beijing Electron Positron Collider BEPC-II

- 2004: start of BEPC-II construction
- 2008: first e⁺e⁻ collisions
- Since 2009: BEPC-II/BES-III data taking

Beam Energy
1.0 - 2.3 GeV

Energy Spread
σ(E)/E = 5.16 · 10⁻⁴

Design Luminosity
10^{33} \text{ cm}^{-2} \text{ s}^{-1} @ \psi(3770)

Achieved Luminosity
0.7 · 10^{33} \text{ cm}^{-2} \text{ s}^{-1} @ \psi(3770)
BESIII Detector

- Main Drift Chamber (MDC)
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dx} = 6.0\%$

- Time-of-flight system (TOF)
  - $\sigma(t) = 90\text{ps} \ (\text{barrel})$
  - $\sigma(t) = 110\text{ps} \ (\text{endcap})$

- EMC
  - 6240 CsI(Tl) crystals
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{Z,\phi}(E) = 0.5 - 0.7 \text{ cm}$

- Muon Chambers
  - 8 – 9 layers of RPC
  - $p > 400 \text{ MeV/c}$
  - $\delta R\phi = 1.4 \sim 1.7 \text{ cm}$

- Superconducting Magnet
  - 1 T magnetic field
1.23 \cdot 10^9 \ J/\Psi

0.52 \cdot 10^9 \ \Psi(2S)

2.9 \ \text{fb}^{-1} \ \Psi(3770)

0.5 \ \text{fb}^{-1} \ @ \ 4.04 \ \text{GeV}

1 \ \text{fb}^{-1} \ @ \ 4.23 \ \text{GeV}

0.8 \ \text{fb}^{-1} \ @ \ 4.26 \ \text{GeV}

0.5 \ \text{fb}^{-1} \ @ \ 4.36 \ \text{GeV}

24 \ \text{pb}^{-1} \ \tau \ \text{mass scan}

800 \ \text{pb}^{-1} \ \text{R scan} \ (104 \ \text{points from 3.85 to 4.6 \ GeV})

World's largest samples of J/\Psi, \ \Psi(2S), \ and \ \Psi(3770)
How to measure TFF at BES-III

**Time – like Transition Form Factors:**

- Dalitz decays
  - $0 < q^2 < M^2$
- Annihilation process
  - $q^2 = s > M^2$

**Space – like Transition Form Factors:**

- Two-photon production of mesons
  - $F(Q_1^2, Q_2^2), \quad Q^2 = -q^2$
Time-like TFF

Dalitz decays $J/\Psi \rightarrow P e^+e^-$

- Unmeasured, rare processes
  - $BR_{\text{theo}} = 10^{-5} - 10^{-7}$  
    J. Fu, H.B. Li, X. Qin and M.Z. Yang,  

- Recent interest in $V \rightarrow P\gamma$ transitions of light unflavored mesons
  - NA60 result on $\omega \rightarrow \pi^0 e^+e^-$ not described by VMD
  - Recent measurements at SND, CMD-2, and KLOE on $\Phi$
    ➔ Test VMD
    \[
    |F_{VP}(q^2)| = \frac{1}{(1 - q^2/\Lambda^2)}
    \]

- Important for understanding of $P \rightarrow \gamma$ transitions
Dalitz Decays of $J/\Psi$

- $J/\psi \to P\, e^+e^-$, with $P = \pi^0, \eta, \eta'$
  
  $\eta' \to \pi^+\pi^-\gamma$
  $\to \pi^+\pi^-\eta \to \gamma\gamma$
  
  $\eta \to \pi^+\pi^-\pi^0 \to \gamma\gamma$
  $\eta \to \gamma\gamma$
  
  $\pi^0 \to \gamma\gamma$

- Background from other $J/\psi$ decays removed by kinematic cuts
- External conversion is main source of background
225 \cdot 10^6 \ J/\psi \text{ decays analyzed}

Background well under control

Good agreement of data and MC
Transition Form Factor

- TFF used to estimate systematic error

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

- Example: \( \eta' \)
  - Fit: \( \Lambda = (3.1 \pm 1.0) \text{ GeV/c}^2 \)
  - \( \Lambda = m_{\psi'} = 3.686 \text{ GeV/c}^2 \)
Branching Ratios

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching fraction</th>
<th>Combined Result</th>
<th>Theoretical prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \to \eta' e^+ e^- (\eta' \to \gamma \pi^+ \pi^-)$</td>
<td>$(6.01 \pm 0.20 \pm 0.34) \times 10^{-5}$</td>
<td>$(5.81 \pm 0.16 \pm 0.31) \times 10^{-5}$</td>
<td>$(5.66 \pm 0.16) \times 10^{-5}$</td>
</tr>
<tr>
<td>$J/\psi \to \eta' e^+ e^- (\eta' \to \pi^+ \pi^- \eta)$</td>
<td>$(5.51 \pm 0.29 \pm 0.32) \times 10^{-5}$</td>
<td>$(5.81 \pm 0.16 \pm 0.31) \times 10^{-5}$</td>
<td>$(5.66 \pm 0.16) \times 10^{-5}$</td>
</tr>
<tr>
<td>$J/\psi \to \eta e^+ e^- (\eta \to \pi^+ \pi^- \pi^0)$</td>
<td>$(1.12 \pm 0.13 \pm 0.06) \times 10^{-5}$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$J/\psi \to \eta e^+ e^- (\eta \to \gamma \gamma)$</td>
<td>$(1.17 \pm 0.08 \pm 0.06) \times 10^{-5}$</td>
<td>$(1.16 \pm 0.07 \pm 0.06) \times 10^{-5}$</td>
<td>$(1.21 \pm 0.04) \times 10^{-5}$</td>
</tr>
<tr>
<td>$J/\psi \to \pi^0 e^+ e^- (\pi^0 \to \gamma \gamma)$</td>
<td>$(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$</td>
<td>$(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$</td>
<td>$(3.89_{-0.33}^{+0.37}) \times 10^{-7}$</td>
</tr>
</tbody>
</table>

- First measurement of Dalitz decays $J/\psi \to P e^+ e^-$, with $P = \pi^0, \eta, \eta'$
- BR of decays with $P = \eta, \eta'$ in agreement with Theory
- $2.5 \sigma$ difference for $P = \pi^0$

**Space-like TFF**

**Single Tag Technique**
- Measure only
  - One scattered lepton
  - Decay products of meson
- Reconstruct second lepton from missing momentum
- Require small scattering angle

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Talk by Y. Guo
Tomorrow
Single Tag Technique

- Measure only
- One scattered lepton
- Decay products of meson
- Reconstruct second lepton from missing momentum
- Require small scattering angle

Example: Monte Carlo, Ψ(3770), L_{int}: 927 pb^{-1}, Tagged Lepton: e^{-}

\[ \begin{align*}
\pi^0 & \quad \text{2-Octet Model} \\
\eta & \quad \text{2-Octet Model} \\
q\bar{q} & \quad \text{continuum} \\
\Psi(3770) & \\
\text{Rad. Return (J/Ψ, Ψ')} & \\
\text{rad. Bhabha} & \\
\text{MC Sum} & \\
\end{align*} \]
Space-like TFF

Single Tag Technique

- Measure only
  - One scattered lepton
  - Decay products of meson
- Reconstruct second lepton from missing momentum
- Require small scattering angle

\[ Q_1^2 : \text{high virtuality} \]
\[ Q_2^2 : \text{quasi real} \]

\[ |F(Q_1^2, Q_2^2)|^2 \rightarrow |F(Q_1^2, 0)|^2 \rightarrow |F(Q^2)|^2 \]
Previous Measurements

- Recent results from B-factories cover only large $Q^2$ ($5 < Q^2 [\text{GeV}^2] < 40$)
- Discrepancy for $\pi^0$ between BaBar and Belle
- Data scarce at lowest $Q^2$
- Region of relevance for $(g-2)_\mu$

     Phys.Rev.D84 (2011) 052001
Feasibility Studies

Assumptions:

- $\sqrt{s} = 3.773$ GeV
- $L_{\text{int}} = 10$ fb$^{-1}$
- Only detector geometry

Result:

- TFF measurable up to $Q^2 = 10$ GeV$^2$
- Unprecedented accuracy below 4 GeV$^2$
- Above 4 GeV$^2$ accuracy comparable to CLEO
Analysis Example: $\pi^0 / \eta$

**Data**

- $\Psi(3770)$ on-peak, available: 2.92 fb$^{-1}$
- Monte Carlo
  - Signal: Ekhara 2.1
  - Background: Babayaga 3.5, KKMC

**Event Selection:**

- exactly one lepton candidate
- At least two, max four photons

**Expected Background Channels**

- Radiative Bhabha Scattering
- Hadronic Final States
- Two-Photon Production with ISR
- Two-Photon Production of other mesons
Analysis Steps

Helicity Condition for $\pi^0$

- Angle between $\gamma$ in $\pi^0$ rest frame and $\pi^0$ in lab
- Flat for signal
- Peaked for background
- Reject events with $\cos(\theta_H) > 0.8$

$L_{int} : 927 \text{ pb}^{-1}$, Tagged Lepton: $e^-$

Polar angle difference of $\gamma$ pair

- Strongly peaked for QED background
- Flat for hadronic background
- Dip for signal
- Reject events with $|\Delta \theta_{\gamma\gamma}| < 1.5^\circ$

$L_{int} : 927 \text{ pb}^{-1}$, Tagged Lepton: $e^-$

- Reduction of QED background

- Reduction of QED background
Analysis Steps

Polar angle of $\pi^0$

- Background enhanced at large $\cos(\theta_{\pi})$
- Signal almost evenly distributed
- Reject events with $\cos(\theta_{\pi}) \cdot q_{\text{tagged}} > 0.8$

$L_{\text{int}}: 927 \text{ pb}^{-1}$, Tagged Lepton: $e^-$

Condition on ISR

- ISR results in wrong $Q^2$
- Useful observable: $r_\gamma = \frac{\sqrt{s} - E_{e^\pm \pi^0 \eta}^{\text{CMS}} - p_{e^\pm \pi^0 \eta}^{\text{CMS}}}{\sqrt{s}}$
- If ISR, $r_\gamma = \frac{2E_\gamma}{\sqrt{s}}$
- Reject events with $r_\gamma < -0.1$ and $r_\gamma > 0.2$

$L_{\text{int}}: 927 \text{ pb}^{-1}$, Tagged Lepton: $e^-$

- Data/MC difference
- QED background reduced
- Hadronic background almost completely removed
Analysis Steps

- Study differential cross section $d\sigma/dQ^2$
- Bin wise background subtraction
- Statistics from $\Psi(3770)$ data only sufficient for $\pi^0$ TFF up to $Q^2 = 3$ GeV$^2$
  - Include large samples from XYZ searches

- Clear signals from $\pi^0 / \eta \to \gamma\gamma$
- Data: Background underestimated
  - Use better MC generators
    - modified Babayaga@NLO
    - two-photon generator

$L_{\text{int}} : 927$ pb$^{-1}$, Tagged Lepton: $e^-$
Expectations for $\pi^0$ TFF

- Full Simulation
  - $L_{\text{int}}$: 2.92 fb$^{-1}$
  - Single Tag with both, $e^\pm$
- Extract TFF for $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

- Expected statistical precision:
  - Unprecedented below $Q^2 = 1.5 \text{ GeV}^2$
  - Important for $(g-2)_\mu$
  - Compatible with CLEO

Next steps:

- Study systematics
  - Largest contribution expected from background subtraction
- Include high energy data
- Other final states
Summary

- BESIII is a good place to study time- and space-like meson transition form factors
- First measurement of Dalitz decays in the charmonium region
- $\gamma\gamma$ Physics program started at BES-III
  - Single tagged measurements of space-like TFF of $\pi^0$, $\eta$, $\eta'$
  - Significant contribution for $Q^2 < 10$ GeV$^2$
  - First result for $\pi^0$ expected soon
    - $0.3 \text{ GeV}^2 < Q^2 < 3.1 \text{ GeV}^2$ covered
    - Agreement with CELLO and CLEO measurements
    - Unprecedented accuracy for $Q^2 < 1.5$ GeV$^2$
  - Analyses of $\eta$ and $\eta'$ ongoing

- Long Term Plan
  - Measurements of scalar and tensor mesons
  - Measurements of polarization observables
  - Double tagged measurements

Talk by Yuping Guo Tomorrow