3-body decays of charmonium states at \textit{B\!A\!B\!A\!R}

Alessandro Pilloni
Thomas Jefferson National Accelerator Facility
on behalf of the B\!A\!B\!A\!R Collaboration

Salamanca September 26\textsuperscript{th}, 2017
Charmonium decays

Charmonium decays can be used to obtain new information on light meson spectroscopy. At $e^+e^-$ colliders, samples of charmonia can be obtained using different processes.

In the Initial State Radiation (ISR) process, we reconstruct events with a (undetected) forward $\gamma_{\text{ISR}}$. Only $J^{PC} = 1^{--}$ states can be produced.

In two-photon interactions we select events where the $e^+$ and $e^-$ are scattered at small angles and remain undetected. Only states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 3^{++}, 4^{\pm+}$ ...
Charmonium decays

- Measurement of the $I = 1/2 \ K\pi \ S$-wave amplitude from Dalitz plot analyses of $\eta_c \to K\bar{K}\pi$ in two-photon interactions
  
  \begin{itemize}
  \item Isobar model
  \item Model Independent Partial Wave Analysis (MIPWA)
  \end{itemize}

- Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^0\pi^0$, and $J/\psi \to K_S^0K^{\pm}\pi^{\mp}$, produced via $e^+e^-$ annihilation with initial-state radiation
  
  \begin{itemize}
  \item Isobar model
  \item Veneziano model
  \end{itemize}

BaBar coll., PRD93, 012005 (2016)
BaBar coll., PRD89, 112004 (2014)

BaBar coll., PRD95, 072007 (2017)

Charge conjugated modes are understood
Motivations

- $\eta_c \to K\bar{K}\pi$
  - The existence of a broad $\kappa$, or $K^*_0(800)$, is controversial
  - The major source for the $I = 1/2$ $K\pi$ $S$-wave is the LASS experiment, $K N \to K\pi N$. However, the extraction of the partial waves is affected by ambiguities, systematics for the extrapolation to the pion pole, and a contamination from $I = 3/2$ events.
  - The $\eta_c$ decay is dominated by $\eta_c \to 0^+ 0^-$, and the $K\pi$ $S$-wave is purely $I = 1/2$

- $J/\psi \to \pi^+ \pi^- \pi^0, J/\psi \to K\bar{K}\pi$
  - Source of the $\rho\pi$ puzzle, relevant for phenomenology
  - At high mass the Dalitz shows a broad structure, with a destructive interference of higher resonances
  - This is naturally realized by models implementing Regge asymptotics (Veneziano)

Charge conjugated modes are understood.
The **BABAR** experiment

The **BABAR** detector was located at the interaction point of PEP II at SLAC
Asymmetric $e^+e^-$ collider, mostly at $\sqrt{s} \sim 10.58$ GeV

\[ \int L \, dt \sim 0.5 \text{ ab}^{-1} \text{ close to the } \Upsilon(4S), \Upsilon(2S), \Upsilon(3S) \text{ peaks, } 670 \times 10^6 \, c\bar{c} \text{ pairs} \]
Measurement of the $I = 1/2$ $K\pi$ S-wave amplitude from Dalitz plot analyses of $\eta_c \to K\bar{K}\pi$ in two-photon interactions

BaBar coll., PRD93, 012005 (2016)
BaBar coll., PRD89, 112004 (2014)
$\gamma\gamma \rightarrow \eta_c \rightarrow K\bar{K}\pi$: Event selection

- $\gamma\gamma \rightarrow \eta_c \rightarrow K^0_S(\rightarrow \pi^+\pi^-)K^-\pi^+$, 4 tracks, $d(K^0_S) > 0.2$ cm
- $\gamma\gamma \rightarrow \eta_c \rightarrow K^+K^-\pi^0$ and, 2 tracks, $E_\gamma > 50$ MeV
- PID applied for Kaons and pions
- To select $\gamma\gamma$ events $p_T(\eta_c) < 80$ MeV for $K^0_SK^-\pi^+$ and $< 100$ MeV for $K^+K^-\pi^0$
- To veto ISR events, $(p_{e^+e^-} - p_{K\bar{K}\pi})^2 > 10$ GeV$^2$

12.8k events, 64% purity

6.5k events, 55% purity
\( \gamma \gamma \rightarrow \eta_c \rightarrow K\bar{K}\pi: \) Dalitz plot

We show the Dalitz plots in the signal region. The two channels look compatible. The sidebands also show resonant content.
$\gamma \gamma \to \eta_c \to K\bar{K}\pi$: Dalitz plot

We show the Dalitz plots in the signal region. The two channels look compatible. The sidebands also show resonant content.
$\gamma \gamma \rightarrow \eta_c \rightarrow K\bar{K}\pi$: DP analysis

$$\mathcal{L} = \prod_{n=1}^{N} \left[ f_{\text{sig}}(m_n) \epsilon(x'_n, y'_n) \frac{\sum_{i,j} c_i c_j^* A_i(x_n, y_n) A_j^*(x_n, y_n)}{\sum_{i,j} c_i c_j^* I_A i A_j^*} + (1 - f_{\text{sig}}(m_n)) \frac{\sum_i k_i B_i(x_n, y_n, m_n)}{\sum_i k_i I_{B_i}} \right]$$

Amplitudes

Signal fraction

Efficiency

Background (from sidebands)

Resonances are parametrized with relativistic Breit-Wigners

$$F = \text{Blatt-Weisskopf barrier factor} \quad \Gamma(m_{K\pi}) \propto \frac{p}{m_{K\pi} F^2} \quad \text{for} \quad K_0^* (1430), \quad \Gamma = \text{constant for the other ones}$$

Alternatively, one can extract the $K\pi$ S-wave without any model assumptions (MIPWA)

E791, PRD73 032004 (2006)

$$A(m_{K\pi}, m_{\bar{K}\pi}) = \frac{1}{\sqrt{2}} \left( a(m_{K\pi}) e^{i\phi_{K\pi}} + a(m_{\bar{K}\pi}) e^{i\phi_{\bar{K}\pi}} \right)$$

- Positive G-parity sets the relative sign of the two terms
- We divide the $K\pi$ mass range in 30 bins, and fit for any bin a complex number
- Still an isobar model, but the lineshape is not predetermined
$\gamma \gamma \rightarrow \eta_c \rightarrow K\bar{K}\pi$: Results

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>$\eta_c \rightarrow K_0^0 K_{\pm}^{\mp} \pi^{\mp}$</th>
<th>$\eta_c \rightarrow K^{\pm} K^{-} \pi^{0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fraction (%)</td>
<td>Phase (rad)</td>
</tr>
<tr>
<td>$K_0^*(1430)\bar{K}$</td>
<td>40.8 ± 2.2</td>
<td>0.</td>
</tr>
<tr>
<td>$K_0^*(1950)\bar{K}$</td>
<td>14.8 ± 1.7</td>
<td>-1.00 ± 0.07</td>
</tr>
<tr>
<td>NR</td>
<td>18.0 ± 2.5</td>
<td>1.94 ± 0.09</td>
</tr>
<tr>
<td>$a_0(980)\pi$</td>
<td>10.5 ± 1.2</td>
<td>0.94 ± 0.12</td>
</tr>
<tr>
<td>$a_0(1450)\pi$</td>
<td>1.7 ± 0.5</td>
<td>2.94 ± 0.13</td>
</tr>
<tr>
<td>$a_1(1500)\pi$</td>
<td>0.7 ± 0.2</td>
<td>-1.76 ± 0.24</td>
</tr>
<tr>
<td>$a_2(1320)\pi$</td>
<td>0.2 ± 0.2</td>
<td>-0.53 ± 0.42</td>
</tr>
<tr>
<td>$K_2^*(1430)\bar{K}$</td>
<td>2.3 ± 0.7</td>
<td>-1.55 ± 0.11</td>
</tr>
<tr>
<td>Total</td>
<td>88.8 ± 4.3</td>
<td>—</td>
</tr>
<tr>
<td>$\chi^2/N_{\text{cells}}$</td>
<td>467/256=1.82</td>
<td>—</td>
</tr>
</tbody>
</table>

Large nonresonant component

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>$\eta_c \rightarrow K_0^0 K_{\pm}^{\mp} \pi^{\mp}$</th>
<th>$\eta_c \rightarrow K^{\pm} K^{-} \pi^{0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fraction (%)</td>
<td>Phase (rad)</td>
</tr>
<tr>
<td>$(K\pi \text{ S-wave}) \bar{K}$</td>
<td>107.3 ± 2.6 ± 17.9</td>
<td>fixed</td>
</tr>
<tr>
<td>$a_0(980)\pi$</td>
<td>0.8 ± 0.5 ± 0.8</td>
<td>1.08 ± 0.18 ± 0.18</td>
</tr>
<tr>
<td>$a_0(1450)\pi$</td>
<td>0.7 ± 0.2 ± 1.4</td>
<td>2.63 ± 0.13 ± 0.17</td>
</tr>
<tr>
<td>$a_1(1500)\pi$</td>
<td>3.1 ± 0.4 ± 1.2</td>
<td>-1.04 ± 0.08 ± 0.77</td>
</tr>
<tr>
<td>$a_2(1320)\pi$</td>
<td>0.2 ± 0.1 ± 0.1</td>
<td>1.85 ± 0.20 ± 0.20</td>
</tr>
<tr>
<td>$K_2^*(1430)\bar{K}$</td>
<td>4.7 ± 0.9 ± 1.4</td>
<td>4.92 ± 0.05 ± 0.10</td>
</tr>
<tr>
<td>Total</td>
<td>116.8 ± 2.8 ± 18.1</td>
<td>—</td>
</tr>
<tr>
<td>$-2 \log \mathcal{L}$</td>
<td>-4314.2</td>
<td>—</td>
</tr>
<tr>
<td>$\chi^2/N_{\text{cells}}$</td>
<td>301/254=1.17</td>
<td>—</td>
</tr>
</tbody>
</table>

$\chi^2$ improved
\[ \gamma \gamma \rightarrow \eta_c \rightarrow K \bar{K} \pi: \text{a new } a_0(1950) \]

The significance is \(2.5\sigma\) for \(K_S^0 K^- \pi^+\) and \(4.0\sigma\) for \(K^+ K^- \pi^0\).
$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: results MIPWA

A. Pilloni – 3-body decays of quarkonium states at BABAR
Clear $K_0^*(1430)$ in amplitude and phase, compatible with a Breit-Wigner expectation
Some evidence for a broad $K_0^*(1950)$ contribution

$K\eta$ $K\eta'$

$K_S^0\pi^+ + K^-\pi^+$ $K^+\pi^0 + K^-\pi^0$
S-wave $K\pi$ from other experiments

This extraction does not agree with the previous ones,
LASS NPB296, 493 (1988)
E791, PRD73, 032004 (2006)
(arbitrarily rescaled)

The phase agrees until the $K\eta'$ threshold, as expected by Watson theorem
Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^-\pi^0$, and $J/\psi \to K_S^0 K^\pm \pi^\mp$, produced via $e^+e^-$ annihilation with initial-state radiation

BaBar coll., PRD95, 072007 (2017)
$J/\psi \rightarrow 3h$: Event selection

- $J/\psi \rightarrow K_S^0(\rightarrow \pi^+\pi^-)K^-\pi^+, 4$ tracks, $d(K_S^0) > 0.2$ cm
- $J/\psi \rightarrow K^+K^-\pi^0$ and $\rightarrow \pi^+\pi^-\pi^0, 2$ tracks, $E_\gamma > 100$ MeV
- PID applied for Kaons and pions
- ISR events, $|(p_{e^+e^-} - p_{h^+h^-\pi^0})^2| < 2$ GeV$^2$, $|(p_{e^+e^-} - p_{K_S^0K^-\pi^+})^2| < 1.5$ GeV$^2$
- If $\gamma_{ISR}$ falls in the acceptance of EMC, the observation of a compatible photon is required
- Small background from $e^+e^- \rightarrow \gamma\pi^+\pi^-$, removed with $|\cos \theta_{\pi}| < 0.95$

**Graphs:**
- $J/\psi \rightarrow \pi^+\pi^-\pi^0$: 20k events, 91.3% purity
- $J/\psi \rightarrow K^+K^-\pi^0$: 2.1k events, 88.8% purity
- $J/\psi \rightarrow K_S^0K^-\pi^+$: 3.9k events, 93.1% purity
\[ J/\psi \rightarrow 3h: \text{Branching ratios and Dalitz plots} \]

\[ R_1 = \frac{BR(J/\psi \rightarrow K_S^0 K^- \pi^+)}{BR(J/\psi \rightarrow \pi^+ \pi^- \pi^0)} = 0.120 \pm 0.003 \pm 0.009 \]

\[ R_2 = \frac{BR(J/\psi \rightarrow K^+ K^- \pi^0)}{BR(J/\psi \rightarrow \pi^+ \pi^- \pi^0)} = 0.265 \pm 0.005 \pm 0.021 \]

\[ R_1^{PDG} = 0.133 \pm 0.038 \quad \text{PDG based on Mark II (25 events) and Mark I (126 events)} \]

\[ R_2^{PDG} = 0.123 \pm 0.033 \]

**Systematics**

<table>
<thead>
<tr>
<th>Effect</th>
<th>( R_1 ) (%)</th>
<th>( R_2 ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>7.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Particle identification</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>( K_S^0 ) reconstruction</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>( \pi^0 ) reconstruction</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Mass fits</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>7.9</td>
<td>8.0</td>
</tr>
</tbody>
</table>
$J/\psi \to \pi^+ \pi^- \pi^0$: Isobar model

Relativistic Breit Wigner are used in the fit.

We free the $\rho(1450)$ and $\rho(1700)$ parameters and get

- $M(\rho(1450)) = 1429 \pm 41$ MeV
- $\Gamma(\rho(1450)) = 576 \pm 29$ MeV
- $M(\rho(1700)) = 1644 \pm 36$ MeV
- $\Gamma(\rho(1700)) = 109 \pm 19$ MeV
$J/\psi \to \pi^+ \pi^- \pi^0$: Veneziano model

\[ A(s, t, \lambda) = \epsilon_{\mu\nu\rho\sigma} p^+_\mu p^-_\nu p^0_\rho \epsilon(p^\psi, \lambda) \sum_{1 \leq m \leq n} \frac{\Gamma(n - \alpha(s)) \Gamma(n - \alpha(t))}{\Gamma(n + m - \alpha(s) - \alpha(t))} \]

\[ \alpha(s) = \alpha_0 + \alpha' s + i \gamma \sqrt{s - s_0} \]

The Veneziano amplitude has a natural smooth behavior at higher energies.

Final state Veneziano fraction (%)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)\pi$</td>
<td>133.1 ± 3.3</td>
</tr>
<tr>
<td>$\rho(1450)\pi$</td>
<td>0.80 ± 0.27</td>
</tr>
<tr>
<td>$\rho(1700)\pi$</td>
<td>2.20 ± 0.60</td>
</tr>
<tr>
<td>$\rho(2150)\pi$</td>
<td>6.00 ± 2.50</td>
</tr>
<tr>
<td>$\omega(783)\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$\rho_3(1690)\pi$</td>
<td>0.40 ± 0.08</td>
</tr>
<tr>
<td>Sum</td>
<td>142.5 ± 2.8</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>596/508 = 1.17</td>
</tr>
</tbody>
</table>

Pennington, Szczepaniak, PLB737, 283 (2014)

Data description equivalent to the isobar model
\[ J/\psi \rightarrow K^+ K^- \pi^0 \text{ and } \rightarrow K_S^0 K^- \pi^+ \]

A. Pilloni – 3-body decays of quarkonium states at BABAR
\[ J/\psi \rightarrow K^+ K^- \pi^0 \text{ and } K_S^0 K^- \pi^+ \]

BESII interpreted the broad peak as an exotic \( 1^{--} \) state

BESII, PRL97, 142002 (2006)

No need for that
$J/\psi \rightarrow K^+ K^- \pi^0$ and $\rightarrow K_s^0 K^- \pi^+$

$$\frac{BR(\rho(1450)^0 \rightarrow K^+ K^-)}{BR(\rho(1450)^0 \rightarrow \pi^+ \pi^-)} = 0.307 \pm 0.084 \pm 0.082$$

<table>
<thead>
<tr>
<th>Final state</th>
<th>fraction (%)</th>
<th>phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^\pm \bar{K}^\mp$</td>
<td>92.4 ± 1.5 ± 3.4</td>
<td>0.</td>
</tr>
<tr>
<td>$\rho(1450)^0 \pi^0$</td>
<td>9.3 ± 2.0 ± 0.6</td>
<td>3.78 ± 0.28 ± 0.08</td>
</tr>
<tr>
<td>$K^*(1410)^\pm \bar{K}^\mp$</td>
<td>2.3 ± 1.1 ± 0.7</td>
<td>3.29 ± 0.26 ± 0.39</td>
</tr>
<tr>
<td>$K_2^*(1430)^\pm \bar{K}^\mp$</td>
<td>3.5 ± 1.3 ± 0.9</td>
<td>−2.32 ± 0.22 ± 0.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>107.4 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>132/137 = 0.96</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final state</th>
<th>fraction (%)</th>
<th>phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)\bar{K}$</td>
<td>90.5 ± 0.9 ± 3.8</td>
<td>0.</td>
</tr>
<tr>
<td>$\rho(1450)^\pm \pi^\mp$</td>
<td>6.3 ± 0.8 ± 0.6</td>
<td>−3.25 ± 0.13 ± 0.21</td>
</tr>
<tr>
<td>$K_1^*(1410)\bar{K}$</td>
<td>1.5 ± 0.5 ± 0.9</td>
<td>1.42 ± 0.31 ± 0.35</td>
</tr>
<tr>
<td>$K_2^*(1430)\bar{K}$</td>
<td>7.1 ± 1.3 ± 1.2</td>
<td>−2.54 ± 0.12 ± 0.12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>105.3 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>274/217 = 1.26</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• Measurement of the \( I = 1/2 \) \( K\pi \) \( S \)-wave amplitude from Dalitz plot analyses of \( \eta_c \rightarrow K\bar{K}\pi \) in two-photon interactions

  BaBar coll., PRD93, 012005 (2016)

  • MIPWA allows to extract a reliable \( K\pi \) \( S \)-wave, which does not look to agree with other experiments

• Dalitz plot analyses of \( J/\psi \rightarrow \pi^+\pi^-\pi^0 \), \( J/\psi \rightarrow K^+K^-\pi^0 \), and \( J/\psi \rightarrow K_S^0K^{\pm}\pi^\mp \), produced via \( e^+e^- \) annihilation with initial-state radiation

  BaBar coll., PRD95, 072007 (2017)

  • The Isobar and Veneziano model offer a complementary description of the Dalitz plot for the \( \pi^+\pi^-\pi^0 \)

  Thank you!
BACKUP
\( \gamma \gamma \rightarrow \eta_c \rightarrow K\bar{K}\pi \): Event selection

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- \( \gamma \gamma \rightarrow \eta_c \rightarrow K^+K^-\pi^0 \) and, 2 tracks, \( E_\gamma > 50 \) MeV
- PID applied for Kaons and pions
- To select \( \gamma \gamma \) events \( p_T(\eta_c) < 80 \) MeV, to veto ISR events, \( (p_{e^+e^-} - p_{\bar{K}K\pi})^2 > 10 \text{ GeV}^2 \)
$\eta_c \rightarrow K\bar{K}\pi$: Sidebands
$\gamma \gamma \rightarrow \eta_c \rightarrow K \overline{K} \pi$: Efficiency

\[
\sum_{L=1}^{12} a_L(m) Y_L(\cos \theta)
\]

$\eta_c \rightarrow K_S^0 K^- \pi^+$

$a_L(m)$: 7th order polynomial

$\eta_c \rightarrow K^+ K^- \pi^0$

A. Pilloni – 3-body decays of quarkonium states at BABAR
$J/\psi \rightarrow 3h$: Event selection

$M_{miss}^2$ cuts

MC data

$J/\psi \rightarrow \pi^+\pi^-\pi^0$

$J/\psi \rightarrow K^+K^-\pi^0$

$J/\psi \rightarrow K_S^0K^+\pi^-$
$J/\psi \rightarrow 3h$: Efficiency

$$\sum_{L=1}^{12} a_L(m) Y_L(\cos \theta)$$

$a_L(m)$: 7th order polynomial