Searches for charmonium-like (exotic) XYZ states decaying to light hadrons at BESIII

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GU Frankfurt, GSI Darmstadt
on behalf of the BESIII Collaboration

QWG 2019
May 13th - 17th 2019, Torino, Italy

Outline

• Introduction & motivation
• Searches for charmless decays
  ➢ Searches for Y(4260) via cross-section line-shapes
  ➢ Searches for Z_c(3900) decays to light hadrons
• Summary
Famous exotic (?) XYZ states

\[ \Upsilon(4260) \rightarrow J/\psi \pi \pi \]

\[ Z_c(3900) \rightarrow J/\psi \pi \]

[1] [PRL 118 (2017) 092001]

Motivation

• Series of unexpected vector charmonium-like states
  - (mainly) observed in decays associated with charmonia
• $R$-value at 4.0 – 4.6 GeV is about $\sim 4$ => total cross-section 16 nb
Motivation

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  - (mainly) observed in decays associated with charmonia
- $R$-value at 4.0 – 4.6 GeV is about $\sim 4 \Rightarrow$ total cross-section 16 nb
  - Open charm: 10 nb $\Rightarrow$ The other 6 nb only charmonium transition?

W.M. Song, [Ph.D. thesis 2015]

Inclusive open charm cross-section
Motivation

- Series of unexpected vector charmonium-like states (mainly) observed in decays associated with charmonia
- $R$-value at $4.0 - 4.6$ GeV is about $\sim 4$ => total cross-section $16\text{nb}$
- Open charm: $10\text{ nb}$ => The other $6\text{ nb}$ only charmonium transition

![Graph showing $R$ value vs. $E_{cm}$](graph.png)

$R = \frac{\sigma(e^-e^+ \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \mu^-\mu^+)}$

[PRL 88 (2002) 101802]
• Series of unexpected vector charmonium-like states
  - (mainly) observed in decays associated with charmonia
• \( R \)-value at 4.0 – 4.6 GeV is about ~ 4 => total cross-section 16 nb
  - Open charm: 10 nb => The other 6 nb only charmonium transition?

Motivation

-> What about charmless decays of \( Y(4260) \) & Co?

As predicted e.g. by:
PLB 628 (2005) 215, or
CPC 39 (2015) 063102
**Cross-section measurement**

$\sigma_B(e^+e^- \rightarrow p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- Cross-sections $e^+e^- \rightarrow \psi(3770) \rightarrow p\bar{p}\pi^0$ around 3.77 GeV measured previously, interferences included (resonant with continuum production):
  - Two solutions of same probability
    - a) $33.8 \pm 1.8 \pm 2.1$ pb, and
    - b) $< 0.22$ pb at 90% CL
  - Both fit solutions consistent with destructive interference ($270^\circ$)

- Cross-section $p\bar{p} \rightarrow \psi(3770)\pi^0$
  - Using constant decay amplitude approximation: $122 \pm 10$ nb, and
  - $< 0.79$ nb at 90% CL at 5.26 GeV (PANDA)

Cross-section measurement
\[ \sigma_B(e^+e^- \rightarrow p\bar{p}\pi^0) \] between 4.0 – 4.6 GeV

- PWA to correctly determine detection efficiencies
  - Dalitz plot at 4.26 GeV
  - MC data generated from PWA result vs. real data

- Multi intermediate baryons:
  - \( N^*, \Delta^* \rightarrow p\bar{p}\pi^0, p\pi^0, \bar{p}\pi^0 \)
  - \( \rho^*, \omega^* \rightarrow p\bar{p} \)

- Partial wave analysis:
  - Covariant tensor formalism
    - [J. Phys. G28,233]
  - Breit-Wigner param. of \( \rho^*N^*, \Delta^* \) [RPD80,052004]
  - Direct process \( e^+e^- \rightarrow p\bar{p}\pi^0: 1^{--} \) or \( 3^{--} p\bar{p} \) system
  - Resonance > 5\( \sigma \) are retained

Cross-section measurement \( \sigma_B(e^+e^- \rightarrow p\bar{p}\pi^0) \) between 4.0 – 4.6 GeV

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  - Resonance > 5\( \sigma \) are retained

Cross-section measurement
$\sigma_B(e^+e^- \rightarrow p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- Born cross section:
  - radiative correction factor $(1 + \delta^r)$
  - vacuum polarisation factor $(1 + \delta^v)$

$$\sigma^B = \frac{N^{\text{obs}}}{\mathcal{L} \cdot (1 + \delta^r) \cdot (1 + \delta^v) \cdot \epsilon \cdot B_{\pi^0}}$$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}$ [pb$^{-1}$]</th>
<th>$(1 + \delta^r)$</th>
<th>$(1 + \delta^v)$</th>
<th>$N^{\text{obs}}$</th>
<th>$\epsilon$ [%]</th>
<th>$\sigma^B$ [pb]</th>
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<td>43.9 ± 0.9</td>
<td>5.09 ± 0.18  ±0.26 -0.24</td>
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<td>106 ± 11</td>
<td>43.7 ± 1.4</td>
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<td>1.025</td>
<td>1.056</td>
<td>75 ± 9</td>
<td>44.7 ± 1.0</td>
<td>3.64 ± 0.43  ±0.19 -0.18</td>
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<td>4.208</td>
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<td>1.057</td>
<td>93 ± 10</td>
<td>44.9 ± 1.6</td>
<td>3.52 ± 0.39  ±0.17 -0.22</td>
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<td>1.034</td>
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<td>43.4 ± 1.3</td>
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<td>45.2 ± 0.5</td>
<td>3.15 ± 0.08  ±0.14</td>
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<td>89 ± 9</td>
<td>44.6 ± 1.1</td>
<td>3.30 ± 0.36  ±0.19 -0.15</td>
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<td>4.258</td>
<td>825.6</td>
<td>1.048</td>
<td>1.054</td>
<td>1203 ± 35</td>
<td>43.4 ± 0.5</td>
<td>3.08 ± 0.10  ±0.14 -0.15</td>
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<td>4.308</td>
<td>44.9</td>
<td>1.063</td>
<td>1.053</td>
<td>53 ± 8</td>
<td>46.0 ± 1.4</td>
<td>2.32 ± 0.33  ±0.15 -0.10</td>
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<td>4.358</td>
<td>539.8</td>
<td>1.081</td>
<td>1.051</td>
<td>668 ± 26</td>
<td>44.7 ± 1.1</td>
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<tr>
<td>4.387</td>
<td>55.2</td>
<td>1.087</td>
<td>1.051</td>
<td>57 ± 8</td>
<td>47.5 ± 1.8</td>
<td>1.92 ± 0.26  ±0.10</td>
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<td>4.416</td>
<td>1028.9</td>
<td>1.098</td>
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<td>1133 ± 34</td>
<td>44.6 ± 0.6</td>
<td>2.16 ± 0.10  ±0.10 -0.11</td>
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<td>4.600</td>
<td>566.9</td>
<td>1.124</td>
<td>1.055</td>
<td>474 ± 22</td>
<td>43.8 ± 0.8</td>
<td>1.63 ± 0.08  ±0.08</td>
</tr>
</tbody>
</table>

Cross-section measurement
\( \sigma_B(e^+e^- \rightarrow p\bar{p}\pi^0) \) between 4.0 – 4.6 GeV

- No significant resonant structure
  - Least square fit to cross-section:
    \[
    \sigma(s) = \left| \sqrt{\sigma_{\text{con}}} + \sqrt{\sigma_Y} \frac{m\Gamma}{s - m^2 + im\Gamma} \exp(i\phi) \right|^2
    \]
  - Continuum process: \( \sqrt{\sigma_{\text{con}}} \propto \frac{1}{s^n} \)
  - \( Y(4260) \) with \( (m,\Gamma) \) from PDG
  - \( \phi = 3.4 \pm 1.0 \), \( \sigma_Y = (1.6 \pm 5.9) \times 10^{-3} \text{ pb} \) (0.5\( \sigma \))
  - No multiple solutions

- Obtained upper limit at 90% CL on
  \( e^+e^- \rightarrow Y(4260) \rightarrow p\bar{p}\pi^0 \)
  (most conservative) estimate:
  \( \Rightarrow \sigma < 0.01 \text{ pb} \)
Precision measurement of $\sigma_B(e^+e^- \to K_s K^{+/−}π^{−/+})$ between 3.8 – 4.6 GeV

- Based on 5.0 fb$^{-1}$ between 3.8 – 4.6 GeV → *energy-dependent Born cross-section*

- Dalitz plots for $e^+e^- \to K_s K^{+−}π^−$ at 4.23 GeV, real vs MC data generated from PWA result

- Various bands visible:
  - $K^*(892), K_2^*(1430) \to K^{+/−}π^{−/+}$ (*vertical*)
  - $K_2^*(1430)^{+−} \to K_s π^{−/+}$ (*horizontal*)
  - e.g. excited $ρ^{+/−}, a_2(1320)^{+−} \to K_s K^−$ (*diagonal*)

- PWA of $K_s K^{+−}π^−$ system at different $E_{cms}$ (relativistic BWs, covariant helicity method)
  - determination of reconstruction efficiencies
Precision measurement of $\sigma_B(e^+e^- \rightarrow K_s K^{+/-}\pi^{-/+})$ between 3.8 – 4.6 GeV

- Amplitude fit result at 4.23 GeV \textit{(MC projections according to PWA result)}

- Inv. masses for $K^+\pi$, $K_s\pi$ and $K_sK$ and polar angle distributions for $\pi$, $K$ and $K_s$ \textit{Good agreement to data}

Precision measurement of $\sigma_B(e^+e^- \rightarrow K_s K^{+/-}\pi^{-/+})$ between 3.8 – 4.6 GeV

- Energy dependent cross section of $e^+e^- \rightarrow K_s K^{+}\pi^{-}$
  - In agreement to BaBar but much higher precision

[BarBar: PRL 95 (2005) 142001]

Precision measurement of $\sigma_B(e^+e^- \to K_s K^{+/-}\pi^{/-/+})$ between 3.8 – 4.6 GeV

- Energy dependent cross section of $e^+e^- \to K_s K^+\pi^-$
  
  $\rightarrow$ In agreement to BaBar but much higher precision

- Zoomed in BESIII data together with fit of continuum process only
  
  $\rightarrow$ does not describe access at about 4.2 GeV

Precision measurement of $\sigma_B(e^+e^- \rightarrow K_s K^{+/−}\pi^{−/+})$ between 3.8 – 4.6 GeV

- Energy dependent cross section of $e^+e^- \rightarrow K_s K^+\pi^-$
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  → and additional resonance, $\psi(4160)$ (left) or $Y(4220)$ (right)

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**Precision measurement of** \( \sigma_B(e^+e^- \rightarrow K_s K^{+/−}π^{−/+}) \) **between 3.8 – 4.6 GeV**

- Energy dependent cross section of \( e^+e^- \rightarrow K_s K^{+}π^- \)
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- More energy points and larger statistics needed for deeper understanding of possible structures and cc-like states ....

- Zoomed in BESIII data together with fit of continuum process
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Search for $Y(4260)$ and $Z_c(3900)$ in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

- Based on 17 $E_{\text{cm}}$ points, in the range of 3.8 – 4.6 GeV
- Invariant mass distributions $\pi\pi$ vs. $\gamma\gamma$ at $\sqrt{s} = 4.26$ GeV
  $\Rightarrow$ clear $K_s$ and $\pi/\eta$ peaks
- Sidebands:
  \[ N_{\text{sig}} = N_A - \sum N_B/2 + \sum N_C/4 \]

Search for $\text{Y}(4260)$ and $\text{Z}_c(3900)$ in $e^+e^- \rightarrow K_S K \pi \pi^0$ and $K_S K \pi \eta$

- Examples of invariant masses for 2- and 3-body final states, here at 4.26 GeV
  $\rightarrow$ intermediate resonances
  such as $\rho(770)$ or $K^*(890)$

- MC shape of $\text{Z}_c(3900)$ as pink dash-dotted line, arbirtary scale

Search for $Y(4260)$ and $Z_c(3900)$ in $e^+e^- \rightarrow K_S K \pi \pi^0$ and $K_S K \pi \eta$

- Energy-dependent Born cross-sections:

$$\sigma_B = \frac{N_{\text{sig}}}{\mathcal{L} \cdot \mathcal{B} \cdot \epsilon \cdot (1 + \delta_{\text{ISR}}) \cdot \frac{1}{|1 - \Pi(s)|^2}}$$

- MC shape of $Y(4220)$ as pink dash-dotted line, arbitrary scale

- No clear structure observed, CL90 ULs
  - $\text{BR} \times \Gamma_{e^+e^-} < 0.05$ eV ($\pi^0$ mode)
  - $\text{BR} \times \Gamma_{e^+e^-} < 0.19$ eV ($\eta$ mode)

- Comparing to $J/\psi \pi \pi$ ($1.5 - 13.3$ eV), much smaller possible couplings for decays to light hadrons

Search for $Y(4260)$ and $Z_c(3900)$ in $e^+e^- \rightarrow K_s K \pi \pi^0$ and $K_s K \pi \eta$

- Search for and upper limits on $Z_c(3900)$ production at 5 $E_{\text{cms}}$

- And ratios

\[ R = \frac{\sigma_B(e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi K^0_S K \pi/\eta)}{\sigma_B(e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi \pi J/\psi)} \]

- No obvious signal observed in charged nor neutral mode

- Unbinned max. likelihood fit to $K_s K \pi \pi^0/\eta, 3.7 - 4.1$ GeV

- CL90 ULs provided at 5 $E_{\text{cms}}$

=> Cross section for decays to light hadrons small

Search for $Y(4260)$ and $Z_c(3900)$ in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

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- CL90 ULs provided at 5 $E_{\text{cms}}$

$$\sqrt{s} \ (\text{GeV}) \quad \sigma_B \ (\text{pb}) \quad R$$

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<th>4.226</th>
<th>&lt; 0.24</th>
<th>&lt; 2.5 \times 10^{-2}</th>
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<td>$e^+e^- \to \pi^0 Z_c(3900)^0$,</td>
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= $\frac{\sqrt{s}}{4.226} < 0.17 < 9.1 \times 10^{-3}$

$$\sqrt{s} \ (\text{GeV}) \quad \sigma_B \ (\text{pb})$$

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$$\frac{\sqrt{s}}{4.226} < 0.18 < 1.0 \times 10^{-2}$$

$$\sqrt{s} \ (\text{GeV}) \quad \sigma_B \ (\text{pb})$$

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Annihilation of $c\bar{c}$ quarks in $Y(4260)$ & $Z_c(3900)$ suppressed

Search for $Z_c(3900)$ in $e^+e^- \to \omega \pi^+ \pi^-$

- Invariant $\pi^+\pi^-\pi^0$ mass distribution for selected $\pi^+\pi^-\pi^+\pi^-\pi^0$ events at $\sqrt{s} = 4.23$ GeV
  \rightarrow clear \eta, \omega and \phi peaks

- Invariant $\omega\pi^\pm$ mass distribution at $\sqrt{s} = 4.23$ GeV
  - Data events in $\omega$ region
  - Events selected from sidebands
  - Inclusive MC events (blue) dominated by continuum

Search for $Z_c(3900)$ in $e^+e^- \to \omega \pi^\mp \pi^\mp$

- Unbinned, extended maximum likelihood fit to $\omega \pi^\pm$ system
  - Separately at $\sqrt{s} = 4.23$ and 4.26 GeV
  - Signal PDF parameterisation S-wave BW convolved with Gaussian
  - Background described by ARGUS function

- Results, Born cross sections and ULs:
  - $\sqrt{s} = 4.23$ GeV: $14 \pm 11$ events, $1.2\sigma$
  - $\sqrt{s} = 4.26$ GeV: $2.2 \pm 8.1$ events, $0.1\sigma$
  - CL90 upper limits, Bayesian method:
    - 33.5 and 18.8 events
  - ULs: $\sigma_B < 0.26$ and 0.18 pb

\[
\sigma(e^+e^- \to Z_c(3900)^\pm \pi^\mp, Z_c(3900)^\pm \to \omega \pi^\pm) = \frac{N^{UL}}{L_{\text{int}} (1 + \delta) \frac{1}{|1 - \Pi|^2} \epsilon (1 - \sigma_\epsilon) B_\omega B_{\pi^0}}
\]

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Non-observation of $Z_c(3900) \rightarrow \omega \pi^\pm$

-> typical decay channel for a $1^+$ resonance, indicates $c\bar{c}$ annihilation in $Z_c(3900)$ suppressed

$\sigma(e^+e^- \rightarrow Z_c(3900) \pi^\mp, Z_c(3900) \rightarrow \omega \pi^\pm) = \frac{N^{UL}}{L_{int}(1+\delta)\frac{1}{|1-\Pi|^2} \epsilon(1-\sigma_e)B_\omega B_{\pi^0}}$

Summary & outlook

• BESIII major contributions to XYZ puzzle
  ➢ Charmless decays predicted for various nature interpretations for both, \( Y(4260) \) and \( Z_c(3900) \)
  ➢ Several possible decay channels for light hadrons checked
    => No obvious signals observed

• Annihilation of \( c\bar{c} \) quarks in \( Y(4260) \) & \( Z_c(3900) \) seems to be heavily suppressed

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>( Y(4260) )</th>
<th>( Z_c(3900) )</th>
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<td>( p\bar{p}\pi^0 )</td>
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<tr>
<td>( K_sK\pi</td>
<td>✓</td>
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<tr>
<td>( K_sK(\pi)\pi^0</td>
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<td>✓</td>
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<tr>
<td>( K_sK(\pi)\eta</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>( \omega\pi</td>
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<tr>
<td>( p\bar{n}K_sK</td>
<td>✓</td>
<td>✓</td>
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</table>

Outlook:

• More precision (energy scan) data around \( Y(4220) \) and further vector states needed (4.1 – 4.4 GeV)
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Stay tuned for more BESIII results, helping to solve the XYZ puzzle ... !
The BESIII Collaboration

14 countries
67 institutions
~500 members
First measurement of $e^+e^- \rightarrow pK^-\bar{n}K$ above open charm threshold

The process $e^+e^- \rightarrow pK^0_S\bar{n}K^- + c.c.$ and its intermediate processes are studied for the first time, using data samples collected with the BESIII detector at BEPCII at center-of-mass energies of 3.773, 4.008, 4.226, 4.258, 4.358, 4.416, and 4.600 GeV, with a total integrated luminosity of 7.4 fb$^{-1}$. The Born cross section of $e^+e^- \rightarrow pK^0_S\bar{n}K^- + c.c.$ is measured at each center-of-mass energy, but no significant resonant structure in the measured cross-section line shape between 3.773 and 4.600 GeV is observed. No evident structure is detected in the $pK^-, nK^0_S, pK^0_S, nK^+, p\bar{n}$, or $K^0_S\bar{K}^-$ invariant mass distributions except for $\Lambda(1520)$. The Born cross sections of $e^+e^- \rightarrow \Lambda(1520)\bar{n}K^0_S + c.c.$ and $e^+e^- \rightarrow \Lambda(1520)pK^+ + c.c.$ are measured, and the 90% confidence level upper limits on the Born cross sections of $e^+e^- \rightarrow \Lambda(1520)\bar{\Lambda}(1520)$ are determined at the seven center-of-mass energies. There is an evident difference in line shape and magnitude of the measured cross sections between $e^+e^- \rightarrow \Lambda(1520)(\rightarrow pK^-)\bar{n}K^0_S$ and $e^+e^- \rightarrow pK^-\bar{\Lambda}(1520)(\rightarrow \bar{n}K^0_S)$. 