Latest results from BESIII

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on behalf of the BESIII Collaboration

Selected Problems In Quantum Field Theory

Seminar devoted to the memory of Prof. E.A. Kuraev

JINR, Dubna, Russia

April 6-8, 2015
BEPCII Storage Rings

- Beam energy: \(1.0 - 2.3\) GeV
- Design Luminosity: \(1 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\)
- Achieved Luminosity: \(
\sim 0.85 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\)
- Optimum energy: \(1.89\) GeV
- Energy spread: \(5.16 \times 10^{-4}\)
- No. of bunches: 93
- Bunch length: 1.5 cm
- Total current: 0.91 A
- Circumference: 237m
The BESIII Spectrometer @ IHEP

BEijing Spectrometer III

e^+e^- collisions

\sqrt{S} tuned depending on energy

Physics program

- Charmonium Physics
- D-Physics
- Light Hadron Spectroscopy
- \tau-Physics
- ...

BESIII Production of Charmonium(like) states

From PDG

BEPCII can reach here!
BESIII Production of Charmonium(like) states

- 3554 MeV: 0.024 fb⁻¹ \( \tau \) mass
- \( 4100 \div 4400 \) MeV: 0.5 fb⁻¹ coarse scan
- \( 3850 \div 4590 \) MeV: 0.5 fb⁻¹ fine scan

From PDG

1.3 \times 10^9

6 \times 10^8

3773
2.9 fb⁻¹

4040
0.5 fb⁻¹

4415
1 fb⁻¹

4600
0.5 fb⁻¹

BEPCII can reach here!
Observation of a charmonium like structure: $Z_c(3900)^\pm$

- 2013: $515 \text{ pb}^{-1} \oplus 4260 \text{ MeV}$
- $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
- Dominant background $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
- $J/\psi$ signal: $[3.08, 3.12] \text{ GeV}$
- $J/\psi$ sideband: $[3.0, 3.06] \text{ GeV}$ or $[3.14, 3.20] \text{ GeV}$
- Structure seen: $Z_c(3900)^\pm \rightarrow \pi^\pm J/\psi$
Dalitz Plots and 1D Projections

\[ M^2(\pi^+ J/\psi) \text{ (GeV/c}^2\text{)}^2 \]

\[ M^2(\pi J/\psi) \text{ (GeV/c}^2\text{)}^2 \]

\[ \text{Events / 0.02 GeV/c}^2 \]

\[ M(\pi^+ J/\psi) \text{ (GeV/c}^2\text{)} \]

\[ M(\pi J/\psi) \text{ (GeV/c}^2\text{)} \]

\[ M(\pi^+ \pi^-) \text{ (GeV/c}^2\text{)} \]
BESIII: $e^+e^- \rightarrow \pi^+\pi^- J/\psi @ 4.26$ GeV

PRL 110, 252001

Z$_c$(3900)$^\pm$

- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?

- S-wave Breit-Wigner with efficiency correction
- Mass = $(3899.0 \pm 3.6 \pm 4.9)$ MeV
- Width = $(46 \pm 10 \pm 20)$ MeV
- Fraction = $(21.5 \pm 3.3 \pm 7.5)$%
BESIII: $e^+e^- \to \pi^+\pi^-J/\psi$ @ 4.26 GeV

K. Seth & co. @ 4.170 GeV

hep-ex:1304.3036

$M = (3885 \pm 5 \pm 1)$ MeV/c$^2$

$\Gamma = (34 \pm 12 \pm 4)$ MeV/c$^2$

81 $\pm$ 20 events

6.1$\sigma$
**BESIII: Z_c Results**

- $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ @ 4.26 GeV
- Preliminary

- $e^+e^- \rightarrow \pi^0\pi^0 h_c$ @ 4.23, 4.26, 4.36 GeV
- Preliminary

- $e^+e^- \rightarrow \pi^+\pi^- \pi^0 J/\psi$ @ 4.23, 4.26, 4.36 GeV

- $e^+e^- \rightarrow \pi^- (D\bar{D}^*)^\pm$ c.c. @ 4.26 GeV

- $e^+e^- \rightarrow \pi^- (D\bar{D}^*)^\pm$ c.c. @ 4.26 GeV

- $e^+e^- \rightarrow \pi^- (D\bar{D}^*)^\pm$ c.c. @ 4.26 GeV
The observed charmonium-like states $Y(4260)$, $Y(4360)$, and $Y(4660)$ cannot be interpreted as conventional charmoniums.

New decay modes searching and the line shape measurement is useful for understanding the nature of these $Y$-states.

Hadronic transitions (by an $\eta$ or $\pi^0$) to lower charmonia like $J/\psi$ are regarded as sensitive probes to study the properties of these $Y$-states.

Nature of these $Y$-states:
- hybrids?
- tetraquarks?
- hadro-charmonium?
- hadronic molecule?
BESIII: Cross Sections Results

**PRL 110, 252001**
\[ e^+e^- \rightarrow \pi^+\pi^- J/\psi \] @ 4.26 GeV

**PRL 111, 242001**
\[ e^+e^- \rightarrow \pi^0\pi^0 J/\psi \] @ 4.19-4.31 GeV

**PRL 112, 132001**
\[ e^+e^- \rightarrow \eta J/\psi \] @ 3.81-4.31 GeV

**BESIII Preliminary!**
\[ e^+e^- \rightarrow \pi^+(D^*\bar{D}^*)^\pm + c.c. \] @ 4.26 GeV

**BESIII Preliminary!**
\[ e^+e^- \rightarrow \pi^+\pi^- h_c \] @ 4.23, 4.26, 4.36 GeV
The mass of Y(4260) is very close to $\omega\chi_{cJ}$ mass threshold

- Observation of $\omega\chi_{c0}$ at 4230, 4260 MeV data
- No evidence at 4360 MeV
- Line shape seems inconsistent with Y(4260)
- BW fitting: a narrow structure around 4230 MeV.

\[ M = (4229 \pm 11 \pm 6) \text{ MeV}/c^2 \]
\[ \Gamma = (40 \pm 14 \pm 2) \text{ MeV}/c^2 \]
BESIII: $e^+e^- \rightarrow \pi^+\pi^-X(3823) \rightarrow \gamma\chi_{c1,2}$ @ 4.19-4.60 GeV

BESIII Preliminary!
BESIII: $e^+e^-\rightarrow \pi^+\pi^-X(3823)\rightarrow \gamma\chi_{c1,2}$ @ 4.19-4.60 GeV

- Simultaneous fit: data-I (4.36, 4.42, 4.60 GeV) & data-II (4.23, 4.26 GeV)
- Signal: MC simulated shape + Background: linear
- $M=3821.7\pm1.3\pm0.7$ MeV; Significance: $6.7\sigma$, observation!
1. Energy dependent cross section of $e^+e^\rightarrow \pi^+\pi^-X(3823)$.
2. Both $Y(4360)$ and $\psi(4415)$ line shape give reasonable description.
**J/ψ Strong and Electromagnetic Decay Amplitudes**

**Resonant contributions**

\[ \Gamma_{J/\psi} \sim 93\text{KeV} \rightarrow \text{pQCD} \]

pQCD: all amplitudes almost real \([1,2]\)

\[ \text{QCD} \rightarrow \Phi_p \sim 10^\circ \] \([1]\)

**Non-resonant continuum**

pQCD regime

\[ A_{EM} \in \mathbb{R} \]

J/ψ Strong and Electromagnetic Decay Amplitudes

- If both real, they must interfere ($\Phi_p \sim 0°/180°$)
- On the contrary $\Phi_p \sim 90° \rightarrow$ No interference

\[
\begin{align*}
J/\psi &\rightarrow N\bar{N} \left( \frac{1}{2}^+\frac{1}{2}^- \right) \quad \Phi_p = 89° \pm 15° \ [1]; \ 89° \pm 9°[2] \\
J/\psi &\rightarrow VP \left( 1^-0^- \right) \quad \Phi_p = 106° \pm 10° \ [3] \\
J/\psi &\rightarrow PP \left( 0^-0^- \right) \quad \Phi_p = 89.6° \pm 9.9° \ [4] \\
J/\psi &\rightarrow VV \left( 1^-1^- \right) \quad \Phi_p = 138° \pm 37° \ [4]
\end{align*}
\]

- Results are model dependent
- Model independent test:

interference with the non resonant continuum

Simulated Yields for $e^+e^- \rightarrow p\bar{p}$

- $\Delta \phi = 0^\circ$
- $\Delta \phi = 90^\circ$
- $\Delta \phi = 180^\circ$

continuum reference $\sigma \sim 11 \text{ pb}$

beam energy spread + radiative corrections (to be optimized)

no corrections

beam energy spread (0.93 MeV)
Summary

• Studies on X, Y, and Z states are ongoing
• Many new results from experimental data
• Extremely good precision

Next plans
• Collect data at higher energies to complete scans
• Higher luminosity expected from BEPCII
• Many analysis are ongoing

Stay tuned
• Many new exciting results on their way
Backup Slides
BESIII Detector

TOF:
\[ \sigma_T = 80 \text{ ps} \quad \text{Barrel} \]
\[ 110 \text{ ps} \quad \text{Endcap} \]

EMC: CsI crystals, 28 cm
\[ \Delta E/E = 2.5\% @ 1 \text{ GeV} \]
\[ \sigma_z = 0.6 \text{ cm}/\sqrt{E} \]

MDC: small cell & He gas
\[ \sigma_{xy} = 130 \mu\text{m} \]
\[ \sigma_p/p = 0.5\% @ 1 \text{ GeV} \]
\[ dE/dx = 6\% \]

Magnet: 1T Superconducting

Muon: 9 layer RPC

Trigger: Tracks & Showers
Pipelined; Latency = 2.4 ms

Data Acquisition:
Event rate = 3 kHz
Thruput ~ 50 MB/s

Zero Degree Detector (ISR)
BESIII Data Set

2.9 fb$^{-1}$ / 20 fb$^{-1}$
0.6 B / 3 B (106 M)
1.3 B / 10 B (225 M)
### BESIII Data Taking

<table>
<thead>
<tr>
<th>$E_{cm}$ (MeV)</th>
<th>run</th>
<th>luminosity (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4190</td>
<td>30372–30437</td>
<td>43.09</td>
</tr>
<tr>
<td>4210</td>
<td>31983–32045</td>
<td>54.55</td>
</tr>
<tr>
<td>4220</td>
<td>32046–32140</td>
<td>54.13</td>
</tr>
<tr>
<td>4230</td>
<td>32239–33484 and 30438–30491</td>
<td>1091.74</td>
</tr>
<tr>
<td>4245</td>
<td>32141–32226</td>
<td>55.59</td>
</tr>
<tr>
<td>4260</td>
<td>29677–30367 and 31561–31981</td>
<td>825.67</td>
</tr>
<tr>
<td>4310</td>
<td>30492–30557</td>
<td>44.90</td>
</tr>
<tr>
<td>4360</td>
<td>30616–31279</td>
<td>539.84</td>
</tr>
<tr>
<td>4390</td>
<td>31281–31325</td>
<td>55.18</td>
</tr>
<tr>
<td>4420</td>
<td>31327–31390</td>
<td>44.67</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2809.36</strong></td>
</tr>
</tbody>
</table>
## BESIII Data Taking

<table>
<thead>
<tr>
<th>Luminosity (fb$^{-1}$)</th>
<th>Energy (GeV)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 \times 10^9</td>
<td>(J/\Psi) @ 3.097 GeV</td>
<td>2009 (0.225 \times 10^9) + 2012</td>
</tr>
<tr>
<td>0.4 \times 10^9</td>
<td>(\Psi') @ 3.686 GeV</td>
<td>2009 (0.106 \times 10^9) + 2012</td>
</tr>
<tr>
<td>2.9 fb$^{-1}$</td>
<td>(\Psi(3770)) @ 3.773 GeV</td>
<td>2010 + 2011</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>(\Psi(4040)) @ 4.009 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>0.024 fb$^{-1}$</td>
<td>(\tau) mass scan at around 3.554 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>1.9 fb$^{-1}$</td>
<td>(Y(4260)) @ 4.23 and 4.26 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>(Y(4360)) @ 4.36 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>(Y(4260)) and (Y(4360)) scan</td>
<td>2013</td>
</tr>
<tr>
<td>0.8 fb$^{-1}$</td>
<td>R scan, 104 energy points between 3.85 and 4.59 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>1.0 fb$^{-1}$</td>
<td>@ 4.42 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.1 fb$^{-1}$</td>
<td>@ 4.47 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.1 fb$^{-1}$</td>
<td>@ 4.53 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.04 fb$^{-1}$</td>
<td>@ 4.575 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>@ 4.60 GeV</td>
<td>2014</td>
</tr>
</tbody>
</table>
The $Z_c(3900)$ signal

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>MC Statistics</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Tracking</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.5</td>
<td>3.4</td>
</tr>
<tr>
<td>$Y(4260)$ line-shape</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Kinematic fit</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Branching ratios</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Decay model</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Others</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.9</strong></td>
<td><strong>6.8</strong></td>
</tr>
</tbody>
</table>

TABLE I: Summary of the systematic errors (%) in the cross section measurement.
BESIII: $e^+e^-\rightarrow \pi Z_c(3885)^-\rightarrow \pi^- (D\bar{D}^*)^++c.c.$ @ 4.260 GeV

525 pb$^{-1}$ data @ 4260 MeV

$\pi Z_c(3885)$ ang. dist. favours $J^P = 1^+$

disfavours $1^- e 0^-$

$M = (3883.9\pm1.5\pm4.2)$ MeV/$c^2$

$\Gamma = (24.8\pm3.3\pm11.0)$ MeV/$c^2$

$>18\sigma$

$\sigma(e^+e^-\rightarrow \pi^- Z_c(3885)^+ \times Z_c(3885)^+ \rightarrow (DD^*)^+ +c.c.) = (83.5\pm6.6\pm22.0)$ pb

$R = \frac{\Gamma(Z_c(3885) \rightarrow D^*\bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = (6.2\pm1.1\pm2.7)$
**BESIII: \( e^+ e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+ + c.c. @ 4.260 \text{ GeV} \)**

\[
\begin{align*}
M &= (4026.3 \pm 2.6 \pm 3.7) \text{ MeV}/c^2 \\
\Gamma &= (24.8 \pm 5.7 \pm 7.7) \text{ MeV}/c^2 \\
&> 10\sigma \\
\sigma(e^+e^- \to \pi^- (D^*\bar{D}^*)^+ + c.c.) &= (137 \pm 9 \pm 15) \text{ pb} \\
R &= \frac{\sigma(e^+e^- \to \pi^- Z_c^+ \to \pi^- (D^*\bar{D}^*)^+ + c.c.)}{\sigma(e^+e^- \to \pi^- (D^*\bar{D}^*)^+ + c.c.)} = (65 \pm 9 \pm 6)\% \\
\end{align*}
\]

PRL 112, 132001
**BESIII: $e^+e^-\rightarrow\pi Z_c(4020)\rightarrow\pi^+\pi^-h_c$ @ 4.23/4.26/4.36 GeV**

Simultaneous fit to 4.26/4.36 GeV data and 16 $\eta_c$ decay modes.

$M = (4022.9\pm0.8\pm2.7)$ MeV/$c^2$

$\Gamma = (7.9\pm2.7\pm2.6)$ MeV/$c^2$

$>8.9\sigma$

4.26 GeV:

$\sigma(e^+e^-\rightarrow\pi Z_c(3900) + \pi^- \rightarrow\pi^+\pi^-h_c) = <11$ pb (90% C.L.)

$\sigma(e^+e^-\rightarrow\pi Z_c(4020)\rightarrow\pi^+\pi^-h_c)$

$\sigma(4.23$ GeV$) = (8.7\pm1.9\pm2.8\pm1.4)$ pb

$\sigma(4.26$ GeV$) = (7.4\pm1.7\pm2.1\pm1.2)$ pb

$\sigma(4.36$ GeV$) = (10.3\pm2.3\pm3.1\pm1.6)$ pb

$B((h_c\rightarrow\gamma\eta_c)$
BESIII: $e^+e^-\rightarrow\pi Z_c(4020)\rightarrow\pi^+\pi^-h_c$ @ 4.23/4.26/4.36 GeV

- all collected energies
  [3.900 ÷ 4.420 GeV]

- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ hadrons
  [16 exclusive decay modes]
BESIII: $e^+e^- \rightarrow \pi Z_c(4020)^0 \rightarrow \pi^0\pi^0 h_c$ @ 4.23/4.26/4.36 GeV

- 2.8 fb$^{-1}$ data at 10 energy points from 4230~4420 MeV
- $Z_c(4020)^0$ is observed clearly at: $E_{cm}=4230, 4260, 4360$ MeV

$Z_c(4020)^0$ is observed clearly at: $E_{cm}=4230, 4260, 4360$ MeV

$M_{Z_c(4020)^0} = (4023.6 \pm 2.2 \pm 3.9)$ MeV/c$^2$

$M_{Z_c(4020)^\pm} = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c$^2$

$\Gamma_{Z_c(4020)^0}$ fixed @ $\Gamma_{Z_c(4020)^\pm} > 5\sigma$

An isospin triplet for $Z_c(3900)$ has also been observed
We extract the $Z_c^0(3900)$ parameters and yield by performing a simultaneous fit to the $\pi^0J/\psi$ invariant mass distributions for three subsamples: 4230 MeV, 4260 MeV and 4360 MeV.

**Signal:** BW convolved with 3-Gaussian

**Bg:** Argus, float all parameters except m0

Mass = $3894.8 \pm 2.3$ MeV
Width = $29.6 \pm 8.2$ MeV
Significance = $10.4 \sigma$
To determine the yields of $Z_c^0(3900)$, at 10 energy points a simultaneous fit is performed to the $\pi^0\pi^0J/\psi$ spectra for each of the ten energy points. Signal: BW convolved with 3-Gaussian, parameters are fixed to the overall fit. Bg: Argus, $m_0$ are fixed based on beam energy. The slope and power are floated, but the same for all points.
To obtain the yields of $\pi^0\pi^0J/\psi$, a simultaneous fit is made to the $J/\psi$ spectra at all ten energy points.

Signal: BW convolved with D-Gaussian instrument resolution (same for all energy points)
Bg: $1^{st}$ ordered poly.
(same for all energy points)
BESIII Preliminary: $e^+e^- \rightarrow \pi^0 Z_c^0(3900) \rightarrow \pi^0\pi^0 J/\psi$ @ 4.19-4.31 GeV

<table>
<thead>
<tr>
<th>$E_{cm}$ GeV</th>
<th>$R(Z_c/\pi^0\pi^0 J/\psi)$</th>
<th>Obs. Xsec (pb)</th>
<th>Born Xsec (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.260</td>
<td>0.14 ± 0.03 ± 0.01</td>
<td>23.68 ± 1.04 ± 1.75</td>
<td>28.95 ± 1.27 ± 2.14</td>
</tr>
<tr>
<td>4.360</td>
<td>0.21 ± 0.06 ± 0.01</td>
<td>15.00 ± 1.10 ± 1.11</td>
<td>14.57 ± 1.07 ± 1.08</td>
</tr>
<tr>
<td>4.230</td>
<td>0.27 ± 0.03 ± 0.01</td>
<td>30.28 ± 1.02 ± 2.24</td>
<td>37.61 ± 1.27 ± 2.78</td>
</tr>
<tr>
<td>4.190</td>
<td>&lt; 1.00</td>
<td>9.45 ± 3.00 ± 0.70</td>
<td>11.37 ± 3.61 ± 0.84</td>
</tr>
<tr>
<td>4.210</td>
<td>&lt; 0.65</td>
<td>20.79 ± 3.85 ± 1.54</td>
<td>25.54 ± 4.73 ± 1.89</td>
</tr>
<tr>
<td>4.220</td>
<td>&lt; 0.41</td>
<td>21.60 ± 3.82 ± 1.60</td>
<td>26.74 ± 4.73 ± 1.98</td>
</tr>
<tr>
<td>4.245</td>
<td>&lt; 0.30</td>
<td>34.24 ± 4.69 ± 2.53</td>
<td>42.38 ± 5.80 ± 3.14</td>
</tr>
<tr>
<td>4.310</td>
<td>&lt; 0.30</td>
<td>22.04 ± 4.16 ± 1.63</td>
<td>24.17 ± 4.56 ± 1.79</td>
</tr>
<tr>
<td>4.390</td>
<td>&lt; 0.55</td>
<td>7.56 ± 2.53 ± 0.56</td>
<td>6.93 ± 2.32 ± 0.51</td>
</tr>
<tr>
<td>4.420</td>
<td>&lt; 1.00</td>
<td>2.87 ± 2.13 ± 0.21</td>
<td>2.52 ± 1.87 ± 0.19</td>
</tr>
</tbody>
</table>
BESIII: $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ events

- 4 charged tracks, $J/\psi$ reconstruct via lepton pairs
- very clean sample, very high efficiency, kinematic fit used
- only use MDC & EMC information, MC simulation reliable
BESIII: Cross Sections Results

**PRL 110, 252001**

e^+e^- \rightarrow \pi^+\pi^-J/\psi @ 4.26 GeV

\[ \sigma(\pi^+\pi^-J/\psi) = (62.9 \pm 1.9 \pm 3.7) \text{ pb} \]

\[ \sigma(\pi^+\pi^-J/\psi) = (61.17 \pm 8.98 \pm 7.5\%) \text{ pb} \]

Z_c R = (21.5 \pm 3.3 \pm 7.5)\%

**BESIII Preliminary!**

e^+e^- \rightarrow \pi^0\pi^0J/\psi @ 4.19-4.31 GeV

7 energy points

Z_{c0}/Z_{c\pm} R = (21.5 \pm 3.3 \pm 7.5)\%

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Belle [PRL 110, 252002]

BESIII preliminary
$\sigma(e^+e^- \rightarrow \pi^-(D\bar{D}^*)^+ + \text{c.c.}) = (137\pm9\pm15)\text{ pb}$

$\sigma(e^+e^- \rightarrow \pi^- (D^*\bar{D}^*)^+ + \text{c.c.}) = (332\pm67\pm80)\text{ pb}$

$R = \frac{\sigma(e^+e^- \rightarrow \pi^- Z_c^+ \rightarrow \pi^- (D^*\bar{D}^*)^+ + \text{c.c.})}{\Gamma(Z_c(3885) \rightarrow \bar{D}D^*)} = (65\pm9\pm6)\%$
BESIII: $h_c$ Results

PRL 111, 242001

BESIII Preliminary!

BESIII

13 energy points

\[ \sigma(e^+e^- \rightarrow \pi Z_c(4020)^\pm \rightarrow \pi^+\pi^- h_c) \]

\[ \sigma(4.23 \text{ GeV}) = (8.7 \pm 1.9 \pm 2.8 \pm 1.4) \text{ pb} \]
\[ \sigma(4.26 \text{ GeV}) = (7.4 \pm 1.7 \pm 2.1 \pm 1.2) \text{ pb} \]
\[ \sigma(4.36 \text{ GeV}) = (10.3 \pm 2.3 \pm 3.1 \pm 1.6) \text{ pb} \]

\[ \sigma(e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi^+\pi^- h_c) \]
\[ \sigma(4.26 \text{ GeV}) = < 11 \text{ pb (90\% C.L.)} \]

10 energy points

\[ \sigma(e^+e^- \rightarrow \pi Z_c(4020)^0 \rightarrow \pi^0\pi^0 h_c) \]
\[ \sigma(4.23 \text{ GeV}) = (6.5 \pm 2.2 \pm 0.7 \pm 1.0) \text{ pb} \]
\[ \sigma(4.26 \text{ GeV}) = (8.5 \pm 2.9 \pm 1.1 \pm 1.3) \text{ pb} \]
\[ \sigma(4.36 \text{ GeV}) = (9.9 \pm 4.1 \pm 1.3 \pm 1.5) \text{ pb} \]
**BESIII: e^+e^- → ηJ/ψ, π^0J/ψ @ 4.009 GeV**

**J/ψ → l^+l^-**

Statistical significance:
\[ η \sim 10 \sigma \]
\[ π^0 \sim 1.1 \sigma \]

Cross sections:
\[ σ (e^+e^- → J/ψ) = (32.1 \pm 2.8 \pm 1.3) \text{ pb} \]
\[ σ (e^+e^- → π^0J/ψ) = 1.6 \text{ pb} \text{ (90\% CL)} \]

Upper limit:
CLEO not contradicted (PRL 96, 162003)
BESIII: $e^+e^- \rightarrow \eta J/\psi$ @ 3.81-4.31 GeV

BESIII Preliminary!
BESIII: $e^+e^- \rightarrow \eta J/\psi @ 3.81-4.31$ GeV

- **Signal:** MC simulated shape.
- **Background:** Polynominal function.
The measured $\sigma(e^+e^- \rightarrow \eta J/\psi)$ agree with previous results but with improved accuracy.

The cross section peaks around 4.2 GeV.
- $h_c \rightarrow \gamma \eta_c, \eta_c \rightarrow$ hadrons [16 exclusive decay modes]
  - $p\ p, \pi^+\pi^-K^+K^-, \pi^+\pi^-p\ p, 2(K^+K^-), 2(\pi^+\pi^-), 3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-, K_S^0K^+\pi^-+c.c., K_S^0K^+\pi^-\pi^+\pi^-+c.c., K^+K^-\pi^0$
  - $p\ p\pi^0, K^+K^-\eta, \pi^+\pi^-\eta, \pi^+\pi^-\pi^0\pi^0, 2(\pi^+\pi^-)\eta, 2(\pi^+\pi^-\pi^0)$
BESIII: $e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$

- $\sigma(e^+e^-\rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^-\rightarrow \pi^+\pi^-J/\psi)$ but line shape different
- Local maximum $\sim 4.23$ GeV
$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$ vs $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

Open circles: Belle $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
Solid dots: BESIII $e^+e^- \rightarrow \pi^+\pi^- h_c$

More data at higher energies needed to complete line shape measurement
The mass of $Y(4260)$ is very close to $\omega\chi_{cJ}$ mass threshold.

Observation of $\omega\chi_{c0}$ at 4230, 4260 MeV data.

No evidence at 4360 MeV.

Line shape seems inconsistent with $Y(4260)$.

BW fitting: a narrow structure around 4230 MeV.

$M = (4229\pm11\pm6)\text{ MeV/c}^2$

$\Gamma = (40\pm14\pm2)\text{ MeV/c}^2$
BESIII data set

3.3 fb\(^{-1}\) for XYZ studies
Hadronic exotic states

- **Experiments:**
  - Hadrons are composed of 2 (meson) or 3 (baryon) quarks
  - Described very well in quark model (QM)

- **QCD suggests:**
  - Confinement: stable hadrons need to be colorless
  - Gluon-gluon interactions: hadron with gluons (hybrids and glueballs) could exist
  - Allow hadrons with $N_{\text{quarks}} \neq 2, 3$ (multi-quarks)

Can we find evidence for these interesting exotic hadrons?

A long history of searching for the exotic hadron, no solid conclusion was reached in past a few decades, some hints on charmomium-like and bottomnium-like particles, recently.
Exotic Meson (Charmonium-Like)

Molecular states:
- Loosely bound states of a pair of mesons,
- bound by the long-range color-singlet pion exchange,
- weakly bound, mesons tend to decay as if they were free.

Tetraquarks:
- bound states of four quarks,
- bound by colored-force between quarks,
- decay through rearrangement,
- many states with the same multiplet, some are with non-zero charge, or strangeness

Hybrids:
- bound states with a pair of quarks and one excited gluon
- Lattice and model predictions for lowest lying charmonium hybrid $m \sim 4200$ MeV
\( Z_c \) states

The most promising way to searching for the exotic hadrons

- Decay into a charmonium or \( D(\ast)D(\ast) \) pair
  - thus contains hidden-cc pair
- Have electric charge.
  - thus has two more light quarks

At least 4 quarks, not a conventional meson

- Observed in final states:
  - \( \pi^\pm J/\psi, \pi^\pm \psi(2S), \pi^\pm h_c, \pi^\pm \chi_{cJ}, (D(\ast)D(\ast))^{\pm} \ldots \)

- Experimental search:
  - BESIII/CLEO-c: \( e^+ e^- \rightarrow \pi^\pm + \text{Exotics,} \ldots \)
  - Belle/BaBar: \( e^+ e^- \rightarrow (\gamma_{\text{ISR}}) \pi^\pm + \text{Exotics,} \ldots \)
  - Belle/BaBar/LHCb: \( B \rightarrow K^\pm + \text{Exotics,} \ldots \)
**BESIII: e^+e^- → πZ_c(4025) → π^- (D*D*)^+ + c.c. @ 4.260 GeV**

- 827 pb^{-1} data at \( E_{CM} = 4.260 \text{ GeV} \)
- Tag a D^+ and a bachelor \( \pi^- \), reconstruct one \( \pi^0 \) to suppress the background.

**Topology of the decays of the signal process:**
- thick line circled: D^+ and \( \pi^- \) detected in the final states
- dashed line circled: at least of \( \pi_1^0 \) or \( \pi_2^0 \) tagged
BESIII: $e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^*D^*)^+ + c.c. \, @ \, 4.260 \, \text{GeV}$

Remove DD, DD*, D*D*, DsDs, …
BESIII: $Z_c(4020) = Z_c(4025)$?

$M(4020) = (4021.8 \pm 1.0 \pm 2.5) \text{ MeV}$

$M(4025) = (4026.3 \pm 2.6 \pm 3.7) \text{ MeV}$

$\Gamma(4020) = (5.7 \pm 3.4 \pm 1.1) \text{ MeV}$

$\Gamma(4025) = (24.8 \pm 5.7 \pm 7.7) \text{ MeV}$

Close to $D^*\bar{D}^*$ threshold (4017 MeV)

Mass consistent with each other but.. width $\sim 2\sigma$ difference

Interference with other amplitudes may change the results

Coupling to $\bar{D}^*D^*$ is much larger than to $\pi h_c$ if they are the same state

Will fit with Flatte formula
BESIII: $e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \gamma X_{c1,2} @ 4.19-4.60$ GeV

$\psi(1^{3}D_{2})$ candidate

- Assume $\pi\pi$ system is dominant by f0(500)
- Many new exciting results on their way
BESIII: $e^+e^- \rightarrow \pi Z_c(3885) \rightarrow \pi^-(DD^*)^++c.c.$ @ 4.260 GeV

BESIII Preliminary!

\begin{align*}
|\cos \theta_{\pi^+}| \\
\text{in } Y(4260) \text{ rest frame}
\end{align*}

\begin{tabular}{|c|c|c|}
\hline
$J^P$ & L & $dN/d|\cos \theta_{\pi^+}|$ \\
\hline
$1^+$ & S-wave & flat \\
$0^-$ & P-wave & $\sin^2 \theta_{\pi}$ \\
$1^-$ & P-wave & $1+\cos^2 \theta_{\pi}$ \\
\hline
\end{tabular}

\begin{align*}
\text{Favor } J^P=1^+ \\
PRL 112, 022001 (2014)
\end{align*}
BESIII: $e^+e^-\rightarrow\pi Z_c(4020)^0\rightarrow\pi^0\pi^0 h_c$ @ 4.23/4.26/4.36 GeV

- 2.8 fb$^{-1}$ data at 10 energy points from 4230~4420 MeV
- $Z_c(4020)^0$ is observed clearly at: $E_{cm}=4230, 4260, 4360$ MeV

- $M_{Z_c(4020)^0} = (4023.6\pm2.2\pm3.9)$ MeV/c$^2$
- $M_{Z_c(4020)^\pm} = (4022.9\pm0.8\pm2.7)$ MeV/c$^2$
- $\Gamma_{Z_c(4020)^0}$ fixed @ $\Gamma_{Z_c(4020)^\pm} > 5\sigma$

An isospin triplet for $Z_c(3900)$ has also been observed.
BESIII: $e^+e^- \rightarrow \pi^+\pi^-X(3823) \rightarrow \gamma X_{C1,2} @ 4.19-4.60$ GeV

BESIII Preliminary!

- D-Wave charmonium still missing
- Triplet ($1^3D_{1,2,3}$)
- $1^3D_2 \rightarrow DD$ forbidden, narrow

Potential model:
Godfrey & Isgur, PRD32, 189 (1985)
BESIII: $e^+e^- \rightarrow \pi^+\pi^-X(3823) \rightarrow \gamma\chi_{c1,2} @ 4.19-4.60$ GeV

$\psi(1^{3}D_{2})$ candidate

1. Assume $\pi\pi$ system is dominant by $f_0(500)$
2. Scattering angle distribution of $\psi(2S)$ and $X(3823)$ in $e^+e^-$ CM frame.
3. Kolmogorov-Smirnov test p-value is given.
4. (Left) $\pi^+\pi^-\psi(2S)$: S-wave (p=0.791), D-wave (p=0.451) $\rightarrow$ S-wave seems to be better.
5. (right) $\pi^+\pi^-X(3823)$: S (p=0.928), D (p=0.978) $\rightarrow$ Can’t distinguish
Investigated Processes

- **Exclusive scenario:** could see interference effects

  - $e^+e^+ \rightarrow J/\psi \rightarrow \bar{p}p, n\bar{n} \quad \text{N\bar{N}}$
    
    $\text{BR} \sim 2.17 \times 10^{-3} \quad \sigma_{\text{cont}} \sim 11 \text{ pb}$

  - $e^+e^- \rightarrow J/\psi \rightarrow \rho\pi \quad \text{VP}$
    
    $\text{BR} \sim 1.69\% \quad \sigma_{\text{cont}} \sim 20 \text{ pb}$

  - $e^+e^- \rightarrow J/\psi \rightarrow 2(\pi^+\pi^-)\pi^0$
    
    $\text{BR} \sim 5.5\% \quad \sigma_{\text{cont}} \sim 500 \text{ pb}$