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On behalf of the BESIII Collaboration

50th Anniversary Meeting, La Thuille - 19-26 March, 2016
OUTLINE

✓ INTRODUCTION: The BESIII experiment
  • BEPCII and the BESIII detector
  • The BESIII dataset and physics programme

✓ Physics highlights
  • Light hadron spectroscopy: X(18??) states
  • Charmonium-like states: XYZ states

✓ Summary and Conclusions
2004: started BEPCII/BESIII construction
- Double rings
- Beam energy: 1-2.3 GeV
- Designed luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

2008: test run

2009 – today: BESIII physics runs
The BESIII Detector

Superconducting solenoid (1T)

RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
\[ \Delta \Omega / 4\pi = 93\% \]

Electromagnetic CsI(Tl) Calorimeter
- \[ \sigma_{E/E} < 2.5\% \quad @ \quad 1 \text{ GeV (barrel)} \]
- \[ \sigma_{E/E} < 5\% \quad @ \quad 1 \text{ GeV (end caps)} \]
- \[ \sigma_{xy} = (6 \, \text{mm})/E^{1/2} \quad @ \quad 1 \text{ GeV} \]

Time of Flight
- \[ \sigma_t = 90 \, \text{ps (barrel)} \]
- \[ \sigma_t = 120 \, \text{ps (end caps)} \]

Drift Chamber
- \[ \sigma_{r\phi} = 130 \, \mu\text{m (single wire)} \]
- \[ \sigma_{pt}/p_t = 0.5 \% \quad @ \quad 1 \text{ GeV} \]
The BESIII data set

From 2009 to 2014/2015:

- $1.3 \times 10^9 \text{ J/}\psi$
- $5 \times 10^8 \psi(2S)$
- $2.9 \text{ fb}^{-1} @ \psi_{3770}$
- $0.5 \text{ fb}^{-1} @ \psi_{4040}$
- $2.3 \text{ fb}^{-1} @ 4230/4260 \text{ MeV}$
- $0.5 \text{ fb}^{-1} @ 4360 \text{ MeV}$
- $0.5 \text{ fb}^{-1} @ 4600 \text{ MeV}$
- $1 \text{ fb}^{-1} @ \psi_{4415}$
- $0.1 \text{ fb}^{-1} @ 4470/4530 \text{ MeV}$
- $0.04 \text{ fb}^{-1}$ around $\Lambda_c$ threshold
- $1 \text{ fb}^{-1} @ 4420 \text{ MeV}$
- R scan:
  - 2-3 GeV, 19 points, $\sim 0.5 \text{ fb}^{-1}$
  - 3.85-4.59 GeV, 104 points, $\sim 0.8 \text{ fb}^{-1}$

MORE:

- $3554 \text{ MeV} 24 \text{ pb}^{-1}$ $\tau$ mass; 4100-4400 MeV 0.5 fb$^{-1}$ coarse scan
- On-going data taking

http://bes3.ihep.ac.cn/datasets/datasets.htm
Selected results

Mesons spectroscopy
• $X(1860)$ in $J/\psi \rightarrow \gamma pp$
• $X(1835)$ in $J/\psi \rightarrow \gamma \pi^- \pi^+ \eta'$
• $X(1560)$ and $X(1835)$ in $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$
• $X(1835)$ line shape and study and connection with $X(pp)$

XYZ states
• $e^+ e^- \rightarrow \pi^- \pi^+ X(3823) \rightarrow \pi^- \pi^+ \gamma \chi_c$
• $Z_c$ states

Many others results not covered in this talk
• $Y(2175)$ resonance and search for $X(1835)$ and $X(1870)$ in $J/\psi \rightarrow \eta \phi \pi^- \pi^+$ (PRD91,052017)
• $e^+ e^- \rightarrow \gamma X(3872) \rightarrow \gamma J/\psi \pi^- \pi^+$ (PRL 112, 092001)
• $e^+ e^- \rightarrow \omega \chi_{cJ}$ (PRL 114, 092003 and PRD 93, 011102)
• $e^+ e^- \rightarrow \eta J/\psi$ (PRD 91, 112005)
• Search for $Y(4140) \rightarrow J/\psi \phi$ (PRD 91, 032002)
• $Z_c(3900)^\pm \rightarrow \omega \pi^\pm$ (PRD 92, 032009)
• Search for isospin violating decay $Y(4260) \rightarrow J/\psi \eta \pi^0$ (PRD 92, 012008)
• ...
$J/\psi \to \gamma p\bar{p}$: threshold enhancement in $p\bar{p}$ mass

- Enhancement observed more than 10 years ago at BESII and confirmed by CLEO-c [PRD82,092002]
- What about its nature?
- No similar structures observed in related channels:

CLEO, $\Upsilon(1S) \to \gamma p\bar{p}$
PRD 73, 032001

BESIII, $J/\psi \to \omega p\bar{p}$
PRD 87, 112004

BES, $\psi' \to \gamma p\bar{p}$
PRL 99, 011802
PWA analysis for the region below 2.2 GeV using 225M $J/\psi$ decays

- Four components included in the PWA fit: $X(p\bar{p})$, $f_2(1910)$, $f_0(2100)$ and $0^{++}$ phase space
- Intermediate resonances described by Breit-Wigner propagators
- $f_2(1910)$ and $f_0(2100)$ parameters fixed at the PDG values

Statistical significance of the $X(p\bar{p})$ component $> 30\sigma$, $5\sigma$ for the other components
- The $0^{-+}$ assignment is better than other $J^{PC}$

$$M = 1832^{+19}_{-5}\text{(stat)}^{+18}_{-17}\text{(syst)} \pm 19\text{(model)} \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 39\text{(stat)}^{+10}_{-13}\text{(syst)} \pm 4\text{(model)} \text{ MeV}/c^2$$

$$BR[J/\psi \to \gamma X] \times BR[X \to p\bar{p}] = (9.0^{+0.4}_{-1.1}\text{(stat)}^{+1.5}_{-5.0}\text{(syst)} \pm 2.3\text{(model)}) \times 10^{-5}$$
$\chi(1835)$ in $J/\psi \rightarrow \gamma \pi^- \pi^+ \eta'$

- $\chi(1835)$ was first observed at BES, and then confirmed at BESII [PRL95,262001]
- Two additional structures observed at BESIII
- Many interpretation: $p\bar{p}$ bound state? Glueballs?
  Radial excitation of the $\eta'$ meson
  - Needed higher statistic
- BESIII $J/\psi \rightarrow \gamma \pi^- \pi^+ \eta'$: PRL 106, 072002
  - 225M $J/\psi$ events
  - $\eta' \rightarrow \eta \gamma \pi^- \pi^+$ and $\eta' \rightarrow \eta' \gamma \pi^- \pi^+
  - 4 resonances (BW$\otimes$Gauss)+non-resonant $\eta' \pi^- \pi^+$ (from MC ) + non- $\eta'$ and $\pi^- \pi^+ \pi^0 \eta'$ bkgs

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
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<tbody>
<tr>
<td>$f_1(1510)$</td>
<td>1522.7 ± 5.0</td>
<td>48 ± 11</td>
</tr>
<tr>
<td>X(1835)</td>
<td>1836.5 ± 3.0</td>
<td>190.1 ± 9.0</td>
</tr>
<tr>
<td>X(2120)</td>
<td>2122.4 ± 6.7</td>
<td>83 ± 16</td>
</tr>
<tr>
<td>X(2370)</td>
<td>2376.3 ± 8.7</td>
<td>83 ± 17</td>
</tr>
</tbody>
</table>

- The polar angle distribution of the photon in the $J/\psi$ center-of-mass system supports $J^{PC}=0^{-+}$
  → need PWA analysis to determine spin-parity assignment
**χ(1835) in J/ψ → γ K_s^0 K_s^0 η**

J/ψ → γ K_s^0 K_s^0 η provides a clear environment

- K_s^0 K_s^0 η and π^0 K_s^0 K_s^0 η bkgs are forbidden by exchange symmetry and CP conservation

- 1.3×10^9 J/ψ events
- (a) Structure around 1.85 GeV/c^2
- (b) Strong enhancement near the K_s^0 K_s^0 threshold interpreted as the f_0(980)
- (c) Strong correlation between the f_0(980) and the structure near 1.85 GeV/c^2
- (d) M(K_s^0 K_s^0)<1.1 GeV/c^2 → the structure near 1.85 GeV/c^2 became more pronounced

PWA of events with M(K_s^0 K_s^0)<1.1 GeV/c^2 and M(K_s^0 K_s^0 η)<2.8 GeV/c^2
Final fit results: the data can be best described with three components: $X(1835) \rightarrow f_0(980) \eta$, $X(1560) \rightarrow f_0(980) \eta$, and a non-resonant $f_0(1500)\eta$ component.

- The $X(1560)$ component improves the fit quality when interference with the $X(1835)$ is allowed.
- Several fits with different $J^{PC}$ hypothesis.
- $J^{PC} = 0^{-+}$ for $X(1835)$, $X(1560)$, and non-resonant component.
- $J^{PC} = 1^{++}$ for non-resonant component cannot be excluded.

Mass and width of $X(1835)$ consistent with PRL106.

$$M = 1844 \pm 9 \text{ (stat)} \oplus 16_{-25}^{+16} \text{ (syst)} \text{ MeV/c}^2$$

$$\Gamma = 192^{+20}_{-17} \text{ (stat)} \oplus 62_{-43}^{+62} \text{ (syst)} \text{ MeV} \quad (>12.9\sigma)$$

$$\text{BR} = (3.3^{+0.33}_{-0.30} \text{ (stat)} \oplus 1.96_{-1.29}^{+1.96} \text{ (syst)}) \times 10^{-5}$$

$$M = 1565 \pm 8 \text{ (stat)} \oplus 0_{-63}^{+0} \text{ (syst)} \text{ MeV/c}^2$$

$$\Gamma = 45^{+14}_{-13} \text{ (stat)} \oplus 21_{-28}^{+21} \text{ (syst)} \text{ MeV} \quad (>8.9\sigma)$$
New: connection between $X(1835)$ and $X(p\bar{p})$

If the $X(1835)$ is a $pp$ bound state, the $\eta'\pi^-\pi^+$ line shape at the $p\bar{p}$ threshold would be affected by the opening of the $X(1835) \to p\bar{p}$ decay mode

- $1.09 \times 10^9 J/\psi$ events collected in 2012
- $\eta' \to \gamma \pi^-\pi^+$ and $\eta' \to \eta \gamma \pi^-\pi^+$
- Clear peaks of $X(1835)$, $X(2120)$, $X(2370)$, $\eta_c$, and a structure near 2.6 GeV/c$^2$

Significant distortion of the $\eta'\pi^-\pi^+$ line shape near the $p\bar{p}$ mass threshold
Connection between $X(1835)$ and $X(pp)$: Fit results

- Three efficiency-corrected Breit-Wigner functions
- Simple BW function fails in describing the $\eta' \pi^- \pi^+$ line shape near the threshold

**MODEL 1**
Threshold structure caused by the opening of additional decay mode
- Flatté formula for the shape (Phys.Lett.B63, 224)
- An additional BW resonance ($X(1920)$) is needed ($5.7\sigma$)

**MODEL 2**
Interference between two resonances
- Use coherent sum of two BW amplitudes for the line shape: $X(1835)$ and a narrow resonance called $X(1870)$
- $X(1920)$ not significant
The two models used to describe the data (Flatté and two interfering resonances) give almost equal fit quality

- MODEL 1: significance of \( g_{pp} / g_0 > 0 \) larger than 7 \( \sigma \) (\( g_{pp} / g_0 \) = ratio between the coupling strength to the pp channel and the summation of all the other channels)

- MODEL 2: significance for the X(1870) larger than 7 \( \sigma \)

- Both fits support the existence of one of
  - Broad state with strong coupling to p\( \bar{p} \)
  - Narrow state just below the p\( \bar{p} \) mass threshold

- Study of the line shape for other decay modes, e.g. \( \gamma p\bar{p}, \gamma K^0_S K^0_S \eta \ldots \)
**Other BESIII observations**

X states near proton-antiproton threshold
- $X(p\bar{p})$ in agreement with $X(1835)$, while its width is significantly different
- **Are they the same particles?**
- More studies are needed to answer this question
Below DD threshold: all the states have been observed and described by the $c\bar{c}$ potential model.

Above the threshold: more complex situation
- only a few of the predicted states above the threshold have been found
- Many new states have been observed with properties that are not consistent with the expectation for charmonium: $X$, $Y$, $Z$

$X$ states: charmonium-like states with $J^{PC} \neq 1^{--}$; Observed in $B$ decays, proton-proton, and proton-antiproton collisions.

$Y$ states: charmonium-like states with $J^{PC} = 1^{--}$; Observed in direct $e^+e^-$ annihilation or initial state radiation (ISR).

$Z$ states: charmonium-like states carrying electric charge; must contain at least $c\bar{c}$ and a light $q\bar{q}$ pair.
**Nature of the XYZ states**

**Molecular state**
Loosely bound state of a pair of mesons. The dominant binding mechanism should be pions exchange.

**Tetraquark**
Bound state of four quarks, i.e. diquark-antidiquark
Distinctive feature of multi-quark picture with respect to charmonium:
- Prediction of many new states
- Possible existence of new states with nonzero charge, strangeness, or both

**Charmonium hybrids**
Bound states with a pair of quarks and one excited gluon; Lattice and model predictions found that the lowest charmonium hybrids lies around 4200 MeV

**Glueball**
Bound states of gluons

Heavy quarkonium: progress, puzzles, and opportunities
1) Establish the spectrum: search for more X, Y, and Z states, determine masses, widths, quantum numbers, and investigates the decays

2) Build connections: look for transitions between different states (i.e. radiative transitions)

BESIII dedicated program started in 2012
Conventional $c\bar{c}$ state: $X(3823)$

- $X(3823)$ first observed by Belle in $B^{\pm} \rightarrow K \gamma X_{c1}$
- $3.8 \sigma$ evidence
- Mass and width compatible with $\psi_2$ state ($1^3D_2$)
- E705 (PRD50,4258(1994)) report a candidate for the $\psi_2$ state with a significance of $2.8 \sigma$

BESIII analysis uses 5 large data sets ($\mathcal{L}_{\text{tot}} \sim 4.7$ fb$^{-1}$) at the center-of-mass energies 4.23, 4.26, 4.36, 4.42, 4.6 GeV
- Reconstructed in $X_{c1,c2} \rightarrow \gamma J/\psi \rightarrow \gamma \ell^+\ell^-$

$e^+e^- \rightarrow \pi^+\pi^- \chi(3823) \rightarrow \pi^+\pi^- \gamma \chi_{c1}$

Two dimensional scatter plot is used to investigate the possible existence of resonances that may decay to $\chi_c \gamma$ states: $M_{\text{reco}}(\pi^+\pi^-) = \sqrt{(P_{e^+e^-} - P_{\pi^+} - P_{\pi^-})^2}$ vs. $M(\gamma_{H}\psi)$, where $\gamma_{H}$ refers to the higher energy photon.

Signals are evident in almost the data sets Accumulation near 3.82 GeV/$c^2$ are evident in the $\gamma \chi_{c1}$ signal region

Remaining backgrounds from $e^+e^- \rightarrow (\eta' / \gamma \omega)J/\psi$, with $\eta' / \omega \rightarrow \gamma \pi^+\pi^-$ or $\gamma \pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^- (\pi^0\gamma\gamma)$
$e^+ e^- \rightarrow \pi^+ \pi^- X(3823) \rightarrow \pi^+ \pi^- \gamma \chi_{c1}$

- $M = 3821.7 \pm 1.3 \pm 0.7$ MeV/c$^2$ and $\Gamma < 16$ MeV (90% C.L.)
- Significance = 6.2 $\sigma$ ($\gamma \chi_{c1}$ channel)
- The $X(3823)$ is a good candidate for the $\psi_2$ charmonium state with $J^{PC} = 2^-$
  - assuming $\pi^+ \pi^-$ system in S-wave $\Rightarrow 1 + \cos^2 \theta$ for spin 2
  - Mass and width are $\sim$ agreement with potential model prediction for $1^3D_2$
  - not enough statistics to distinguish between D- and S-wave hypothesis
- The fit of the energy-dependent cross section for the process is compatible with both $Y(4360)$ and $\psi(4415)$ line shapes

**Discovery of \(Z_c(3900)\)**

Study of the \(e^+e^- \rightarrow \pi^+\pi^- J/\psi\) process at the c.m. energy of 4.26 GeV using 525 pb\(^{-1}\)

- Reflection effect removed by choosing the heavier \(J/\psi\) combination per event (\(M_{\text{max}}(\pi^{\pm}J/\psi)\))
- Significance greater than 8 \(\sigma\)
- \(M = (3899.0 \pm 3.6 \pm 4.9)\) MeV/c\(^2\) and \(\Gamma = (46 \pm 10 \pm 20)\) MeV
- Mass very close to the DD\(^*\) threshold
- It couples to charmonium (c\(\bar{c}\)), has electric charge (contains ud) \(\Rightarrow\) at least 4 quark

**What is its nature?**

**BELLE**: PRL 110, 252002 (2013)

**Northwestern Uni.**: PLB 727, 366(2013)

**BELLE**

\(e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi \pi^+\pi^-\)

\(M = (3894.5\pm6.6\pm4.5)\) MeV/c\(^2\)

\(\Gamma = (63\pm24\pm26)\) MeV

**NWU (CLEO-c data)**

\(e^+e^- \rightarrow J/\psi \pi^+\pi^-\) at \(\sqrt{s} = 4.17\) GeV

\(M = (3886\pm4\pm2)\) MeV/c\(^2\)

\(\Gamma = (37\pm4\pm8)\) MeV
Search for a neutral $Z_c(3900)$ isospin partner

Study of $e^+e^-\rightarrow\pi^0\pi^0J/\psi$ process

- Data sample of 2809.4 pb$^{-1}$ distributed over the c.m. energy range from 4.190 to 4.420 GeV
- New structure ($Z_c(3900)^0$) observed in the $\pi^0J/\psi$ mass spectra
- **Isospin triplet established**: the measured Born cross sections are about half of those for $e^+e^-\rightarrow\pi^+\pi^-J/\psi$ [PRL110,252002], consistent with isospin symmetry expectation

$M = (3894.8 \pm 2.3 \pm 3.2) \text{ MeV}/c^2$

$\Gamma = (29.6 \pm 8.2 \pm 8.2) \text{ MeV}$

Significance $>10\sigma$
Z_{c}(3885) \pm \text{ in } e^+e^- \rightarrow (D\bar{D}^*)^\pm \pi^\mp

The Z_{c}(3900) lies close to the DD* threshold \Rightarrow it is interesting to investigate this region

- \mathcal{L} \sim 1092 \text{ pb}^{-1} @ 4.23 \text{ GeV} and \sim 826 \text{ pb}^{-1} @ 4.26 \text{ GeV}

- Double tag method: reconstruction of the bachelor π and D pair

The data agree well with \( J^P = 1^+ \) quantum numbers

\[
M_{\text{pole}} = (3881.7 \pm 1.6 \pm 1.6) \text{ MeV/c}^2 \quad \Gamma_{\text{pole}} = (26.6 \pm 2.0 \pm 2.1) \text{ MeV}
\]

\[
\sigma \times B = (108.4 \pm 6.9 \pm 8.8) \text{ pb}
\]

Significance >10\( \sigma \)
\(Z_c(3885)^0 \text{ in } e^+e^- \rightarrow (\bar{D}D^*)^0\pi^0\)

- \(L \sim 1092\, \text{pb}^{-1} \text{ at } 4.23\, \text{GeV} \text{ and } \sim 826\, \text{pb}^{-1} \text{ at } 4.26\, \text{GeV}\)
- Simultaneous fit to both charge combinations in the two datasets
- Significance > 10 \(\sigma\)
- Pole parameters of the relativistic BW extracted (c)

<table>
<thead>
<tr>
<th>State</th>
<th>(m_{\text{pole}}(\text{MeV}/c^2))</th>
<th>(\Gamma_{\text{pole}}(\text{MeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_c(3885)^+)</td>
<td>3883.9 (\pm 1.5 \pm 4.2)</td>
<td>24.8 (\pm 3.3 \pm 11.0)</td>
</tr>
<tr>
<td>(Z_c(3885)^+)</td>
<td>3881.7 (\pm 1.6 \pm 2.1)</td>
<td>26.6 (\pm 2.0 \pm 2.3)</td>
</tr>
<tr>
<td>(Z_c(3885)^0)</td>
<td>3885.7 (^{+4.3}_{-5.7}) (\pm 8.4)</td>
<td>35 (^{+11}_{-12}) (\pm 15)</td>
</tr>
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</table>

- Born cross section consistent with half of the charged channel
- Favours the assumption that \(Z_c(3885)^0\) is the neutral isospin partner of \(Z_c(3885)^+\)

(a) PRL112,022001(2014)  
(b) PRD92,092006 (2015)
$Z_c(4020)^{\pm,0}$: study of $e^+e^-\rightarrow h_c\pi^+\pi^-$, and $h_c\pi^0\pi^0$

- 13 center-of-mass energies from 3.9 to 4.42 GeV
- Reconstruction of $h_c\rightarrow \gamma \eta_c$ including 16 exclusive hadronic $\eta_c$ decay modes
- Narrow state very close to the $(D^*\bar{D}^*)^\pm$ threshold
  - $M = (4022.9\pm 0.8 \pm 2.7)$ MeV/c$^2$
  - $\Gamma = (7.9\pm 2.7 \pm 2.6)$ MeV
  - Significance $>8.9\sigma$
  - Significance of 2.1 $\sigma$ for $Z_c(3900)^+$

- $\sqrt{s}$=4.23, 4.26, 4.36 GeV

PRL113,212002(2014)

- 16 exclusive hadronic $\eta_c$ decay modes
  - $M = (4023.9\pm 2.2 \pm 3.8)$ MeV/c$^2$
  - $\Gamma$ = fixed to be the same as its charged partner
  - Significance $>5\sigma$
  - Ratios of Born cross section for neutral and charged modes agree with isospin symmetry

Another isospin triplet is established!
$Z_c(4025)^{\pm,0}$: study of $(D^*\bar{D}^*)^{\pm0}$ system

- Study the $e^+e^-\rightarrow D^*\bar{D}^{*0}\pi^-$ and $D^*-\bar{D}^{*0}\pi^+$ at $\sqrt{s}=4.26$ GeV (827 pb$^{-1}$), and $e^+e^-\rightarrow(D^*\bar{D}^*)^{0}\pi^0$ at $\sqrt{s}=4.26$ GeV (827 pb$^{-1}$) and at $\sqrt{s}=4.23$ GeV (1092 pb$^{-1}$)
- Partial reconstruction technique: bachelor pion and one $D^{*\pm}$ reconstruction
- Fit to the $\pi$ recoiling mass spectra

$Z_c(4025)^{0}$:
$$ M = (4025.5^{+2.0}_{-4.7} \pm 3.1) \text{ MeV/c}^2 $$
$$ \Gamma = (23.0 \pm 6.0 \pm 1.0) \text{ MeV} $$

$Z_c(4025)^{\pm,0}$:
$$ M = (4026.3^{+2.6}_{-3.7}) \pm 3.7 \text{ MeV/c}^2 $$
$$ \Gamma = (24.8 \pm 5.6 \pm 7.7) \text{ MeV} $$

- Enhancement cannot be explained by three-body non-resonant processes
- $Z_c(4025)^0$ is a good candidate to be the isospin partner of $Z_c(4025)^\pm$
- Parameter very similar to $Z_c(4020)$ ⇒ needed rigorous spin analysis
Summary: all $Z_c$ s from BESIII

- $e^+e^- \rightarrow \pi^+(0)\pi^-(0)J/\psi$
  - $Z_c(3900)^{\pm}$
  - $Z_c(3900)^0$

- $e^+e^- \rightarrow (D\overline{D}^*)^{\pm(0)}\pi^{(0)}$
  - $Z_c(3885)^{\pm}$
  - $Z_c(3885)^0$

- $e^+e^- \rightarrow (D^*\overline{D}^*)^{\pm(0)}\pi^{(0)}$
  - $Z_c(4025)^{\pm}$
  - $Z_c(4025)^0$

- $e^+e^- \rightarrow (DD^*)^{\pm(0)}\pi^- (0)$
  - $Z_c(4025)^{0}$

- $e^+e^- \rightarrow (D^*\overline{D}^*)^{\pm(0)}\pi^{(0)}$
  - $Z_c(4025)^{0}$

- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?
Conclusions

- BESIII is successfully operating since 2008, and continues to take data
- Excellent laboratory to study hadron spectroscopy, complementary to scattering and photo production experiments
  - High statistics
  - Low backgrounds
- Many interesting results have been obtained, and only a small part are covered in this talk
- A lot of work must be done
  - Clarify the nature of the XYZ states
  - Observation of transition between these states
  - More detailed studies: PWA, other decay modes, …

FUTURE
- More data will be collected
- Higher luminosity expected from BEPCII
- More detailed studies will be done
Back-up slides
The BESIII Collaboration

USA
5 institutions:
Carnegie Mellon University; Indiana University; University of Hawaii; University of Minnesota; University of Rochester

CHINA
34 institutions:
IHEP, CCAST, UCAS, Beijing Institute of Petro-chemical Technology, Beihang Univ., Guangxi Normal Univ., Guangxi Univ., Hangzhou Normal Univ., Henan Normal Univ., Henan Univ. of Science and Technology, Huazhong Normal Univ., Huazhong University of Science and Technology, University of Jinan, Joint Institute for Nuclear Research (JINR), KVI/University of Groningen, Turkish Accelerator Center Particle Factory Group (TAC-PF), Universitàet Giessen, University of Münster, University of Turin, Uppsala University

EUROPE
14 institutions:
Bochum University, Budker Institute of Nuclear Physics, Ferrara University, GSI Darmstadt, Helmholtz Institute Mainz, INFN, Laboratori Nazionali di Frascati, Johannes Gutenberg University of Mainz, Joint Institute for Nuclear Research (JINR), KVI/University of Groningen, Turkish Accelerator Center Particle Factory Group (TAC-PF), Universitàet Giessen, University of Münster, University of Turin, Uppsala University

OTHER IN ASIA
5 institutions:
COMSATS Institute of Information Technology (CIIT), Institute of Physics and Technology, Mongolia; Tokyo University; Seoul National University; University of the Punjab

~350 members
58 institutions from 12 countries

http://bes3.ihep.ac.cn
BESIII physics programme

Light hadron physics
• Meson and baryon spectroscopy
• Multiquark states
• Threshold effects
• Glueballs and hybrids
• two-photon physics
• Form factors

QCD and τ
• Precision R measurement
• τ decay

Charmonium physics
• Precision spectroscopy
• Transitions and decays

XYZ meson physics
• Y(4260), Y(4360) properties
• Zc(3900)⁺, …

Charm physics
• Semi-leptonic form factors
• Decay constants f_D and f_Ds
• CKM matrix: |V_{cd}| and |V_{cs}|
• D⁰-D̅⁰ mixing, CPV
• Strong phases

Precision mass measurements
• τ mass
• D, D* mass
Study of $J/\psi \rightarrow \eta \phi \pi^+\pi^-$

- Study based on $2.25 \times 10^8$ $J/\psi$ events
- Unbinned maximum likelihood fit is performed to the $\phi f_0(980)$ invariant mass distribution
- No interference between $Y(2175)$ and direct three-body decay of $J/\psi \rightarrow \eta \phi f_0(980)$
- $Y(2175)$ resonance observed with a significance greater than 10 $\sigma$

$M = 2200 \pm 6 \pm 5$ MeV/c$^2$, $\Gamma = 104 \pm 15 \pm 15$ MeV

$\eta \pi \pi$ mass spectrum recoiling against the $\phi$:
- Fit includes contributions from the $f_1(1285)$ and $\eta(1405)$ signals, the $J/\psi \rightarrow \eta \phi \pi\pi$ decay, and backgrounds from non-$\eta$ and non-$\phi$ processes
- No evidence of $X(1835)$ and $X(1870)$ states

$\mathcal{B}(J/\psi \rightarrow \phi f_1 \rightarrow \phi \eta \pi \pi) = (1.20 \pm 0.06 \pm 0.14) \times 10^{-4}$

$\mathcal{B}(J/\psi \rightarrow \phi \eta(1405) \rightarrow \phi \eta \pi \pi) = (2.01 \pm 0.58 \pm 0.82) \times 10^{-5}$
**ppbar enhancement in other reactions**

Belle: PRL**88**, 181803  
\[ B^+ \rightarrow p\bar{p}K^+ \]

BaBar: PRD**73**, 012005  
\[ e^+e^- \rightarrow \gamma pp\bar{p} \]

CLEO: PRD**82**, 092002  
\[ \psi' \rightarrow \pi^+\pi^- J/\psi \]

- Enhancement also seen in other B decays
- FSI? Sub-threshold resonance?
- Not enough statistic to draw any conclusion
$J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta :$ PWA results
Discovery of $Z_c(3900)$

Study of the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ process at the c.m. energy of 4.26 GeV using 525 pb$^{-1}$

- $\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb
- Study the substructures in the $Y(4260) \rightarrow \pi^+\pi^-J/\psi$
  - Dalitz plot analysis: structures in the $\pi^+\pi^-$ and $J/\psi\pi^+$ systems

MC includes $\sigma(500)$, $f_0(980)$, and non-resonant $\pi^+\pi^-$ amplitude
Search of $Z_c(3900) \rightarrow \omega \pi$ in $e^+e^- \rightarrow \omega \pi^+\pi^-$

No $Z_c(3900)$ signal is observed

- As $\pi\omega$ is a typical light hadron decay mode, the non-observation of this decay mode may indicates that the annihilation of ccbar in $Z_c(3900)^\pm$ is suppressed
Y states: $e^+e^- \to \eta J/\psi$

Several non conventional charmoniumlike Y states have been observed in recent years

- The study of hadronic transitions to $J/\psi$ allows to probe their properties
- BESIII analysis: $e^+e^- \to \eta(\pi^0)J/\psi$ from 3.81 to 4.60 GeV (17 c.m. points)

Clear $\eta$ signal observed (no significant for $\pi^0$)

- Unbinned maximum likelihood fit
- Signal: signal MC shape $\otimes$ Gaussian function
- BKG: 2th-order Chebishev

- Good agreement with Belle $\gamma_{\text{ISR}}\eta J/\psi$
- Better precision
- Cross section peaks around 4.2 GeV
- Different shape if compared to Belle $\pi^-\pi^+ J/\psi$ data
- Different dynamic at work in $e^+e^- \to \eta J/\psi$ and $e^+e^- \to \pi^-\pi^+ J/\psi$
The $Z_c(3900)$ mass is 24 MeV/c$^2$ above the $D\bar{D}^*$ mass threshold

- Study the $e^+e^-\rightarrow D^0D^*\pi^+$ and $D^+D^*0\pi^-$ at $\sqrt{s}=4.26$ GeV (525 pb$^{-1}$)
- Partial reconstruction technique: detection of the bachelor $\pi^\pm$ and one D-meson final state ($D^0\rightarrow K\pi$ and $D^+\rightarrow K^-\pi^+\pi^+$)
- Presence of $D^*$ inferred from energy momentum conservation

$$M = (3883.9 \pm 1.5 \pm 4.2) \text{ MeV/c}^2$$
$$\Gamma = (24.8 \pm 3.3 \pm 11.0) \text{ MeV}$$
$$\sigma \times B = (83.5 \pm 6.6 \pm 22.0) \text{ pb}$$

Significance $>18\sigma$

Open charm decay are suppressed w.r.t. conventional charmonium states $\Rightarrow$ different dynamics in the $Y(4260)-Z_c(3900)$ system
Observation of $e^+e^- \rightarrow \gamma X(3872)$

Significance = 6.3 $\sigma$

$N = 20.1 \pm 4.5$ events

$M = 3871.9 \pm 0.7 \pm 0.2$ MeV

$\Gamma$ consistent with detector resolution

The resonant contribution with $Y(4260)$ line shape provides a better description of the data than either a linear continuum or a E1-transition phase space distribution.

The $Y(4260) \rightarrow \gamma X(3872)$ could be another previously unseen decay mode of the $Y(4260)$ resonance.
Search for Y(4140) → J/ψφ

Observed by CDF in the decay $B^+ → φ J/ψ K^+$ with a significance > 5 σ

- Not confirmed by Belle (PRL104), BaBar (PRD91), and LHCb (PRD85)
- Enhancement observed recently by CMS (PLB734), and D0 (PRD89)
- It is the first charmoniumlike state decaying into two vector mesons
- $C=+1 \Rightarrow$ search in radiative transition of Y(4260) (or other $1^{--}$ states)

- Large BESIII samples from 4.23-4.36 GeV (tot. $2.47 fb^{-1}$)

$e^+e^- → γ φ J/ψ$
$J/ψ → e^+e^-, μ^+μ^-$
$φ → K^+K^-, K_SK_L, π^+π^−π^0$

Combined distributions of the six modes
Search for $Y(4140) \to J/\psi \phi$

No significant signal found @ BESIII

- Place upper limit (UL) on $\sigma(e^+e^-\to\gamma Y(4140)) \times \mathcal{B}(Y(4140) \to \phi J/\psi)$ @ 90% C.L.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Luminosity (pb$^{-1}$)</th>
<th>$\sigma \mathcal{B}(Y(4140))$ (pb) (*)</th>
<th>$\sigma \mathcal{B}(X(3872))$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.23</td>
<td>1094</td>
<td>&lt; 0.35</td>
<td>0.27 ± 0.09</td>
</tr>
<tr>
<td>4.26</td>
<td>827</td>
<td>&lt; 0.28</td>
<td>0.33 ± 0.12</td>
</tr>
<tr>
<td>4.36</td>
<td>545</td>
<td>&lt; 0.33</td>
<td>0.11 ± 0.09</td>
</tr>
</tbody>
</table>

(*)Systematic errors included

UL of the same order of magnitude as $\sigma(e^+e^-\to\gamma X(3872)) \times \mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-)$

Assuming:

- $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) \sim 5\%$ (arXiv:0910.3138)
- $\mathcal{B}(Y(4140) \to \phi J/\psi) \sim 30\%$ (using partial width of $Y(4140) \to \phi J/\psi$ calculated under the molecular hypothesis (PRD80, 054019) and the total width measured by CDF (arXiv:1101.6058))

@ 4.23 and 4.26 GeV
First observation of $e^+e^- \rightarrow \omega \chi_{c1,2}$

Clear and signal

PRD93,011102(R) (2016)

5 data samples with GeV

Fit to distribution

coherent sum of BW function and phase-space term

Different line shape for $\omega \chi_{cj}$: different production mechanism