Recent results on spectroscopy
at BES III

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Hadronic Physics with Lepton and Hadron Beams, JLab
Outline

• Introduction

• Selected results from BESIII
  – Light meson spectroscopy
  – Charmonium spectroscopy

• Summary
Beijing Electron Positron Collider (BEPC)

beam energy: 1.0 – 2.3 GeV

2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  \[ L_{\text{peak}} = 1.0 \times 10^{31} / \text{cm}^2\text{s} \]
- 2009-now (BEPCII): \( \times 100 \)
  \[ L_{\text{peak}} = 1 \times 10^{33} / \text{cm}^2\text{s} \]
Physics at BESIII

Charmonium physics:
- spectroscopy
- transitions and decays

Light hadron physics:
- meson & baryon spectroscopy
- two-photon physics
- e.m. form factors of nucleon

Open Charm physics:
- decay constant, form factors
- CKM matrix: V_{cd}, V_{cs}
- D^0-D^0\bar{b}ar mixing and CPV
- rare/forbidden decays

Tau physics:
- tau decays near threshold
- tau mass scan

...and many more.
BESIII data samples

World largest J/ψ, ψ(2S), ψ(3770), Y(4260), ... produced directly from e⁺e⁻ collision
Hadron spectrum

Continuous efforts in experiment and theory

- Hadron spectroscopy is a key tool to investigate QCD
  - testing QCD in the confinement regime
  - providing insights into the fundamental degrees of freedom

Not established yet
Light meson spectroscopy

- X(νν-bar) and X(1835)

- \( \eta \) (1405)
- PWA of J/ψ → γ φφ
- PWA of J/ψ → γ η η
- PWA of J/ψ → γ π^0 π^0

- PWA of \( \chi_{c1} \) → ηπ^+ π^−
Charmonium decays provides an ideal hunting ground for light glueballs and hybrids

◆ “Gluon-rich” process
◆ Clean high statistics data samples from $e^+e^-$ production
◆ $I(J^{PC})$ filter in strong decays of charmonium
PWA of $J/\psi \rightarrow \gamma pp\bar{p}$


- The fit with a BW and S-wave FSI (l=0) factor can well describe $pp\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect ($\Delta 2\ln L = 5, 7.1\sigma$)
- Different FSI models $\rightarrow$ Model dependent uncertainty

Spin parity, mass, width and branching ratio:

$J^{PC} = 0^{-+}, > 6.8\sigma$ better than other $J^{PC}$ assignments, $M = 1832^{+19}_{-5} (stat)^{+18}_{-17} (sys) \pm 19 (model) MeV/c^2$,

$\Gamma = 13 \pm 39 (stat)^{+10}_{-13} (sys) \pm 4 (model) MeV/c^2, \quad \Gamma < 76 MeV/c^2 (90\% \text{ CL}),$

$B(J/\psi \rightarrow \gamma X)B(X \rightarrow pp\bar{p}) = (9.0^{+0.4}_{-1.1} (stat)^{+1.5}_{-5.0} (sys) \pm 2.3 (model)) \times 10^{-5}$
In $J/\psi$ hadronic decays

Study of $J/\psi \rightarrow \omega p\bar{p}$ and $J/\psi \rightarrow \Phi p\bar{p}$ may shed further light on the nature of $X(p\bar{p})$

$J/\psi \rightarrow \omega p\bar{p}$

$B(J/\psi \rightarrow \omega X(p\bar{p}) \rightarrow \omega p\bar{p}) < 3.7 \times 10^{-6}$ (95% CL)

>10x suppressed compared to $J/\psi \rightarrow \gamma X(p\bar{p}) \rightarrow \gamma p\bar{p}$

$J/\psi \rightarrow \Phi p\bar{p}$

$B(J/\psi \rightarrow \Phi X(p\bar{p}) \rightarrow \Phi p\bar{p}) < 2 \times 10^{-7}$ (90% CL)

>100x suppressed compared to $J/\psi \rightarrow \gamma X(p\bar{p}) \rightarrow \gamma p\bar{p}$
X(1835)

- Discovered by BESII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$
- Confirmed by BESIII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- $M = 1836.5 \pm 3.0^{+5.6}_{-2.1} \text{ MeV}/c^2$
- $\Gamma = 190 \pm 9^{+38}_{-36} \text{ MeV}/c^2$
- Angular distribution is consistent with $0^-$

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**Phys. Rev. Lett. 95, 262001 (2005)**
The structure around 1.85 GeV/$c^2$ in the $K_S K_S \eta$ mass spectrum is strongly correlated to $f_0(980)$

Partial Wave Analysis for $M(K_S K_S) < 1.1$ GeV/$c^2$

- $X(1835) \rightarrow K_S K_S \eta$ (the $K_S K_S$ system is dominantly produced through the $f_0(980)$)
  $J^{PC}=0^+, (>12.9 \sigma)$
  $M = 1844 \pm 9 \text{(stat)} ^{+16}_{-25} \text{(syst)} \text{ MeV}/c^2$, $\Gamma = 192^{+20}_{-17} ^{+62}_{-43} \text{ MeV}$
  Consistent with $X(1835)$ observed in $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$
  $B(J/\psi \rightarrow \gamma X(1835)) * B(X(1835) \rightarrow K_S K_S \eta) = (3.31^{+0.33}_{-0.30} ^{+1.96}_{-1.29}) * 10^{-5}$

- $X(1560) \rightarrow f_0(980) \eta$: $J^{PC}=0^+, (>8.9 \sigma)$
  $M = 1565 \pm 8^{+6}_{-63} \text{ MeV}/c^2$, $\Gamma = 45^{+14}_{-13} ^{+21}_{-28} \text{ MeV}$
  Consistent with those of $\eta(1405) / \eta(1475)$ within 2.0 $\sigma$
- Any relations?
- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes
New: connection is emerging

- Use $1.09 \times 10^9$ $J/\psi$ events collected by BESIII in 2012
- Two decay modes of $\eta'$
  - $\eta' \rightarrow \gamma \pi^+ \pi^-$
  - $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \gamma \gamma$
- Clear peaks of $X(1835)$, $X(2120)$, $X(2370)$, $\eta_c$, and a structure near 2.6 GeV/$c^2$
- A significant distortion of the $\eta' \pi^+ \pi^-$ line shape near the $p\bar{p}$ mass threshold
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between $X(1835)$ and $X(p\bar{p})$

$X(1835)$ observed in $J/\psi \rightarrow \gamma \eta'\pi^+\pi^-$


$X(1835)^{J^{PC}=0^{-+}}$

$M = 1844^{+9}_{-12} \text{ MeV/c}^2$

$\Gamma = 192^{+20+62}_{-17-43} \text{ MeV/c}^2$

$X(p\bar{p})$ observed in $J/\psi \rightarrow \gamma p\bar{p}$

PRL 108, 112003 (2012)
PRL 115, 091803 (2015)

$X(p\bar{p})^{J^{PC}=0^{-+}}$

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

$\Gamma = 13 \pm 19 \text{ MeV/c}^2$

(< 76 MeV/c$^2$ @ 90% C.L.)

Connection is emerging

PRL 117, 042002 (2016)

Model 1:
Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at $\sim 1920 \text{ MeV/c}^2$

Model 2:
Coherent sum of $X(1835)$ Breit-Wigner and one additional, narrow Breit-Wigner at $\sim 1870 \text{ MeV/c}^2$

The anomalous line shape can be modeled two models with equally good fit quality.

• Suggest the existence of a state, either a broad state with strong couplings to $pp$, or a narrow state just below the $p\bar{p}$ mass threshold
• Support the existence of a $p\bar{p}$ molecule-like state or bound state
Low lying glueballs have ordinary quantum number
$0^{++}(1.5 \sim 1.7 \text{ GeV})$, $2^{++}(2.3 \sim 2.4 \text{ GeV})$,
$0^+(2.3 \sim 2.6 \text{ GeV})$
mixing with qqbar mesons

Large Br in J/ψ radiative decays

Systematic exp. studies are required:

→ Over-population
   Map out the resonances

→ Production patterns
   $J/\psi \rightarrow \gamma / \omega / \phi + X$
   Other experiments: $\gamma \gamma$ processes from Belle2, ...

→ Decay patterns
   “flavor blind”, “chiral suppression”, ...

LQCD and QCD inspired models
Isospin-violating decay of $\eta(1405) \rightarrow f_0(980)\pi$

The long standing $E-\eta$ puzzle:
$\eta(1405) \rightarrow a_0\pi$, $\eta(1475) \rightarrow K^*\bar{K}$, overpopulation?

Anomalously large isospin violation:

$$\frac{Br(\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\eta(1405) \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} \equiv (17.9 \pm 4.2)\%$$

Much larger than $a_0$-$f_0$ mixing (PRD 83 032003)

$\xi_{\sigma} = \frac{Br(\chi_{c1} \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} < 1\% (90\% C.L.)$

$f_0(980)$ is extremely narrow: $\Gamma \approx 10$ MeV.

PDG: $\Gamma(f_0(980)) \approx 40$-$100$ MeV.

Triangle singularity is proposed
(PRL 108 081803)

An important dynamical effect of threshold

$a_1(1420)$
PRD 89 054038
In J/$\psi$ hadronic decays

\[ f_1(1285) \]

\[ \eta(1405) \]

\[ X(1870) \]

In J/$\psi$ double radiative decays

\[ J/\psi \rightarrow \gamma\gamma\phi \]

[preliminary]

PRD 91, 052017 (2015)

\[ f_1(1285) \]

\[ \eta(1405) \]
Confirmed the enhancement observed at BESII

\[ M = 1795 \pm 7^{+13}_{-5} \pm 19 \text{(model)} \text{ MeV/c}^2, \]

\[ \Gamma = 95 \pm 10^{+21}_{-34} \pm 75 \text{(model)} \text{ MeV} \]

Spin-parity is determined to be \( 0^+ \)

- the same as \( f_0(1710)/f_0(1790) \), or a new state?
PWA of $J/\psi \rightarrow \gamma \eta \eta$
(Phys. Rev. D87 092009 (2013))

- Br of $f_0(1710)$ and $f_0(2100)$ are $\sim 10x$ larger than that of $f_0(1500)$
- Possible large overlap with LQCD predictions of 0+ Glueball: PRL 110 021601 (2013)
- Strong production of $f_2(2340)$
Model Independent PWA of $J/\psi \rightarrow \gamma \pi^0 \pi^0$

- Extract amplitudes in each $M(\pi^0 \pi^0)$ mass bin
- Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 GeV/$c^2$
- Multi-solution problem in MIPWA is usually unavoidable.
- Model Dependent PWA of global PWA fit is still needed to extract resonance parameters

- Solution 1
- Solution 2

Dominant contribution from pseudoscalars
  • η(2225) is confirmed;
  • η(2100) and X(2500) are observed with large significance.

The three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are also observed with a strong production of $f_2(2340)$.

Model-dependent PWA results are well consistent with the results from MIPWA.
Hybrids

Lattice QCD Predictions:

- $\pi_1 \: IG(J^{PC})=1^-(1^-)$
- $\eta_1 \: IG(J^{PC})=0^+(1^-)$
- $K_1 \: IG(J^{PC})=\frac{1}{2} \: (1^-)$

Not observed yet

Complementary studies at BESIII

<table>
<thead>
<tr>
<th>Approximate Mass (MeV)</th>
<th>$J^{PC}$</th>
<th>Total Width (MeV)</th>
<th>Relevant Decays</th>
<th>Final States</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1$ 1900</td>
<td>1$^+$</td>
<td>80 - 170</td>
<td>$b_1\pi^+, \rho\pi^+$</td>
<td>$\omega\pi^+, 3\pi^+$</td>
</tr>
<tr>
<td>$\eta_1$ 2100</td>
<td>1$^-$</td>
<td>60 - 160</td>
<td>$a_1\pi, f_1\pi^+$</td>
<td>4$\pi^+$, $\eta\pi\pi^+$</td>
</tr>
<tr>
<td>$\eta'_1$ 2300</td>
<td>1$^+$</td>
<td>100 - 220</td>
<td>$K_1(1400)K^+, K_1(1270)K^+$</td>
<td>$KK\pi^+, KK\pi^+$</td>
</tr>
<tr>
<td>$b_0$ 2140</td>
<td>0$^+$</td>
<td>250 - 430</td>
<td>$\pi(1300)\pi, h_1\pi$</td>
<td>4$\pi$</td>
</tr>
<tr>
<td>$h_0$ 2140</td>
<td>0$^+$</td>
<td>60 - 260</td>
<td>$b_1\pi^+, h_1\eta, K(1460)K$</td>
<td>$\omega\pi^+, 3\pi^+$, $KK\pi^+$</td>
</tr>
<tr>
<td>$b_0$ 2500</td>
<td>0$^+$</td>
<td>260 - 490</td>
<td>$K(1460)K, K_1(1270)K^+$, $h_1\eta$</td>
<td>$KK\pi^+$, $\eta\pi\pi^+$</td>
</tr>
<tr>
<td>$b_2$ 2500</td>
<td>2$^+$</td>
<td>10 - 20</td>
<td>$a_2\pi^+, a_1\pi, h_1\pi$</td>
<td>4$\pi^+$, $\eta\pi\pi^+$</td>
</tr>
<tr>
<td>$h_2$ 2500</td>
<td>2$^+$</td>
<td>10 - 20</td>
<td>$b_1\pi^+, \rho\pi^+$</td>
<td>$\omega\pi^+, 3\pi^+$</td>
</tr>
<tr>
<td>$b_2$ 2600</td>
<td>2$^+$</td>
<td>10 - 20</td>
<td>$K_1(1400)K^+, K_1(1270)K^+$, $K_2^0K^+$</td>
<td>$KK\pi^+$</td>
</tr>
</tbody>
</table>

PRD 83 111502 (2011)
Amplitude analysis of $\chi_{c1} \rightarrow \eta \pi^+ \pi^-$

- Clear evidence for $a_2(1700)$ in $\chi_{c1}$ decays.
- First measurement of $g'_{\eta \pi} \neq 0$ using $a_0(980) \rightarrow \eta \pi$ line shape.
- Measured upper limits for $\pi_1(1^{-+})$ in 1.4 – 2.0 GeV/c² region.
Charmonium spectroscopy
XYZ states:
Cannot fit in the spectrum of conventional heavy quarkonia

Additional degree of freedom from light quarks and gluons?

Open charm threshold

c- and b-quark are heavy
Non-relativistic QM applies

NRQCD approach is a spectacular success, validated by the consistency between (c\bar{c}) and (b\bar{b})
Observations of $Z_c$

\[ e^+ e^- \rightarrow \pi^+ \pi^- J/\Psi \]

\[ e^+ e^- \rightarrow \pi^0 \pi^0 J/\Psi \]

\[ e^+ e^- \rightarrow \pi^+ \pi^- h_c \]

\[ e^+ e^- \rightarrow \pi^0 \pi^0 h_c \]

\[ \text{BES} \]

\[ e^+ e^- \rightarrow \pi^+ (D\bar{D}^*)^- \]

\[ Z_c(3900) \pm? \]

\[ Z_c(3900)^0? \]

\[ e^+ e^- \rightarrow \pi^+ (D^* \bar{D}^*)^- \]

\[ Z_c(4020) \pm? \]

\[ e^+ e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0 \]

\[ Z_c(4020)^0? \]

Tetraquark? Hadroquarkonium? Molecule? Threshold effect?
Summary of the $Z_c$ at BESIII

<table>
<thead>
<tr>
<th>$Z_c^{\pm}(3900)$</th>
<th>$Z_c^{\pm}(4020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \pi^+\pi^- J/\psi$</td>
<td>$e^+e^- \rightarrow \pi^+\pi^- h_c$</td>
</tr>
<tr>
<td>$M = 3899.0 \pm 3.6 \pm 4.9 \text{MeV}$</td>
<td>$M = 4022.9 \pm 0.8 \pm 2.7 \text{MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 46 \pm 10 \pm 20 \text{MeV}$</td>
<td>$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{MeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z_c^0(3900)$</th>
<th>$Z_c^0(4020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$</td>
<td>$e^+e^- \rightarrow \pi^0\pi^0 h_c$</td>
</tr>
<tr>
<td>$M = 3894.8 \pm 2.3 \text{MeV}$</td>
<td>$M = 4023.9 \pm 2.2 \pm 3.8 \text{MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 29.6 \pm 8.2 \text{MeV}$</td>
<td>$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{MeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z_c^{\pm}(3885)$</th>
<th>$Z_c^{\pm}(4025)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \pi(D\bar{D}^*)^{\pm}$</td>
<td>$e^+e^- \rightarrow \pi(D^<em>\bar{D}^</em>)^{\pm}$</td>
</tr>
<tr>
<td>$M = 3882.2 \pm 1.1 \pm 1.5 \text{MeV}$</td>
<td>$M = 4026.3 \pm 2.6 \pm 3.7 \text{MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 26.5 \pm 1.7 \pm 2.1 \text{MeV}$</td>
<td>$\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{MeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z_c^0(3885)$</th>
<th>$Z_c^0(4025)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \pi^0(D\bar{D}^*)^0$</td>
<td>$e^+e^- \rightarrow \pi^0(D^<em>\bar{D}^</em>)^0$</td>
</tr>
<tr>
<td>$M = 3885.7 \pm 5.7 \pm 8.4 \text{MeV}$</td>
<td>$M = 4025.5 \pm 4.7 \pm 3.1 \text{MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 35 \pm 12 \pm 15 \text{MeV}$</td>
<td>$\Gamma = 23.0 \pm 6.0 \pm 1.0 \text{MeV}$</td>
</tr>
</tbody>
</table>

- $J^P$ of $Z_c(3900)=1^+$ determined from PWA
- DD* dominates $Z_c(3900)$ decays and D*D* dominates $Z_c(4025)$ decays
- No significant $Z_c(3900) \rightarrow h_c\pi,Zc(4020) \rightarrow J/\psi\pi$

DD* threshold (3875 MeV)
D*D* threshold (4017 MeV)

Two isospin triplets established

Mass/width difference in two modes to be understood
Determination of $J^p$ of Zc(3900)


$J^p$ of Zc favor to be $1^+$ with statistical significance larger than 7.3σ over other quantum numbers

- Amplitude analysis with helicity formalism formalism taking $\pi^+\pi^- J/\psi$ as final states
- Simultaneous fit to data samples at 4.23GeV and 4.26GeV
- $\pi^+\pi^-$ spectrum is parameterized with $\sigma$, f0(980), f2(1270) and f0(1370)
Determination of $J^p$ of Zc(3900)

<table>
<thead>
<tr>
<th>$Z_c$ : $J^P$</th>
<th>M (MeV)</th>
<th>$g'_1$(GeV$^2$)</th>
<th>$g'_2/g'_1$</th>
<th>$-\ln L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^-$</td>
<td>3906.3 ± 2.3</td>
<td>0.079 ± 0.007</td>
<td>25.8 ± 2.9</td>
<td>−1528.8</td>
</tr>
<tr>
<td>1$^-$</td>
<td>3903.1 ± 1.9</td>
<td>0.063 ± 0.005</td>
<td>26.5 ± 2.6</td>
<td>−1457.7</td>
</tr>
<tr>
<td>1$^+$</td>
<td>3900.2 ± 1.5</td>
<td>0.075 ± 0.006</td>
<td>21.8 ± 1.7</td>
<td>−1569.8</td>
</tr>
<tr>
<td>2$^-$</td>
<td>3905.2 ± 2.1</td>
<td>0.060 ± 0.004</td>
<td>28.7 ± 2.7</td>
<td>−1516.5</td>
</tr>
<tr>
<td>2$^+$</td>
<td>3894.3 ± 1.9</td>
<td>0.051 ± 0.005</td>
<td>23.4 ± 3.3</td>
<td>−1316.2</td>
</tr>
</tbody>
</table>

- $J^p$ of Zc favor to be 1$^+$ with statistical significance larger than 7.3$\sigma$ over other quantum numbers

- Significance for $e^+e^- \rightarrow Z^+_c (4020) \pi^- + c.c \rightarrow \pi^+\pi^- J/\psi$ is ~3$\sigma$.

Upper limits at 90% C.L.:

$$\frac{\sigma(e^+e^- \rightarrow Z^+_c (4020) \pi^- + c.c \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow Z^+_c (3900) \pi^- + c.c \rightarrow \pi^+\pi^- J/\psi)} < 3.3\% \text{ at } 4.23 \text{ GeV}$$

$$< 25.1\% \text{ at } 4.26 \text{ GeV}$$
A charged structure in $\pi\psi'$

- $M = (4032.1 \pm 2.4)$ MeV/c$^2$
- $\Gamma = (26.1 \pm 5.3)$ MeV
Observation of $e^+e^- \rightarrow \gamma X(3872)$

Strong evidence for
$X(3872) \rightarrow \pi\pi J/\psi$

$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c$^2$

PRL 112, 092001 (2014)

Suggestive of
$Y(4260) \rightarrow \gamma X(3872)$

New mode of production of $X(3872)$ and $Y(4260)$ decay?

If we take $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) \sim 5\%$, ( $>2.6\%$ in PDG)

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim : 10\%$$  Large transition ratio!
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$


- Simultaneous fit to XYZ data (left) and R-scan data (right)
- Coherent sum of two Breit-Wigner like structure plus one incoherent $\psi(3770)$
  - $M = (4222.0\pm3.1\pm1.4)$ MeV, $\Gamma = (44.1\pm4.3\pm2.0)$ MeV, Lower and narrower than previous $Y(4260)$ PDG value
  - $M = (4320.0\pm10.4\pm7)$ MeV, $\Gamma = (101.4\pm25\pm10)$ MeV, a little bit lower than $Y(4360)$ PDG
- Compare with one Breit-Wigner fit, the significance of the second Breit-wigner is 7.6σ
- Is this $Y(4260) + Y(4360)$? The first observation of $Y(4360) \rightarrow \pi^+\pi^- J/\psi$?
- $Y(4008)$ is not confirmed
Cross section of $e^+e^- \rightarrow \pi^+\pi^-\psi'(3686)$ has been measured at 16 energy points from 4.008 to 4.600 GeV.

A clear peak around $Y(4360)$, consistent with Belle & BaBar’s results, but with much improved precision

A fitting on the cross sections is ongoing
Fitted with coherent sum of two Breit-Wigner like structure

- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ MeV/c$^2$, $\Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4$ MeV $\rightarrow Y(4220)$
- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0$ MeV/c$^2$, $\Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6$ MeV $\rightarrow Y(4390)$

- The $Y(4220)$ here is consistent with the states observed in $\pi^+\pi^- J/\psi$ around 4222 MeV
Only $\omega\chi_{c0}$ has significant signal.

The cross section is fitted with coherent sum of a Breit-Wigner and a phase space term.

$$M = 4230 \pm 8 \pm 6 \text{ MeV} , \Gamma = 38 \pm 12 \pm 2 \text{ MeV}$$

The mass and width here is compatible with the Y observed in $\pi^+\pi^- J/\psi$ and $e^+e^- \rightarrow \pi^+\pi^- h_c$.
$e^+ e^- \to \pi^+ D^0 D^{*-}$

Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8 \pm 5.6 \pm 4.0) \text{ MeV}/c^2$, $\Gamma(Y(4220)) = (72.3 \pm 9.1 \pm 0.9) \text{ MeV}$.

$M(Y(4390)) = (4400.1 \pm 9.3 \pm 2.1) \text{ MeV}/c^2$, $\Gamma(Y(4220)) = (181.7 \pm 16.9 \pm 7.4) \text{ MeV}$.  

$$
\sigma_{\text{dress}} = \frac{N^{\text{obs}}}{\mathcal{L}(1 + \delta r) B(D^0 \to K^- \pi^+) \epsilon}
$$

$$
\sigma_{\text{dress}}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m) \sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2} B_2(m) \sqrt{\frac{P(m)}{P(M_2)}}|^2
$$
The statistical significance of two resonances assumption over one resonance is greater than 10s.

The resonant parameters of $Y(4220)$ and $Y(4390)$ states are consistent with the structures observed in $e^+e^- \rightarrow \pi^+\pi^- h_c$. The resonant parameters of $Y(4220)$ are also consistent with those of the resonance observed in $e^+e^- \rightarrow \omega\chi_{c0}$ and $e^+e^- \rightarrow \pi^+\pi^- J/\psi$. 

$e^+e^- \rightarrow \pi^+D^0D^{*-}$
Prospects of hadron spectroscopy at BESIII

### BESIII data taking status & plan (run ~8-10 years)

<table>
<thead>
<tr>
<th></th>
<th>Previous data</th>
<th>BESIII present &amp; future</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ</td>
<td>BESII 58M</td>
<td>1.2 B 20* BESII</td>
<td>10 B</td>
</tr>
<tr>
<td>ψ’</td>
<td>CLEO: 28 M</td>
<td>0.5 B 20* CLEOc</td>
<td>3B</td>
</tr>
<tr>
<td>ψ’’</td>
<td>CLEO: 0.8/fb</td>
<td>2.9/fb 3.5*CLEOc</td>
<td>20 /fb</td>
</tr>
<tr>
<td>Above open charm</td>
<td>CLEO: 0.6/fb</td>
<td>0.5/fb @ ψ(4040)</td>
<td>5-10 /fb</td>
</tr>
<tr>
<td>threshold</td>
<td>@ ψ(4160)</td>
<td>2.3/fb@~4260, 0.5/fb@4360</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5/fb@4600, 1/fb@4420</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scan from 4.19 – 4.28, 10 MeV step, 500 pb-1 point</td>
<td></td>
</tr>
<tr>
<td>R scan &amp; Tau</td>
<td>BESII</td>
<td>3.8-4.6 GeV at 105 energy points</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0-3.1 GeV at 20 energy points</td>
<td></td>
</tr>
<tr>
<td>Y(2175)</td>
<td></td>
<td>100 pb⁻¹</td>
<td></td>
</tr>
<tr>
<td>ψ(4170)</td>
<td></td>
<td>3 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

- The data with unprecedented statistical accuracy and clearly defined initial and final state properties brings BESIII great opportunities to investigate QCD exotics and many other topics.
Thank you
Charmonium decays can provide novel insights into baryons and complementary information to other experiments

- Missing N* with small couplings to $\pi N$ & $\gamma N$, but large coupling to $gggN$:
  $$\psi \rightarrow N\bar{N}\pi/\eta/\eta'/\omega/\phi, \bar{p}\Sigma\pi, \bar{p}\Lambda K...$$
- Not only N*, but also $\Lambda^*, \Sigma^*, \Xi^*$
- Gluon-rich environment: a favorable place for producing hybrid (qqqg) baryons
- High statistics of charmonium @ BES III
Observation of two new N* resonances in $\psi(3686) \to p\bar{p}\pi^0$

- In photon or meson beam studies, isospin 1/2 and 3/2 resonances are excited, complicating the analysis
- $\Delta$ resonances suppressed in charmonium decays to $p\bar{p}\pi^0$, giving a cleaner spectrum
  - Thought to be dominated by two body decays involving N* intermediate states
  - Also consider $p\bar{p}$ resonances ($\psi(3686) \to R\pi^0$)
- Seven N* states observed in partial wave analysis
  - Two new resonances, N(2300) with $J^P = 1/2^+$ and N(2570) with $J^P = 5/2^-$
  - Other five consistent with previous results

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>$\Delta S$</th>
<th>$\Delta N_{dof}$</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1440)</td>
<td>1390$^{+11+21}_{-21-30}$</td>
<td>346$^{+46}_{-40}$</td>
<td>72.5</td>
<td>4</td>
<td>11.5σ</td>
</tr>
<tr>
<td>N(1520)</td>
<td>1510$^{+3+11}_{-7-15}$</td>
<td>115$^{+20}_{-15+40}$</td>
<td>19.8</td>
<td>6</td>
<td>5.0σ</td>
</tr>
<tr>
<td>N(1535)</td>
<td>1535$^{+9+15}_{-8-22}$</td>
<td>120$^{+20-42}_{-20+4}$</td>
<td>49.4</td>
<td>4</td>
<td>9.3σ</td>
</tr>
<tr>
<td>N(1650)</td>
<td>1650$^{+5+11}_{-8-22}$</td>
<td>82.1</td>
<td>4</td>
<td>12.2σ</td>
<td></td>
</tr>
<tr>
<td>N(1720)</td>
<td>1700$^{+28+30}_{-30-32}$</td>
<td>450$^{+89}_{-149}$</td>
<td>55.6</td>
<td>6</td>
<td>9.6σ</td>
</tr>
<tr>
<td>N(2300)</td>
<td>2300$^{+40+109}_{-30-0}$</td>
<td>340$^{+30+110}_{-30-58}$</td>
<td>120.7</td>
<td>4</td>
<td>15.0σ</td>
</tr>
<tr>
<td>N(2570)</td>
<td>2570$^{+19+34}_{-10-10}$</td>
<td>250$^{+14+69}_{-24-21}$</td>
<td>78.9</td>
<td>6</td>
<td>11.7σ</td>
</tr>
</tbody>
</table>
Measurements of $\psi(3686) \rightarrow (\gamma)K^+\Lambda\Xi^\pm$

- $\psi(3686) \rightarrow (\gamma)K^+\Lambda\Xi^\pm$; $\Lambda \rightarrow p\pi$, $\Xi \rightarrow \Lambda\pi$; $\Lambda \rightarrow p\pi$

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(3686) \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow \Xi(1690)^-\Xi^+$, $\Xi(1690)^- \rightarrow K^-\Lambda$</td>
<td>$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow \Xi(1820)^-\Xi^+$, $\Xi(1820)^- \rightarrow K^-\Lambda$</td>
<td>$(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow K^-\Sigma^0\Xi^+$</td>
<td>$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow \gamma\chi_{c0}$, $\chi_{c0} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow \gamma\chi_{c1}$, $\chi_{c1} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\psi(3686) \rightarrow \gamma\chi_{c2}$, $\chi_{c2} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.96 \pm 0.31 \pm 0.16) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.43 \pm 0.22 \pm 0.12) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow K^-\Lambda\Xi^+$</td>
<td>$(1.93 \pm 0.30 \pm 0.15) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- Observe two hyperons, $\Xi(1690)$ and $\Xi(1820)$ in $M(K\Lambda)$
  - Both are well established states
  - Resonance parameters consistent with the PDG