# BESI



# Vector charmonium and charmoniumlike states at BESIII

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# Outline

Introduction

BESIII detector and data samples

Results on Y states at BESIII

Summary

# **The Charmonium System**

- $c\bar{c}$  bound states can be described using potential models
- All predicted states below the  $D\overline{D}$  threshold have been found!
- Properties are in agreement with predictions
- Clean environment to search for exotic states
- Many unpredicted states were reported above the  $\sin D\overline{D}$  threshold, called "XYZ" states
- "XYZ" states
  - ≻ "X": Neutral,  $J^{pc} \neq 1^{--}$ 
    - Observed in radiative or hadronic transitions from Y.
  - ▶ "Y": Neutral,  $J^{pc} = 1^{--}$ 
    - Direct access in  $e^+e^-$  annihilation.
  - "Z": Charged, isospin triplete
    - Observed in hadronic transitions from Y.

(for "X" and "Z", please refer to Zhiqing Liu and Ronggang Ping's report)



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## **The BESIII Detector and Data Samples**



- Main drift Chamber (MDC) :  $\sigma_{dE/dx} = 6\%$ ,  $\sigma_{xy} = 130 \,\mu\text{m}$ ,  $\sigma_p/p=0.5\%$
- Time of flight system (TOF):  $\delta_{t,barrel} = 80 \text{ ps}, \ \delta_{t,endcaps} = 65 \text{ ps}$
- Electromagnetic Calorimeter:  $\sigma_E = 2.5\%$ ,  $\sigma_l = 6$  mm
- Superconducting Solenoid: B = 1.0 T
- RPC muon chamber:  $\delta_R = 1.48$  cm



- Data samples used for XYZ study in this report:
- XYZ data :5 fb<sup>-1</sup> e<sup>+</sup>e<sup>-</sup> collision data event in open charm region from 3.8 to 4.6 GeV
- R-scan data: 104 energy points from 3.85 to 4.59 GeV, integrated luminoisity~0.83 fb<sup>-1</sup>

New large XYZ samples with energy range from 4.18 to 4.28 GeV have been taken since 2016

# The Y states

- Why "exotic"
  - > No natural place within quark model.
  - > Strongly coupling to  $\pi^+\pi^- J/\psi$  rather charm decay modes.
  - ➢ Dip on R-value

- Theoretical interpretation
  - ➢ Hybrid charmonium
  - > Tetraquark
  - > Hadronic molecule
  - ▶ ...

### • Y(4260) in $e^+e^- \to \pi^+\pi^- J/\psi$

- Discovery in ISR process by BaBar
- > Confirmed by Belle.
- > At BESIII, two resonant structures observed. New!

4.6 4.8 5 5.2 5.4



#### • Y(4360) in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$

- > Discovery in ISR process by BaBar
- > Confirmed by Belle.
- $\succ$  No evidence for the Y(4260)
- > At BESIII, two structures observed in 4.2 4.4 GeV. New!

(c)

5 5



 $e^+e^- 
ightarrow \pi^+\pi^- J/\psi$ 

#### Phys. Rev. Lett. 118, 092001 (2017)



Simultaneous fit of two independent data sets ("XYZ" and "Scan")

- Two resonant structures observed in the energy region of Y(4260) reported before
- Y(4320) observed for the first time in  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
- Significance of Y(4320):  $7.6\sigma$
- No hint of Y(4008) seen in Belle

 $M_1 = 4222.5 \pm 3.1 \pm 1.4 \text{ MeV/c}^2, \Gamma_1 = 44.1 \pm 4.3 \pm 2.0 \text{ MeV}$  $M_2 = 4320.0 \pm 10.4 \pm 7.0 \text{ MeV/c}^2, \Gamma_2 = 101.4 \substack{+25.3 \\ -19.7} \pm 10.2 \text{ MeV}$ 

 $e^+e^- \rightarrow \pi^+\pi^-h_c$ 

#### Phys. Rev. Lett. 118, 092002 (2017)

Data samples:  $\mathcal{L}=5.77 \text{ fb}^{-1}$  from 3.868 to 4.60 GeV



Simultaneous fit of two independent data sets ("XYZ" and "Scan")

• Two resonant structures observed with a significance over  $10\sigma$ 

■ Y(4220) is compatible with the state found in  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ 

 $M_{1} = 4218.0^{+5.5}_{-4.5} \pm 0.9 \text{ MeV/c}^{2}, \Gamma_{1} = 66.0^{+12.3}_{-8.3} \pm 0.4 \text{ MeV}$  $M_{2} = 4391.5^{+6.3}_{-6.8} \pm 1.0 \text{ MeV/c}^{2}, \Gamma_{2} = 139.5^{+16.2}_{-20.6} \pm 0.6 \text{ MeV}$ 

 $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ 

Data samples:

- > 16 energy points from  $\sqrt{s} = 4.008$  to 4.600 GeV
- > The total integrated luminosity is 5.1 fb<sup>-1</sup>
- Reconstructed modes:
  - > Mode I:  $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow l^+ l^-$
  - Mode II: ψ(3686) → neutrals + J/ψ, J/ψ → l<sup>+</sup>l<sup>-</sup> neutrals = (π<sup>0</sup>π<sup>0</sup>, π<sup>0</sup>, η and γγ)



Phys. Rev. D96, 132004 (2017)



- Black solid curve: with three resonances  $\chi^2/ndf=9.98/7$
- Pink dashed curve: without Y(4220),  $\chi^2/ndf = 54.54/11$
- Significance of Y(4220) is  $5.8\sigma$
- Y(4220) observed in  $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$  for the first time !

 $M_1 = 4209.5 \pm 7.4 \pm 1.4 \text{ MeV}/c^2$ ,  $\Gamma_1 = 80.1 \pm 24.6 \pm 2.9 \text{ MeV}$  $M_2 = 4383.8 \pm 4.2 \pm 0.8 \text{ MeV}/c^2$ ,  $\Gamma_2 = 84.2 \pm 12.5 \pm 2.1 \text{ MeV}$ 

 $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ 

#### arXiv: 1710.10740 [hep-ex]

Reconstructed channel:

$$\succ \psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow l^+l^-(l=e/\mu).$$



- Number of signals are extracted from  $\pi^+\pi^- J/\psi$  invariant mass.
- The dominant background is from the charged mode  $e^+e^ \rightarrow \pi^+\pi^-\psi(3686)$ , and described with corresponding MC shape convoluted with a Gaussian function.

# $e^+e^- \rightarrow \pi^+ D^0 D^{*-}$

- Using data sample from 4.05 to 4.60 GeV
- Reconstructed channel:  $D^0 \rightarrow K^- \pi^+$
- Using  $RM(D^0\pi^+) + M(D^0) m(D^0)$  to select  $D^{*-}$  signal
- Peaking background comes from isospin partner  $e^+e^- \rightarrow \pi^+ D^- D^{*0}$





- Fit with a coherent sum of three-body PHSP and two Breit-Wigner functions
- Significance of two structures greater than  $10\sigma$  over one structure assumption

$$\begin{split} M_1 &= 4228.6 \pm 4.1 \pm 5.0 \; \text{MeV}/\text{c}^2, \\ \Gamma_1 &= 77.1 \pm 6.8 \pm 2.7 \; \text{MeV} \\ M_2 &= 4404.6 \pm 7.4 \pm 4.8 \; \text{MeV}/\text{c}^2, \\ \Gamma_2 &= 191.7 \pm 13.0 \pm 15.1 \; \text{MeV} \end{split}$$

$$e^+e^- \rightarrow \omega \chi_{c0}$$

#### Phys. Rev. Lett. 114, 092003 (2015)



- Using 9 energy points from 4.21 to 4.42 GeV, the process  $e^+e^- \rightarrow \omega \chi_{c0}$  is observed at 4.23 and 4.26 GeV.
- Assuming the  $\omega \chi_{c0}$  signals come from a single resonace, the mass and width are extracted as:

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

• Y(4220) is compatible with the state found in  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$  and  $e^+e^- \rightarrow \pi^+\pi^- h_c$ 

 $e^+e^- \rightarrow K\overline{K} I/\psi$ 

- Data samples:  $\mathcal{L}=4.7 \text{ fb}^{-1} \text{ from } 4.189 \text{ to } 4.600 \text{ GeV}$
- Born cross sections of  $e^+e^- \rightarrow K^+K^- J/\psi$  and  $e^+e^- \rightarrow K_s^0 K_s^0 J/\psi$  are measured
- $\sigma_E (K^+ K^- J/\psi) / \sigma_E (\pi^+ \pi^- J/\psi)$  inconsistent with flat ratio in 4.226 4.358 GeV.
- The combined ratio of  $\sigma_E(K_s^0 K_s^0 J/\psi)/\sigma_E(K^+ K^- J/\psi)$  is  $0.370_{-0.058}^{+0.064} \pm 0.018$ , while the isospin symmetry prediction is  $\frac{1}{2}$ .

No conclusive result of Y(4260) decays to  $K\bar{K}J/\psi$ Enhancement in  $e^+e^- \rightarrow K\bar{K}J/\psi$  in higher mass region More data are needed to investigate the nature of this structure



 $e^+e^- \rightarrow \eta J/\psi$ 

#### Phys. Rev. D 91, 112005 (2015)



- Data sample: 17 energy points from 3.810 to 4.600 GeV
- Cross sections agree with previous result with Belle's results
- Enhancement around 4.2 GeV ( $\psi(4160)$  or Y(4220)?)
- Different line-shape from  $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ , indicating a rich spectrum of Y states in this energy region.

 $e^+e^- 
ightarrow \eta' J/\psi$ 

Phys. Rev. D 94, 032009 (2016)



- Significant  $e^+e^- \rightarrow \eta' J/\psi$  signals are observed at 4.226 and 4.258 GeV
- The measured cross sections support the hypothesis that signal events from  $\psi(4160)$  in PDG (6.6 $\sigma$ )
- The contribution of  $\psi(4415)$  is not evident  $(1.3\sigma)$

# **Summary**

- BESIII observed a series of vector charmonium-like states from various processes
- Masses and widths of vector charmonium-like observed at BESIII in mass region 4.2 and 4.4 GeV/c<sup>2</sup>:

| Process                                   | $M_1 \; ({\rm MeV}/c^2)$     | $\Gamma_1$ (MeV)            | $M_2 \; ({\rm MeV}/c^2)$     | $\Gamma_2$ (MeV)               |
|---|------------------------------|-----------------------------|------------------------------|--------------------------------|
| $e^+e^- \rightarrow \omega \chi_{c0}$     | $4230\pm8\pm6$               | $38\pm12\pm2$               |                              |                                |
| $e^+e^-  ightarrow \pi^+\pi^- J/\psi$     | $4220.0 \pm 3.1 \pm 1.4$     | $44.1\pm4.3\pm2.0$          | $4320.0 \pm 10.4 \pm 7.0$    | $101.4^{+25.3}_{-19.7}\pm10.2$ |
| $+e^+e^- \rightarrow \pi^+\pi^-h_c$       | $4218.4^{+5.5}_{-4.5}\pm0.9$ | $66.0^{+12.3}_{-8.3}\pm0.4$ | $4391.5^{+6.3}_{-6.8}\pm1.0$ | $139.5^{+16.2}_{-20.6}\pm0.6$  |
| $e^+e^-  ightarrow \pi^+D^0D^{*-} + c.c$  | $4224.8 \pm 5.6 \pm 4.0$     | $72.3 \pm 9.1 \pm 0.9$      | $4400.1 \pm 9.3 \pm 2.1$     | $181.7 \pm 16.9 \pm 7.4$       |
| $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ | $4209.5 \pm 7.4 \pm 1.4$     | $80.1 \pm 24.6 \pm 2.9$     | $4383.8 \pm 4.2 \pm 0.8$     | $84.2 \pm 12.5 \pm 2.1$        |



Possible structures in other processes  $(\eta J/\psi, K\overline{K} J/\psi...)$  are expected to be determined with more data taking at BESIII.

