# Spectroscopy at BESIII: <br> Open Questions 

Ryan Mitchell<br>Indiana University<br>Exotic Hadrons Workshop<br>May 29, 2018, Stony Brook, NY


$e^{+} e^{-} \rightarrow Y(4260) \rightarrow \pi^{+} \pi^{-} J / \psi$

## Spectroscopy at BESIII:

## Open Questions

BESIII at BEPCII (Beijing, China):
$\mathrm{e}^{+\mathrm{e}^{-} \text {Collisions at } \mathrm{E}_{\mathrm{CM}} \text { between } 2.0 \text { and } 4.6 \mathrm{GeV}}$



## Spectroscopy at BESIII:

## BESIII Data Sets and Physics Reach

Example of Precision Spectroscopy
Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the Z question

Common Theme:
$\Rightarrow$ the need for collaboration between theory and experiment

$$
e^{+} e^{-} \rightarrow Y(4260) \rightarrow \pi^{+} \pi^{-} J / \psi
$$

## The Broad Physics Reach of BESIII

## Charmonium Spectrum

predictions based on PRD 72, 054026 (2005)
measurements from PDG


BESIII Data Sets (primary):
( $e^{+} e^{-}$collisions at $E_{C M}$ between 2.0 and 4.6 GeV )

```
2009: 106M \psi(2S)
    225M J/\psi
2010: 975 pb-1 at \psi(3770)
2011: 2.9 fb-1 at \psi(3770) (total)
    482 pb-1 at 4.01 GeV
2012:0.45B \psi(2S) (total)
    1.3B J/\psi (total)
2013: }1092\mp@subsup{\textrm{pb}}{}{-1}\mathrm{ at 4.23 GeV
            826 pb-1 at 4.26 GeV
            540 \mp@subsup{\textrm{pb}}{}{-1}\mathrm{ at 4.36 GeV}
            ~50 \mp@subsup{\textrm{pb}}{}{-1}\mathrm{ at 3.81, 3.90, 4.09, 4.19, 4.21,}
            4.22, 4.245, 4.31, 4.39, 4.42 GeV
```

2014: $1029 \mathrm{pb}^{-1}$ at 4.42 GeV
$110 \mathrm{pb}^{-1}$ at $4.47 \mathbf{~ G e V}$
$110 \mathrm{pb}^{-1}$ at 4.53 GeV
$48 \mathrm{pb}^{-1}$ at $4.575 \mathbf{~ G e V}$
$567 \mathrm{pb}^{-1}$ at 4.6 GeV
$0.8 \mathrm{fb}^{-1} \mathbf{R}$-scan from 3.85 to 4.59 GeV (104 points)
2015: R-scan from $2-3 \mathrm{GeV}+\mathbf{2 . 1 7 5} \mathbf{~ G e V}$ data
2016: $\sim 3 \mathrm{fb}^{-1}$ at 4.18 GeV (for $\mathbf{D}_{\text {s }}$ )
2017: $7 \times 500 \mathrm{pb}^{-1}$ between 4.19 and 4.27 GeV
2018: $\mathbf{J} / \boldsymbol{\psi}$ (and tuning new RF cavity)
+ Initial State Radiation (ISR)
(data sets from BESII are much smaller (e.g. $58 M \mathrm{~J} / \psi$ decays))

## Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach

## Example of Precision Spectroscopy

Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the $Z$ question

Common Theme:
$\Rightarrow$ the need for collaboration between theory and experiment

## Precision Studies in Charmonium

## Charmonium Spectrum

predictions based on PRD 72, 054026 (2005)
measurements from PDG


$$
\begin{gathered}
\psi(2 S) \rightarrow \gamma+\text { anything } \\
{[\text { PRD 96, } 032001 \text { (2017)] }}
\end{gathered}
$$



(using $106 M \psi(2 S)$ decays)

## Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach
Example of Precision Spectroscopy
Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the $Z$ question

Common Theme:
$\Rightarrow$ the need for collaboration between theory and experiment

# Examples of Open Questions in Spectroscopy at BESIII 

## (1) The proton antiproton Question

What is the $X(1835)$ ?
(2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question

Why are there anomalous differences between $\mathrm{J} / \psi$ and $\psi(2 S)$ decays?
(3) The Y Question

Why are there so many different peaks in exclusive $e^{+} e^{-}$cross sections?
e.g. $Y(4230), Y(4260), Y(4360), Y(4660)$, etc.
(4) The Z Question

What are the electrically charged "charmoniumlike" peaks?
e.g. $Z_{c}(3900), Z_{c}(4020), Z_{c}(4055)$, etc.

## (1) The proton antiproton Question

$$
\begin{gathered}
J / \psi \rightarrow \gamma p \bar{p} \\
{[\text { BESII, PRL 91, } 022001(2003)]}
\end{gathered}
$$



## (1) The proton antiproton Question

$J / \psi \rightarrow \gamma p \bar{p}$
$[\mathrm{PRL} 108,112003(2012)]$


Fit Components: $\mathrm{X}(1835), 0^{++}$phase space, $\mathrm{f}_{0}(2100), \mathrm{f}_{2}(1910)$

$$
M=1832_{-5}^{+19}(\text { stat })_{-17}^{+18}(\text { syst }) \pm 19(\text { model }) ; \Gamma<76 \mathrm{MeV} / c^{2} ; J^{P C}=0^{-+}
$$

## (1) The proton antiproton Question



$$
M=1833.7 \pm 6.1 \text { (stat) } \pm 2.7 \text { (syst) } \mathrm{MeV} / c^{2} ; \Gamma=67.7 \pm 20.3 \text { (stat) } \pm 7.7 \text { (syst) } \mathrm{MeV} / c^{2} ;
$$

## (1) The proton antiproton Question



## (1) The proton antiproton Question

$$
\begin{gathered}
J / \psi \rightarrow \gamma \pi^{+} \pi^{-} \eta^{\prime} \\
{[\text { PRL 117, } 042002(2016)]}
\end{gathered}
$$



| The state around $1.85 \mathrm{GeV} / c^{2}$ |  |
| :--- | :---: |
| $\mathcal{M}\left(\mathrm{MeV} / c^{2}\right)$ | $1638.0 \pm 121.9_{-254.8}^{+127.8}$ |
| $g_{0}^{2}\left[\left(\mathrm{GeV} / c^{2}\right)^{2}\right]$ | $93.7 \pm 35.4_{-4.9}^{+4.6}$ |
| $g_{p \bar{p}}^{2} / g_{0}^{2}$ | $2.31 \pm 0.37_{-0.60}^{+0.83}$ |
| $M_{\text {pole }}\left(\mathrm{MeV} / c^{2}\right)$ | $1909.5 \pm 15.9_{-2.4 .5}^{+9.4}$ |
| $\Gamma_{\text {pole }}\left(\mathrm{MeV} / c^{2}\right)$ | $273.5 \pm 21.4_{-64.1}^{+6.1}$ |
| Branching ratio | $\left(3.93 \pm 0.38_{-0.84}^{+0.31}\right) \times 10^{-4}$ |



| $X(1835)$ |  |
| :--- | :---: |
| Mass $\left(\mathrm{MeV} / c^{2}\right)$ | $1825.3 \pm 2.4_{-2.4}^{+17.3}$ |
| Width $\left(\mathrm{MeV} / c^{2}\right)$ | $245.2 \pm 13.1_{-9.6}^{+4.6}$ |
| B.R. (constructive interference) | $\left(3.01 \pm 0.17_{-0.28}^{+0.26}\right) \times 10^{-4}$ |
| B.R. (destructive interference) | $\left(3.72 \pm 0.21_{-0.35}^{+0.18}\right) \times 10^{-4}$ |


| $X(1870)$ |  |
| :--- | :---: |
| Mass $\left(\mathrm{MeV} / c^{2}\right)$ | $1870.2 \pm 2.2_{-0.7}^{+2.3}$ |
| Width $\left(\mathrm{MeV} / c^{2}\right)$ | $13.0 \pm 6.1_{-3.1}^{+2.1}$ |
| B.R. (constructive interference) | $\left(2.03 \pm 0.12_{-0.73}^{+0.43}\right) \times 10^{-7}$ |
| B.R. (destructive interference) | $\left(1.57 \pm 0.09_{-0.86}^{+0.49}\right) \times 10^{-5}$ |

## (1) The proton antiproton Question

$$
\begin{gathered}
J / \psi \rightarrow \gamma \gamma \phi \\
{[\mathrm{PRD} 97,051101(2018)]}
\end{gathered}
$$



$$
\begin{gathered}
\mathrm{X}(1835) \rightarrow \gamma \phi ? \\
\text { * angles consistent with } 0^{-+} \text {assignment } \\
\text { * mass and with consistent with } \mathrm{X}(1835)
\end{gathered}
$$

# Examples of Open Questions in Spectroscopy at BESIII 

## (1) The proton antiproton Question

What is the $X(1835)$ ?
(2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question

Why are there anomalous differences between $\mathrm{J} / \psi$ and $\psi(2 S)$ decays?
(3) The Y Question

Why are there so many different peaks in exclusive $e^{+} e^{-}$cross sections?
e.g. $Y(4230), Y(4260), Y(4360), Y(4660)$, etc.
(4) The Z Question

What are the electrically charged "charmoniumlike" peaks?
e.g. $Z_{c}(3900), Z_{c}(4020), Z_{c}(4055)$, etc.

## (2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question


implies:

$$
\frac{\mathcal{B}(\psi(2 S) \rightarrow X)}{\mathcal{B}(J / \psi \rightarrow X)} \approx 12 \%
$$

but:

$$
\begin{aligned}
& \frac{\mathcal{B}\left(\psi(2 S) \rightarrow \pi^{+} \pi^{-} \pi^{0}\right)}{\mathcal{B}\left(J / \psi \rightarrow \pi^{+} \pi^{-} \pi^{0}\right)} \\
= & \left.(1.00 \pm 0.01 \text { (stat. })_{-0.05}^{+0.06} \text { (syst.) }\right) \%
\end{aligned}
$$

$$
\underset{[\text { PLB 710, } 594(2012)]}{J / \psi} \underset{ }{\text { and } \psi(2 S) \rightarrow \pi^{+} \pi^{-} \pi^{0}}
$$





(using $225 \mathrm{M} \mathrm{J} / \psi$ decays and $106 \mathrm{M} \psi(2 S)$ decays)

## (2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question


implies:

$$
\frac{\mathcal{B}(J / \psi \rightarrow \gamma \eta)}{\mathcal{B}\left(J / \psi \rightarrow \gamma \eta^{\prime}\right)} \approx \frac{\mathcal{B}(\psi(2 S) \rightarrow \gamma \eta)}{\mathcal{B}\left(\psi(2 S) \rightarrow \gamma \eta^{\prime}\right)}
$$

$$
\begin{aligned}
& \psi(2 S) \rightarrow \gamma \eta \text { and } \gamma \eta^{\prime} \\
& {[\text { PRD 96, } 052003 \text { (2017)] }}
\end{aligned}
$$


but:

$$
\frac{\mathcal{B}(J / \psi \rightarrow \gamma \eta)}{\mathcal{B}\left(J / \psi \rightarrow \gamma \eta^{\prime}\right)}=(21.4 \pm 0.9) \%
$$

and:

$$
\begin{aligned}
& \frac{\mathcal{B}(\psi(2 S) \rightarrow \gamma \eta)}{\mathcal{B}\left(\psi(2 S) \rightarrow \gamma \eta^{\prime}\right)} \\
& \quad \quad=(0.66 \pm 0.13 \pm 0.02) \%
\end{aligned}
$$


(using $448 M \psi(2 S)$ decays)

# Examples of Open Questions in Spectroscopy at BESIII 

## (1) The proton antiproton Question

What is the $X(1835)$ ?
(2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question

Why are there anomalous differences between $\mathrm{J} / \psi$ and $\psi(2 S)$ decays?
(3) The Y Question

Why are there so many different peaks in exclusive $e^{+} e^{-}$cross sections?
e.g. $Y(4230), Y(4260), Y(4360), Y(4660)$, etc.
(4) The Z Question

What are the electrically charged "charmoniumlike" peaks?
e.g. $Z_{c}(3900), Z_{c}(4020), Z_{c}(4055)$, etc.

## (3) The $\mathbf{Y}$ Question

$e^{+} e^{-} \rightarrow$ hadrons
[BESII, PLB 660, 315 (2008)]


$$
\begin{aligned}
\mathrm{J} / \psi & =1^{3} \mathrm{~S}_{1} & \psi(3770)=1^{3} \mathrm{D}_{1} & \psi(4160)=2^{3} \mathrm{D}_{1} \\
\psi(2 \mathrm{~S}) & =2^{3} \mathrm{~S}_{1} & \psi(4040)=3^{3} \mathrm{~S}_{1} & \psi(4415)=4^{3} \mathrm{~S}_{1}
\end{aligned}
$$

## (3) The $\mathbf{Y}$ Question



## (3) The $\mathbf{Y}$ Question

$$
\begin{gathered}
e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} J / \psi \\
{[\text { BaBar, PRL 95, 142001 (2005)] }}
\end{gathered} \quad \text { vs. } \quad \begin{gathered}
e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} J / \psi \\
{[\text { PRL 118, 092001 (2017)] }}
\end{gathered}
$$




## (3) The $\mathbf{Y}$ Question



## (3) The $\mathbf{Y}$ Question

$$
\begin{aligned}
& e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} \psi(2 S) \quad \text { vs } \quad e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} h_{c}(1 P) \\
& \text { [PRD 96, } 032004 \text { (2017)] VS. [PRL 118, } 092002 \text { (2017)] }
\end{aligned}
$$

## (3) The $\mathbf{Y}$ Question

$$
\begin{array}{ccc}
e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} h_{c}(1 P) & \text { vs. } & e^{+} e^{-} \rightarrow \pi^{+} D^{0} D^{*-}+c . c . \\
{[\text { PRL 118, 092002(2017)] }} & {[\text { preliminary }(2017)]}
\end{array}
$$




## (3) The $\mathbf{Y}$ Question

## Parameters of the Peaks in $\mathrm{e}^{+} \mathrm{e}^{-}$Cross Sections



# Examples of Open Questions in Spectroscopy at BESIII 

## (1) The proton antiproton Question

What is the $X(1835)$ ?
(2) The $\boldsymbol{\varrho} \boldsymbol{\pi}$ Question

Why are there anomalous differences between $\mathrm{J} / \psi$ and $\psi(2 S)$ decays?
(3) The Y Question

Why are there so many different peaks in exclusive $e^{+} e^{-}$cross sections?
e.g. $Y(4230), Y(4260), Y(4360), Y(4660)$, etc.
(4) The Z Question

What are the electrically charged "charmoniumlike" peaks?
e.g. $Z_{c}(3900), Z_{c}(4020), Z_{c}(4055)$, etc.

## (4) The $\mathbf{Z}$ Question

$$
\begin{aligned}
& e^{+} e^{-} \rightarrow \pi^{ \pm}\left(\pi^{\mp} J / \psi\right) \\
& {[\text { PRL 110, 252001 (2013)] }}
\end{aligned}
$$

$e^{+} e^{-} \rightarrow \pi^{ \pm}\left(D \bar{D}^{*}\right)^{\mp}$
$[\operatorname{PRL} 112,022001(2014)]$

(using $525 \mathrm{pb}^{-1}$ at 4.26 GeV )

$$
\begin{gathered}
M=(3899.0 \pm 3.6 \pm 4.9) \mathrm{MeV} / c^{2} \\
\Gamma=(46 \pm 10 \pm 20) \mathrm{MeV} / c^{2}
\end{gathered}
$$


(using $525 \mathrm{pb}^{-1}$ at 4.26 GeV )
$M=(3883.9 \pm 1.5 \pm 4.2) \mathrm{MeV} / c^{2} ;$
$\Gamma=(24.8 \pm 3.3 \pm 11.0) \mathrm{MeV} / c^{2} ;$

$$
J^{P}=1^{+}
$$

## (4) The $\mathbf{Z}$ Question

$$
\begin{gathered}
e^{+} e^{-} \rightarrow \pi^{ \pm}\left(\pi^{\mp} J / \psi\right) \\
{[\text { PRL 119, } 072001 \text { (2017) (Aug. 16)] }}
\end{gathered}
$$





$$
\begin{gathered}
M=(3881.2 \pm 4.2 \pm 52.7) \mathrm{MeV} / c^{2} \\
\Gamma=(51.8 \pm 4.6 \pm 36.0) \mathrm{MeV} / c^{2} \\
J^{P}=1^{+}
\end{gathered}
$$

## (4) The $\mathbf{Z}$ Question

$$
\begin{gathered}
e^{+} e^{-} \rightarrow \pi^{ \pm}\left(\pi^{\mp} h_{c}(1 P)\right) \\
\quad[\text { PRL 111, } 242001(2013)]
\end{gathered}
$$


(using $1090 \mathrm{pb}^{-1}$ at 4.23 GeV,
$827 \mathrm{pb}^{-1}$ at 4.26 GeV , $545 \mathrm{pb}^{-1}$ at 4.36 GeV )

$$
\begin{gathered}
M=(4022.9 \pm 0.8 \pm 2.7) \mathrm{MeV} / c^{2} \\
\Gamma=(7.9 \pm 2.7 \pm 2.6) \mathrm{MeV} / c^{2}
\end{gathered}
$$

$e^{+} e^{-} \rightarrow \pi^{ \pm}\left(D^{*} \bar{D}^{*}\right)^{\mp}$
[PRL 112, 132001 (2014)]

(using $827 \mathrm{pb}^{-1}$ at 4.26 GeV )

$$
\begin{gathered}
M=(4026.3 \pm 2.6 \pm 3.7) \mathrm{MeV} / c^{2} \\
\Gamma=(24.8 \pm 5.6 \pm 7.7) \mathrm{MeV} / c^{2}
\end{gathered}
$$

## (4) The $\mathbf{Z}$ Question

$$
\begin{aligned}
& e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} \psi(2 S) \\
& {[\text { PRD 96, } 032004 \text { (2017)] }}
\end{aligned}
$$



$$
\begin{gathered}
M=(4032.1 \pm 2.4) \mathrm{MeV} / c^{2} \\
\Gamma=(26.1 \pm 5.3) \mathrm{MeV} / c^{2}
\end{gathered}
$$

## (4) The $\mathbf{Z}$ Question

$$
\begin{aligned}
& e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} \psi(2 S) \\
& {[\text { PRD 96, } 032004 \text { (2017)] }}
\end{aligned}
$$


(1092 $\mathrm{pb}^{-1}$ at $4.23 \mathrm{GeV} ; 826 \mathrm{pb}^{-1}$ at $4.26 \mathrm{GeV} ; 540 \mathrm{pb}^{-1}$ at $4.36 \mathrm{GeV} ; \quad 1074 \mathrm{pb}^{-1}$ at 4.42 GeV )

$$
\begin{gathered}
M=(4032.1 \pm 2.4) \mathrm{MeV} / c^{2} ; \\
\Gamma=(26.1 \pm 5.3) \mathrm{MeV} / c^{2}
\end{gathered}
$$

## (4) The $\mathbf{Z}$ Question

$$
\begin{aligned}
& e^{+} e^{-} \rightarrow \pi^{+} \pi^{-} \psi(2 S) \\
& {[\text { PRD 96, } 032004 \text { (2017)] }}
\end{aligned}
$$




For $M^{2}\left(\pi^{+} \pi^{-}\right)>0.3 \mathrm{GeV}^{2} / c^{4}$ :

$$
\begin{gathered}
M=(4030.3 \pm 0.1) \mathrm{MeV} / c^{2} \\
\Gamma=(5.1 \pm 0.2) \mathrm{MeV} / c^{2}
\end{gathered}
$$

## (4) The $\mathbf{Z}$ Question



## (4) The $\mathbf{Z}$ Question

Alex Bondar, CHARM 2018


## Spectroscopy at BESIII:

## BESIII Data Sets and Physics Reach

Example of Precision Spectroscopy
Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the $Z$ question

Common Theme:
$\Rightarrow$ the need for collaboration between theory and experiment

$$
e^{+} e^{-} \rightarrow Y(4260) \rightarrow \pi^{+} \pi^{-} J / \psi
$$

Progress is Limited (in many cases) by Theory and Methodology
(1) The proton antiproton Question

(3) The Y Question

(2) The $\varrho \pi$ Question

(4) The Z Question


## Spectroscopy at BESIII:

## BESIII Data Sets and Physics Reach

Example of Precision Spectroscopy
Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the $Z$ question

Common Theme:
$\Rightarrow$ the need for collaboration between theory and experiment

$$
e^{+} e^{-} \rightarrow Y(4260) \rightarrow \pi^{+} \pi^{-} J / \psi
$$

## Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach
Example of Precision Spectroscopy
Four Open Questions in Spectroscopy:
(1) the proton antiproton question
(2) the $\varrho \pi$ question
(3) the Y question
(4) the $Z$ question

## Conclusions:

$\Rightarrow$ There is much still to learn about spectroscopy at BESIII.
$\Rightarrow$ Spectroscopy is in an era where experiment-theory collaboration is crucial.

