# Experimental Status of the XYZ Structures

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### Hadrons

Quark model:

#### Mesons



#### Baryons



lowest configuration

• Exotic hadrons:



# **Charmonium Spectroscopy**



[Predictions: PRD 72,054026 (2005); Measurements: PDG]

# **Charmonium Spectroscopy**



[Predictions: PRD 72,054026 (2005); Measurements: PDG]

# **Charmonium Production**

**Direct Production** 



**Initial State Radiation** 



Double Charmonium Production



**Two Photon Production** 



# **Charmonium Production**

#### **B-meson Decays**



#### pp(-bar) Annihilation



All quantum numbers

#### **Charmonium Transitions**



 $\Lambda_{\rm b}$  Decays, Muoproduction





Calorimeter

**Ring Imaging Cherenkov** Detector Drift Chamber

Beampipe

Endcap

Calorimeter

Iron

Polepiece

Barrel Muon Chambers





OMPA



sć

Quadrupoles **Rare Earth** 

Quadrupole

Magnet Iron

X(3872) & X(3915)

# X(3872)

- First observation:
   B<sup>±</sup> → K<sup>±</sup>π<sup>+</sup>π<sup>-</sup>J/ψ
- Mass: 3871.69±0.17 MeV/c<sup>2</sup>
  - Very close to D<sup>0</sup>D<sup>\*0</sup> threshold
- Width: <1.2 MeV [PRD 84, 052004 (2011) Belle]</p>
- J<sup>PC</sup>=1<sup>++</sup>
- Decay:
  - π<sup>+</sup>π<sup>-</sup>J/ψ, π<sup>+</sup>π<sup>-</sup>π<sup>0</sup>J/ψ, D<sup>0</sup>D¯<sup>0</sup>π<sup>0</sup>, D<sup>0</sup>D¯\*<sup>0</sup>, γJ/ψ, γψ(2S)(?), π<sup>0</sup>χ<sub>c1</sub>









### X(3872) – New Production



#### X(3872) – New Production ս' μ MA $\pi^+$ $\gamma^*N \to X [\to \pi^+\pi^- J/\psi] \pi^\pm N'$ γ\* **J/**ψ [PLB 783, 334-340 (2018)] $\pi^{\pm}$ counts Ν N' ATLAS COMPASS counts/(0.02 GeV/c<sup>2</sup>) 14 a) 4.1 σ 10 8 6 0.4 <sup>0.8</sup> 0.9 1 m<sub>ππ</sub> [GeV/c<sup>2</sup>] 0.5 0.3 0.6 0.7 0.2 2 Ŷ [ATLAS: JHEP 01, 117 (2017)] 3.8 3.6 4.2 4.4 4.6 4.8 \_\_\_\_\_5\_ M<sub>J/ψ π<sup>+</sup>π<sup>-</sup></sub> [GeV/c<sup>2</sup>] $\tilde{X}(3872)$ $[(3860.0 \pm 10.4) \text{ MeV}/c^2, < 51 \text{ MeV}]$















\* <0.97 90% C.L. from B decays @ Belle [PRD 99, 111101 (2019)]



No evidence in  $\gamma \psi(3686)$ !

 $\frac{\mathcal{B}[\chi_{c1}(3872) \to \gamma \psi(3686)]}{\mathcal{B}[\chi_{c1}(3872) \to \gamma J/\psi]} < 0.59$ BaBar, LHCb, Belle:  $2.31 \pm 0.57$ [arXiv: 1907.07583]

# **X(3872) - Decays**

#### [arXiv: 1907.09149]

Parameter	index Decay mode	Branching fraction
1	$X(3872) \rightarrow \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872)  ightarrow \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872)  ightarrow \gamma \psi(3686)$ *	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0 \chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872)  ightarrow \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \rightarrow X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \rightarrow \text{unknown}$	$(31.9^{+18.1}_{-31.5})\%$

\* X(3872) $\rightarrow \gamma \psi$ (3686) from BESIII not included

\*\* might contain non-X(3872) contribution





#### [PRD 86,072002(2012)]



[PRD 86,072002(2012)]



[PRD 86,072002(2012)]

4.8



 $e^+e^- \rightarrow \gamma \omega J/\psi$ 







# Discovery

- First state Y(4260), discovered in ISR process at BaBar
  - $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$
  - M > 4 GeV above DD threshold
  - Not observed in inclusive hadron cross section
  - Not observed in open charm pair cross section
  - Confirmed by CLEO and Belle
- Quantum number: 1<sup>--</sup>



### **Y from ISR Process**



# **Over Population 1<sup>-</sup> States**

#### Above open charm threshold, 5 expected, 7 observed



# High Lumi. Scan Sample



19

#### **Improved Measurement**

















[PRD 100, 032005 (2019)]





22





#### 

### Y in b-flavored Decays







#### **Z** States

State	$M \; ({\rm MeV}/c^2)$	$\Gamma (MeV)$	$J^{PC}$	Process	Experiment
$Z_c(3900)^{(\pm,0)}$	$3887.2\pm2.3$	$28.2\pm2.6$	$1^{+-}$	$e^+e^- \to \pi^{(+,0)}(\pi^{(-,0)}J/\psi)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)} (D\bar{D}^*)^{(-,0)}$	BESIII
				$H_b \to X \pi^+ (\pi^- J/\psi)$	D0
$Z_c(4020)^{(\pm,0)}$	$4024.1\pm1.9$	$13 \pm 5$	$1^{+-}(?)$	$e^+e^- \to \pi^{(+,0)}(\pi^-h_c)$	BESIII
				$e^+e^- \to \pi^{(+,0)} (D^*\bar{D}^*)^{(-,0)}$	BESIII
$Z(4050)^{\pm}$	$4051^{+24}_{-40}$	$82^{+50}_{-28}$	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4100)^{\pm}$ 3.4	$\sigma 4096 \pm 28$	$152_{-70}^{+80}$	???	$B^0 \to K^+(\pi^-\eta_c)$	LHCb
$Z(4200)^{\pm}$	$4196_{32}^{+35}$	$370^{+100}_{-150}$	$1^{+-}$	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle, LHCb
$Z(4250)^{\pm}$	$4248_{-50}^{+190}$	$177^{+320}_{-70}$	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4430)^{\pm}$	$4478_{-18}^{+15}$	$181 \pm 31$	$1^{+-}$	$B^0 \to K^+(\pi^-\psi(2S))$	Belle, LHCb
	-			$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle
$R_{c0}(4240)$	$4239_{21}^{+50}$	$220^{+120}_{-90}$	0	$B^0 \to K^+ \pi^- \psi(2S)$	LHCb

[PDG 2019]

### **Z** States from **Y**

#### Both charged and neutral modes



[PRL 111,242001 (2013)]



 $Z_{\rm c}(3900)/Z_{\rm c}(3885)$ 





### Z States from Y

 $Z_c$  in  $\pi\psi(2S)$ 







#### 



#### $H_b \to \pi^+ \pi^- J/\psi + X$

- Total fit

---- Background

3.8

3.9

M(J/ψπ<sup>±</sup>) [GeV]

---- Signal

3.7

0<mark>1.</mark> 3.6





- Total fit

···· Background

3.8

3.9

4

M(J/ψπ<sup>±</sup>) [GeV]

---- Signal

3.7

---- Signal

3.8

····· Background

3.9

4.1

M(J/ψπ<sup>±</sup>) [GeV]

Δ

4.2

200

0<u>11</u> 3.7



 $H_b \to \pi^+ \pi^- J/\psi + X$ 





[PRD100 012005 (2019)]

# **Z<sub>c</sub>(3900)**

 $Z_c(3900)^{\pm} \rightarrow \rho^{\pm}\eta_c$ 







[PLB 746, 194 (2015)]

	$\sqrt{s} = 4.226 \mathrm{GeV}$	$\sqrt{s} = 4.258 \mathrm{GeV}$	$\sqrt{s} = 4.358 \mathrm{GeV}$	Type-I	Type-II	Molecule
$R_{Z_{c}(3900)}$	$2.2 \pm 0.9$ <b>3.9</b>	$\sigma$ < 5.6	•••	$230^{+330}_{-140}$	$0.27\substack{+0.40 \\ -0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_{c}(4020)}$	< 1.6	< 0.9	< 1.4	6.6	+56.8 -5.8	$0.010\substack{+0.006\\-0.004}$

4230: 
$$\sigma[e^+e^- \to \pi^+\pi^-\pi^0\eta_c] = (46^{+12}_{-11} \pm 10) \text{ pb}$$
  
 $\sigma[e^+e^- \to \pi Z_c, Z_c \to \pi \eta_c] = (48 \pm 11 \pm 11) \text{ pb}$ 

# **Connection: XYZ**

#### Y → Z

- Z<sub>c</sub> states from Y states above 4 GeV
- Z<sub>c</sub> cross section vs E<sub>cms</sub> measurement
- $Y \rightarrow X$ 
  - e<sup>+</sup>e<sup>-</sup> →γX(3872)



#### [PRD98 052010 (2018)]



# Summary

- Great progress in charmonium-like states
  - Numerous X(3872) measurements: mass, quantum number, production and decay modes
  - Overpopulation of 1<sup>--</sup> states above 4 GeV
    - Cross section measurement with much improved precision, Y(4260) ⇒ Y(4230); multi decay modes
    - Light hadron final states
  - New measurement of Z properties
  - Building relations between exotic states
  - Improved understanding of conventional charmonium states above open charm threshold,  $\chi_{c0}(2P)$ ,  $\chi_{c2}(2P)$  candidates

#### THANK YOU!

#### X(3872) Radiative Decays

- Ratio of X(3872)  $\rightarrow \gamma \psi$ (2S) to  $\gamma J/\psi$ :
  - Theoretical predictions:
    - Pure DD\* molecule: (3-4)×10<sup>-3</sup>;Charmonium: 1.2-15; Mixture: 0.5-5
  - Experimental measurements:
    - BaBar: 3.4±1.4, 3.5σ [PRL102, 132001 (2009)]
    - Belle: <2.1 @ 90% C.L. [PRL107, 091803 (2011)]</p>
    - LHCb: 2.46±0.64±0.29, 4.4σ [NPB 886, 665 (2014)]







[PRD91, 051101(R) (2015)] K\*(892) 711 fb<sup>-1</sup> data, 2D fit (a) Events / (0.1 GeV/c<sup>2</sup> 40 B<sup>0</sup>→X(3872)(K<sup>+</sup>π<sup>-</sup>) (7.9±1.3±0.4)×10<sup>-6</sup> non resonant 20 100 (a) Events / ( 0.004 GeV/c<sup>2</sup> (b) Events / ( 0.004 GeV ) 100-7 σ 0.8 1.4 1 1.2  $M_{\rm H}$  (GeV/ $c^2$ ) -0.1 3.82 -0.05 0.05 3.84 3.9 3.92 0.1 3.86 3.88  ${
m M}_{{
m J}/\psi\pi\pi}\,({
m GeV}/c^2)$ ΔE (GeV) (b) B<sup>+</sup>→X(3872)(K<sup>0</sup> $\pi$ <sup>+</sup>) (10.6±3.0±0.9)×10<sup>-6</sup> 30-Events / ( 0.004 GeV/c<sup>2</sup> Events / ( 0.004 GeV ) (b) (a) 30ŀ 3.7 σ 20 **Ö.**6 0.8 1.2 1.4 -8.1 3.82 -0.05 0 0.05 0.1 3.84 3.86 3.88 3.9 3.92  ${
m M}_{{
m J}/\psi\pi\pi}~({
m GeV}/c^2)$  $M_{K\pi}$  (GeV/c<sup>2</sup>) ΔE (GeV)



First observation:

- [PRL100, 142001 (2008)]
- Belle,  $B \rightarrow K\pi^{\pm}\psi(2S)$ , 605 fb<sup>-1</sup> data at  $\Upsilon(4S)$
- Fit to the mass spectrum of  $\pi^{\pm}\psi(2S)$ , 6.5 $\sigma$
- Not confirmed by BaBar, found data can be explained by K\* reflections: [PRD79, 112001 (2009)]
  - Two dimensional analysis, 413 fb<sup>-1</sup> data at Υ(4S)
- Updated Belle results:
  - Two dimensional analysis using same data as first publication
  - Four dimensional amplitude analysis, 711 fb<sup>-1</sup> Y(4S), Z(4430) favor 1<sup>+</sup>
  - Larger width, higher mass





# **Confirmation of Z(4430)**





#### 25176±174 B<sup>0</sup> $\rightarrow$ $\psi$ 'K<sup>+</sup> $\pi$ <sup>-</sup>, $\psi$ ' $\rightarrow$ $\mu$ <sup>+</sup> $\mu$ <sup>-</sup>

[PRL 112, 222002] 3 fb<sup>-1</sup>

Four dimensional analysis:  $\Phi$ =(M<sup>2</sup><sub>Kπ</sub>, M<sup>2</sup><sub>ψ'π</sub>,  $\theta_{\psi'}$ ,  $\phi$ )

Mass and width consistent with Belle latest result JP=1+

Second peak:  $4239 \pm 18^{+45}_{-10} \text{ MeV/c}^2$  $220 \pm 47^{+108}_{-74} \text{ MeV}$ 

Argand diagram resonance behavior character

### **Ζ(4430) in** π**J**/ψ

- Belle  $\overline{B}^0 \rightarrow K^-\pi^+ J/\psi, J/\psi \rightarrow I^+I^-$ 
  - 711 fb<sup>-1</sup> data at Y(4S), 2999
  - Four dimensional analysis: Φ=(M<sup>2</sup><sub>Kπ</sub>, M<sup>2</sup><sub>ψπ</sub>, θ<sub>ψ</sub>, φ)
- Z(4200)<sup>+</sup> observed
  - $J^{P} = 1^{+}$

Events / 0.254 GeV<sup>2</sup>/c<sup>4</sup>

40

20

12

14

16

Global significance: 6.2  $\sigma$ 

20

 $M^{2}(J/\psi,\pi), GeV^{2}/c^{4}$ 

18

22



12

14

16

18 20 22 M²(J/ψ,π), GeV²/c<sup>4</sup>

#### Z(4050) and Z(4250)



B<sup>0</sup>→K<sup>+</sup>π<sup>-</sup>χ<sub>c1</sub> 605 fb<sup>-1</sup>



[PRD78, 072004 (2008)]

$$M_{1} = (4051 \pm 14^{+20}_{-41}) \text{ MeV}/c^{2},$$
  

$$\Gamma_{1} = (82^{+21+47}_{-17-22}) \text{ MeV},$$
  

$$M_{2} = (4248^{+44+180}_{-29-35}) \text{ MeV}/c^{2},$$
  

$$\Gamma_{2} = (177^{+54+316}_{-39-61}) \text{ MeV},$$

