

News and plan on hadron spectroscopy at BESIII

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(On behalf of the BESIII collaboration)

Outline

- Previous inputs to the Snowmass 2021 RF7
- New results on hadron spectroscopy
 - heavy hadrons
 - light hadrons
- Prospects for the future
- Summary

BESIII inputs

June 24,2020 Oct. 2, 2020

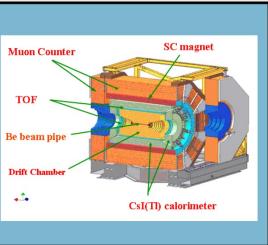
Spectroscopy at the BESIII Experiment

Ryan Mitchell
Indiana University

BEPCII: Beijing Electron Positron Collider
symmetric e^+e^- collisions at E_{CM} between 2.0 and 4.7 GeV



BESIII: Beijing Spectrometer
a versatile detector covering 93% of 4π



running since 2009 at the Institute of High Energy Physics in Beijing, China

Ryan Mitchell (Indiana University) — Spectroscopy at the BESIII Experiment 1

Oct. 2, 2020

Light QCD exotics at **BESIII**

Beijiang Liu
Institute of High Energy Physics, Chinese Academy of Sciences
on behalf of BESIII

Workshop of Light-Quark Exotic Hadrons, Snowmass Hadron Spectroscopy group
September 30, 2020

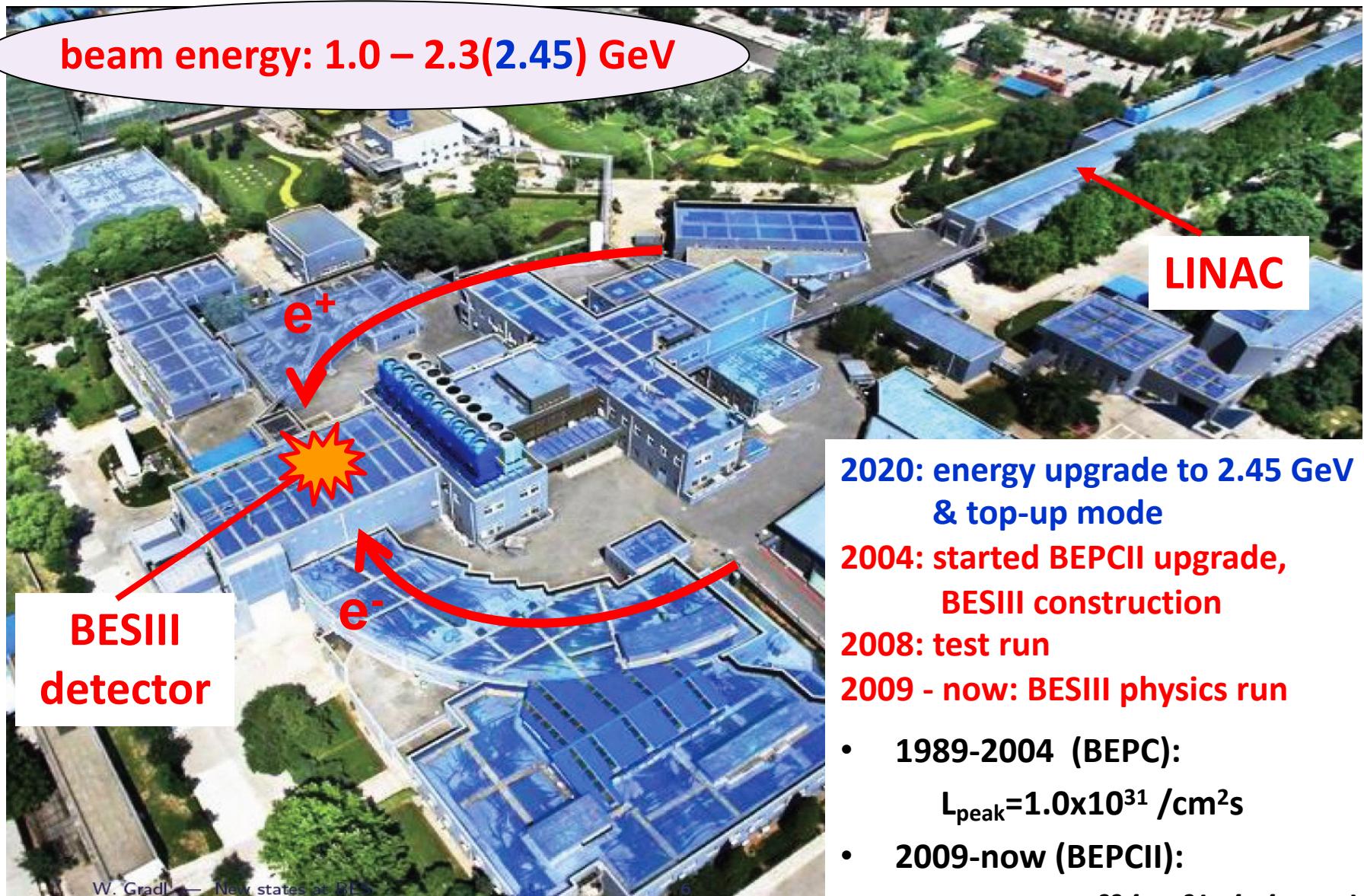
Letter of Interest for Snowmass 2021

Physics in the τ -charm Region at BESIII

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BESIII data sample

2009: 106M $\psi(2S)$

225M J/ψ

2010: 975 pb $^{-1}$ at $\psi(3770)$

2011: 2.9 fb $^{-1}$ (total) at $\psi(3770)$

482 pb $^{-1}$ at 4.01 GeV

2012: 0.45B (total) $\psi(2S)$

1.3B (total) J/ψ

2013: 1092 pb $^{-1}$ at 4.23 GeV

826 pb $^{-1}$ at 4.26 GeV

540 pb $^{-1}$ at 4.36 GeV

10 \times 50 pb $^{-1}$ scan 3.81 – 4.42 GeV

2014: 1029 pb $^{-1}$ at 4.42 GeV

110 pb $^{-1}$ at 4.47 GeV

110 pb $^{-1}$ at 4.53 GeV

48 pb $^{-1}$ at 4.575 GeV

567 pb $^{-1}$ at 4.6 GeV

0.8 fb $^{-1}$ R-scan 3.85 – 4.59 GeV

2015: R-scan 2 – 3 GeV + 2.175 GeV

2016: ~3fb $^{-1}$ at 4.18 GeV (for D_s)

2017: 7 \times 500 pb $^{-1}$ scan 4.19 – 4.27 GeV

2018: more J/ψ (and tuning new RF cavity)

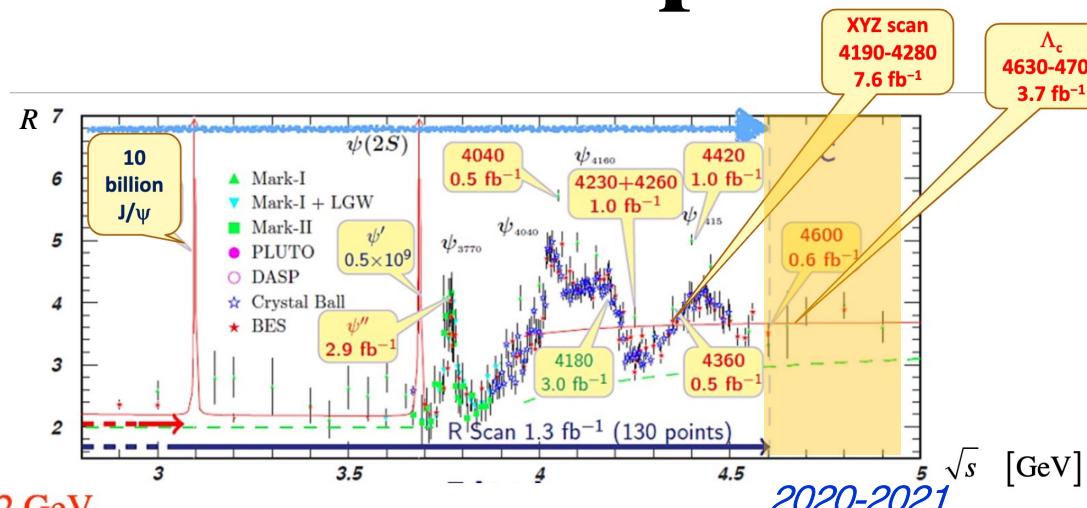
2019: 10B (total) J/ψ

8 \times 500 pb $^{-1}$ scan 4.13, 4.16, 4.29 – 4.44 GeV

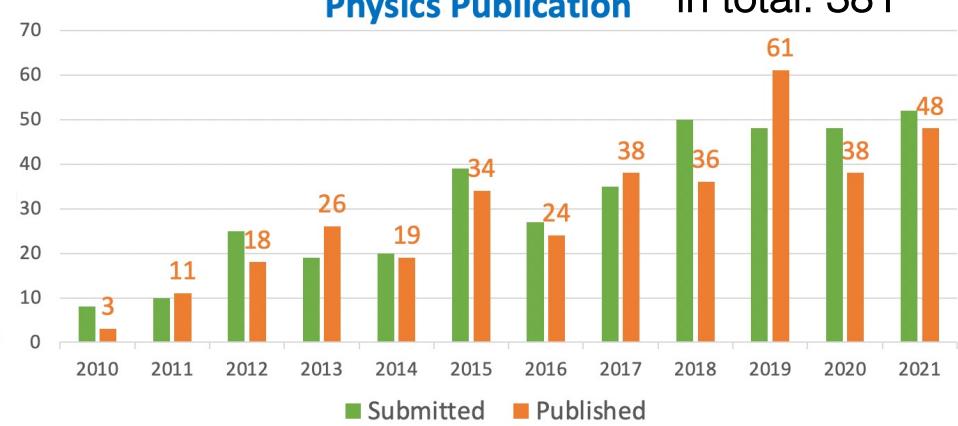
2020 : 3.8 fb $^{-1}$ scan 4.61-4.7 GeV

2021 : 2 fb $^{-1}$ scan 4.74-4.95 GeV;

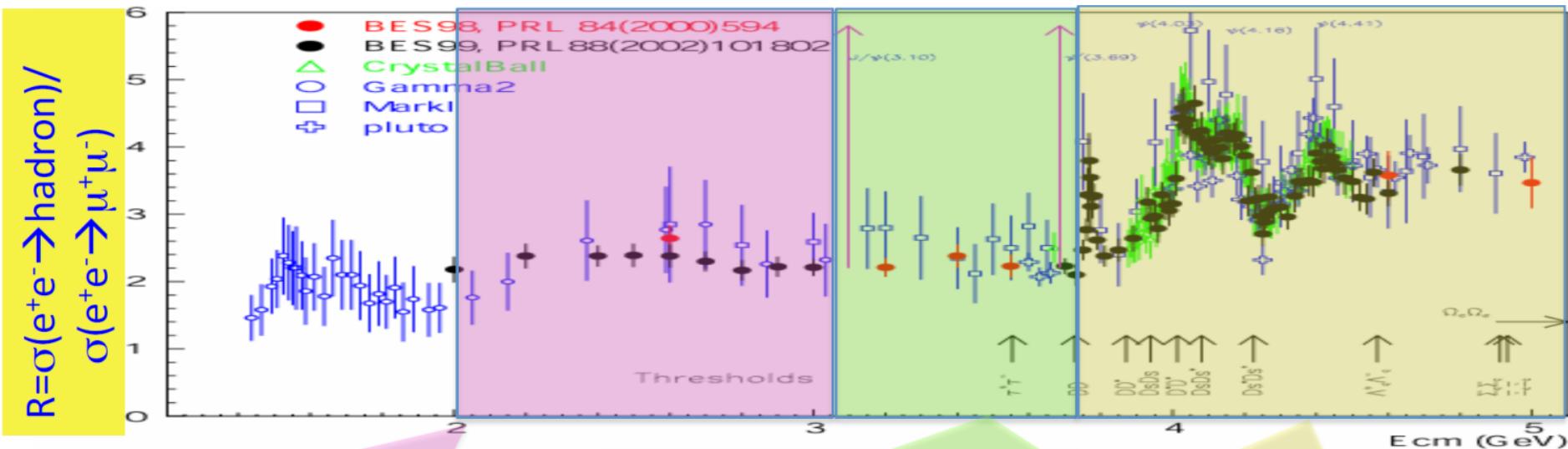
2.55B $\psi(2S)$



Physics Publication in total: 381



Physics at tau-charm Energy Region

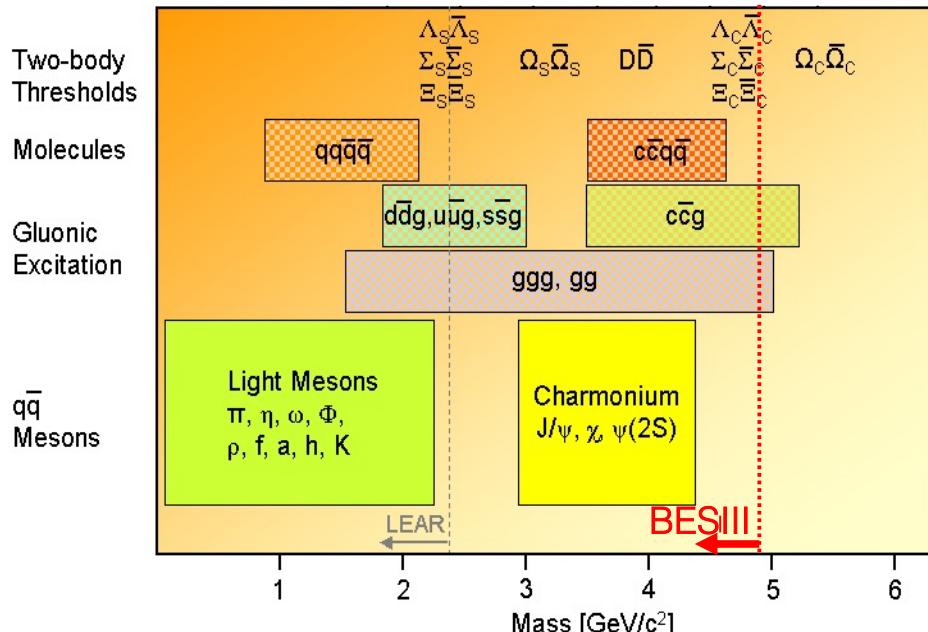


- Hadron form factors
- $\Upsilon(2175)$ resonance
- Multiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{D_s}
- D_0 - \bar{D}_0 mixing
- Charm baryons

Hadron Landscape

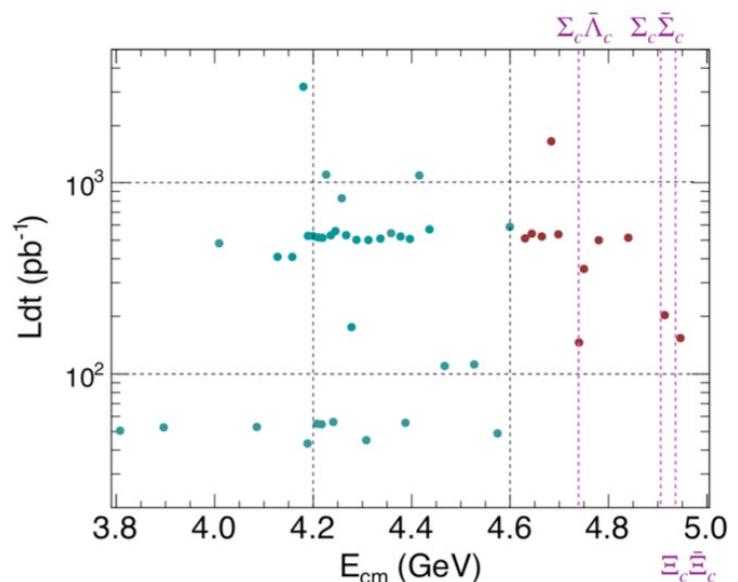


At BESIII, two golden measures to study hadron spectroscopy, esp., to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter) (**10 B J/ψ and 3 B $\psi(2S)$**)
- Heavy hadrons: direct production, radiative and hadronic transitions (**data above 3.8 GeV**)

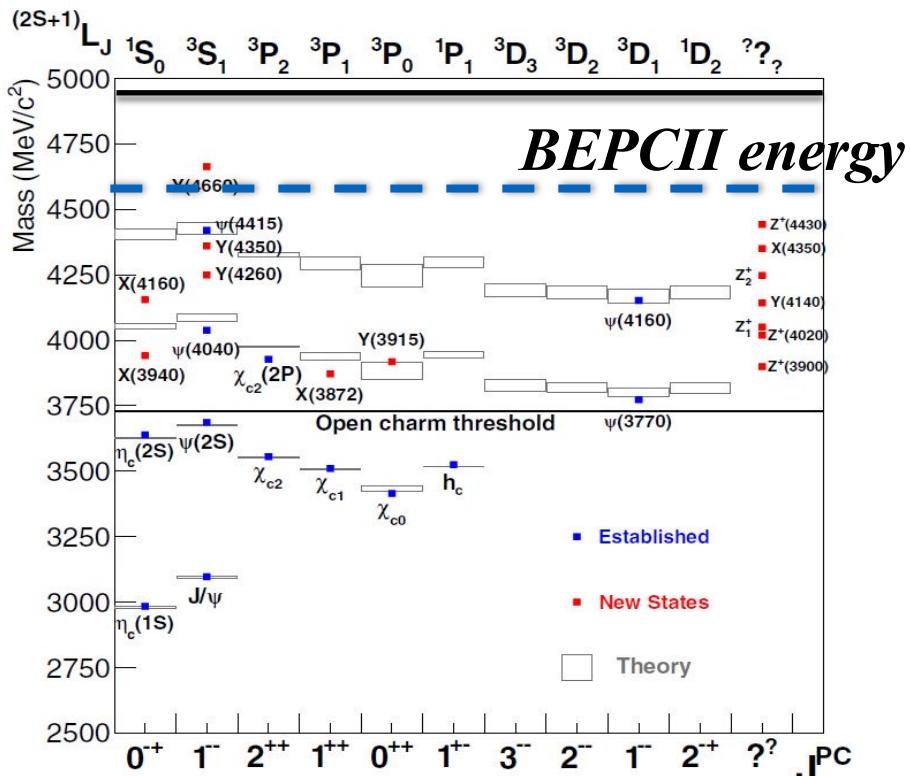
Hadron-physics challenges:

- Understanding of established states: **precision spectroscopy**
- Nature of exotic states: **search and spectroscopy of unexpected states**

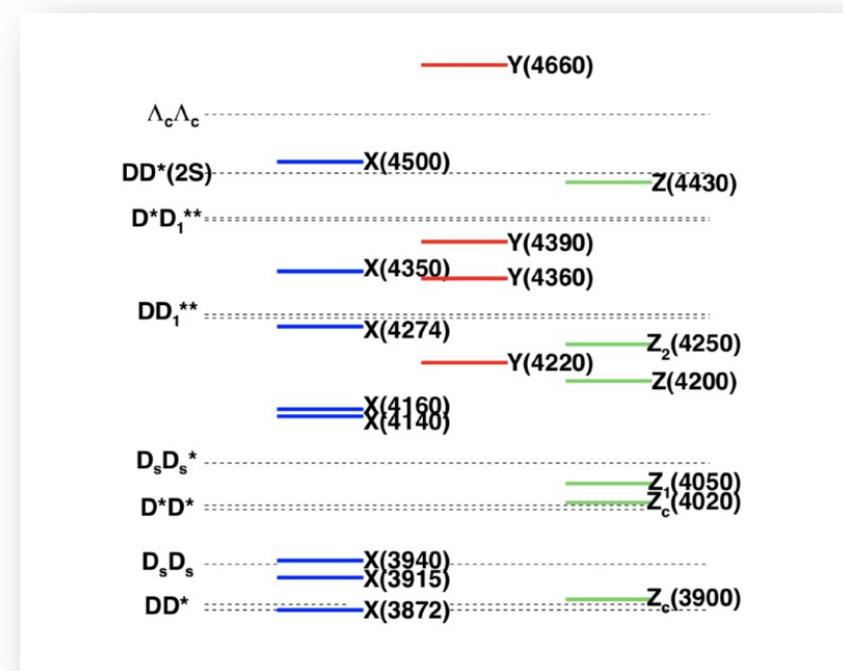


XYZ studies: about 23 /fb data above 3.8 GeV

Overpopulated charmonium spectrum



arXiv:1511.01589, arXiv:1812.10947

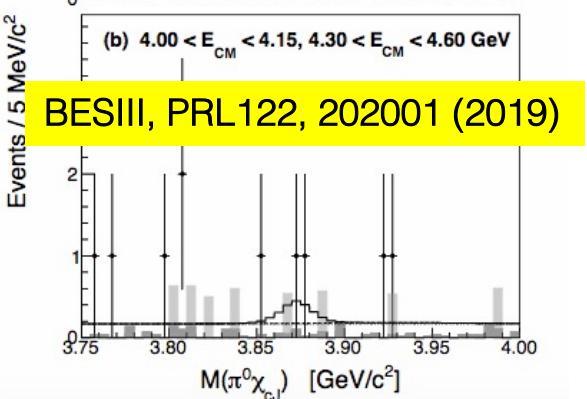
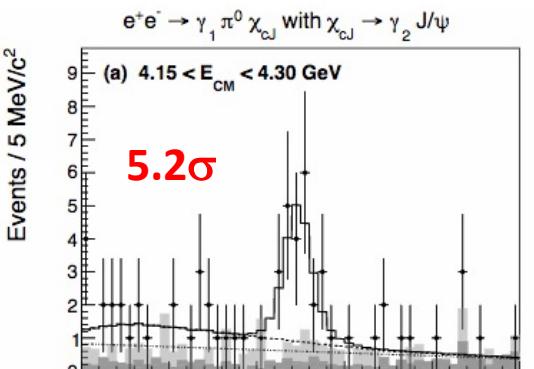


Overpopulated observed new charmonium-like states, i.e. “XYZ”:

- Most of them are close to the mass thresholds of charmed meson pairs
- Some are not accommodated as conventional meson
==> candidate of exotic hadron states
- More efforts are needed to pin down their nature

More X(3872) decay information

- Observation of $X(3872) \rightarrow \pi^0 \chi_{c1}$



- Observation of $X(3872) \rightarrow \omega J/\psi$

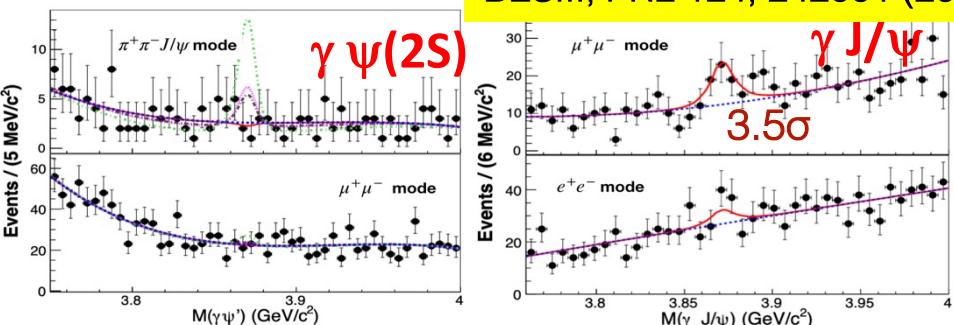
BESIII, PRL 122, 232002 (2019)

- Observation of $X(3872) \rightarrow D^0 \bar{D}^{*0}$

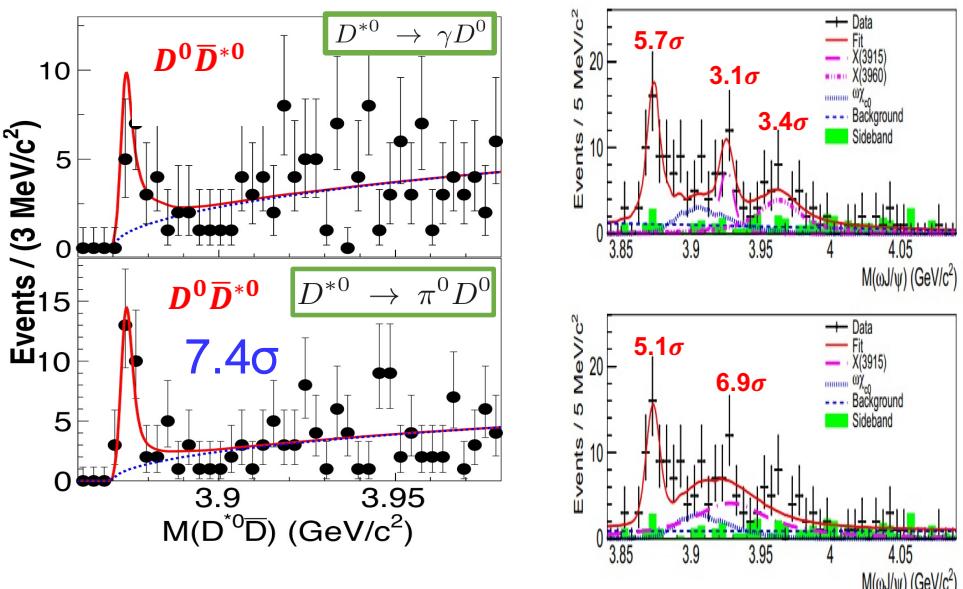
BESIII, PRL 124, 242001 (2020)

- Transition of $X(3872) \rightarrow \gamma J/\psi, \gamma \psi(2S)$

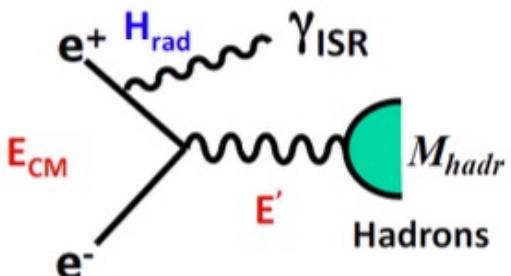
BESIII, PRL 124, 242001 (2020)



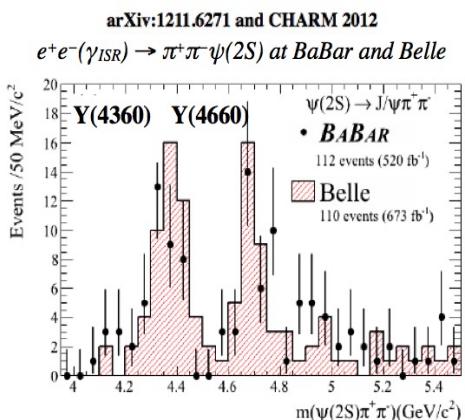
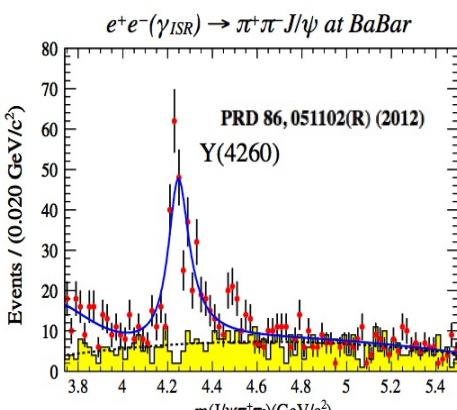
$R = \frac{\text{BF}(X(3872) \rightarrow \gamma \psi(2S))}{\text{BF}(X(3872) \rightarrow \gamma J/\psi)} < 0.59$ at 90% C.L., agrees with Belle(<2.1), while challenges Babar(3.4 ± 1.1) and LHCb results (2.46 ± 0.70)



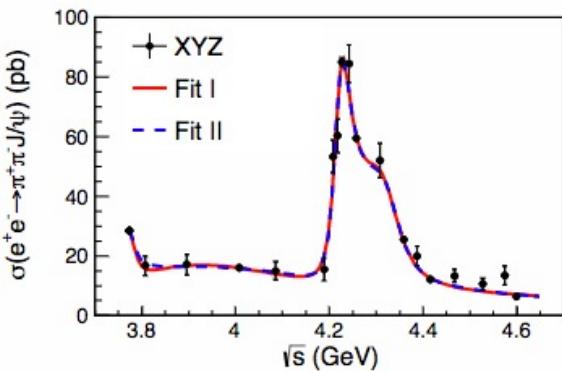
The Y states



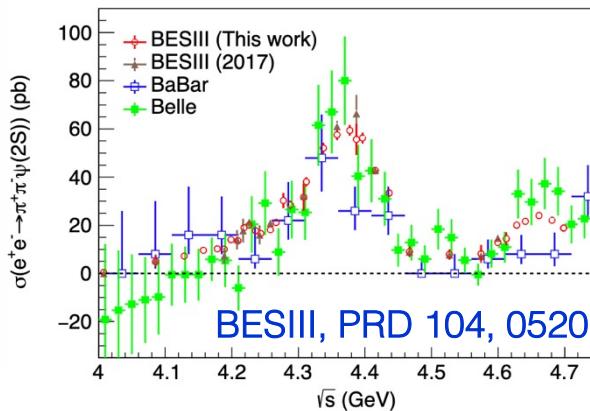
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e^+e^- annihilation or initial state radiation (ISR).



- Improved knowledges from BESIII

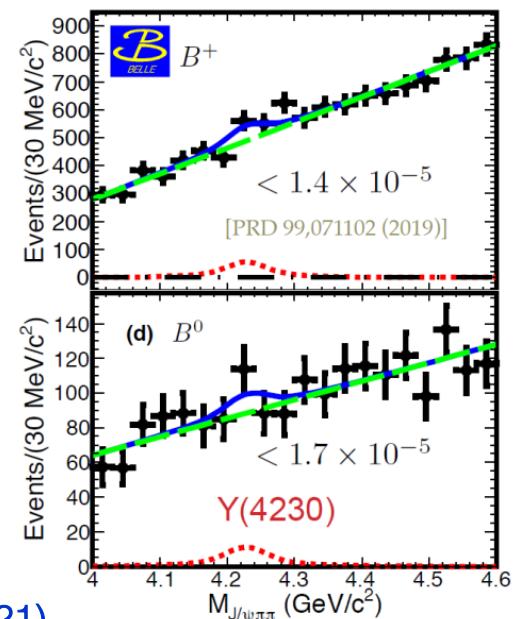


BESIII, PRL118, 092001 (2017)

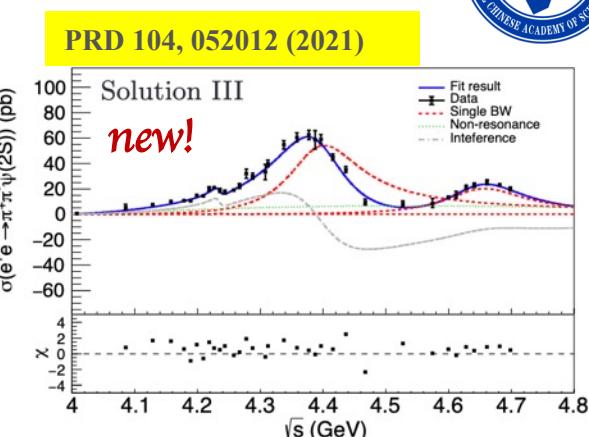
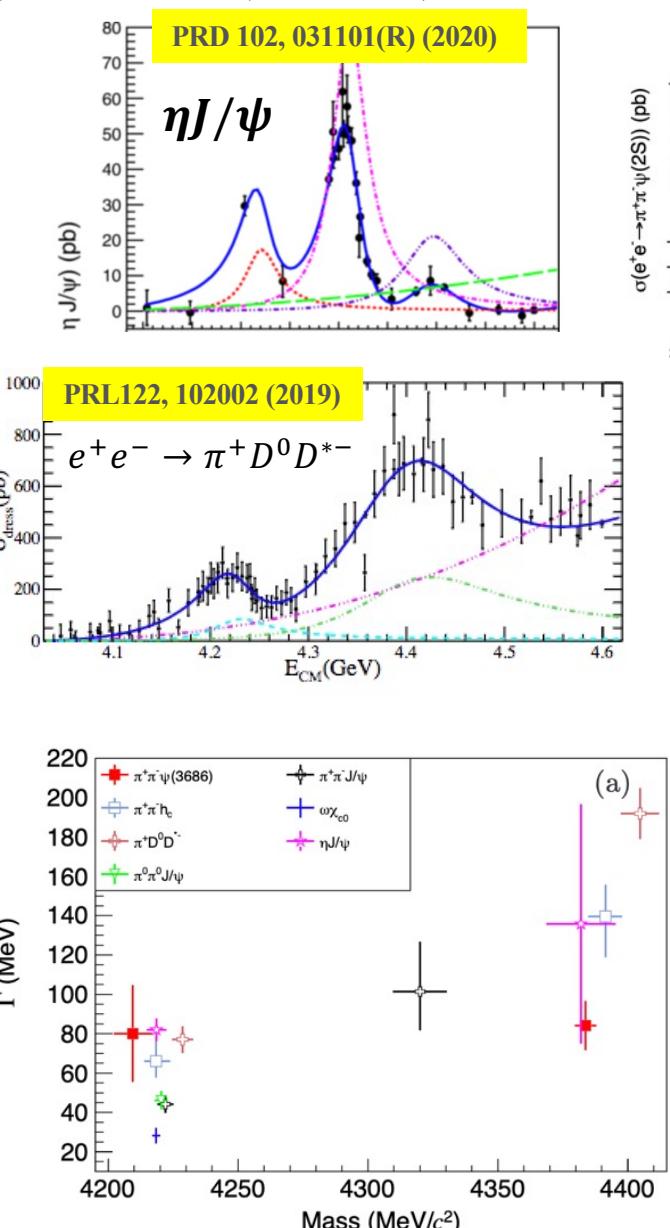
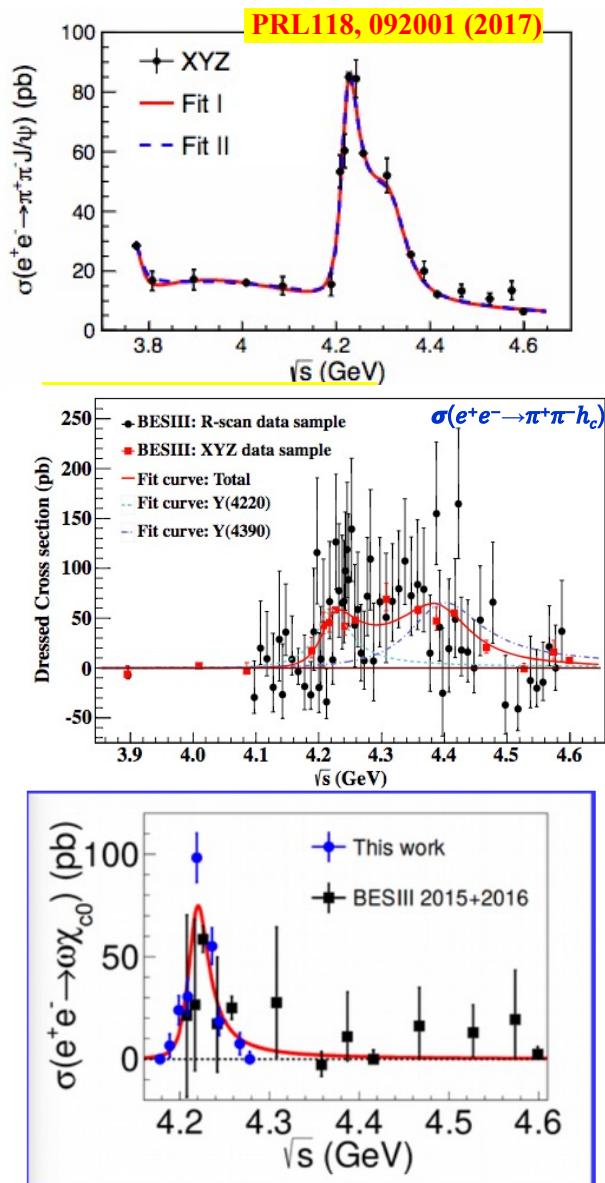


- While not seen yet in B decays

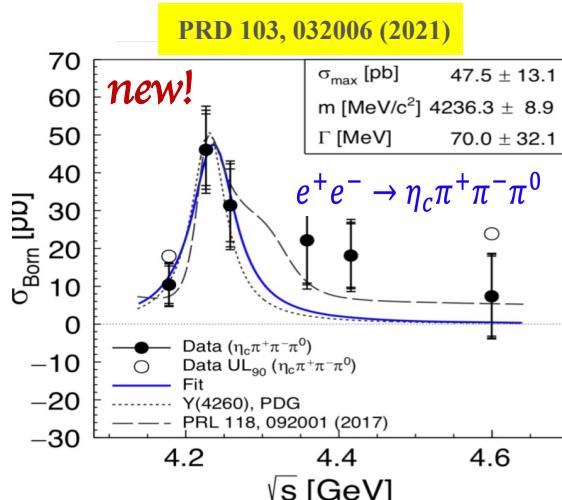
$$B^{\pm,0} \rightarrow K^{\pm,0} \pi^+ \pi^- J/\psi$$



$Y(4260) \rightarrow Y(4220)$ and new Y's

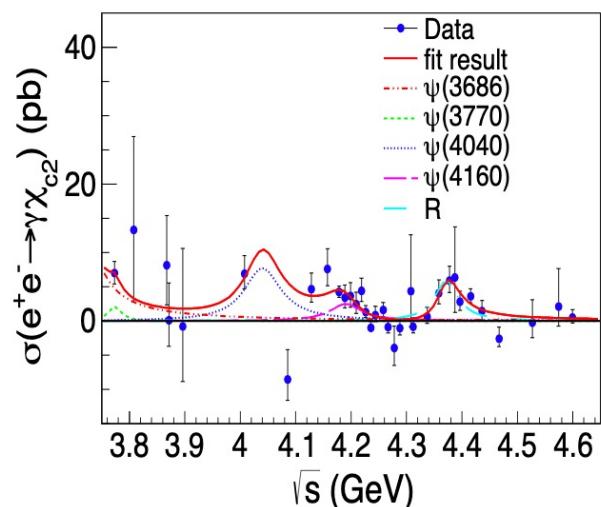
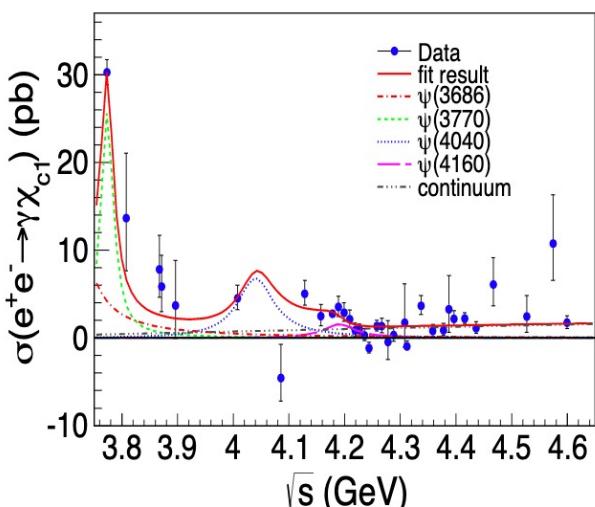
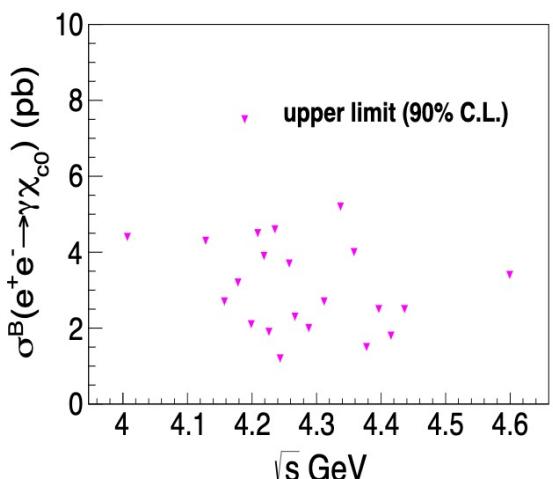


Evidence for
 $Y(4220) \rightarrow \eta_c \pi^+ \pi^- \pi^0$



arXiv:2107.03604

- No signals for $e^+e^- \rightarrow \gamma\chi_{c0}$
- Observations of $e^+e^- \rightarrow \gamma\chi_{c1,2}$



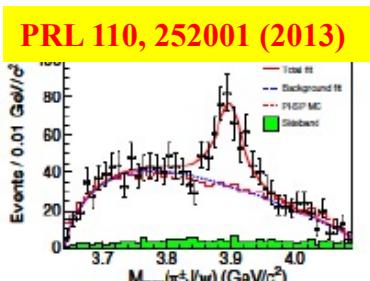
- $\gamma\chi_{c1}$: Well describe with conventional charmonium states
- $\gamma\chi_{c2}$: Along with conventional ones, an additional Y state is needed

$$M = 4371.7 \pm 7.5 \pm 1.8 \text{ MeV}/c^2, \quad \Gamma = 51.1 \pm 17.6 \pm 1.9 \text{ MeV}$$

- ✓ statistical significance of 5.8σ
- ✓ consistent with the Y(4360)/Y(4390)

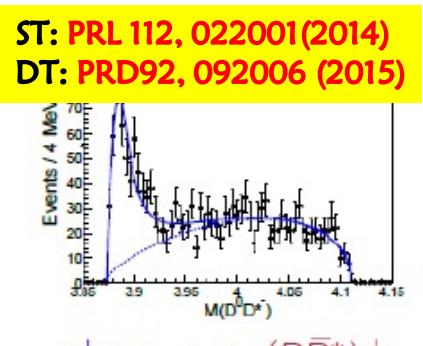
The Zc Family at BESIII

Zc(3900)⁺



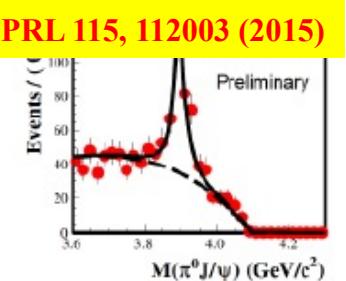
$$e^+e^- \rightarrow \pi^-\pi^+J/\psi$$

Zc(3885)⁺



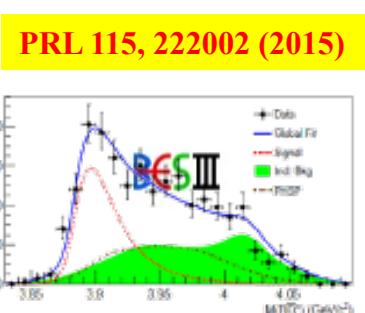
$$e^+e^- \rightarrow \pi^-(D\bar{D}^*)^+$$

Zc(3900)⁰



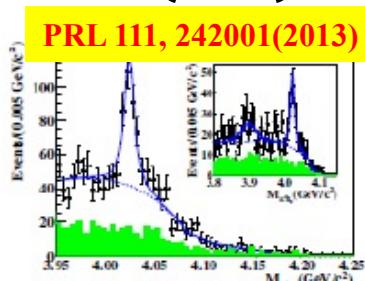
$$e^+e^- \rightarrow \pi^0\pi^0J/\psi$$

Zc(3885)⁰



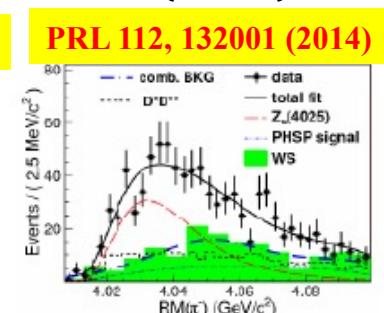
$$e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$$

Zc(4020)⁺



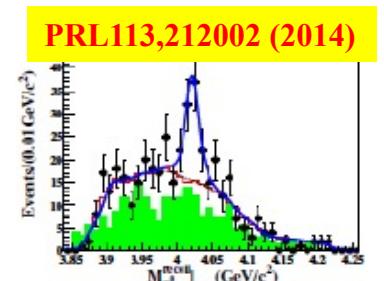
$$e^+e^- \rightarrow \pi^-\pi^+h_c$$

Zc(4025)⁺



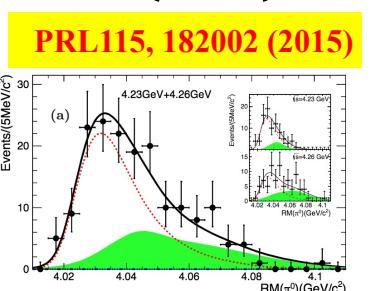
$$e^+e^- \rightarrow \pi^-(D^*\bar{D}^*)^+$$

Zc(4020)⁰



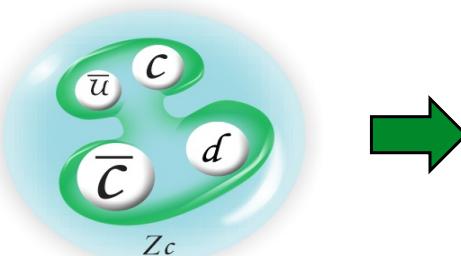
$$e^+e^- \rightarrow \pi^0\pi^0h_c$$

Zc(4025)⁰



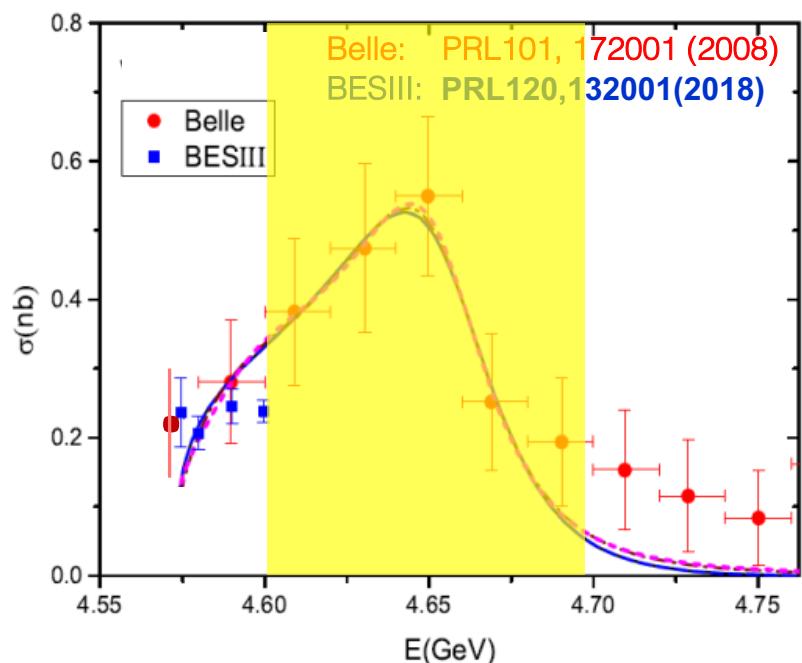
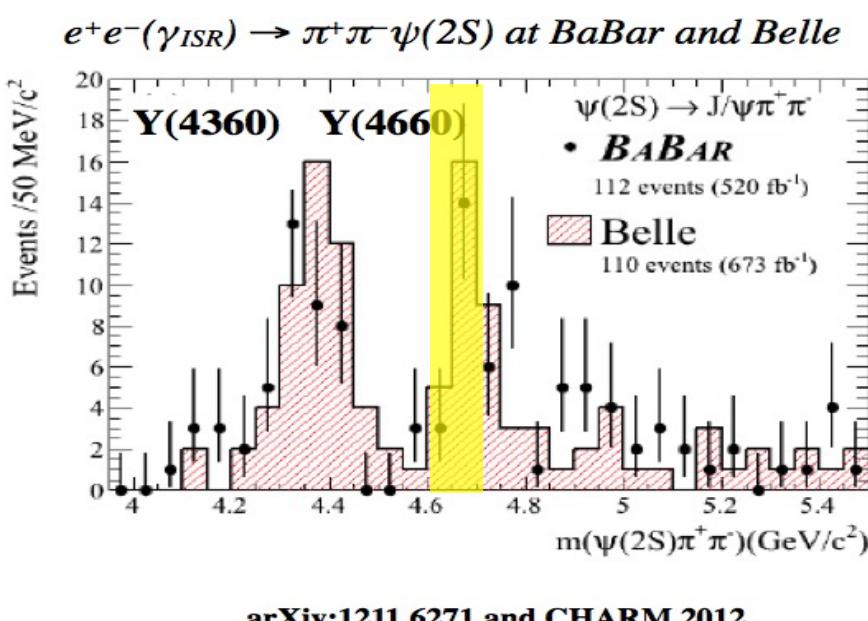
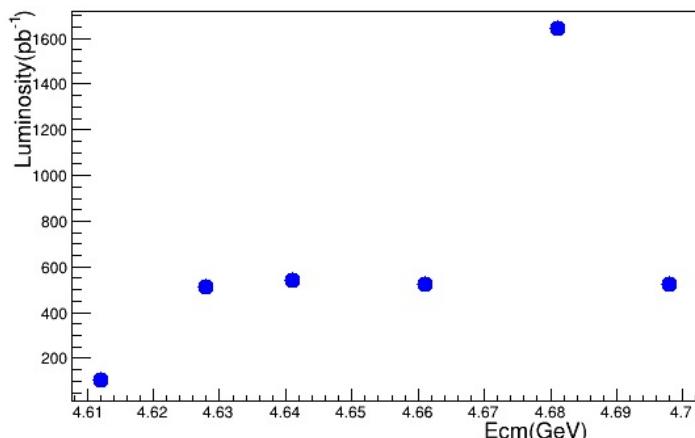
$$e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$$

Which is the nature of these states?
If exists, there should be SU(3)
counter-part **Zcs** state with strangeness



Data taking in 4.6-4.7 GeV in 2020

- 3.7 fb^{-1} data was accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- Y(4630) & Y(4660)

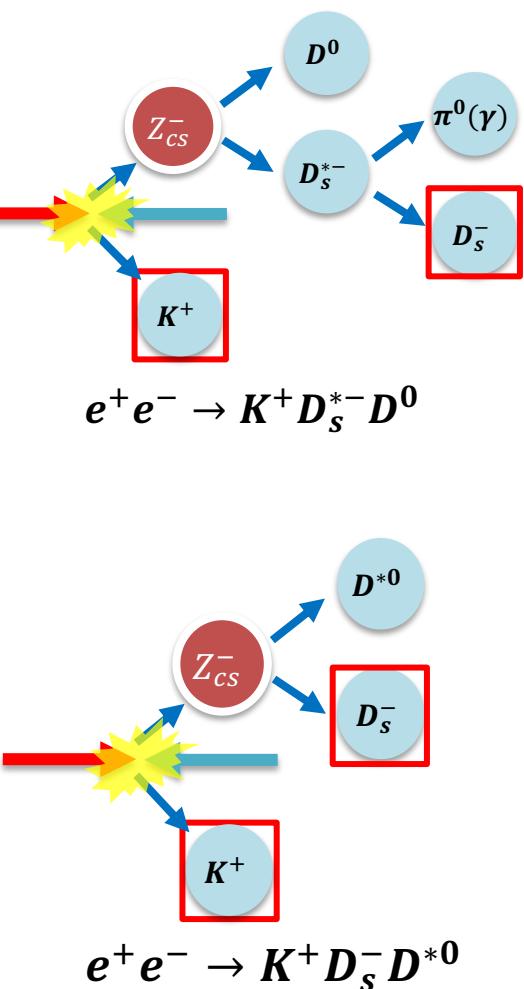
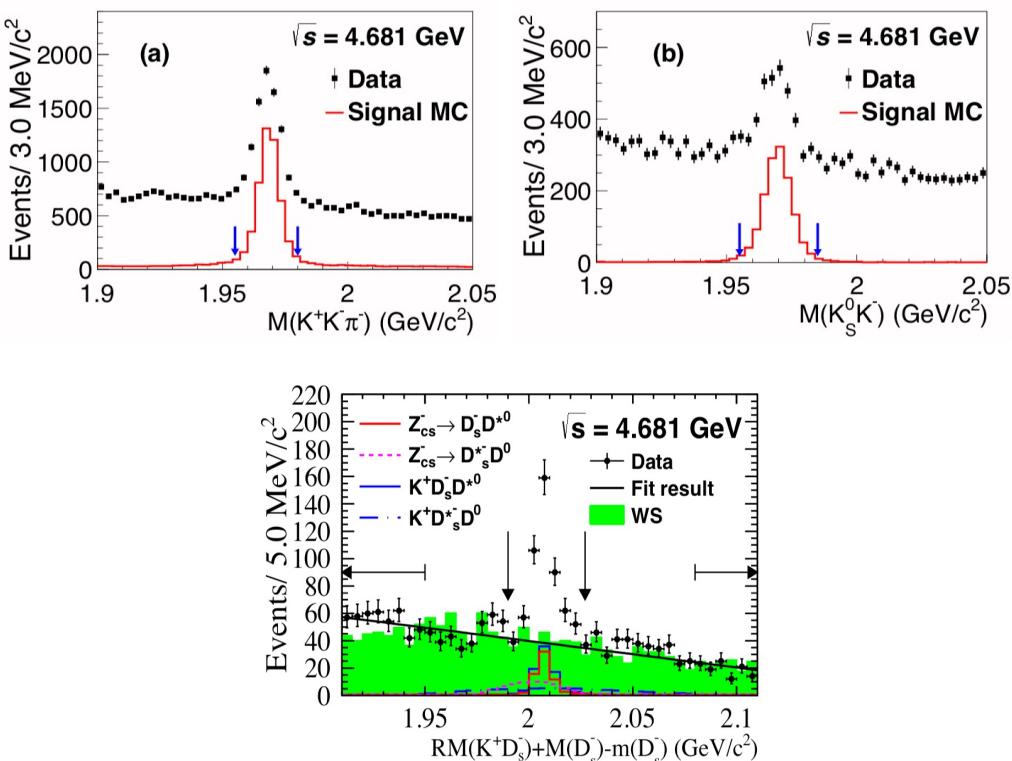


Observation of the $Z_{cs}(3985)^{\pm}$



PRL126, 102001 (2021)

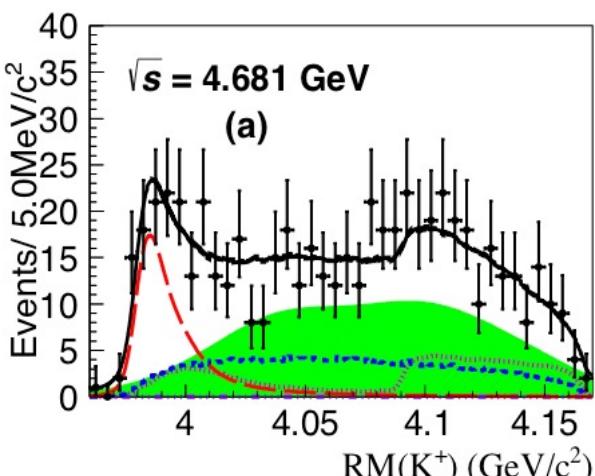
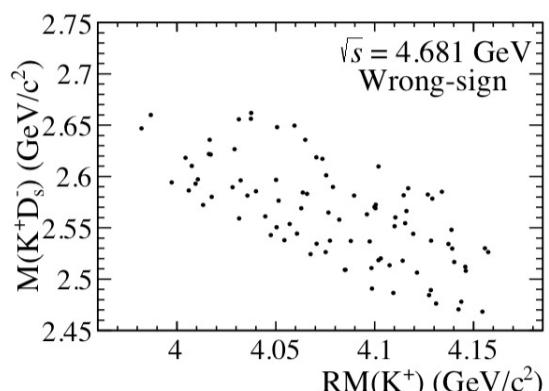
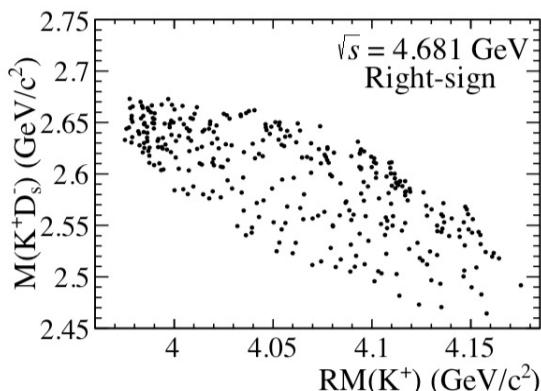
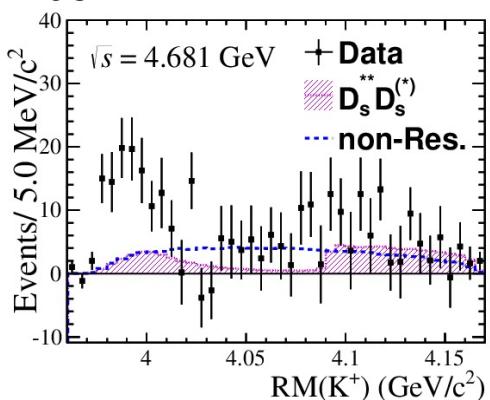
- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \rightarrow K^+(D_s^-D^{*0} + D_s^{*-}D^0)$



Observation of the $Z_{cs}(3985)^{\pm}$

PRL126, 102001 (2021)

- Data driven background description: wrong Sign (WS) combination of D_s^- and K^-
- Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c^2 at 4.681 GeV



- Assume the structure as a $D_s^- D^{*0} / D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- A fit of $J^P=1^+$ S-wave Breit-Wigner with mass dependent width returns:

$$m = 3985.2^{+2.1}_{-2.0} \pm 1.7 \text{ MeV}/c^2$$

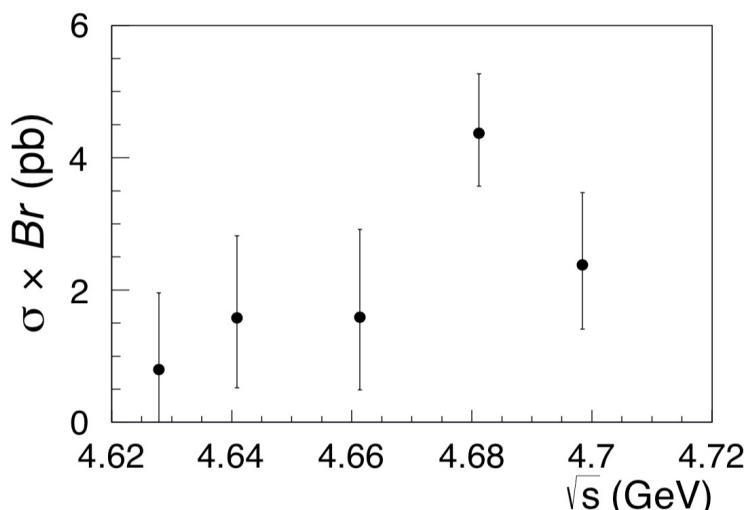
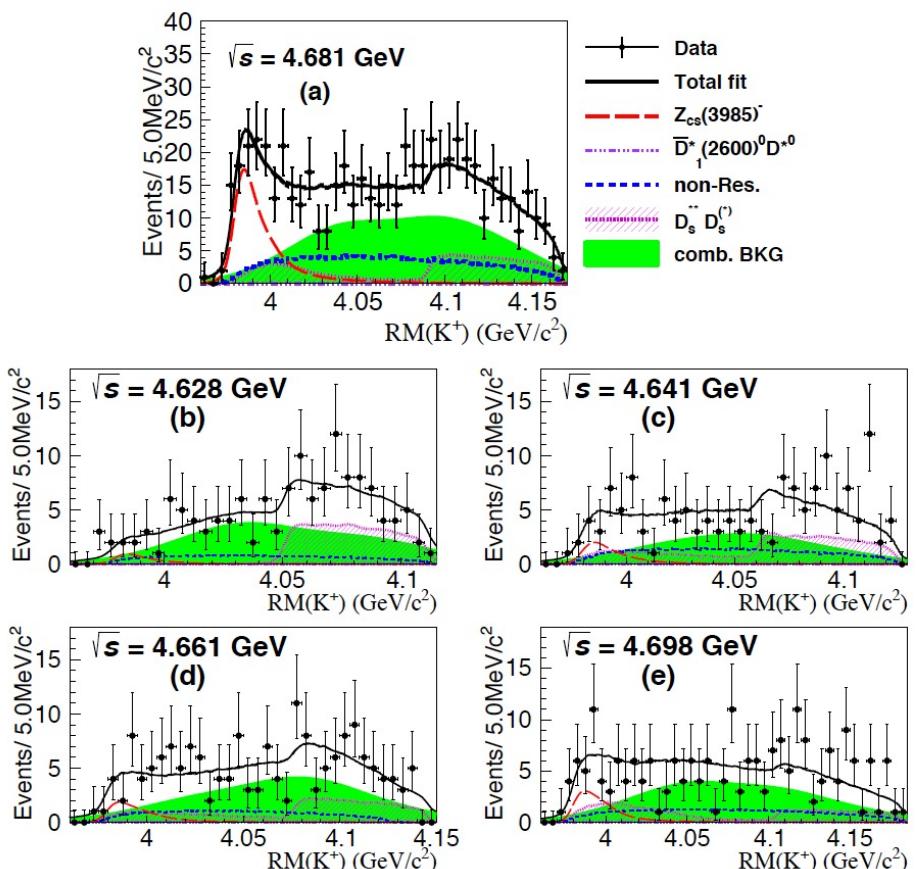
$$\Gamma = 13.8^{+8.1}_{-5.2} \pm 4.9 \text{ MeV}$$
- Global significance: $>5.3 \sigma$

First candidate of the hidden-charm tetraquark with strangeness

Cross sections of the $Z_{cs}(3985)^{\pm}$ production

PRL126, 102001 (2021)

- Simultaneous fit to the five energy points



- Largest cross sections around 4.681 GeV

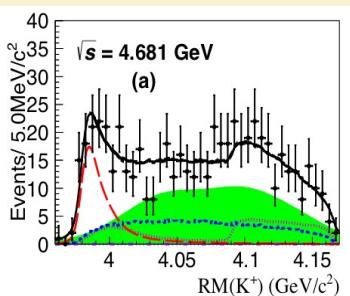
The $Z_{cs}(3985)^\pm$ and $Z_c(3885)^\pm$

1643/pb data
@4.681 GeV

	$Z_{cs}(3985)^\pm$	$Z_c(3900)^\pm$	$Z_c(3885)^\pm$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$3899.0 \pm 3.6 \pm 4.9$	$3883.9 \pm 1.5 \pm 4.2$
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	$46 \pm 10 \pm 26$	$24.8 \pm 3.3 \pm 11.0$
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	$13.5 \pm 2.1 \pm 4.8$	$83.5 \pm 6.6 \pm 22.0$

~10 MeV above $D_s D^*$ / $D_s D$ thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

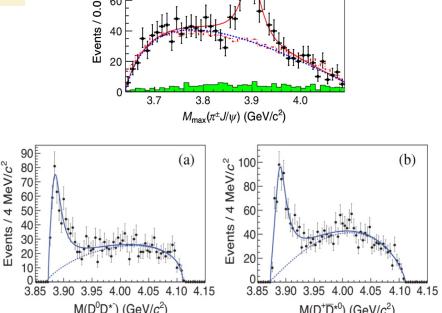
SU(3) partner of $Z_c(3900)$?



$Z_{cs}(3985)$

$$\begin{array}{cccc} K^- Z_{cs}^+ & \bar{K}^0 Z_{cs}^0 & K^0 \bar{Z}_{cs}^0 & K^+ Z_{cs}^- \\ 1/4 & 1/4 & 1/4 & 1/4 \end{array}$$

neutral/charged = 1



$Z_c(3900)$

$$\begin{array}{ccc} \pi^- Z_c^+ & \pi^0 Z_c^0 & \pi^+ Z_c^- \\ 1/3 & 1/3 & 1/3 \end{array}$$

neutral/charged = 1/2

525/pb data @4.26 GeV

$Z_c(3885)^\pm$

	$Z_{cs}(3985)^\pm$	$Z_c(3900)^\pm$	$Z_c(3885)^\pm$
Mass (MeV/c^2)	$3899.0 \pm 3.6 \pm 4.9$	$3883.9 \pm 1.5 \pm 4.2$	
Width (MeV)	$46 \pm 10 \pm 26$	$24.8 \pm 3.3 \pm 11.0$	
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$13.5 \pm 2.1 \pm 4.8$	$83.5 \pm 6.6 \pm 22.0$	

from Marek Karliner in Nov. 2020

two general comments about charm-tau factory program

- $J/\psi K^\pm$ resonances:

$Z_c(3900)$ analogue?

$Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \rightarrow s$: $(c\bar{c}u\bar{s}) \sim D_s \bar{D}^*$

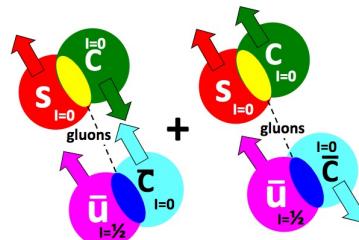
no natural molecular binding,
so if discovered, would indicate
 Tq or a novel mechanism

$Z_{cs}: 3985.2 \text{ MeV}$

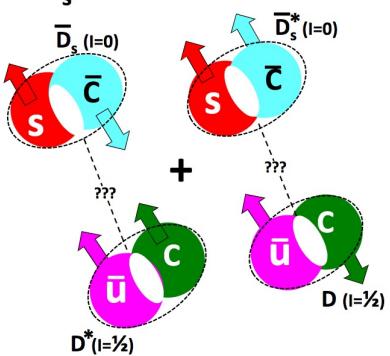
9.2 MeV 10 MeV

$D_s^{*-} D^0 3977.0 \text{ MeV}$
 $D_s^- D^{*0} 3975.2 \text{ MeV}$

diquark-antidiquark?



$D^* \bar{D}_s + cc$ molecule?



Discussions on the nature of $Z_{cs}(3985)^{\pm}$



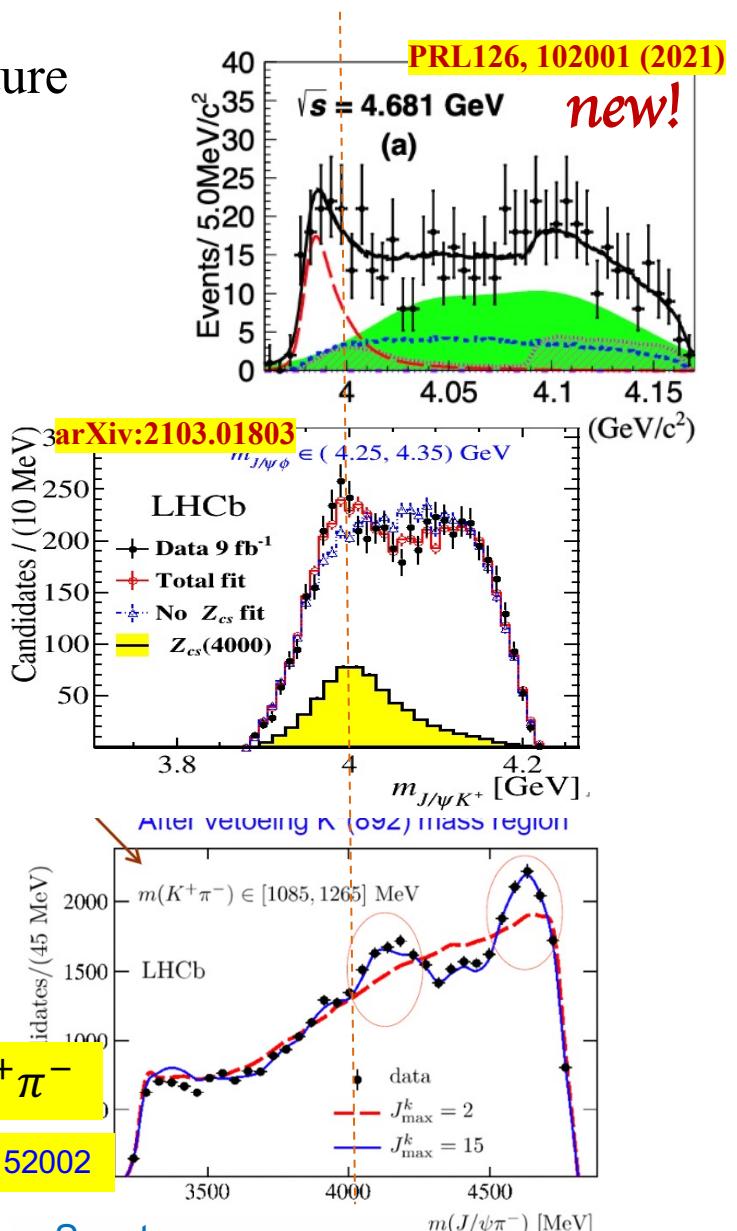
- Various interpretations are possible for the structure
 - Tetraquark state
 - Molecule
 - $D_{s2}^*(2573)^+ D_s^{*-}$ threshold kinematic effects
(Re-scattering, Reflection, Triangle singularity)
 - Mixture of molecular and tetraquark
 - ...

$Z_{cs}(3985)$ from e^+e^- annihilations and
 $Z_{cs}(4000)$ from B decays

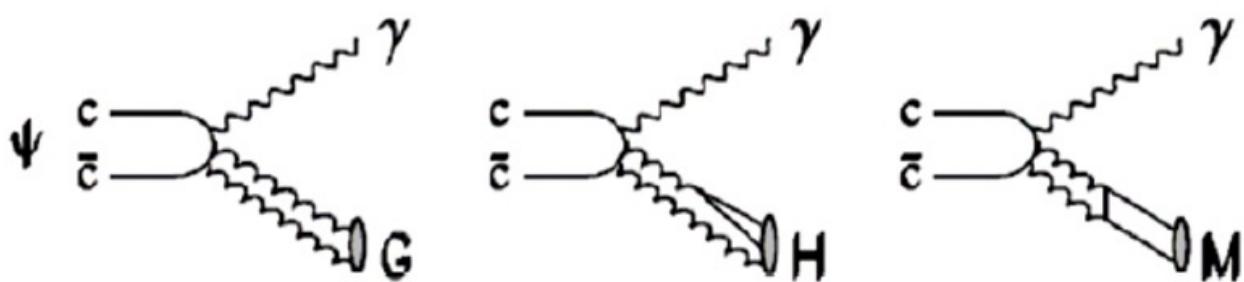
- their masses are close, but widths are different
- If they are same, why width so different?
- If they are not same, is there the corresponding wide $Z_c(3900)$?
- Looking for more channels will be useful

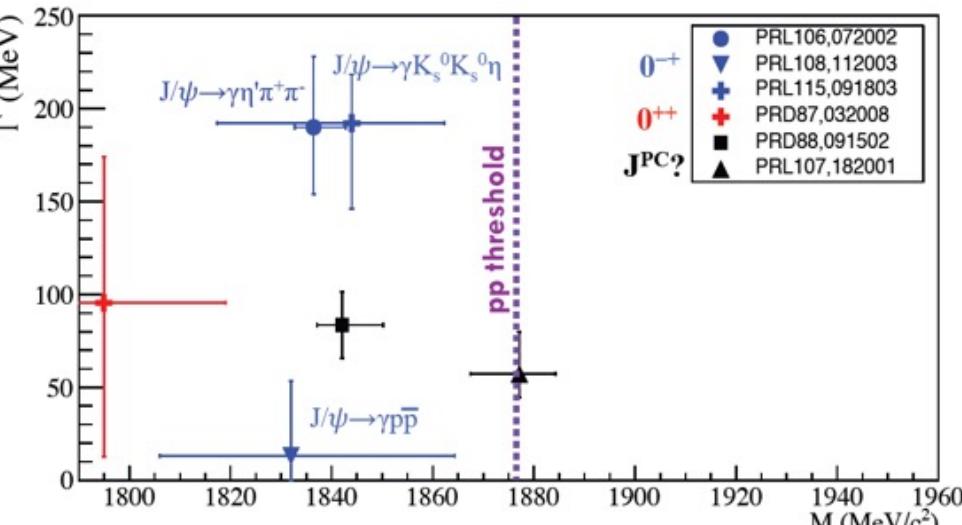
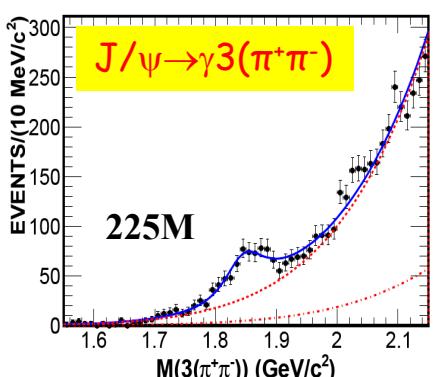
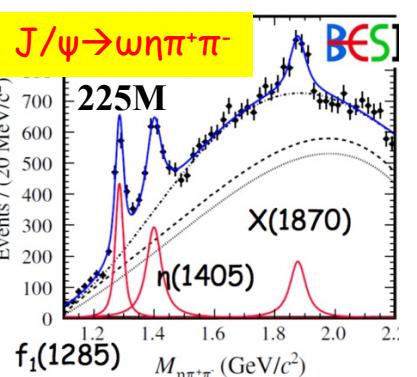
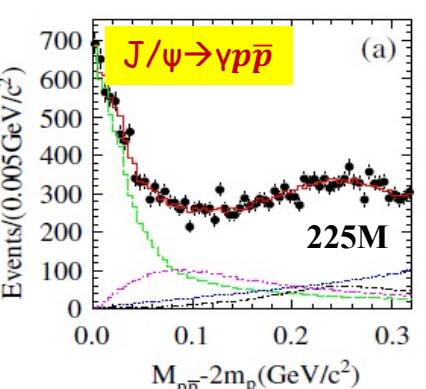
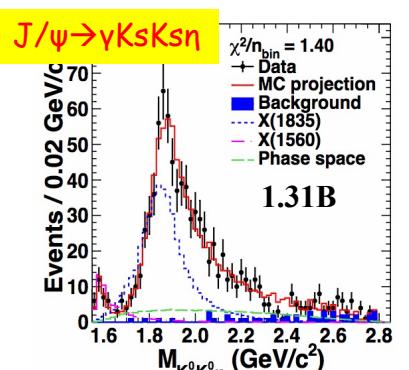
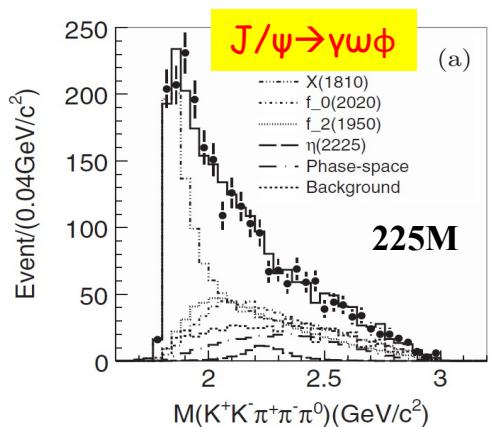
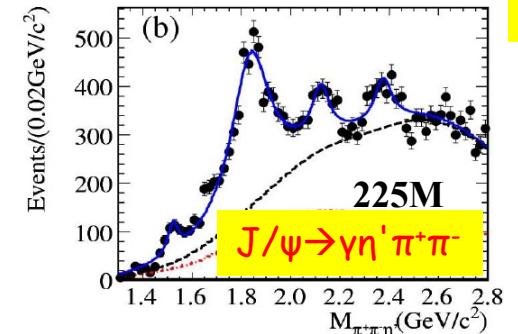
$$B^0 \rightarrow J/\psi K^+ \pi^-$$

PRL 122 (2019) 152002



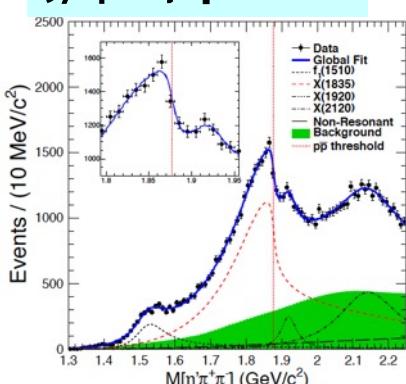
Light hadrons (containing $u/d/s$ quarks)





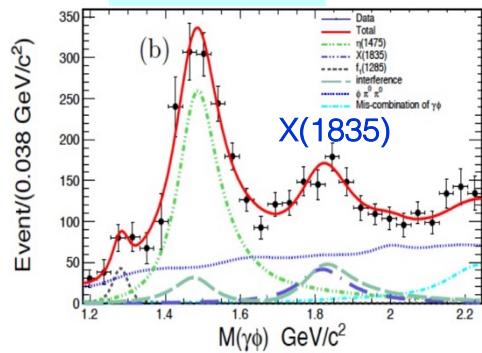
PRL117, 042002 (2016)

$J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$



PRD97, 051101(R)(2018)

$J/\psi \rightarrow \gamma \gamma \phi$

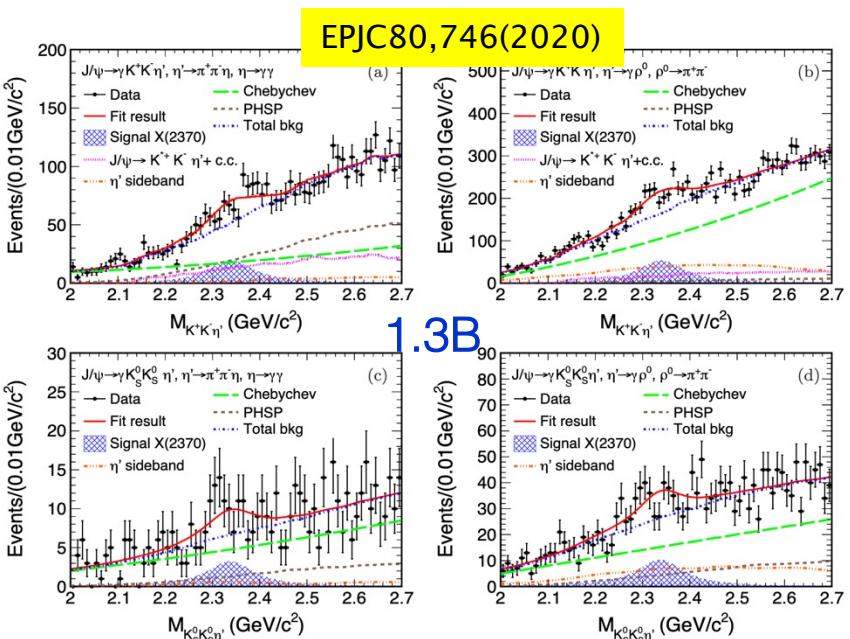


Are they the same state? It is crucial to understand their connections.

The X(2120) and X(2370)

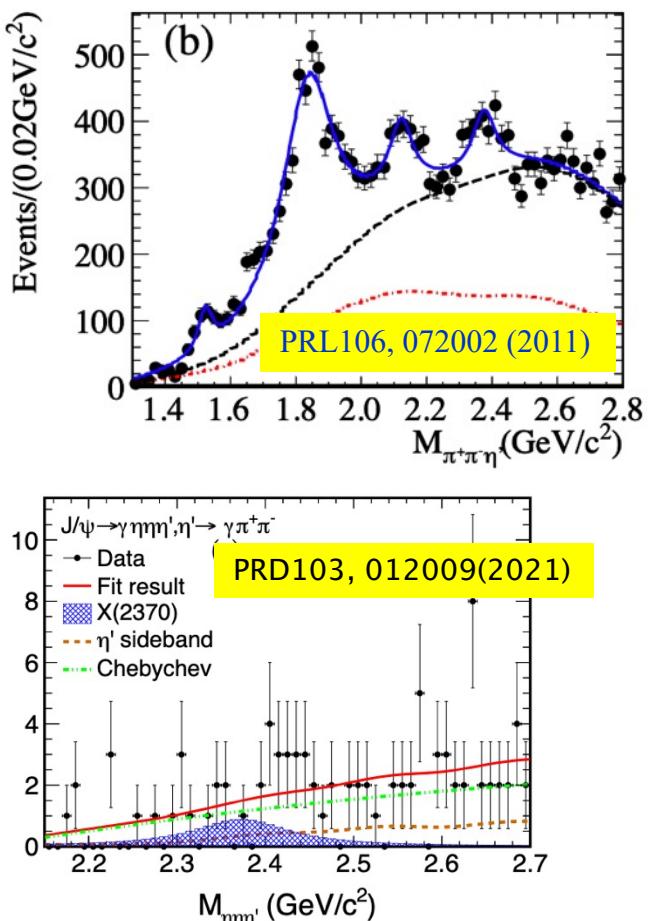


- Observed in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$ at BESIII
[PRL106, 072002 (2011)][PRL117, 042002(2016)]
- Candidates of glueball states
- Combined analysis of $J/\psi \rightarrow \gamma K^+K^-\eta'$ and $\gamma K_S K_S \eta'$
- Search for X(2370) in $J/\psi \rightarrow \gamma\eta\eta\eta'$



$$M_{X(2370)} = 2341.6 \pm 6.5(\text{stat.}) \pm 5.7(\text{syst.}) \text{ MeV}/c^2,$$

$$\Gamma_{X(2370)} = 117 \pm 10(\text{stat.}) \pm 8(\text{syst.}) \text{ MeV},$$



- Observation of $X(2370) \rightarrow K\bar{K}\eta'$ with stat. significance of 8.3σ
- No evidence of $X(2120) \rightarrow K\bar{K}\eta'$
- No evidence of $X(2370) \rightarrow \eta\eta\eta'$

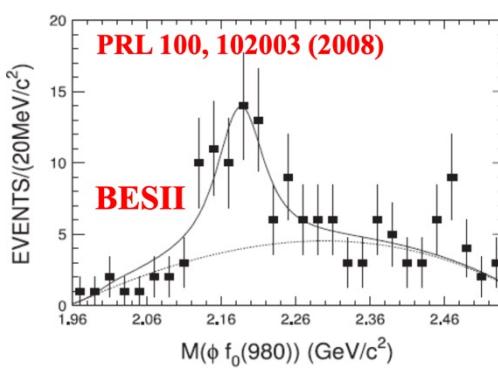
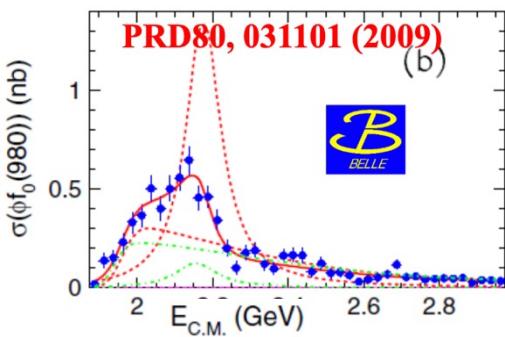
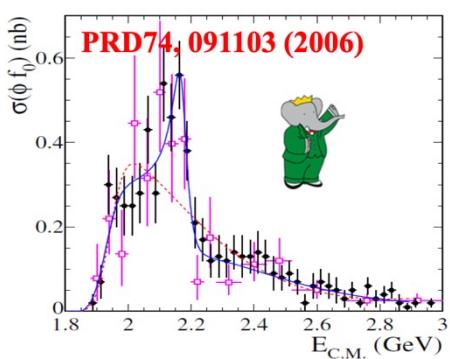
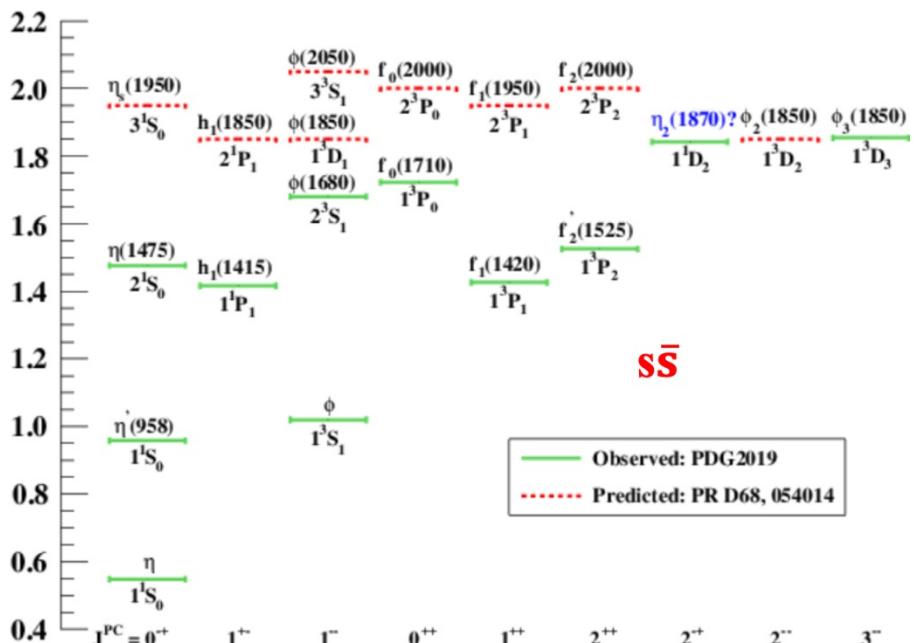
Studies on the $\phi(2170)/Y(2175)$



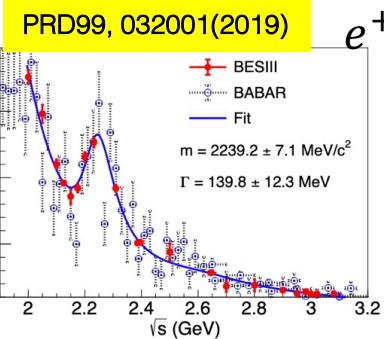
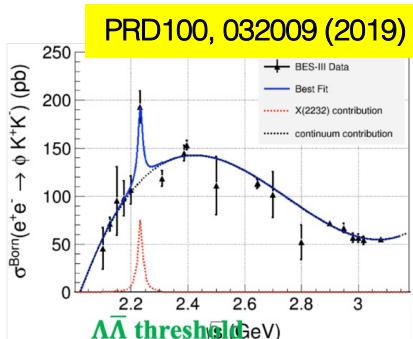
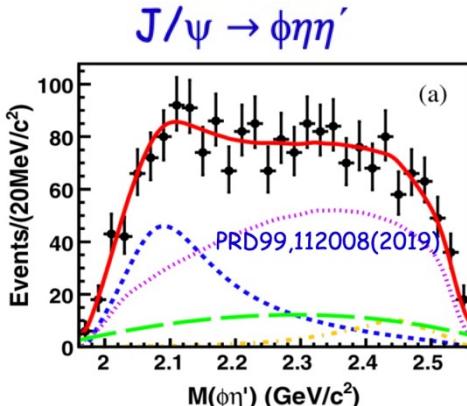
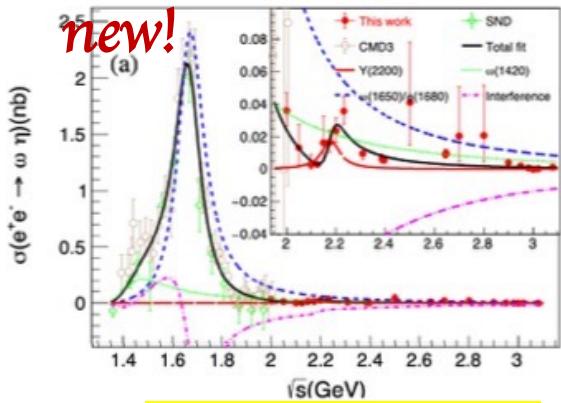
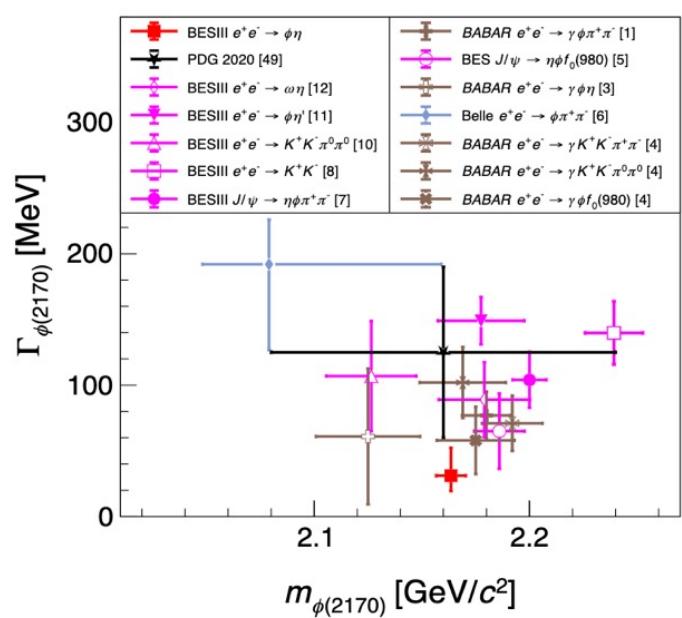
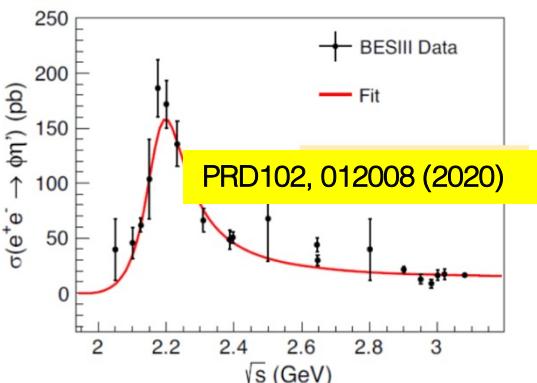
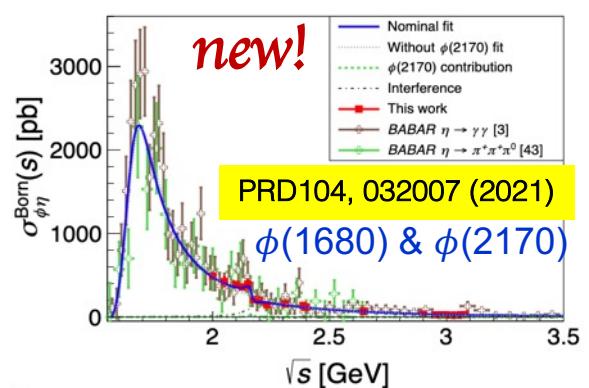
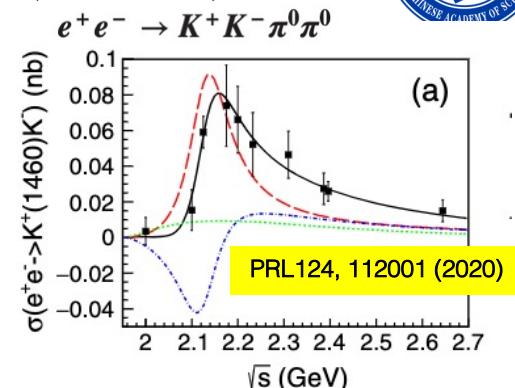
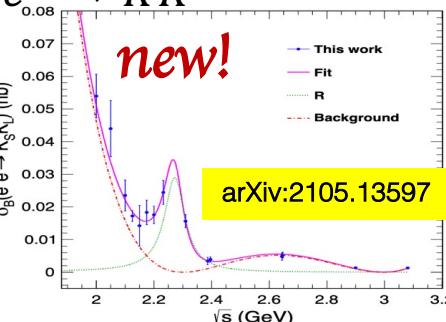
- A strangeonium(-like) state: Y -particle with strange quark

➤ Theorists explain $\phi(2170)$ as

- ✓ s \bar{s} g hybrid
- ✓ 2^3D_1 or 3^3S_1 s \bar{s}
- ✓ tetraquark
- ✓ Molecular state $\Lambda\bar{\Lambda}$
- ✓ $\phi f_0(980)$ resonance with FSI
- ✓ Three body system ϕKK



More results on the $\phi(2170)/Y(2175)$

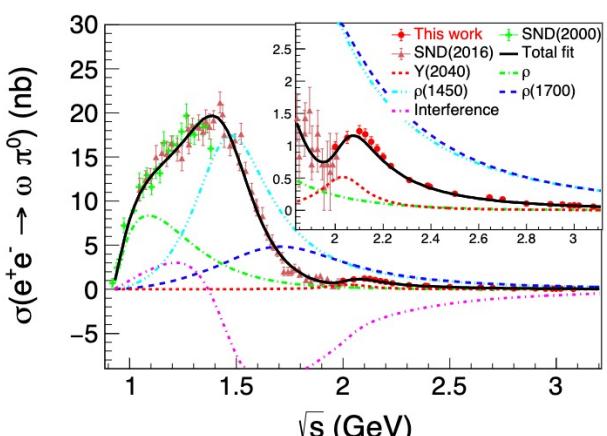

 $e^+e^- \rightarrow K\bar{K}$


$\phi(2170)/Y(2175)$ is still a mystery

The isovector states

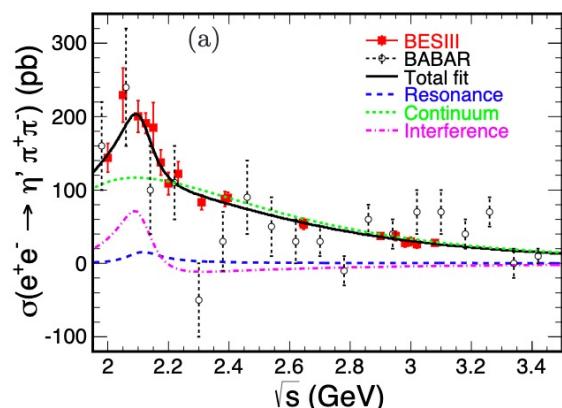
$$e^+ e^- \rightarrow \omega \pi^0$$

PLB 813, 136059 (2021)



$$e^+ e^- \rightarrow \eta' \pi^+ \pi^-$$

PRD 103, 072007 (2021)



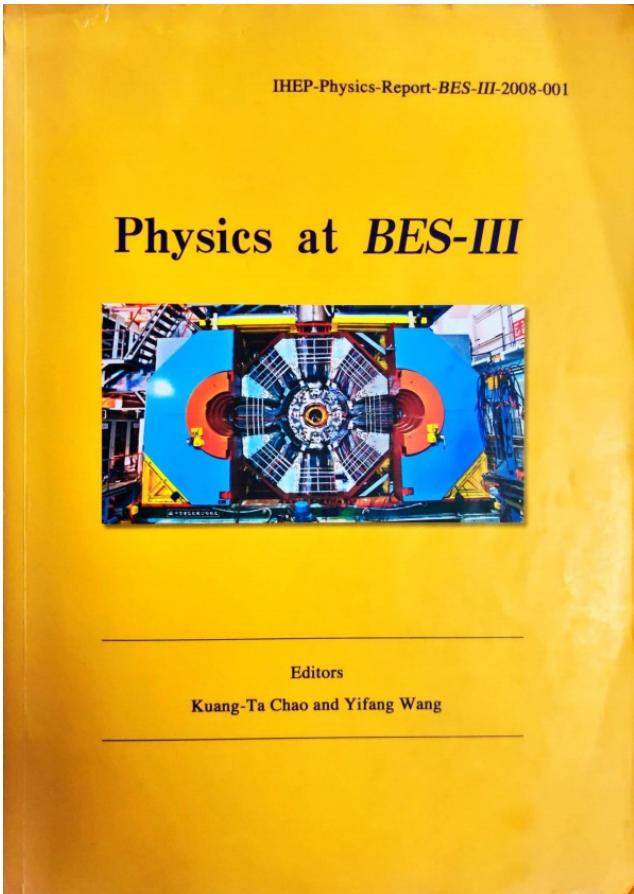
- a structure $\text{Y}(2040)$ with stat. significance $>10\sigma$
 $M = 2034 \pm 14 \pm 9 \text{ MeV}/c^2$
 $\Gamma = 234 \pm 30 \pm 25 \text{ MeV}$
- close to the isovector state $\rho(2000)$ or $\rho(2150)$

- a structure around 2.1 GeV: stat. significance $>6.3\sigma$
 $M = 2111 \pm 43 \pm 25 \text{ MeV}/c^2$
 $\Gamma = 135 \pm 34 \pm 30 \text{ MeV}$
- consistent with the $\text{Y}(2040)$ in $e^+ e^- \rightarrow \omega \pi^0$





BESIII Physics



Int. J. Mod. Phys. A 24, S1-794 (2009)
[arXiv:0809.1869 [hep-ex]].

Chinese Physics C Vol. 44, No. 4 (2020)

Future Physics Programme of BESIII*

Abstract: There has recently been a dramatic renewal of interest in hadron spectroscopy and charm physics. This renaissance has been driven in part by the discovery of a plethora of charmonium-like XYZ states at BESIII and B factories, and the observation of an intriguing proton-antiproton threshold enhancement and the possibly related $X(1835)$ meson state at BESIII, as well as the threshold measurements of charm mesons and charm baryons. We present a detailed survey of the important topics in tau-charm physics and hadron physics that can be further explored at BESIII during the remaining operation period of BEPCII. This survey will help in the optimization of the data-taking plan over the coming years, and provides physics motivation for the possible upgrade of BEPCII to higher luminosity.

DOI: 10.1088/1674-1137/44/4/040001

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Chin. Phys. C 44, 040001 (2020)
doi:10.1088/1674-1137/44/4/040001
[arXiv:1912.05983 [hep-ex]].

Planned future data set

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
✓ $\psi(3770)$ peak	D^0/D^\pm decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ /Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ /Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ /Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different \sqrt{s}	30 fb^{-1} at different \sqrt{s}	770/310 days
4.6 - 4.9 GeV	Charmed baryon/ XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different \sqrt{s}	1490/600 days
4.74 GeV	$\Sigma_c^+ \Lambda_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c \Sigma_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

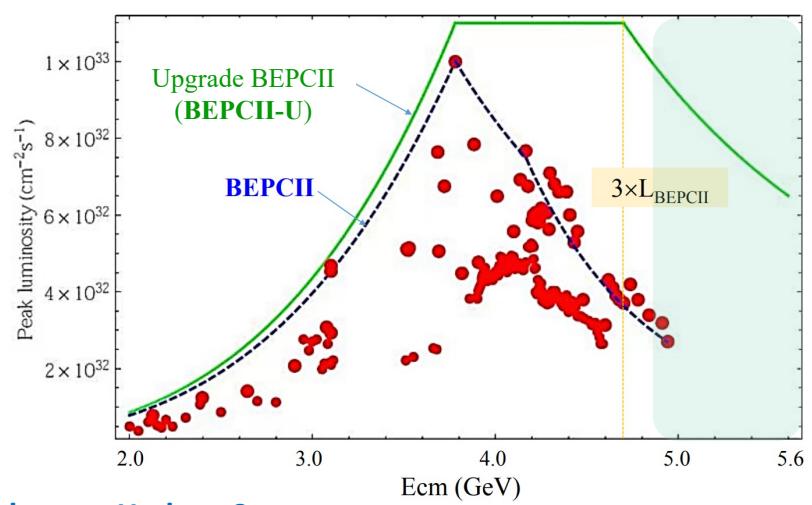
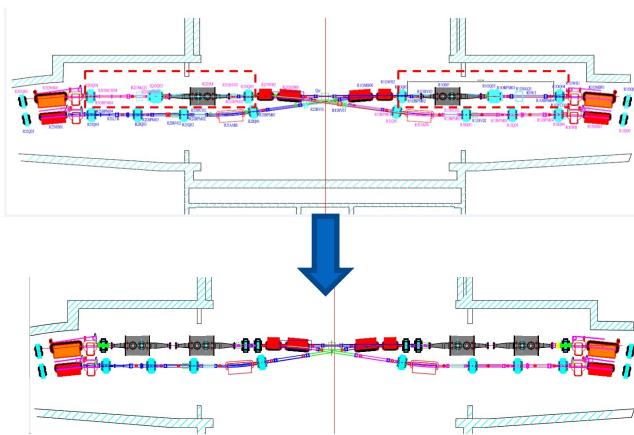
~55 fb^{-1}

Proposal of the upgrade BEPCII

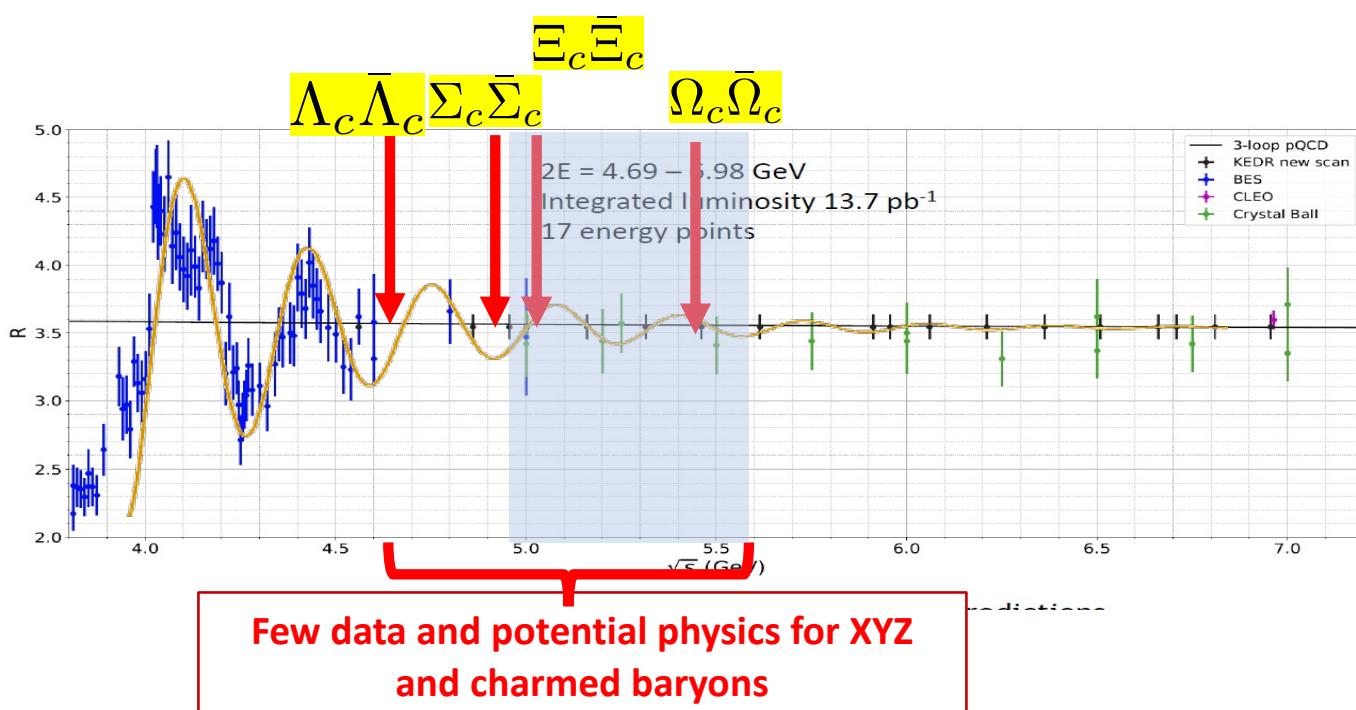


- ✓ An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021:
the optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum energy to 5.6 GeV

- Add another cavity per beam to improve the RF power
- Change optics slightly, increase number of bunches
- Challenges: high beam intensities, backgrounds and aging effect in the detector
- Small risk: can continue running with better performance than BEPCII
- Timescale: 2.5 years construction + 0.5 year installation
- Installation: July – December 2024 and the upgraded machine ready in Jan. 2025



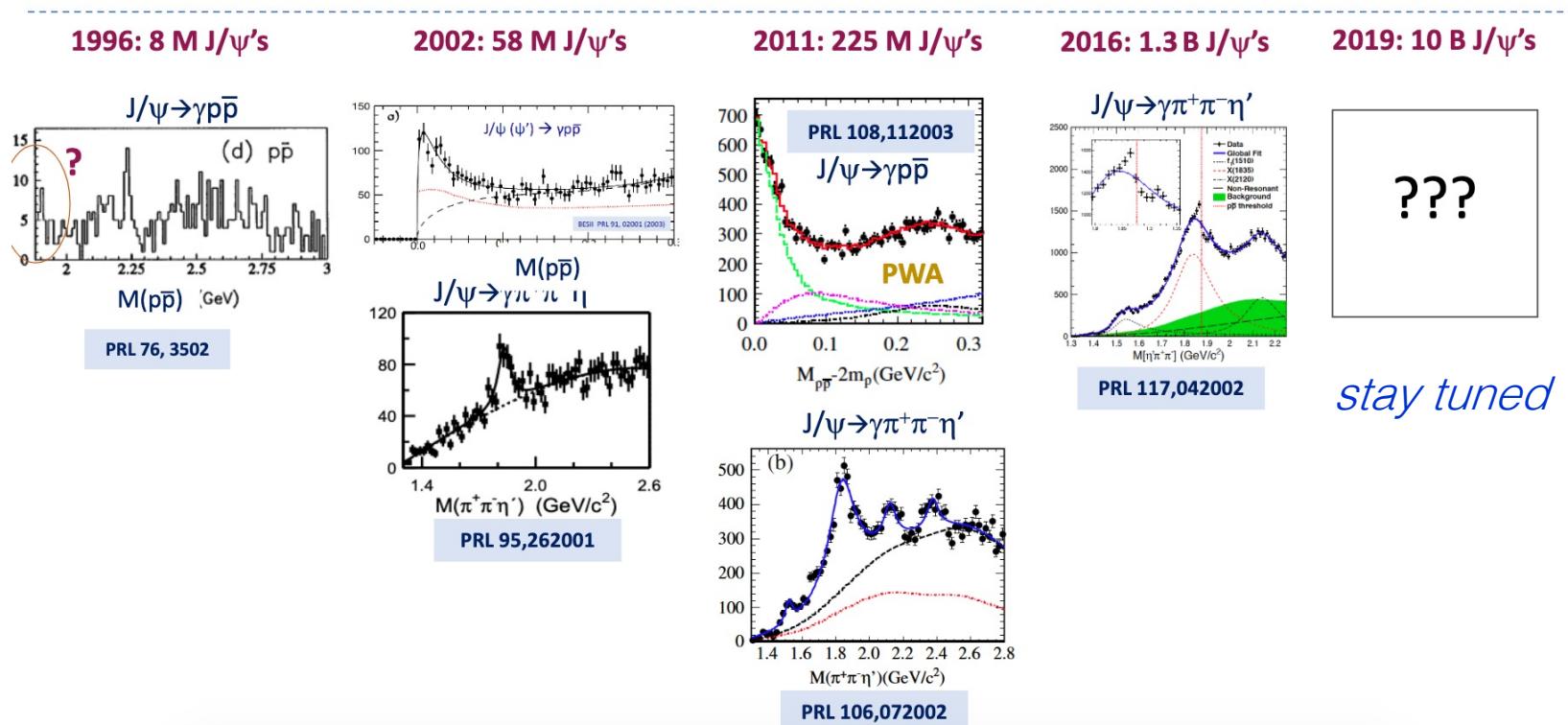
- ✓ Detailed studies of the known $Z_{c(s)}$ states and search for 'black swans' in the higher energy region within a considerable amount of data sets.
- ✓ Cover all the ground-state charmed baryons: production & decays, CPV search



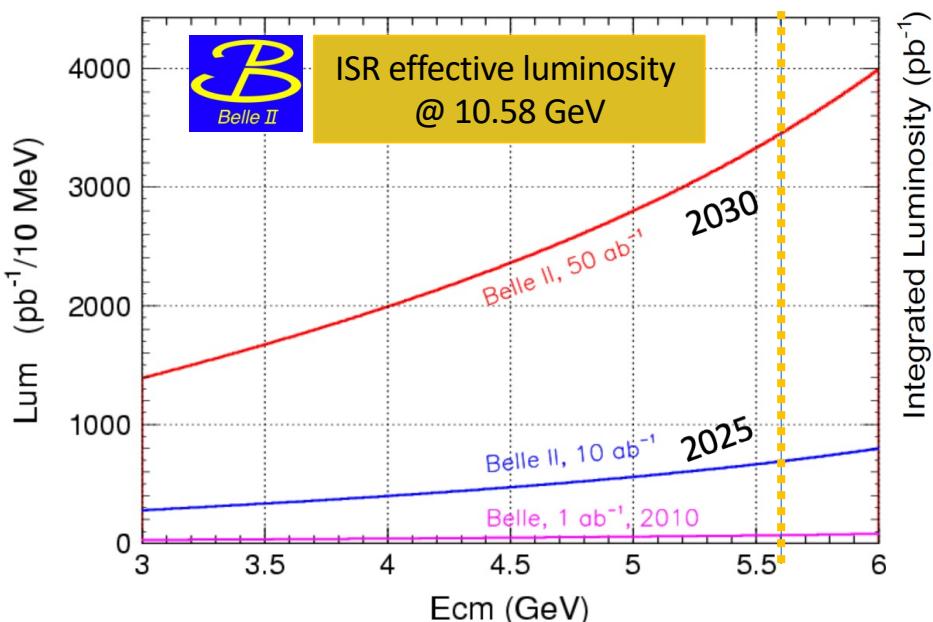
10 billion J/ψ events on tape!

from Stephen Olsen

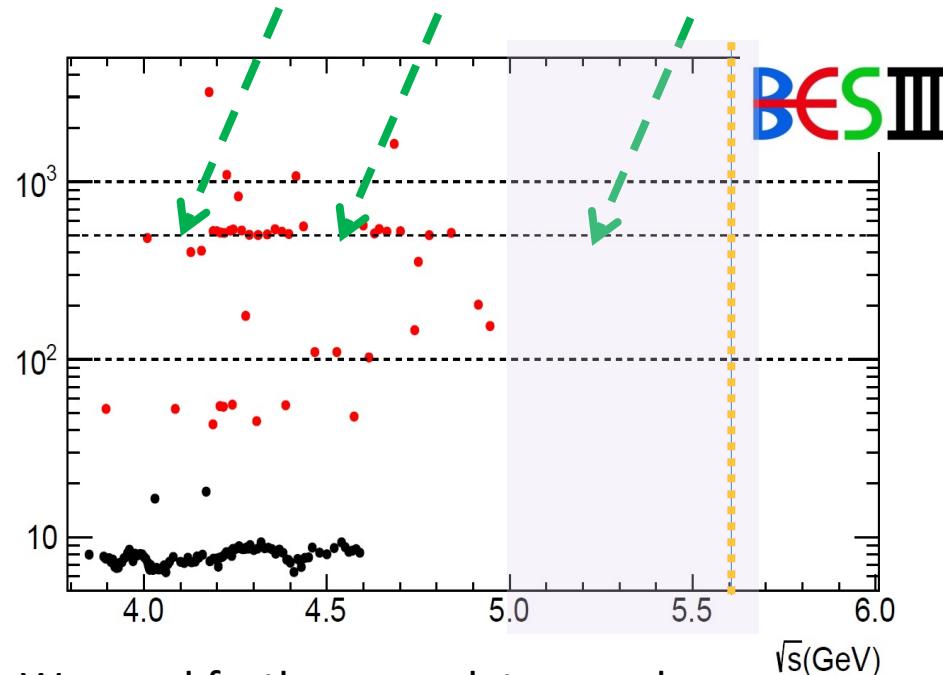
you never have enough J/ψ events



Some (personal) thoughts for future data taking



Competition with Belle II exists, and the scan energy points between 4.0 and 5.6 GeV need to be optimized



We need further scan data samples for $\text{Ecm}=4.00-4.15, 4.43-4.59, 4.90-5.60 \text{ GeV}$, and some other energy points around charmed baryon threshold, such as

- ✓ 4.01 GeV: $D_s D_s$
- ✓ 4.6-4.7 GeV: $\Lambda_c \bar{\Lambda}_c$
- ✓ 4.95 -4.97 GeV: $\Xi_c \bar{\Xi}_c$
- 5.4 -5.6 GeV: $\Omega_c^0 \bar{\Omega}_c^0$



- It is crucial that different experiments, such as BESIII, LHCb and Belle II, exchange information in the efforts of amplitude analyses
 - ✓ Sharing the knowledge on analysis tools
eg, **TF-PWA** (talks given inside BESIII and LHCb) <https://github.com/jiangyi15/tf-pwa>
 - ✓ Constraints on properties of the hadronic states
- A few cases:
 - Zc/Zcs productions (e^+e^- annihilations or b-hadron decays) and decays (to open or hidden charm states)

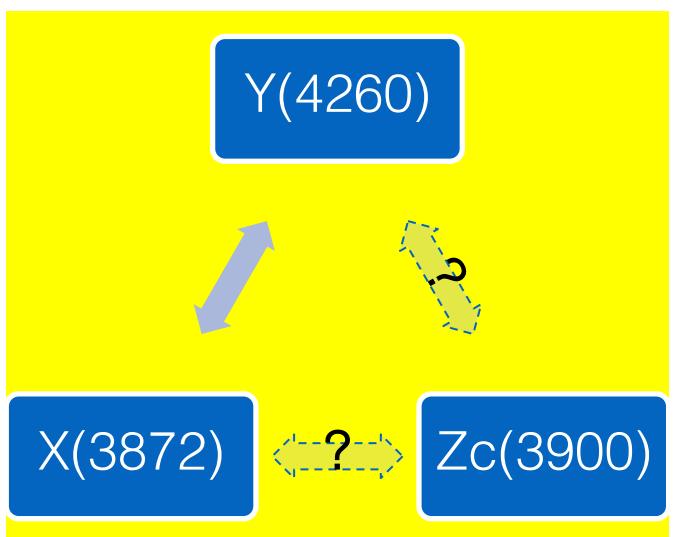
State	Decay modes	Seen by
$Z_c(3900)^{\pm,0}$	$\pi^\pm J/\psi, (D^*\bar{D})^\pm$	BESIII, Belle CLEO
$Z_c(4020)^{\pm,0}$	$\pi^\pm h_c, (D^*\bar{D}^*)^\pm$	BESIII
$Z_c(4430)^\pm$	$\pi^\pm \psi(2S)$ $\pi^\pm J/\psi$	Belle, BaBar, LHCb

in $e^+e^- \rightarrow \pi^- Zc$

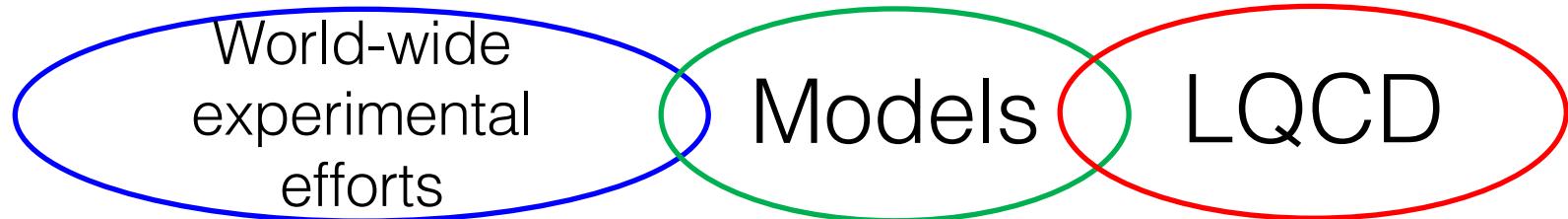
in $e^+e^- \rightarrow \pi^- Zc$

in $B \rightarrow K Zc$

Pole properties



- Energy-dependence
- Patterns in productions and decays



Summary

- BESIII is successfully operating since 2008, and will continue to run for 5–10 years
 - collected large data samples in the energy range 2.0~5.6 GeV
- Many new results have been published regarding to spectroscopies
 - ✓ observation of the Zcs(3985)
 - ✓ studies of the Y states in different final states
 - ✓ more decay patterns of light mesons: conventional and exotics
 - ✓ ...
- Future plan:
high-lumi. fine scan between 3.8 GeV and 5.6 GeV
→ BEPCII-U: 3x upgrade on luminosity

Thank you !

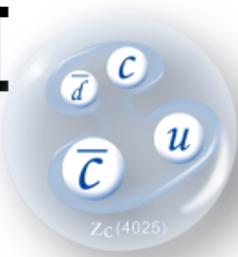
谢谢！

What have we learnt about $X(3872)$



- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
 - $J^{PC} = 1^{++}$
 - Mass = 3871.69 ± 0.17 MeV
 - Width < 1.2 MeV @90% CL
 $\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20$ MeV
- Production
 - In e^+e^- collision, see strong connection of Y(4260) resonance decays
[\[BESIII, PRL 112. 092001 \(2014\); 122, 202001 \(2019\)\]](#)
 - In b -hadron decays: B, Bs, Λ_b , ...
 - Prompt production in $pp/p\bar{p}$ and heavy ion collision
- What is it?
 - Loosely $D^0\bar{D}^{0*}$ bound state?
 - Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$?
- Important to fully explore its production and decay properties

Mode	Fraction (Γ_i / Γ)
$\Gamma_1 e^+e^-$	$< 2.8 \times 10^{-6}$
$\Gamma_2 \pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
$\Gamma_3 \pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
$\Gamma_4 \alpha J/\psi(1S)$	$< 33\%$
$\Gamma_5 \star \alpha J/\psi(1S)$	$(4.3 \pm 2.1)\%$
$\Gamma_6 \phi\phi$	not seen
$\Gamma_7 D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
$\Gamma_8 \star \bar{D}^{*0}D^0$	$(37 \pm 9)\%$
$\Gamma_9 \eta\eta$	$< 11\%$
$\Gamma_{10} D^0\bar{D}^0$	$< 29\%$
$\Gamma_{11} D^+D^-$	$< 19\%$
$\Gamma_{12} \pi^0\chi_{c2}$	$< 4\%$
$\Gamma_{13} \star \pi^0\chi_{c1}$	$(3.4 \pm 1.6)\%$
$\Gamma_{14} \pi^0\chi_{c0}$	$< 70\%$
$\Gamma_{15} \pi^+\pi^-\eta_c(1S)$	$< 14\%$
$\Gamma_{16} \pi^+\pi^-\chi_{c1}$	$< 7 \times 10^{-3}$
$\Gamma_{17} p\bar{p}$	$< 2.4 \times 10^{-5}$
▼ Radiative decays	
$\Gamma_{18} \gamma D^+D^-$	$< 4\%$
$\Gamma_{19} \gamma \bar{D}^0D^0$	$< 6\%$
$\Gamma_{20} \star \gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$
$\Gamma_{21} \gamma\chi_{c1}$	$< 9 \times 10^{-3}$
$\Gamma_{22} \gamma\chi_{c2}$	$< 3.2\%$
$\Gamma_{23} \star \gamma\psi(2S)$	$(4.5 \pm 2.0)\%$



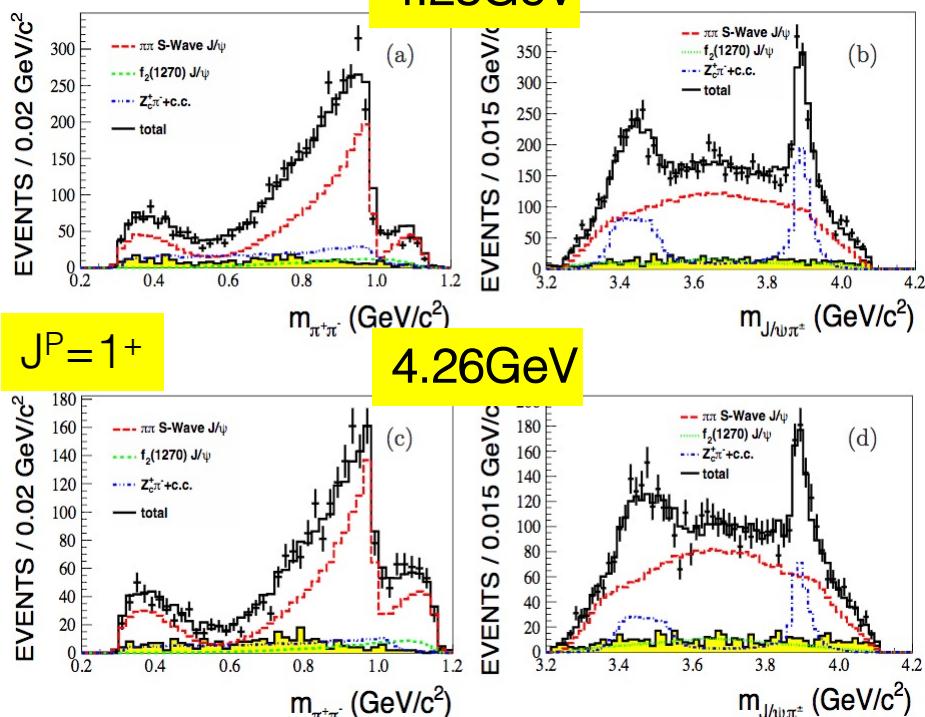
The Zc Family at BESIII



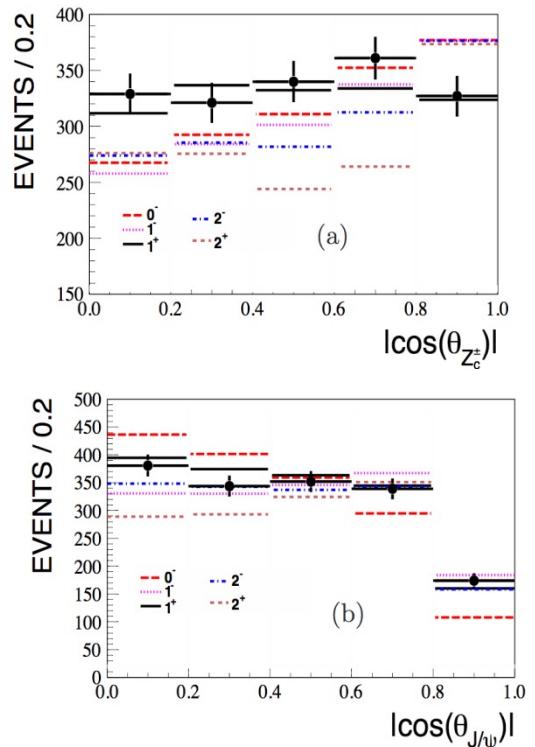
State	Mass (MeV/c ²)	Width (MeV)	Decay	Process
Z _c (3900) [±]	3899.0 ± 3.6 ± 4.9	46 ± 10 ± 20	$\pi^\pm J/\psi$	$e^+e^- \rightarrow \pi^\pm\pi^\mp J/\psi$
Z _c (3900) ⁰	3894.8 ± 2.3 ± 2.7	29.6 ± 8.2 ± 8.2	$\pi^0 J/\psi$	$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$
	3883.9 ± 1.5 ± 4.2	24.8 ± 3.3 ± 11.0	$(D\bar{D}^*)^\pm$	$e^+e^- \rightarrow (D\bar{D}^*)^\pm\pi^\mp$
	Single D tag	Single D tag		
Z _c (3885) [±]	3881.7 ± 1.6 ± 2.1	26.6 ± 2.0 ± 2.3	$(D\bar{D}^*)^\pm$	$e^+e^- \rightarrow (D\bar{D}^*)^\pm\pi^\mp$
	Double D tag	Double D tag		
Z _c (3885) ⁰	3885.7 ^{+4.3} _{-5.7} ± 8.4	35 ⁺¹¹ ₋₁₂ ± 15	$(D\bar{D}^*)^0$	$e^+e^- \rightarrow (D\bar{D}^*)^0\pi^0$
<hr/>				
Z _c (4020) [±]	4022.9 ± 0.8 ± 2.7	7.9 ± 2.7 ± 2.6	$\pi^\pm h_c$	$e^+e^- \rightarrow \pi^\pm\pi^\mp h_c$
Z _c (4020) ⁰	4023.9 ± 2.2 ± 3.8	fixed	$\pi^0 h_c$	$e^+e^- \rightarrow \pi^0\pi^0 h_c$
Z _c (4025) [±]	4026.3 ± 2.6 ± 3.7	24.8 ± 5.6 ± 7.7	$D^*\bar{D}^*$	$e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$
Z _c (4025) ⁰	4025.5 ^{+2.0} _{-4.7} ± 3.1	23.0 ± 6.0 ± 1.0	$D^*\bar{D}^*$	$e^+e^- \rightarrow (D^*\bar{D}^*)^0\pi^0$

- Z_c line shape parameterized with Flatte-like formula

PRL 119.072001 (2017)



$$BW(s) = \frac{1}{s - M^2 + i(g'_1 \rho_{\pi J/\psi}(s) + g'_2 \rho_{D^* D}(s))},$$

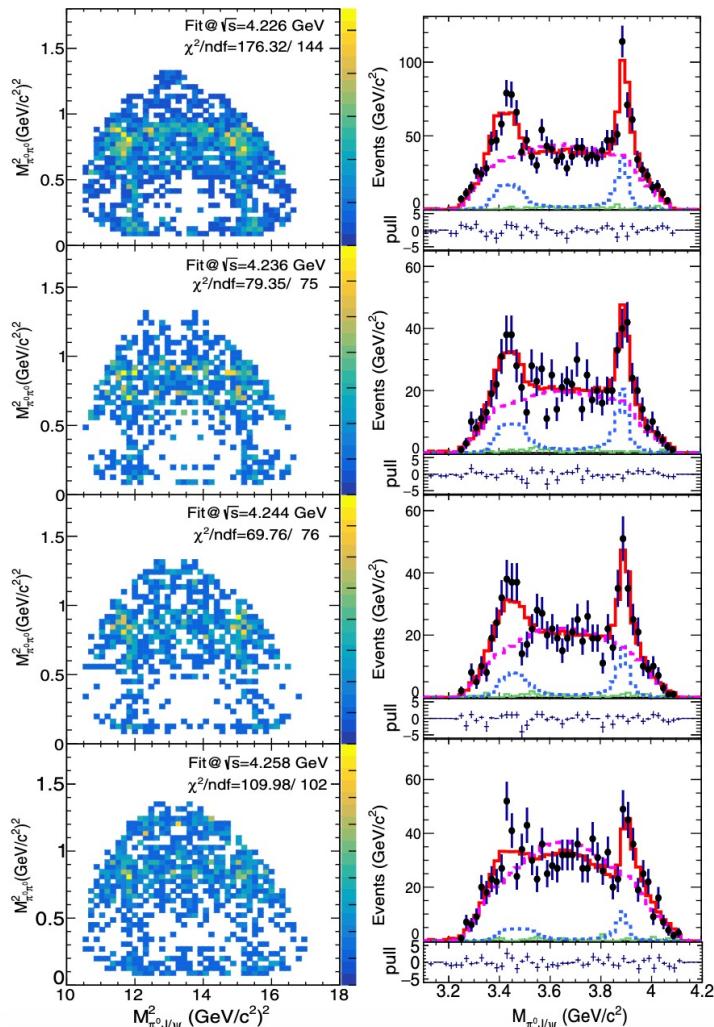


Hypothesis	$\Delta(-2 \ln L)$	$\Delta(\text{ndf})$	Significance
1^+ over 0^-	94.0	13	7.6σ
1^+ over 1^-	158.3	13	10.8σ
1^+ over 2^-	151.9	13	10.5σ
1^+ over 2^+	96.0	13	7.7σ

J^P is measured to be 1^+ with significance larger than 7.6σ

PWA of the $Z_c(3900)^0$

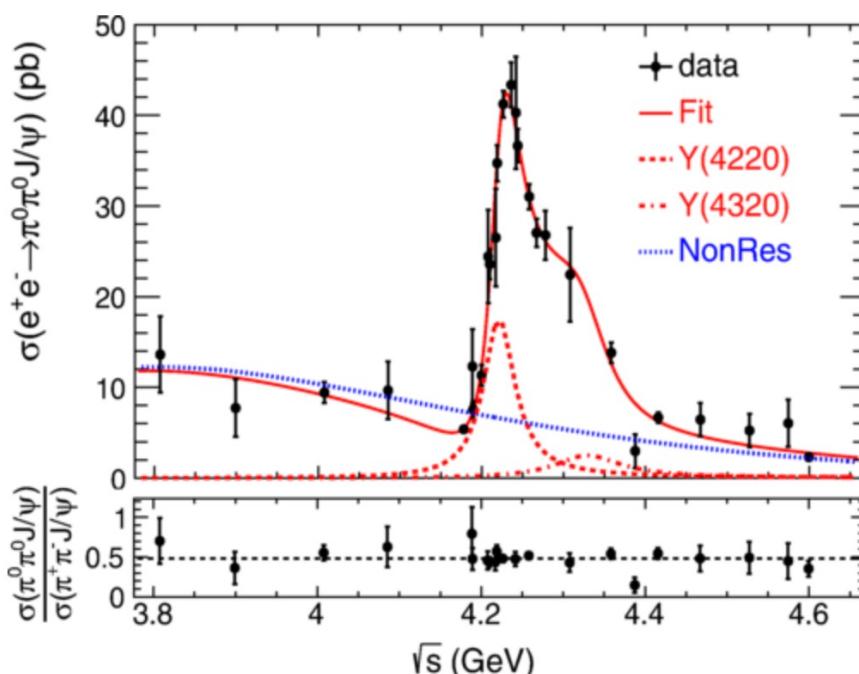
PRD 102, 012009 (2020)



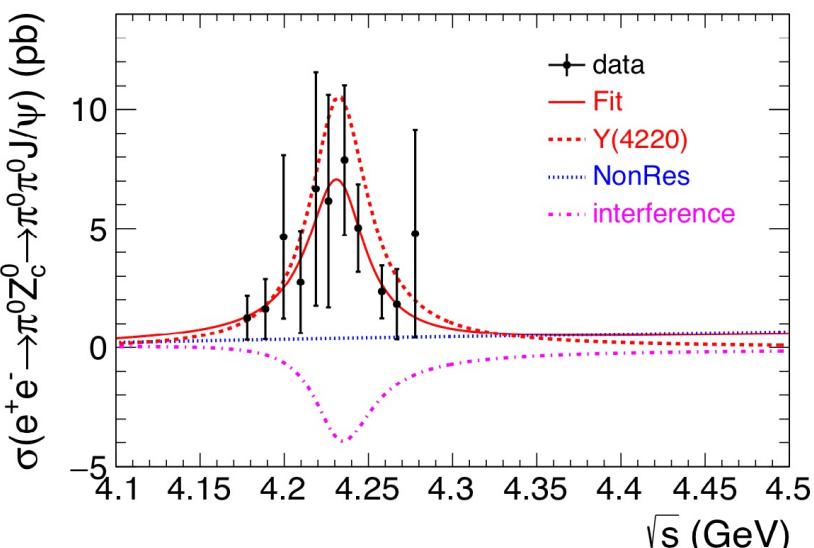
- Simultaneous PWA fit of $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ to the four energy points
- The spin-parity of $Z_c(3900)^0$ is determined to be 1^+
- The nominal fit includes the intermediate process $\sigma J/\psi$, $f(980)J/\psi$, $f(1370)J/\psi$ and $\pi^0 Z_c(3900)^0$.
- Mass and width of $Z_c(3900)^0$ is measured:
 - $M(Z_c(3900)^0) = (3893.0 \pm 2.3 \pm 3.2) \text{ MeV}/c^2$,
 - $\Gamma(Z_c(3900)^0) = (44.2 \pm 5.4 \pm 8.3) \text{ MeV}$.

PRD 102, 012009 (2020)

- Cross sections relative to those of the charged channel $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ follows isospin symmetry
- Fit to the $e^+e^- \rightarrow \pi^0\pi^0J/\psi$ returns $M(Y4220) = (4220.4 \pm 2.4 \pm 2.3) \text{ MeV}/c^2$; $\Gamma(Y(4220)) = (46.2 \pm 4.7 \pm 2.1) \text{ MeV}$
- Stat. significance of the Y(4320) (fixed to the charged channel) is 4.2σ
- The mass and width are consistent with those measured in the charged process



PRD 102, 012009 (2020)



Parameters	Solution I	Solution II
$p_0(c^2/\text{MeV})$	0.0 ± 11.3	
p_1	$(1.8 \pm 1.9) \times 10^{-2}$	
$M(R) (\text{MeV}/c^2)$	4231.9 ± 5.3	
$\Gamma_{\text{tot}}(R) (\text{MeV})$	41.2 ± 16.0	
$\Gamma_{ee} \mathcal{B}_{R \rightarrow \pi^0 Z_c(3900)^0} (\text{eV})$	0.53 ± 0.15	0.22 ± 0.25
$\phi(R)$	$(-103.9 \pm 33.9)^\circ$	$(112.7 \pm 43.0)^\circ$

- $Z_c(3900)^0$ resonance parameters are fixed to the results of the previous four-energy-point fit
- The Born cross section of $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0 \pi^0 J/\psi$ is extracted.
- Clear structure around 4.2 GeV is observed
 - $M = (4231.9 \pm 5.3 \pm 4.9) \text{ MeV}/c^2$,
 - $\Gamma = (41.2 \pm 16.0 \pm 16.4) \text{ MeV}$.
- Compatible with the $Y(4220)$ line shape
- Indication of correlation between the production of the $Y(4220)$ and $Z_c(3900)$.

Search for $Z_c^{(\prime)+} \rightarrow \rho^+ \eta_c$

- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(\prime)} \rightarrow \rho \eta_c$ to $Z_c^{(\prime)} \rightarrow \pi J/\psi (\pi h_c)$ may discriminate **the tetra-quark** and **molecule** models.

Date sets:

- $\sim 4 \text{ fb}^{-1}$ data set distributed at $\sqrt{s} = 4.23, 4.26, 4.36, 4.40, 4.60 \text{ GeV}$

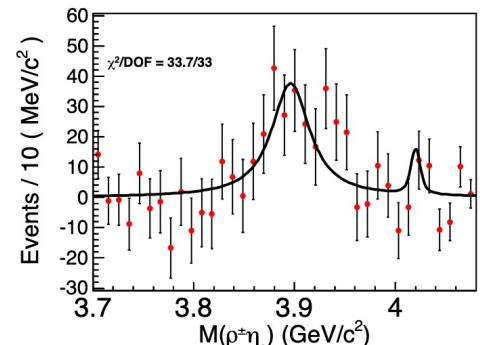
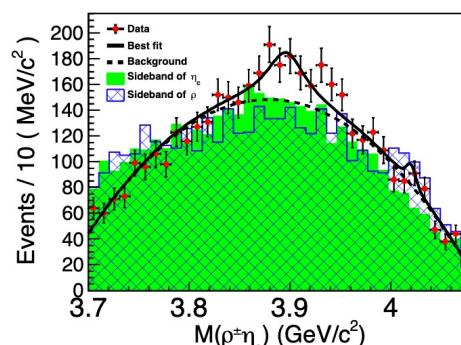
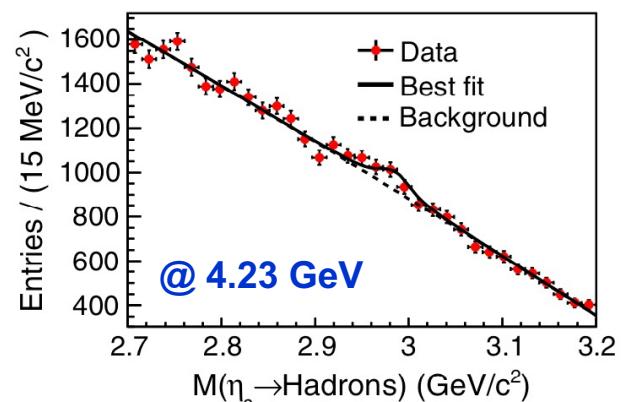
Strategy of this analysis:

- Start with looking for $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \eta_c, \eta_c \rightarrow 9$ hadronic decays
- Strong evidence of $e^+ e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho \eta_c$ is observed at $\sqrt{s} = 4.23$, statistical significance is 4.3σ . (3.9σ including systematics)
- $e^+ e^- \rightarrow \pi Z'_c, Z'_c \rightarrow \rho \eta_c$ is not seen in all data sets.

PRD 100, 111102(R) (2019)

$$R_z = \frac{B(Z_c \rightarrow \rho \eta_c)}{B(Z_c \rightarrow \pi J/\psi)}$$

$$R_{z'} = \frac{B(Z'_c \rightarrow \rho \eta_c)}{B(Z'_c \rightarrow \pi h_c)}$$

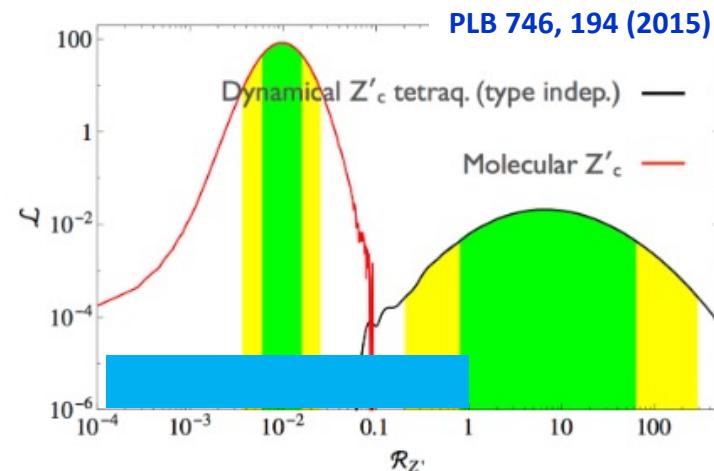
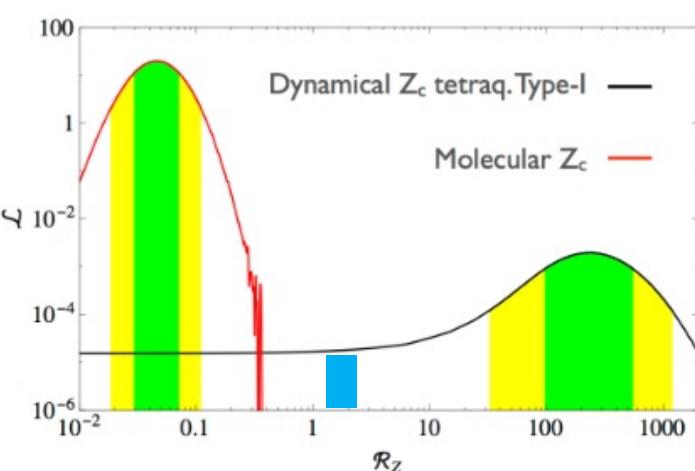


@ 4.23 GeV

Evidence for $Z_c(3900)^+ \rightarrow \rho^+ \eta_c$

Ratio	Measurement	Tetraquark	Molecule
$R_{Z_c(3900)}$	2.3 ± 0.8 [29]	230^{+330}_{-140} [12] $0.27^{+0.40}_{-0.17}$ [12] 0.66 [13] 0.56 ± 0.24 [14] 0.95 ± 0.40 [15] 1.08 ± 0.88 [16] 1.28 ± 0.37 [17] 1.86 ± 0.41 [17]	$0.046^{+0.025}_{-0.017}$ [12] 1.78 ± 0.41 [17] 6.84×10^{-3} [18] 0.12 [19]
$R_{Z_c(4020)}$	< 1.2 [4]	$6.6^{+56.8}_{-5.8}$ [12]	$0.010^{+0.006}_{-0.004}$ [12]

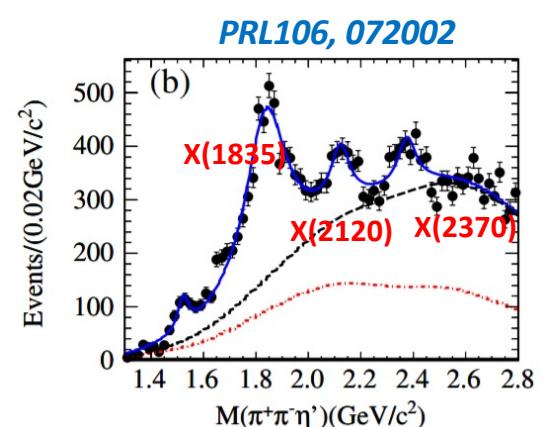
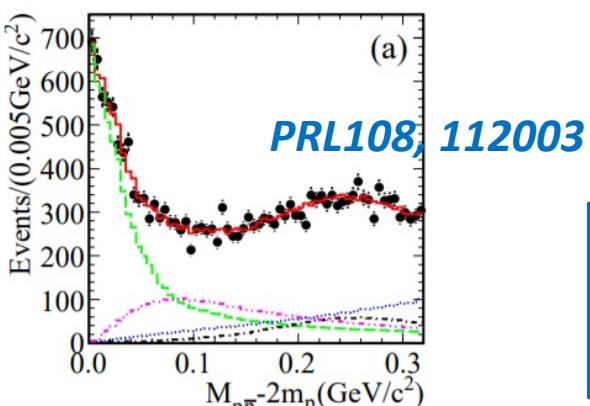
PRD 100, 111102(R) (2019)



- BESIII measurement of $R_{Z_c(3900)}$ is closer to tetraquark model overall.
- Molecule calculation is highly model dependent.
- Inconsistent with hadron-charmonium model.

X($p\bar{p}$)/X(1835) from J/ψ radiative decays

- X($p\bar{p}$)
 - An anomalous strong $p\bar{p}$ threshold enhancement structure which was first observed by BESII in $J/\psi \rightarrow \gamma p\bar{p}$
 - BESIII confirmed its existence with much higher significance and PWA (with FSI considered) is performed
 - 0^{-+}
 - Mass = $1836.5^{+19+18}_{-5-17} \pm 19$ MeV/c²
 - Width < 76 MeV/c² @ 90% C.L.
- X(1835)
 - First observed by BESII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$
 - BESIII confirmed its existence with much higher significance
 - **Spin-parity is not known**
 - Mass = $1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c²
 - Width = $190 \pm 9^{+38}_{-36}$ MeV/c²

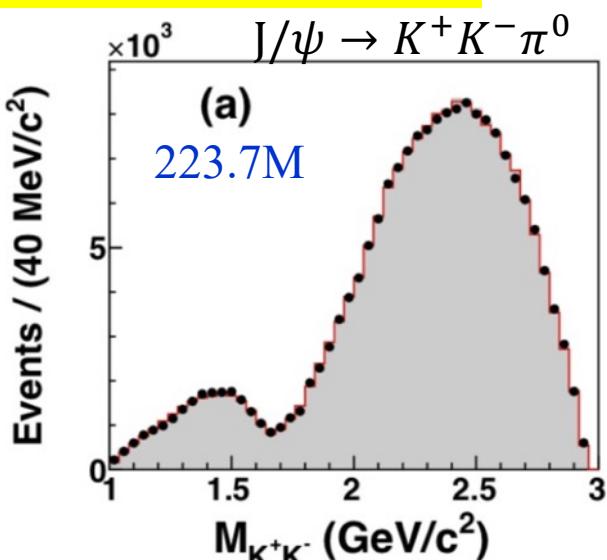


*Are they the same state? A $p\bar{p}$ bound state?
 What's the spin-parity of X(1835)?
 Why their widths are so different?*

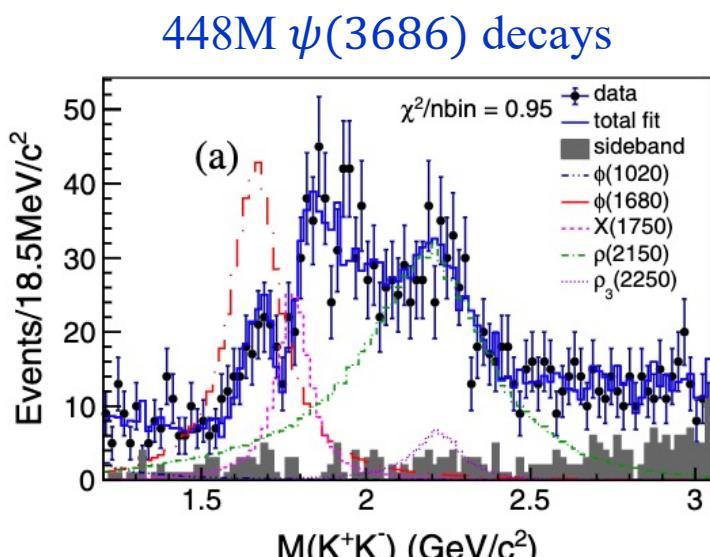
Strangeonium and strange-mesons in $J/\psi \rightarrow K^+K^-\pi^0$ and $\psi(3686) \rightarrow K^+K^-\eta$

PRD101, 032008 (2020)

PRD100, 032004 (2019)



- First observations of $K_2^*(1980)$ and $K_4^*(2045)$ in J/ψ decays
- Two broad K^+K^- 1⁻⁻ structures are observed: possible from $\omega(1650)$ and $\rho(2150)$



- Dip around 1.75 GeV requires another 1⁻⁻ resonance $X(1750)$ to introduce interference with $\phi(1680)$: could be $\rho(1700)$ or $X(1750)$ (photoproduction at FOCUS)
- Broad K^+K^- structure around 2.2 GeV: contributions from $\rho(2150)$ and/or $\rho_3(2250)$ resonances