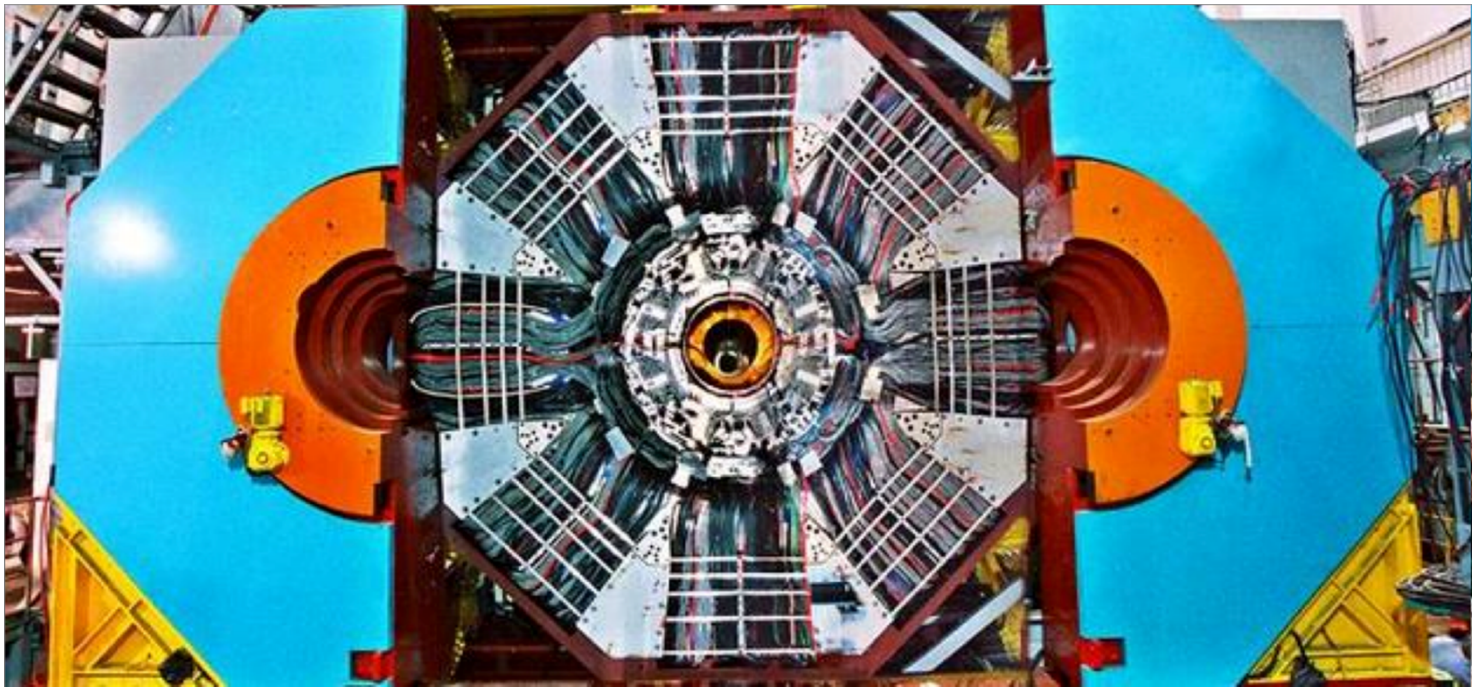


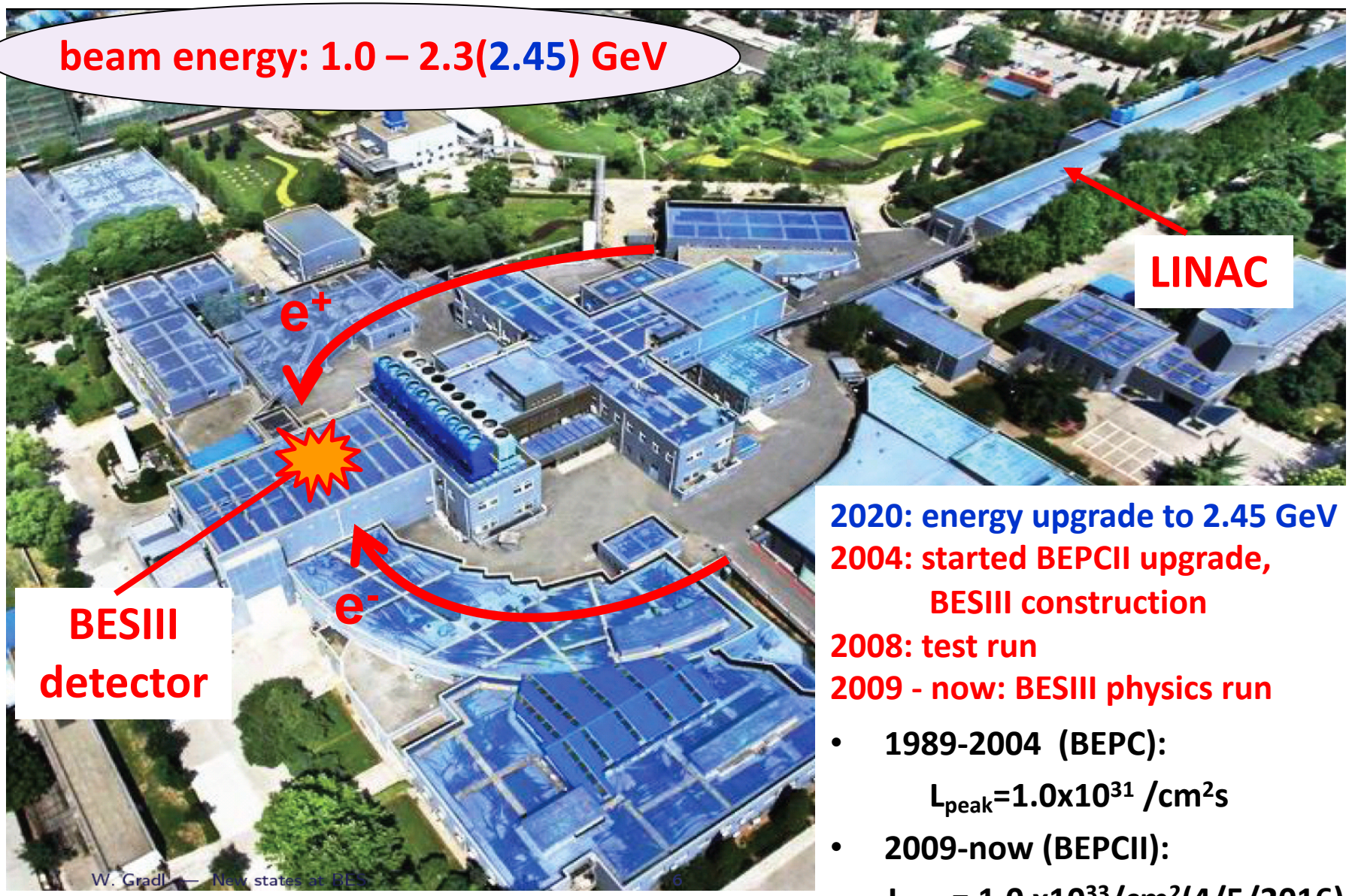
Tetraquark states at BESIII

Xiao-Rui Lyu（吕晓睿）
University of Chinese Academy of Sciences (UCAS)
(On behalf of the BESIII collaboration)

Outline

- **Introduction**
- **The tetraquark states**
  - Observation of the Zcs(3985)
  - PWA of $e^+e^- \to \pi^0\pi^0 J/\psi$ and $\pi^0 Z_c(3900)^0$ cross sections
  - Evidence of $Z_c(3900)^+ \to \rho^+\eta_c$
  - Search for $Z_c \to \pi\chi_{cJ}, \pi\eta_c$
- **Future prospects**
- **Summary**

Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade,
BESIII construction

2008: test run

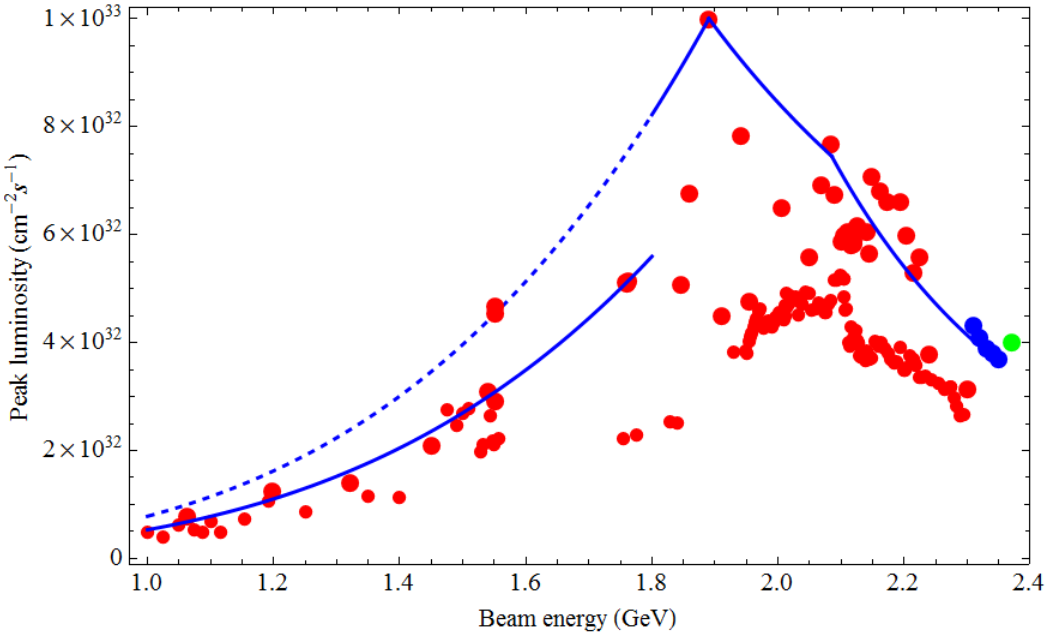
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

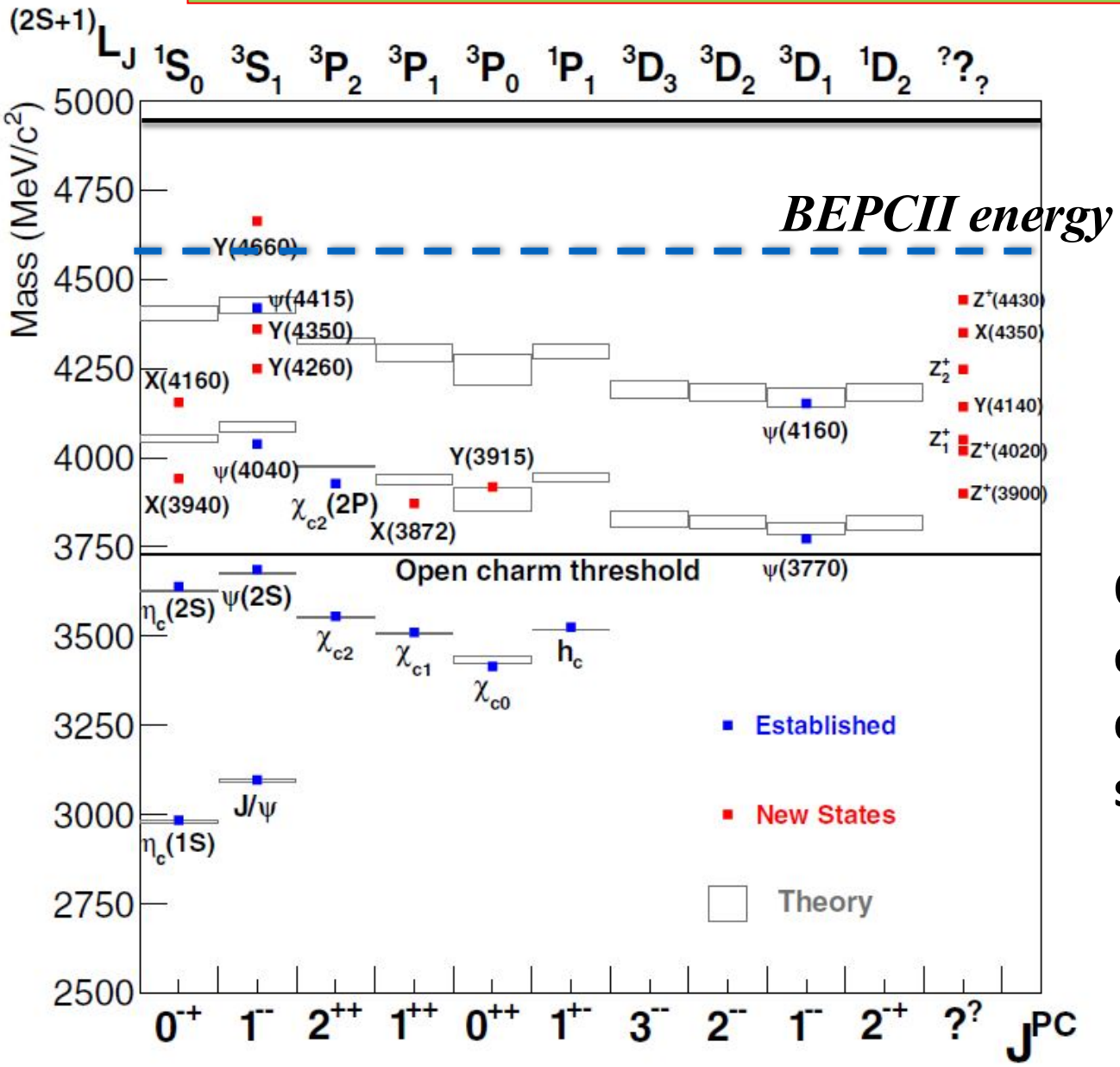
BEPCII upgrade

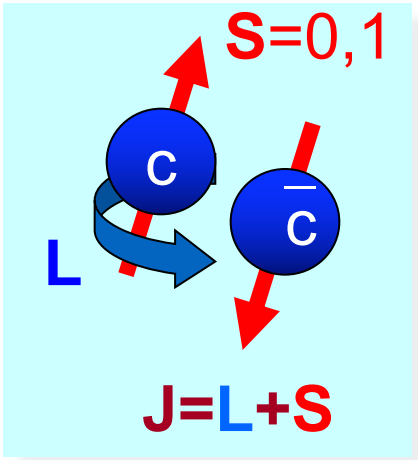
- Increase of beam energy 2.30→2.35(2018)→2.45 GeV(2020')
  - → 2.35 GeV in 2018 summer (done)
  - → 2.45 GeV in 2020 summer (done),
    change ISPB (Interaction region SePtum Bending) magnet
- Top-up injection (done)
  - Data taking efficiency increases by 20~30%

Now we are running at 2.37 GeV



Charmonium Spectrum

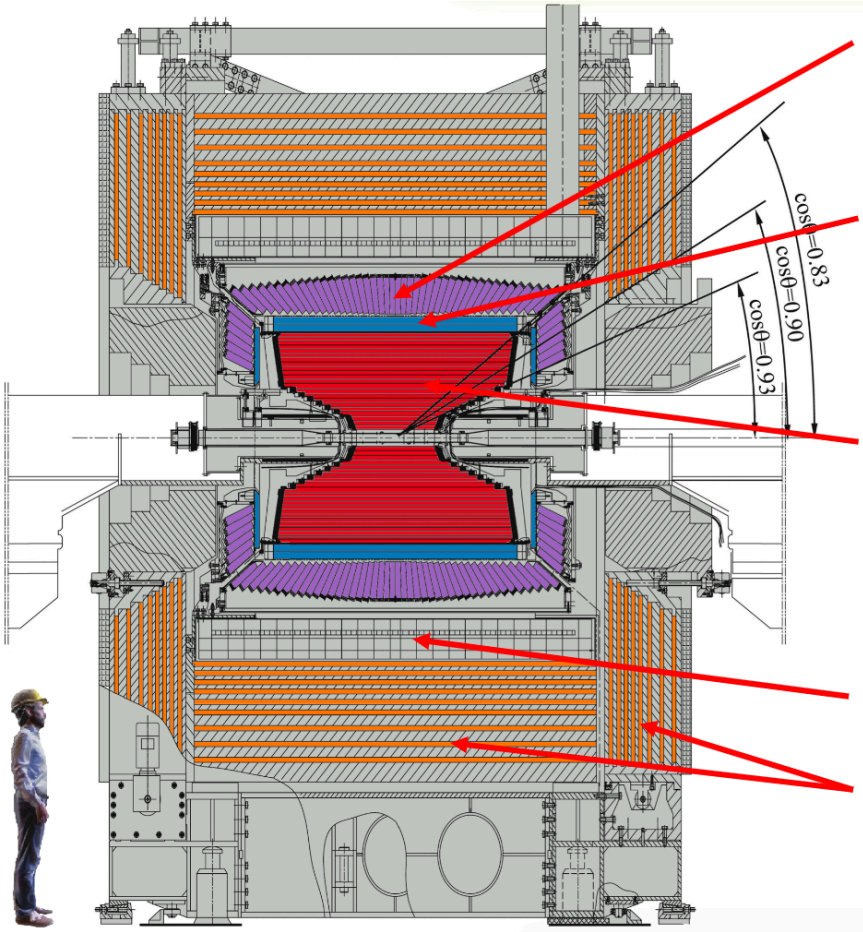




Overpopulated observed new charmonium-like states, i.e. "XYZ".

The BESIII detector

NIM A614, 345 (2010)



EMC: CsI crystals
$\Delta E/E$ = 2.5% @ 1 GeV - Barrel
$\Delta E/E$ = 5.0% @ 1 GeV - Endcaps

TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

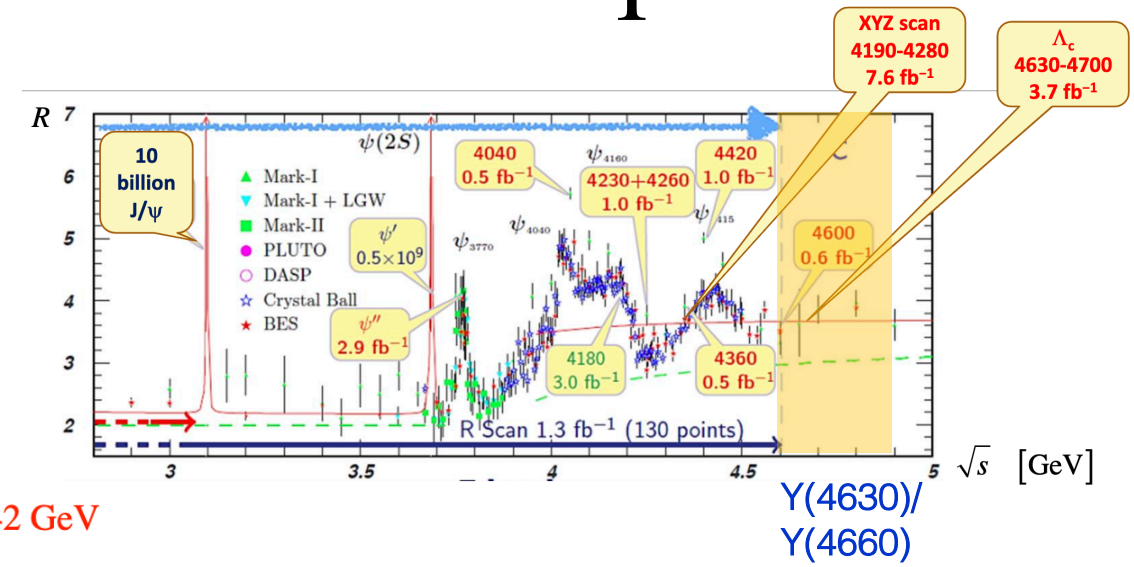
Muon ID: 9 layer RPC

Trigger: Tracks & Showers

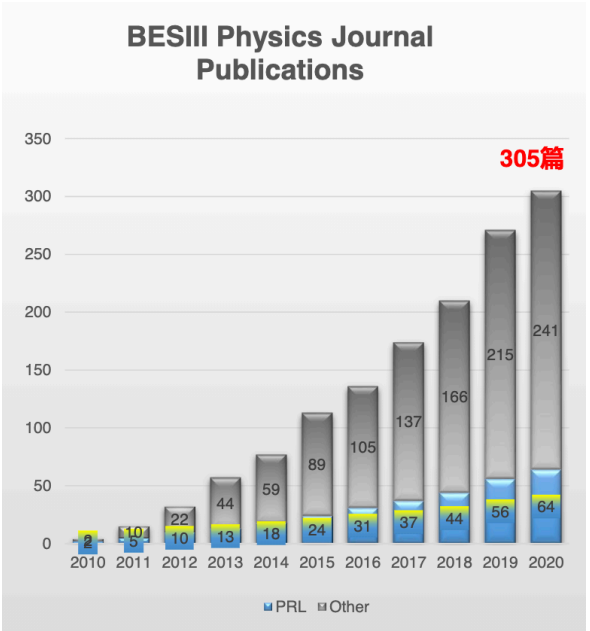
The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

BESIII data sample

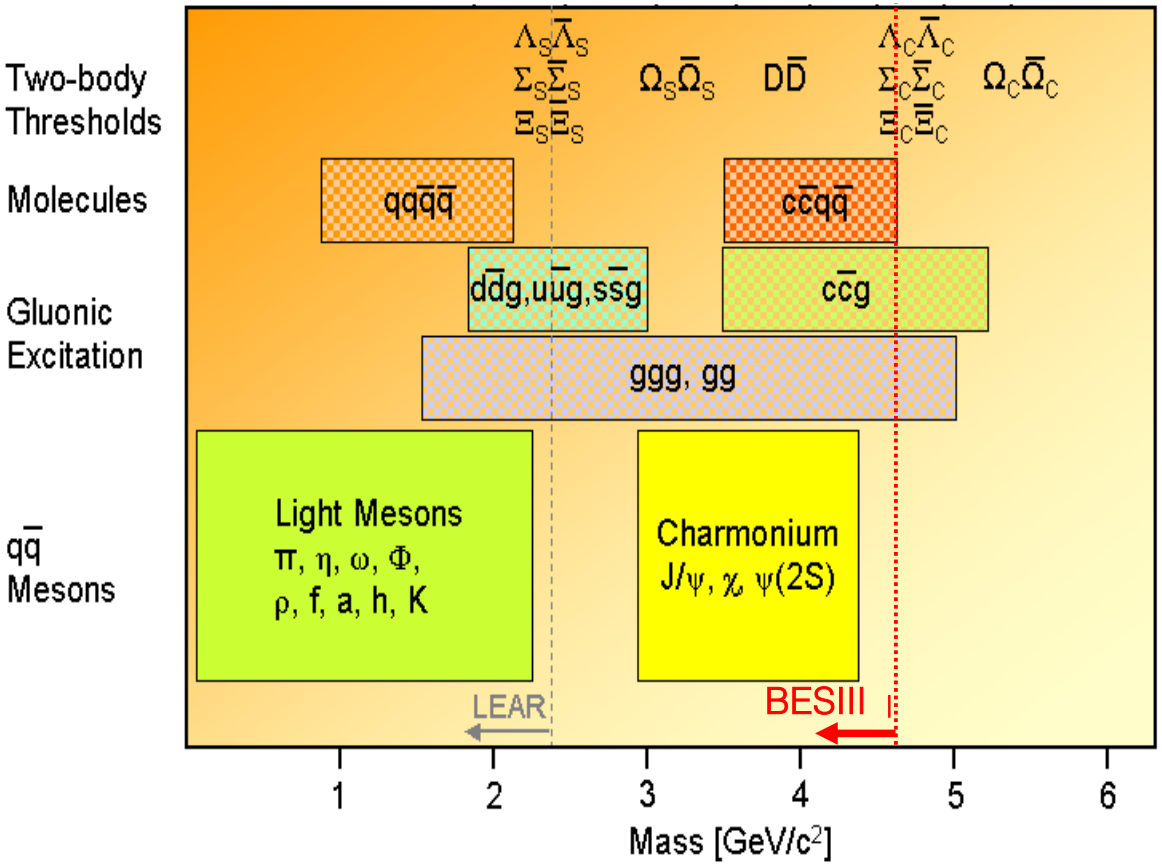
2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10 × 50 pb^{-1} scan 3.81 — 4.42 GeV
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 × 500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8 × 500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020: 5 × 500 pb^{-1} scan 4.63 — 4.70 GeV *(+ extra)*



Y(4630)/
Y(4660)



Hadron Landscape



Hadron-physics challenges:

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

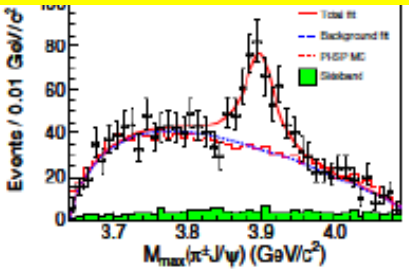
At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter)
- Heavy hadrons: direct production, radiative and hadronic transitions

The Zc Family at BESIII

$Zc(3900)^+$

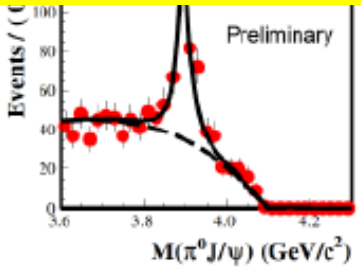
PRL 110, 252001 (2013)



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

$Zc(3900)^0$

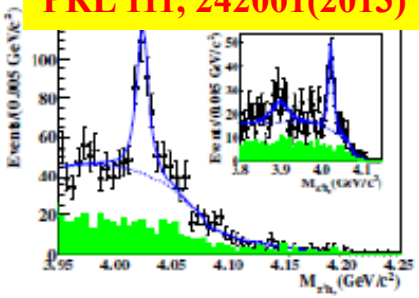
PRL 115, 112003 (2015)



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

$Zc(4020)^+$

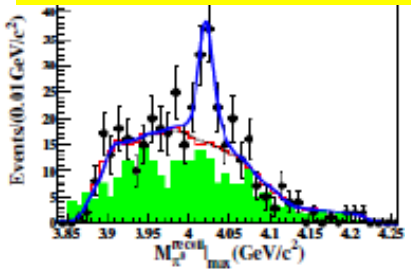
PRL 111, 242001(2013)



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

$Zc(4020)^0$

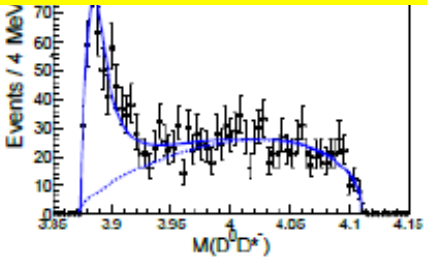
PRL113,212002 (2014)



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

$Zc(3885)^+$

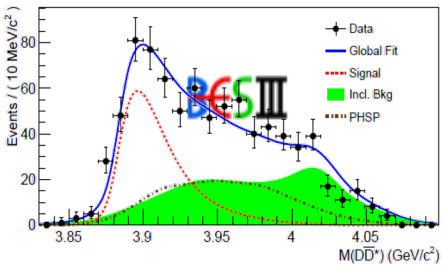
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

$Zc(3885)^0$

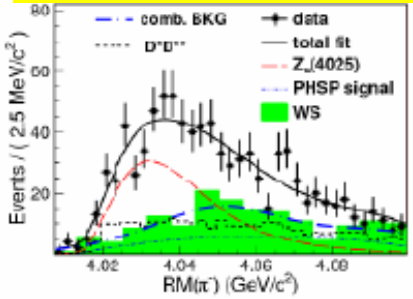
PRL 115, 222002 (2015)



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

$Zc(4025)^+$

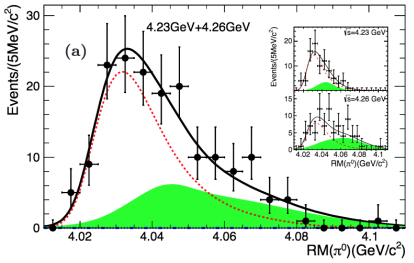
PRL 112, 132001 (2014)



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

$Zc(4025)^0$

PRL115, 182002 (2015)



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

Which is the nature of these states?

Different decay channels of the same observed states? Other decay modes?

SU(3) counter part Zcs (d ➔ s) ?

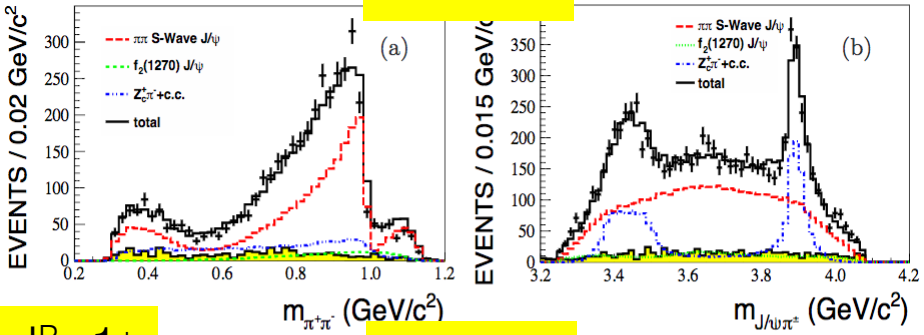
Spin-parity determination of the $Z_c^+(3900)$

- Zc line shape parameterized with Flatte-like formula

PRL 119.072001 (2017)

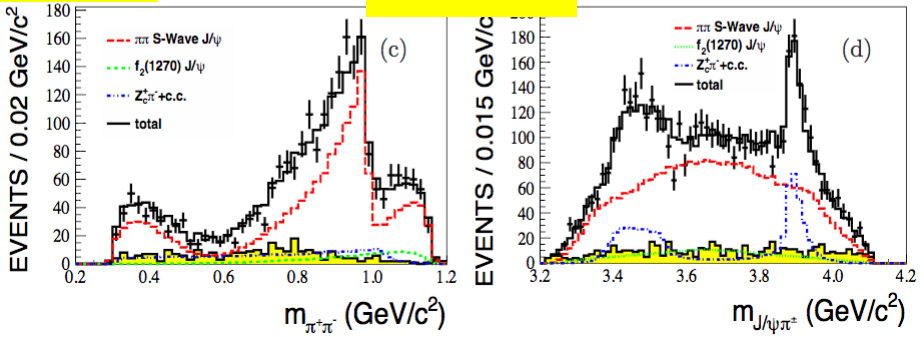
$$BW(s) = \frac{1}{s - M^2 + i(g_1' \rho_{\pi J/\psi}(s) + g_2' \rho_{D^* D}(s))},$$

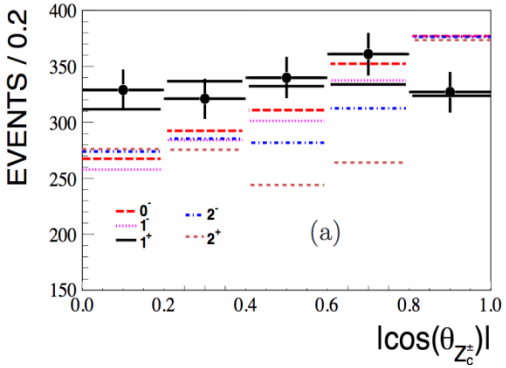
4.23GeV

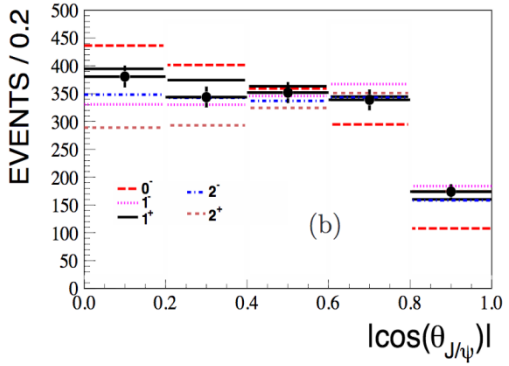


$J^P = 1^+$

4.26GeV







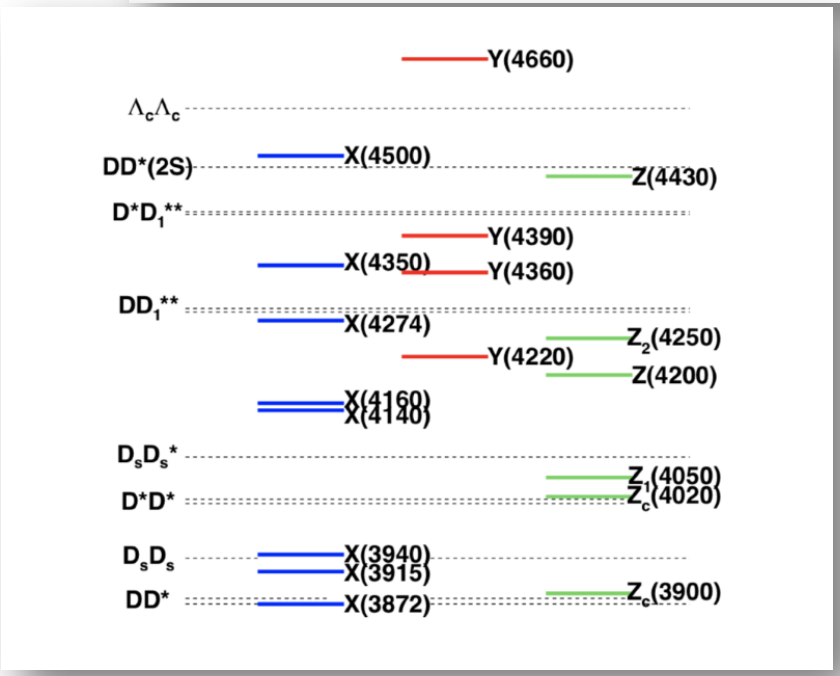
Hypothesis	$\Delta(-2\ln L)$	Δ(ndf)	Significance
1^+ over 0^-	94.0	13	7.6σ
1^+ over 1^-	158.3	13	10.8σ
1^+ over 2^-	151.9	13	10.5σ
1^+ over 2^+	96.0	13	7.7σ

J^P is measured to be 1^+ with significance larger than $7.6\boldsymbol{\sigma}$

Summary of the reported Zc states

from S. L. Olsen, arXiv:1511.01589, arXiv:1812.10947

$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [49], Belle [50]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [69]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [51]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [52]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [62]
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [54, 56, 57], LHCb [58]
				$B \to K + (J\psi\,\pi^+)$	Belle [62]

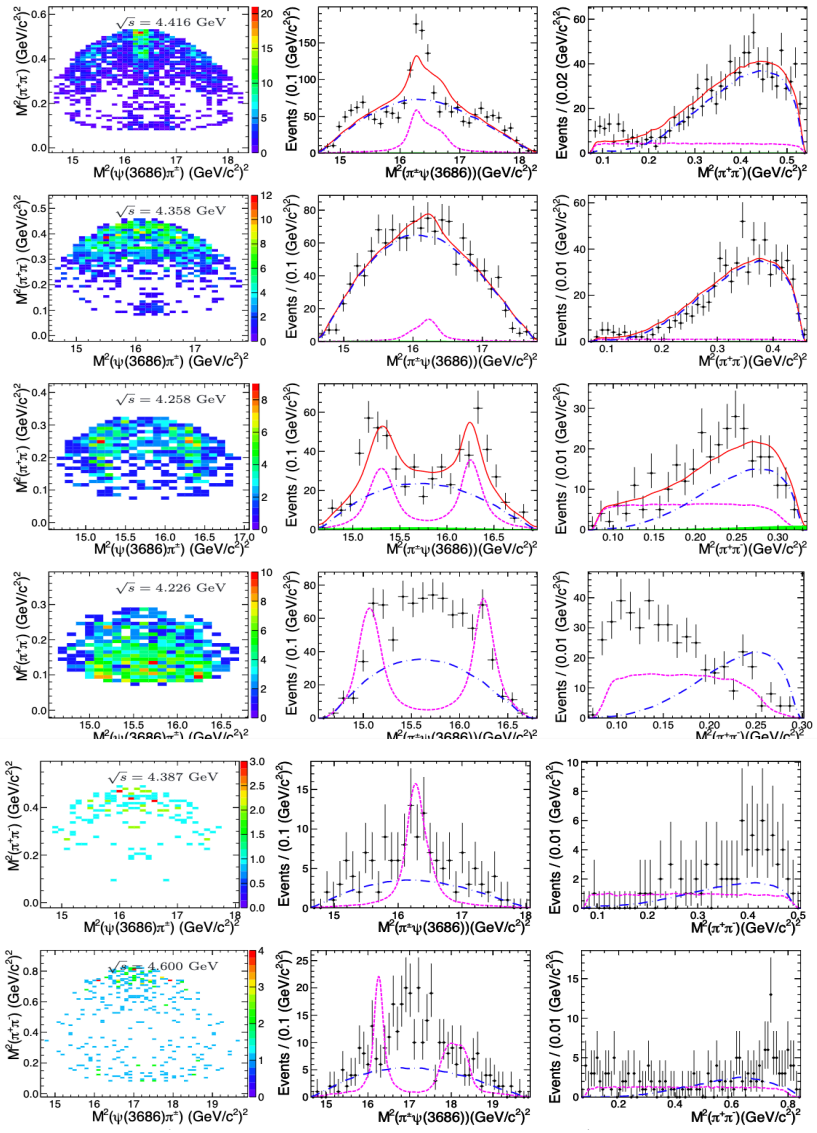


Most of them are close to the mass thresholds of charmed meson pairs

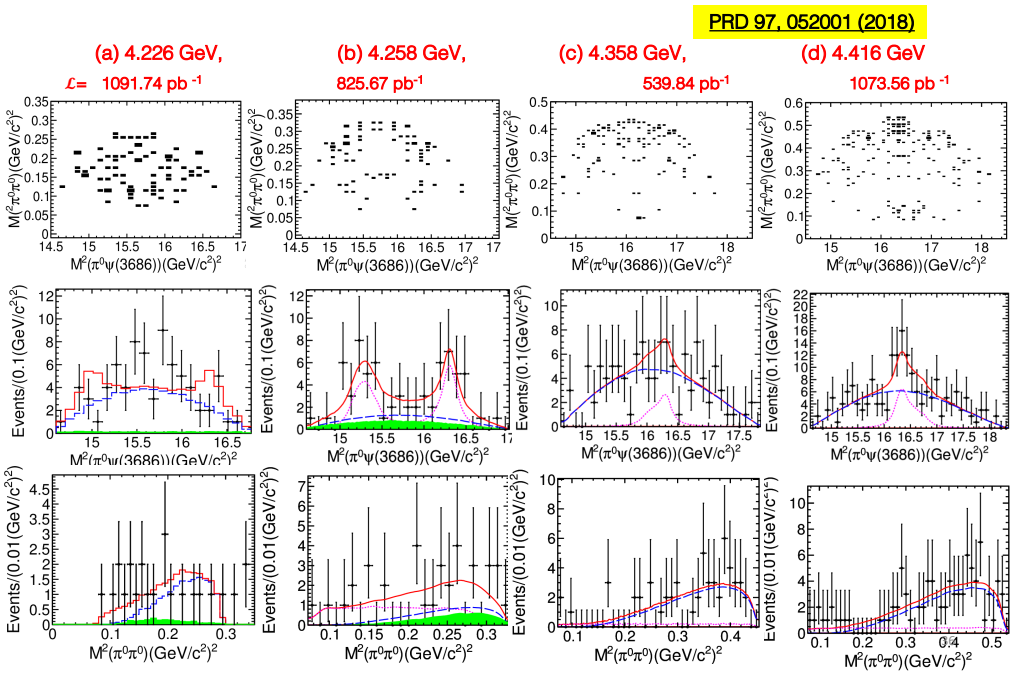
More efforts are needed to pin down their nature

Resonant structure of $\pi\psi(3686)$ in $e^+e^-\to\pi\pi\psi(3686)$

PRD 96, 032004 (2017)

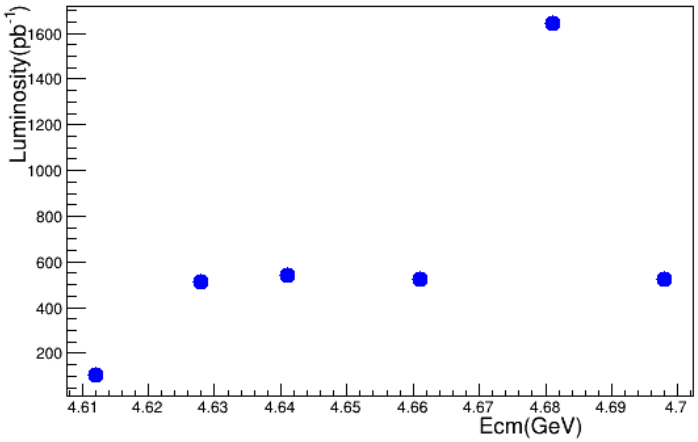


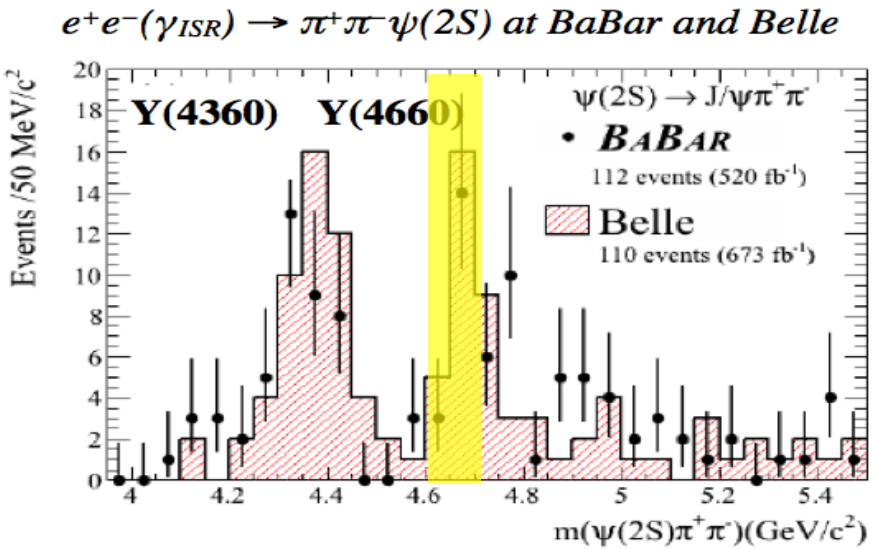
PRD 97, 052001 (2018)



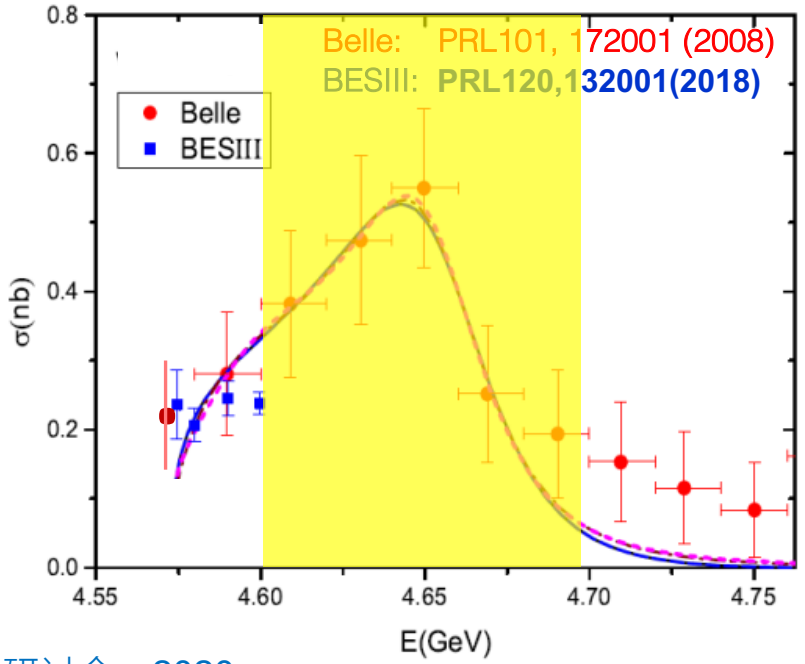
Data taking in 4.6-4.7 GeV in 2020

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





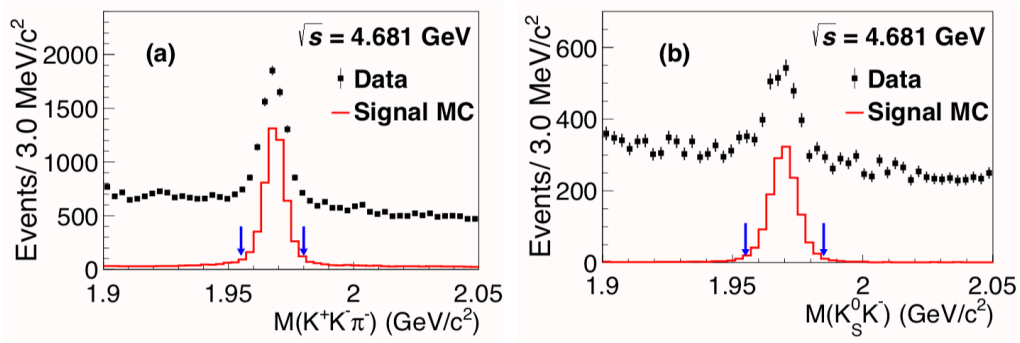
arXiv:1211.6271 and CHARM 2012

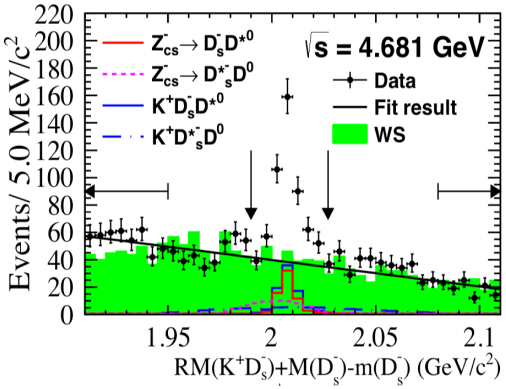


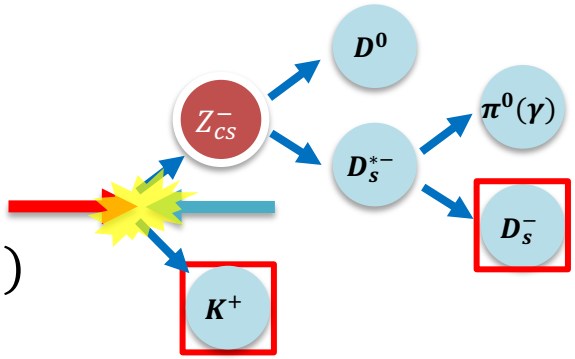
Observation of the $Z_{cs}(3985)^{\pm}$

arXiv: 2011.07855

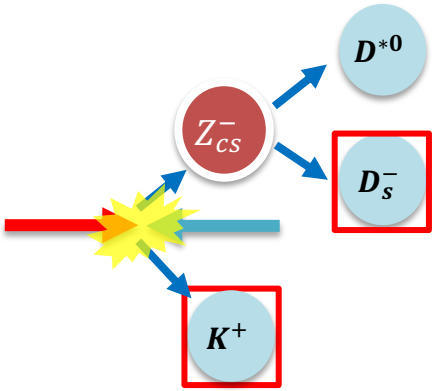
- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- **Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$







$e^+e^- \to K^+D_s^{*-}D^0$

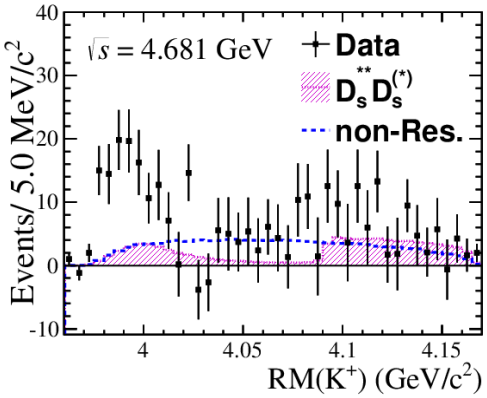


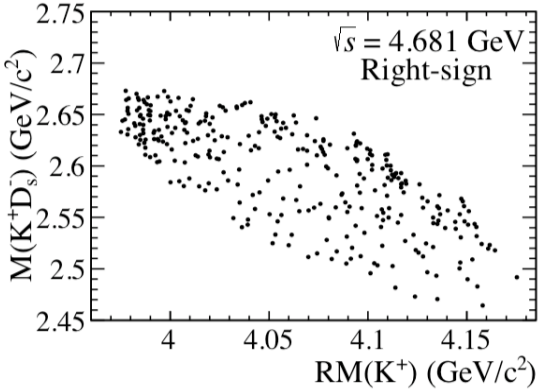
$e^+e^- \to K^+D_s^-D^{*0}$

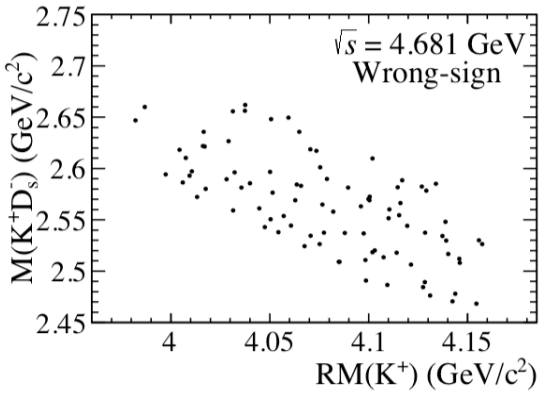
Observation of the $Z_{cs}(3985)^{\pm}$

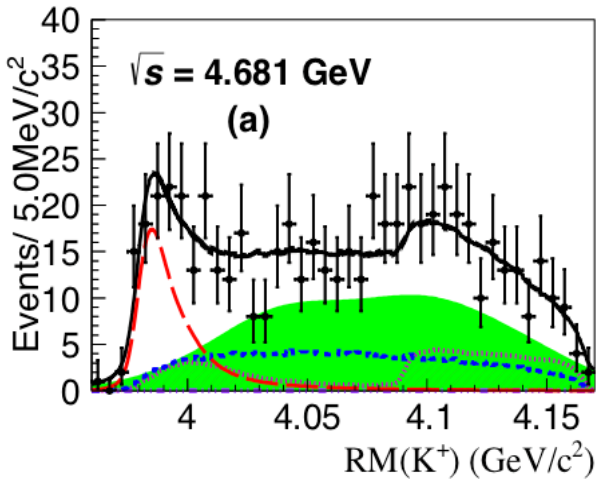
arXiv: 2011.07855

- 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/c² 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:

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

$$\boldsymbol{\Gamma} = 13.8^{+8.1}_{-5.2} \pm 4.9\ \mathrm{MeV}$$

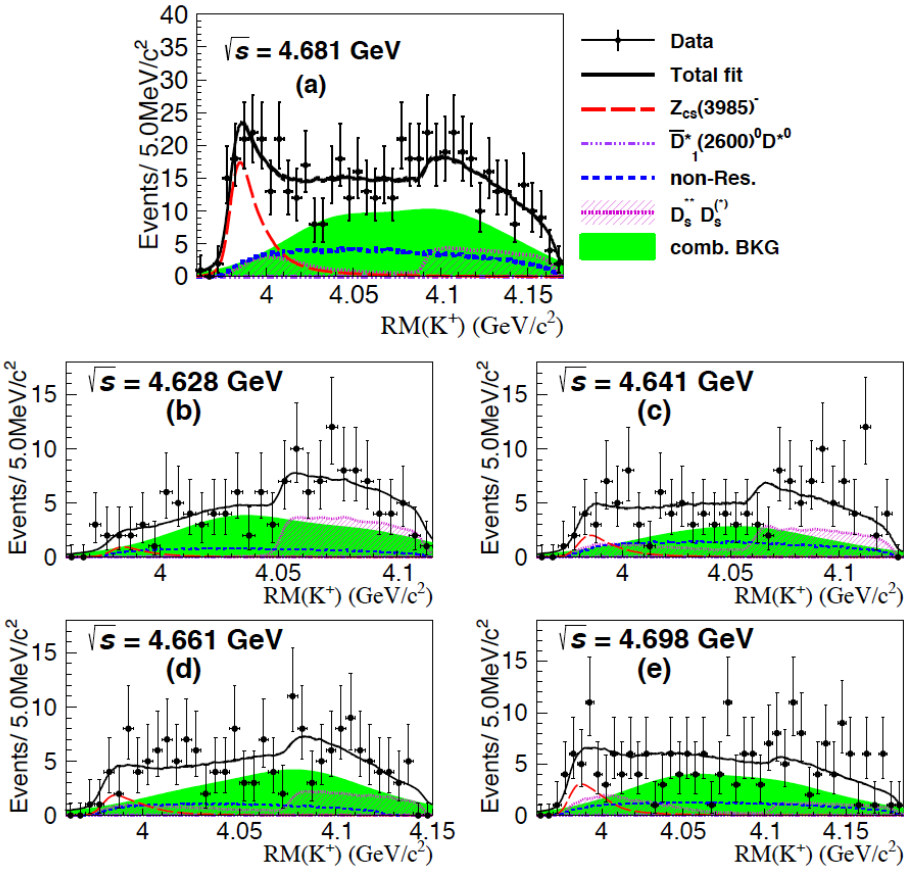
- Global significance: >5.3 $\boldsymbol{\sigma}$

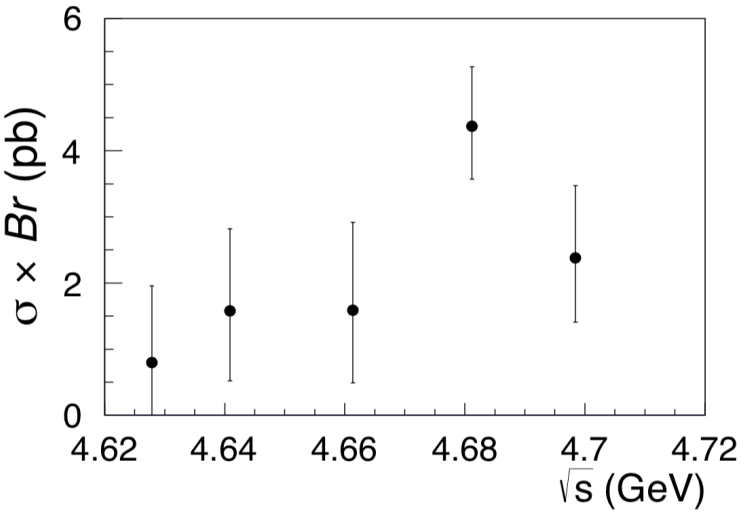
First candidate of the hidden-charm tetraquark with strangeness

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

arXiv: 2011.07855

- Simultaneous fit to the five energy points

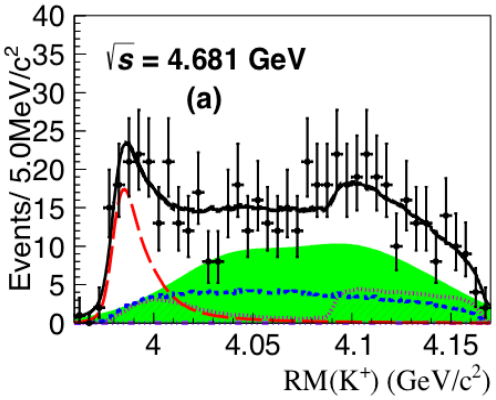


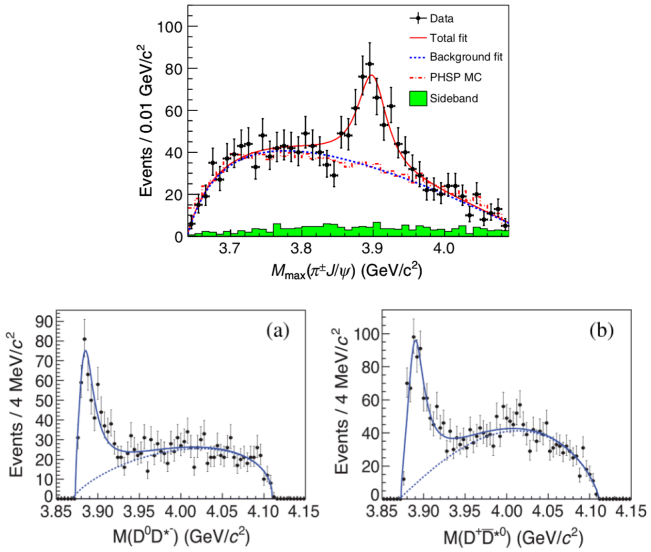


- Largest cross sections around 4.681 GeV

The Zcs (3985)$^{\pm}$ and Zc(3885)$^{\pm}$

	1643/pb data @4.681 GeV	525/pb data @4.26 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±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathcal{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0





two general comments about charm-tau factory program

- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism

from Marek Karliner

$Z_{cs}(3985)$

$K^- Z_{cs}^+$	$\bar{K}^0 Z_{cs}^0$	$K^0 \bar{Z}_{cs}^0$	$K^+ Z_{cs}^-$
1/4	1/4	1/4	1/4

neutral/charged = 1

$Z_c(3900)$

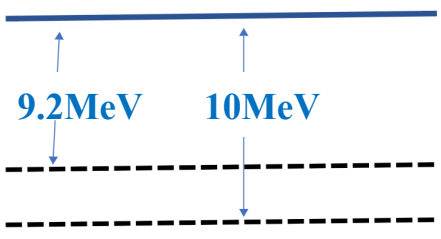
$\pi^- Z_c^+$	$\pi^0 Z_c^0$	$\pi^+ Z_c^-$
1/3	1/3	1/3

neutral/charged = 1/2

SU(3) partner of Zc(3900)?

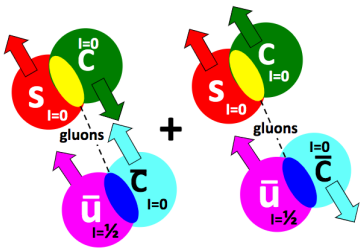
Interpretation on the nature of $Z_{cs}(3985)^{\pm}$

- 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

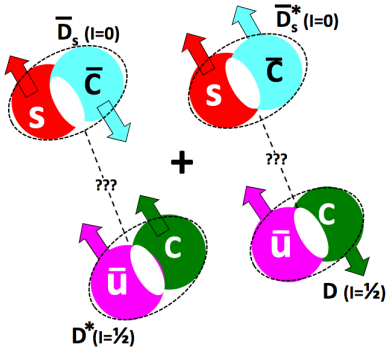


~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

diquark-antidiquark?



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



arXiv:2011.08501
arXiv:2011.08628
arXiv:2011.08656
arXiv:2011.08725
arXiv:2011.08747
arXiv:2011.09156
arXiv:2011.09225
arXiv:2011.09244
arXiv:2011.09404
arXiv:2011.10495
arXiv:2011.10922
arXiv:2011.10959
arXiv:2011.11488
arXiv:2011.12230
arXiv:2011.12326
arXiv: 2011.13013
arXiv: 2011.13425
arXiv: 2011.14313
arXiv: 2011.14517

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

PRD 100, 111102(R) (2019)

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

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

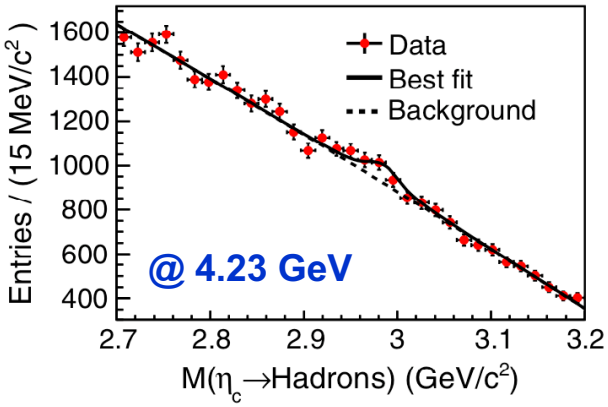
$$R_{z\prime} = \frac{B(Z_c' \to \rho\eta_c)}{B(Z_c' \to \pi h_c)}$$

Date sets:

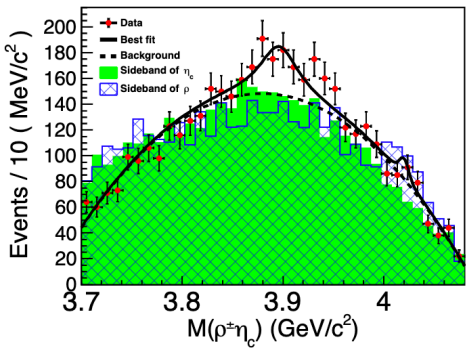
- ~4 fb^{-1} data set distributed at $\sqrt{s}$ = 4.23,4.26,4.36,4.40,4.60 GeV

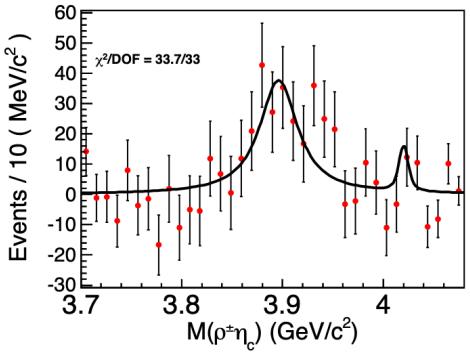
Strategy of this analysis:

- Start with looking for $e^+e^- \to \pi^+\pi^-\pi^0\eta_c, \eta_c \to 9$ hadronic decays



- Strong evidence of $e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c$ is observed at $\sqrt{s} = 4.23$, statistical significance is 4.3σ. (3.9σ including systematics)
- $e^+e^- \to \pi Z_c', Z_c' \to \rho\eta_c$ is not seen in all data sets.





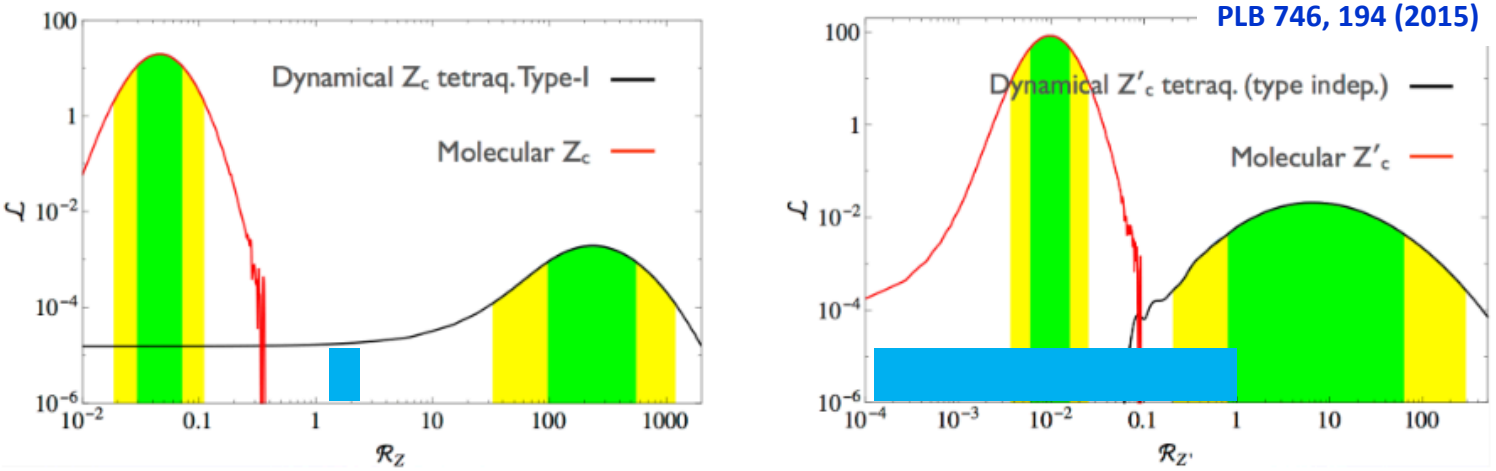
@ 4.23 GeV

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

PRD 100, 111102(R) (2019)

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

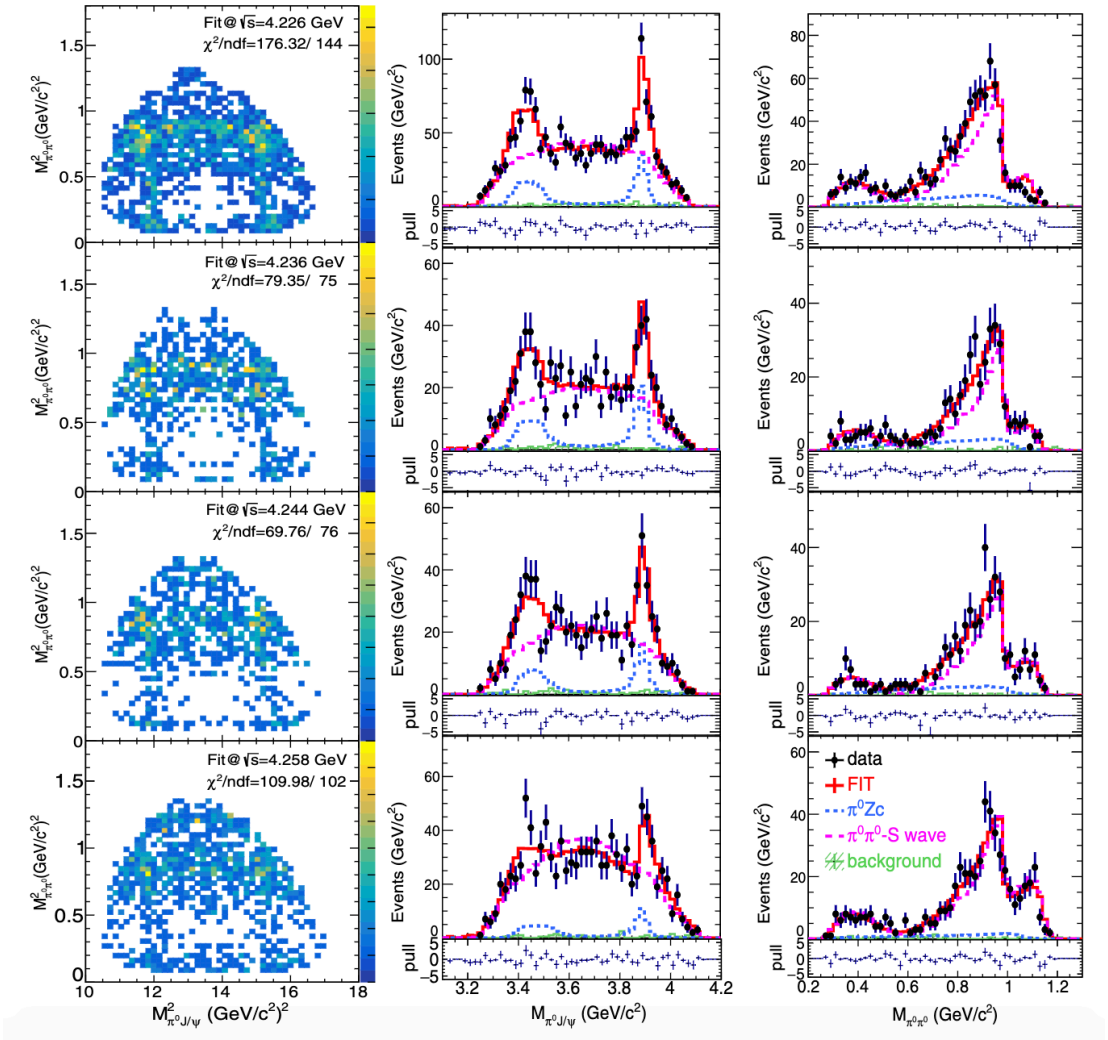
PLB 746, 194 (2015)



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

PWA of the $Z_c(3900)^0$

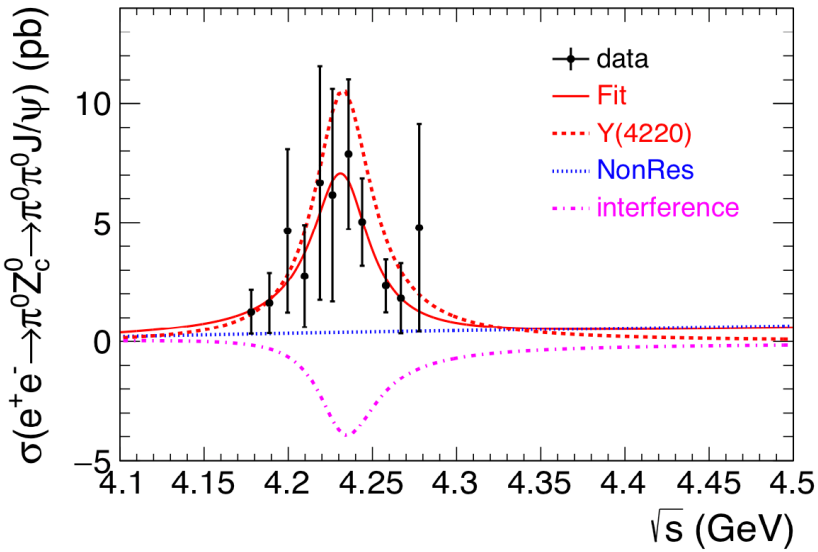
PRD 102, 012009 (2020)



- Simultaneous PWA fit of $e^+e^-\to\pi^0\pi^0 J/\psi$ 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 π^0 $Z_c(3900)^0$.
- Mass and width of $Z_c(3900)^0$ is measured:
  - $M(Z_c(3900)^0) = (3893.0\pm2.3\pm19.9)$ MeV/c^2,
  - $\Gamma(Z_c(3900)^0) = (44.2\pm5.4\pm9.1)$ MeV.

Cross section of $e^+e^- \to \pi^0 Z_c(3900)^0$

PRD 102, 012009 (2020)



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

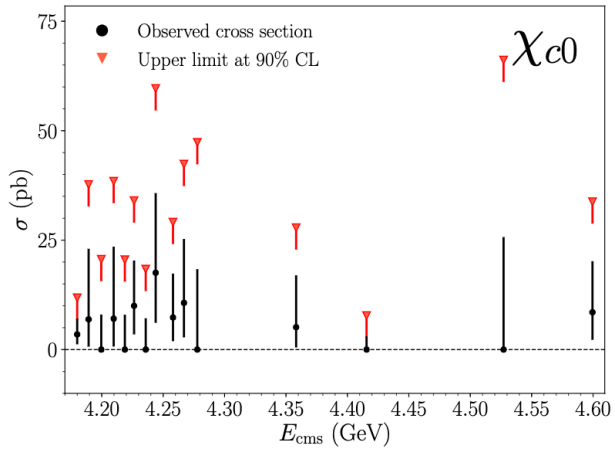
- $Zc(3900)^0$ resonance parameters are fixed to the results of the previous four-energy-point fit
- The Born cross section of $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\ \pi^0 J/\psi$ is extracted.
- Clear structure around 4.2 GeV is observed
  - $M = (4231.9 \pm 5.3 \pm 4.9)\ \mathrm{MeV}/c^2$,
  - $\Gamma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

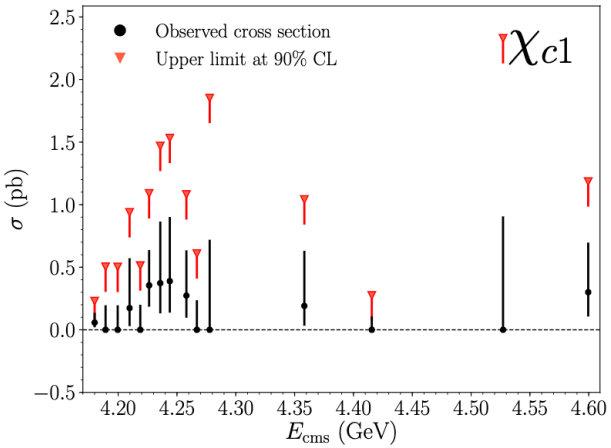
Search for $Z_c^+ \to \pi^+ \chi_{cJ}$

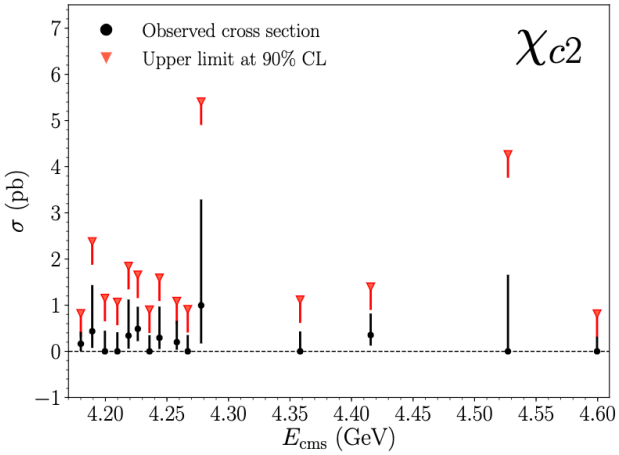
arXiv: 2012.02682

- Belle reported the results of $Z_c\ (4050)^+$ and $Z_c\ (4250)^+$ in $\bar{B}^0 \to K^- Z_c^+, Z_c^+ \to \pi^+ \chi_{c1}$, while BaBar did not confirm them
- BESIII studies $e^+e^- \to \pi^+\pi^- \chi_{cJ}, \chi_{cJ} \to \gamma J/\psi$ from 4.178 GeV to 4.600 GeV
- None of the processes are observed and upper limits of the production cross sections are determined
- Hence, they can be the upper limits of the product cross sections of

$$e^+e^- \to \pi^- Z_c\ (4050)^+ + c.c., Z_c\ (4050)^+ \to \pi^+ \chi_{cJ}$$





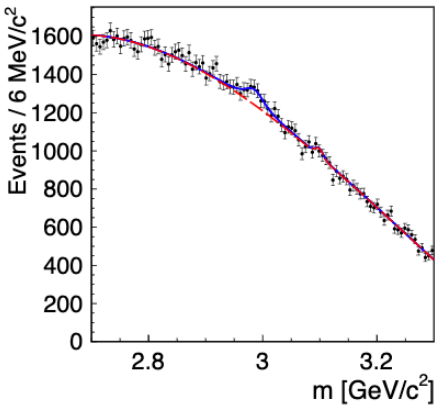


Search for $Z_c \to \pi \ \eta_c$

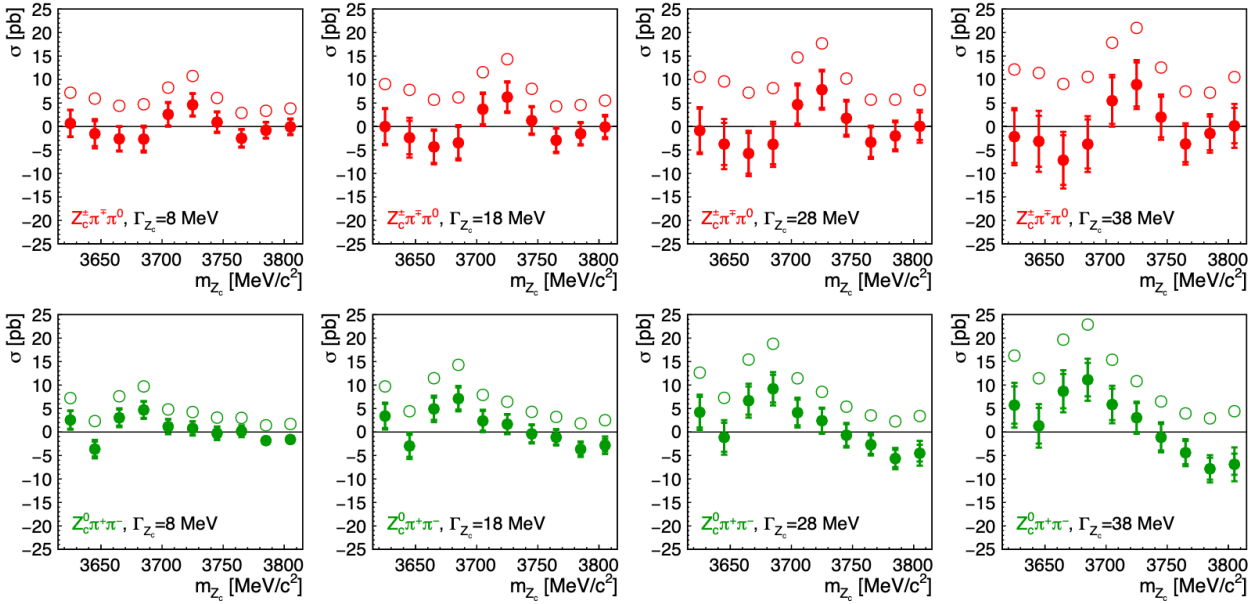
arXiv:2010.14415

- LHCb reported an evidence of $Z_c^+(4100) \to \pi^+\eta_c$ in $\bar{B}^0 \to K^- Z_c^+(4100)$ *LHCb, EPJ C78, 1019 (2018)*
- Studies of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c, \pi^+\pi^-\eta_c, \gamma\pi^+\pi^-\eta_c$ at 6 energy points from 4.178 to 4.600 GeV
- 16 hadronic η_c channels are reconstructed
- Only evidence of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ @ 4.226 GeV (4.1σ)
- Different mass and width assumptions in the vicinity of $D\bar{D}$ mass are tested for $Z_c^+ \to \pi^+\eta_c$ and $Z_c^0 \to \pi^0\eta_c$ in $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ at 4.226 GeV and found to be not significant

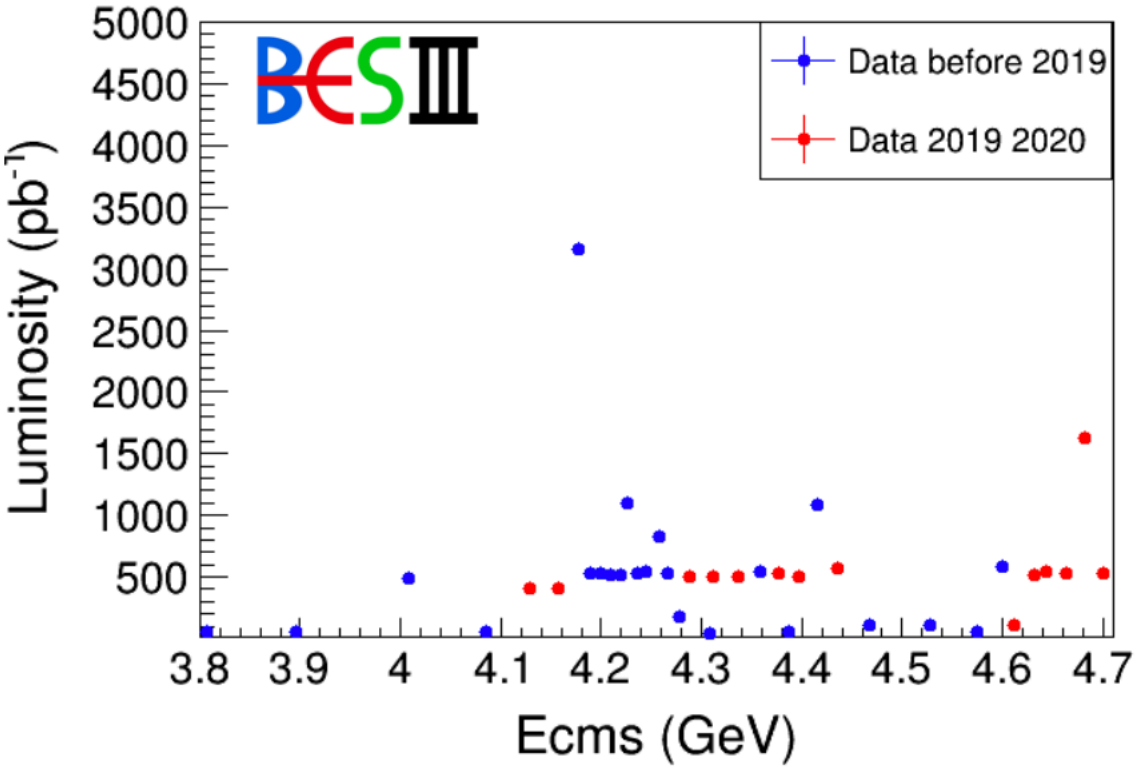
$Z_c(4100)^-$
$M = 4096 \pm 20^{+18}_{-22}$ MeV
$\Gamma = 152 \pm 58^{+60}_{-35}$ MeV
$J^P = 0^+/1^-$



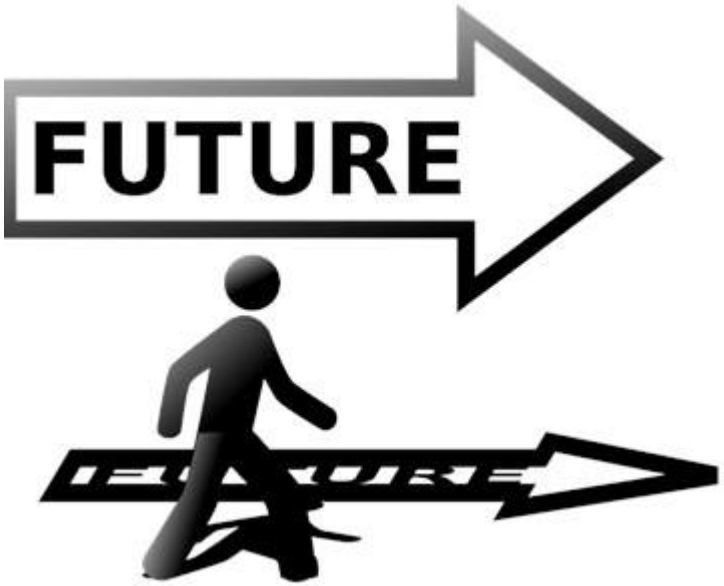
4.226 GeV



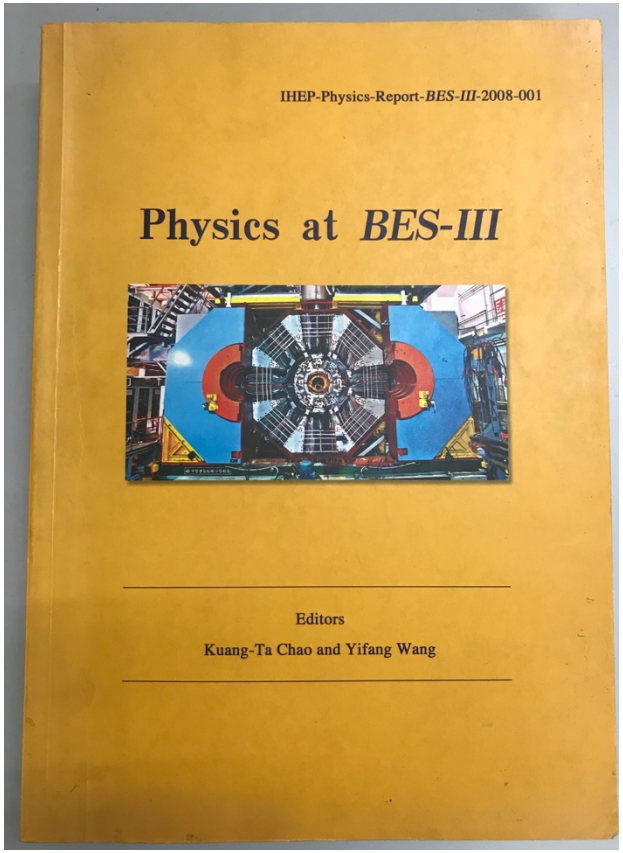
More XYZ data set to be analyzed



- Global descriptions of the Zc states at different energy points in the same mode
  - ✓ $\pi J/\psi, \pi\psi(3686), \pi h_c, D^*D^{(*)}, \ \ldots$
- Couple channel analyses of the above modes
- Synergies with LHCb


FUTURE

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

Received 25 December 2019, Published online 26 March 2020

* Supported in part by National Key Basic Research Program of China (2015CB856700); National Natural Science Foundation of China (NSFC) (11335008, 11425524, 11625523, 11635010, 11735014, 11822506, 11935018); the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS (U1532257, U1532258, U1732263); CAS Key Research Program of Frontier Science (QYZDJ-SSW-SLH003, QYZDJ-SSW-SLH040); 100 Talents Program of CAS; CAS PIFI; the Thousand Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts Nos. Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) (530-4CDP03); Ministry of Development of Turkey (DPT2006K-120470); National Science and Technology fund; The Knut and Alice Wallenberg Foundation (Sweden) (2016.0157); The Swedish Research Council; U. S. Department of Energy (DE-FG02-05ER41374, DESC-0010118, DE-SC-0012069); University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; the Russian Ministry of Science and Higher Education (14.W03.31.0026)

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

Planned future data set

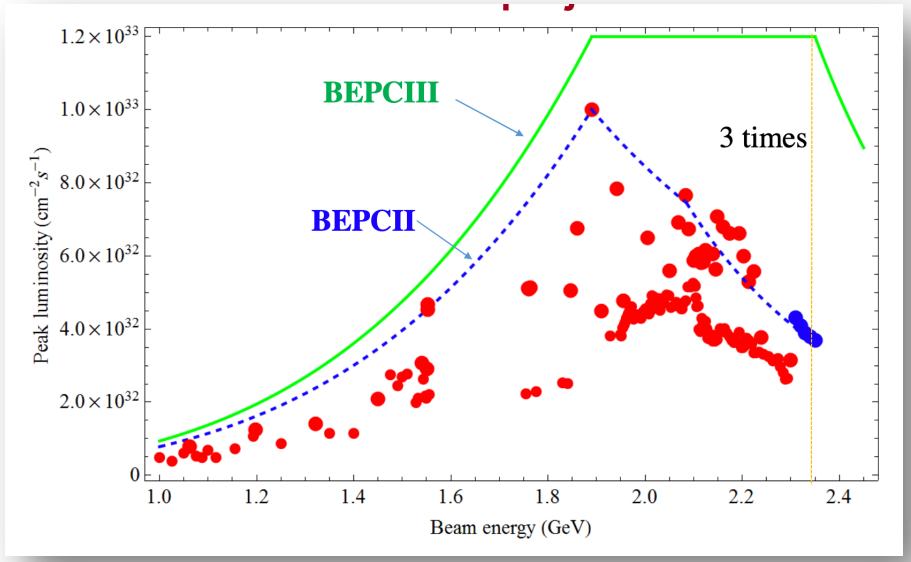
Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation 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	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ 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

Proposal of the BEPCIII

- Following up with the beam energy and top-up upgrade, we are planning the next generation of BEPCIII (200 million CNY), to be implemented around 2022: the optimized energy is 2.35 GeV with luminosity 3 times higher than BEPCII.

	BEPCII	BEPCIII
Lum. [10^{33}cm^{-2}s^{-1}] @2.35GeV	**0.35**	**1.2**
β_y^* [cm]	**1.5**	**1.35**
Bunch current	7.1 mA	7.5 mA
Bunch number	56	120
SR Power [kW]	**110**	**250**
$\xi_{y,\mathrm{lum}}$	**0.029**	**0.039**
Emittance [nmrad]	**138**	**120**
Coupling [%]	**0.53**	**0.40**
Bucket Height	0.0069	0.091
$\sigma_{z,0}$ [cm]	1.54	1.24
σ_z [cm]	**1.69**	**1.39**
RF voltage	**1.6MV**	**3.5MV**



Major modification
- RF region
- Vacuum chamber
- Beam parameters

Joint efforts among experiments and theories

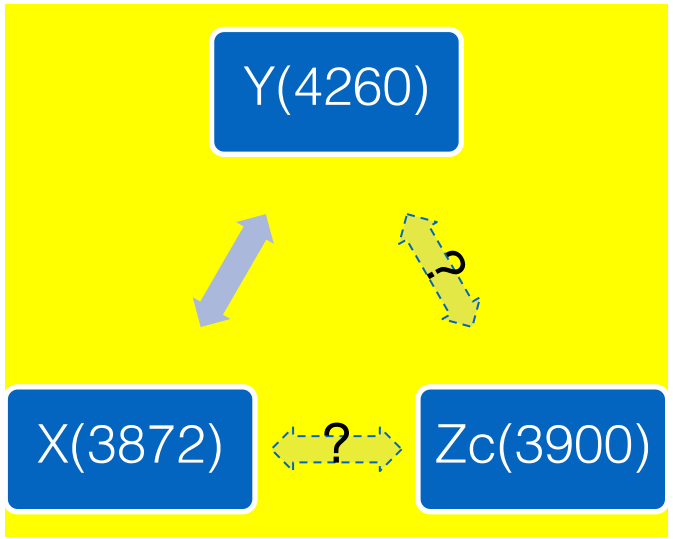
- It is crucial that different experiments, such as LHCb, BESIII and Belle II, exchange information in the efforts of amplitude analyses
  - ✓ Sharing the knowledge on analysis tools
    eg, **TF-PWA** (talks given inside BESIII and LHCb) https://github.com/jiangyi15/tf-pwa
  - ✓ Constraints on properties 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
$Z_c(3900)^{\pm,0}$	$\pi^{\mp}J/\psi$, $(D^*\bar{D})^{\mp}$	BESIII, Belle CLEO
$Z_c(4020)^{\pm,0}$	$\pi^{\mp}h_c$, $(D^*\bar{D}^*)^{\mp}$	BESIII
$Z_c(4430)^{\pm}$	$\pi^{\mp}\psi(2S)$ $\pi^{\pm}J/\psi$	Belle, ~~BaBar,~~ LHCb

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

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

in $B \to KZc$



- Energy-dependence
- Patterns in productions and decays

Pole properties

World-wide experimental efforts

Models

LQCD

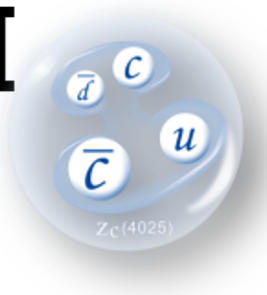
Summary

- BESIII is continuously producing many new results on tetraquark states
  - observation of Zcs(3985) as the first candidate of hidden-charm tetraquark with-strangeness
- Improved understanding of the previous reported Zc states
- Continuously, more data set will be recorded and new analyses will be publicized …
- The future BEPCIII with 3x luminosity upgrade enables BESIII to study the tetraquark states with better precisions

Thank you!

谢谢!

The Zc Family at BESIII



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

Determiend properties of the $Z_c^+(3900)$

PRL 119.072001 (2017)

- If Z_c is parameterized with a Flatte-like formula

  $M_{\text{pole}} = 3881.2 \pm 4.2 \pm 52.7$ MeV, $\Gamma_{\text{pole}} = 51.8 \pm 4.6 \pm 36.0$ MeV

  $g_1' = 0.075 \pm 0.006 \pm 0.025 \text{GeV}^2$

  $g_2'/g_1' = 27.1 \pm 2.0 \pm 1.9$

  (consistent with the previous published results)

- Born cross section for $e^+e^- \to Z_c^+\pi^- + c.c. \to \pi^+\pi^- J/\psi$

  $21.8 \pm 1.0 \pm 4.4$ pb at 4.23 GeV

  $11.0 \pm 1.2 \pm 5.4$ pb at 4.26 GeV

- Search for $e^+e^- \to Z_c^+(4020)\pi^- + c.c. \to \pi^+\pi^- J/\psi$ gives upper limits at 90% C.L.:

  <0.9 pb at 4.23 GeV; <1.4 pb at 4.26 GeV

then $\dfrac{\sigma(e^+e^- \to Z_c^+(4020)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to Z_c^+(3900)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)} < 4\%$ at 4.23 GeV

$<13\%$ at 4.26 GeV

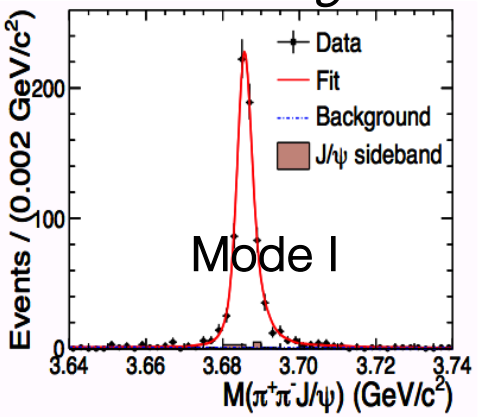
Further couple channel amplitude analysis is on-going on more energy points.

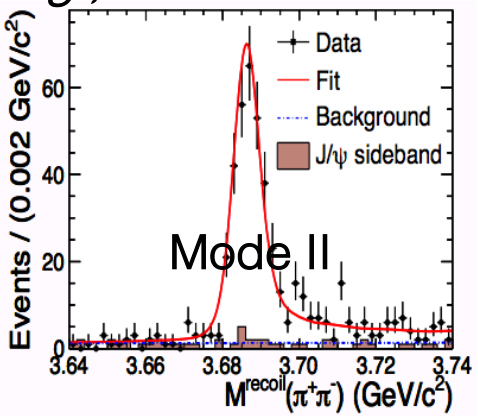
Study of $e^+e^- \to \pi^+\pi^-\psi(2S)$

PRD 96, 032004 (2017)

- **Data samples:**
  - 16 energy points from $\sqrt{s}$=4.008 to 4.600 GeV.
  - The total integrated luminosity (L_{int}) is 5.1 fb^{-1}.
- **Reconstructed modes:**
  - **Mode I:** $\Psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ (l=e/μ)
  - **Mode II:** $\Psi(3686) \to$ *neutrals*$+J/\psi$, *neutrals*$=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi \to l^+l^-$ (l=e/μ)

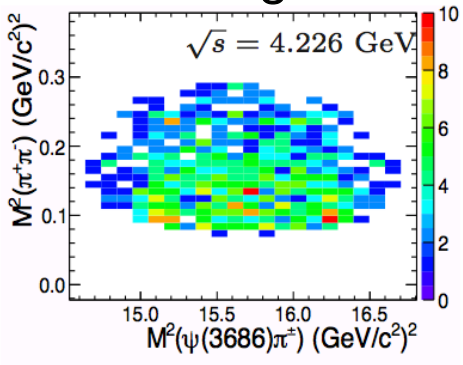
Clean signals at e.g., 4.416 GeV

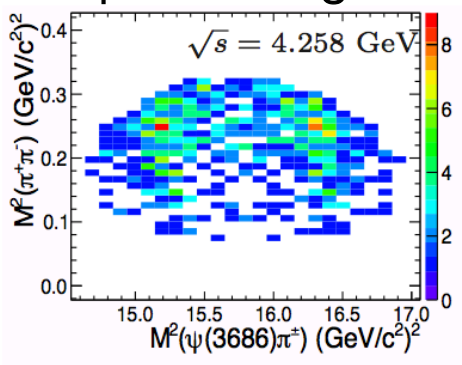


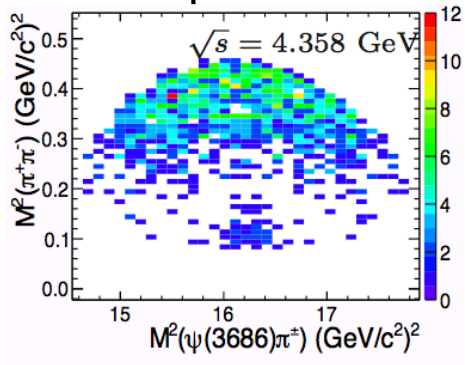


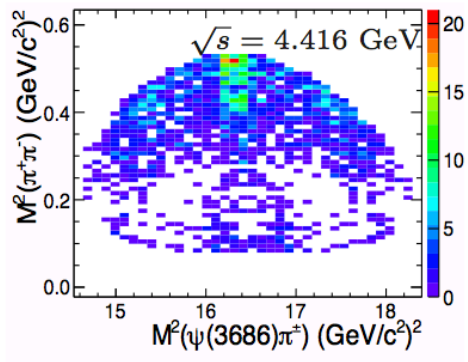
Cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$ has been measured at 16 energy points from 4.008 to 4.600 GeV, consistent with the reported line shape. (see Zhiyong's talk)

Looking at the Dalitz plots in large data set ➔ quite different behaviors









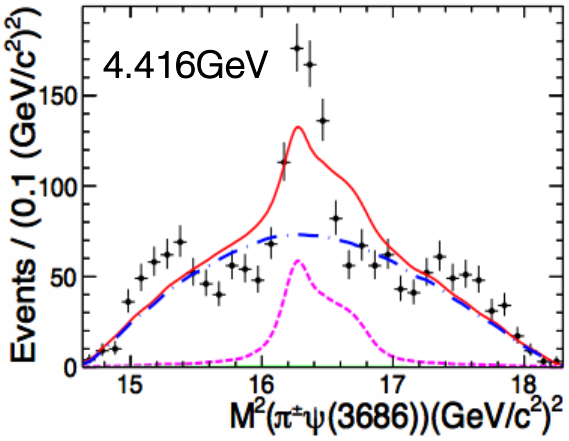
Resonant structure of $\pi^+\psi(3686)$ in $e^+e^-\to\pi^+\pi^-\psi(3686)$ at 4.416GeV

PRD 96, 032004 (2017)

- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$

$$\frac{p\cdot q/c^2}{(M_R^2-x)^2+M_R^2\cdot\Gamma^2/c^4}+\frac{p\cdot q/c^2}{(M_R^2-y)+M_R^2\cdot\Gamma^2/c^4}$$

- The fit yields a mass of M=4032.1±2.4 MeV/c^2 and a width of Γ=26.1±5.3 MeV, with a significance of 9.2σ

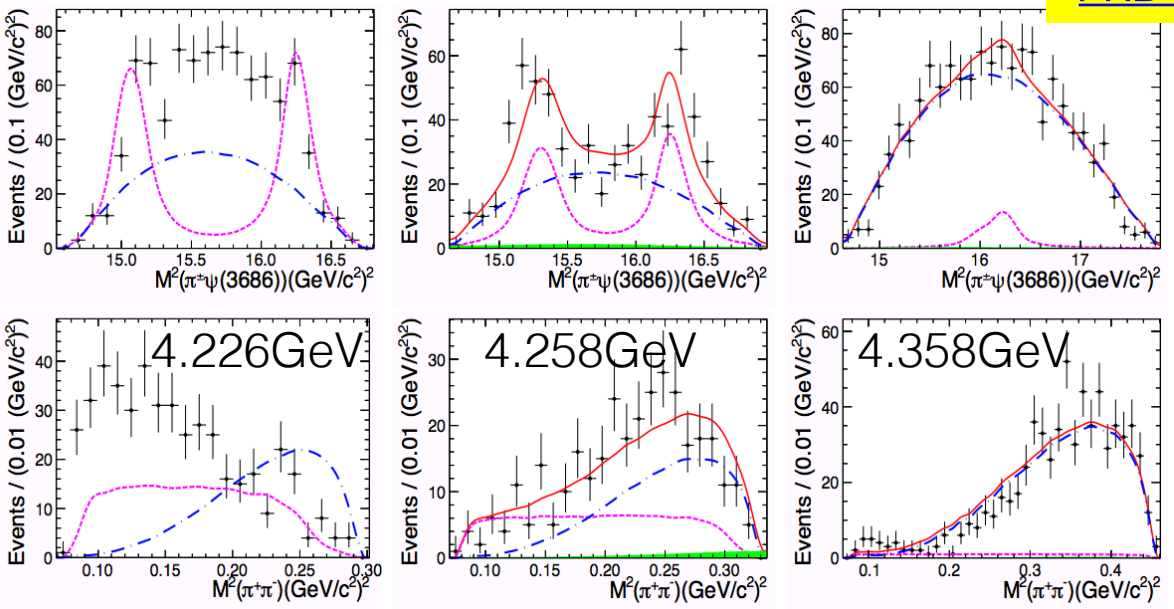


- *Quality of simple fit is not good*
- *A sophisticated amplitude analysis is carrying out*

Check on the resonance structures at other energy points

- Similar fits are carried out to data at $\sqrt{s}$ =4.258 and 4.358 GeV.
- No fit is applied at $\sqrt{s}$ =4.226 GeV due to its different behavior on the Dalitz plot and anomalous spectrum in $M^2(\pi^+\pi^-)$.

PRD 96, 032004 (2017)



- In the fits to data of 4.258 and 4.358 GeV, the $\pi^+\psi(3686)$ resonance parameters are fixed to that at 4.416 GeV. The resonances are confirmed with stat. significances of 9.6 σ and 3.6 σ at 4.258 and 4.358 GeV, respectively.
- At 4.226 GeV, the resonance structures are close to the kinematic boundary

Study of $e^+e^- \to \pi^0\pi^0\psi(3686)$

PRD 97, 052001 (2018)

Decay channel:

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

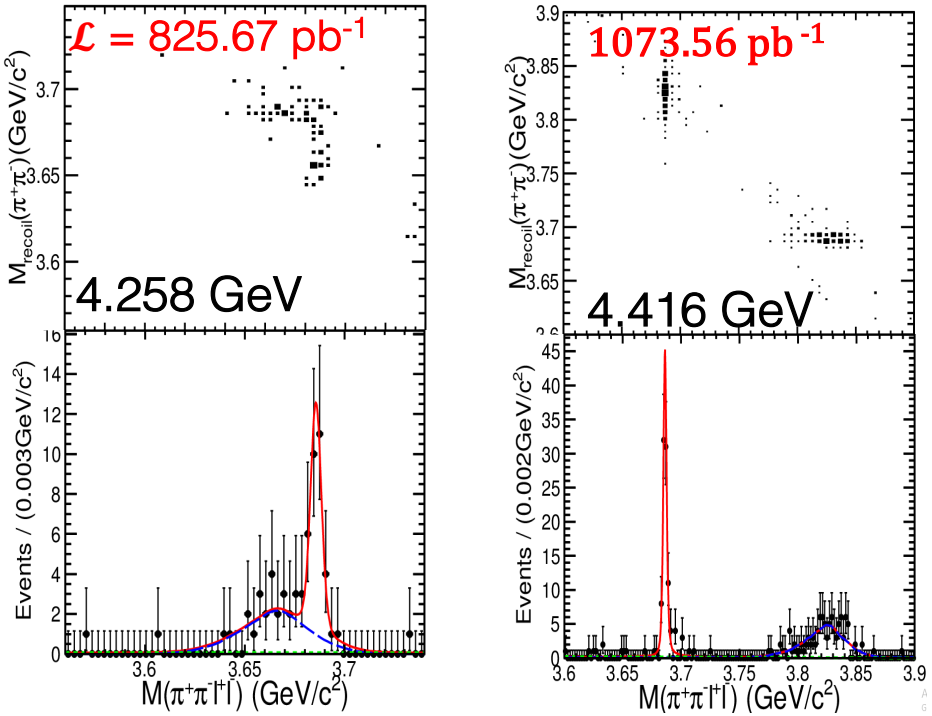
$\psi(3686) \to \pi^+\pi^-\mathrm{J}/\psi$, $\mathrm{J}/\psi \to l^+l^-(l = e/\mu)$.

Data sample

- 16 energy point from $\sqrt{s}$ =4.008 to 4.600 GeV.
- The total luminosity($\mathcal{L}$): 5.2 fb^{-1}.

Clear Signals in data

Broad bumps are from backgrounds of the charged mode $e^+e^- \to \pi^+\pi^-\psi(2S)$



Exploration of the intermediate structure

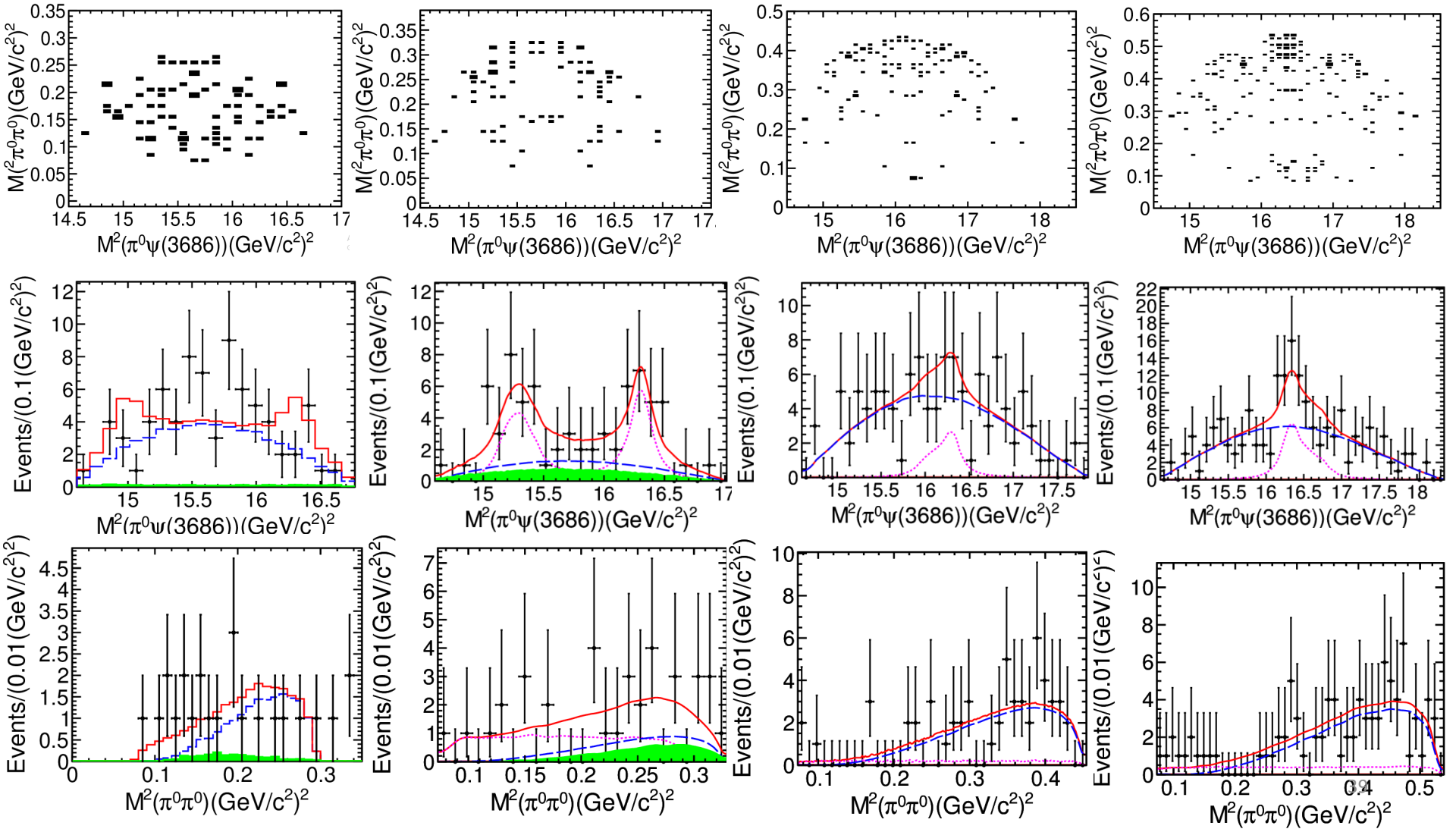
PRD 97, 052001 (2018)

(a) 4.226 GeV, $\mathcal{L}$= 1091.74 pb^{-1}

(b) 4.258 GeV, 825.67 pb^{-1}

(c) 4.358 GeV, 539.84 pb^{-1}

(d) 4.416 GeV 1073.56 pb^{-1}



Simple fits to the $\pi^0\psi(3686)$ resonance

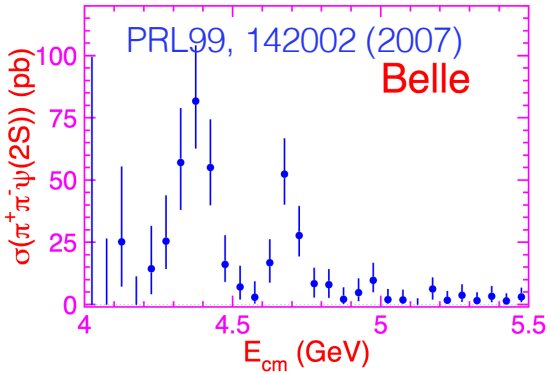
PRD 97, 052001 (2018)

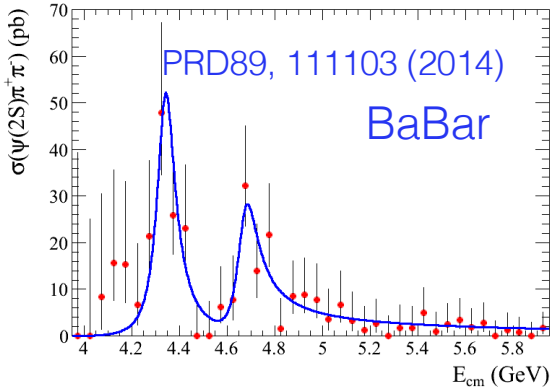
- A possible intermediate state is also observed in the $\pi^0\psi(3686)$ spectrum at 4.416 GeV.
- A 2D fit with a fixed width to charged structure observed in e^+e^- → $\pi^+\pi^-\psi(3686)$ is performed on the Dalitz distribution of $M^2(\pi_1^0\psi(3686))$ vs $M^2\left(\pi_2^0\psi(3686)\right)$.

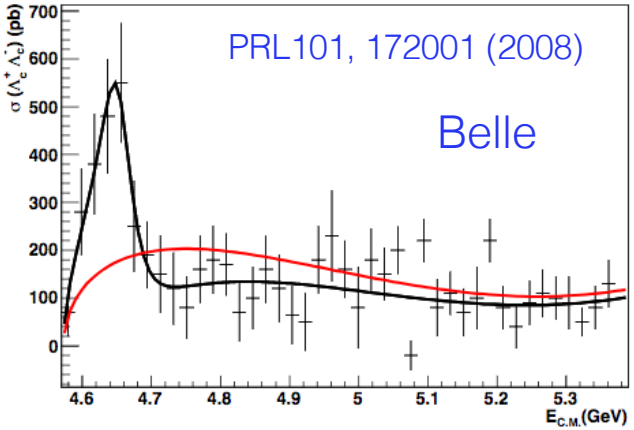
$$\frac{p_1 \cdot q_1/c^2}{(x - M_R^2)^2 + M_R^2 \cdot \Gamma^2/c^4} + \frac{p_2 \cdot q_2/c^2}{(y - M_R^2)^2 + M_R^2 \cdot \Gamma^2/c^4}$$

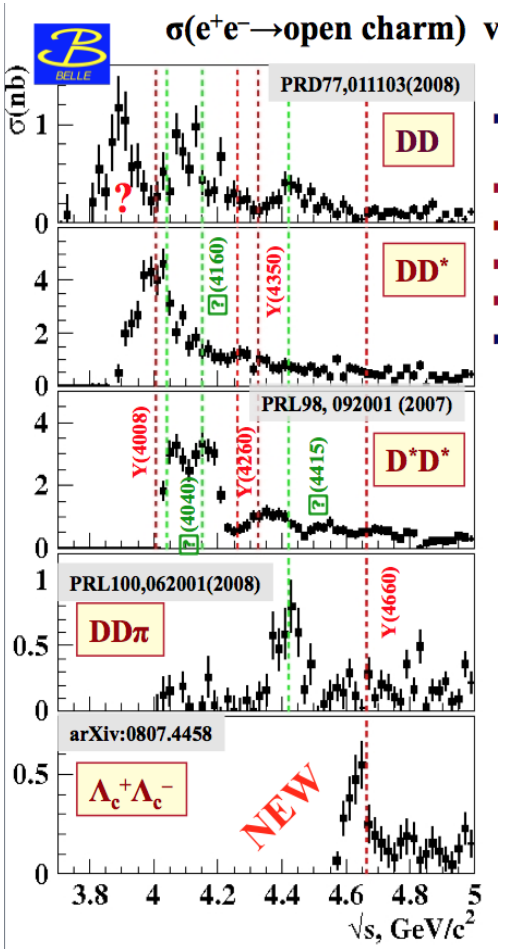
- The fit yields a mass (4038.7± 6.5) MeV/c^2 with a significance 6.0σ.
  → consistent with the resonance in the charged mode $\pi^+\psi(3686)$
- Similar fits with fixed width and mass of the $\pi^0\psi(3686)$ resonance are carried out to the data sample at 4.258 GeV and 4.358 GeV
  - the corresponding stat. significances are 3.6 σ and 4.5 σ, respectively
- Zc(3900) is not significant in either energy points

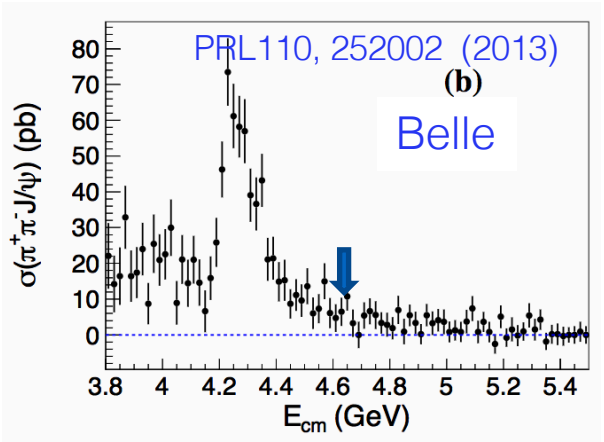
The Y(4630)/Y(4660)











$$\frac{\mathcal{B}(Y_B \to \Lambda_c \bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7,$$

Phys.Rev.Lett. 104 (2010) 132005

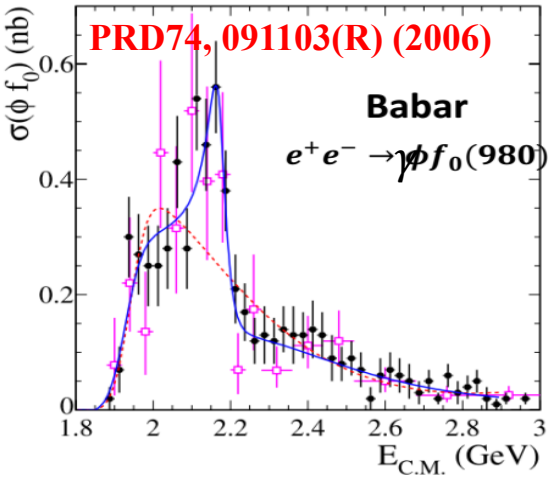
$$\frac{B(Y_B \to D^0 D^{*-}\pi^+)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} < 10$$

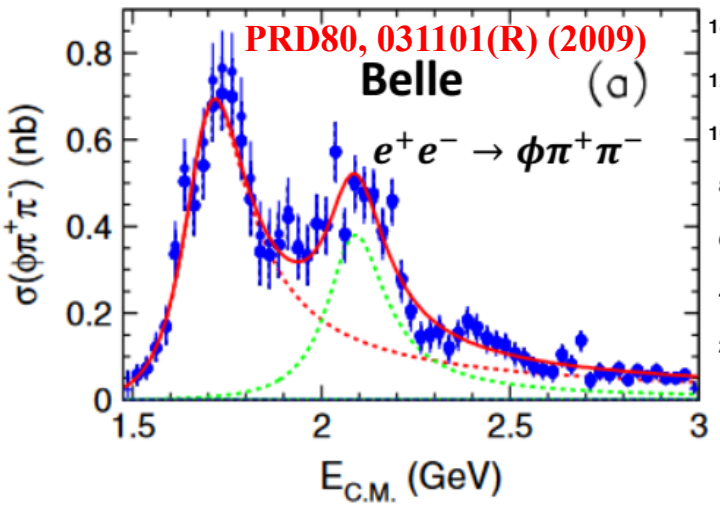
PDG

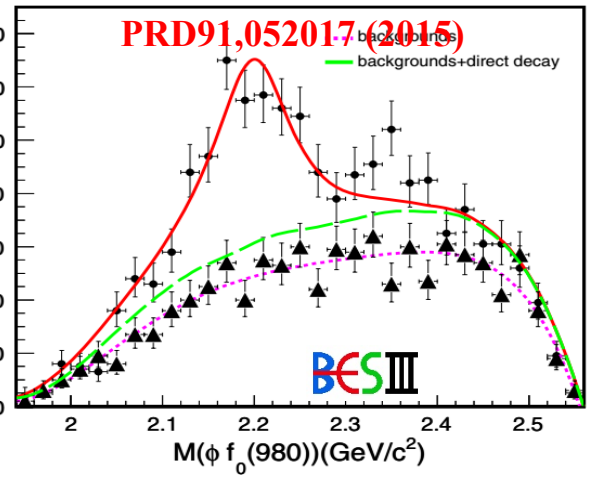
- Y(4660) baryonic coupling $\geq$ 10 mesonic coupling (unexpected!)
- Another missing large mesonic decay? Or Y(4660) is a charmed baryonium?

Y(2175) and the strangeonium-like Z_S

- **Y(2175) (denoted as $\phi(2170)$ by PDG) was observed by BaBar, and confirmed by Belle, BESII and BESIII**
  - A candidate for a tetraquark state, a strangeonium hybrid state, or a conventional $s\bar{s}$ state
- **Unique place to search for the Z_S:**
  - Y(2175) is regarded as strangeonium-like state analogous to Y(4260)
  - Mode: $Z_S \to \pi^{\pm}\phi$ **(Expected mass $M_{Z_S} \approx 1.4$ GeV/c^2)**



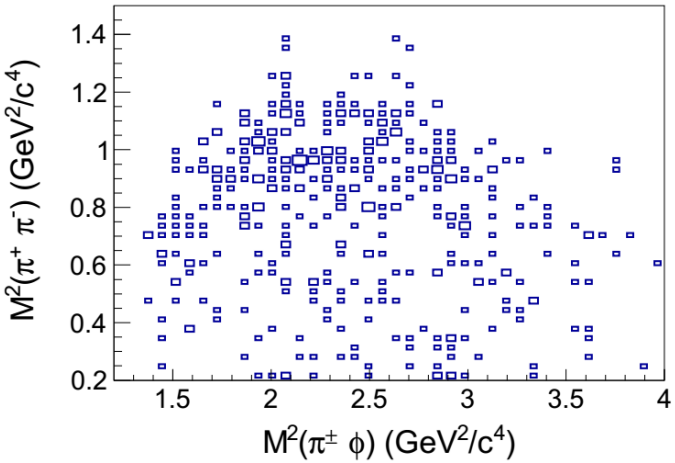


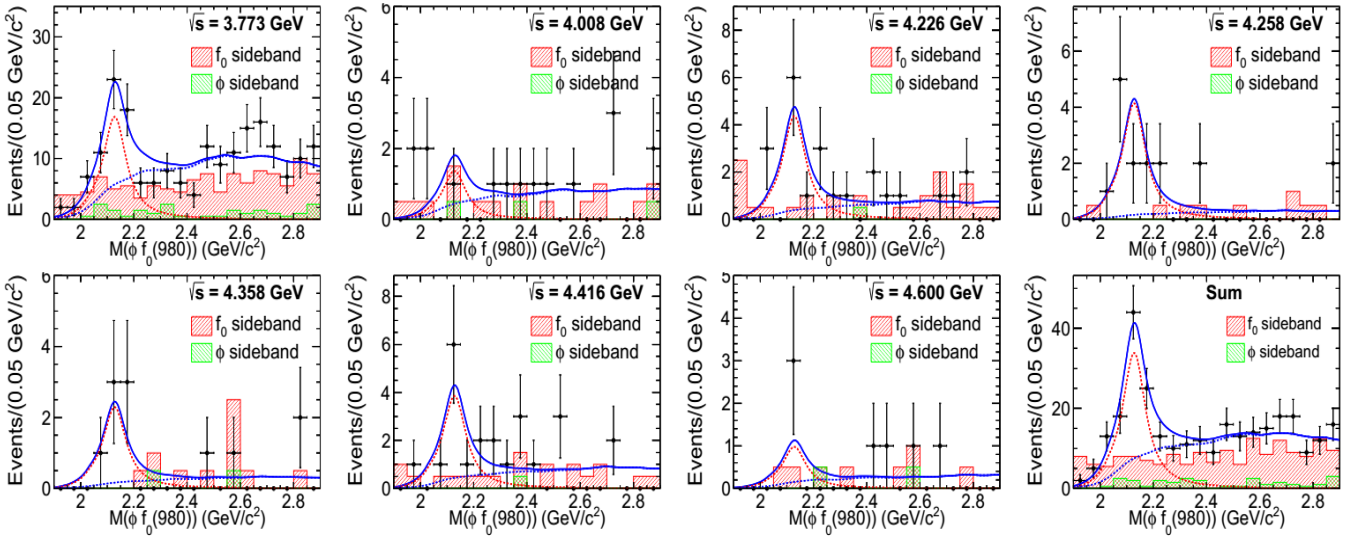


Observation of $e^+e^- \to \eta Y(2175)$ at $\sqrt{s} > 3.7$ GeV

PRD 99, 012014 (2019)

- Perform the search for Y(2175) resonance in the process $e^+e^- \to \eta\phi f_0(980)$ at $\sqrt{s}$ between 3.7 and 4.6 GeV.
- Combined significance for Y(2175) signal is observed to be larger than **10σ**.
- No significant Z_S signals in $\phi\pi^\pm$ spectrum.



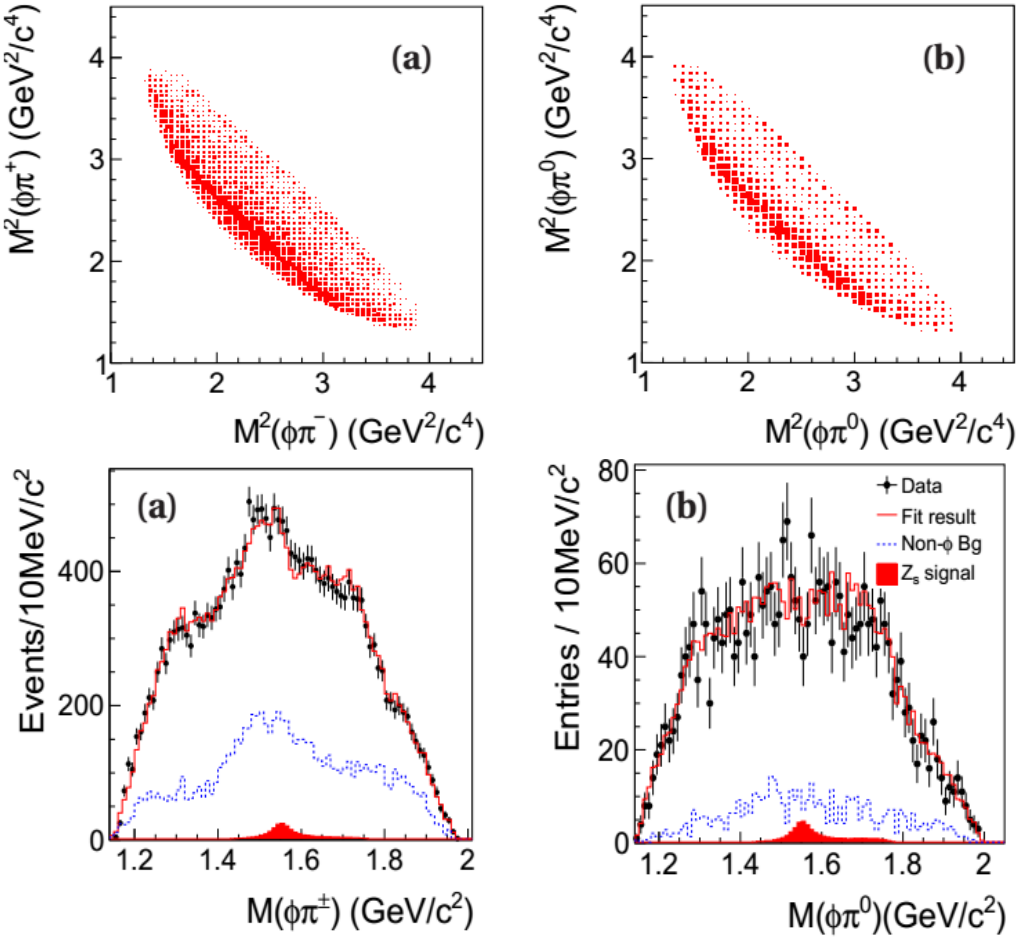


Search for the Z_S at 2.125 GeV

PRD99, 011101(2019)

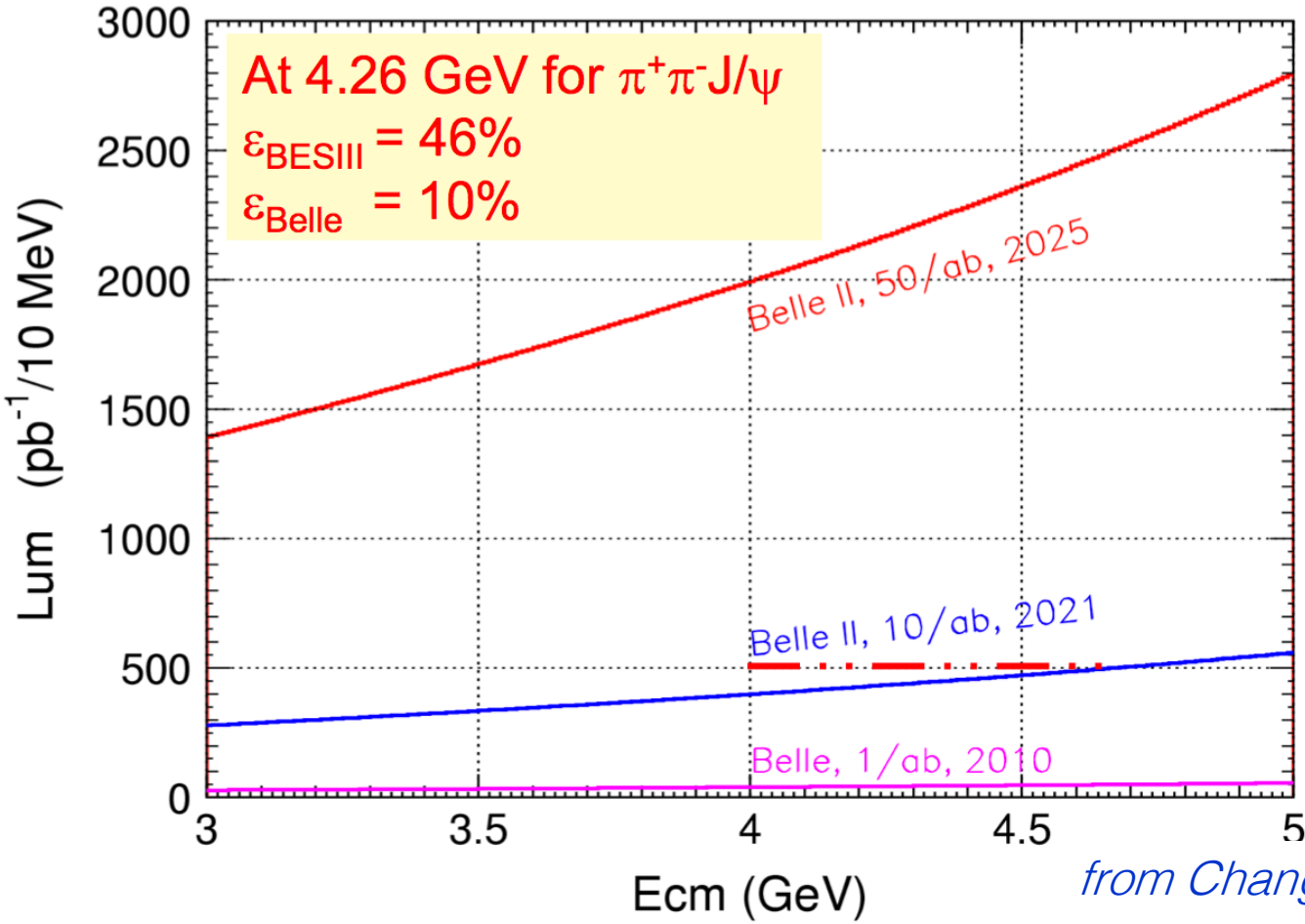
- Perform the search for Z_S via $e^+e^- \to \phi\pi^+\pi^-$ ($\phi\pi^0\pi^0$) using 108 pb^{-1} data collected at $\sqrt{s} = 2.125$ GeV.
- PWA is performed
  - $\phi\sigma$
  - $\phi f_0(980)$
  - $\phi f_0(1370)$
  - $\phi f_2(1270)$
  - $Z_s\pi$

- No clear Z_S signal is observed in the $\phi\pi$ mass spectrums around 1.5 GeV/c^2.



BELLE-II versus BESIII

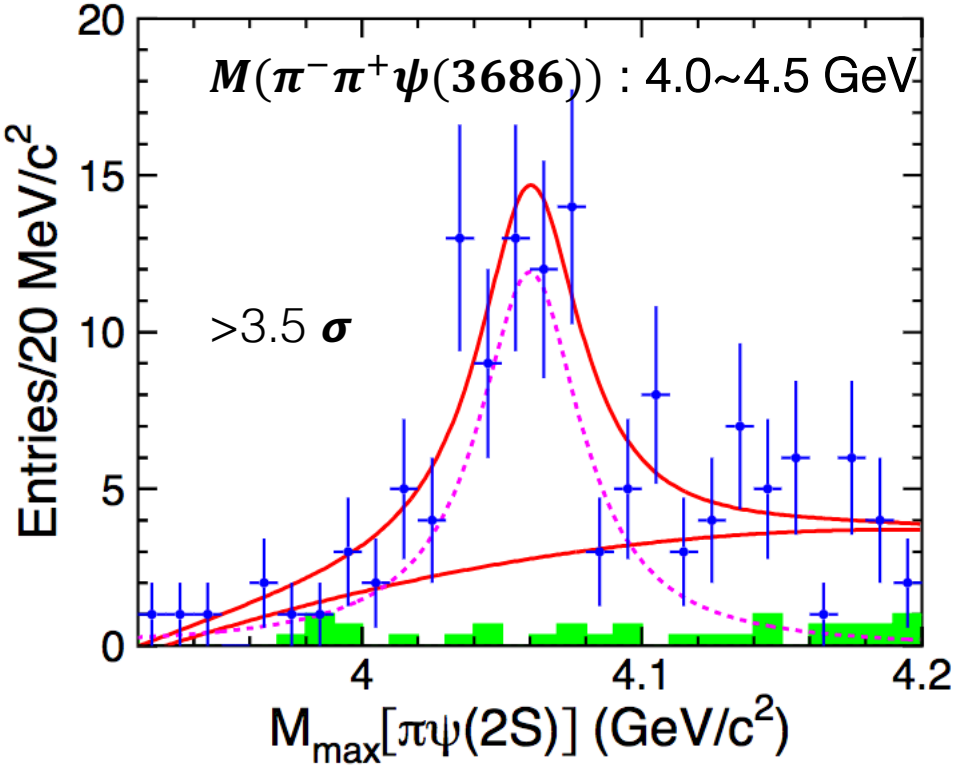
ISR produces events at all CM energies BESIII can reach



from Changzheng

Comparison to the study of $Z' \to \pi^+\psi(3686)$ at Belle

ISR returned productions of $\pi^-\pi^+\psi(2S)$ at Belle



M = (4054±3±1) MeV/c^2

Γ = (45±11±6) MeV

Belle, Phys.Rev. D91, 112007 (2015)

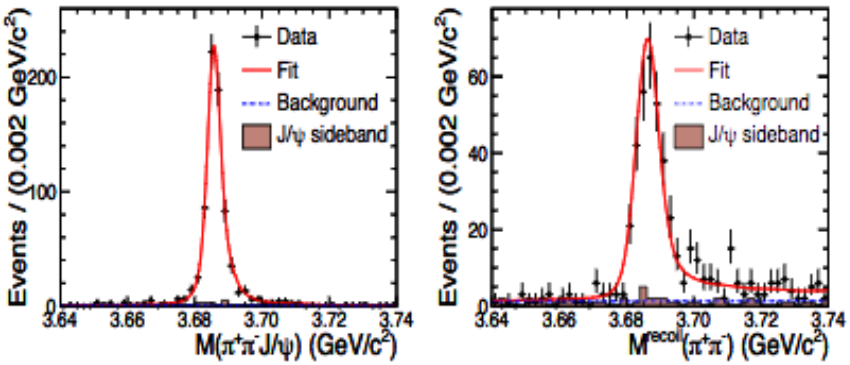
- The charged $\pi^+\psi(3686)$ structure is about 4.030 GeV/c^2 at BESIII

  M=4030.3±0.1 MeV/c^2

  Γ=5.1±0.2 MeV

- BESIII's result deviates from that of the structure observed by Belle by over 3σ.

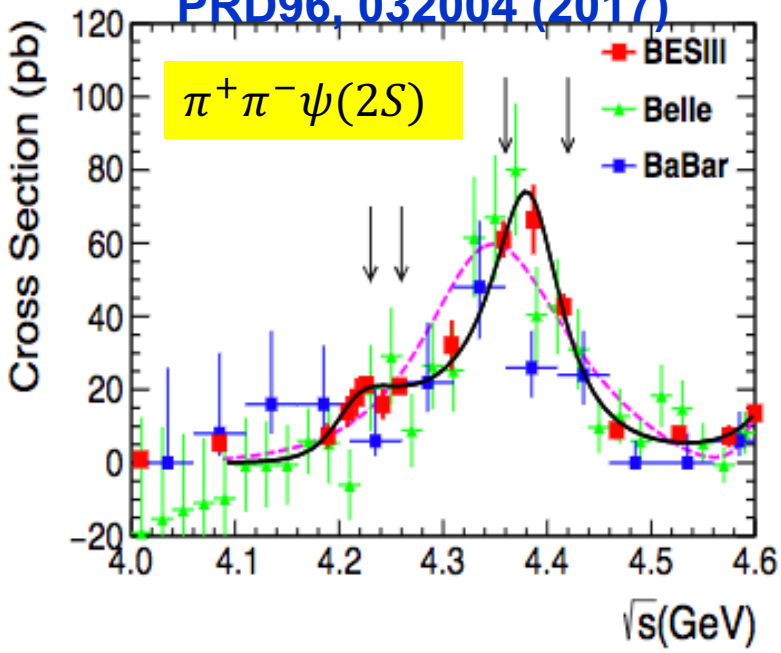
Cross sections of $e^+e^- \to \pi\pi\psi(2S)$



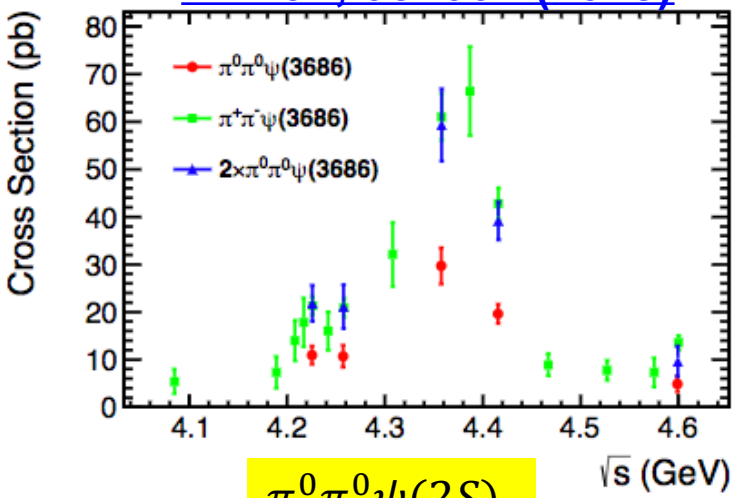
Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

- Confirm the lineshape of the Y(4360)
- Y(4220) and Y(4390) are confirmed

PRD96, 032004 (2017)

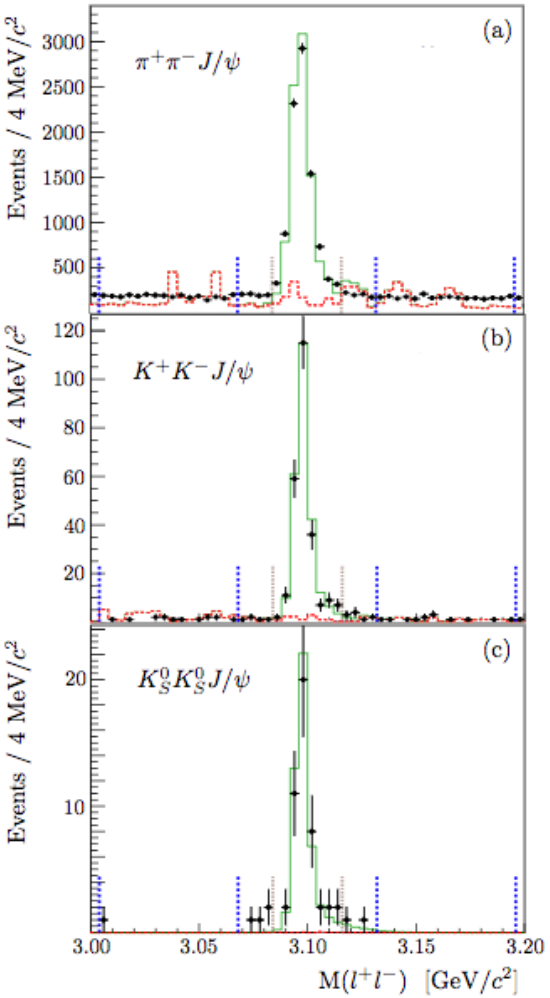


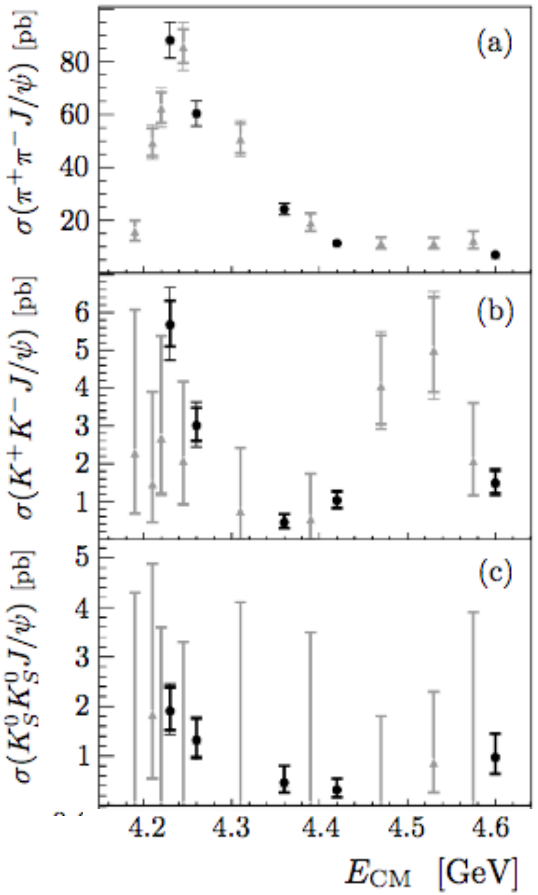
PRD97, 052001 (2018)

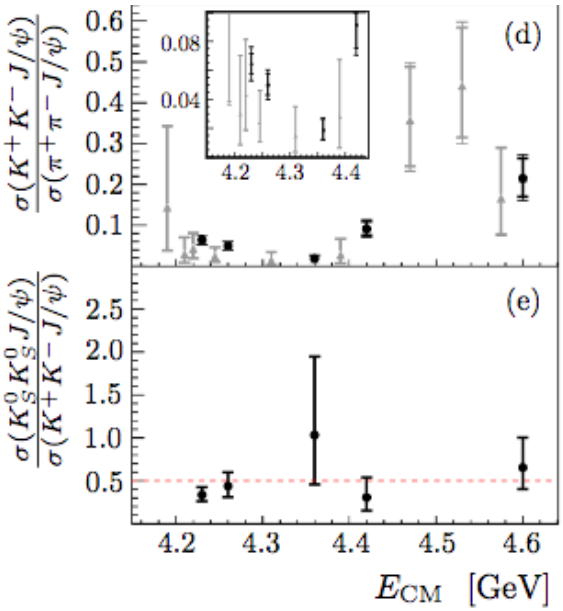


$\pi^0\pi^0\psi(2S)$

$e^+e^- \to K^+K^-J/\psi$





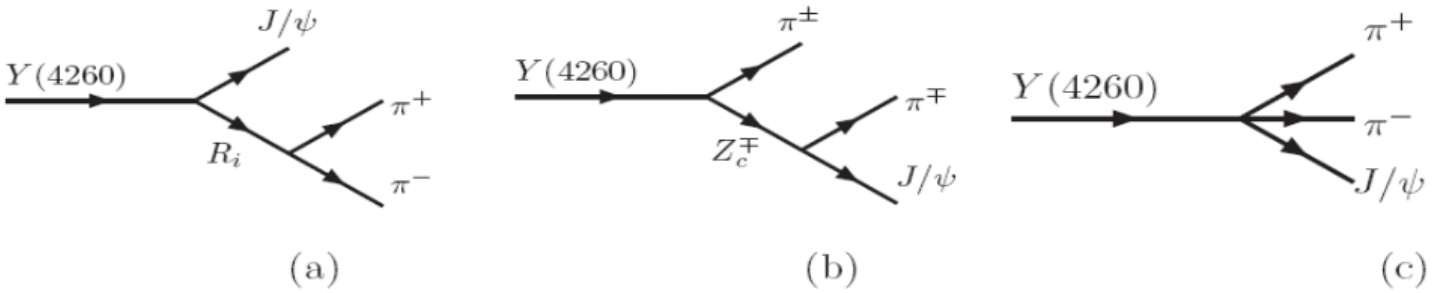


PRD 97, 071101 (2018)

- $\sigma\ (KKJ/\psi)$ lineshape is quite different from $\sigma\ (\pi^+\pi^- J/\psi)$ around Y(4220)/Y(4260)
- Higher bump around 4.5GeV is clear and need further investigation

Amplitude analysis of $e^+e^- \to \pi^+\pi^- J/\psi$

PRL 119.072001 (2017)



In the process $e^+e^- \to \gamma^* \to \pi^+\pi^- J/\psi$

- **The helicity value of γ^* is taken as $\lambda_0 = \pm 1$ due to from e+e- annihination**
- **$\gamma^* \to Z_c^\pm \pi^\mp$, $Z_c^\pm \to J/\psi\pi^\pm$, we try J^p for X: 0^-, 1^-, 1^+, 2^-, 2^+, and 0^+ is not allowed**
- **Z_c^+ and Z_c^- states are assumed as isospin partner, with the same mass and coupling constant**
- **Six proceses are inclued in fitting to data:**

$\sigma_0, f_0(980), f_2(1270), f_0(1370), Z_c^\pm$, and $\pi^+\pi^- J/\psi$