News on Zc states

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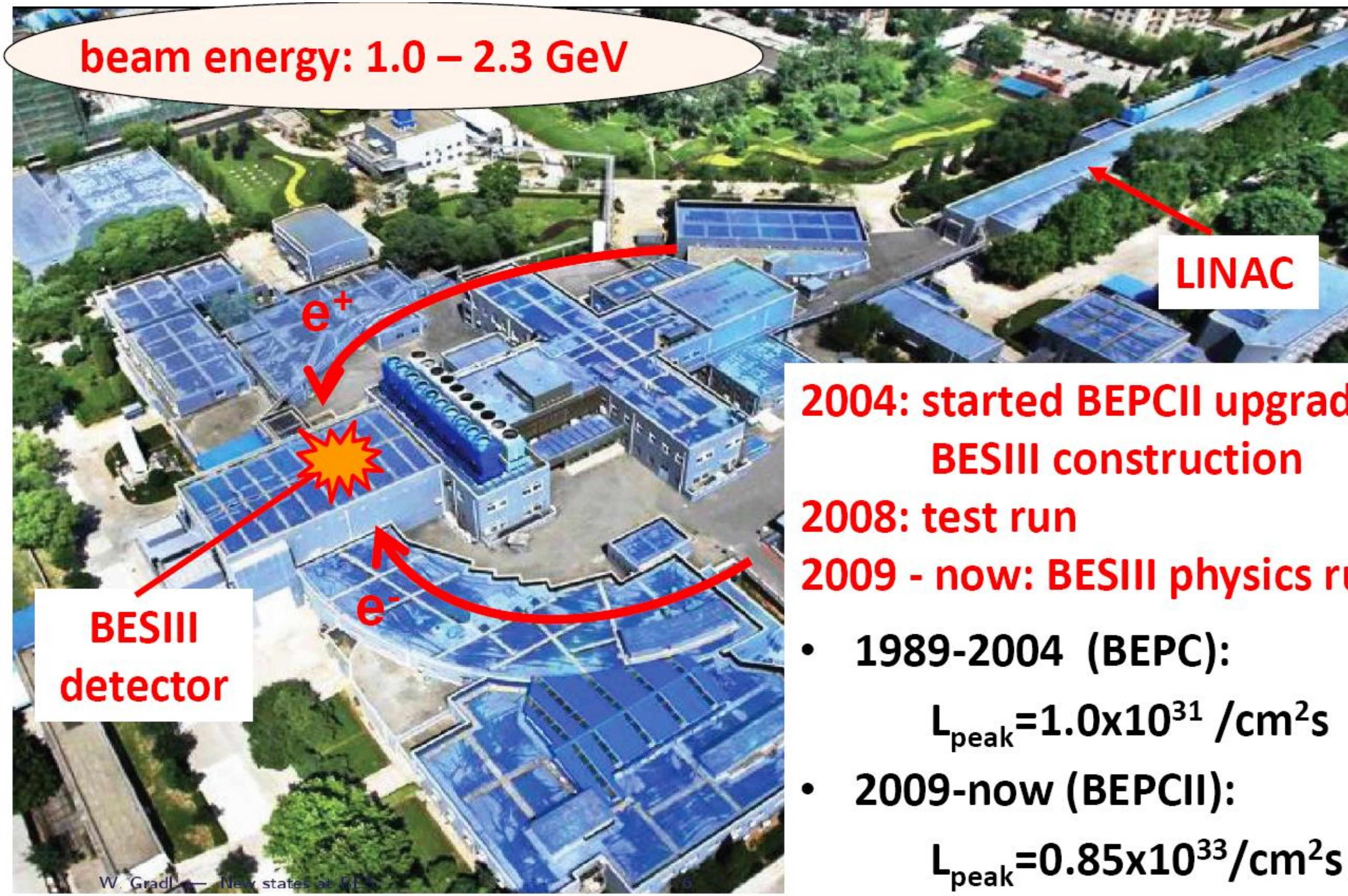
Outline:

- **Introduction**
- **Data sets**
- **Amplitude of partial wave analysis**
- **Z_c(3900) spin and parity**
- **Systematic uncertainties**
- **Summary**

Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade,
BESIII construction

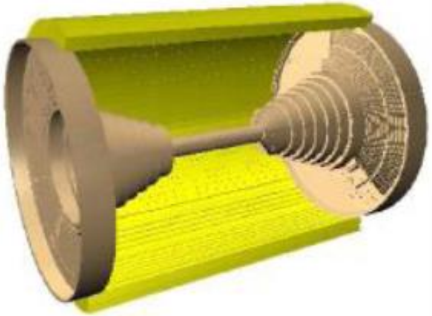
2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  $L_{peak}=1.0\text{x}10^{31}$ /cm^{2}s
- 2009-now (BEPCII):
  $L_{peak}=0.85\text{x}10^{33}$/cm^{2}s

BESIII Detector

MDC

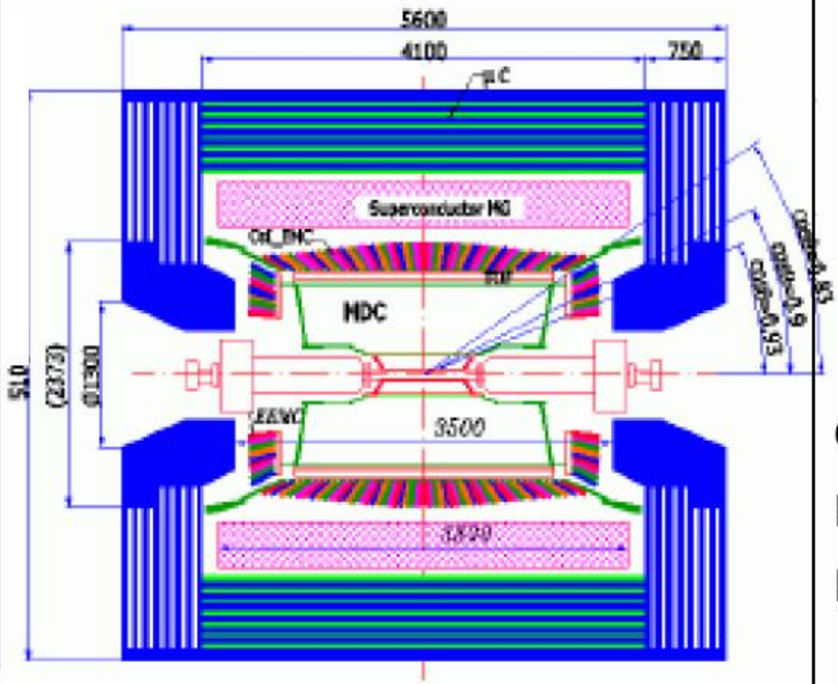


R inner: 63mm ;

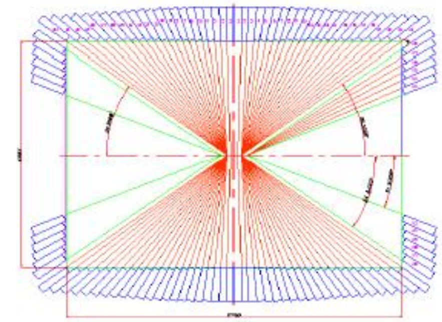
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



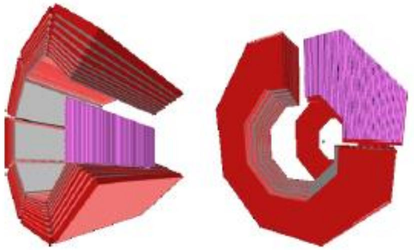
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

TOF

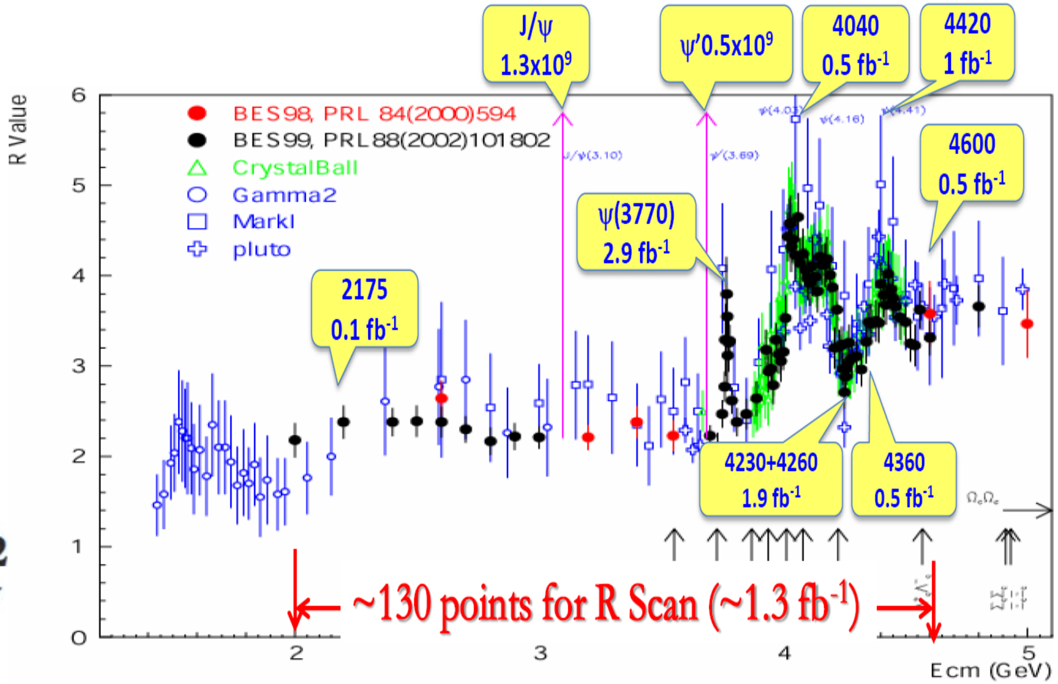
BTOF: two layers

ETOF: 48 scintillators for each

MRPC --- new ETOF

BESIII data samples

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} at **$\psi(3770)$** *(total)*
482 pb^{-1} at **4.01 GeV**
2012: 0.45B **$\psi(2S)$** *(total)*
1.3B **J/ψ** *(total)*
2013: 1092 pb^{-1} at **4.23 GeV**
826 pb^{-1} at **4.26 GeV**
540 pb^{-1} at **4.36 GeV**
~50 pb^{-1} at **3.81, 3.90, 4.09, 4.19, 4.2**
4.22, 4.245, 4.31, 4.39, 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** from 3.85 to 4.59 GeV (104 points)
2015: **R-scan** from 2-3 GeV + **2.175 GeV** data
2016: ~3fb^{-1} at 4.18 GeV (for D_s) *JUST COMPLETED*



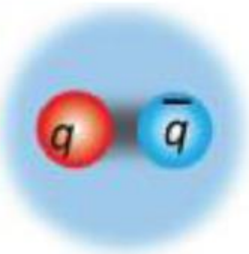
2017: 500/pb each for 7 energy points between 4.19~4.28 GeV
400/pb around chic_c1
200/pb around X(3872)

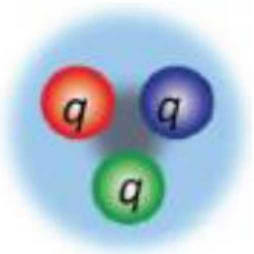
New forms of hadron

- Conventional hadrons consist of 2 or 3 quarks：

Naive Quark Model：

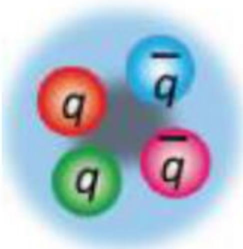
meson

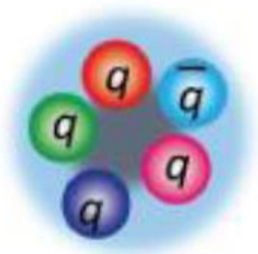




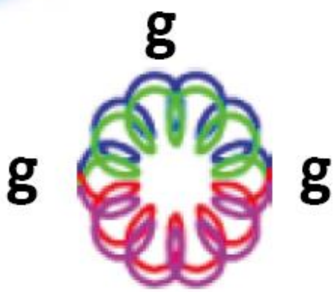
baryon

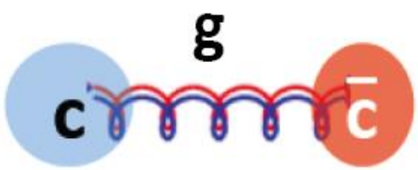
- QCD predicts the new forms of hadrons:
  - Multi-quark states： Number of quarks >= 4





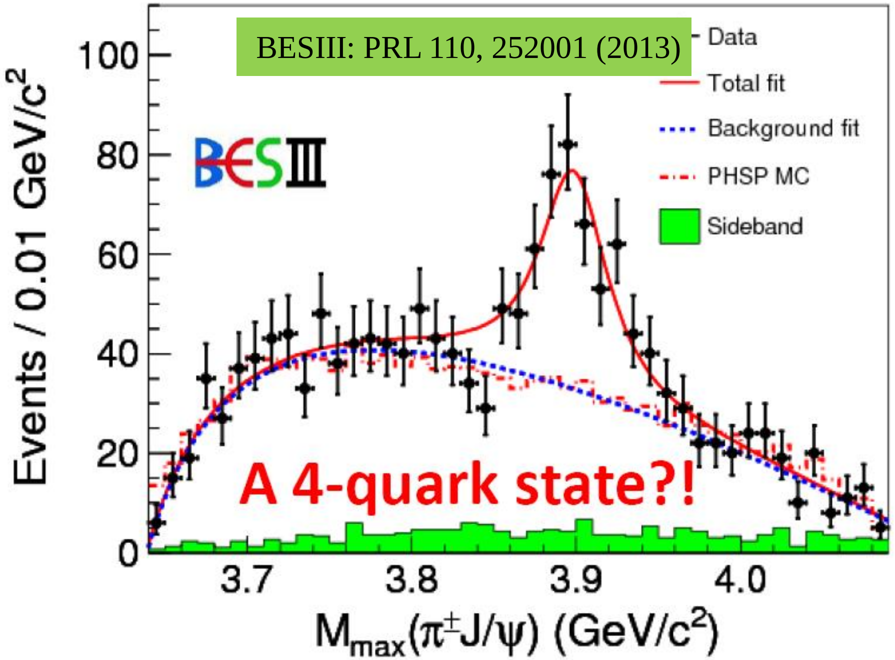
  - Hybrids： $q\bar{q}g$， qqqg …
  - Glueballs： gg， ggg …





Observation of Zc(3900)

BESIII: PRL 110, 252001 (2013)



$Z_c(3900)^+$: J^P=?

$m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$

$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$

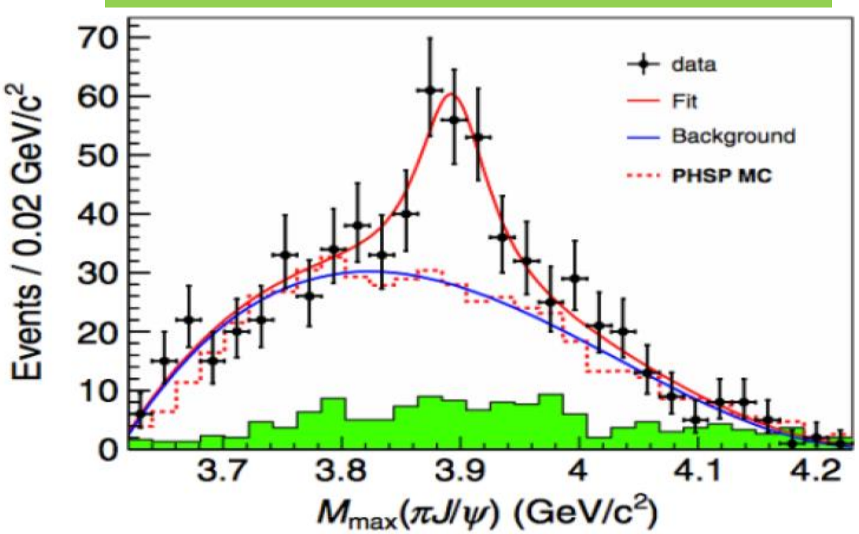
Mass close to $D\bar{D}^*$ threshold

Decays to J/ψ → contains $c\bar{c}$
Electric charge → contains $u\bar{d}$

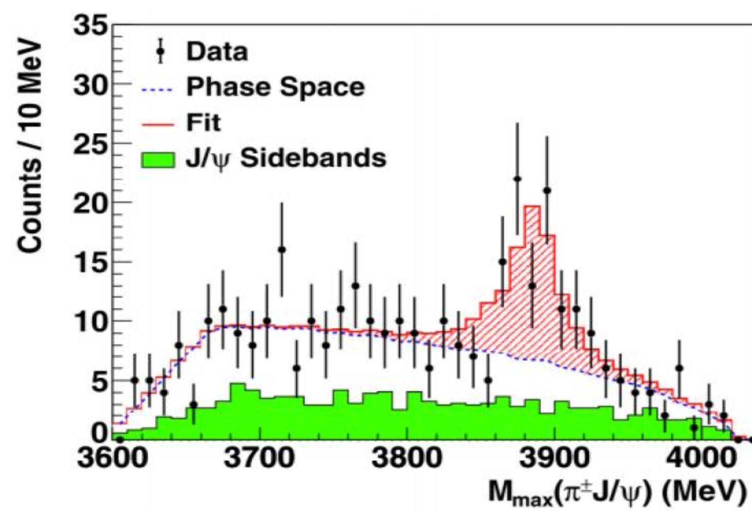
$$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi]}{\sigma[e^+e^- \to \pi^+\pi^- J/\psi]} = (21.5 \pm 3.3 \pm 7.5)\% \text{ at } 4.26 \text{ GeV}$$

Belle with ISR data (PRL110,252002)

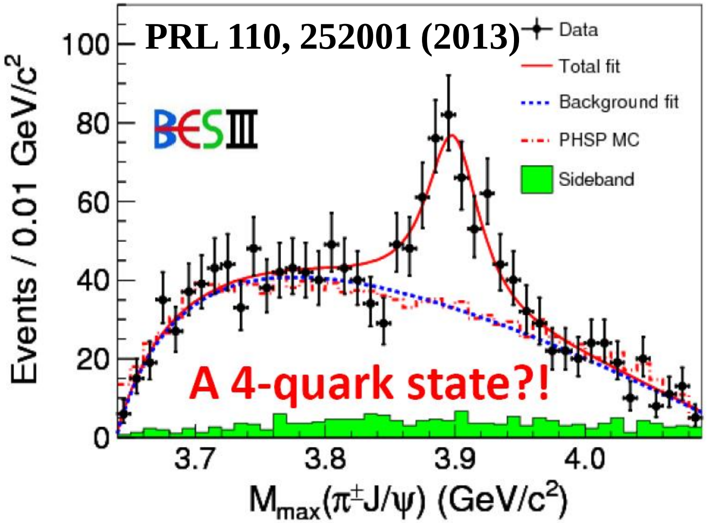


CLEOc data at 4.17 GeV (PLB 727,366)

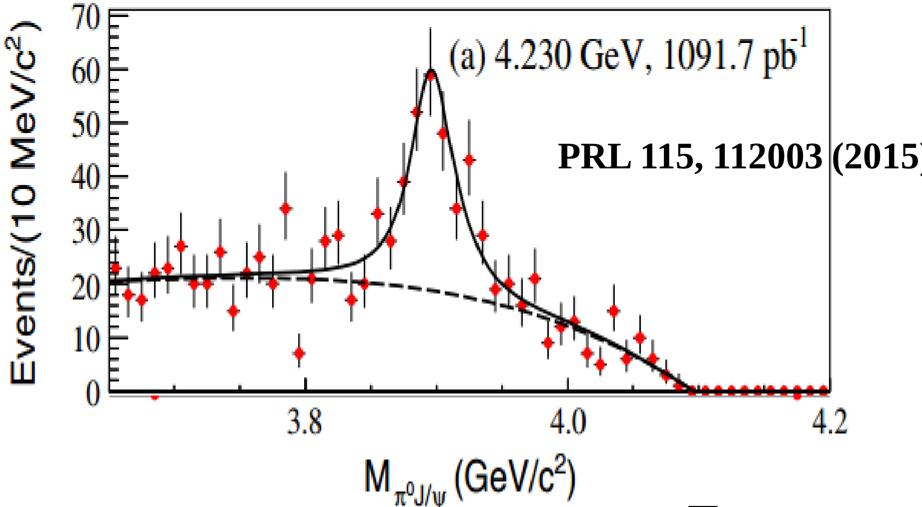


Overview Zc states from BESIII

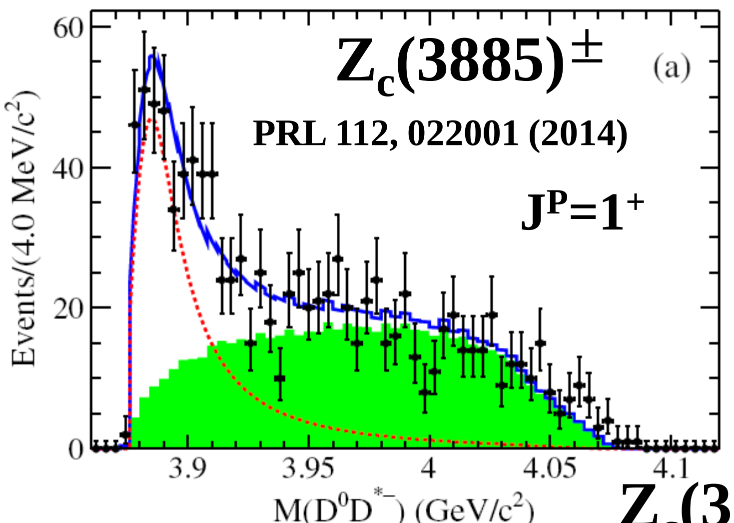
$Z_c(3900)^{\pm}$: $e^+e^- \to \pi^+\pi^- J/\psi$



$Z_c(3900)^0$: $e^+e^- \to \pi^0\pi^0 J/\psi$

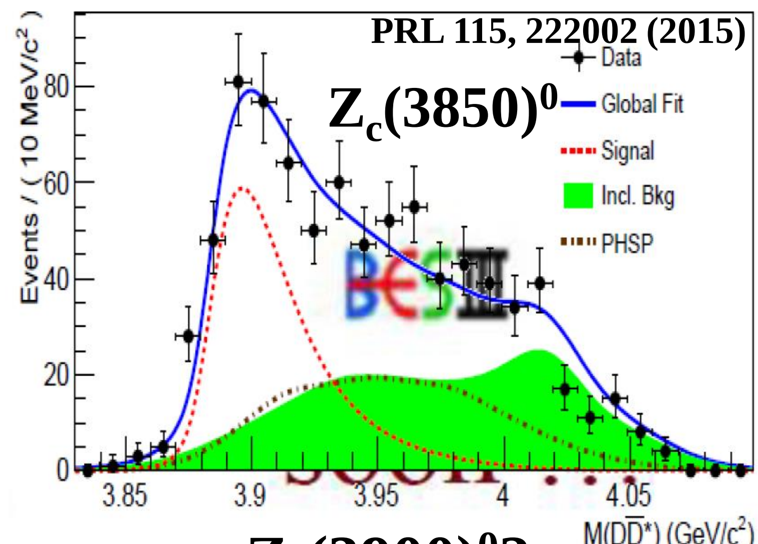


$Z_c(3885)^{\pm}$: $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$



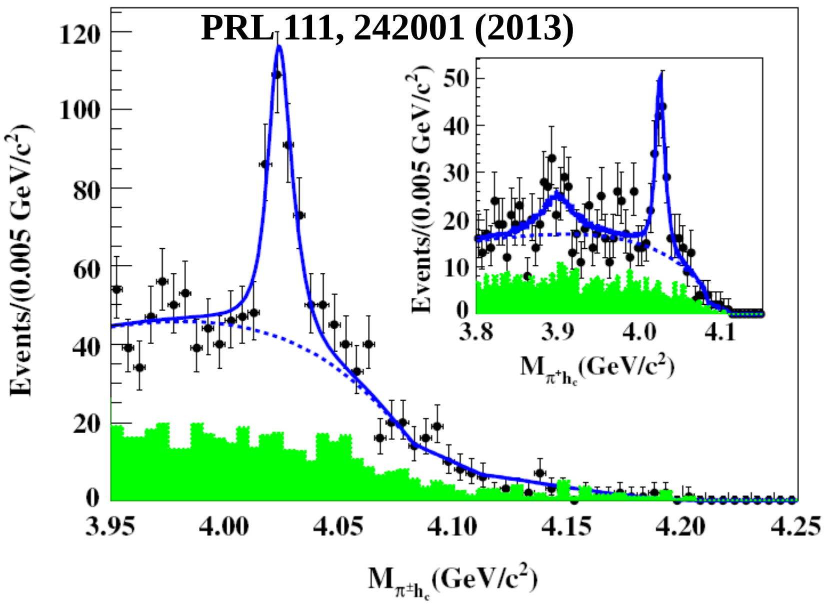
$Z_c(3900)^{\pm}$?

$Z_c(3885)^0$: $e^+e^- \to \pi^0(D\bar{D}^*)^0$

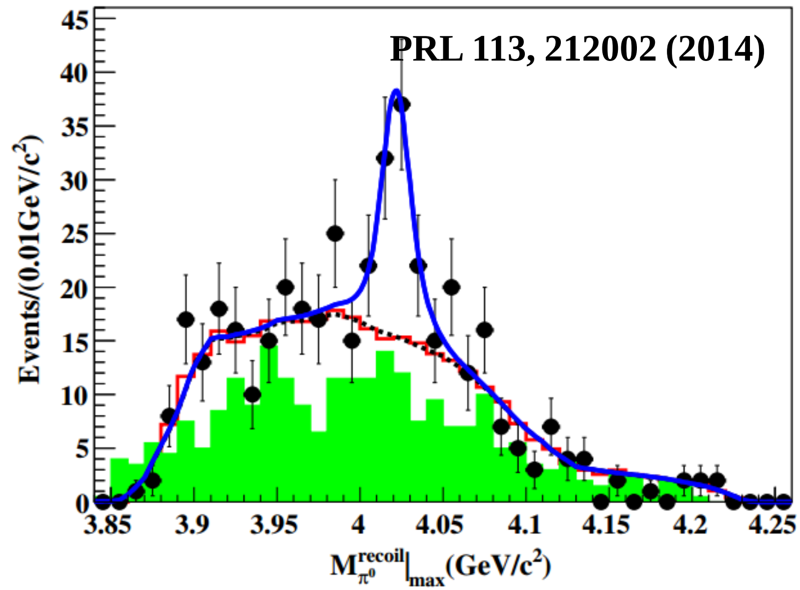


$Z_c(3900)^0$?

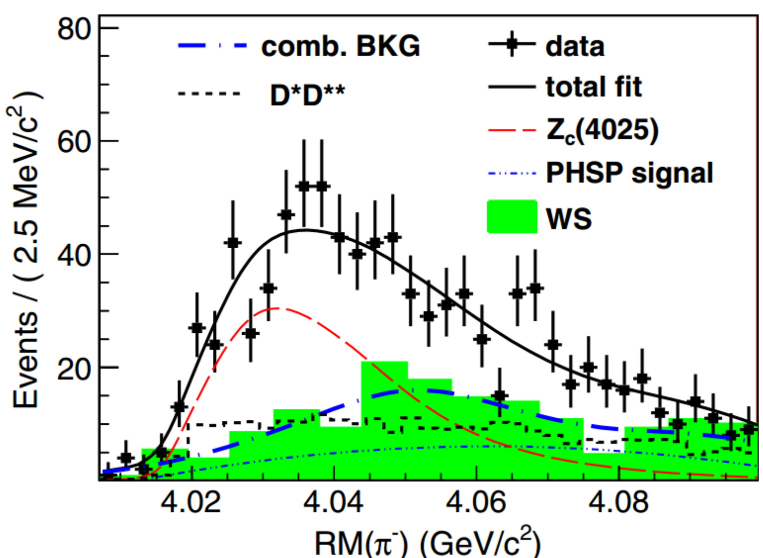
$Z_c(4020)^{\pm} : e^+e^- \to \pi^+\pi^-h_c$



$Z_c(4020)^{0} : e^+e^- \to \pi^0\pi^0h_c$

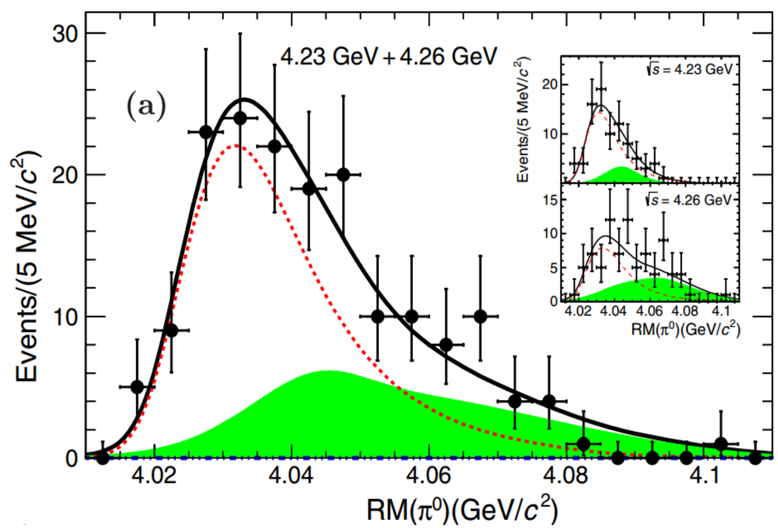


$Z_c(4025)^{\pm} : e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$



PRL 112, 132001 (2014)

$Z_c(4025)^{0} : e^+e^- \to \pi^0(D^*\bar{D}^*)^0$



PRL 115, 182002 (2015)

■ Theoretical investigation on $Z_c(3900)$

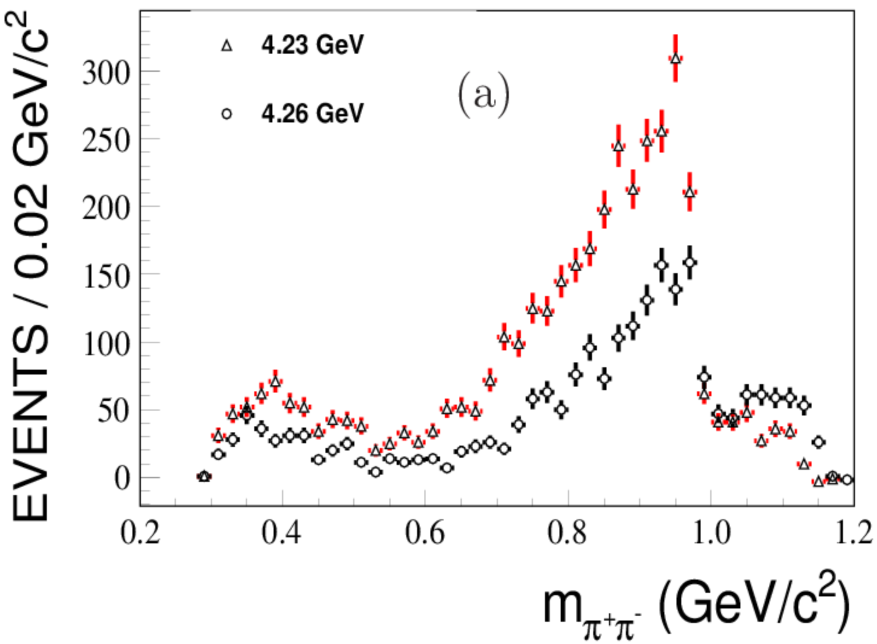
Tetraquarks: PRD85, 054011 (2012) , PRD87, 111102 (2013), JHEP 1307, 153 (2013), arXiv: 1304.1301, …
Hadronic molecules: PRD88, 054007 (2013), PL B726, 326 (2013), JPG41, 075003 (2014), …
Meson loop: PRL 111, 132003 (2013), EPJ C73, 2621 (2013), …
ISPE model: PRD88, 025021 (2013) , …

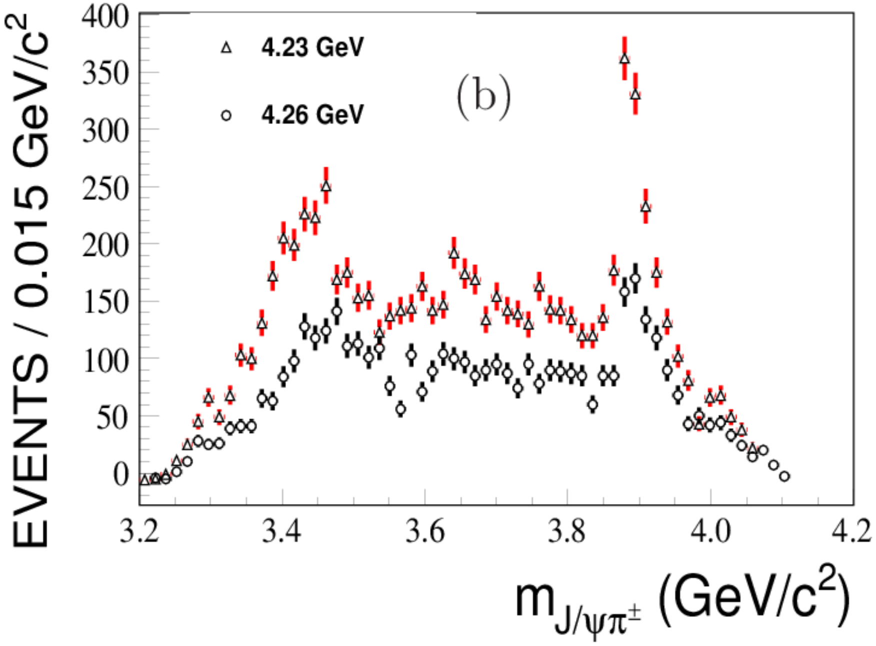
■ More experimental information desired

(i) establishing the spin and parity of $Z_c(3900)$;
(ii) a search for a peak around 4030 MeV in the $\pi J/\psi$ invariant mass spectrum in the process $Y(4260) \to \pi\pi J/\psi$;
(iii) a measurement of the branching fraction for decays of $Z_c(3900)$ into heavy meson pairs, $Z_c \to D^{*+}\bar{D}^0$, $D^+\bar{D}^{*0}$;
(iv) a measurement of the rate of the decay $Z_c(3900) \to \pi\psi'$ relative to that of $Z_c(3900) \to \pi J/\psi$;
(v) a search for the decays $Z_c(3900) \to \pi h_c$ and $Z_c \to \rho\eta_c$.

M. B. Voloshin, PRD87, 091501 (2013)

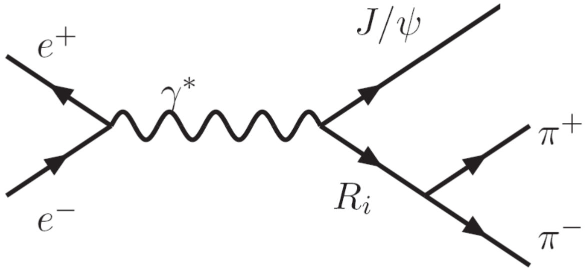
Consistency of Zc(3900) at 4.23 and 4.26 GeV



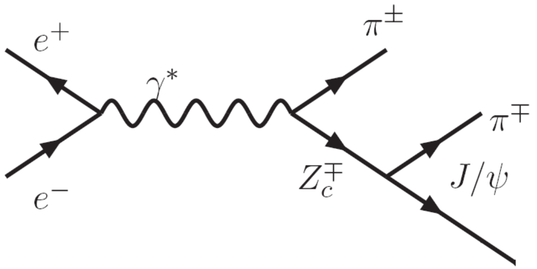


- Events selected from e+e-→$\pi^+\pi^- J/\psi$, J/ψ→l^+l^-
- Total ~6,000 events (4,400 at 4.23GeV, 2,400 at 4.26 GeV)
- Z_c peak consistent at two energy point
- σ and f_0(980) significantly observed
- Two pion spectrum above 1GeV shows difference.

Amplitude construction



(a)



(b)

(a): $$A_1(\lambda_0,\lambda_2) = \sum_{\lambda_1,j} F^Y_{\lambda_1,\lambda_2}(r_1) D^{1*}_{\lambda_0,\lambda_1-\lambda_2}(\theta_0,\phi_0) BW_j(m_{\pi^+\pi^-}) F^{R_j}_{0,0}(r_2) D^{J_1*}_{\lambda_1,0}(\theta_1,\phi_1),$$

(b): $$A_2(\lambda_0,\lambda_2) = \sum_{\lambda_1,j} F^Y_{\lambda_1,0}(r_1) D^{1*}_{\lambda_0,\lambda_1}(\theta_0,\phi_0) BW_j(m_{J/\psi\pi}) \sum_{\lambda_2'} F^{Z_c}_{\lambda_2',0}(r_2) D^{J_1*}_{\lambda_1,\lambda_2'}(\theta_1,\phi_1) d^1_{\lambda_2',\lambda_2}(\tilde{\theta}_2),$$

$d^1_{\lambda_2',\lambda_2}(\tilde{\theta})$: to align the J/ψ momentum to that from γ^*

PRL,115,072001.
PRD88,074026
PRD95,076010

$$F_{\lambda,\nu} = \sum_{lS} g_{lS} \sqrt{\frac{2l+1}{2J+1}} \langle l0S\delta|J\delta\rangle \langle s\lambda\sigma-\nu|S\delta\rangle r^l \frac{B_l(r)}{B_l(r_0)},$$

See Refs.

1 S. U. Chung, Phys. Rev. D57, 431 (1998);
2 S. U. Chung, Phys. Rev. D48, 1225 (1993).

Study Z_c as $J^P=1^+$ state

- **Baseline solution**

  $\pi\pi$-S wave [σ,$f_0(980)$,$f_0(1370)$], $\pi\pi$-D wave [$f_2(1270)$], $Z_c(3900)^{\pm}$

- **$f_0(980)$ line shape parametrized with Flatte function**
- **Z_c lineshape parametrized with Flatte-like function**

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

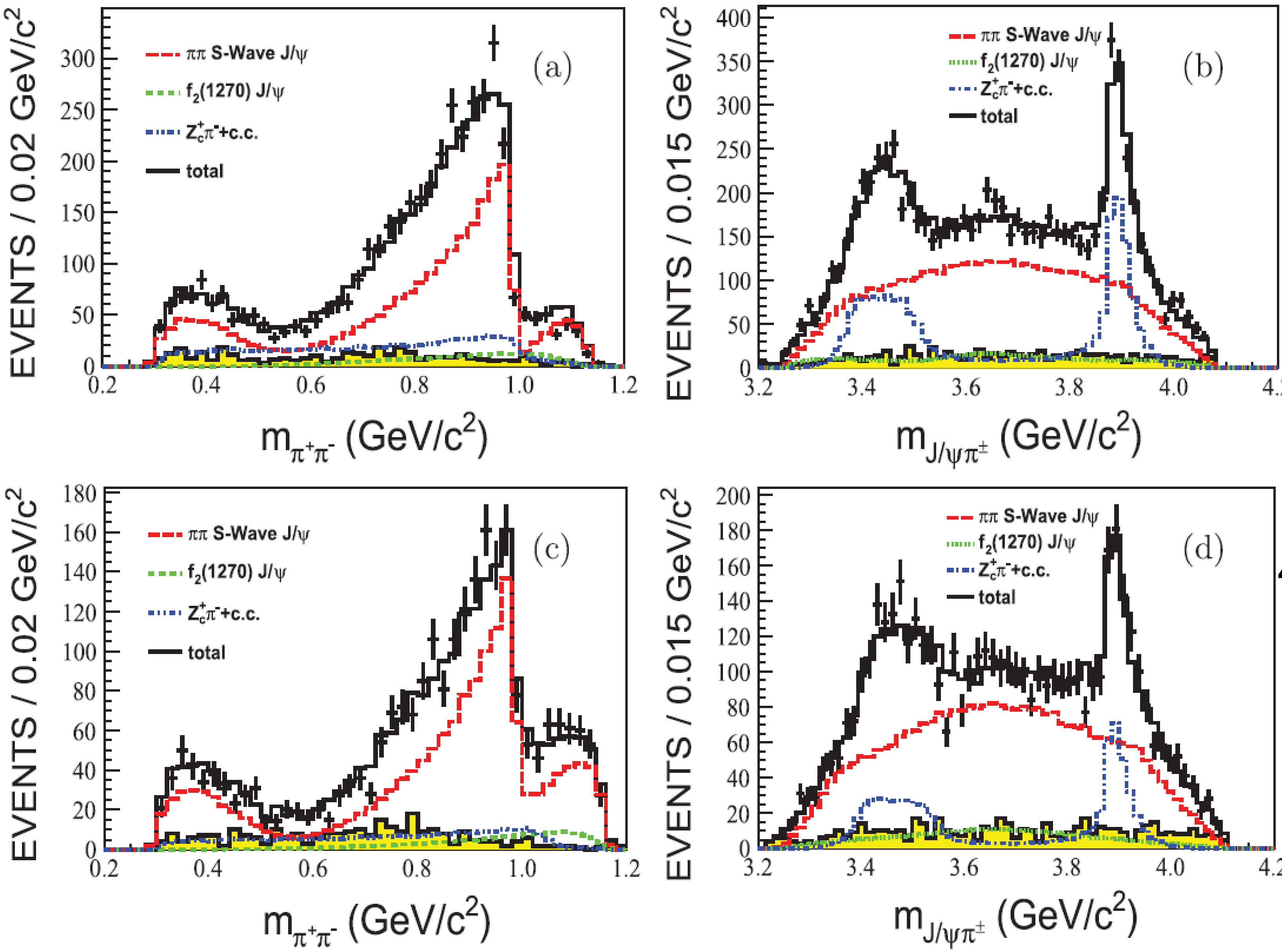
- **Z_c^+ and Z_c^- assumed as isospin partner**
- **Simultaneous fit to data, background subtracted from data ln*L***

The fitted mass, g_1', g_2'/g_1' and $-\ln L$ for the Z_c resonance.

$Z_c : J^P$	M (MeV)	g_1' (GeV^2)	g_2'/g_1'	$-\ln L$
1^+	3901.5 ± 2.7	0.075 ± 0.006	27.1 ± 2.0	-1599.1

Fit results assuming Z_c to be 1^+

PRL 119, 072001 (2017), BESIII



$\sqrt{s}$ = 4.23 GeV

4.26 GeV

- **Fit quality check of Dalitz plots**

  χ^2 / ndf: 1.3 (4.23 GeV), 1.2 (4.26 GeV)

- Z_c pole mass and width:

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

- **Data disfavor Breit-Wigner parametrization of Z_c**

  $M = (3897.6 \pm 1.2_{\rm stat.})$ MeV, $\Gamma = (43.5 \pm 1.5_{\rm stat.})$ MeV

  $-\ln L$ increases by 22 with $\Delta(\rm ndf) = 1$

- **Helicity amplitudes for Z_c production and decays**

For $e^+e^- \to Z_c^\pm \pi^\mp$,

$|F_{1,0}^{Zc}|^2/|F_{0,0}^{Zc}|^2 = 0.22 \pm 0.05_{\rm stat}$ at 4.23 GeV

$= 0.21 \pm 0.11_{\rm stat}$ at 4.26 GeV

For $Z_c^\pm \to J/\psi \pi^\pm$:

$|F_{1,0}^{\psi}|^2/|F_{0,0}^{\psi}|^2 = 0.45 \pm 0.15_{\rm stat}$

- **$\pi\pi$-S wave dominates the process**

Fraction: $(61.7 \pm 2.1_{\text{stat.}})\%$ at 4.23 GeV,
$(71.4 \pm 4.1_{\text{stat}})\%$ at 4.26 GeV

- **Signal yields for $Z_c(1^+)$**

$N_{Z_c^\pm} = 952.3 \pm 39.3_{\text{stat}}$ at 4.23 GeV, $343.3 \pm 23.3_{\text{stat}}$ at 4.26 GeV

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

$(21.8 \pm 1.0_{\text{stat}} \pm 4.4_{\text{sys}})$ pb at 4.23 GeV

$(11.0 \pm 1.2_{\text{stat}} \pm 5.4_{\text{sys}})$ pb at 4.26 GeV

- **Significance for $e^+e^- \to Z_c^+(4020)\ \pi^- + c.c \to \pi^+\pi^- J/\psi$ is ~3σ.**

$\sqrt{s} = 4.23$ **GeV**	**4.26 GeV**
$(0.2 \pm 0.1_{\text{stat}})$ pb ,	**$(0.8 \pm 0.4_{\text{stat}})$ pb**
<0.9 pb @90% C.L.	**<1.4 pb @90% C.L.**

Comparison of fit results with different J^P for Z_c

- **Mass, g_1' , g_2' / g_1' and Log-likelihood**

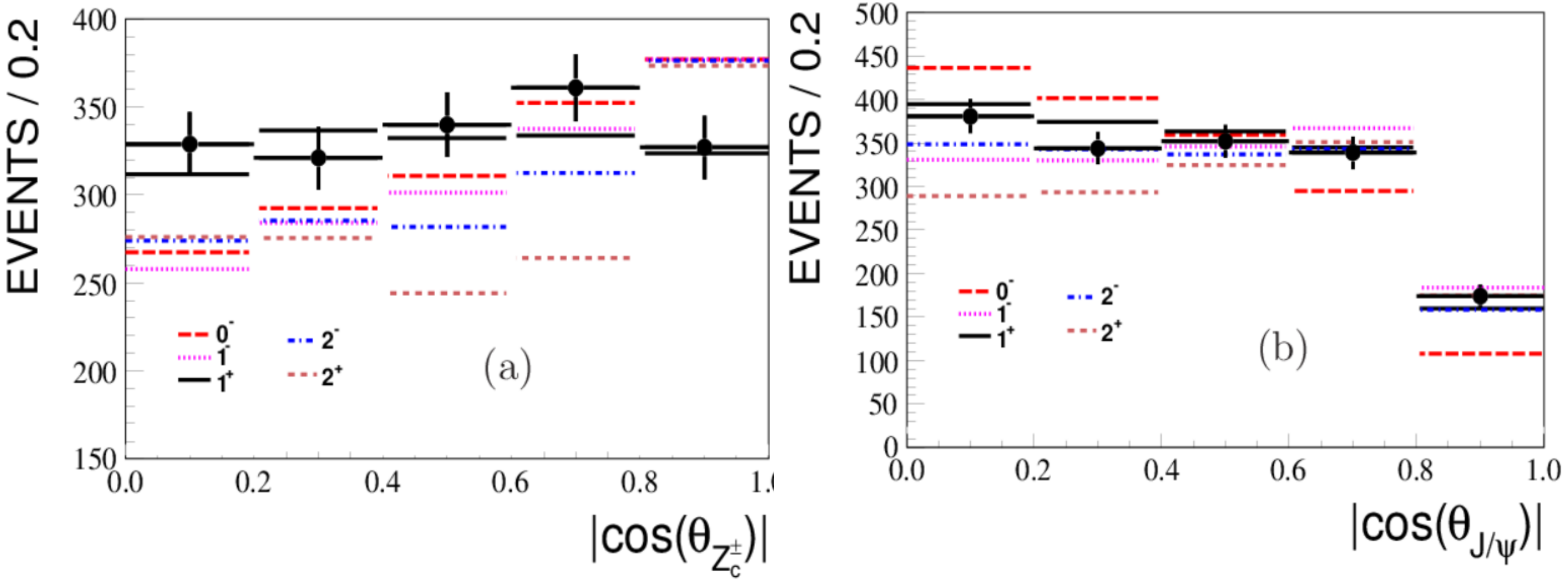
$Z_c : J^P$	M (MeV)	$g_1'(\mathrm{GeV}^2)$	g_2'/g_1'	$-\ln L$
0^-	3899.7 ± 2.1	0.079 ± 0.005	25.8 ± 2.9	-1491.6
1^-	3901.1 ± 1.8	0.063 ± 0.005	24.1 ± 2.3	-1434.4
1^+	3901.5 ± 2.7	0.075 ± 0.006	27.1 ± 2.0	-1599.1
2^-	3900.9 ± 1.6	0.060 ± 0.004	25.3 ± 2.4	-1464.6
2^+	3893.6 ± 1.6	0.051 ± 0.005	25.3 ± 2.9	-1369.5

- **Z_c favors the quantum numbers $J^P=1^+$**

If Z_c is assigned as 0^-, the fit quality gets worse by about $\Delta(LnL)=107.5$. To figure out the Z_c quantum numbers, the information on the statistical significance is desirable.

Angular distributions for different J^P within Z_c mass region

PRL 119, 072001 (2017), BESIII



- Events in the Z_c mass region $M_{\pi J/\psi} \in (3.86, 3.92)$ GeV
- Background events subtracted
- θ_{Zc} : the polar angle of Z_c, $\theta_{J/\psi}$: helicity angle of J/ψ
- Data favors the spin-parity 1^+ for Z_c

Statistical significance for the Z_c as 1^+ state

■ Test two hypothesises

Null hypothesis H_0 :

data described with $[\sigma_0, f_0(980), f_2(1270), f_0(1370), Z_c(J^P \neq 1^+)]$

Alternative hypothesis H_1:

data described with $[\sigma_0, f_0(980), f_2(1270), f_0(1370), Z_c(1^+),$ **other** $Z_c(J^P \neq 1^+)]$

Significance to distinguish the quantum number 1^+ over other quantum numbers.

Hypothesis	$2\Delta(-\ln L)$	$\Delta(ndf)$	significance
1^+ over 0^-	94.0	$4\times2+5$	7.6σ
1^+ over 1^-	158.3	$4\times2+5$	10.8σ
1^+ over 2^-	151.9	$4\times2+5$	10.5σ
1^+ over 2^+	96.0	$4\times2+5$	7.7σ

Systematic uncertainties

- **Luminosity, tracking, lineshape, kinematic fit and branching fraction, and PWA**

Sources	M_{Z_c}	$g_1' \times 10^3$	g_2'/g_1'	$N_{Z_c}^{\mathrm{I}}$ (%)	$N_{Z_c}^{\mathrm{II}}$ (%)
Event selection	1.8	$\cdots$	$\cdots$	4.8	4.8
σ line shape	19.5	12.0	0.3	2.5	31.0
Z_c parametrization	3.9	$\cdots$	$\cdots$	15.5	7.9
Backgrounds	13.9	8.0	0.1	1.9	9.3
$f_0(980)$, g_1, g_2/g_1	17.5	14.0	0.6	2.4	24.6
$f_0(1370)$	16.7	11.0	0.4	11.5	14.0
Barrier radius	7.9	2.0	1.7	0.5	12.9
Z_c mass resolution	1.0	2.0	$\cdots$	0.4	0.5
Nonresonance	14.3	9.0	0.0	0.1	18.0
Total	38.0	24.8	1.9	20.3	49.2

Summary

- Z_c spin parity are studied with 1.92fb^{-1} data taken at 4.23 and 4.26 GeV, the data favors $J^P=1^+$ with statistical significance larger than 7σ over other quantum numbers, e.g. 0^-,1^-,2^+ and 2^-.
- 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
- Born cross section for $e^+e^- \to Z_c^+ \pi^- + c.c. \to \pi^+\pi^- J/\psi$
  $(21.8 \pm 1.0_{\text{stat}} \pm 4.4_{\text{syst}})$pb at 4.23 GeV
  $(11.0 \pm 1.2_{\text{stat}} \pm 5.4_{\text{syst}})$ pb at 4.26 GeV
- Significance for $e^+e^- \to Z_c^+(4020)\ \pi^- + c.c. \to \pi^+\pi^- J/\psi$ is ~3σ.
  Upper limits of cross section at 90% C.L.:
  0.9 pb (at 4.23 GeV), 1.4 pb (at 4.26 GeV)

PRL 119, 072001 (2017), BESIII

- **Ongoing partial wave analyses**

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

  determine the J^P of Zc(3900)^0 and its cross section

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

  determine the J^P of Zc(3885)$^\mp$ and its cross section

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

  determine the J^P of Zc(4020)$^\pm$ /Zc(4025) and its cross section

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

  determine the J^P of Zc(4025)$^\mp$ and its cross section

Thanks for your attention!