Determination of spin and parity of **Zc(3900)**

Ping Ronggang

Institute of High Energy Physics, CAS

(For BESIII collaboration)

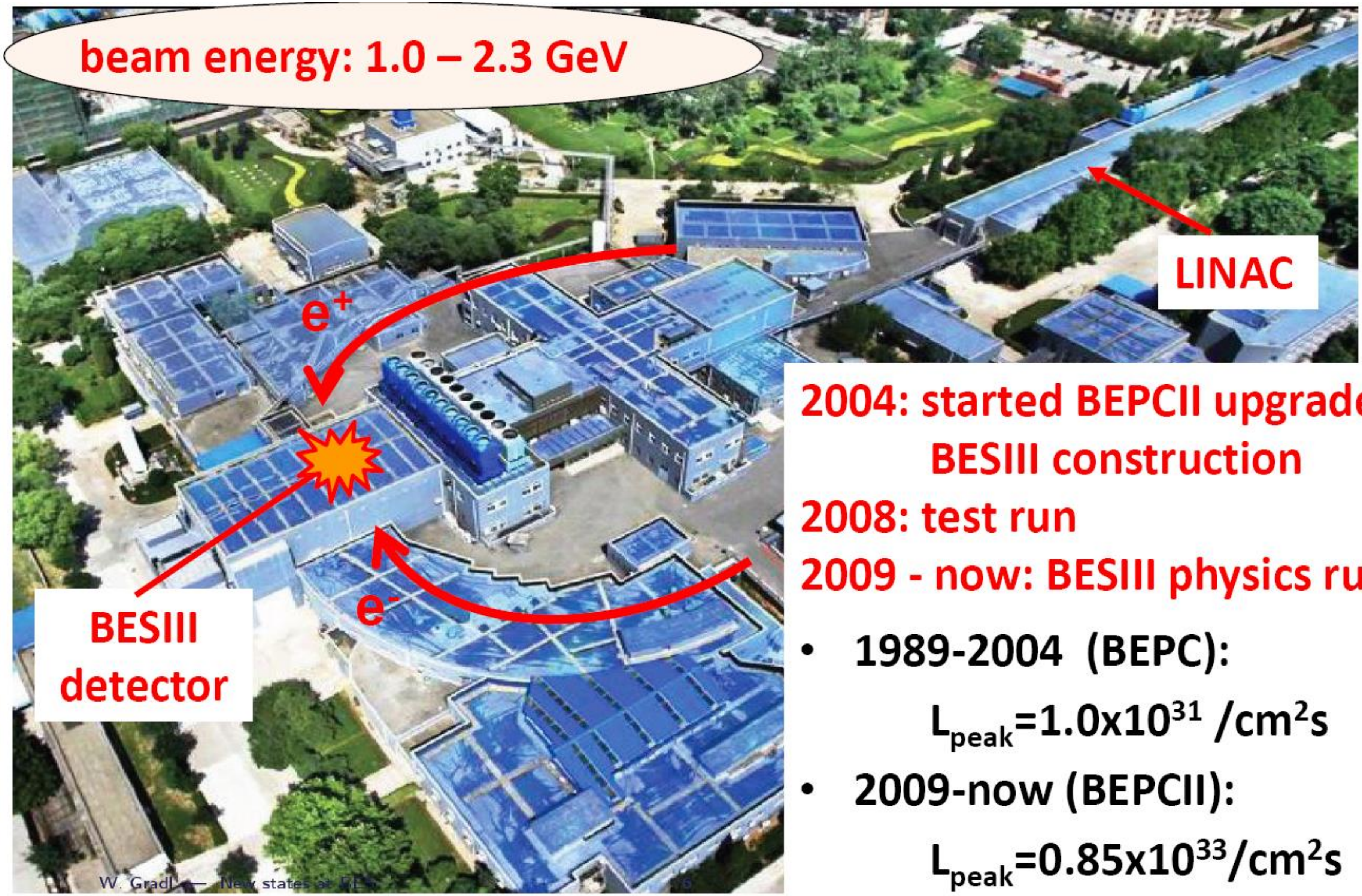
全国第十五届重味物理与CP破坏研讨会, 武汉，华中师大

HFCPV, Central China Normal University, Wuhai 2017-10-26

Outline:

- **Introduction**
- **Data sets**
- **Amplitude construction**
- **Partial wave analysis results**
- **Systematic uncertainties**
- **Summary**

Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade, BESIII construction

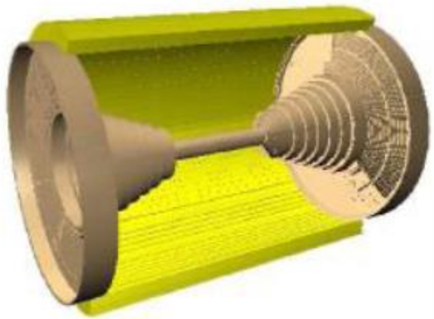
2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  $L_{peak}=1.0\times10^{31}\ /cm^2s$
- 2009-now (BEPCII):
  $L_{peak}=0.85\times10^{33}/cm^2s$

BESIII Detector

MDC

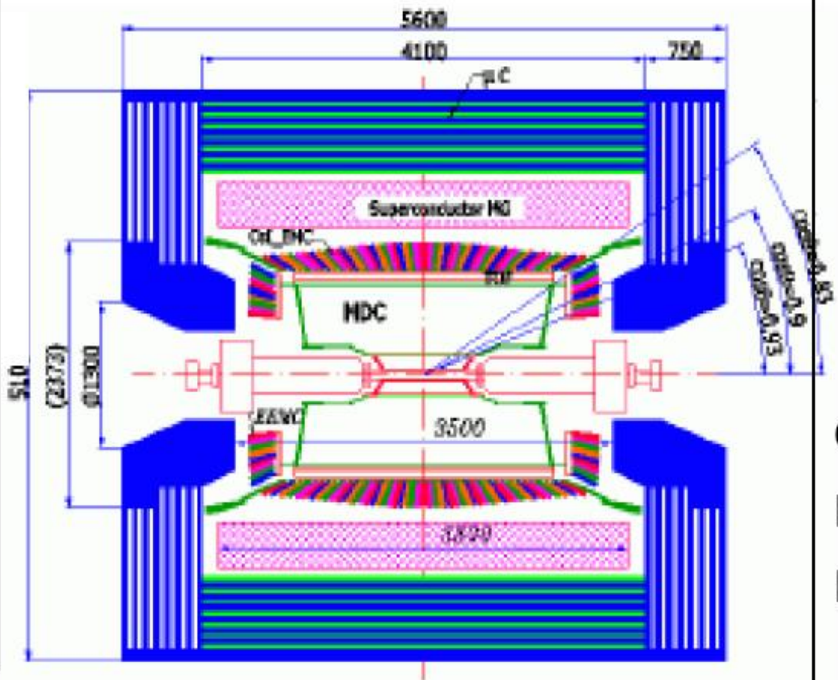


R inner: 63mm ;

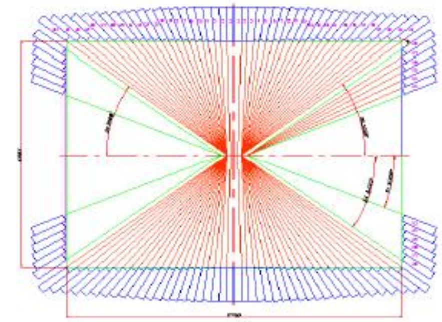
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



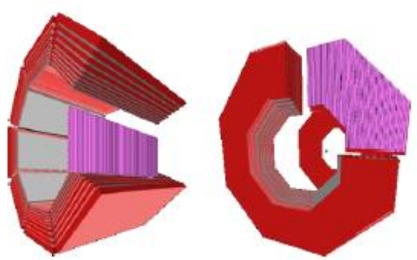
Crystals: 28 cm(15 X_0)

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

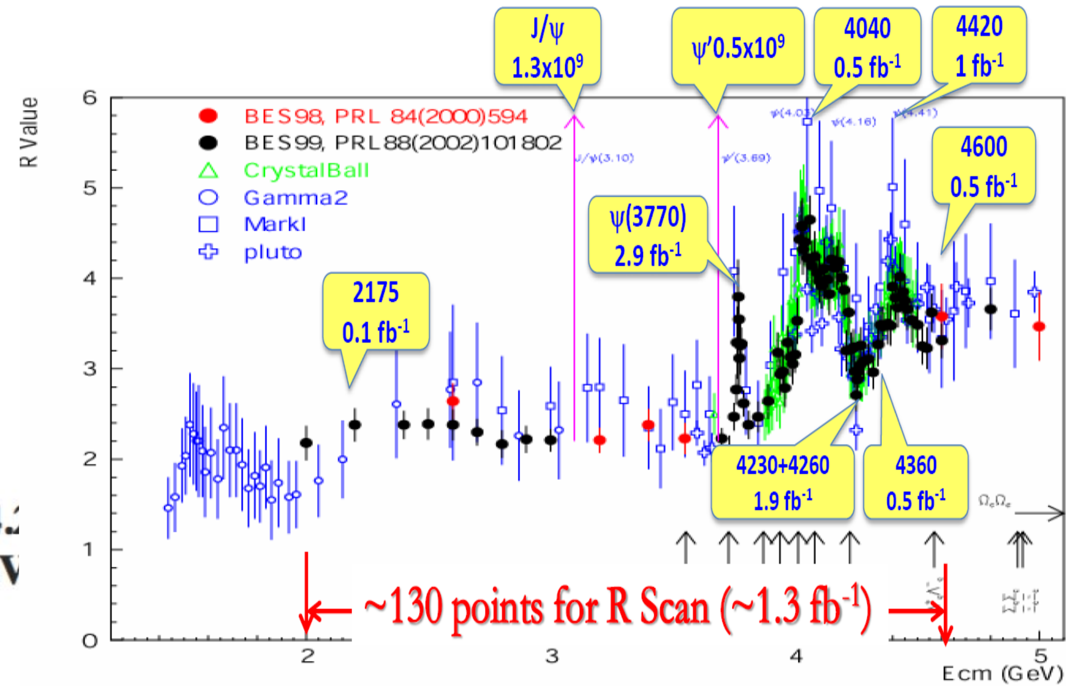
BTOF: two layers

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 $\boldsymbol{\psi(3770)}$ *(total)*
482 pb^{-1} at **4.01 GeV**
2012: 0.45B $\boldsymbol{\psi(2S)}$ *(total)*
1.3B $\boldsymbol{J/\psi}$ *(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.**
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 $\mathbf{D_s}$) *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)

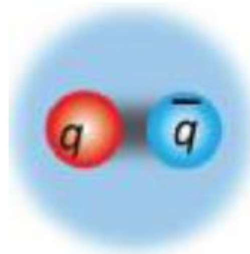


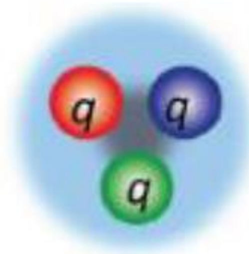
New forms of hadron

- **Conventional hadrons consist of 2 or 3 quarks:**

Naive Quark Model:

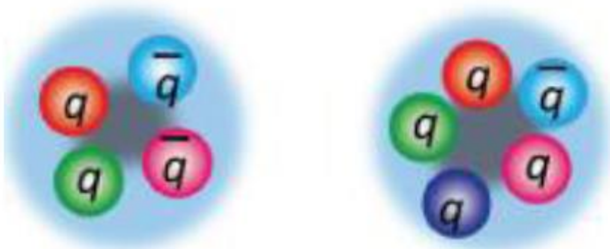
meson



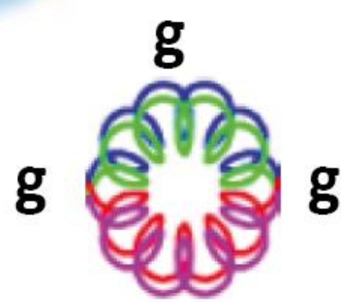


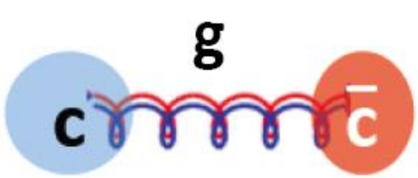
baryon

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



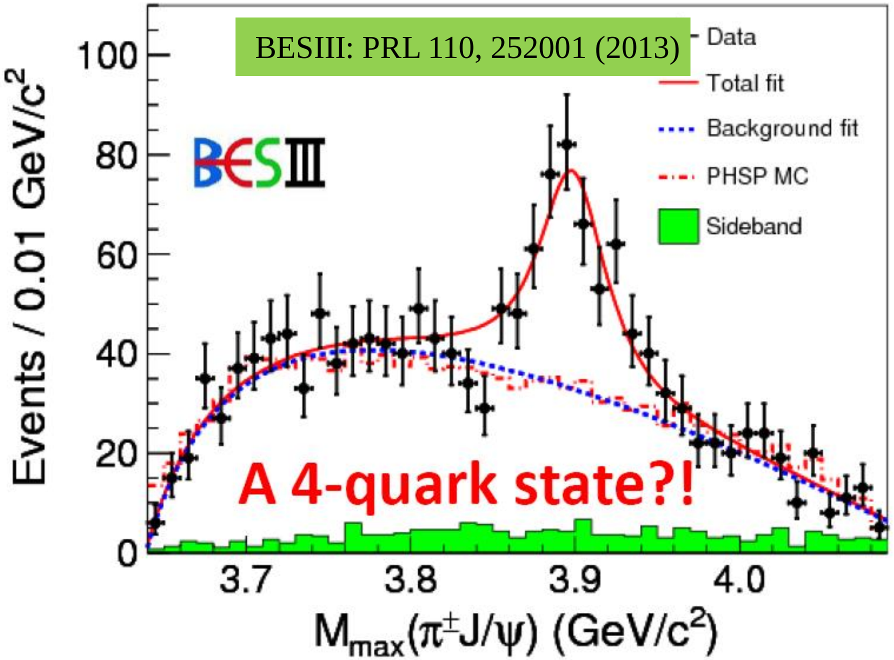
  - Hybrids： $q\bar{q}g$， $qqqg$ ...
  - Glueballs： gg， ggg ...





Observation of Zc(3900)

BESIII: PRL 110, 252001 (2013)



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

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

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

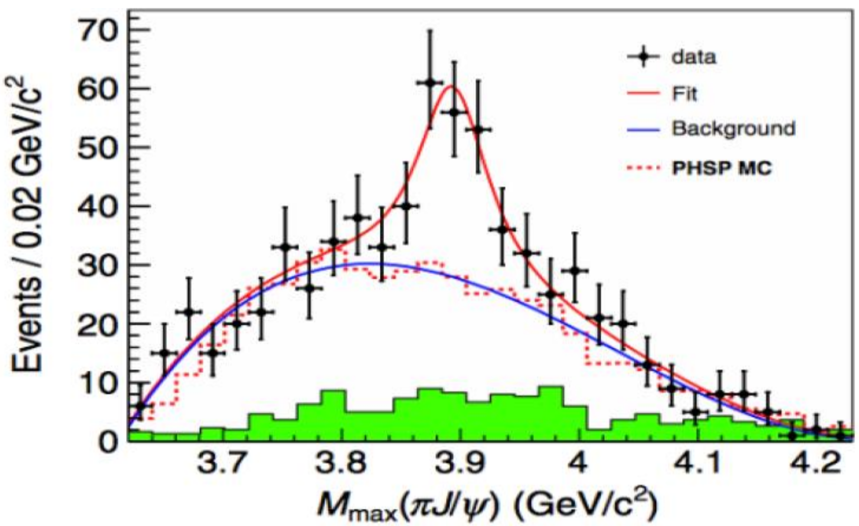
Mass close to $D\bar{D}^*$ threshold

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

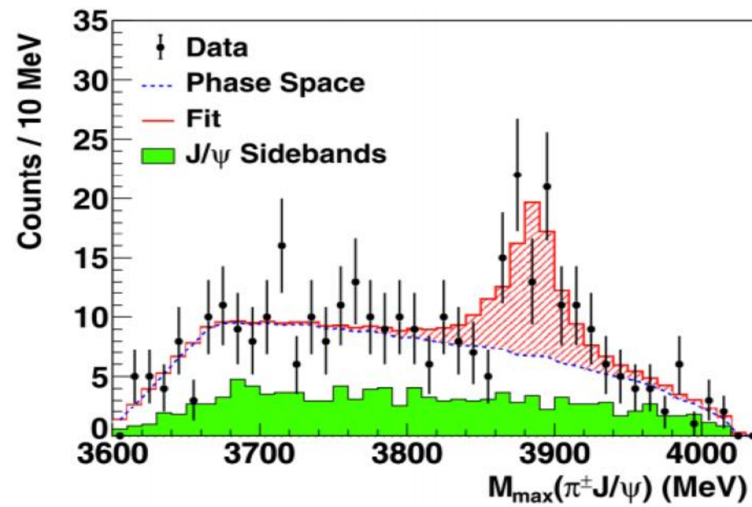
$$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7 \text{ pb at } 4.26 \text{ GeV}$$

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

Belle with ISR data (PRL110,252002)

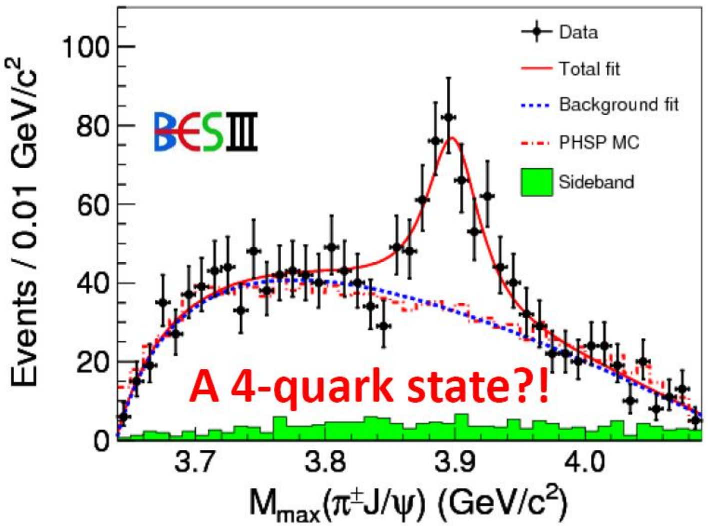


CLEOc data at 4.17 GeV (PLB 727,366)

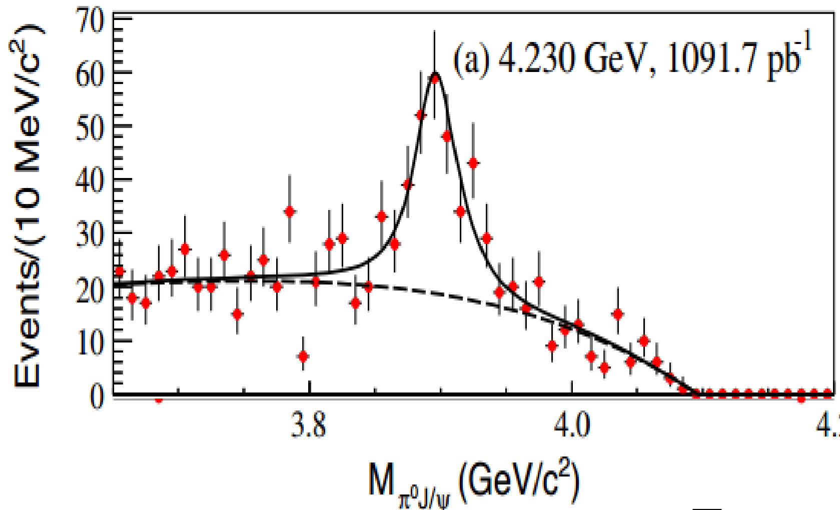


Overview Zc states from BESIII

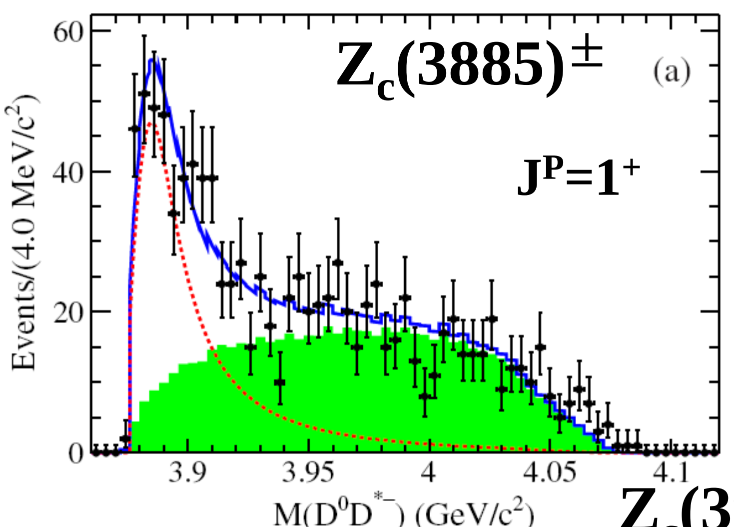
$Z_c(3900)^{\pm}: e^+e^- \to \pi^+\pi^- J/\psi$



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

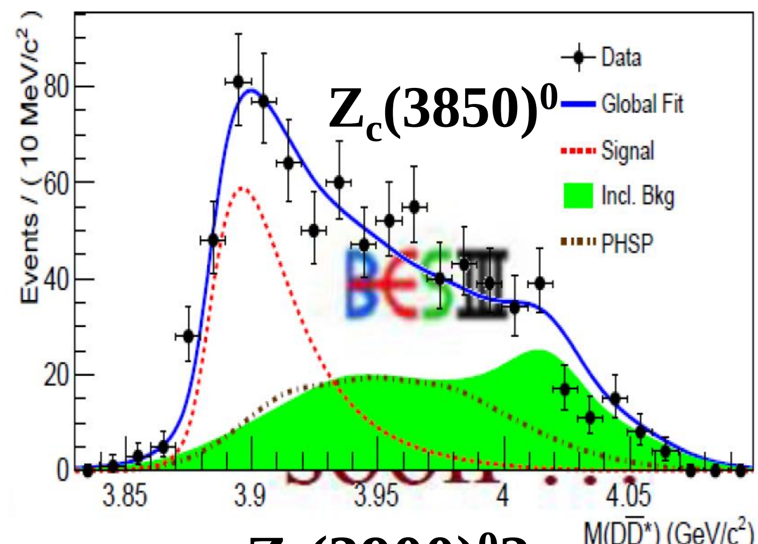


$Z_c(3885)^{\pm}: e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$



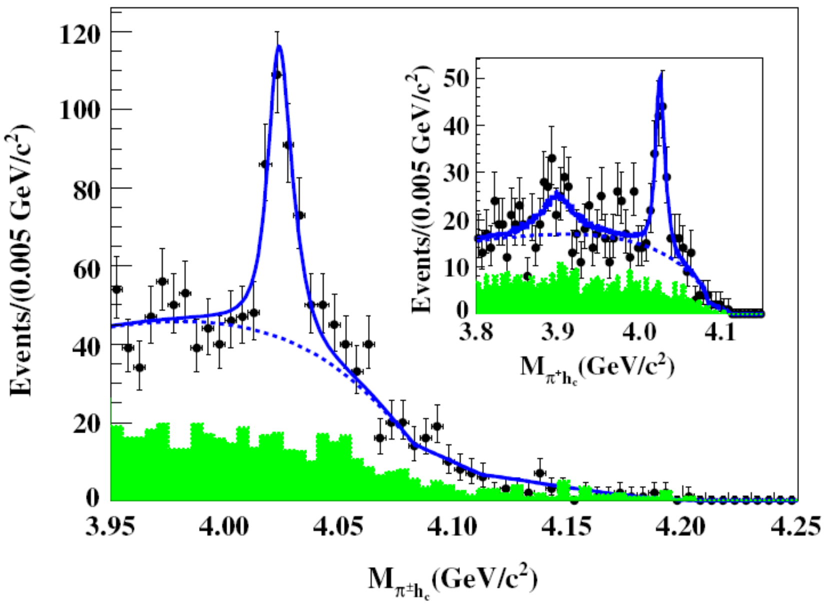
$Z_c(3900)^{\pm}$?

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

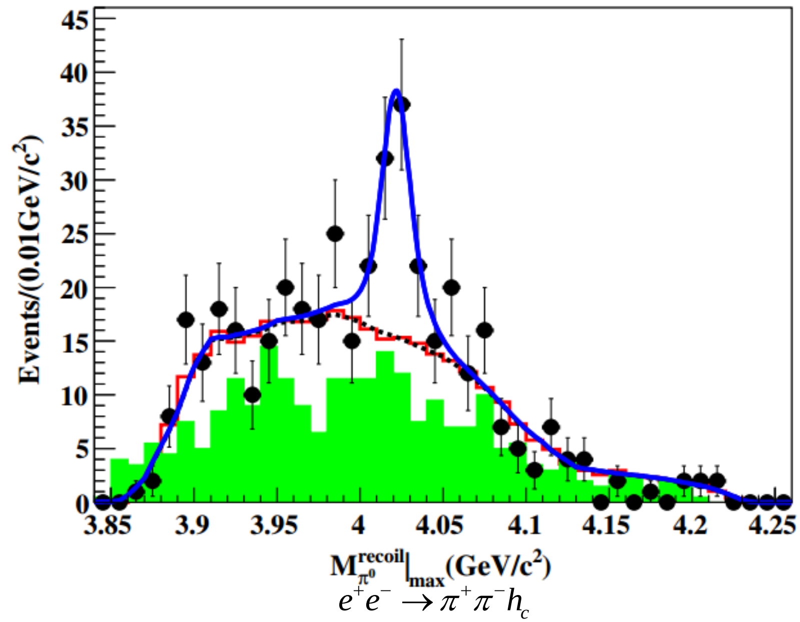


$Z_c(3900)^0$?

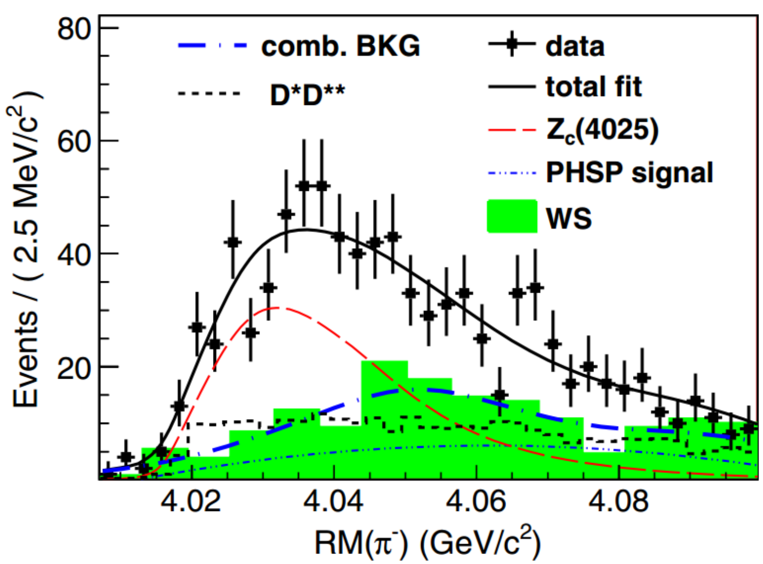
$Z_c(4020)^{\pm}: e^+e^- \to \pi^+\pi^- h_c$



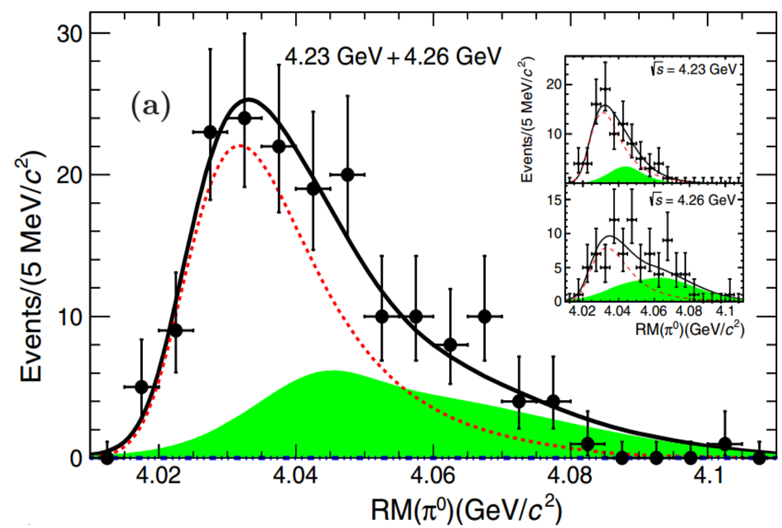
$Z_c(4020)^{\pm}: e^+e^- \to \pi^0\pi^0 h_c$



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



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



- Theoretical investigation on $Z_c(3900)$

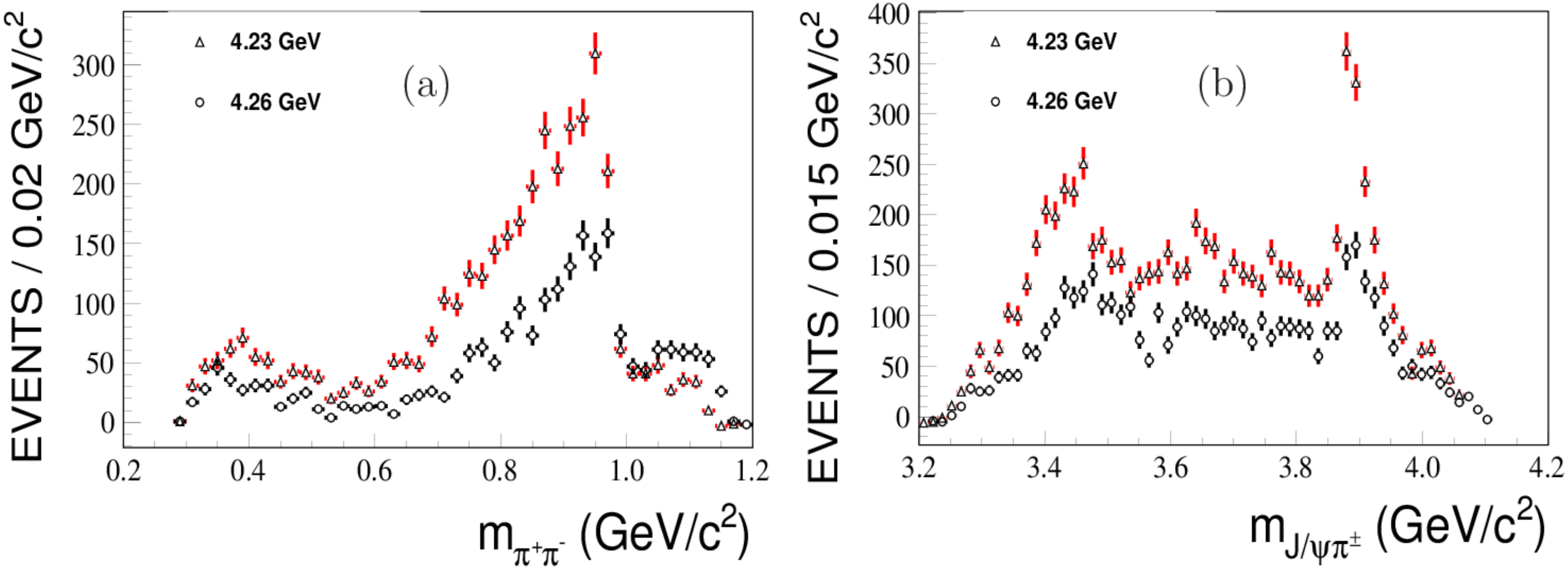
  Tetraquarks: PRD85, 054011 (2012) , PRD87, 111102 (2013), JHEP 1307, 153 (2013), arXiv: 1304.1301
  Hadronic molecules: PRD88, 054007 (2013), PL B726, 326 (2013), JPG41, 075003 (2014)
  Meson loop: PRL 111, 132003 (2013), EPJ C73, 2621 (2013)
  ISPE model: PRD88, 025021 (2013)

- 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 $Z_c \to \rho\eta_c$.

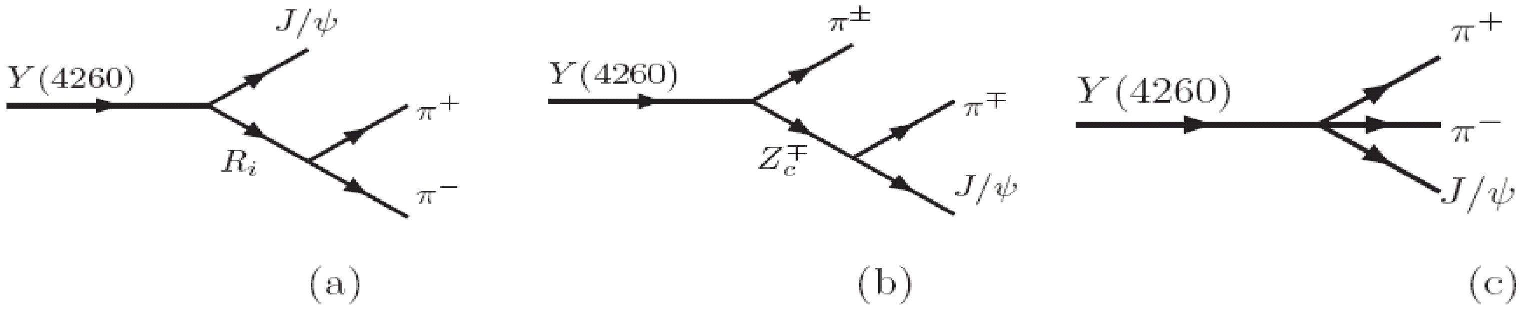
M. B. Voloshin, PRD87, 091501 (2013)

Consistency of Zc(3900) at 4.23 and 4.26 GeV



- Total ~6,000 events (4,400 at 4.23GeV, 2,400 at 4.26 GeV)
- Zc peak consistent at two energy point
- σ and f_0(980) significantly observed
- Two pion spectrum above 1GeV shows difference.

Amplitude construction



(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 Zc 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 parameterized with Flatte function

- Z_c lineshape parameterized with Flatte-like function

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

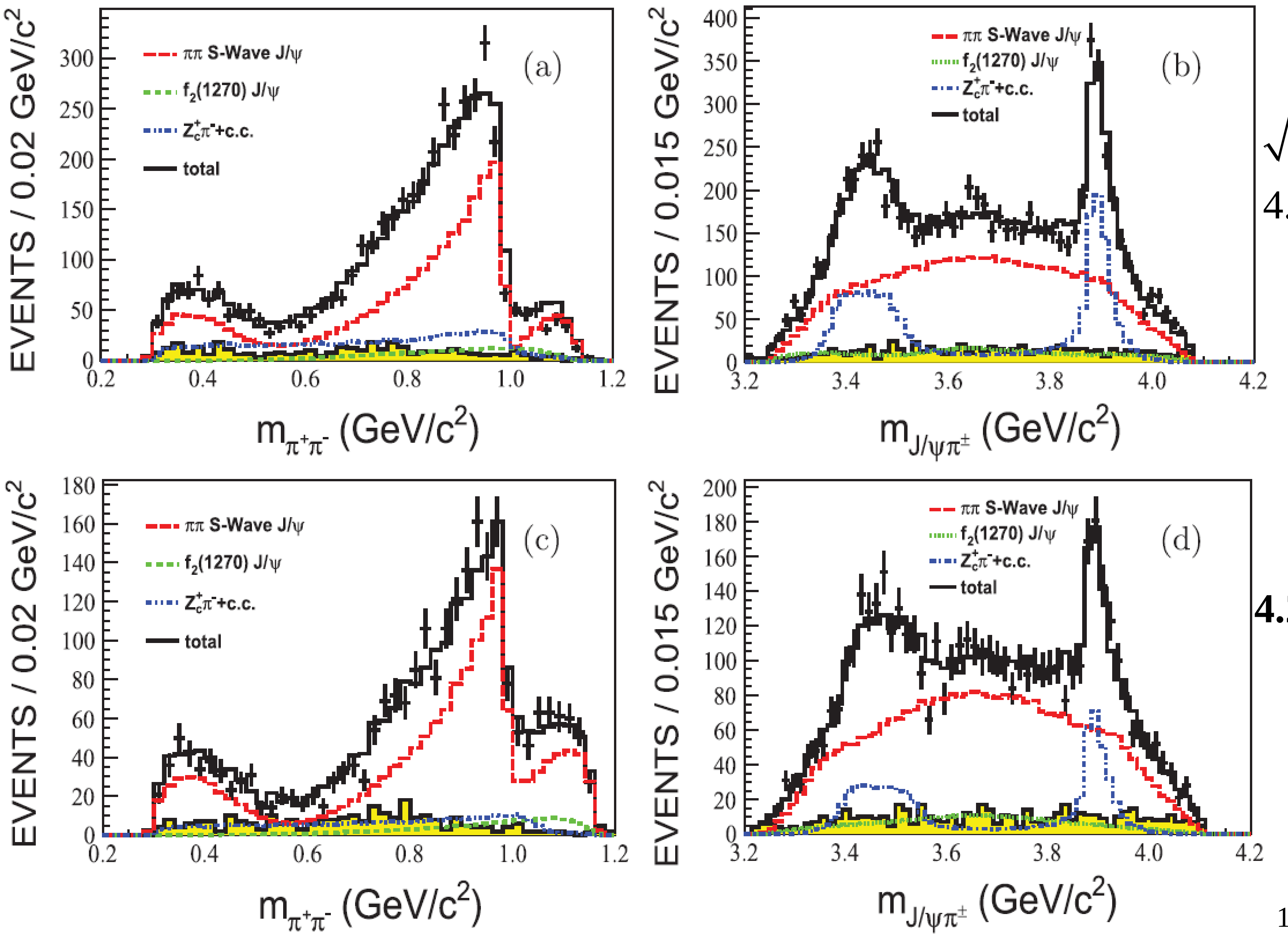
- Z_c^+ and Z_c^+ assumed as isospin partner

- 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^+



$\sqrt{s}$ = 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 with:

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

- Data disfavor constant width Breit-Wigner parametrization of Z_c

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

  $-\ln L$ increases by 22 with $\Delta(\text{ndf}) = 1$

- Helicity amplitudes for Z_c production and decays

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

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

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

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

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

- $\pi\pi$-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 $e^+e^- \to Z_c^+ \pi^- + c.c \to \pi^+\pi^- J/\psi$

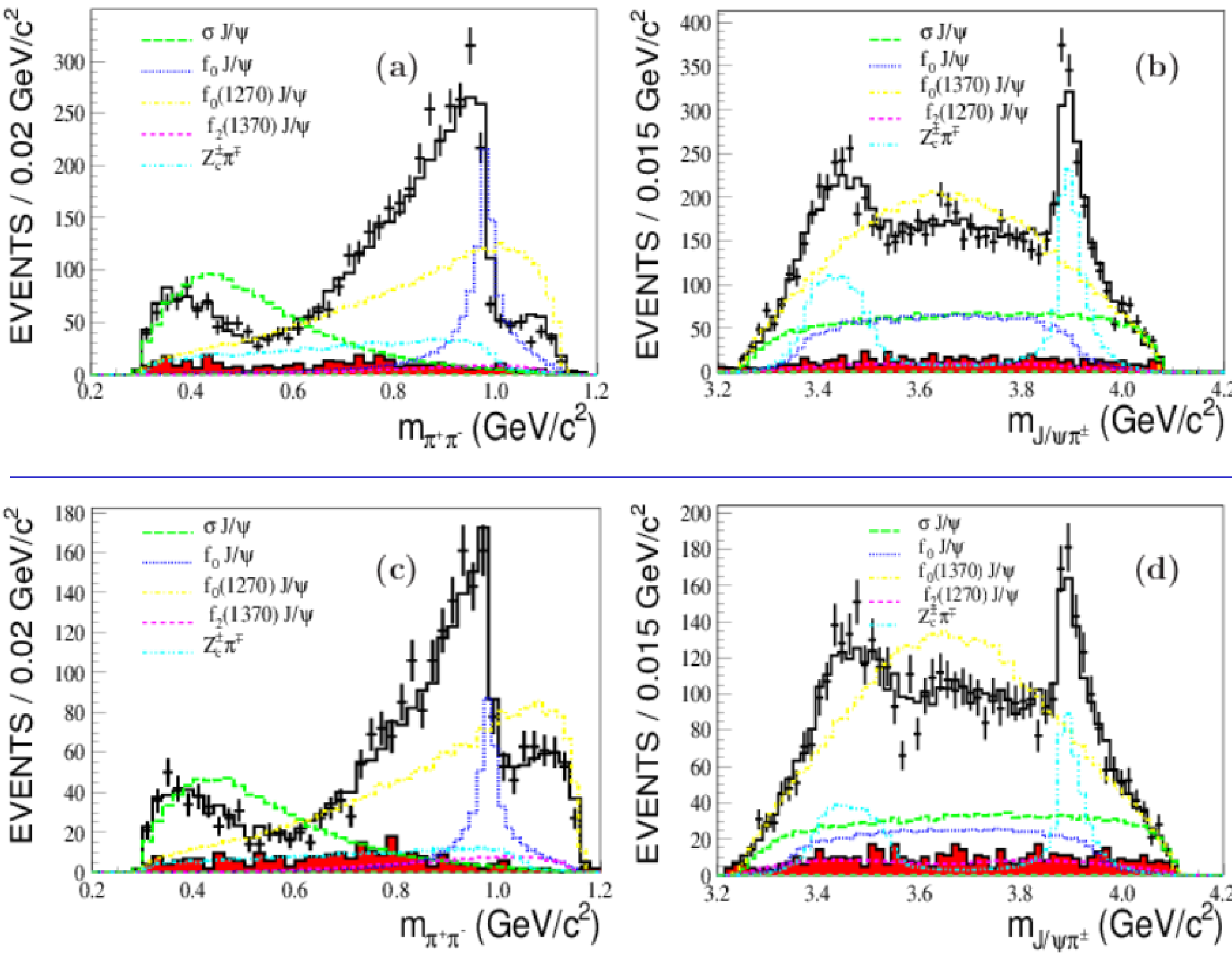
$(21.8 \pm 1.0_{\text{stat}} \pm 4.4_{\text{sys}})$ pb at 4.23 GeV

$(11.0 \pm 1.2_{\text{stat}} \pm 5.4_{\text{sys}})$ 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.

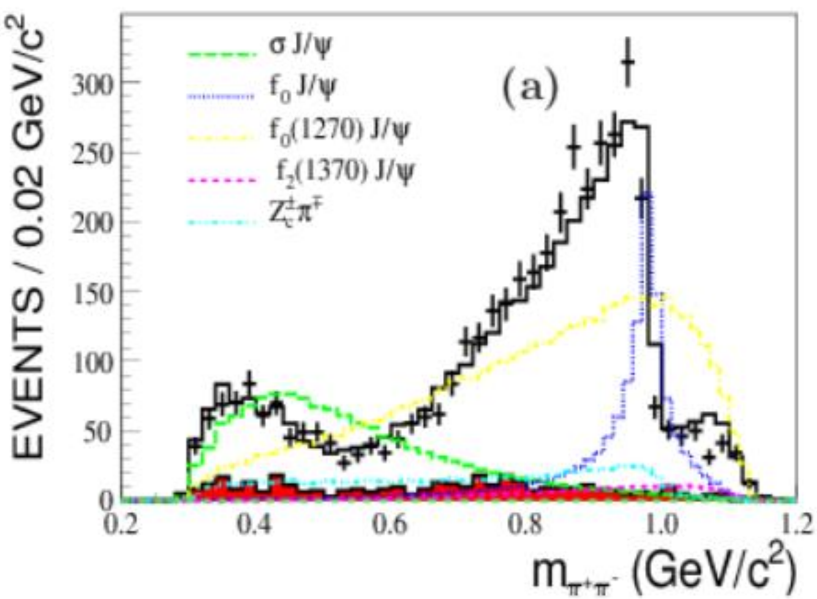
Check other spin-parity numbers for Z_c

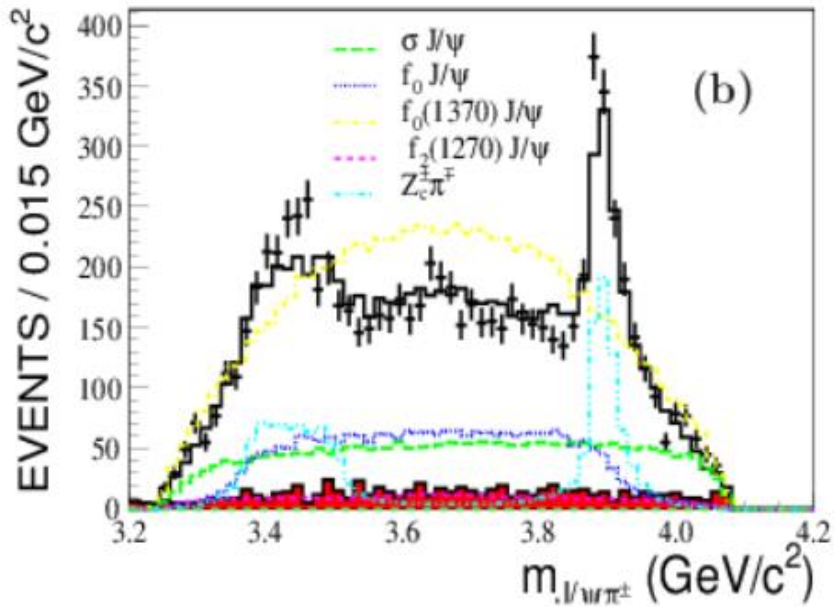


$J^P=0^-$

$\sqrt{s}=$ 4.23 GeV

4.26 GeV

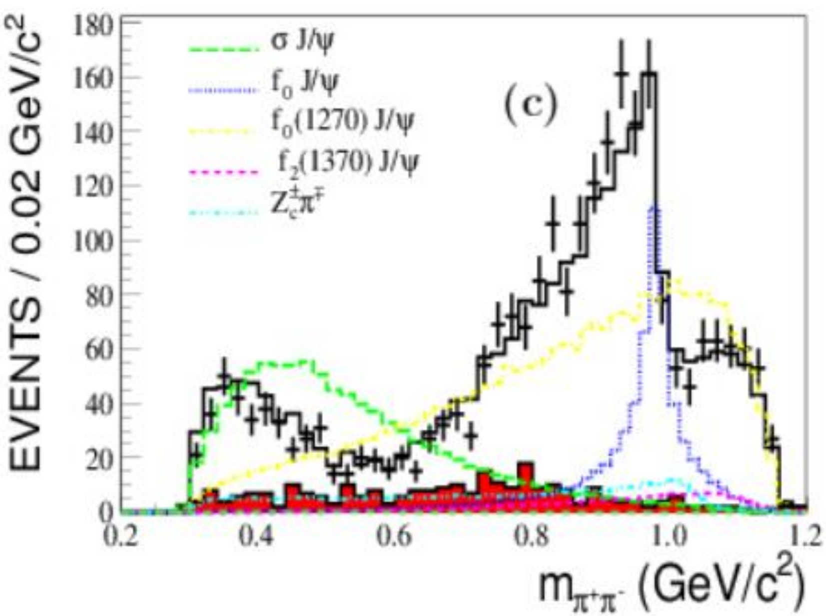


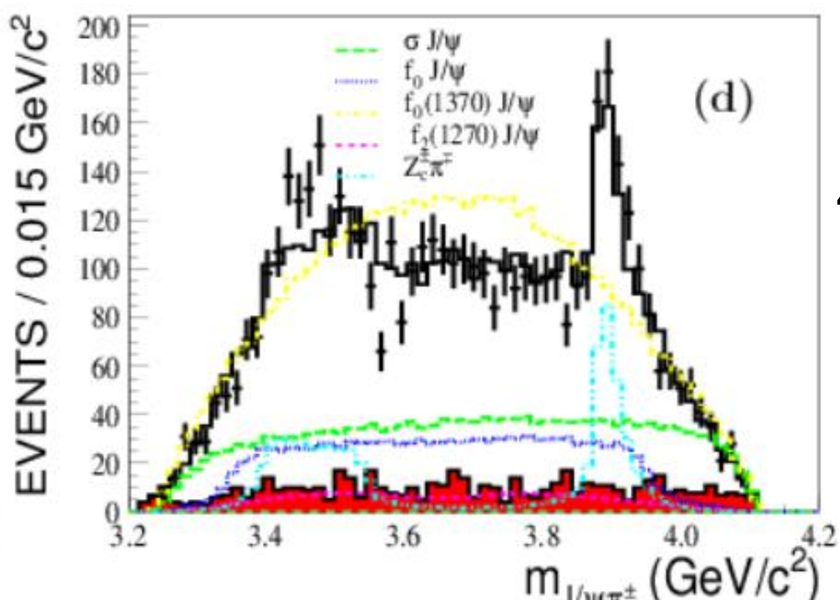


$J^P=1^-$

$\sqrt{s}$ =

4.23 GeV

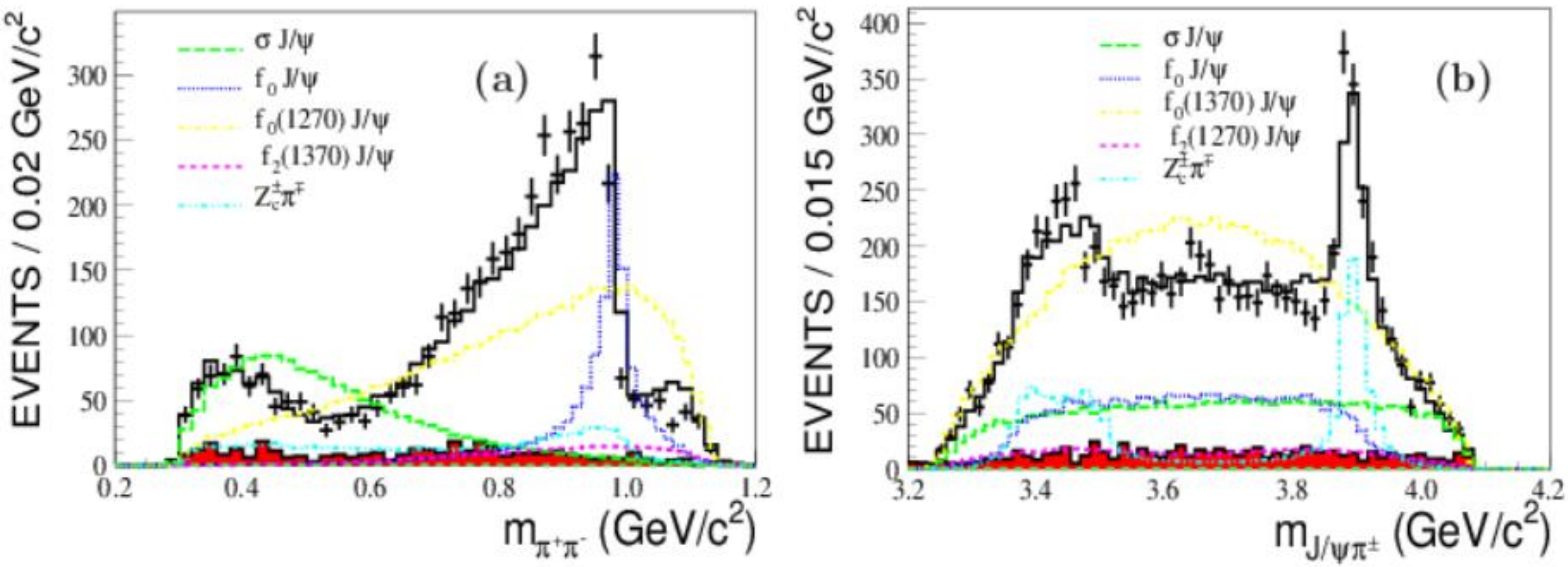




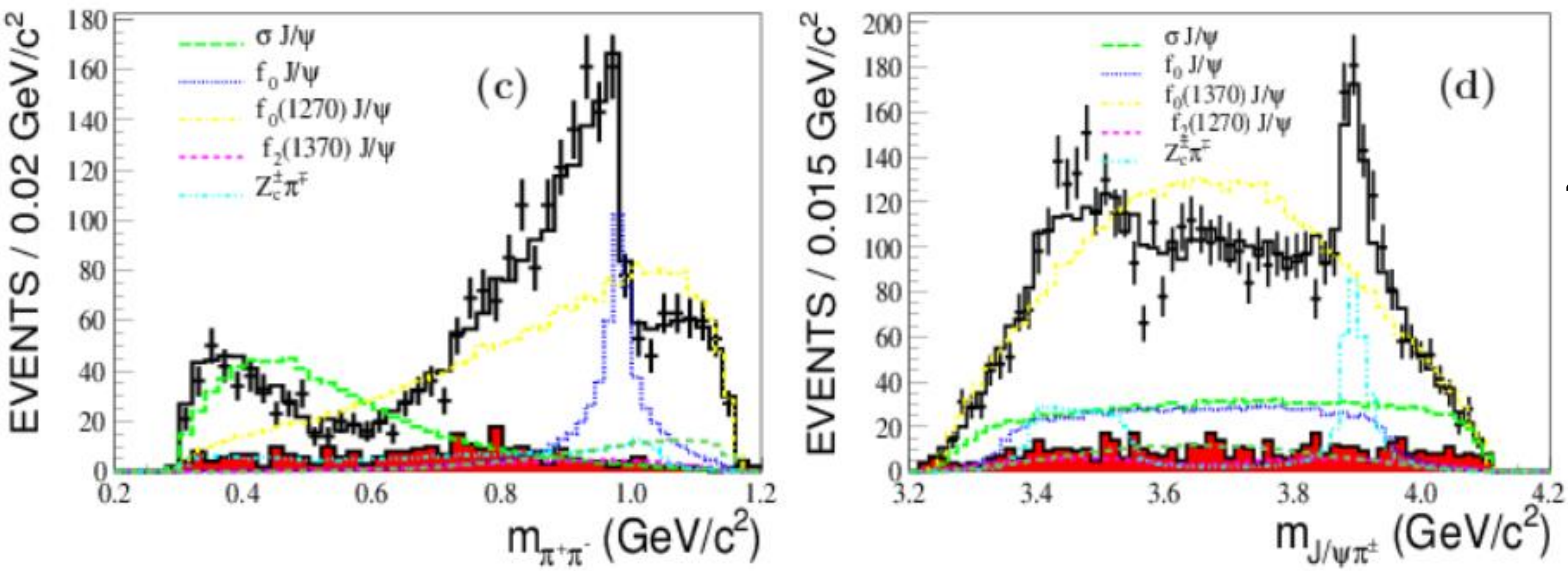
4.26 GeV

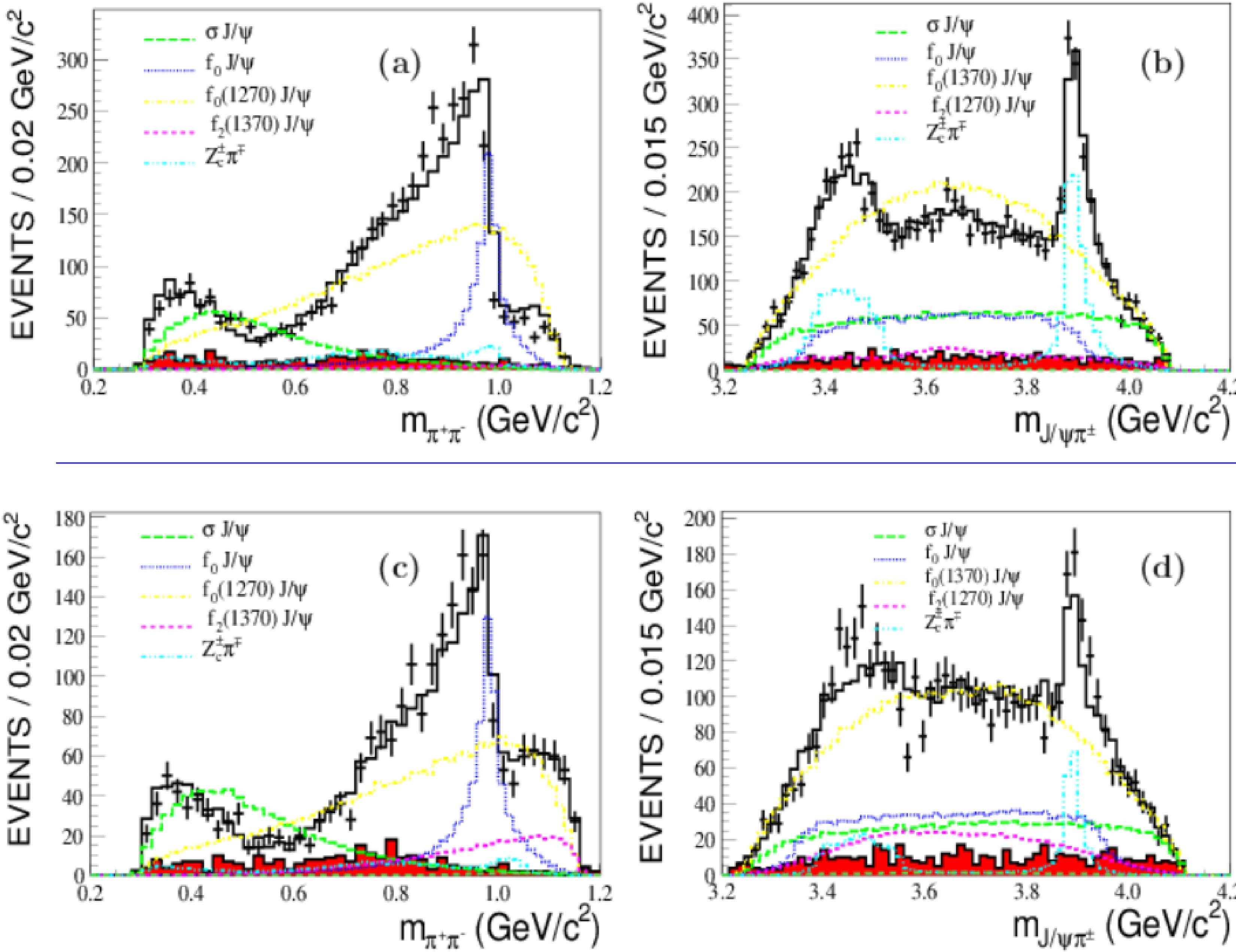
$J^P=2^-$

$\sqrt{s}$ = 4.23 GeV



4.26 GeV





$J^P=2^+$

$\sqrt{s}$ =

4.23 GeV

4.26 GeV

Comparison of fit results with different J^P for Z_c

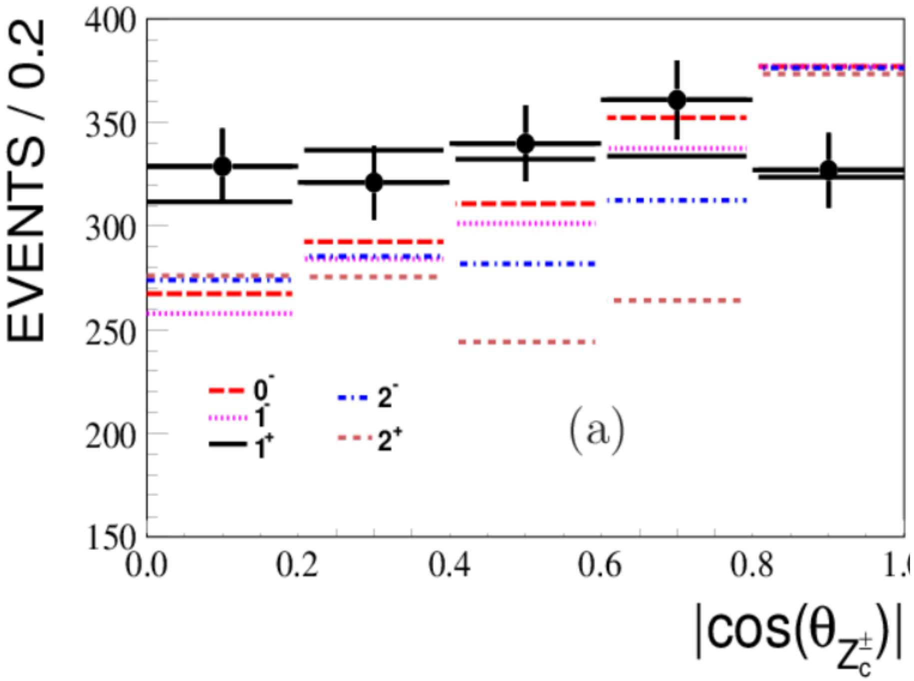
- Mass, g_1' and Log-likelihood

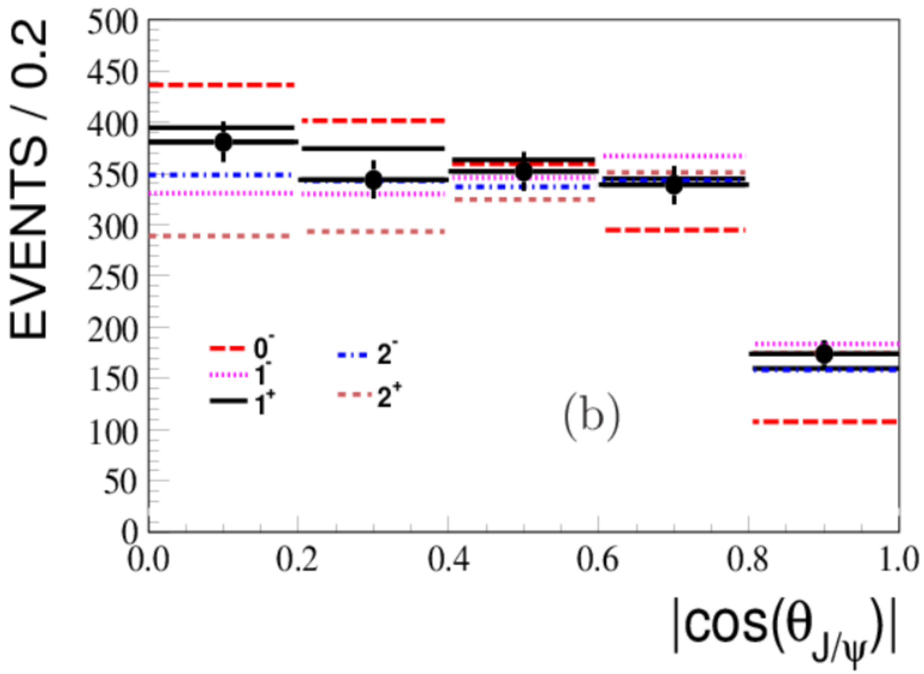
$Z_c : J^P$	M (MeV)	$g_1'(\mathrm{GeV}^2)$	g_2'/g_1'	$-\ln L$
0^-	3899.7 ± 2.1	0.079 ± 0.005	25.8 ± 2.9	-1491.6
1^-	3901.1 ± 1.8	0.063 ± 0.005	24.1 ± 2.3	-1434.4
1^+	3901.5 ± 2.7	0.075 ± 0.006	27.1 ± 2.0	-1599.1
2^-	3900.9 ± 1.6	0.060 ± 0.004	25.3 ± 2.4	-1464.6
2^+	3893.6 ± 1.6	0.051 ± 0.005	25.3 ± 2.9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

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

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 Zc mass region





- Events in the Z_c mass region $M_{\pi J/\psi} \in (3.86, 3.92)$ GeV
- Background events substrated
- θ_{Zc} : the polar angle of Zc, $\theta_{J/\psi}$: 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 $[\sigma_0, f_0(980), f_2(1270), f_0(1370), Zc(J^P \neq 1^+)]$

Alternative hypothesis H_1:

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

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

Comments from PRL referees and editor

■ Comments from PRL referees arXiv:1706.04100

The BESIII collaboration has an excellent track record in the field of spectroscopy in the sector of charmonia and charmonium-like mesons…..

Using partial-wave analyses, spin and parity of one of the charged states containing a pair of charm-anticharm and, thus, exhibiting a structure that cannot be reduced to simple quark-antiquark dynamics are addressed.

This is a very important contribution in view of the ongoing discussion of the nature of these puzzling states.

Besides mass, width, and production cross sections, open questions remained, and in particular spin and parity are crucial properties to know in order to understand the structure of this and make connections to other observations. The present paper unambiguously answers this question, by ruling out other than the 1+ spin-parity assignment with significances exceeding seven standard deviations.

The measurement will undoubtedly trigger a significant number of phenomenological publications.

- **Selected as Physics synopsis by the PRL Journal**

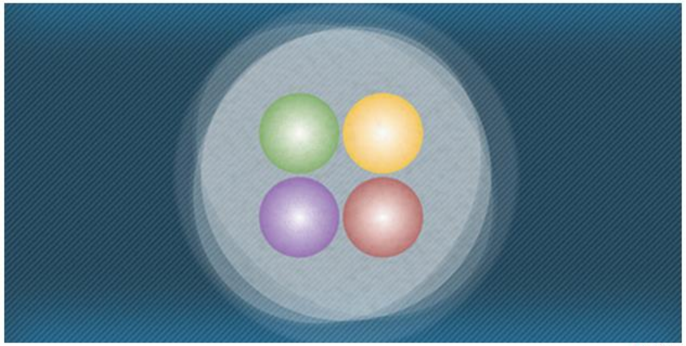
Determination of the Spin and Parity of the Zc(3900), M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **119**, 072001 – Published 16 August 2017

Physics synopsis: https://physics.aps.org/synopsis-for/10.1103/PhysRevLett.119.072001

Synopsis: Filling in a Tetraquark's Profile

August 16, 2017

An analysis of electron-positron collision data has determined the spin and parity of a particle thought to consist of four quarks.



Fermilab

- 高能物理研究所/ 2017高能新闻

Zc(3900)的自旋和宇称量子数确立

Summary

- Z_c spin parity are studied with 1.92pb^{-1} data taken at 4.23 and 4.26 GeV, the data suggests $J^P=1^+$ 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

  $M_{pole} = (3881.2 \pm 4.2 \pm 52.7)$ MeV, $\Gamma_{pole} = (51.8 \pm 4.6 \pm 36.0)$ MeV
- Born cross section for $e^+e^- \to Z_c^+ \pi^- + c.c \to \pi^+\pi^- J/\psi$

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

  $(11.0 \pm 1.2_{stat} \pm 5.4_{syst})$ 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)

- Ongoing partial wave analyses

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

determine the J^P of $Zc(3900)^{\pm}$ 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!