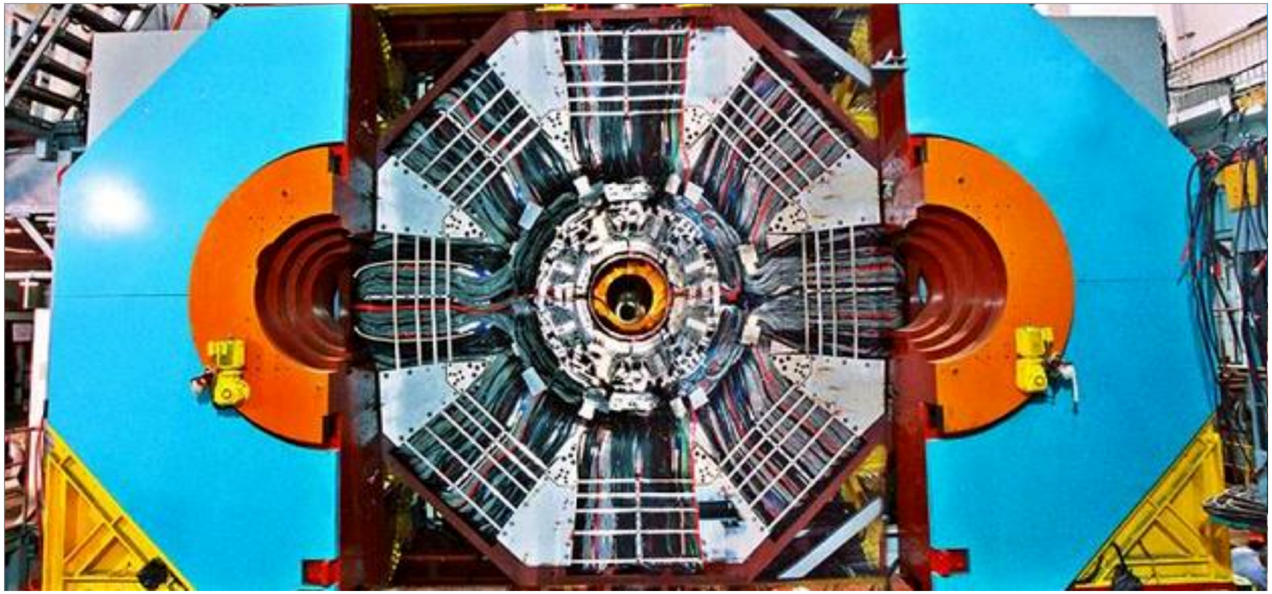


The charged and neutral Zc states at BESIII

Pei-Rong Li

University of Chinese Academy of Sciences, Beijing

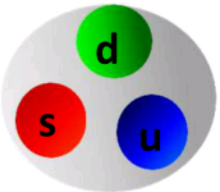
(On behalf of the BESIII collaboration)

XVII International Conference on Hadron Spectroscopy and Structure(Hadron2017)

Outline

- **Introduction**
- **The BESIII Experiment**
- **The Z_c states**
- **Summary**

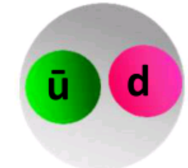
Constitution of hadrons in QCD



Baryons are red-blue-green triplets

ordinary matter

Mesons are color-anticolor pairs



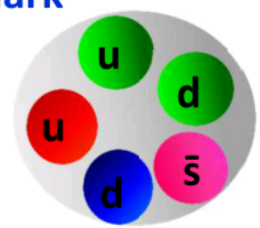
Λ=usd

π=ūd

Other possible combinations of quarks and gluons :

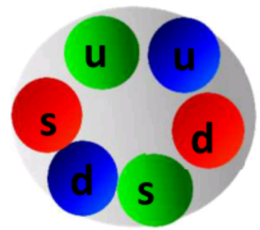
Pentaquark

S= +1 Baryon



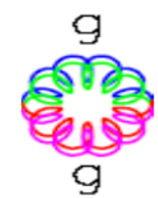
H di-Baryon

Tightly bound 6 quark state



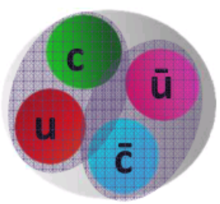
Glueball

Color-singlet multi-gluon bound state



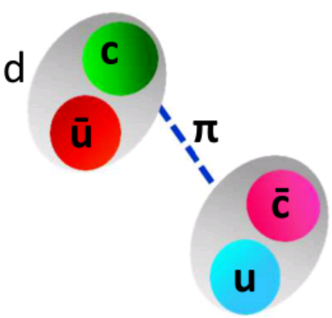
Tetraquark

Tightly bound diquark & anti-diquark

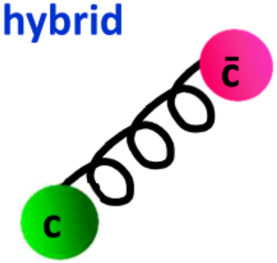


Molecule

loosely bound meson-antimeson “molecule”

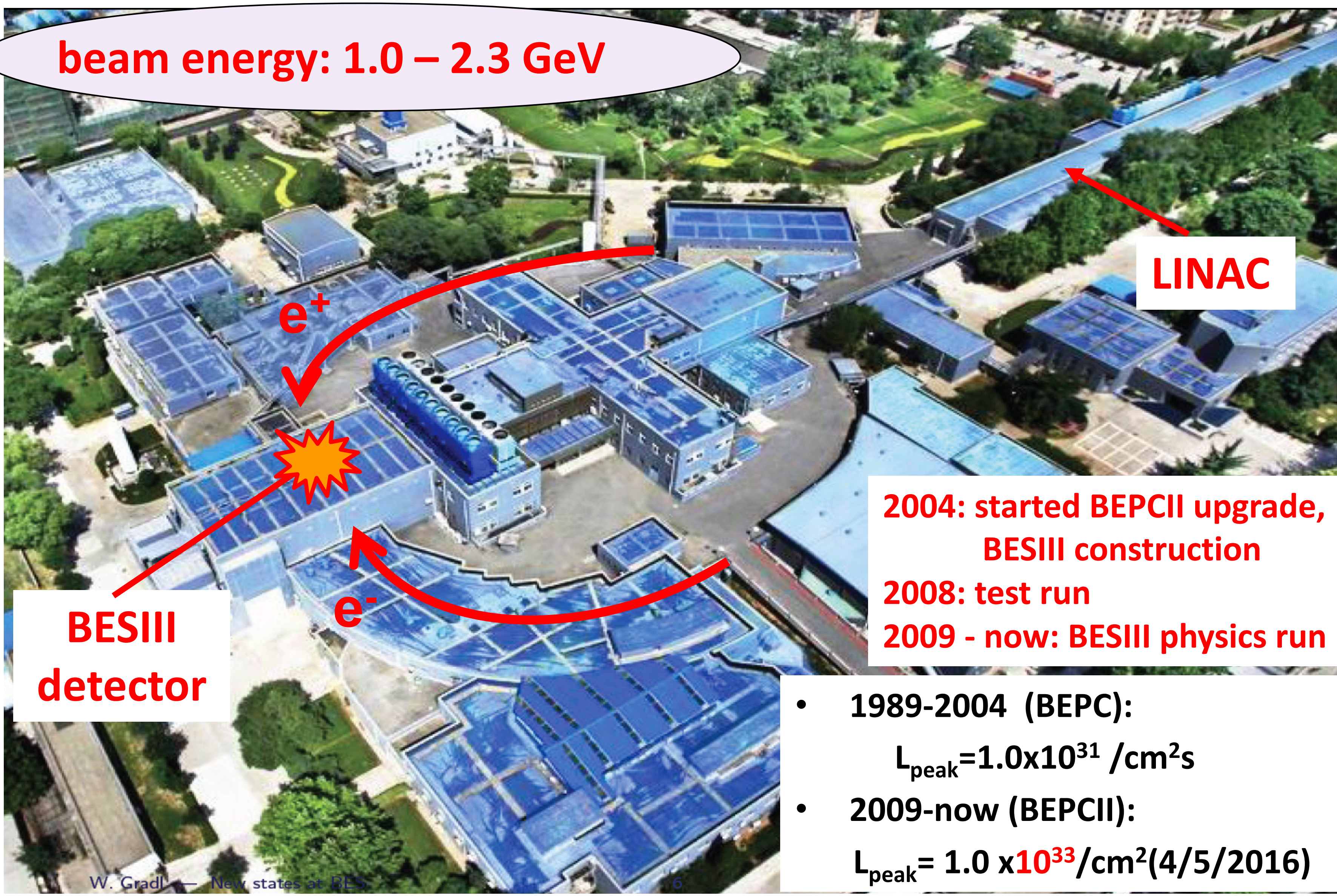


$q\bar{q}$ -gluon hybrid mesons



However, none of them are established and they are exotica!!!

Beijing Electron Positron Collider (BEPC)

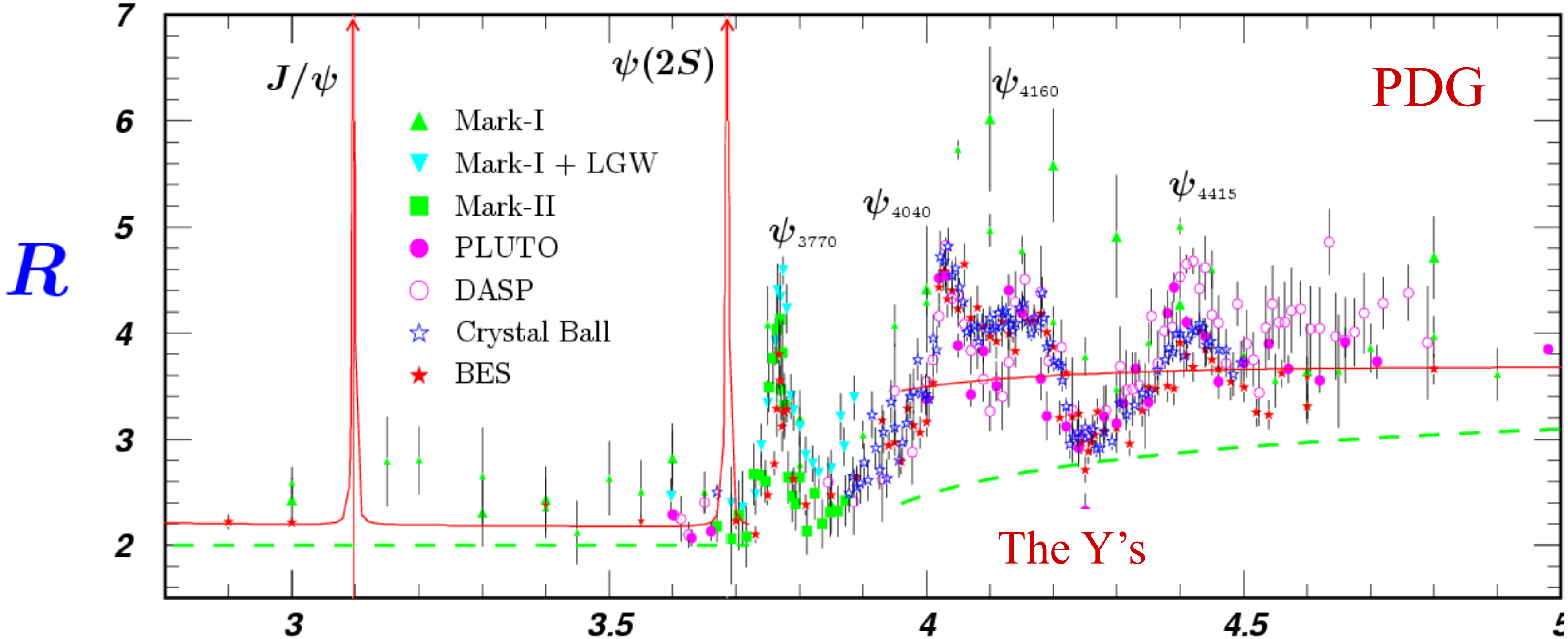


2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run

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

Features of the BEPC Energy Region

- **Rich of resonances: charmonia(-like) and charmed hadrons**
- **Threshold characteristics (pairs of τ, D, D_s, Λ_c ...)**
- **Transition between smooth and resonances, perturbative and non-perturbative QCD**
- **Energy location of the new hadrons: glueballs, hybrids, multi-quark states**

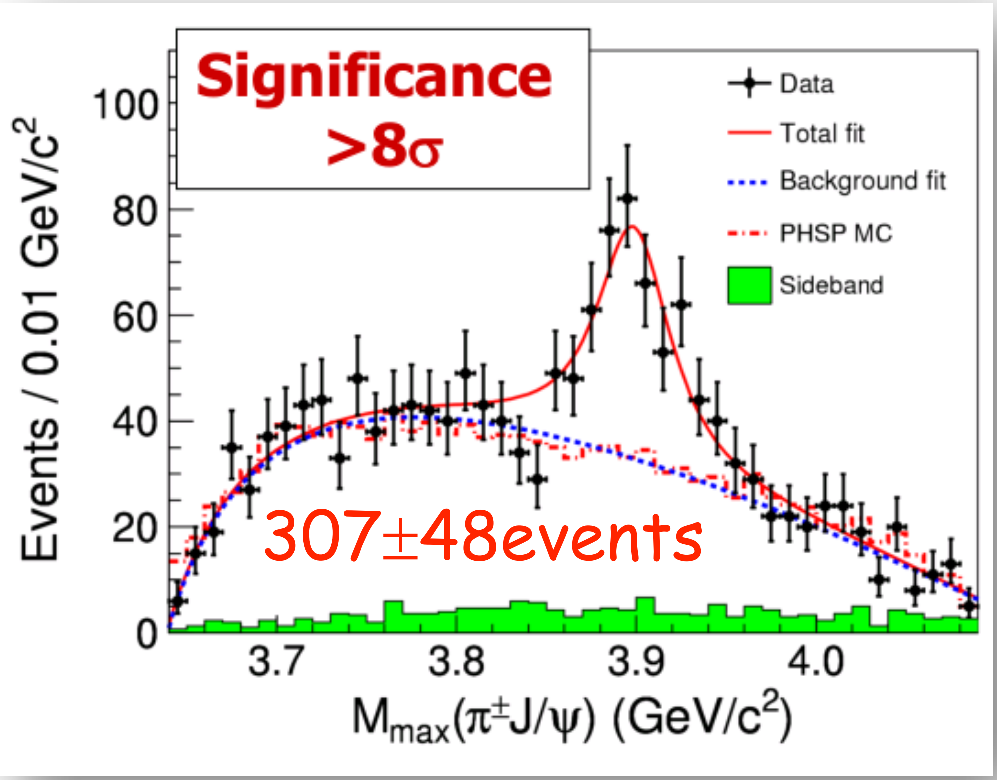


The Zc states

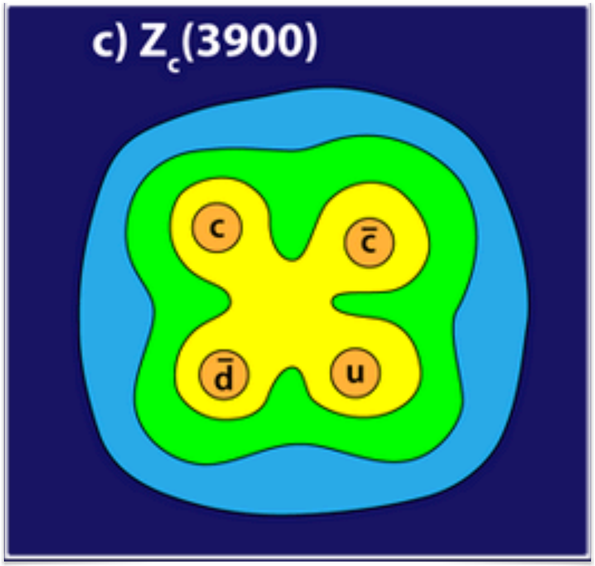
Z states: charmonium-like states **carrying electric charge**; must contain at least cc and a light qq pair

$Z_c^+(3900)$ discovery

PRL110, 252001 (2013)



Mass = (3899.0±3.6±4.9) MeV
Width = (46±10±20) MeV



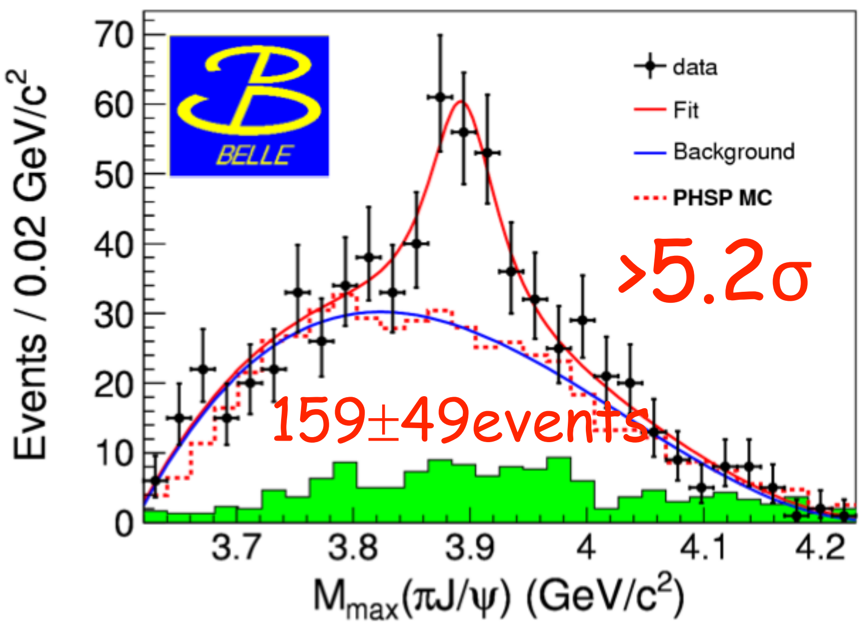
from APS/Alan Stonebraker

- Couples to $c\bar{c}$
- Has electric charge **1**

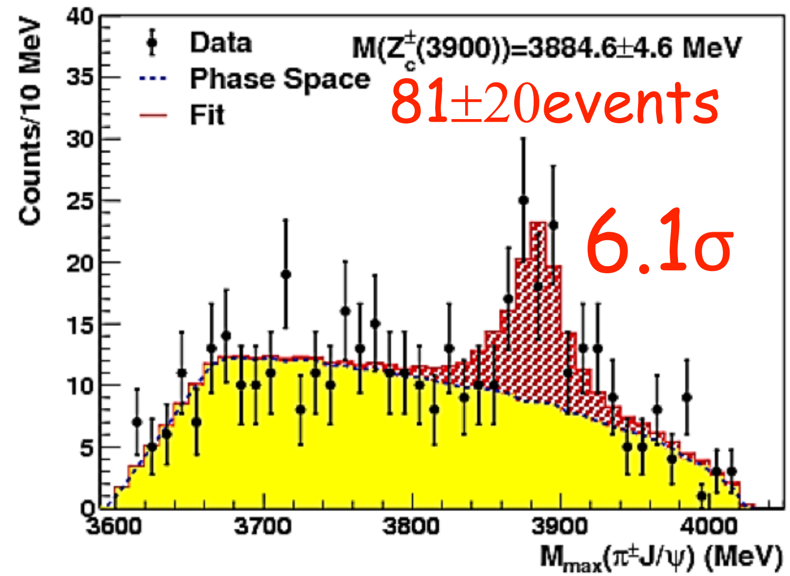
➔ consists of at least four quarks of $c\bar{c}u\bar{d}$

BESIII Confirmations from other experiments

Belle with ISR-return from Y(nS) data set
PRL110, 252002 (2013)



CLEOc data at 4.17 GeV:
PLB 727, 366 (2013)



Mass = (3894.5±6.6±4.5) MeV
Width = (63±24±26) MeV

Mass = (3885±5±1) MeV
Width = (34±12±4) MeV

Consistent results from other electron-positron annihilation experiments!

Nature of the exotic $Zc^{+}(3900)$

- ➢ Its mass lies close to the threshold of m(D)+m(D*)

DD* molecule?

tetraquark?

and other scenarios:

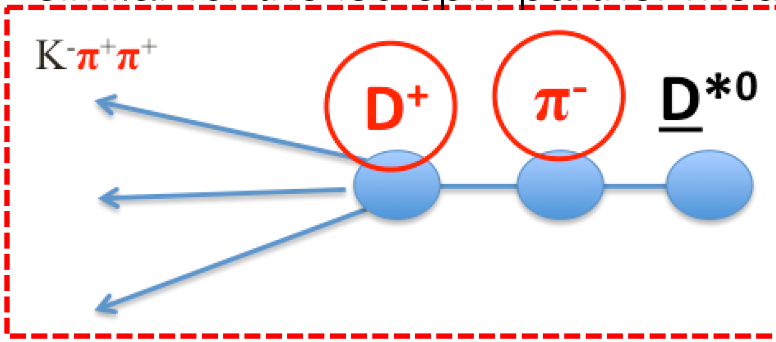
- Cusp?
- Threshold effect?
- ...

- ➢ Other decay mode of the Zc(3900)?
- ➢ Partner(s) of the Zc?

BESIII $e^+e^- \rightarrow \pi^- Z^+_c(3885) \rightarrow \pi^-(DD^*)^+$ at 4.26GeV

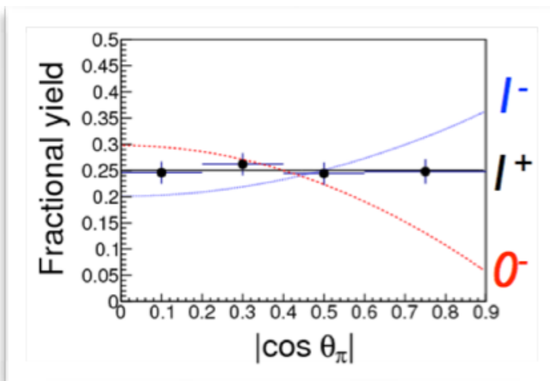
PRL110, 252001 (2013)

similar for the iso-spin partner mode



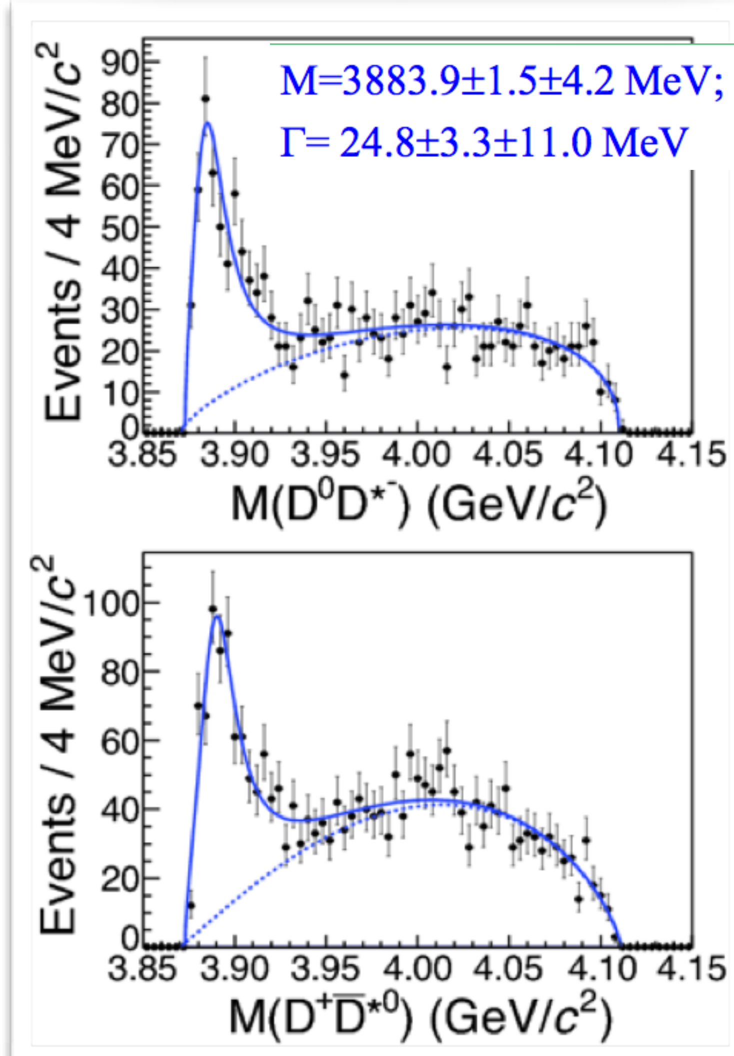
If $Z_c(3885)$ is $Z_c(3900)$:

$$R = \frac{\Gamma(Z_c(3885) \rightarrow (\bar{D}D^*)^+)}{\Gamma(Z_c(3900) \rightarrow \pi^+ J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$



Angular distribution favors **1⁺** and disfavors 1⁻ or 0⁻

$\sigma(e^+e^- \rightarrow \pi^- Z_c(3885)^+, Z_c(3885)^+ \rightarrow (D\bar{D}^*)^+ + c.c.)$
$= (83.5 \pm 6.6 \pm 22.0)$ pb

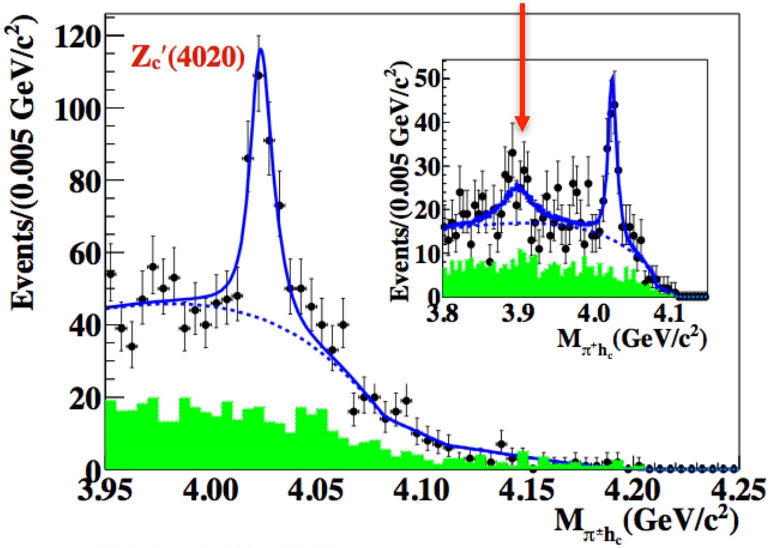


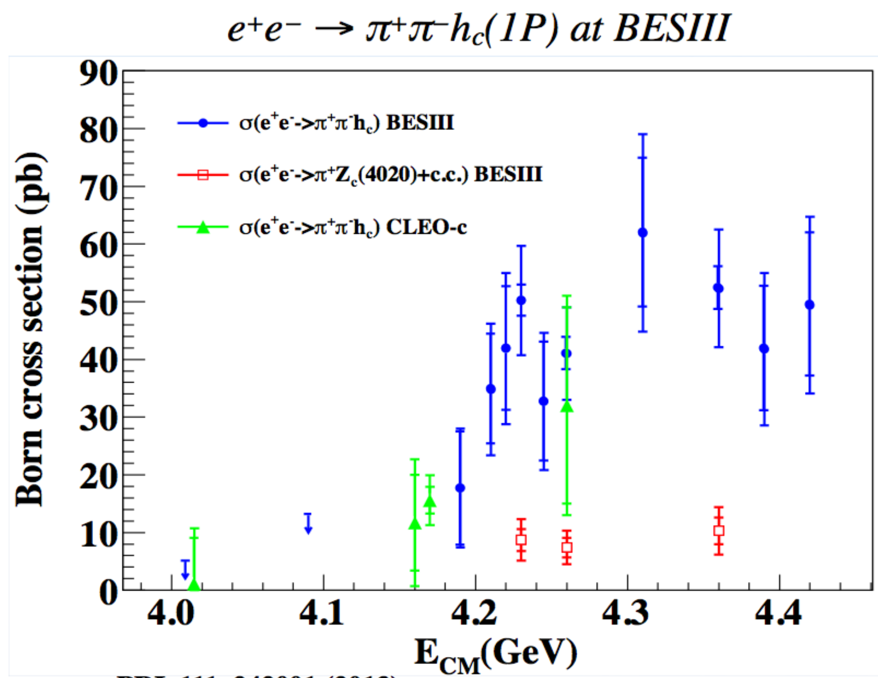
Structures and Cross sections in $e^+e^- \to \pi^+\pi^- h_c(1P)$

PRL111, 242001 (2013)

No significant Zc(3900) signal is observed

Reflection and possible $Z_c(3900)$ signal





Simultaneous fit to 4.23/4.26/4.36 GeV data and 16 η_c decay modes: 8.9σ

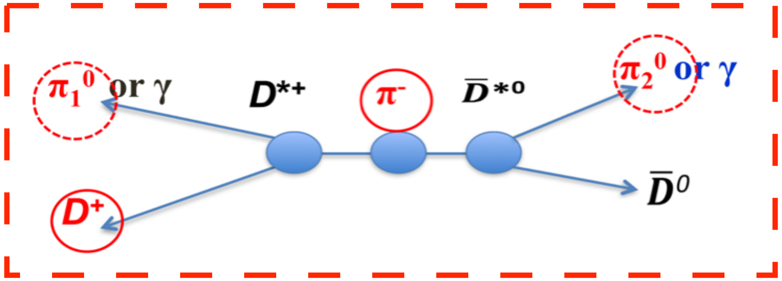
$M(Z_c(4020)) = 4022.9\pm0.8\pm2.7$ MeV; $\Gamma(Z_c(4020)) = 7.9\pm2.7\pm2.6$ MeV

$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c)$

< 13 pb @4.23GeV

< 11 pb @4.26GeV

$e^+e^- \to \pi^- Z^+_c(4025) \to \pi^-(D^*D^*)^+$ at 4.26GeV

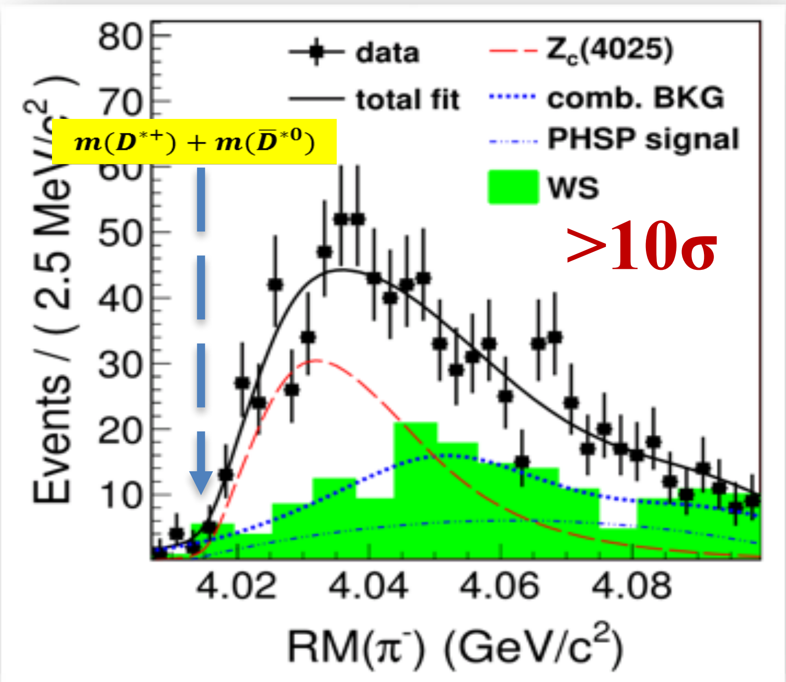


PRL113, 132001 (2014)

assume it as a particle, Zc(4025), and fit to the π^- recoil mass distribution

resonance parameter:

$$m(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7\,\mathrm{MeV/c^2},$$
$$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7\,\mathrm{MeV}.$$



401±47 $Z_c(4025)$ events

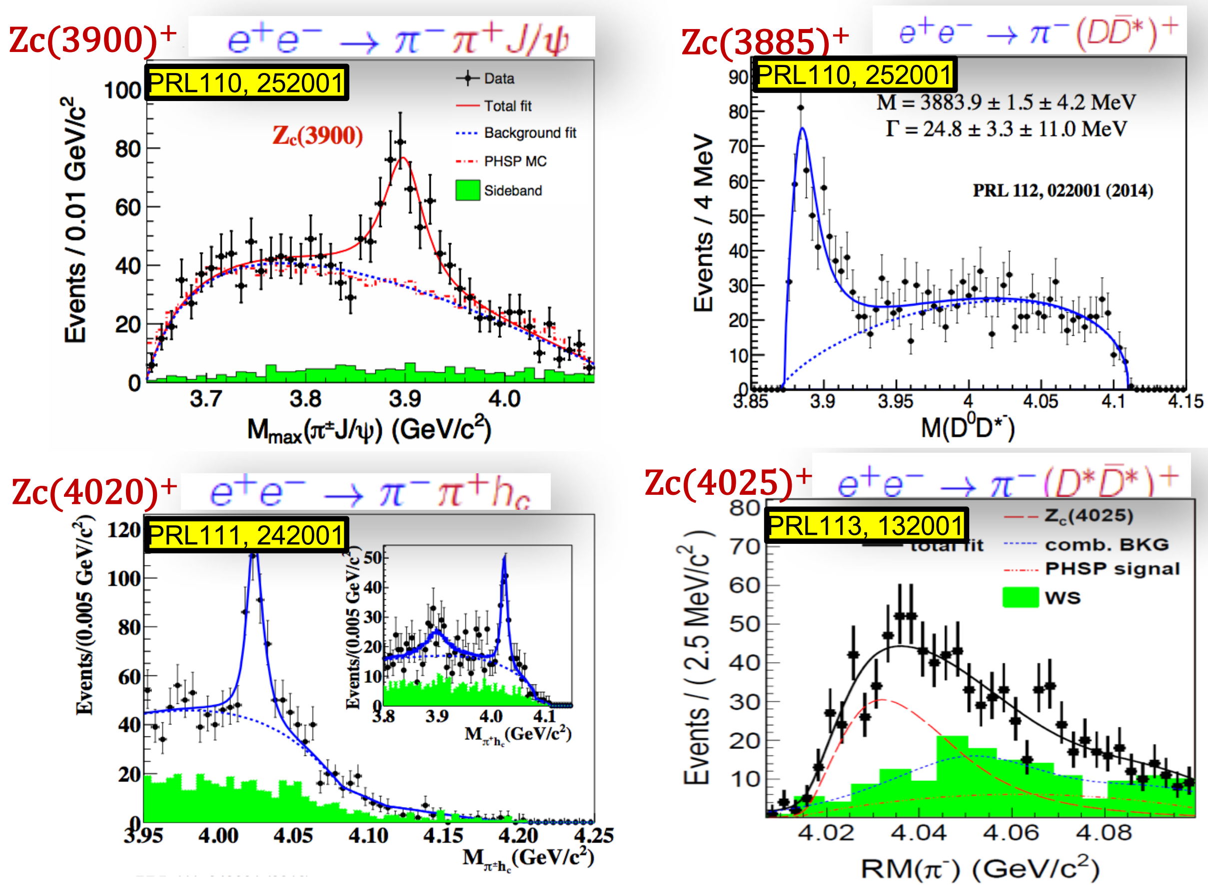
$$\sigma(e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}) = (137 \pm 9 \pm 15)\,\mathrm{pb}$$

$$\frac{\sigma(e^+e^- \to Z_c^{\pm}(4025)\pi^{\mp} \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})}{\sigma(e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})} = 0.65 \pm 0.09 \pm 0.06$$

$Z_c(4020)=Z_c(4025)$?

Coupling to D*D* is much larger than to $\pi^- h_c$ if they are the same state

Discoveries of the charged $Z_c^{\pm}$'s by 2014

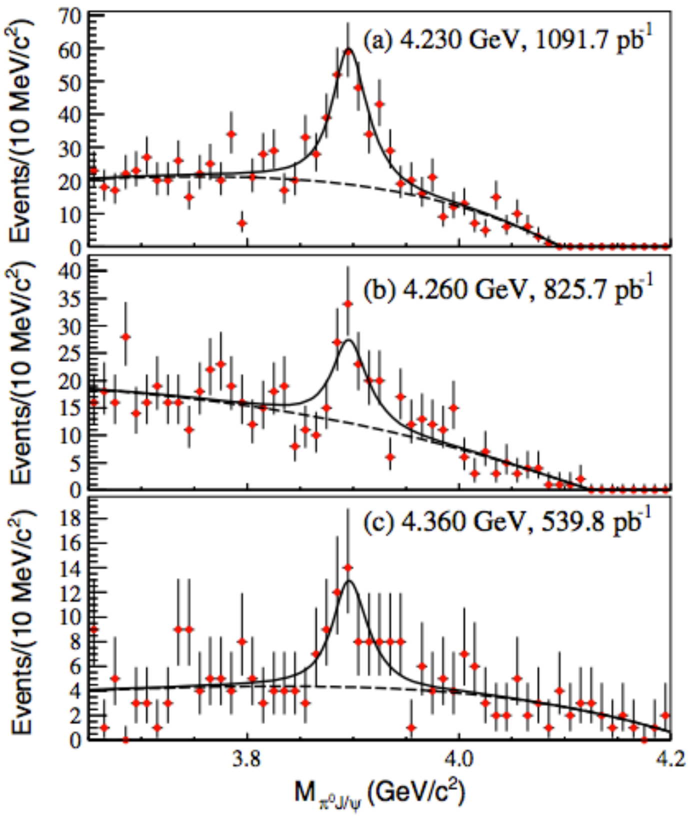


- Searching for isospin partners of these states are important to identify the nature
- Measurement of their quantum numbers

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

PRL 115, 112003 (2015)

$M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c²
$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV



Evidence for neutral isospin partner!

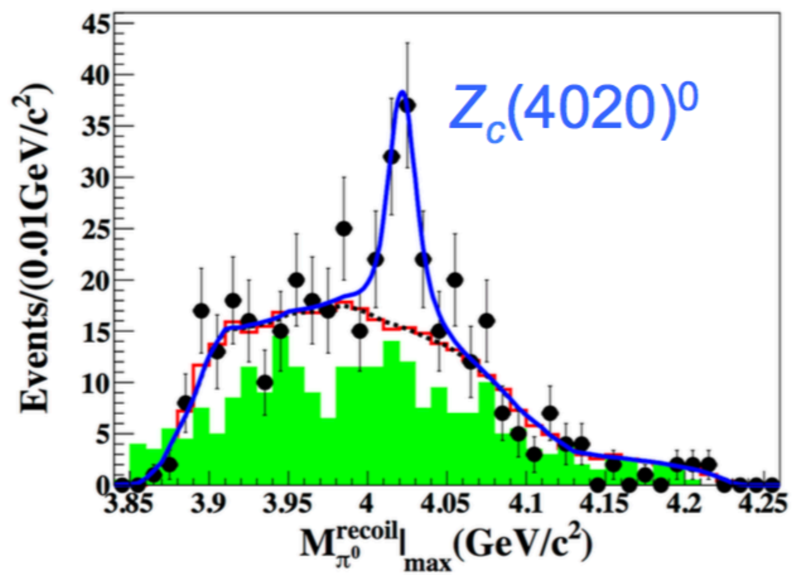
[T. Xiao et al., PLB 727, 366 (2013)]

Search for $Z_c(4020)^0$ in $e^+e^- \to \pi^0\pi^0 h_c$

PRL113, 212002 (2014)

h_c reconstructed through E1 transition $h_c \to \gamma\eta_c$, reconstructed from 16 exclusive hadronic modes.

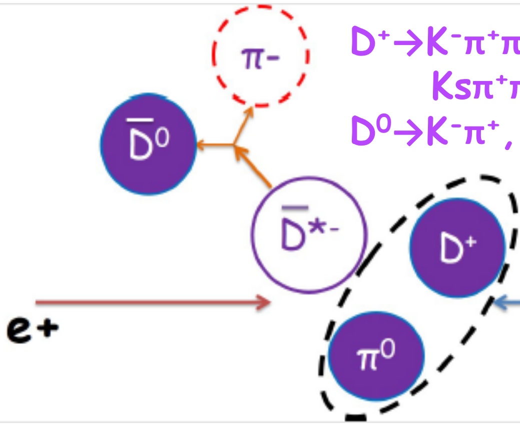
M = (4023.6±2.2 ± 3.9) MeV/c²
Width fixed to the Zc(4020)⁺



Isospin triplet is established: $Z_c(3900)^{\pm/0}$ & $Z_c(4020)^{\pm/0}$

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

PRL 115, 222002 (2015)



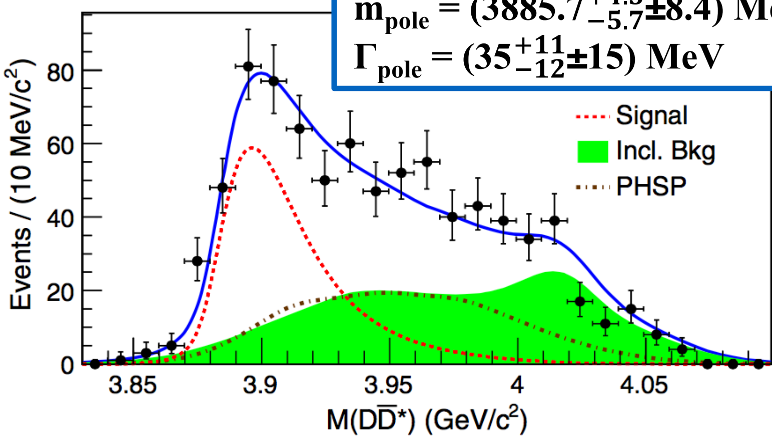
$D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+$, $K_S\pi^+\pi^0$, $K_S\pi^+\pi^+\pi^-$

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^-\pi^+\pi^+$

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

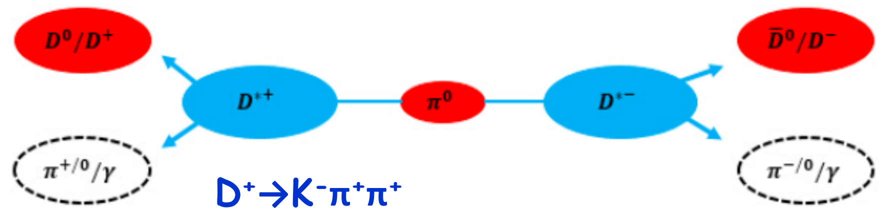
$m_{pole} = (3885.7^{+4.3}_{-5.7} \pm 8.4)$ MeV/c²

$\Gamma_{pole} = (35^{+11}_{-12} \pm 15)$ MeV



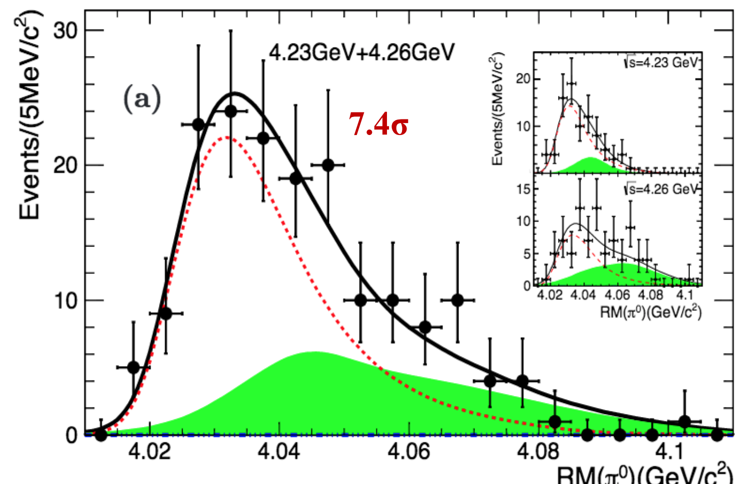
Search for $Z_c(4025)^0$ in $e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

PRL115, 182002 (2015)



$D^+ \to K^-\pi^+\pi^+$

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^-\pi^+\pi^+$



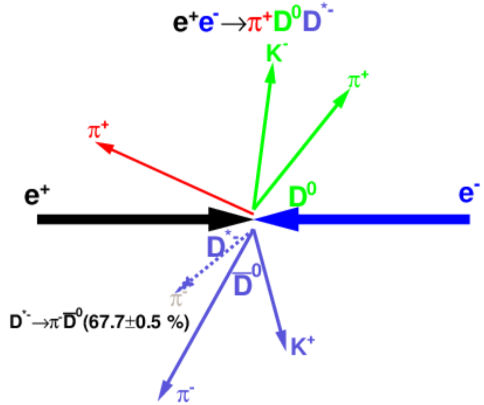
$m_{pole} = (4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c²

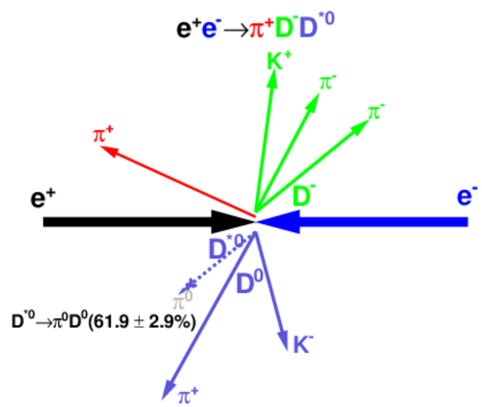
$\Gamma_{pole} = (23.0 \pm 6.0 \pm 1.0)$ MeV

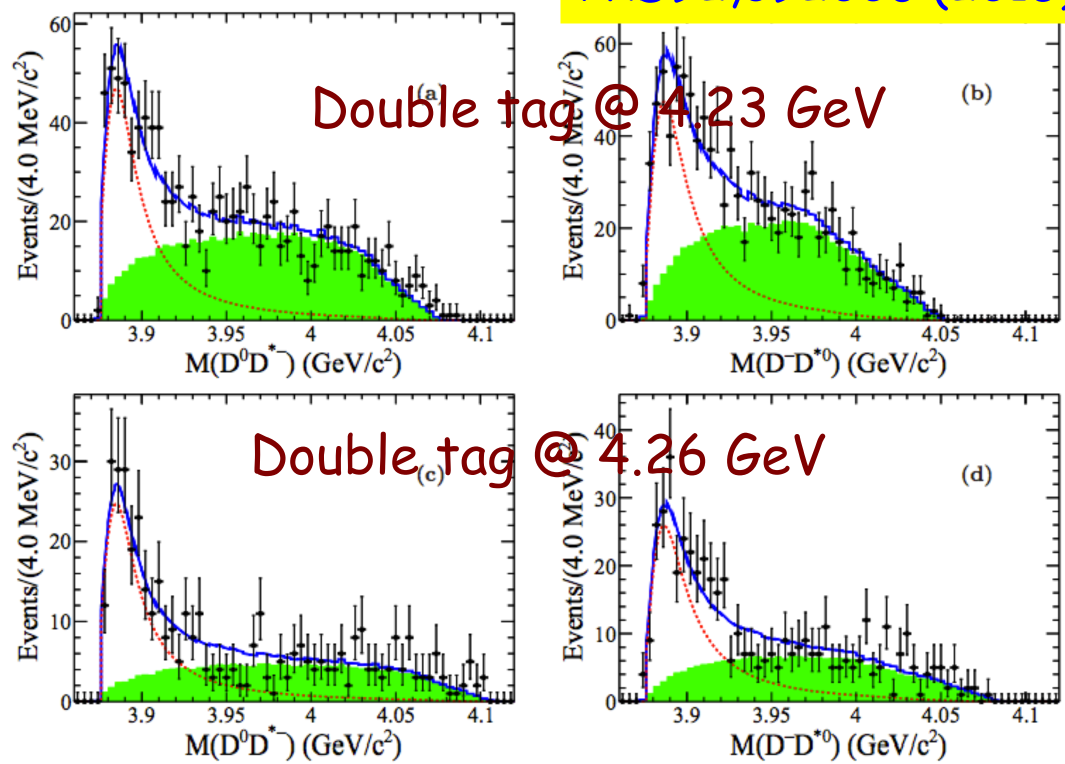
Isospin triplet is established: $Z_c(3885)^{\pm/0}$ & $Z_c(4025)^{\pm/0}$

$e^+e^- \rightarrow (D\bar{D}^*)^+\pi^- + c.c.$ (DT method)

PRD92,092006 (2015)







PRL 112, 022001 (2014)

PRD92,092006 (2015)

Single tag	Double tag
M=3883.9±1.5±4.2 MeV	M=3881.7±1.6±2.1 MeV
Γ=24.8±3.3±11.0 MeV	Γ=26.6±2.0±2.3 MeV
$J^P=1^+$	$J^P=1^+$

$Z_c(4020) \rightarrow \bar{D}D^*$ is not observed

$\rightarrow \frac{\Gamma(Z_c(4020)\rightarrow\bar{D}D^*)}{\Gamma(Z_c(3885)\rightarrow\bar{D}D^*)} < 0.13$

Good agreement between ST & DT method

The Zc Family at BESIII

State	Mass (MeV/c²)	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	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^\pm \pi^\mp$
$Z_c(4025)^0$	$4025.5^{+2,0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0 \pi^0$

Which is the nature of these states?

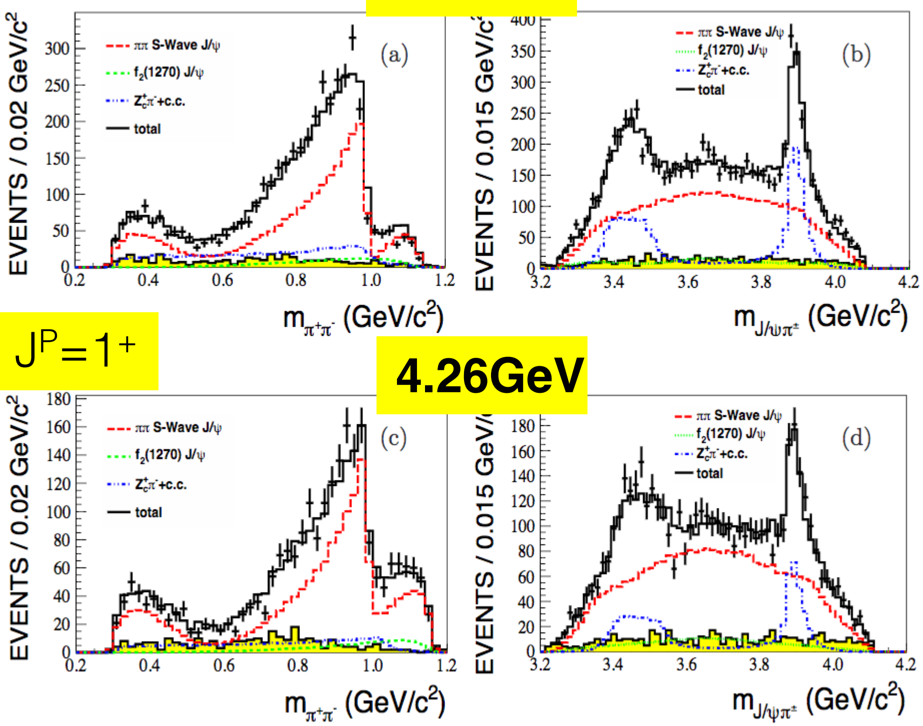
Different decay channels of the same observed states? Other decay modes?

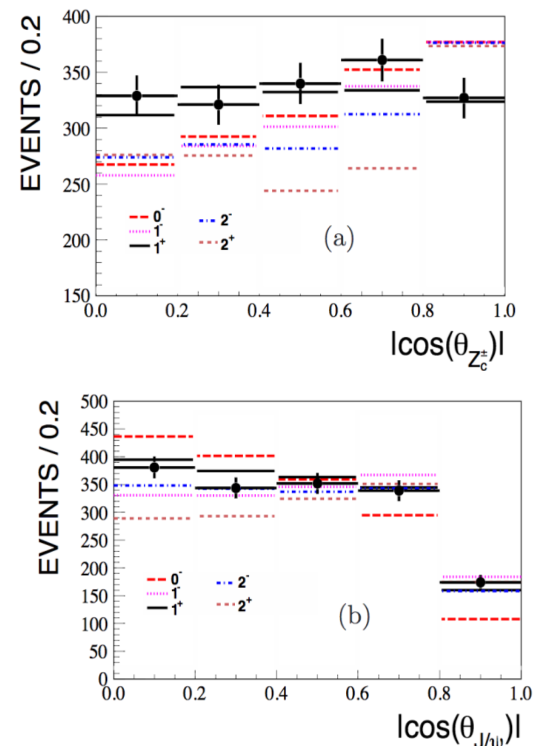
Spin-parity determination of the $Z_c^+(3900)$

- Zc line shape parameterized with Flatte-like formula

PRL 119.072001 (2017)

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





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** by perform amplitude analysis of e+e- → $\pi^+\pi^- J/\psi$

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

PRD96,032004 (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}.

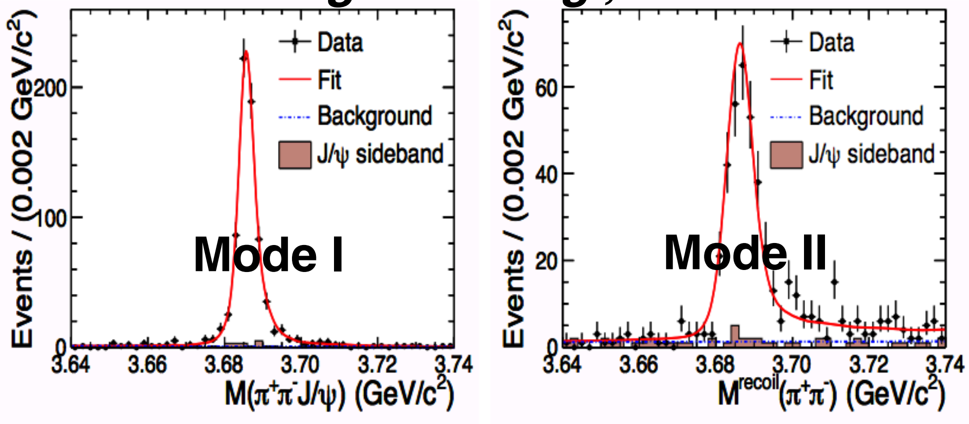
- **Reconstructed modes:**

  Mode I: $\Psi(3686)\rightarrow\pi^+\pi^-J/\psi$, $J/\psi\rightarrow l^+l^-$ (l=e/μ)

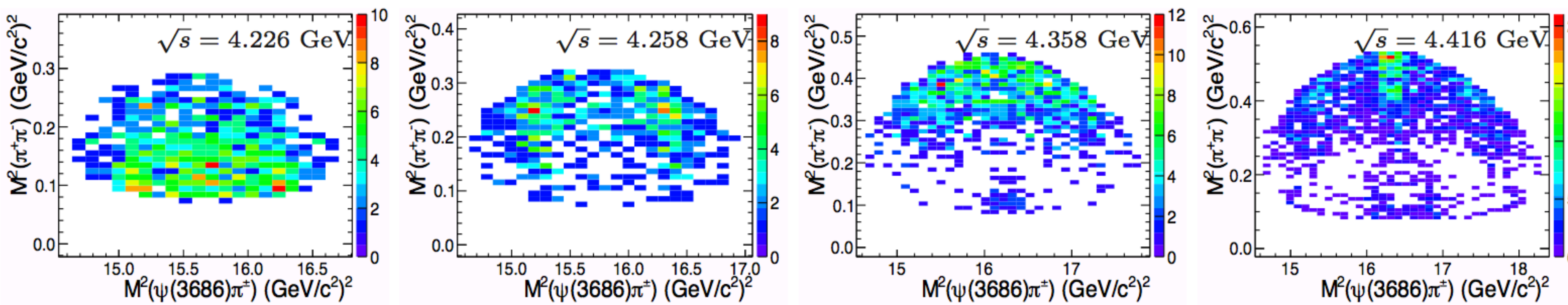
  Mode II: $\Psi(3686)\rightarrow$*neutrals*+J/ψ,

  neutrals=($\pi^0\pi^0$, π^0, η and $\gamma\gamma$) $J/\psi\rightarrow l^+l^-$ (l=e/μ)

Clean signals at e.g., 4.416 GeV



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



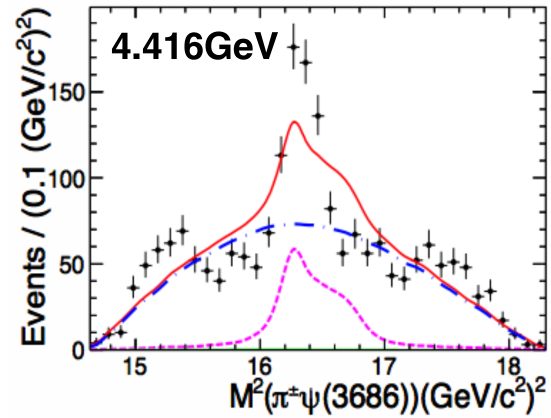
Simple fit to the resonant structure of $\pi^{+}\psi(3686)$ at 4.416GeV

PRD96,032004 (2017)

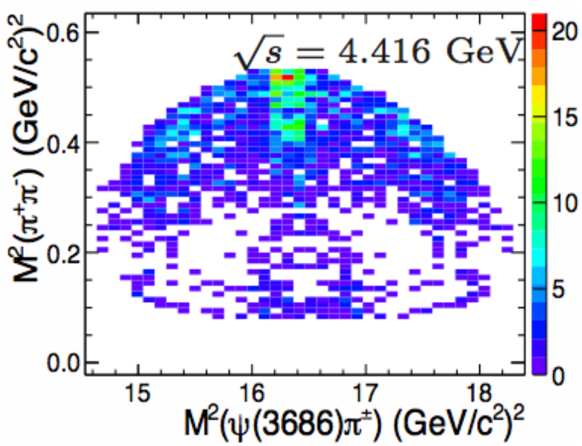
- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$

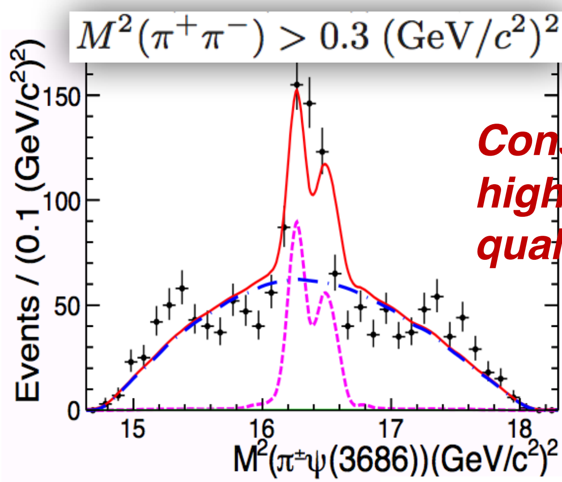
$$\frac{p\cdot q/c^2}{(M_R^2 - x)^2 + M_R^2\cdot\Gamma^2/c^4} + \frac{p\cdot q/c^2}{(M_R^2 - y) + M_R^2\cdot\Gamma^2/c^4}$$

- The fit yields a mass of $M=4032.1\pm2.4$ MeV/c^2 and a width of $\Gamma=26.1\pm5.3$ MeV, with a significance of 9.2σ



However, the fitting quality is not good.





Constrain $M(\pi^+\pi^-)$ in higher region, fitting quality is improved

Different behavior between high and low $M^2(\pi^+\pi^-)$!

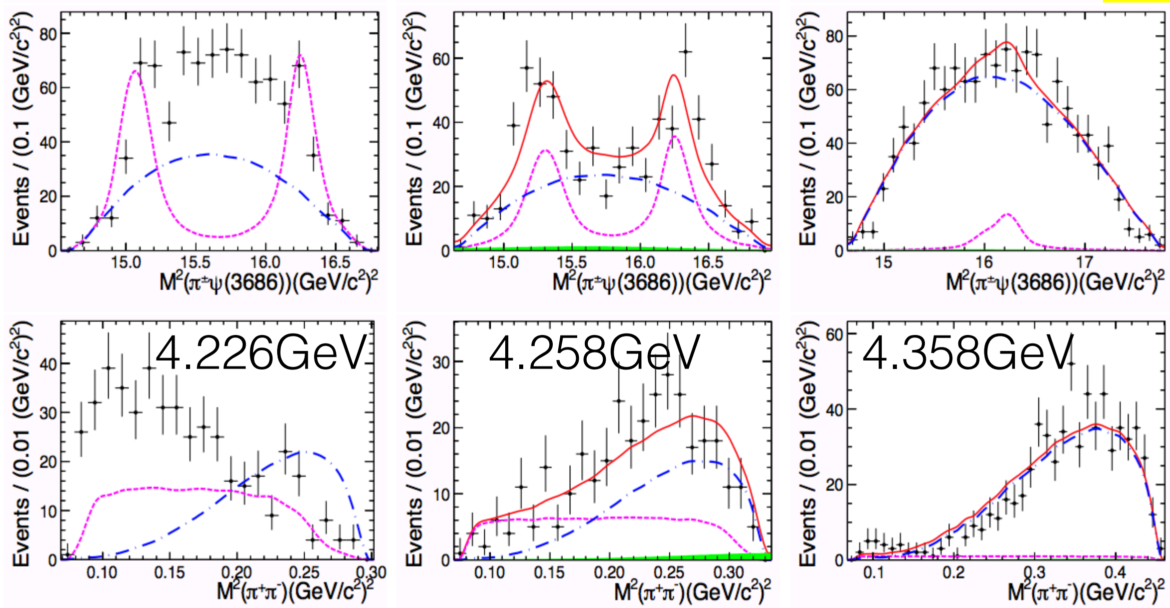
$M=4030.3\pm0.1$ MeV/c^2

$\Gamma=5.1\pm0.2$ MeV

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 $M^2(\pi^+\pi^-)$.

PRD96,032004 (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 $e^+e^- \to \pi^0\pi^0\psi(3686)$

Decay channel:

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

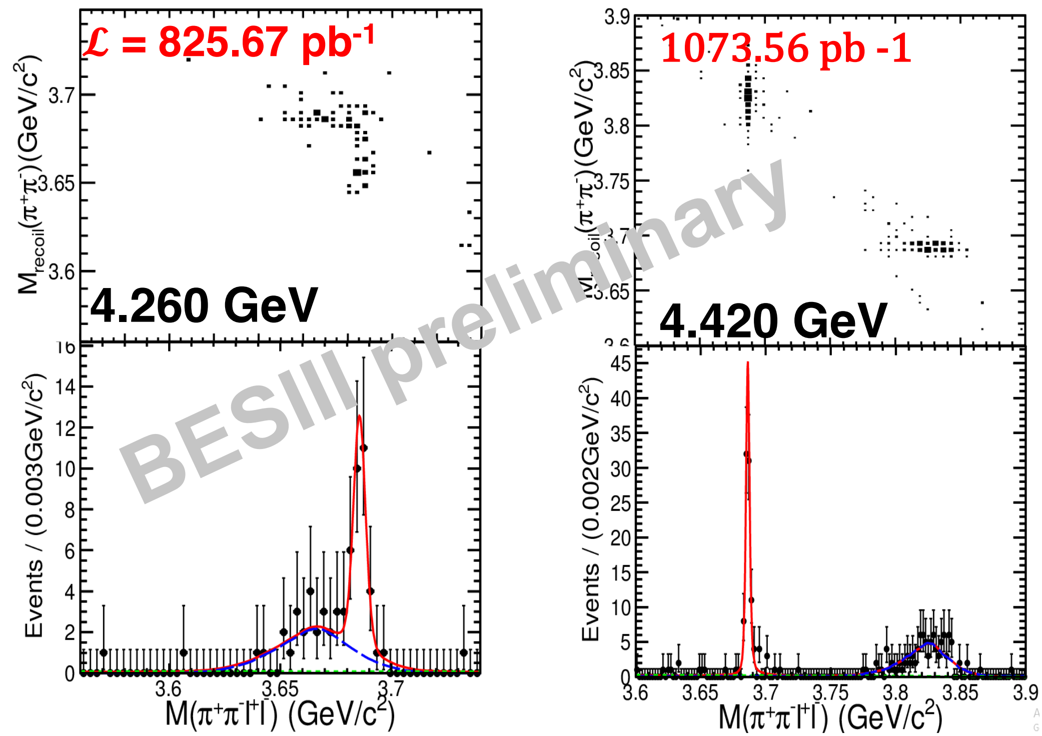
$\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^- (l = e/\mu)$.

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

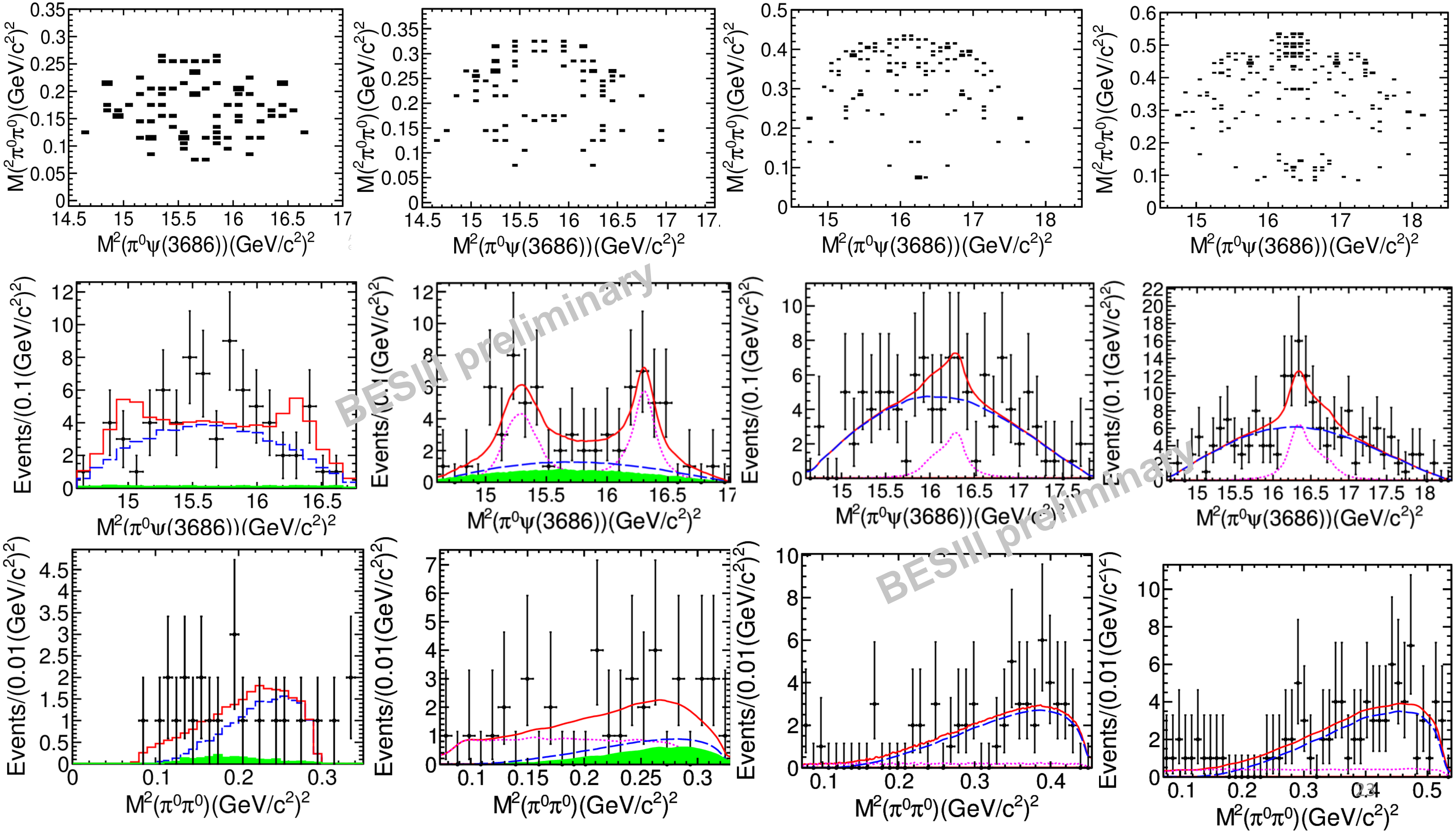
Broad bumps are from backgrounds of the charged mode $e^+e^- \to \pi^+\pi^-\psi(2S)$



Exploration of the intermediate structure

(a) 4.226 GeV, (b) 4.258 GeV, (c) 4.358 GeV, (d) 4.416 GeV

$\mathcal{L}$= 1091.74 pb^{-1} 825.67 pb^{-1} 539.84 pb^{-1} 1073.56 pb^{-1}



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

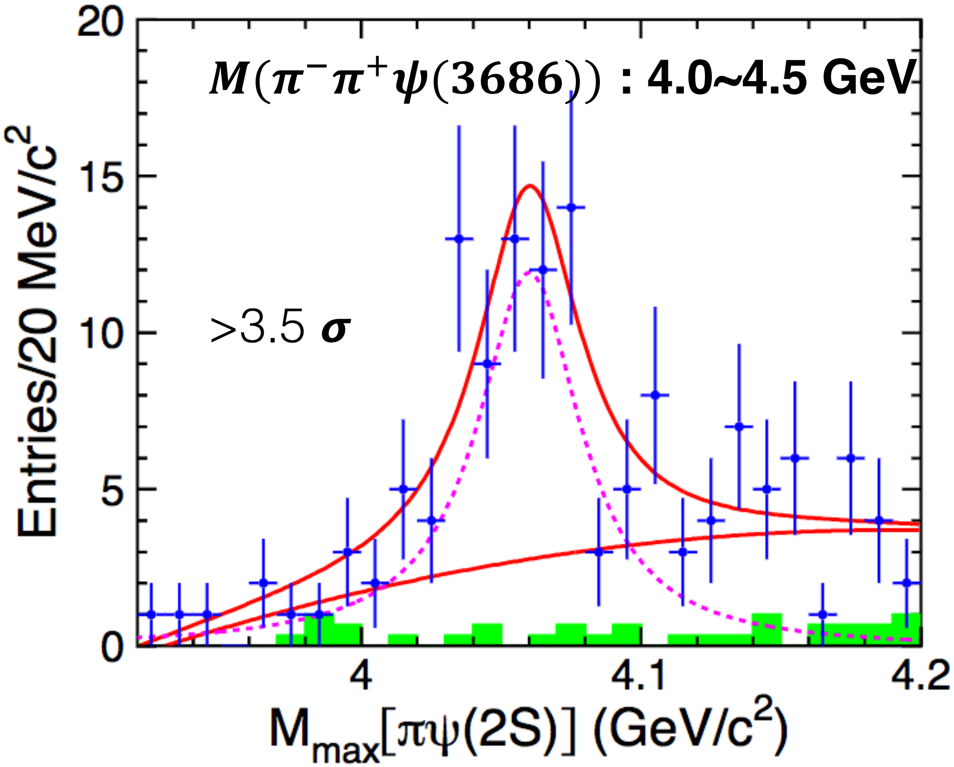
- A possible intermediate state is also observed in the $\pi^0\psi(3686)$ spectrum at 4.416 GeV.
- A 2D fit with a fixed width to charged structure observed in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ is performed on the Dalitz distribution of $M^2(\pi^0\psi(3686))$ vs $M^2(\pi^0\psi(3686))$.

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

- The fit yields a mass (4038.7 ± 6.5) MeV/c^2 (Prel.) with a significance 6.0σ.
  $\rightarrow$ consistent with the resonance in the charged mode $\pi^+\psi(3686)$
- Similar fits with fixed width and mass are carried out to the data sample at 4.258 and 4.358 GeV.

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

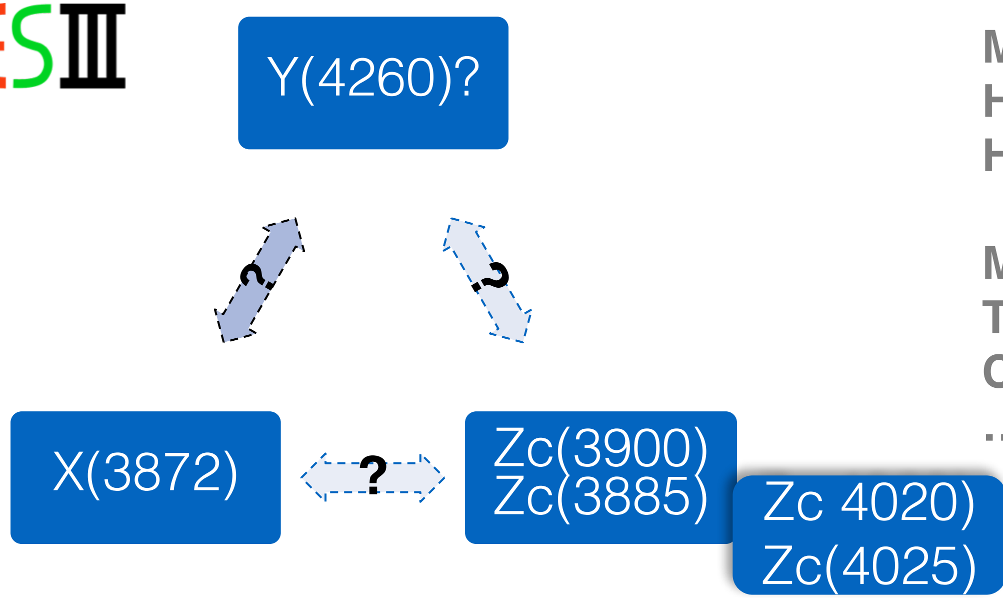
Belle, Phys.Rev. D91, 112007 (2015)

- 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.



Multiquark
Hybrid
Hadrocharmonium

Molecule
Threshold effects
Cusps
…

States or/and interactions

What is the role of threshold

--Many new observations near thresholds: D*D,D*D*, D_1D, …

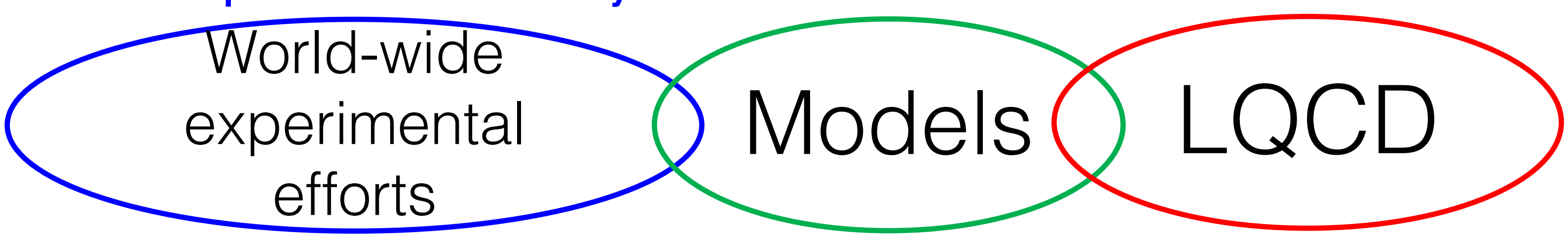
* Phase variations appear in many process: not unique for resonance

To have a complete picture, more findings are desired

- **Energy-dependence**
- **Patterns in productions and decays**

Pole properties

For XYZ, the picture is still unclear



Summary

- **BESIII is successfully operating since 2008**
  – Continue taking data beyond 2020 in the τ-charm mass region

- Observations of the Zc states in the final states of $\pi^+ J/\psi$, $\pi^+ h_c$, $\pi^+ \psi(3686)$, $D\underline{D}^*$ and $D^*\underline{D}^*$

- **Amplitude analysis on the Zc(3900) gives $J^P=1^+$**
  ➔ more similar works on other Zc candidate states are ongoing

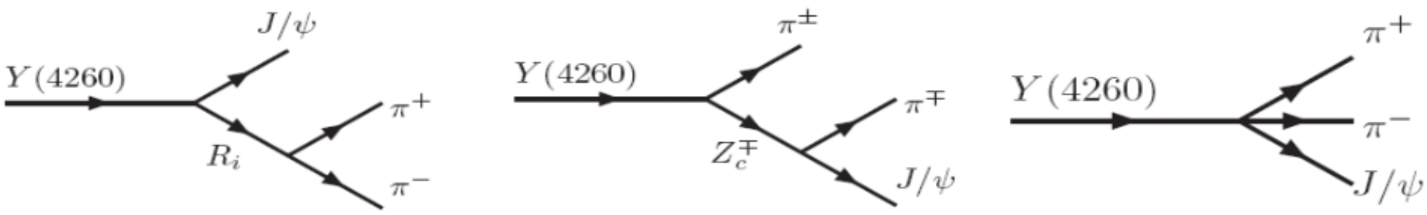
- We find complex behavior in Dalitz plots in the charged mode $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ and the neutral mode $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$
  - ✓ A resonance structure of $\pi\psi(3686)$ around 4.030 GeV is observed
  - ✓ Still unresolved discrepancies between the fit model and data.
  - ✓ This deviates from that of the structure observed by Belle

Thank you!

谢谢!

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

PRL 119.072001 (2017)



(a) (b) (c)

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

- **The helicity value of** γ^* **is taken as** $\lambda_0 = \pm 1$ **due to from e+e- annihination**
- $\gamma^* \rightarrow Z_c^\pm \pi^{\mathrm{m}}$, $Z_c^\pm \rightarrow J/\psi\pi^\pm$, **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:**

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

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