Recent Z_c results at BESIII and prospects

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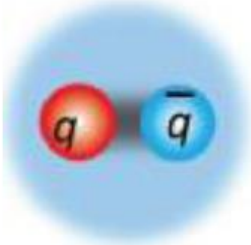
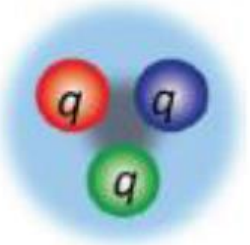
New forms of hadron

- Conventional hadrons consist of 2 or 3 quarks:

Naive Quark Model:

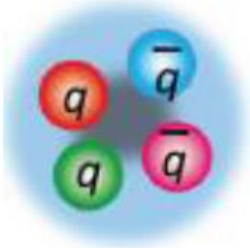
meson



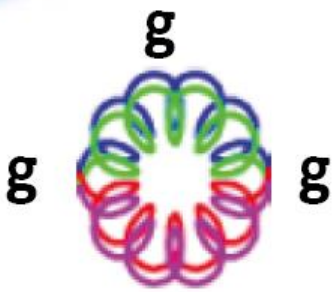


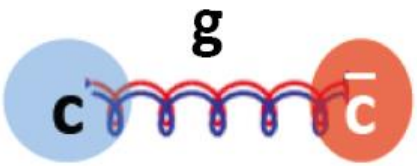
baryon

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

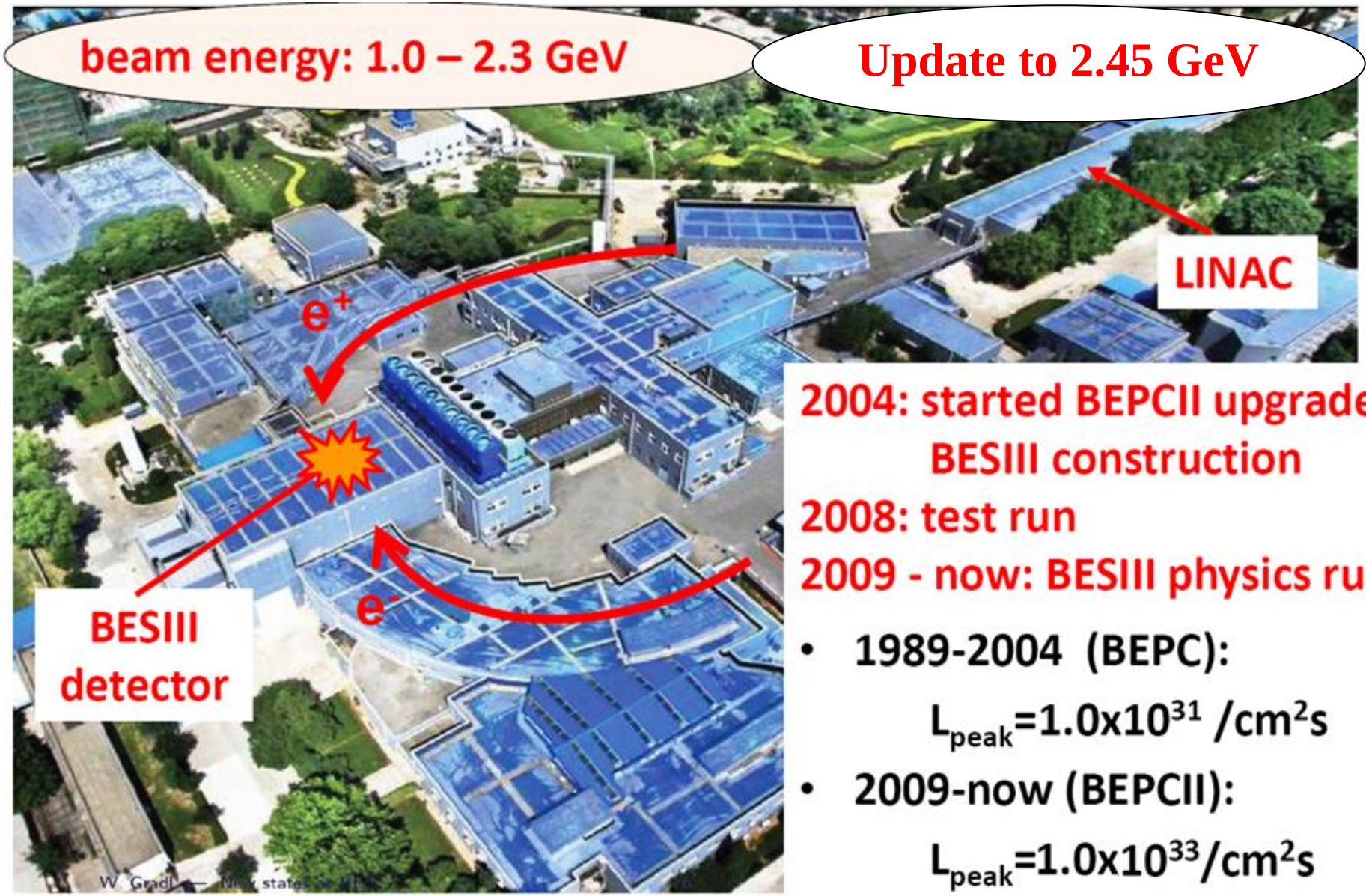


  - Hybrids： $q\bar{q}g$， qqqg …
  - Glueballs： gg， ggg …





Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):

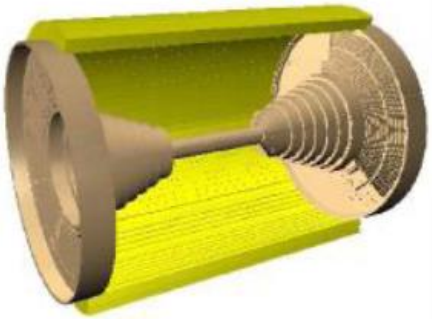
  $L_{peak}=1.0\times10^{31}$ /cm^{2}s

- 2009-now (BEPCII):

  $L_{peak}=1.0\times10^{33}$/cm^{2}s

BESIII Detector

MDC

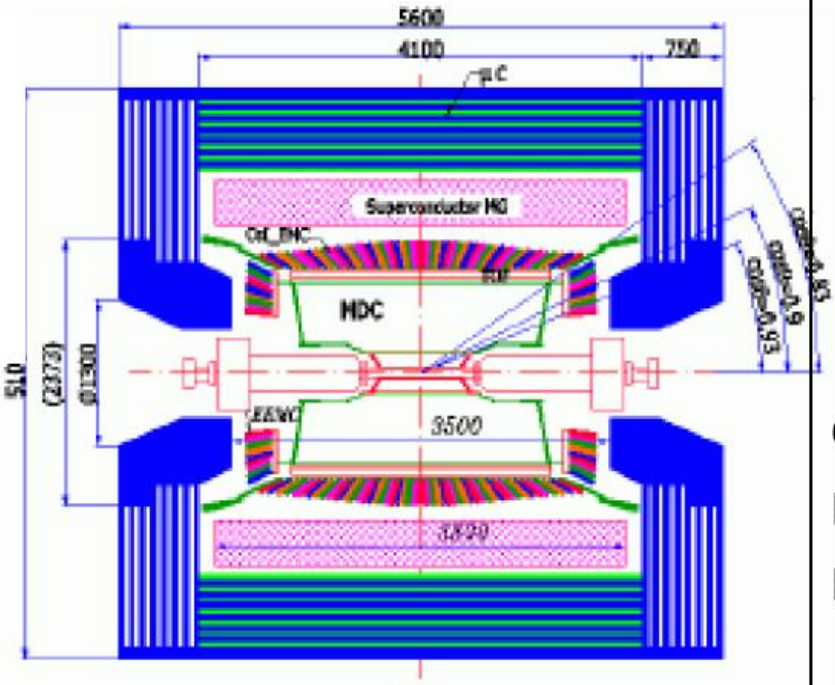


R inner: 63mm ;

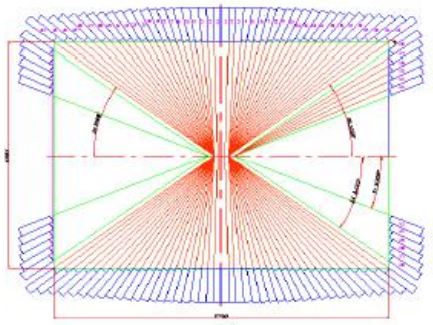
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



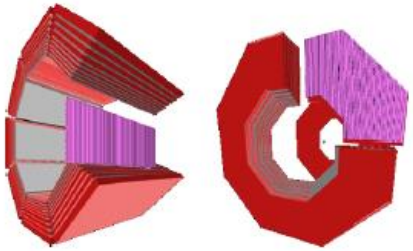
Crystals: 28 cm(15 X_0)

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

Endcap:

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

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

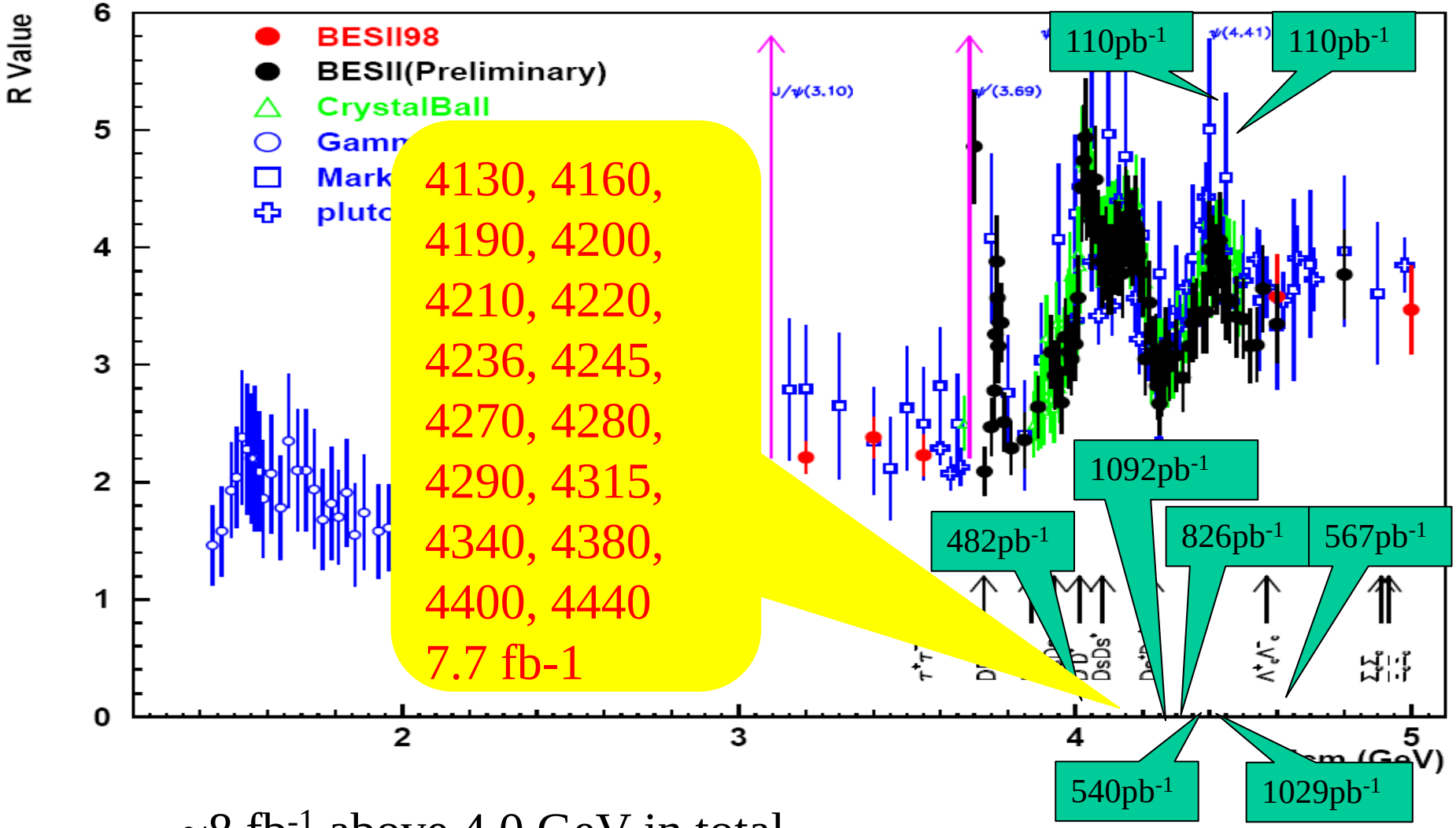
TOF

BTOF: two layers

ETOF: 48 scintillators for each

MRPC --- new ETOF

Data sets for *XYZ* study



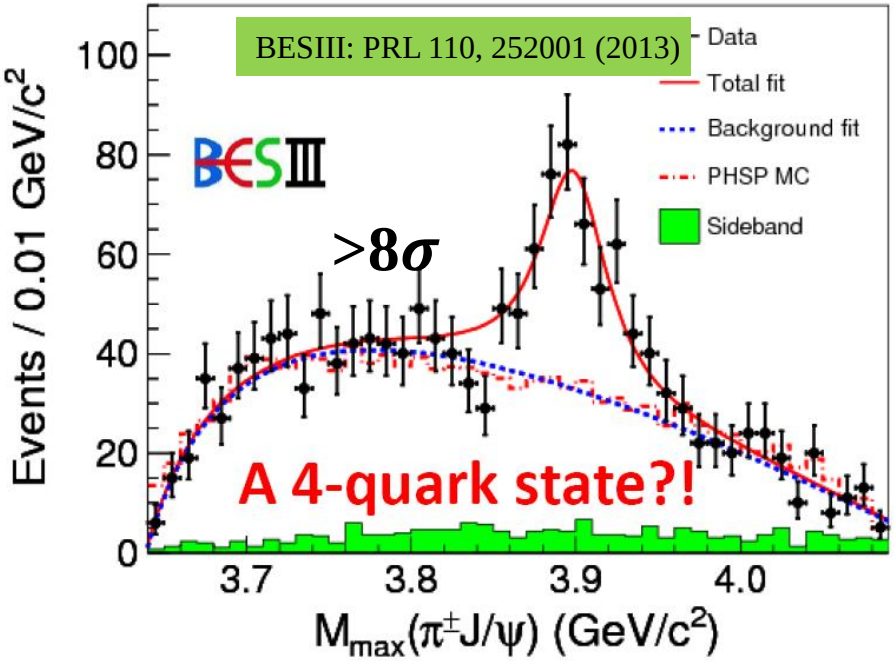
~8 fb^{-1} above 4.0 GeV in total

Z_c calendar at BESIII

Year	State	M (MeV)	Γ (MeV)	Process
2013	$Z_c(3900)^{\pm}$	3891.2±3.3	40±8	$Y(4260) \to \pi^{\pm}(J/\psi\pi^{\mp})$
2013	$Z'_c(4020)^{\pm}$	4022.9 ± 2.8	7.9 ± 3.7	$Y(4260,4360) \to \pi^{\pm}(h_c\pi^{\mp})$
2014	$Z'_c(4025)^{\pm}$	4026.3 ± 4.5	24.8±9.5	$Y(4260) \to \pi^{-}(\bar{D}^{*-}D^{*+})$
2014	$Z'_c(4020)^{0}$	4023.9 ± 4.3	7.9 ± 3.7	$Y(4260,4360) \to \pi^{0}(h_c\pi^{0})$
2014	$Z_c(3885)^{\pm}$	3883.9 ± 4.5	25 ±12	$Y(4260) \to \pi^{-}(\bar{D}^{*-}D^{+})$
2015	$Z'_c(4025)^{0}$	4025.5±4.6	23.0 ±6.1	$e^+e^- \to \pi^0(\bar{D}^*D^*)^0$
2015	$Z_c(3885)^{0}$	3885.7 ± 9.8	35 ±19	$e^+e^- \to \pi^0(\bar{D}^*D)^0$

PDG naming: $Z_c(3900) = X(3900),\ Z'_c(4020) = X(4020)$

First observation of $Z_c(3900)^{\pm}$



$Z_c(3900)^+$: $J^P=1^+$

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

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

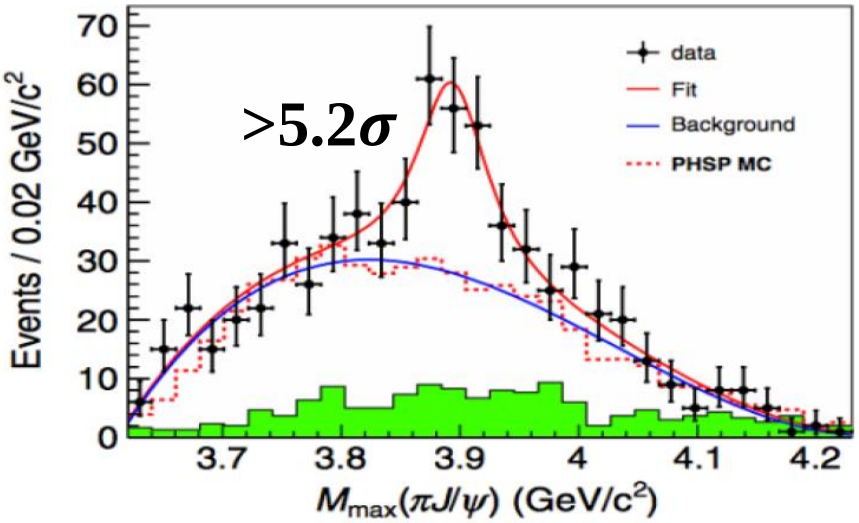
Mass close to $D\bar{D}^*$ threshold

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

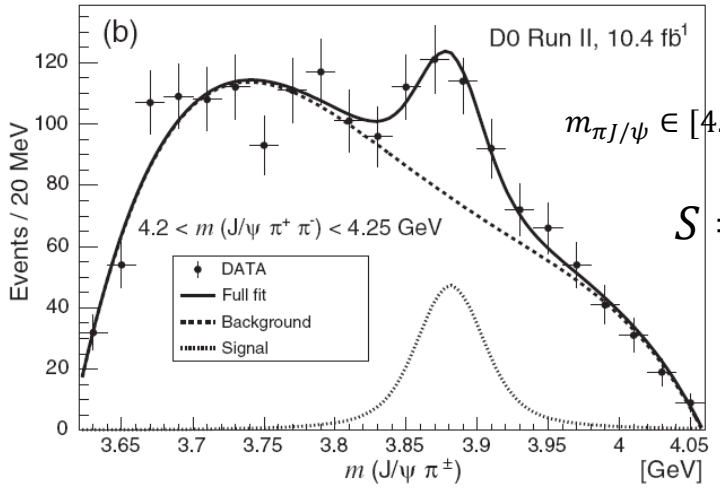
$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV

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

Belle with ISR data (PRL110,252002)



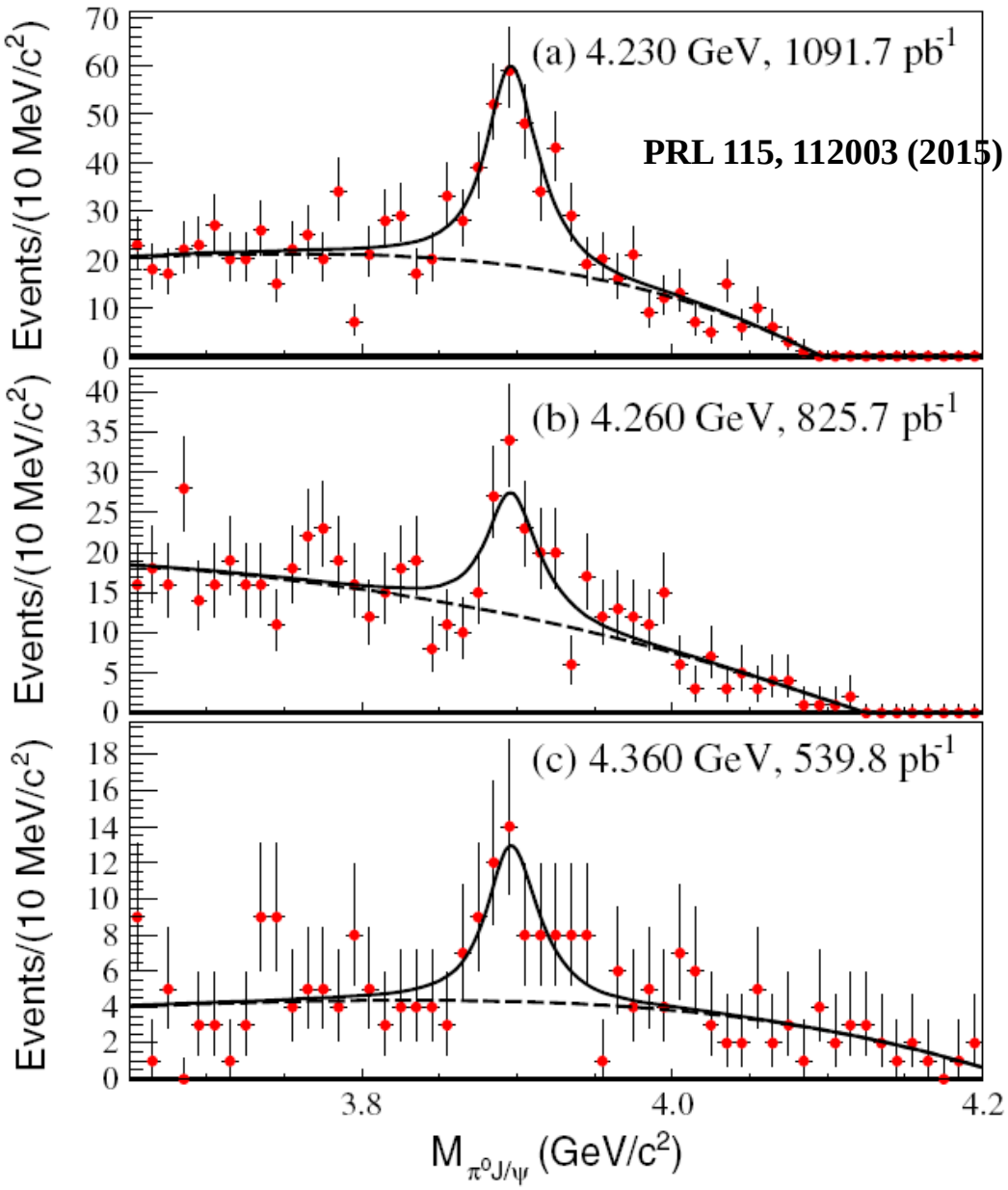
D0 with 10.4fb^{-1} $p\bar{p}$ data (PRD98, 052010 (2018))



$m_{\pi J/\psi} \in [4.2, 4.25]$ GeV

$S = 4.3\sigma$

$Z_c(3900)^0$: isospin vector, $I^G = 1^+$



PRL 115, 112003 (2015)

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

Simultaneous fit:

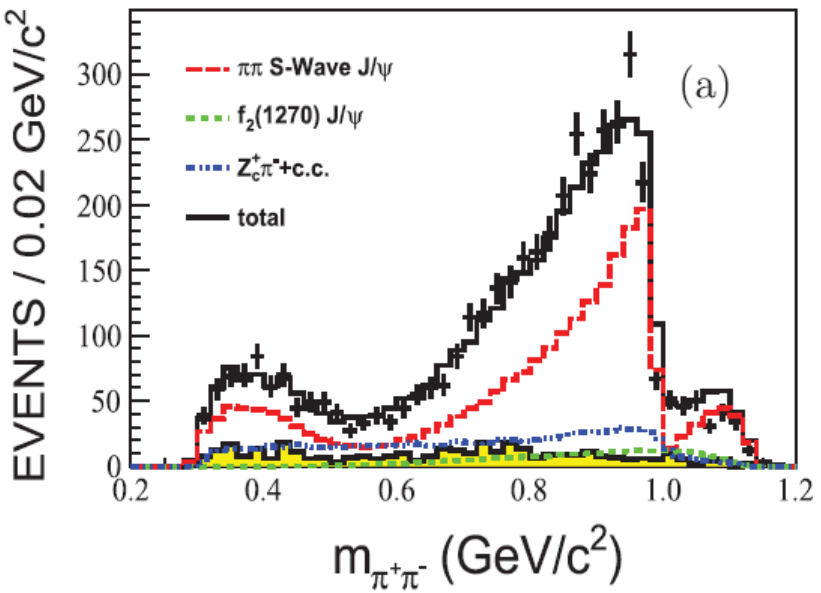
Mass:

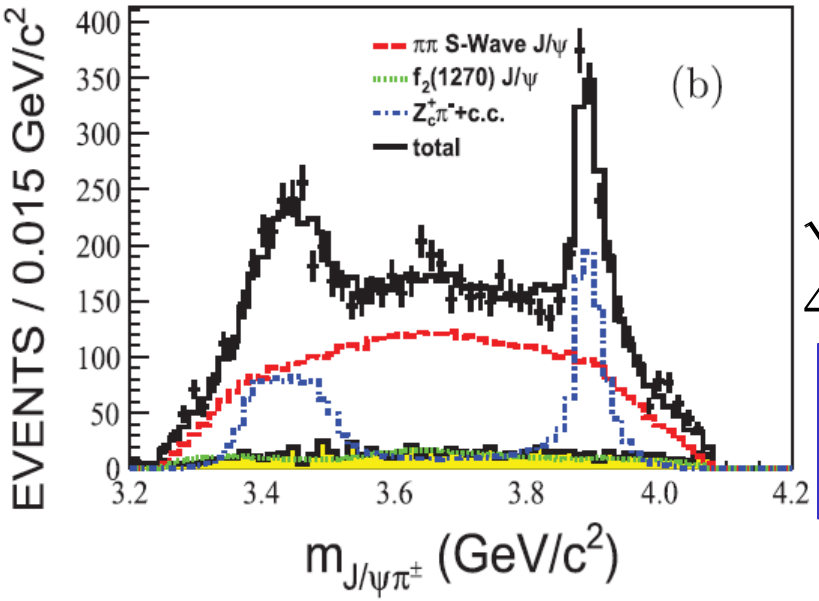
$3894.8 \pm 2.3 \pm 3.2$ MeV

Width:

$29.6 \pm 8.2 \pm 8.2$ MeV

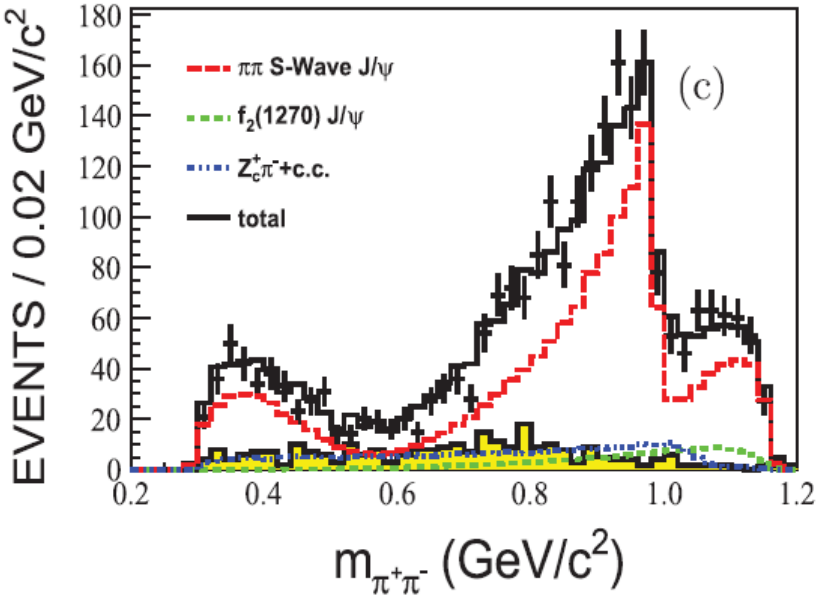
PWA determination of $J^P = 1^+$ for $Z_c(3900)^{\pm}$

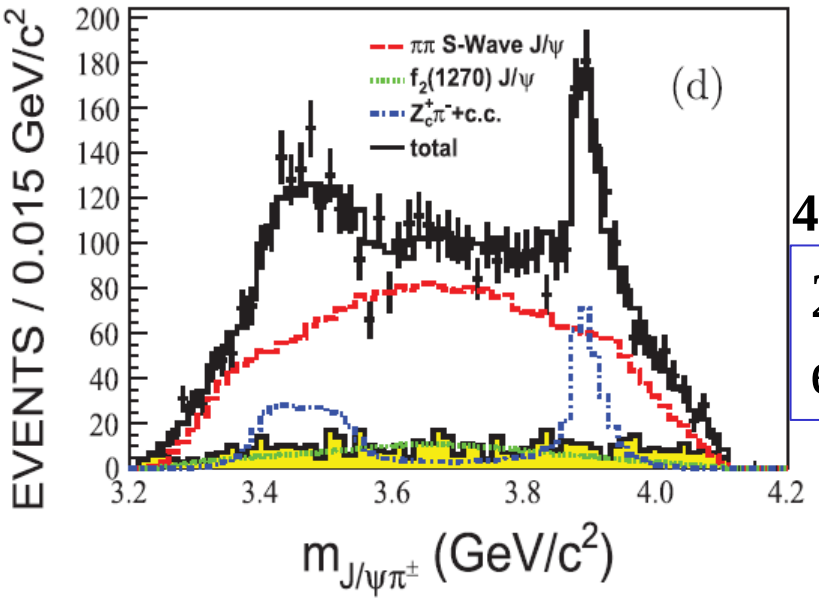




$\sqrt{s}$ = 4.23 GeV

4154 events





4.26 GeV

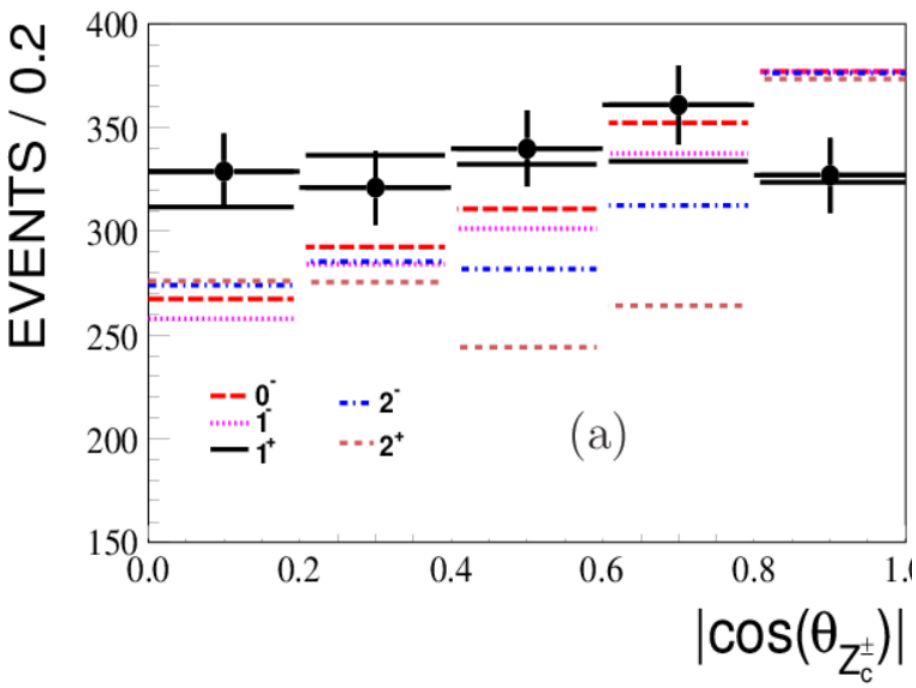
2447 events.

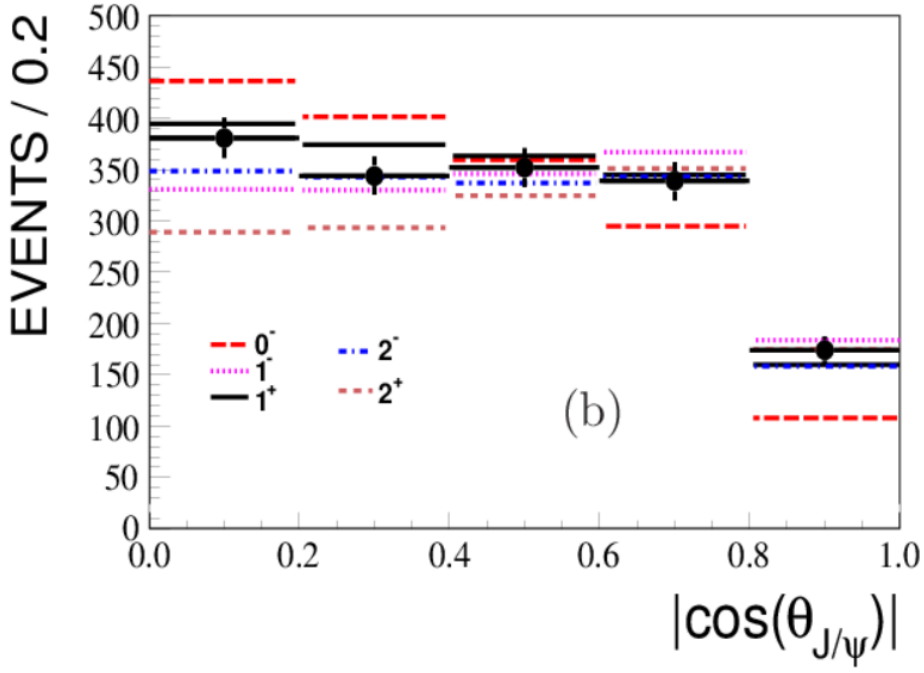
$\pi\pi$-S wave: $\sigma, f_0(980)$

PRL 119, 072001 (2017), BESIII

Angular distributions for different J^P within Z_c mass region

PRL 119, 072001 (2017), BESIII



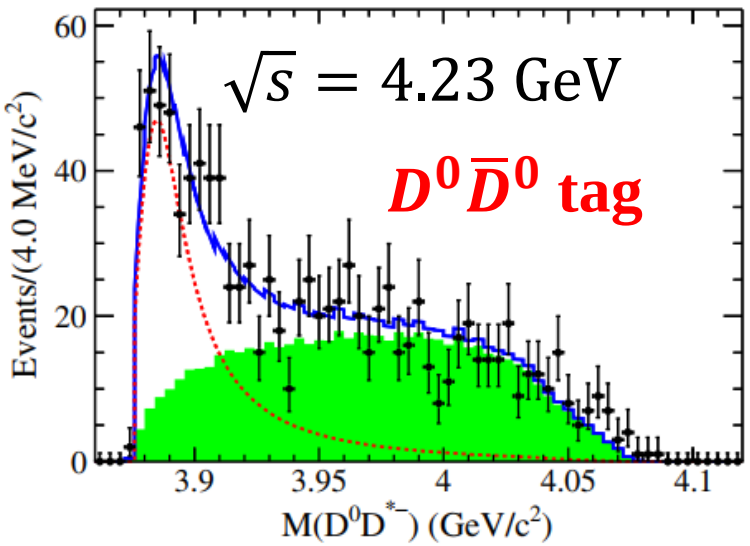


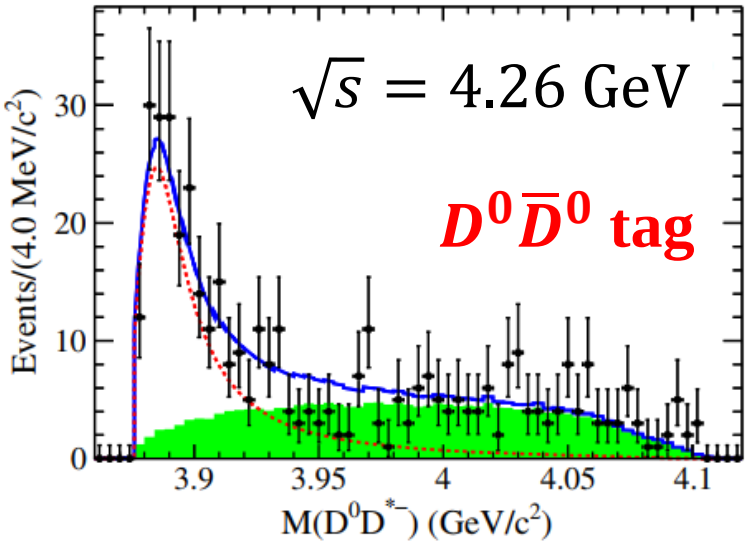
- Events in the Z_c mass region $M_{\pi J/\psi} \in (3.86, 3.92)$ GeV
- Background events subtracted
- θ_{Z_c} : the polar angle of Z_c, $\theta_{J/\psi}$: helicity angle of J/ψ
- Spin and parity for Z_c determined 1^+ with significance >7.5σ

Search for $Z_c(3900)^{\pm}$ open charm decays

$e^+e^- \to \pi^{\pm}(DD^*)^{\mp}$

PRD92, 092006 (2015)



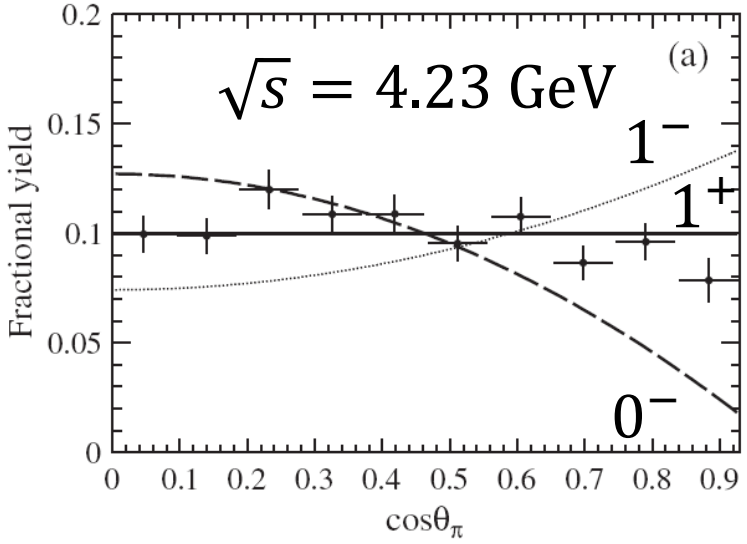


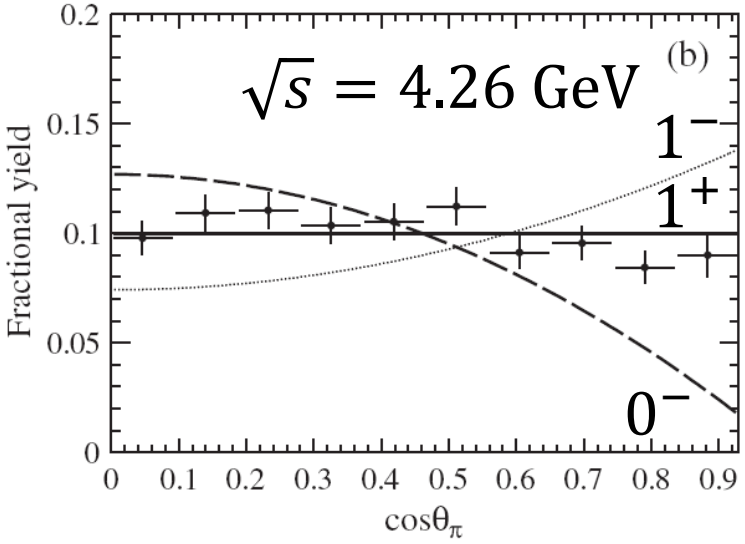
Pole mass

$3881.7 \pm 1.6 \pm 1.6$ MeV

Pole width

$26.6 \pm 2.0 \pm 2.1$ MeV

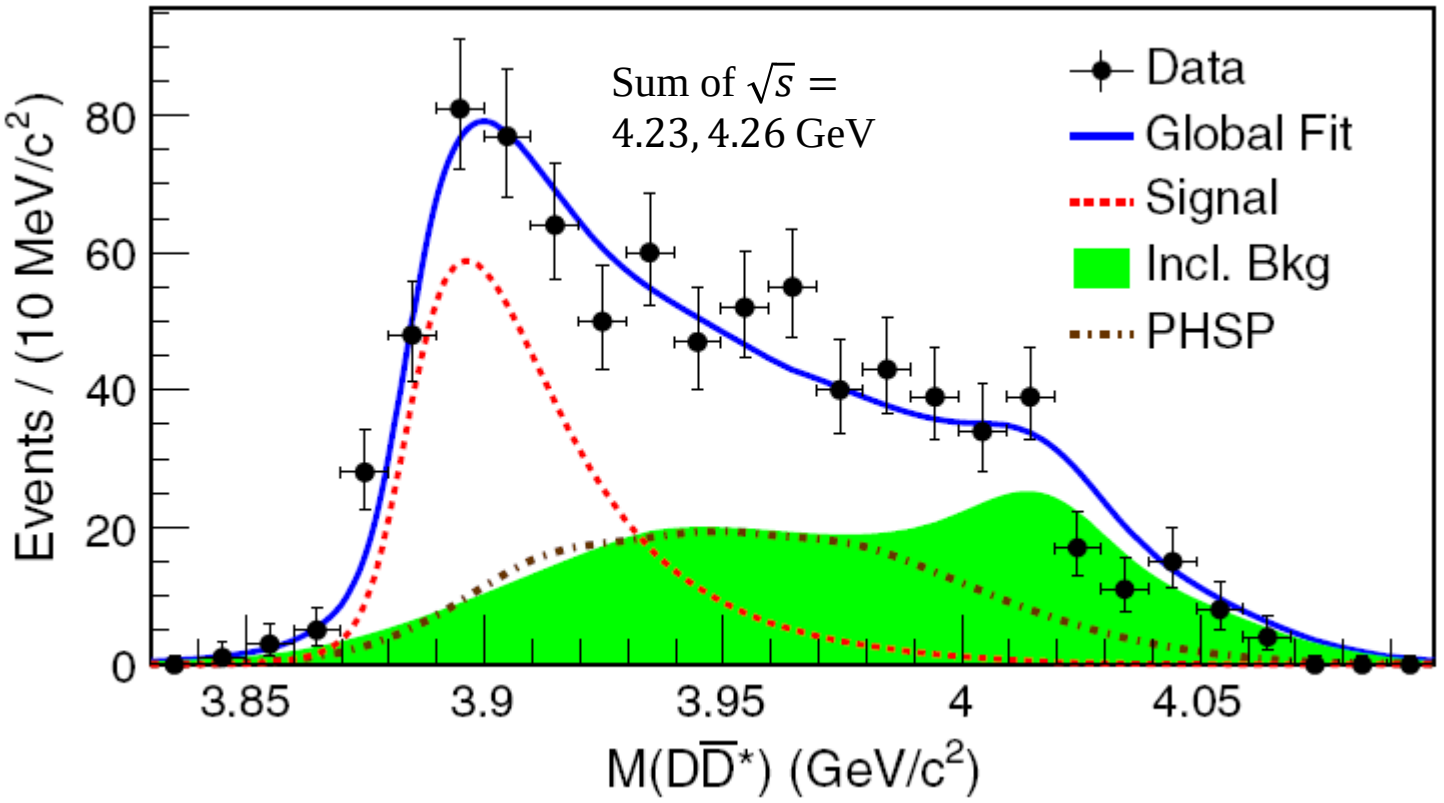




Favor $J^P = 1^+$

Search for $Z_c(3900)^0$ open charm decays

$e^+e^- \to \pi^0(DD^*)^0$, tag $D^+\bar{D}^0$ or $D^0\bar{D}^0$ PRL 115, 222002 (2015)



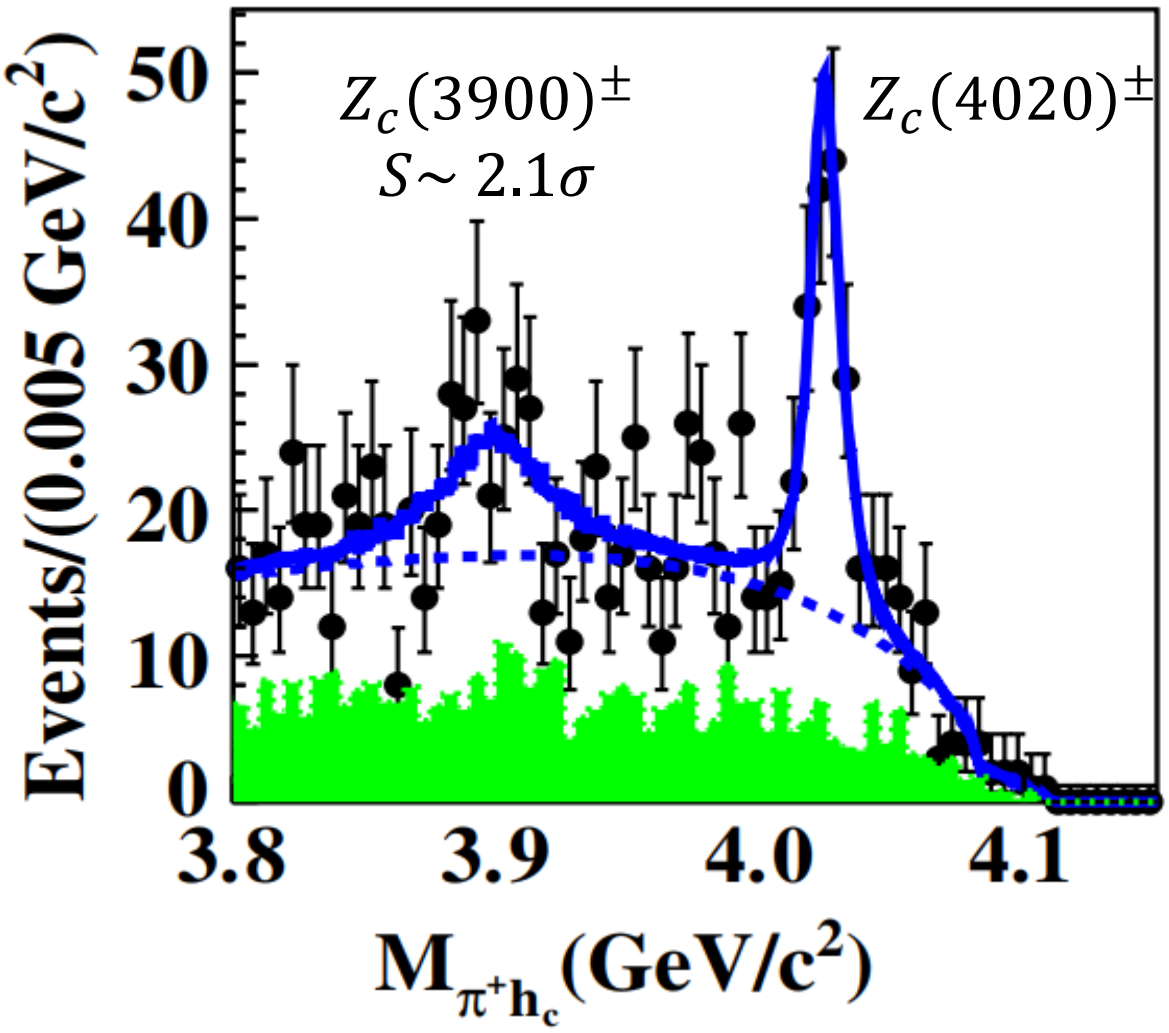
Z_c: S-wave Breit-Wigner function with $\Gamma(s) = \Gamma_0 \frac{p}{p^*}\frac{m}{M}$

Pole mass: $3885.7^{+4.3}_{5.7} \pm 8.4$ MeV

Pole width: $35^{+11}_{-12} \pm 15$ MeV

Insignificant decay of $Z_c(3900)^{\pm} \to \pi^{\pm} h_c$

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



PRL 111, 242001 (2013)

$\mathcal{L}_{total} = 2.46\ \text{fb}^{-1}$ at $\sqrt{s}$ =4.23, 4.26 and 4.36 GeV

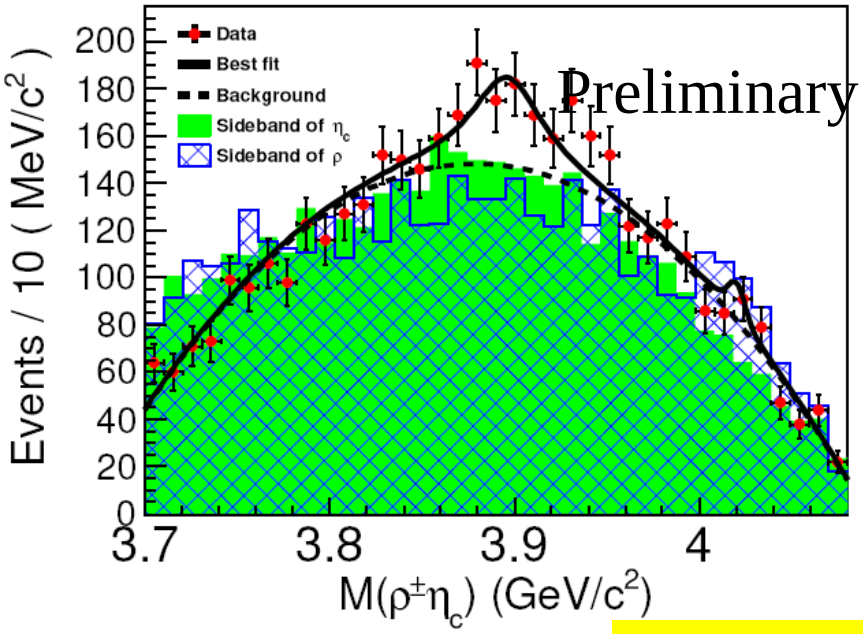
η_c reconstructed exclusively with 16 light hadron modes

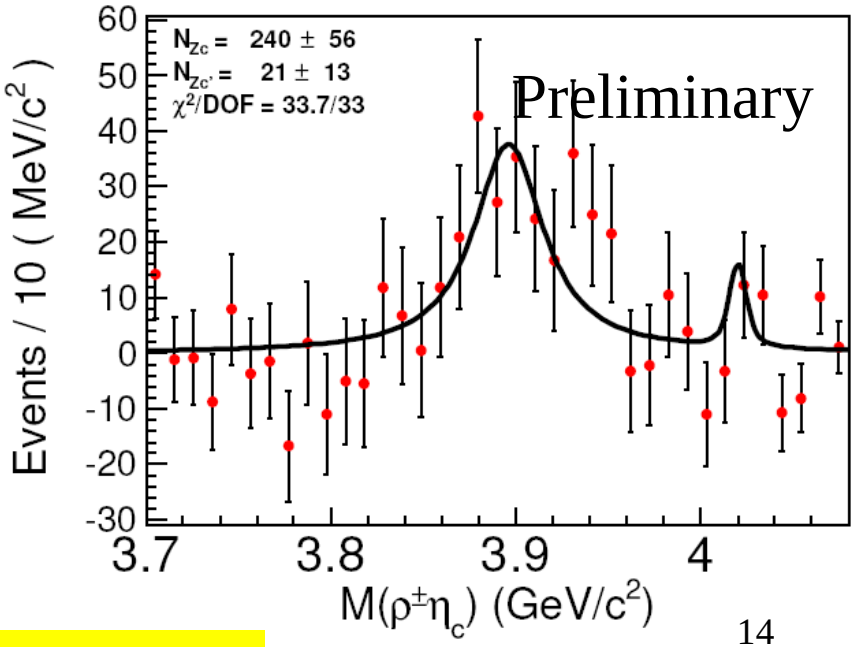
Fixing $Z_c(3900)$ mass and width in the fit yields

$\sigma(e^+e^- \to \pi^{\pm} Z_c, Z_c \to \pi^{\mp} h_c)$
$< 13\ \text{pb}^{-1}$ at 4.23 GeV
$< 11\ \text{pb}^{-1}$ at 4.26 GeV
@90% C.L.

Strong evidence for $Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$

- $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$, with $\eta_c \to$ 9 hadronic decays ($\eta_c \to p\bar{p}, 2(K^+K^-), \pi^+\pi^-K^+K^-, K^+K^-\pi^0, p\bar{p}\pi^0, K_SK\pi, \pi^+\pi^-\eta, K^+K^-\eta, \pi^+\pi^-\pi^0\pi^0$)
- Strong evidence of $e^+e^- \to \pi Z_c,\ Z_c \to \rho\eta_c$ only at $\sqrt{s} = 4.23$ GeV (3.9σ including systematics)
- $e^+e^- \to \pi Z_c',\ Z_c' \to \rho\eta_c$ not seen.





PRD 100, 111102(R) (2019)

Strong evidence for $Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$

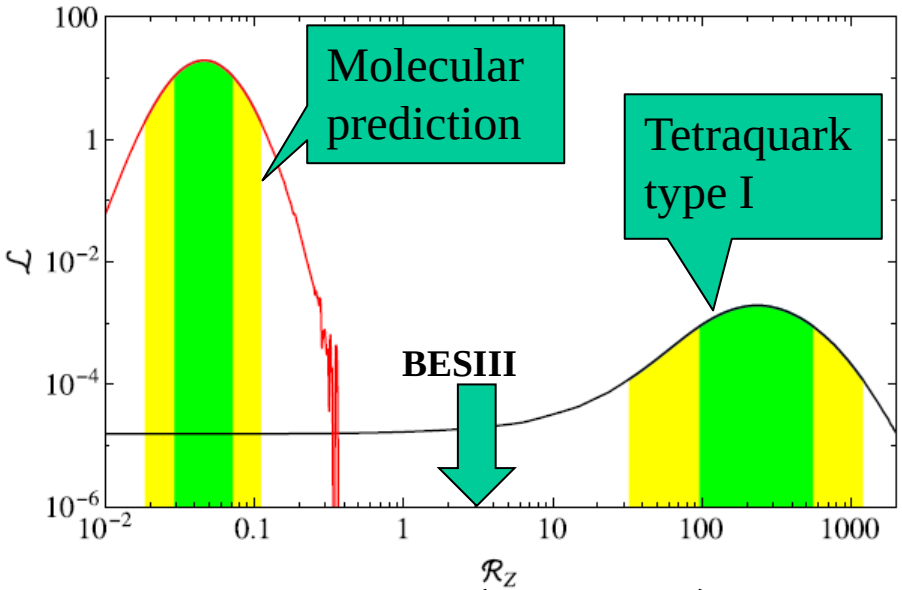
- Measured Born cross section at 4.23 GeV:

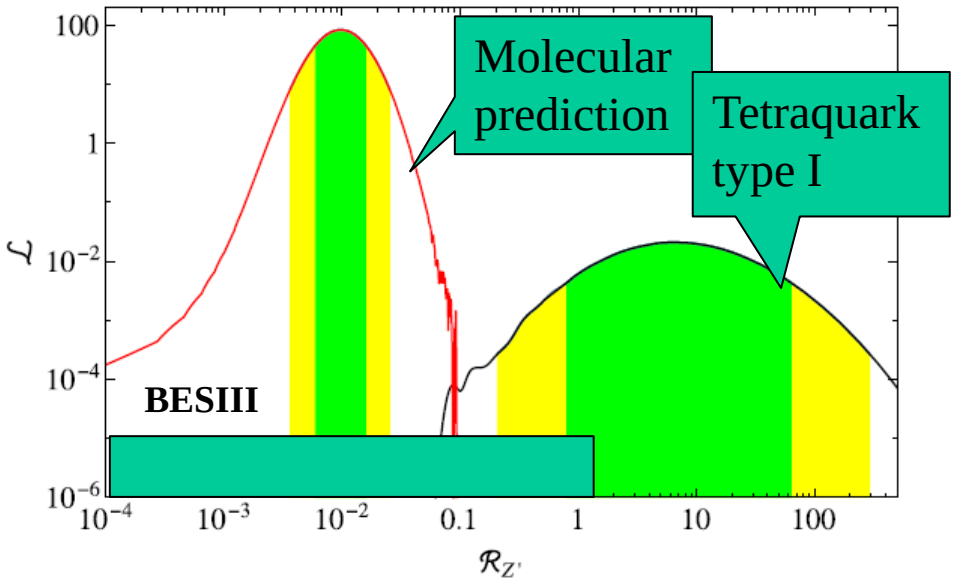
$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10)$ pb

$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c) = (47 \pm 11 \pm 11)$ pb

PRD 100, 111102(R) (2019)

	$\sqrt{s} = 4.226$ GeV	$\sqrt{s} = 4.258$ GeV	$\sqrt{s} = 4.358$ GeV	Type-I	Type-II	Molecule
$R_{Z_c(3900)}$	2.2 ± 0.9	< 5.6	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.6	< 0.9	< 1.4	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$





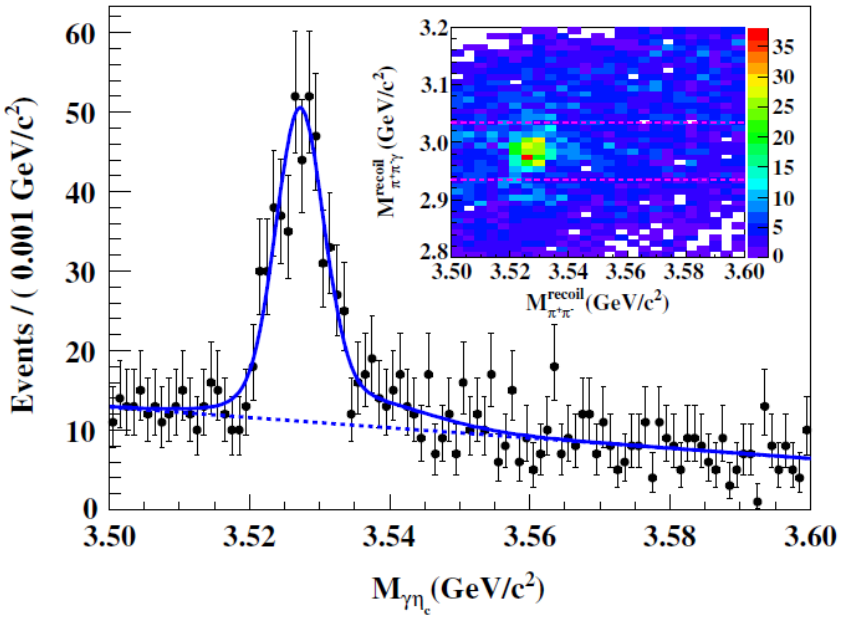
$$\mathcal{R}_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$

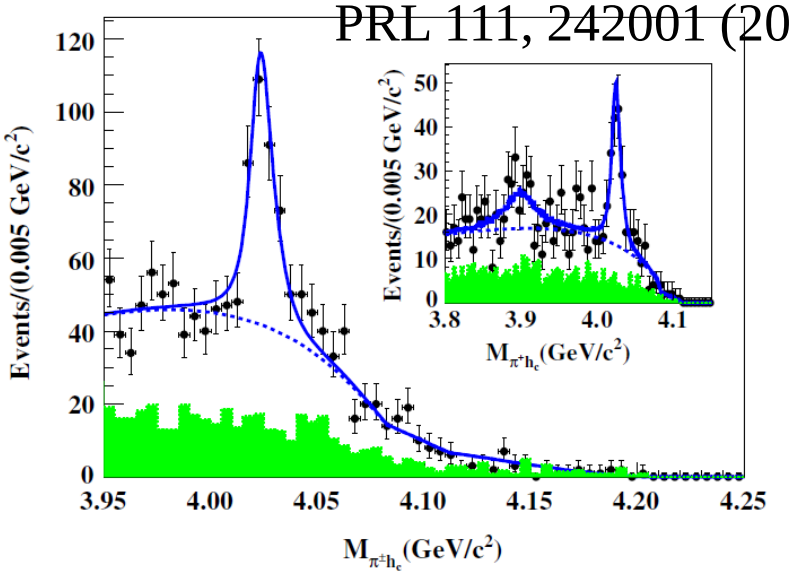
$$\mathcal{R}_{z'} = \frac{Br(Z'_c \to \rho\eta_c)}{Br(Z'_c \to \pi J/\psi)}$$

Observation of charged $Z_c(4020) \to \pi h_c$

$$e^+e^- \to \pi^+\pi^- h_c, h_c \to \gamma\eta_c, \eta_c \to 16\ modes$$

PRL 111, 242001 (2013)





$\boldsymbol{M = 4022.9 \pm 0.8 \pm 2.7\ \text{MeV}, \quad \Gamma = 7.9 \pm 2.7 \pm 2.6\ \text{MeV}, \quad S > 8.9\sigma}$

Cross section $\sigma(e^+e^- \to \pi^{\pm} Zc(4020)^{\mp} \to \pi^+\pi^- h_c)$

$\sqrt{s} = 4.23$ GeV: $(8.7 \pm 1.9 \pm 2.8 \pm 1.4)$ pb

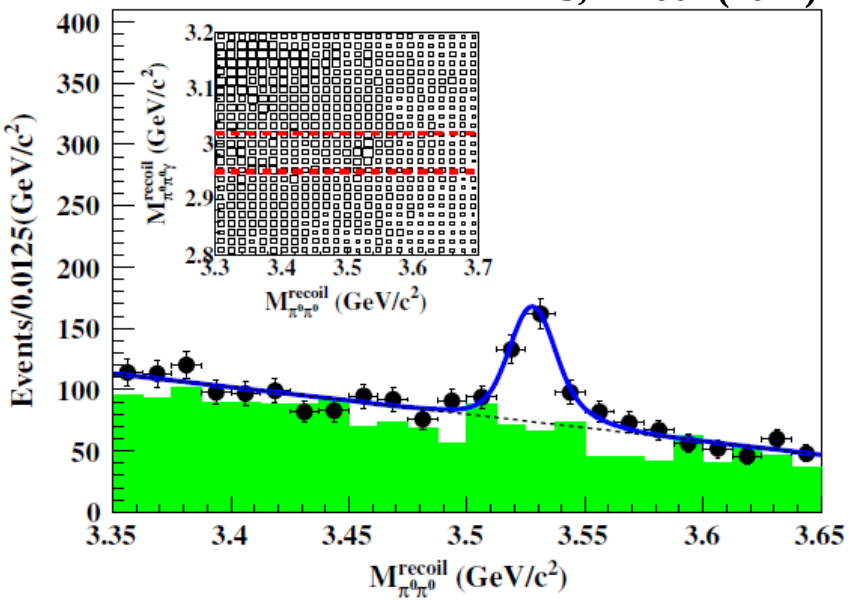
$\sqrt{s} = 4.26$ GeV: $(7.4 \pm 1.7 \pm 2.1 \pm 1.2)$ pb

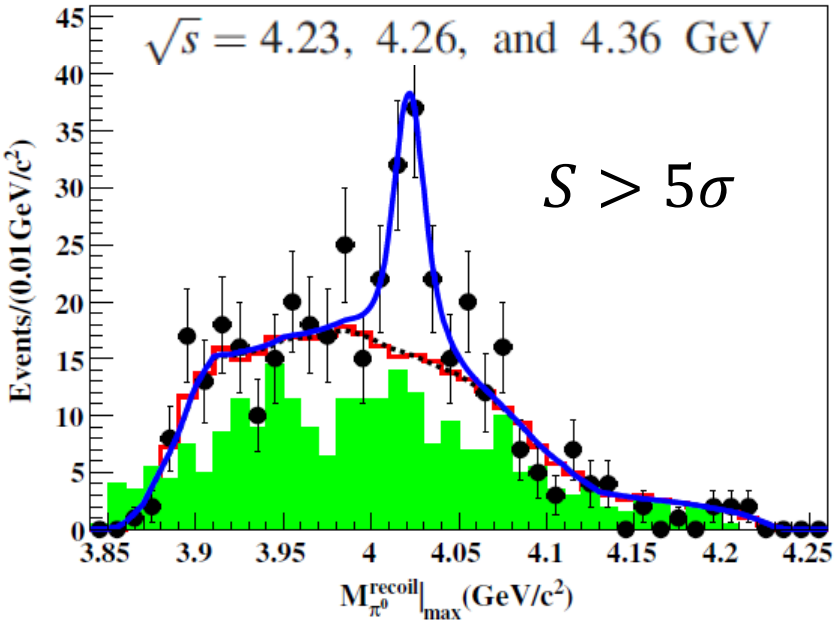
$\sqrt{s} = 4.36$ GeV: $(10.3 \pm 2.3 \pm 3.1 \pm 1.6)$ pb

Observation of neutral $Z_c(4020) \to \pi h_c$

$$e^+e^- \to \pi^0\pi^0 h_c, h_c \to \gamma\eta_c, \eta_c \to 16\,modes$$

PRL 113, 212002 (2014)





$Z_c(4020)^0$: $M = (4023.9 \pm 2.2 \pm 3.8)$ MeV , Γ : fixed

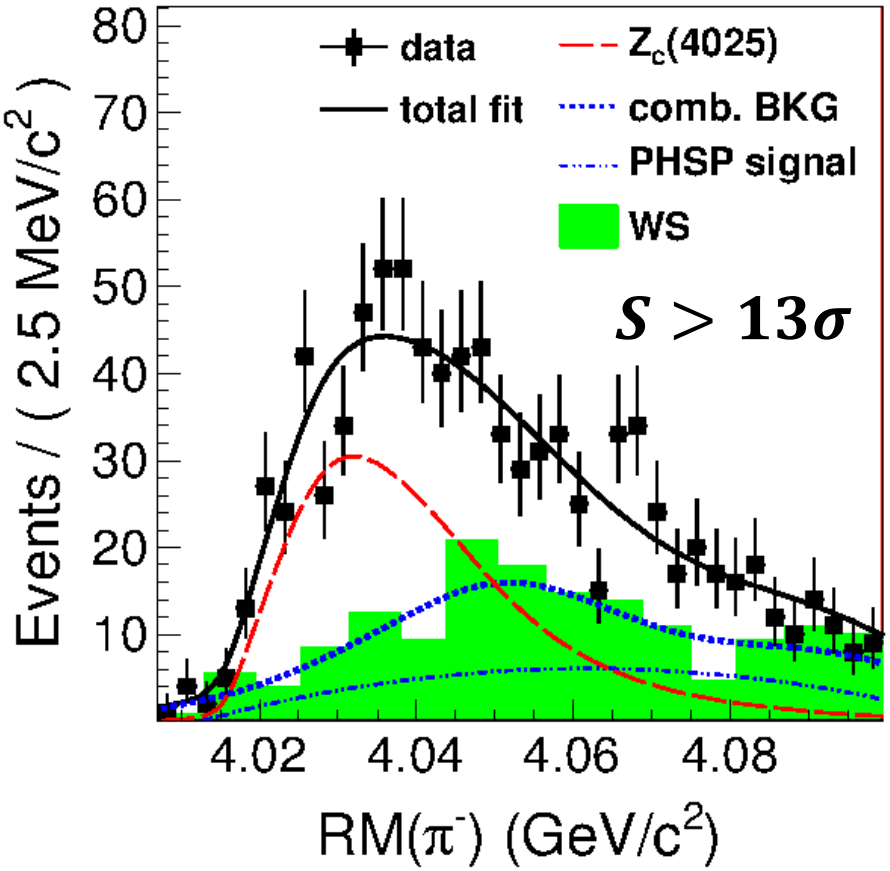
Cross sections and ratio to that of charged $Z_c(4020)$

$\sqrt{s}$ (GeV)	$n^{obs}_{Z_c(4020)^0}$	$\sigma^B(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c)$ (pb)	$R_{\pi Z_c(4020)}$
4.230	21.7 ± 7.4	$6.5 \pm 2.2 \pm 0.7 \pm 1.0$	$0.77 \pm 0.31 \pm 0.25$
4.260	22.5 ± 7.7	$8.5 \pm 2.9 \pm 1.1 \pm 1.3$	$1.21 \pm 0.50 \pm 0.38$
4.360	17.2 ± 7.2	$9.9 \pm 4.1 \pm 1.3 \pm 1.5$	$1.00 \pm 0.48 \pm 0.32$

Observation of charged $Z_c(4020) \to D^*\bar{D}^*$

$$e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp \; [(D^*\bar{D}^*)^\pm = D^{*+}\bar{D}^{*0} \text{ and } D^{*-}D^{*0}]$$

$\mathcal{L}(\sqrt{s} = 4.26) = 826\ \text{pb}^{-1}$, only bachelor pion & one D^* reconstructed



PRL 112, 132001 (2014)

S-wave Breit-Wigner

Mass:

$$(4026.3 \pm 2.6 \pm 3.7)\ \text{MeV}$$

Width:

$$(24.8 \pm 5.6 \pm 7.7)\ \text{MeV},$$

$$\frac{\sigma[e^+e^- \to Z_c(4020)^\pm\pi^\mp \to (D^*\bar{D}^*)^\pm\pi^\mp]}{\sigma[e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp]}$$

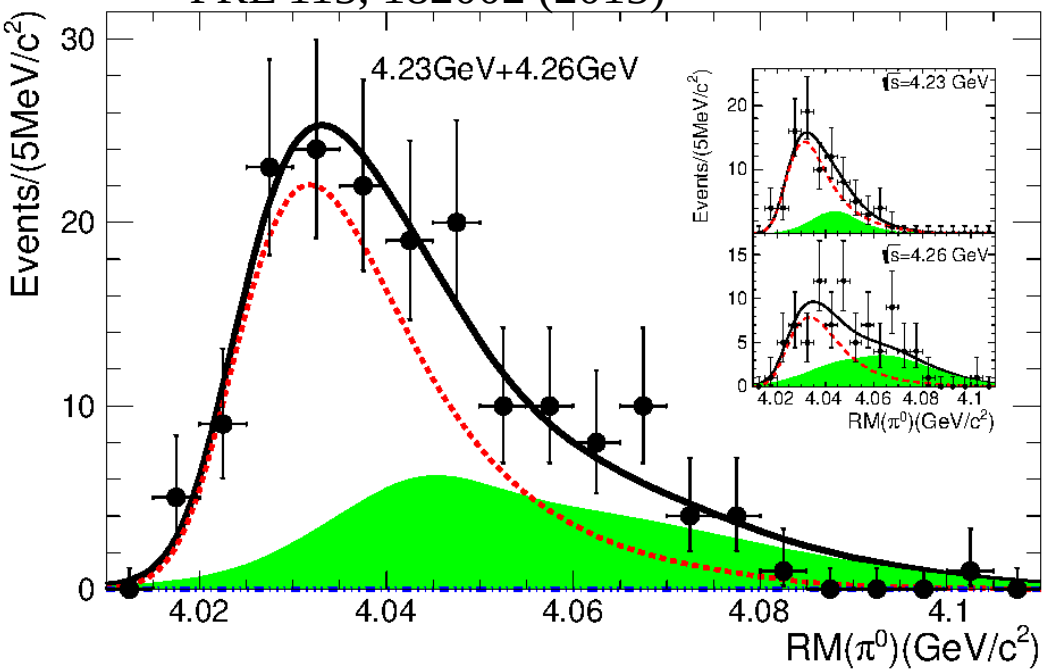
$$= 0.65 \pm 0.09 \pm 0.06.$$

Observation of neutral $Z_c(4020) \to D^*\bar{D}^*$

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

only bachelor pion & two D reconstructed, use $\mathcal{L} = 1092 + 826\ \text{pb}^{-1}$ at $\sqrt{s} = 4.23$ and 4.26 GeV, respectively

PRL 115, 182002 (2015)



- $S > 5.9\sigma$
- Pole mass

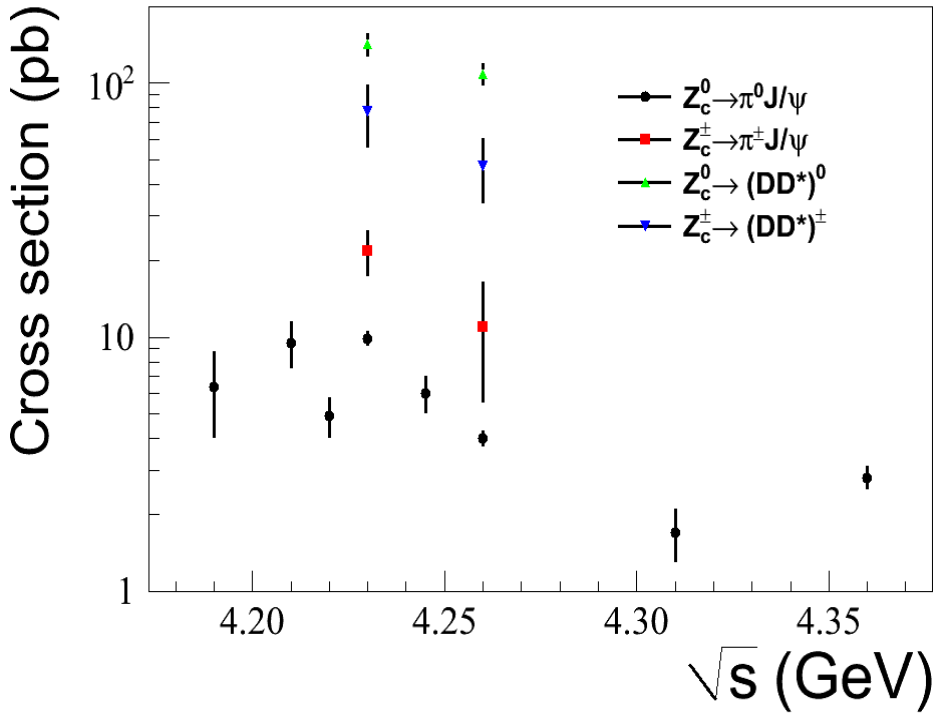
  $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV
- Pole width

  $(23.0 \pm 6.0 \pm 1.0)$ MeV

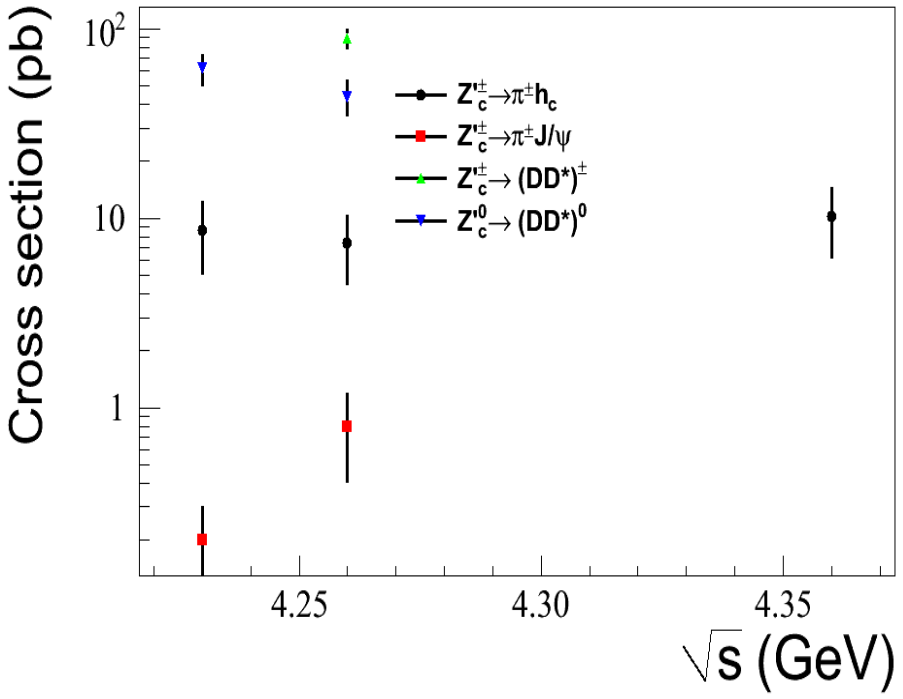
$$\frac{\sigma[e^+e^- \to Z_c(4020)^0\pi^0 \to (D^*\bar{D}^*)^0\pi^0]}{\sigma[e^+e^- \to Z_c(4020)^+\pi^- \to (D^*\bar{D}^*)^+\pi^-]} \approx 1$$

$Z_c(3900)$ and $Z'_c(4020)$ production cross section

$e^+e^- \to \pi^\mp Z_c^\pm, \pi^0 Z_c^0,$



$e^+e^- \to \pi^\mp Z'^\pm_c, \pi^0 Z'^0_c,$

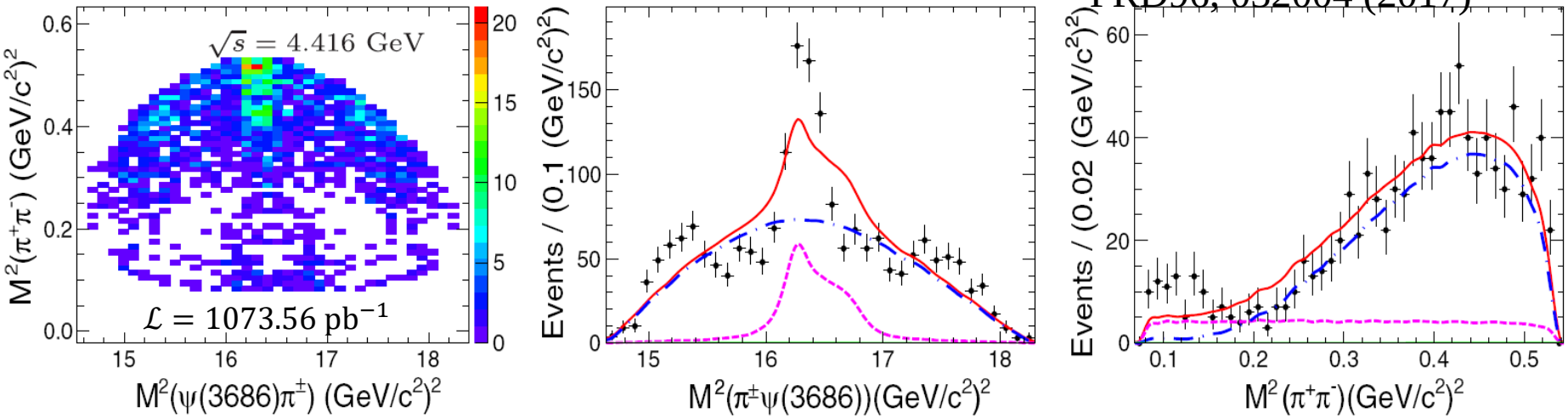


$Z_c(3900)^\pm \to (DD^*)^\pm$, PRD92, 092006
$Z_c(3900)^0 \to \pi^0 J/\psi$, PRL115, 112003
$Z_c(3900)^\pm \to \pi^\pm J/\psi$, PRL119, 072001

$Z'_c(4020)^\pm \to \pi^\pm h_c$, PR111, 242001
$Z'_c(4020)^\pm \to \pi^\pm J/\psi$: PRL119, 072001
$Z'_c(4020)^\pm \to (D^*D^*)^\pm$: PRL112, 132001
$Z'_c(4020)^0 \to (D^*D^*)^0$: PRL115, 182002

New Z_c in $e^+e^- \to \pi^+\pi^-\psi'$?

PRD96, 032004 (2017)



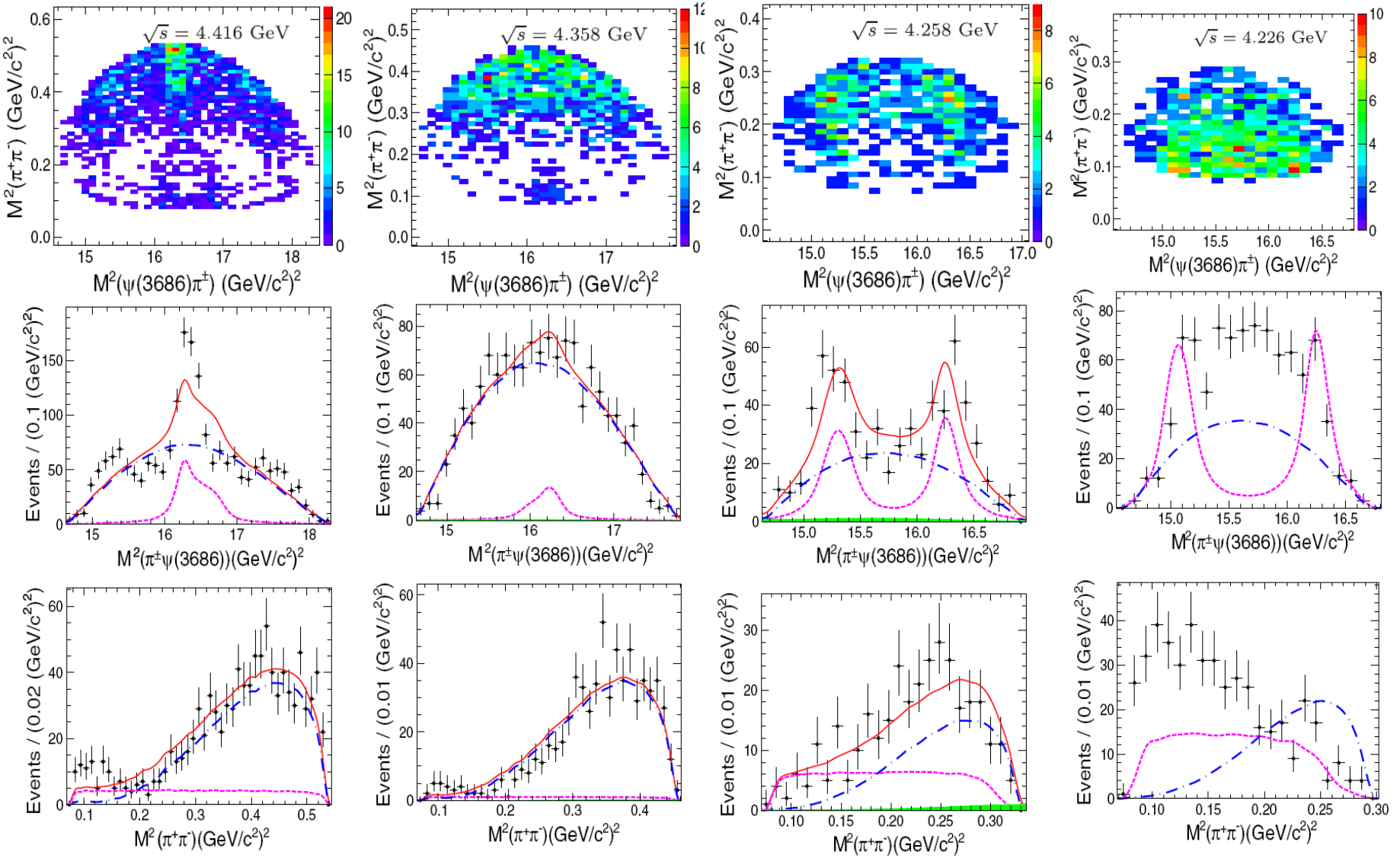
- A narrow structure observed in $\pi\psi'$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- Perform fit to Dalitz plot of $M^2(\pi^+\psi')$ versus $M^2(\pi^-\psi')$ with a S-wave Breit-Wigner function.

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

- A fit yields a mass $M = 4032.1 \pm 2.4$ MeV and width $\Gamma = 26.1 \pm 5.3$ MeV with significance 9.2σ.

New Z_c in $e^+e^- \to \pi^+\pi^-\psi'$?

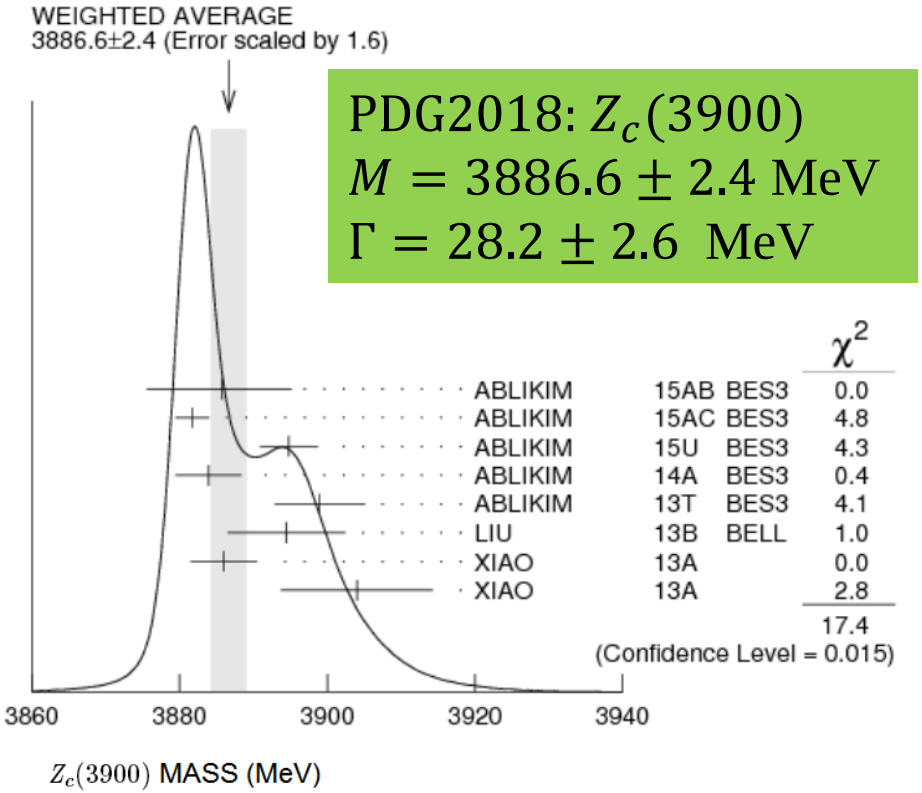
Fit intermediate states: ignore interference & fit can't describe date well



PRD96, 032004 (2017)

Open issues for Z_c/ Z_c' states

- Inconsistent mass and width of $Z_c(3900)$ measured in experiments.



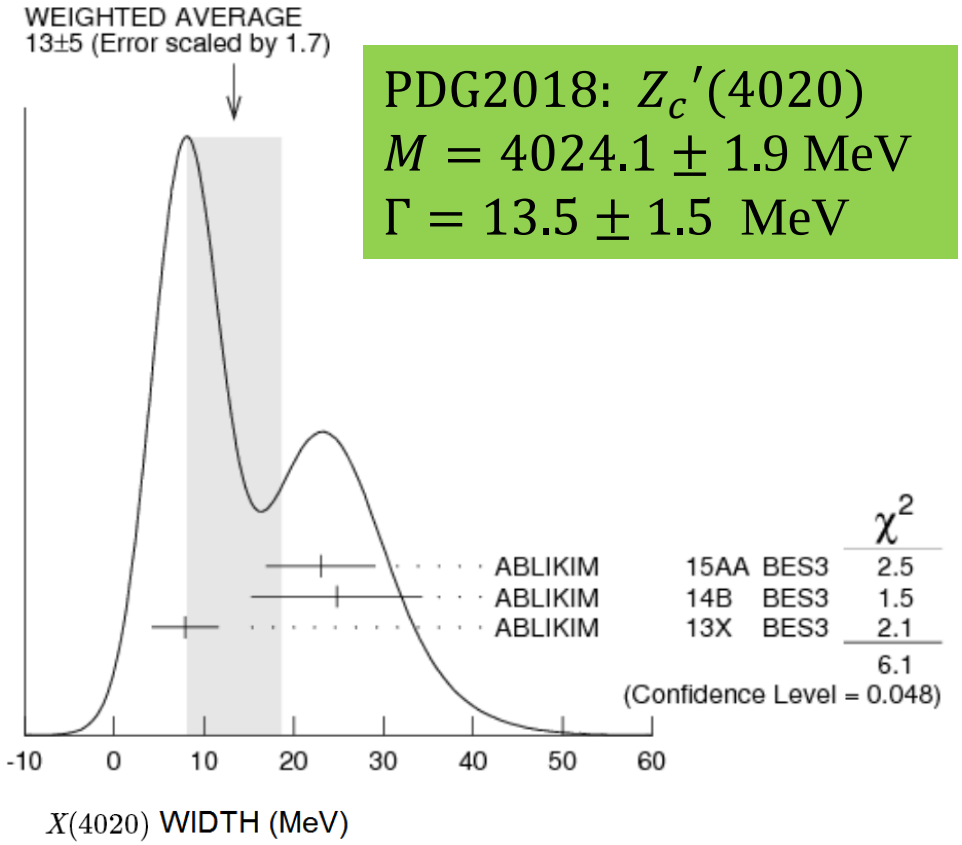
width (MeV)	experiment
$51.8 \pm 4.6 \pm 36.0$	$e^+ e^- \to \pi^+\pi^- J/\psi$
$35\ ^{+11}_{-12} \pm 15$	$e^+ e^- \to \pi^0 (D\overline{D}^*)^0$
$26.6 \pm 2.0 \pm 2.1$	$e^+ e^- \to \pi^\pm (D\overline{D}^*)^{-+}$
$29.6 \pm 8.2 \pm 8.2$	$e^+ e^- \to \pi^0\pi^0 J/\psi$
$24.8 \pm 3.3 \pm 11.0$	$e^+ e^- \to \pi^\pm (D\overline{D}^*)^{-+}$
$46 \pm 10 \pm 20$	$e^+ e^- \to \pi^+\pi^- J/\psi$

Comments:

- Inconsistent width definition, e.g. pole width, BW width
- No interference effect considered

Open issues for Z_c / Z_c' states

- $Z'_c(4020)$ mass and width.



PDG2018: $Z_c'(4020)$
$M = 4024.1 \pm 1.9$ MeV
$\Gamma = 13.5 \pm 1.5$ MeV

Mass (MeV)	experiment
$4025.5\ ^{+2.0}_{-4.7} \pm 3.1$	$e^+ e^- \to (D^* \overline{D}^*)^0 \pi^0$
$4026.3 \pm 2.6 \pm 3.7$	$e^+ e^- \to (D^* \overline{D}^*)^{+-} \pi^{\mp}$
$4023.9 \pm 2.2 \pm 3.8$	$e^+ e^- \to \pi^0 \pi^0 h_c$
$4022.9 \pm 0.8 \pm 2.7$	$e^+ e^- \to \pi^+ \pi^- h_c$

Z_c problem and prospects

- Complex $\pi\pi J/\psi, \pi\pi\psi'$ Dalitz plot at higher energy → How to understand the Z_c properties?
- Lacks of Z_c argand plots
- Insufficient experimental information on the Z_c decays and new excited Z_c states.

Huge XYZ data plan

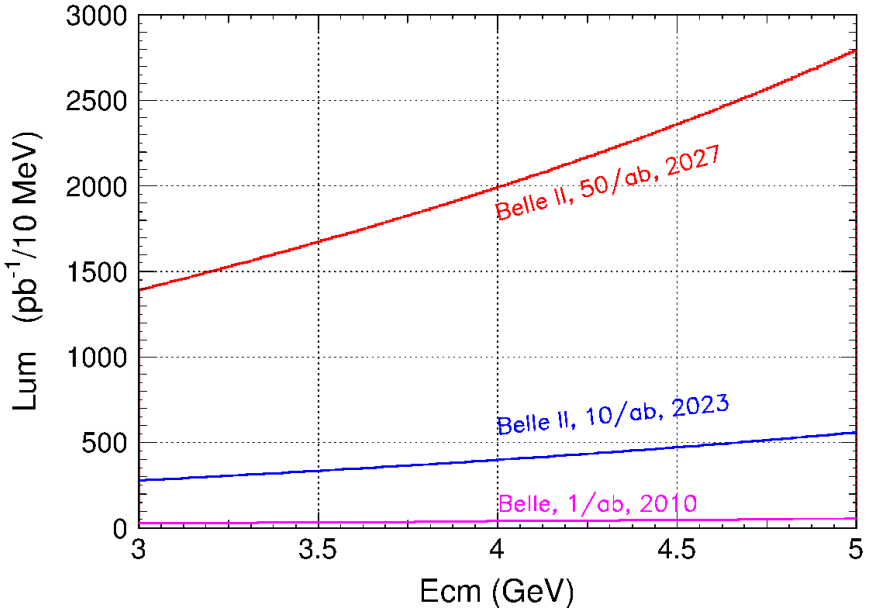
- Large integrated scan luminosity from 4.0 ~ 4.6 GeV
  500 pb^{-1} at interval 10 MeV
- Huge luminosity at some specific points

arXiv:1912.05983

channel	data plan	luminosity	cross section precision	# of events
$\pi^+\pi^- J/\psi$	(1)	500 pb^{-1} at 4.30 GeV	3%	1270
$\pi^+\pi^- h_c(1P)$	(1)	500 pb^{-1} at 4.30 GeV	9%	220
$\eta J/\psi$	(1)	500 pb^{-1} at 4.30 GeV	30%	28
$\pi^+\pi^-\psi(3686)$	(1)	500 pb^{-1} at 4.30 GeV	3%	230
$\pi^+\pi^- J/\psi$	(2)	5 fb^{-1} at 4.23 GeV	<1%	18k
$\pi^+\pi^- J/\psi$	(2)	5 fb^{-1} at 4.42 GeV	3%	3k
$\pi^+\pi^-\psi(3686)$	(2)	5 fb^{-1} at 4.42 GeV	2%	4k

Competition with other experiments

arXiv:1912.05983



Assume 50 ab^{-1} of Belle II data in 10 MeV energy bins.

ISR mode	$L_{\rm BESIII}/L_{\rm Belle\ II}$	$\varepsilon_{\rm BESIII}/\varepsilon_{\rm Belle\ II}$	$N_{\rm BESIII}/N_{\rm Belle\ II}$
$\pi^+\pi^- J/\psi$ at 4.26 GeV	0.5 fb^{-1} / 2.2 fb^{-1}	46% / 10%	1.07
$\pi^+\pi^-\psi(3686)$ at 4.36 GeV	0.5 fb^{-1} / 2.3 fb^{-1}	41% / 5%	1.82
$\pi^+\pi^-\psi(3686)$ at 4.66 GeV	0.5 fb^{-1} / 2.5 fb^{-1}	35% / 6%	1.19
$\pi^+\pi^- h_c$ at 4.26 GeV	0.5 fb^{-1} / 2.2 fb^{-1}	2.7% / %	> 5
$K^+K^- J/\psi$ at 4.6 GeV	0.5 fb^{-1} / 2.4 fb^{-1}	29% / 7.5%	0.81
$K^+K^- J/\psi$ at 4.9 GeV	0.5 fb^{-1} / 2.7 fb^{-1}	≈29% / 10%	0.54
$\Lambda_c^+\bar{\Lambda}_c^-$ at 4.6 GeV	0.5 fb^{-1} / 2.4 fb^{-1}	51% / 7.5%	1.42
$\Lambda_c^+\bar{\Lambda}_c^-$ at 4.9 GeV	0.5 fb^{-1} / 2.7 fb^{-1}	≈37% / 7.5%	0.91

Future data taking plan of BESIII

Plan	Data Sets
XYZ plan (1)	500 pb^{-1} at a large number of points between 4.0 and 4.6 GeV
XYZ plan (2)	5 fb^{-1} at 4.23, 4.42 GeV for large Z_c samples
XYZ plan (3)	5 fb^{-1} above 4.6 GeV
charmonium plan	3×10^9 $\psi(3686)$ decays

Along with top-up technique

Summary and remarks

- Quantum numbers are established for $Z_c(3900)$ as $I^G(J^{PC}) = 1^+(1^{+-})$. It is observed in $Z_c \to \pi J/\psi, \rho\eta_c$ and DD^*
- Spin and parity for $Z'_c(4020)$ are not known, but it's $I^G = 1^+$ established. It is observed in $Z'_c \to \pi h_c, D^*D^*$ modes.
- To resolve the continuum or resonant production of these Z_c sates, measurements of production cross sections above 4.0 GeV is necessary.
- To resolve inconsistent mass and width measurement for Z_c and Z'_c states, coupled channel analysis is desirable.
- Other measurements, such as Argand plot, and tests of Z_c production model are helpful to figure out the structure of Z_c states.
- BESIII plans to take more XYZ data and continue the study.

Thanks for your attention.