XYZ STATES AT BESIII

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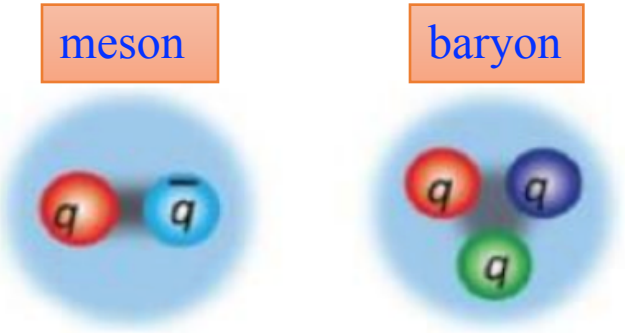
Outline

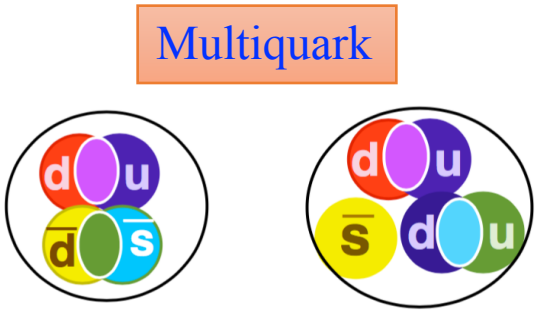
- Introduction
  - Hadrons
  - Charmonium and XYZ spectrum
  - BESIII Data Samples for XYZ Study
- Results on X states
- Results on Y states
- Results on Z states
- Summary and Outlook

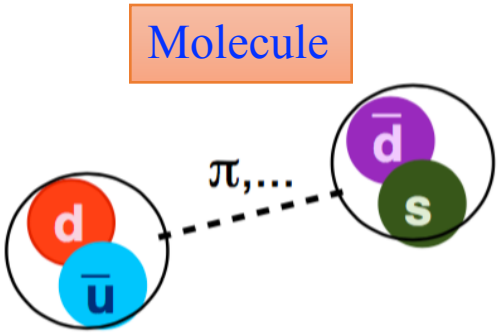
Introduction

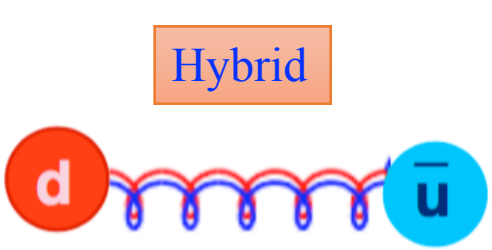
Hadrons: naive and exotic

- Naive quark model:
  - 2 quarks: meson ($q\bar{q}$)
  - 3 quarks: baryon (qqq)
- QCD predicts the exotic states:
  - Multiquark states: $N_{quarks} >= 4$
  - Molecule: bound state of hadrons
  - Hybrid: $N_{quarks} >= 2$ + gluon
  - Glueball: $N_{quarks} = 0$ (gg, ggg, ...)



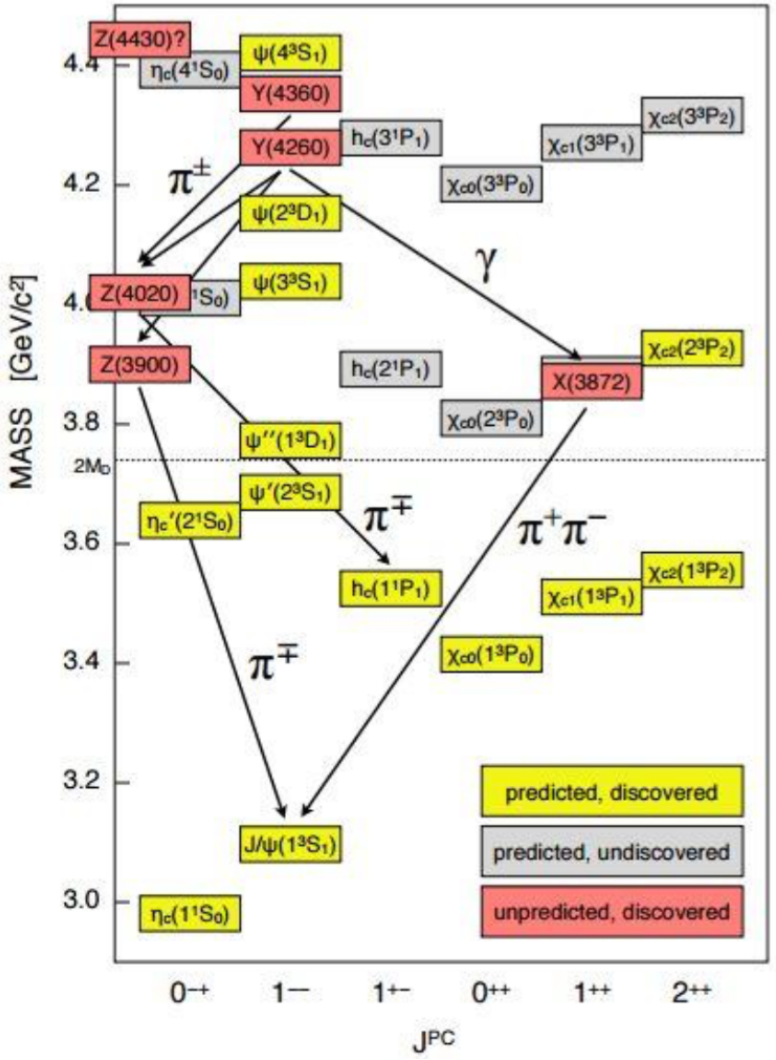






S. L. Olsen, Front. Phys. 10, 101401 (2015)

Charmonium and XYZ spectrum



➢ **Below open-charm threshold**

✓ Good agreement between experimental measurements and theoretical predictions

➢ **Above open-charm threshold**

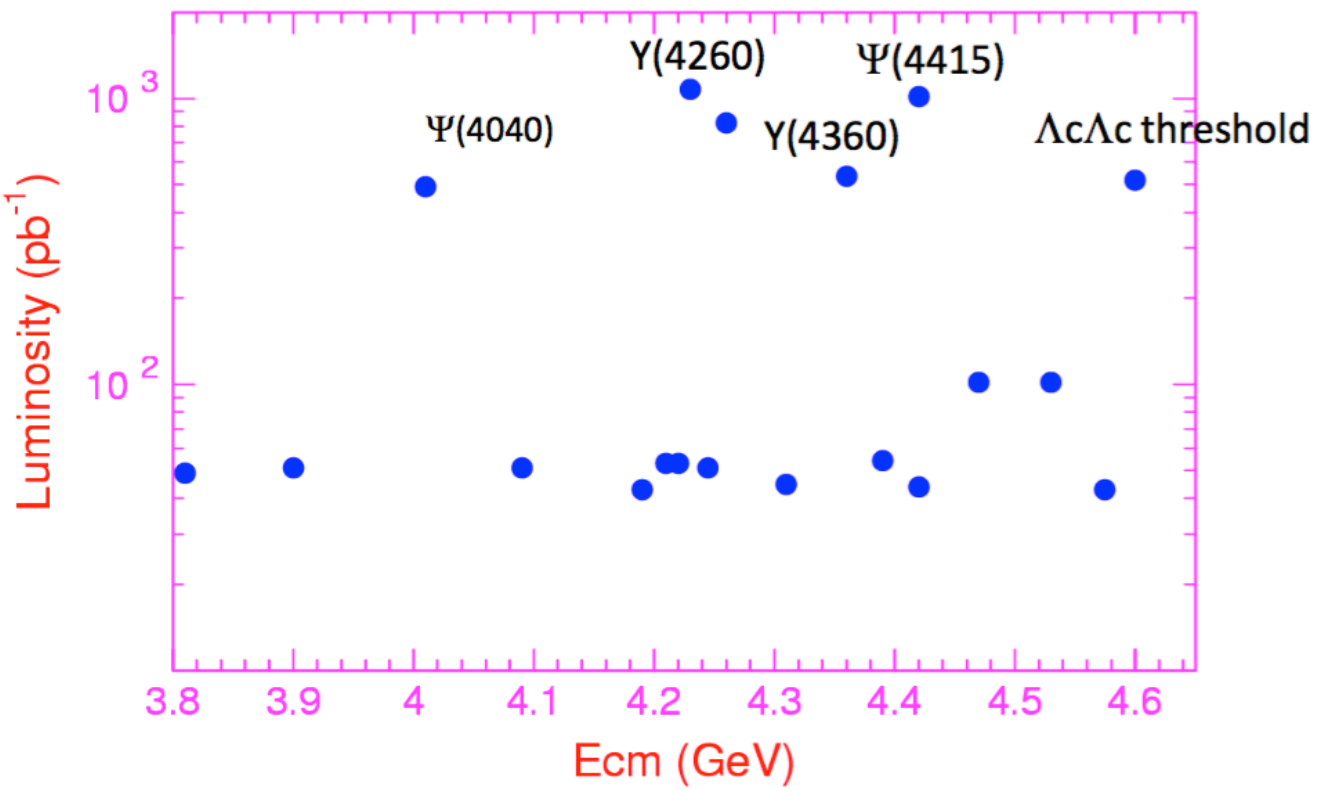
- Many expected states not discovered
- Many unexpected states observed:
  - charmonium in final states
  - no conventional charmonium states assignment
  - called **charmonium-like or XYZ states**

➢ **To do list**

☐ New decay modes of known charmonium(-like) states

☐ New charmonium(-like) states

BESIII Data Samples for XYZ Study (~5 fb^{-1})



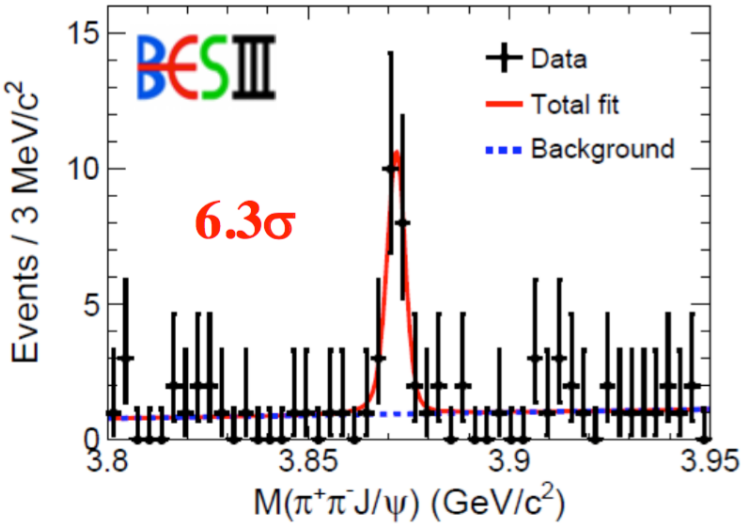
CM energy (GeV)	L (pb^{-1})
3.810	50.54±0.03
3.900	52.61±0.03
4.009	481.96±0.01
4.090	52.63±0.03
4.190	43.09±0.03
4.210	54.55±0.03
4.220	54.13±0.03
4.230[1]	44.40±0.03
4.230[2]	1047.34±0.14
4.245	55.59±0.04
4.260[1]	523.74±0.10
4.260[2]	301.93±0.08
4.310	44.90±0.03
4.360	539.84±0.10
4.390	55.18±0.04
4.420[1]	44.67±0.03
4.420[2]	1028.89±0.13
4.470	109.94±0.04
4.530	109.98±0.04
4.575	47.67±0.03
4.600	566.93±0.11

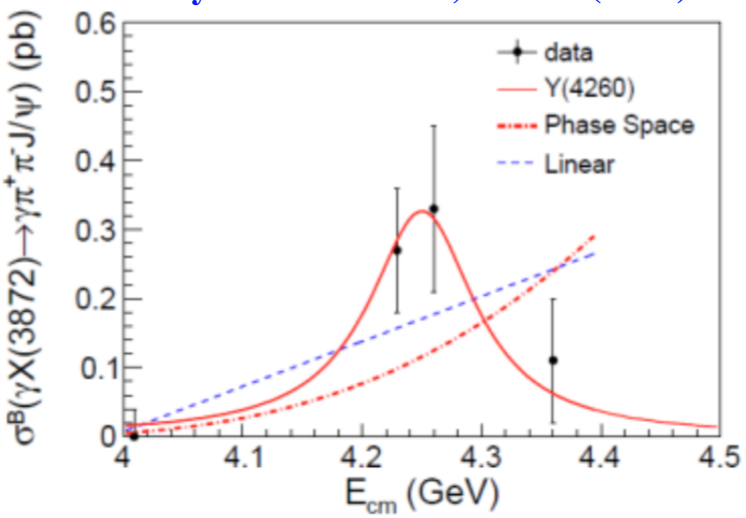
- XYZ physics: 3.8 ~ 4.6 GeV
- Integrated luminosity: ~5 fb^{-1}

Results on X states

$e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

Phys. Rev. Lett 112, 092001 (2014)

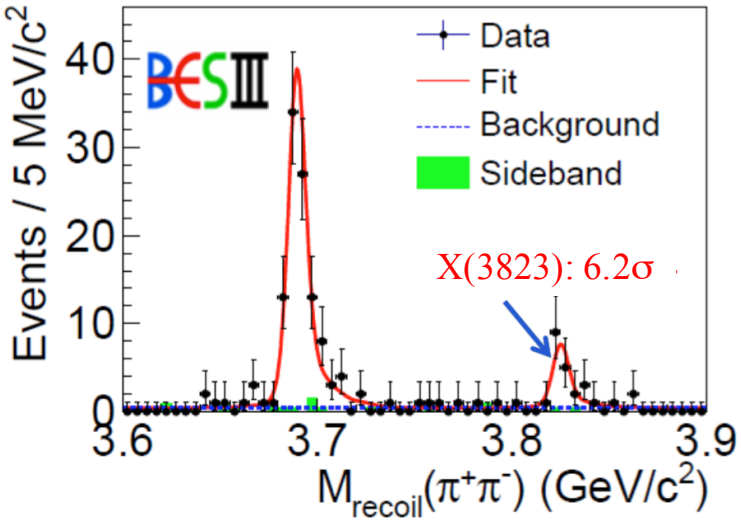


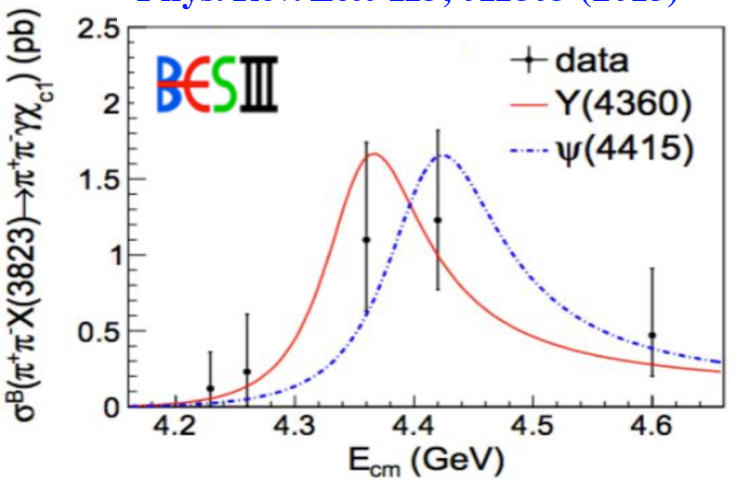


- The first observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$
- $M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2, $\Gamma < 2.4$ MeV, consistent with Belle's result
- Suggestive of $Y(4260) \to \gamma X(3872)$
- If $B(X(3872) \to \pi^+\pi^- J/\psi) = 5\%$, $\mathcal{R} = \dfrac{\mathrm{Br}(e^+e^- \to \gamma X(3872))}{\mathrm{Br}(e^+e^- \to \pi^+\pi^- J/\psi)} = 0.1$

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^- \gamma\chi_{c1}$

Phys. Rev. Lett 115, 011803 (2015)



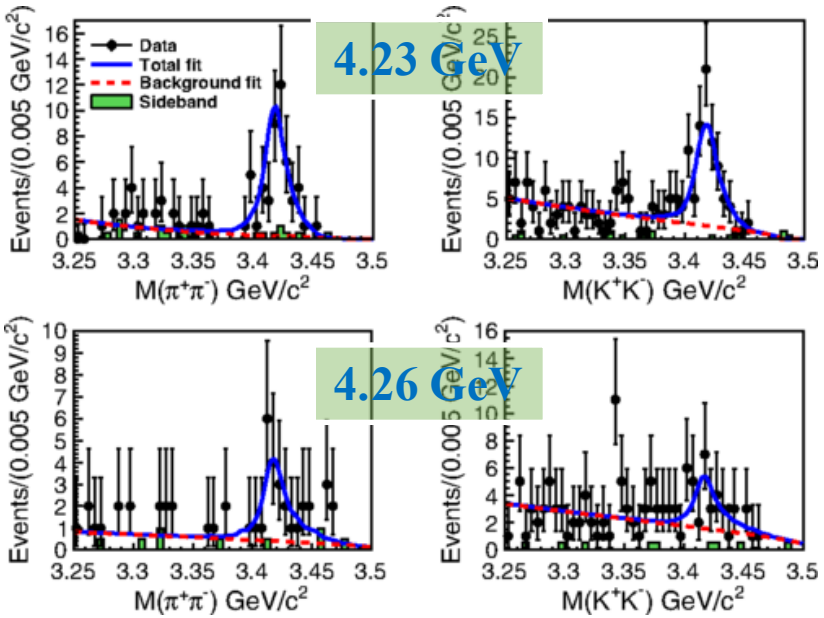


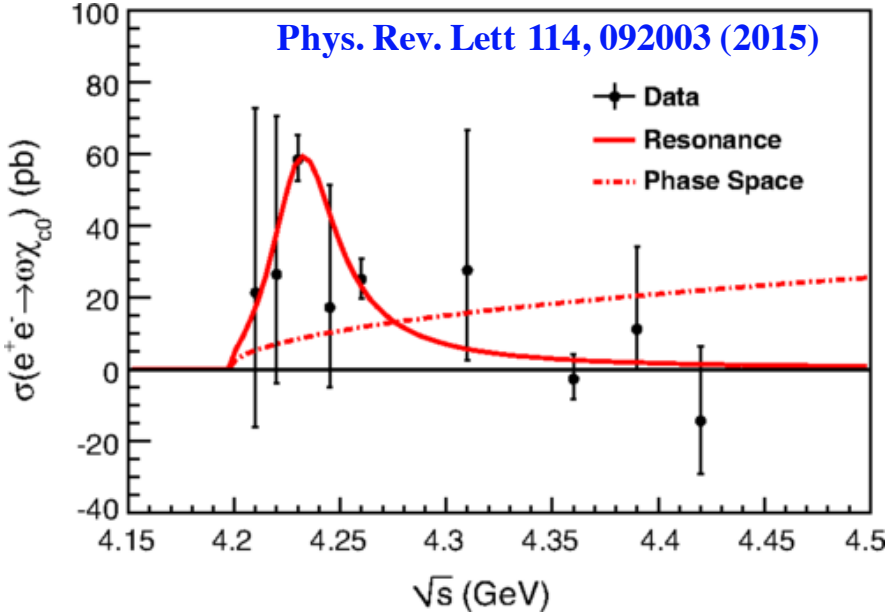
- Observed a narrow resonance X(3823), a good candidate for $\psi(1^3D_2)$
- Dominant decay $\psi(1^3D_2) \to \gamma\chi_{c1}$, no obvious signal for $\psi(1^3D_2) \to \gamma\chi_{c2}$.

  The production ratio $\mathcal{R} = \frac{\mathrm{Br}(X(3823) \to \gamma\chi_{c2})}{\mathrm{Br}(X(3823) \to \gamma\chi_{c1})} < 0.42$ @ 90% C.L, agree with $\mathcal{R}$~0.2 prediction.
- M = 3821.7±1.3±0.7 MeV/c², Γ < 16 MeV, consistent with Belle's result
- Both Y(4360) and ψ(4415) line shape give reasonable description.

Results on Y states

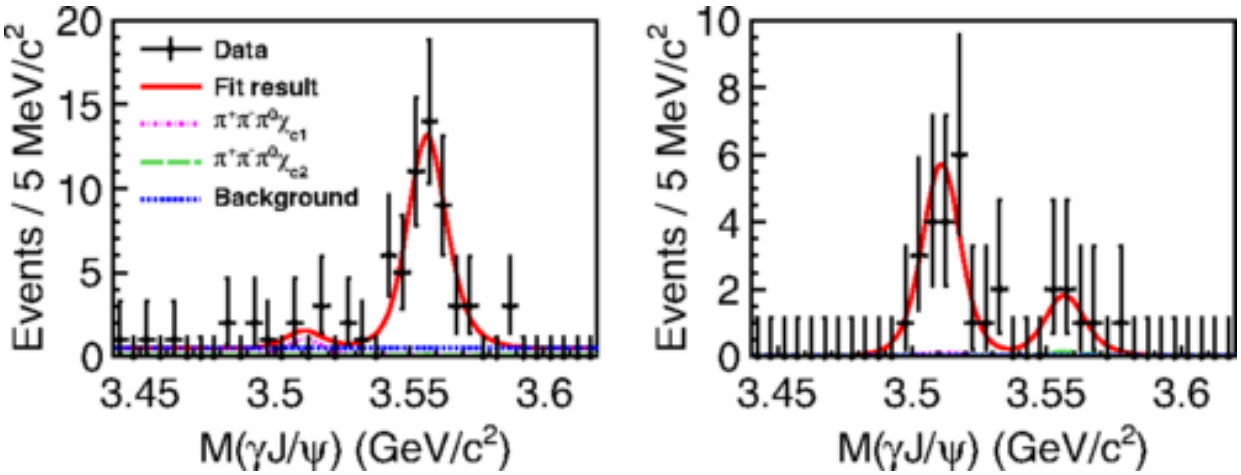
$e^+e^- \to \omega\chi_{c0}$



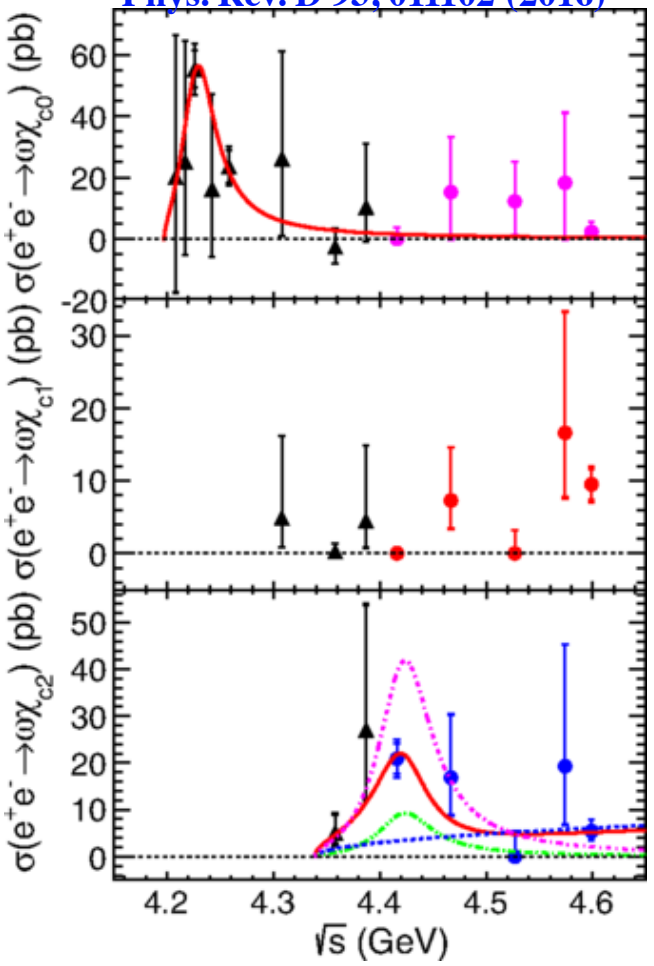


- $e^+e^- \to \omega\chi_{c0}$ are observed at E_{cm}=4.23 (11.9σ) and 4.26 GeV (5.5σ).
- Using scan data over 4.21 and 4.42 GeV, cross section peak near 4.23 GeV, fit with a single BW:
  - M = 4230±8±6 MeV/c^2, Γ = 38±12±2 MeV (>9σ)
  - A new structure?
  - ψ(4S)? Tetraquark? Threshold effect?

$e^+e^- \to \omega\chi_{c1,2}$

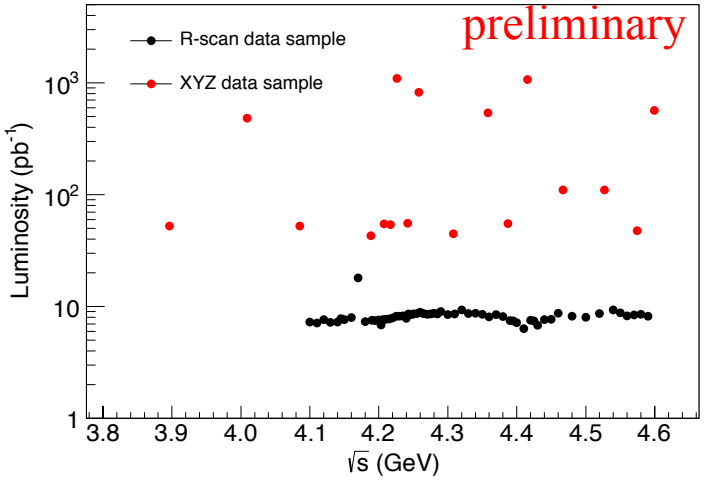


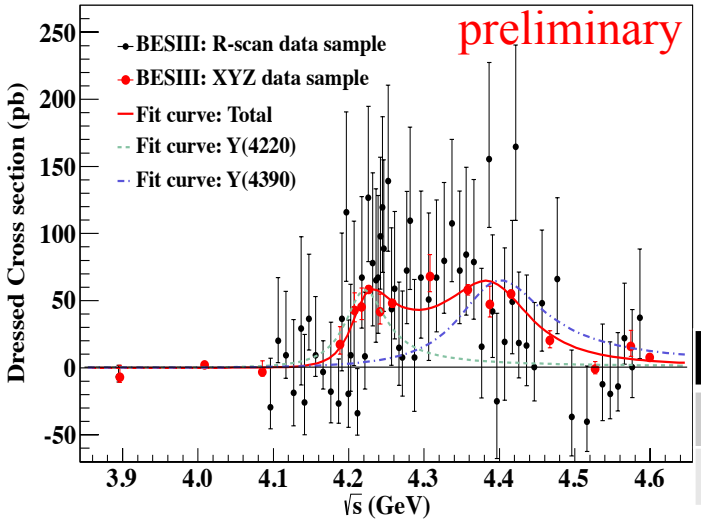
Phys. Rev. D 93, 011102 (2016)



- Clear χ_{c1}, χ_{c2} are observed at E_{cm}=4.42 and 4.6 GeV, respectively
- The Born cross section have been measured for $e^+e^- \to \omega\chi_{c1,2}$
- $\sigma(e^+e^- \to \omega\chi_{c2})$ is fitted with the coherent sum of the ψ(4415) BW function and a phase-space term. Two solutions are obtained: constructive, destructive

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





- Data samples:
  - XYZ samples (5.26 fb^{-1}):
    17 energy points from 3896 MeV to 4600 MeV
  - R-scan data samples (0.51 fb^{-1}):
    62 energy points from 4097 MeV to 4587 MeV
- Decay channels:

$e^+e^- \to \pi^+\pi^- h_c, h_c \to \gamma\eta_c, \eta_c \to X_i, X_i$ signifies 16 hadronic decay channels

$$\sigma(m) = \left| B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi}B_2(m)\sqrt{\frac{P(m)}{P(M_2)}} \right|^2$$

$B_i(m)$: constant width Breit-Wigner function

$P(m)$: 3-body phase space factor

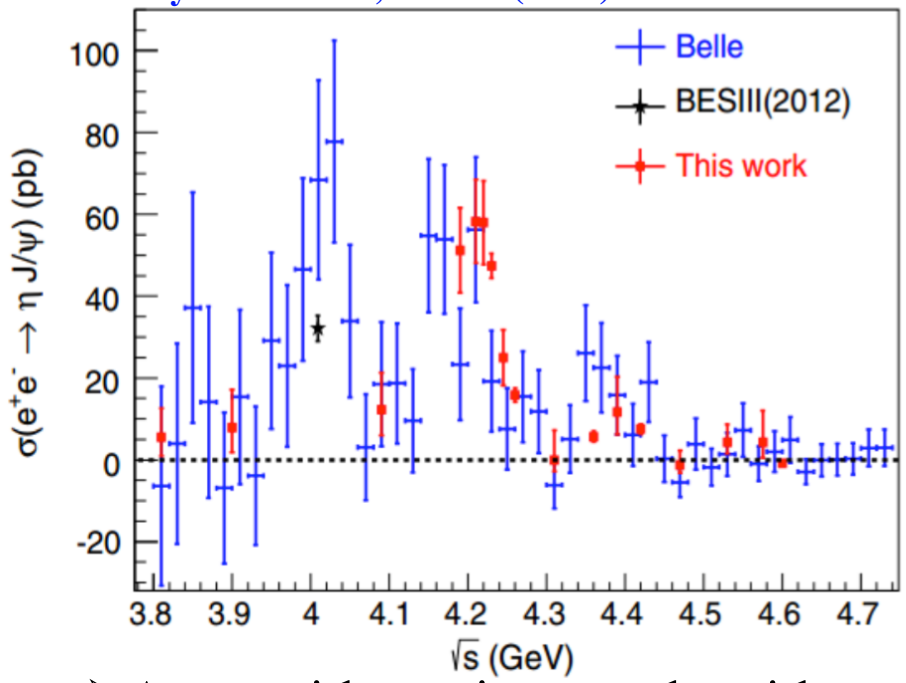
ϕ: relative phase between two resonances

significance of two structures assumption over one structure $> 10\sigma$

	M (MeV/c^2)	Γ_{tot} (MeV)	Γ_{ee}•Br (eV)	ϕ (rad)
Y(4220)	4218.4±4.0±0.9	66.0±9.0±0.4	4.6±4.1±0.8	--
Y(4390)	4391.6±6.3±1.0	139.5±16.1±0.6	11.8±9.7±1.9	3.1±1.5±0.2

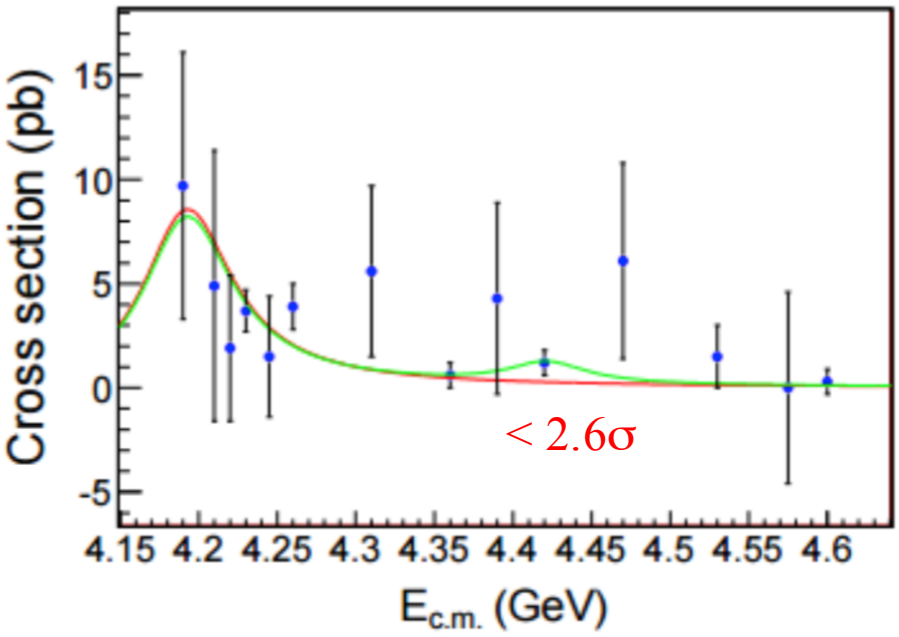
$e^+e^- \to \eta J/\psi$ & $e^+e^- \to \eta' J/\psi$

Phys. Rev. D 91, 112005 (2015)



- Agree with previous results with improved precision
- The cross section peaks around 4.2 GeV

arXiv: 1605.03256

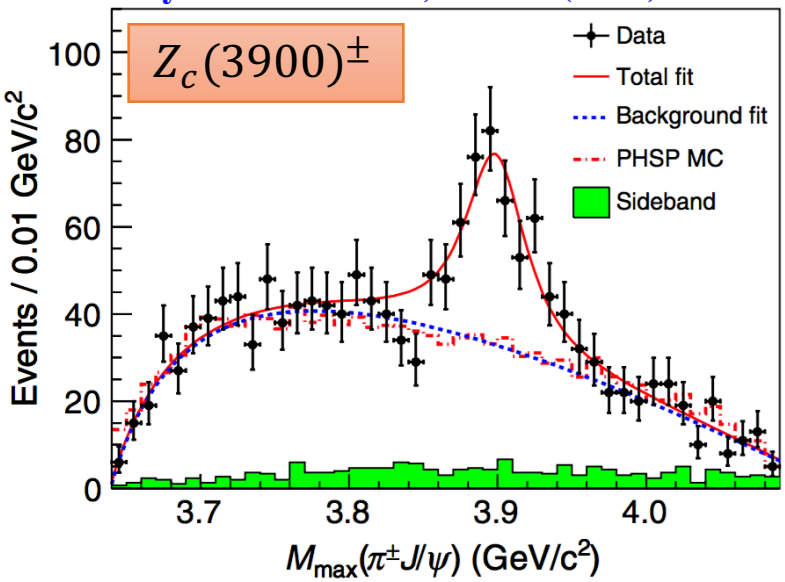


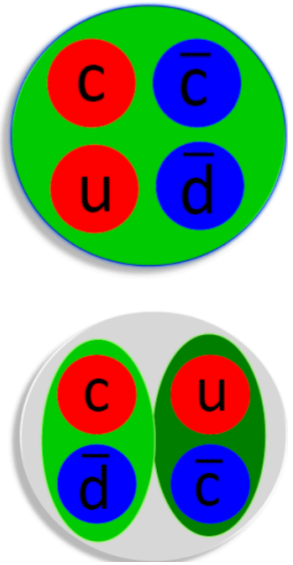
- Fit with $\psi(4160)$ and $\psi(4415)$ resonances (fixed mass and width)
  - $\psi(4415)$ is not significant ($<2.6\sigma$)
- $\sigma(\eta' J/\psi)$ is much lower than $\sigma(\eta J/\psi)$ and NRQCD calculation

Results on Z states

Discovery of $Z_c(3900)^{\pm/0}$

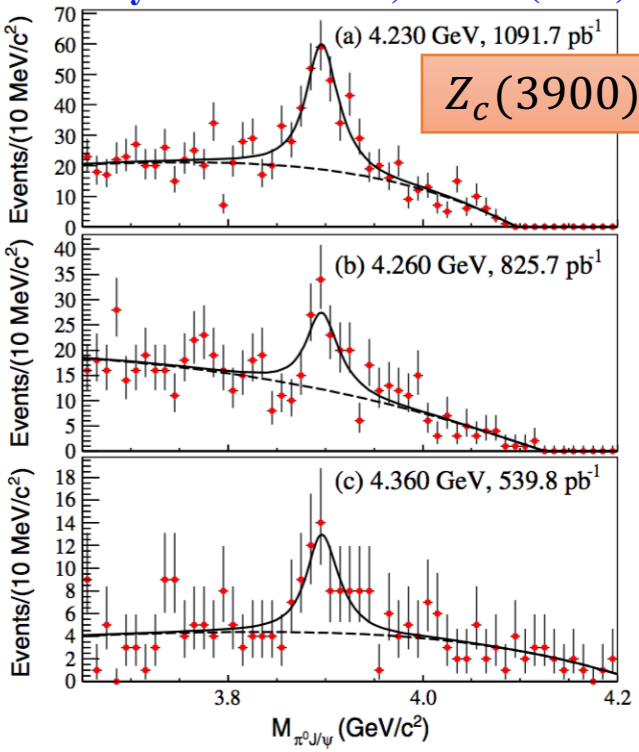
Phys. Rev. Lett 110, 252001 (2013)





- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\dfrac{\sigma(e^+e^- \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

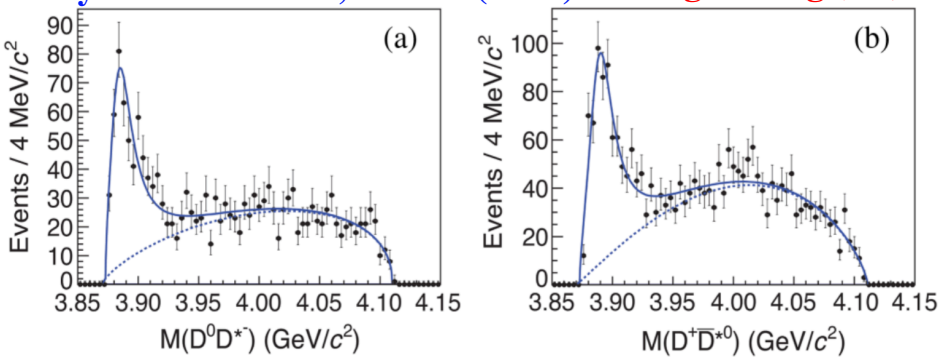
Phys. Rev. Lett 115, 112003 (2015)



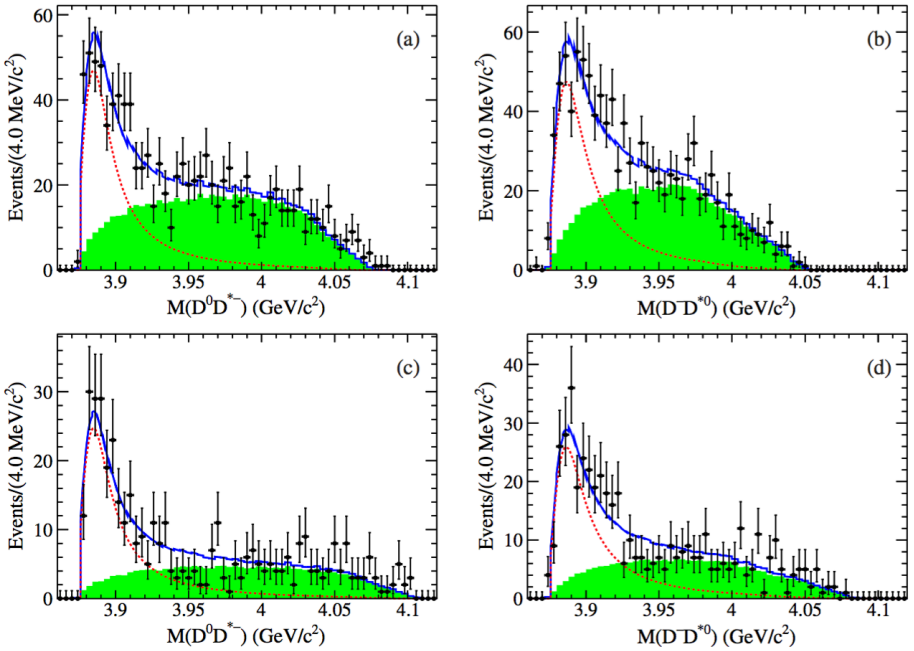
- Neutral charmonium-like structure (10.4 σ)
- Using 3 data samples (~2.5 fb^{-1})
- Evidence with 3.7σ by using CLEO-c data
- $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- An iso-spin triplet is established!

$Z_c(3885)^{\pm/0} \to (D\bar{D}^*)^{\pm/0}$

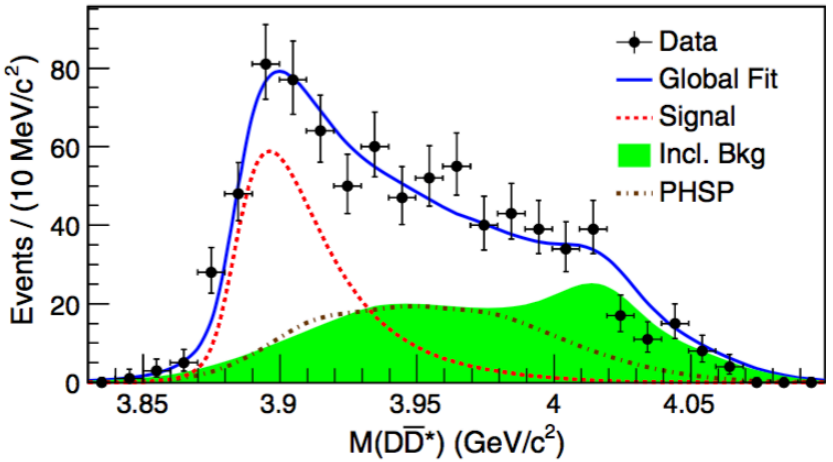
Phys. Rev. Lett 112, 022001 (2014) **Single D tag (ST)**



Phys. Rev. D 92, 092006 (2015) **Double D tag (DT)**



Double D tag (DT)

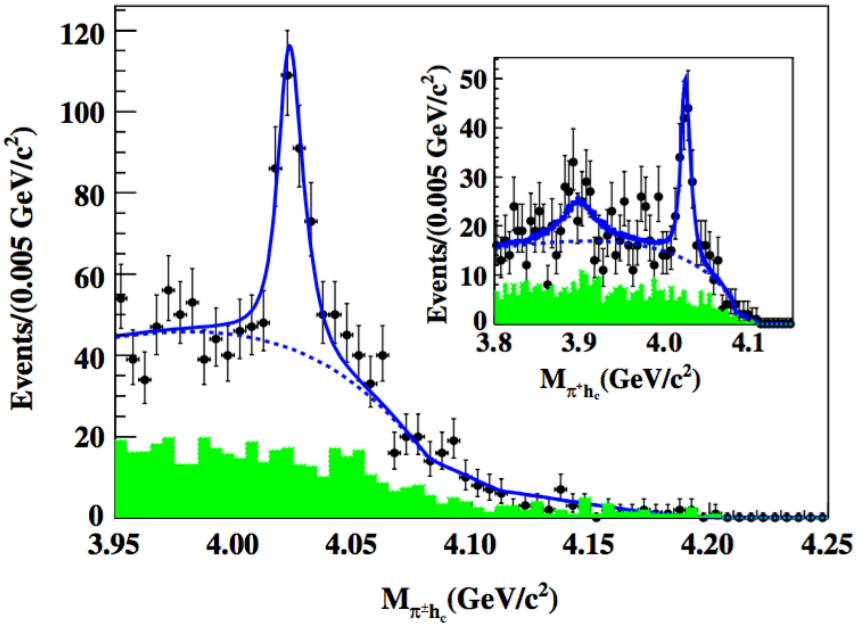


State	Mass (MeV/c²)	Width (MeV)
$Z_c(3885)^{\pm}$ (ST)	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^{\pm}$ (DT)	$3881.7 \pm 1.6 \pm 1.6$	$26.6 \pm 2.0 \pm 2.1$
Weighted average	$3882.2 \pm 1.1 \pm 1.5$	$26.5 \pm 1.7 \pm 2.1$
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

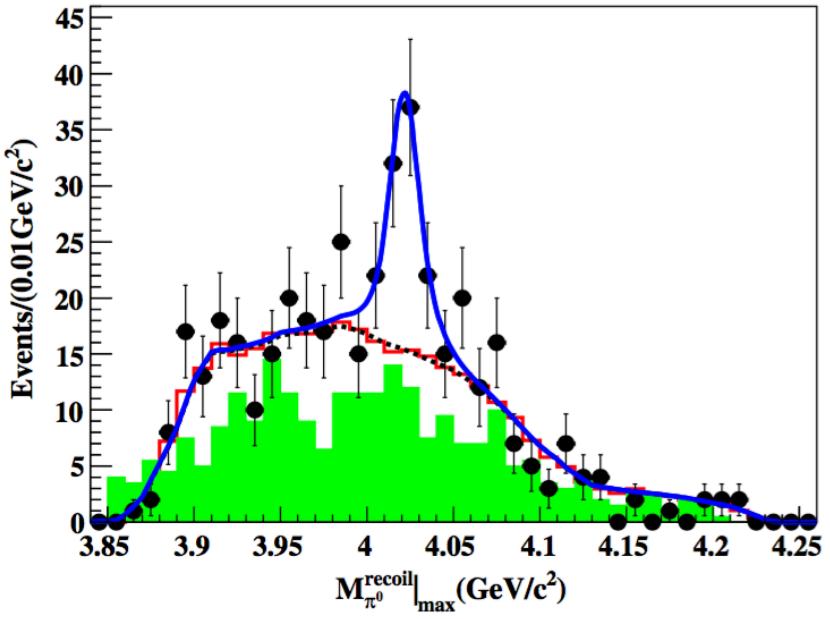
- Good agreement between ST and DT method
- Good agreement between charged state and neutral state
- Another iso-spin triplet is established!
- $Z_c(3885) = Z_c(3900)$?
- Tetraquark? Molecule state?

$Z_c(4020)^{\pm/0} \to \pi^{\pm/0} h_c$

Phys. Rev. Lett 111, 242001 (2013)



Phys. Rev. Lett 113, 212002 (2014)

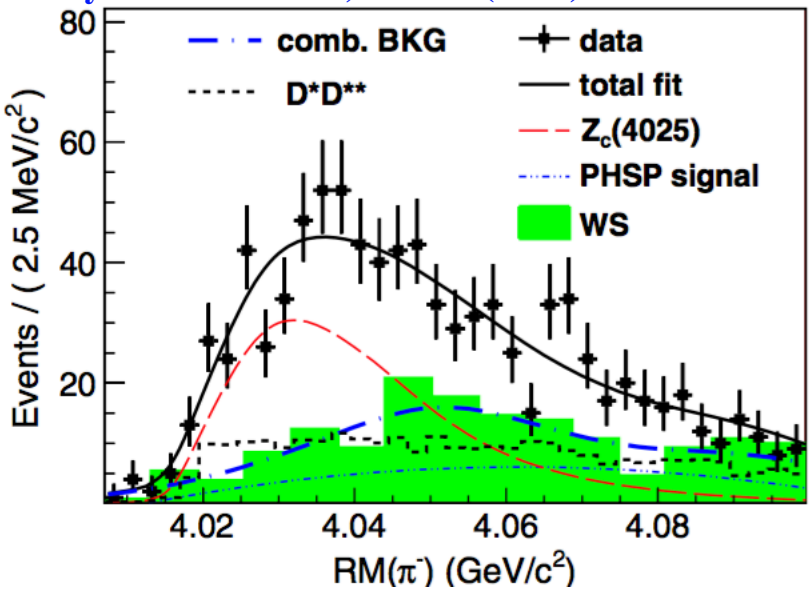


- $Z_c(4020)^{\pm/0}$ observed
- Another iso-spin triplet is established!
- No significant $Z_c(3900)^{\pm} \to \pi^{\pm} h_c$ is observed

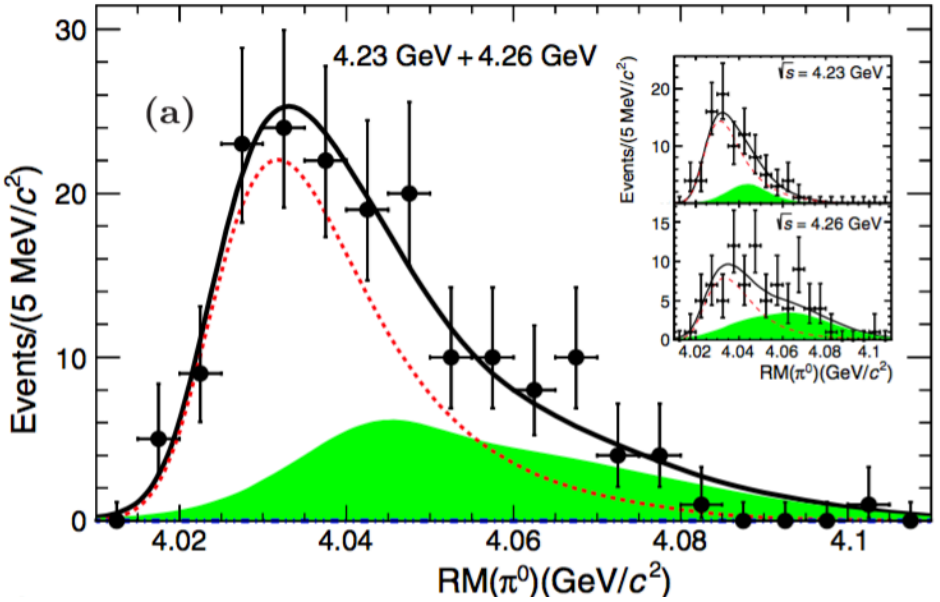
State	Mass (MeV/c²)	Width (MeV)
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6
$Z_c(4020)^{0}$	4023.9±2.2±3.8	7.9 (fixed)

$Z_c(4025)^{\pm/0} \to (D^*\overline{D}^*)^{\pm/0}$

Phys. Rev. Lett 112, 132001 (2014)



Phys. Rev. Lett 115, 182002 (2015)

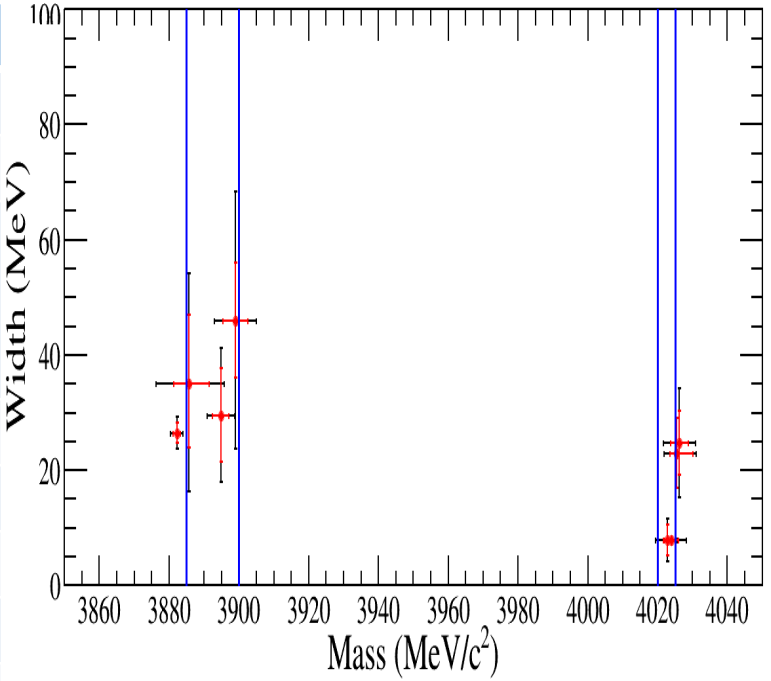


- $Z_c(4025)^{\pm/0}$ observed
- Another iso-spin triplet is established!

State	Mass (MeV/c²)	Width (MeV)
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$

Summary Z states at BESIII

State	Mass (MeV/c^2)	Width (MeV)	Process
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20	$e^+e^-\to\pi^+\pi^- J/\psi$
$Z_c(3900)^0$	3894.8±2.3±3.2	29.6±8.2±8.2	$e^+e^-\to\pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$ (ST)	3883.9±1.5±4.2	24.8±3.3±11.0	$e^+e^-\to\pi^{\mp}(D\bar{D}^*)^{\pm}$
$Z_c(3885)^{\pm}$ (DT)	3881.7±1.6±1.6	26.6±2.0±2.1	
Weighted average	3882.2±1.1±1.5	26.5±1.7±2.1	
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7}\pm 8.4$	$35^{+11}_{-12}\pm 15$	$e^+e^-\to\pi^0(D\bar{D}^*)^0$
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6	$e^+e^-\to\pi^+\pi^- h_c$
$Z_c(4020)^0$	4023.9±2.2±3.8	7.9 (fixed)	$e^+e^-\to\pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$e^+e^-\to\pi^{\mp}(D^*\bar{D}^*)^{\pm}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm 3.1$	23.0±6.0±1.0	$e^+e^-\to\pi^0(D^*\bar{D}^*)^0$



- $Z_c(3885)^{\pm}$ mass is about 2.6σ lower and the width 1.5σ lower than $Z_c(3900)^{\pm}$ value. If $Z_c(3885) = Z_c(3900)$, $\frac{\Gamma(Z_c(3885)^{\pm}\to(D\bar{D}^*)^{\pm})}{\Gamma(Z_c(3900)^{\pm}\to\pi^{\pm}J/\psi)} = 6.2\pm1.1\pm2.7$, coupling to $D\bar{D}^*$ is larger than to πJ/ψ;
- $Z_c(4020)^{\pm}$ and $Z_c(4025)^{\pm}$ mass and width are consistent within 1.5σ. If $Z_c(4020) = Z_c(4025)$, $\frac{\Gamma(Z_c(4025)^{\pm}\to(D^*\bar{D}^*)^{\pm})}{\Gamma(Z_c(4020)^{\pm}\to\pi^{\pm}h_c)} = 12\pm5$, coupling to $D^*\bar{D}^*$ is larger than to πh_c.

Summary & Outlook

- Present the recent results of XYZ states at BESIII
  - ? The nature of XYZ states is unclear
  - ? The relations between XYZ states are unclear
  - ? Some expected states and decay modes are missing

➢BESIII will collect more data for XYZ study

➢More exciting results of BESIII will come up soon

Thank You!