Exotic and Charmonium(-like) states at BESIII

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Outline

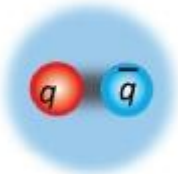
- **Introduction**

  Charmonia, XYZ states
- **Apparatus: BEPCII Collider and BESIII Detector**
- **XYZ Physics at BESIII**
  - **BESIII data samples**
  - **Results on XYZ states**
    I. X(3872), X(3823)
    II. Structures above 4 GeV
    III. $Z_c(3900)/Z_c(3885)$, $Z_c(4020)/Z_c(4025)$
- **Summary**

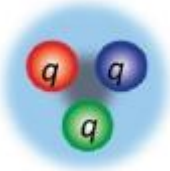
Hadrons and charmonia

- **Quark Model**
  - 2 quarks($q\bar{q}$) -- **meson**
  - 3 quarks(qqq) -- **baryon**

meson

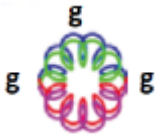


baryon

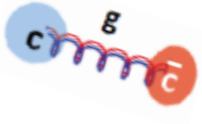


- **QCD predicts the exotic states**
  - **Glueball**: $N_{quarks} = 0$ (gg, ggg, …)
  - **Hybrid**: $N_{quarks} >= 2$ ($q\bar{q}g$,qqqg)
  - **Molecule**: bound state of hadrons
  - **Multiquark state**: $N_{quarks} >= 4$

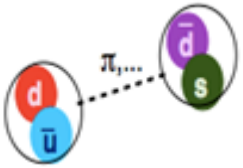
Glueball



Hybrid

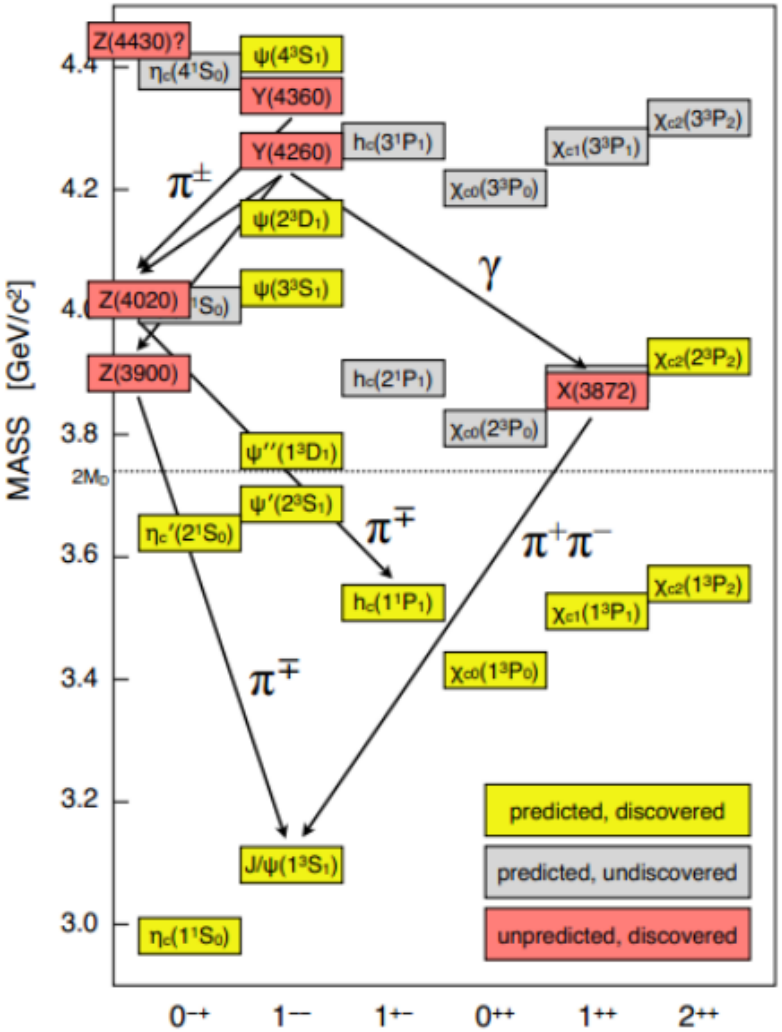


Molecule



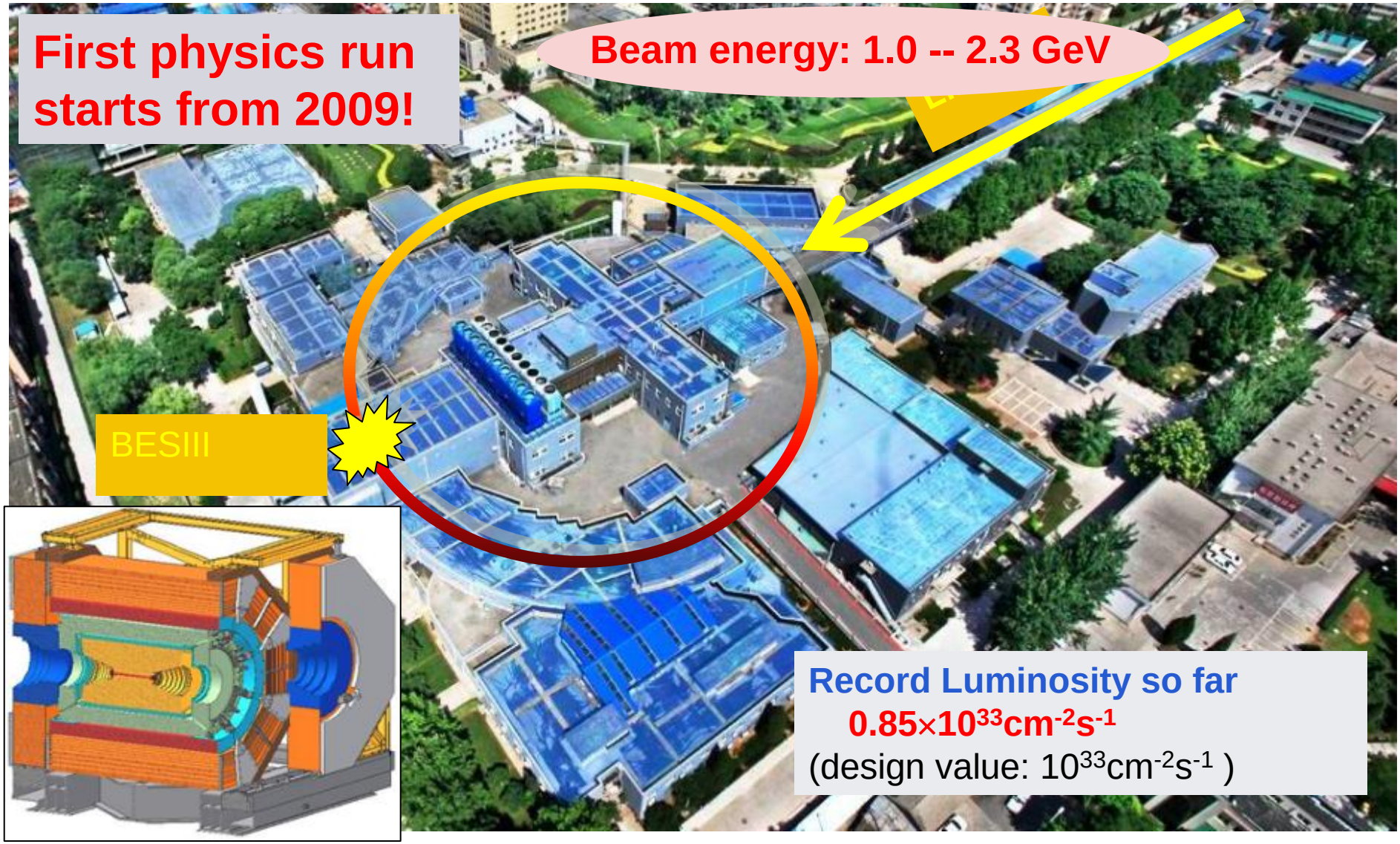
Multiquark

Charmonium and XYZ states

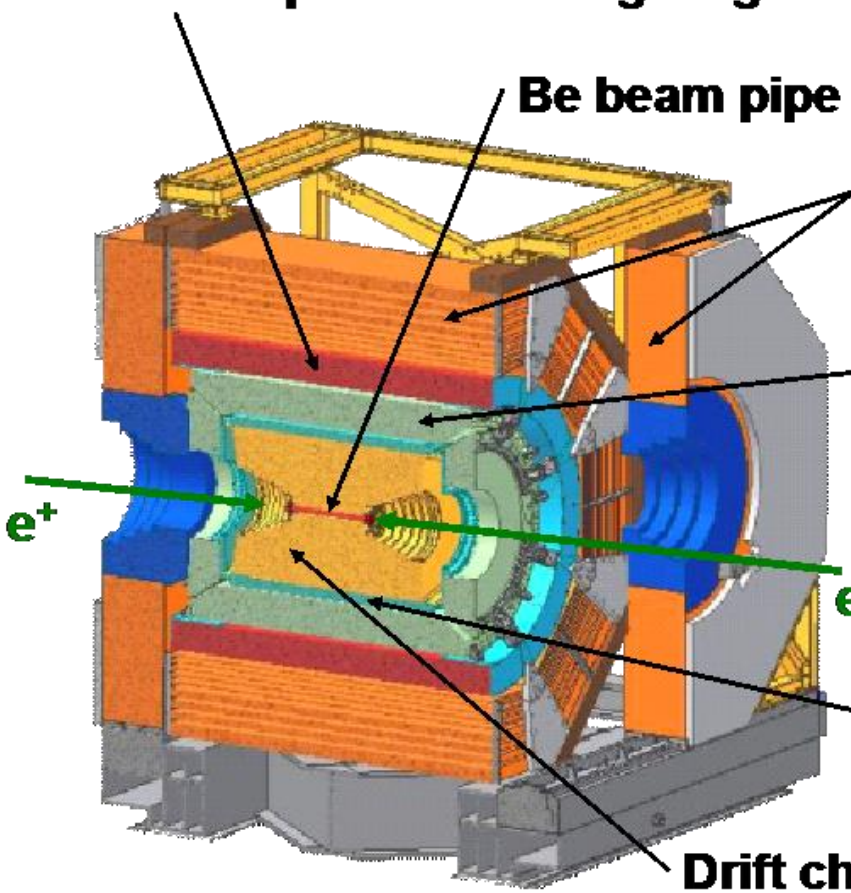


- **Below open-charm threshold**
  - ✓ Good agreement between observations and theoretical predictions
- **Above open-charm threshold**
  - ✓ Many expected states not observed
  - ✓ Many unexpected observed: with charmonium in final states, but not conventional charmonium states (**charmonium-like or XYZ**)
- **To further verify the QCD**
  - ✓ New decay modes of known charmonium states
  - ✓ New charmonium(-like) states

Beijing Electron Positron Collider (BEPCII)



BESIII Detector



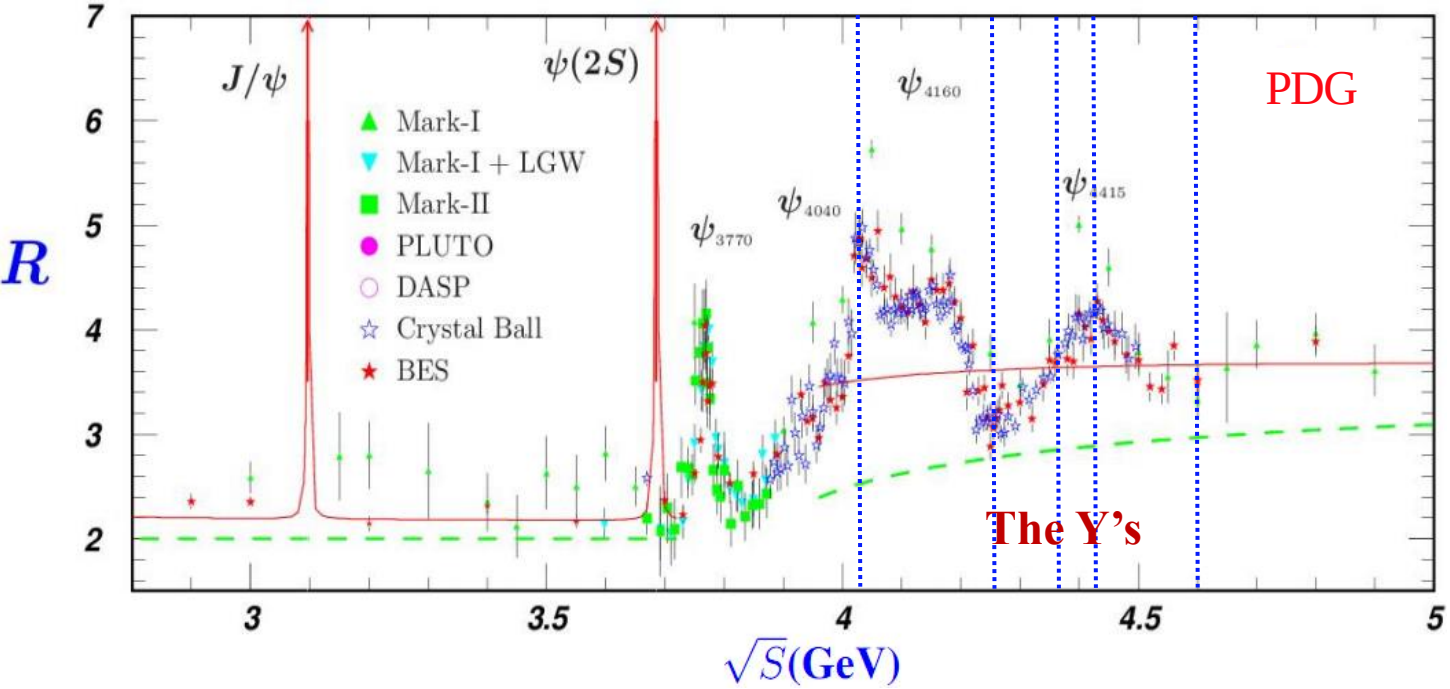
Muon counters:
9/8 RPC layers (barrel/endcaps)

CsI(Tl) **ElectroMagnetic Calorimeter:**
σ_E/E (at 1 GeV): 2.3%
$\sigma_{z,\phi}$ (at 1 GeV): 5 ~ 7 mm

Time Of Flight (TOF):
σ_T: 68/100 ps (barrel/endcaps)

Drift chambers (MDC):
σ_p/p (at 1 GeV): 0.32%
$\sigma_{dE/dx}$: <5% (Bhabha)

Data samples collected by BESIII



XYZ physics~5/fb

CM energy (GeV)	L (pb^{-1})
3.81	50.54±0.03
3.90	52.61±0.03
4.009	481.96±0.01
4.09	52.63±0.03
4.19	43.09±0.03
4.21	54.55±0.03
4.22	54.13±0.03
4.23^1	44.40±0.03
4.23^2	1047.34±0.14
4.245	55.59±0.04
4.26^1	523.74±0.10
4.26^2	301.93±0.08
4.31	44.90±0.03
4.36	539.84±0.10
4.39	55.18±0.04
4.42^1	44.67±0.03
4.42^2	1028.89±0.13
4.47	109.94±0.04
4.53	109.98±0.04
4.575	47.67±0.03
4.60	566.93±0.11

- ✓ **World's largest samples of direct e^+e^- collisions in the tau-charm region**
- ✓ **1.3B J/ψ + 0.6B ψ(2S) + 2.9/fb ψ(3770)**
- ✓ **XYZ physics: 3.8 - 4.6 GeV**
- ✓ **Other scan and continuum data below the J/ψ**

X states

X(3872): the 1st observed charmonium-like state

- ✓ X(3872) discovered in $B^{\pm} \rightarrow K^{\pm} \pi^{+}\pi^{-} J/\psi$ process by Belle in 2003, and confirmed by BaBar, CDF and D0
- ✓ The best established state among the XYZ
- ✓ The potential model did not expect the X(3872)
- ✓ $M(X(3872)) \sim M(D\bar{D}^{*})$ candidate for hadronic molecule or tetraquark

Study of the internal structure of X(3872)

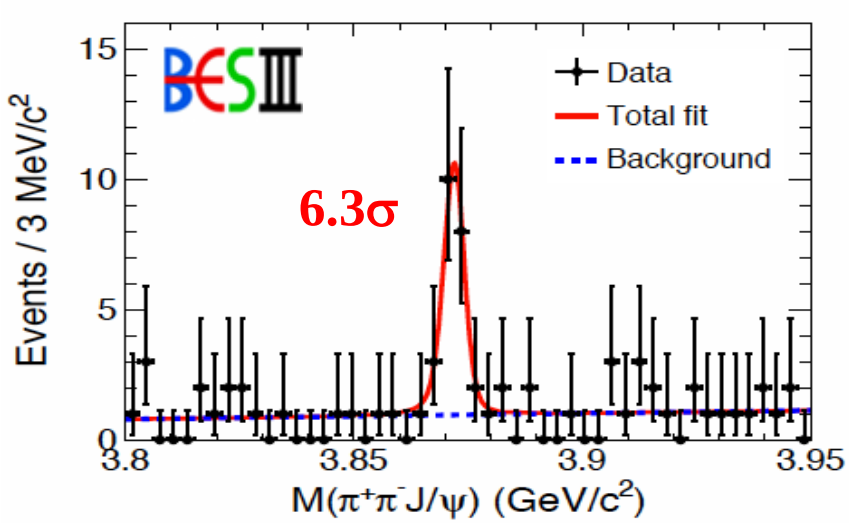
- ✓ Produced via the radiative transition of 1^{--} ψ/Y

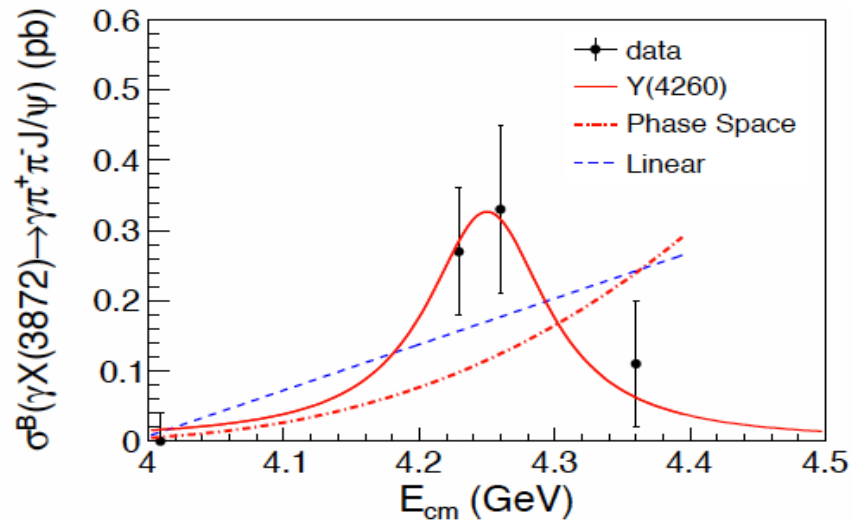
  X(3872): 1^{++}

- ✓ **Search for new decay modes and its partners of X**

Y(4260)→γX(3872)→γπ⁺π⁻J/ψ

PRL 112, 092001 (2014)



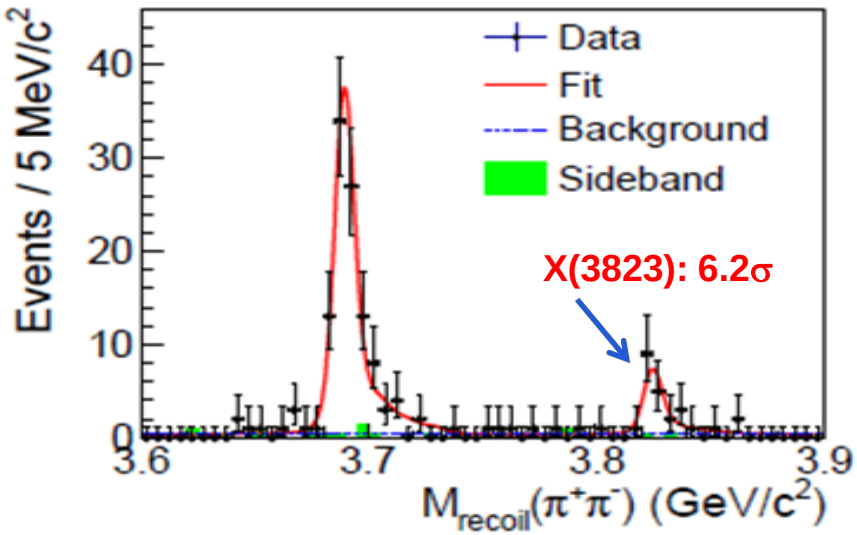


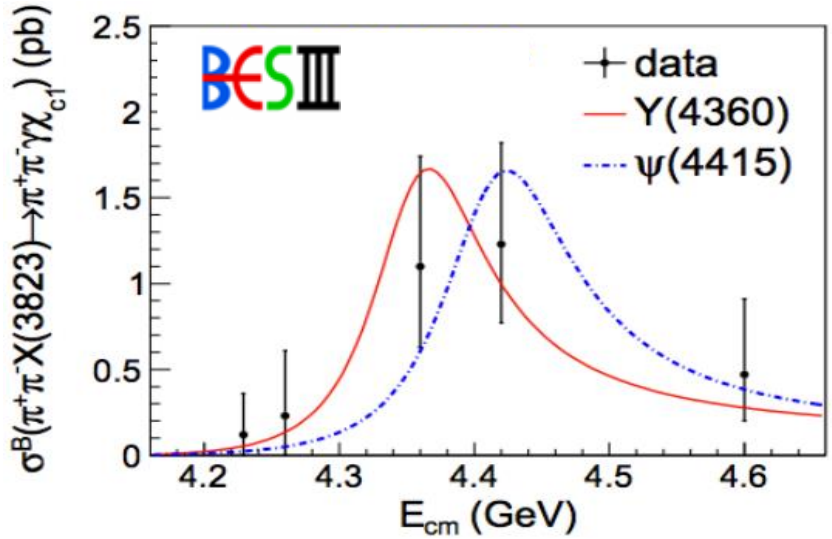
- ✓ **1st observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$**
- ✓ **M = 3871.9±0.7±0.2 MeV, Γ < 2.4 MeV** consistent with Belle's result
- ✓ **A new Y(4260) decay mode and new X(3872) production: Y(4260) → γX(3872)**
- ✓ If we take $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$ (>2.6% in PDG)

$$\frac{\sigma^B(e^+e^- \to \gamma X(3872))}{\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)} = 0.1 \text{ @4.26GeV}$$ Large transition ratio

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

PRL115, 011803 (2015)





Search for the spin-triplet partner of ψ(3770): $1^3D_2(\psi_2)$

- ✓ Potential model: $\psi_2 \to \gamma\chi_{c1}, \gamma\chi_{c2}$ with large width.

Enhancement in $M_{recoil}(\pi^+\pi^-)$

- ✓ $M = 3821.7 \pm 1.3 \pm 0.7$ MeV, $\Gamma < 16$ MeV

Good candidate of ψ_2

- ✓ mass of ψ_2: 3.81~3.84 GeV/c^2
- ✓ narrow
- ✓ dominant decay $\psi_2 \to \gamma\chi_{c1}$: no X(3823) in the $\gamma\chi_{c2}$ mode

Both Y(4360) and ψ(4415) line shape give reasonable description.

History of $1^3D_2(\psi_2)$

- ✓ **1994, E705 reported a candidate for ψ_2 (2.8σ)**
  - M= 3836±13 MeV/c^2
  - Decaying to $\pi\pi J/\psi$
- ✓ **2013, Belle reported evidence for $X(3823) \to \gamma\chi_{c1}$ in $B \to K\gamma\chi_{c1}$ (3.8σ)**
  - M= 3823.1±1.8 ±0.7 MeV/c^2

Y states

New charmonium-like vector states: Y(4260), Y(4360), Y(4660)

- ✓ Not predicted by the potential model
- ✓ A surprisingly large coupling to final states w/o open-charm mesons
- ✓ Lack of observation in the inclusive hadronic cross section

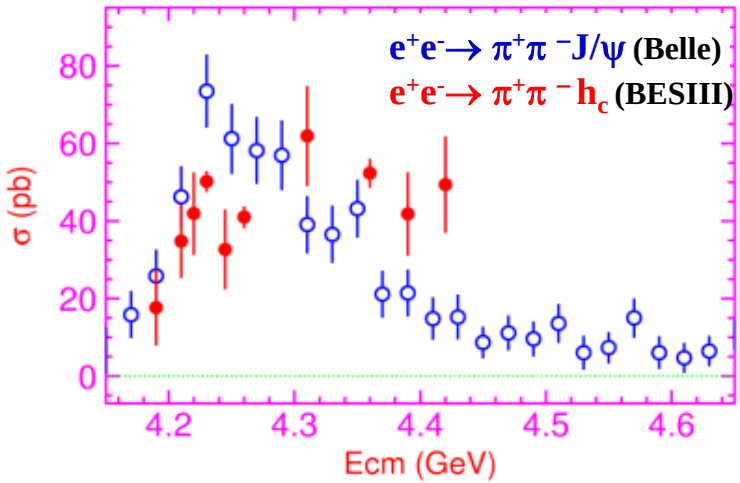
To understand the Y states

- ✓ **Search for new decay modes and measurement of the line shapes of cross sections**
- ✓ **Study hadronic transitions**

  -- **Y**→ $\eta/\pi^0/\pi\pi$ + **J/ψ**

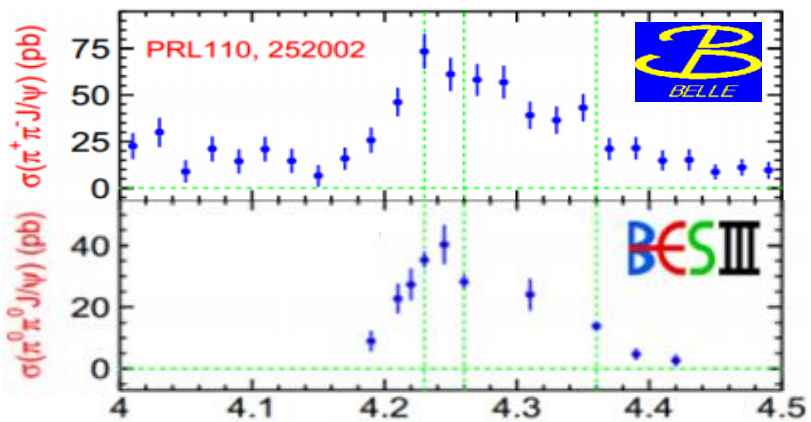
$e^+e^- \to \pi\pi J/\psi(h_c)$

BESIII arXiv: 1506.06018 $\sigma(\pi^0\pi^0 J/\psi)$
PRL 111, 242001 (2013) $\sigma(\pi^+\pi^- h_c)$
PRL 113, 212002 (2014) $\sigma(\pi^0\pi^0 h_c)$



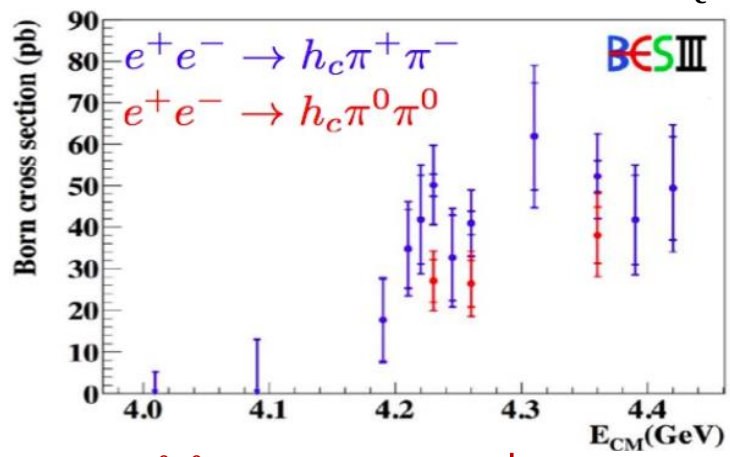
- $e^+e^- \to \pi^+\pi^- h_c$
  - ✓ This process has been studied by CLEO in 2011
  - ✓ BESIII provides an improved measurement
    - $\sigma(\pi^+\pi^- h_c) \sim \sigma(\pi^+\pi^- J/\psi)$, but different line shape
      - -- Unlikely originate from Y(4260)
      - -- Hint of a more complicated underlying dynamics
    - A possible structure near 4.23 GeV for $\sigma(\pi^+\pi^- h_c)$

- The 1st measurement of $\sigma(e^+e^- \to \pi^0\pi^0 J/\psi)$



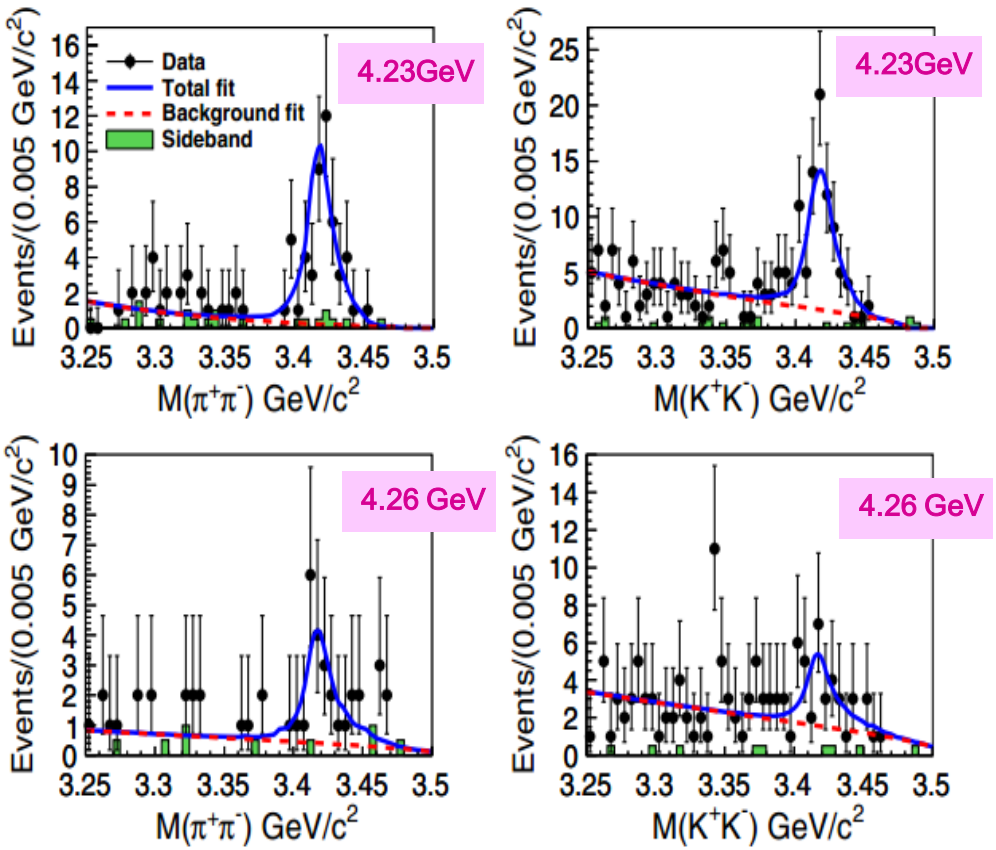
$\sigma(\pi^0\pi^0 J/\psi)/\sigma(\pi^+\pi^- J/\psi) \sim 0.5$

- The 1st observation of $e^+e^- \to \pi^0\pi^0 h_c$

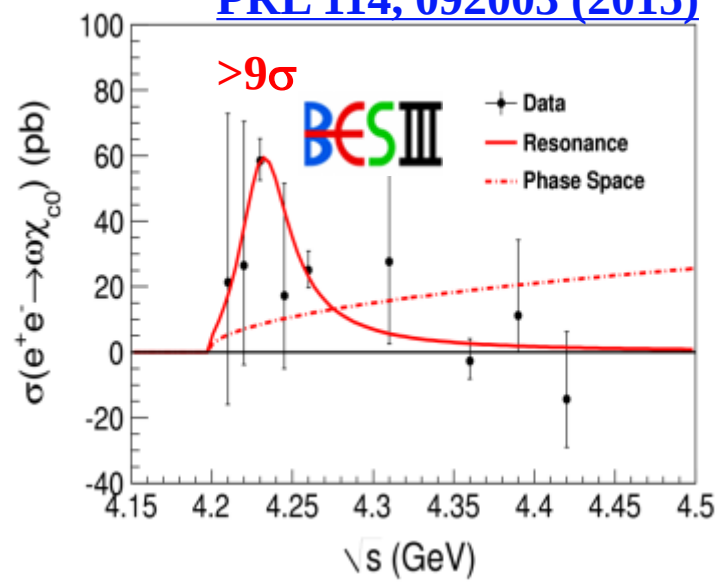


$\sigma(\pi^0\pi^0 h_c)/\sigma(\pi^+\pi^- h_c) = 0.63 \pm 0.09$

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



PRL 114, 092003 (2015)

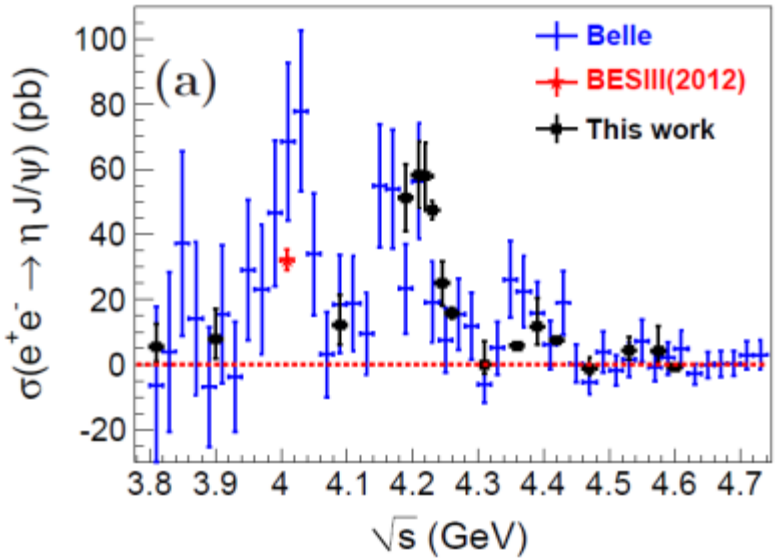


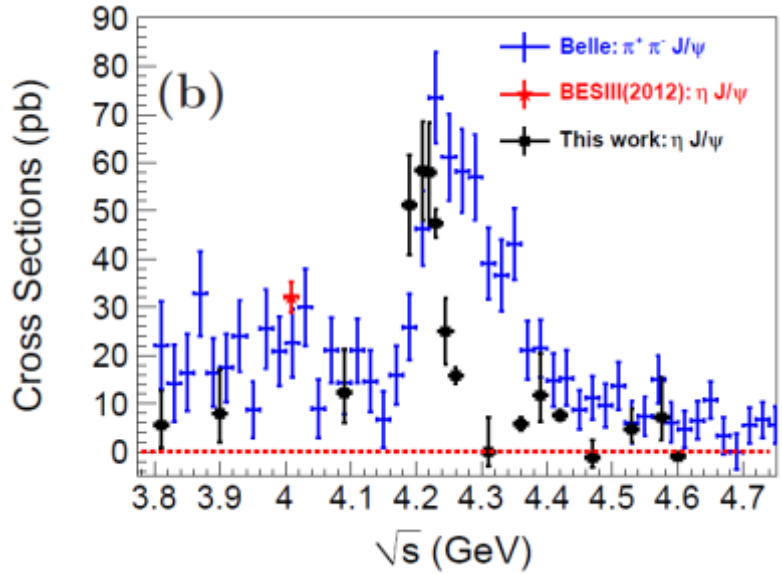
- ✓ **Cross section peak near 4.23 GeV**
- ✓ **Fit with BW + phase space**
  - ◆ **M = 4230±8±6 MeV; Γ = 38±12±2 MeV**
  - ◆ **Not from Y(4260)**
- ✓ **The statistical significance of this resonance is estimated to be > 9 σ**

- ■ **The 1st observation of $e^+e^- \to \omega\chi_{c0}$**
  $\chi_{c0} \to KK/\pi\pi$; $\omega \to \pi^+\pi^-\pi^0$
- ■ **No obvious signals for $\omega\chi_{c1/c2}$**

Observation of $e^+e^- \to \eta J/\psi$

PRD 91, 112005 (2015)

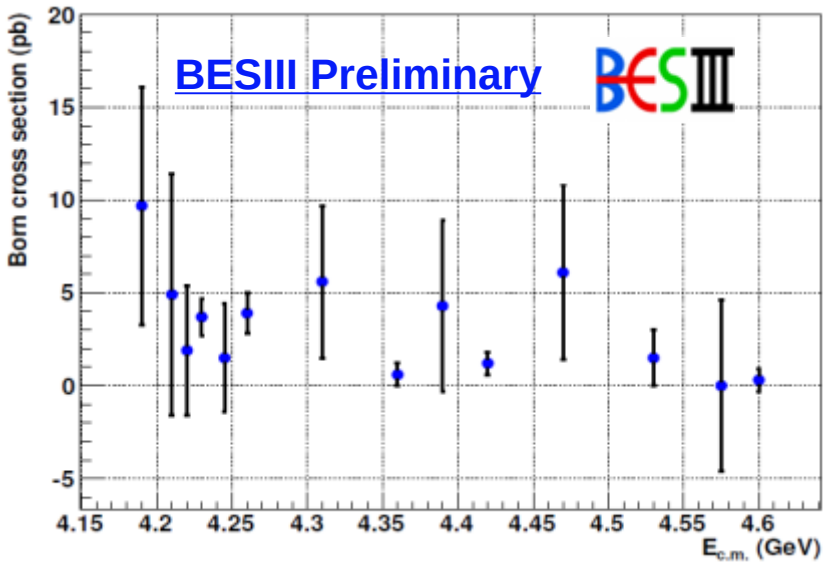




η is reconstructed with γγ

- ✓ **Agree with previous results with improved precision**
- ✓ **Structure near 4.2 GeV**
- ✓ **Production of ηJ/ψ differs from ππJ/ψ**
  - -- existence of a rich spectrum of Y states?
  - -- different coupling strength to the various decay modes
- ✓ **Production of ηJ/ψ and $\omega\chi_{c0}$ maybe the same**
  - -- $\frac{\sigma^{4.260}(e^+e^- \to \eta J/\psi)}{\sigma^{4.230}(e^+e^- \to \eta J/\psi)} = 0.33 \pm 0.04$
  - -- $\frac{\sigma^{4.260}(e^+e^- \to \omega\chi_{c0})}{\sigma^{4.230}(e^+e^- \to \omega\chi_{c0})} = 0.43 \pm 0.13$

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



- ✓ η' is reconstructed with two modes
  - $\pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$)
  - $\gamma\pi^+\pi^-$
- ✓ First observation at $\sqrt{s}$ = 4.23 & 4.26 GeV, cannot tell the lineshape due to statistics
  - $\sigma = 3.7 \pm 0.7 \pm 0.3$ pb @4.23 GeV
  - $\sigma = 3.9 \pm 0.8 \pm 0.3$ pb @4.26 GeV

- ✓ $\sigma(\eta' J/\psi)$ is much lower than $\sigma(\eta J/\psi)$, in contradiction to the calculation in the framework of NRQCD (PRD 89, 074006 (2014)).
  - $\sigma(e^+e^- \to \eta' J/\psi)$ is investigated at order of $O(\alpha_s^4)$; higher order correction might need to be considered
  - Gluonium component contributions may affect the results

Z_c States

Charged Z_c provides convincing evidence of multi-quark states

It is difficult to distinguish neutral charmonium-like states from the conventional charmonium states

$Z_c^{\pm}$ could not be a conventional qqbar meson

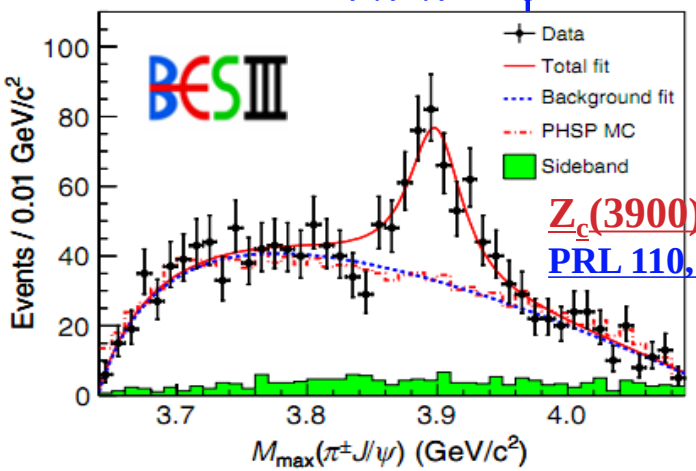
- ✓ Coupling to charmonium with electric charge
- ✓ ccbar + qqbar (q = u, d, s)

Several Z_c states are observed in the mass region of Y states

- ✓ **$Z_c(3900)^{\pm}$, $Z_c(3885)^{\pm}$, $Z_c(4020)^{\pm}$, $Z_c(4025)^{\pm}$**
- ✓ **and neutral partners**

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

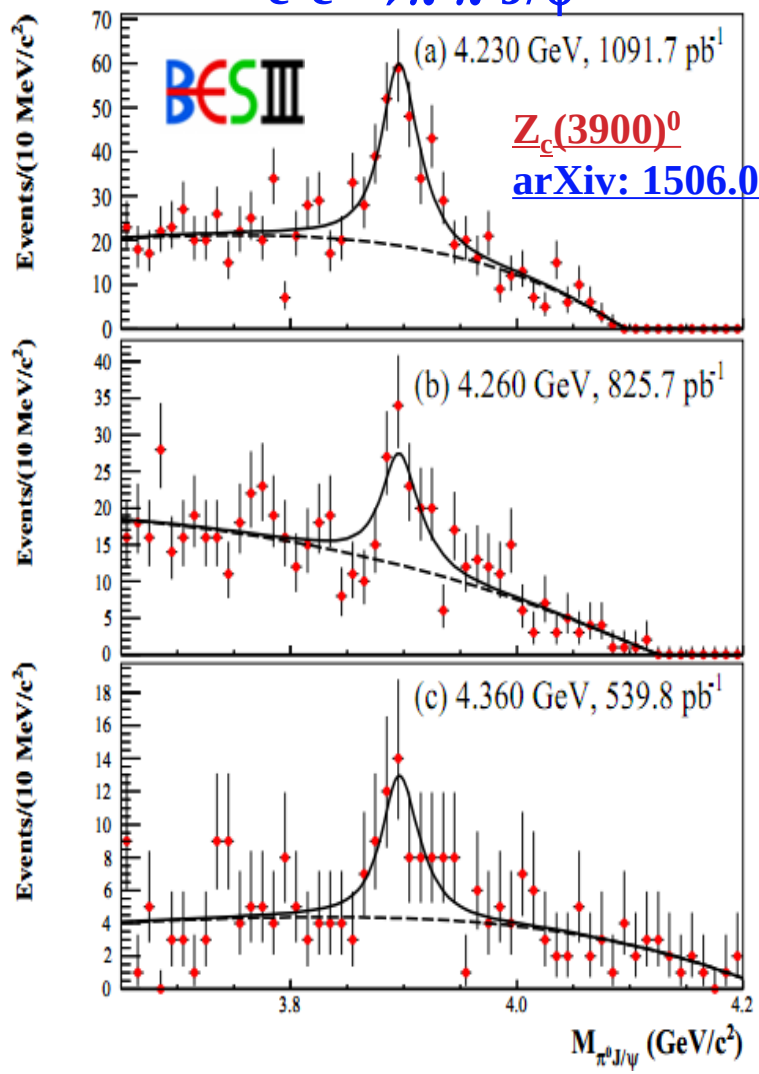
$e^+e^- \to \pi^+\pi^- J/\psi$



$Z_c(3900)^\pm$

PRL 110, 252001 (2013)

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



$Z_c(3900)^0$

arXiv: 1506.06018

- ✓ $Z_c(3900)^\pm$ observed by BESIII in 2013, well confirmed by Belle and CLEO-c.
- ✓ $Z_c(3900)^0$ evidence with 3.7σ by CLEO-c, observed with >10σ by BESIII.

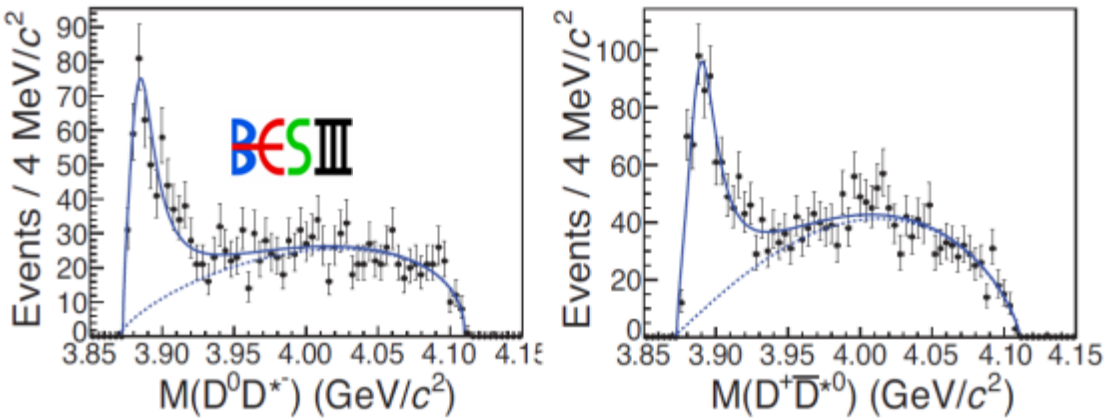
An isospin triplet $Z_c(3900)$ established

Zc(3900)	Mass(MeV)	Width(MeV)
$Z_c(3900)^\pm$	3899.0±3.6±4.9	46±10±20
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2

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

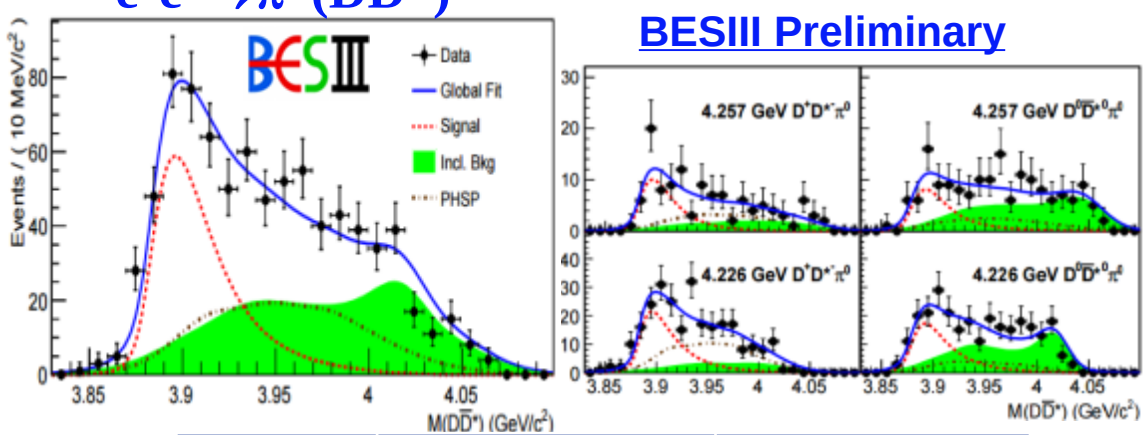
$e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{-/+}$

PRL 112, 022001 (2014)



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

BESIII Preliminary



$Z_c(3885)$	Mass(MeV)	Width(MeV)
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

- ✓ $Z_c(3900)$ close to $M(D\bar{D}^*) \sim 3875$ MeV
- ✓ Search of $Z_c \to D\bar{D}^*$
  - Observed $Z_c(3885)^{\pm/0}$
  - Mass and width close to $Z_c(3900)$

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

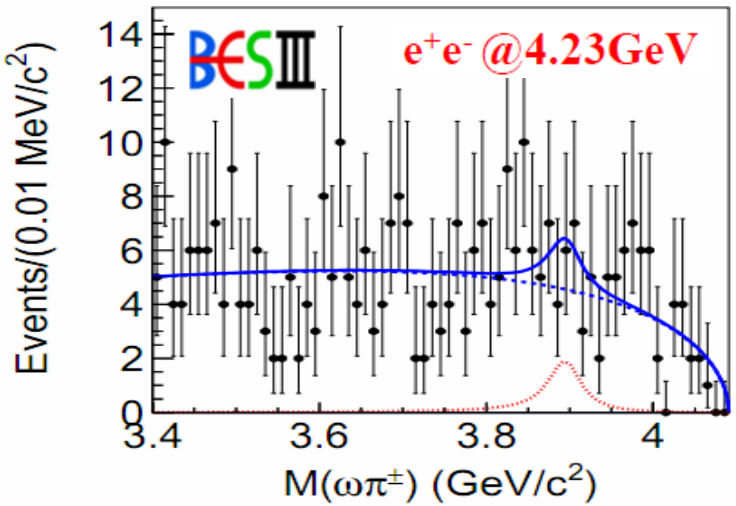
$$\approx 0.5\times \sigma(e^+e^- \to Z_c(3885)^+\pi^- \to (D\bar{D}^*)^+\pi^- + c.c.)$$

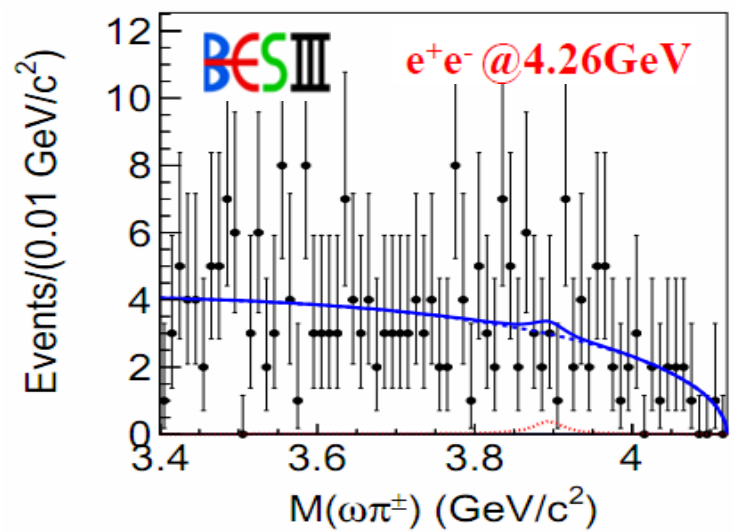
- ✓ Coupling to DD* is larger than to $\pi J/\psi$
- ✓ If $Z_c(3900)$ and $Z_c(3885)$ are the same states

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

$e^+e^- \to \pi Z_c(3900)^\pm \to \pi\omega\pi^\pm$

arXiv: 1507.02068





- ✓ **Searching for new decays of $Z_c(3900)$ to light hadrons**

  -- **distinguishing a resonance from threshold effects**

- ✓ **No significant $Z_c \to \omega\pi$ is observed**

  -- **$\sigma(e^+e^- \to Z_c\pi, Z_c \to \omega\pi) < 0.26$ pb @ 4.23 GeV**

  -- **$\sigma(e^+e^- \to Z_c\pi, Z_c \to \omega\pi) < 0.18$ pb @ 4.26 GeV**

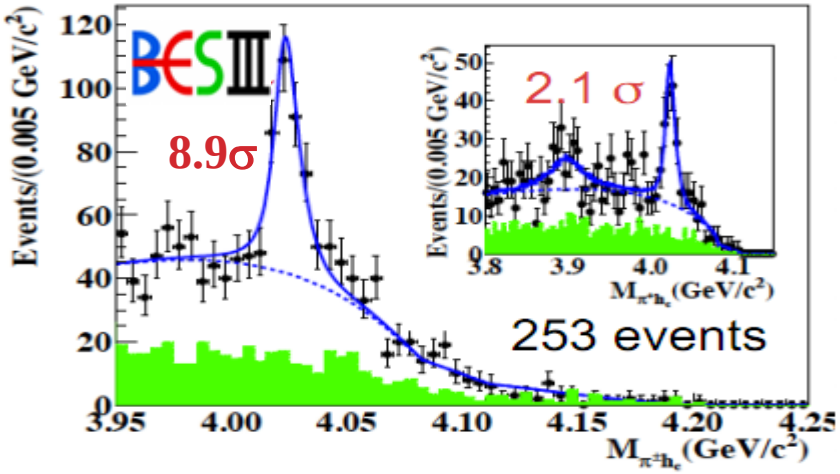
- ✓ **$\sigma(e^+e^- \to Z_c\pi, Z_c \to \omega\pi)/\sigma(e^+e^- \to Z_c\pi, Z_c \to J/\psi\pi) = (1.3\pm0.5)\%$**

  -- By assigning $\sigma(e^+e^- \to Z_c\pi, Z_c \to \omega\pi)$ to be 0.18 pb

  -- $\sigma(e^+e^- \to Z_c\pi, Z_c \to J/\psi\pi) = 13.5\pm 5.2$ pb

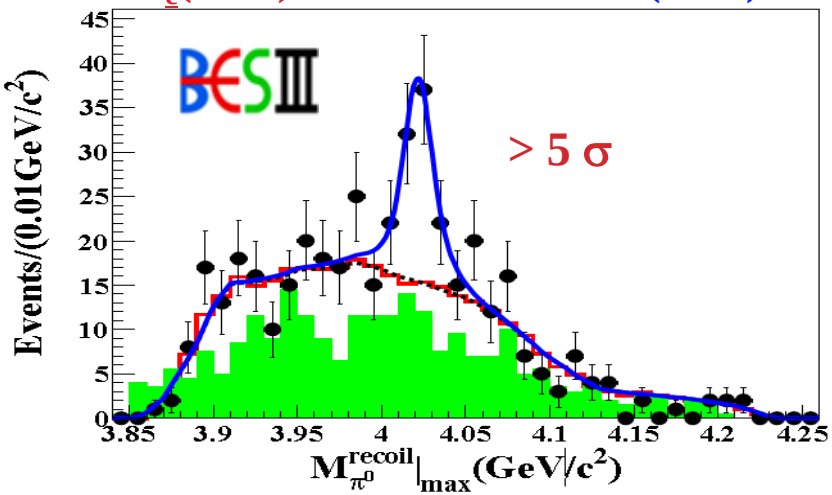
$e^+e^- \to \pi Z_c(4020)^{\pm/0} \to \pi\pi^{\pm/0} h_c$

$Z_c(4020)^{\pm}$: PRL 111, 242001 (2013)



- ✓ $Z_c(4020)^{\pm/0}$ observed
- ✓ A weak evidence for $Z_c(3900) \to \pi^{\pm} h_c$
- ✓ $Z_c(4020)$, near the threshold of $D^*\bar{D}^*$bar

$Z_c(4020)^0$: PRL 113, 212002 (2014)

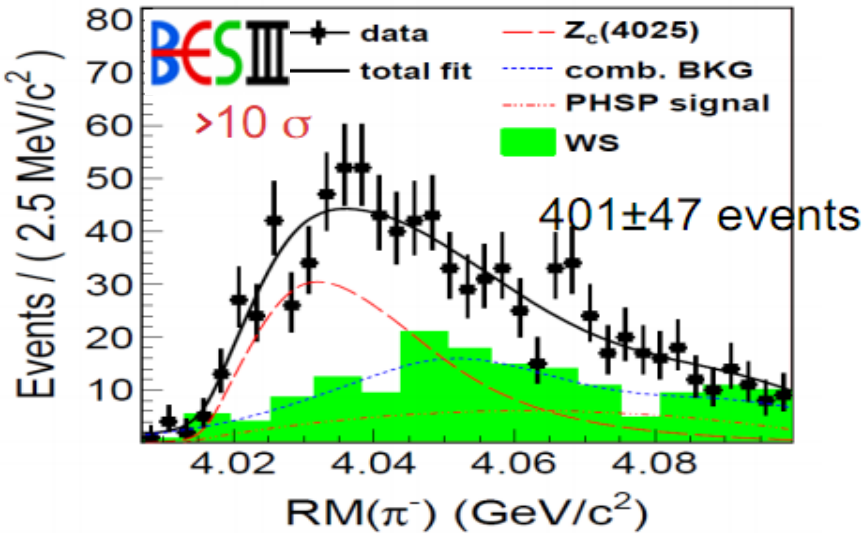


Another isospin triplet is established

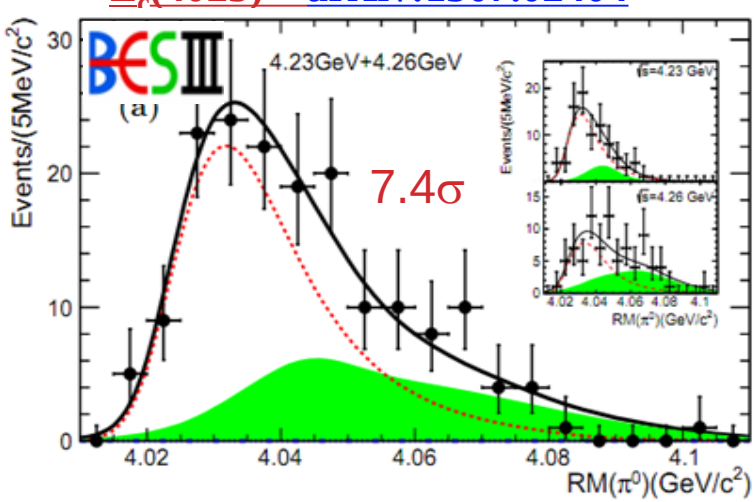
Zc(4020)	Mass(MeV)	Width(MeV)
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6
$Z_c(4020)^0$	4023.8±2.2±3.8	Fixed(=7.9)

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

$Z_c(4025)^{\pm}$ PRL 112, 132001 (2013)



$Z_c(4025)^0$ arXiv:1507.02404



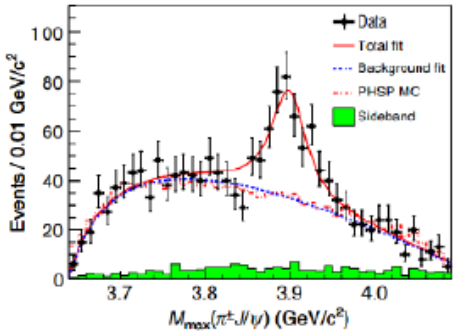
- ✓ $Z_c(4025)^{\pm/0}$ observed.
- ✓ The resonance parameters of $Z_c(4020)$ and $Z_c(4025)$ are consistent within 1.5σ.
- ✓ Coupling to $D^*\bar{D}^*$ is much larger than to πh_c
- ✓ If $Z_c(4025)$ and $Z_c(4020)$ are the same states

$$\frac{\Gamma(Z_c(4020) \to D^*\bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

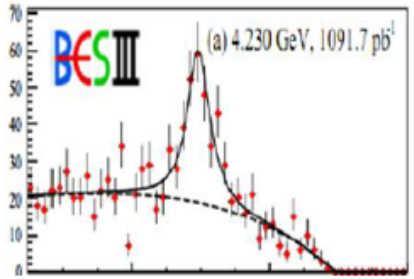
$$\frac{\sigma(e^+e^- \to Z_c(4025)^0\pi^0) \to (D^*\bar{D}^*)^0\pi^0}{\sigma(e^+e^- \to Z_c(4025)^+\pi^-) \to (D^*\bar{D}^*)^+\pi^-} \sim 1$$

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

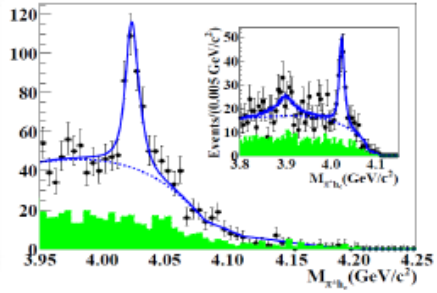
Summary of Z_c states at BESIII



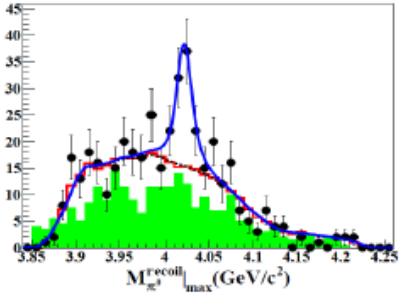
$e^+e^- \to \pi^-\pi^+ J/\psi$



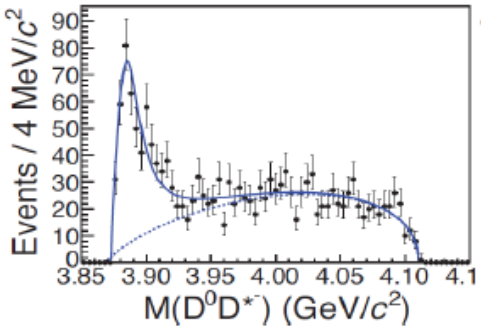
$e^+e^- \to \pi^0\pi^0 J/\psi$



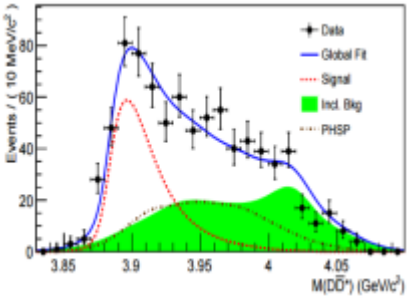
$e^+e^- \to \pi^-\pi^+ h_c$



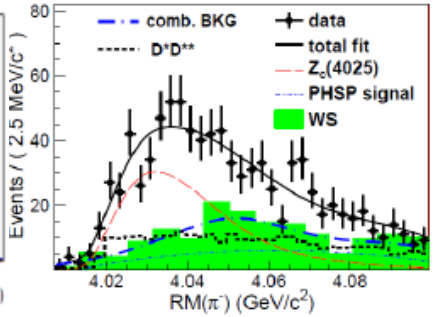
$e^+e^- \to \pi^0\pi^0 h_c$



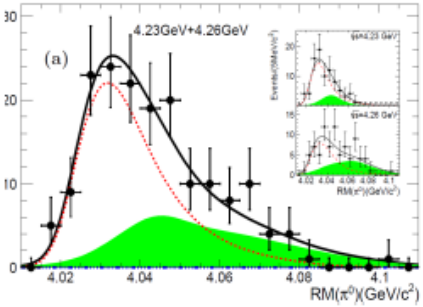
$e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{-/+}$



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



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



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

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

$Z_c(3900)^0$?

$Z_c(4020)^{\pm}$?

$Z_c(4020)^0$?

Summary

- **Significant progress in XYZ studies at BESIII**
- **Issues**
  - ✓ **The nature of them is mysterious**
  - ✓ **The relations between XYZ states are unclear**

    A number of transitions between different charmonium-like states are observed, starting to make connections
  - ✓ **Some expected states and decay modes are missing**
- **Future**
  - ✓ **More results will come up soon with some analysis are on going**
  - ✓ **BESIII will collect more data for XYZ study**

    -- **Exploring XYZ states and their transitions**

Thanks!

BACKUP

Summary of Z_c states at BESIII

State	Mass(MeV)	Width(MeV)	Decay mode	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] $3884.3 \pm 1.2 \pm 1.5$ [double D tag]	$24.8 \pm 3.3 \pm 11.0$ [single D tag] $23.8 \pm 2.1 \pm 2.6$ [double D tag]	$D^0 D^{*-}$ $D^- D^{*0}$	$e^+e^- \to \pi^+ D^0 D^{*-}$ $e^+e^- \to \pi^+ D^- D^{*0}$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^{*0} D^{*-}$	$e^+e^- \to \pi^+ (D^* \bar{D}^*)^-$

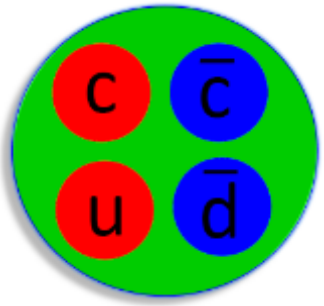
Nature of Z_c States

- ✓ At least 4 quarks, not a conventional meson

- ✓ Tetraquark state?

Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);

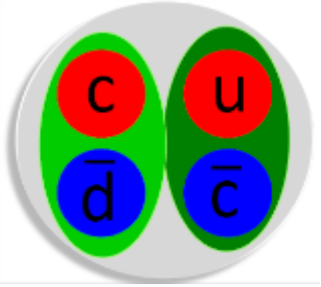
Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); etc



- ✓ $D^{(*)}\bar{D}^{(*)}$ molecule state?

Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)

Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc



- ✓ Final States Interactions?
- ✓ …