Exotic and Charmonium(-like) states at BESIII

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DPF2015, Aug. 4 – 8, Ann Arbor, MI

Outline

- **Introduction**

    Hadrons, XYZ states

- **XYZ Physics at BESIII**

    - **BESIII data samples for XYZ study**
    - **The XYZ states**
        - I. X(3872), X(3823)
        - II. Abundant structures above 4GeV
        - III. $Z_c(3900)/Z_c(3885)$, $Z_c(4020)/Z_c(4025)$
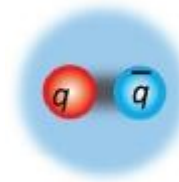
- **Summary**

What's exotic states?

■ **Quark Model**

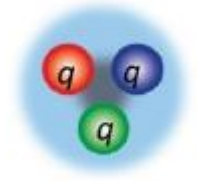 ■ 2 quarks(q$\bar{q}$) -- **meson**

  ■ 3 quarks(qqq) -- **baryon**

meson   baryon

■ **QCD predicts the exotic sates**

  ■ **Glueball**: $N_{quarks} = 0$ (gg, ggg, …)

  ■ **Hybrid**: $N_{quarks} >= 2$ (q$\bar{q}$g,qqqg, …)

  ■ **Molecule**: bound state of more than 2 hadrons

  ■ **Mutiquark state**: $N_{quarks} >= 4$
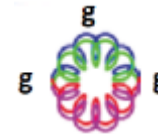
  ■ …
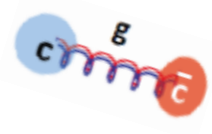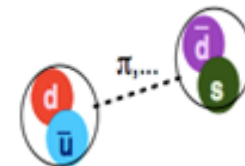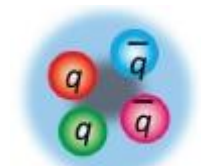
Glueball   Hybrid

Molecule   Mutiquark

BEPCII and BESIII

First physics run starts from 2009!
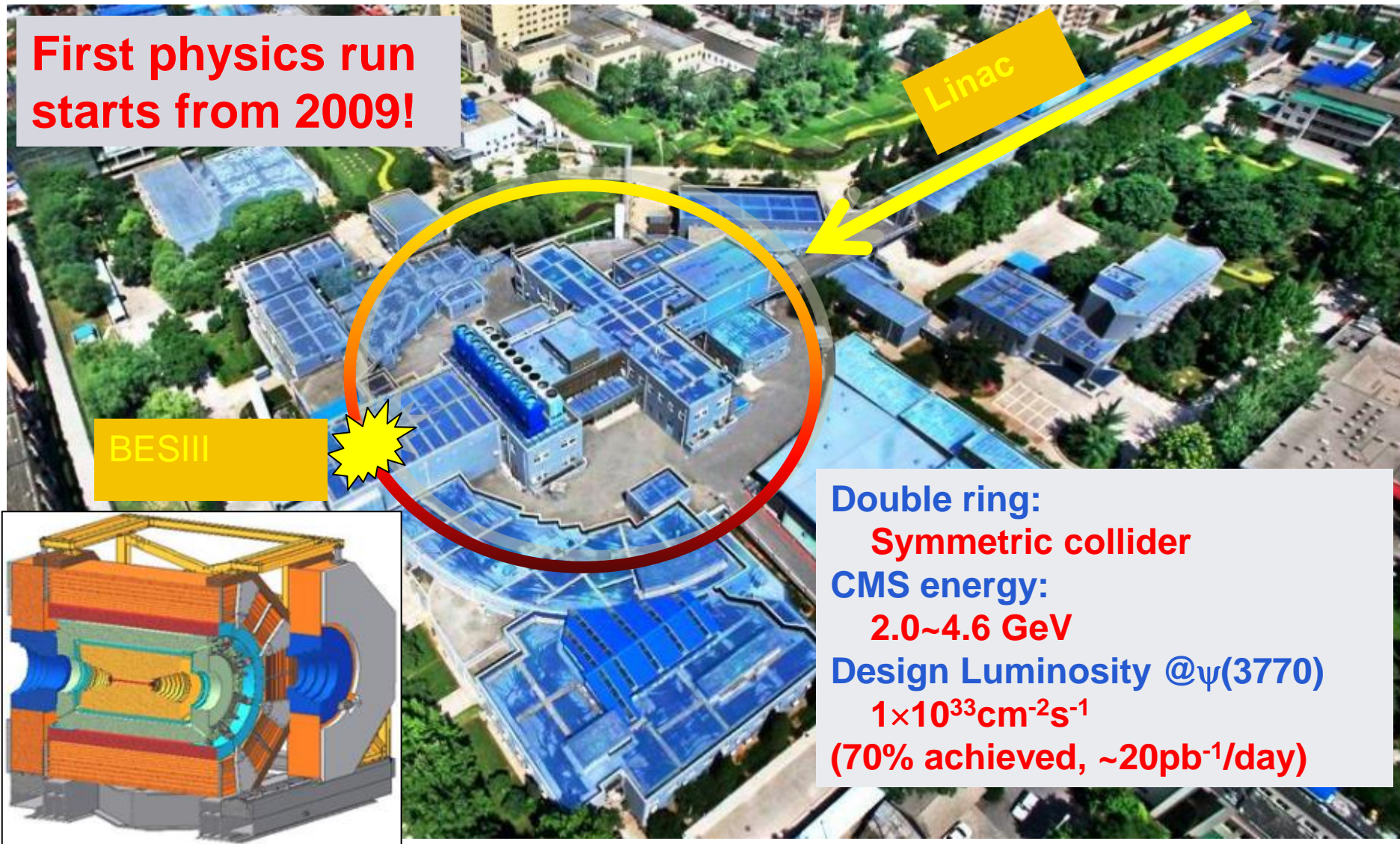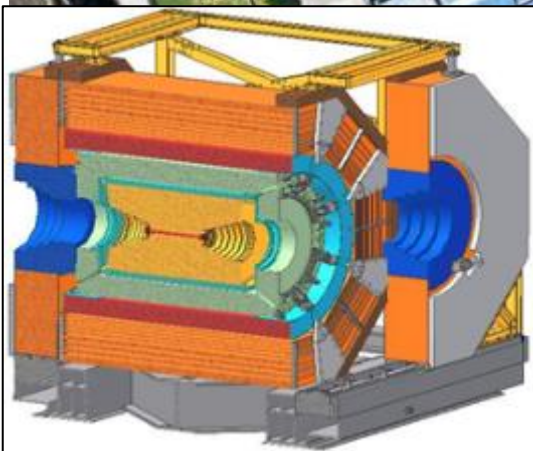
Linac

BESIII

Double ring:
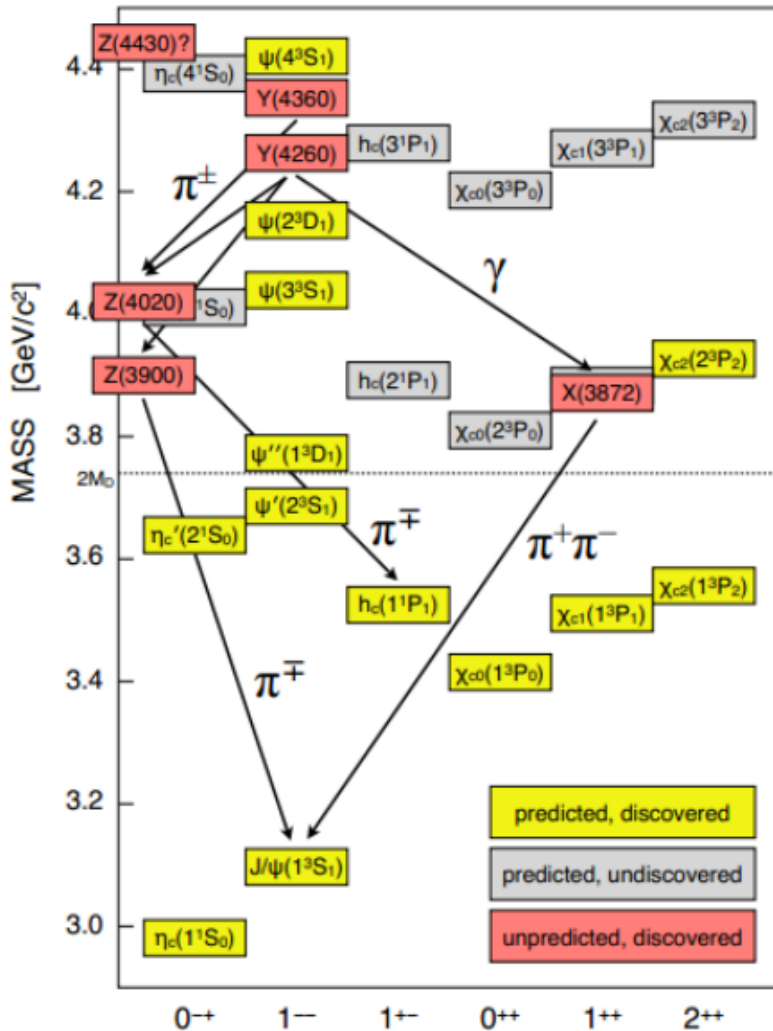**Symmetric collider**
CMS energy:
2.0~4.6 GeV
Design Luminosity @ψ(3770)
$1\times10^{33}cm^{-2}s^{-1}$
(70% achieved, ~20pb^{-1}/day)

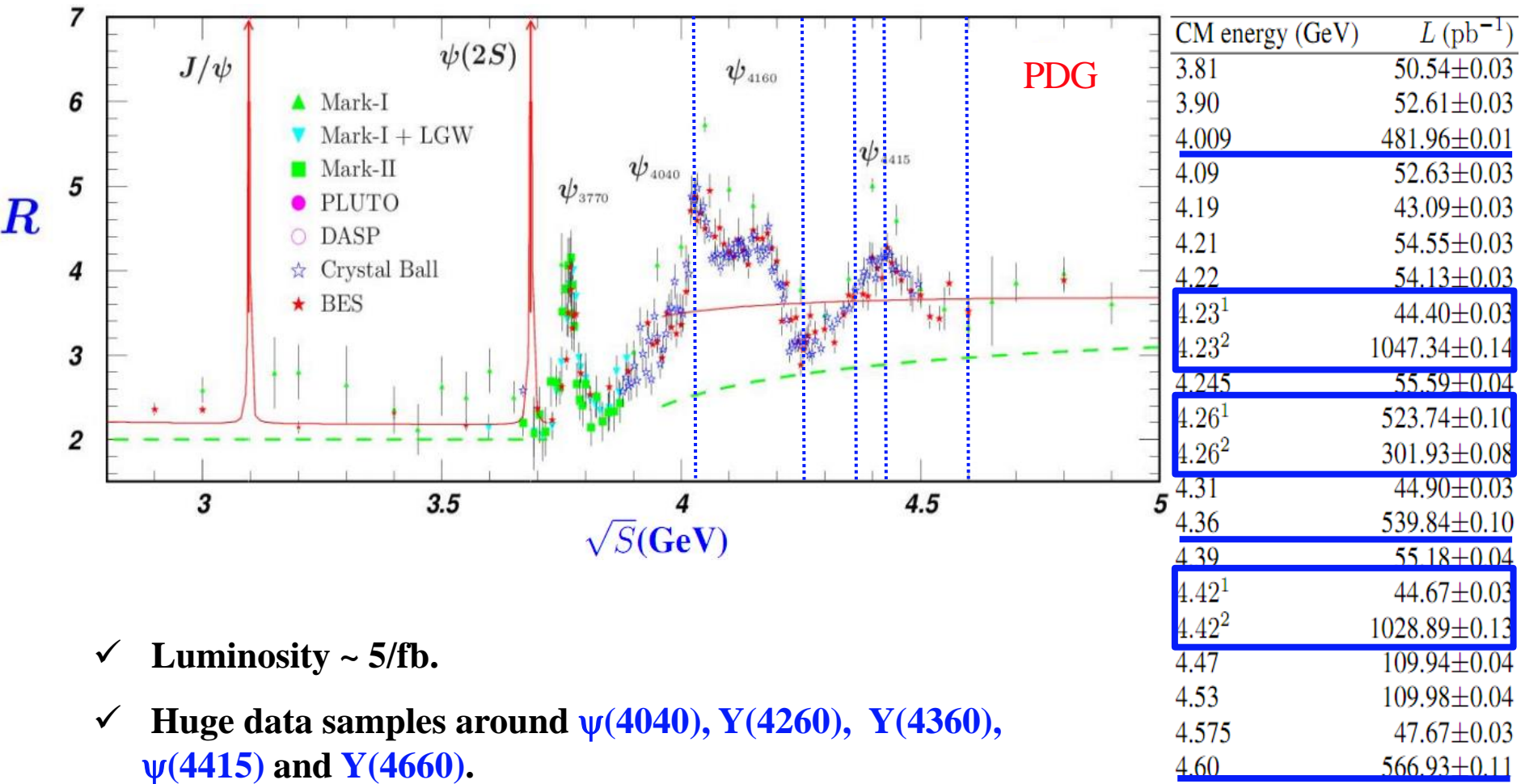# Charmonium and XYZ states

◆ **Below open-charm threshold**

✓ Good agreement between discovery and theoretical prediction

◆ **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**)

Data samples for XYZ physics at BESIII

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

✓ **Luminosity ~ 5/fb.**

✓ **Huge data samples around ψ(4040), Y(4260), Y(4360), ψ(4415) and Y(4660).**

X(3823)/X(3872)

1. $X(3823)$ in $e^+e^- \rightarrow \pi^+\pi^- \gamma\chi_{c1}$

2. $X(3872)$ in $Y(4260) \rightarrow \gamma\pi^+\pi^- J/\psi$

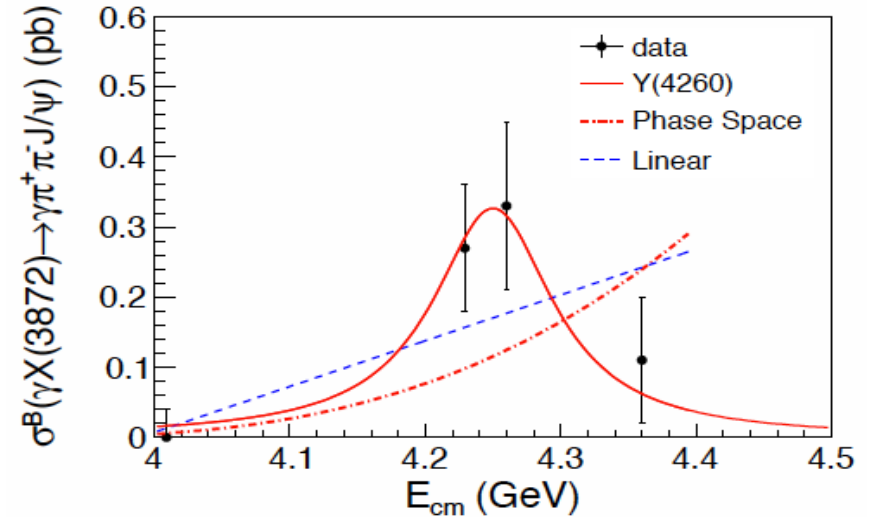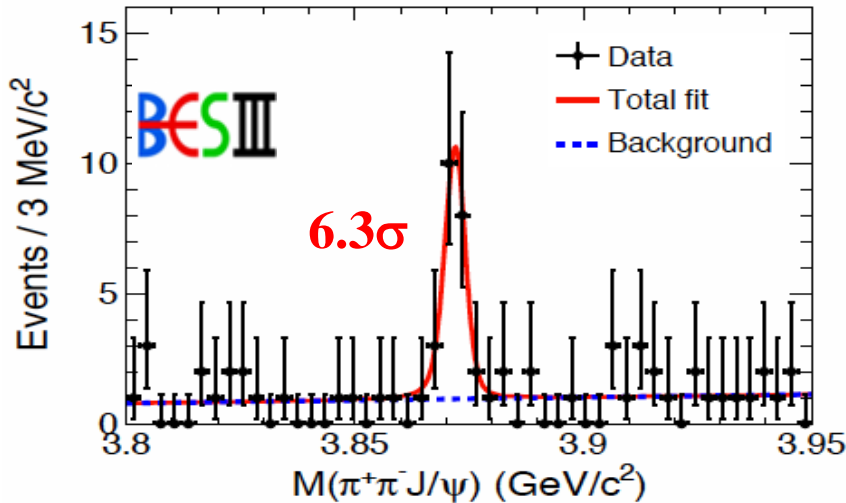# $e^+e^- \rightarrow \pi^+\pi^-$ **X(3823)** $\rightarrow \pi^+\pi^- \gamma\chi_{c1}$
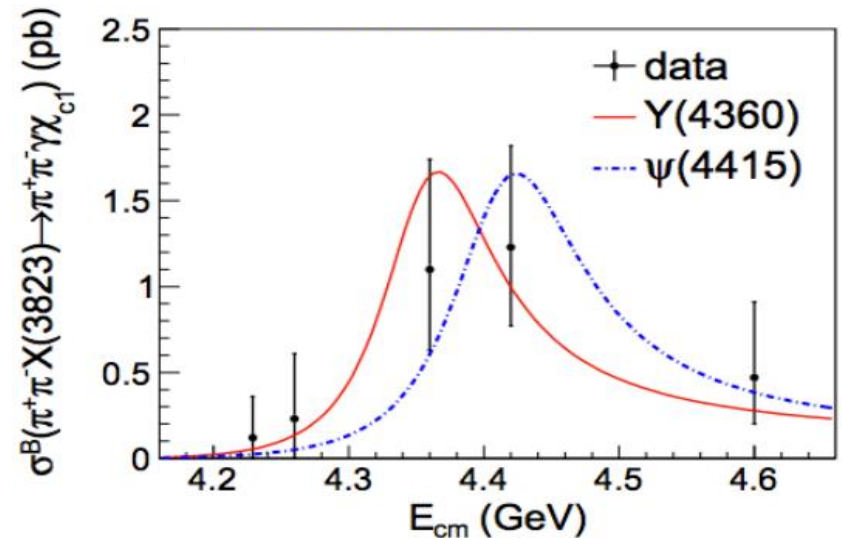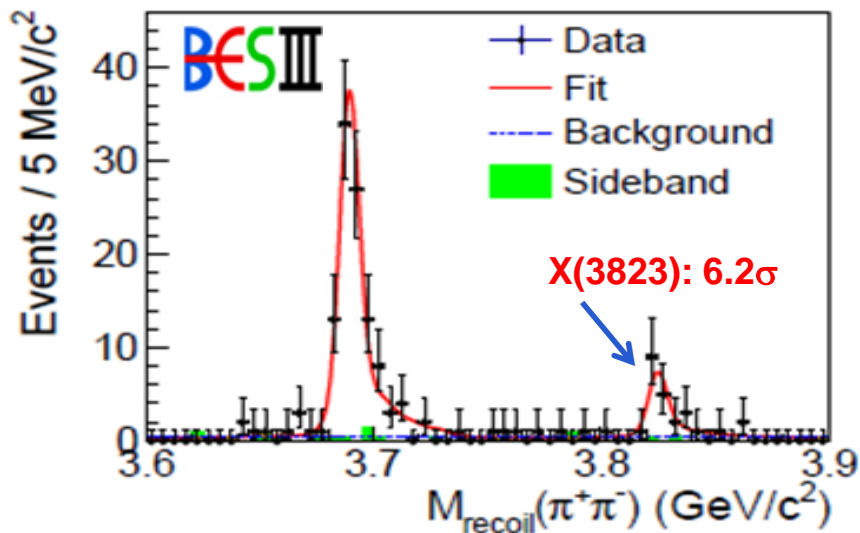
Agree with BELLE's 3.7s evidence (PRL111,032001(2013))

- **Potential model: $1^3D_2 \rightarrow \gamma\chi_{c1}, \gamma\chi_{c2}$ with large width.**

- **M = 3821.7 $\pm$ 1.3 $\pm$ 0.7 MeV, Γ < 16 MeV**

- **Good candidate of $\psi(1^3D_2)$**

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

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$\Upsilon(4260) \rightarrow \gamma$ **X(3872)** $\rightarrow \gamma \pi^+ \pi^- \mathbf{J}/\psi$

- **M = 3871.9±0.7±0.2 MeV, Γ < 2.4 MeV**

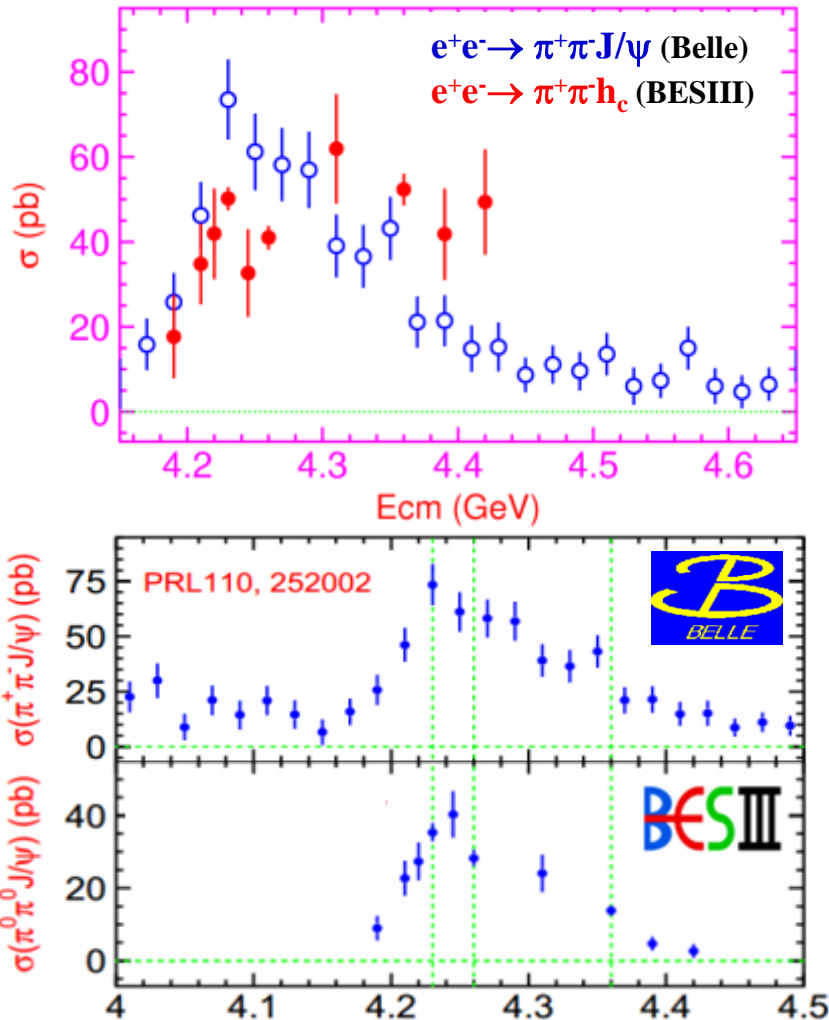- **a new Y(4260) decay mode and new X(3872) production mode: Y(4260)$\rightarrow\gamma$X(3872)**

If we take $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)

$\dfrac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim 11.2\%$ Large transition ratio !

Abundant structures above 4GeV

1. Cross section of $e^+e^- \rightarrow \pi\pi J/\psi(h_c)$

2. Cross section of $e^+e^- \rightarrow \omega\chi_{c0}$

3. Cross section $e^+e^- \rightarrow \eta J/\psi$
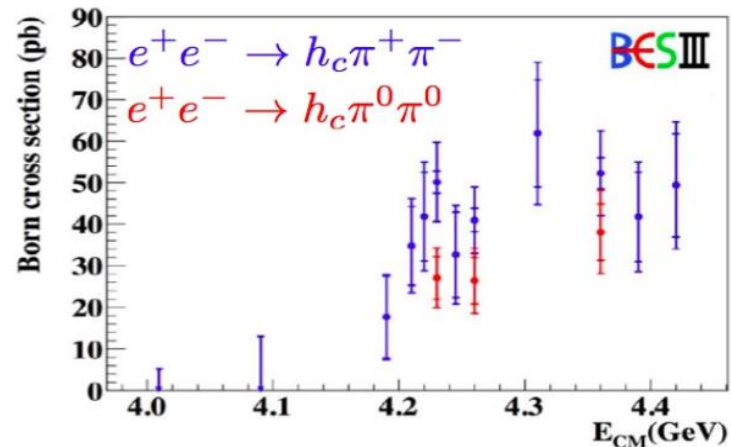
4. Cross section $e^+e^- \rightarrow \eta' J/\psi$

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

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (Belle)
$e^+e^- \rightarrow \pi^+\pi^- h_c$ (BESIII)

PRL110, 252002

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

BESIII   arXiv: 1506.06018 $\sigma(\pi^0\pi^0 J/\psi)$
        PRL 111, 242001 (2013) $\sigma(\pi^+\pi^- h_c)$
        PRL 113, 212002 (2014) $\sigma(\pi^0\pi^0 h_c)$
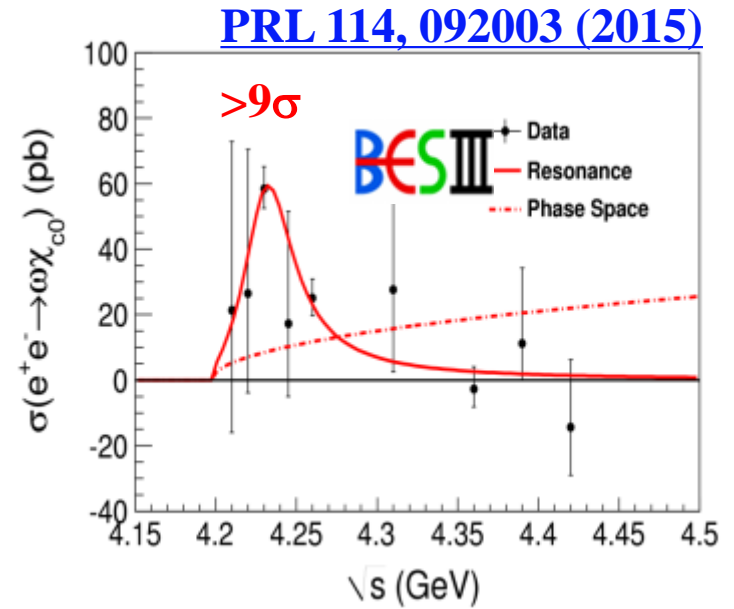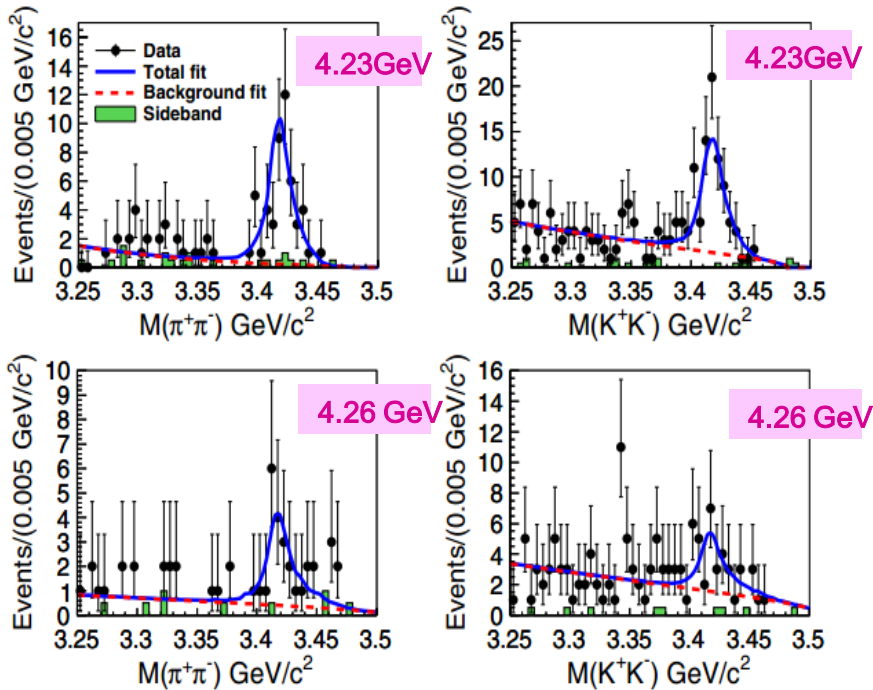
- ✓ $\sigma(\pi^+\pi^- h_c) \sim \sigma(\pi^+\pi^- J/\psi)$, **but different line shape**
- ✓ **A possible structure near 4.23 GeV for** $\sigma(\pi^+\pi^- h_c)$

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

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

no large iso-spin violation in $\sigma(\pi\pi h_c)$ **and** $\sigma(\pi\pi J/\psi)$ **!**

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Observation of e⁺e⁻→ωχ$_{c0}$

PRL 114, 092003 (2015)

>9σ

✓ **Cross section peak near 4.23 GeV**

✓ **fit with BW**

- M = 4230±8±6 MeV
- Γ = 38±12±2 MeV

Note for this structure:
✓ A tetraquark? (PRD 91,117501(2015))
✓ ψ(4S)? (EPJC 74:3208 (2014))
✓ Threshold effect?
✓ …

Observation of e⁺e⁻→ηJ/ψ
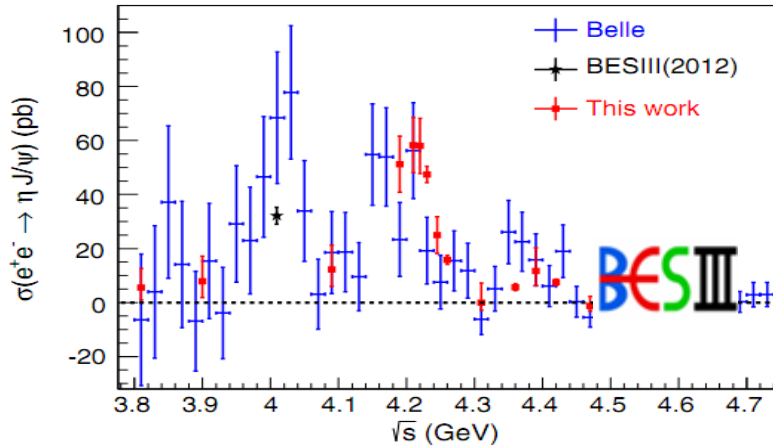
PRD 91, 112005 (2015)

✓ **Agree with previous results with improved precision**

✓ **Structure near 4.2 GeV: ψ(4160) →ηJ/ψ**

   More data 4.10~4.20 GeV is needed!

Observation of e⁺e⁻→η′J/ψ

σ = 3.1±0.6±0.3 pb @4.23 GeV
σ = 3.9±0.8±0.4 pb @4.26 GeV
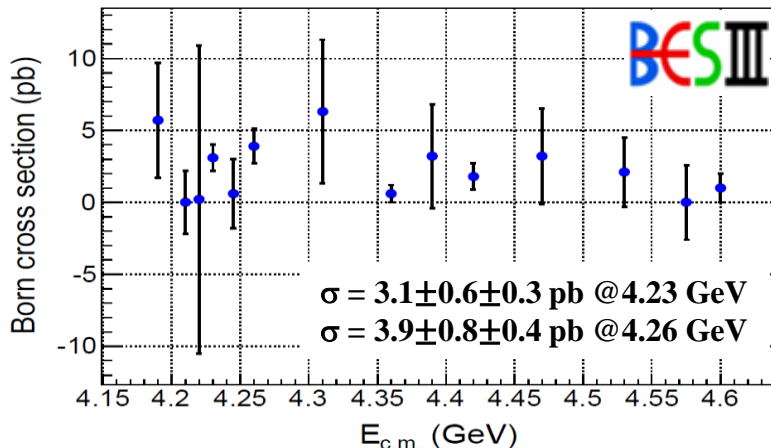
BESIII Preliminary

✓ **First observation at √s = 4.23 & 4.26 GeV, cannot tell the line-shape due to statistics.**

✓ **σ(η′J/ψ) is much lower than σ(ηJ/ψ) , in contradiction to the calculation in the framework of NRQCD (PRD 89, 074006 (2014)).**
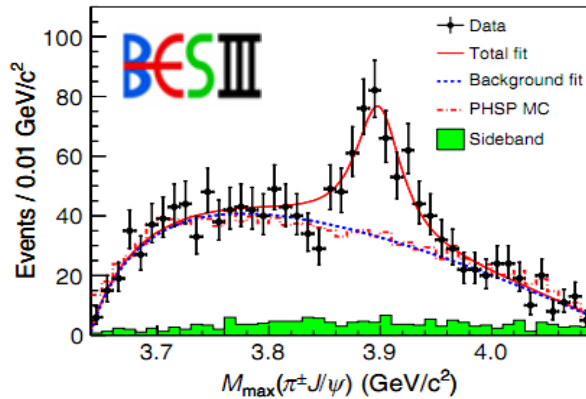
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Z_c States

1. $Z_c(3900)^{\pm/0}$ in $e^+e^- \rightarrow \pi\pi^{\pm/0}\, J/\psi$

2. $Z_c(3900)^{\pm}$ in $e^+e^- \rightarrow \pi\omega\pi^{\pm}$

3. $Z_c(3885)^{\pm/0}$ in $e^+e^- \rightarrow \pi\, (D\bar{D}^*)^{\pm/0}$

4. $Z_c(4020)^{\pm/0}$ in $e^+e^- \rightarrow \pi\pi^{\pm/0}\, h_c$

5. $Z_c(4025)^{\pm/0}$ in $e^+e^- \rightarrow \pi\, (D^*\bar{D}^*)^{\pm/0}$

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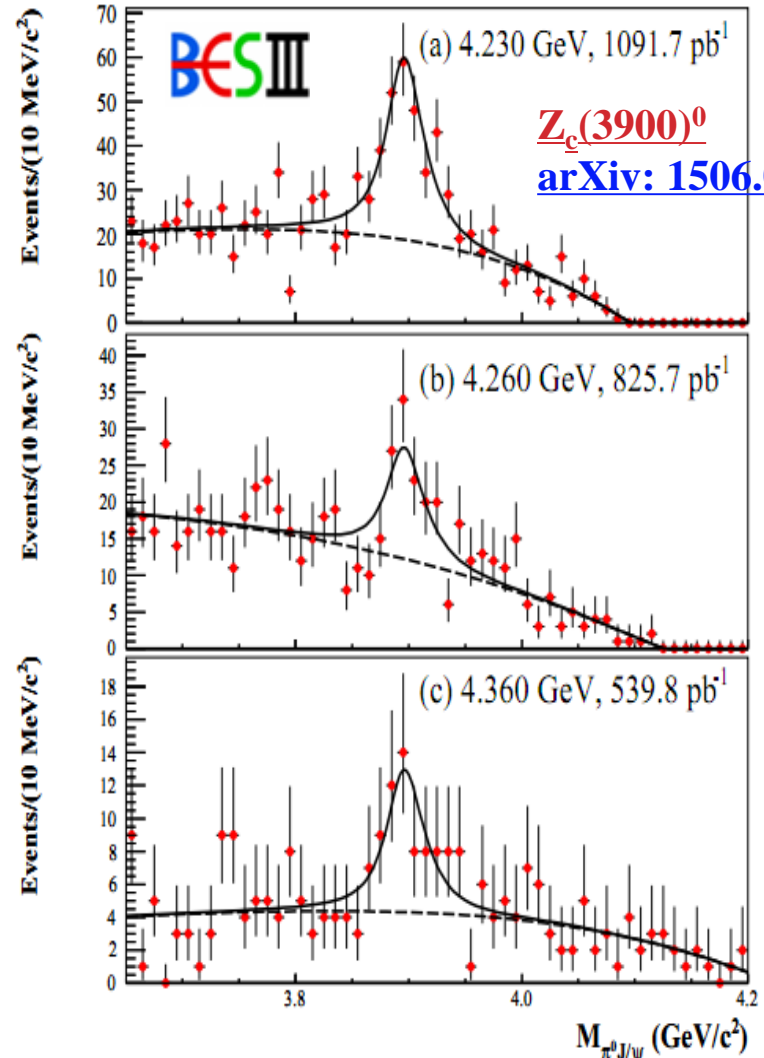# $e^+e^- \rightarrow \pi\ Z_c(3900)^{\pm/0} \rightarrow \pi\pi^{\pm/0}J/\psi$

$Z_c(3900)^\pm$: PRL 110, 252001 (2013)

$Z_c(3900)^0$
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.
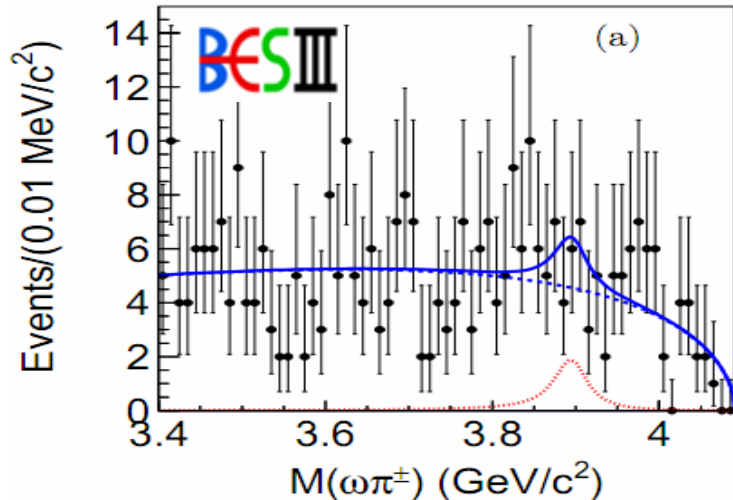
An iso-spin triplet $Z_c(3900)$ established!

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

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

arXiv: 1507.02068
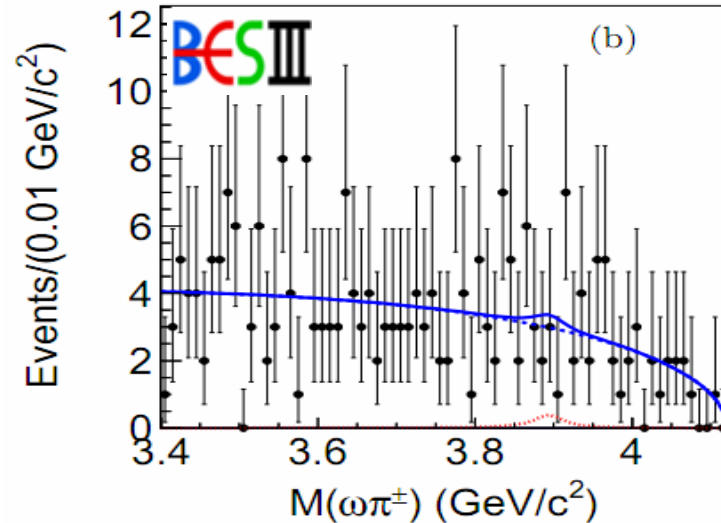
✓ **$Z_c(3900)^+$: mass close to DD*-bar threshold**

- **Decays to J/ψ → contains cc-bar**

- **Electric charge → contains ud-bar**

- **A 4-quark particle?!**

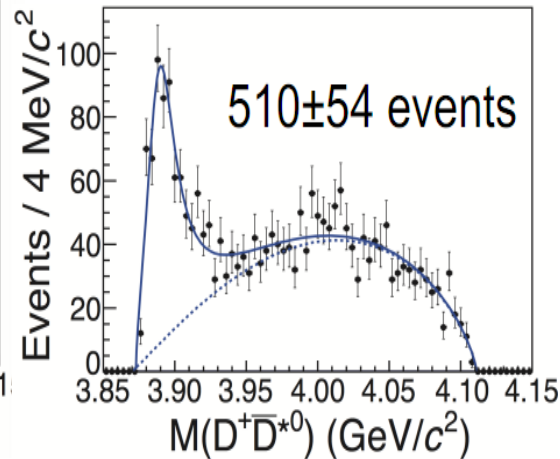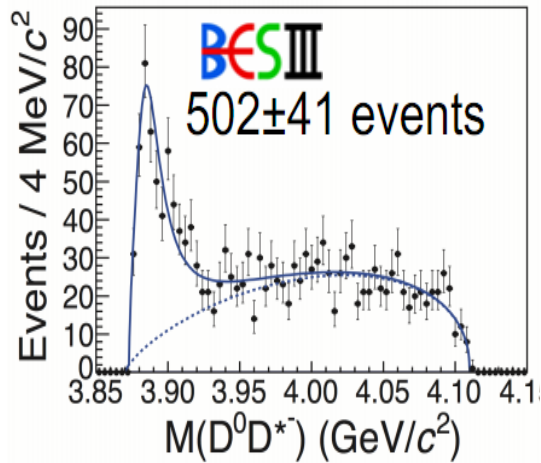✓ **Searching for new decay of $Z_c(3900)$ can provide useful information on its internal structure.**

✓ **No significant $Z_c \rightarrow \omega\pi$ is observed**

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

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

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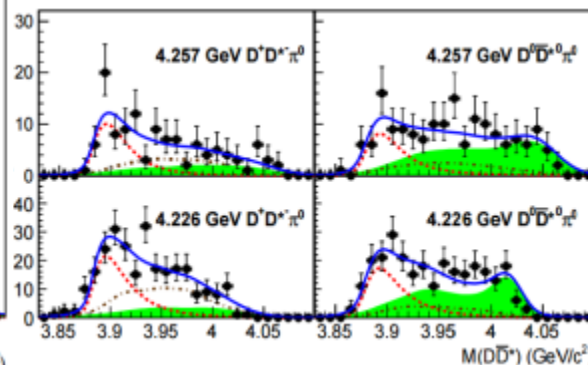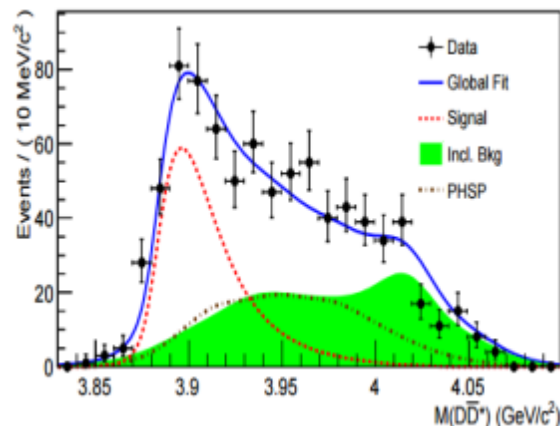# $e^+e^- \rightarrow \pi Z_c(3885)^{\pm/0} \rightarrow \pi(D\bar{D}^*)^{\pm/0}$

✓ **Enhancement at $D\bar{D}^*$ threshold.**

✓ **Observed $Z_c(3885)^{\pm/0}$**

mass and width close to $Z_c(3900)$

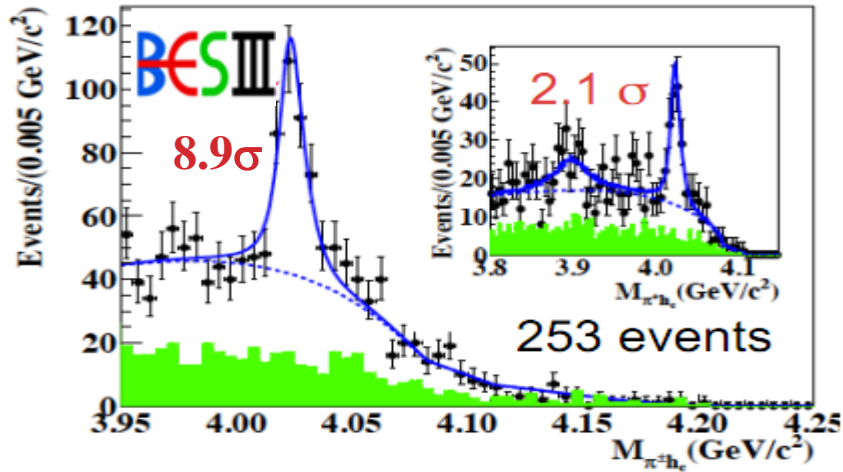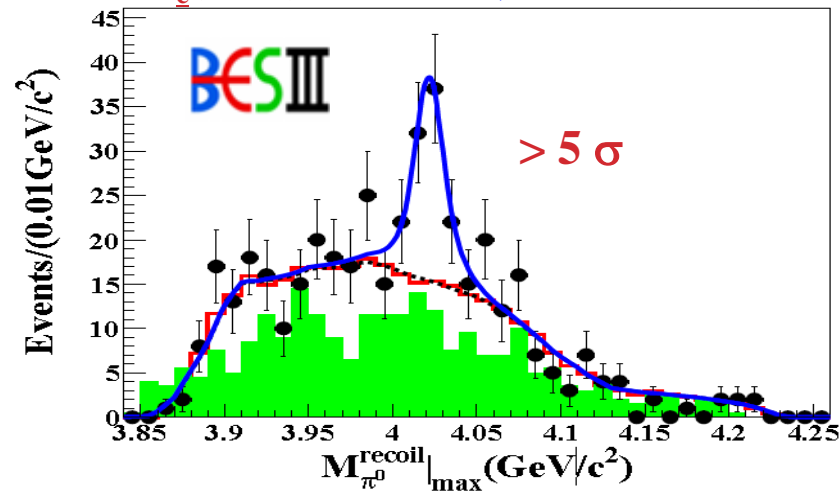| $Z_c(3885)$	Mass(MeV)	Width(MeV)
$Z_c(3885)^\pm$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

BESIII Preliminary

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

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

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

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

Another iso-spin triplet is established !

$Z_c(4020)$	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)

$e^+e^- \rightarrow \pi Z_c(4025)^{\pm/0} \rightarrow \pi(D^*\bar{D}^*)^{\pm/0}$
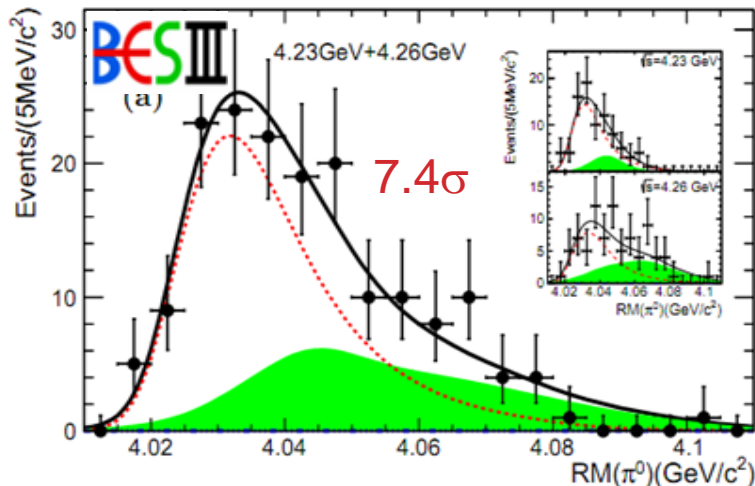
$Z_c(4025)^{\pm}$ **PRL 112, 132001 (2013)**

$Z_c(4025)^0$ **arXiv:1507.02404**
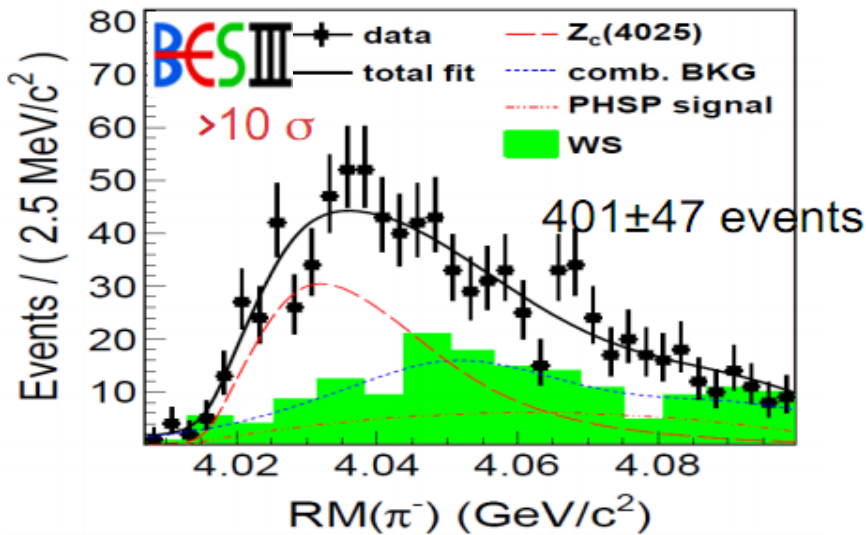
✓ $Z_c(4025)^{\pm/0}$ observed.

✓ 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
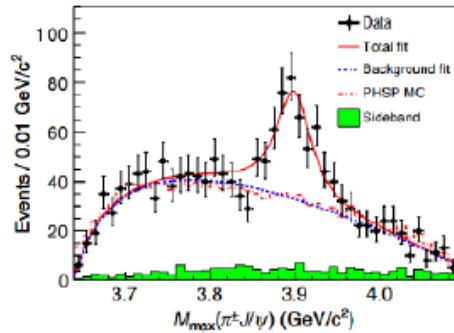
✓ if $Z_c(4025)$ and $Z_c(4020)$ are the same states

$$\frac{\Gamma(Z_c(4020) \rightarrow D^*\bar{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12 \pm 5$$
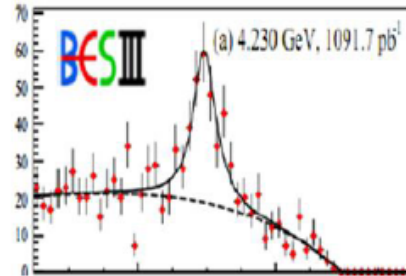
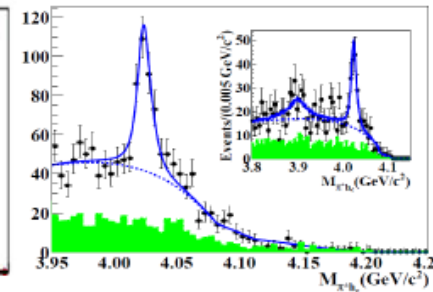| Zc(4025)	Mass(MeV)	Width(MeV)
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7
$Z_c(4025)^0$	4025.5$^{+2.0}_{-4.7}$±3.1	23.0±6.0±1.0

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Summary of Zc states
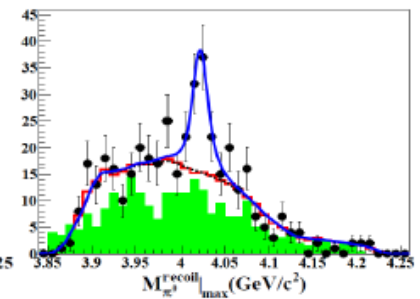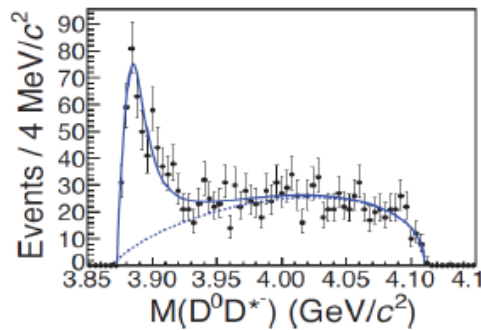

$e^+e^- \rightarrow \pi^-\pi^+ J/\psi$

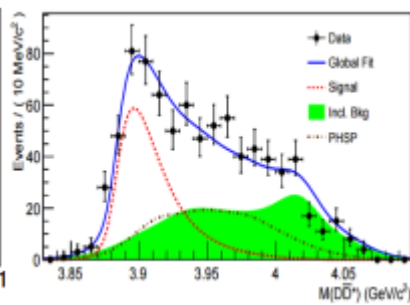$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$

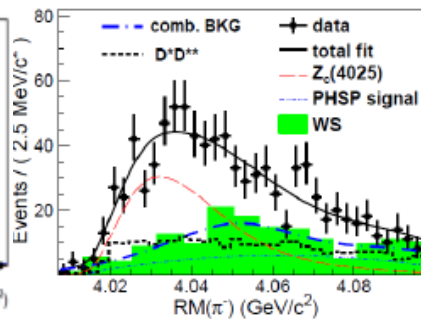$e^+e^- \rightarrow \pi^-\pi^+ h_c$

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

$e^+e^- \rightarrow \pi^\pm(D\overline{D}^*)^{-/+}$

$e^+e^- \rightarrow \pi^0(D\overline{D}^*)^0$

$e^+e^- \rightarrow \pi^\pm(D^*\overline{D}^*)^{-/+}$

$e^+e^- \rightarrow \pi^0(D^*\overline{D}^*)^0$

$Z_c(3900)^\pm$?

$Z_c(3900)^0$?
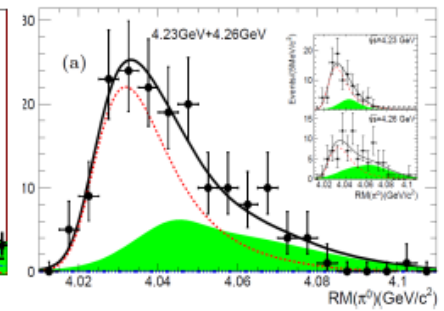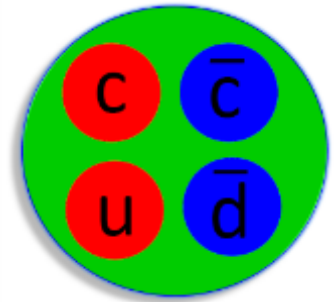
$Z_c(4020)^\pm$?

$Z_c(4020)^0$?

Nature of Z_c States

✓ **At least 4 quarks, not a conventional meson**
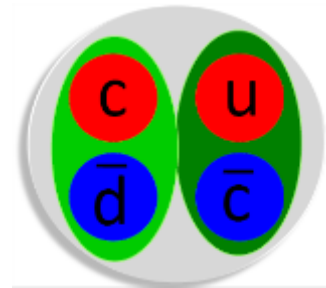
✓ **Tetraquark state?**

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)

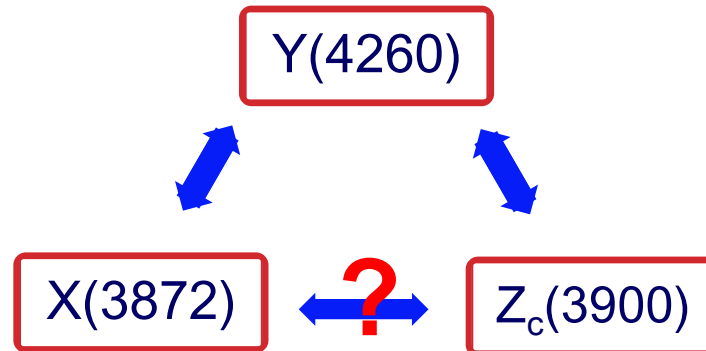Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

✓ **Final States Interactions?**

✓ **…**

Summary

- **Lots of progress in charmonium-like studies at BESIII recently**

- **Observation of Z_c states**

- **X、 Y、 Z particles are correlated!**

- **Measurements of many hidden charm final states**

- **BESIII may continue data taking for XYZ study until 2020-2022.**

Thanks!

Y(4260)

X(3872) **?** Z_c(3900)

BACKUP

Summary of Z_c states at BESIII

State	Mass(MeV)	Width(MeV)	Decay mode	Process
$Z_c(3900)^\pm$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$	$\pi^\pm J/\psi$	$e^+e^-\rightarrow\pi^+\pi^-J/\psi$
$Z_c(3900)^0$	$3894.8\pm2.3\pm2.7$	$29.6\pm8.2\pm8.2$	$\pi^0 J/\psi$	$e^+e^-\rightarrow\pi^0\pi^0 J/\psi$
$Z_c(3885)^\pm$	$3883.9\pm1.5\pm4.2$ [single D tag] $3884.3\pm1.2\pm1.5$ [double D tag]	$24.8\pm3.3\pm11.0$ [single D tag] $23.8\pm2.1\pm2.6$ [double D tag]	D^0D^{*-} D^-D^{*0}	$e^+e^-\rightarrow\pi^+D^0D^{*-}$ $e^+e^-\rightarrow\pi^+D^-D^{*0}$
$Z_c(4020)^\pm$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$	$\pi^\pm h_c$	$e^+e^-\rightarrow\pi^+\pi^-h_c$
$Z_c(4020)^0$	$4023.9\pm2.2\pm3.8$	fixed	$\pi^0 h_c$	$e^+e^-\rightarrow\pi^0\pi^0 h_c$
$Z_c(4025)^\pm$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$	$D^{*0}D^{*-}$	$e^+e^-\rightarrow\pi^+(D^*\bar{D}^*)^-$