Highlights on the XYZ Physics

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HFHF, GSI & GU Frankfurt

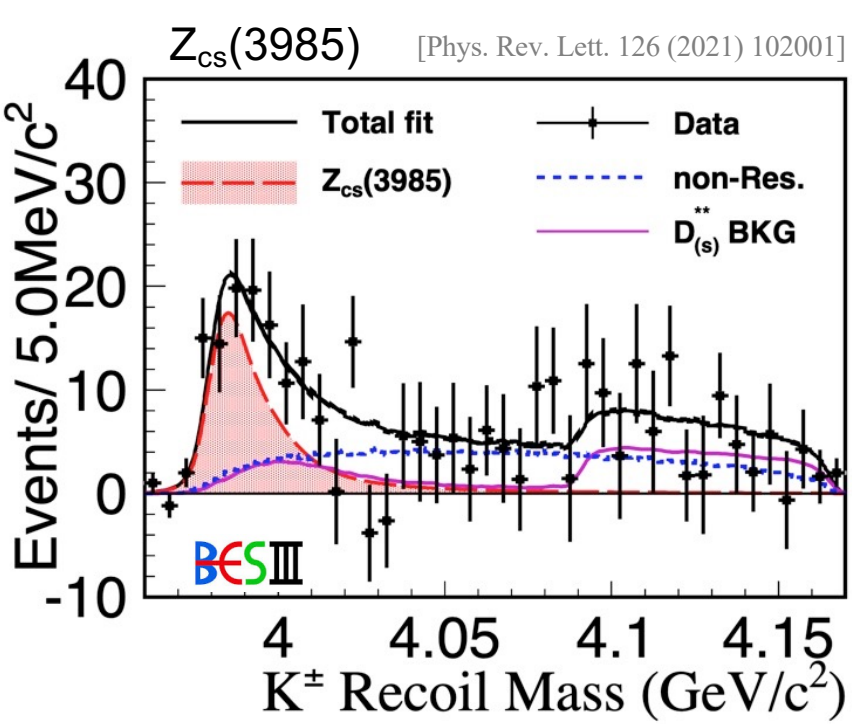
Celebration Ceremony of the 500 Publications of BESIII Collaboration,
May 31st 2023, IHEP, Beijing, China

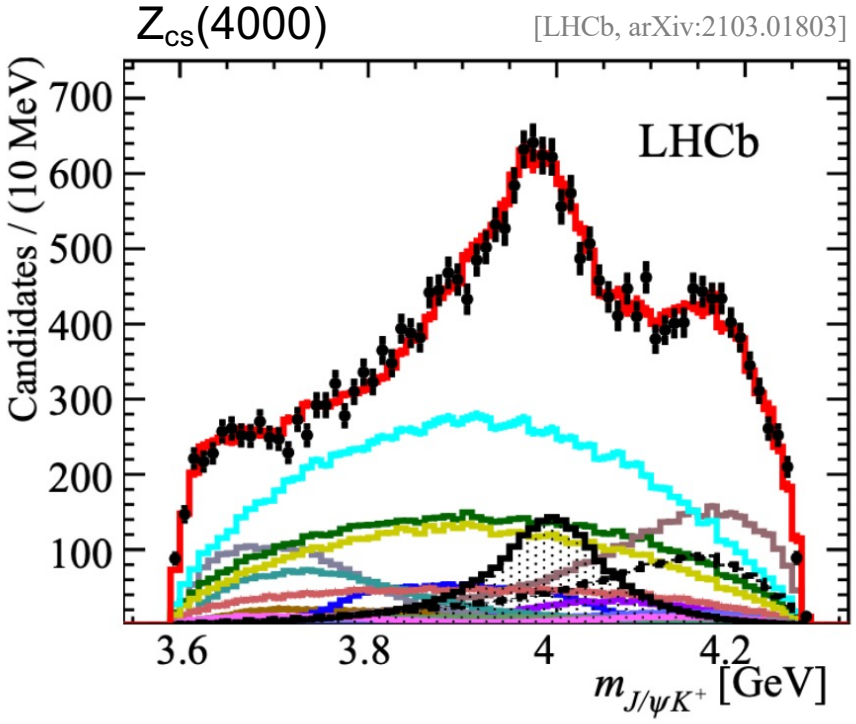
Outline

- **Introduction**
- **The BESIII experiments and data sets**
- **A selection of recent results**
  - Supernumerary vector Y states
  - Manifestly exotic Z_c states
  - The X(3872) and other X states
- **Summary**

Recent hot topics

Hadron Spectroscopy



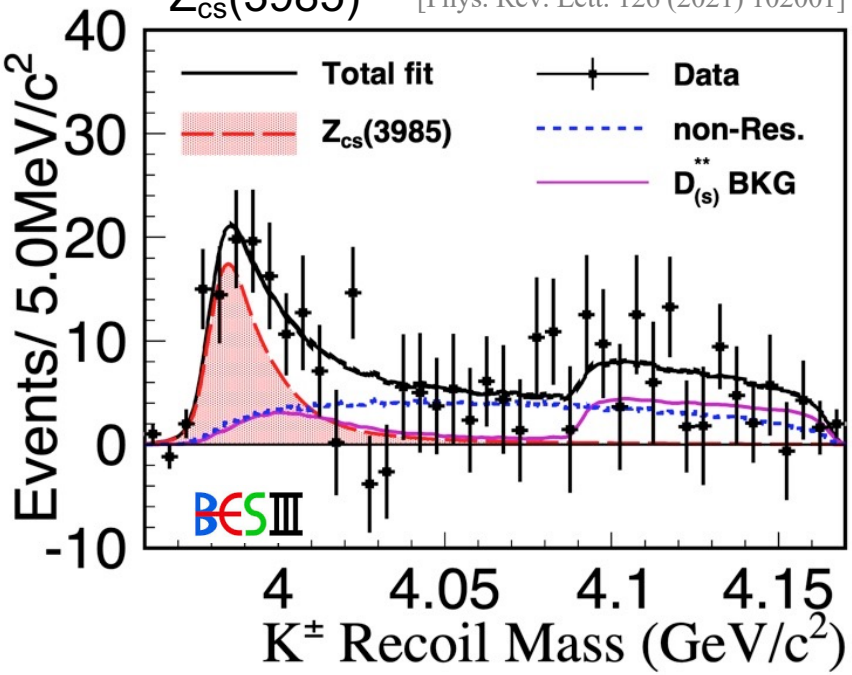


Strange partner of the famous,
unexpected, manifestly exotic $Z_c(3900)$?

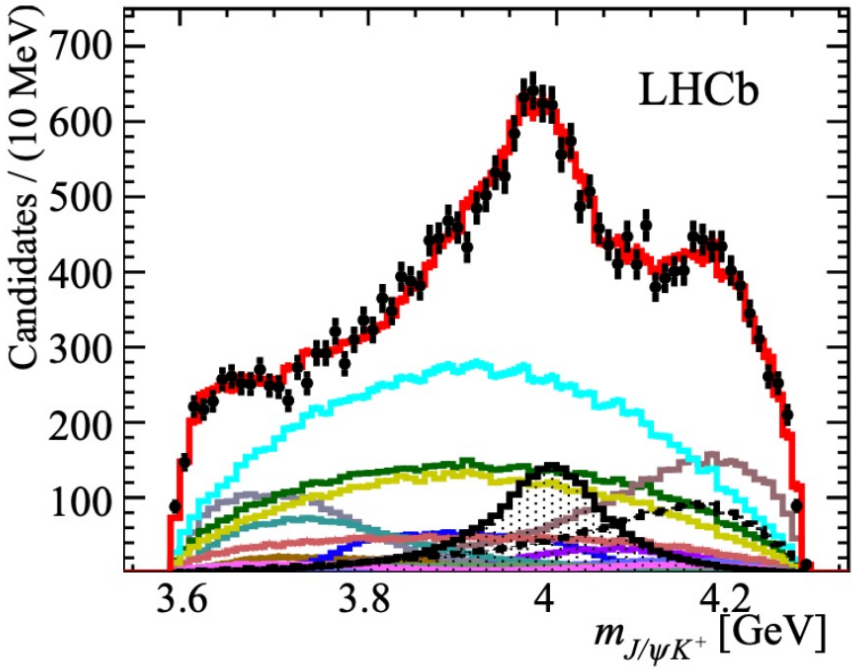
Recent hot topics

Hadron Spectroscopy

$Z_{cs}(3985)$ [Phys. Rev. Lett. 126 (2021) 102001]



$Z_{cs}(4000)$ [LHCb, arXiv:2103.01803]



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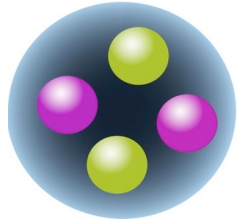
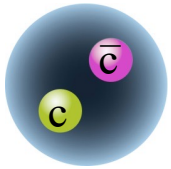
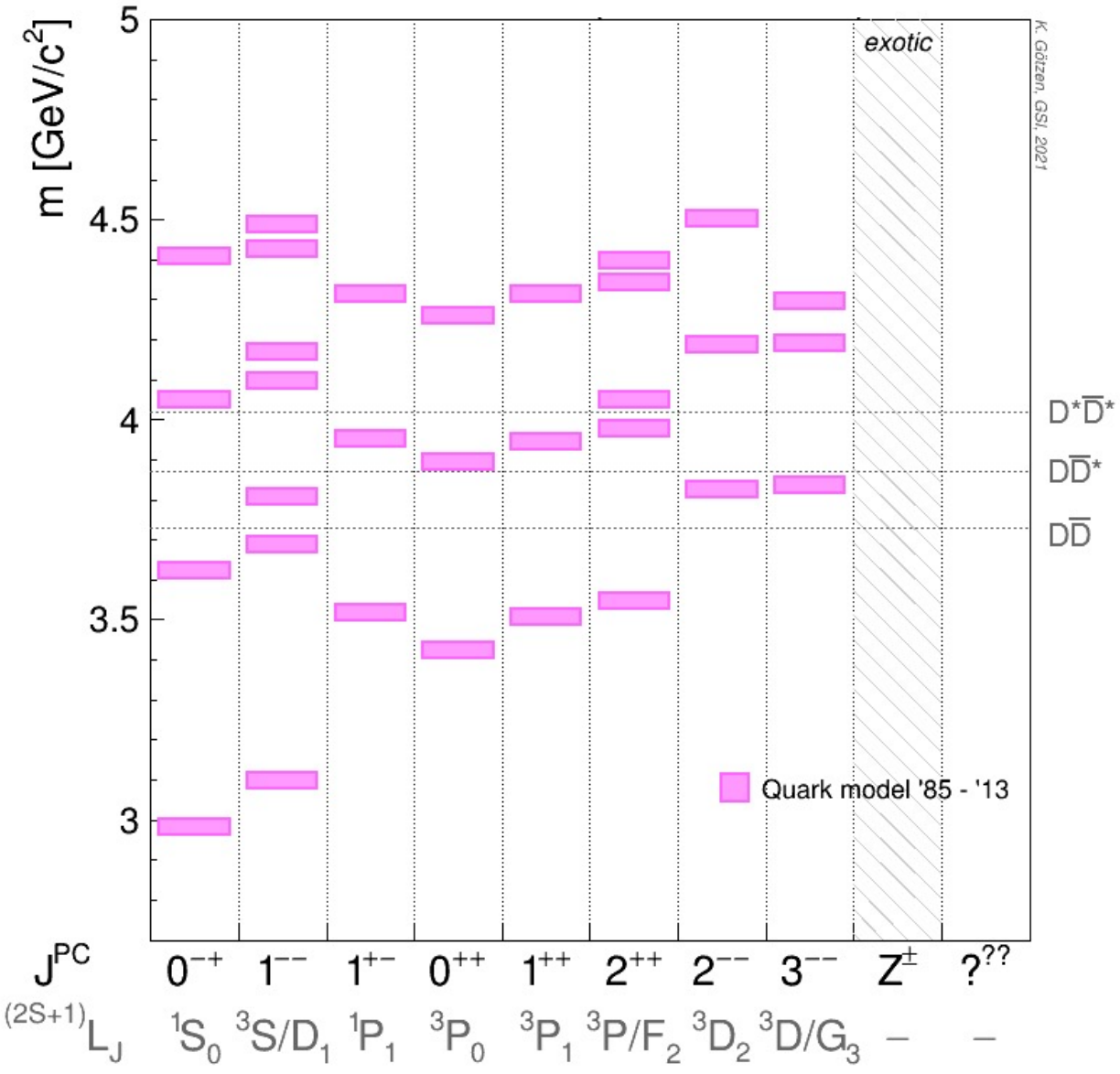


Charmonium spectrum ($c\bar{c}$)





Potential model:

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]

[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

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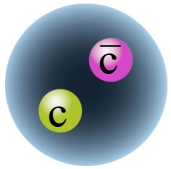

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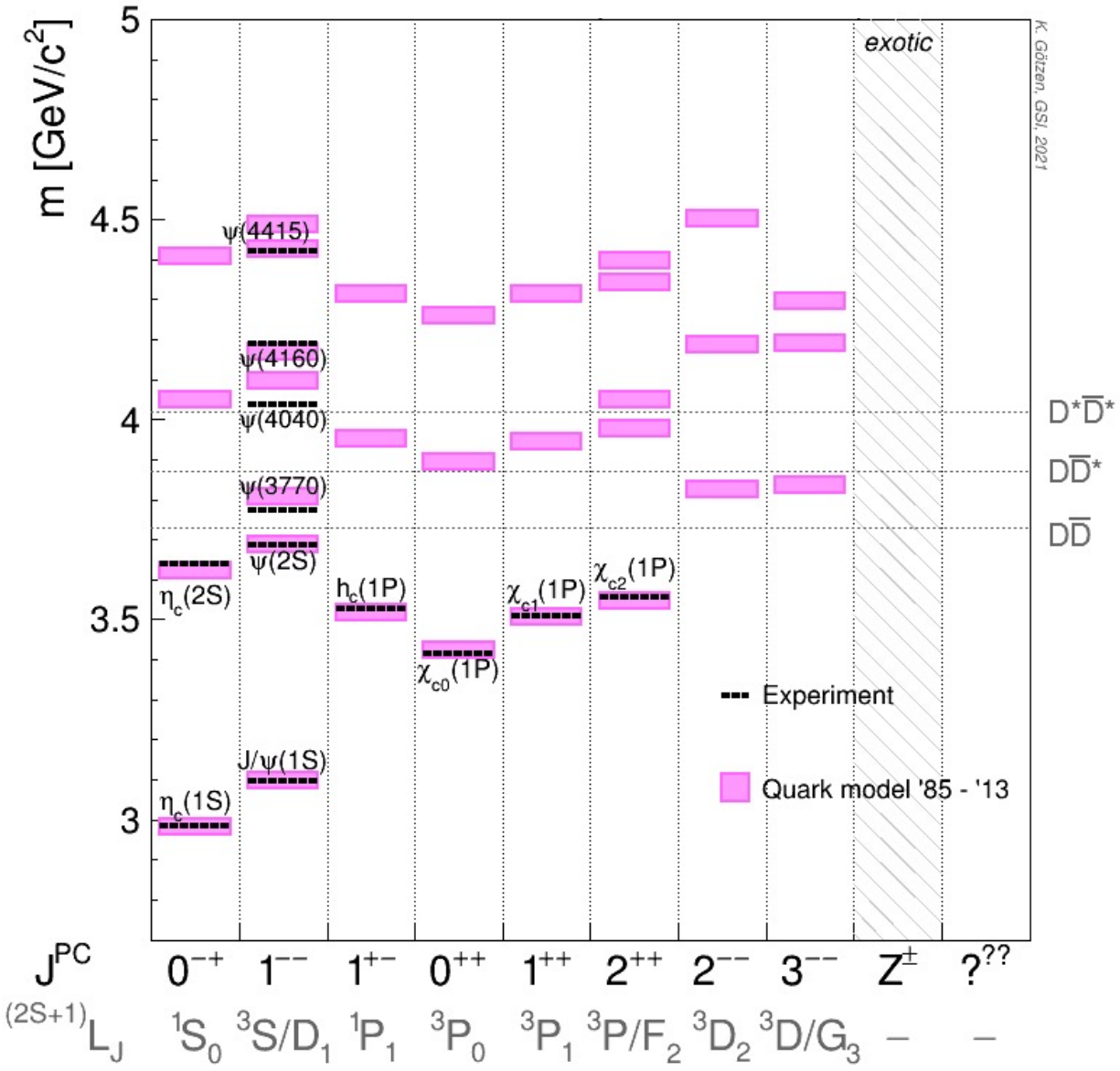

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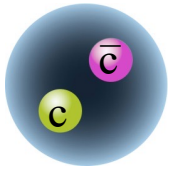

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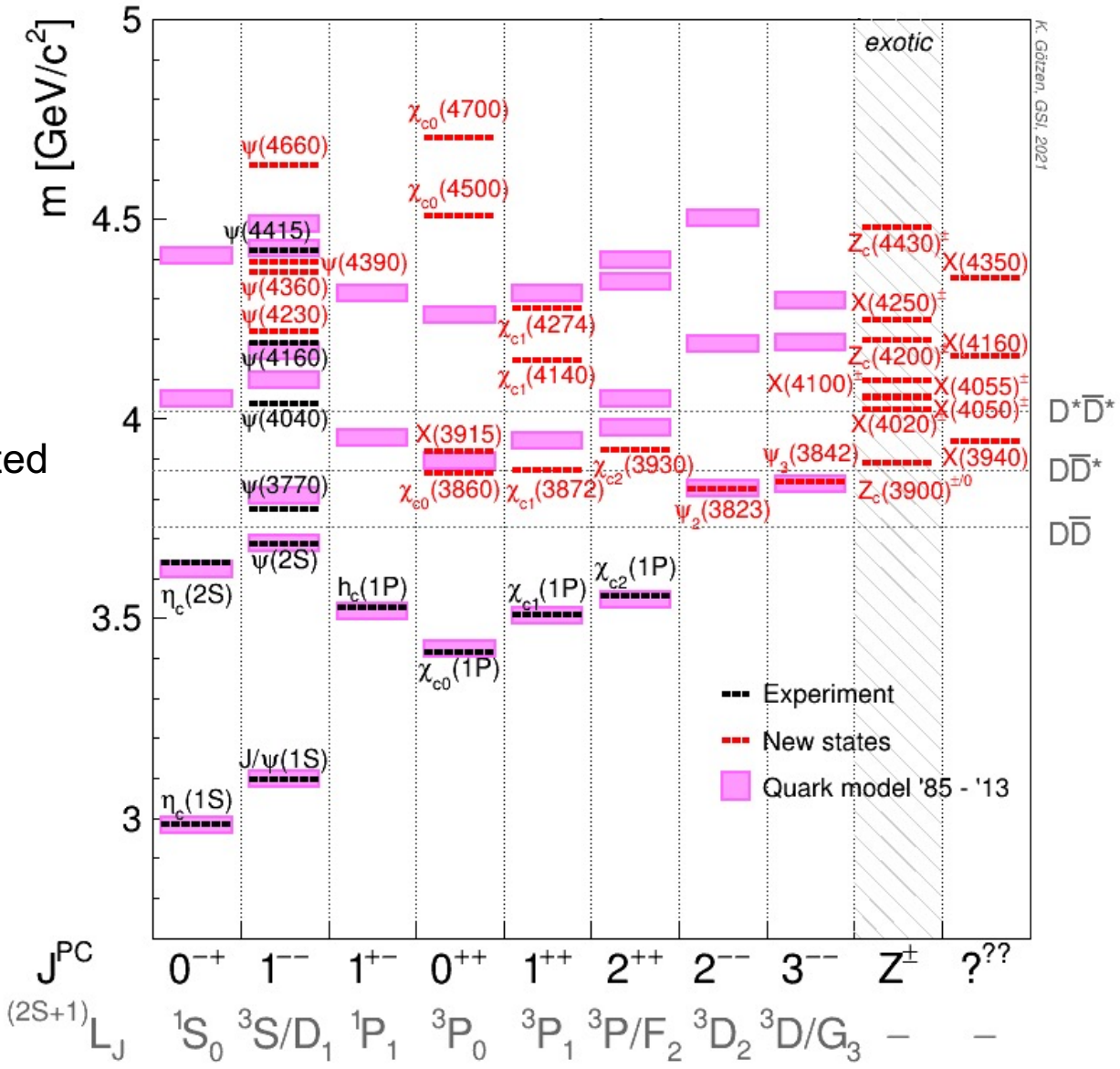

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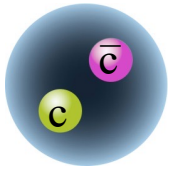

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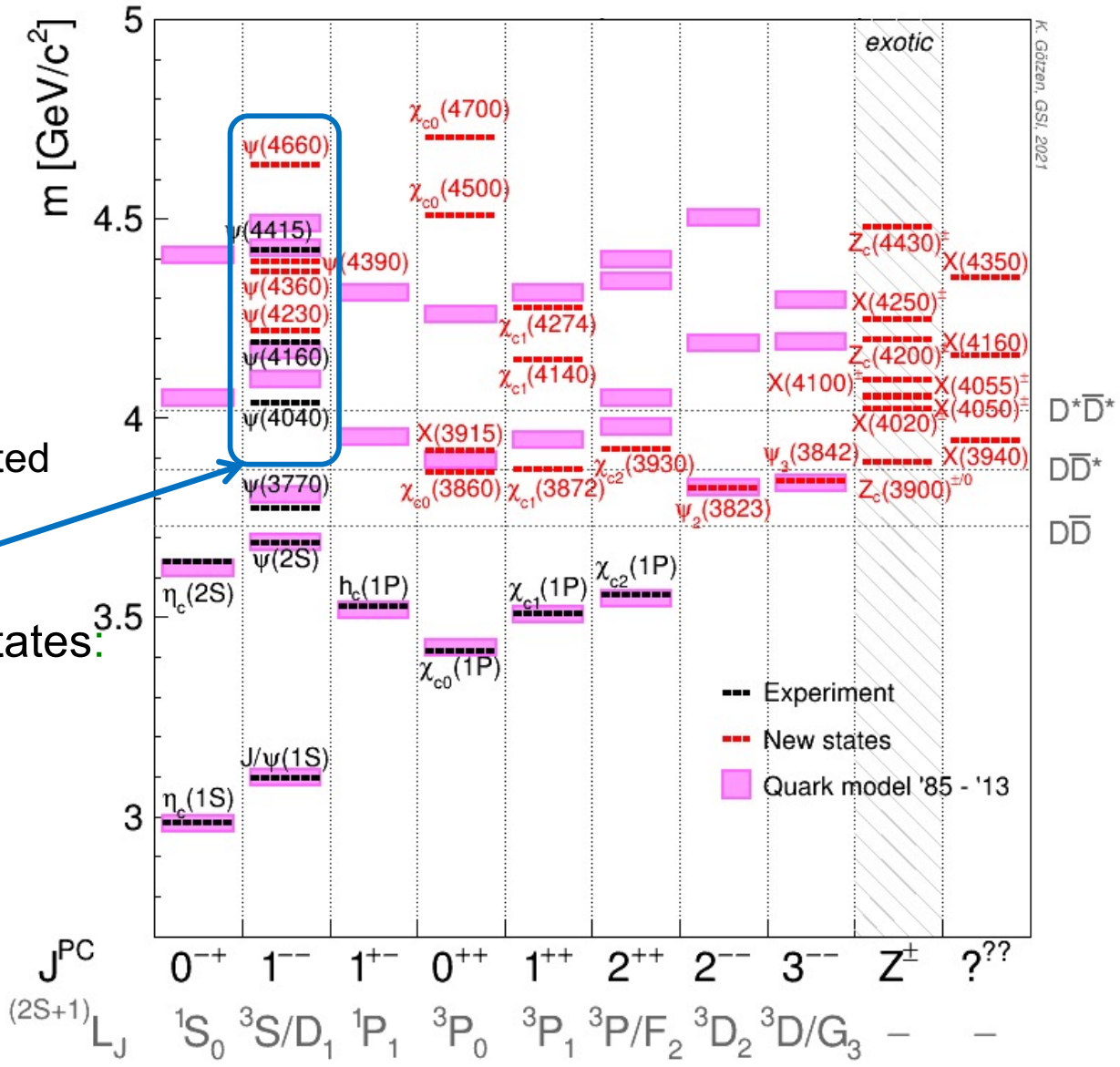

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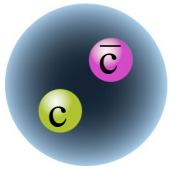

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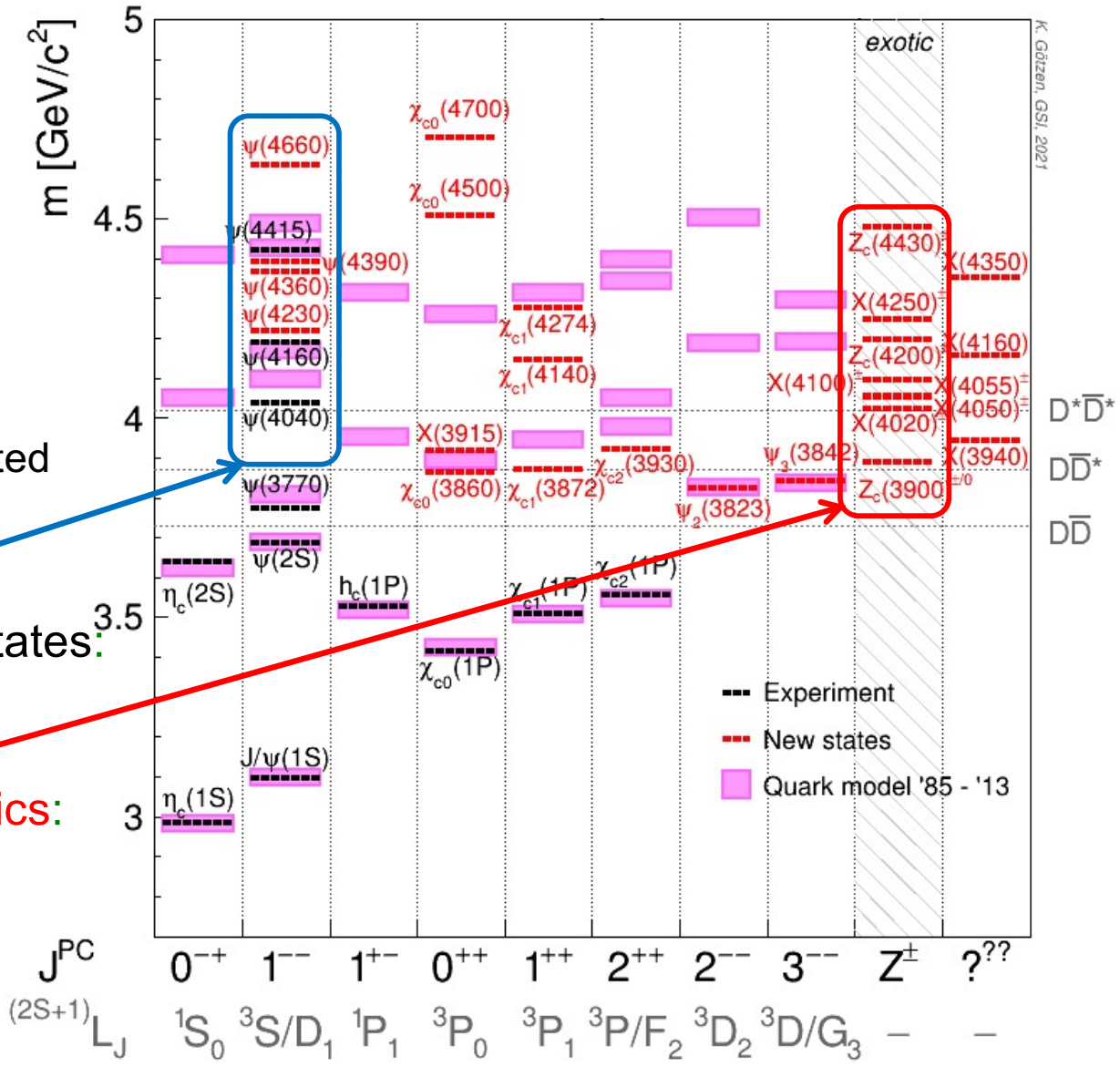

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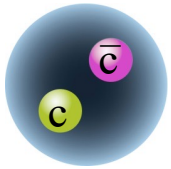

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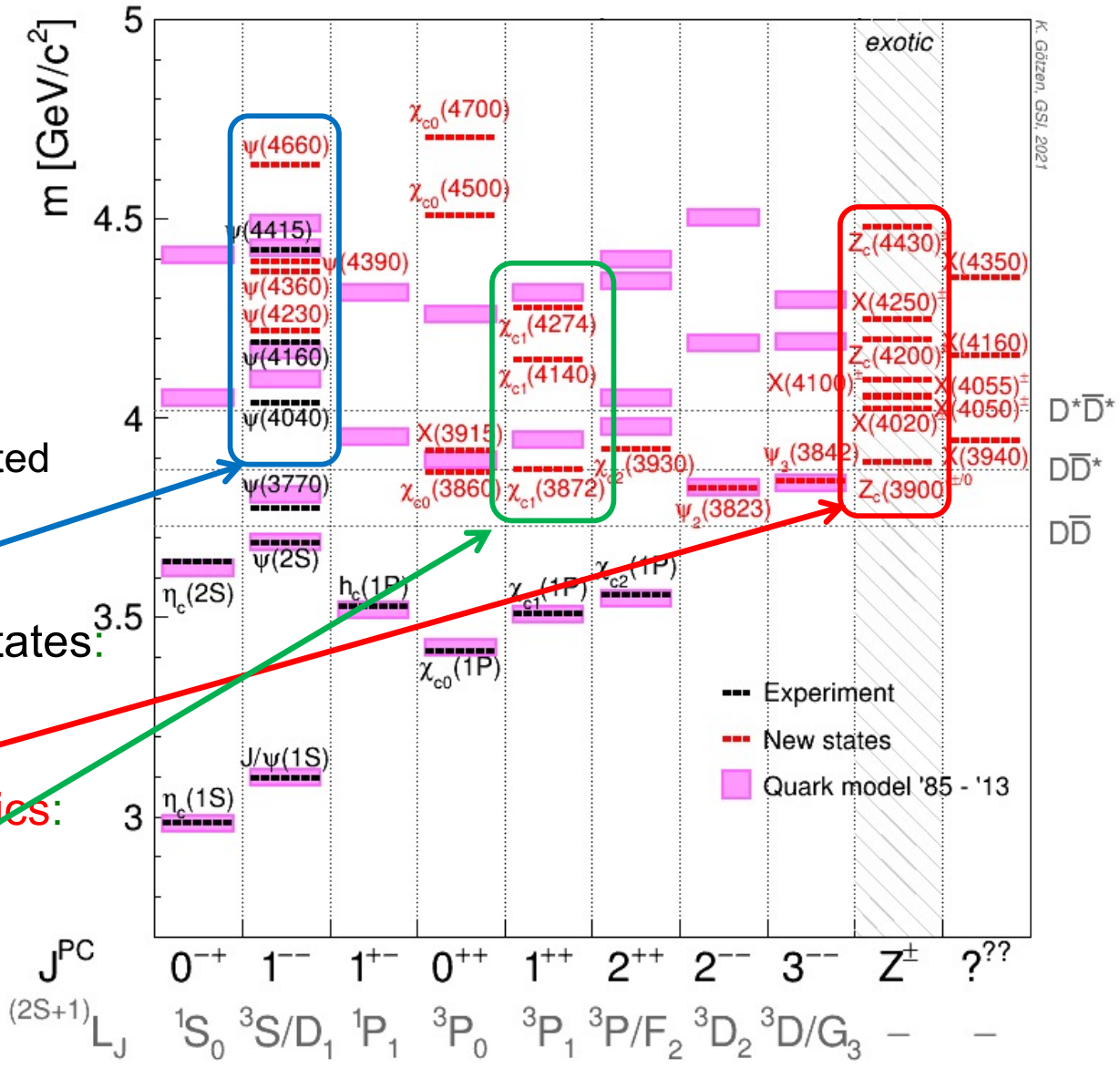
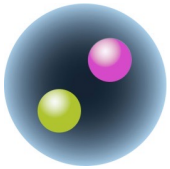
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



Mesons and exotic states

Simple Quark model

- Mesons: Color neutral $q\bar{q}$ systems



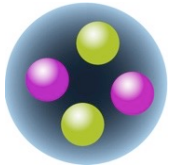
Conventional $(q\bar{q})$

QCD

- Meson states beyond $q\bar{q}$

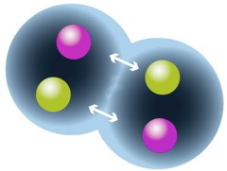
Alternative 4-quark configurations:

Hybrid $(q\bar{q})\,g$

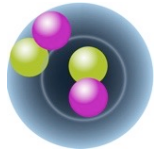


Tetraquark $(q\bar{q}q\bar{q})$

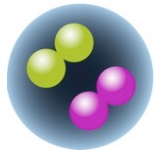
Glue-ball (gg) or (ggg)



Molecule $(q\bar{q})(q\bar{q})$



Hadro-quarkonium $(Q\bar{Q})(q\bar{q})$



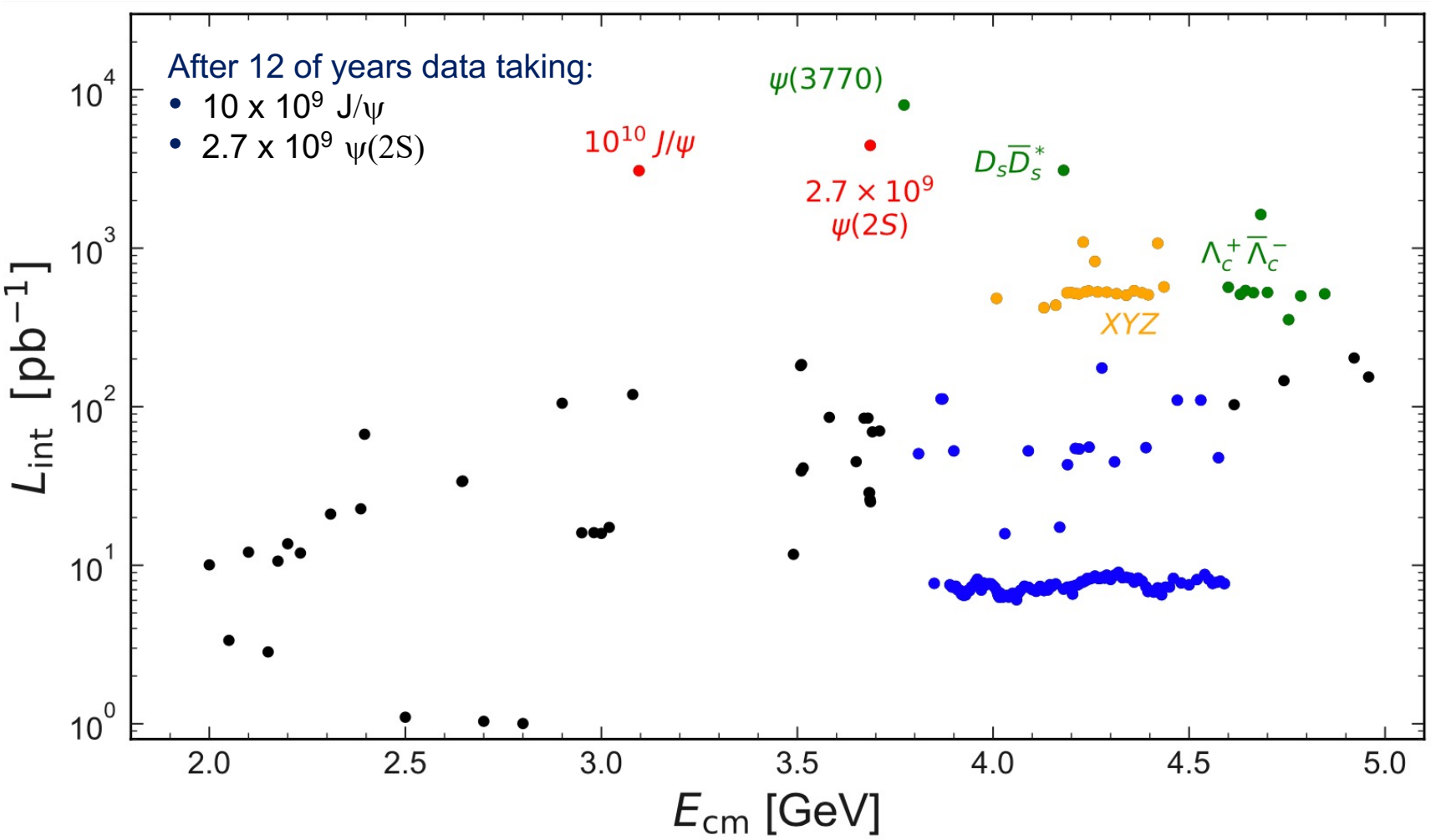
Di-quarkonium $(qq)(\bar{q}\bar{q})$

BESIII at BEPCII

- Symmetric e^+e^- collider:
  - $\sqrt{s}$ = 2.0 - 4.6 GeV
- Design luminosity:
  - 1×10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$, achieved in 04/2016)

- Multi-purpose 4π detector with
  - good tracking
  - calorimetry
  - PID and muon detection
- Operating since March 2008

Unique BESIII data set (collected so far ...)



- XYZ region: > 3.8 GeV, integrated luminosity: ~22 fb^{-1}
- 104 energy points between 3.85 and 4.59 GeV *(R scan)*
- ~20 energy points between 2.0 and 3.1 GeV

[Courtesy: W. Gradl]

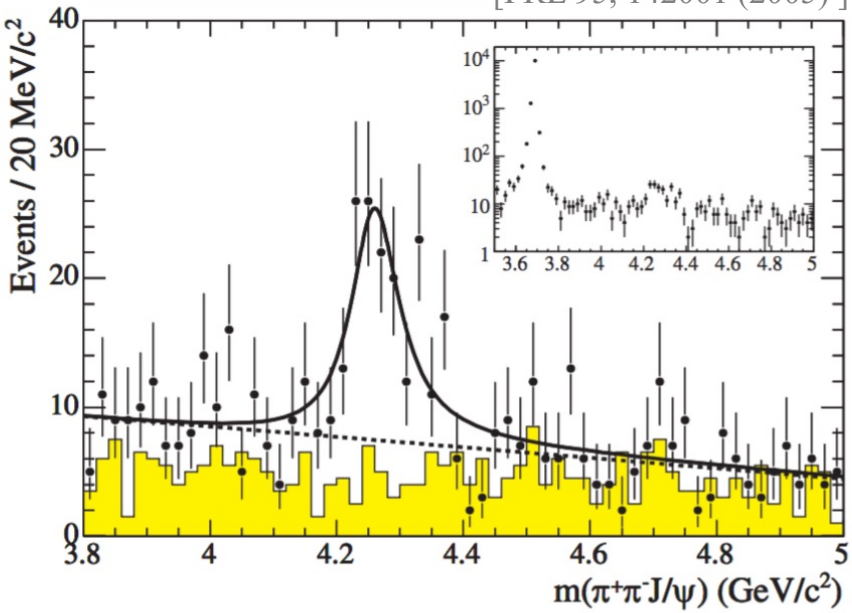
The Y(4260) and further supernumerary vector states

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

Some history:

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

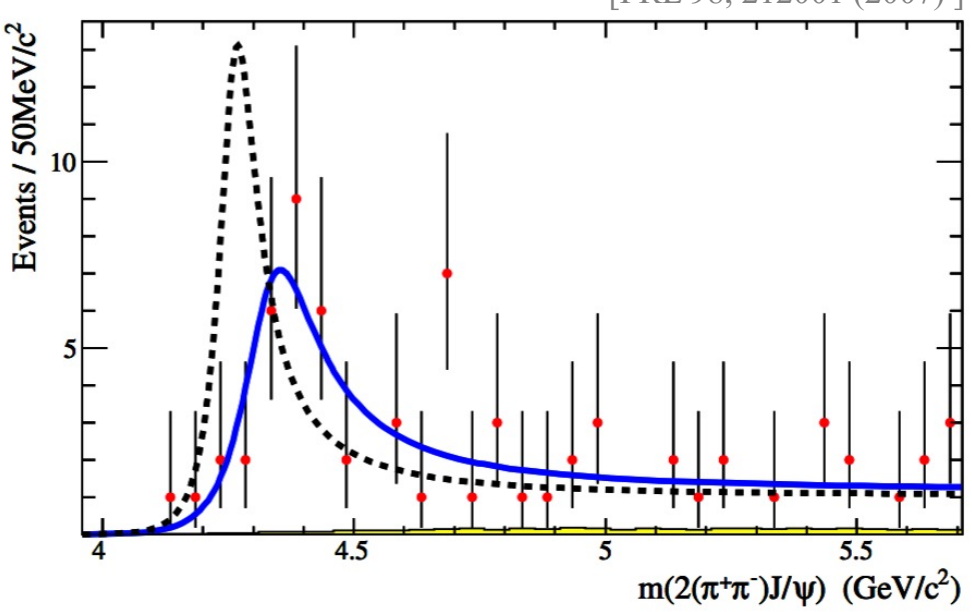
[PRL 95, 142001 (2005)]



- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$

$e^+e^- \to \psi(2S)\pi^+\pi^-$

[PRL 98, 212001 (2007)]



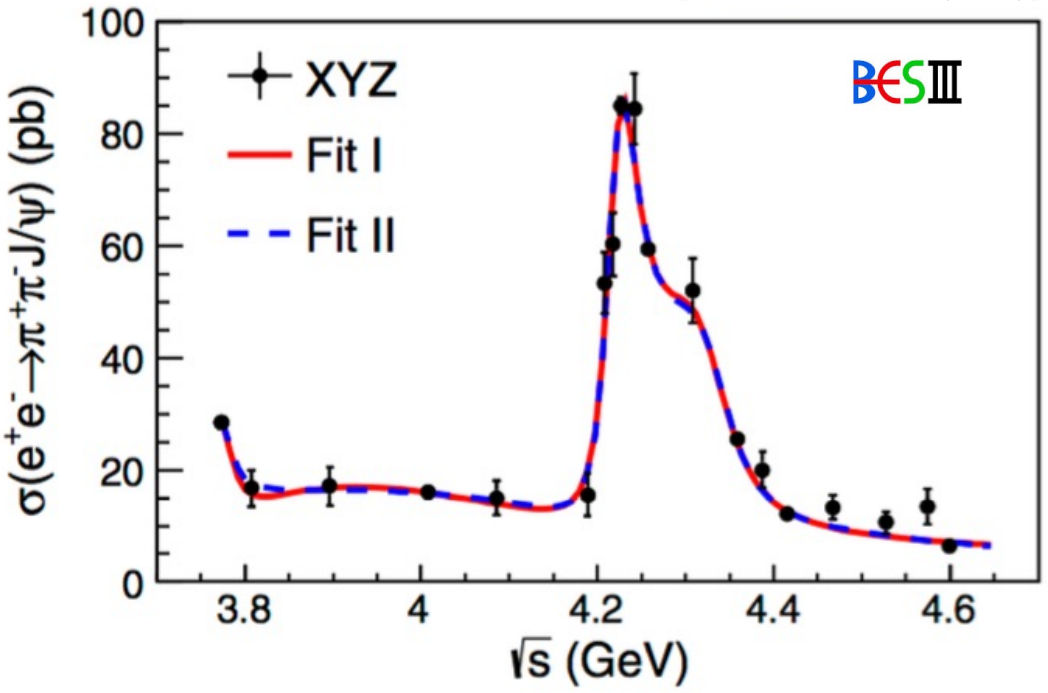
- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^+\pi^-$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

BESIII result, published

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

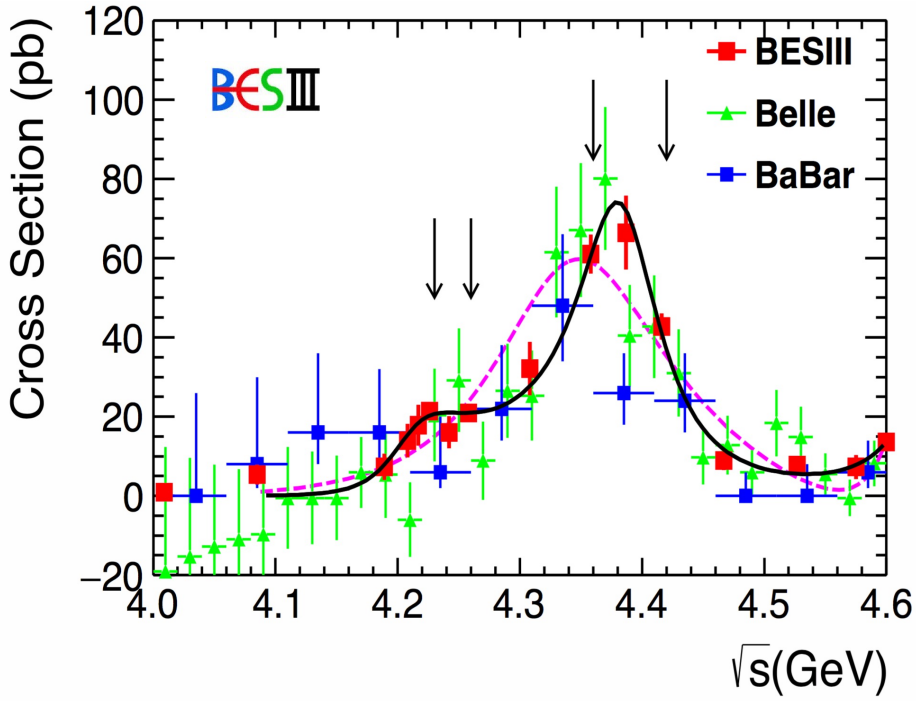
[PRL 118, 092001 (2017)]



- Cross-section inconsistent with the single resonance Y(4260)!
  - ➢ Two favoured over one by >7σ

$e^+e^- \to \psi(2S)\pi^+\pi^-$

[Phys. Rev. D 96, 032004 (2017)]



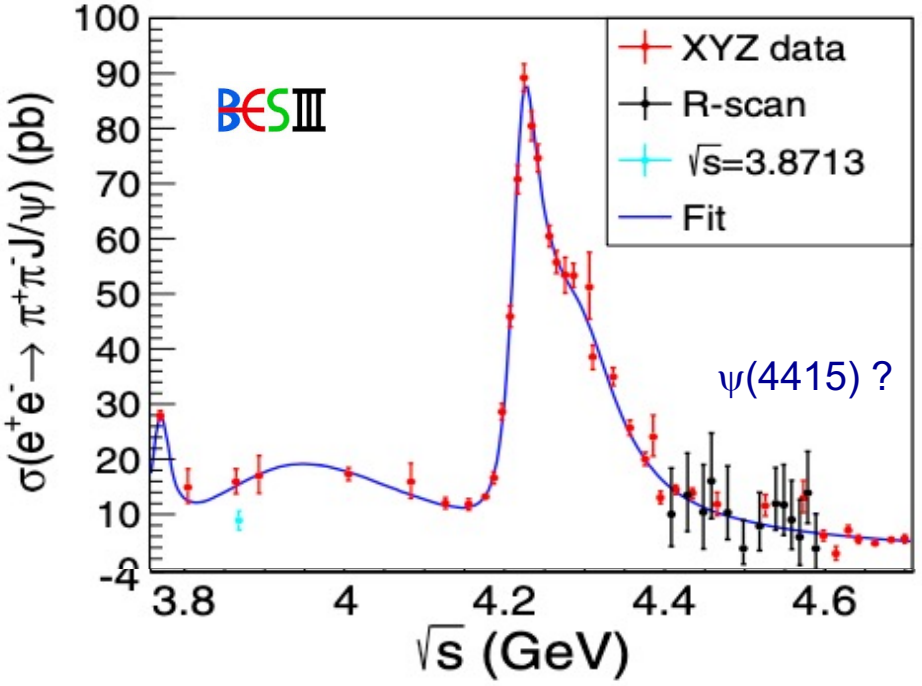
- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4360)

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

BESIII result, published

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

[Phys. Rev. D 106, 072001 (2022)]



$e^+e^- \to \psi(2S)\pi^+\pi^-$

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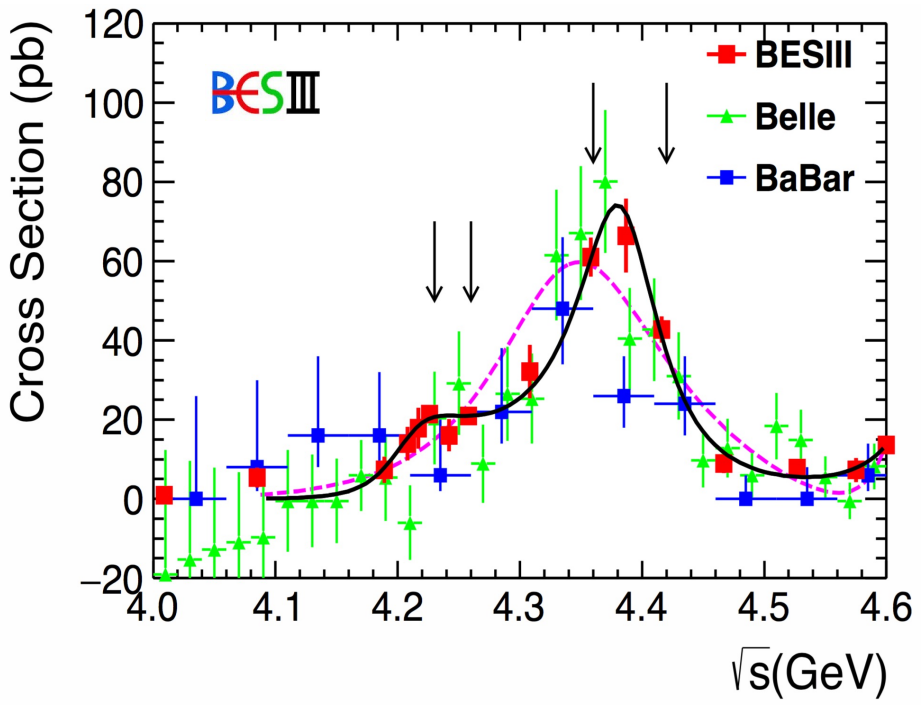


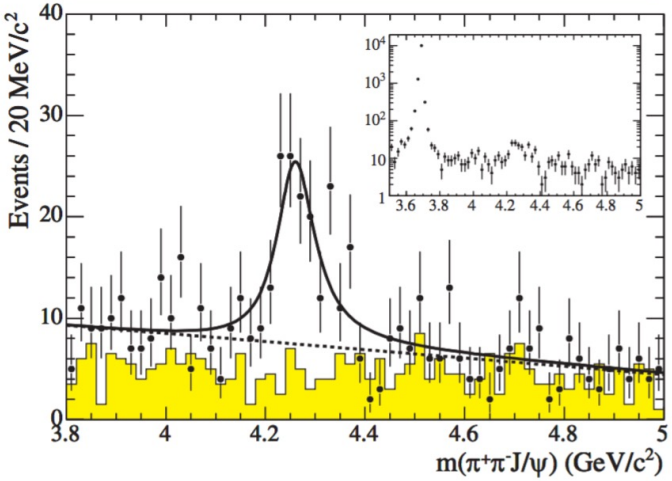
- Cross-section inconsistent with the single resonance Y(4260)
  - ➢ Additional structure at ~4.5 GeV needed (?), influences Y(4230) parameters

- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4360)

What happened to the Y states?

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

[BaBar, PRL 95, 142001 (2005)]



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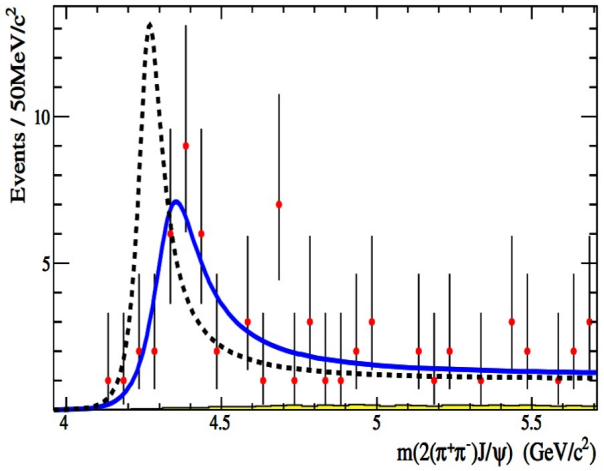

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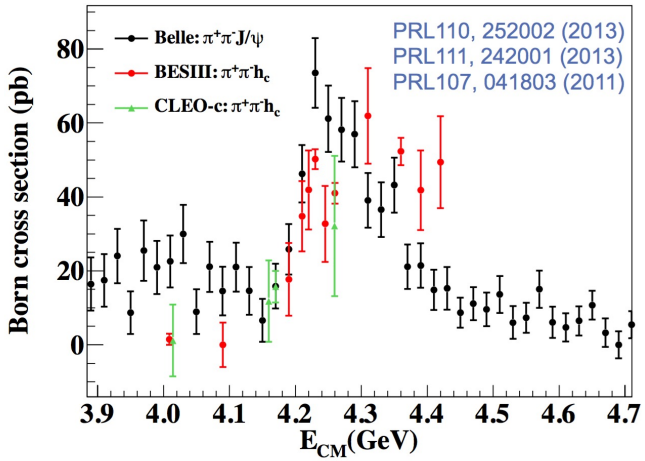

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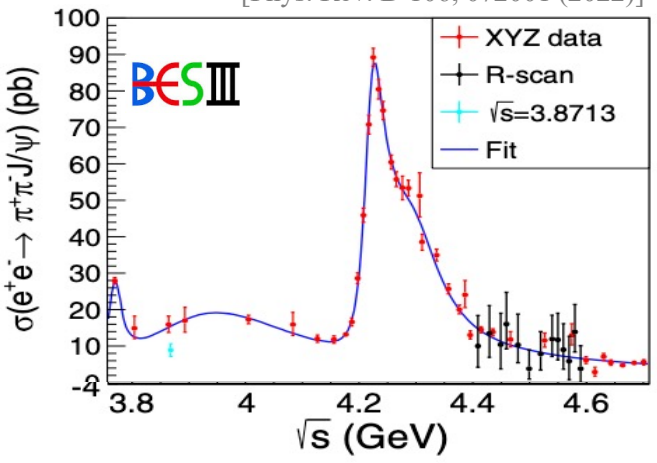

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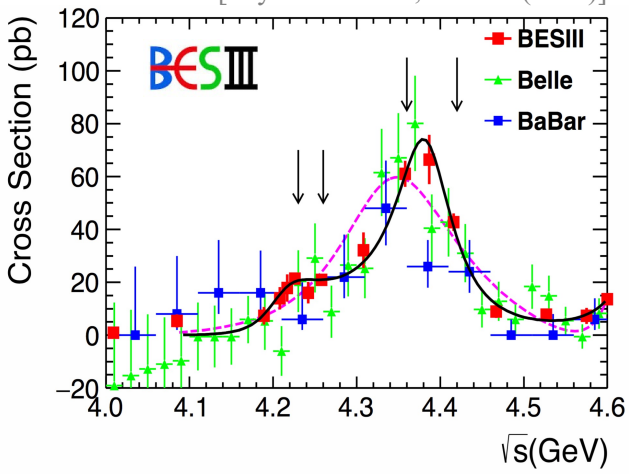
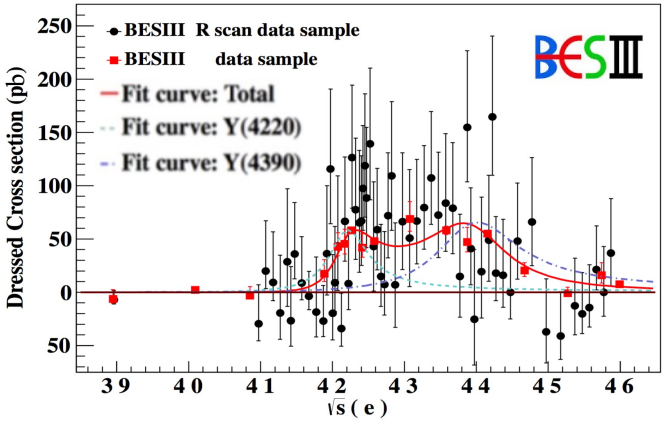


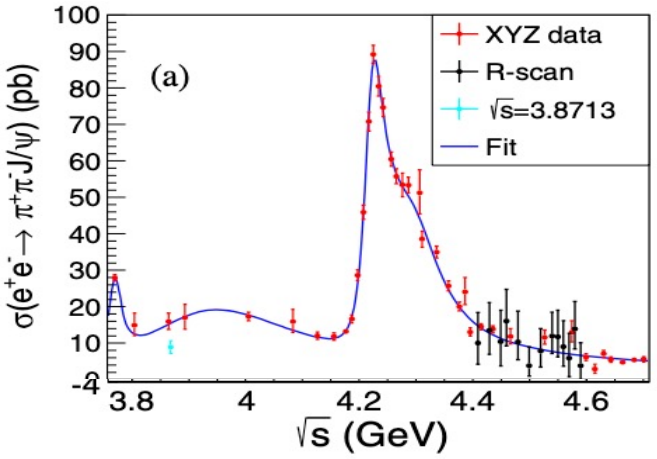
[Phys. Rev. Lett. 118 092002 (2017)]



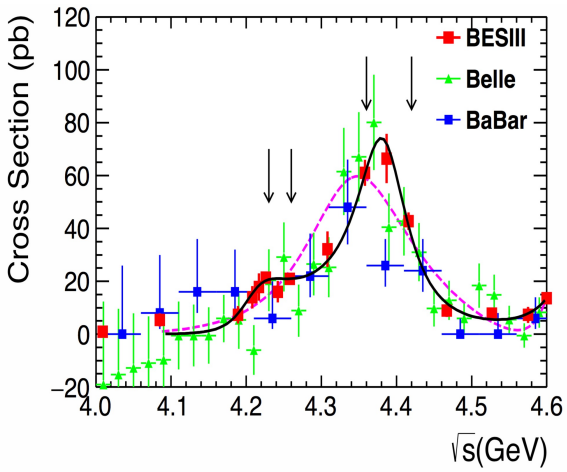
Two structures now resolved: Y(4260) → Y(4230) , and Y(4360)

What happened to the Y states?

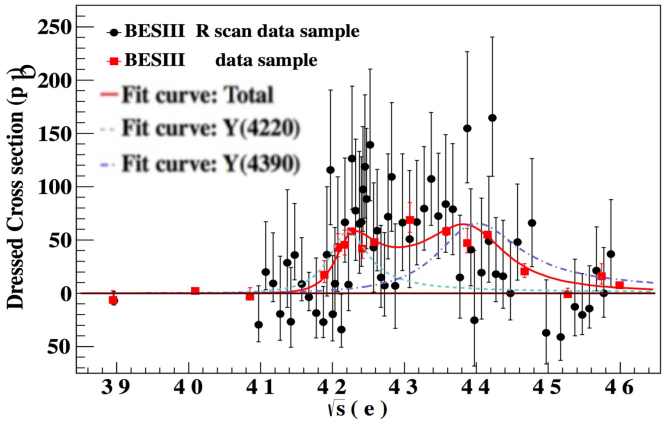
$e^+e^- \to J/\psi\pi^+\pi^-$



$e^+e^- \to \psi(2S)\pi^+\pi^-$

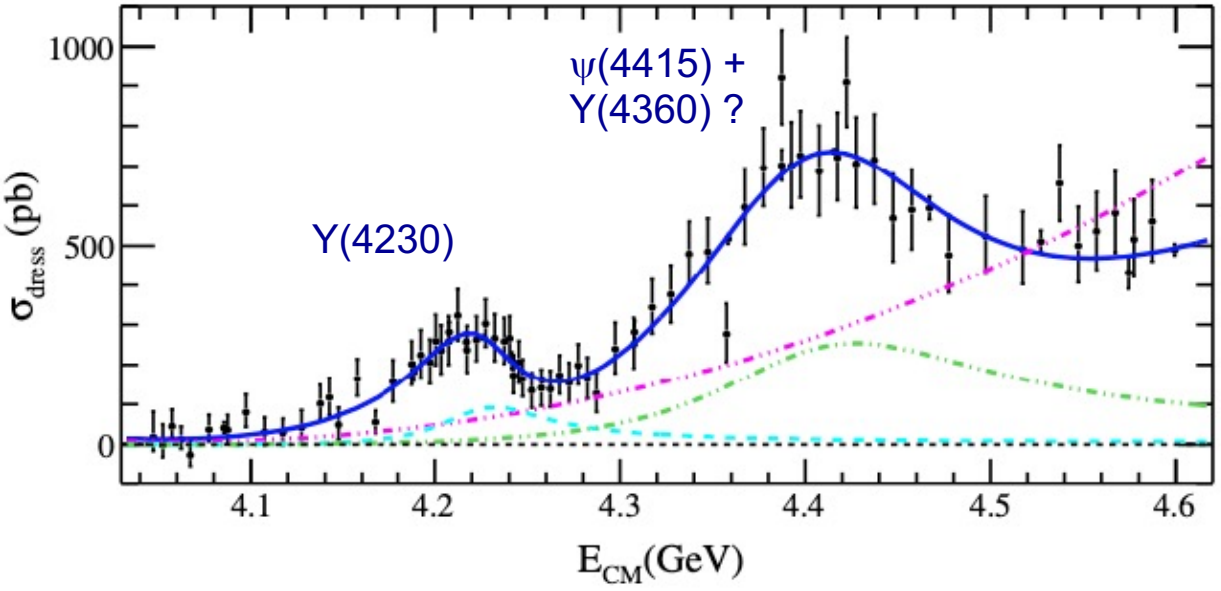


$e^+e^- \to h_c\pi^+\pi^-$



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

[PRL 122, 102002 (2019)]



Y(4230):

- $M = (4228.6 \pm 4.1 \pm 6.3)$ MeV/c²
- $\Gamma = (77.0 \pm 6.8 \pm 6.3)$ MeV/c²

Y state at about 4.40 GeV:

- strongly model dependent

=> First Y decays to open-charm

=> Consistency with structures in J/ψ / h_c / $\psi(2S)\,\pi\pi$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

$e^+e^- \to \psi(2S)\pi^+\pi^-$

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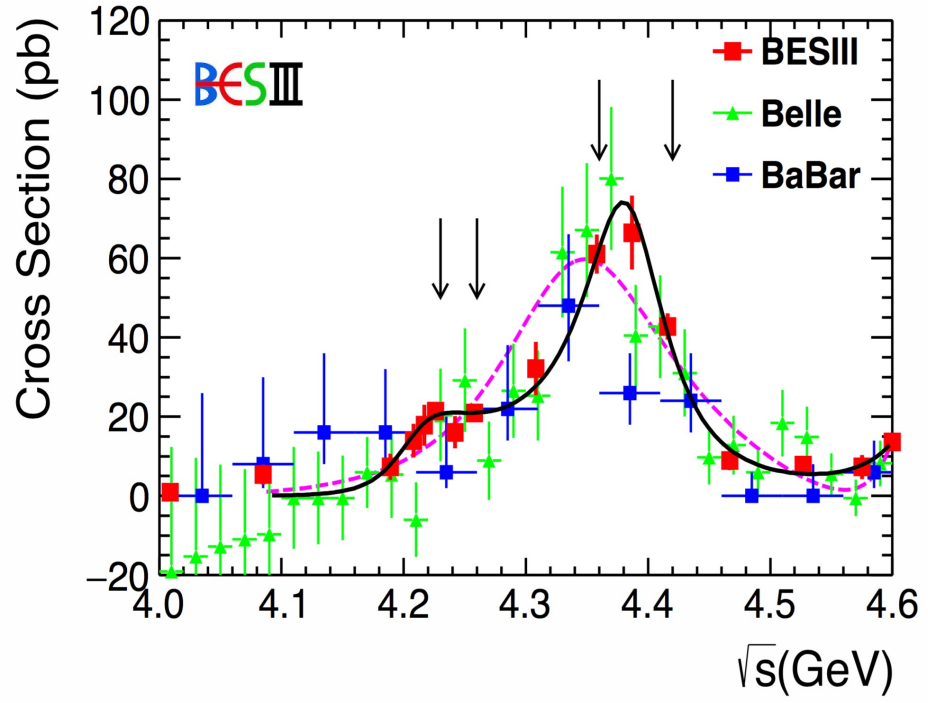

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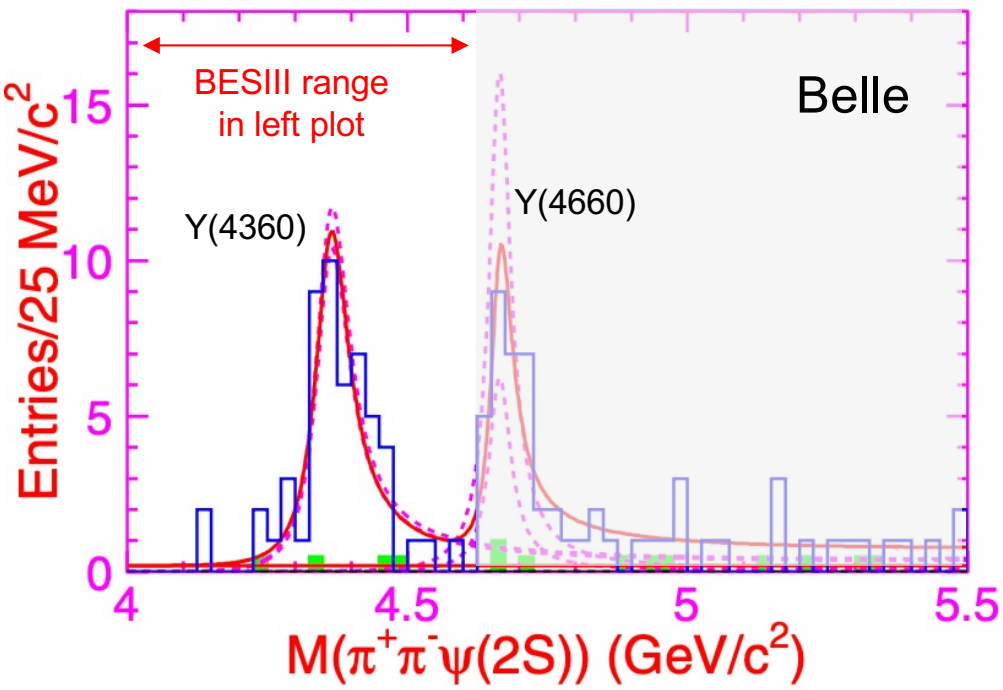
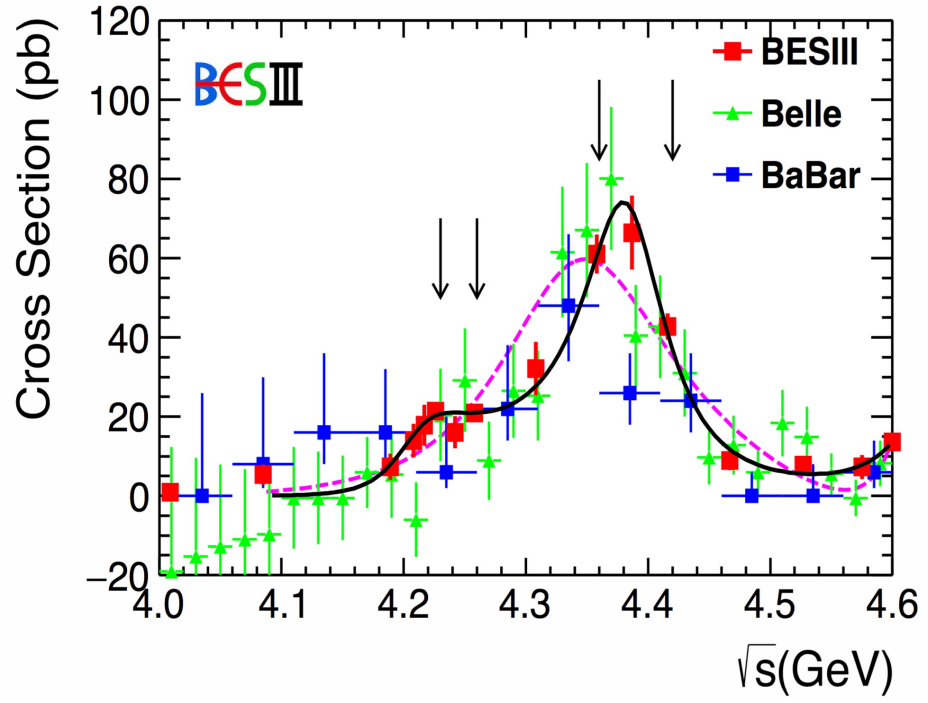


- Confirmation of the Y(4360) in $\psi(2S)\pi^-\pi^+$ with a significance of 8σ
- First observation of Y(4660) with 5.8σ

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

$e^+e^- \to \psi(2S)\pi^+\pi^-$

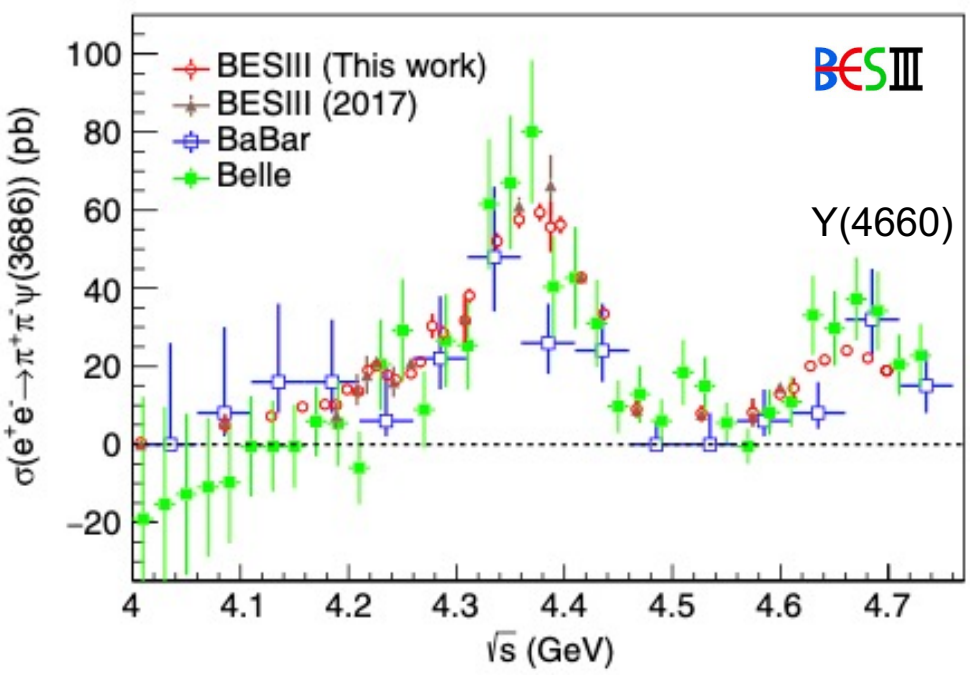
[Phys. Rev. D 96, 032004 (2017)]



- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4360)

$e^+e^- \to \psi(2S)\pi^+\pi^-$

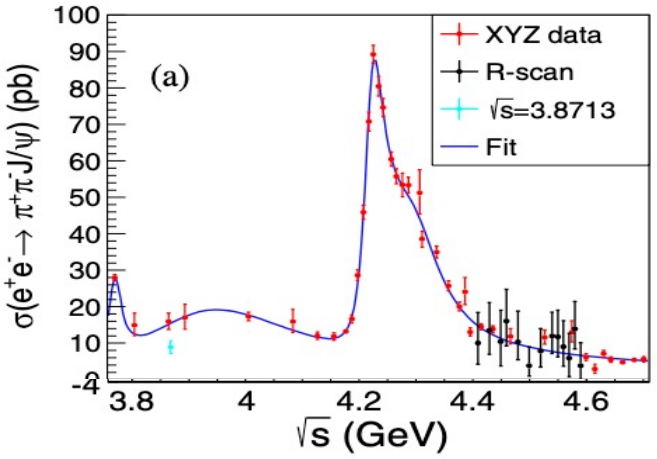
[PRD 104, 052012 (2021)]



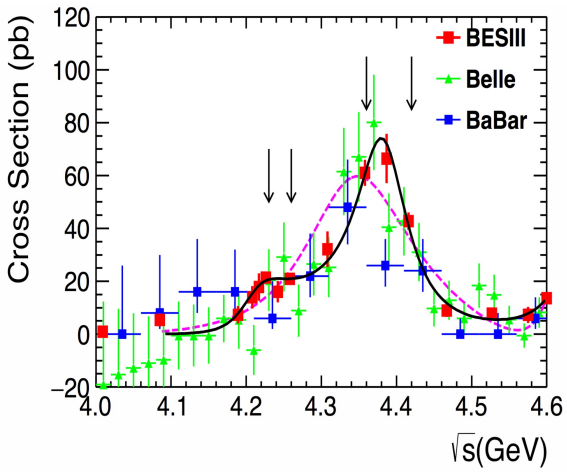
- Observation of Y(4660) $\to \psi(2S)\pi^-\pi^+$ with a significance of 8.1σ
- First observation of Y(4660) at BESIII

What about Y states to open charm?

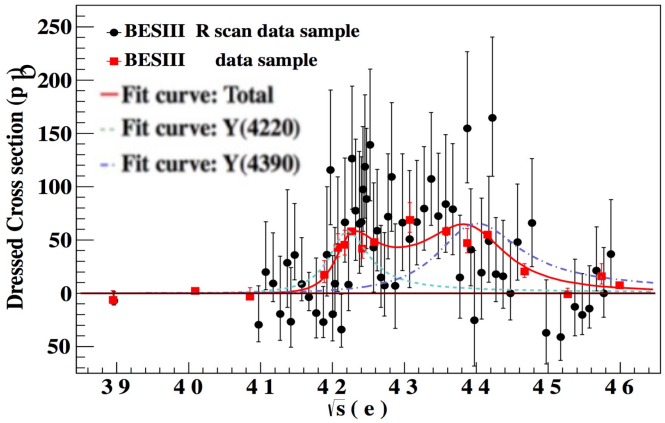
$e^+e^- \to J/\psi\pi^+\pi^-$



$e^+e^- \to \psi(2S)\pi^+\pi^-$

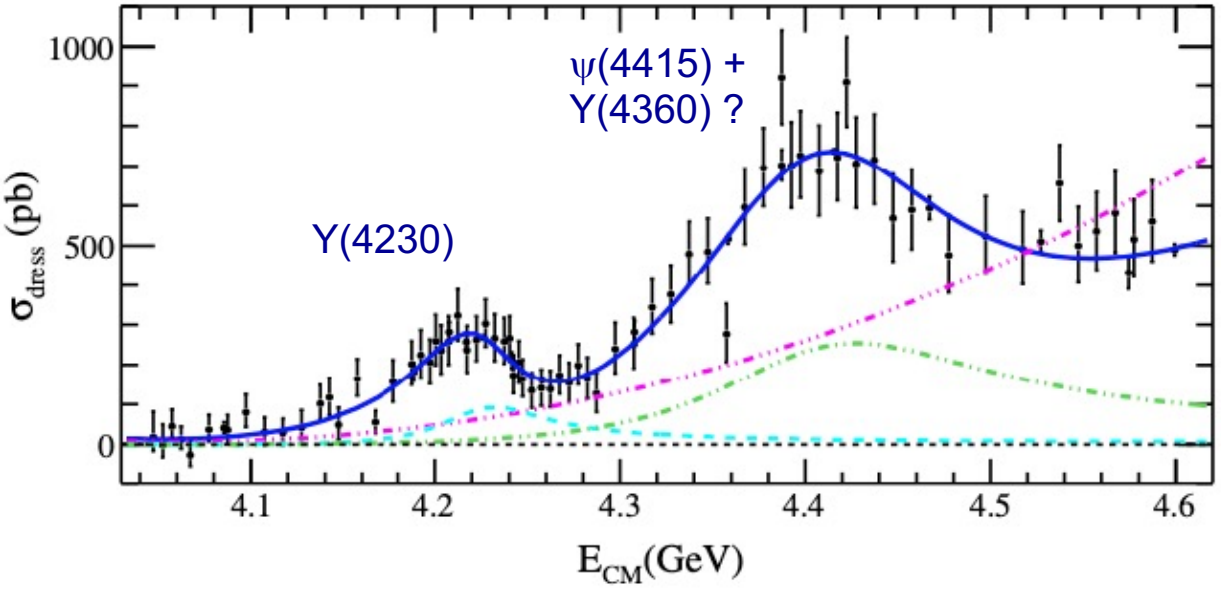


$e^+e^- \to h_c\pi^+\pi^-$



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

[PRL 122, 102002 (2019)]



Y(4230):

- $M = (4228.6 \pm 4.1 \pm 6.3)$ MeV/c²
- $\Gamma = (77.0 \pm 6.8 \pm 6.3)$ MeV/c²

Y state at about 4.40 GeV:

- strongly model dependent

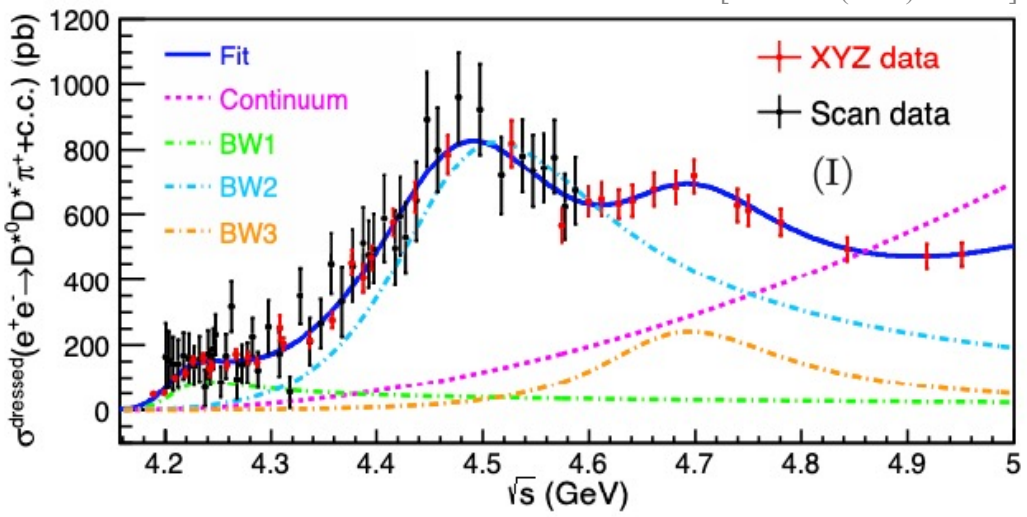
=> First Y decays to open-charm

=> Consistency with structures in J/ψ / h_c / $\psi(2S)\,\pi\pi$

What happened to the Y states?

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

[PRL 130 (2023) 121901]



Y(4230):
- M = (4209.6 ±4.7 ±5.9) MeV/c^2
- Γ = (81.6 ±17.8 ±9.0) MeV

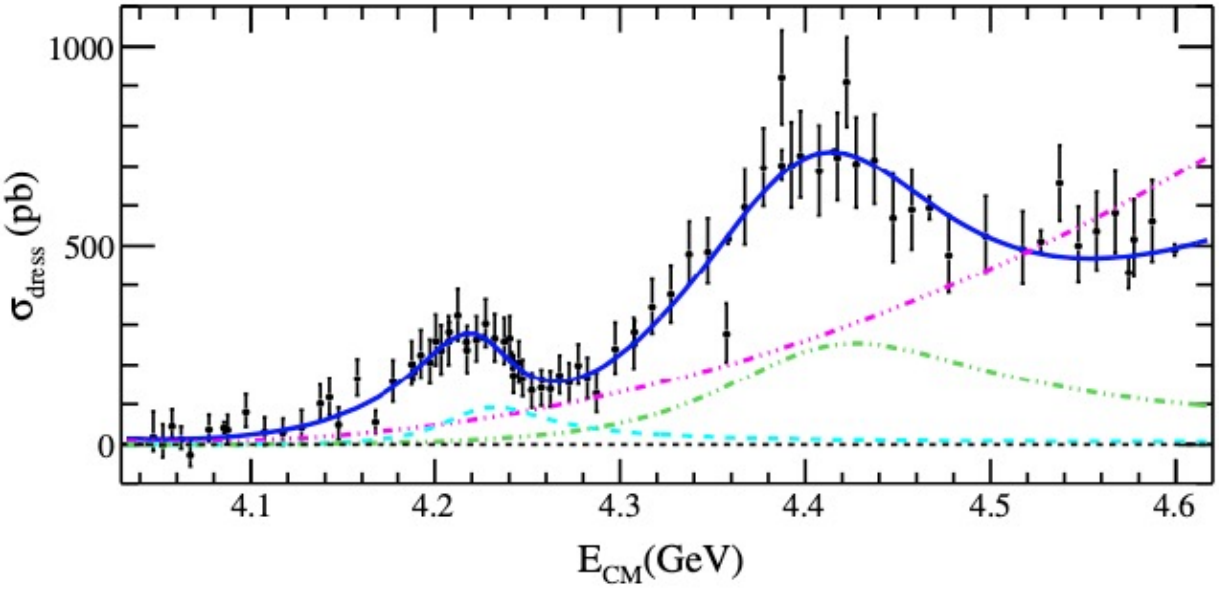
Y(4500):
- M = (4469.1 ±26.2 ±3.6) MeV/c^2
- Γ = (81.6 ±17.8 ±9.0) MeV

Y(4660):
- M = (4675.3 ±29.5±3.5) MeV/c^2
- Γ = (218.2 ±72.9 ±9.3) MeV

=> Consistency with structures in
J/ψ / h_c / $\psi(2S)\pi\pi$ & $J/\psi KK$

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

[PRL 122, 102002 (2019)]



Y(4230):
- M = (4228.6 ± 4.1 ±6.3) MeV/c^2
- Γ = (77.0 ± 6.8 ±6.3) MeV/c^2

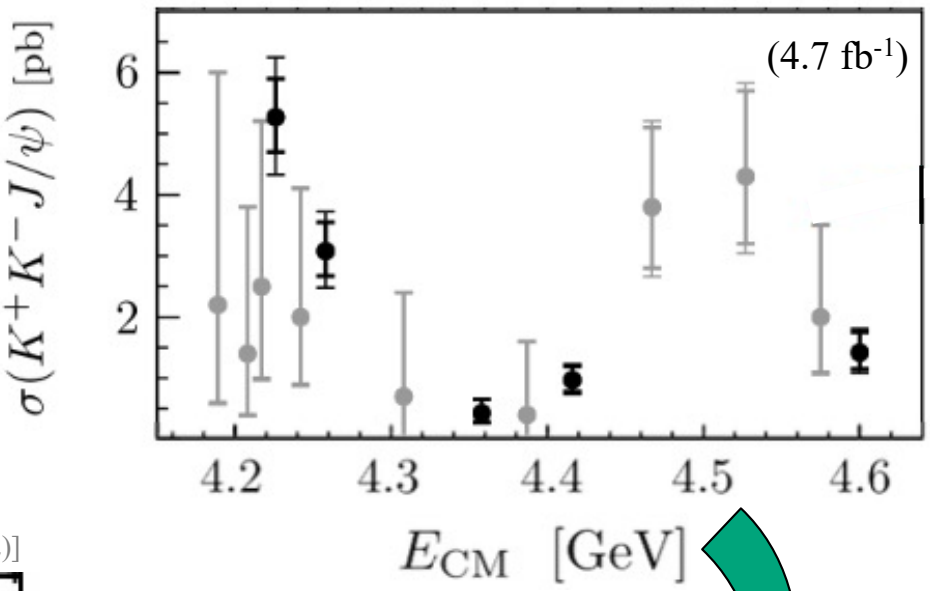
Y state at about 4.40 GeV:
- strongly model dependent

=> First Y decays to open-charm
=> Consistency with structures in
J/ψ / h_c / $\psi(2S)$ $\pi\pi$

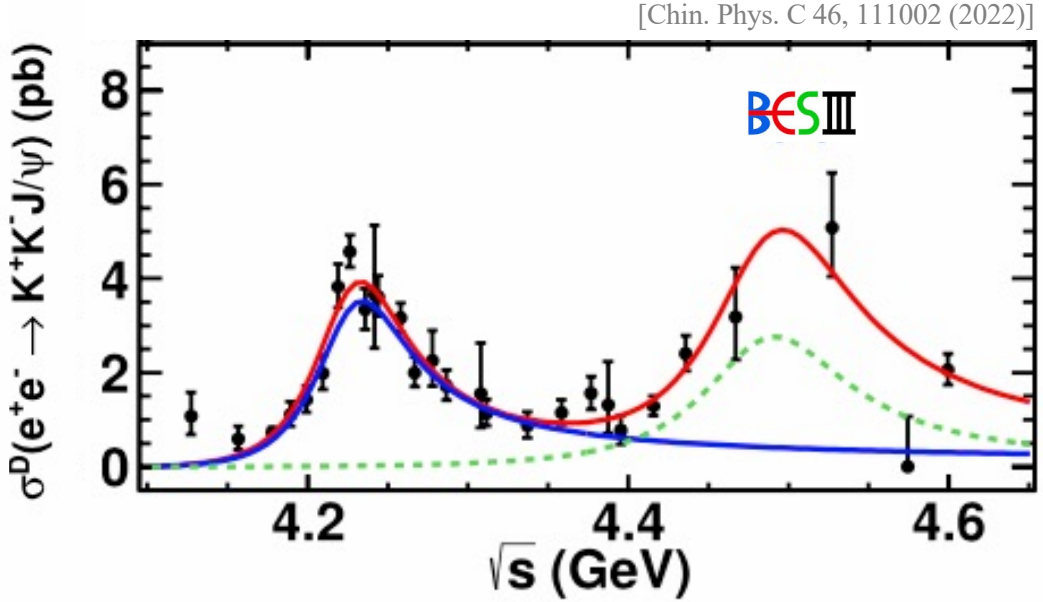
The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$, $\psi(2S)\pi\pi$ and $J/\psi K^+K^-$

- Data samples from 4.13 to 4.60 GeV (15.6 fb^{-1})
- Dressed cross-section measurement of
  $e^+e^- \rightarrow K^+K^- J/\psi$
- Y(4230) and Y(4500) observed (29σ / 8σ)
  - M = (4484.7 ± 13.3 ± 24.1) MeV/c^2
  - Γ = (77.0 ± 6.8 ±6.3) MeV

[PRD 97, 071101 (2018)]



[Chin. Phys. C 46, 111002 (2022)]

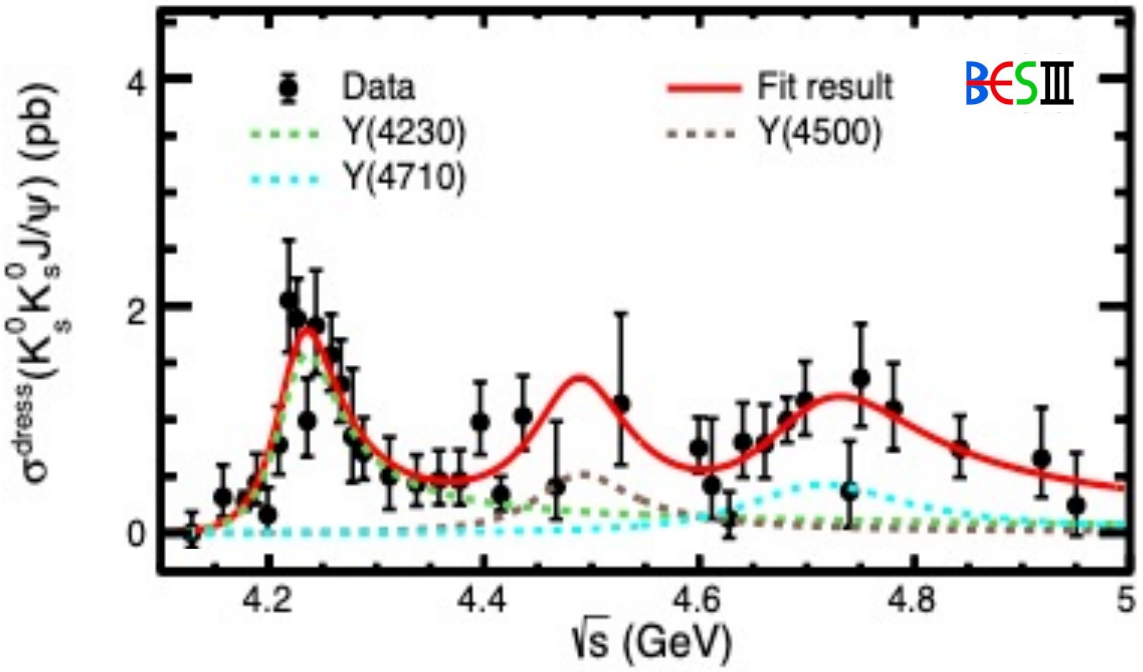


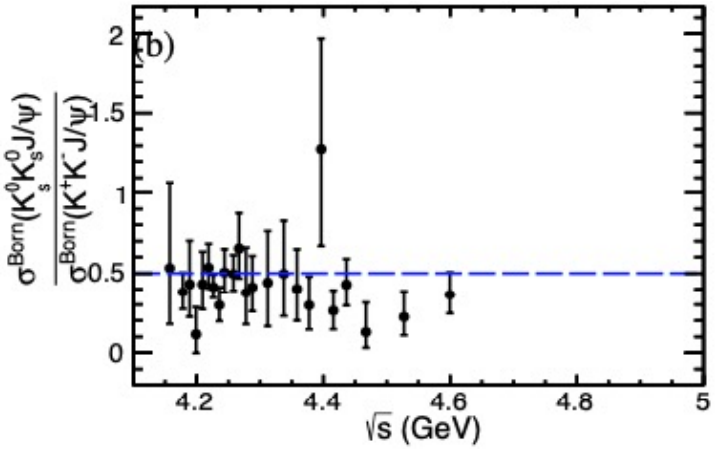
larger statistics, more data points & improved detection efficienices

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$, $\psi(2S)\pi\pi$ and $J/\psi K_s K_s$

- Data samples from 4.13 to 4.95 GeV (21.2 fb^{-1})
- Dressed cross-section measurement of $e^+e^- \to K_s^0 K_s^0\, J/\psi$

[Chin. Phys. C 46, 111002 (2022)]





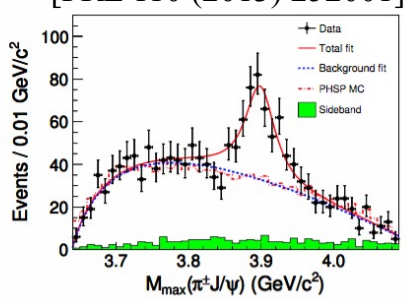
- Evidence for Y(4710) $\to K_s^0 K_s^0\, J/\psi$ (4.0σ)
  - $M = (4704.0 \pm 52.3 \pm 69.5)\ MeV/c^2$
  - $\Gamma = (183.2 \pm 114.0 \pm 96.1)\ MeV$
- Y(4230) $\to K_s^0 K_s^0\, J/\psi$ observed for the first time (26σ)

=> isospin violation effect at 1.9σ

The (charged) Zc states

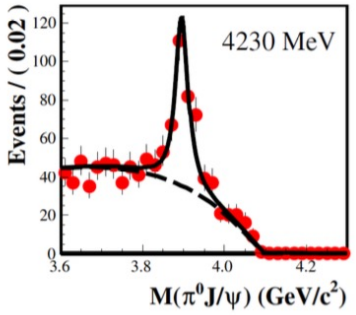
Two Z_c triplets established at BESIII

[PRL 110 (2013) 252001]



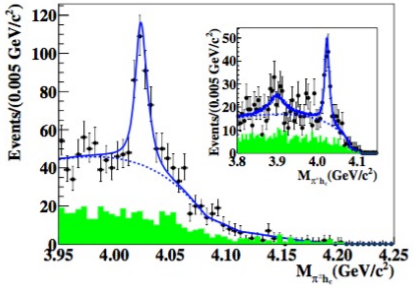
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]



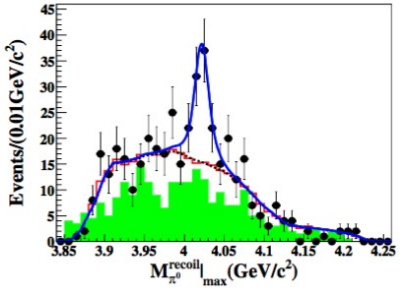
$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 111 (2013) 242002]



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

[PRL 113 (2014) 212002]



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

Charged **Neutral**

$Z_c(3900)^{\pm,0} \to J^P = 1^+$

Charged **Neutral**

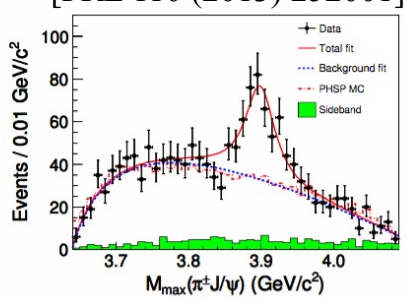
$Z_c(4020)^{\pm,0}$?

- Two isospin triplets of charmonium-like exotic states established

Two Z_c triplets established at BESIII

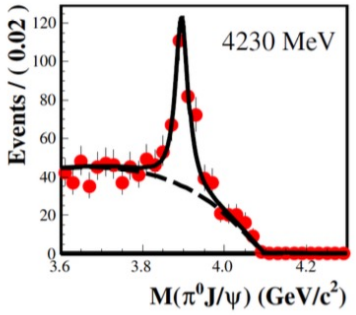
Hidden Charm

[PRL 110 (2013) 252001]



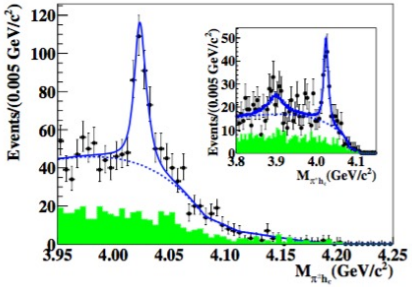
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]



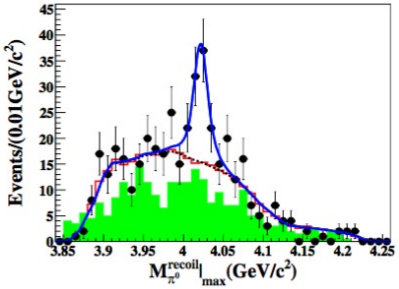
$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 111 (2013) 242002]



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

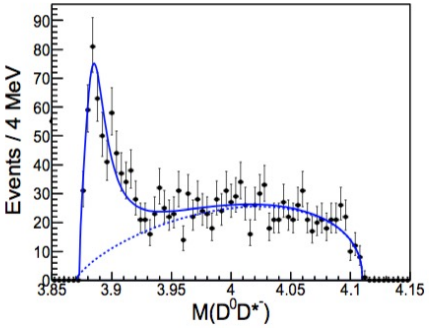
[PRL 113 (2014) 212002]



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

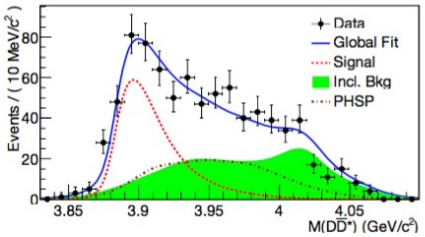
Open Charm

[PRL 112 (2014) 022001]

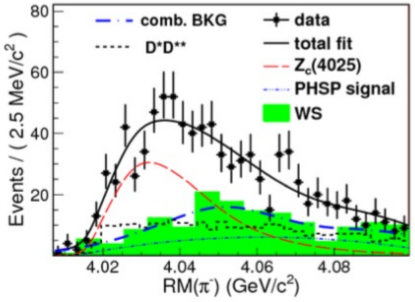


$e^+e^- \to \pi^-(D\bar{D}^*)^+$

[PRL 115 (2015) 222002]

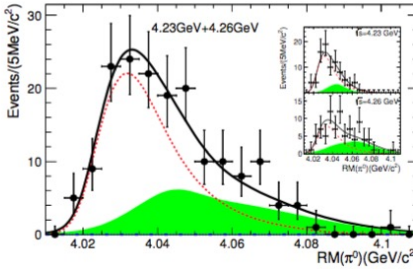


[PRL 112 (2013) 132001]



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

[PRL 115 (2015) 182002]



Charged Neutral

$Z_c(3900)^{\pm,0} \to J^P = 1^+$

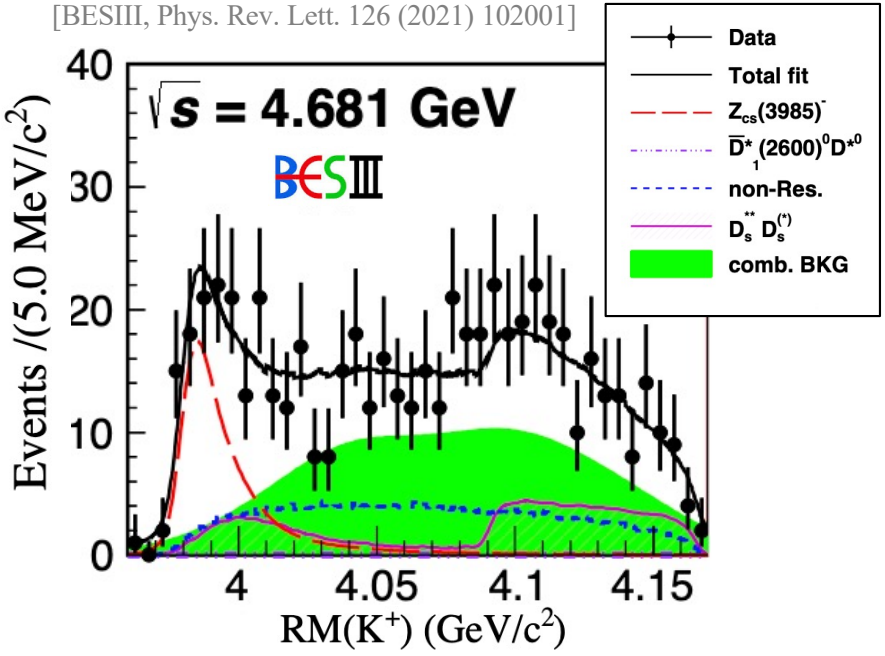
Charged Neutral

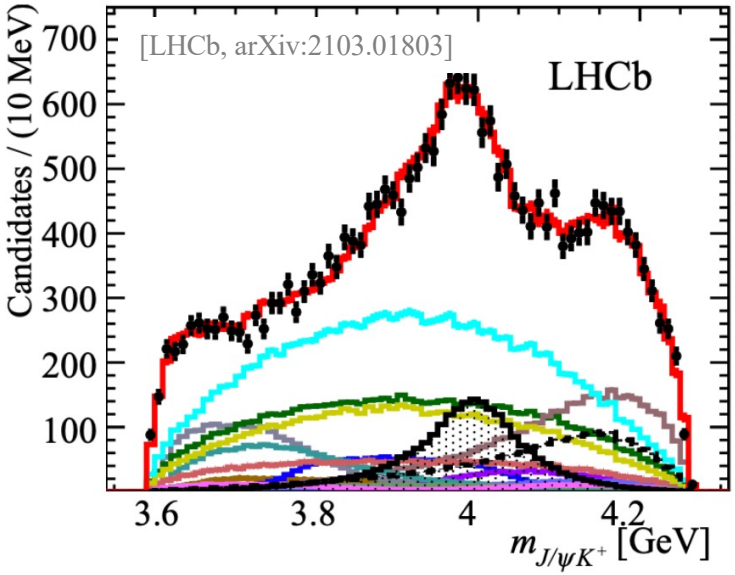
$Z_c(4020)^{\pm,0}$?

- Two isospin triplets of charmonium-like exotic states established
- Different decay modes *(hidden vs. open charm)* of same state observed?

First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



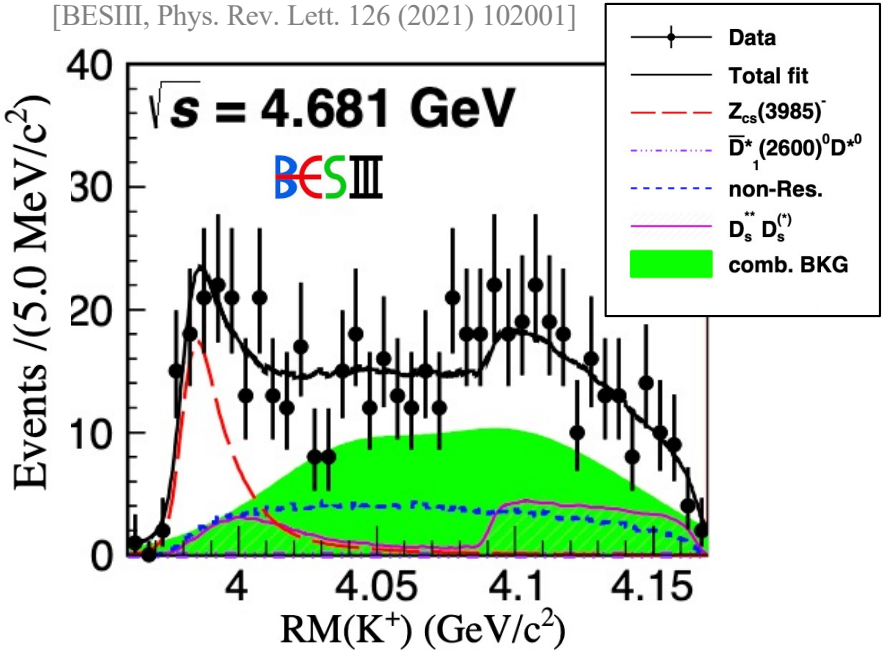


- Search for strange partner of $Z_c(3900)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^+(D_sD^*/D_s^*D)^-$
  - Narrow threshold enhancement (5.3σ)
  - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\mathrm{MeV}/c^2,$ $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\mathrm{MeV}$
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]
- LHCb reports a $Z_{cs}(4000)$ in $B \to \phi(J/\psi K^+)$
  - $M = (4000.3 \pm 6^{+4}_{-14})\mathrm{MeV}/c^2,$ $\Gamma = (131 \pm 15 \pm 26)\mathrm{MeV}$
  - $J^P = 1^+$, hidden charm final state
  - 10x broader …

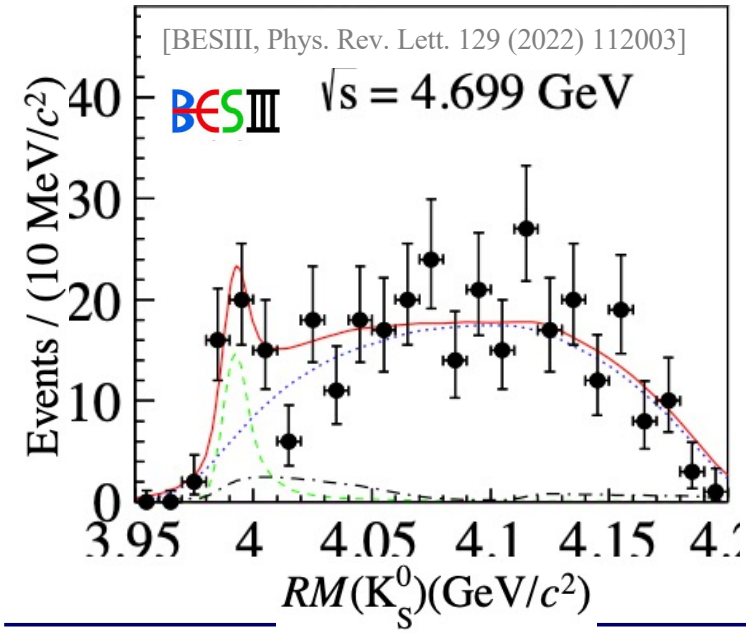
=> Same state observed in different decays (open/hidden charm) at two experiments?

First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



[BESIII, Phys. Rev. Lett. 129 (2022) 112003]

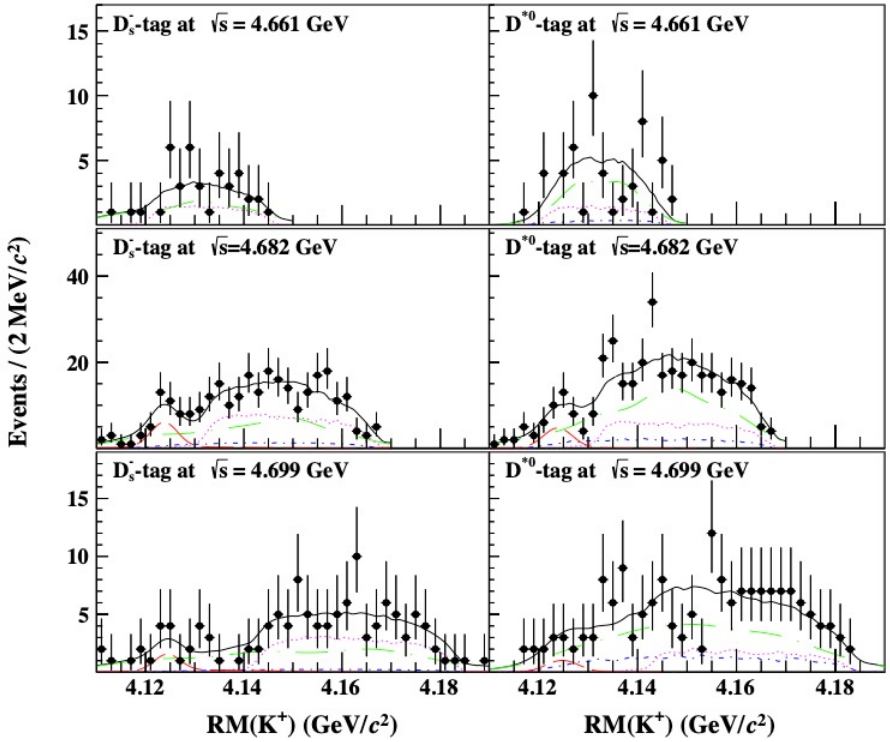


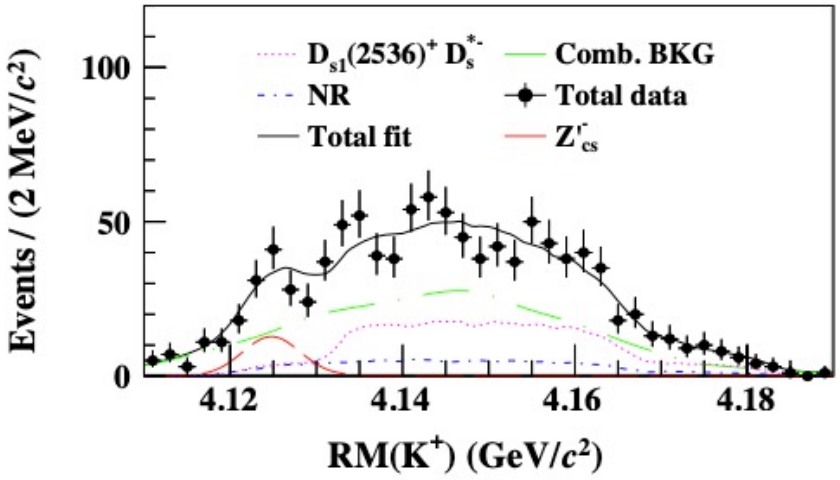
- Search for strange partner of $Z_c(3900)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^+(D_sD^*/D_s^*D)^-$
  - Narrow threshold enhancement (5.3σ)
  - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\mathrm{MeV}/c^2,$
    $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\mathrm{MeV}$
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]
- Search for neutral partner of $Z_{cs}(3985)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^0_S(D_s^+D^{*-} + D_s^{*+}D^-)$
  - Narrow threshold enhancement (4.6σ)
  - $M = (3992.2 \pm 1.7 \pm 1.6)\ \mathrm{MeV}/c^2$
    $\Gamma = (7.7^{+4.1}_{-3.8} \pm 4.3)\ \mathrm{MeV}$

=> Seem to be isospinpartners

The charged Z_{cs}'

[Chin. Phys. C 47, 033001 (2023)]





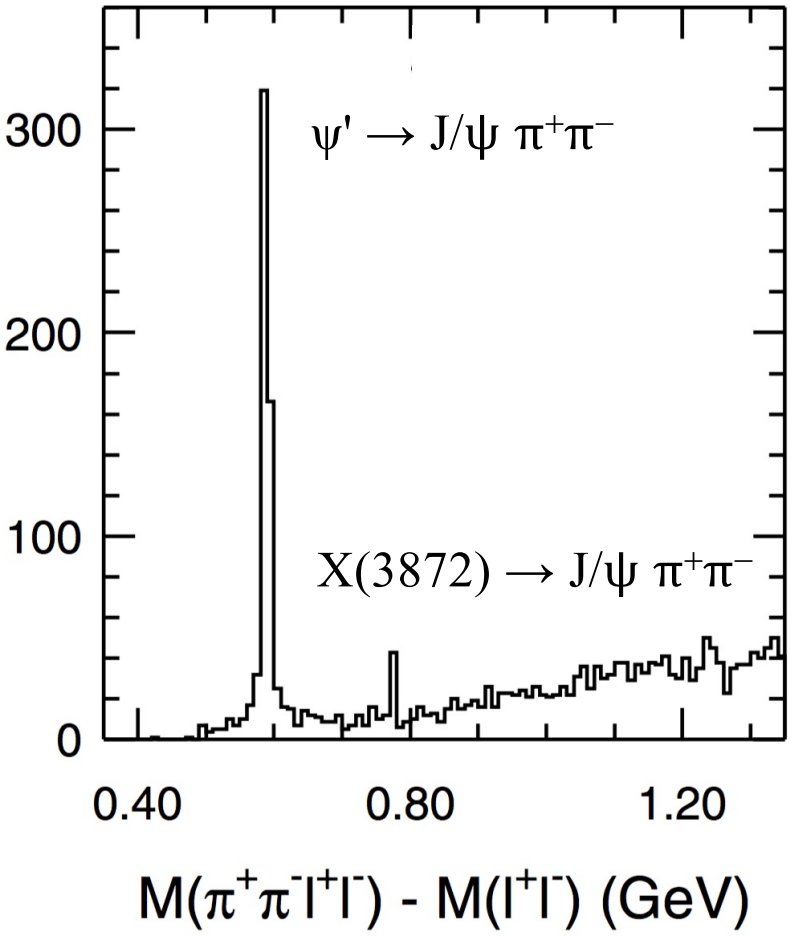
- Search for excited partner of $Z_{cs}(3985)$
  - 3 different data samples at $\sqrt{s}$ = 4.661, 4.682 and 4.699 GeV (2.7 fb^{-1})
  - $e^+e^- \to K^+ D_s^{*-} D^{*0} + c.c.$
  - two different tag-methods (D_s^--/D^{*0}-tags)
- Evidence for a Z_{cs}' state
  - $M = (4123.5 \pm 0.7) MeV/c^2$
  - 2.1σ significance (3.9σ \wo systematics)
- Statistics limited, test of decay width hypotheses, local statistical 4.1σ for: $(M_0, \Gamma_0) = (4124.1 MeV/c^2, 10 MeV)$
- Upper Limits (CL90) provided: on σ_{Born} x BR: $\mathcal{O}(1)$ pb
  - UL on σ_{Born} x BR: : $\mathcal{O}(1)$ pb
  - at each $\sqrt{s}$ = 4.661, 4.682 and 4.699

=> More data will be taken

The X(3872)
and further X states

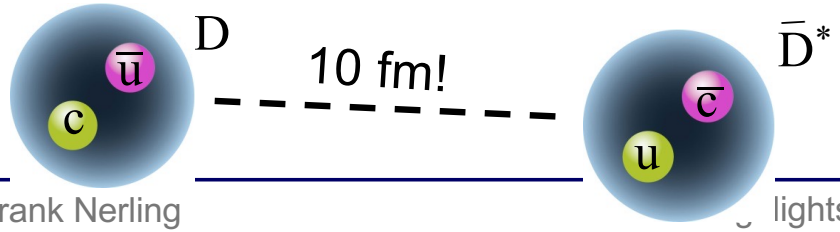
Experimental review of the X(3872)

[Belle Collab., PRL 91 (2003) 262001]



- First observed by Belle in 2003
  - $X(3872) \to J/\psi\pi^+\pi^-$
  - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
  - $X(3872) \to D^0\bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$
  $= (-0.07 \pm 0.12)\ \text{MeV}/c^2$ (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.13$ MeV (2020, LHCb)

Analogy to deuteron:



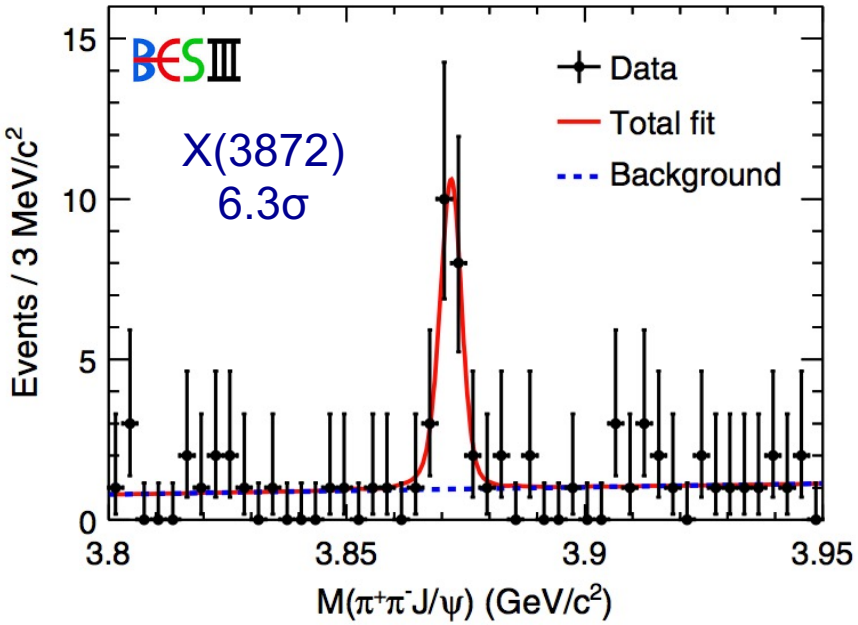
For clarification:
=> Precision measurement with sub-MeV resolution needed!

First observation of $e^+e^- \to \gamma X(3872)$

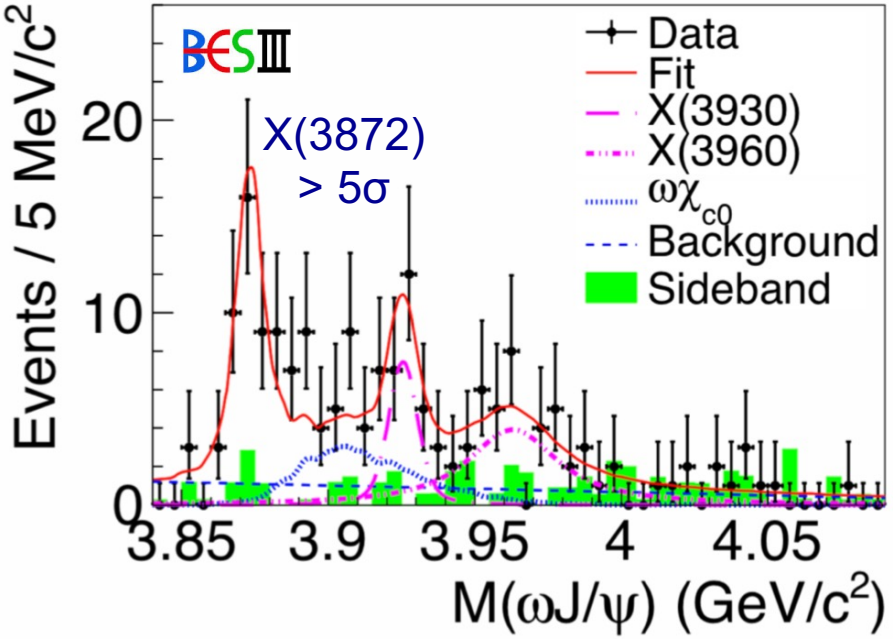
BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

First observation of $e^+e^- \to \gamma X(3872) \to \gamma\omega J/\psi$

[Phys. Rev. Lett. 112 (2014) 092001]



[Phys. Rev. Lett., 122 (2019) 232002]



- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

- Fit with three Breit-Wigner resonances
  => Evidence for two more structures

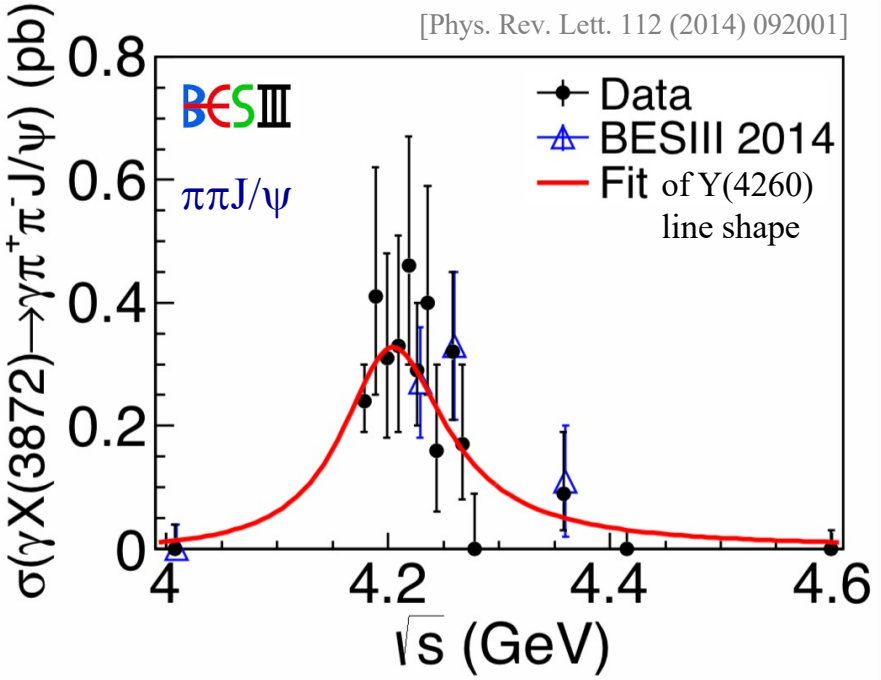
First observation of $e^+e^- \to \gamma X(3872)$

BESIII: First observation of $e^+e^- \to Y(4260) \to \gamma X(3872) \to \gamma\omega J/\psi$

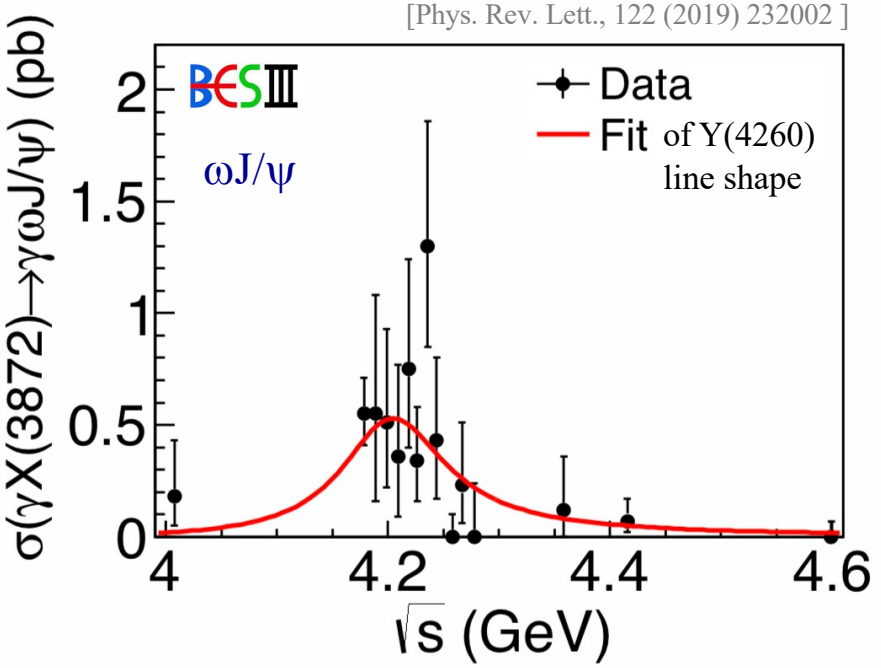
First observation of $e^+e^- \to Y(4260) \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

cross section

[Phys. Rev. Lett. 112 (2014) 092001]



[Phys. Rev. Lett., 122 (2019) 232002]

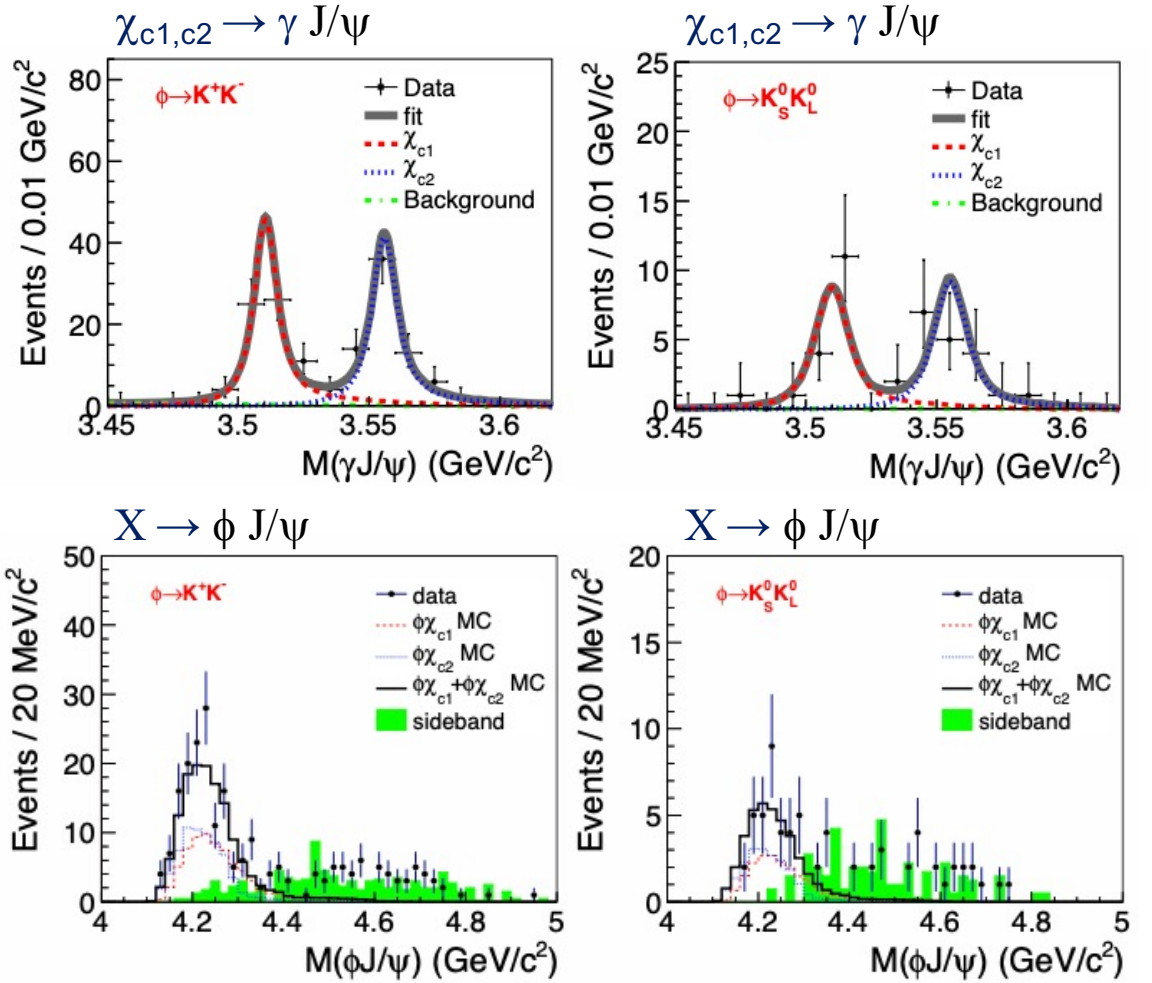


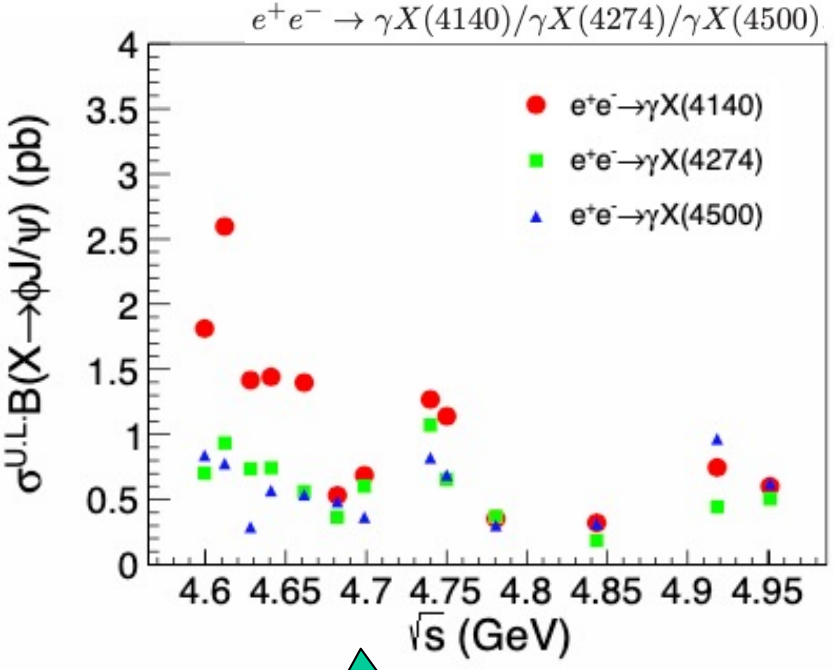
- $m = (4200.6^{+7.9}_{-13.3} \pm 3.0)\ \mathrm{MeV}/c^2$
- $\Gamma = (115^{+38}_{-26} \pm 12)\ \mathrm{MeV}/c^2$

- Shape consistent with production via a Y(4260) state

[Subm. to Phys. Rev. Lett., arXiv:1903.04695 [hep-ex]]

Study of $e^+e^- \to \gamma \phi J/\psi$





- No evidence for X(4140), X(4274), X(4500)
- CL90 Upper Limits provided, see plot

[arXiv: 2210.13058, JHEP01(2023)132]

Summary and Prospectives

- BESIII successfully operating since 2008
  - World largest data sets in tau-charm mass region, unique XYZ data
  - Recent machine upgrade extends studies up to E_{cms} = ~4.9 GeV

- BESIII successfully operating since 2008
  - Supernumerary vector Y states consistently resolved (statistics)
    - *Y(4260) and Y(4360) → Y(4230), Y(4360)*
    - *First decays to open charm, further new decay modes to $c\bar{c}$ and/or light hadrons investigated*
    - *More candidates reported, especially Y(4500), Y(4710), and Y(4660)*
  - Charged Z_c states are manifestly exotic states
    - *First complete isospin triplets established*
    - *First strange partner(s) reported, isospin triplet $Z_{cs}(3895)$*
  - The first of these states discovered, the X(3872) still not understood
    - *Line shape to be measured precisely*
    - *X(4140,), X(4274), X(4500) → $\phi J/\psi$ not seen*

- Next machine upgrade planned (summer 2024) => E_{cms} > 5GeV

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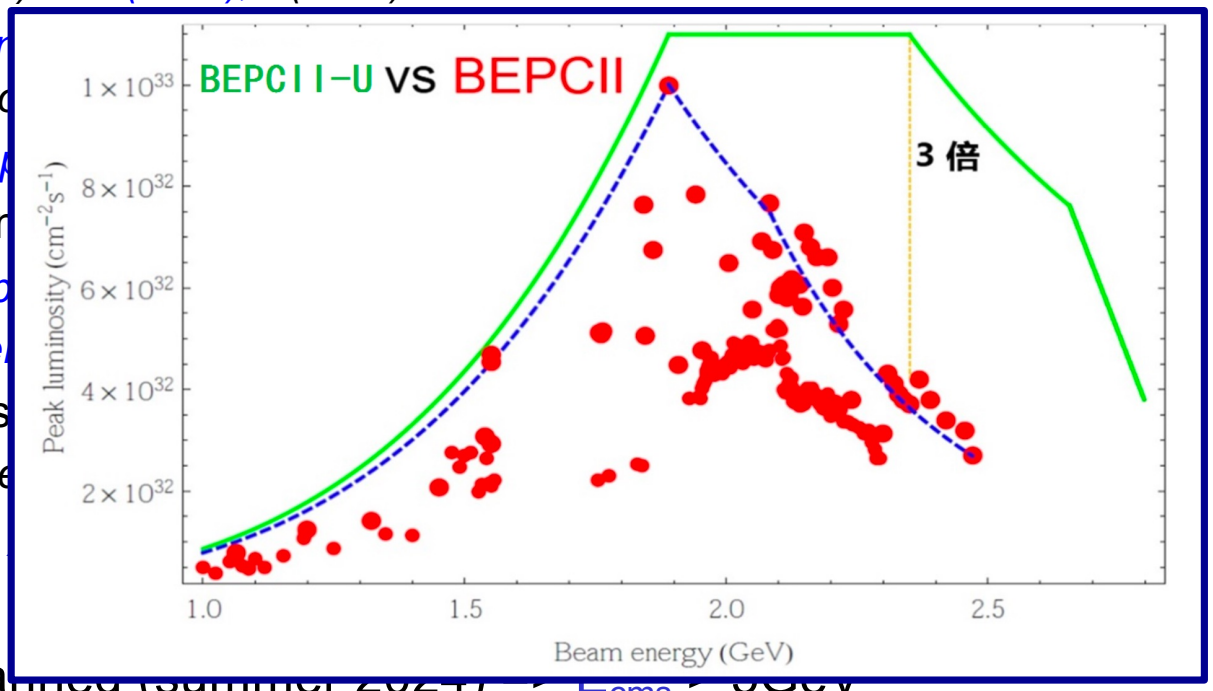
Thank you!



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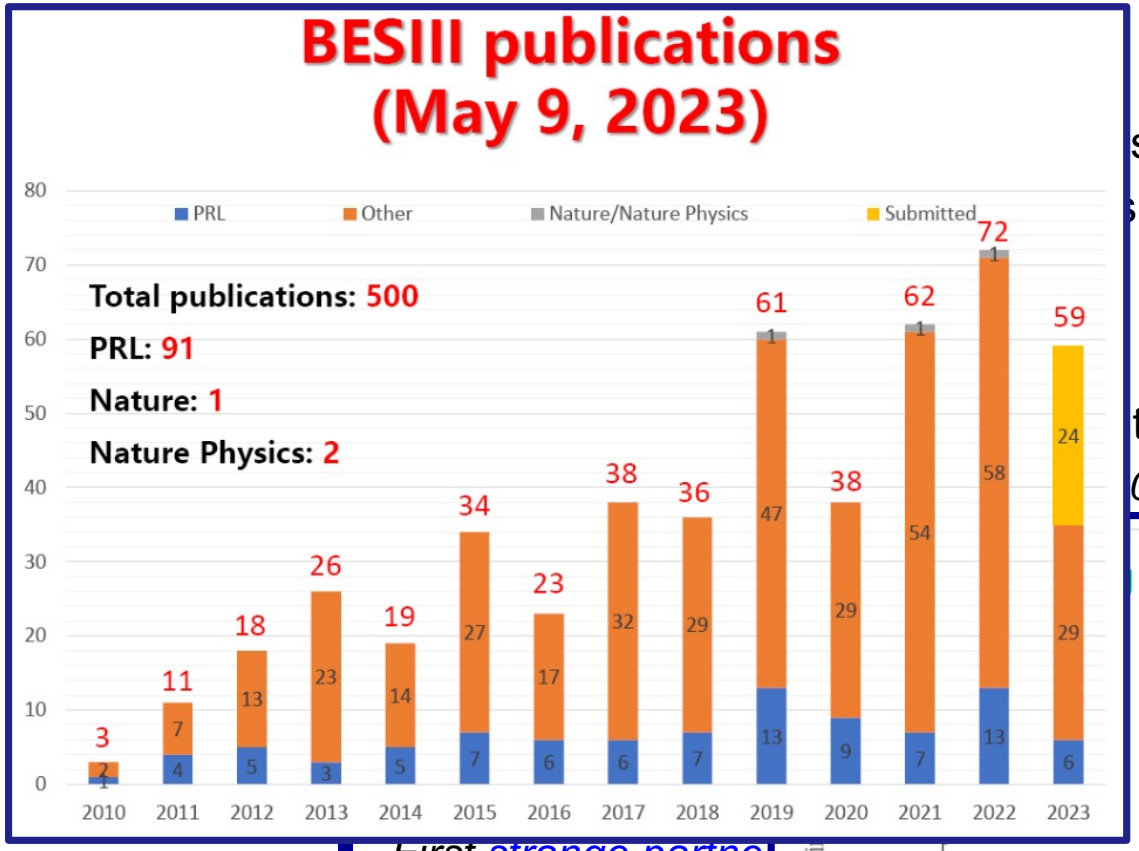
Summary and Prospectives



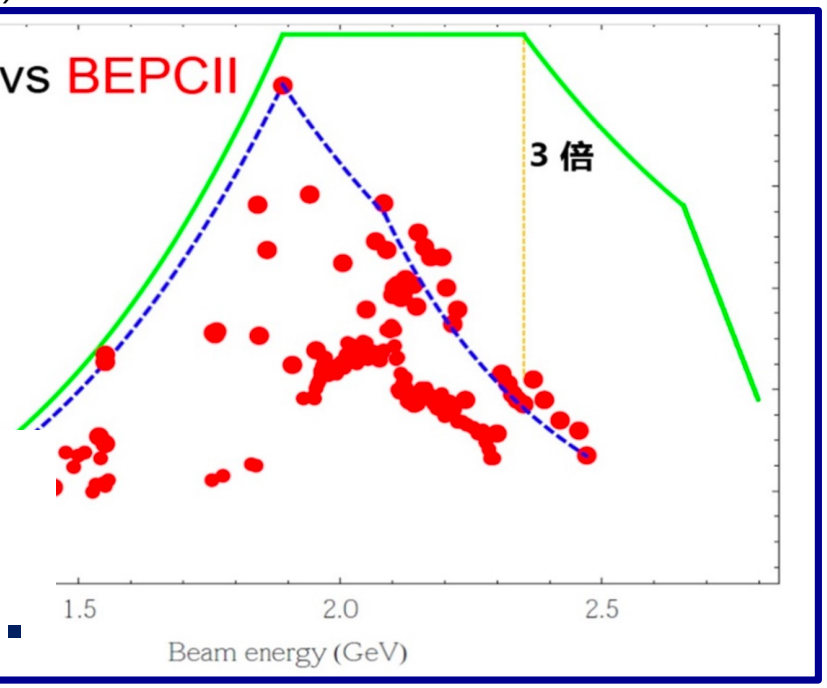
s region, unique XYZ data

s up to E_{cms} = ~4.9 GeV

tly resolved (sta

0)

Thank you!



- *First strange partner*

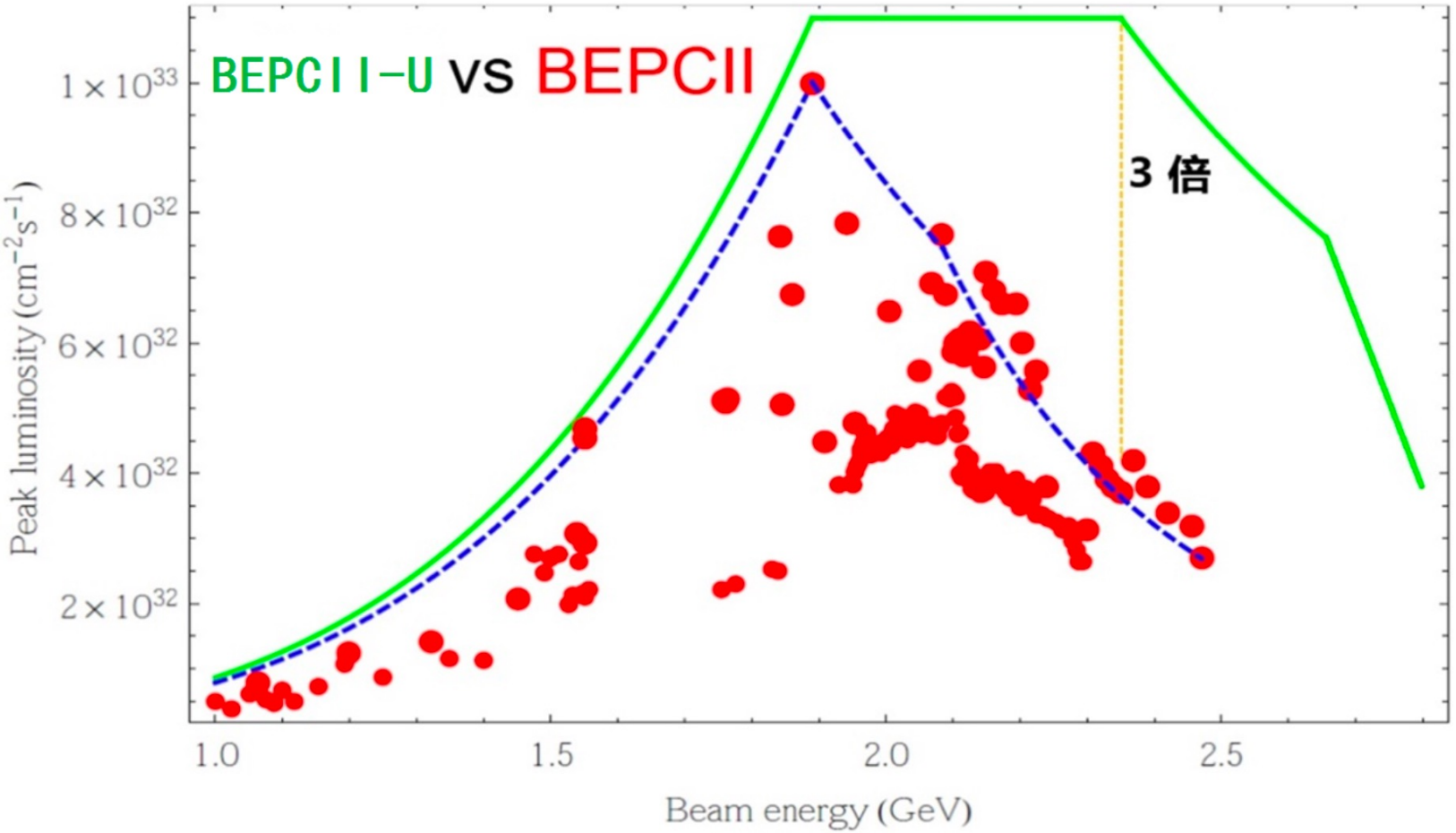
The first of these states

4×10^{32}

Data for our next 500 publications ...

- Next machine upgrade planned (summer 2024) => E_{cms} > 5GeV

BEPCII Upgrade
(higher luminosity at higher energies)

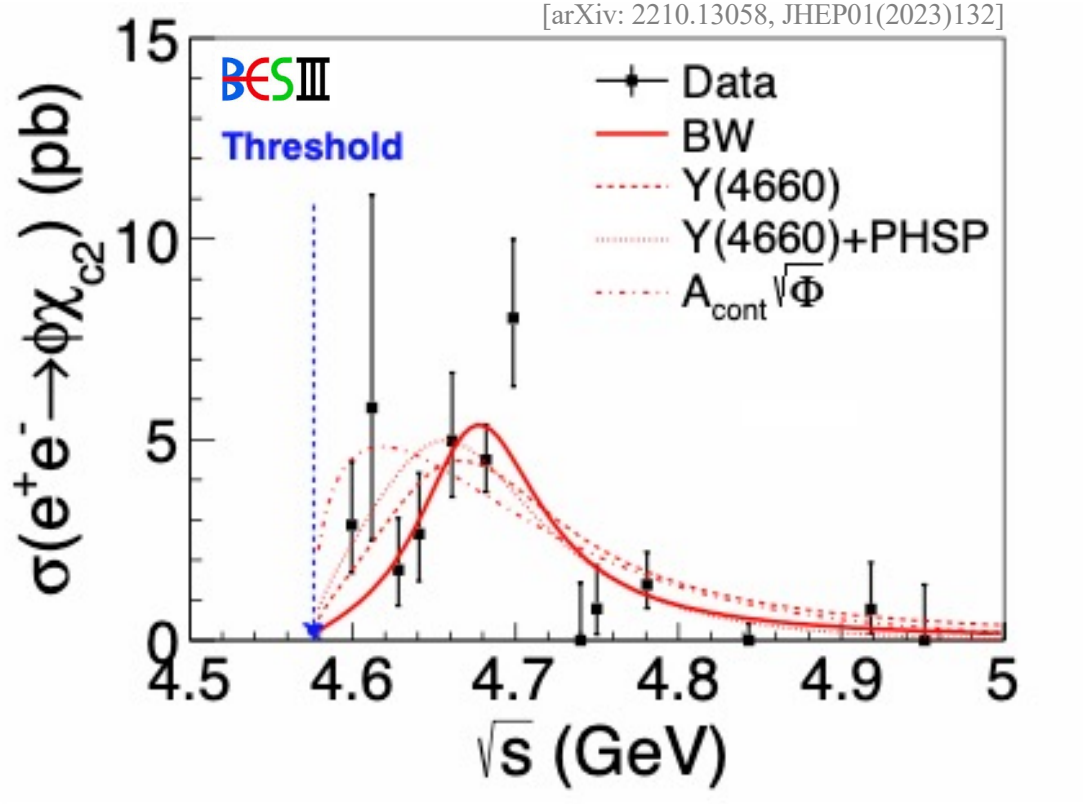


- Machine upgrade: 2 new cavities (RF), higher currents
- Higher luminosities at higher energies, e.g. factor ~3 at 2.3 GeV
- After shutdown collect more XYZ data at 4.6 – 5.5 GeV

Study of $e^+e^- \to \gamma\,\phi\,J/\psi$

$e^+e^- \to \gamma\,\phi\,\chi_{c2}$

[arXiv: 2210.13058, JHEP01(2023)132]



- Cross section measurement:

  $e^+e^- \to \phi\chi_{c2}$

- Evidence for Y(4660) $\to \phi\chi_{c2}$
- Statistical significance of 3.1σ
- No signal for Y(4660) $\to \phi\chi_{c1}$

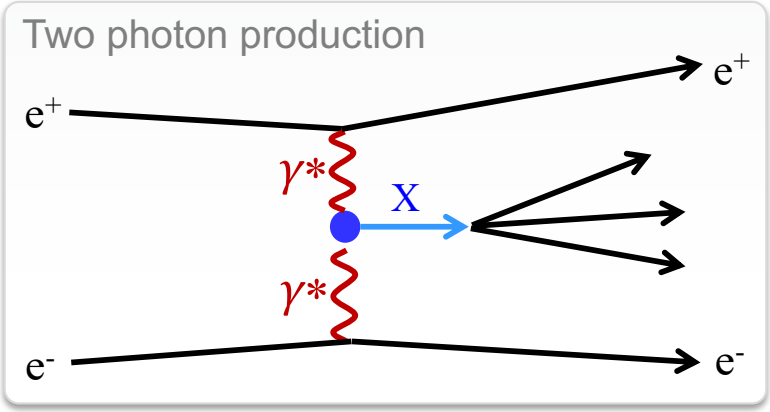
- Different fit models:
  - Single BW model (red line)

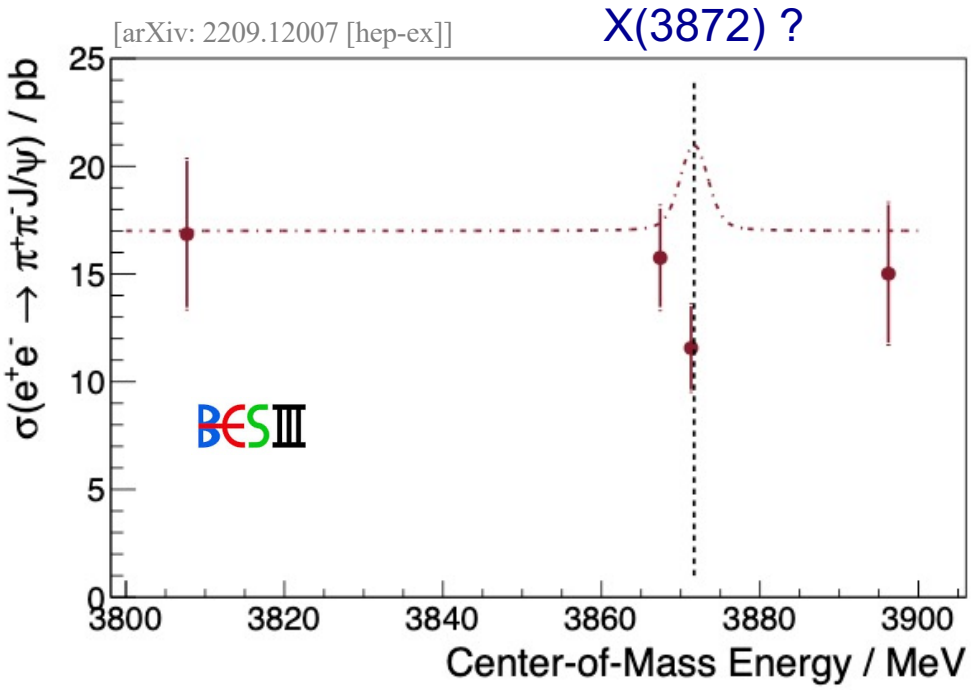
$$M = (4672.8 \pm 10.8 \pm 3.9)\ \mathrm{MeV}/c^2$$
$$\Gamma = (93.2 \pm 19.8 \pm 9.4)\ \mathrm{MeV}$$

New production processes of X(3872)

Production mechanisms

- B meson decays *(discovery by Belle, 2003)*
- Radiative transitions *(e.g. from Y(4230), BESIII)*
- Prompt production *(e.g. pp collisions, e.g .CMS)*
- Two-photon fusion *(evidence by Belle, 2021)*





Two-photon fusion at BESIII

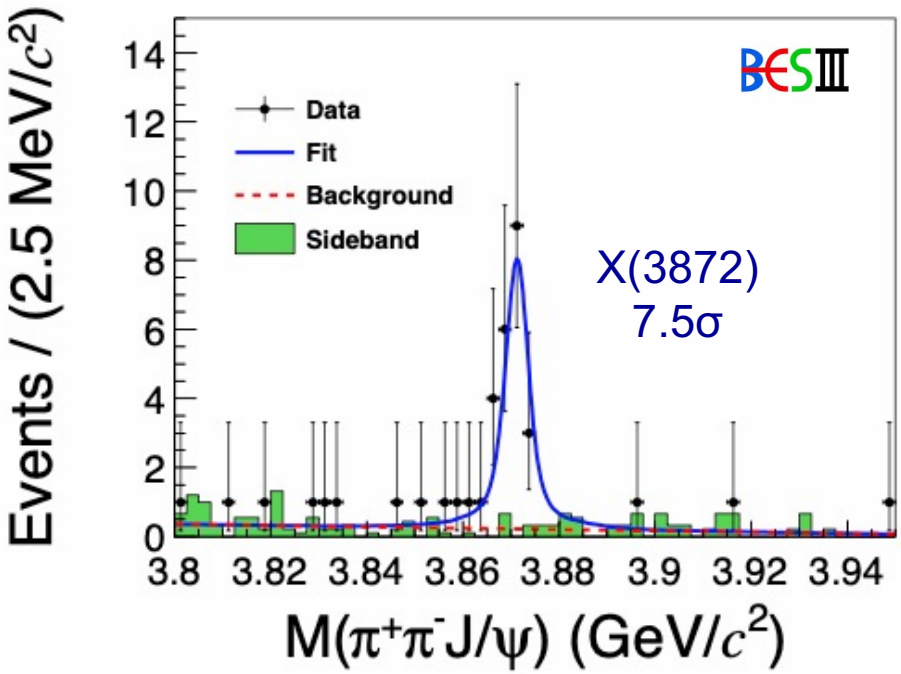
- VMD prediction: $\Gamma_{ee} \gtrsim 0.036$ eV
  [A.Denig et al. PLB 736 (2014) 221]
- After observation (5.1σ) of $e^+e^- \to \chi_{c1}$
  [BESIII, PRL 129 (2022) 122001]
- Search for $e^+e^- \to X(3872)$
  - No enhancment observed in cross section
  - Provide UL(CL90) assuming average value: $\Gamma_{\rm tot} = 1.19\,\text{MeV}$

$$\Rightarrow \quad \Gamma_{ee} \times \mathcal{B} < 7.5 \times 10^{-3}\ \text{eV}$$
$$\Gamma_{ee}(\text{X}(3872)) < 0.32\ \text{eV}$$

Observation of $e^+e^- \to \omega X(3872)$

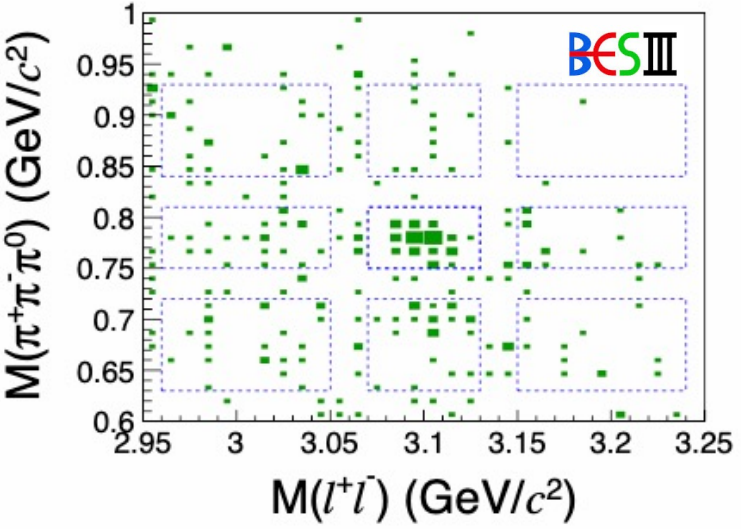
- 9 data samples from 4.66 to 4.95 GeV (4.7 fb^{-1})
- First observation of this production process
  → *just above threshold*

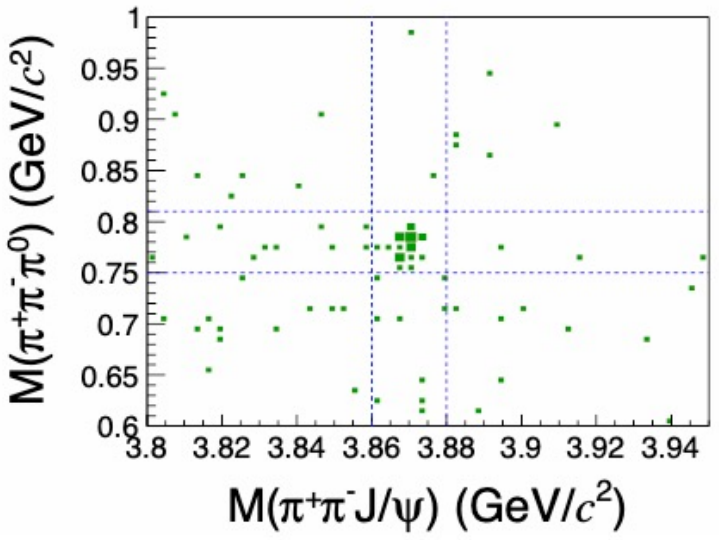
[arXiv:2212.07291 [hep-ex]]



- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

J/ψ and ω signal & sideband regions

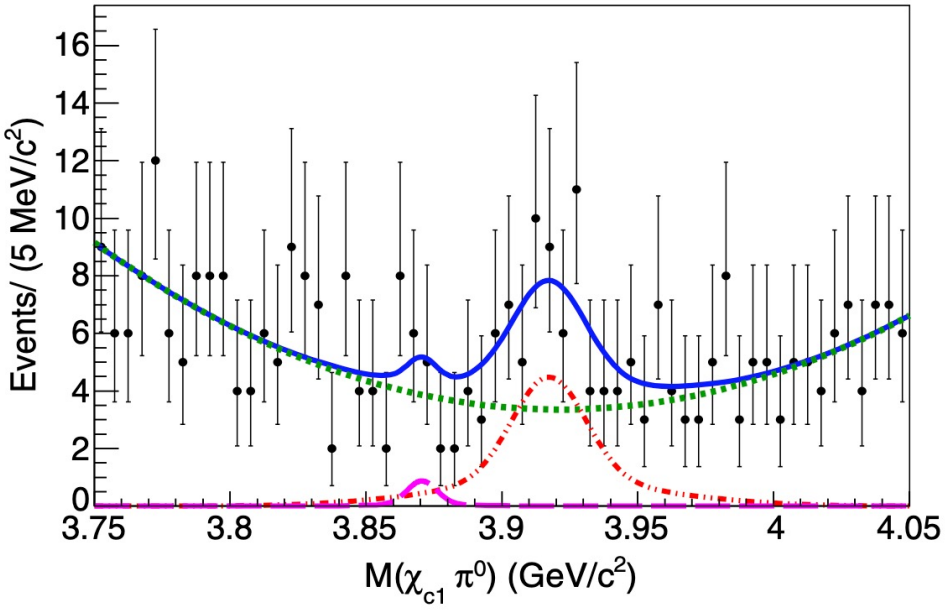




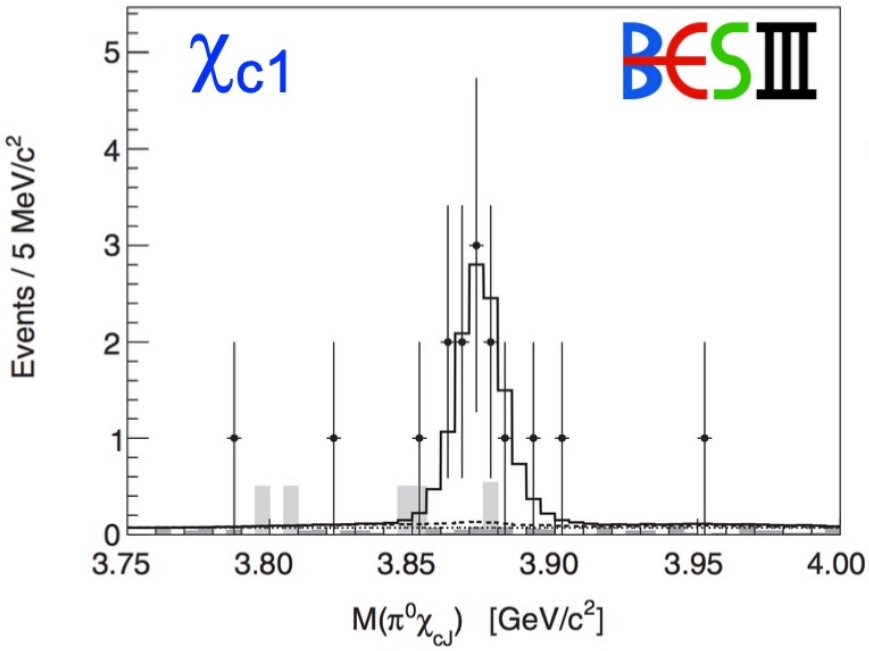
X(3872) and ω signal regions

First observation of $X(3872) \to \chi_{c1}\pi^0$

[Belle, Phys. Rev. D 99 111101 (2019)]



[BESIII, Phys. Rev. Lett., 122 (2019) 202001]



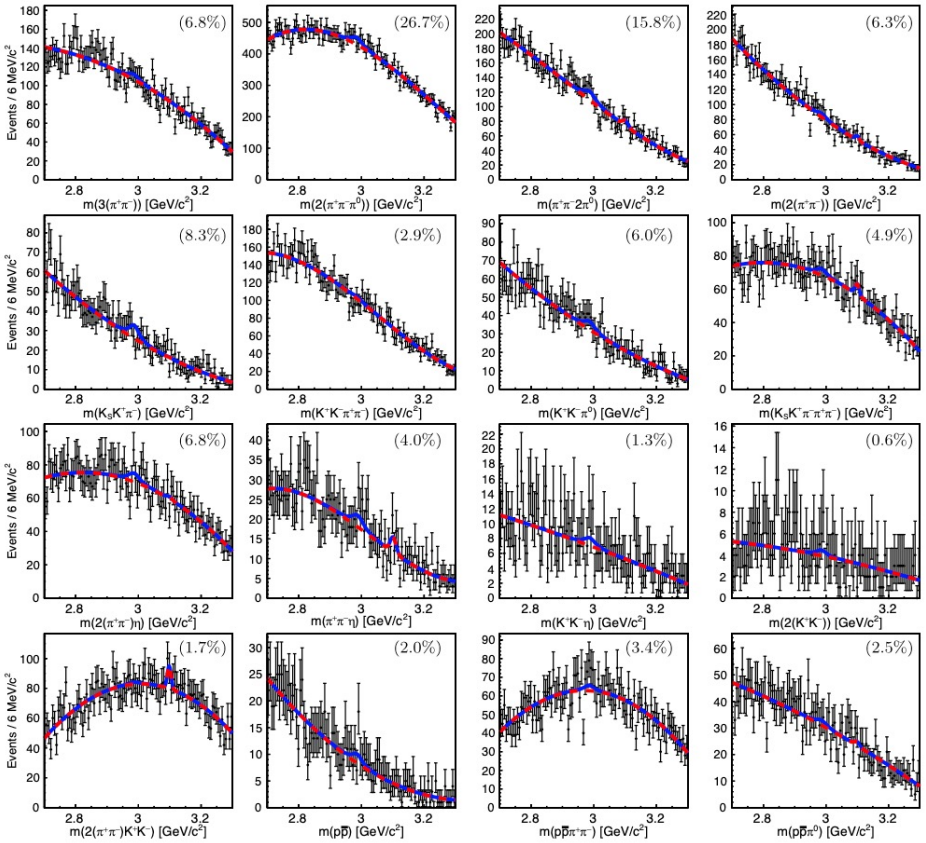
- No significant signals were found by Belle in search for X(3872) and X(3915) to $\chi_{c0}\,\pi^0$ (0.3σ / 2.3σ)
  - $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.)
- BESIII observes now X(3872) decay to $\chi_{c0}\,\pi^0$ (> 5σ)
  - $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 0.88^{+0.33}_{-0.27} \pm 0.10$

Isospin violation, comparable decay rate to J/ψρ

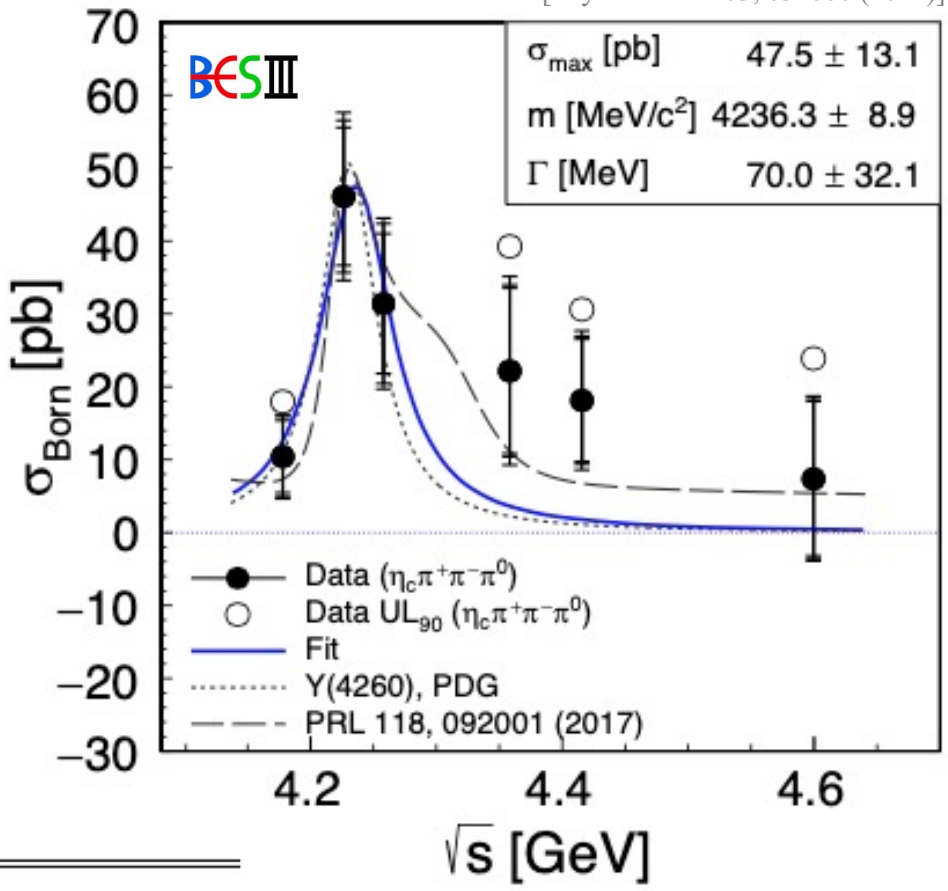
=> Disfavours $\chi_{c1}(2P)$

Further decays of Y(4260)

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



[Phys. Rev. D 103, 032006 (2021)]



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

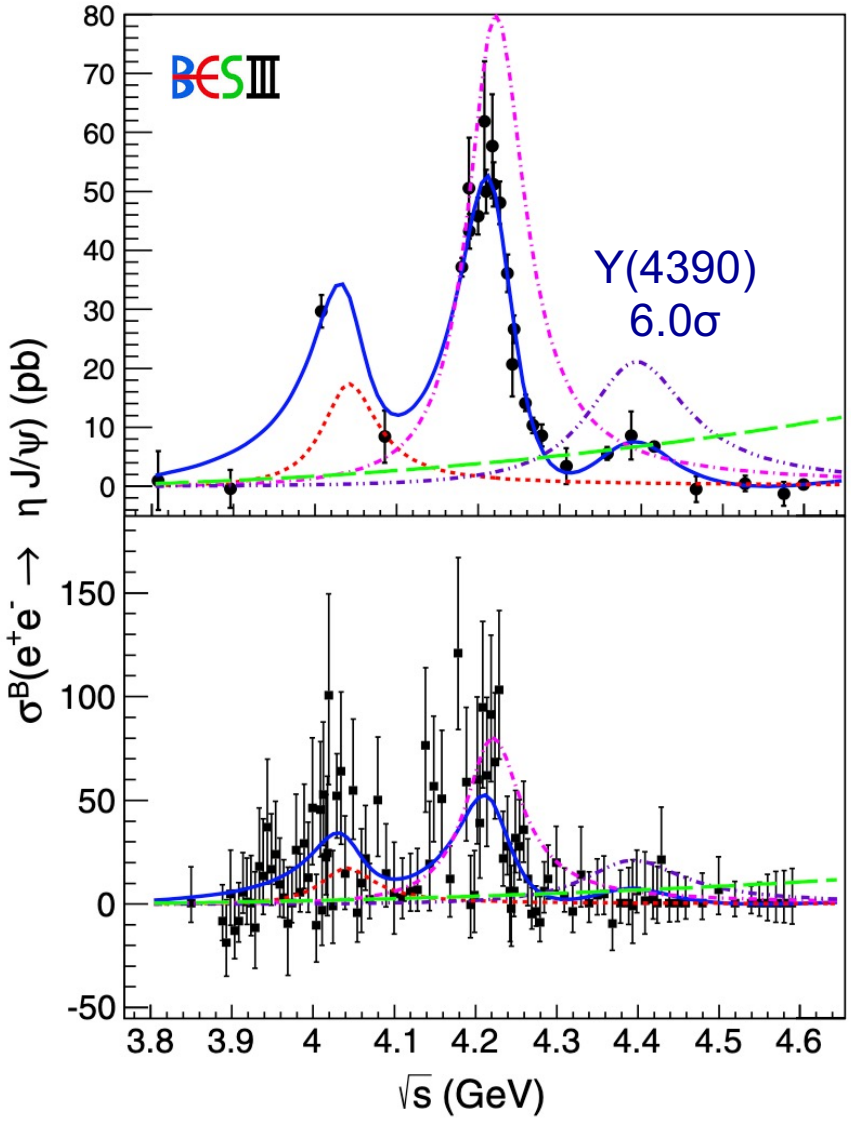
$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N_{obs}	κ	f_{VP}	$\sum \varepsilon_i\mathcal{B}_i$ [%]	σ_{Born} [pb]	UL$_{90}$ [pb]	$\mathcal{S}_{stat}/\mathcal{S}_{tot}$ [σ]
4.1780	3189.0	530 ± 246	[0.720, 0.734]	1.056	2.0	$10.4^{+5.0}_{-4.9} \pm 2.9$	17.9	2.2/1.9
4.2263	1091.7	786 ± 159	[0.716, 0.731]	1.056	2.0	$46.1^{+9.5}_{-9.4} \pm 6.6$	61.0	5.1/4.6
4.2580	825.7	465 ± 134	[0.786, 0.824]	1.054	2.0	$31.4^{+9.6}_{-9.6} \pm 6.7$	46.6	3.5/3.2
4.3583	539.8	242 ± 115	[0.802, 0.880]	1.051	2.1	$22.2^{+11.4}_{-11.3} \pm 6.2$	39.2	2.2/1.9
4.4156	1073.6	379 ± 165	[0.780, 0.850]	1.053	2.2	$18.1^{+8.4}_{-8.4} \pm 4.5$	30.6	2.3/2.1
4.5995	566.9	79 ± 102	[0.763, 0.807]	1.055	2.0	$7.4^{+10.6}_{-10.5} \pm 3.9$	23.9	0.8/0.7

=> Clear evidence for
Y(4230) $\to \eta_c \pi^+\pi^-\pi^0$

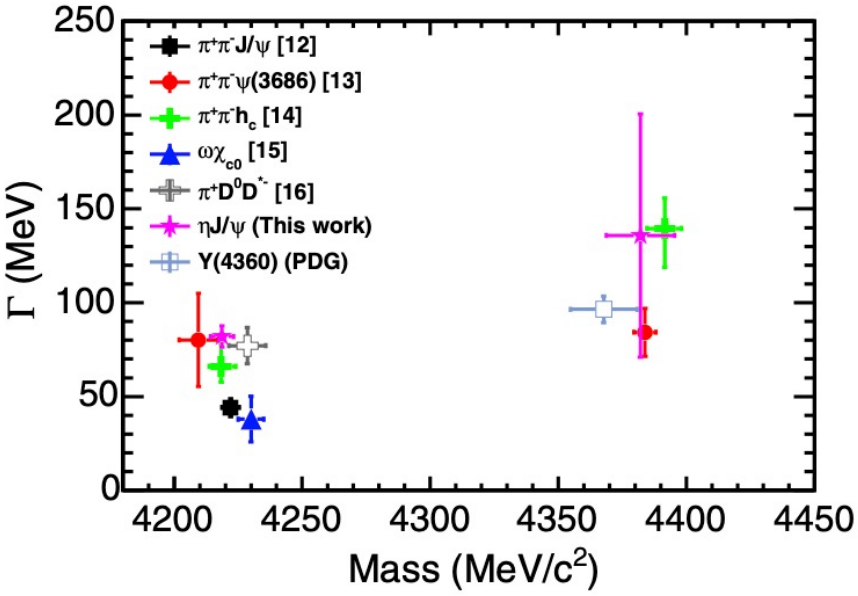
Further decays of Y(4260)

$e^+e^- \to J/\psi\,\eta$

[Phys. Rev. D 102, 031101 (2020)]



- Simultaneous maximum-likelihood fit
  (*Top: High stat. XYZ data, Bottom: Scan data)*
- $\psi(4040)$ assumed, Y(4220), Y(4390) ?
- Significance of Y(4390) = 6.0 σ
- Y(4220) & Y(4390) mass and width compilation vs. Y(4360) from PDG:



"Y(4260)" in different decay channels

$c\bar{c}$ MESONS > $\psi(4230)$ > $\psi(4230)$ MASS

$\psi(4230)$ MASS

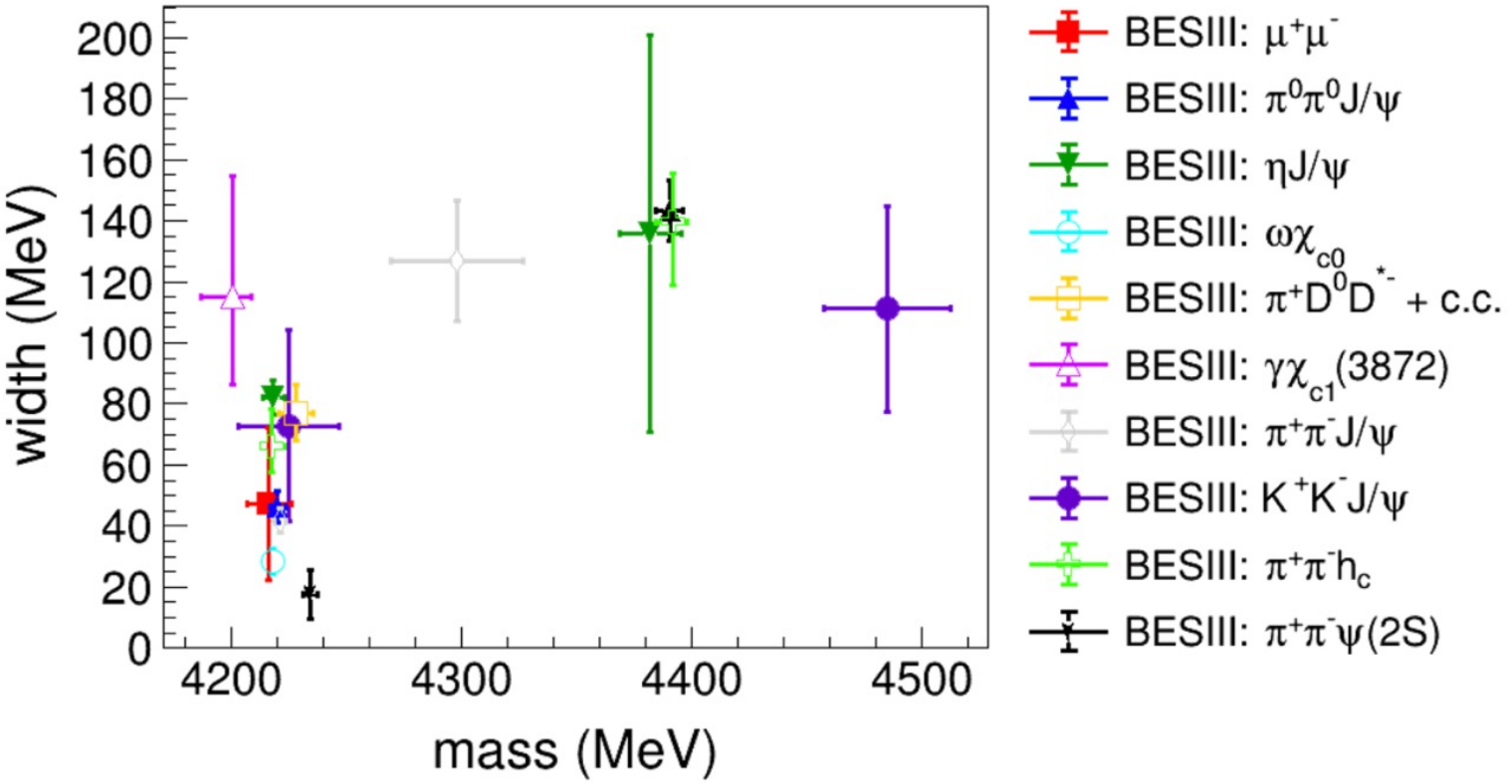
INSPIRE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4222.7 ± 2.6	**OUR AVERAGE**	Error includes scale factor of 1.7. See the ideogram below.			
$4234.4 \pm 3.2 \pm 0.2$		[1] ABLIKIM	2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4216.7 \pm 8.9 \pm 4.1$		[2] ABLIKIM	2020AG	BES3	$e^+ e^- \to \mu^+\mu^-$
$4220.4 \pm 2.4 \pm 2.3$		[3] ABLIKIM	2020N	BES3	$e^+ e^- \to \pi^0\pi^0 J/\psi$
$4218.6 \pm 3.8 \pm 2.5$		[3] ABLIKIM	2020O	BES3	$e^+ e^- \to \eta J/\psi$
$4218.5 \pm 1.6 \pm 4.0$		[4] ABLIKIM	2019AI	BES3	$e^+ e^- \to \omega\chi_{c0}$
$4228.6 \pm 4.1 \pm 6.3$		ABLIKIM	2019R	BES3	$e^+ e^- \to \pi^+ D^0 D^{*-}$ + c.c.
$4200.6\ ^{+7.9}_{-13.3} \pm 3.0$		[5] ABLIKIM	2019V	BES3	$e^+ e^- \to \gamma\chi_{c1}(3872)$
$4222.0 \pm 3.1 \pm 1.4$		[6] ABLIKIM	2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
$4218\ ^{+5.5}_{-4.5} \pm 0.9$		ABLIKIM	2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$

PDG calls the narrow structure meanwhile $\psi(4230)$ — seen in many different decay modes, mainly charmonium + light meson(s)

Vector states: Hidden-charm production

- different channels show (slightly) different masses and widths



- coupled channel studies are needed!

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