

Recent results on spectroscopy of XYZ states from BESIII

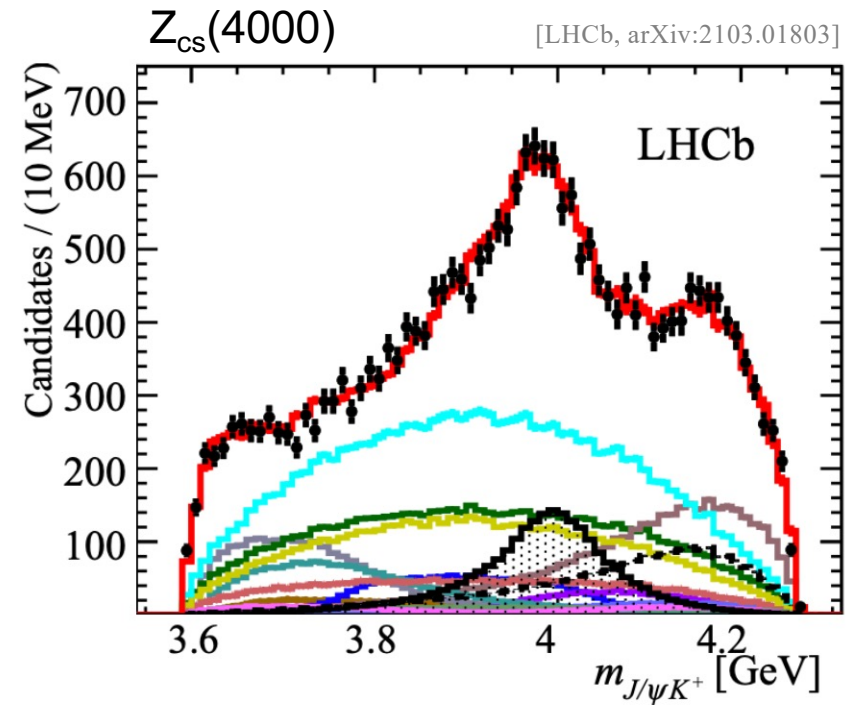
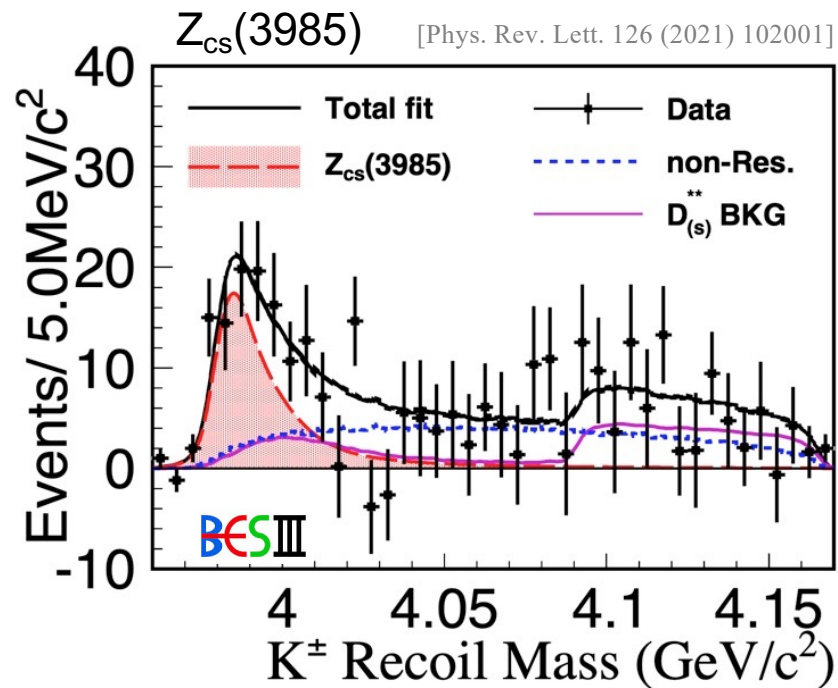
Frank Nerling
HFHF, GSI & GU Frankfurt

17th Intern. Workshop on Meson Physics – MESON2023,
June 22nd - June 27th 2023, KRAKÓW, Poland

Outline

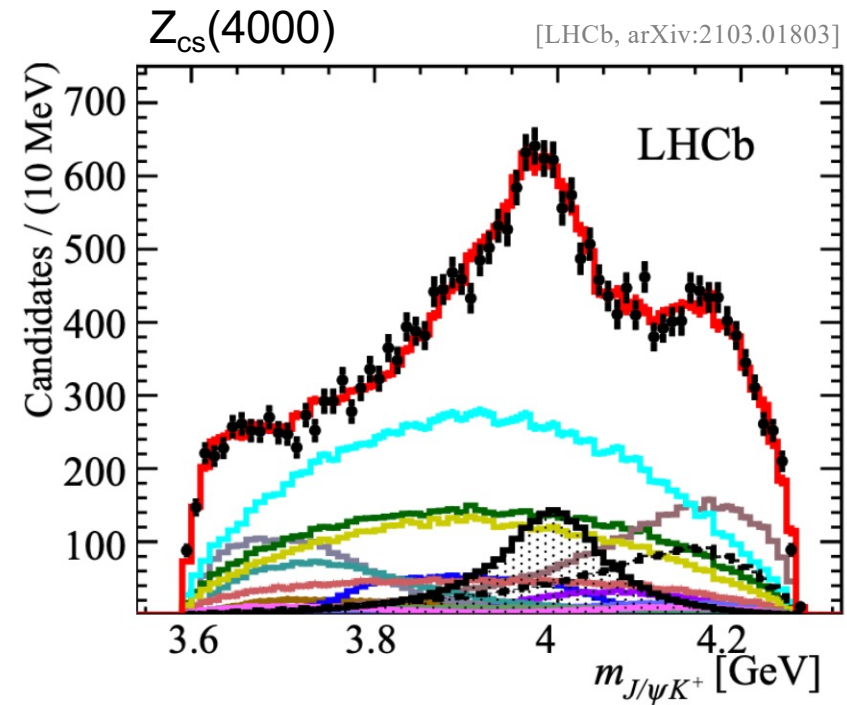
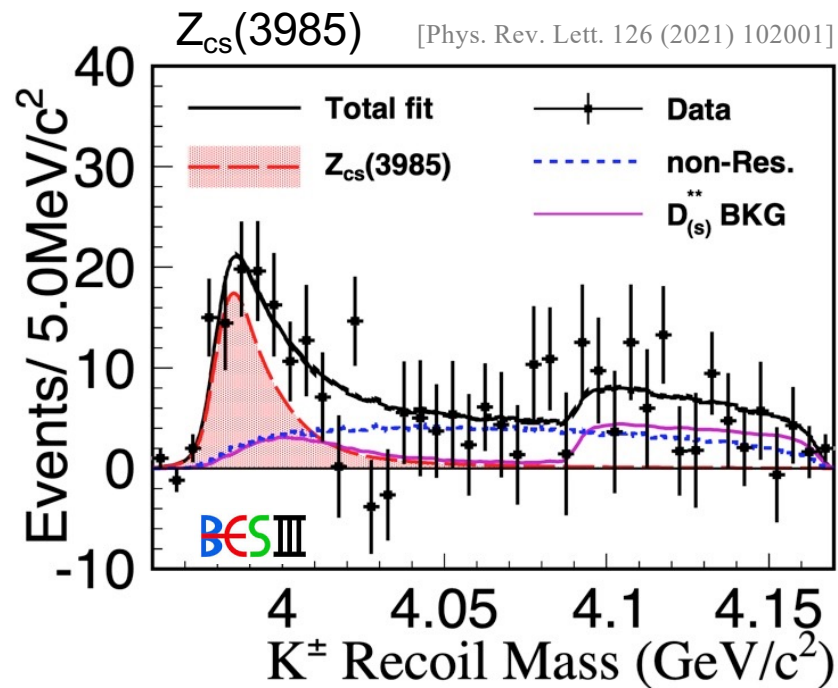
- Introduction
- The BESIII experiments and data sets
- A selection of recent results
 - Supernumerary vector Y states
 - Manifestly exotic Z_c states
 - The X(3872) and other X states
- Summary

Hadron Spectroscopy

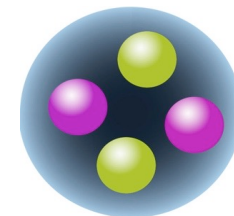


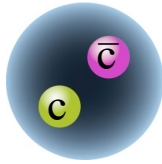
Strange partner of the famous,
unexpected, manifestly exotic $Z_c(3900)$?

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Potential model:

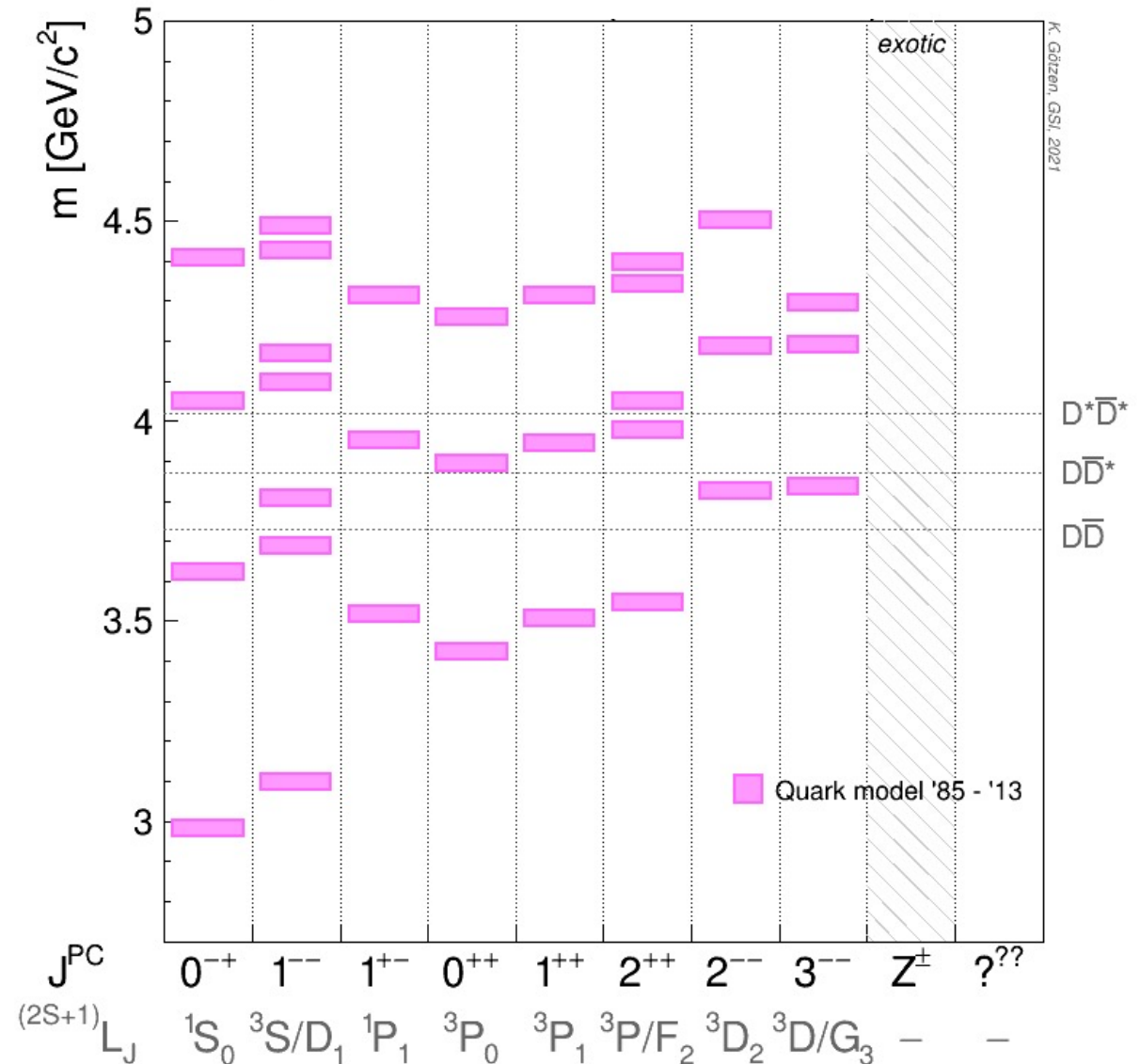
$$V_0^{c\bar{c}} = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta(r) \vec{S}_c \vec{S}_{\bar{c}}$$

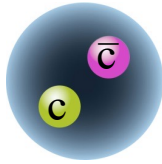
$$V_{\text{spin-dep.}} = \frac{1}{m_c^2} \left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} T \right]$$

+ relativistic corrections!

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

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





- Before 2003:
 - Good agreement between theory and experiment, particularly beneath open charm thresholds

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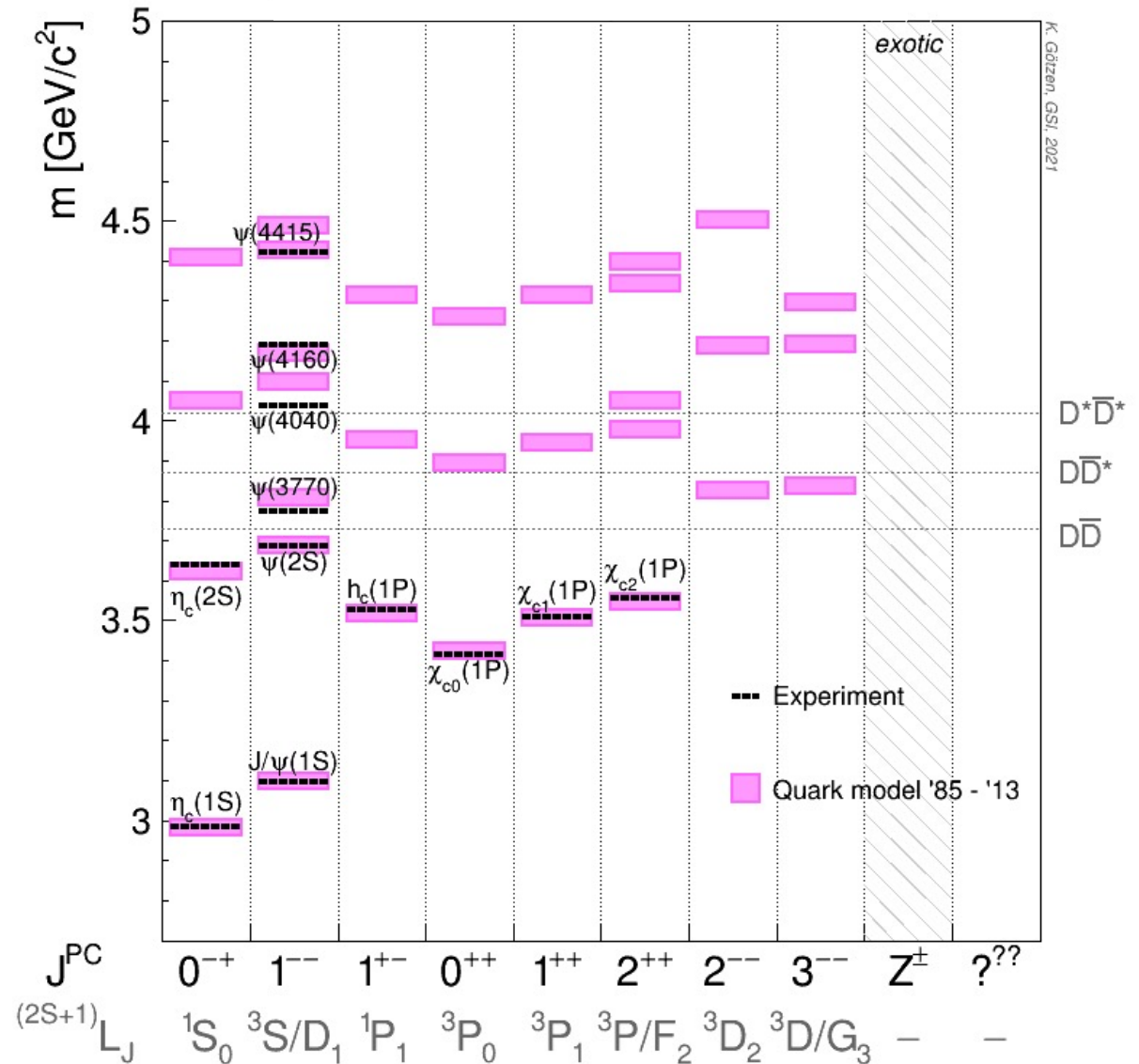
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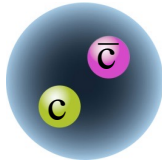
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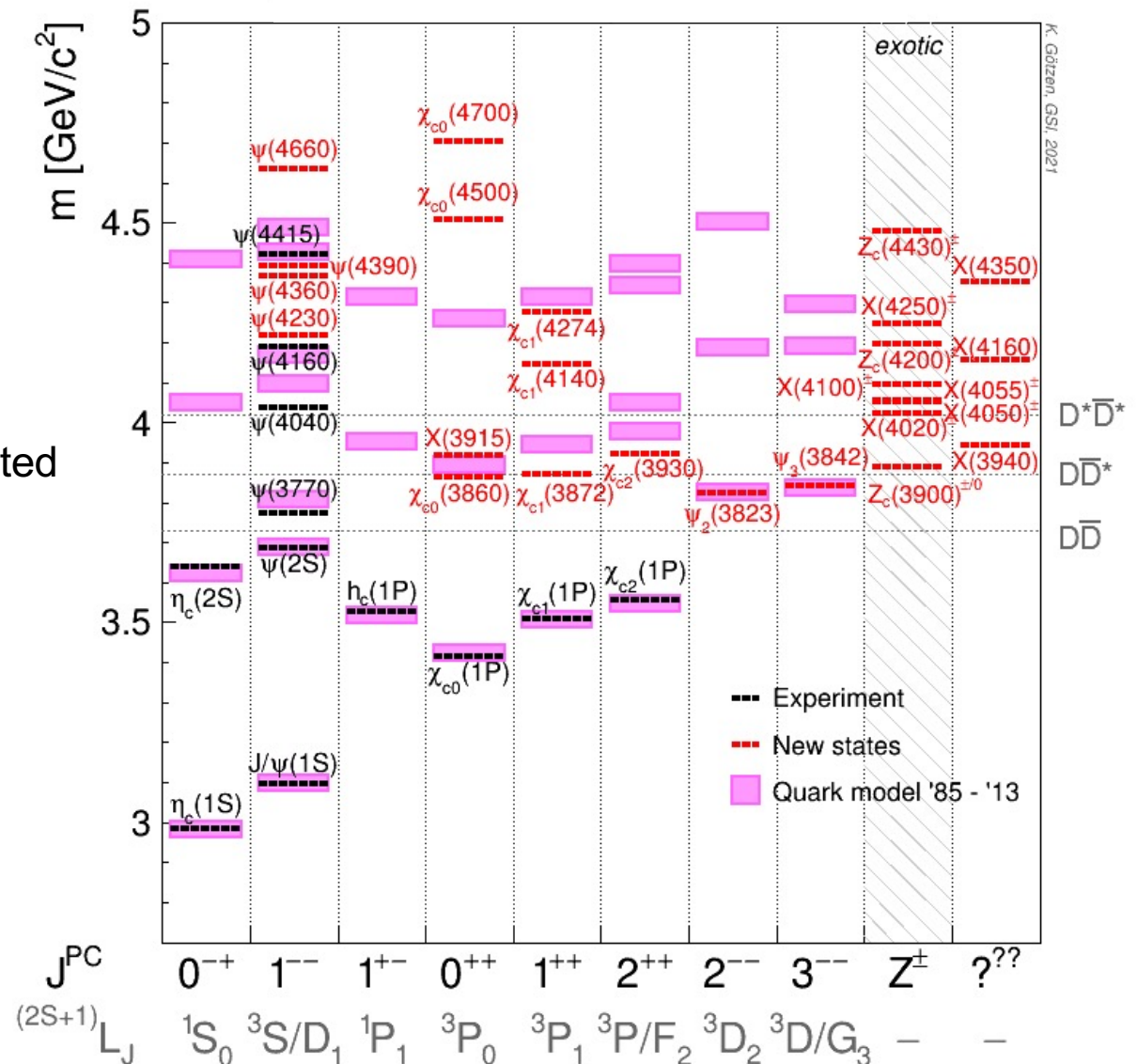
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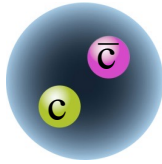
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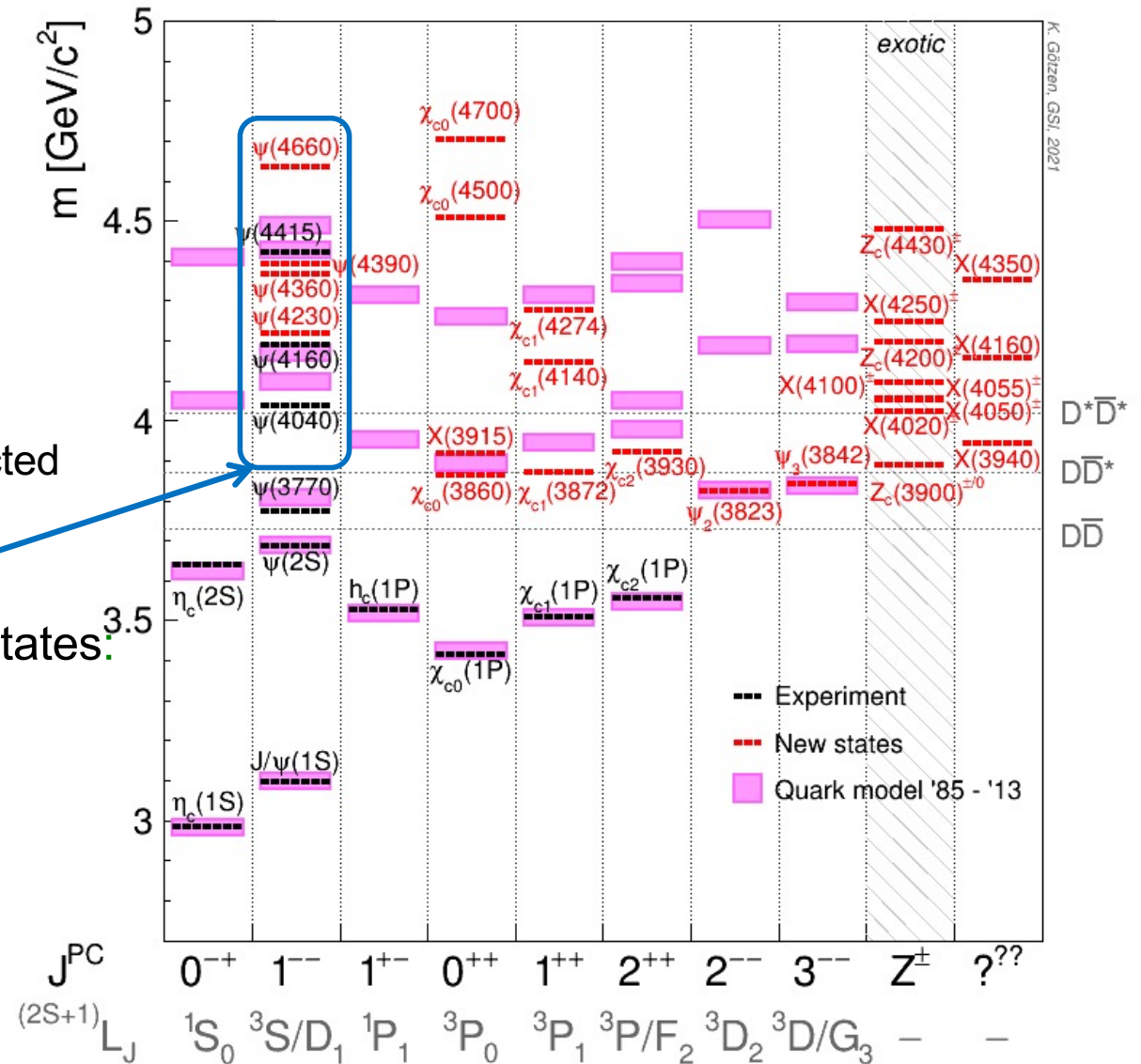
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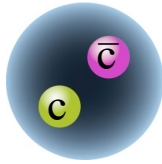
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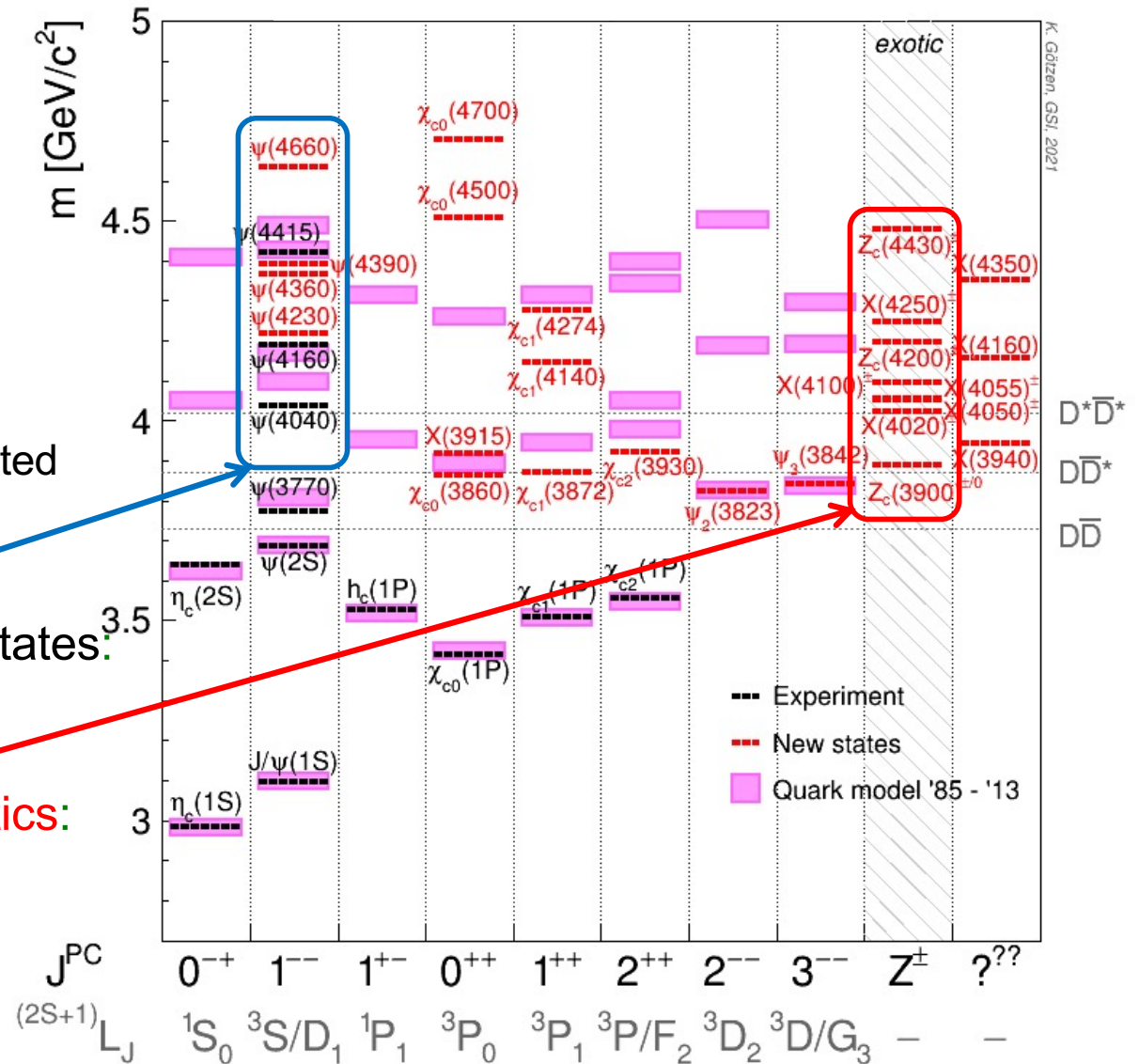


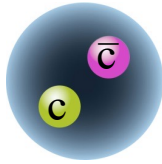
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- Several supernumerary vector states:
Y(4260), ..., Y(4660)



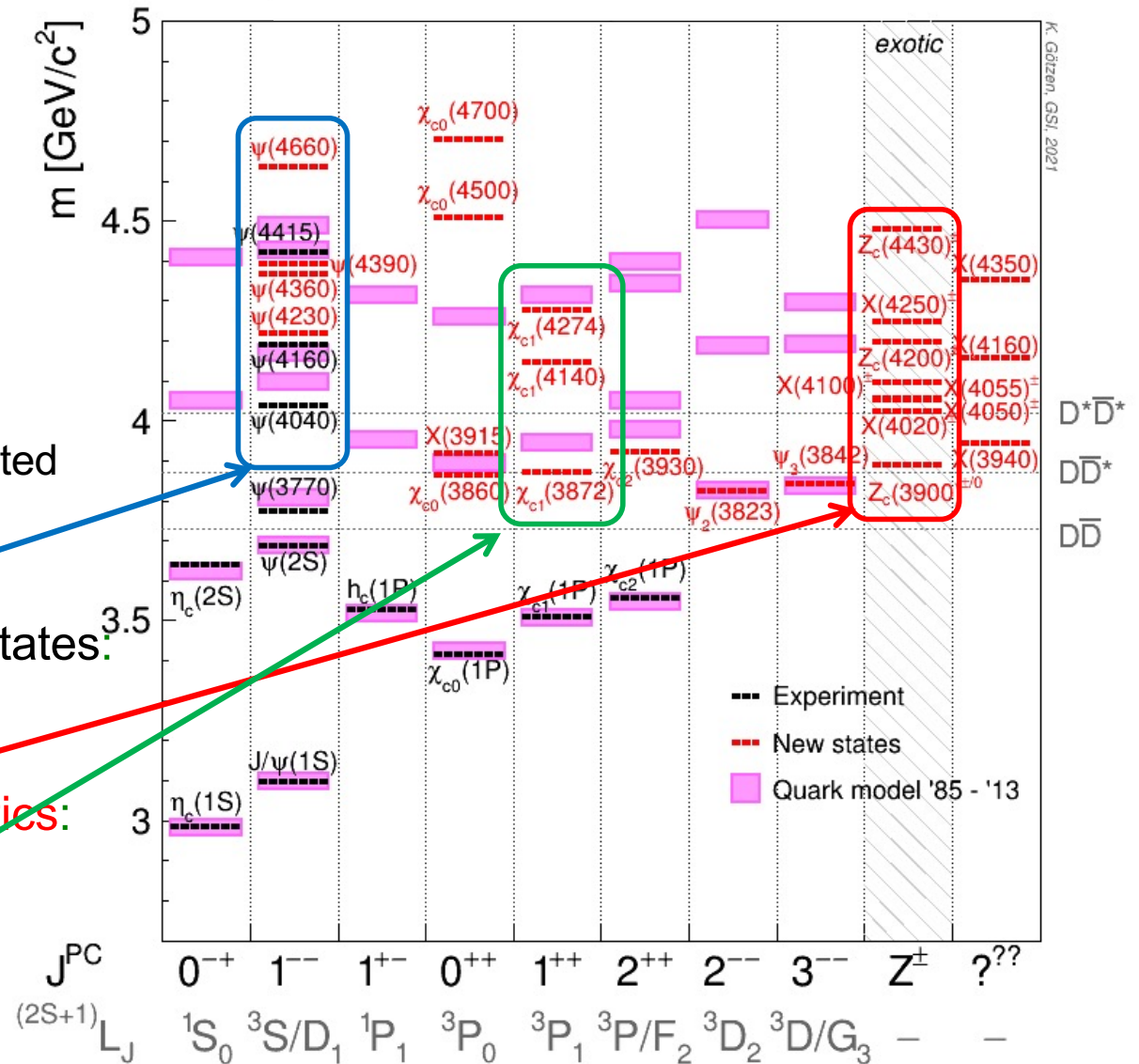


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 $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$



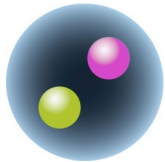


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- Several supernumerary vector states: $Y(4260)$, ..., $Y(4660)$
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



Simple Quark model

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



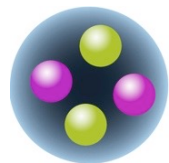
Conventional ($q\bar{q}$)

QCD

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



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

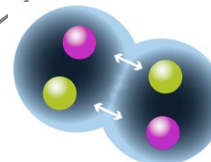


Tetraquark ($qq\bar{q}\bar{q}$)

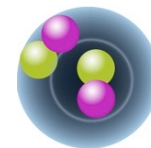


Glue-ball (gg) or (ggg)

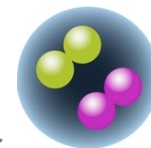
Alternative 4-quark configurations:



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



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



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



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

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





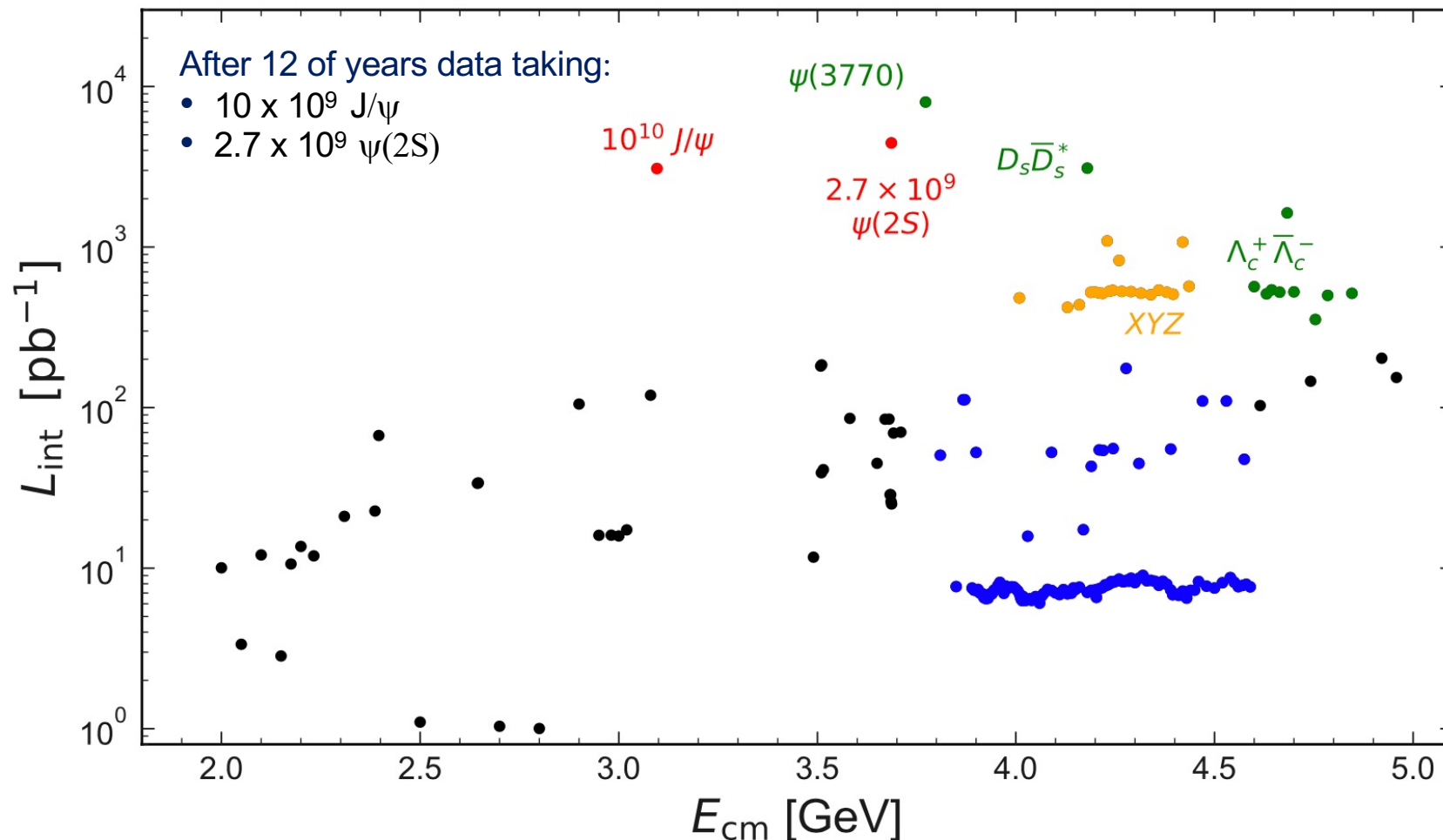
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See also:
2nd plenary talk by M. Küßner
 → *light quark sector*
And further parallel talks
 → *more details and results*

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



- XYZ region: > 3.8 GeV, integrated luminosity: $\sim 22 \text{ fb}^{-1}$
- 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]

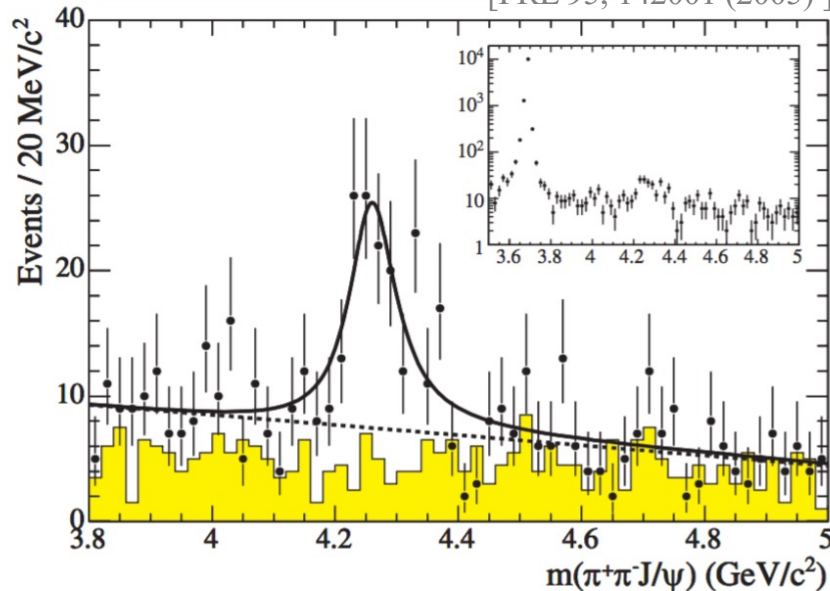
The $Y(4260)$ and further supernumerary vector states

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

Some history:

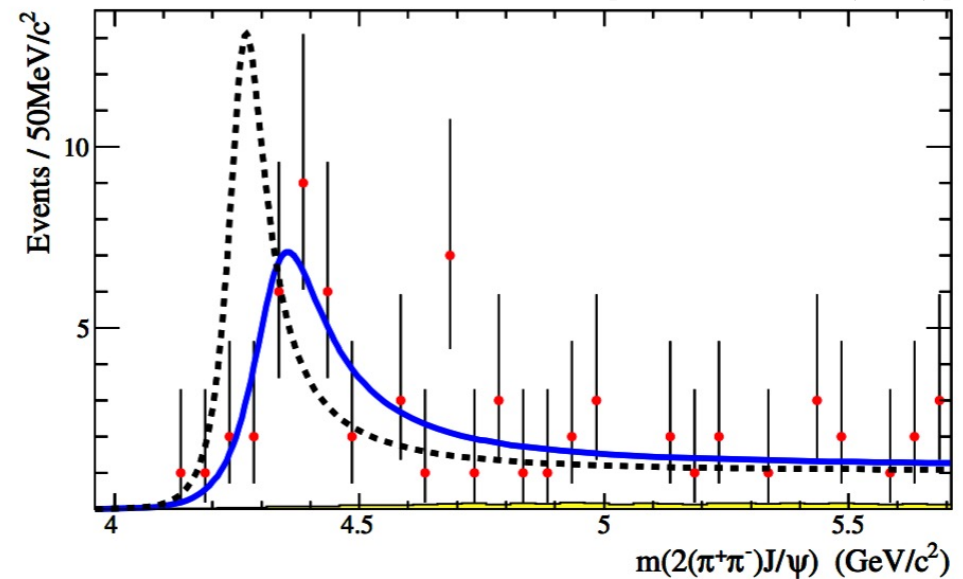
$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$

[PRL 95, 142001 (2005)]



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

[PRL 98, 212001 (2007)]



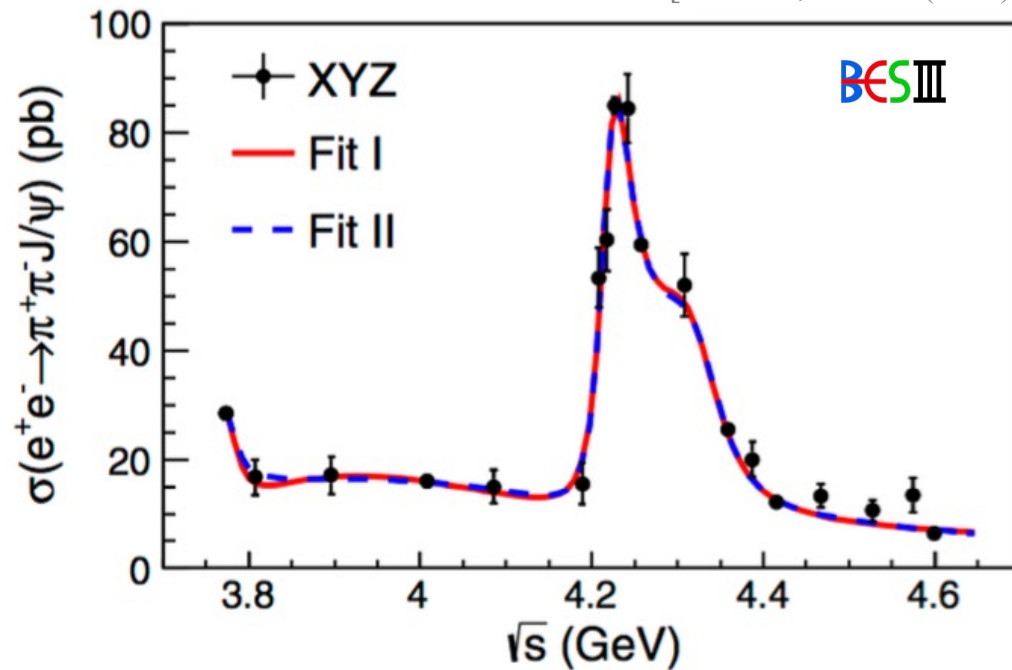
- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$

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

BESIII result, published

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

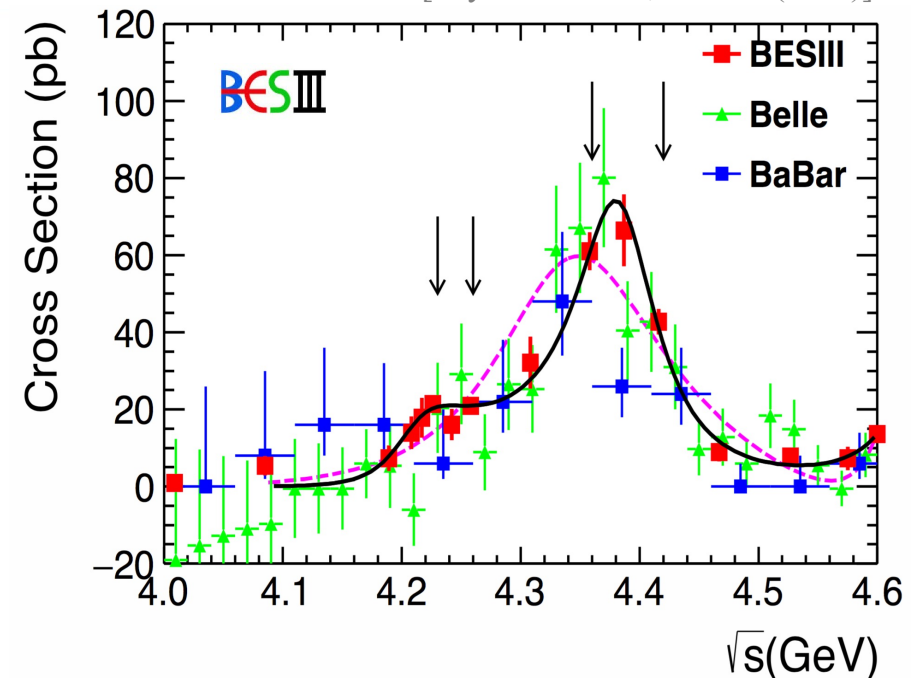
[PRL 118, 092001 (2017)]



- Cross-section inconsistent with the single resonance Y(4260)
- Two favoured over one by $>7\sigma$

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

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



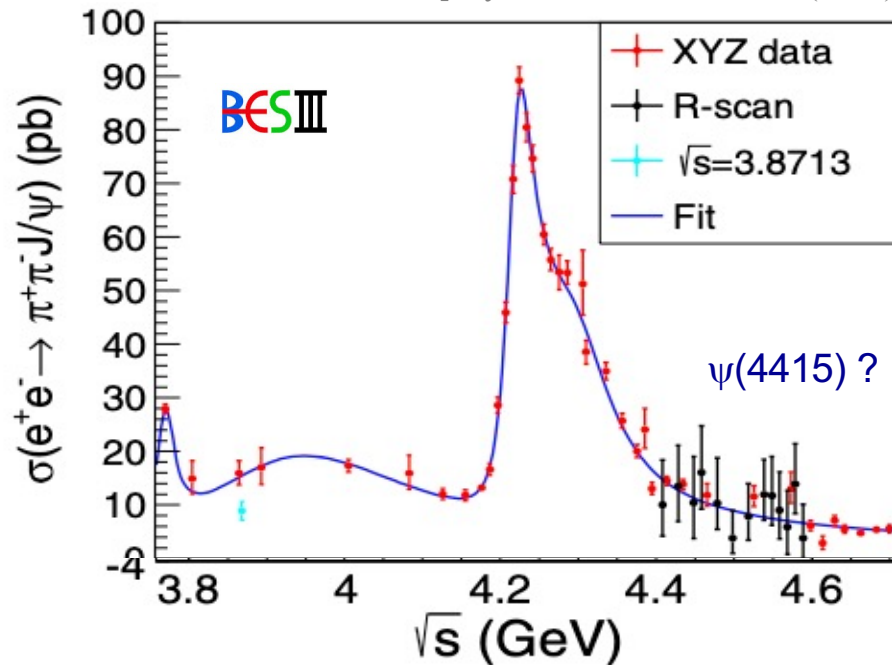
- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4360)

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

BESIII result, published

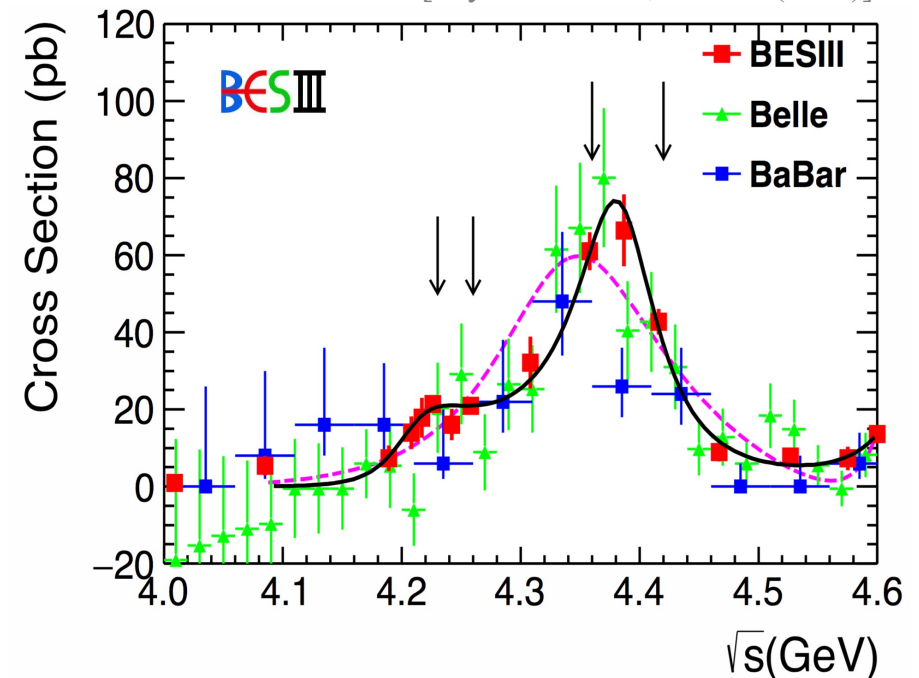
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[Phys. Rev. D 106, 072001 (2022)]



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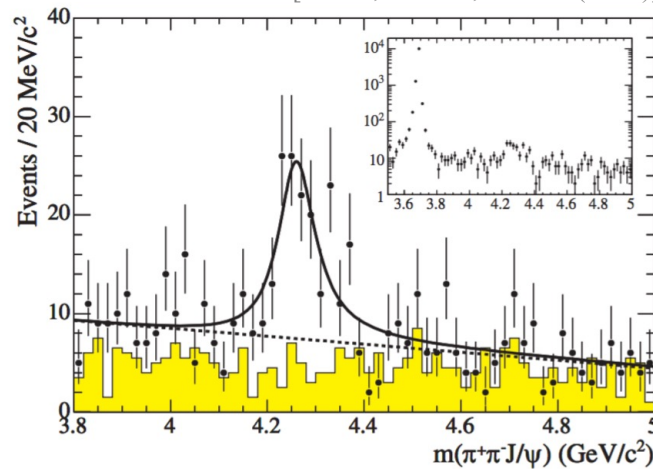


- Cross-section inconsistent with the single resonance $Y(4260)$
 - Additional structure at ~ 4.5 GeV needed (?), influences $Y(4230)$ parameters

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

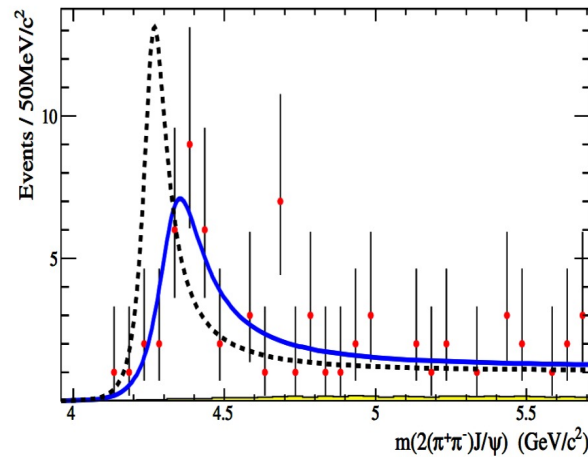
$$e^+e^- \rightarrow J/\psi \pi^+ \pi^-$$

[BaBar, PRL 95, 142001 (2005)]

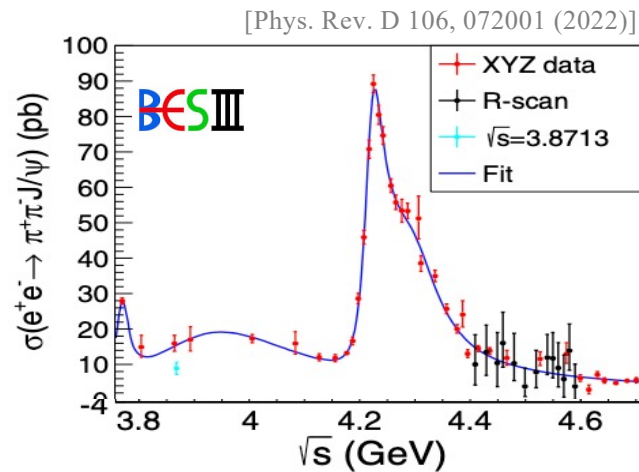
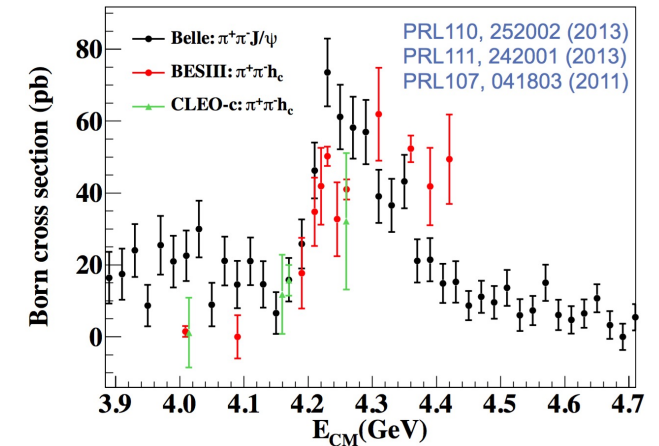


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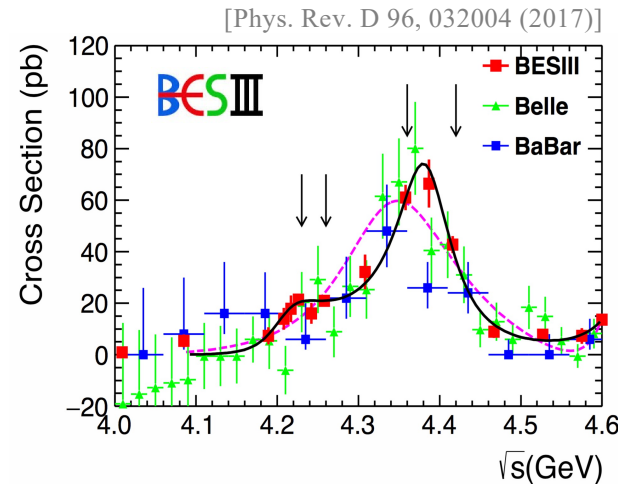
[BaBar, PRL 98, 212001 (2007)]



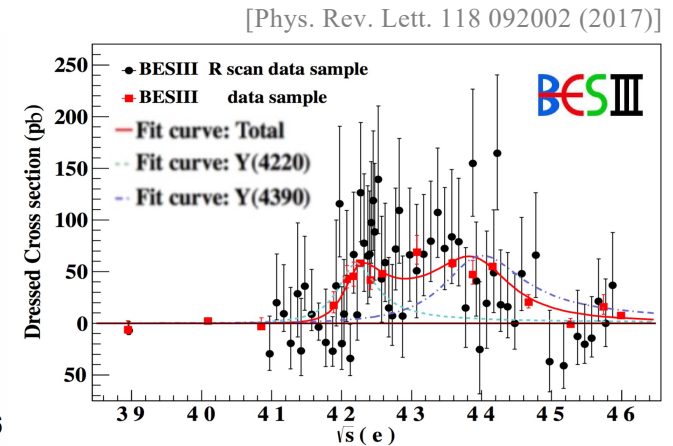
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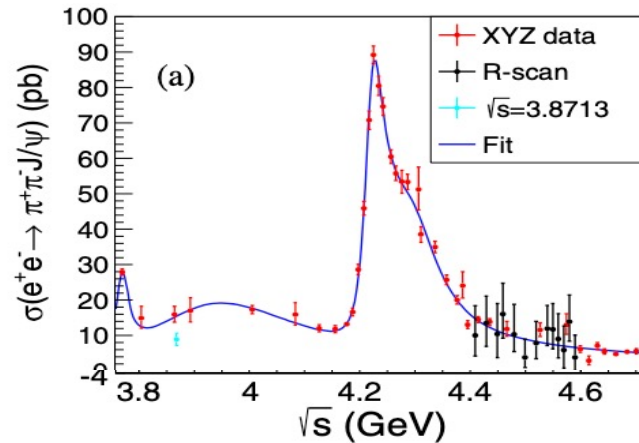
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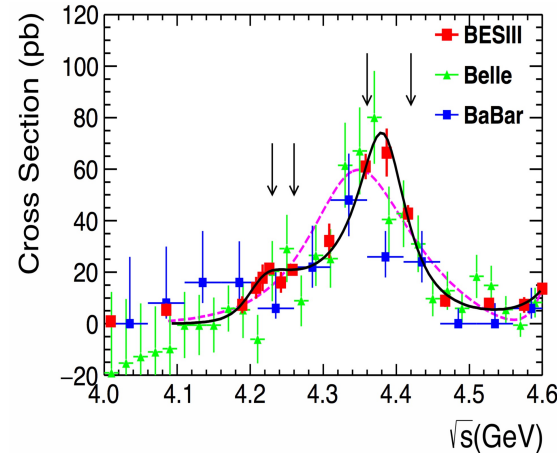
[Phys. Rev. Lett. 118 092002 (2017)]

Two structures now resolved: $Y(4260) \rightarrow Y(4230)$, and $Y(4360)$

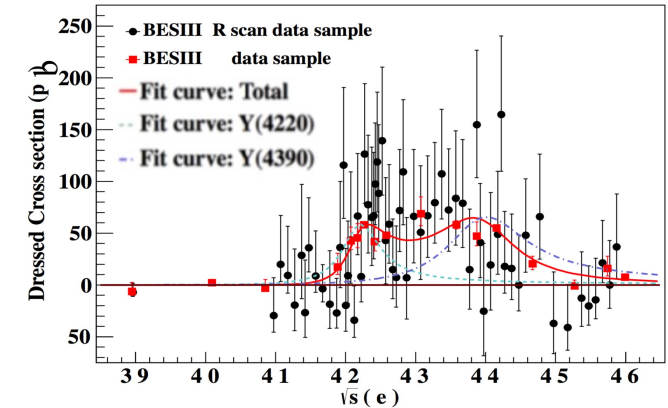
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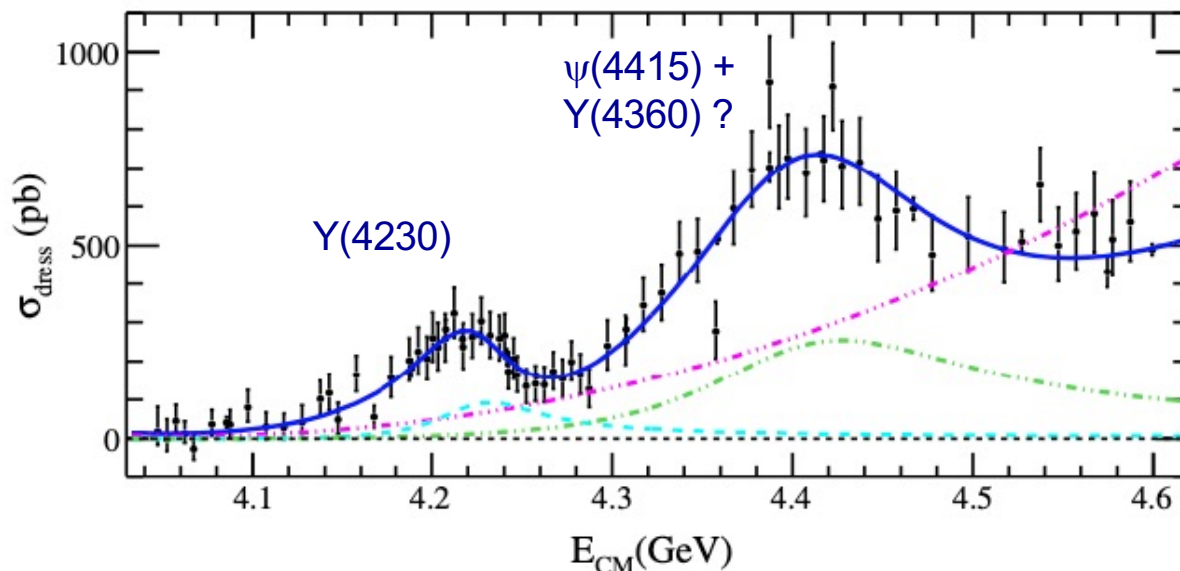


$$e^+e^- \rightarrow h_c \pi^+ \pi^-$$



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

[PRL 122, 102002 (2019)]



Y(4230):

- $M = (4228.6 \pm 4.1 \pm 6.3) \text{ MeV}/c^2$
- $\Gamma = (77.0 \pm 6.8 \pm 6.3) \text{ MeV}/c^2$

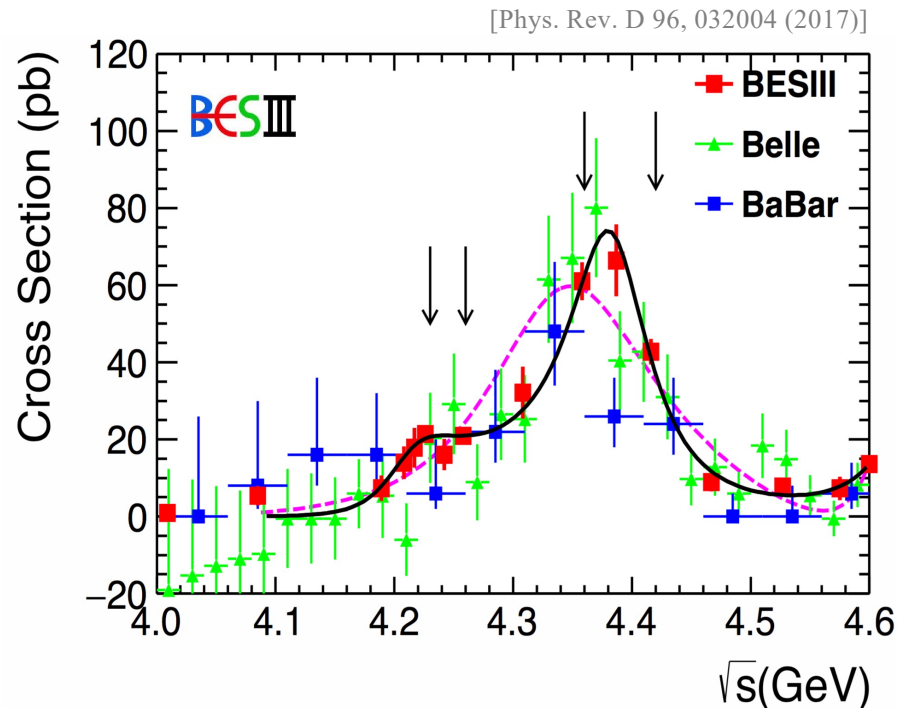
Y state at about 4.40 GeV:

- strongly model dependent

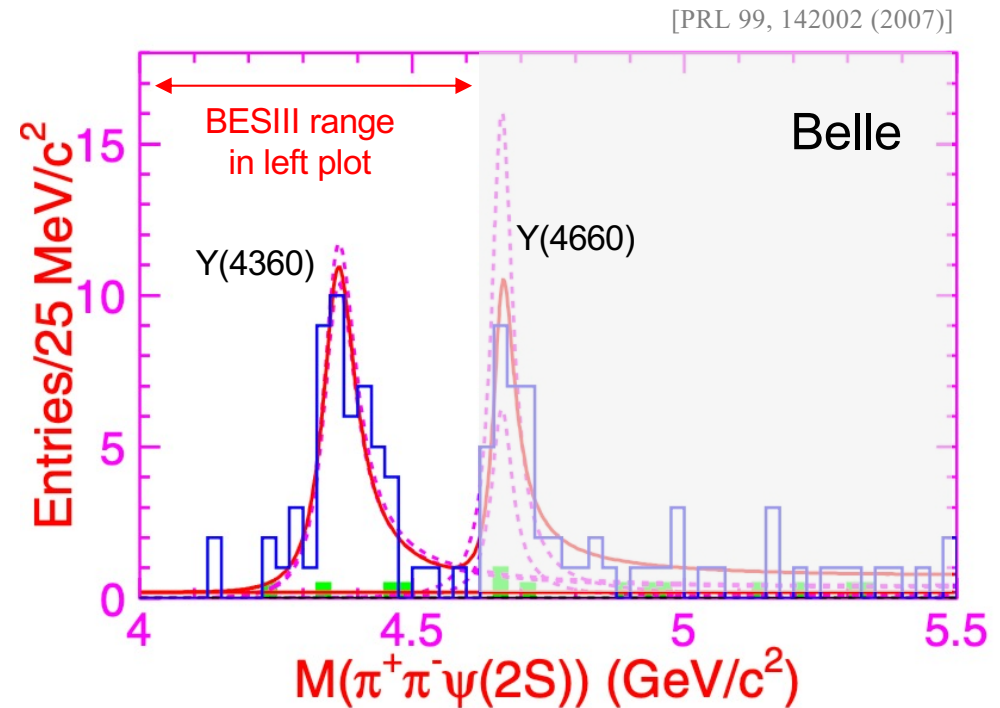
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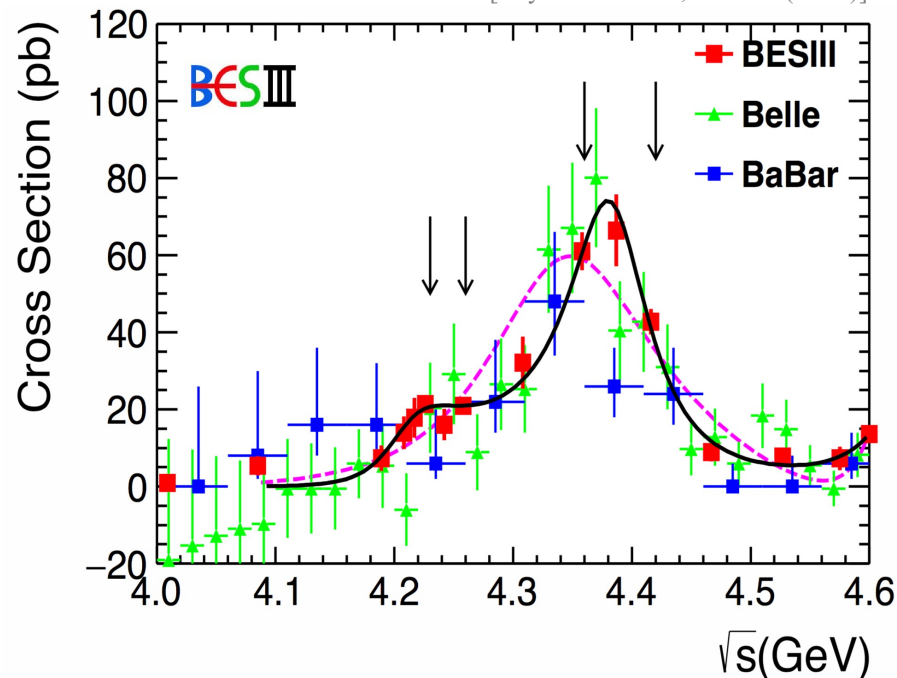


- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4360)
- Confirmation of the Y(4360) in $\psi(2S)\pi^-\pi^+$ with a significance of 8σ
- First observation of Y(4660) with 5.8σ

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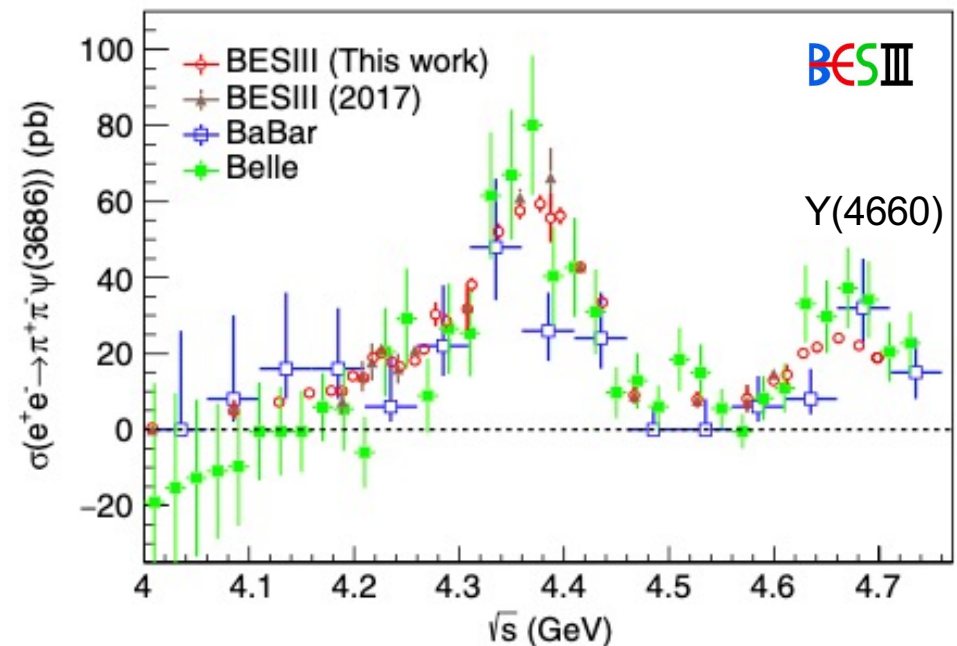
[Phys. Rev. D 96, 032004 (2017)]



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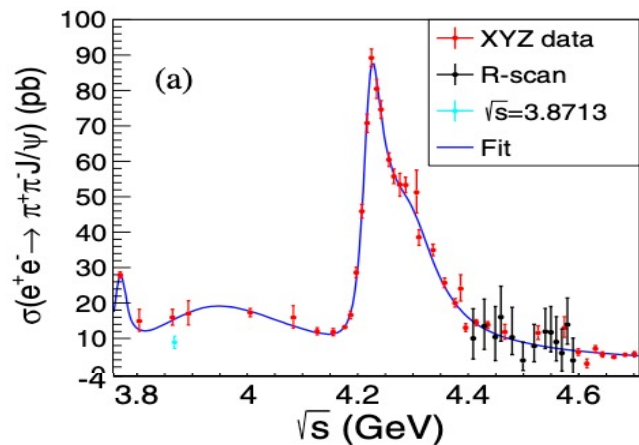
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[PRD 104, 052012 (2021)]

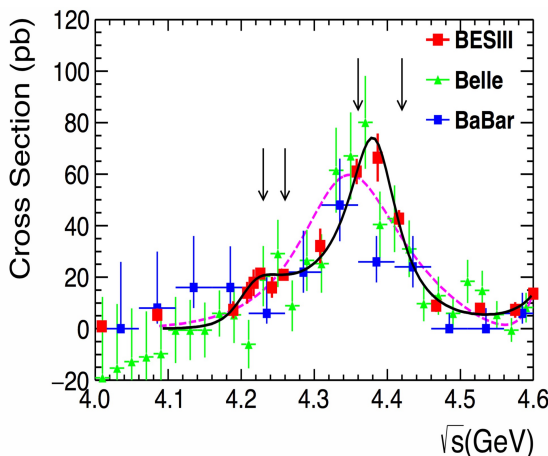


- Observation of Y(4660) $\rightarrow \psi(2S)\pi^-\pi^+$ with a significance of 8.1σ
- First observation of Y(4660) at BESIII

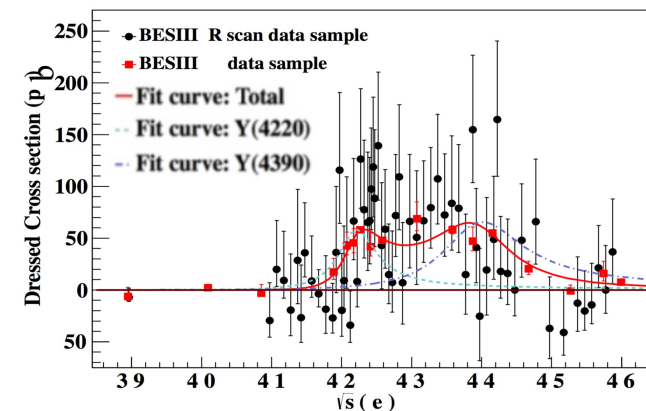
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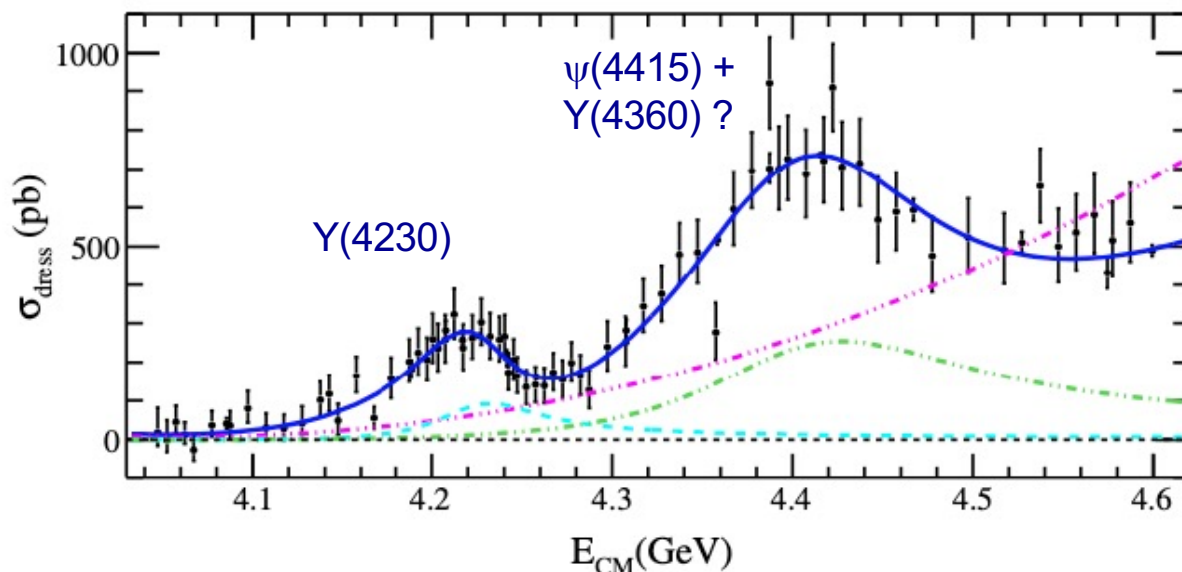


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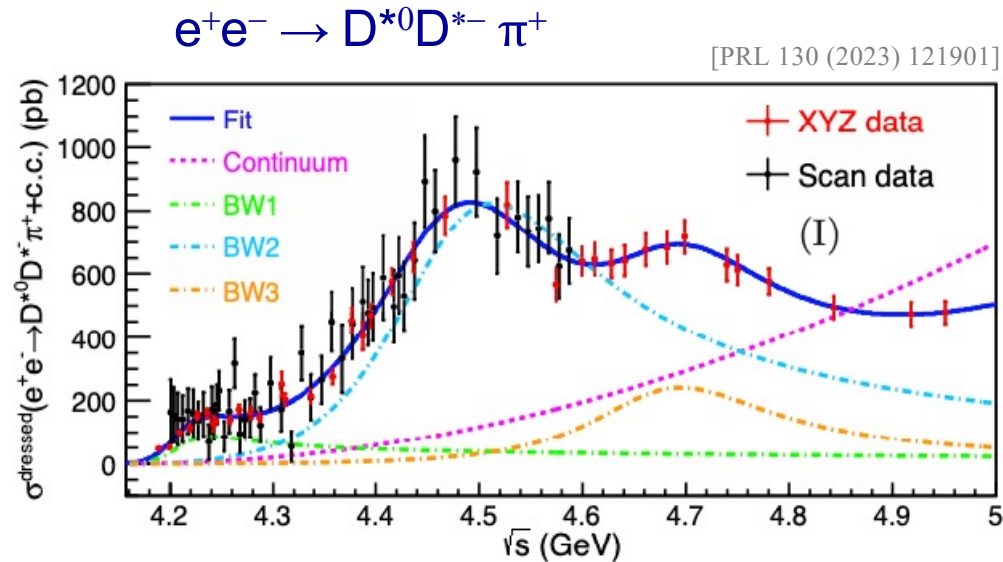
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 => **Consistency** with structures in
 $J/\psi / h_c / \psi(2S) \pi\pi$



Y(4230):

- $M = (4209.6 \pm 4.7 \pm 5.9) \text{ MeV}/c^2$
- $\Gamma = (81.6 \pm 17.8 \pm 9.0) \text{ MeV}$

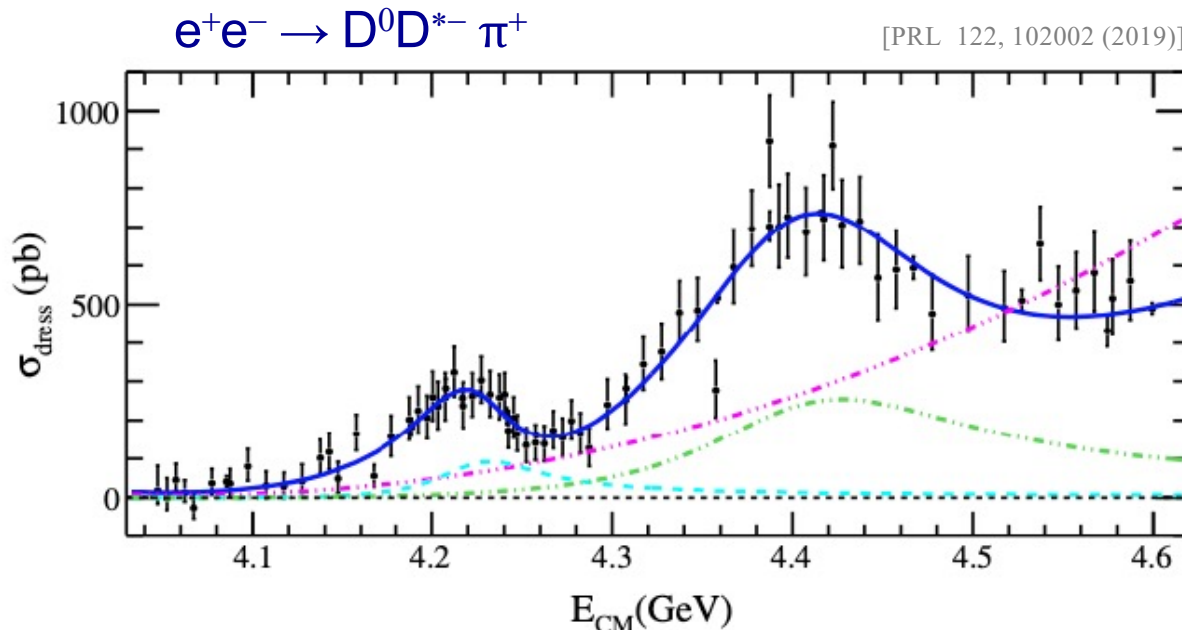
Y(4500):

- $M = (4469.1 \pm 26.2 \pm 3.6) \text{ MeV}/c^2$
- $\Gamma = (81.6 \pm 17.8 \pm 9.0) \text{ MeV}$

Y(4660):

- $M = (4675.3 \pm 29.5 \pm 3.5) \text{ MeV}/c^2$
- $\Gamma = (218.2 \pm 72.9 \pm 9.3) \text{ MeV}$

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



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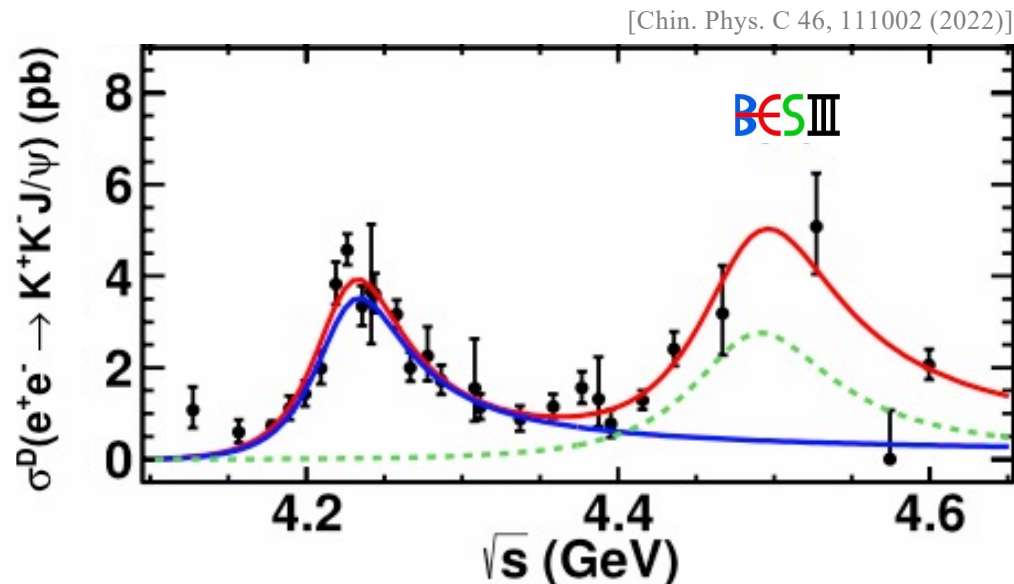
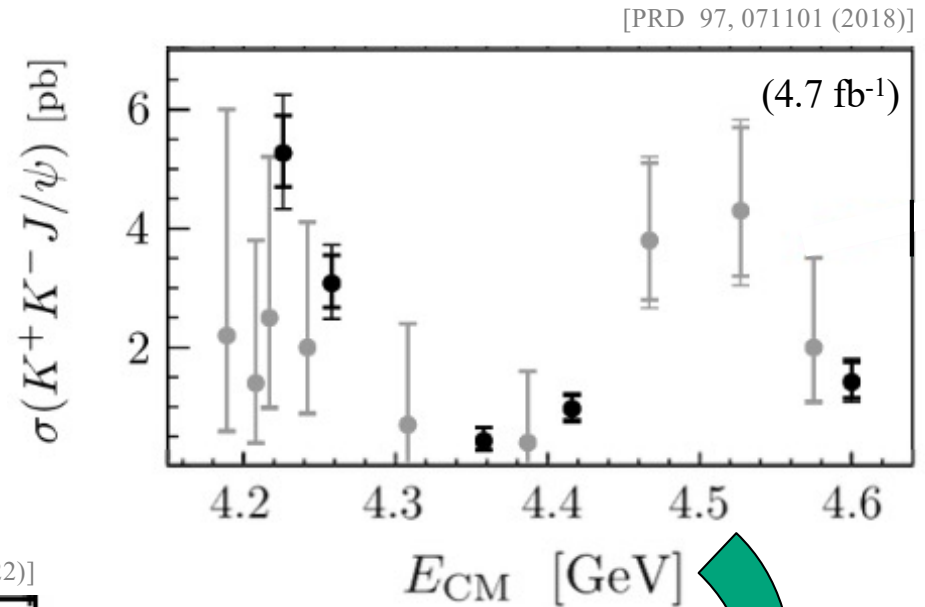
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- Data samples from 4.13 to 4.60 GeV (15.6 fb^{-1})
- Dressed cross-section measurement of $e^+e^- \rightarrow K^+K^- J/\psi$
- Y(4230) and Y(4500) observed ($29\sigma / 8\sigma$)
 - $M = (4484.7 \pm 13.3 \pm 24.1) \text{ MeV}/c^2$
 - $\Gamma = (77.0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

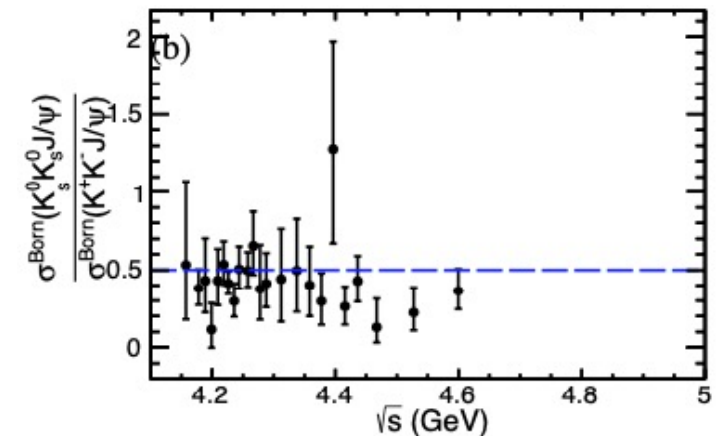
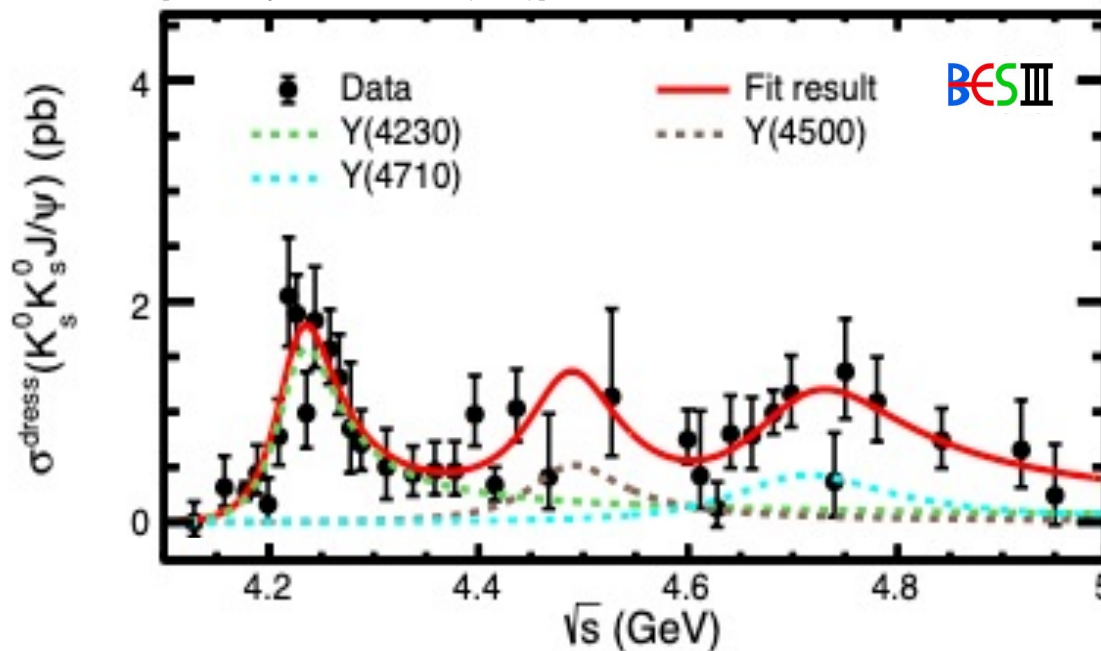


larger statistics, more
data points & improved
detection efficiencies

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

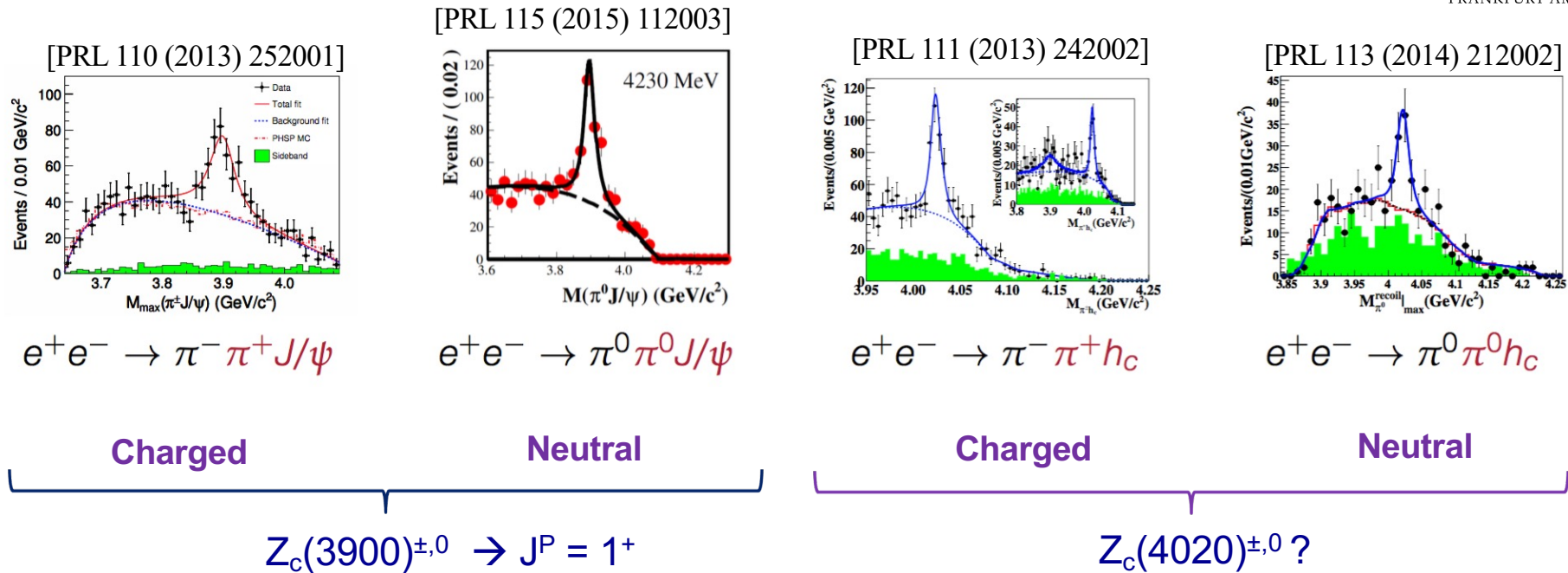
[Chin. Phys. C 46, 111002 (2022)]



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

=> isospin violation effect at 1.9σ

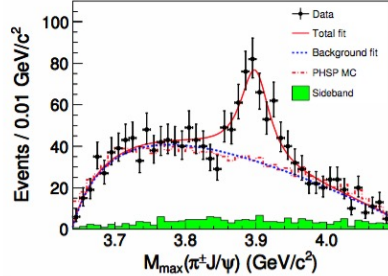
The (charged) Zc states



- Two isospin triplets of charmonium-like exotic states established

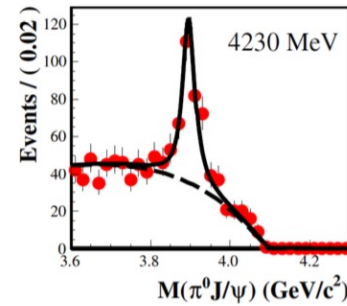
Hidden Charm

[PRL 110 (2013) 252001]



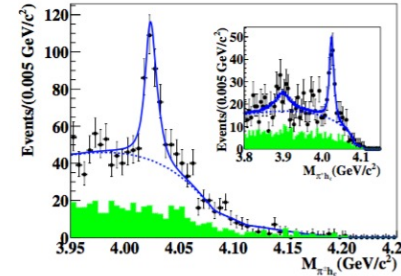
$$e^+e^- \rightarrow \pi^- \pi^+ J/\psi$$

[PRL 115 (2015) 112003]



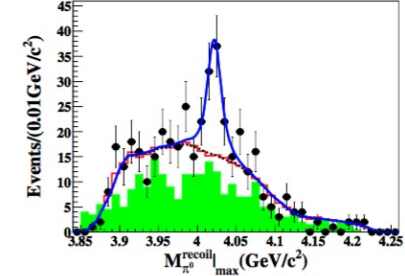
$$e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$$

[PRL 111 (2013) 242002]



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

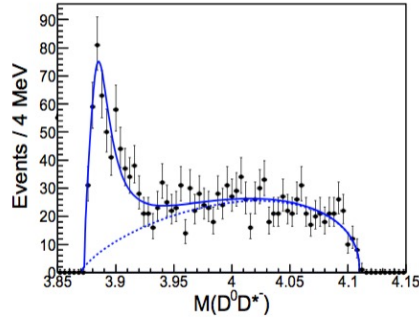
[PRL 113 (2014) 212002]



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

Open Charm

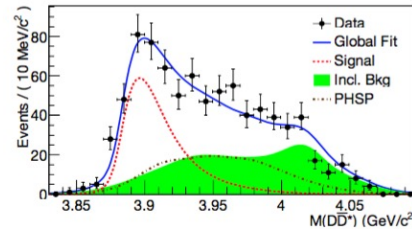
[PRL 112 (2014) 022001]



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

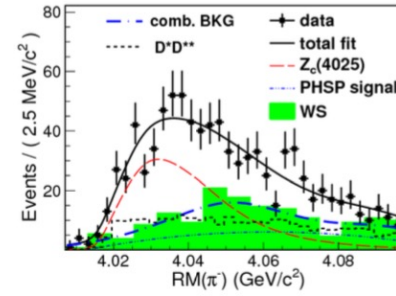
Charged

[PRL 115 (2015) 222002]



Neutral

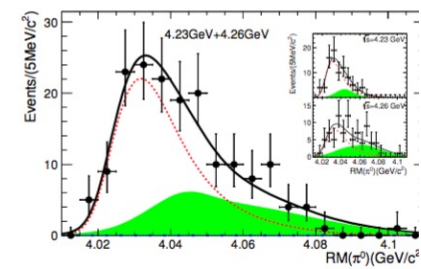
[PRL 112 (2013) 132001]



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

Charged

[PRL 115 (2015) 182002]

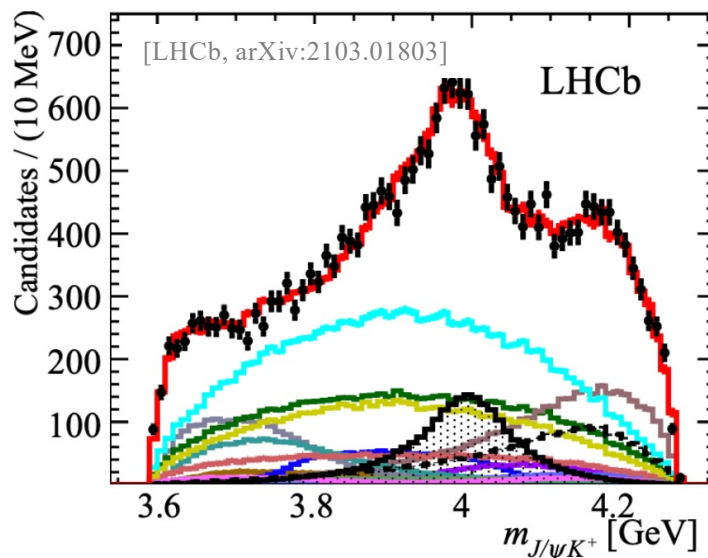
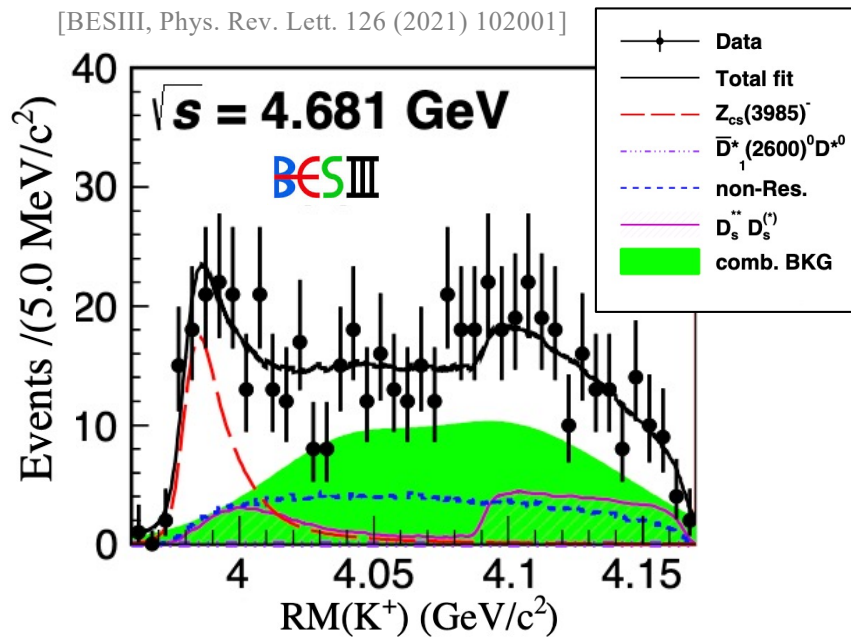


Neutral

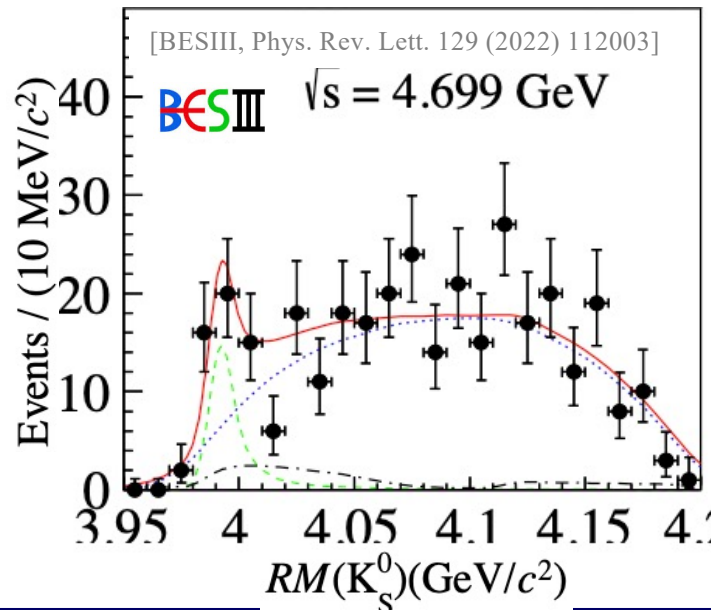
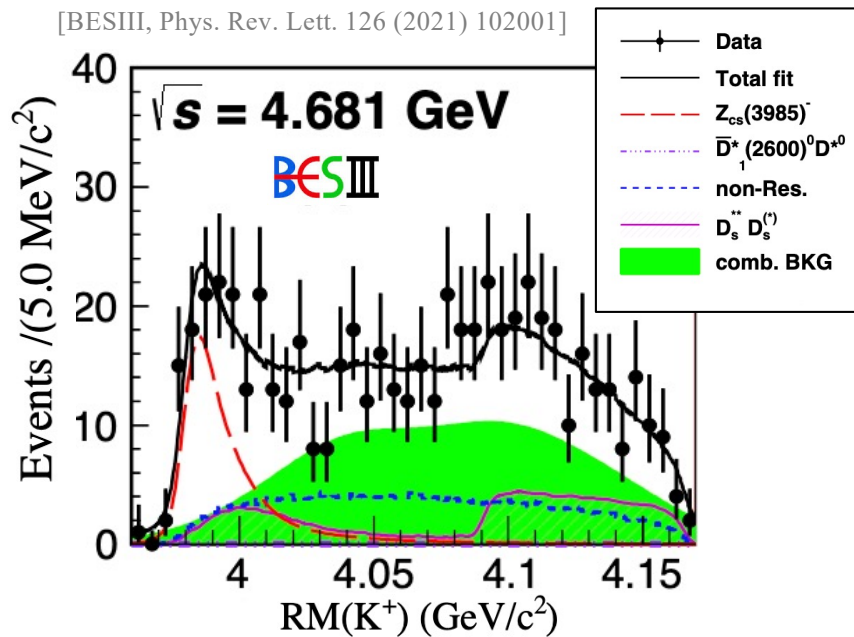
$$Z_c(3900)^{\pm,0} \rightarrow J^P = 1^+$$

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

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

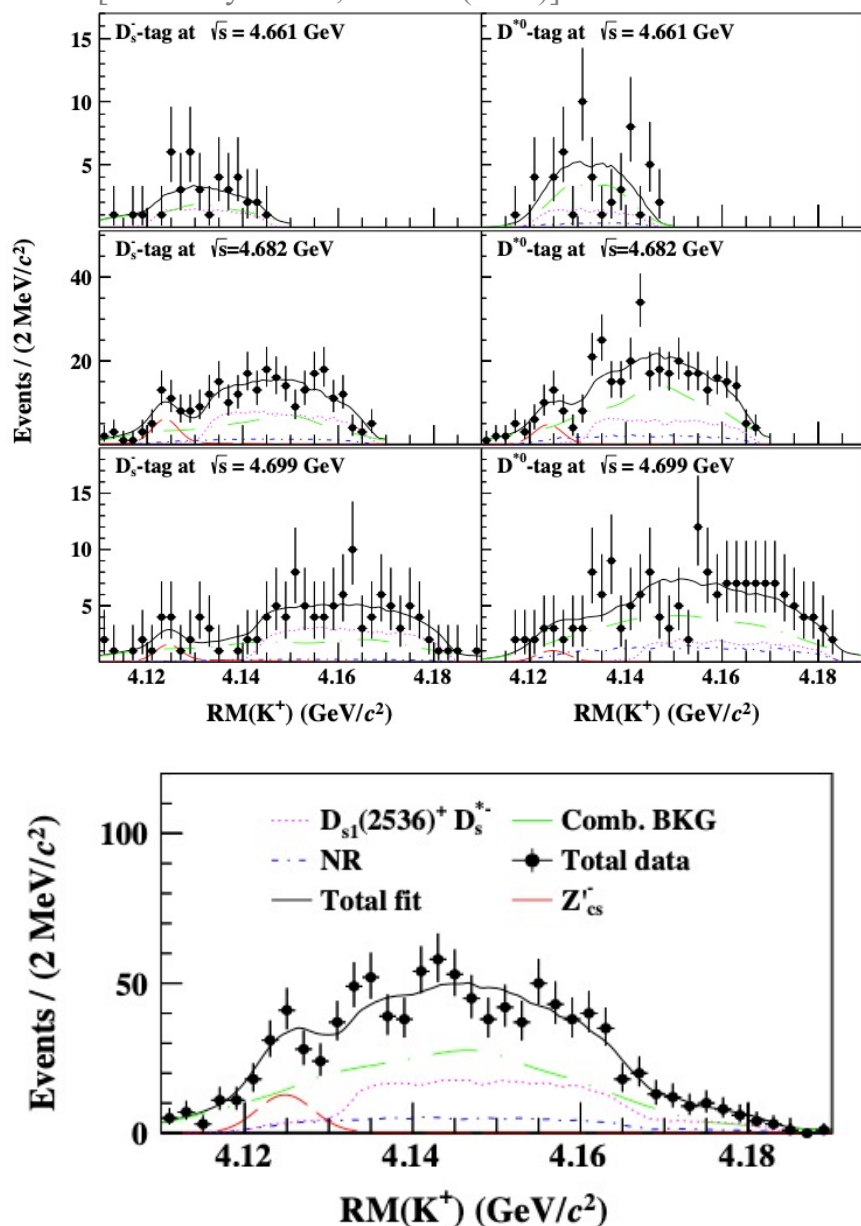


- Search for **strange partner** of $Z_c(3900)$
 - Containing s quark in open charm decay
 - $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D)^-$
 - Narrow threshold enhancement (5.3σ)
 - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1) \text{ MeV}/c^2$,
 $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0) \text{ MeV}$
 - Manifestly exotic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



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

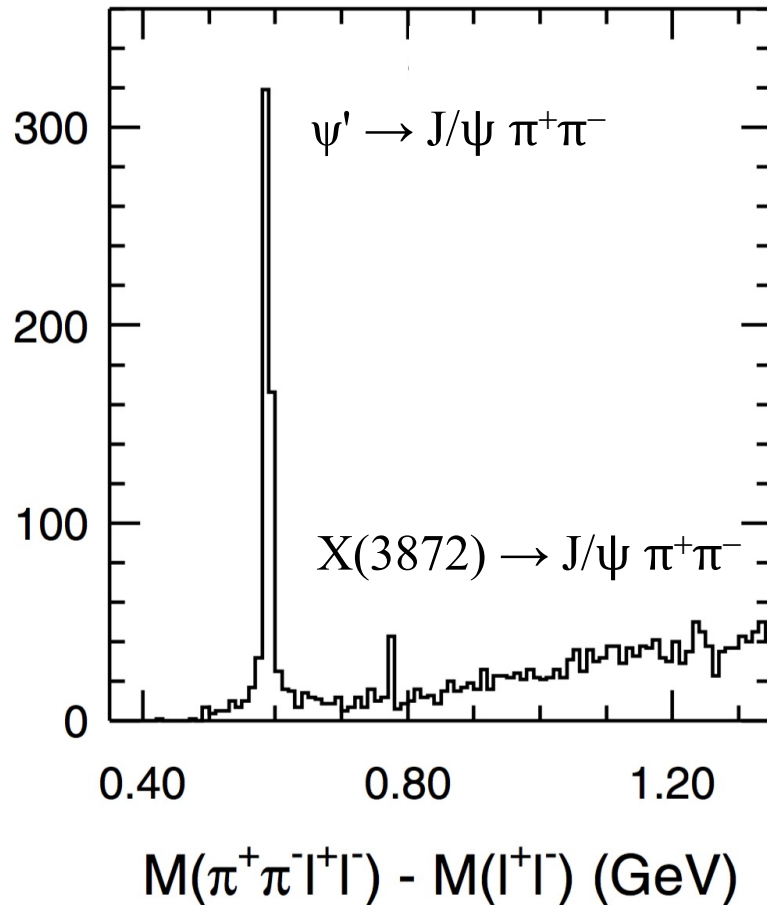
[Chin. Phys. C 47, 033001 (2023)]



- 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})
 - $e^+e^- \rightarrow K^+ D_s^{*-} D^{*0} + c.c.$
 - two different tag-methods (D_s^- -/ D^{*0} -tags)
 - Evidence for a Z_{cs}' state
 - $M = (4123.5 \pm 0.7) \text{ MeV}/c^2$
 - 2.1σ significance (3.9σ \two sys)
 - Statistics limited, test of decay width hypotheses, local statistical 4.1σ for: $(M_0, \Gamma_0) = (4124.1 \text{ MeV}/c^2, 10 \text{ MeV})$
 - Upper Limits (CL90) provided: on $\sigma_{\text{Born}} \times \text{BR}$: $\mathcal{O}(1) \text{ pb}$
 - UL on $\sigma_{\text{Born}} \times \text{BR}$: : $\mathcal{O}(1) \text{ pb}$
 - at each $\sqrt{s} = 4.661, 4.682$ and 4.699
- => More data will be taken

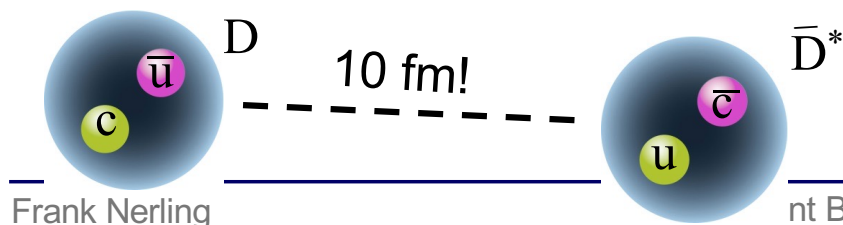
The X(3872) and further X states

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



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

Analogy to deuteron:

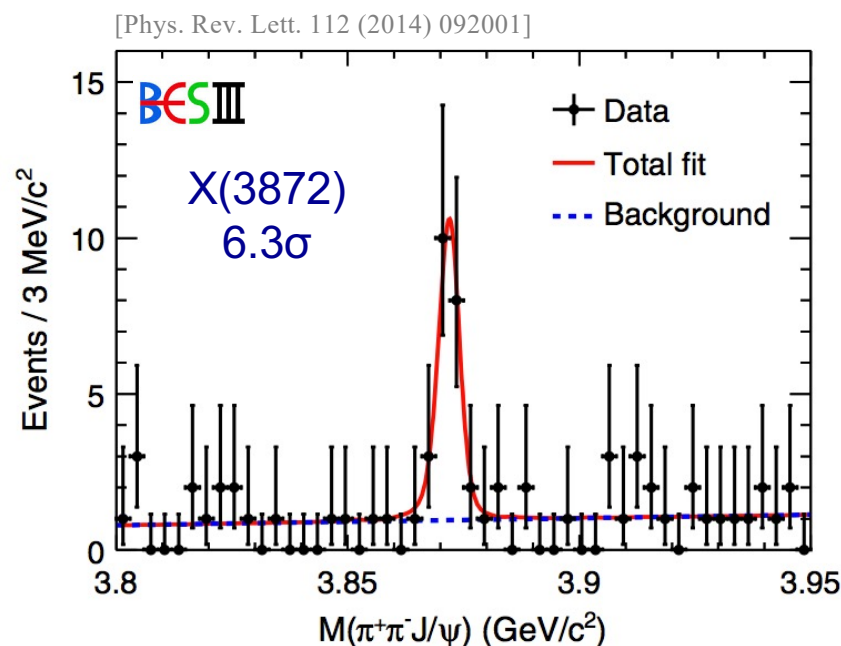


For clarification:

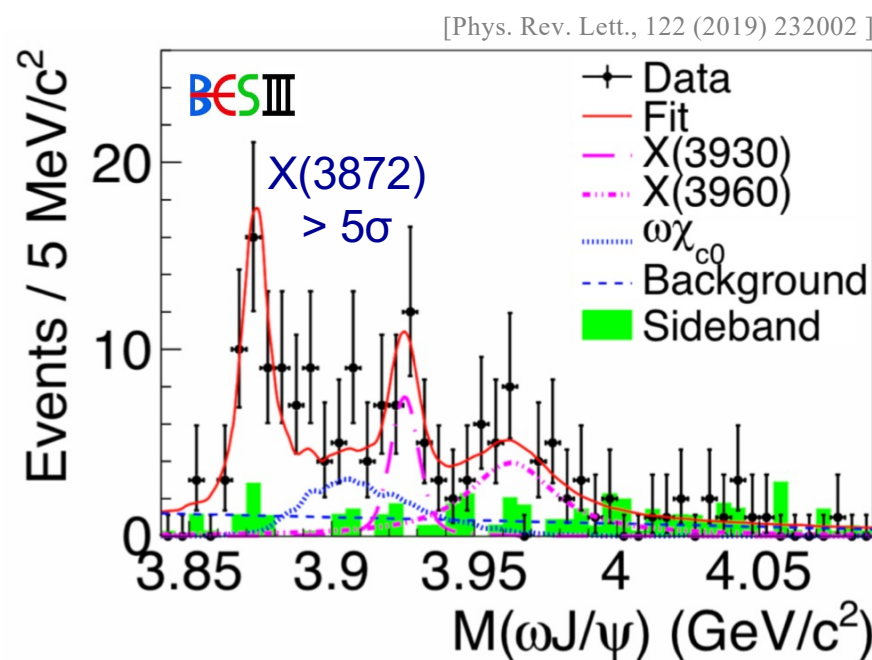
=> Precision measurement with
sub-MeV resolution needed!

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

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



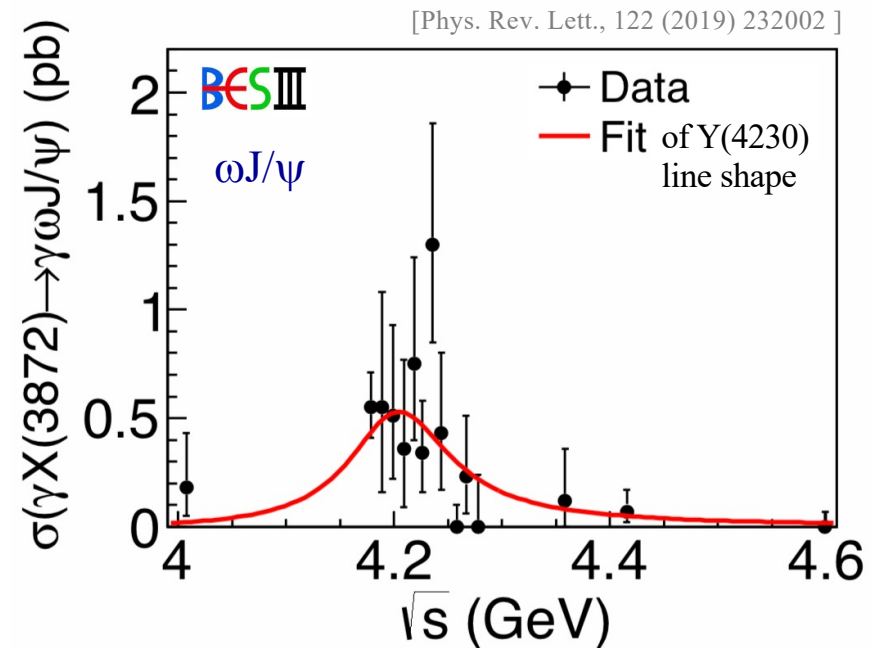
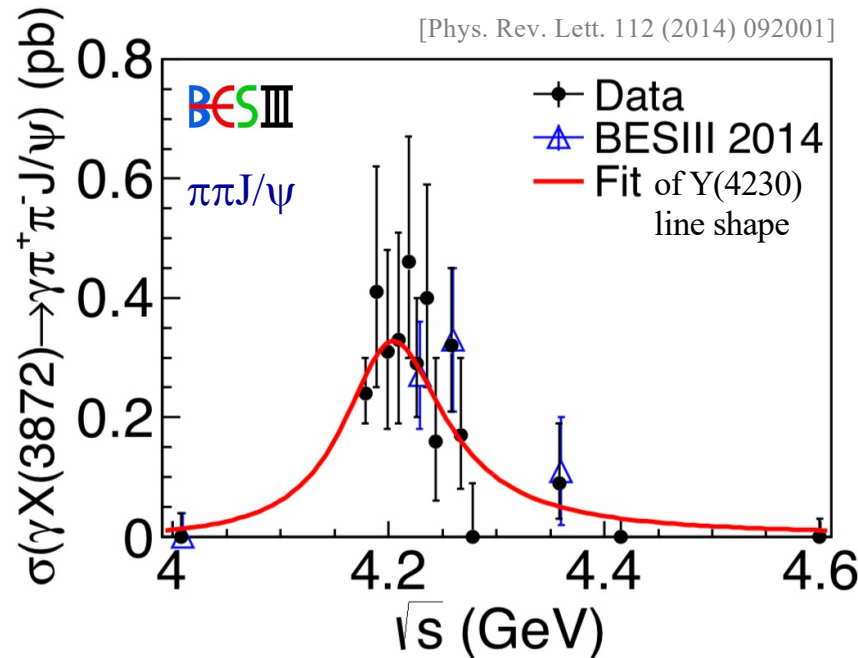
- $m = (3871.9 \pm 0.7 \pm 0.2) \text{ MeV}/c^2$
- $\Gamma < 2.4 \text{ MeV}$ (90% CL)



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

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

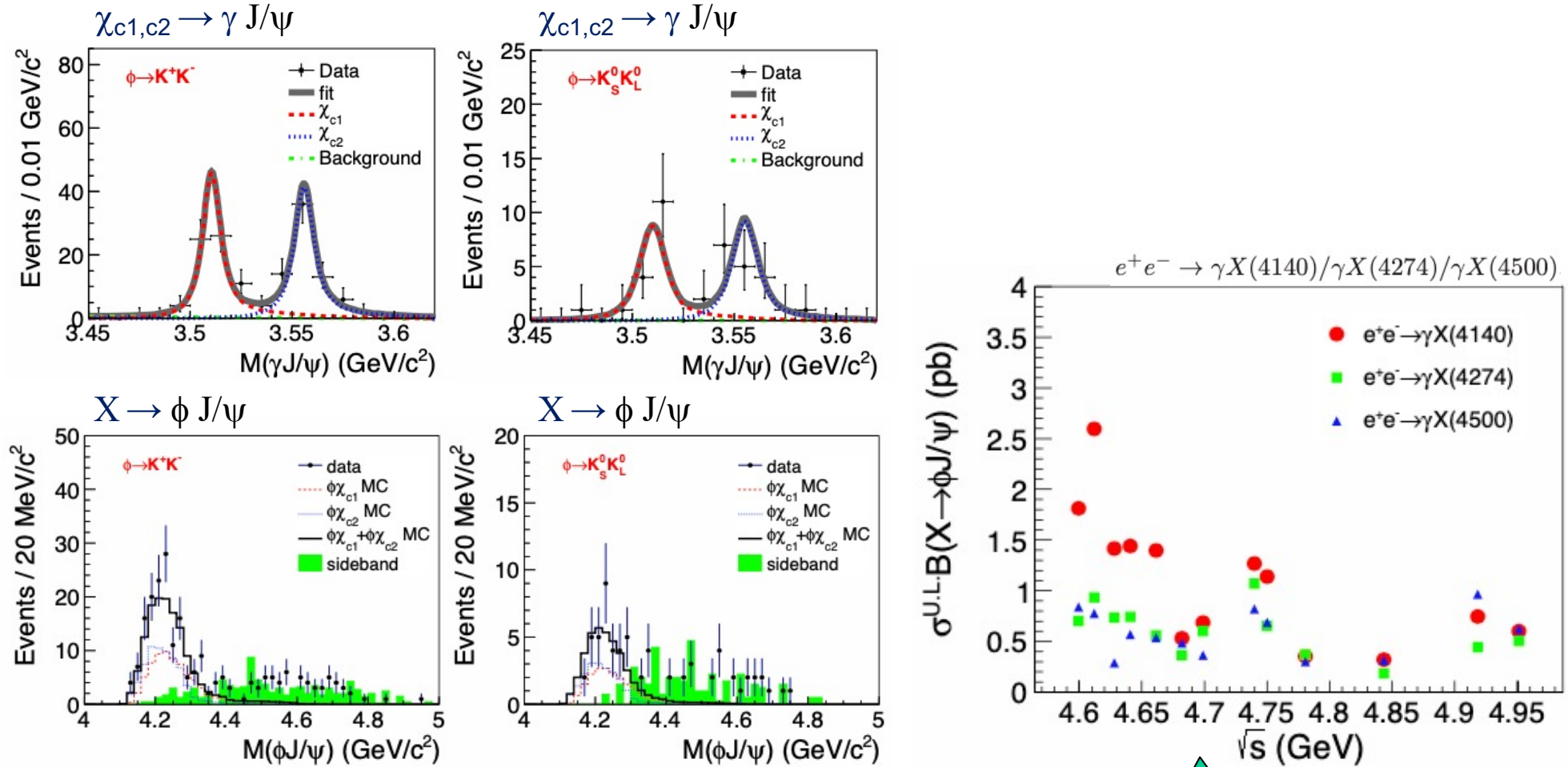
cross section



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

- Shape consistent with production via a Y(4230) state

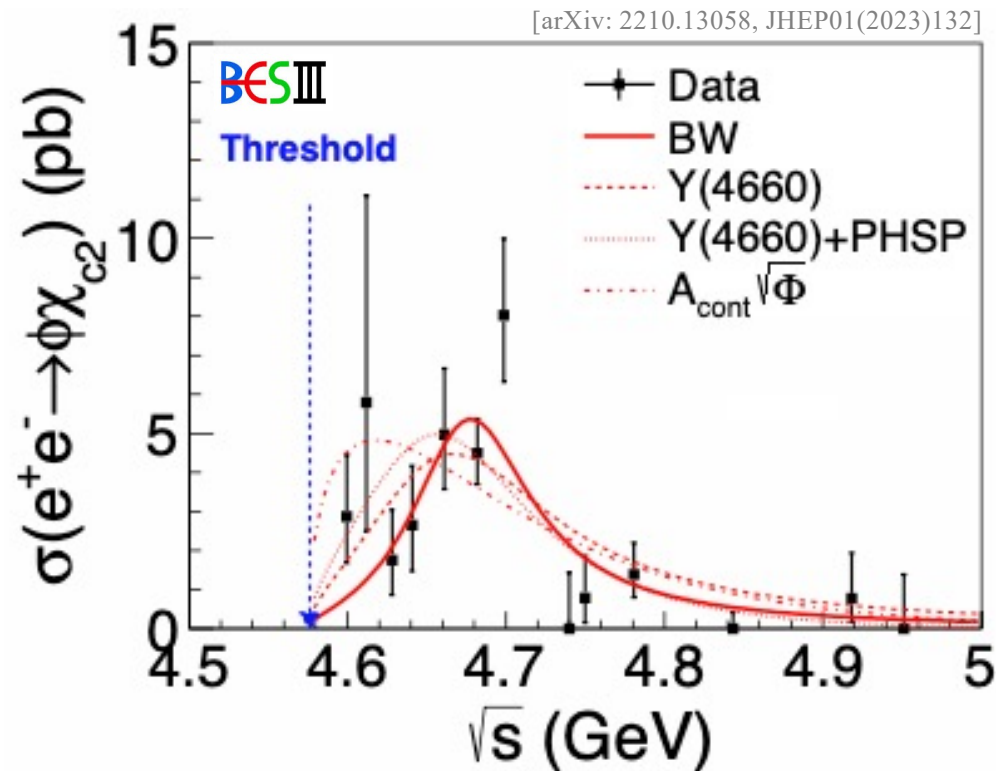
[Subm. to Phys. Rev. Lett., arXiv:1903.04695 [hep-ex]]



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

[arXiv: 2210.13058, JHEP01(2023)132]

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



- Cross section measurement:
 $e^+e^- \rightarrow \phi \chi_{c2}$
- Evidence for $Y(4660) \rightarrow \phi \chi_{c2}$
- Statistical significance of 3.1σ
- No signal for $Y(4660) \rightarrow \phi \chi_{c1}$

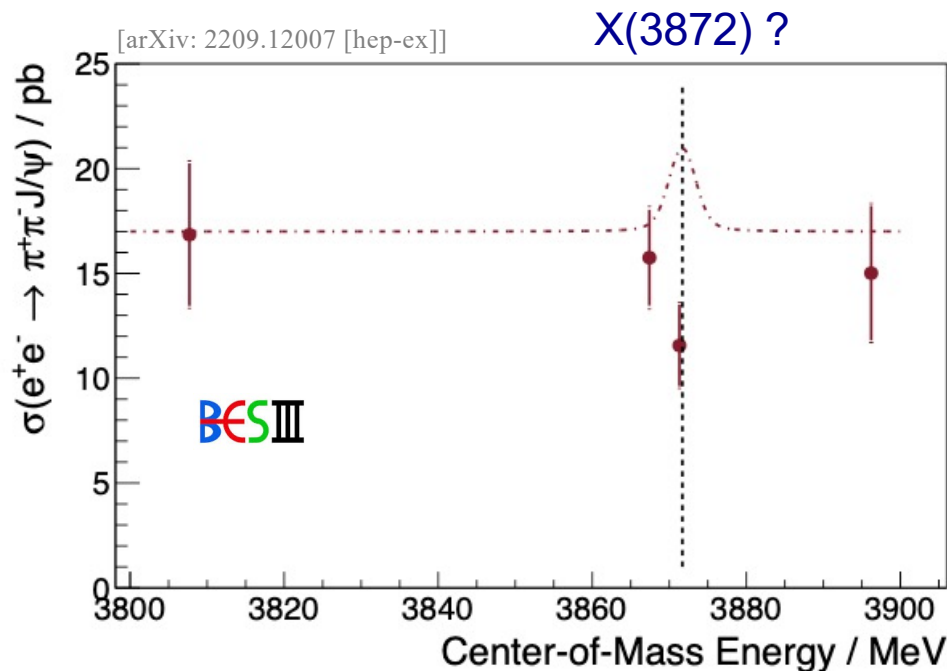
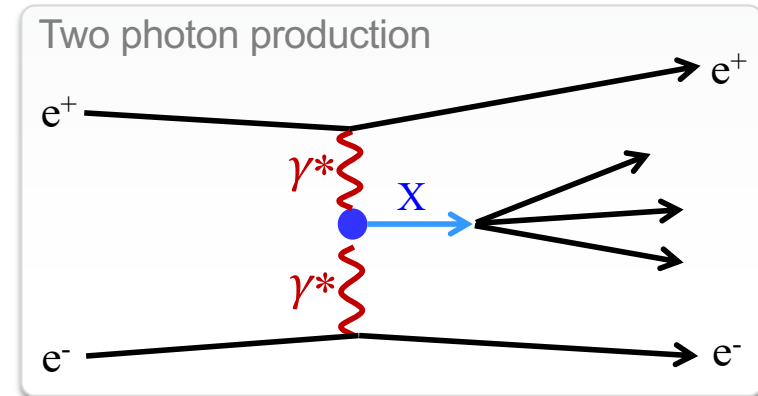
- Different fit models:
 - Single BW model (red line)

$$M = (4672.8 \pm 10.8 \pm 3.9) \text{ MeV}/c^2$$

$$\Gamma = (93.2 \pm 19.8 \pm 9.4) \text{ MeV}$$

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*)



Direct production in e^+e^- annihilation at BESIII:

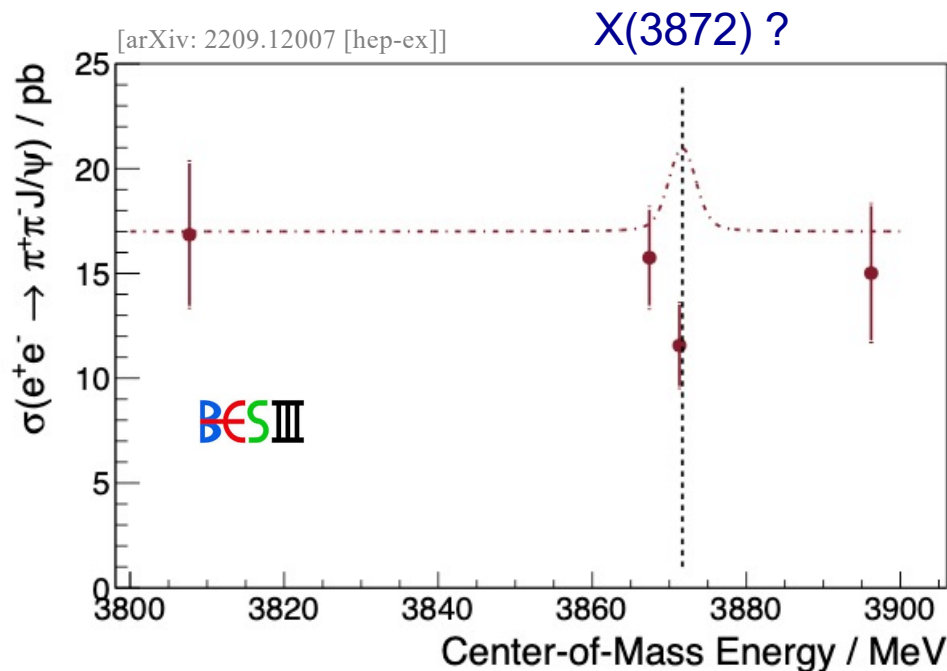
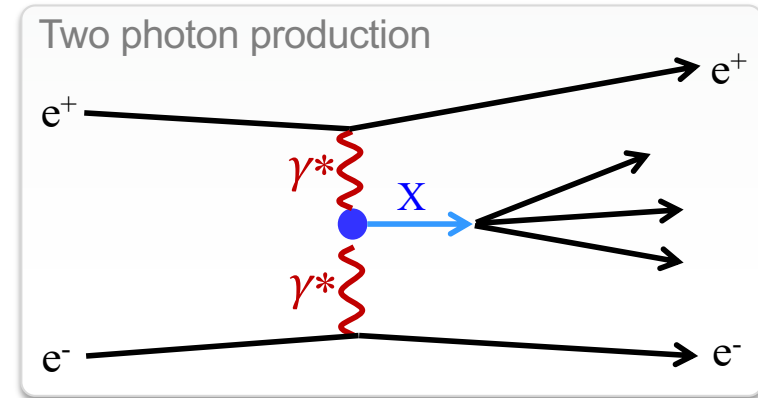
- VMD prediction: $\Gamma_{ee} \gtrsim 0.036 \text{ eV}$
[A.Denig et al. PLB 736 (2014) 221]
- After observation (5.1σ) of $e^+e^- \rightarrow \chi_{c1}$
[BESIII, PRL 129 (2022) 122001]
- Search for $e^+e^- \rightarrow X(3872)$
 - No enhancement observed in cross section
 - Provide UL(CL90) assuming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

$$\Rightarrow \Gamma_{ee} \times \mathcal{B} < 7.5 \times 10^{-3} \text{ eV}$$

$$\Gamma_{ee}(X(3872)) < 0.32 \text{ eV}$$

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*)



Direct production in e^+e^- annihilation at BESIII:

- VMD prediction: $\Gamma_{ee} \gtrsim 0.036 \text{ eV}$
[A.Denig et al. PLB 736 (2014) 221]
- After observation (5.1σ) of $e^+e^- \rightarrow \chi_{c1}$

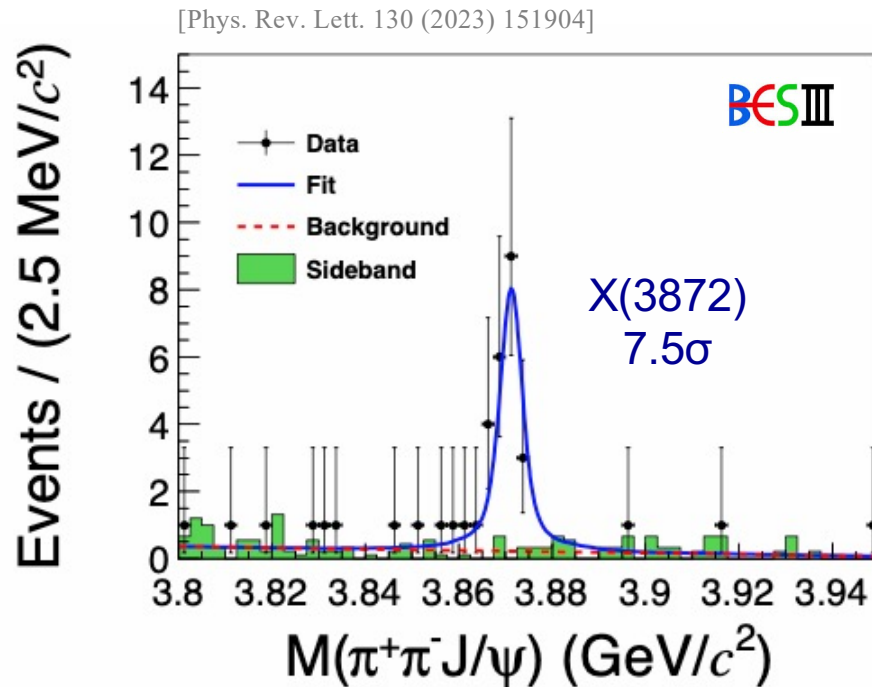
**See dedicated talk by M. Lellmann
→ this afternoon's parallel session**

- Provide $\text{UL}(\text{CL90})$ assuming average value:
 $\Gamma_{\text{tot}} = 1.19 \text{ MeV}$

$$\Rightarrow \Gamma_{ee} \times \mathcal{B} < 7.5 \times 10^{-3} \text{ eV}$$

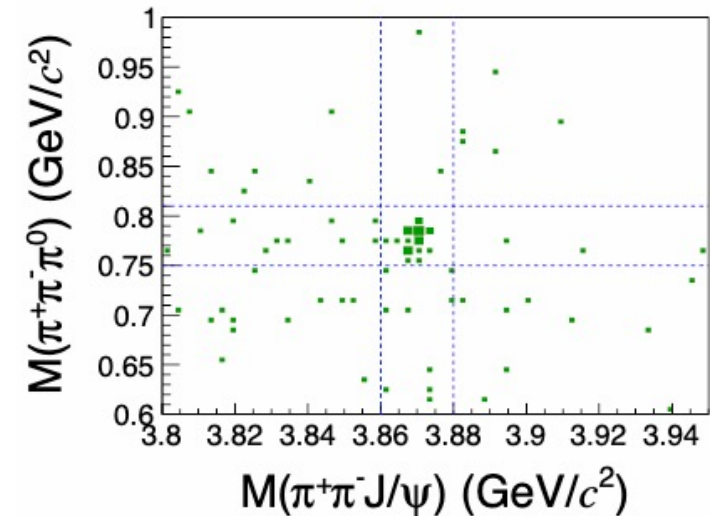
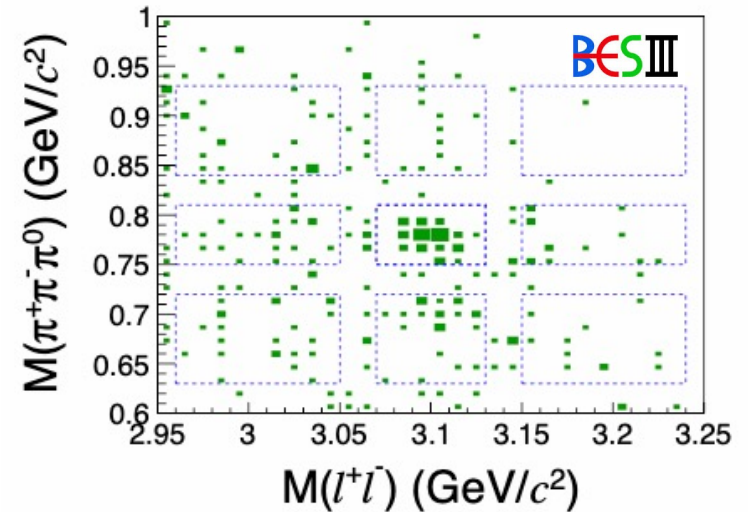
$$\Gamma_{ee}(\text{X}(3872)) < 0.32 \text{ eV}$$

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



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

J/ψ and ω signal & sideband regions



$X(3872)$ and ω signal regions

- BESIII successfully operating since 2008
 - World largest data sets in tau-charm mass region, unique XYZ data
 - Recent machine upgrade extends studies up to $E_{\text{cms}} = \sim 4.9 \text{ GeV}$
- BESIII successfully operating since 2008
 - Supernumerary vector Y states consistently resolved (statistics)
 - $Y(4260)$ and $Y(4360) \rightarrow Y(4230), Y(4360)$
 - 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
 - $X(4140,), X(4274), X(4500) \rightarrow \phi J/\psi$ not seen
- Next *machine upgrade* planned (summer 2024) $\Rightarrow E_{\text{cms}} > 5 \text{ GeV}$

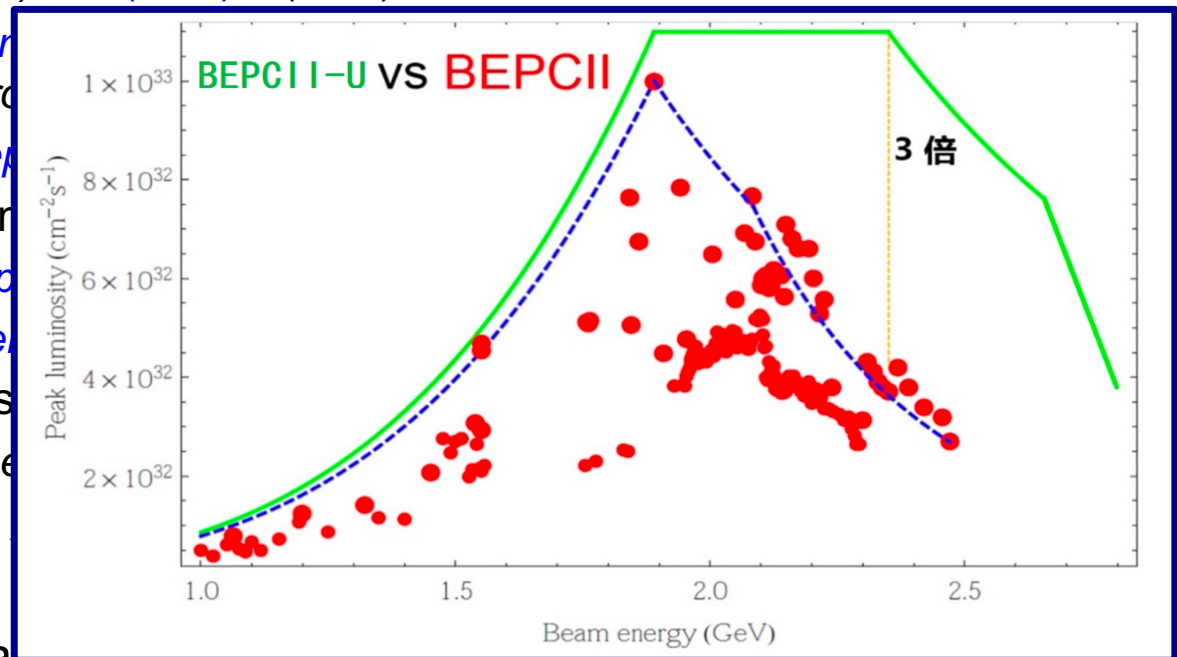
- BESIII successfully operating since 2008
 - World largest data sets in tau-charm mass region, unique XYZ data
 - Recent machine upgrade extends studies up to $E_{\text{cms}} = \sim 4.9$ GeV

- BESIII successfully operating since 2008

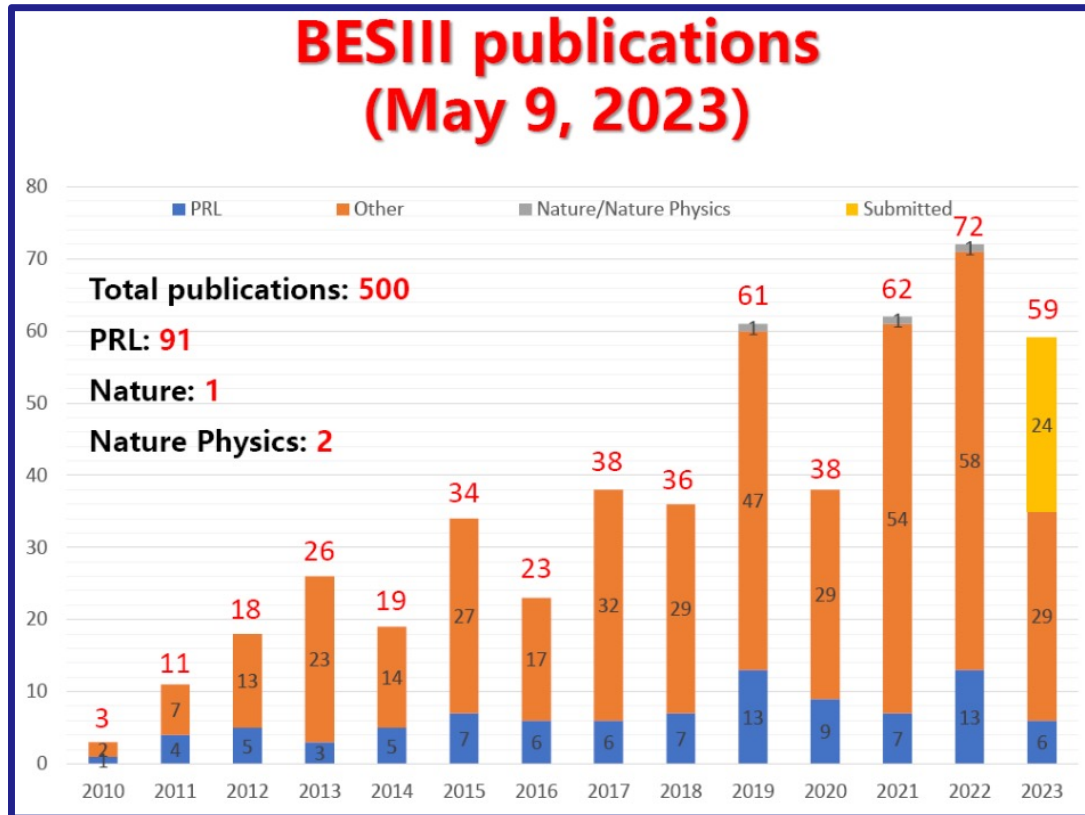
- Supernumerary vector Y states consistently resolved (sta

Thank you!

- $Y(4260)$ and $Y(4360) \rightarrow Y(4230), Y(4360)$
 - First *decays to open* $c\bar{c}$ and/or light hadrons
 - More *candidates* reported
- Charged Z_c states are now observed
 - First complete *isospin* multiplets
 - First *strange* partners
- The first of these states are now confirmed
 - *Line shape* to be measured
 - $X(4140, \pm), X(4274), \dots$



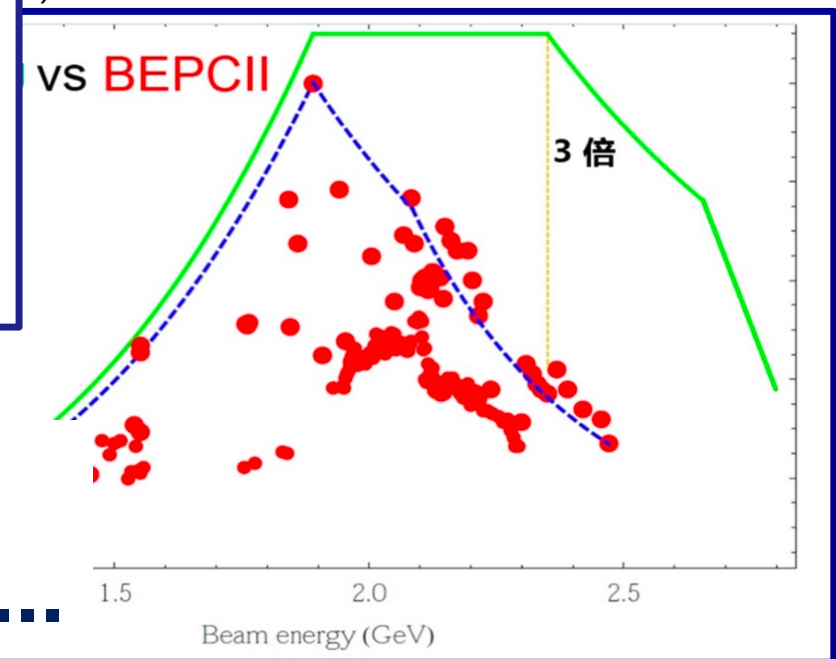
- Next machine upgrade planned (summer 2021) $E_{\text{cms}} > 6.0$ GeV



... region, unique XYZ data
 ... up to $E_{\text{cms}} = \sim 4.9 \text{ GeV}$

... resolved (sta
 0)

Thank you!



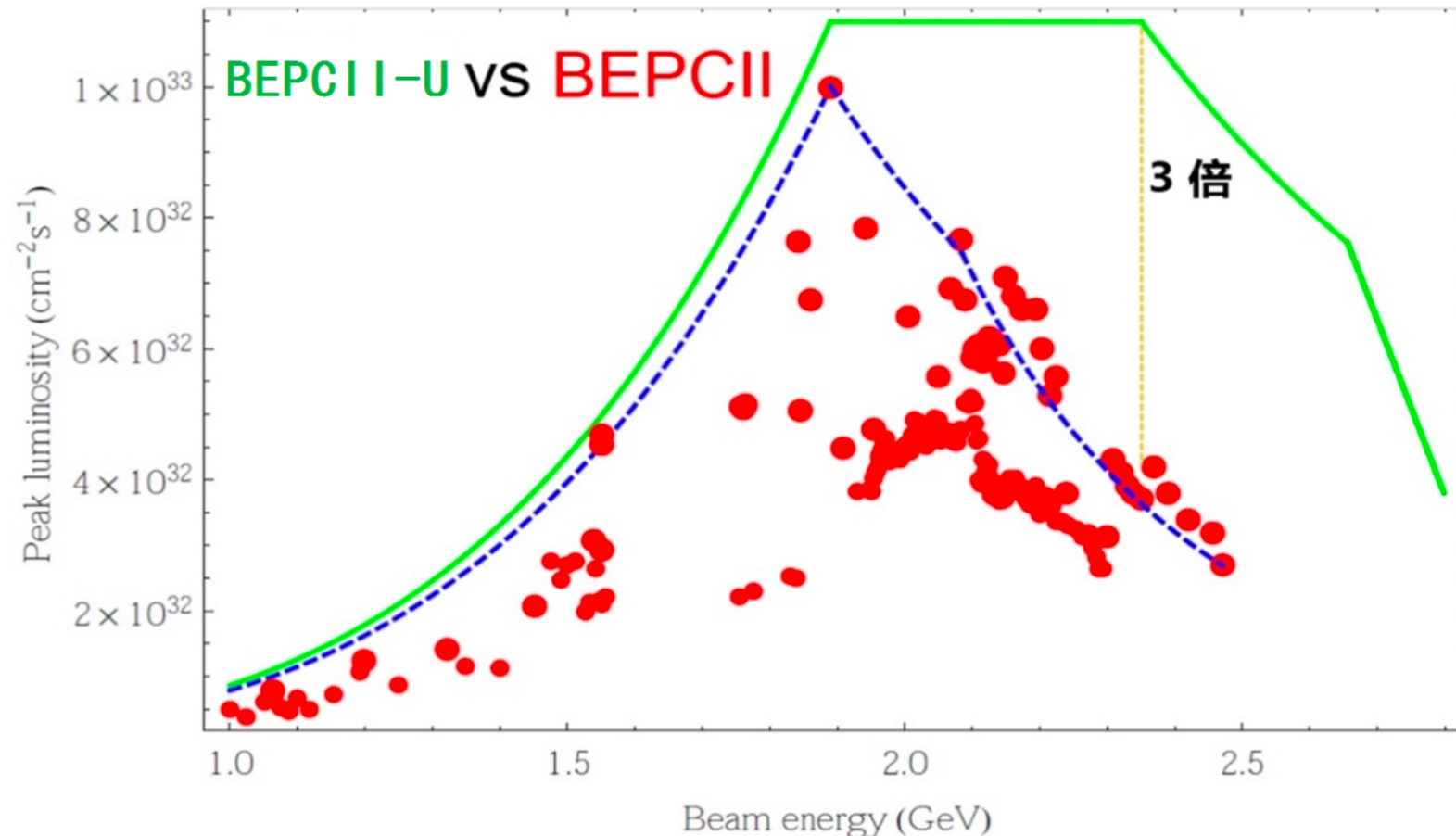
First strange partner
 The first of these states

Data for our next 500 publications ...

- Next machine upgrade planned (summer 2024) $\Rightarrow E_{\text{cms}} > 5 \text{ GeV}$

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