XYZ states in BESIII

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On behalf of BESIII Collaboration

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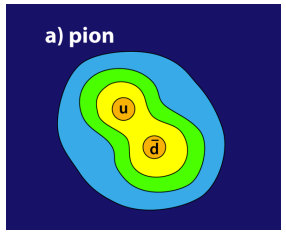
Arenzano, May, 2019

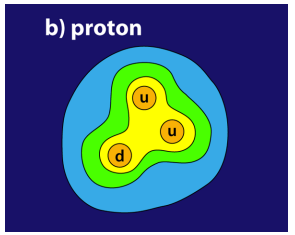
Quark Model

- In 1964, the model was proposed independently by Gell-Mann and Zweig

Mesons



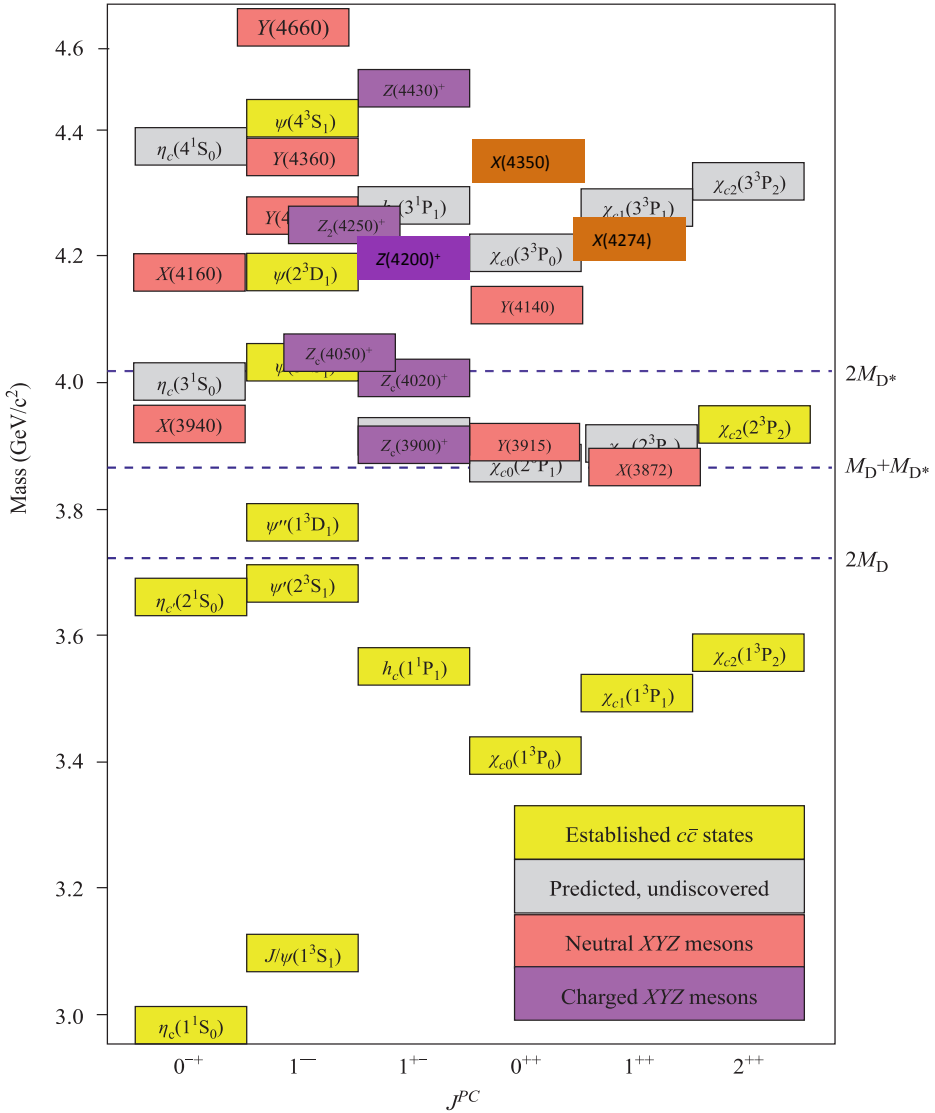
Baryons



- Additions to the Original Quark Model – Charm
  - J/ψ, ψ(3686), ψ(3770), ψ(4040), ψ(4160), ψ(4415), etc.

- Cornell model was proposed to depict the interaction between the charm and anti-charm quarks.

Charmonium Spectroscopy

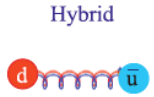


Front.Phys. 10 (2015) no.2, 121-154,the latest results added.

QCD tetraquarks

Bound states of diquark anti-diquark, Large number of states(charged and neutral) foreseen

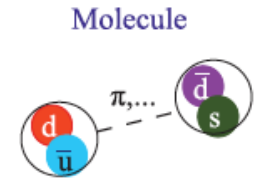
QCD hybrids



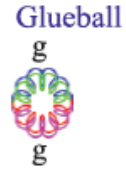
Bound states with a pair of quarks and excited gluonic degrees of freedom. Lattice and model predictions for the lowest-mass hybrid ~4.2 GeV/c^2

Molecules

Loosely bound states of a pair of mesons, Small number of states, Small widths above threshold



Glueball



HadroCharmonium

Compact charmonium embedded in light quark mesonic excitation interacting by analog of Van der Waals force

Others: Threshold, cusp, or coupled-channel effect produce a cross section enhancement

X(3872)

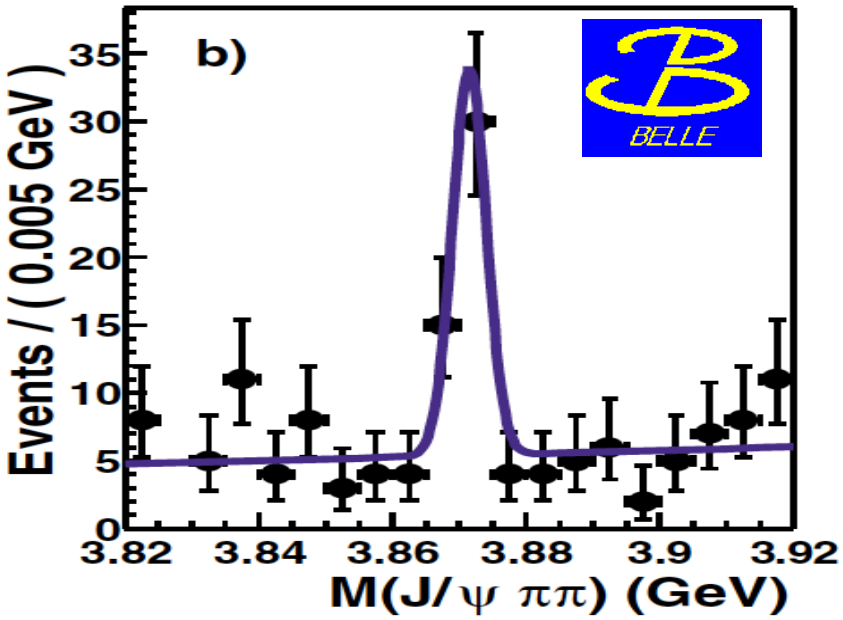
The first particle in charmonium-like XYZ family, discovered by Belle Collaboration in $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$

[PRL 91,262001(2003)]

Confirmed by CDF, D0, BaBar, LHCb, and BESIII

- $M = (3871.69 \pm 4.1 \pm 6.3)\ MeV/c^2$
- Very close to $D^0\ D^{*0}$ threshold
- Very narrow width (< 1.2 MeV)
- No isopin partner found
- Decay into $J/\psi\ \pi^{+}\ \pi^{-}$, $J/\psi\ \pi^{+}\ \pi^{-}\ \pi^{0}$,

  $D^0\ D^{*0}$, $D^0D^0\pi^0$, $\gamma J/\psi$, $\gamma\psi(2S)$
- Isospin? $\rho J/\psi$ and $\omega J/\psi$



X(3872) Spin Parity

[PRD 92,011102(2015)]

Decay into $\gamma J/\psi$: C=+ state

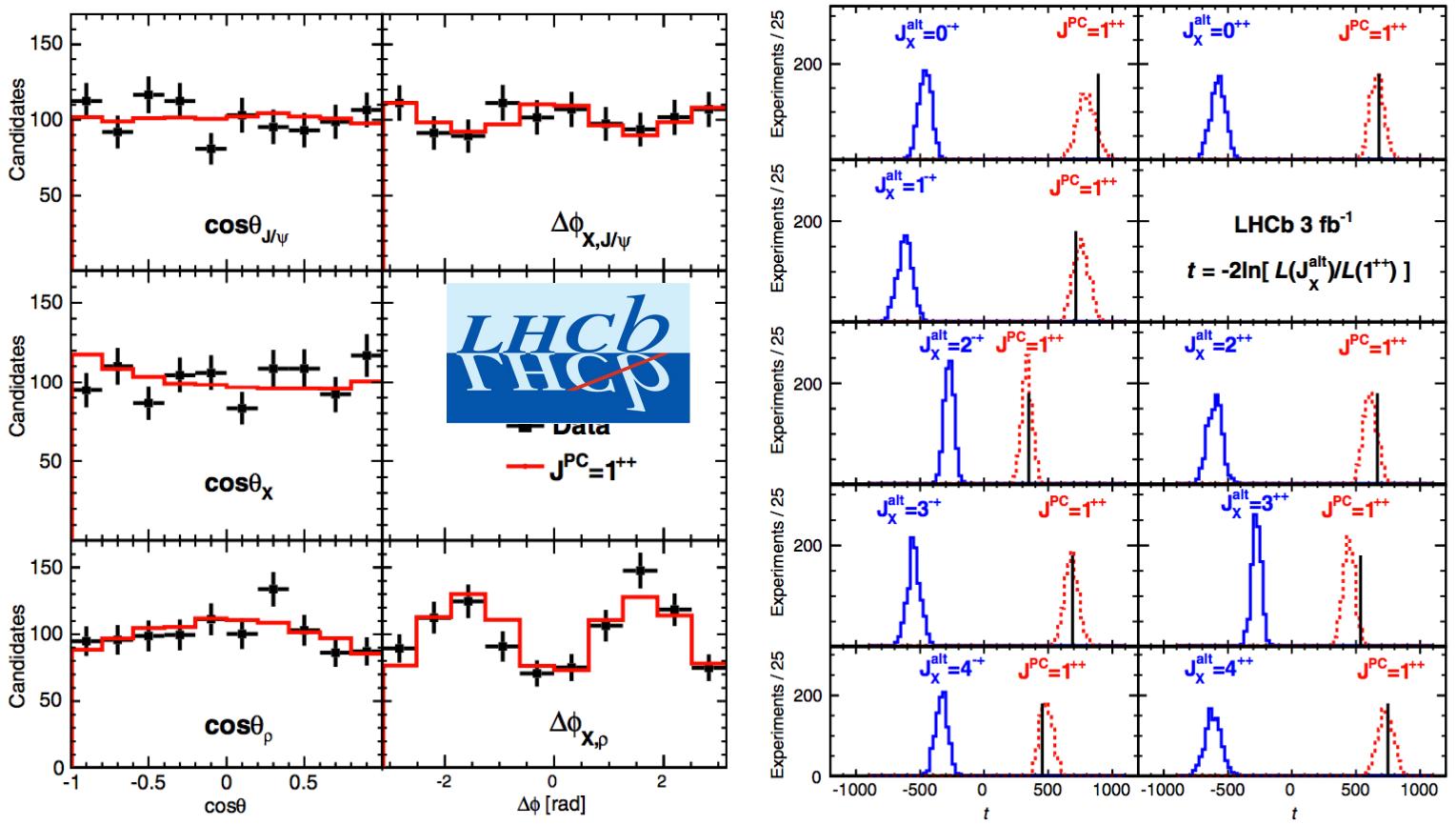
CDFII narrow it to 1^{++} or 2^{-+}

[PRL 98,132002 (2007)]

LHCb: 2^{-+} rejected > 8σ

[PRL 110, 222001 (2013)]

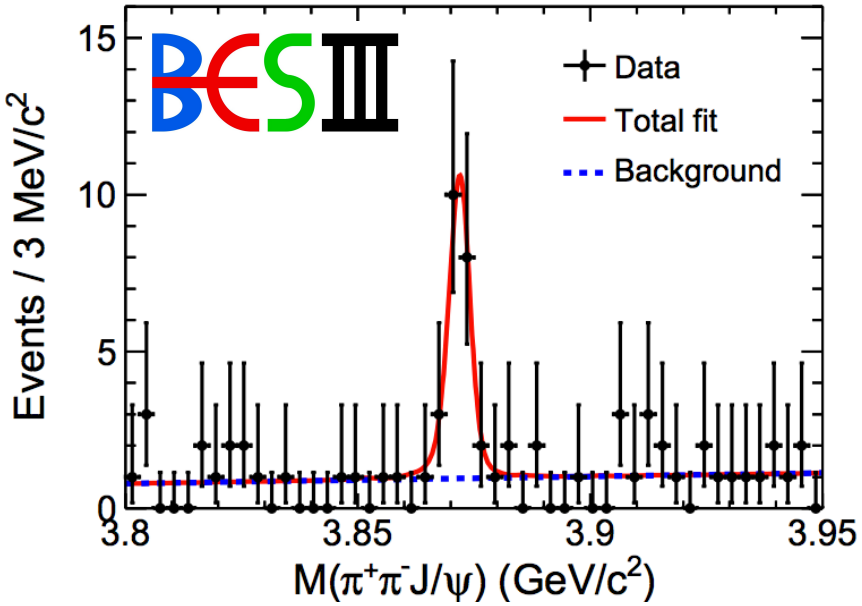
$J^{pc} = 1^{++}$

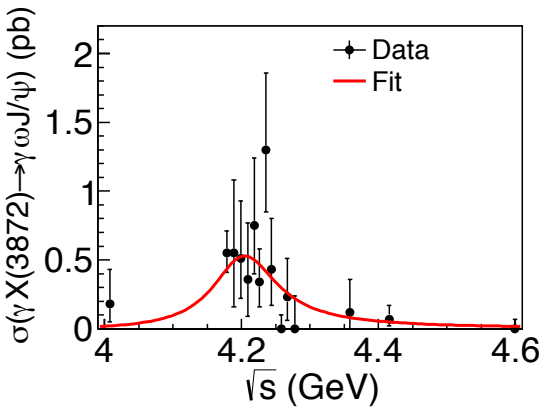


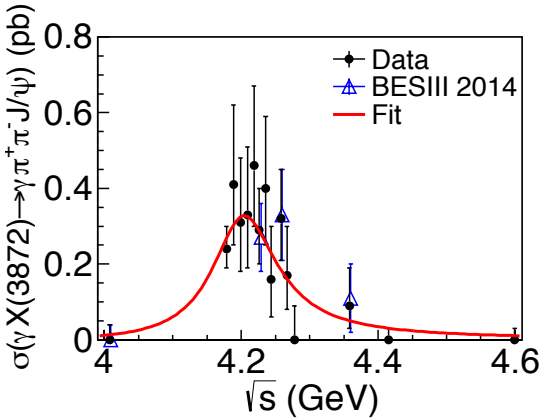
The analysis of the angular correlations is performed with 3 fb^{-1} data collected in proton-proton collision

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

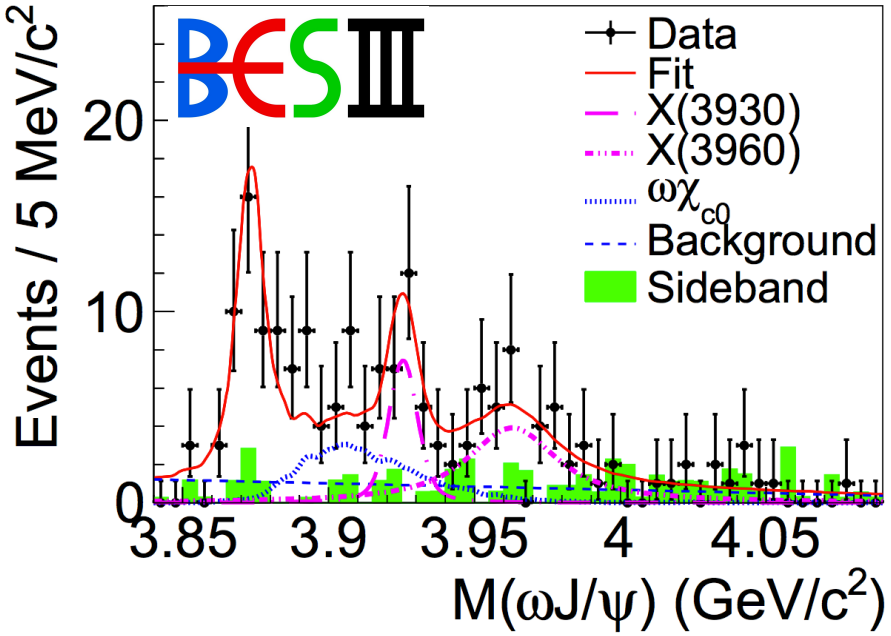
[PRL 112,092001(2014)]







[arXiv:1903.04695]

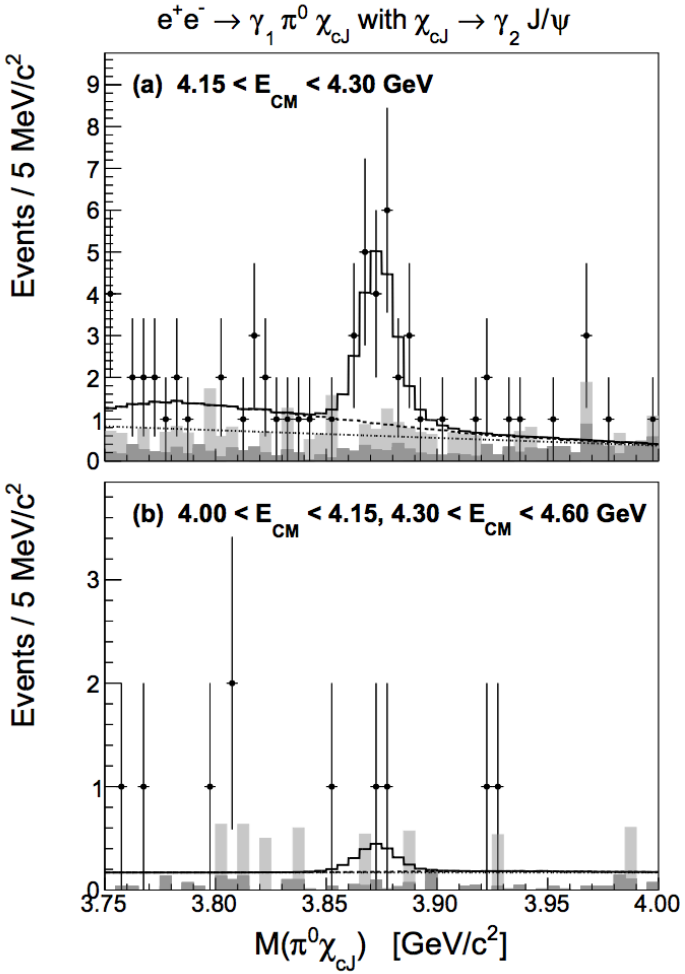


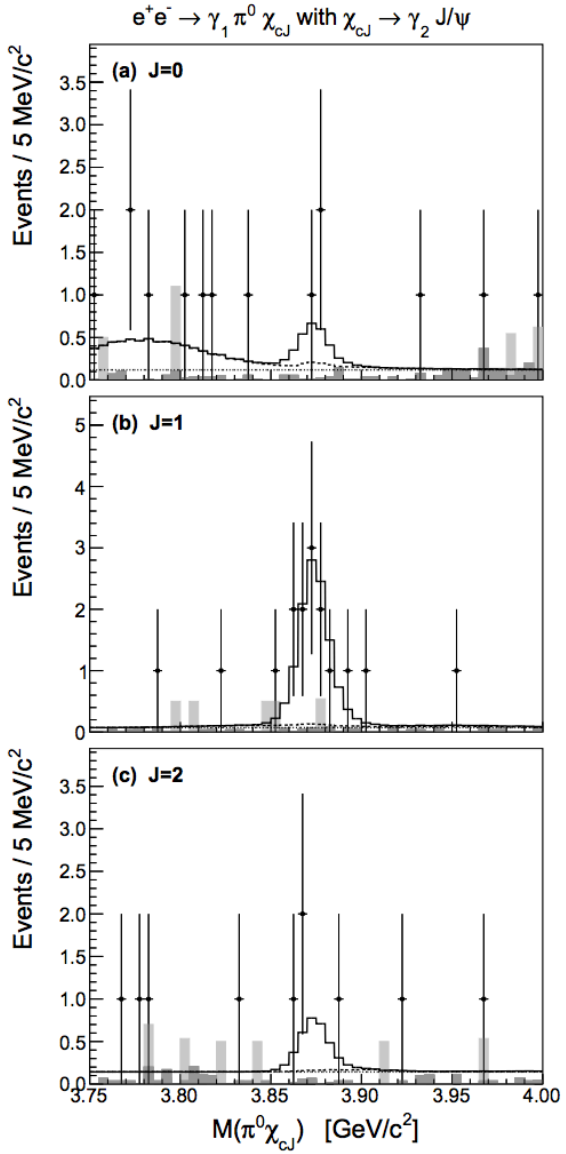
$$\mathcal{R} = \frac{\mathcal{B}[X(3872)\to\omega J/\psi]}{\mathcal{B}[X(3872)\to\pi^+\pi^- J/\psi]} = 1.6^{+0.4}_{-0.3} \pm 0.2$$

M = $(4200.6^{+7.9}_{-13.3} \pm 3.0)$ MeV/c^2

Γ = $(115\ ^{+38}_{-26} \pm 12)$ MeV

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





$R_J = B(X \to \pi^0\chi_{cJ}) / B(X \to \pi^+\pi^- J/\psi)$:

$R_0 < 19$ (90% U.L.)

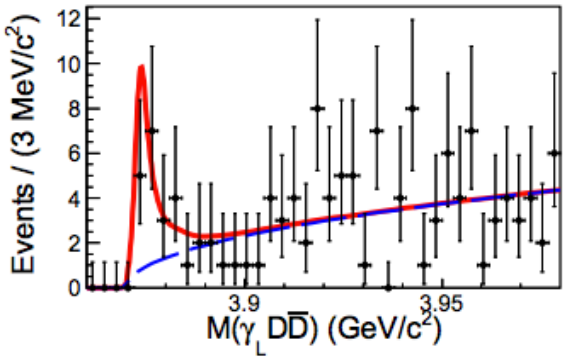
$R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$

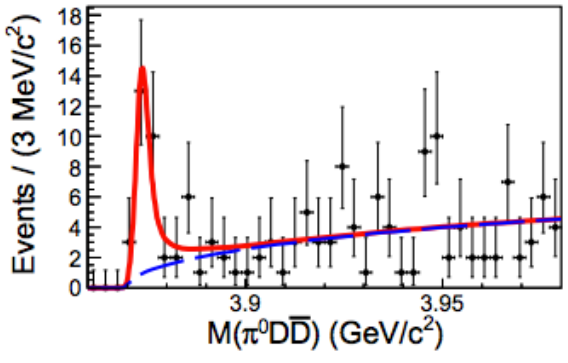
$R_2 < 1.0$ (90% U.L.)

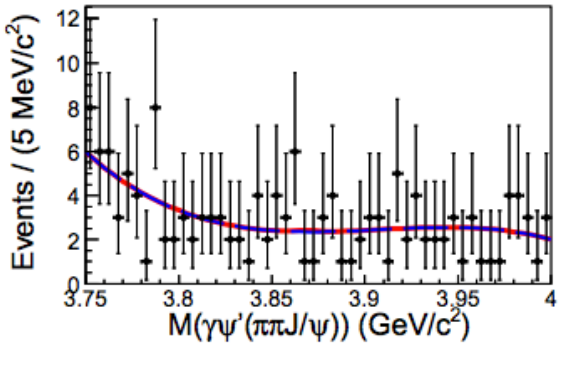
Large value of R1 supports the tetraquark interpretation of X(3872)

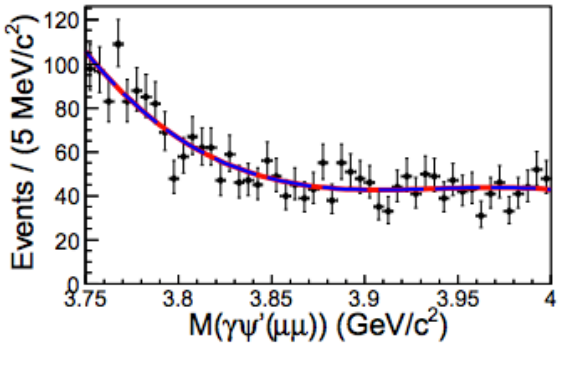
[arXiv:1901.03992]

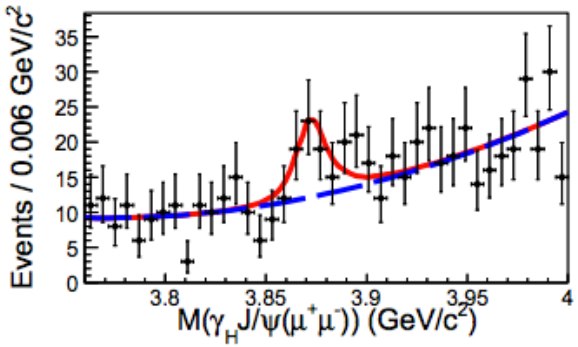
Open charm and radiative decay of X(3872)

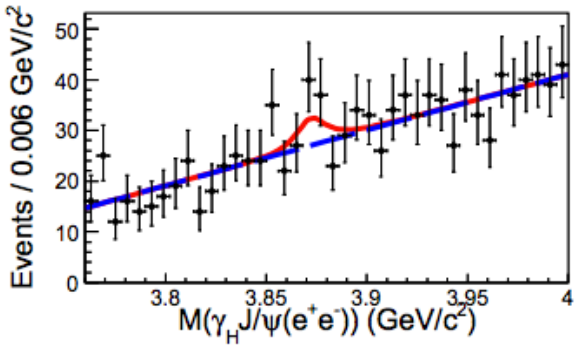


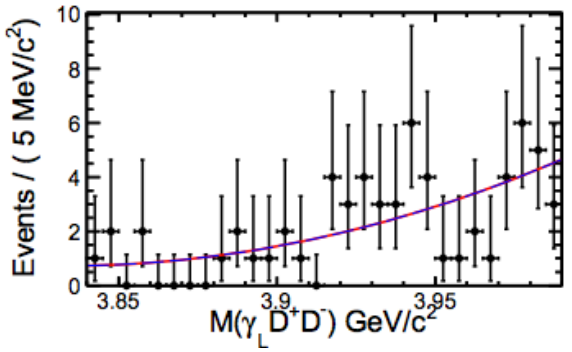












Preliminary results

BESIII

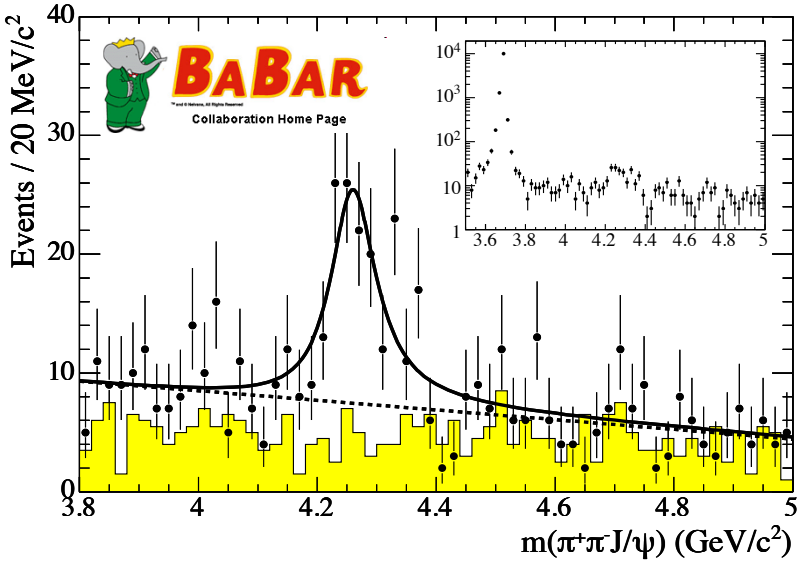
mode	$D^{*0}\bar{D}^0 + c.c.$	$\gamma J/\psi$	$\gamma\psi'$	γD^+D^-	$\omega J/\psi$	$\pi^0\chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]

Y state ($\pi^+\pi^-J/\psi$)

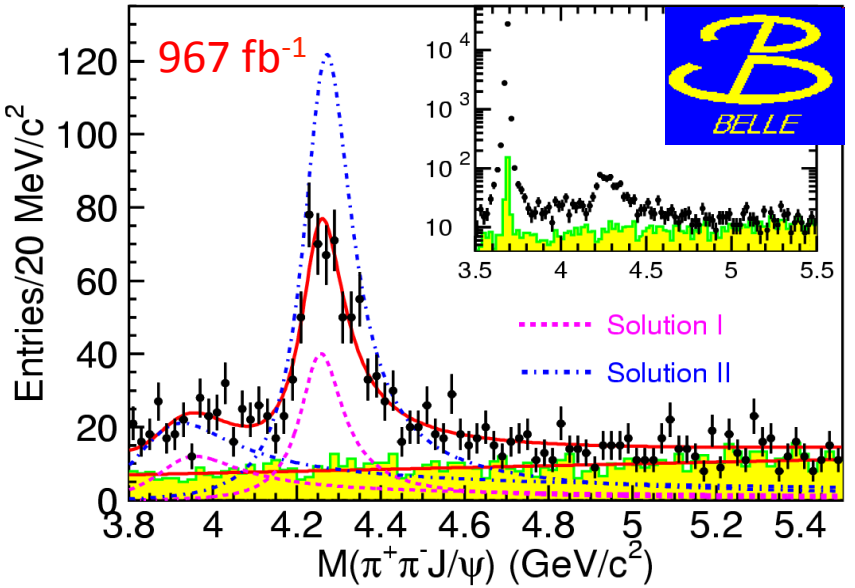
First state - Y(4260), discovered in ISR process at BaBar, confirmed by Belle and CLEO.

BaBar and Belle improve the measurements with full data samples.

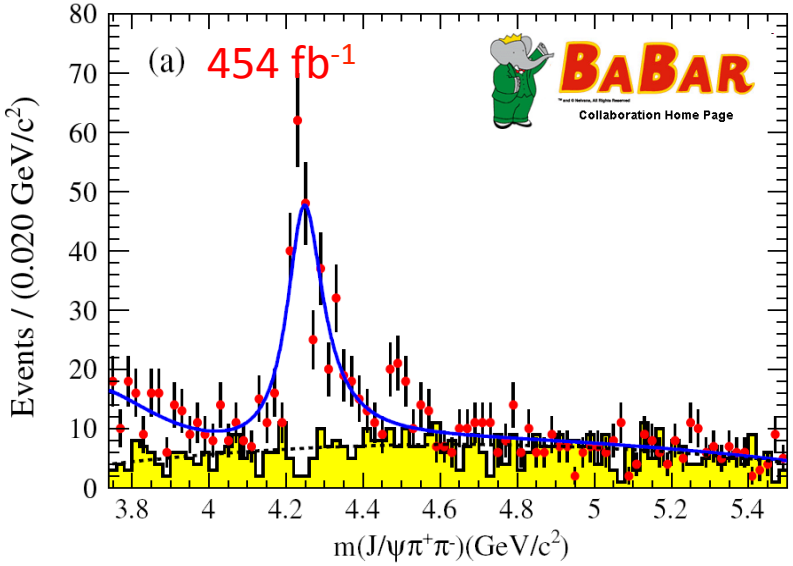
[PRL95, 142001 (2005)]



[PRL110, 252002 (2013)]

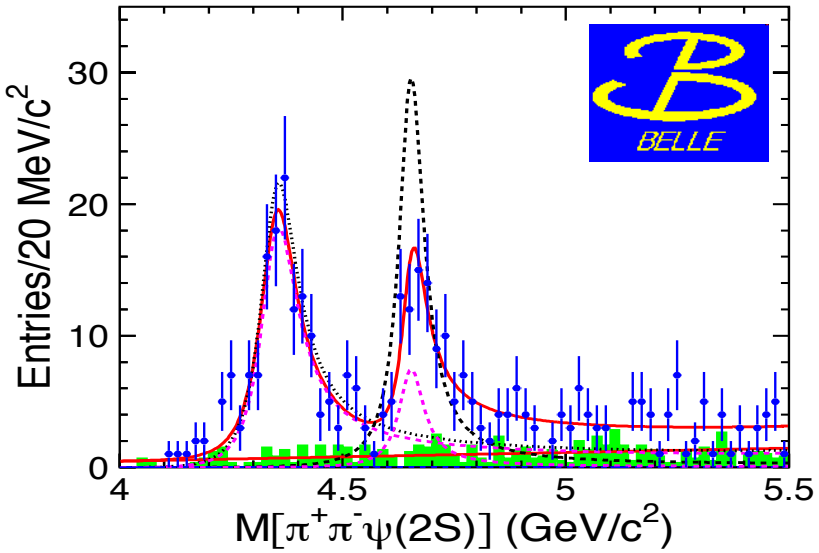


[PRD86, 051102 (2012)]

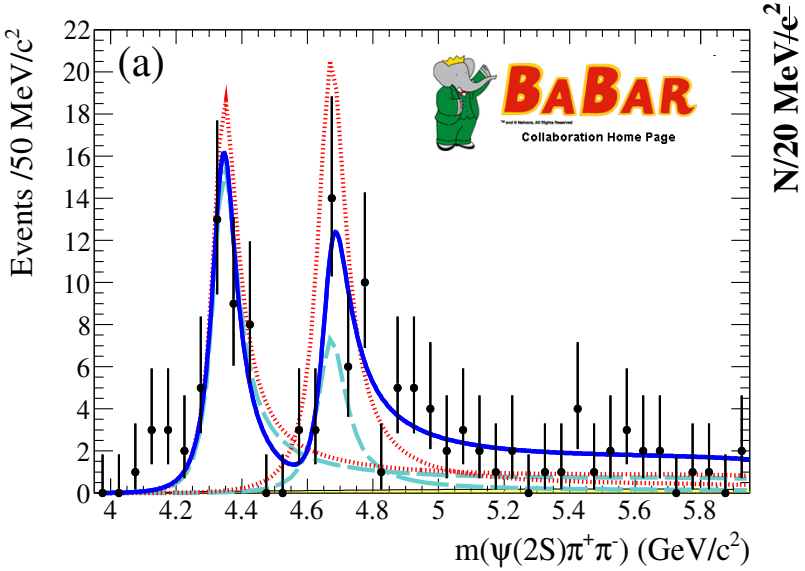


More Y states

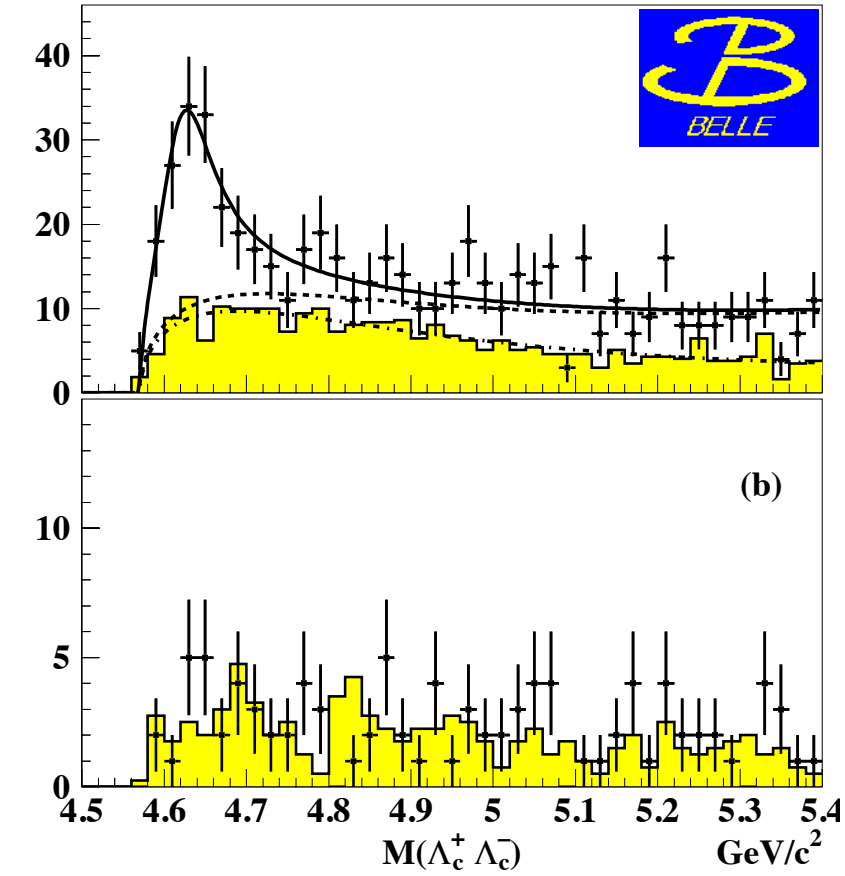
[PRD91, 112007 (2014)]



[PRD89, 111103 (2014)]



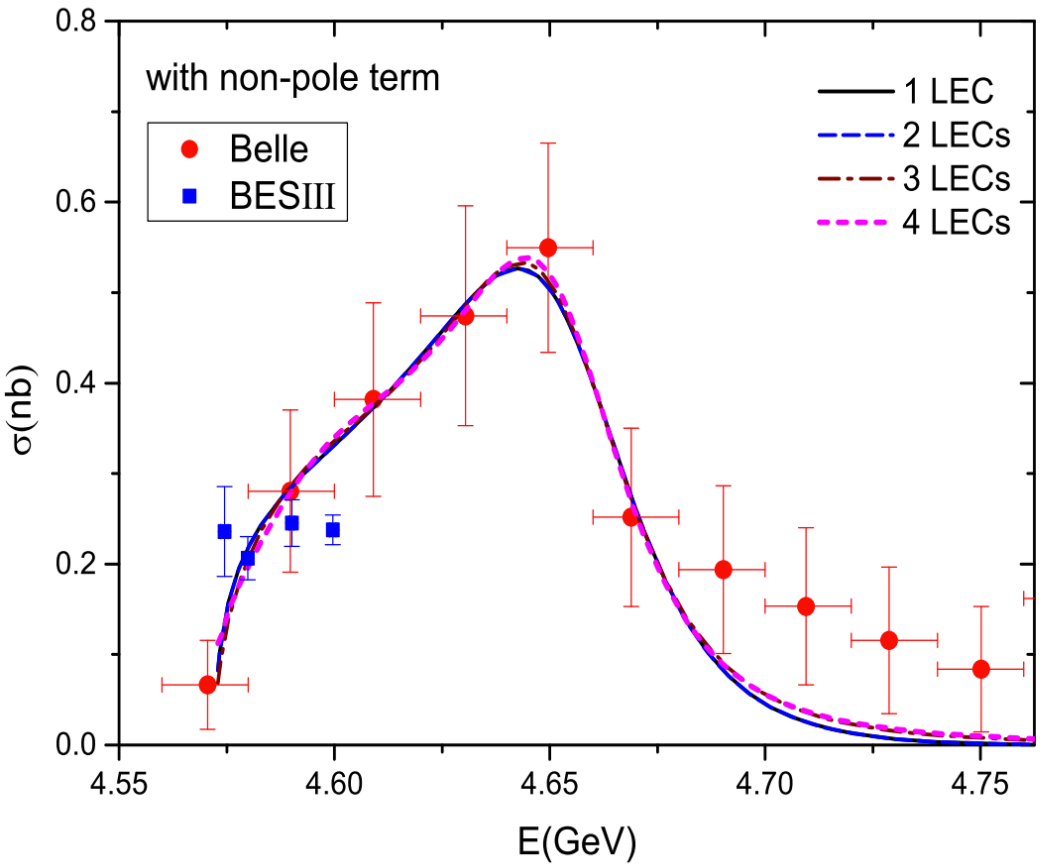
[PRL101, 172001 (2008)]



Y(4360) is found in $\pi^+ \pi^- \psi(2S)$

A peak around 4660 MeV is found both in $\pi^+ \pi^- \psi(2S)$ and Λc pair.
The mass and width are consistent with each other

Y(4660)



Y(4660) baryonic coupling is 10 times larger than mesonic coupling

[PRD91, 112007 (2014)] [PRL101, 172001 (2008)]

A hidden charm Baryonium?

[PRL104, 132005 (2010)]

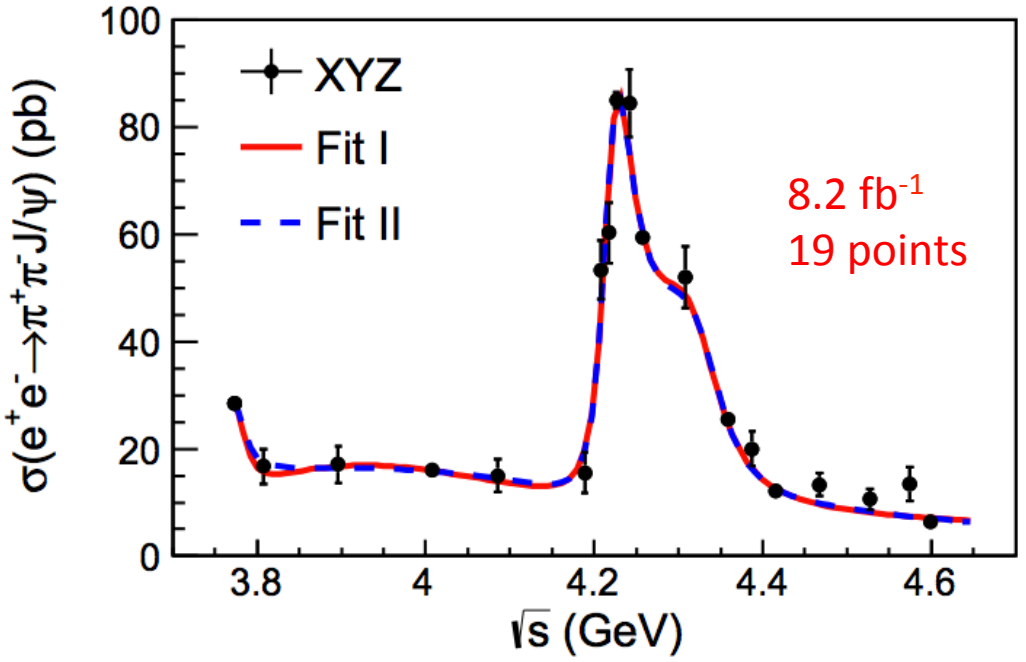
BESIII indicates different trend for energy dependence comparing with Belle

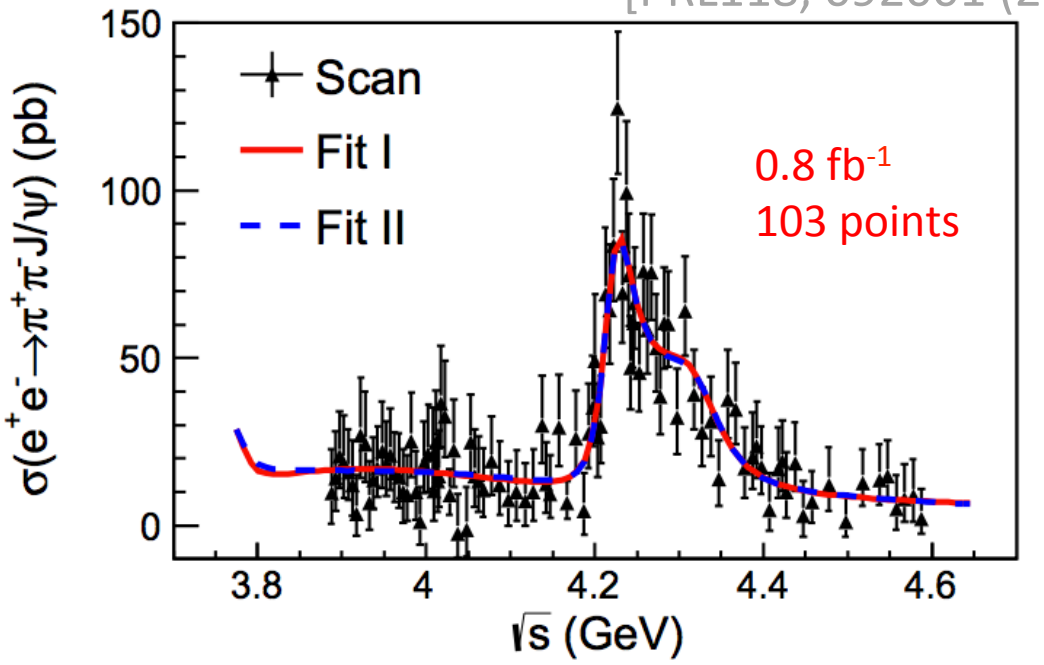
[PRL120, 132001 (2018)] [PRD96, 116001 (2017)]

More data from BESIII at threshold and above 4.6 GeV in the future

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

[PRL118, 092001 (2017)]





$M_1 = (4222.0 \pm 3.1 \pm 1.4)$ MeV/c^2

$\Gamma_1 = (44.1 \pm 4.3 \pm 2.0)$ MeV

Lower mass and narrower width comparing to Y(4260)

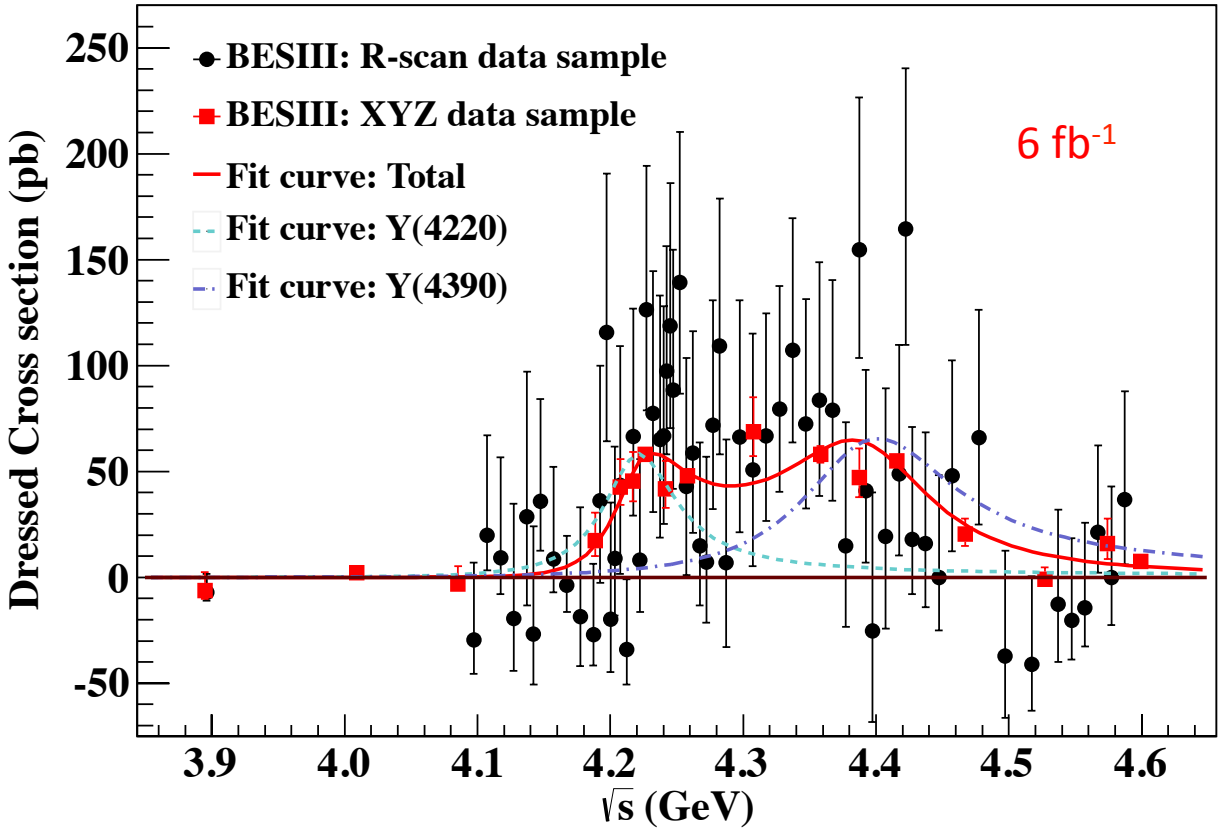
$M_2 = (4320.0 \pm 10.4 \pm 7.0)$ MeV/c^2

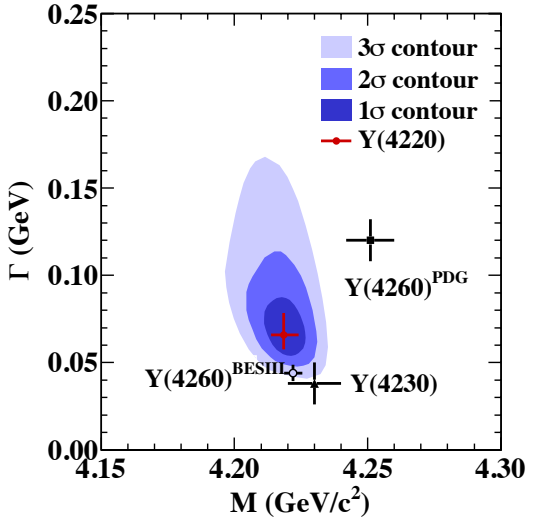
$\Gamma_2 = (1014\ ^{+25.3}_{-19.7} \pm 10.2)$ MeV

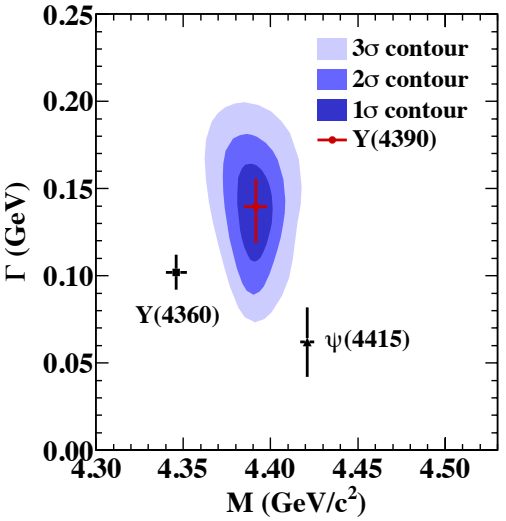
Observed for the first time !

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

[PRL118, 092002 (2017)]







$M_1 = (4218.4^{+5.5}_{-4.5} \pm 0.9)$ MeV/c^2

$\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 0.4)$ MeV

$M_2 = (4391.5^{+6.3}_{-6.8} \pm 1.0)$ MeV/c^2

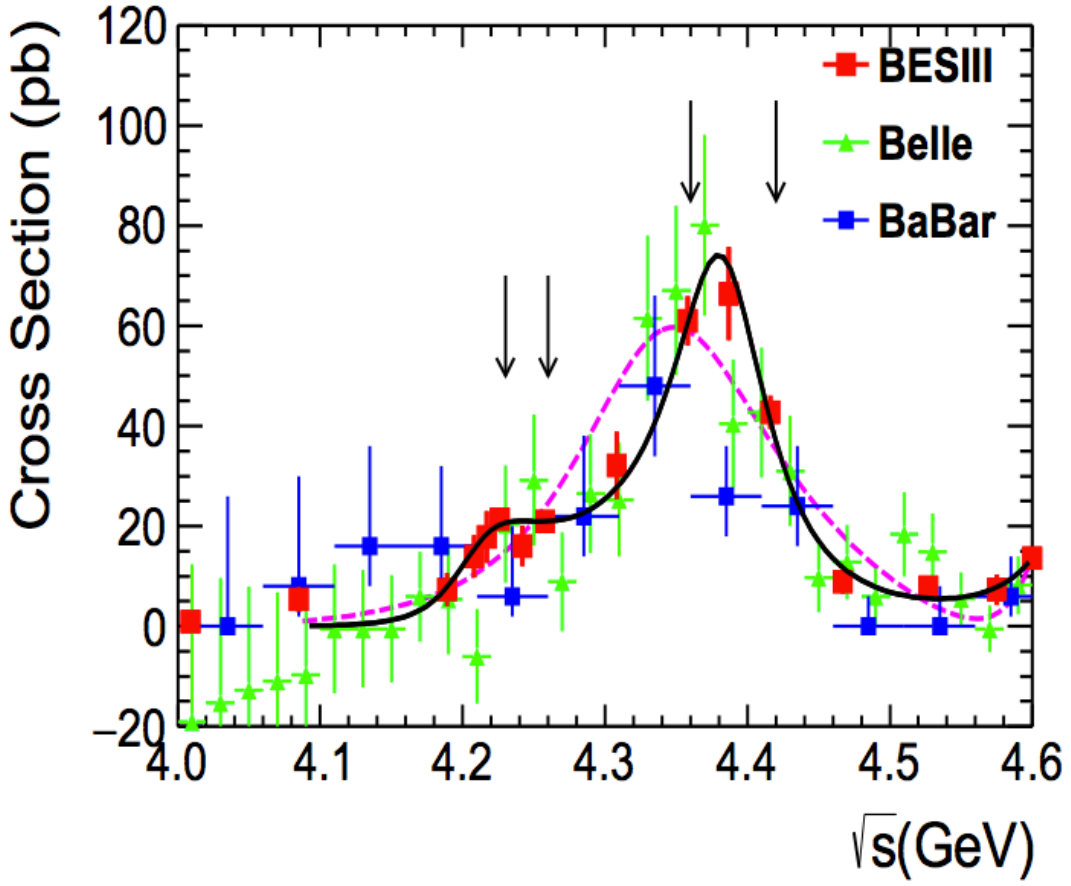
$\Gamma_2 = (139.5^{+16.2}_{-20.6} \pm 0.6)$ MeV

$e^+ e^- \to \pi^+ \pi^- \psi(3686)$

[PRD96, 032004 (2017)]

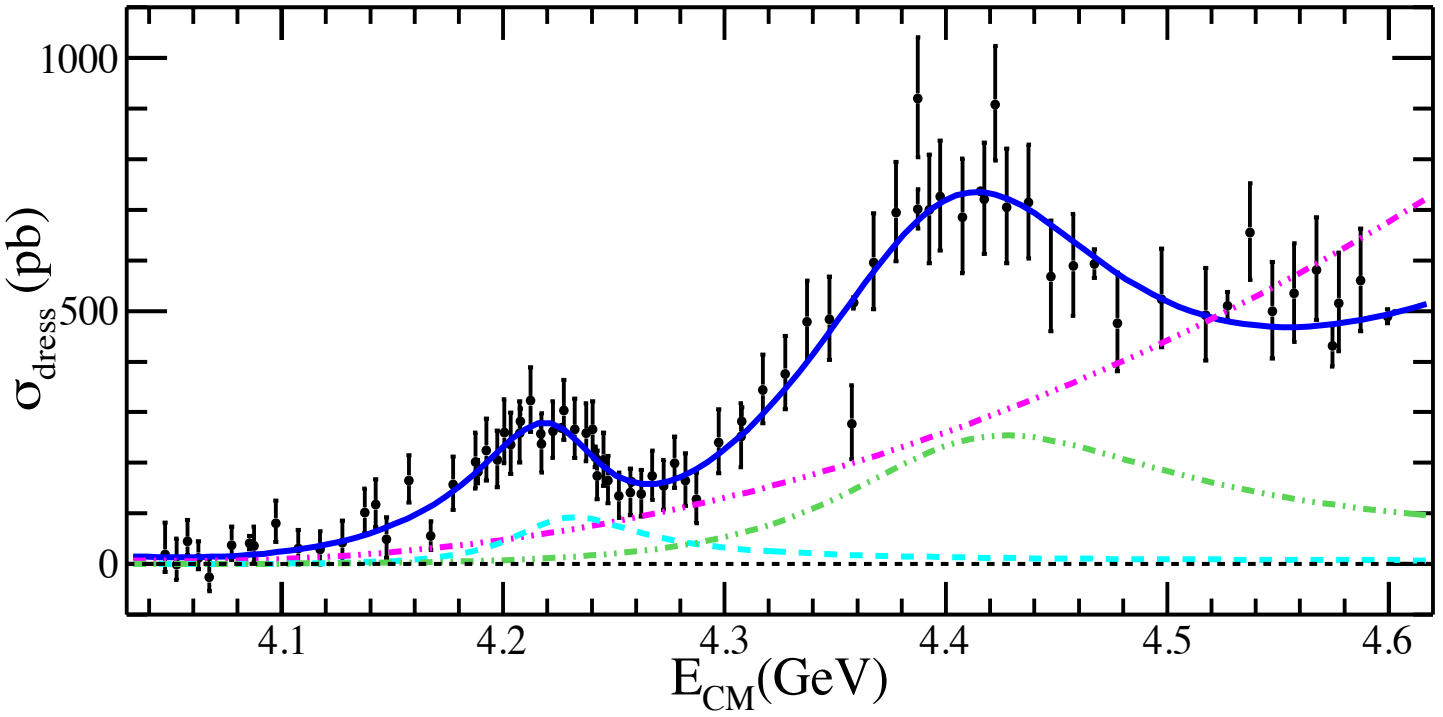
Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	1.61 ± 1.27	1.80 ± 1.41
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	7.25 ± 2.8	10.96 ± 3.8
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

Y(4220) is necessary
significance = 5.8σ



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

[PRL122, 102002 (2019)]



M_1 = (4228.6 ± 4.1 ± 6.3) MeV/c^2

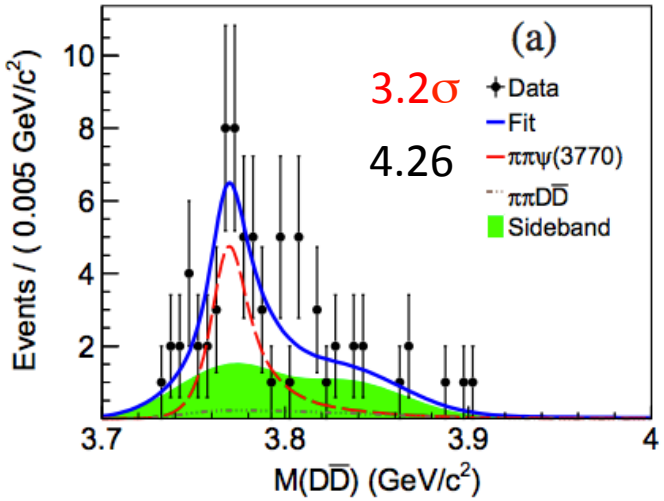
Γ_1 = (77.0 ± 6.8 ± 6.3) MeV

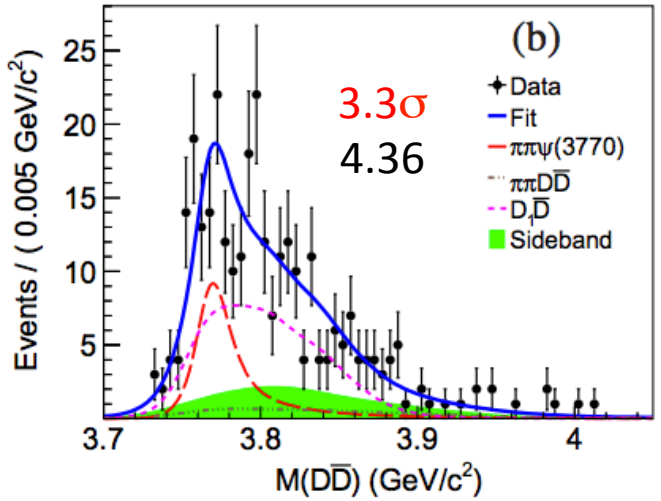
Consistent with previous observations of the Y (4220) state and the theoretical prediction of a $D\bar{D}_1(2420)$ molecule.

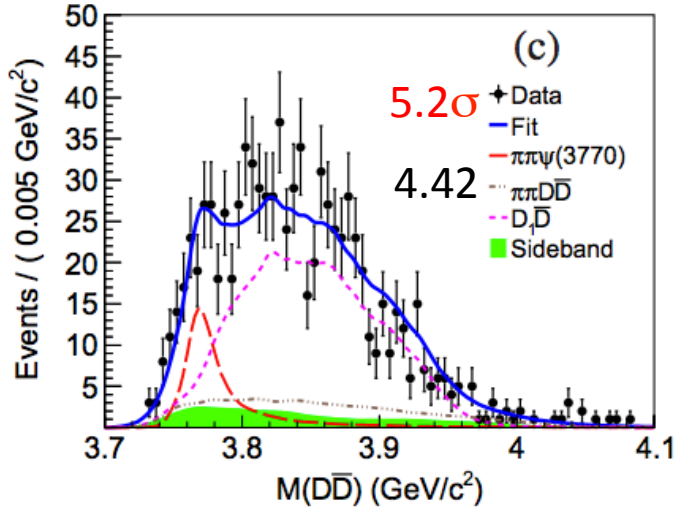
First observation of Y (4220) associated with an open-charm final state.

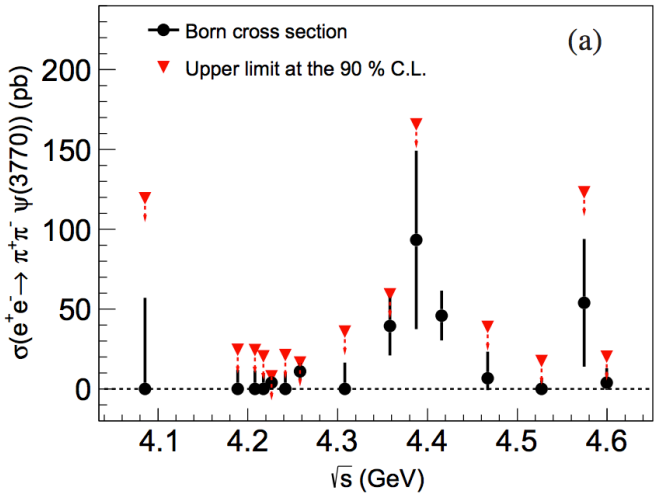
$e^+ e^- \to \pi^+ \pi^- \psi(3770)$

[arXiv:1903.08126]







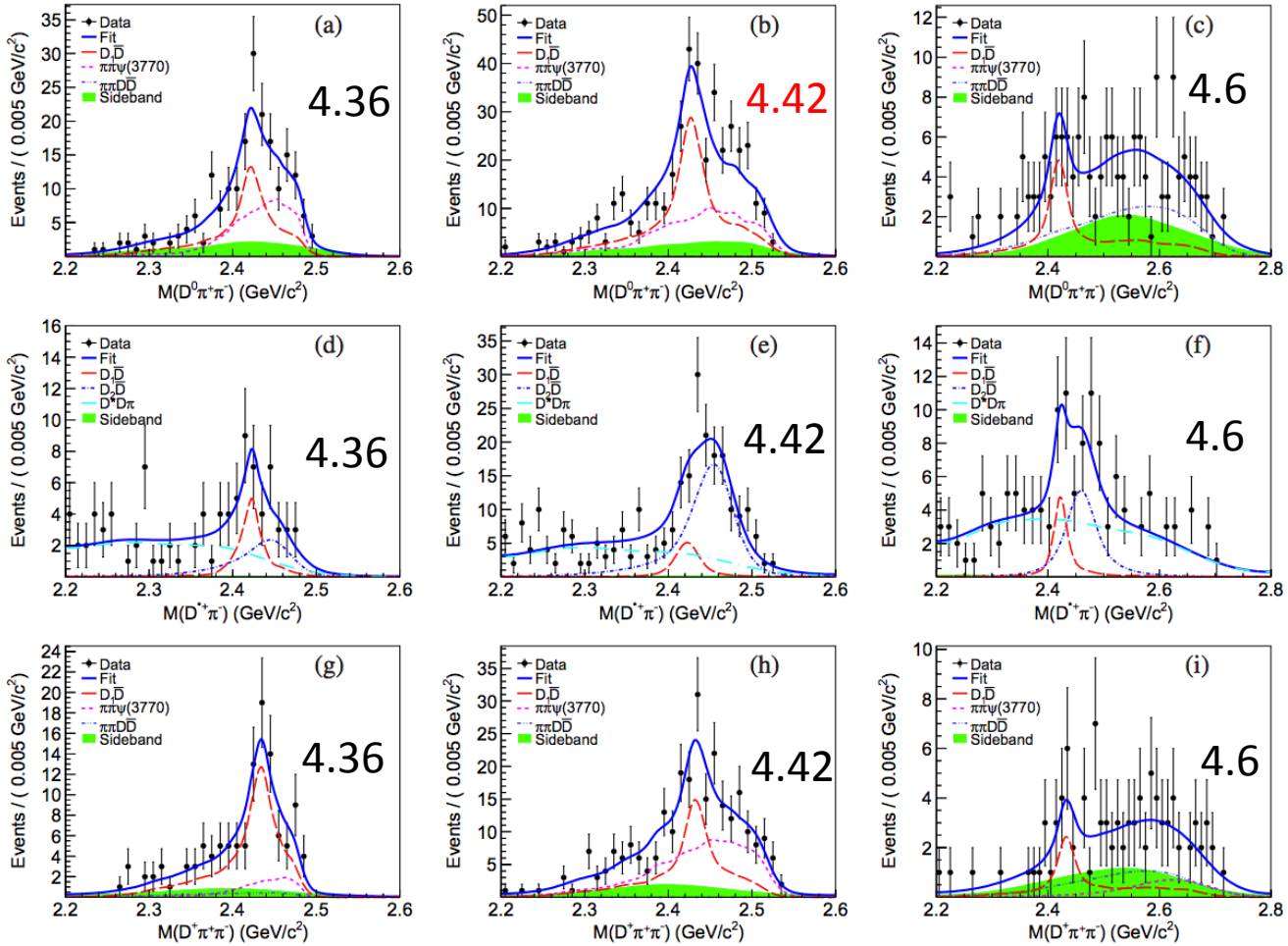


We observe $e^+ e^- \to \pi^+ \pi^- \psi(3770)$ for the first time @ 4.42 GeV

The events are from the Y (4390) or the $\psi(4415)$ resonance or from any other resonance cannot be distinguished based on the current statistics.

$e^+ e^- \rightarrow D_1(2420)^0 D^0$

[arXiv:1903.08126]

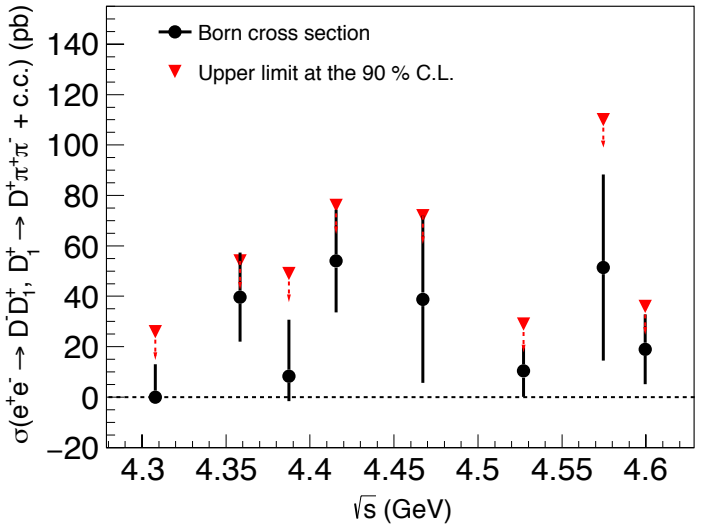


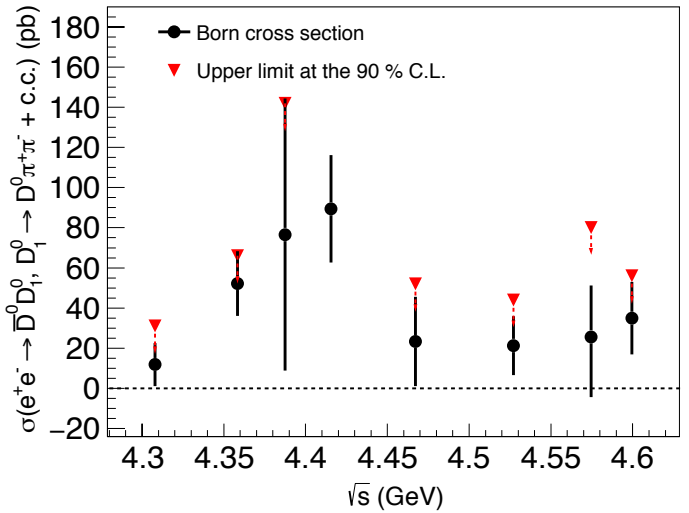
Three different decay channels are used to search for $D_1(2420)^0$.

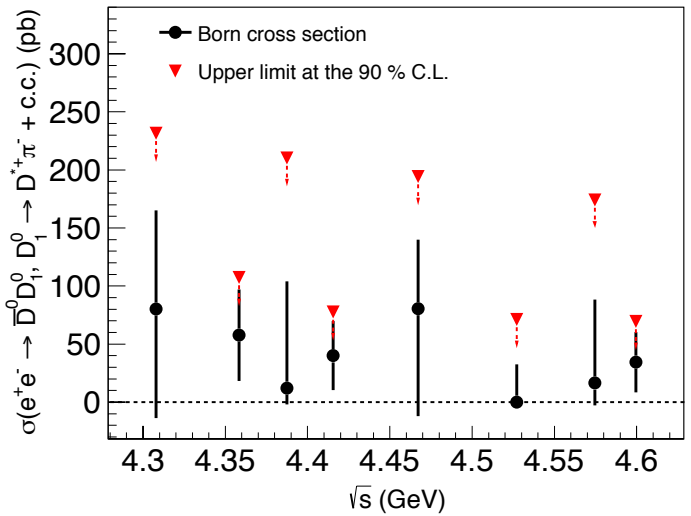
$D_1(2420)^0 \rightarrow D^0\pi^+\pi^-$ is reported with statistical significance of 7.4σ at 4.42 GeV

$e^+ e^- \to D_1(2420)^0 D^0$

[arXiv:1903.08126]





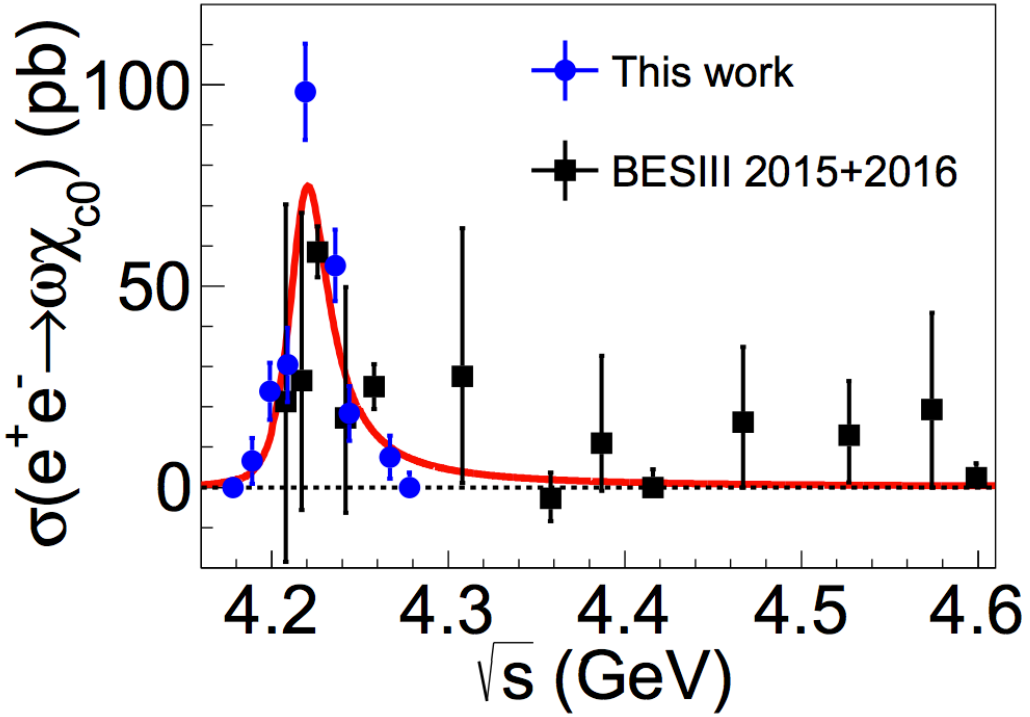


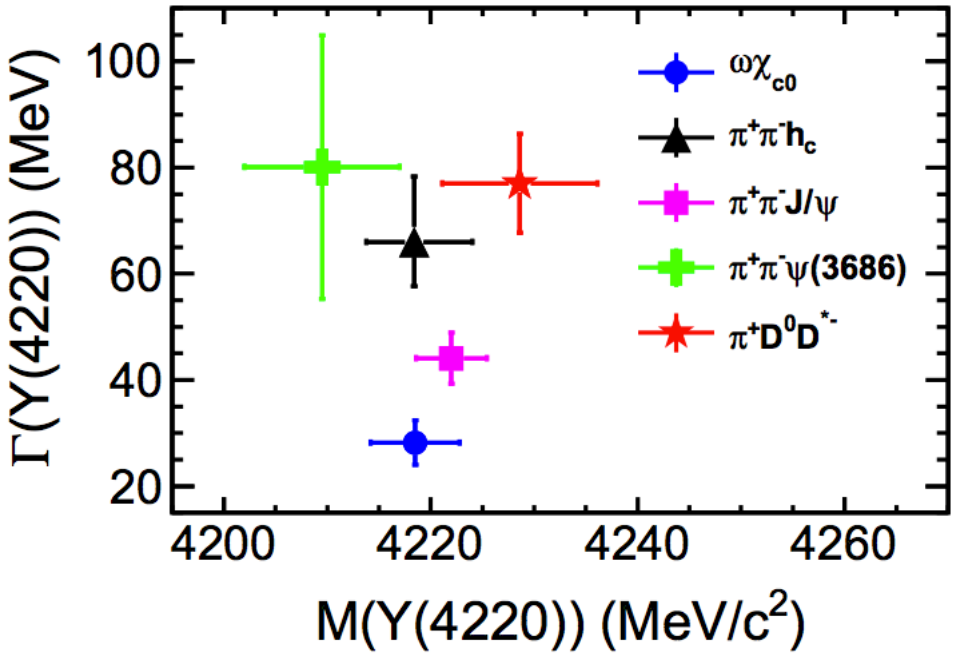
Three different decay channels are used to search for $D_1(2420)^0$.

$D_1(2420)^0 \to D^0\pi^+\pi^-$ is reported with statistical significance of 7.4σ at 4.42 GeV

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

[arXiv:1903.02359]



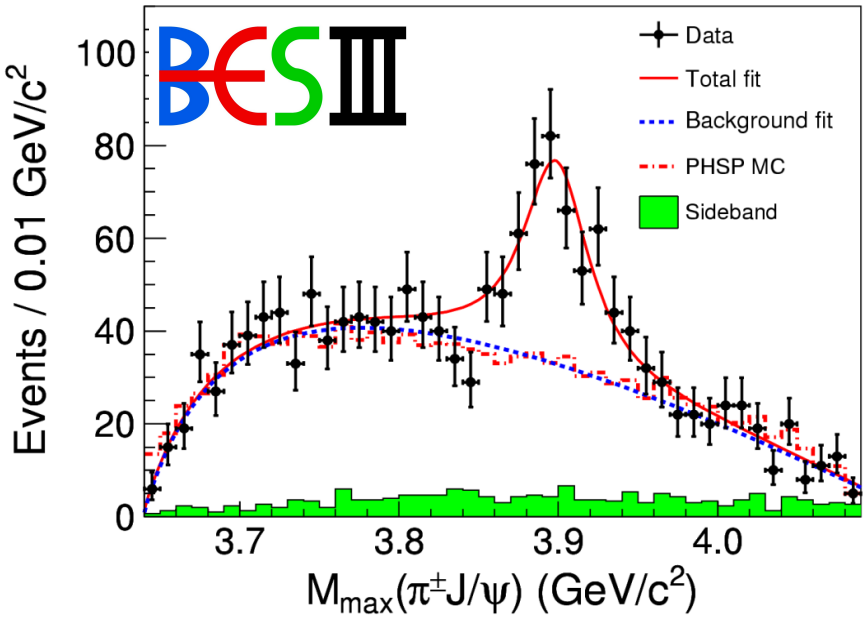


M = (4218.5 ± 1.6 ± 4.0) MeV/c^2

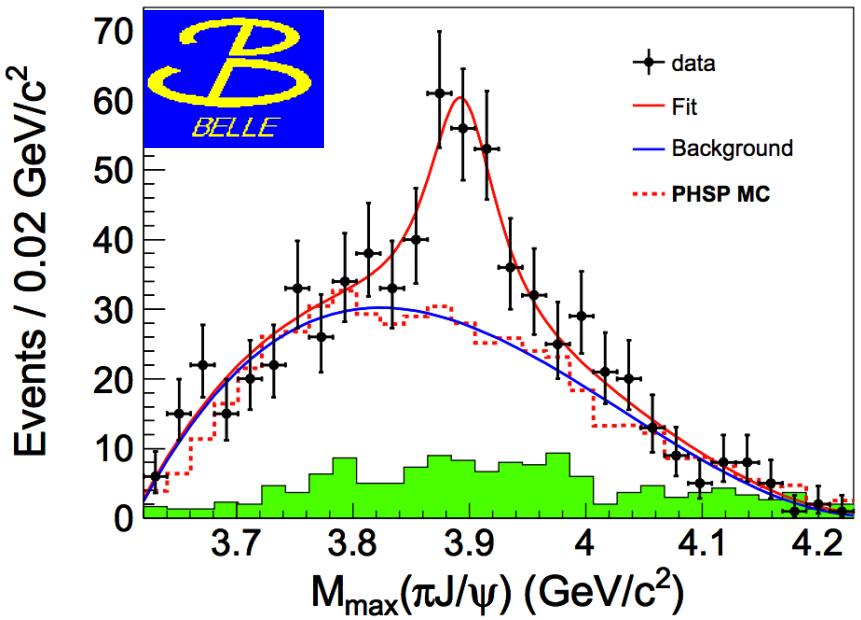
Γ = (28.2.0 ± 3.9 ± 1.6) MeV

$Z_c(3900)$ (π J/ψ)

[PRL110, 252001 (2013)]



[PRL110, 252002 (2013)]



Observed in $e^+ e^- \rightarrow \pi^+ \pi^-$ J/ψ in BESIII and Belle experiments, confirmed by CLEO-c data.

[PLB727,366-370 (2013)]

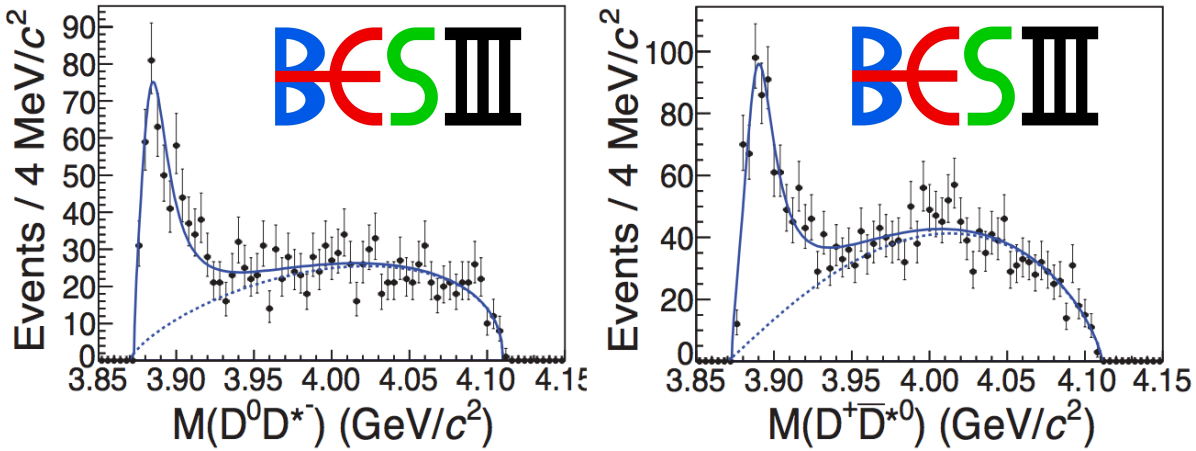
And with CLEO-c data, a hint (3.5σ) for neutral $Z_c(3900)$ in the invariant mass of π^0J/ψ,
BESIII observed neutral $Z_c(3900)$ with 10.4σ.

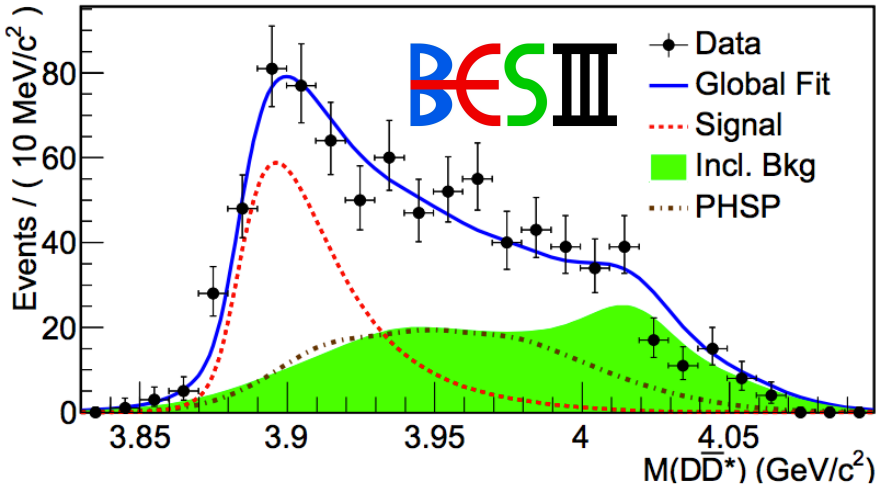
[PRL115, 112003 (2015)]

A half production rate comparing with charged $Z_c(3900)$. isospin triplet state

$Z_c(3900)$ (D D*)

[PRL112, 022001 (2014)]





[PRL115, 222002 (2015)]

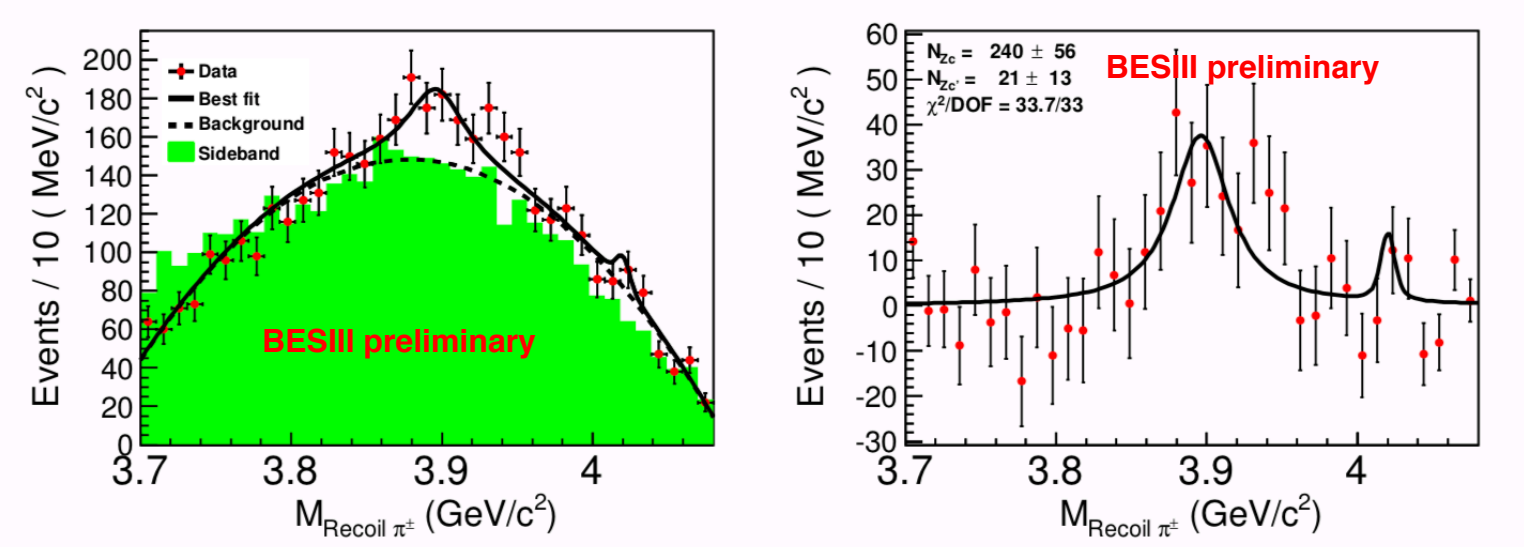
BESIII: single D-tag observed
double D-tag confirmed
[PRD115, 092006 (2015)]

$$\frac{\Gamma(Z_c(3885)\text{->}DD^*)}{\Gamma(Z_c(3900)\text{->}\pi J/\psi)} = 6.2\pm1.1\pm2.7$$

BESIII: Neutral mode as the expectation from isospin symmetry.

$Z_c(3900)$ $(\rho\,\eta_c)$

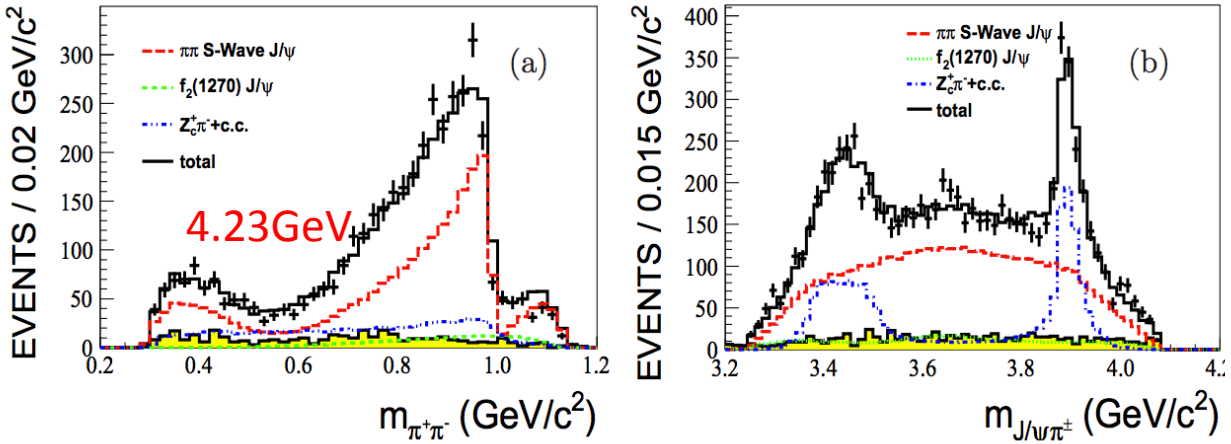
Decay mode	BR
$\eta_c \rightarrow$	~0.13%
$\eta_c \rightarrow 2(K^+K^-)$	~0.15%
$\eta_c \rightarrow \pi^+\pi^-K^+K^-$	~1.50%
$\eta_c \rightarrow K^+K^-\pi^0$	~1.20%
$\eta_c \rightarrow \pi^0$	~0.18%
$\eta_c \rightarrow K_SK\pi$	~1.80%
$\eta_c \rightarrow \pi^+\pi^-\eta$	~1.60%
$\eta_c \rightarrow K^+K^-\eta$	~0.57%
$\eta_c \rightarrow \pi^+\pi^-\pi^0\pi^0$	~2.40%

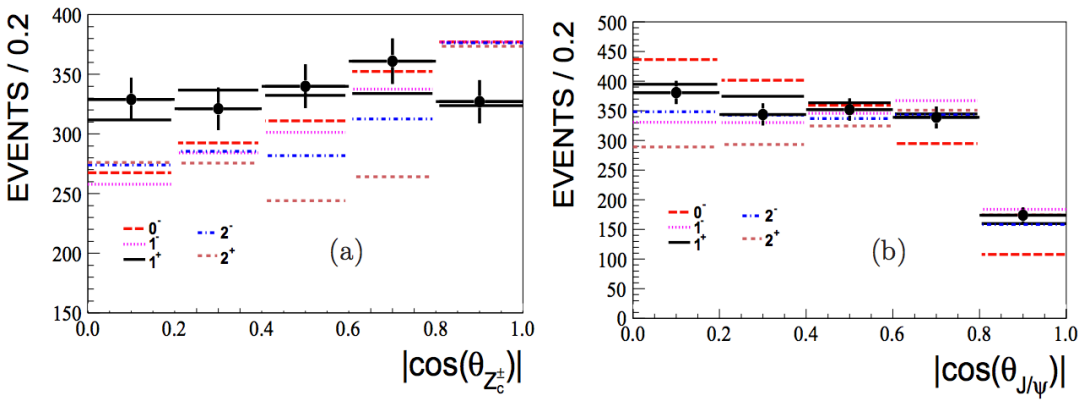


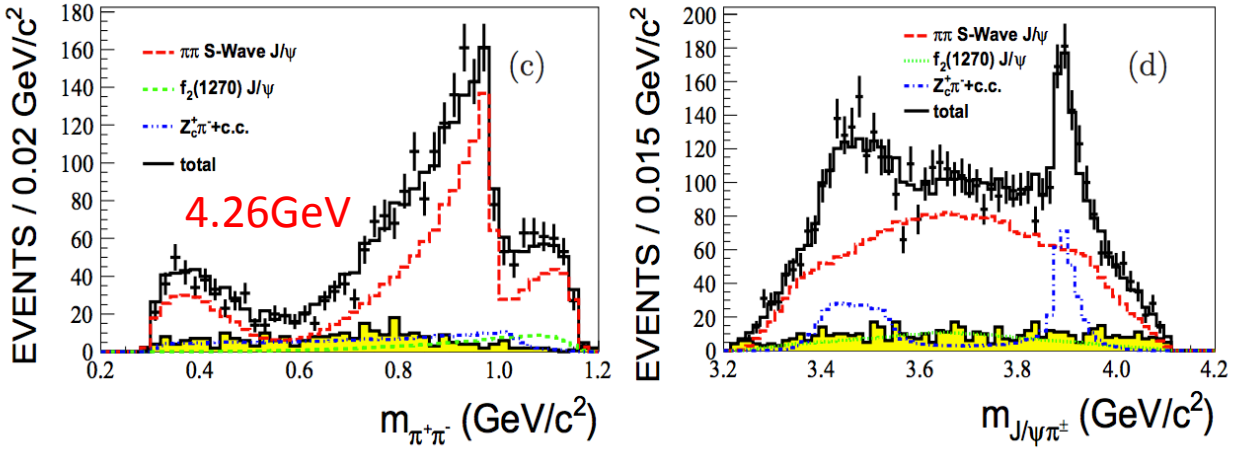
Strong evidence of $e^+e^-\rightarrow\pi Z_c$, $Z_c\rightarrow\rho\eta_c$ is observed at Sqrt(S) = 4.23 GeV, statistical significance is 4.3σ

	$\sqrt{s} = 4.23\,\text{GeV}$	$\sqrt{s} = 4.26\,\text{GeV}$	$\sqrt{s} = 4.36\,\text{GeV}$	Tetra-quarks-I	Tetra-quarks-II	Molecule
$R_{Z_c(3900)}$	2.1 ± 0.8	< 6.4	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.9	< 1.2	< 1.0	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$

$Z_c(3900)$ Spin Parity







Flatté-like formula for $Z_c(3900)$ lineshape

Pole mass = (3881.2 ± 4.2 ± 52.7) MeV/c^2

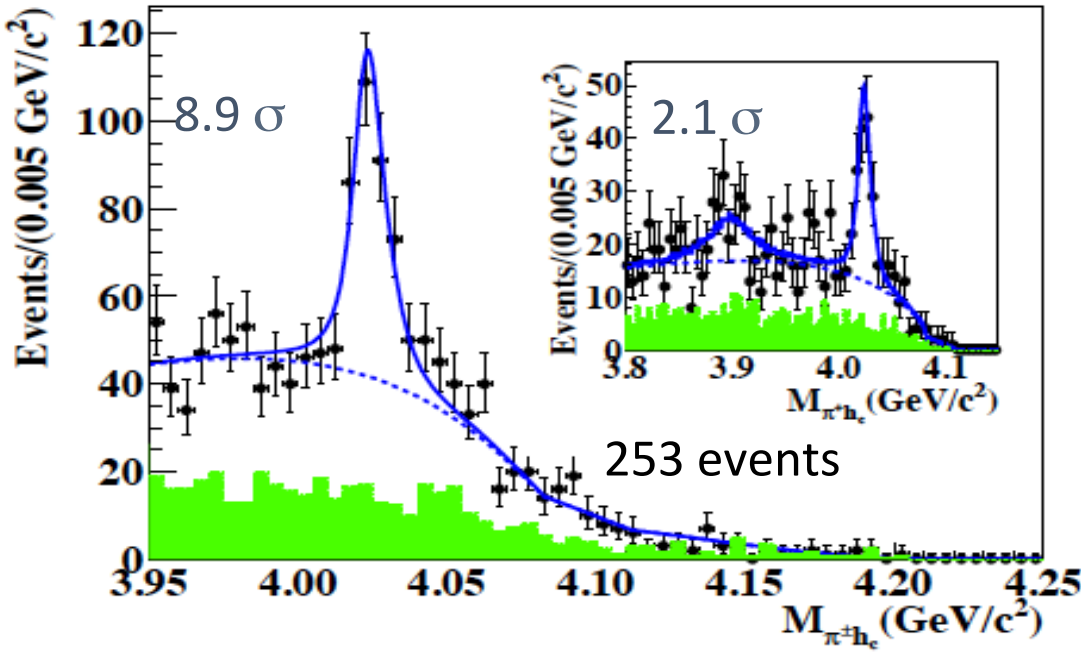
Pole width = (51.8 ± 4.6 ± 36.0) MeV

$J^P = 1^+$

[PRL119, 072001 (2017)]

$Z_c(4020)$ $(\pi\, h_c)$

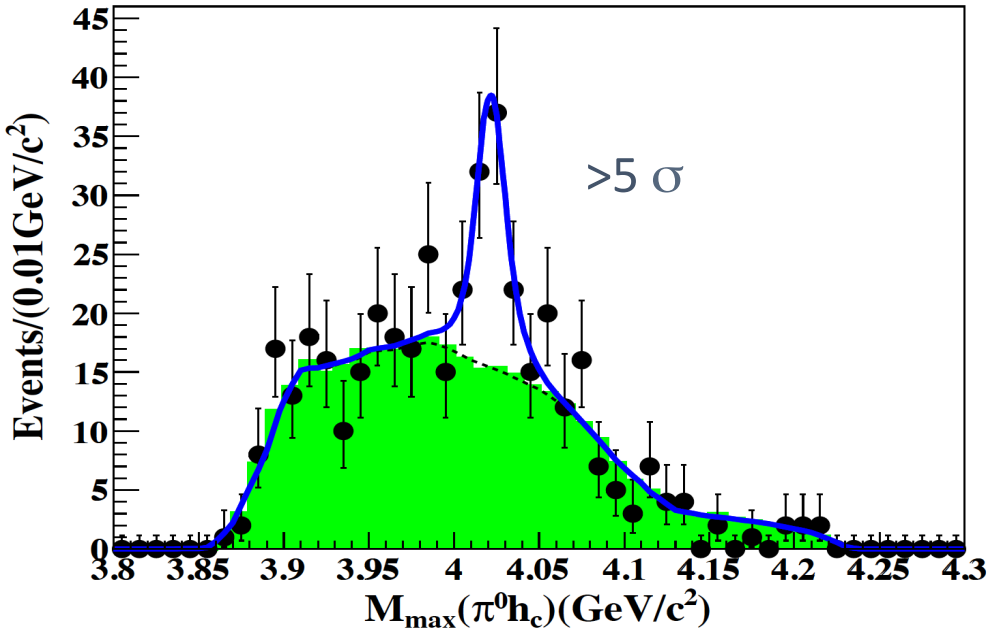
[PRL111, 242001 (2013)]



$M(Z_c(4020)) = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2

$\Gamma(Z_c(4020)) = (7.9 \pm 2.7 \pm 2.6)$ MeV

[PRL113, 212002 (2014)]

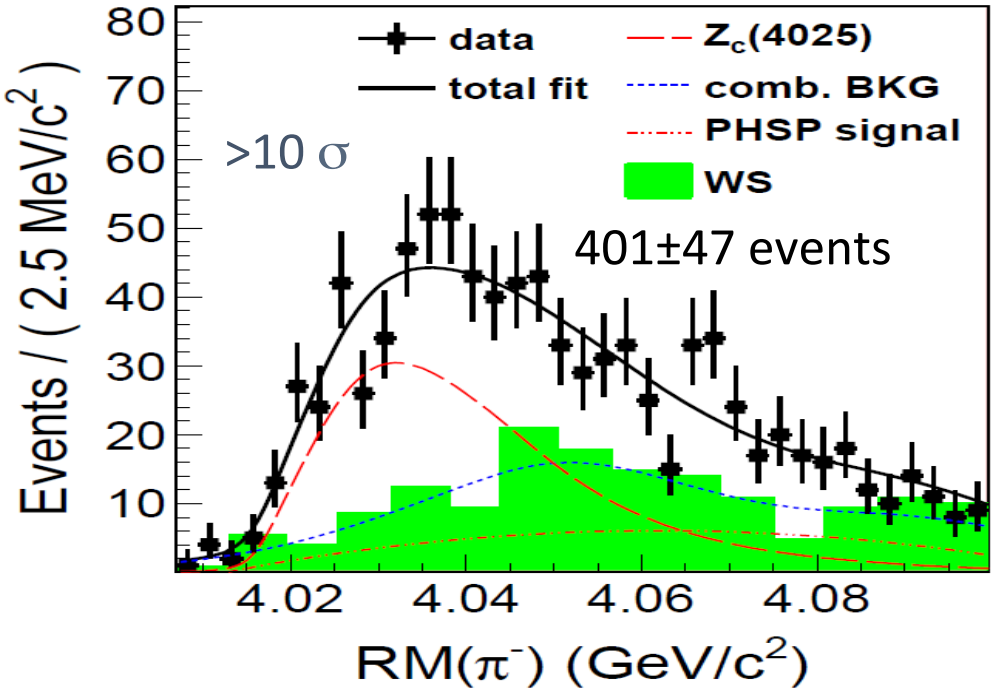


Neutral channel observed, similar to $Z_c(3900)$

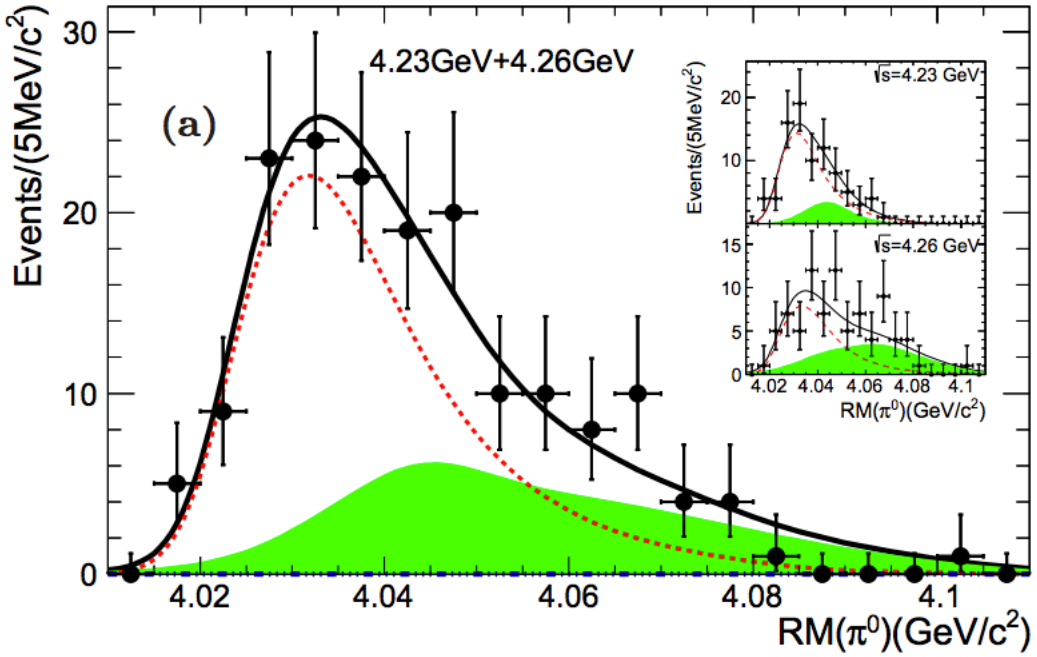
isospin triplet state

$Z_c(4020)$ $(D^* D^*)$

[PRL112, 132001 (2014)]



[PRL115, 182002 (2015)]

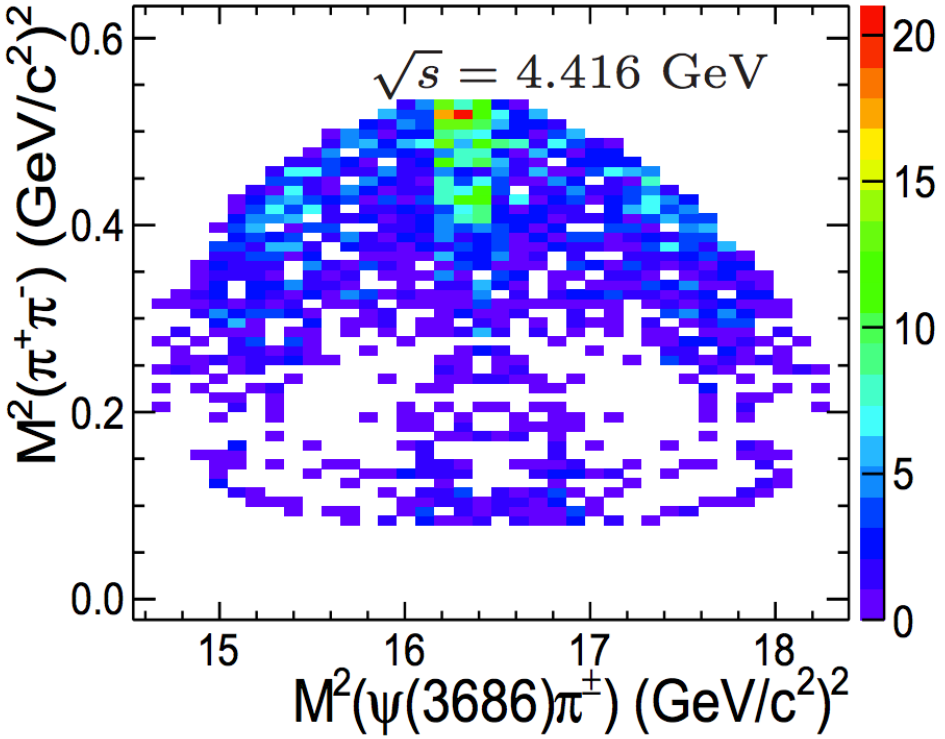


$M(Z_c(4020)) = (4026.3 \pm 2.6 \pm 2.7)$ MeV/c^2

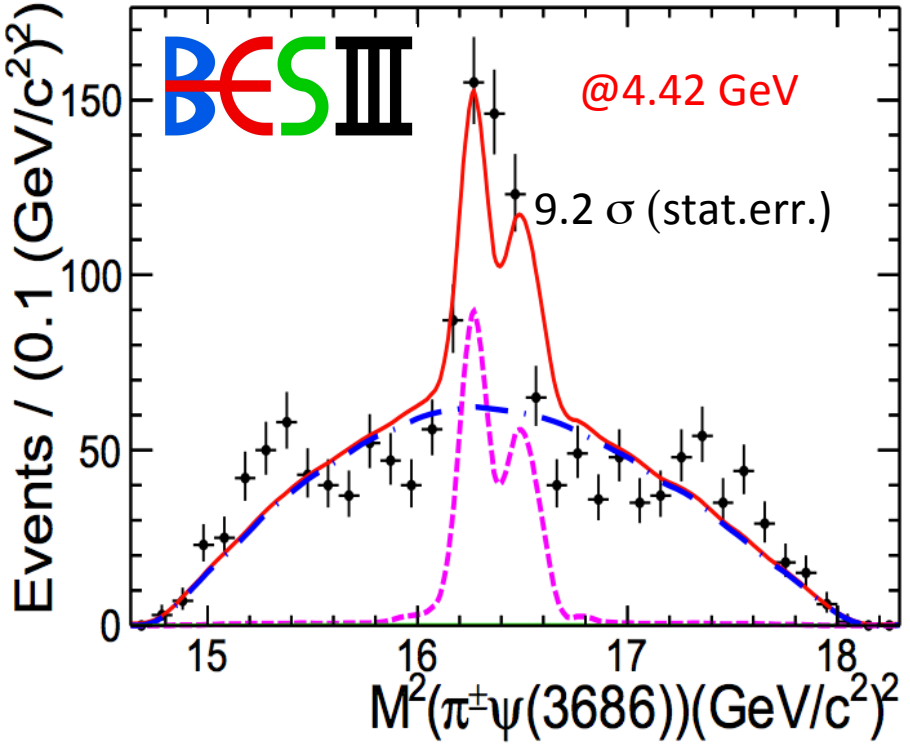
$\Gamma(Z_c(4020)) = (24.8 \pm 5.6 \pm 7.7)$ MeV

$Z_c(4032)$ $(\pi\,\psi(3686))$

[PRD96, 032004 (2017)]



Different behaviors between high and low $M^2(\pi^+\pi^-)$



M = (4023.1 ± 2.4) MeV/c^2

Γ = (26.1 ± 5.3) MeV

Summary

- Great progress achieved recently:
  - Properties of X(3872) measurements: mass, quantum number, production and decays;
  - Quantum numbers of $Z_c(3900)$ have been decided;
  - Many studies for Y(4260) structure;
  - Building relations between exotic states.
- Many remain unanswered questions;
- More data is expected in the future.

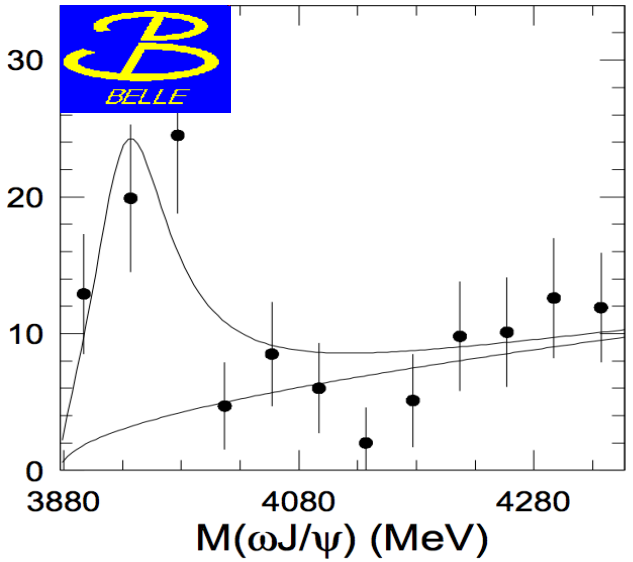
Thank you!

BACK UP

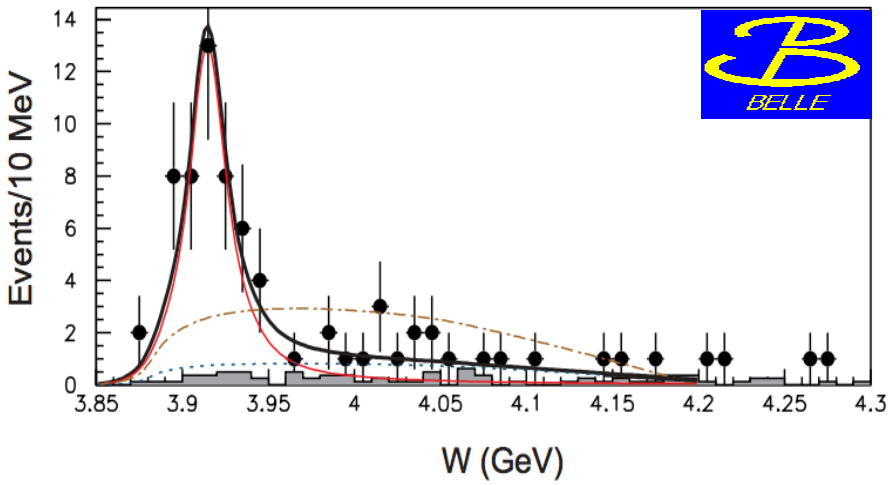
X(3915)

- First observed in the decay of B → KωJ/ψ at Belle
- Confirmed by BaBar in B^+ and B^0 decay
- Seen in γγ → ωJ/ψ at Belle and BaBar.

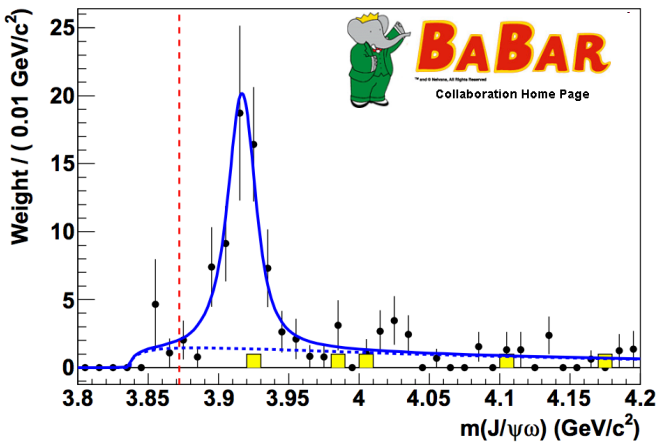
[PRL 94,18002(2005)]



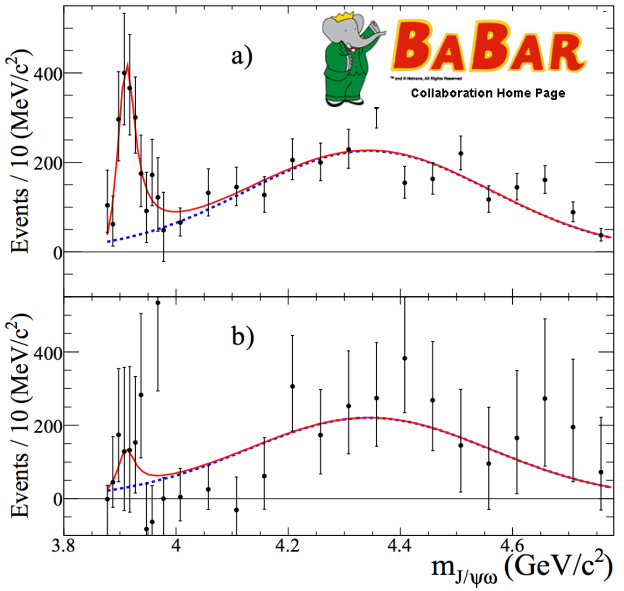
[PRL 104,092001(2010)]



[PRD 86,072002(2012)]

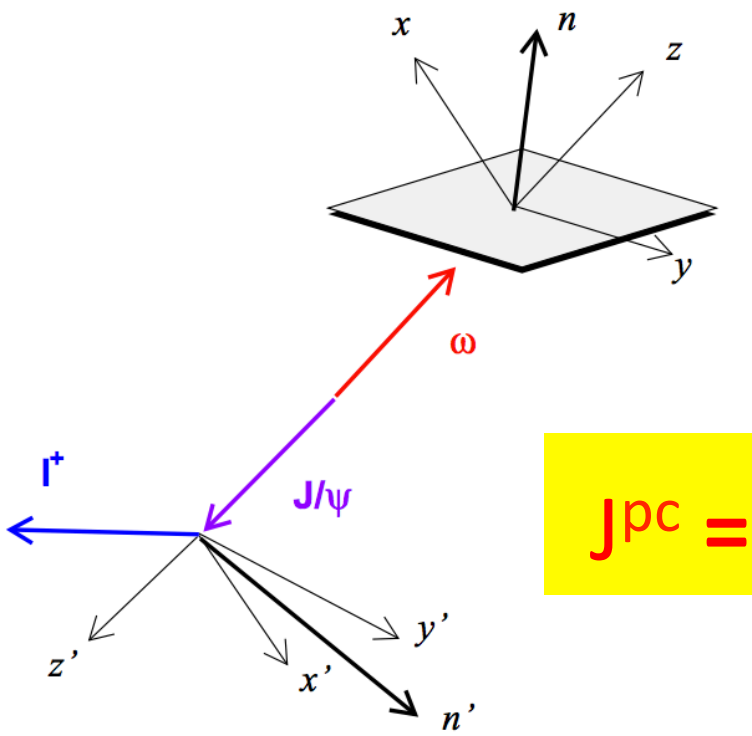


[PRL 101,02001(2008)]



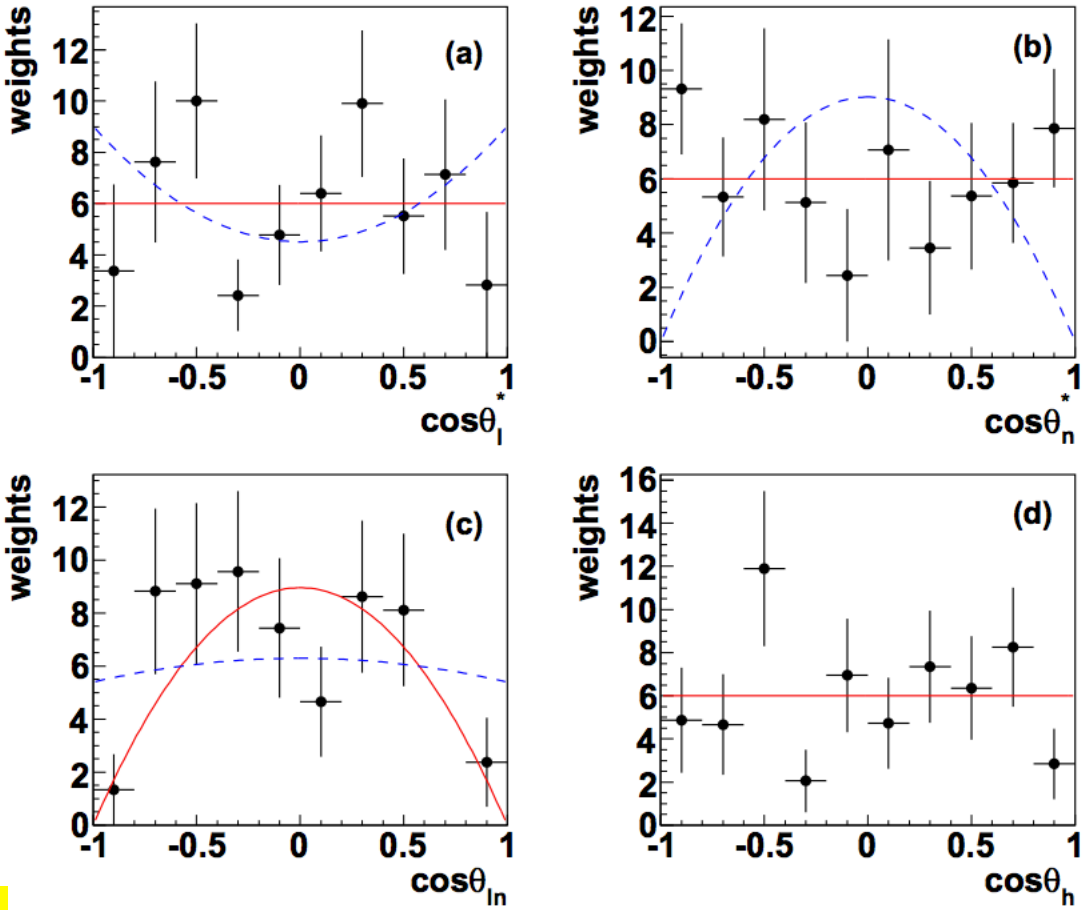
X(3915) Spin Parity

[PRD 86,072002(2012)]



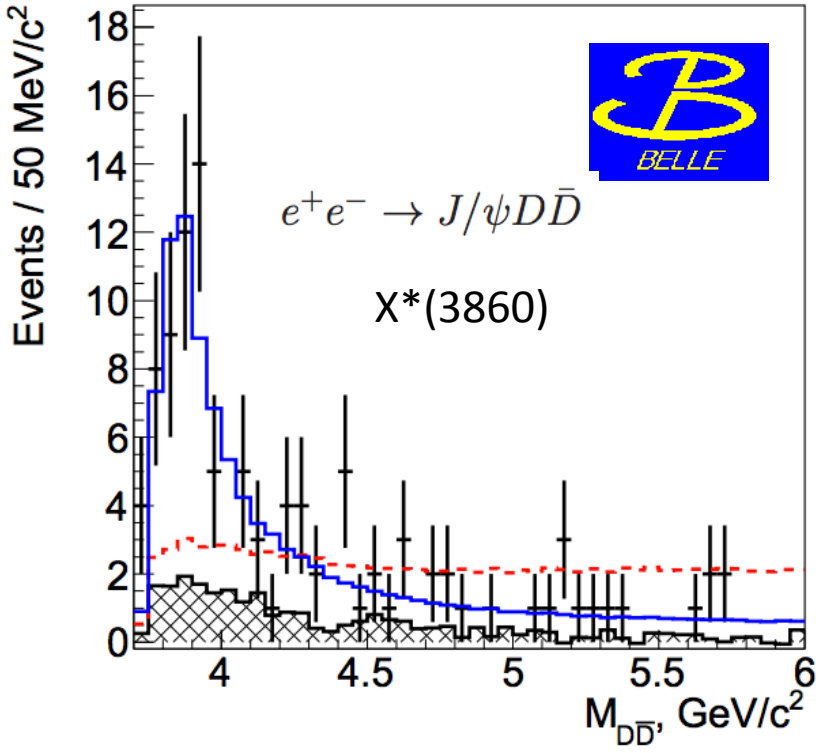
$J^{pc} = 0^{++}$

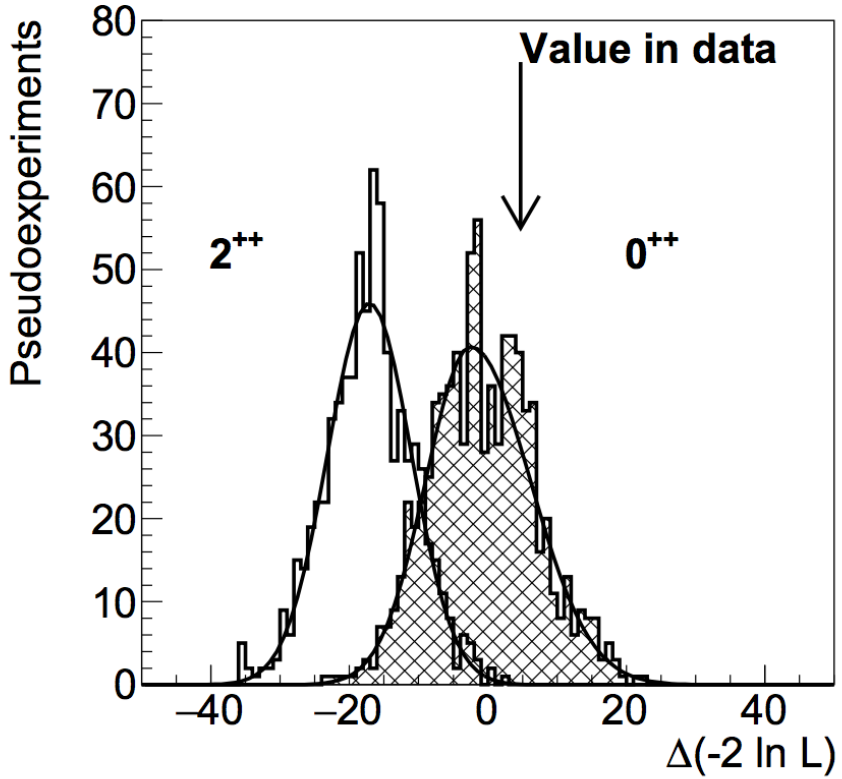
$\chi_{c0}(2P)$ state ?



A Better $\chi_{c0}(2P)$ Candidate

[PRD 95,112003(2017)]





Close to potential model exception for $\chi_{c0}(2P)$

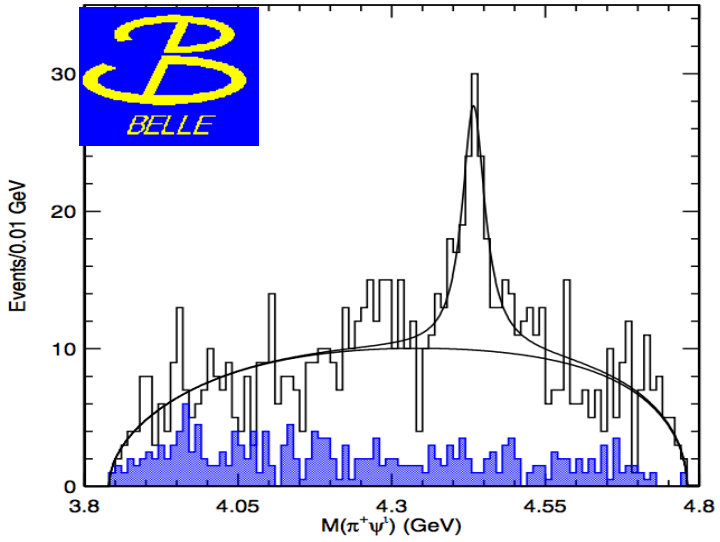
Decay primary to $D\bar{D}$

Decay to $J/\psi\,\omega$ is expected OZI-suppressed for $\chi_{c0}(2P)$

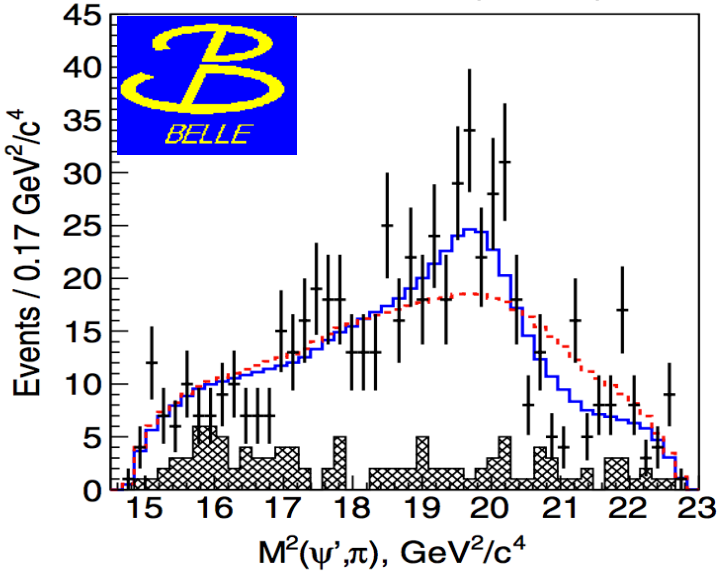
Z(4430)

- First observation in $B \to K\pi^{\pm}\psi(2S)$ in Belle, not confirmed by BaBar (not contradict, due to low statistics)
- Updated Belle results:
  - ✓ Two dimensional analysis using same data as first publication
  - ✓ Four dimensional amplitude analysis, 711 fb^{-1} $\Upsilon(4S)$, Z(4430) favor 1^+
  - ✓ Larger width, higher mass

[PRL100, 142001 (2008)]

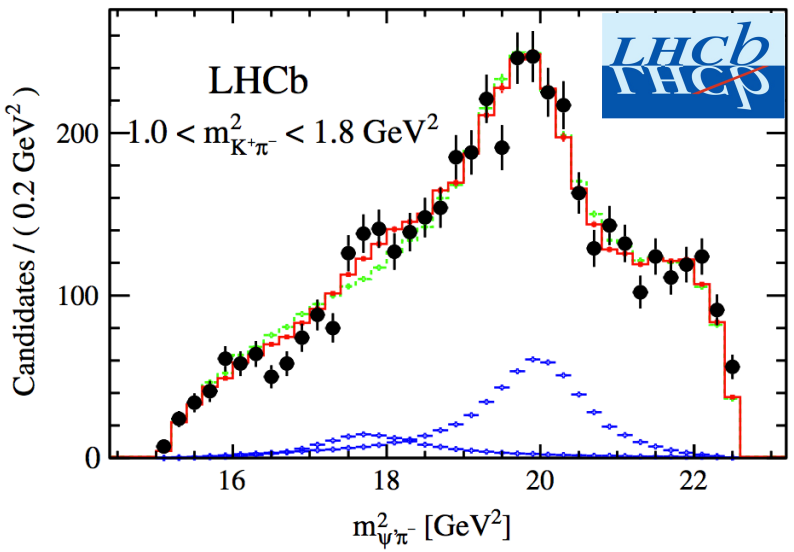


[PRD88, 074026 (2013)]



Confirmation of Z(4430)

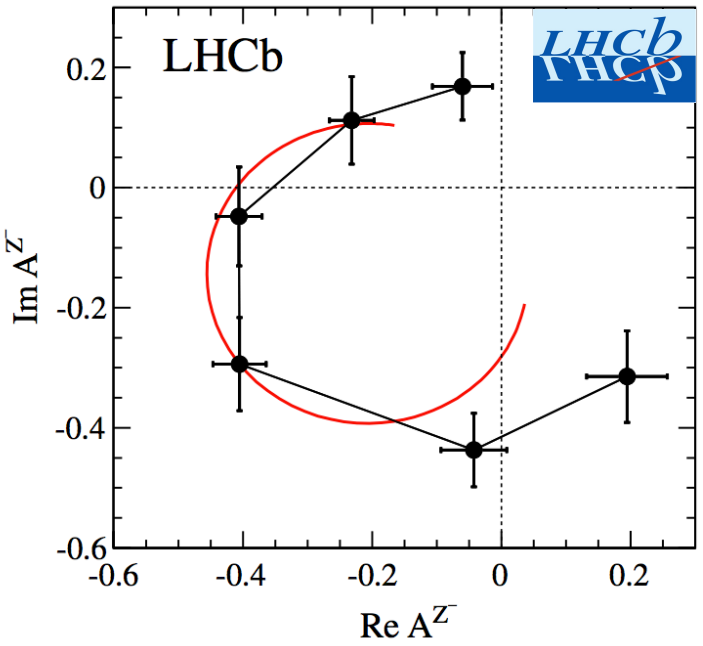
[PRL112, 222002 (2014)]



$B^0 \rightarrow \psi' K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$

Four dimensional analysis:
$\Phi=(M^2_{K\pi'}, M^2_{\psi'\pi}, \theta_{\psi'}, \varphi)$

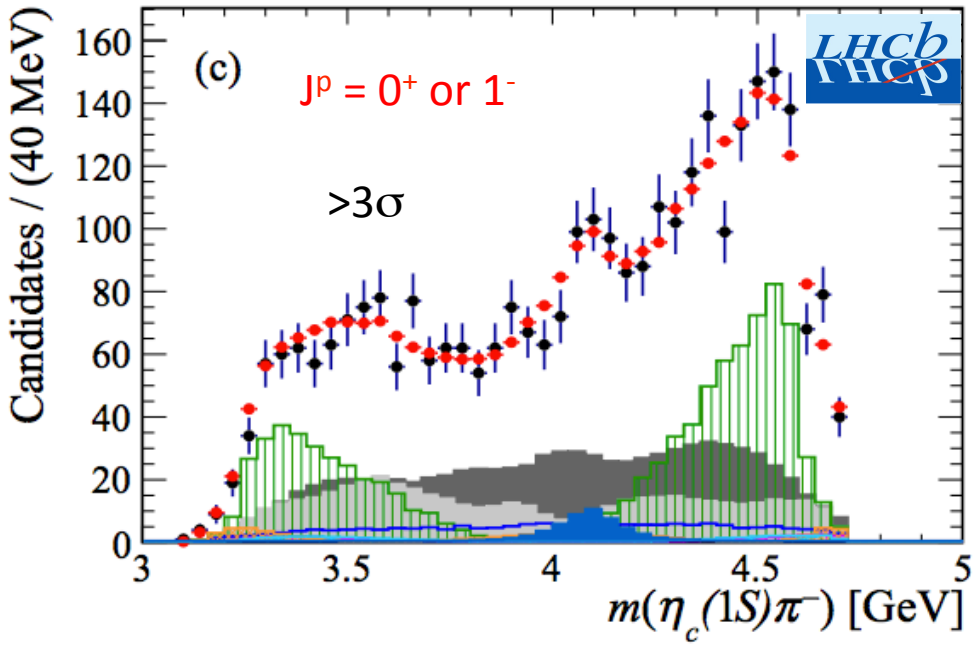
Mass and width consistent with Belle latest result
$J^P=1^+$



Argand diagram
consistent with a rapid change of the Z(4430) phase when its magnitude reaches the maximum
a behavior characteristic of a resonance

$Z_c(4100)$, $Z(4050)$, $Z(4250)$

[Eur. Phys. J. C 78 1019 (2018)]

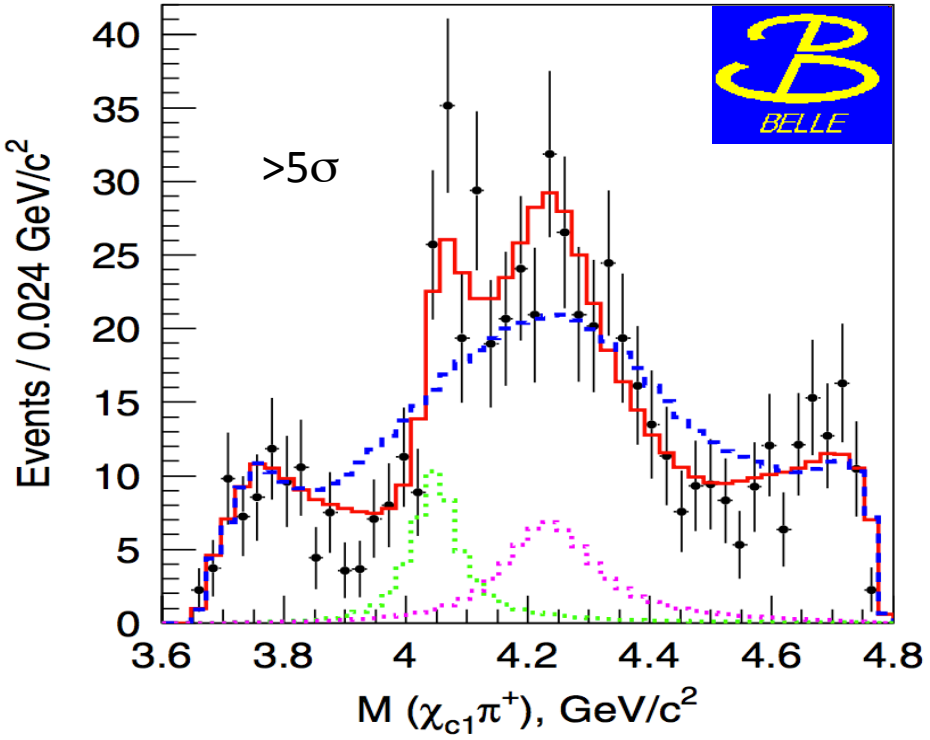


$B^0 \rightarrow K^+\pi^-\eta_c$

M = (4096 ± 20 $^{+18}_{-22}$) MeV/c^2

Γ = (152 ± 58 $^{+60}_{-35}$) MeV

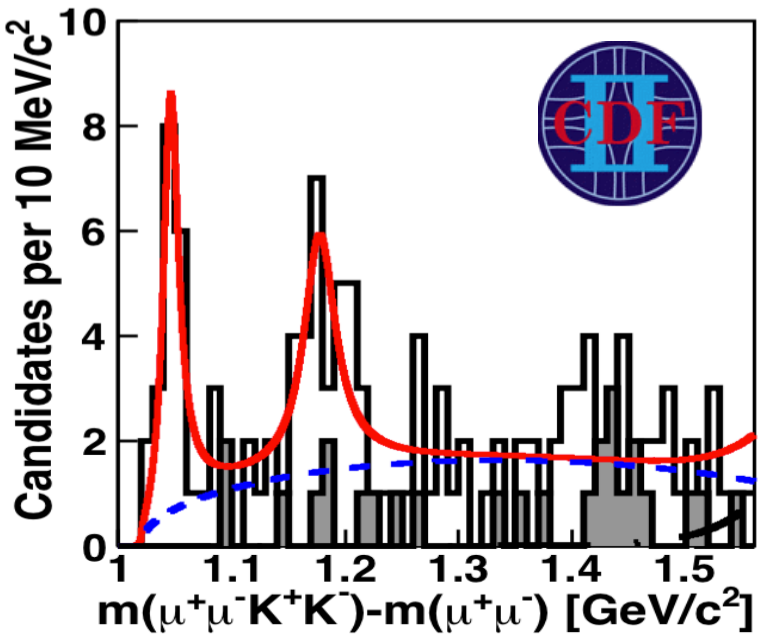
[PRD78, 072004 (2008)]



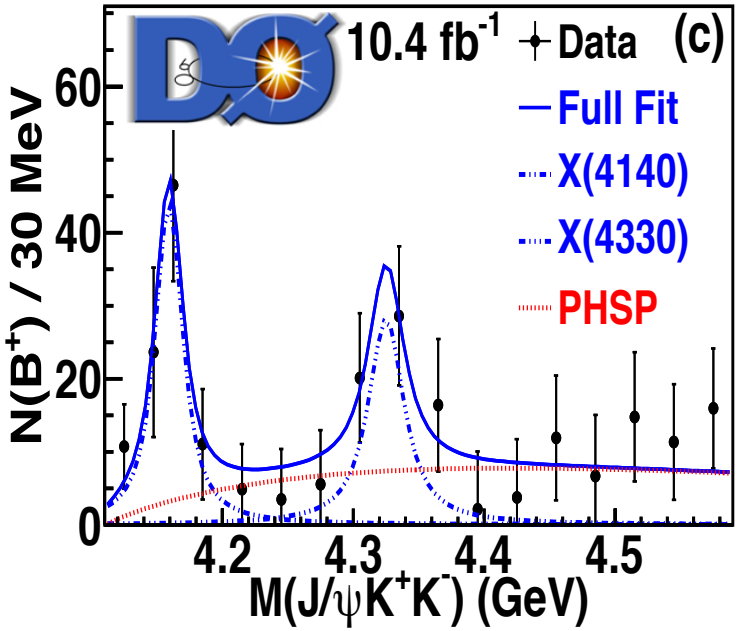
$$M_1 = (4051 \pm 14^{+20}_{-41})\ \text{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \text{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \text{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \text{MeV},$$

X(4140) and J/ψφ family

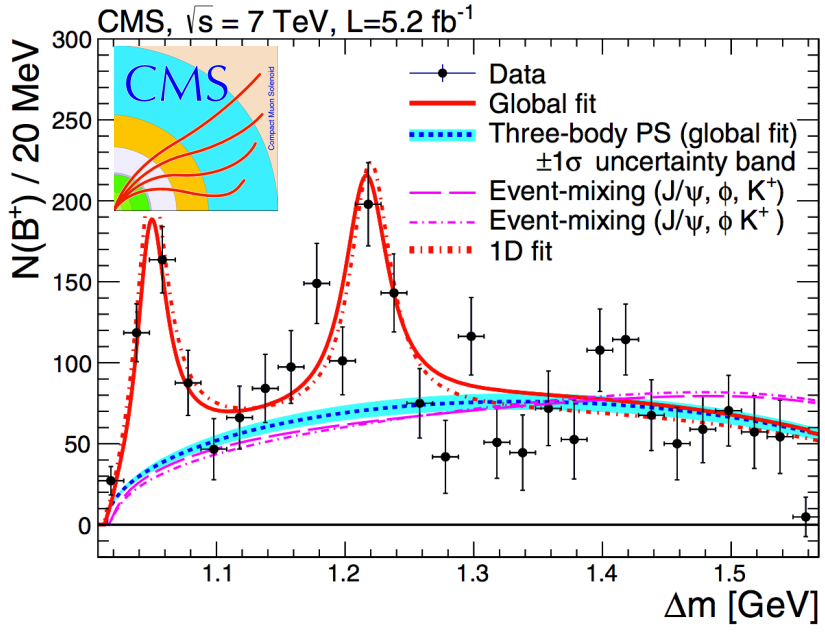
Two peaks around 4140 and 4274 MeV/c^2 in J/ψ φ are found by CDF, and confirmed by D0 and CMS ($B^+ \rightarrow J/\psi\, \phi K^+$)



[PRL102, 242002 (2009)]



[PRD89, 012004 (2014)]

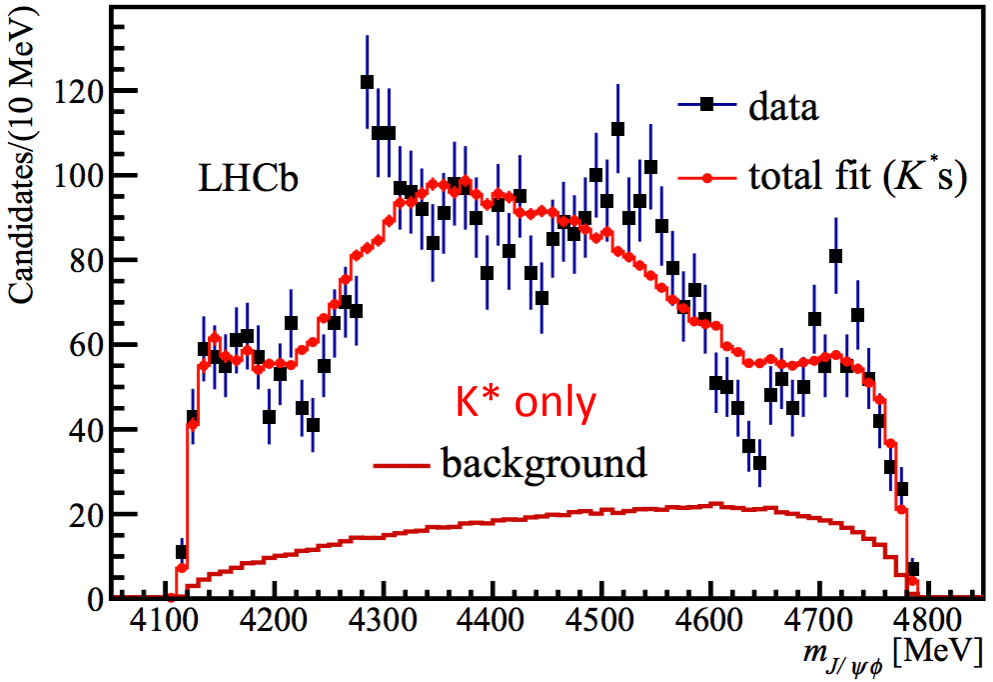


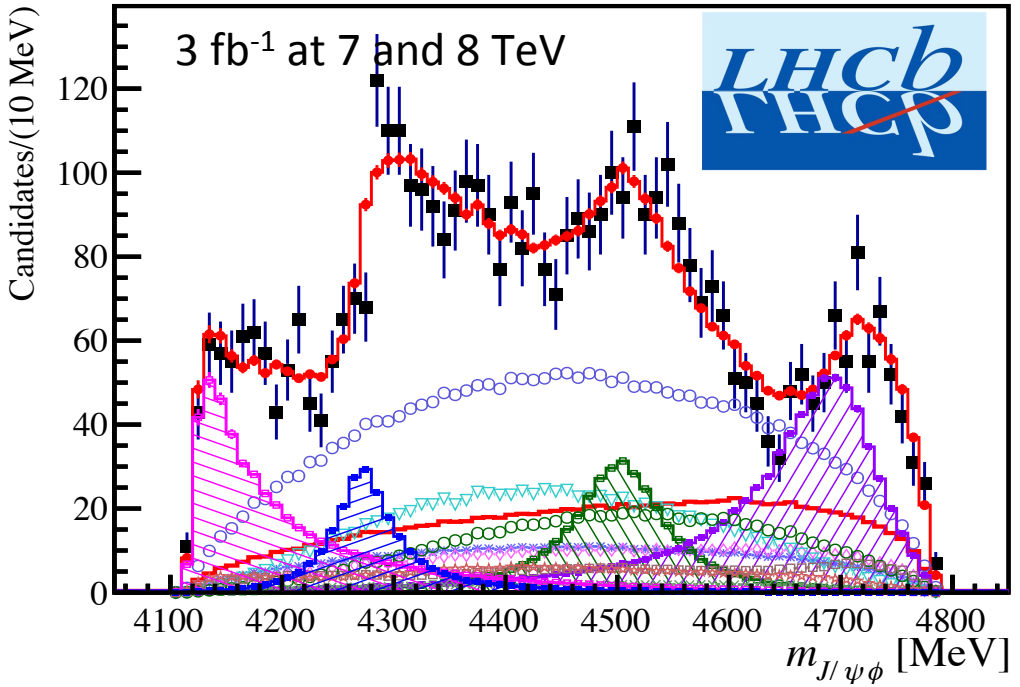
[PLB734, 261 (2014)]

X(4140) and J/ψφ family

[PRL118, 022003 (2017)]

[PRD95, 012002 (2017)]





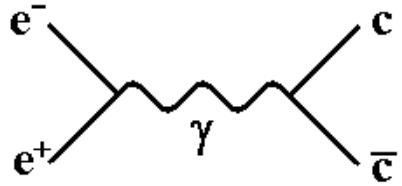
Masses of X(4140) and X(4274) are consistent with previous measurements, but widths significantly larger

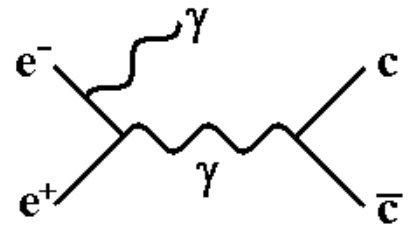
$J^P = 1^+$ assignment rules out interpretation of X(4140) as a $D^*_S D^*_S$ molecule

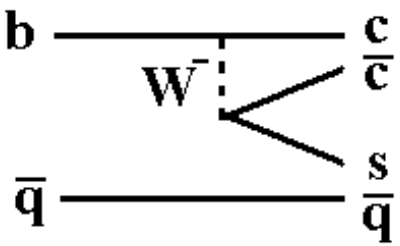
States	Significance	J^{PC}	Mass (MeV/c^2)	Width (MeV)
$Y(4140)$	8.4σ	1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
$Y(4274)$	6.0σ	1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$
$X(4500)$	6.1σ	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
$X(4700)$	5.6σ	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

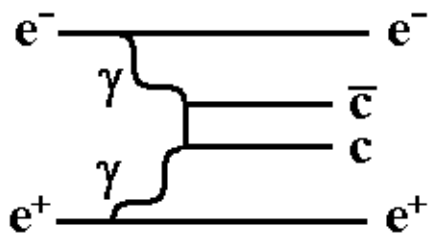
XYZ Productions

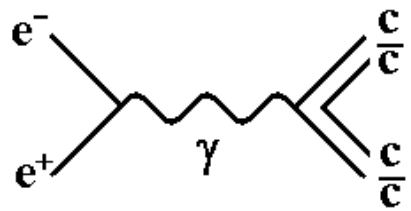
- $e^+ e^-$ annihilations
- B decays
- $\gamma\ \gamma$ fusion
- Double charmonium decays
- Hadronic/radiative transitions
- pp annihilations

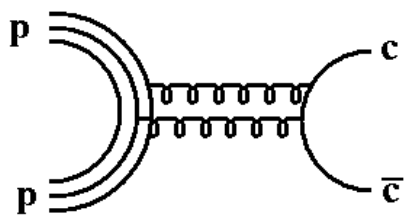


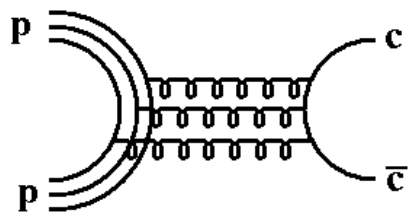




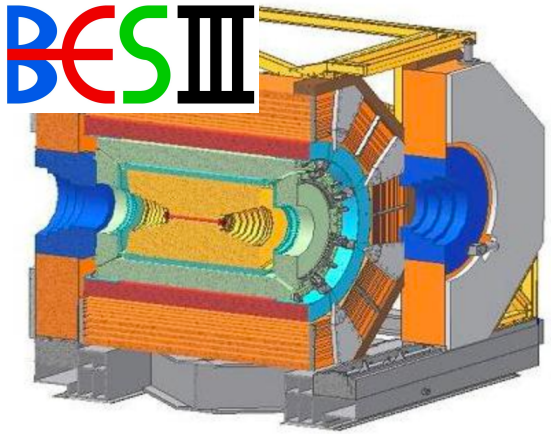








Experiments



CLEO-c