university of groningen

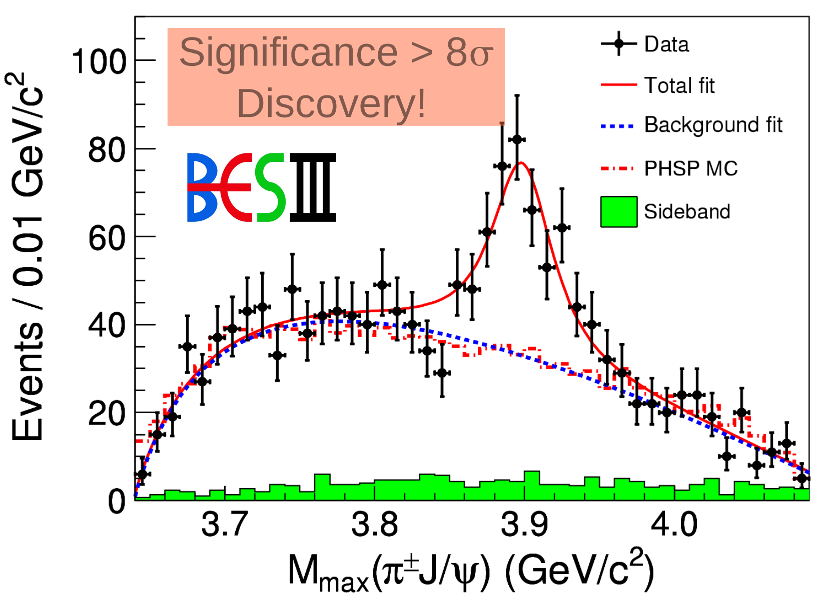
kvi - center for advanced radiation technology

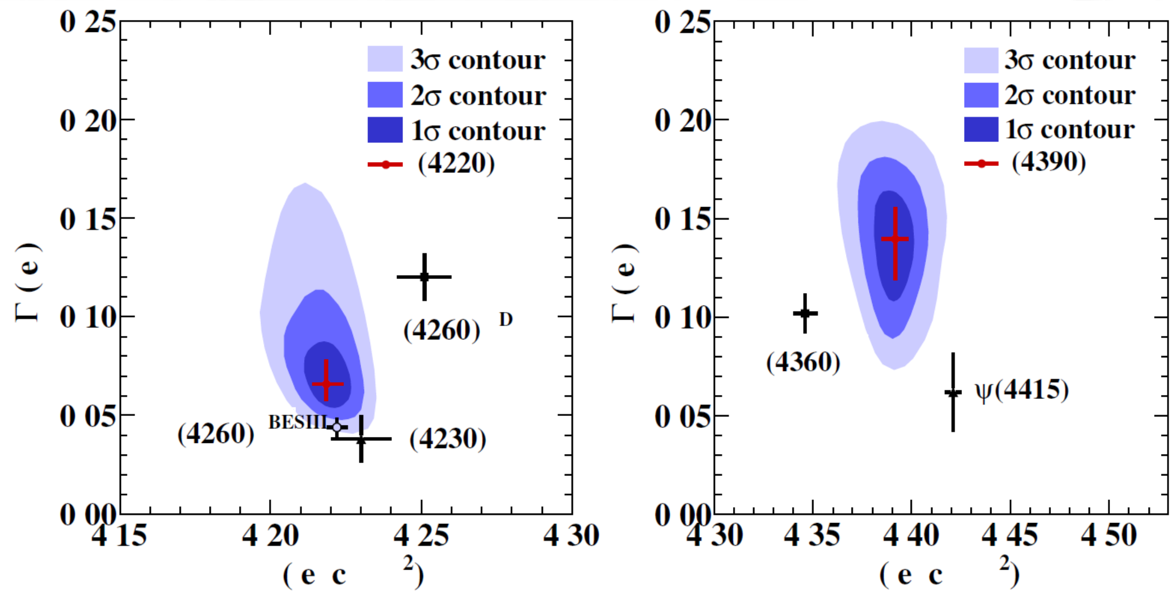
New XYZ results from BESIII

Myroslav Kavatsyuk

KVI – Center for Advanced Radiation Technology, University of Groningen

For the BESIII collaboration

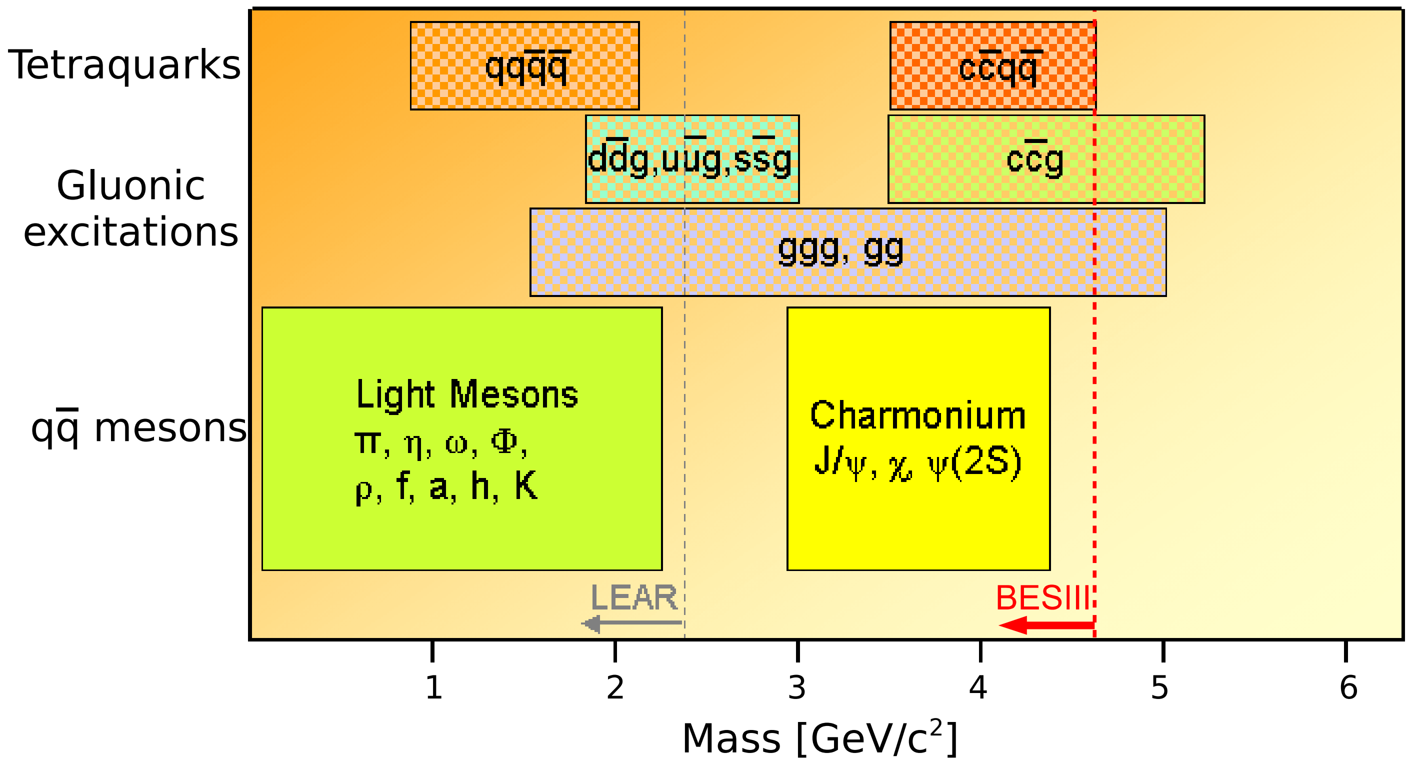




Hadron Landscape

Hadron-physics challenges:

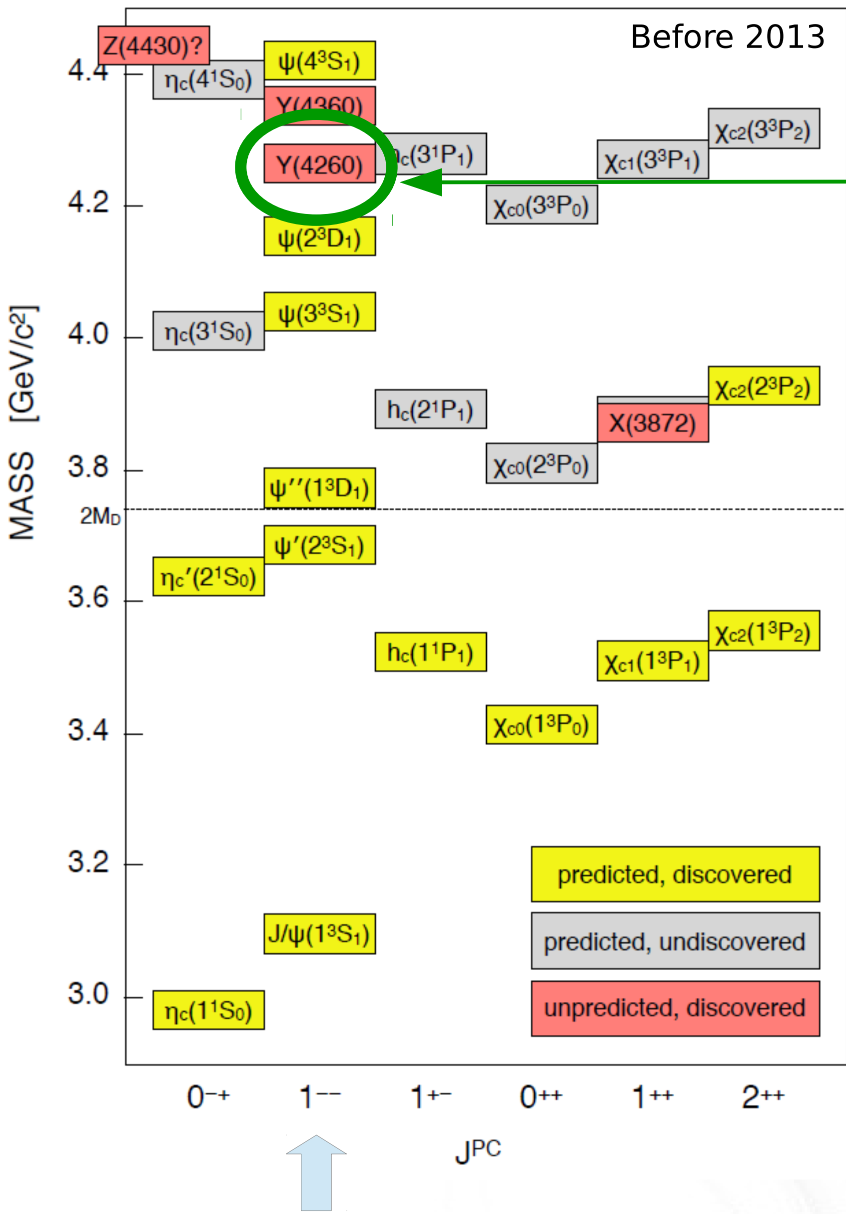
- Understanding of established states
- Nature of exotic states



To complete the Hadron-physics puzzle we have to:

- find pieces (discover states, identify symmetry properties);
- understand relation between the pieces (study transitions between the states).

Discoveries Come Unexpected...



States can be directly populated in annihilation e^+e^-

Initial idea: Try to populate directly one of the known, but not well understood state **Y(4260)**.

Realization: Tune e^+e^- BEPCII collider to 4260 MeV …

… and measure decay products with the BESIII detector…

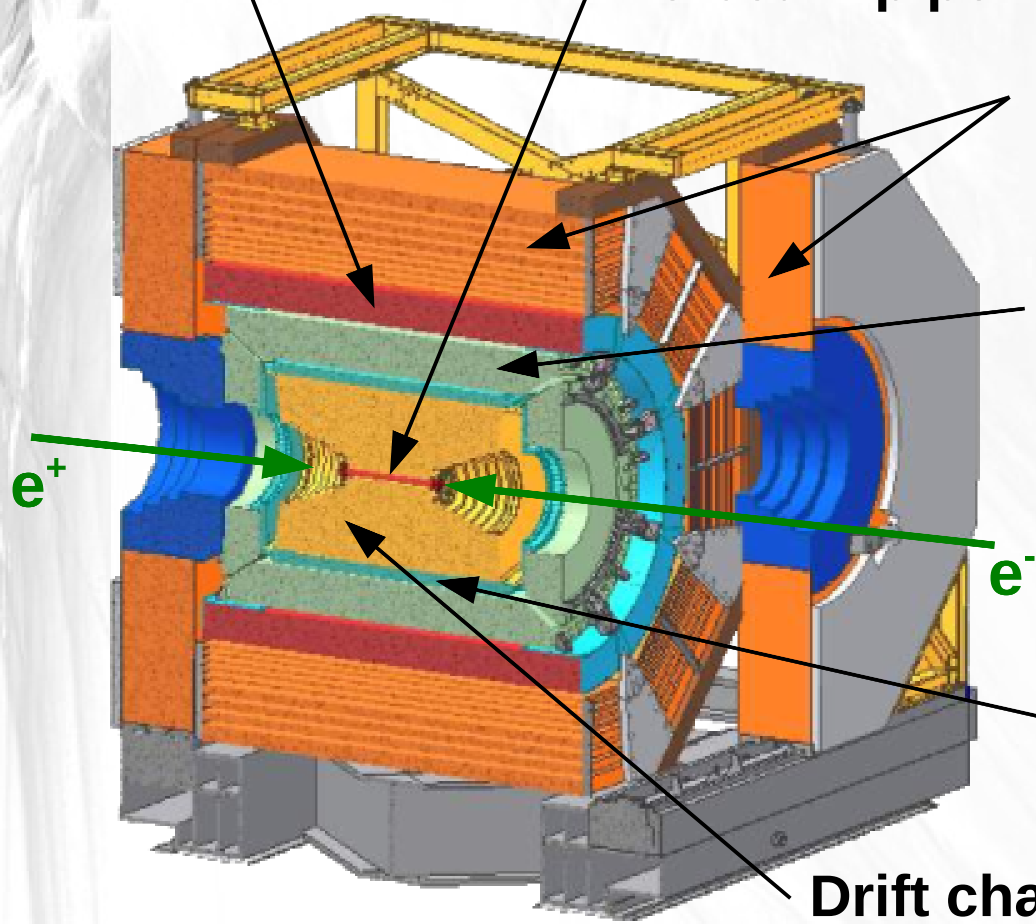
… check if there are transitions to known states (e.g. J/Ψ)…

… direct transitions or via intermediate resonances…

BESIII Detector

1.0 Tesla **super-conducting magnet**

Be beam pipe



Muon counters:
9/8 RPC layers (barrel/endcaps)
Cut-off momentum: 0.4 GeV/c

CsI(Tl) **ElectroMagnetic Calorimeter:**
σ_E/E (at 1 GeV): 2.5 %
$\sigma_{z,\phi}$ (at 1 GeV): 6 mm

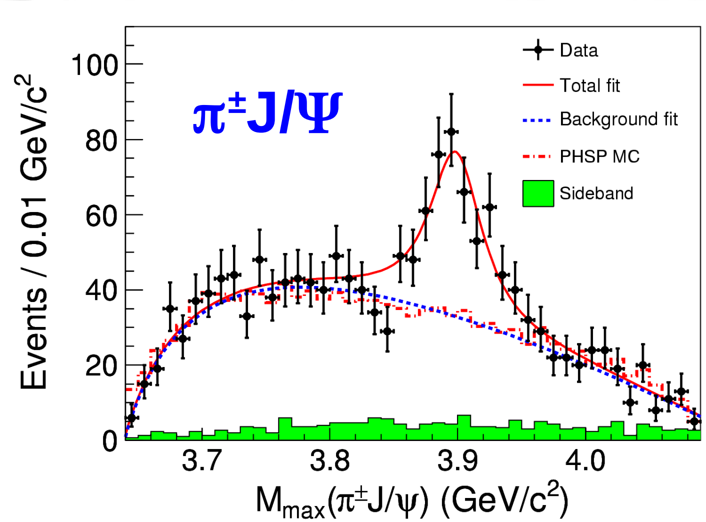
Time Of Flight (TOF):
σ_T: 100/110 ps (barrel/endcaps)

Drift chambers (MDC):
σ_p/p (at 1 GeV): 0.5 %
$\sigma_{dE/dx}$: 6 %

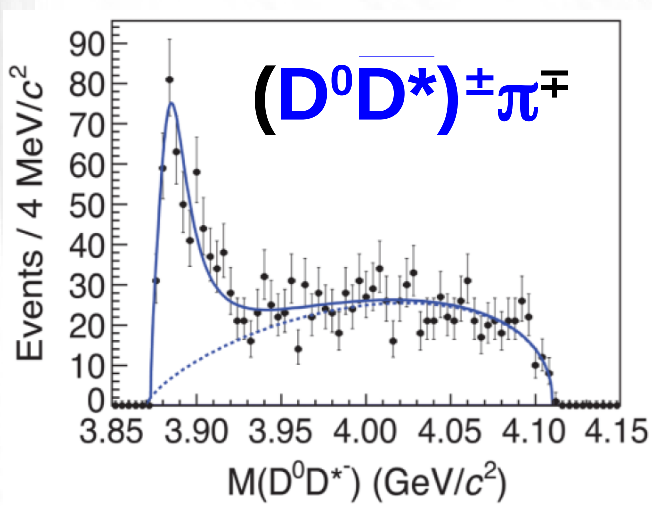
M. Ablikim *et al.*, Nucl. Instr. and Meth. **A 614** (2010) 345–399

Discovered Z_c states at BESIII

$Z_c(3900)^{\pm}$



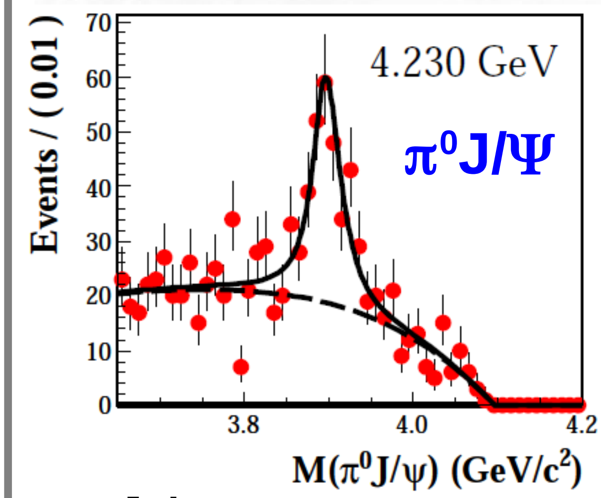
[Phys. Rev. Lett. 110, 252001 (2013)]



[Phys. Rev. Lett. 112, 022001 (2014)]

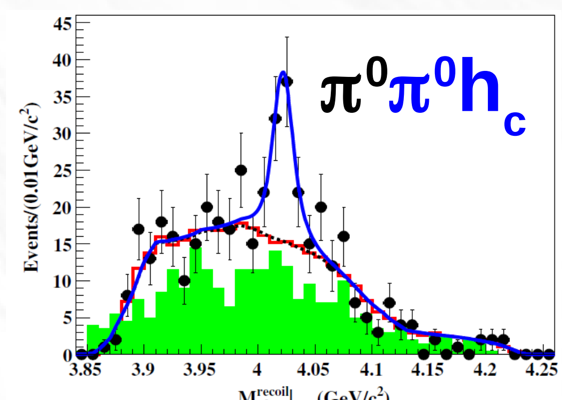
$\Gamma(Z_c \rightarrow DD^*)/\Gamma(Z_c \rightarrow \pi J/\Psi) =$ $6.2 \pm 1.1 \pm 2.7$

$Z_c(3895)^0$



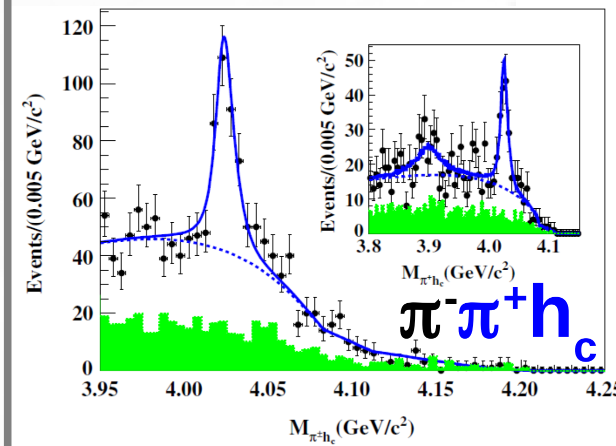
[Phys. Rev. Lett. 115, 112003 (2015)]

$Z_c(4020)^0/Z_c(4025)^0$

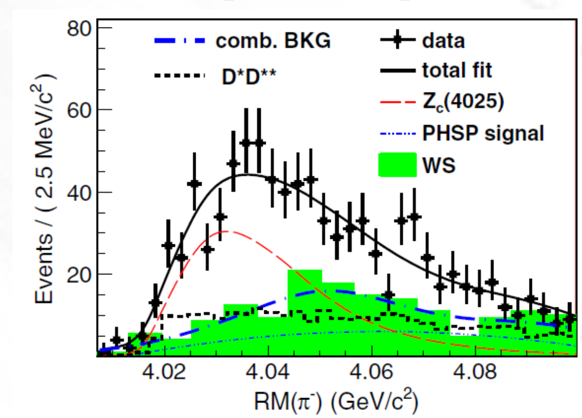


[Phys. Rev. Lett. 113, 212002 (2014)]
[Phys. Rev. Lett. 115, 182002 (2015)]

$Z_c(4020)^{\pm}$

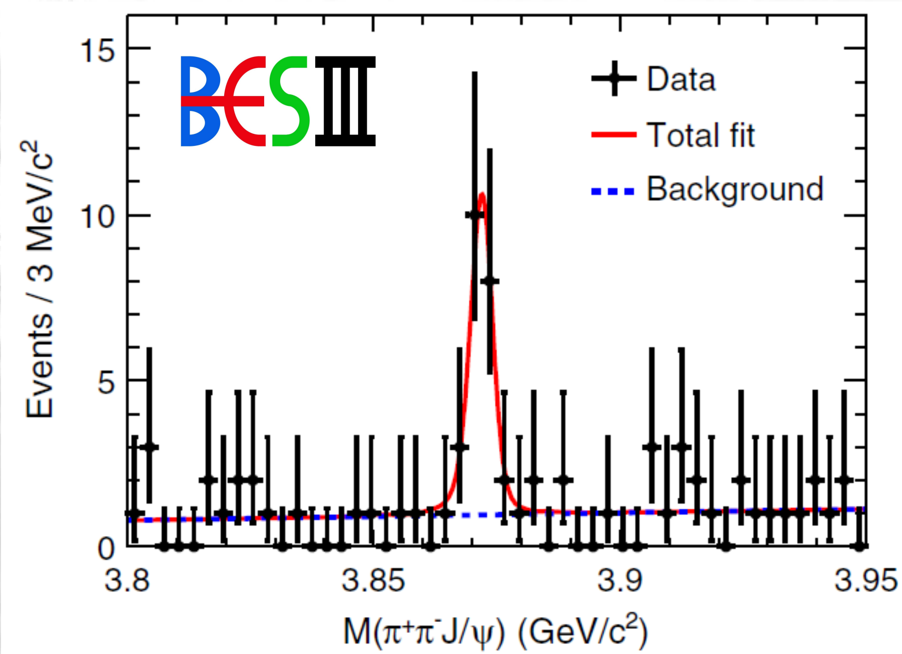


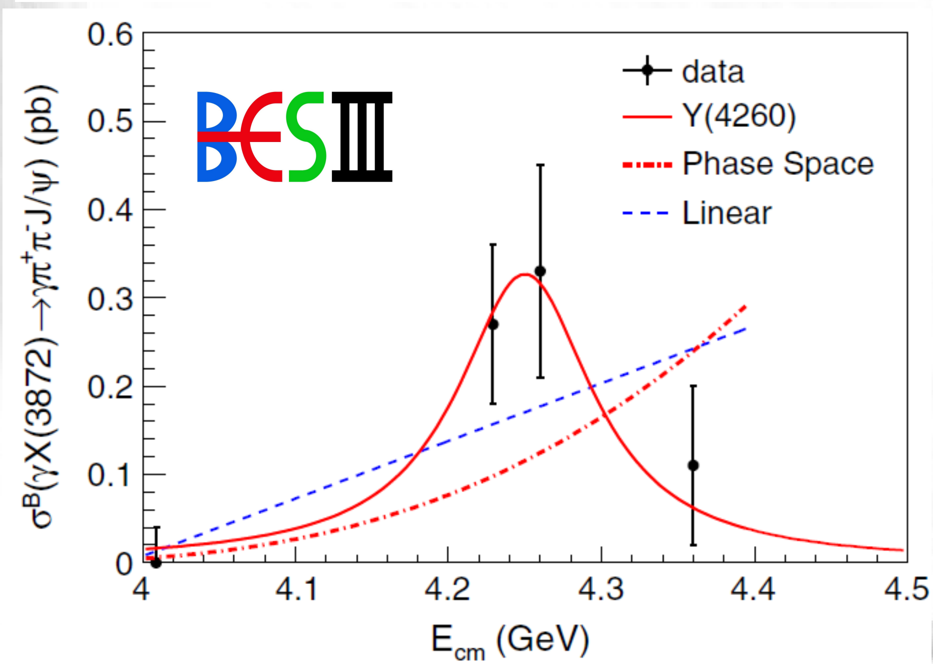
[Phys. Rev. Lett. 111, 242001 (2013)]



[Phys. Rev. Lett. 112, 132001 (2014)]

Evidence of transition between Y(4260) and X(3872) states





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

$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma J/\Psi\pi^+\pi^-$

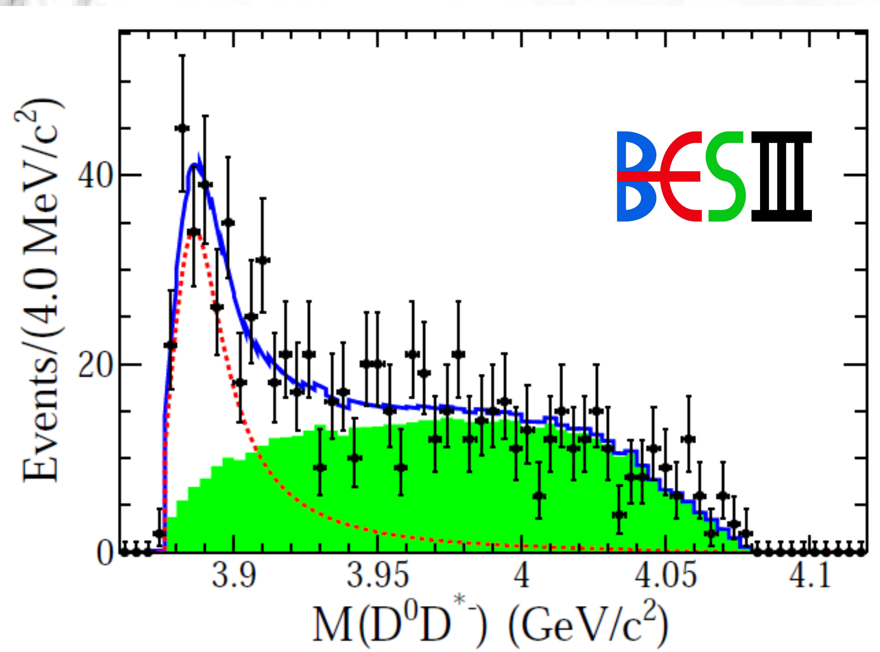
- **The X(3872) signal is clearly observed: significance 6.3σ**
- **Cross-section hints radiative transition between Y(4260) and X(3872)**
- **Existence of transitions between Y(4260) X(3872) and Z_c states suggest that there might be some commonality in the nature of these three different states**
- **Assuming that measured transition is from Y(4260):**

$$\frac{B(Y(4260)\rightarrow\gamma X(3872))}{B(Y(4260)\rightarrow\pi^+\pi^- J/\psi)} \sim 0.1$$

$Z_c(3900)$ Quantum Numbers

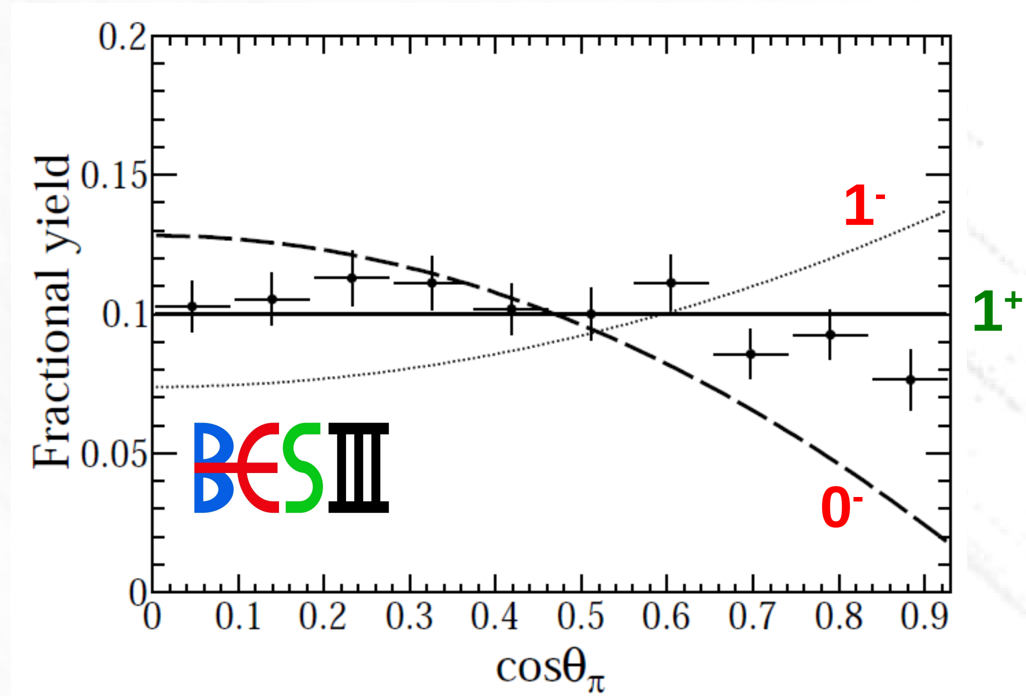
$e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^{\mp}$

$\sqrt{s}$ = 4.23 and 4.26 GeV



- **M = (3881.7±1.6±1.6) MeV/c^2**
- **Γ = (26.6±2.0±2.1) MeV**
  [Phys. Rev. D 92, 092006 (2015)]

Fits to |cosθ| distributions for $\pi^+ D^0 \bar{D}^0$ – tagged events



Spin-parity of $Z_c(3900)$ 1^+

Reconstruction method:

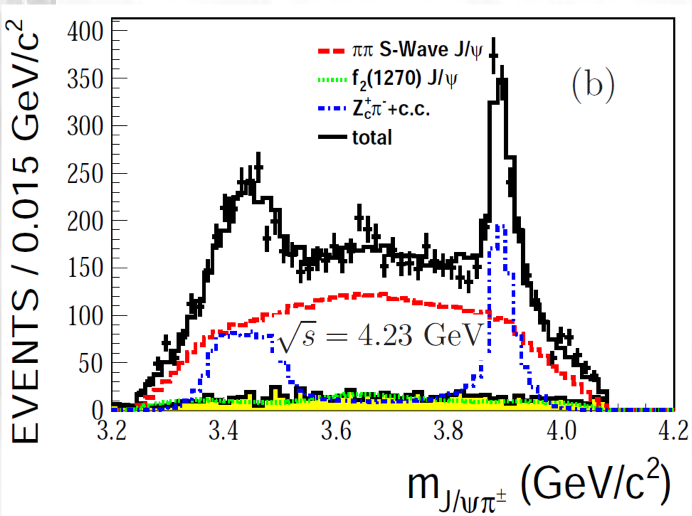
- Complete reconstruction of decay

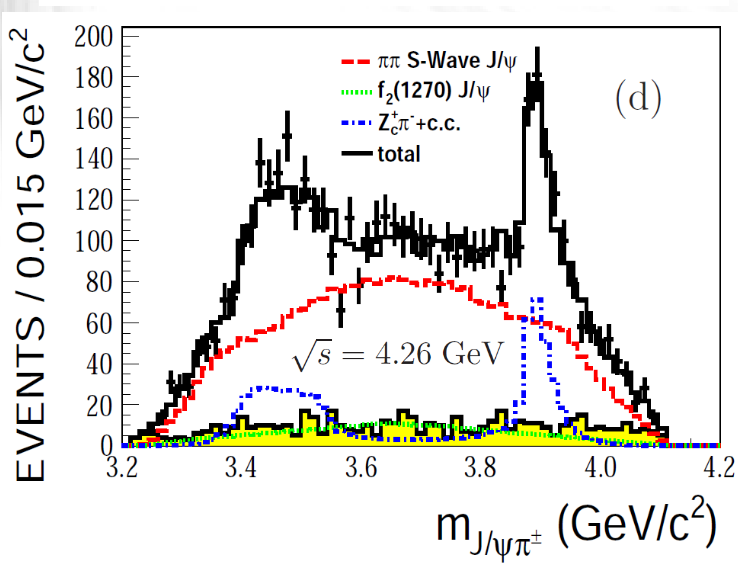
Z_c(3900) Quantum Numbers (PWA)

BESIII preliminary

Complete PWA of Zc(3900) in $e^+e^- \to \pi^+\pi^- J/\psi$ at √s=4.23 GeV and √s=4.26 GeV

Projections to $m_{J\Psi\pi\pm}$



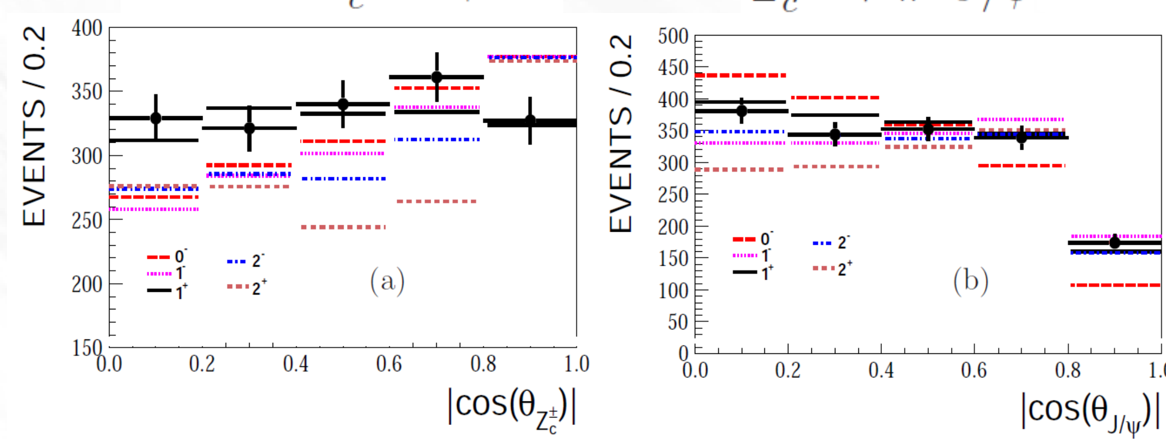


Significance of 1^+ hypothesis over other quantum numbers

Hypothesis	$\Delta(-2\ln L)$	significance
1^+ over 0^-	94.0	12.0σ
1^+ over 1^-	158.3	16.3σ
1^+ over 2^-	151.9	15.9σ
1^+ over 2^+	96.0	12.1σ

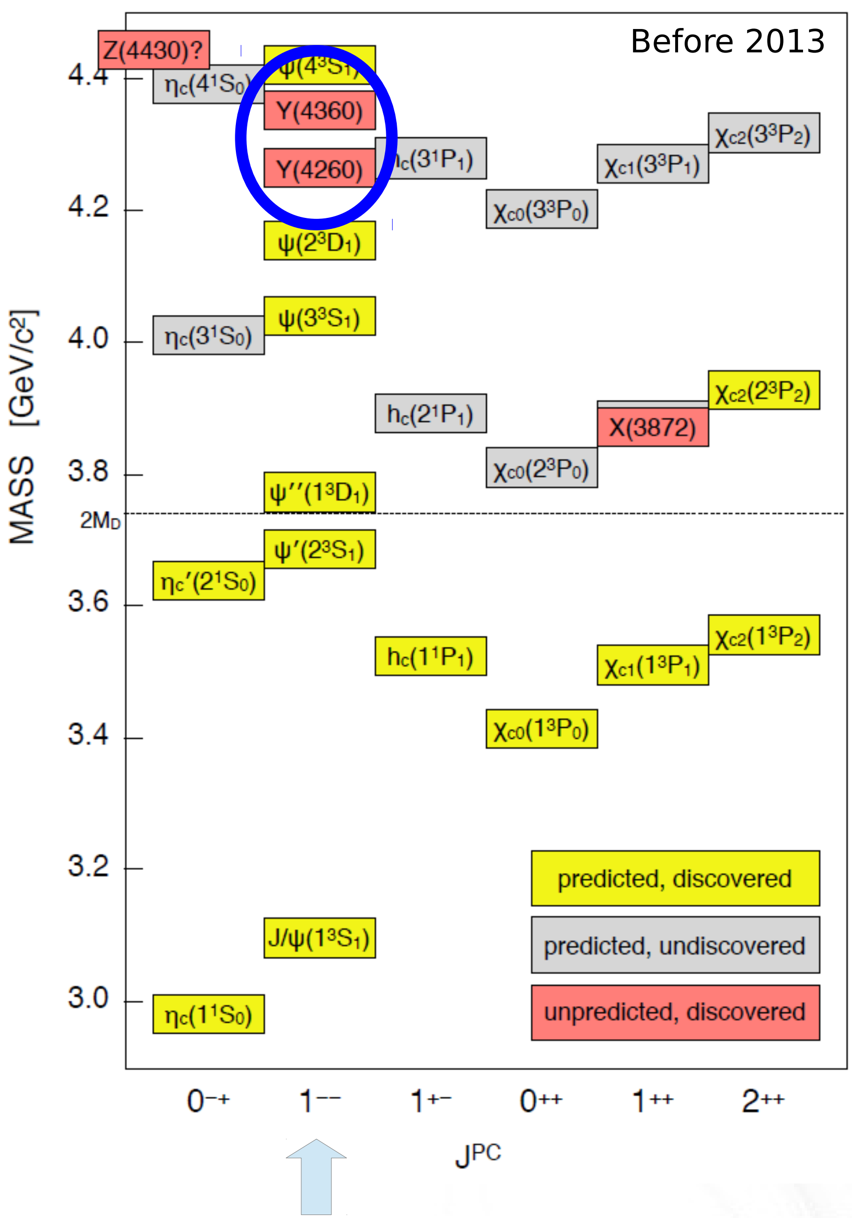
Polar and helicity angle distributions in

$e^+e^- \to Z_c^+\pi^- + c.c.$ $Z_c^\pm \to \pi^\pm J/\psi$



Spin-parity of Z_c(3900) 1^+

Discoveries Come Unexpected...



States can be directly populated in annihilation e^+e^-

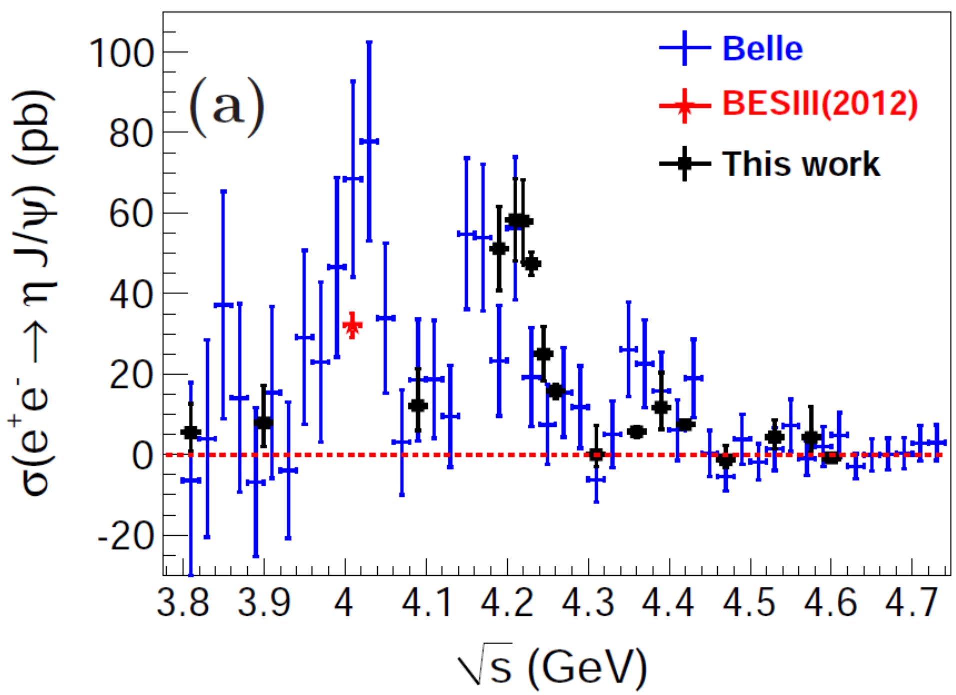
Direct formation of 1^{--} states allows us to study in details Y states

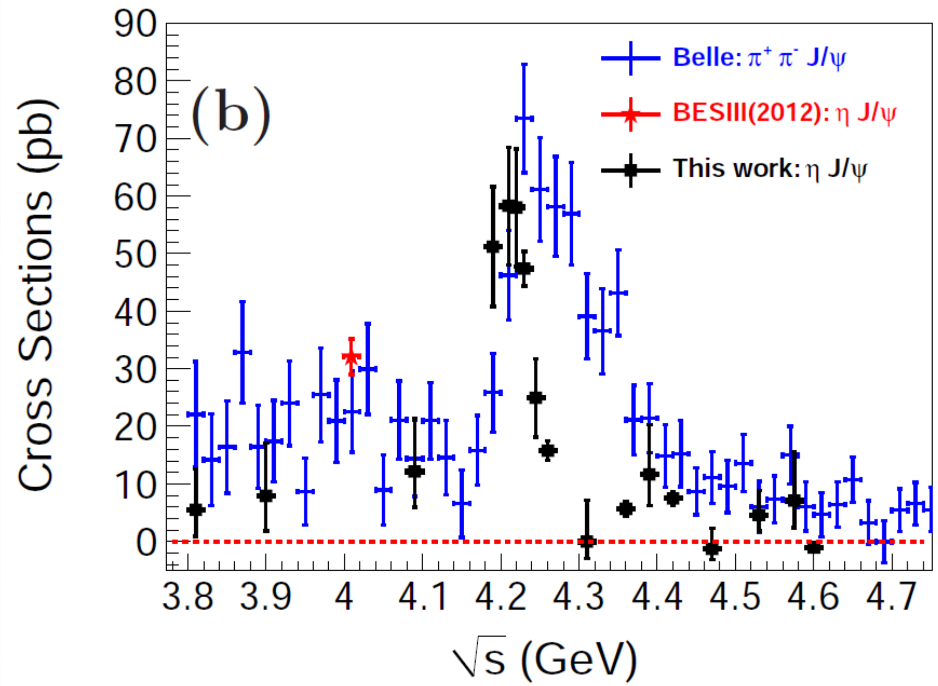
In the process $e^+e^- \to \pi^+\pi^- J/\psi$ we discovered exotic matter…

Will the energy scan of the Y state reveal new structures?

Y states: $e^+e^- \to \eta J/\Psi$

Energy-dependent cross-section compared to Belle data obtained in:
$\eta J/\Psi$ and **$\pi^+\pi^- J/\Psi$**





- **Agree with previous results with improved precision.**
- **Non-trivial structure around 4.2 GeV:**
  This could indicate the existence of a rich spectrum of Y states in this energy region with different coupling strengths to the various decay modes.

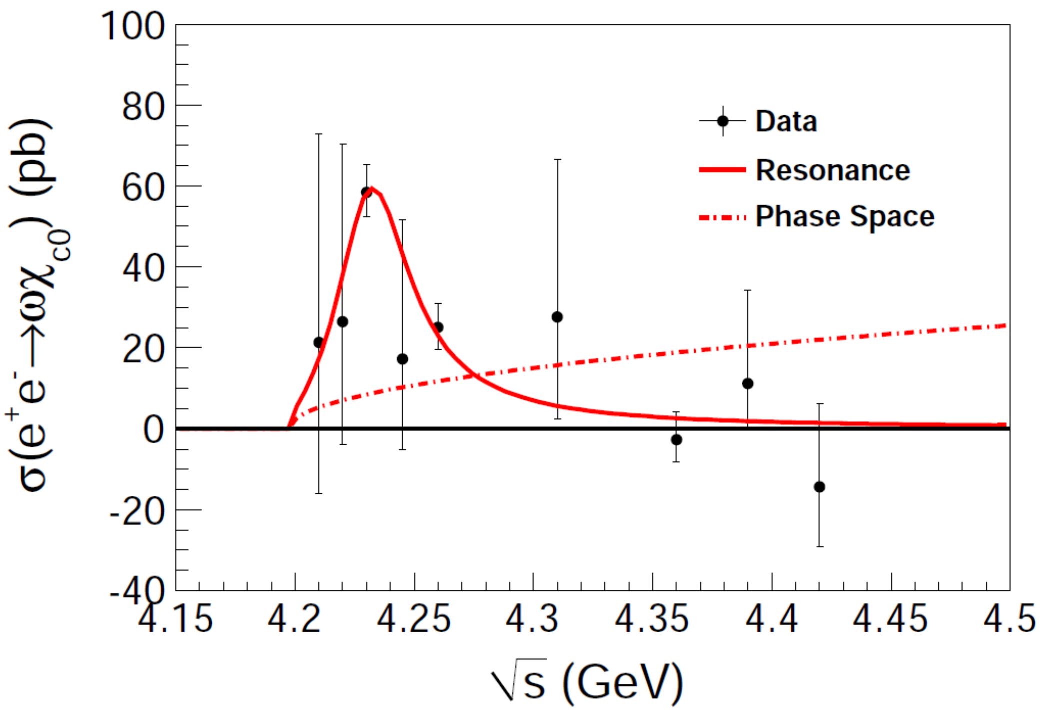
[Phys. Rev. D 91, 112005 (2015)]

Scan of Y states

$e^+e^- \rightarrow \omega\chi_{C0}$

[Phys. Rev. Lett. 114, 092003 (2015)]

Energy-dependent cross-section



Resonance structure is observed (significance > 9σ)!
Assuming single BW:

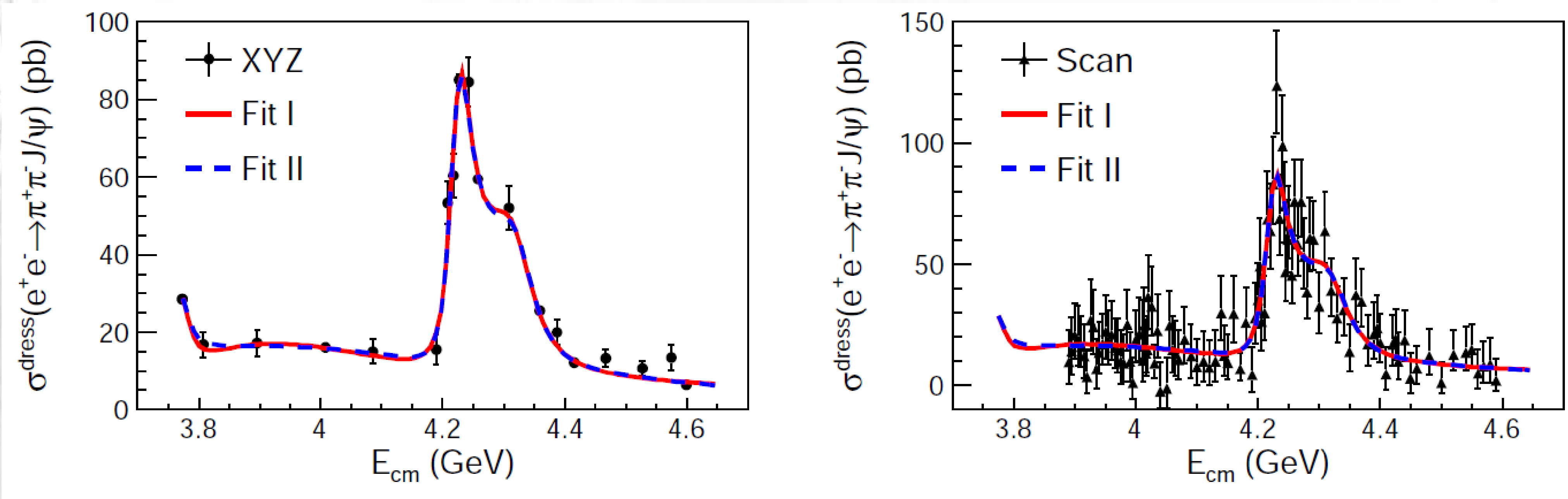
- **M = (4230±8±6) MeV/c^2**
- **Γ = (38±12±2) MeV**

- **Inconsistent with Y(4260) from ππJ/Ψ**
- **No significant signals for $e^+e^- \rightarrow \omega\chi_{C1,2}$**

Scan of Y states

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

[Phys. Rev. Lett. 118, 092001 (2017)]



Simultaneous fit of two independent data sets ("XYZ" and "Scan") revealed two resonances:

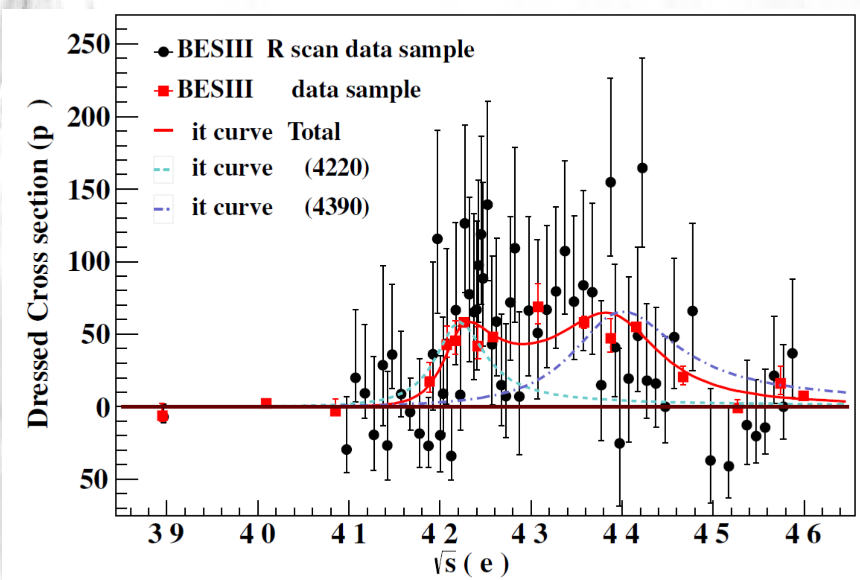
- **Known Y(4260)?, M = (4222.0±3.1±1.4) MeV/c^2 Γ = (44.1±4.3±2.0) MeV**
- **Y(4360)? M = (4320.0±10.4±7) MeV/c^2 Γ = (101.4±25±10) MeV**

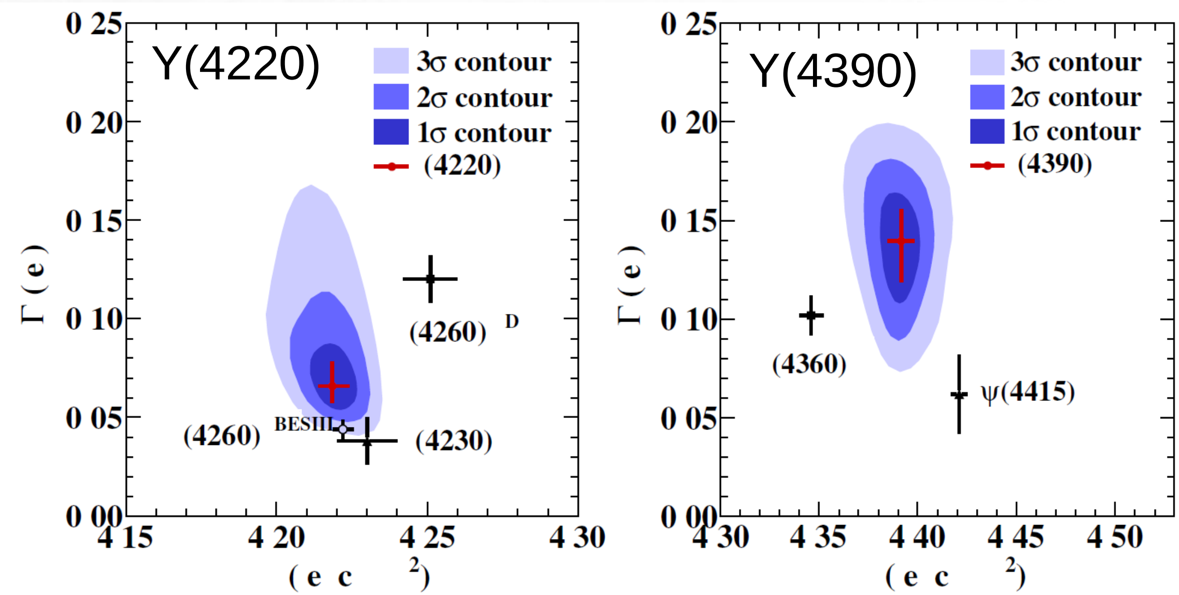
- **Improved measurements for Y(4260)?**
- **Y(4360) observed for the first time in $\pi^+\pi^-$J/Ψ, seen by Belle and BABAR in $\pi^+\pi^-$ Ψ(2S)**
- **No hints for Y(4008) seen by Belle**

Scan of Y states

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

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





Simultaneous fit of two independent data sets (“XYZ” and “Scan”) revealed two resonances:

- **Y(4220): M = (4218.0±5±0.9) MeV/c^2 Γ = (66±12±0.4) MeV**
- **Y(4390): M = (4391.5±6.8±1.0) MeV/c^2 Γ = (139.5±20±0.6) MeV**

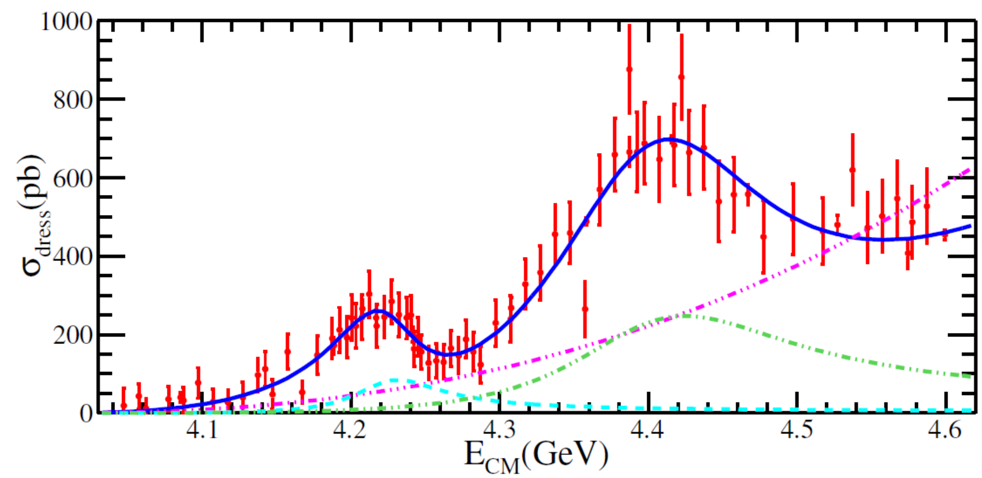
- **The parameters of these structures are different from those of Y(4260), Y(4360) and Ψ(4415)**
- **Y (4220) consistent with the resonance observed in $e^+e^- \to \omega\chi_{c0}$**

Scan of Y states

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

BESIII preliminary

Fit to the dressed cross sections



Fit reveals two resonances (significance >10σ):

- **Y(4220): M = (4224.8±5.6±4) MeV/c^2**
  Γ = (72.3±9.1±0.9) MeV
- **Y(4390): M = (4400.1±9.3±2.1) MeV/c^2**
  Γ = (181.7±16.9±7.4) MeV

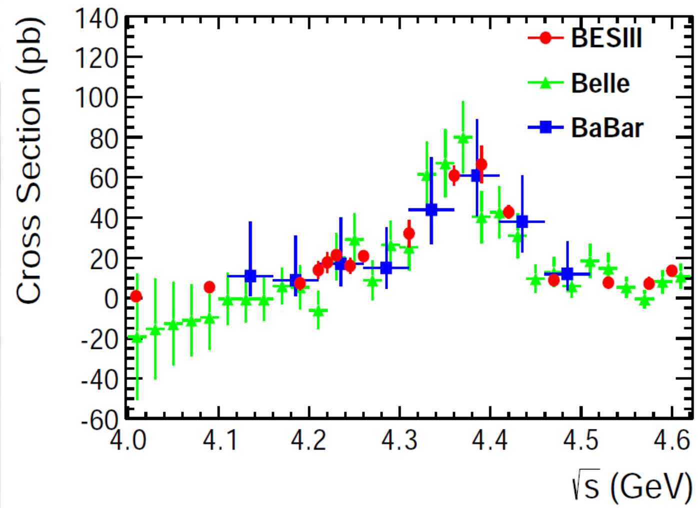
- **The parameters of observed structures consistent with ones seen in**
  - **Y(4220): $\pi^+\pi^- h_C$, $\pi^+\pi^- J/\Psi$, $\omega\chi_{c0}$,**
  - **Y(4390): $\pi^+\pi^- h_C$**
- **The mass of Y(4220) is lower by about 30 MeV/c^2 than that of the Y(4260), but consistent with the prediction of $D\bar{D}_1$ molecule interpretation within errors**
- **Assuming that Y(4220) is the same resonance as the Y(4260) the $\pi^+ D_0 D^{*-}$ could be the dominant decay channel of the Y (4260)**

Scan of Y states

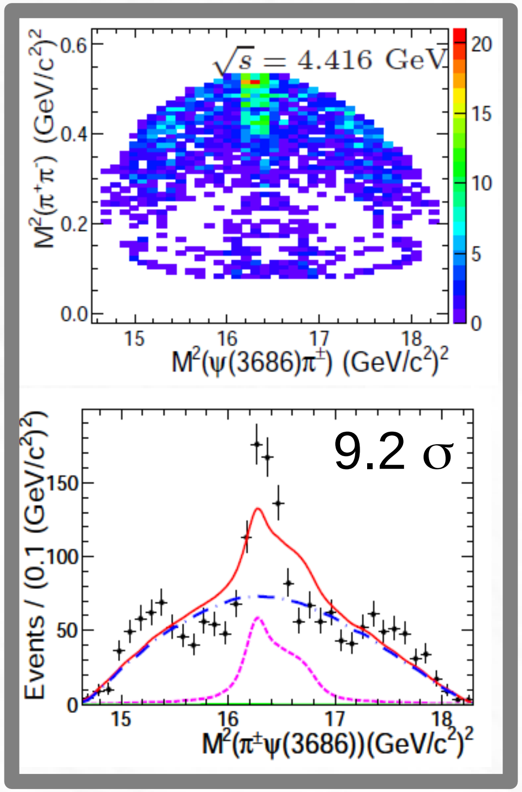
$$e^+e^- \to \pi^+\pi^-\psi(3686)$$

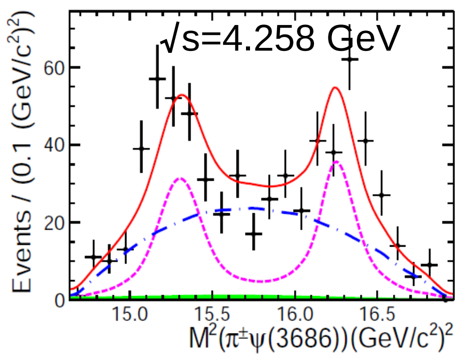
[arXiv:1703.08787]

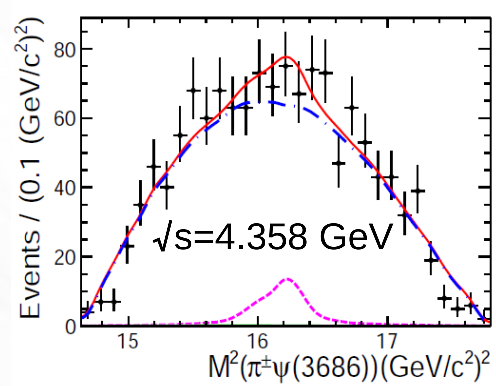
The measured Born cross sections



A prominent narrow structure observed in πΨ(3686) mass spectrum for √s=4.416 GeV







Assuming 1^+ charmonium-like state fit yields:

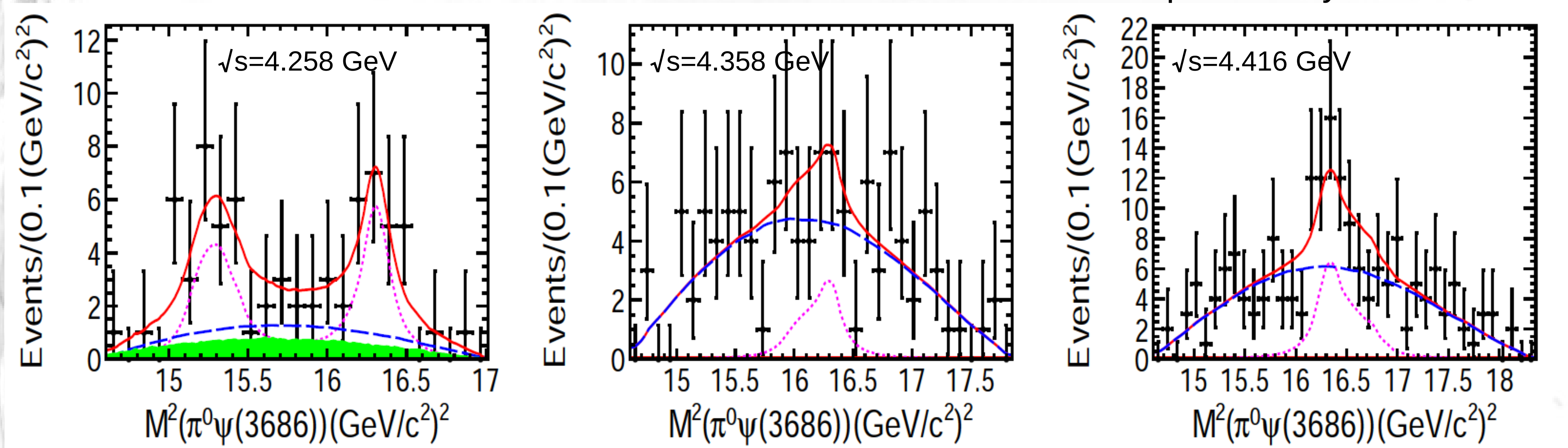
- **M = (4032.1 ± 2.4) MeV/c^2**
- **Γ = (26.1 ± 5.3) MeV**

Does the same structure exists in the neutral channel?

Scan of Y states

$$e^+e^- \to \pi^0\pi^0\psi(3686)$$

BESIII preliminary



Assuming 1^+ charmonium-like state fit yields: **M = (4038.7 ± 6.5) MeV/c^2**

Γ = (32 ± 15) MeV

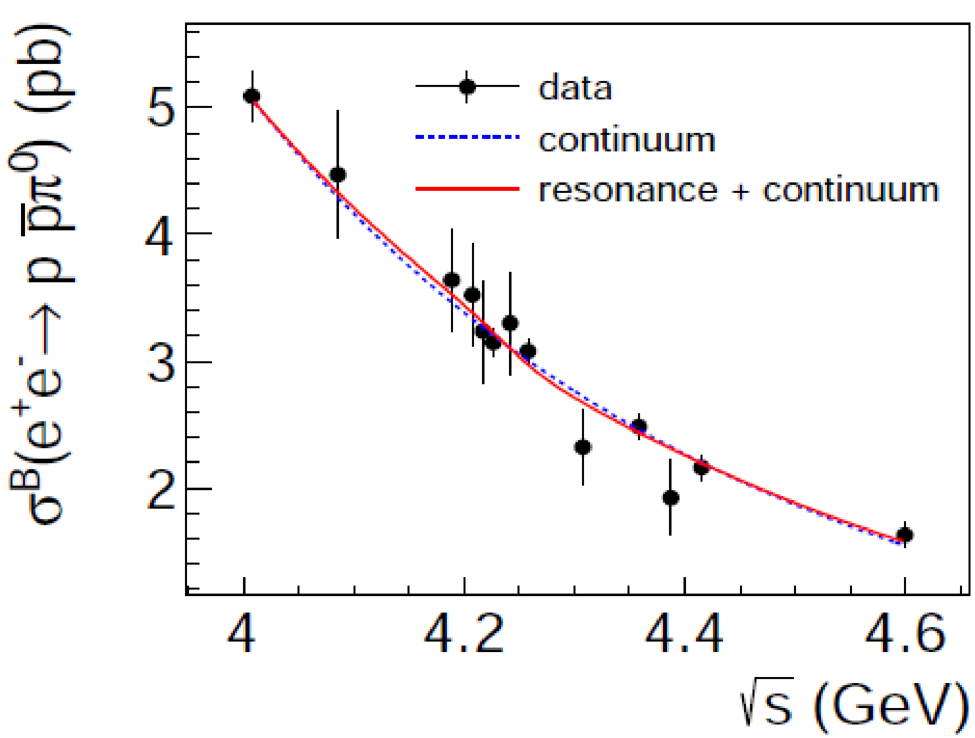
- **The measured Born cross sections: ~half of those for $\pi^\pm\Psi(3686)$ (as expected)**
- **The Dalitz distributions of $\pi^0\pi^0\Psi(3686)$ are consistent with those in $\pi^+\pi^-\Psi(3686)$ for all energy points**
- **Observed structure at M = (4038.7 ± 6.5) MeV/c^2 confirms one seen in the charged mode:**
  - **the fit curve does not match the data perfectly**
  - **A future larger statistics sample of data could lead to a better understanding of the structure.**

Scan of Y states

$$e^+e^- \to p\bar{p}\pi^0$$

[arXiv:1701.08591]

Searches for new decay modes of the Y(4260) may shed light on its nature



Hybrid model predicts a sizable coupling between the Y(4260) and charmless decays.

Not observed: upper limit for Born cross section 0.01 pb at 90% C.L.

Scan of Y states

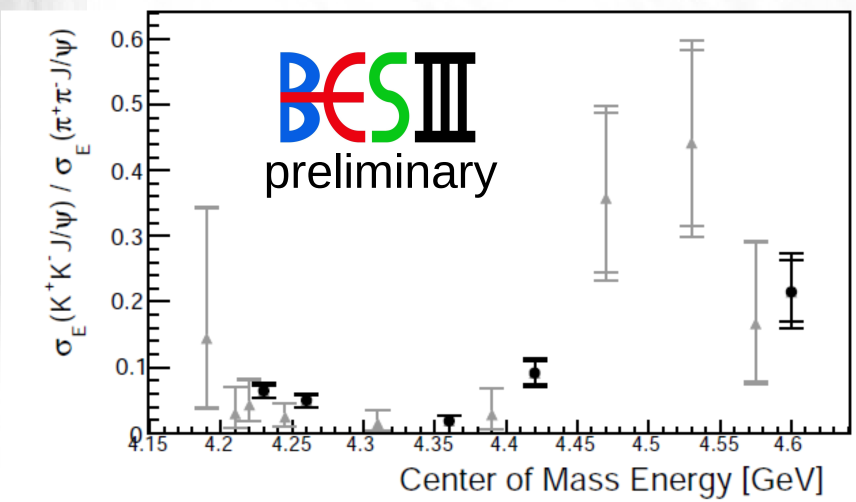
$$e^+e^- \to K\bar{K}J/\psi$$

preliminary

Searches for new decay modes of the Y states

- So far no conclusive evidence for a Y(4260) decay (from cross-section measurements)
- Few of the cross section measurements hint a more complex pattern than just the production of a Y (4260).

Cross-section ratio for two independent data sets



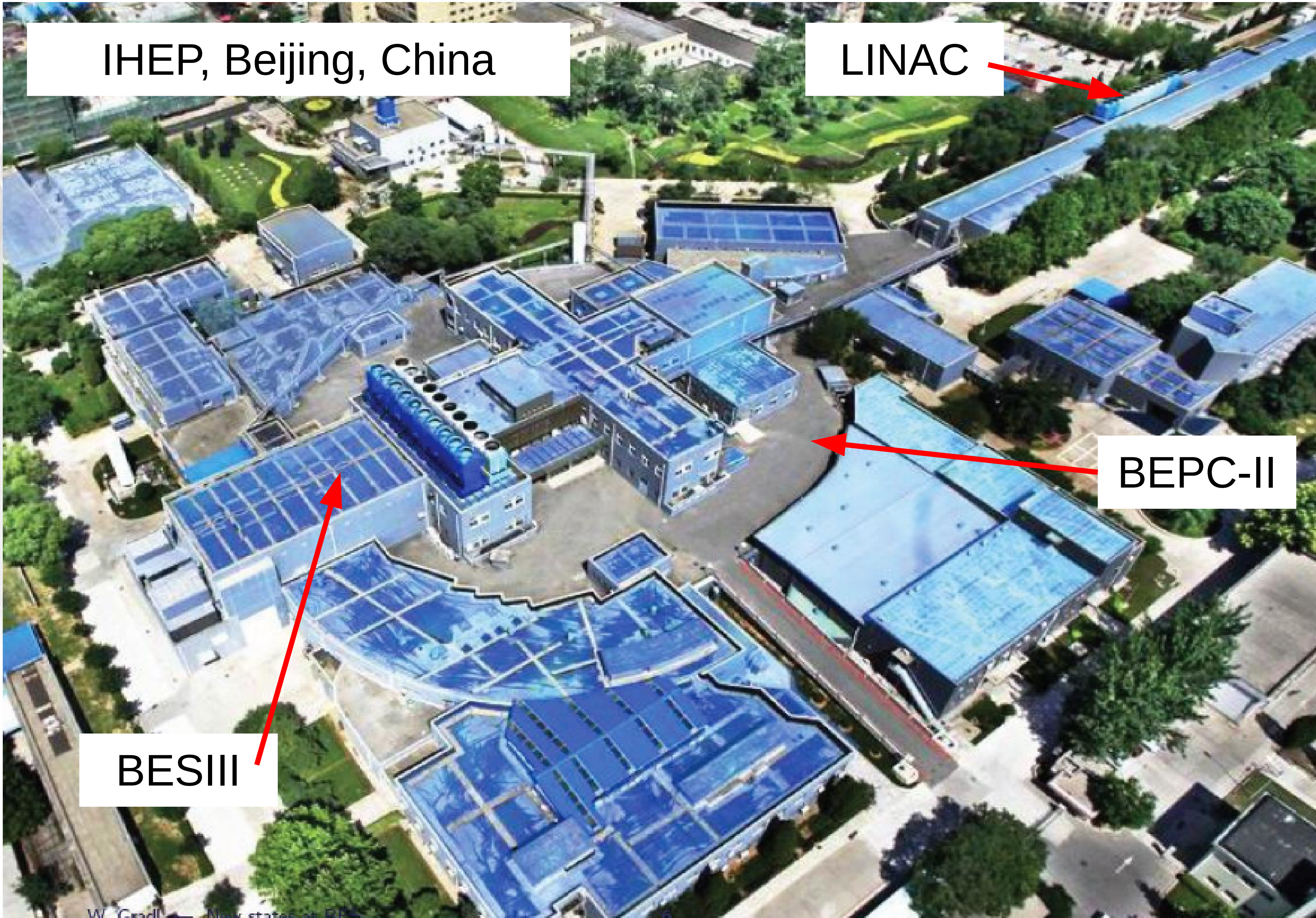
- **$\sigma_E(K^+K^- J/\Psi)/\sigma_E(\pi^+\pi^- J/\Psi)$ inconsistent with flat ratio (3.5σ significance) at 4.226 – 4.358 GeV**
  - **Y(4260) as defined by $\pi^+\pi^- J/\Psi$ inconsistent with $K^+K^- J/\Psi$**

- **More complex structure observed at ~4.6 GeV**

Summary

- BESIII collaboration performs systematic studies of XYZ states to reveal their nature
- Several Z_c states are established in open-charm region
  - Decay rates to open- and hidden-charm states are measured and are not consistent with conventional open-charm mesons (sensitive probe to discriminate between theoretical models)
- Hadron and radiative transitions are observed between Y and Z, and Y and X states, respectively
- Measurement of Born cross-section for different channels in the region between 4 and 4.6 GeV reveal complex structures and new Y states

BESIII at BEPC-II

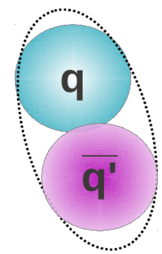


Hadron Matter

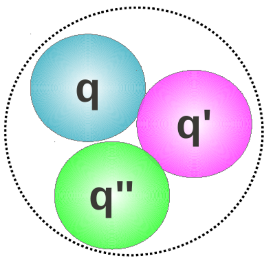
BESIII

Colour-neutral states allowed by QCD

Pions, charmonium, etc



Mesons

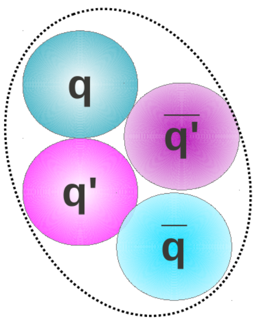


Baryons

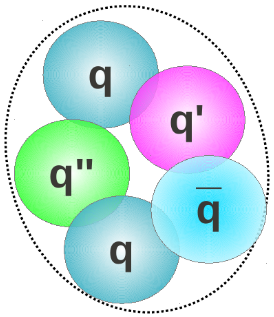
Protons, neutrons, etc

Conventional matter

Z_c and **Z_b** states



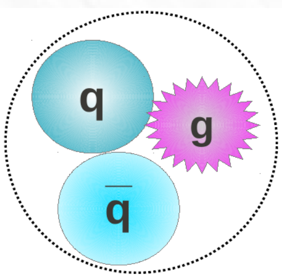
Four-quark state



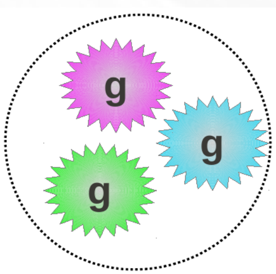
Five-quark state

Pentaquark?

XY states?



Hybrid



Glueball

$f_0(1500)$?

$f_0(1500)$?

XY states?

...

Exotic matter

XYZ States, Nomenclature

Conventional quarkonium ($c\bar{c}$), meson molecule ($c\bar{q}$ + $\bar{c}q$), tetraquark ($c\bar{c}q\bar{q}$), hybrid state ($c\bar{c}$ + g ...) et.al.

e^+e^- annihilation

↓

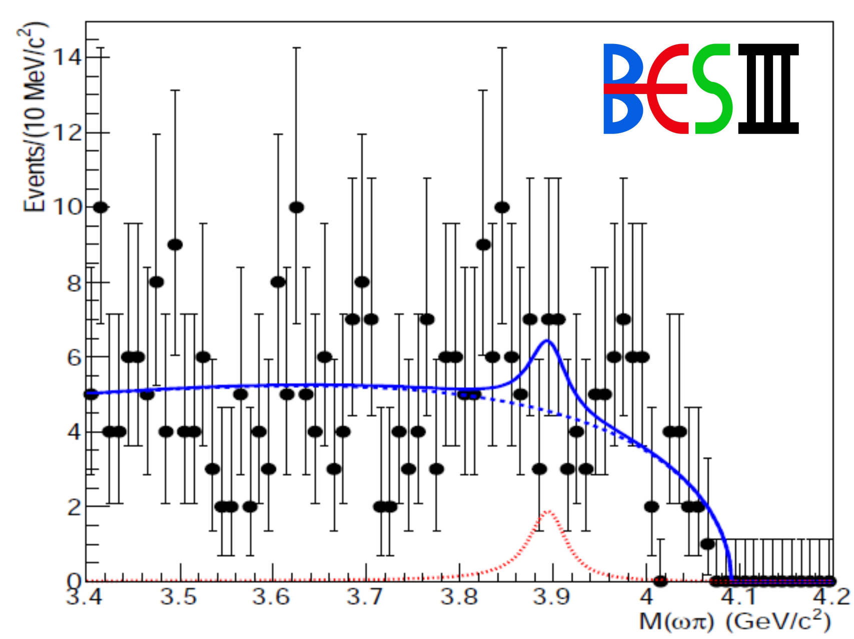
X: 1^{++}, et. al ← **Y: 1^{--}** → **Z: isospin triplet**

Radiative or hadronic transitions:
Y → γ X(3872)

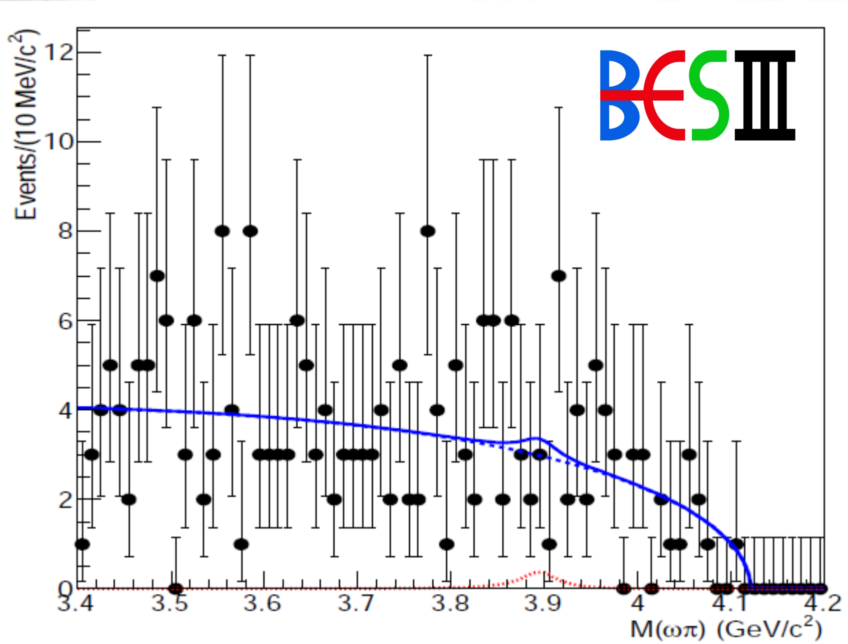
Hadronic transitions:
Y → π Z_c(3900)

More Mysteries of $Z_c(3900)$

$\sqrt{s}$ = 4.23 GeV



$\sqrt{s}$ = 4.26 GeV



Search for $Z_c(3900) \rightarrow \pi^{\pm}\omega$

There are three important decay modes for charmonium-like states:

- the fall-apart to open charm mesons;
- the cascade to hidden charm mesons;
- decays to light hadrons via intermediate gluons.

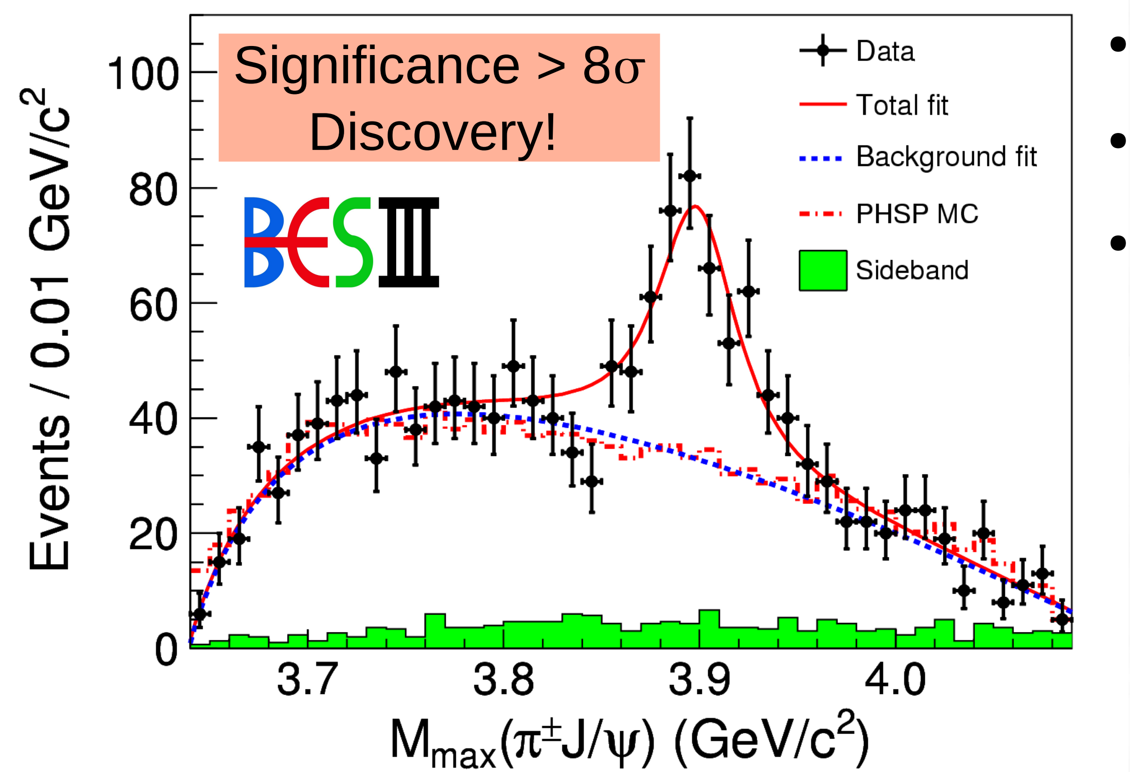
Since **$Z_c(3900)$** decays to $J/\Psi\pi$, a sizeable annihilation rate could be expected with $\bar{c}c$ in S − wave (as for χ_c)

No significant signal observed:
$\Gamma(Z_c(3900) \rightarrow \omega\pi) < 0.2\% \, \Gamma(Z_c(3900))$

Annihilation to $\bar{c}c$ is suppressed?

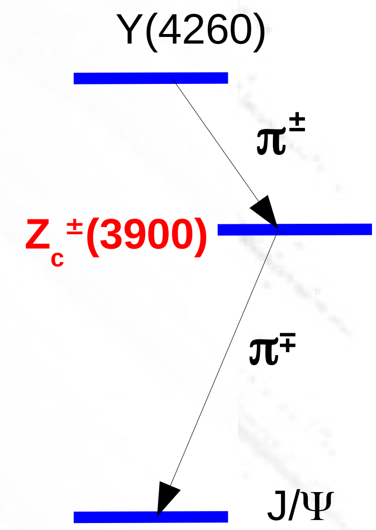
[Phys. Rev. D 92, 032009 (2015)]

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

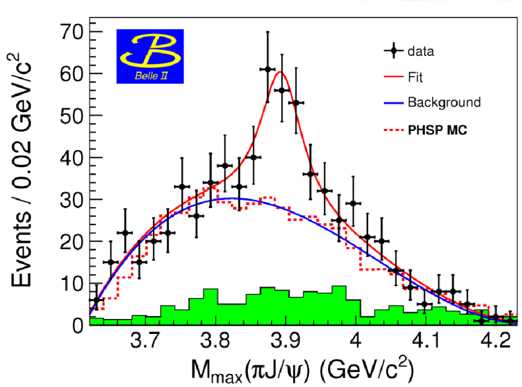


[Phys. Rev. Lett. 110, 252001 (2013)]

- Fit with S-wave Breit-Wigner
- **M = (3899.0±3.6±4.9) MeV/c²**
- **Γ = (46±10±20) MeV**



Discovered by BESIII, promptly confirmed by:

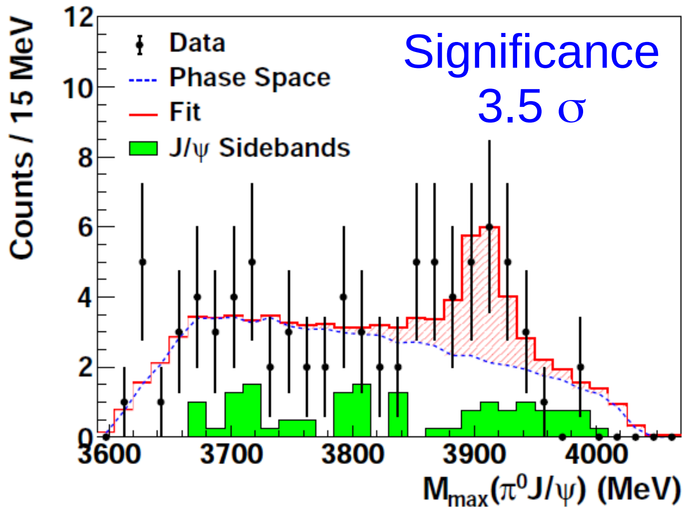


Belle: [Phys. Rev. Lett. 110, 252002 (2013)]

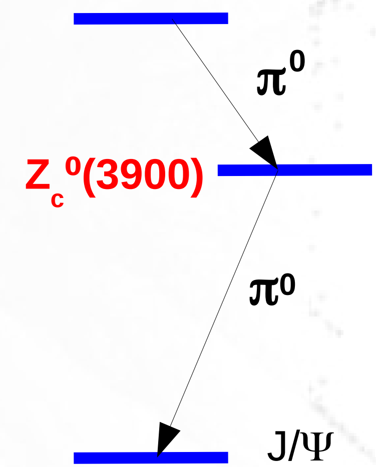
$M = 3894.5 \pm 6.6 \pm 4.5$ MeV/c²
$\Gamma = 63 \pm 24 \pm 26$ MeV

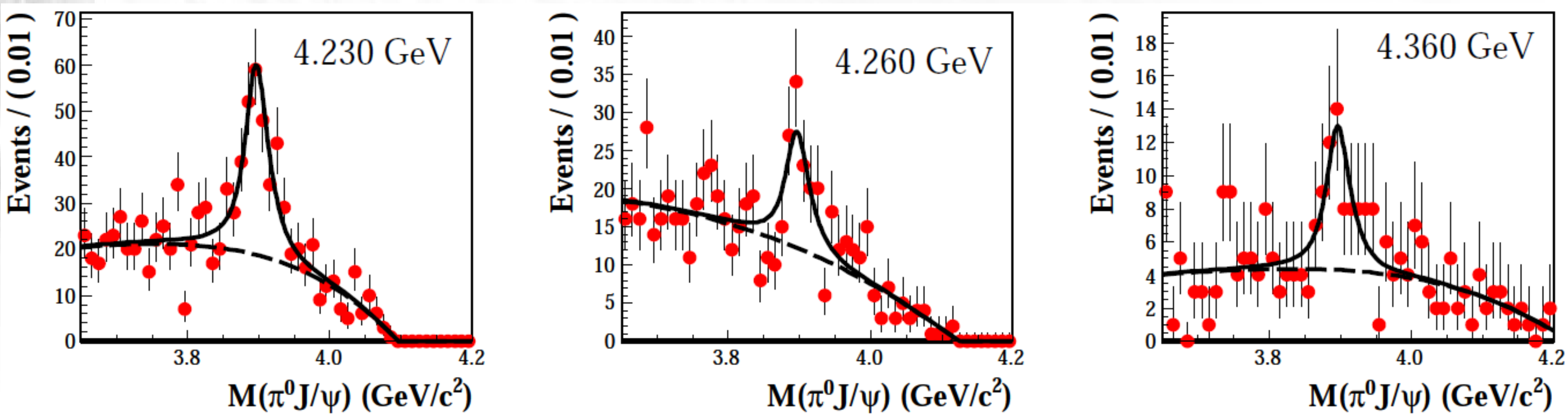
CLEO-c data: [Phys. Lett. B 727, 366 (2013)]

The $Z_c(3900)^0$



Evidence for $Z_c(3900)^0$ is seen in the CLEO-c data
[Phys. Lett. B 727, 366 (2013)]





Structure is seen in $\pi^0 J/\Psi$ (10 σ significance):

- **M = (3894.8±2.3±3.2) MeV/c^2**
- **Γ = (29±8.2±8.2) MeV**

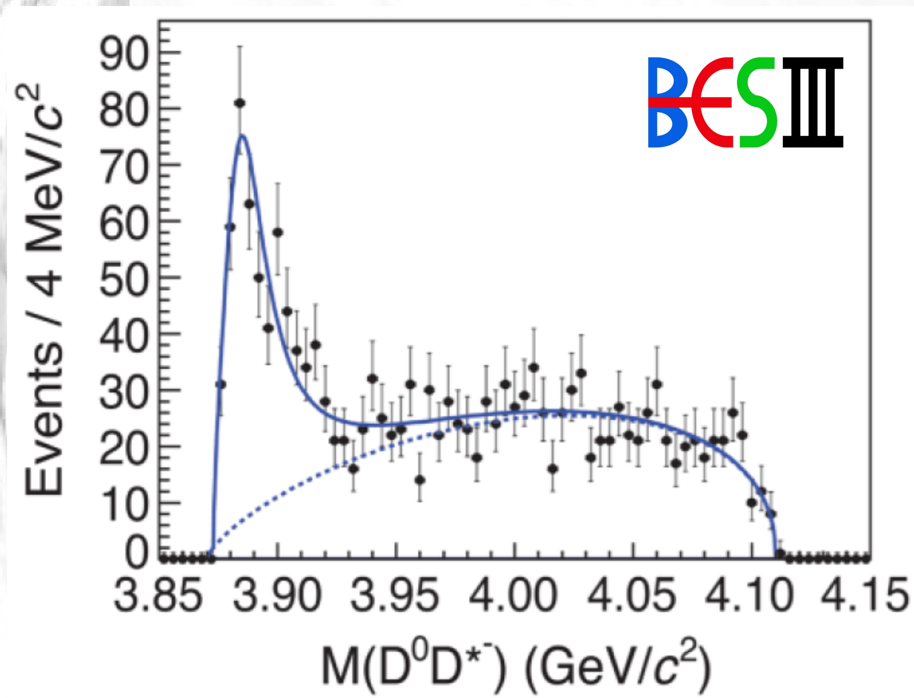
[Phys. Rev. Lett. 115, 112003 (2015)]

$Z_c(3900)$ – four-quark isospin triplet?

$Z_c(3900)$ Decay Rates

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

$\sqrt{s}$ = 4.26 GeV



- **M = (3883.9±1.5±4.2) MeV/c^2**
- **Γ = (24.8±3.3±11) MeV**

[Phys. Rev. Lett. 112, 022001 (2014)]

Reconstruction method:

- Reconstruct π^+ and $D^0 \to K^-\pi^+$
- Infer D^{*-}
- Analyse as well $\pi^+D^-D^{*0}$

- **Is found structure** (referred as $Z_c(3885)$) **different decay mode of the $Z_c(3900)$?**

$Z_c(3900)^\pm$ properties:

- M = (3899.0±3.6±4.9) MeV/c^2
- Γ = (46±10±20) MeV

- Assuming it is, the partial width ratio: **$\Gamma(Z_c \to DD^*)/\Gamma(Z_c \to \pi J/\Psi)$ = 6.2±1.1±2.7**

Tetraquark model disfavoured ?