XYZ particles and Charmonium studies at BESIII

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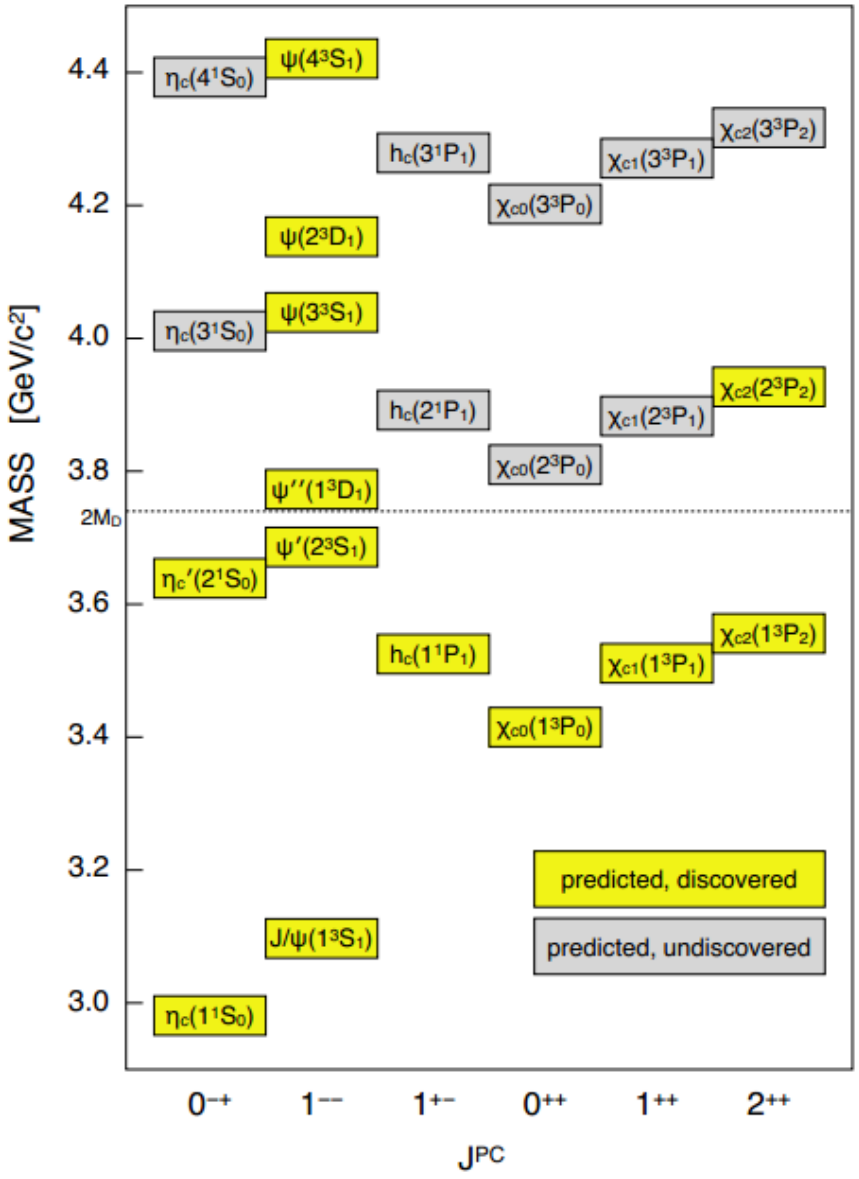
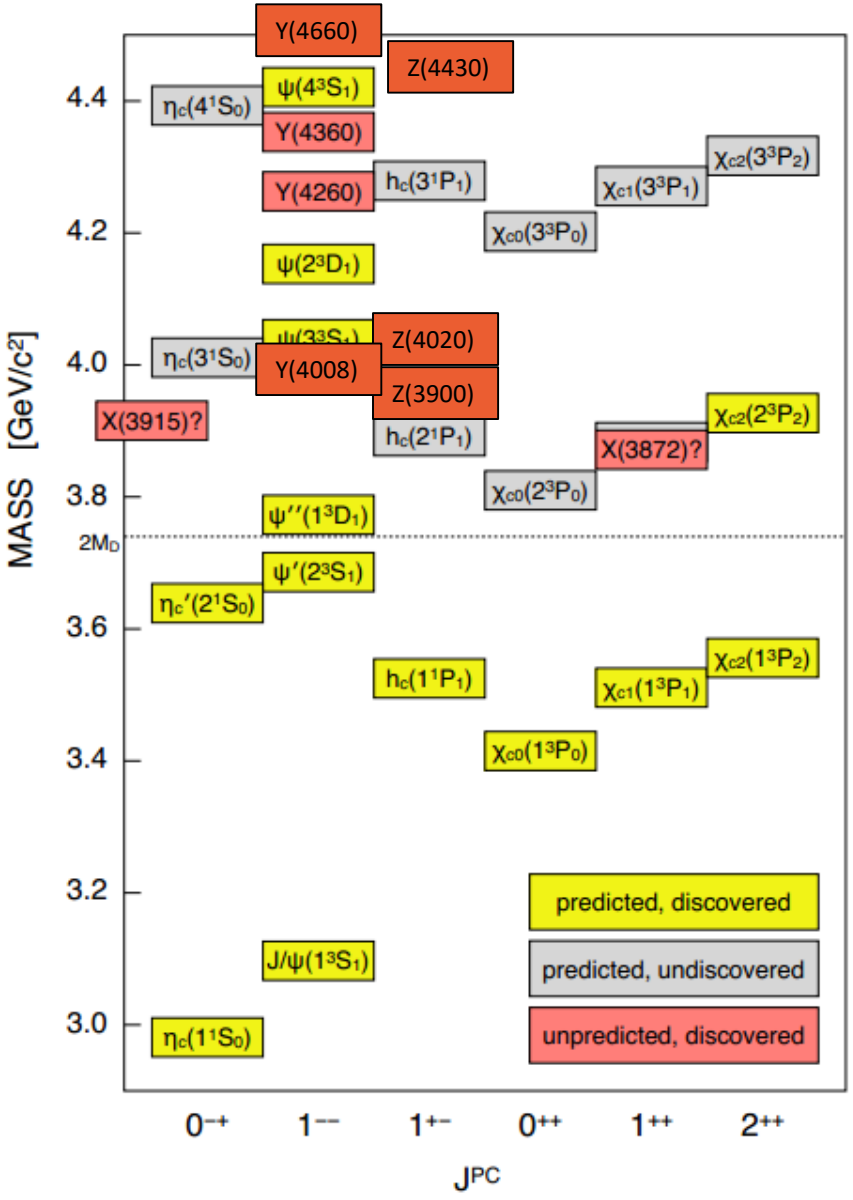
BESIII

Charmonium spectroscopy



- Below open-charm threshold, all states have been observed. Charm anti-charm potential models describe spectrum very well.
- Many missing states above open-charm threshold.

There are lots of XYZ states



- A number of new states above open-charm threshold.
- Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or XYZ)
- X: neutral, in B decays, Y transitions and hadron machines.
- Y: neutral, vectors in e^+e^- colliders.
- $Z^{\pm}$: charged quarkonium-like

What are they?

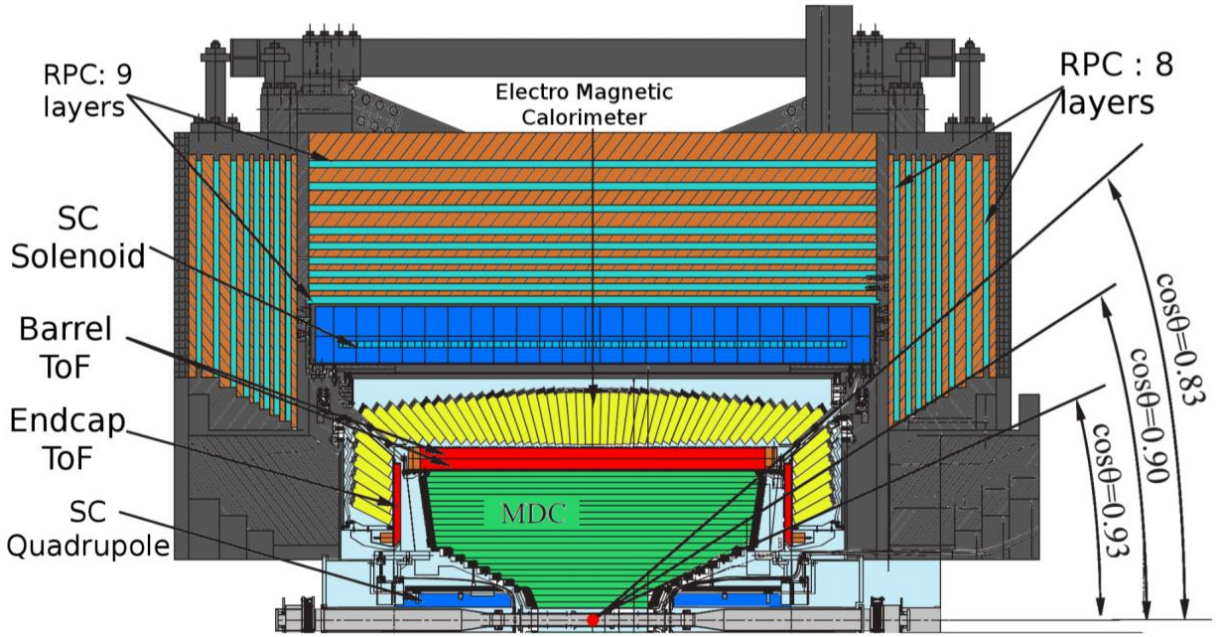
- Charmonium?
- Tetraquark?
- Molecule?
- Hybrid?
- Hadrocharmonium?
- …

BESIII Experiment

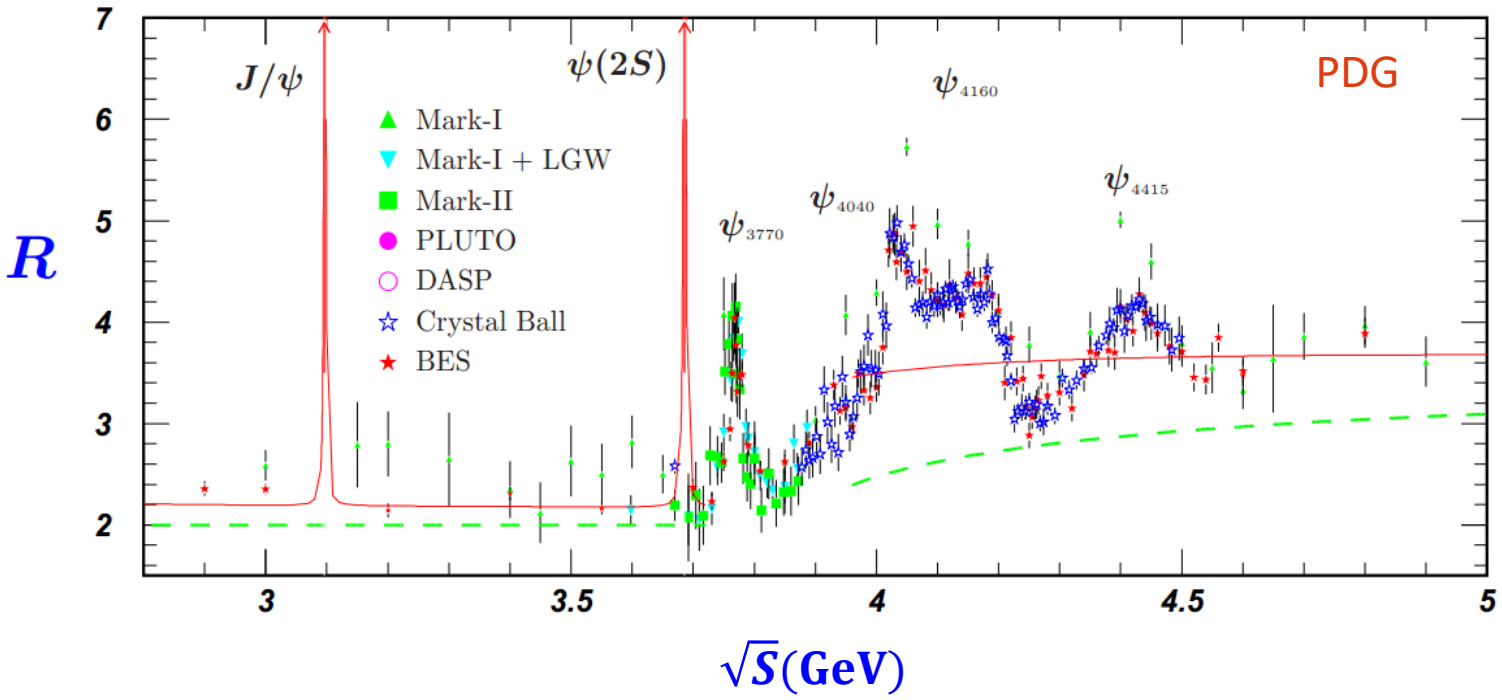
BEPCII Collider

- Symmetric e^+e^- collider, double-rings, 2.0 GeV<ECM<4.6 GeV
- Design luminosity: $10^{33}\ cm^{-2}s^{-1}$ @ 1.89GeV, achieved on 5th April, 2016!

BESIII Detector

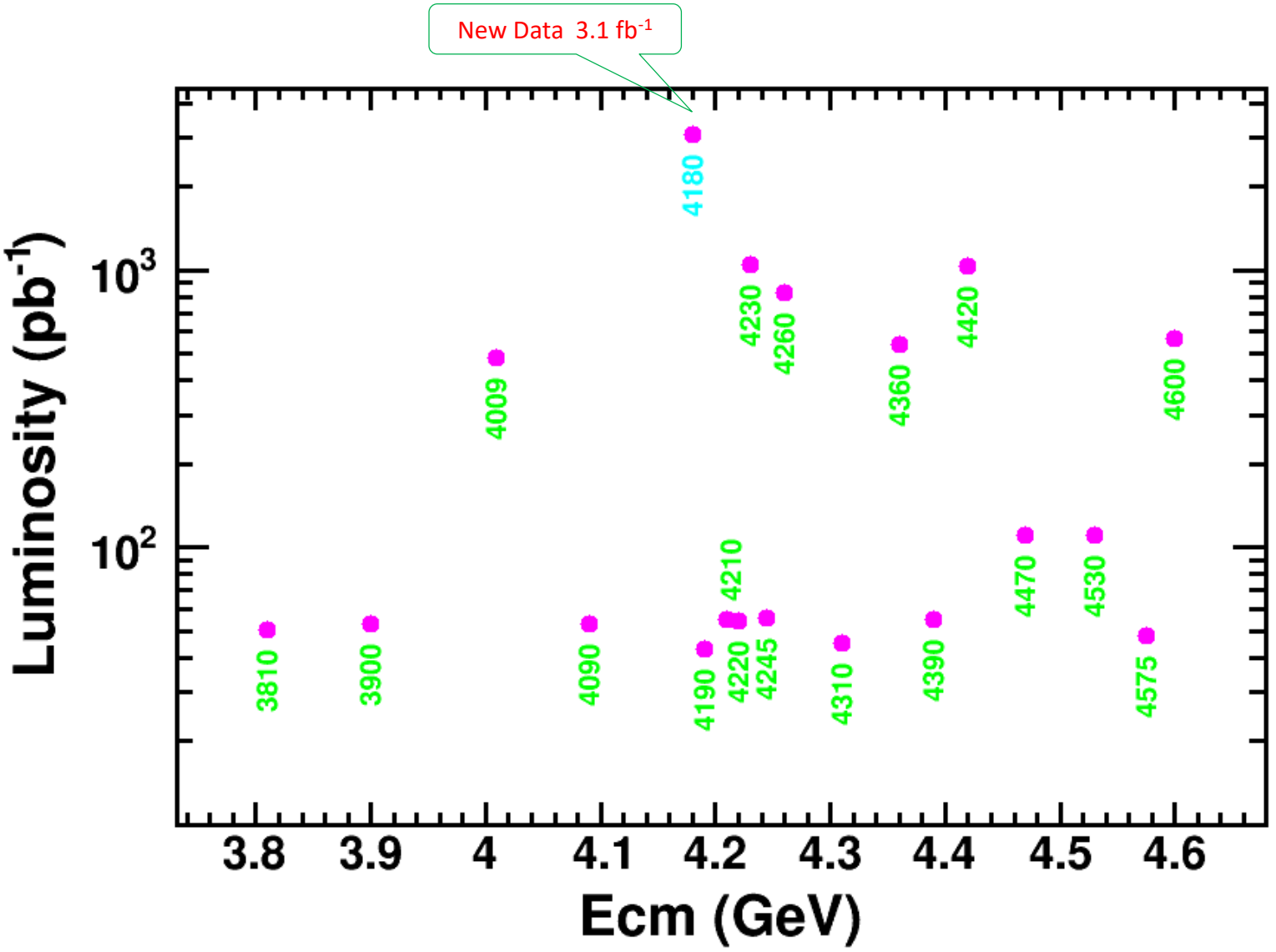


BESIII data samples



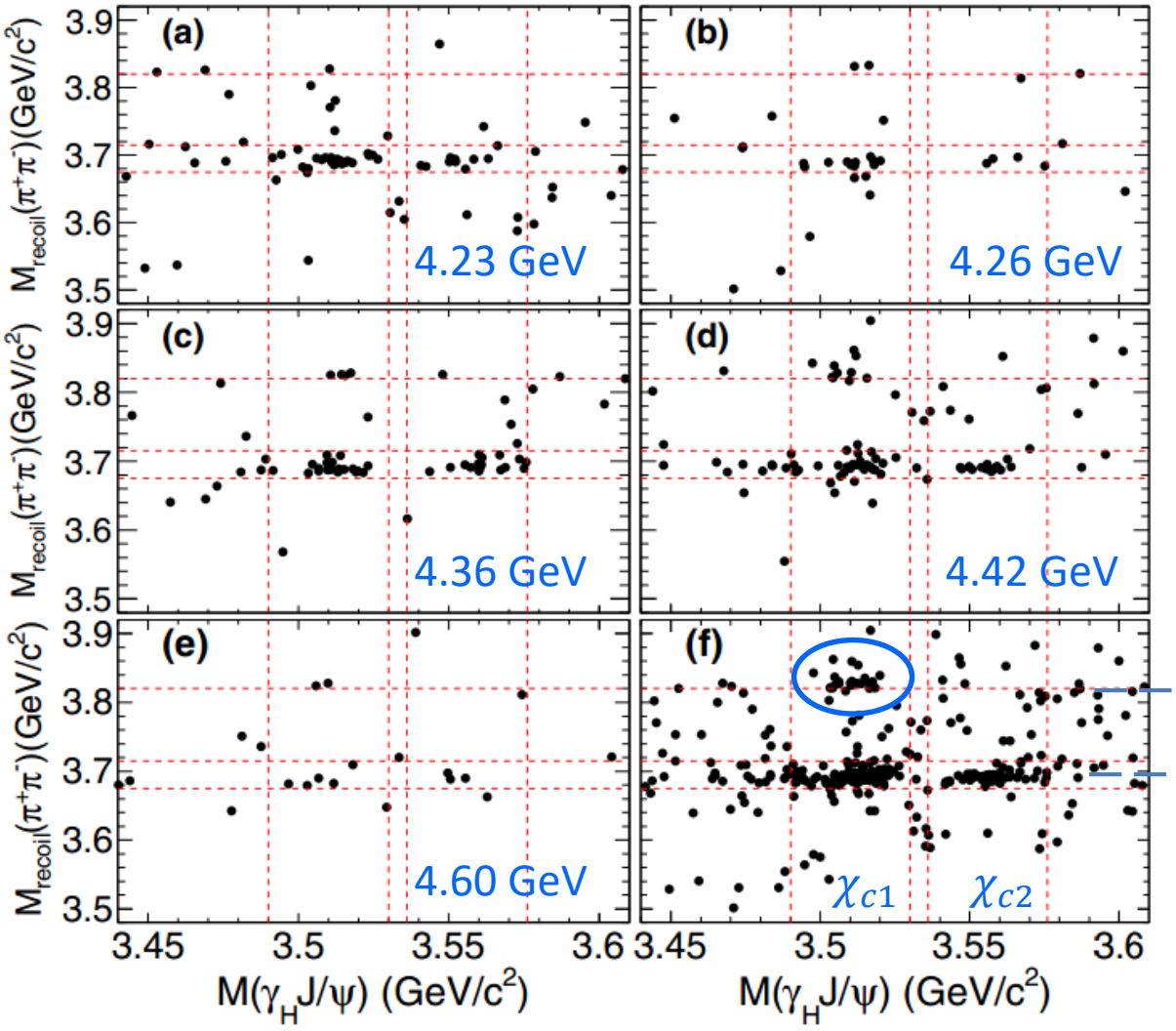
- World's largest samples of direct e^+e^- collisions in the tau-charm region
- 1.3B J/ψ + 0.6 B $\psi(2S)$ + 2.9/fb $\psi(3770)$
- XYZ physics: 3.8 – 4.6 GeV
- Other scan and continuum data below the J/ψ

BESIII data samples for XYZ study



The X states

$e^+e^- \to \pi^+\pi^- X(3823), X(3823) \to \gamma\chi_{c1}$



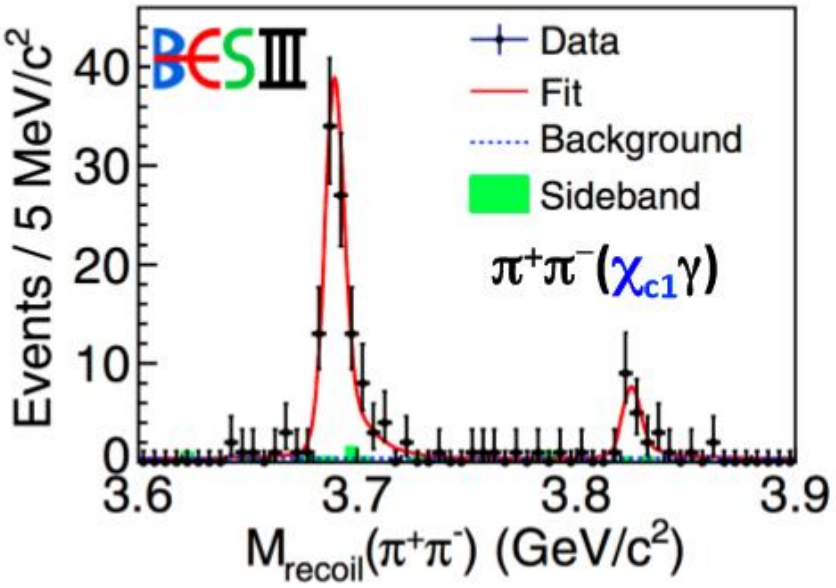
PRL 115, 011803

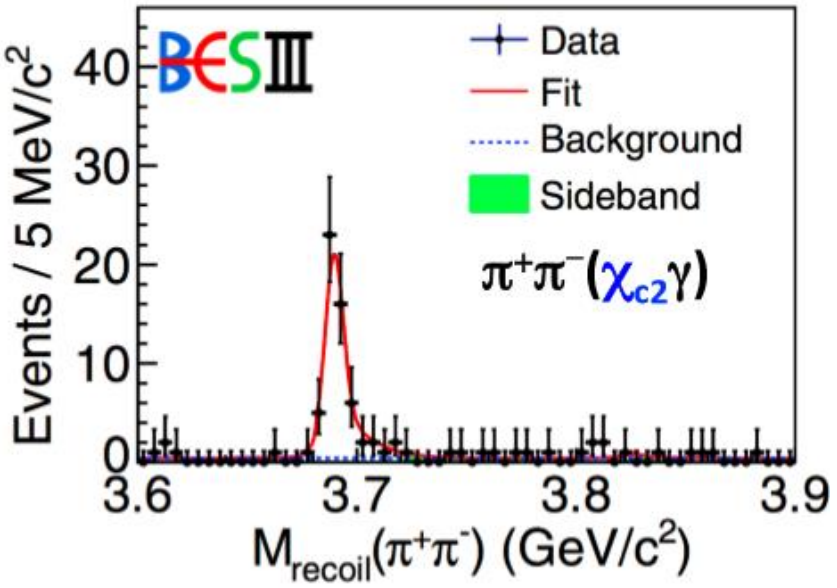
- Reconstruct $\chi_{c1} \to \gamma J/\psi$, $J/\psi \to ll$(e/mu)
- Five large datasets used (~ 4.1 fb^{-1})

X(3823)

$\psi(2S)$

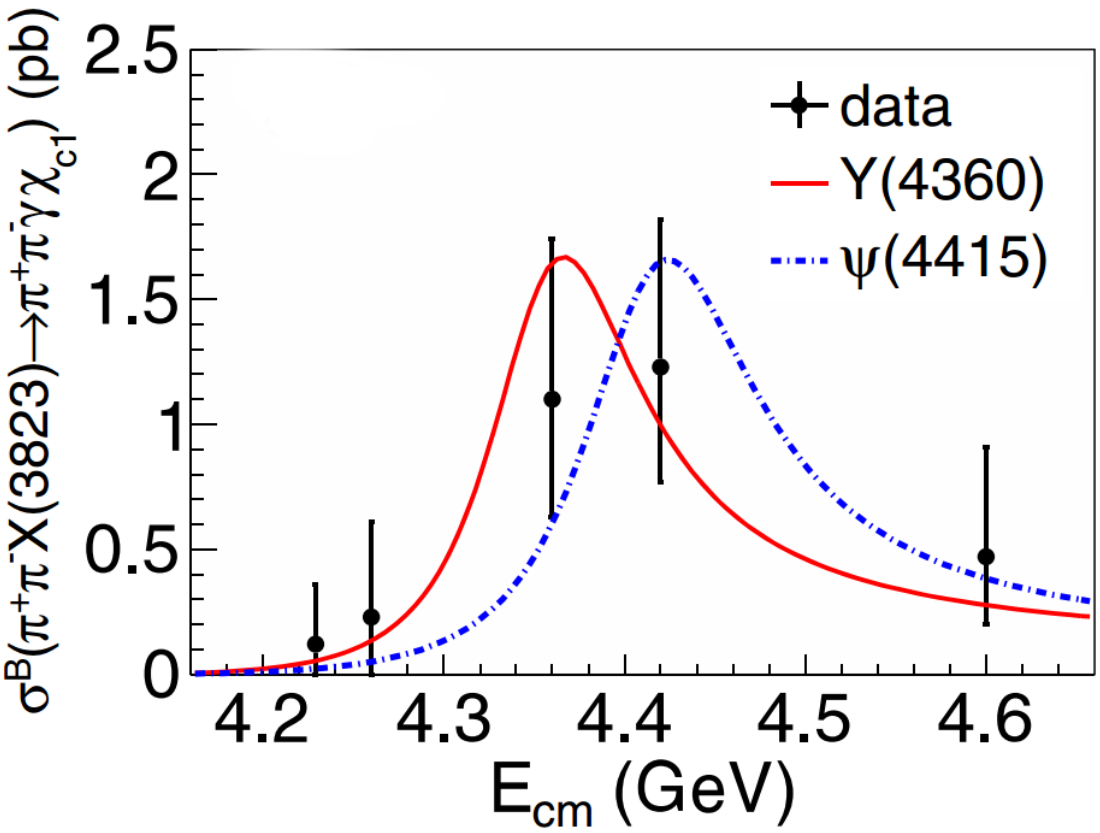
$e^+e^- \to \pi^+\pi^- X(3823), X(3823) \to \gamma\chi_{c1}$





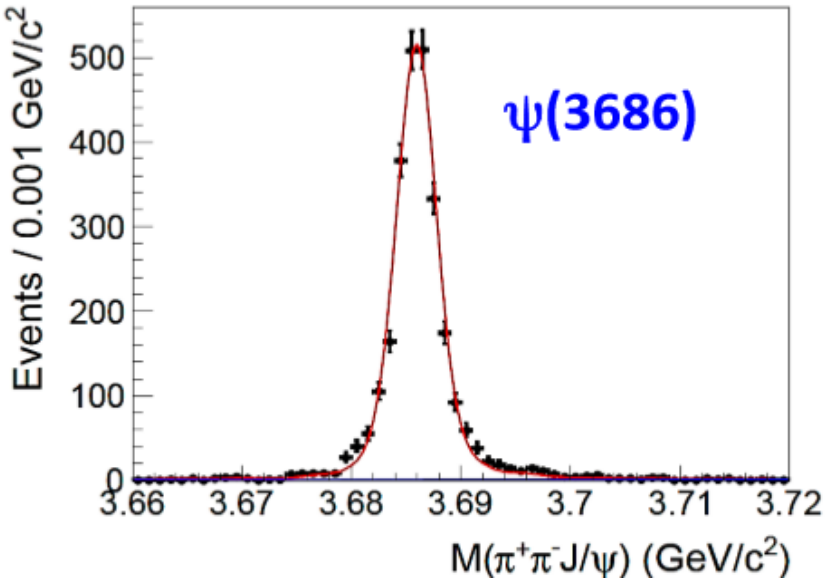
- A simultaneous fit of different data sets
- Signal: MC simulated shape
  Background: linear function
- M = 3821.7 $\pm$ 1.3 $\pm$ 0.7 MeV; Significance: 6.2σ
- Mass and narrow width agree with potential model prediction for $\psi(1^3D_2)$

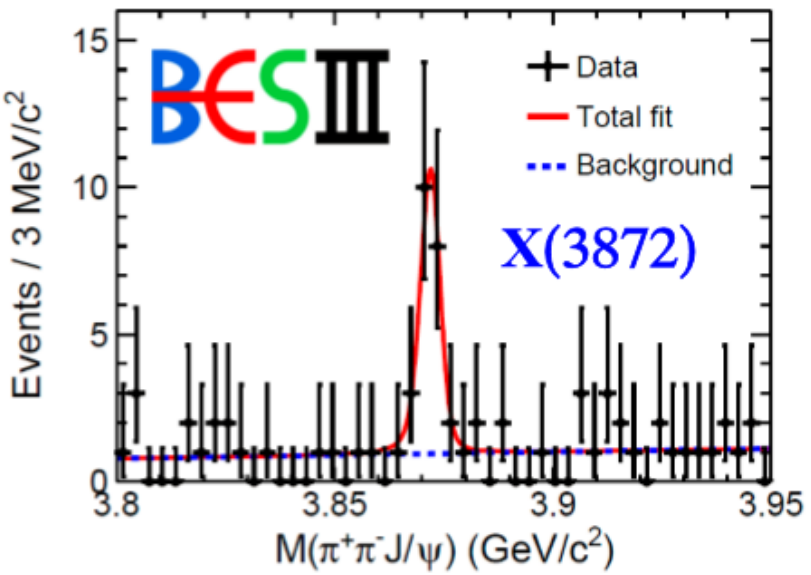
$e^+e^- \to \pi^+\pi^- X(3823), X(3823) \to \gamma\chi_{c1}$



- Energy dependent cross section of $e^+e^- \to \pi^+\pi^- X(3823)$, Both Y(4360) and (4415) line shape give reasonable description.

$e^+e^- \to \gamma X(3872), X(3872) \to \pi^+\pi^- J/\psi$





- ISR ψ' signal is used for mass, and mass resolution calibration.
  N=1818; $\Delta M = 0.34 \pm 0.04$ MeV; $\Delta\sigma_M = 1.14 \pm 0.07$ MeV

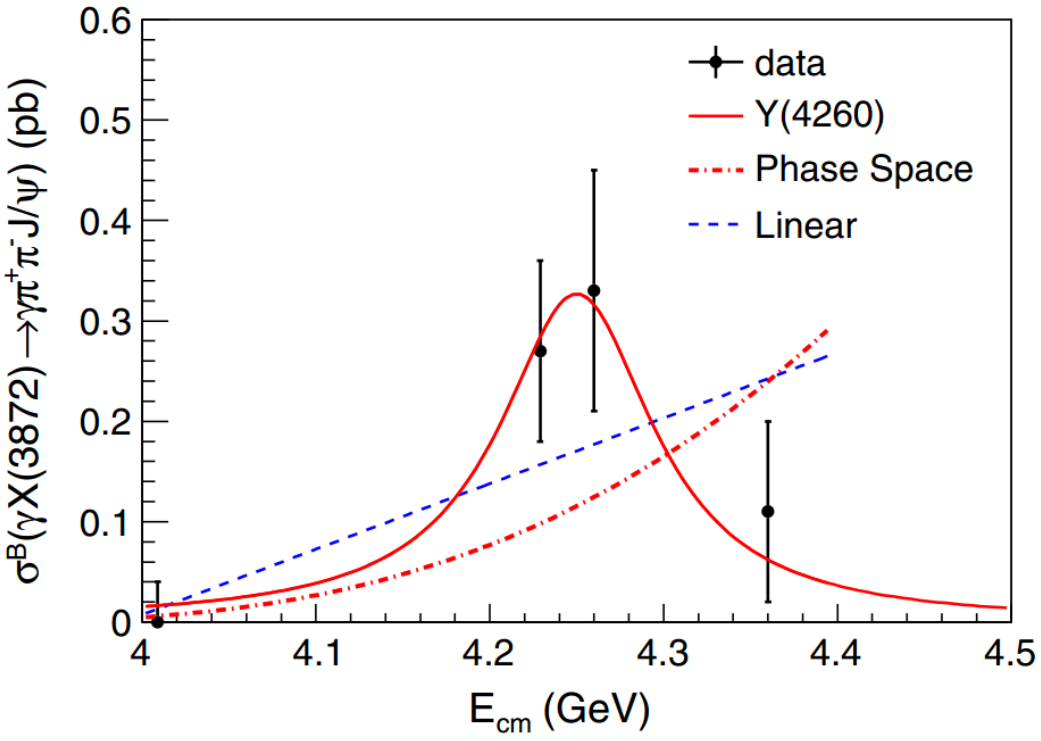
N(X(3872)) = 20.1 ± 4.5 6.3σ

M(X(3872)) = $3871.9 \pm 0.7 \pm 0.2$ MeV

PRL 112, 092001 (2014)

[PDG: 3871.68 ± 0.17 MeV]

$e^+e^- \to \gamma X(3872), X(3872) \to \pi^+\pi^- J/\psi$



- A new Y(4260) decay mode and new X(3872) production: Y(4260) $\to \gamma X(3872)$
- If we take $B(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$ (>2.6 in PDG):

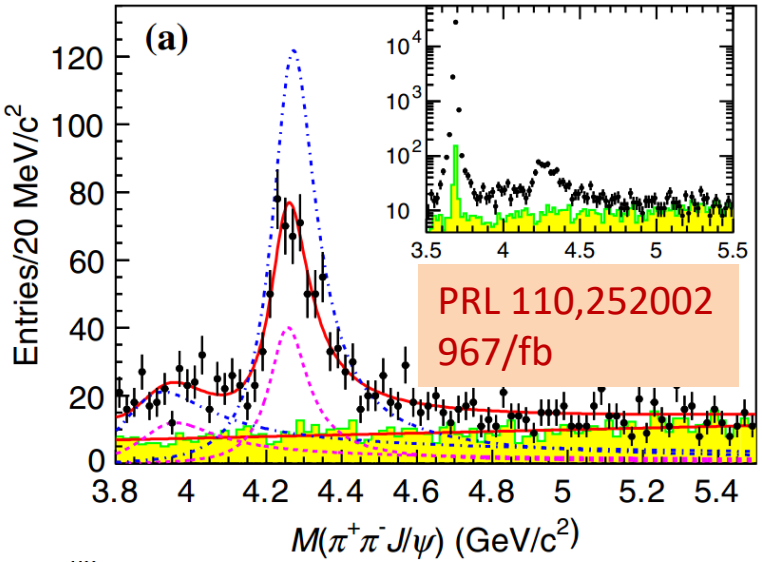
$$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 10\%$$ Large transition ratio!

The Y states (vectors)

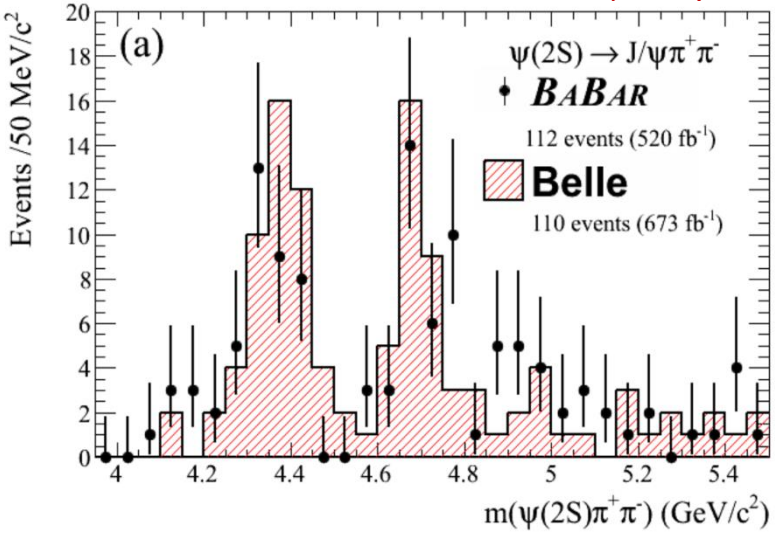
The Y states

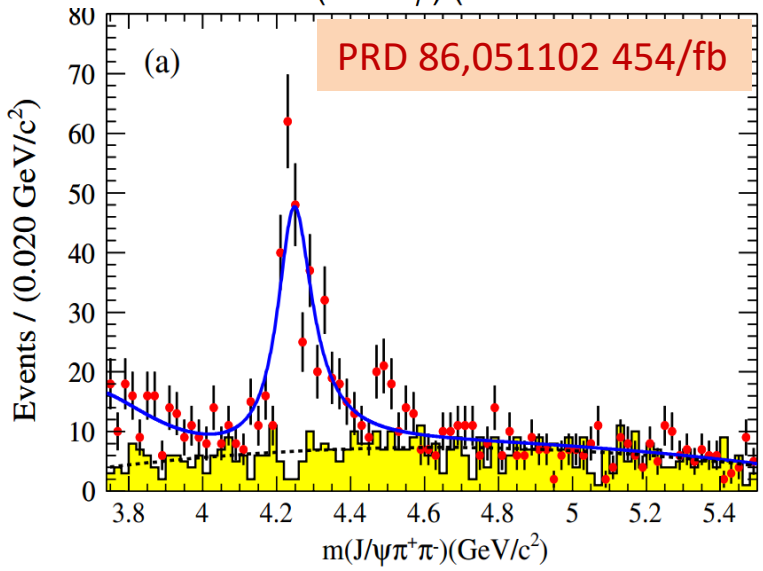
Belle: PRL99,142002, 670/fb

BaBar: PRD.89.111103, 520/fb

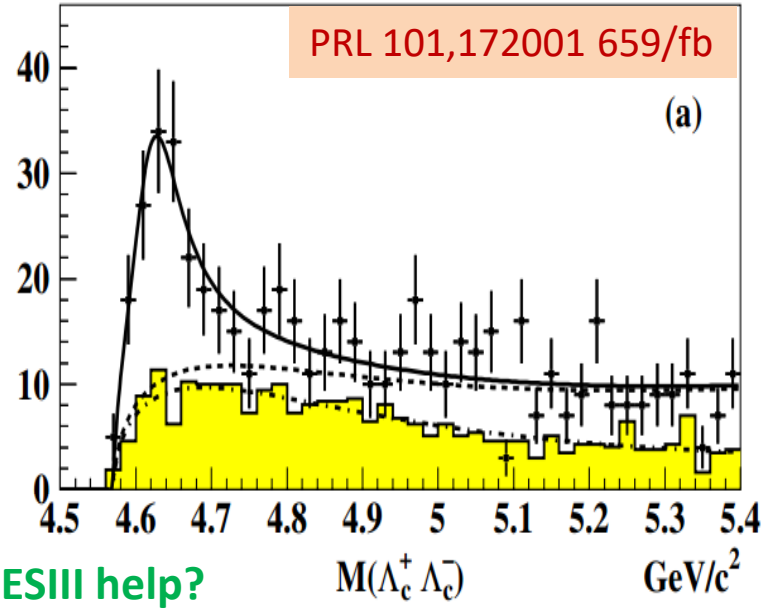


PRL 110,252002
967/fb





PRD 86,051102 454/fb

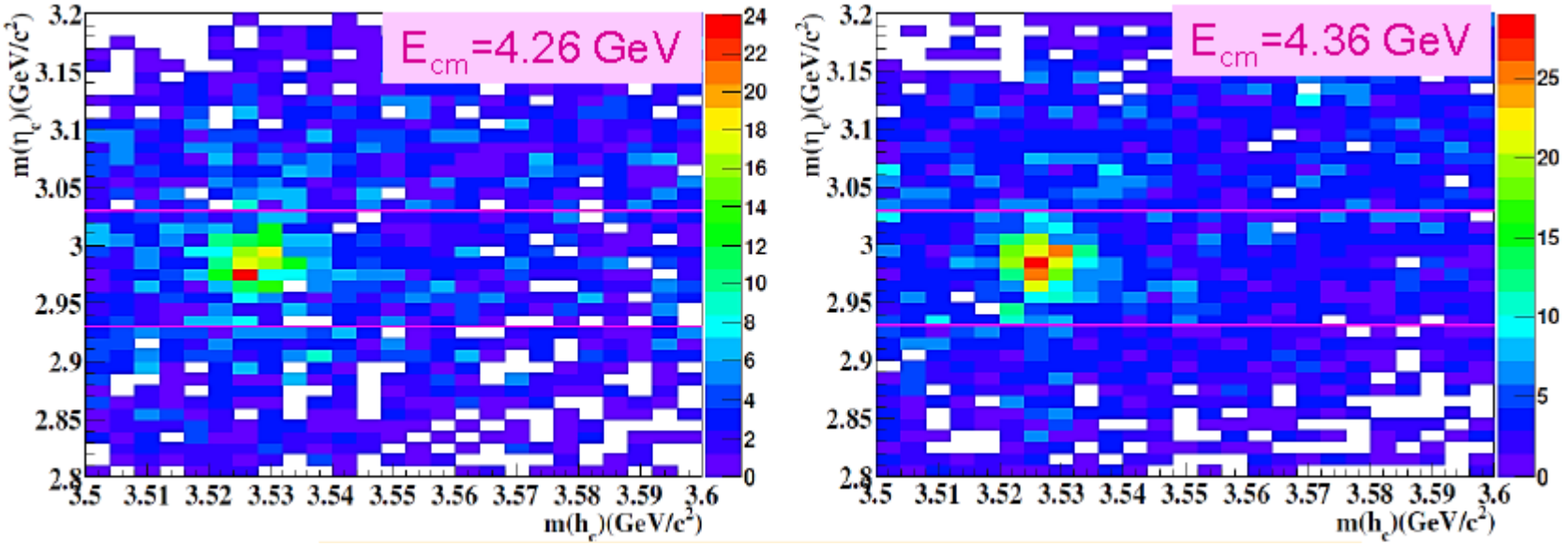


PRL 101,172001 659/fb

May BESIII help?

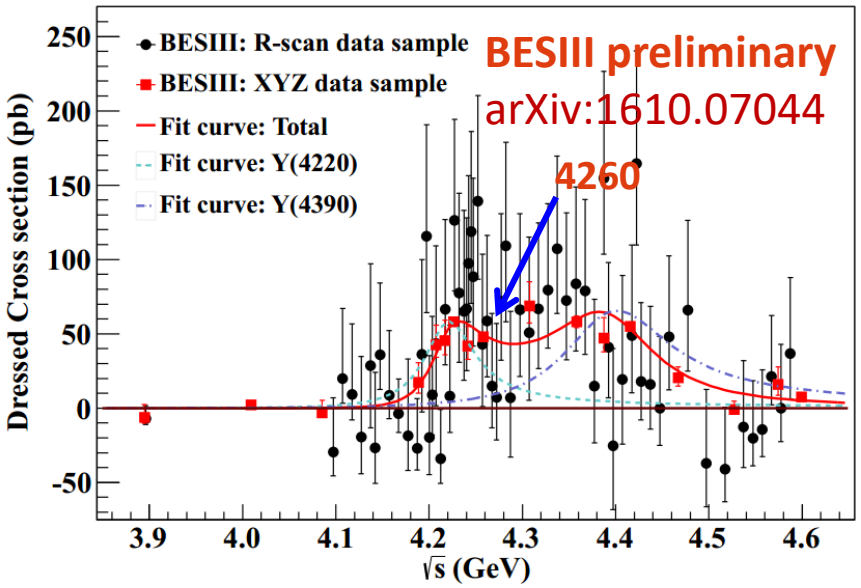
$e^+e^- \to \pi\pi h_c(1P)$

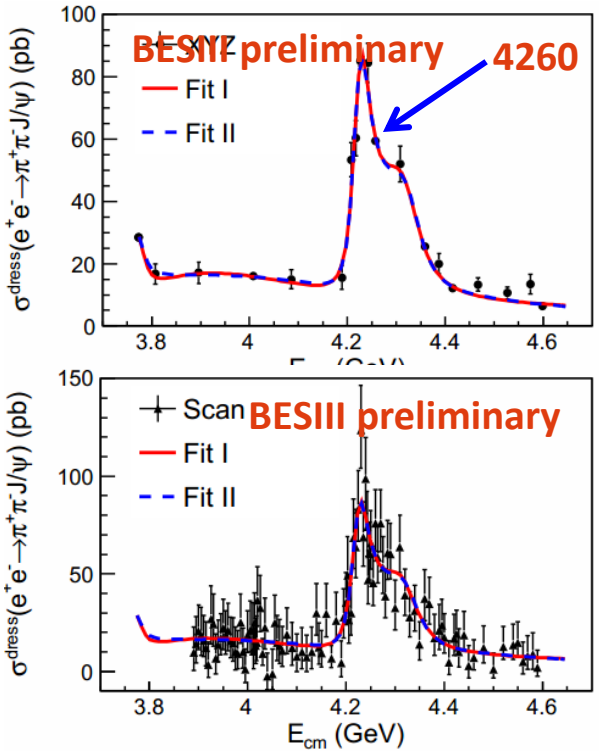
- $h_c \to \gamma\eta_c$, $\eta_c \to$hadrons [16 exclusive decay modes]
  - $p\bar{p}$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$+c.c., $K_S^0K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$



BESIII: PRL111, 242001

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





- Significance of two structures assumption over one structure 10σ!

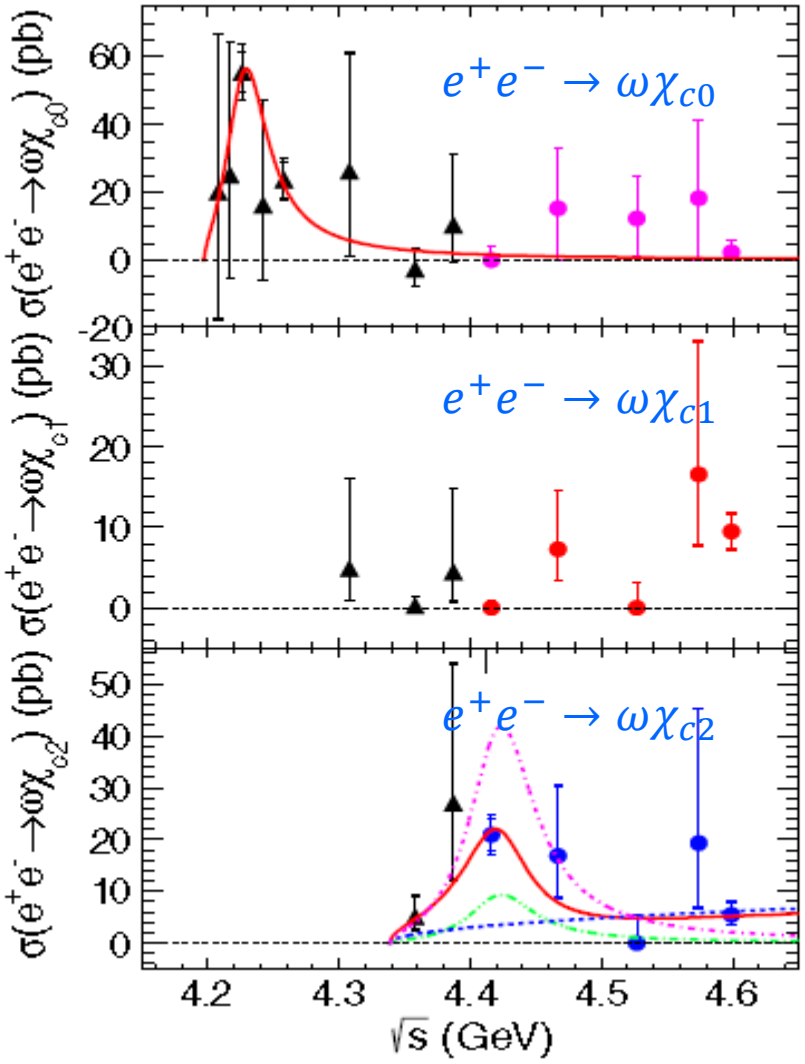
	M(Mev/c^2)	Γ_{tot}(MeV)
Y(4220)	4218.4±4.0±0.9	66.0±9.0±0.4
Y(4390)	4391.6±6.3±1.0	139.5±16.1±0.6

- $\sigma(\pi^0\pi^0 h_c)/\sigma(\pi^+\pi^- h_c)$=0.63±0.09
- $\sigma(\pi^+\pi^- h_c) \sim \sigma(\pi^+\pi^- J/\psi)$, but different line shape

- BESIII result is inconsistent with a single peak for Y(4260)

M(Mev/c^2)	Γ_{tot}(MeV)
4222.0±3.1±1.4	44.1±4.3±2.0
4320.0±10.4±7.0	$101.4^{25.3}_{19.7}$±10.2

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



Peak at ~ 4.23 GeV

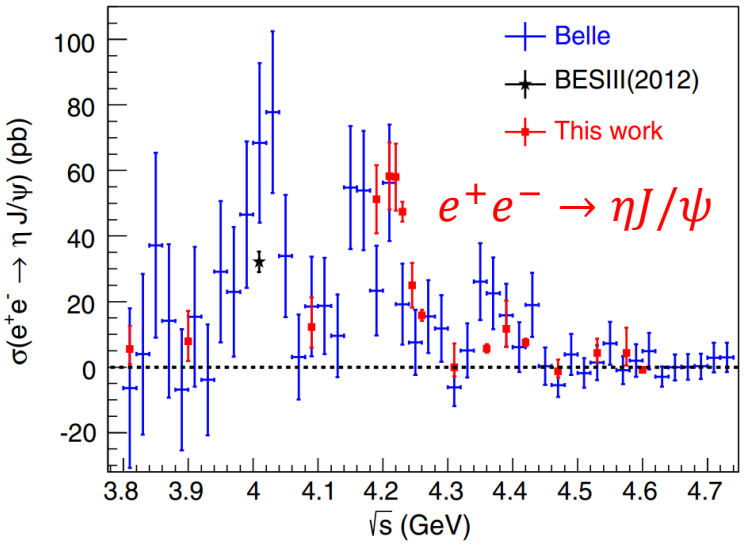
- Fit to a phase-space modified BW:
  m = $4230 \pm 8 \pm 6$ MeV/c^2
  Γ= $38 \pm 12 \pm 2$ MeV
- Inconsistent with Y(4260), it seems consistent with the first structure in $\pi^+\pi^- J/\psi$ line shape.
- A tetraquark ? Phys.Rev.D91, 117501 (2015)
- ψ(4S)? EPJC 74:3208 (2014)
- Threshold effect?

- No significant $e^+e^- \to \omega\chi_{c1}$ events

- Can be described by $\psi(4415)$
- Fit to |BW+Phase-Space|^2
- Mass and width fixed to ψ(4415)
- Two solutions with the same fitting quality

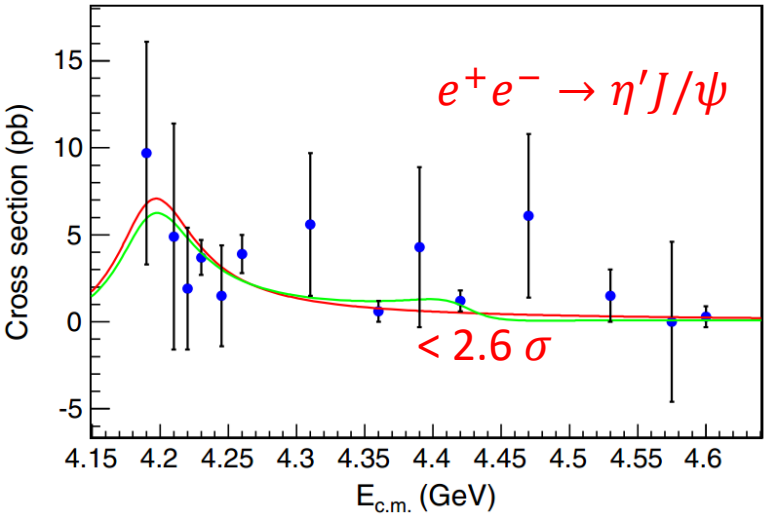
PRL 114, 092003 (2015)
PRD 93, 011102(R) (2016)

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



- Agree with previous results with improved precision
- The cross section peaks around 4.2 GeV

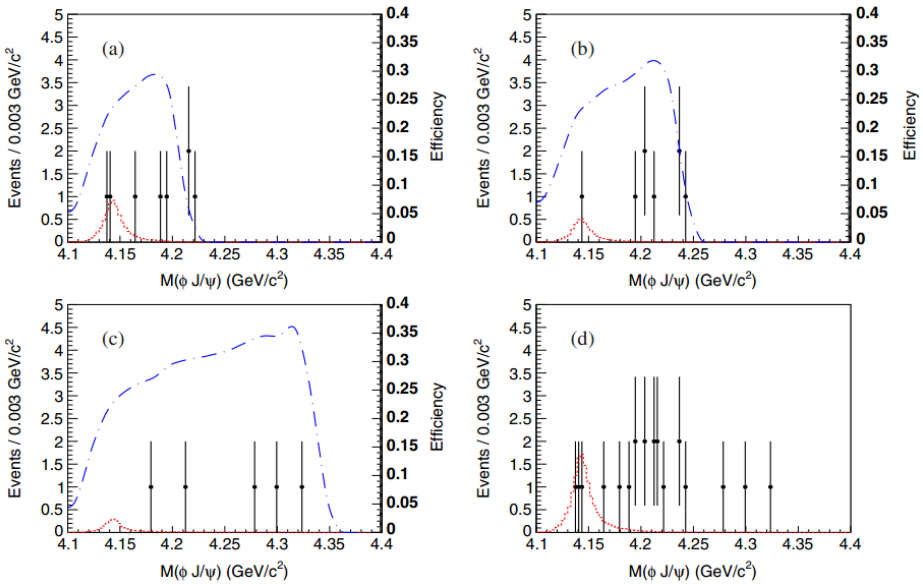
PRD 91, 112005 (2015)



- First observation at √ s = 4.23 & 4.26 GeV .
- Fit with ψ (4160) and ψ (4415) resonances (fixed mass and width)
- σ (η′ J/ ψ) is much lower than σ (η J/ ψ) , in contradiction to the calculation in the framework of NRQCD

PRD 94, 032009 (2016)

No significant $e^+e^- \to \gamma Y(4140)$



PRD 91,032002(2015)

Upper limit at the 90% C.L. for $\sigma^B \cdot B$:

$\sqrt{s}(GeV/c^2)$	Luminosity(pb^{-1})	$\sigma^B \cdot B$(pb)
4.23	1094	<0.35
4.26	827	<0.28
4.36	545	<0.33

Systematic uncertainty is considered.

Compared with (3872) production. PRL 112, 092001

$$\sigma^B(e^+e^- \to \gamma X(3872)) \cdot B(X(3872) \to \pi^+\pi^- J/\psi)$$

= $0.27 \pm 0.09(\text{stat}) \pm 0.02(\text{syst})$ pb at $\sqrt{s}$ = 4.23 GeV,

= $0.33 \pm 0.12(\text{stat}) \pm 0.02(\text{syst})$ pb at $\sqrt{s}$ = 4.26 GeV.

Take $\mathcal{B}(3872 \to \pi^+\pi^- J/\psi)$ = 5%. arXiv: 0910.3138

And $\mathcal{B}(4140 \to \phi J/\psi)$ = 30%, molecular calculation, PRD 80, 054019.

$$\frac{\sigma^B(e^+e^- \to \gamma Y(4140))}{\sigma^B(e^+e^- \to \gamma X(3872))} \leq 0.1 \text{ at } \sqrt{s} = \text{ 4.23 and 4.26 GeV.}$$

The Z_C states

Discovery of $Z_C(3900)^{\pm}$

BESIII: PRL 110, 252001 (2013)

$Z_c(3900)^+$:

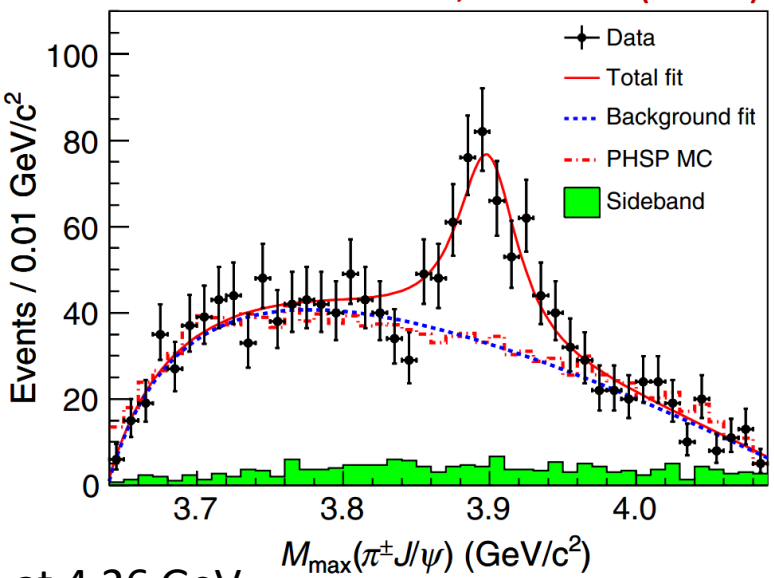
$m = (3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2

$\Gamma = (46 \pm 10 \pm 20)$ MeV

Mass close to $D\bar{D}^*$ threshold

Decays to J/ψ → contains $c\bar{c}$

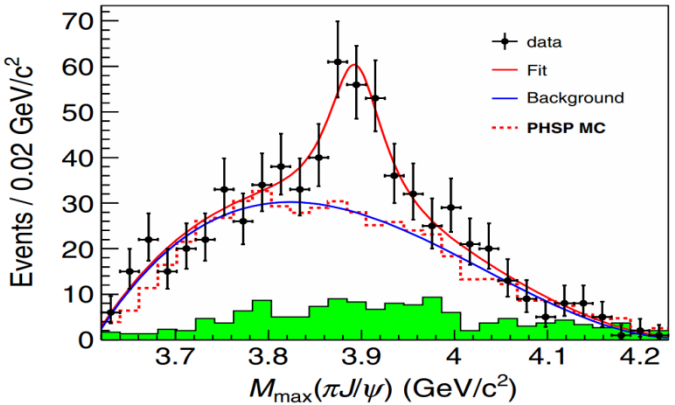
Electric charge → contains $c\bar{d}$



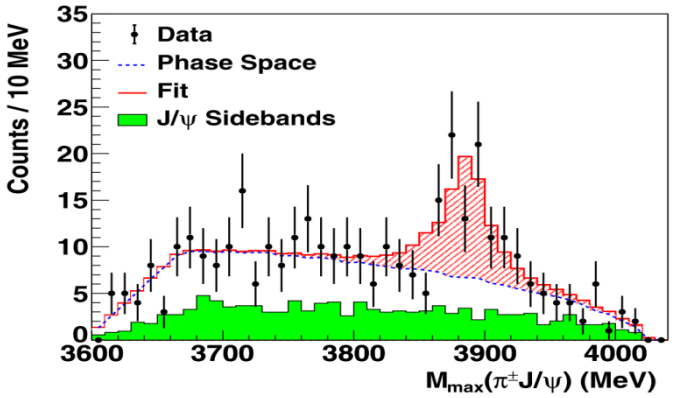
$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV

$$\frac{\sigma(e^+e^- \to \pi^\pm Z_C(3900)^\pm \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\% \text{ at 4.26 GeV}$$

Belle with ISR data (PRL 110, 252002)

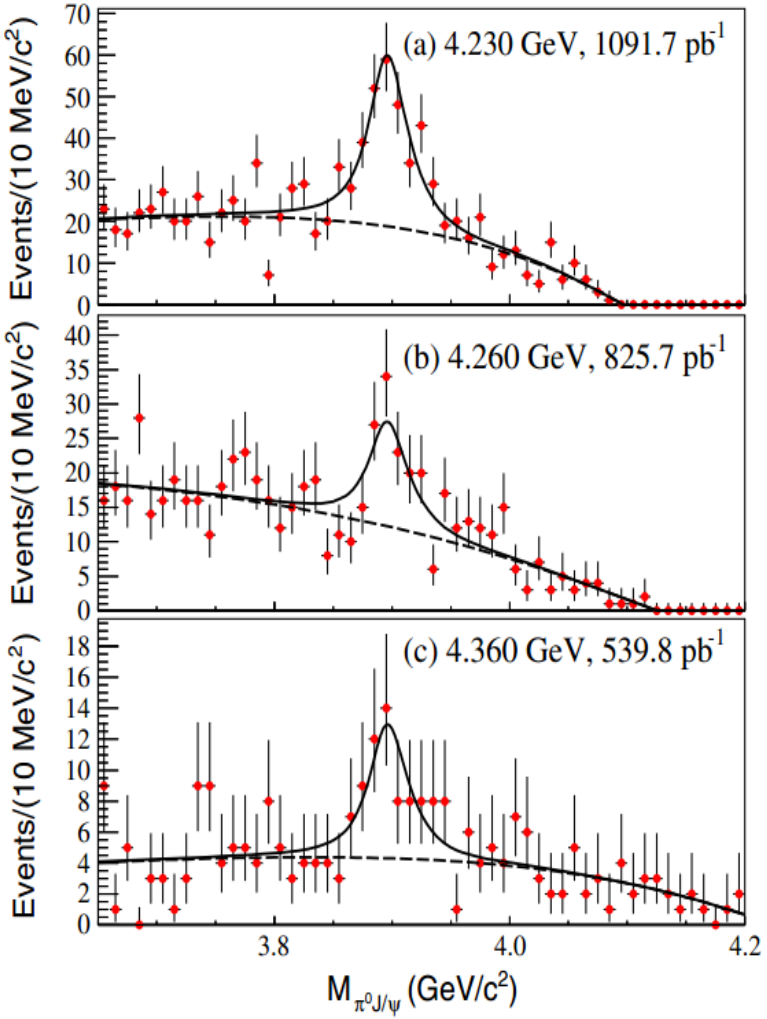


CLEOc data at 4.17 GeV (PLB 727, 366)



Discovery of $Z_C(3900)^0$

PRL 115,112003(2015)



- Via $e^+e^- \to \pi^0\pi^0 J/\psi$
- A structure on $\pi^0 J/\psi$ invariant mass spectrum can be observed:

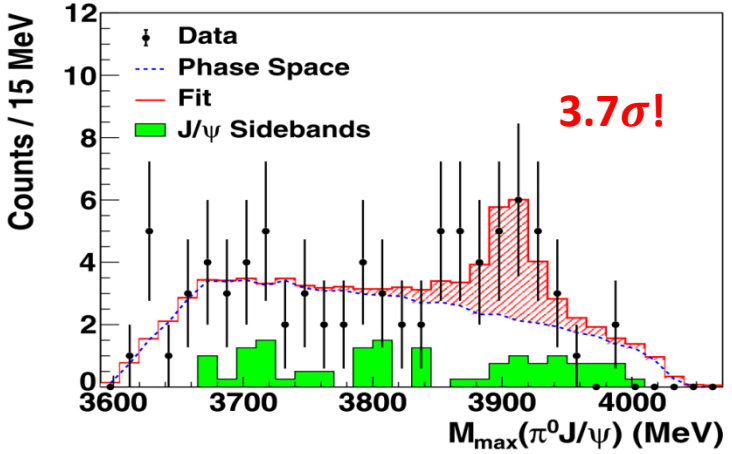
$m = 3894.8 \pm 2.3 \pm 2.7$ MeV/c^2

$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV

Significance = **10.4σ**

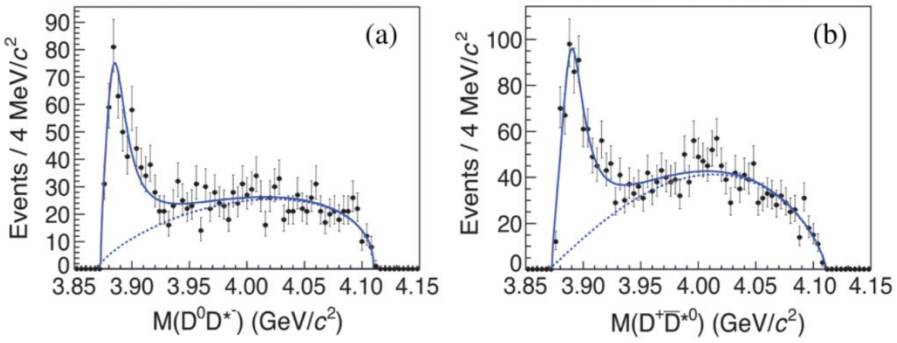
- Isospin triplet is established!

CLEOc data at 4.17 GeV (PLB 727, 366)

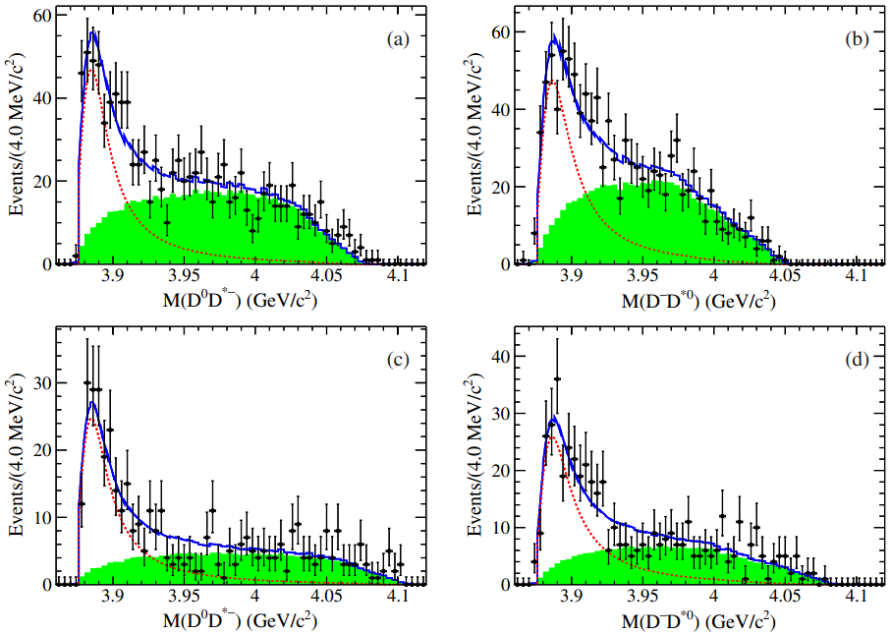


$Z_C(3885)^{\pm/0} \to (D\bar{D}^*)^{\pm/0}$

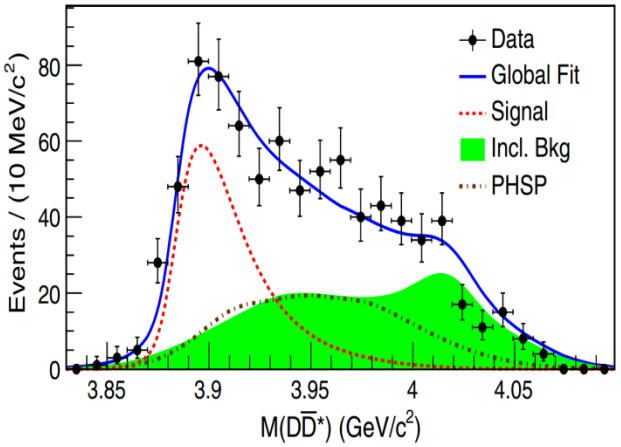
PRL112, 022001 (2014) Single D tag (ST)



PRD 92, 092006 (2015) Double D tag (DT)



PRL 115, 182002 (2015) Double D tag (DT)

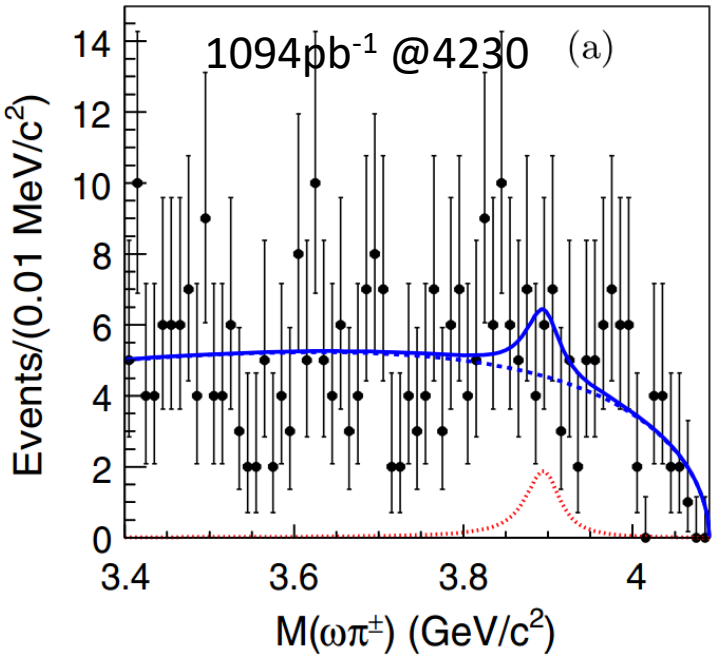


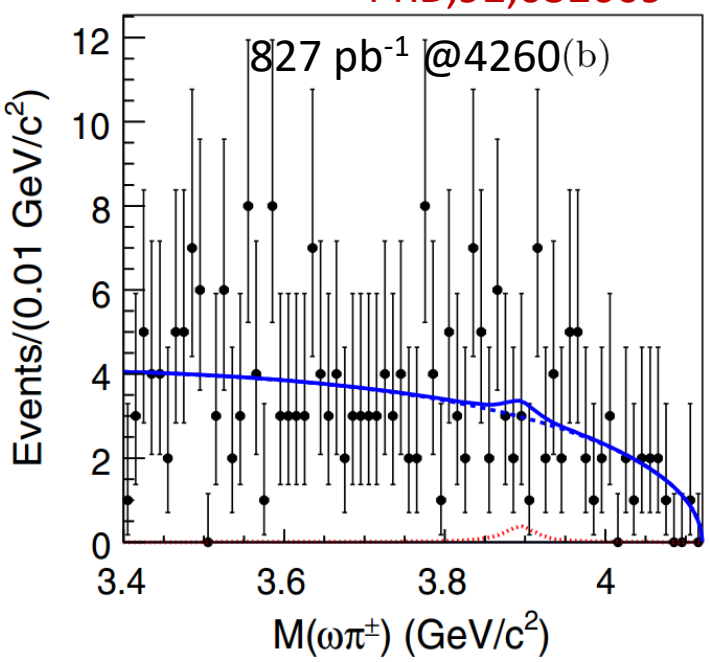
State	Mass(Mev/c^2)	Width(MeV)
$Z_C(3885)^{\pm}(ST)$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_C(3885)^{\pm}(DT)$	$3881.7 \pm 1.6 \pm 2.6$	$26.6 \pm 2.0 \pm 2.3$
$Z_C(3885)^{0}(ST)$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

- Via $e^+e^- \to \pi^{\mp/0} Z_C(3885)^{\pm/0} \to \pi^{\mp/0}(D\bar{D}^*)^{\pm/0}$
- Good agreement between ST and DT method
- Good agreement between charged state and neutral state
- Another iso-spin triplet is established !
- $Z_c(3885) = Z_c(3900)$?
- Tetraquark? Molecule state?

Search for $Z_C(3900)^{\pm} \to \omega\pi^{\pm}$ in $e^+e^- \to \omega\pi\pi$

PRD,92,032009





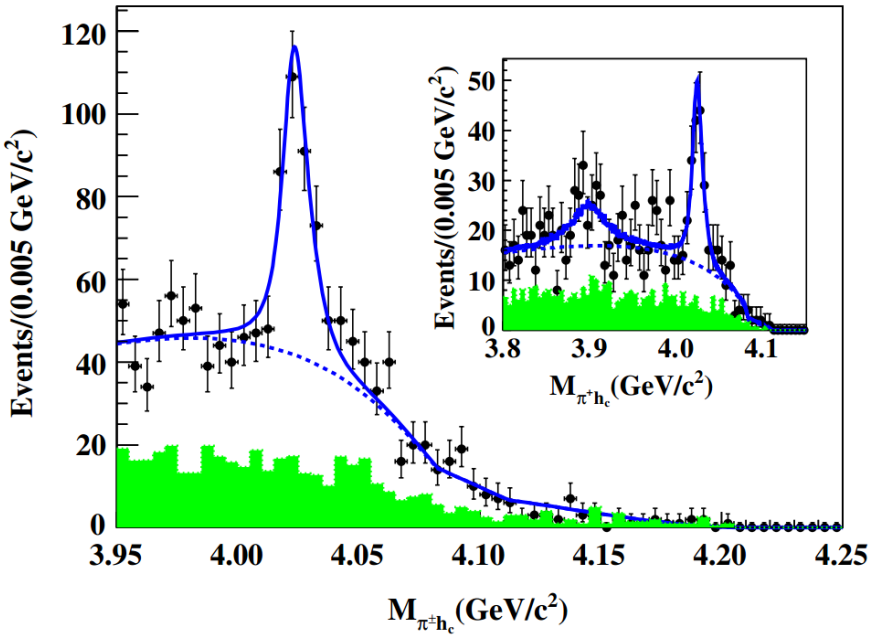
$\sigma\left(e^+e^- \to Z_C^{\pm}\pi^{\mp}, Z_C^{\pm} \to \omega\pi^{\pm}\right)$<0.27 pb

$\sigma\left(e^+e^- \to Z_C^{\pm}\pi^{\mp}, Z_C^{\pm} \to \omega\pi^{\pm}\right)$<0.18 pb

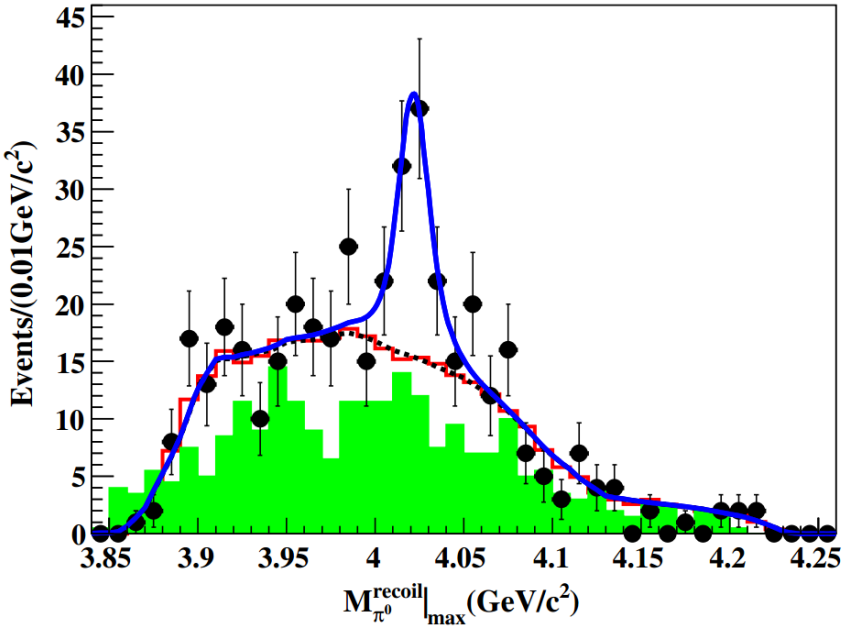
- UML Fitting with acceptance weighted S-wave BW folded with Gaussian + ARGUS background, interference effect neglected
- No significant signal found for this typical decay mode of a 1^+ resonance
- Compared to the sum of ${Z_C}^{\pm} \to J/\psi\pi^{\pm}$ and $Z_C \to D\overline{D}^*$ is less than 0.2%

$Z_C(4020)^{\pm/0} \to \pi^{\pm/0} h_c$

PRL 111, 242001(2013)



PRL 113, 212002 (2014)

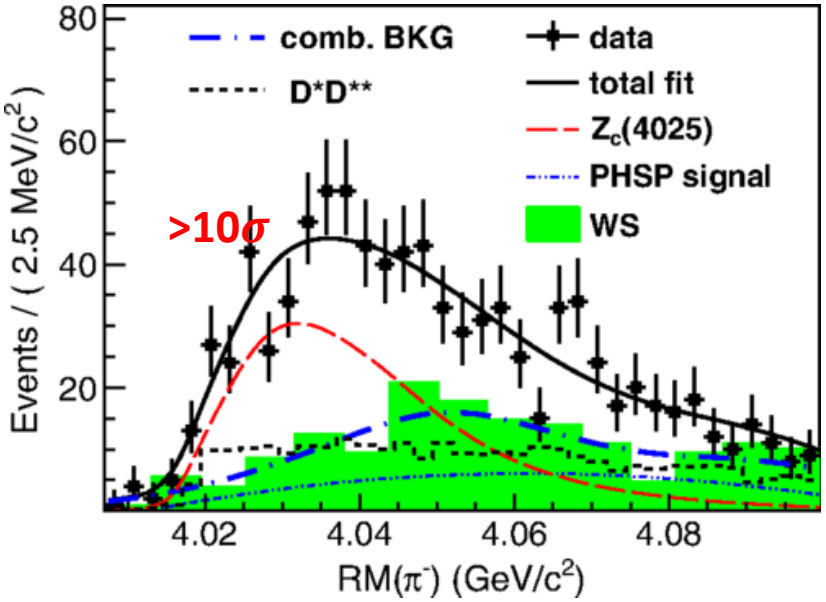


- Via $e^+e^- \to \pi\pi h_c$
- $h_c \to \gamma\eta_c, \eta_c \to$ 16 hadronic decay modes
- $Z_C(4020)^{\pm/0}$ observed
- Another iso-spin triplet is established.
- No significant $Z_C(3900)^{\pm/0} \to \pi^{\pm/0} h_c$ is observed

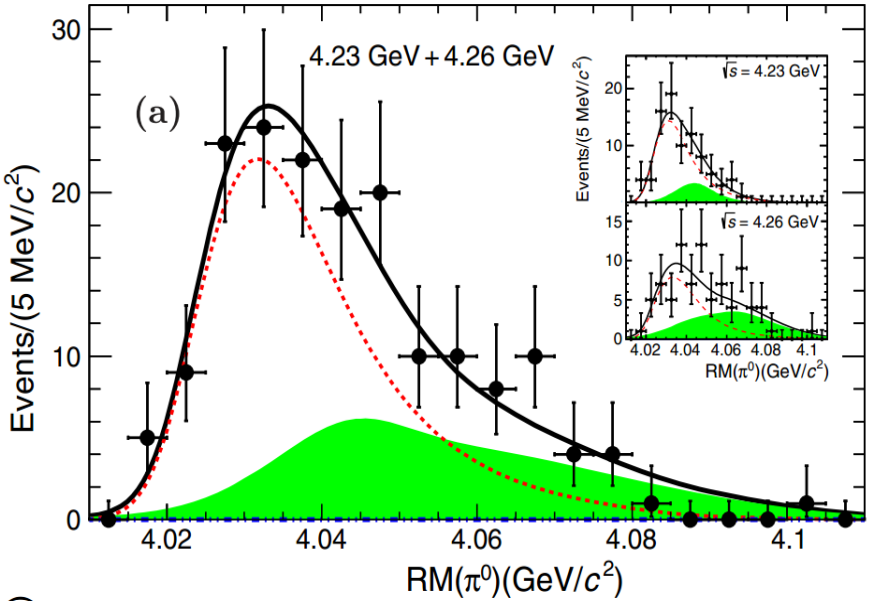
State	Mass(MeV/c²)	Width(MeV)
$Z_C(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$Z_C(4020)^{0}$	$4023.9 \pm 2.2 \pm 3.8$	7.9(fixed)

$Z_C(4025)^{\pm/0} \to (D^*\overline{D}^*)^{\pm/0}$

PRL 112, 132001(2014)



PRL 115, 182002(2015)



- $Z_C(4025)^{\pm/0}$ observed
- Another iso-spin triplet is established.

State	Mass(MeV/c²)	Width(MeV)
$Z_C(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
$Z_C(4025)^{0}$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$

$$\sigma\left(e^+e^+ \to \pi^{\pm}(D^*\overline{D}^*)^{\pm}\right) = 137 \pm 9 \pm 15\ pb$$

$$\frac{\sigma(e^+e^+ \to \pi^{\pm} Z_C(4025)^{\pm} \to \pi^{\pm}(D^*\overline{D}^*)^{\pm})}{\sigma(e^+e^+ \to \pi^{\pm}(D^*\overline{D}^*)^{\pm})} = 0.65 \pm 0.09 \pm 0.06 \text{ at } 4.26\text{GeV}$$

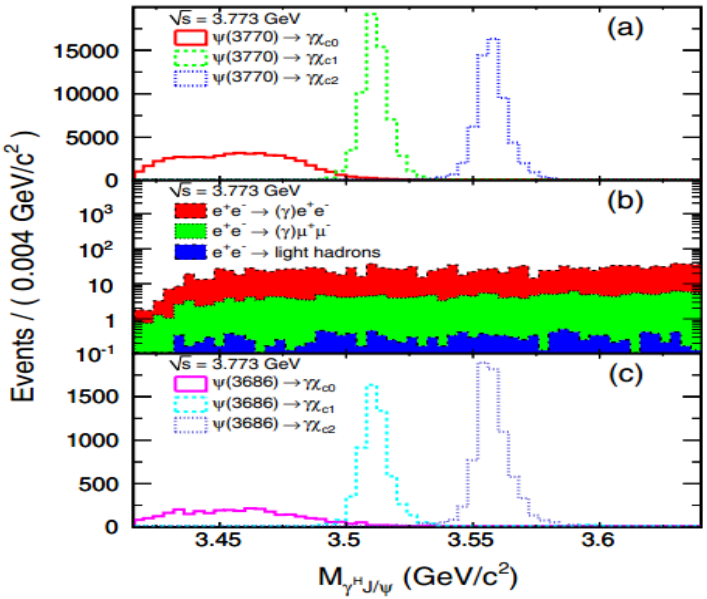
Double D Tag

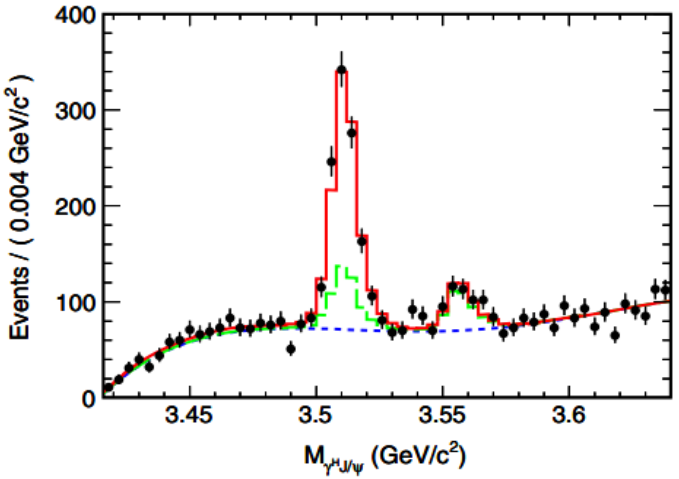
- Coupling to $\overline{D}^*D^*$ is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

Charmonium

Measurement of B($\psi(3770) \rightarrow \gamma\chi_{c1}$) and search for $\psi(3770) \rightarrow \gamma\chi_{c2}$

PRD 91, 092009 (2015)





- The $\chi_{c1,2}$ are reconstructed with the decay

$$\chi_{c1,2} \rightarrow \gamma J/\psi \, , J/\psi \rightarrow l^+l^-$$

$\mathcal{B}(\psi(3770) \rightarrow \gamma\chi_{c1}) = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3}$
$\mathcal{B}(\psi(3770) \rightarrow \gamma\chi_{c2}) < 0.64 \times 10^{-3}$ at 90% C.L.

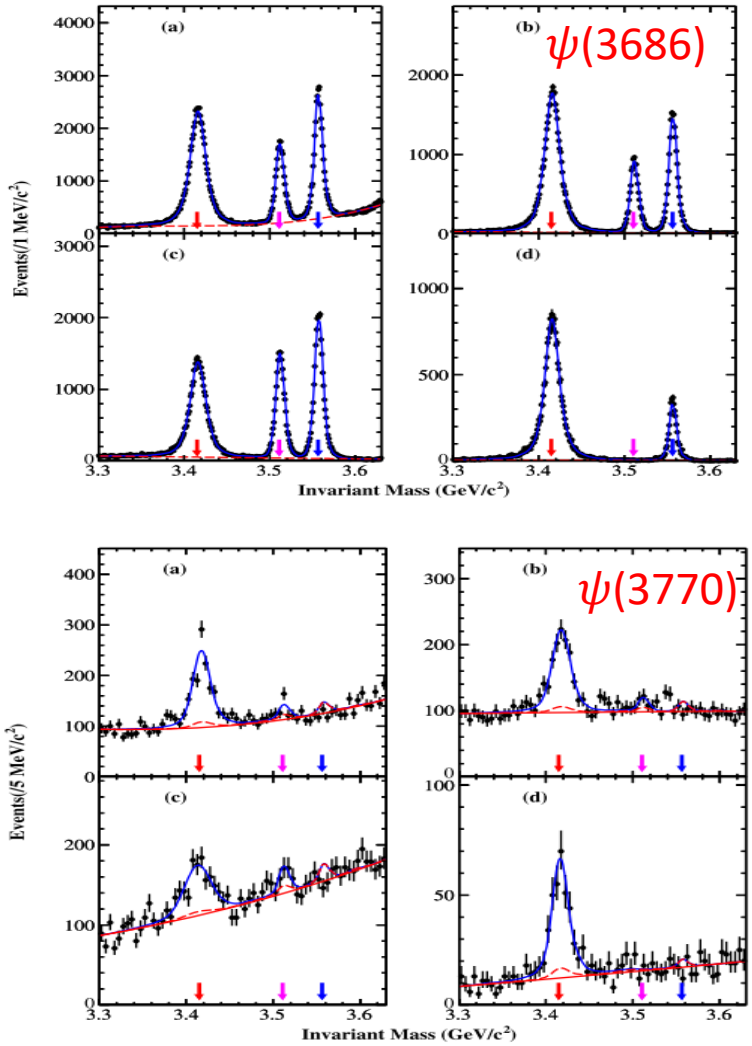
Experiment/theory	$\Gamma(\psi(3770) \rightarrow \gamma\chi_{cJ})$ (keV)	
	$J = 1$	$J = 2$
This work	$67.5 \pm 4.1 \pm 6.7$	< 17.4
Ding-Qin-Chao [12]		
Nonrelativistic	95	3.6
Relativistic	72	3.0
Rosner *S-D* mixing [13]		
$\phi = 12°$ [13]	73 ± 9	24 ± 4
$\phi = (10.6 \pm 1.3)°$ [32]	79 ± 6	21 ± 3
$\phi = 0°$ (pure 1^3D_1 state) [32]	133	4.8
Eichten-Lane-Quigg [14]		
Nonrelativistic	183	3.2
With coupled-channel corr.	59	3.9
Barnes-Godfrey-Swanson [15]		
Nonrelativistic	125	4.9
Relativistic	77	3.3

Measurement of the $\mathcal{B}(\psi(3770) \rightarrow \gamma\chi_{c0})$

PLB 753 (2016) 103–109

Experiment Method:

- The analysis is based on the 2.92 fb^{-1} $\psi(3770)$ data and 106 million $\psi(3686)$ data .
- Via $\chi_{cJ} \rightarrow LH(2(\pi^+\pi^-),\ K^+K^-\pi^+\pi^-,\ 3(\pi^+\pi^-),\ K^+K^-$.
- Obtained by taking the relative strength to the $\psi(3686)$ E1 transition, avoiding introducing large uncertainties of the branching fractions for $\chi_{cJ} \rightarrow LH$.



- The ratio of the $\mathcal{B}(\psi(3770) \rightarrow \gamma\chi_{cJ})$ and $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$ is determined channel by channel:

$$R_{cJ} = \frac{\mathcal{B}[\psi(3770) \rightarrow \gamma\chi_{cJ}]}{\mathcal{B}[\psi(3686) \rightarrow \gamma\chi_{cJ}]} = \frac{N_{\psi(3770)} \cdot N^{tot}_{\psi(3686)} \cdot \epsilon_{\psi(3686)}}{N_{\psi(3686)} \cdot N^{tot}_{\psi(3770)} \cdot \epsilon_{\psi(3770)}}$$

BESII PLB 650(2006)111

$N^{tot}_{\psi(3686)} = 106$ M $\quad N^{tot}_{\psi(3770)} = \sigma^{3.773\,\mathrm{GeV}}_{\psi(3770)} \times L \quad \sigma^{3.773\,\mathrm{GeV}}_{\psi(3770)} = (7.15 \pm 0.27 \pm 0.27)$ nb

	R_{cJ}[%]		
	χ_{c0}	χ_{c1}	χ_{c2}
$2(\pi^+\pi^-)$	6.64 ± 0.45	2.13 ± 0.69	-
$K^+K^-\pi^+\pi^-$	7.56 ± 0.57	2.00 ± 1.04	-
$3((\pi^+\pi^-)$	6.86 ± 0.74	1.94 ± 0.69	-
K^+K^-	6.65 ± 0.57	-	-
Weighted R_{cJ}	$6.89 \pm 0.28 \pm 0.65$	$2.03 \pm 0.44 \pm 0.66$	N/A
CLEO 281 pb^{-1}[%]	$7.9 \pm 0.8 \pm 0.6$	$4.3 \pm 1.6 \pm 0.6$	<2.2

- Branching fraction for $\psi(3770) \rightarrow \gamma\chi_{cJ}$:

$$\mathcal{B}\left(\psi(3770) \rightarrow \gamma\chi_{cJ}\right) = R_{cJ} \times \mathcal{B}\left(\psi(3686) \rightarrow \gamma\chi_{cJ}\right)$$

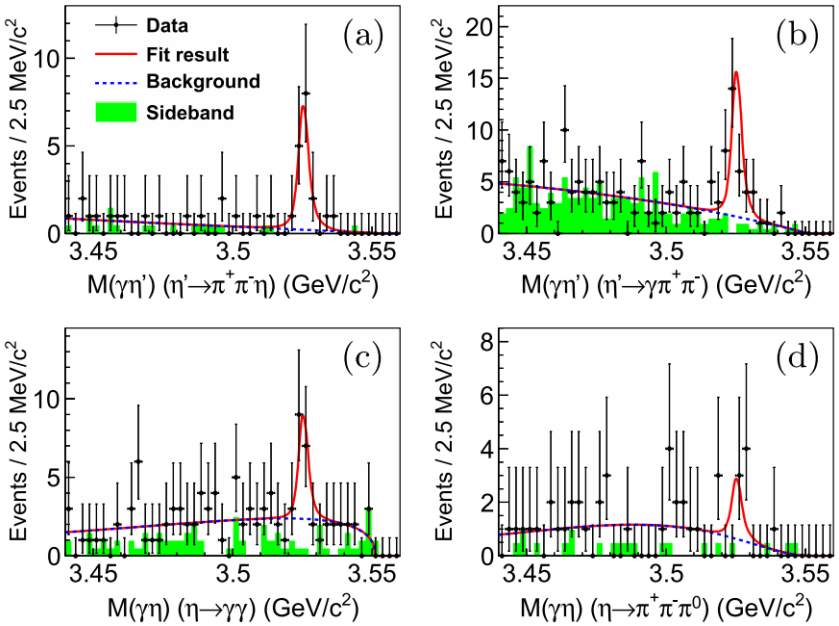
From PDG

Experiments	$J=0$	$J=1$
$\mathcal{B}^{\mathrm{BESIII}}(\times 10^{-3})$	$6.88 \pm 0.28 \pm 0.67$	$1.94 \pm 0.42 \pm 0.64$
$\mathcal{B}^{\mathrm{BESIII}}(\times 10^{-3})$ [10]	–	$2.48 \pm 0.15 \pm 0.23$
Γ^{BESIII}	$187 \pm 8 \pm 19$	$53 \pm 12 \pm 18$
Γ^{BESIII} [10]	–	$67.5 \pm 4.1 \pm 6.7$
Γ^{CLEO} [7,8]	172 ± 30	70 ± 17
$\Gamma^{\mathrm{CLEO}}_{\mathrm{corrected}}$	192 ± 24	72 ± 16
Theories		
Rosner [2] (non-relativistic)	523 ± 12	73 ± 9
Ding–Qing–Chao [3]		
non-relativistic	312	95
relativistic	199	72
Eichten–Lane–Quigg [4]		
non-relativistic	254	183
with coupled channels corrections	225	59
Barnes–Godfrey–Swanson [5]		
non-relativistic	403	125
relativistic	213	77
NRCQM [6]	218	70

This work

$h_c \to \gamma\eta/\gamma\eta'$

- Only a few decay modes of h_c have been observed, $h_c \to \gamma\eta_c$(Br~50%), $h_c \to 2(\pi^+\pi^-)\pi^0$ (Br~2%).
- Searches for the new h_c decay modes are useful for providing constraints to theoretical models in the charmonium region.
- Via $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta/\gamma\eta'$, $\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$, $\eta' \to \pi^+\pi^-\eta/\gamma\pi^+\pi^-$ based on the 0.5 billion ψ' data sample..



PRL116, 251802 (2016)

Mode	$N_{h_c\to\gamma\eta'(\eta)}$	$W_{\eta'(\eta)}(\times10^{-2})$	$\mathcal{B}[h_c \to \gamma\eta'(\eta)]$	Significance	$[\mathcal{B}(h_c \to \gamma\eta)/\mathcal{B}(h_c \to \gamma\eta')](\%)$
$h_c \to \gamma\eta'$	44.3 ± 7.8(stat)	7.67 ± 0.38(sys)	$[1.52 \pm 0.27(\text{stat}) \pm 0.29(\text{sys})] \times 10^{-3}$	8.4σ	$30.7 \pm 11.3(\text{stat}) \pm 8.7(\text{sys})$
$h_c \to \gamma\eta$	18.1 ± 5.8(stat)	10.22 ± 0.55(sys)	$[4.7 \pm 1.5(\text{stat}) \pm 1.4(\text{sys.})] \times 10^{-4}$	4.0σ	

Summary

- BESIII is successfully operating since 2008, and continues to take data
- It is an excellent laboratory to study charmonium spectroscopy:
  - ✓ High statistics
  - ✓ Low background
- Many interesting results have been obtained, only few of them are covered in this talk. Lots of progress in the study of charmoniumlike states at BESIII recently
- Future:
  - ✓ More data will be collected
  - ✓ More detailed studies will be done

THANKS FOR YOUR ATTENTION!