Vector states above open charm threshold

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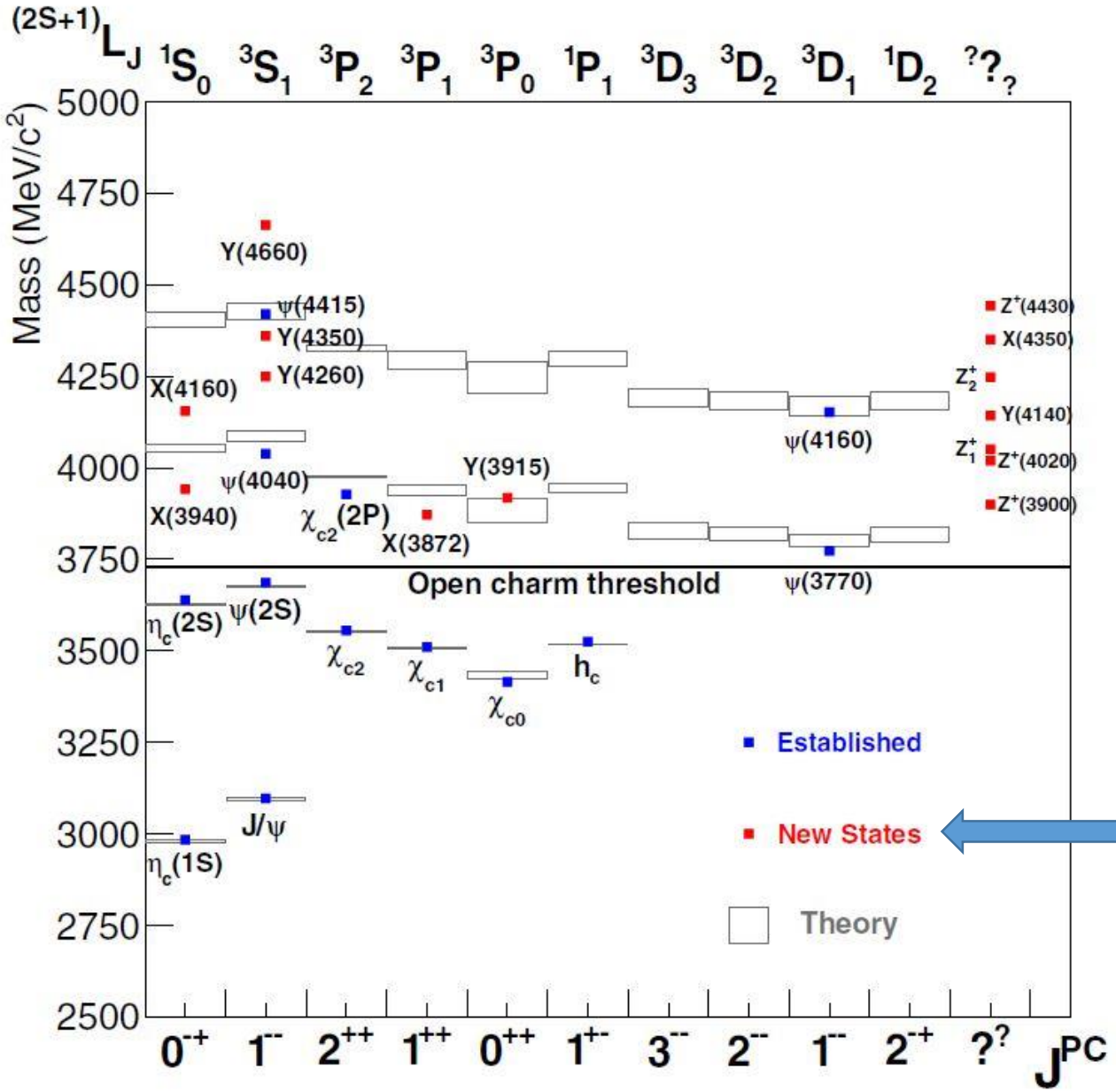
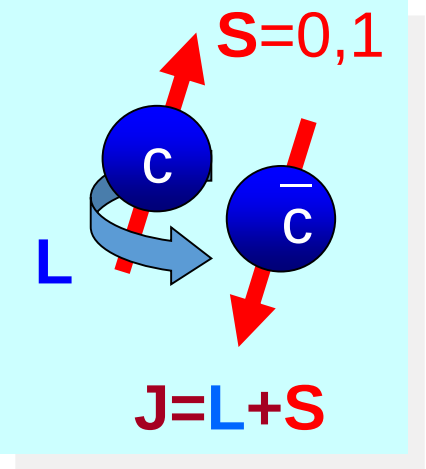
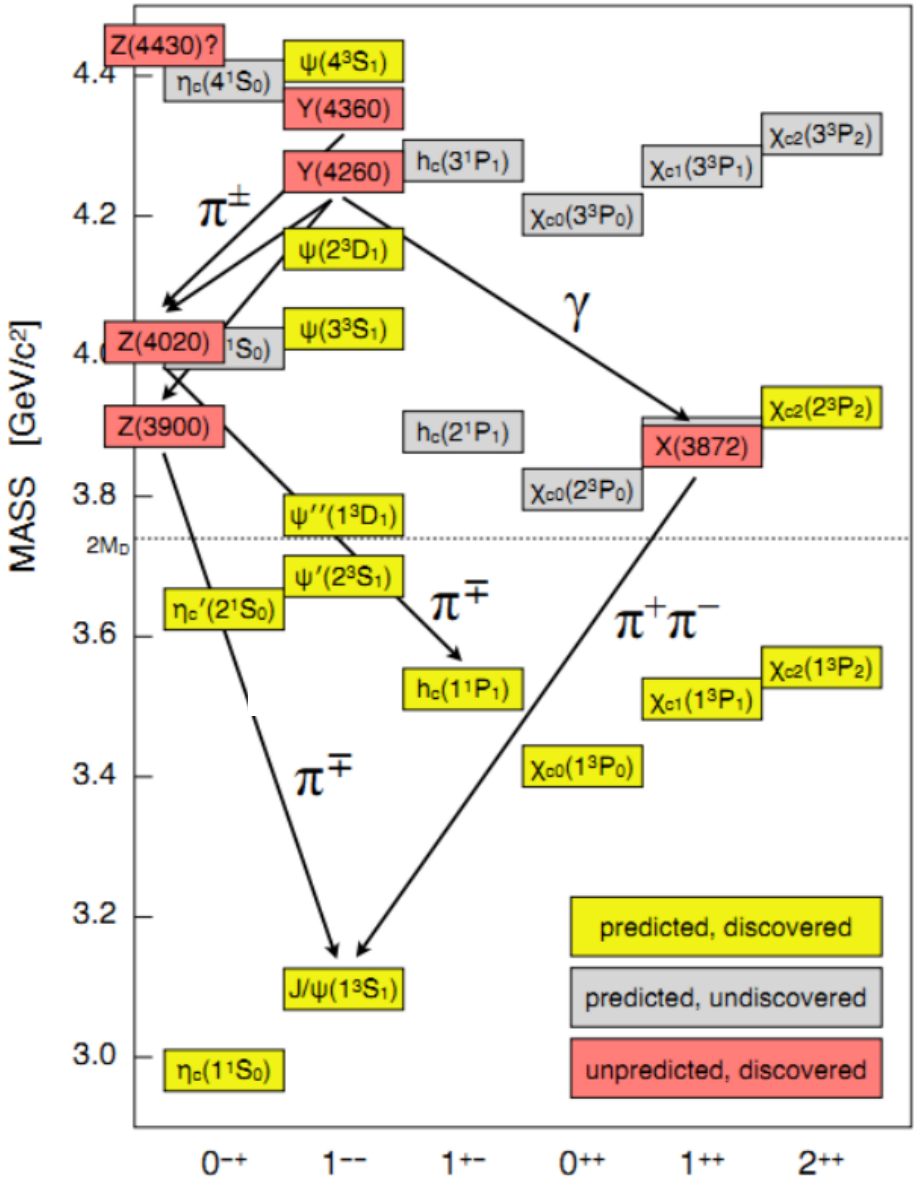
Charmonium Spectrum (1)





New charmonium-like states, i.e. "XYZ" states, are observed in experiment

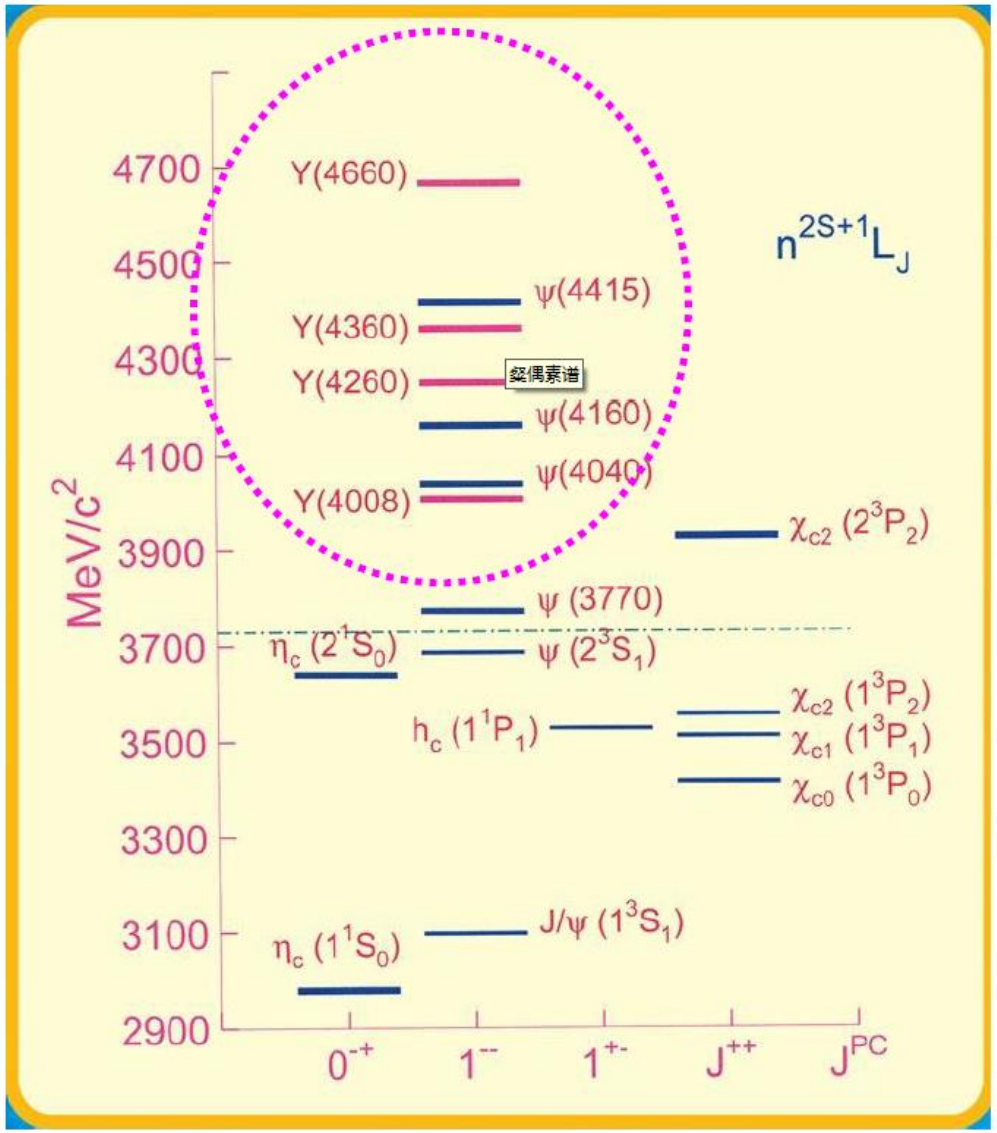
Charmnonium spectrum (2)



- **Below the open charm threshold the spectrums well understood**
  - **very good agreement between predicted and discovered states**
- **Above the threshold the situation in more complex**
  - **only few of the predicted states have been found**
  - **in the last decades many new states have been observed with properties that are not consistent with expectations for charmonium: X, Y, Z**

what I mainly focus on: Y states

What are the Y states?



- A bit similar to $c\bar{c}$ states with $J^{PC} = 1^{--}$, but they are charmonium-like states
- Observed in direct e^+e^- annihilation or in ISR.
- Possible final state: $\pi\pi(KK)J/\psi$, $\pi\pi(KK)\psi(2S)$, $\pi\pi h_c$, $\pi\pi X$, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, $\omega\chi_c$, πDD^*,γX …..
- Cannot rule out threshold effect/FSI/….

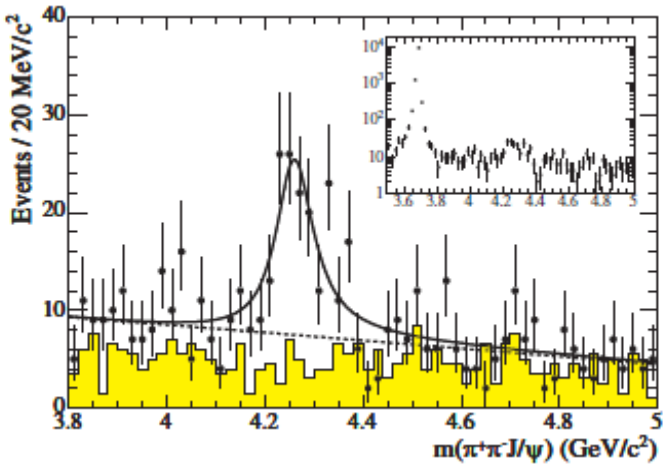
Outline

- $e^+e^- \to \gamma_{ISR}\, \pi^+\pi^- J/\psi$ ($\psi(2S)$):Y(4260)&Y(4008)&Y(4360)&Y(4660)
- $e^+e^- \to \pi^0\pi^0\, \psi(2S)$: Y(4360)?
- $e^+e^- \to \pi^+\pi^-(\pi^0\pi^0, KK) J/\psi$: Y(4260)&& Y(4222)&&Y(4320)
- $e^+e^- \to \pi^+\pi^-(\pi^0\pi^0) J/\psi$
- $e^+e^- \to \pi^0\eta J/\psi$: No Y(4260)
- $e^+e^- \to \pi^+\pi^- h_c$: Y(4218) && Y(4391) or Y(4360)?
- $e^+e^- \to \pi^+\pi^- X(3823)$: Y(4360) or $\psi(4415)$?
- $e^+e^- \to \gamma X(3872)$: Y(4260)?
- $e^+e^- \to \omega\chi_{c0,1,2}$: Y(4230) or more?
- $e^+e^- \to \pi^+ D^0 D^{*-}$(Y(4220&Y(4440)?)
- Search for Y(4140) in $\phi J/\psi$ mass spectrum
- $e^+e^- \to P J/\psi$ ($P=\eta,\eta'$) : $\psi(4040)$&$\psi(4160)$& $\psi(4415)$?
- summary

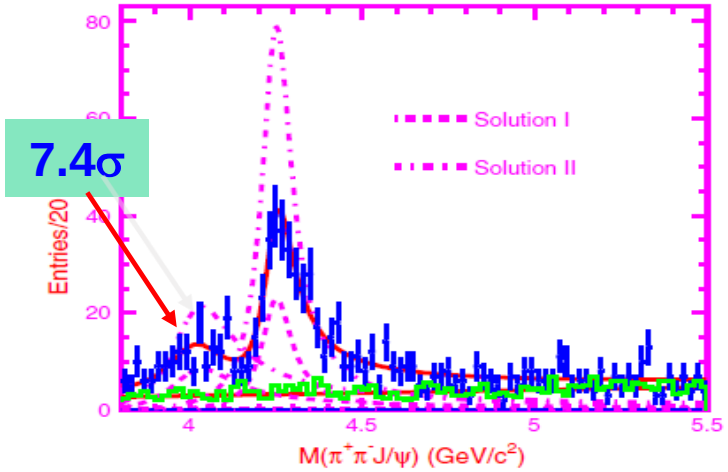
$e^+e^- \to \gamma_{ISR}\, \pi^+\pi^- J/\psi$ (Y(4260))

- **Babar:**
  - **First observation of Y(4260) in $\pi^+\pi^- J/\psi$ mass spectrum via ISR events. M=4259±8$^{+2}_{-6}$ MeV/c², Γ=88±23$^{+6}_{-4}$ MeV/c²**

- **Belle:**
  - **Confirm Y(4260) in $\pi^+\pi^- J/\psi$ mass spectrum**
  - **Observe a new structure Y(4008)**



Babar:PRL95,142001(2005)

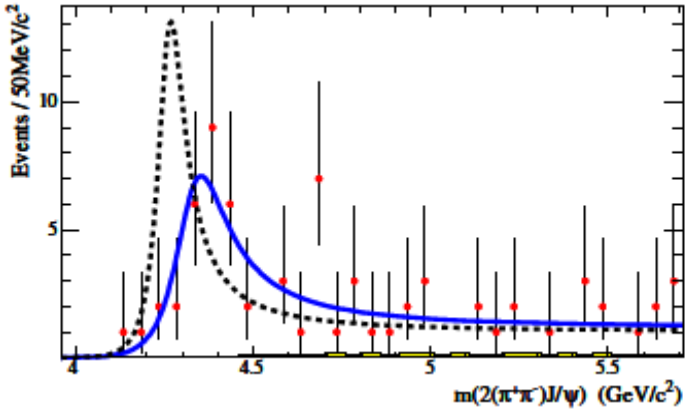


Belle:PRL99,182004(2007)

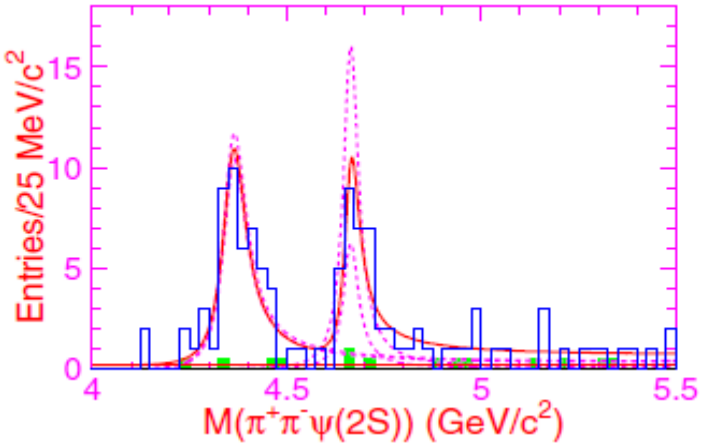
	constructive	destructive
Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B}\Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B}\Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

$e^+e^- \to \gamma_{ISR}\, \pi^+\pi^-\psi(2S)$ (Y(4360)&Y(4660))

- **Babar:**
  - **First observation of Y(4360) in $\pi^+\pi^-\psi(2S)$ mass spectrum. M=4324±24 MeV/c², Γ=172±33 MeV/c²**
- **Belle:**
  - **Confirm Y(4360) in $\pi^+\pi^-\psi(2S)$ mass spectrum**
  - **Observe a new Y(4660) state**



Babar:PRL98, 212001 (2007)



Belle:PRL99, 142002 (2007)

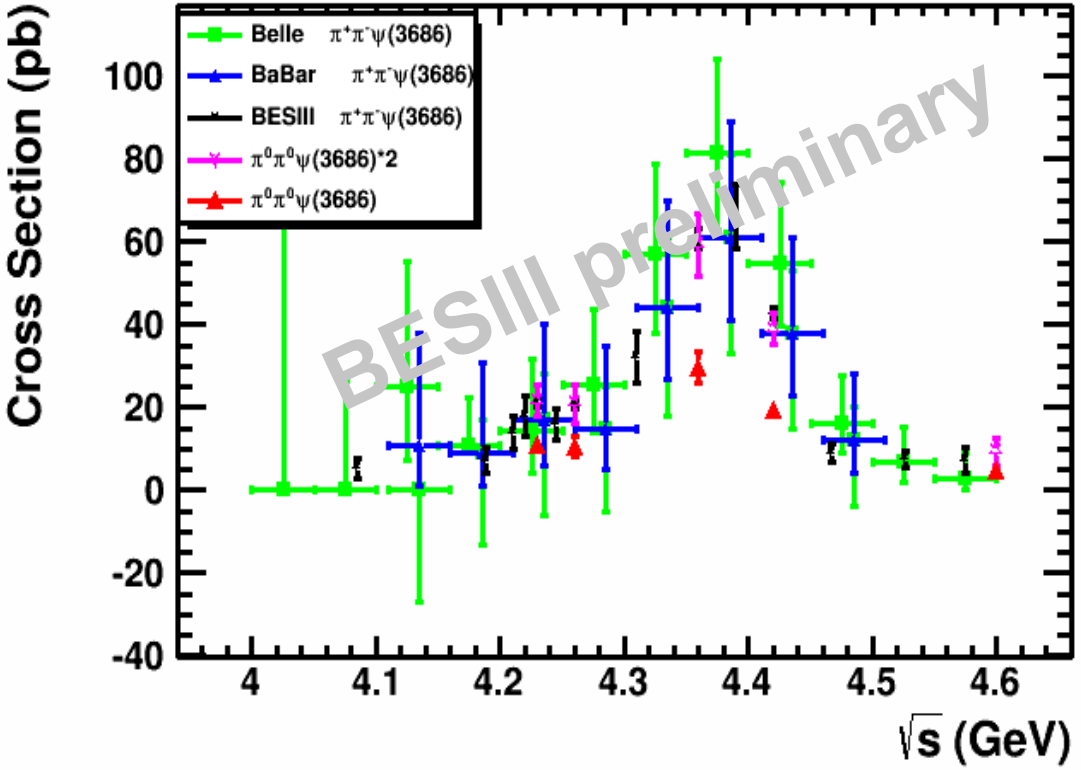
	constructive	destructive
Parameters	Solution I	Solution II
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B}\Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B}\Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

$e^+e^- \to \pi^0\pi^0\psi(2S)$ (Y(4360)?)

- BESIII measured the Born cross section of $e^+e^- \to \pi^0\pi^0\psi(2S)$ at 8 energies. Our results agree with the previous experiments

- There is a bump near 4.36 GeV. Is it Y(4360)?

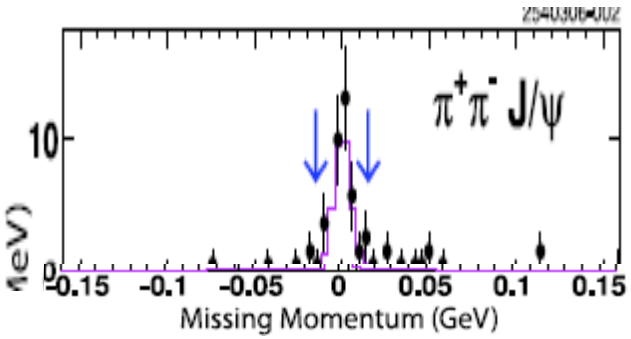
$$\sigma^B = \frac{N^{sig}}{\mathcal{L}_{int}\ (1+\delta)^r\ (1+\delta)^v\ \mathcal{B}r\ \epsilon}$$



$e^+e^- \to \pi^+\pi^- J/\psi$ (Y(4260), or Y(4220)&Y(4320)?)

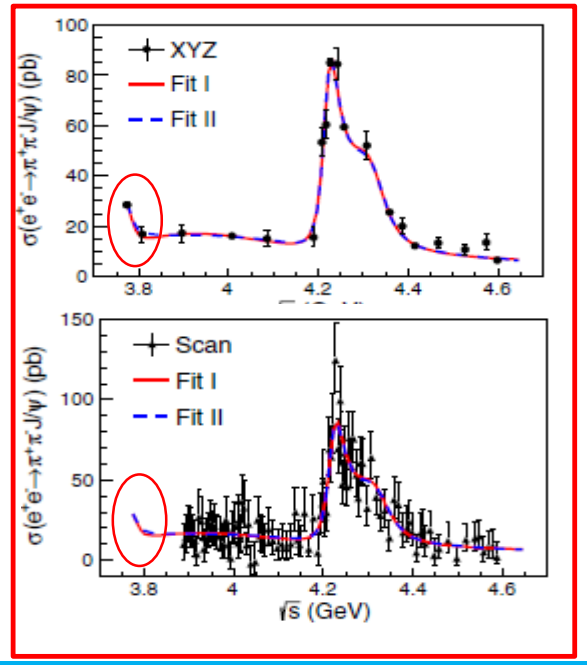
- **CLEO:**
  - **Confirm Y(4260) via the missing momentum ($\sqrt{s}$=4.26 GeV)**

$$\mathcal{A}(\sqrt{s}) = \frac{M}{\sqrt{s}} \frac{\sqrt{12\pi\Gamma_{e^+e^-}\Gamma_{tot}\mathcal{B}_R}}{s - M^2 + iM\Gamma_{tot}} \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M)}} e^{i\phi},$$



CLEO:PRL96, 162003(2006)

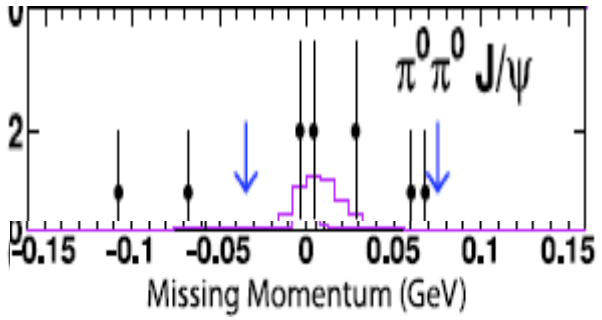
- **BESIII:**
  - **Resonance 1: M=4222.0±3.1±1.4 MeV/c², Γ=44.1±4.3±2.0 MeV/c². Its mass is similar to Y(4260), but its width is much less than that of average Y(4260)**
  - **Resonance 2: M=4320±10.4±7.0 MeV/c², Γ=$101.4^{+25.3}_{-19.7}$±10.2 MeV/c² (new!)**
  - **Rule out only one resonance with 5.4σ**



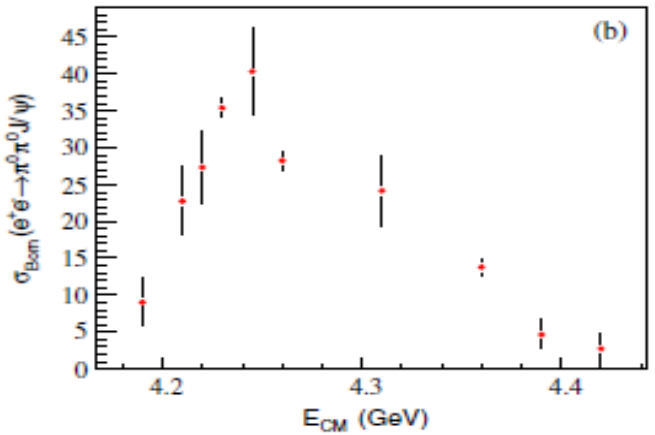
BESIII:PRL118,092001 (2017)

$e^+e^- \to \pi^0\pi^0 J/\psi$ (Y(4260)?)

- CLEO: a weak evidence of Y(4260) signal
- BESIII: hard to determine any clear structure around 4.26 GeV



CLEO: PRL96, 162003(2006)

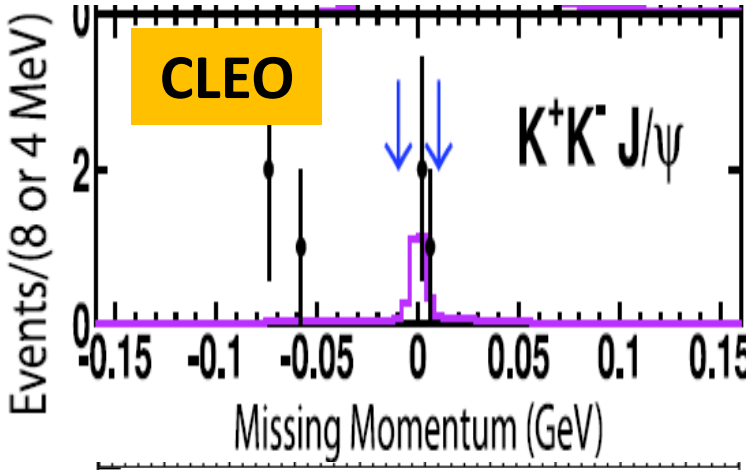


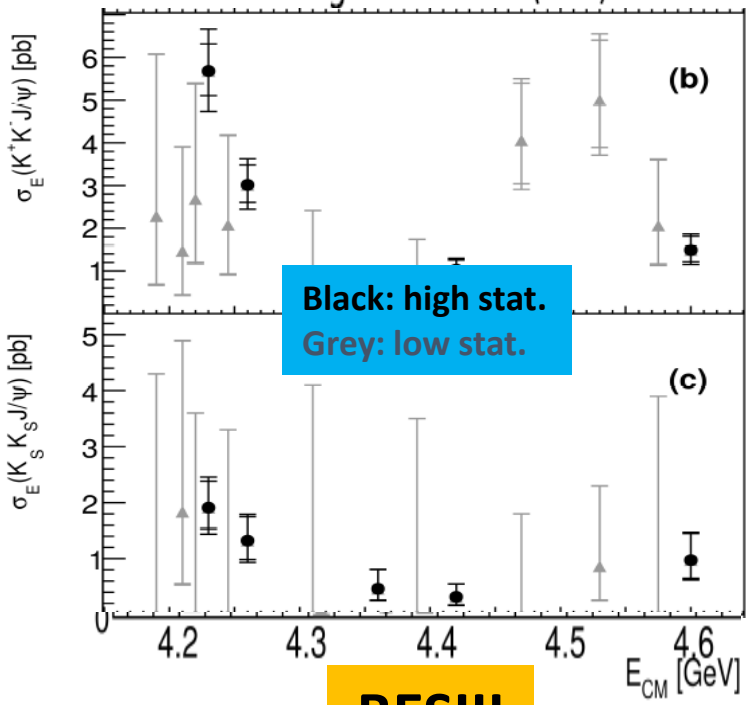
BESIII:PRL115,112003 (2015)

$e^+e^- \to KKJ/\psi$ (Y(4260)?)

- CLEO: a weak evidence of Y(4260) signal in K^+K^-J/ψ

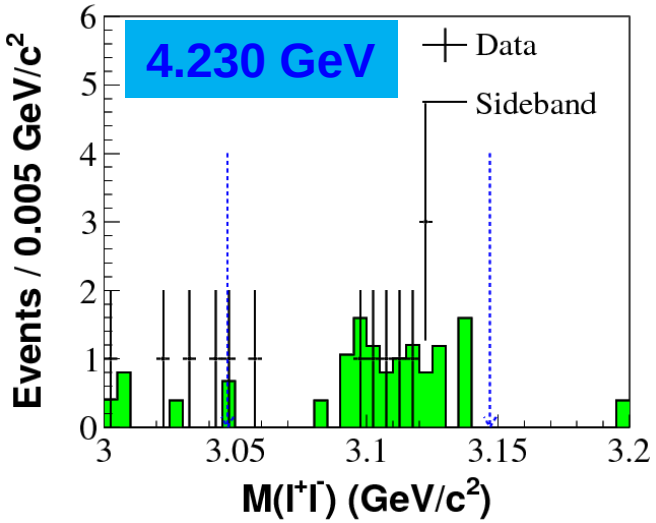
- BESIII(preliminary): inconclusive as to whether Y (4260) decays to $K\bar{K}$ $(K^+K^-, K_S^0 K_S^0)$J/ψ .

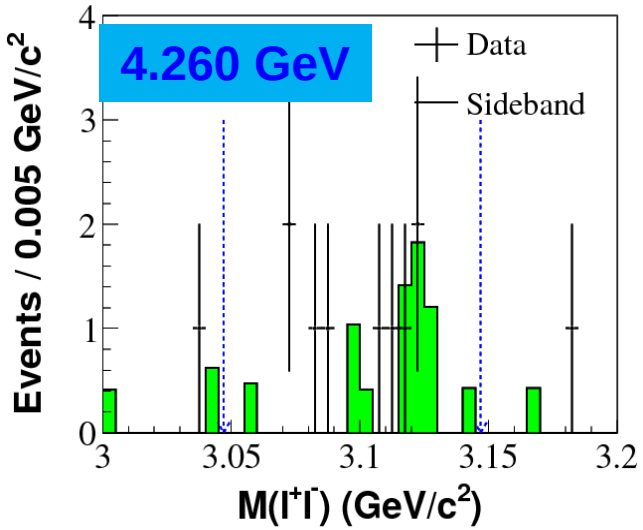


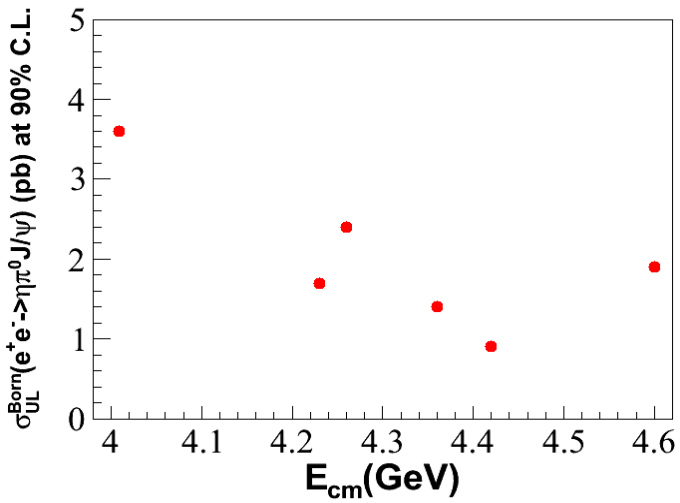


BESIII

$e^+e^- \to \pi^0 \eta J/\psi$ (Y(4260)?)







- Search for the isospin violation decay of Y(4260)
- No signal is observed
- Can not provide effective constraint to models……

BESIII: PRD92,012008 (2015)

$e^+e^- \to \pi^+\pi^- h_c$ (two Y states?)

$$\sigma(m) = \left| B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi} B_2(m)\sqrt{\frac{P(m)}{P(M_2)}} \right|^2$$

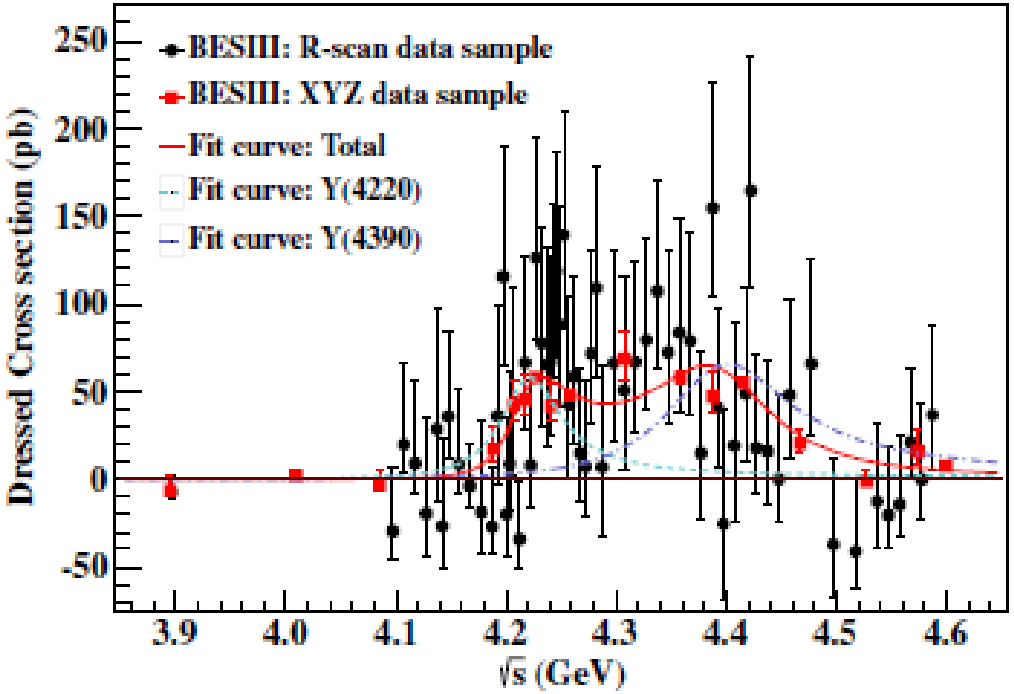
PRL118,092002 (2017)

$B_j(m) = [\sqrt{12\pi(\Gamma_{ee}\mathcal{B})_j\Gamma_j}/(m^2 - M_j^2 + iM_j\Gamma_j)$: constant width BW function

P(m) : 3-body phase space factor

ϕ : relative phase between two resonances

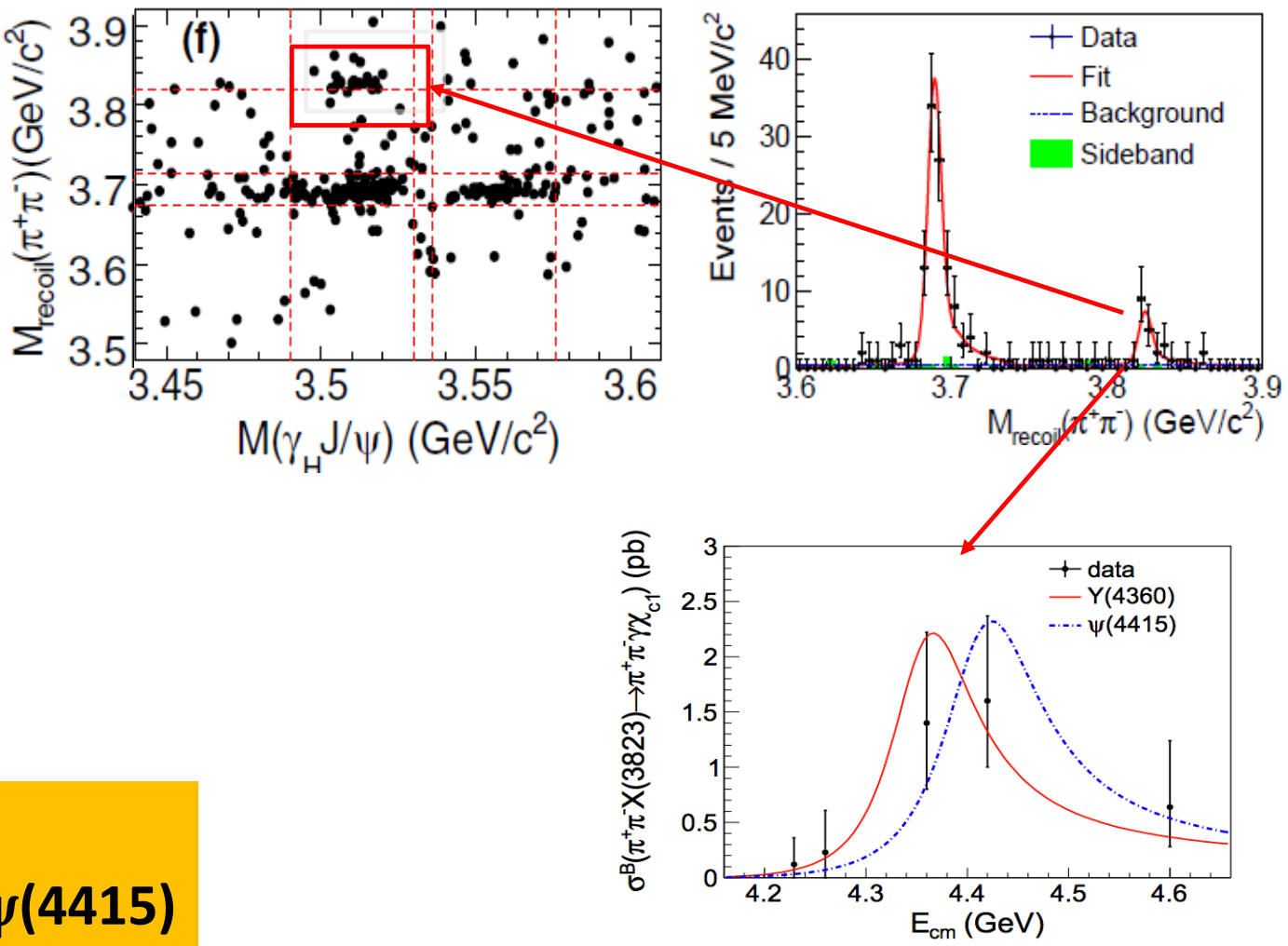
- Significance of two resonant structures over that of one structure is 10σ
- The parameters of these two structures are different from those of Y(4260) and Y(4360), and ψ(4415)



	M (MeV)	Γ_{tot} (MeV)	Γ_{ee}•Br (eV)	ϕ (rad)
Y(4220)	$4218.4^{+5.5}_{-4.5}$±0.9	$66.0^{+12.3}_{-8.3}$±0.4	$4.6^{+2.9}_{-1.4}$±0.8	--
Y(4390)	$4391.5^{+6.3}_{-1.4}$±1.0	$139.5^{+16.2}_{-20.6}$±0.6	$11.6^{+5.0}_{-4.4}$±1.9	$3.1^{+0.7}_{-0.9}$±0.2

$e^+e^- \to \pi^+\pi^- X(3823)$ (Y or ψ?)

- Clear X(3823) is seen in χ_{c1} mass region
- Line-shape of $\pi^+\pi^- X(3823)$
  - Y(4360)?
  - ψ(4415)?
  - Both?
  - More?

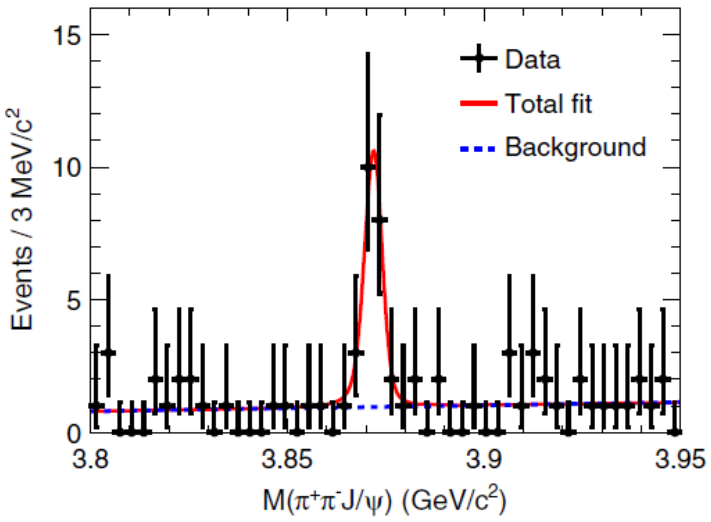


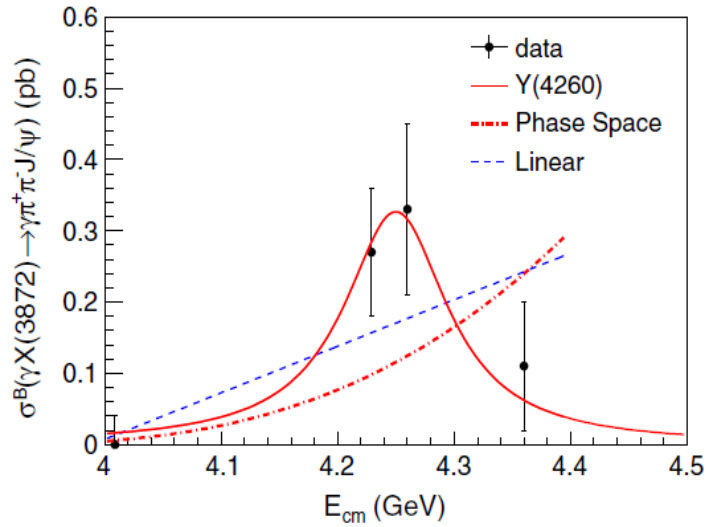
Kolmogorov test:
$D^{H1}_{5,obs}$=0.151 for Y(4360), $D^{H2}_{5,obs}$=0.169 for ψ(4415)
Considering $D_{5,0.1}$=0.509, we accept both Y and ψ hypothesis at the 90% C.L.

PRL115,011803 (2015)

$e^+e^- \to \gamma X(3872)$ (Y(4260)?)

- Clear X(3872) is seen in $\pi^+\pi^- J/\psi$ mass spectrum via $e^+e^- \to \gamma\pi^+\pi^- J/\psi$
- Try to fit $\sigma^B(\gamma X(3872) \to \gamma\pi^+\pi^- J/\psi)$ with Y(4260) , linear and phase-space shape
- Y(4260) $\to \gamma X(3872)$? Need to be confirmed

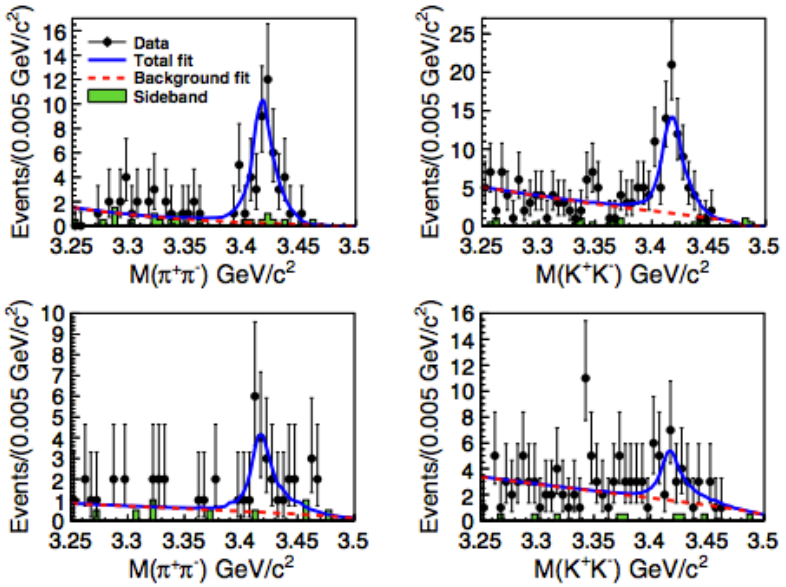




$e^+e^- \to \omega\chi_{c0}$ (Y(4220)?)

PRL114, 092003 (2015)

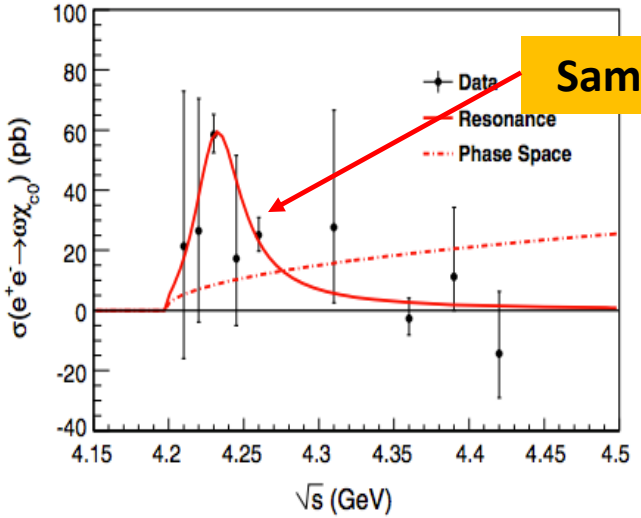
- Using scan data over 4.23 and 4.6 GeV, $e^+e^- \to \omega\chi_{c0}$ are significant.
- Cross section peak near 4.23 GeV, fit with BW yields Mass=(4230±8±6) MeV, Width=(38±12±2) MeV.
  - A new structure?
  - Tetraquark [PRD 91, 117501 (2015)]?
  - Threshold effect?
  - Similar to the first structure Y(4220) in $e^+e^- \to \pi^+\pi^- h_c$ line-shape

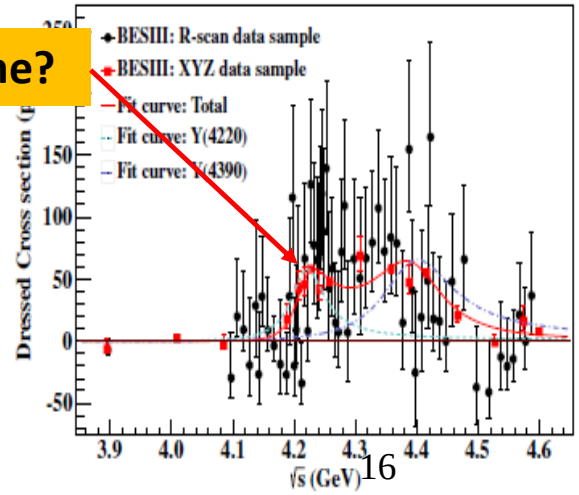


4.23 GeV

4.26 GeV

Same?

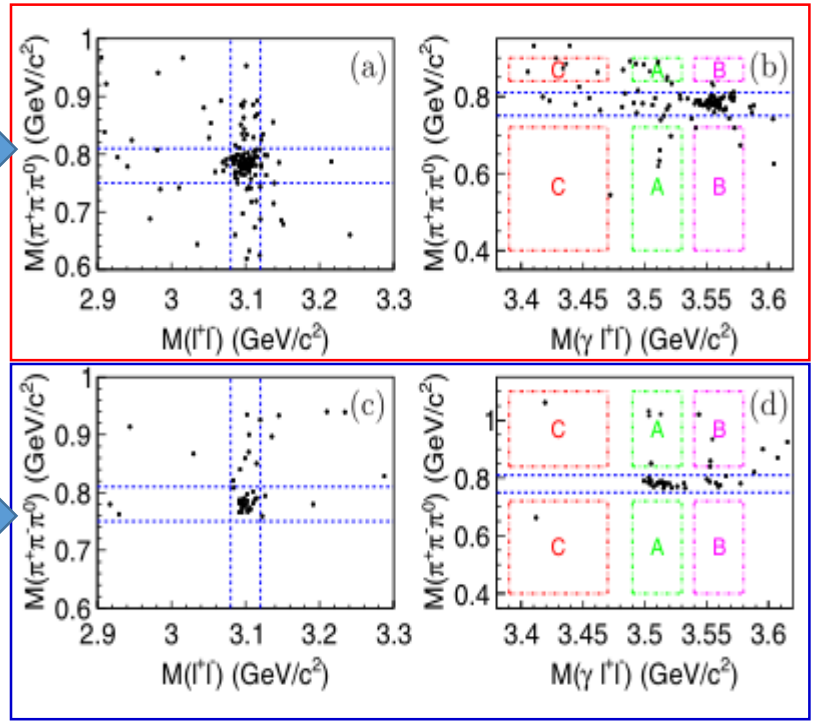


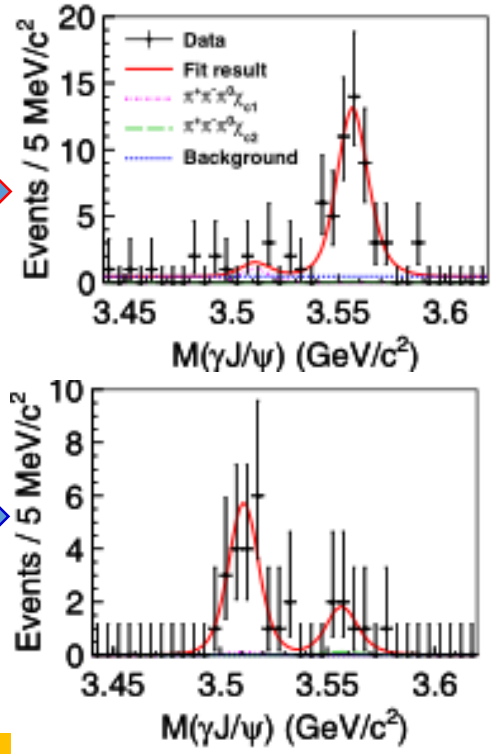


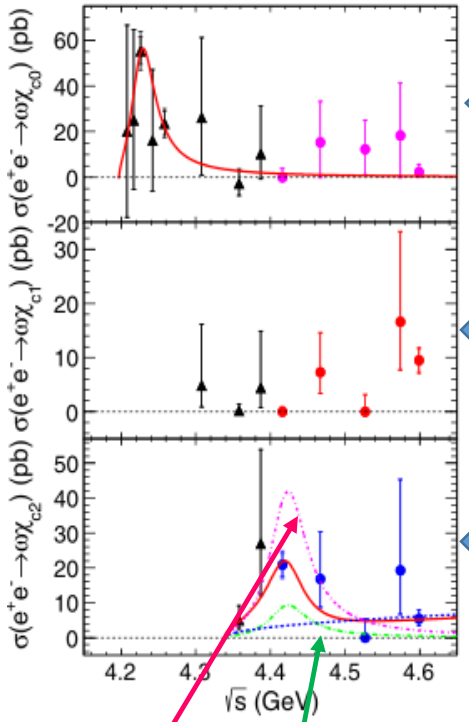
$e^+e^- \to \omega\chi_{c1,2}$ (Y or ψ?)

4.42 GeV

4.6 GeV







$\omega\chi_{c0}$

$\omega\chi_{c1}$

$\omega\chi_{c2}$

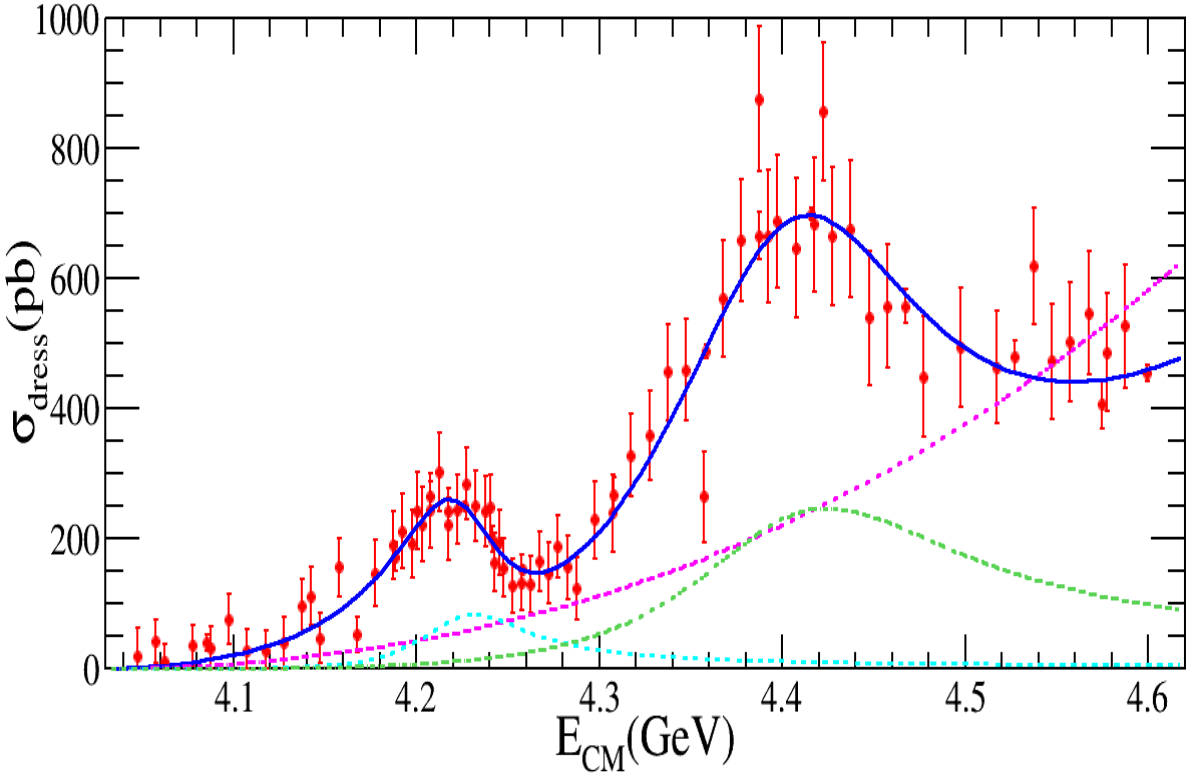
Phys. Rev. D 93, 011102 (2016)

- Clear χ_{c2},χ_{c1} are observed at $\sqrt{s}$=4.42, 4.6 GeV, respectively
- The Born cross section have been measured for $e^+e^- \to \omega\chi_{c1,2}$
- $\sigma(e^+e^- \to \omega\chi_{c2})$ is fitted with the coherent sum of the ψ(4415) BW function and a phase-space term. Two solutions are obtained: ·····constructive, - - - destructive

$e^+e^- \to \pi^+ D^0 D^{*-}$ (Y(4220)&Y(4440)?)

$$\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1+\delta^r)B(D^0 \to K^-\pi^+)\varepsilon}$$

$$\sigma_{\rm dress}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2} B_2(m)\sqrt{\frac{P(m)}{P(M_2)}}|^2$$

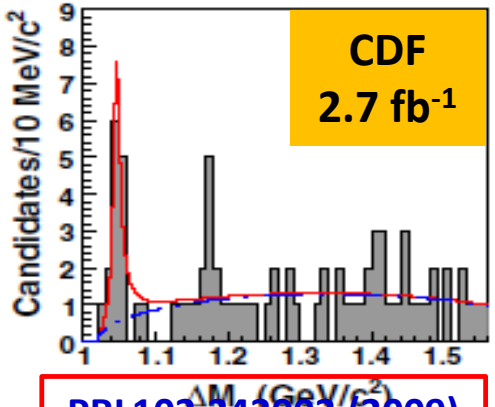


Parameters	SolutionI	SolutionII	SolutionIII	SolutionIV
c (10^{-4})		5.5±0.6		
M_1 (MeV/c^2)		4224.8±5.6		
Γ_1 (MeV)		72.3±9.1		
M_2 (MeV/c^2)		4400.1±9.3		
Γ_2 (MeV)		181.7±16.9		
Γ_1^{el} (eV)	62.9±11.5	7.2±1.8	81.6±15.9	9.3±2.7
Γ_2^{el} (eV)	88.5±15.8	55.3±8.7	551.9±85.3	344.9±70.6
ϕ_1	-2.1±0.1	2.8±0.3	-0.9±0.1	-2.3±0.2
ϕ_2	1.9±0.3	2.3±0.2	2.3±0.1	-1.9±0.1

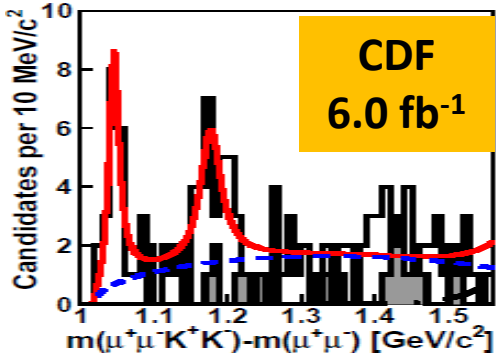
BESIII Preliminary

- The statistical significance of two resonances assumption over one resonance is greater than 10σ.
- The resonant parameters of Y(4220) and Y(4390) states are consistent with the structures observed in $e^+e^- \to \pi^+\pi^- h_c$. The resonant parameters of Y(4220) are also consistent with those of the resonance observed in $e^+e^- \to \omega\chi_{c0}$ and $e^+e^- \to \pi^+\pi^- J/\psi$.

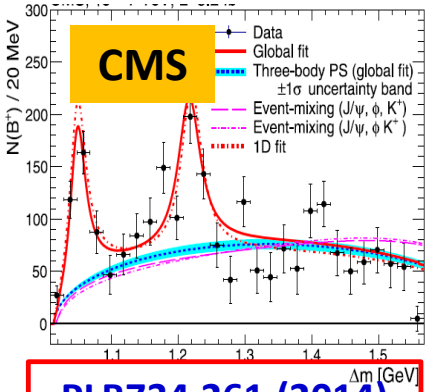
Y(4140) & Y(4330) & more?



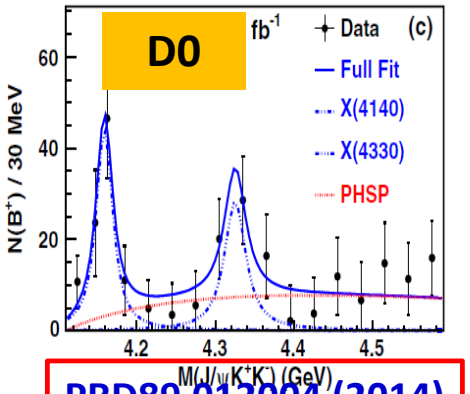
PRL102,242002 (2009)



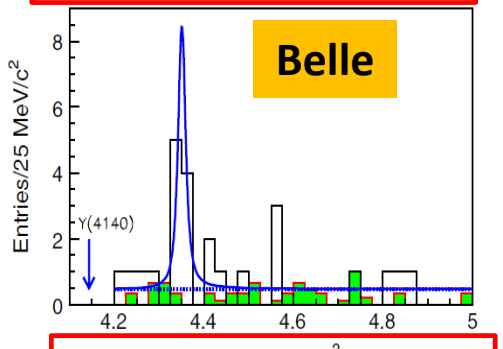
arXiv:1101.6058



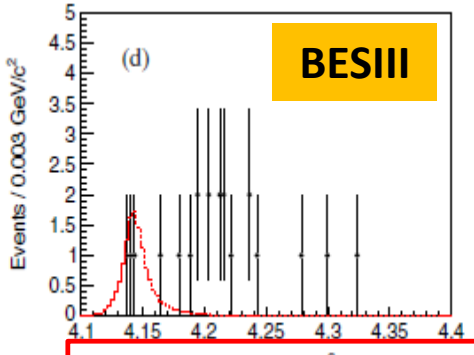
PLB734,261 (2014)



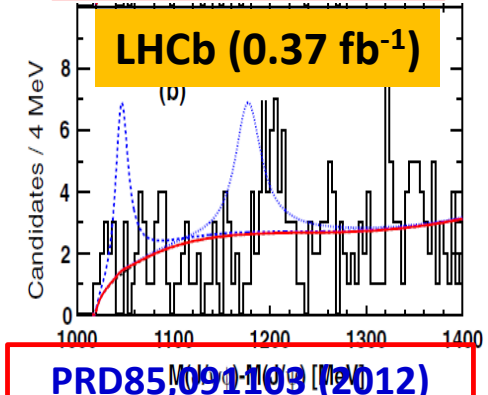
PRD89,012004 (2014)



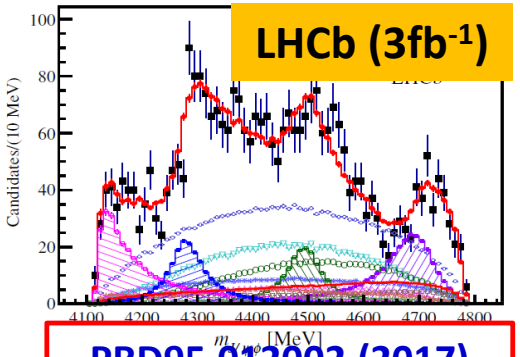
PRL104,112004 (2010)



PRD91,032002 (2015)



PRD85,091103 (2012)

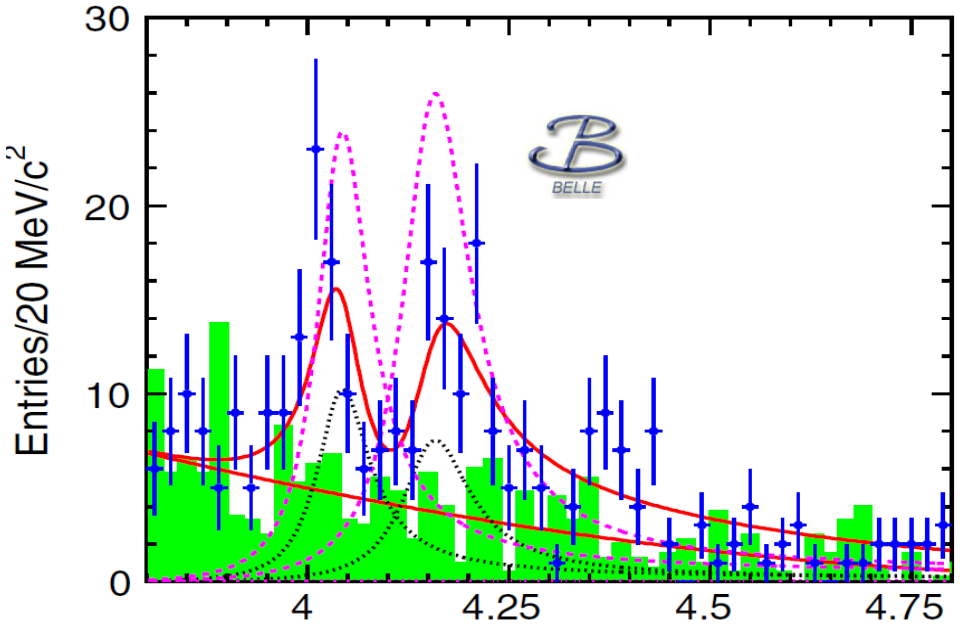


PRD95,012002 (2017)

- First observation in CDF via $B^+ \to \phi J/\psi K^+$ with 6.0 fb^{-1} data (an evidence with 2.7 pb^{-1} data)
- CMS and D0 confirm with the same process
- Belle and Babar failed to confirm with the same process
- LHCb hasn't observed any structure firstly, but observed 4 structures with a large sample
- Belle hasn't confirmed with two-photon process, either
- BESIII hasn't observed Y(4140) via $e^+e^- \to \gamma\phi J/\psi$

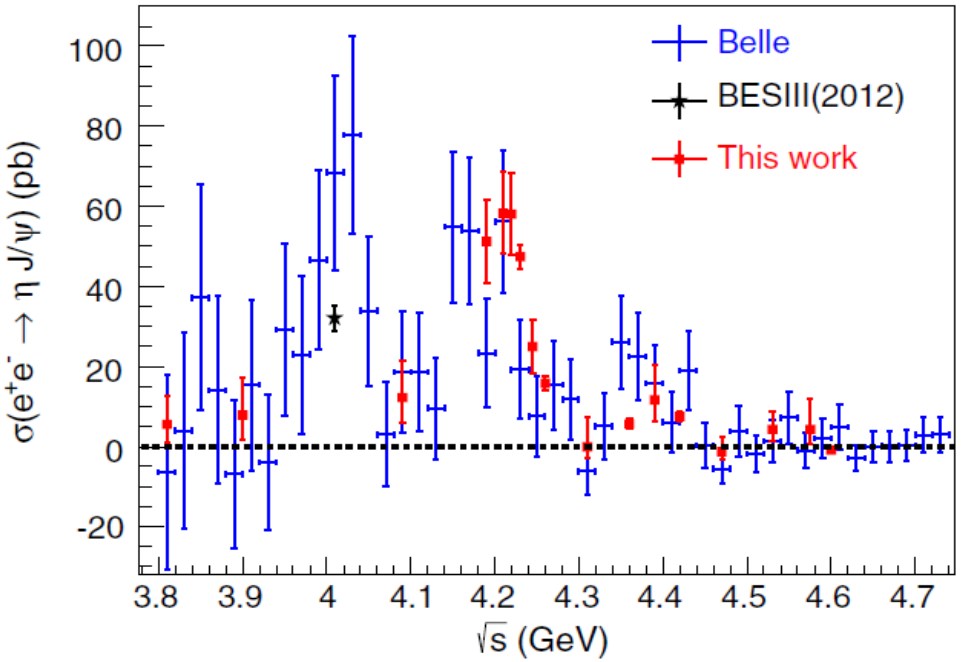
$e^+e^- \to \eta J/\psi$ ($\psi(4040)$&$\psi(4160)$?)

PRD87,051101(R), 2013



Ψ(4040) and Ψ(4160) with interference

PRD 91,112005 (2015)



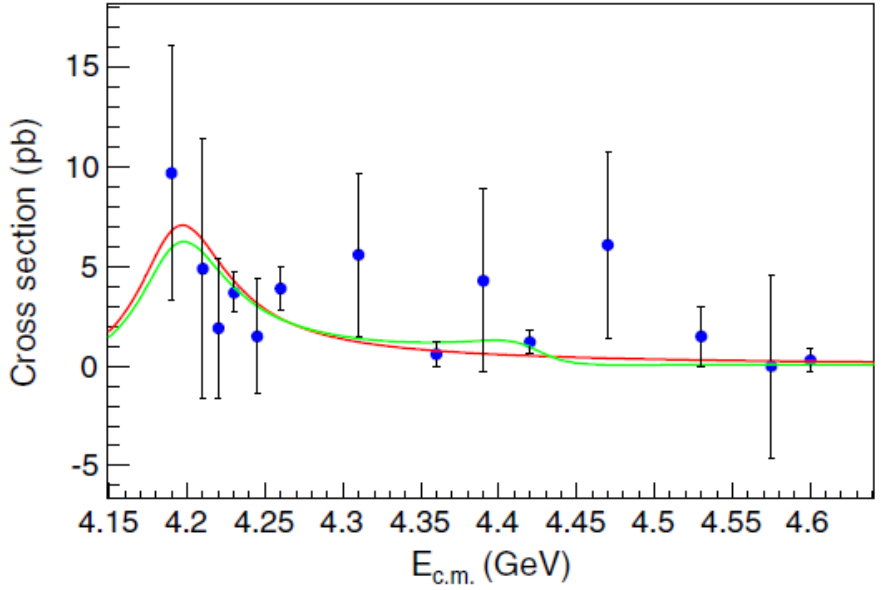
- Belle observed two structures in Born cross section of $e^+e^- \to \eta J/\psi$ and fit them using $\psi(4040)$&$\psi(4160)$ line-shapes
- BESIII's results agree with Belle's results with improved precision in some points
- The cross section also peaks around 4.2 GeV

$e^+e^- \to \eta' J/\psi$ ($\psi(4160)$?)

Phys. Rev. D 94,032009 (2016)

$$\sigma(m) = |\mathcal{A}_{\psi(4160)}(m) \cdot \sqrt{\Phi(m)/\Phi(M)}|^2,$$

$$\mathcal{A}_{\psi(4160)}(m) = \frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{\rm tot}\mathcal{B}(\psi(4160)\to\eta' J/\psi)}}{m^2 - M^2 + iM\Gamma_{\rm tot}},$$



- **Significant signals are observed at $\sqrt{s}$ = 4.23 and 4.26 GeV**
- **The measured cross section support the hypothesis that signal events of $\eta' J/\psi$ come from $\psi(4160)$ decay; not from $\psi(4415)$**

Summary

- Many candidates of charmonium-like vector states are observed above open charm threshold.
- They are difficult to distinguish from the traditional charmonium states.
- Some potential new structures need to be further confirmed.

Thank you (谢谢)！

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