中国科学技术大学
University of Science and Technology of China

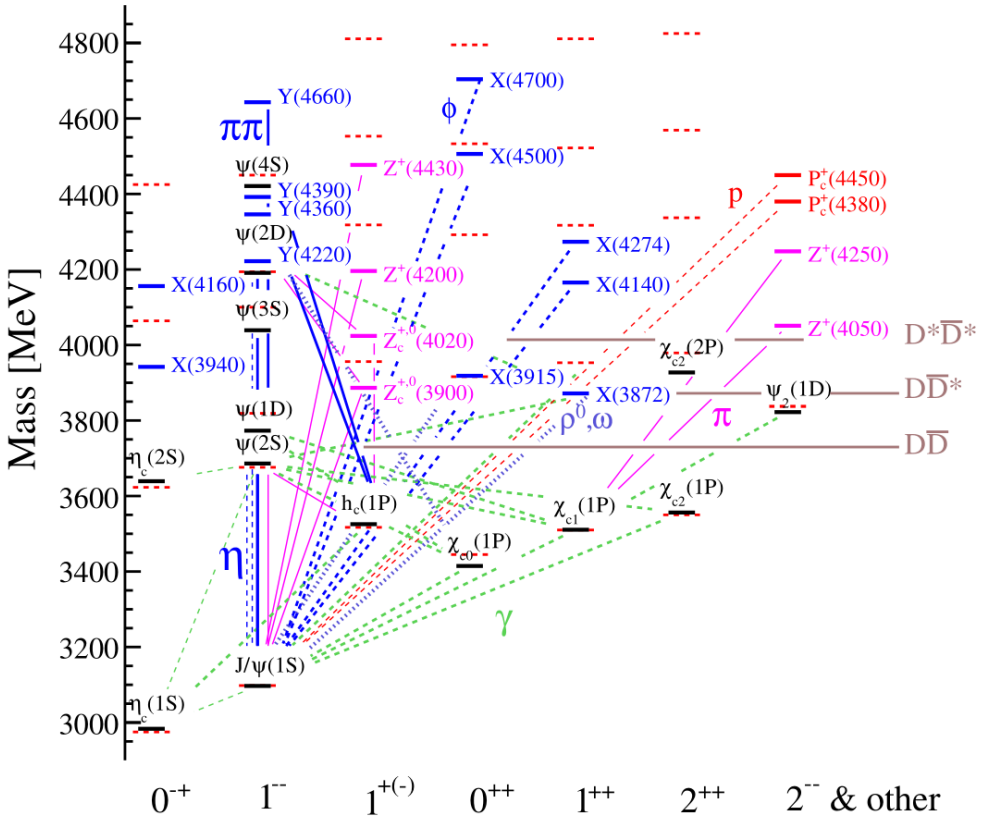
BESIII

The charmonium-like Y states at BESIII

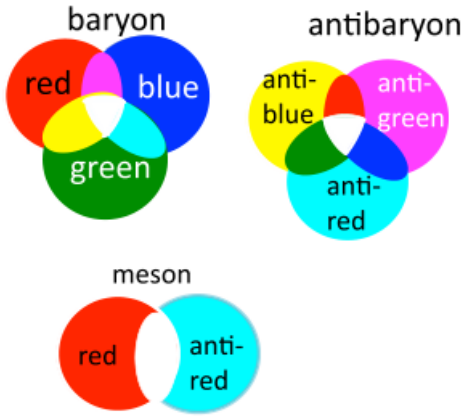
Xuhong Li
University of Science and Technology of China
State Key Laboratory of Particle Detection and Electronics
2021, 15-18 May

Introduction

Rev. Mod. Phys., 2018, 90, 015003

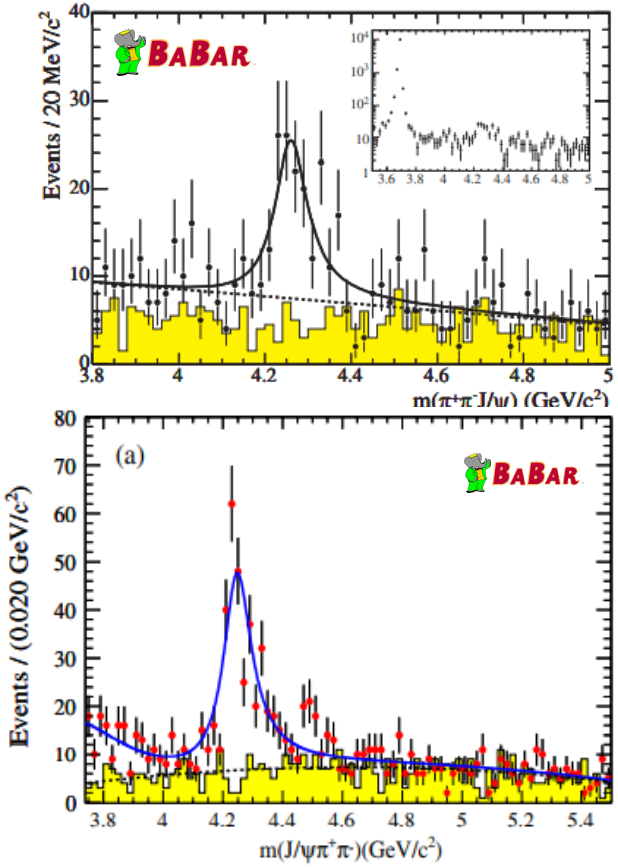


- Since the discovery of J/ψ, a series of excited charmonium states ($\psi(2S)$, $\psi(3770)$, …)
- Many charmonium-like states are observed beyond the prediction of quark model
- A series of Y states (Y(4220), Y(4390), Y(4660)…) are found

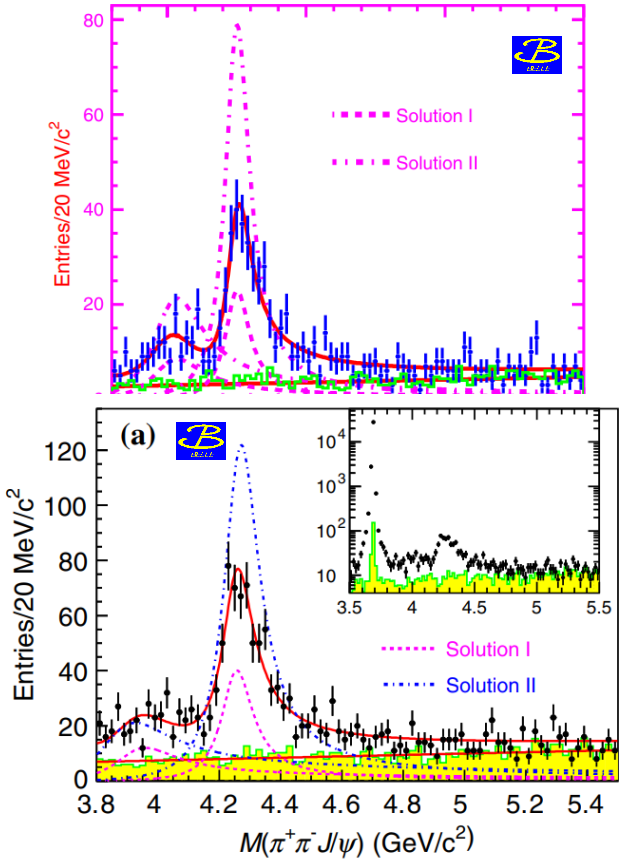


Some history of Y-states

Phys. Rev. Lett. 95, 142001 (2005)
Phys. Rev. D 86, 051102(R) (2012)



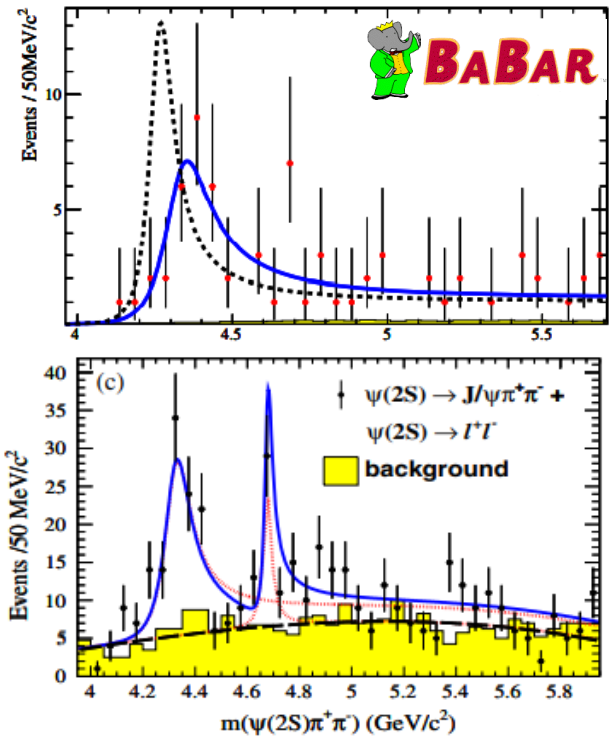
Phys. Rev. Lett. 99, 182004 (2007)
Phys. Rev. Lett. 110, 252002 (2013)



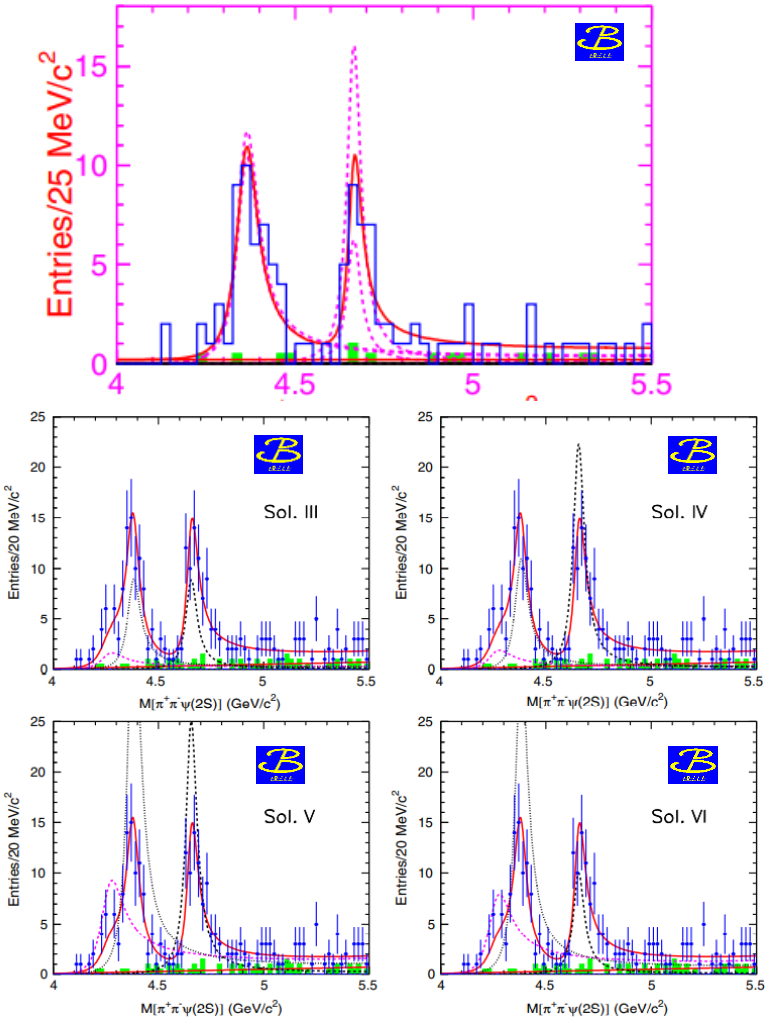
- BaBar study $e^+e^- \to \pi^+\pi^- J/\psi$ by ISR, Y(4260) was observed for the first
- Belle confirmed the Y(4260) in the same process

Some history of Y-states

Phys. Rev. Lett. 98, 212001 (2007)
Phys. Rev. D 89, 111103(R) (2014)

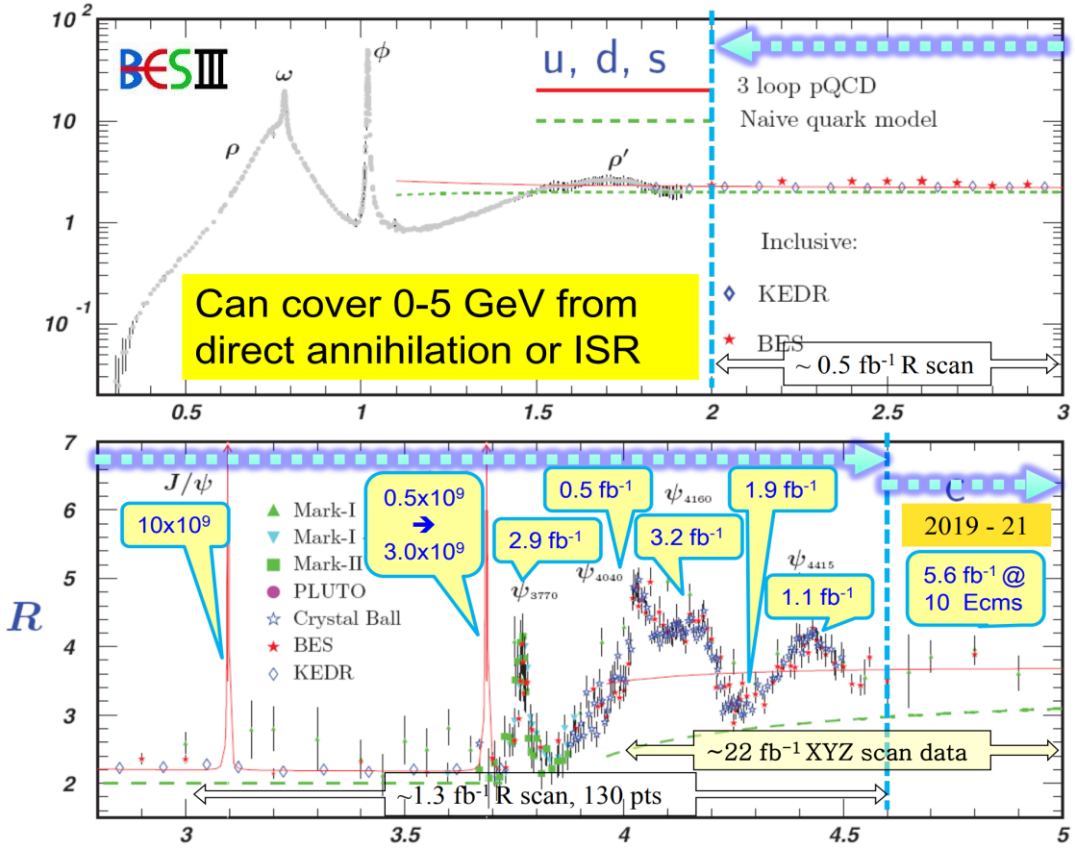


Phys. Rev. Lett. 98, 212001 (2007)
Phys. Rev. D 91, 112007 (2015)



- BaBar and Belle study $e^+e^- \to \pi^+\pi^-\psi(2S)$ by ISR, Y(4360) and Y(4660) were observed

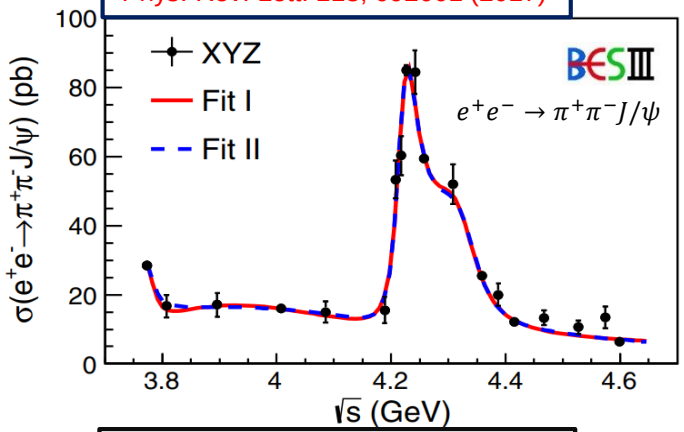
BESIII data sets for XYZ study



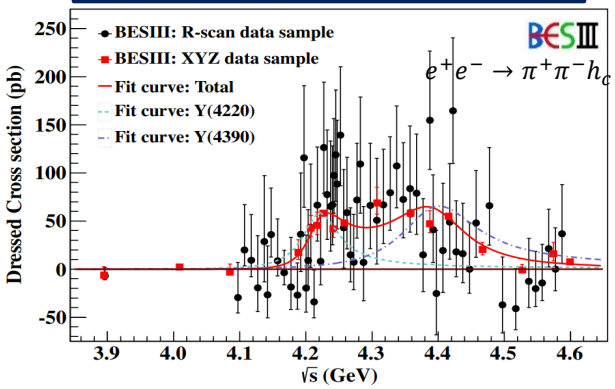
- Over 20 fb^{-1} data samples above 3.8 GeV
- BESIII can directly generate Y states ($J^P = 1^{--}$) by e^+e^- annihilation
- Search for more possible Y states and more decay modes

Y(4220) and Y(4390)

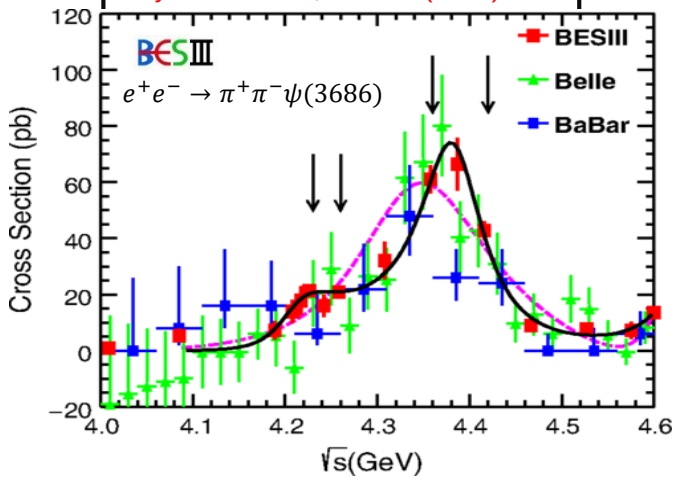
Phys. Rev. Lett. 118, 092001 (2017)



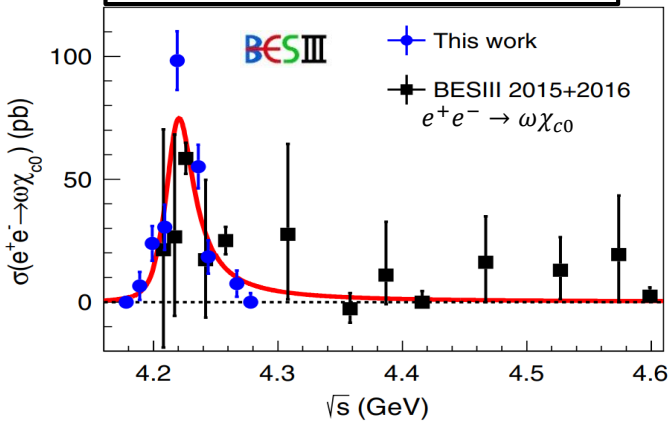
Phys. Rev. Lett. 118, 092002 (2017)



Phys. Rev. D 96, 032004 (2017)



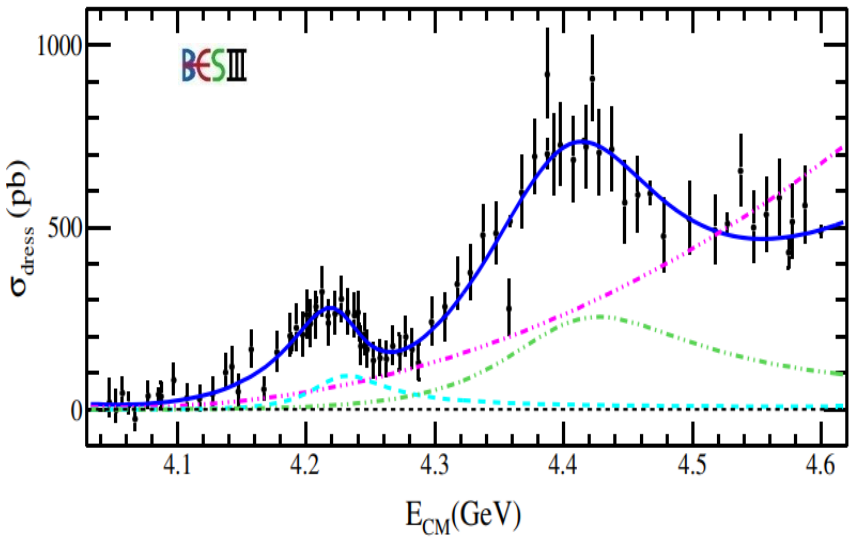
Phys. Rev. D 99, 091103(R) (2019)



- The Y(4260) observed by Belle and BaBar consists of Y(4220) and Y(4320)
- The Y(4360) observed by Belle and BaBar consists of Y(4220) and Y(4390)

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

Phys. Rev. Lett. 122, 102002 (2019)

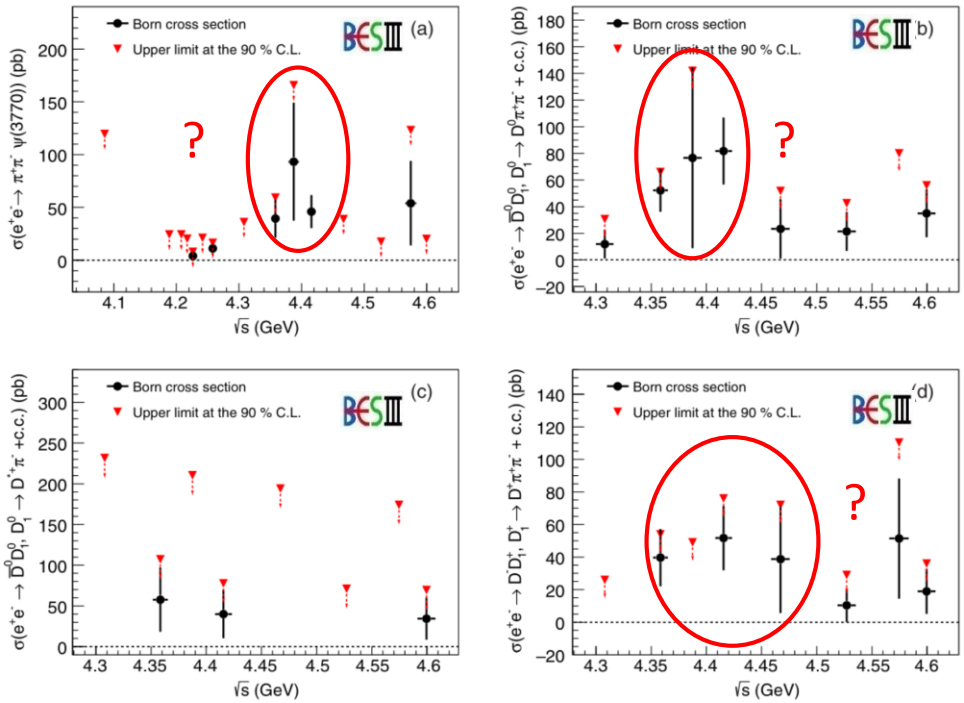


Parameter	Solution I	Solution II	Solution III	Solution IV
c (MeV$^{-3/2}$)		$(6.2 \pm 0.5) \times 10^{-4}$		
M_1 (MeV/c^2)		4228.6 ± 4.1		
Γ_1 (MeV)		77.0 ± 6.8		
M_2 (MeV/c^2)		4404.7 ± 7.4		
Γ_2 (MeV)		191.9 ± 13.0		
Γ_1^{el} (eV)	77.4 ± 10.1	8.6 ± 1.6	99.5 ± 14.6	11.1 ± 2.3
Γ_2^{el} (eV)	100.4 ± 13.3	64.2 ± 8.0	664.2 ± 80.0	423.0 ± 47.0
ϕ_1 (rad)	-2.0 ± 0.1	3.0 ± 0.2	-0.9 ± 0.1	-2.2 ± 0.1
ϕ_2 (rad)	2.1 ± 0.2	2.5 ± 0.2	-2.3 ± 0.1	-1.9 ± 0.1

- D^0 is reconstructed by channel $D^0 \to K^-\pi^+$, D^{*-} is reconstructed by recoiling $\pi^+ D^0$
- Two resonant structures are in good agreement with Y(4220) and Y(4390)
  - $M = (4228.6 \pm 4.1 \pm 6.3)\text{MeV}/c^2$, $\Gamma = (77.0 \pm 6.8 \pm 6.3)\text{MeV}$
- The first observation of Y(4220) associated with an open-charm final state
- The parameters of second enhancement are strongly dependent on the model assumptions, and need further analysis to understand

Process $e^+e^- \to \pi^+\pi^- D^+D^- \& \pi^+\pi^- D^0\bar{D}^0$

Phys. Rev. D. 100, 032005 (2019)



(a) $e^+e^- \to \pi^+\pi^-\psi(3770) \to \pi^+\pi^- D^+D^-$
(b) $e^+e^- \to D_1(2420)^0\bar{D}^0 \to \pi^+\pi^- D^0\bar{D}^0$
(c) $e^+e^- \to D_1(2420)^0\bar{D}^0 \to D^{*+}\bar{D}^0\pi^- \to \pi^+\pi^- D^0\bar{D}^0$
(d) $e^+e^- \to D_1(2420)^+D^- \to \pi^+\pi^- D^+D^-$

$\psi(3770)$ is seen in the $D\bar{D}$ final states at 4.42 GeV (5.2σ)

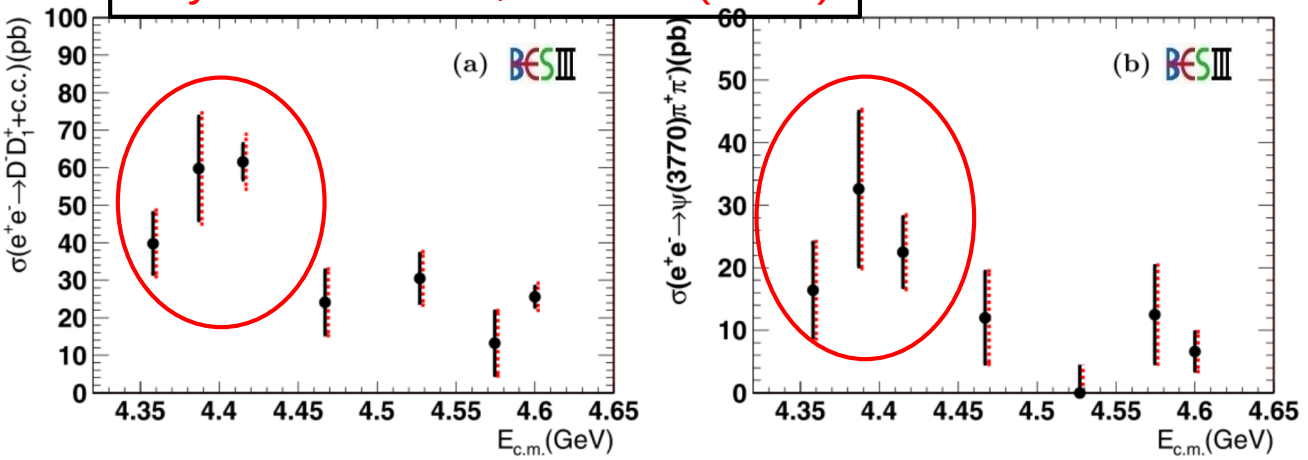
$e^+e^- \to D_1(2420)^0\bar{D}^0, \mathrm{D}_1(2420)^0 \to \mathrm{D}^0\pi^+\pi^-$ is observed 4.42 GeV (7.4σ)

Y(4390) ?
or
$\psi(4415)$?

- Double D tag to reconstruct D mesons
- Cross section line shape are shown
- The Y(4390) or the $\psi(4415)$ resonance or any other resonance cannot be distinguished

Process $e^+e^- \to \pi^+\pi^- D^+ D^-$

Phys. Lett. B 804, 135395 (2020)



Y(4390) ?
or
$\psi(4415)$?

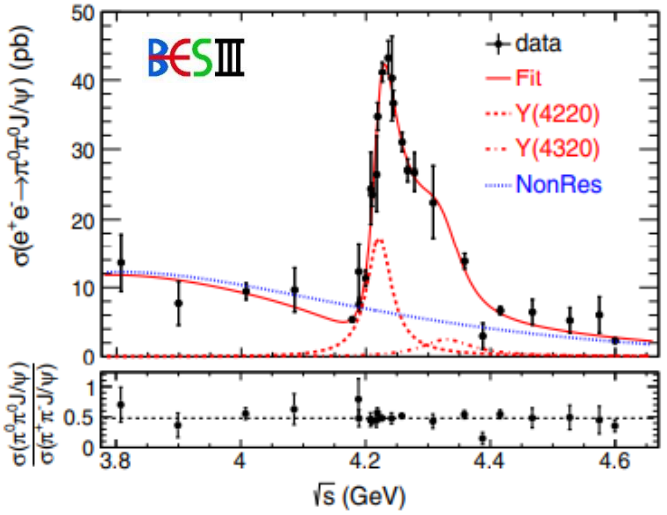
(a) $e^+e^- \to D_1(2420)^+ D^- + c.c$
(b) $e^+e^- \to \pi^+\pi^-\psi(3770) \to \pi^+\pi^- D^+ D^-$

- D^+ is reconstructed by channel $D^+ \to K^-\pi^+\pi^+$, D^- is reconstructed by recoiling mass
- Clear signals of the $D_1(2420)$ and $\psi(3770)$
- Some indications of enhanced cross sections for between 4.36 and 4 . 42 GeV

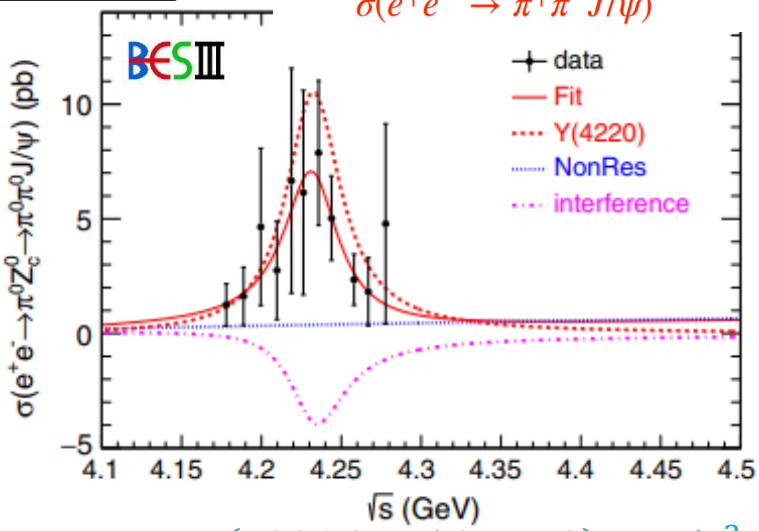
Process $e^+e^- \to \pi^0\pi^0 J/\psi$

Phys. Rev. D 102, 012009 (2020)

$$\mathcal{R} = \frac{\sigma(e^+e^- \to \pi^0\pi^0 J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 0.48 \pm 0.02$$



$M = (4220.4 \pm 2.4 \pm 2.3)\mathrm{MeV}/c^2$
$\Gamma = (46.2 \pm 4.7 \pm 2.1)\mathrm{MeV}$



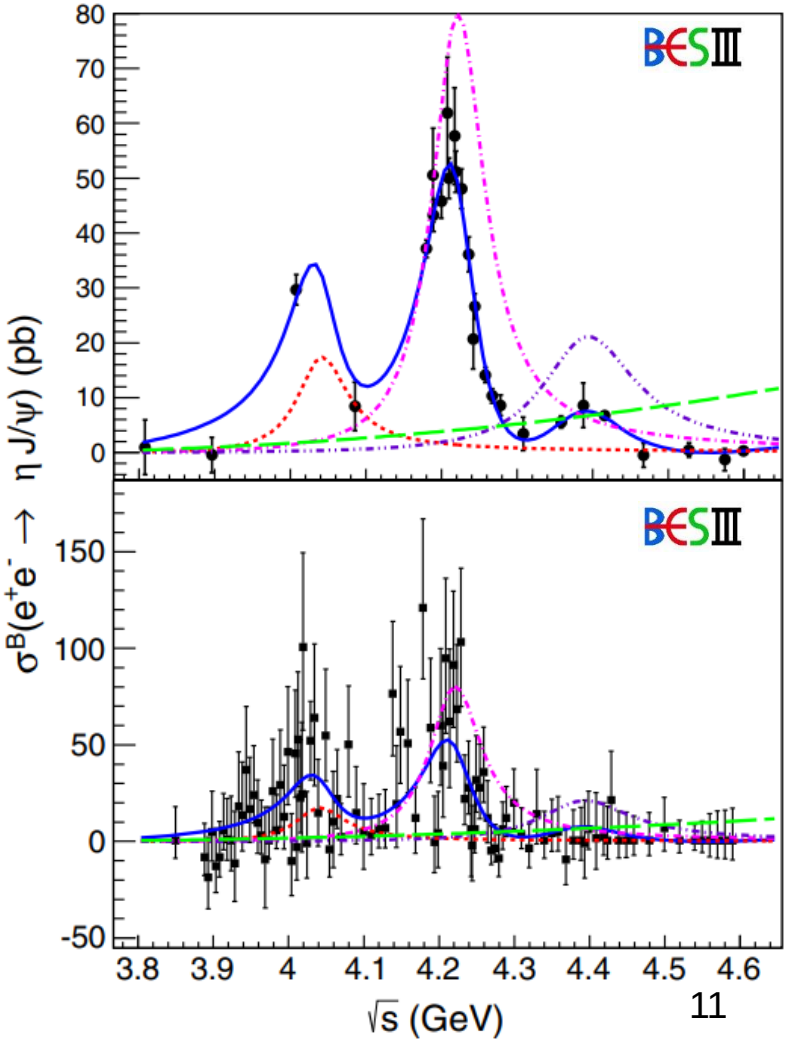
$M = (4231.9 \pm 5.3 \pm 4.9)\mathrm{MeV}/c^2$
$\Gamma = (41.2 \pm 16.0 \pm 16.4)\mathrm{MeV}$

- The average ratio consistent with the isospin symmetry
- Fit with two resonant structures, mass and width of Y(4320) are fixed to results of $e^+e^- \to \pi^+\pi^- J/\psi$
- Y(4220) is confirmed in both $\pi^0\pi^0 J/\psi$ and $\pi^0 Z_c^0(3900)$ line shape
- The relationship of Y(4220) and $Z_c^0(3900)$ is established

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

Parameters	Solution 1	Solution 2	Solution 3
$M_1(\mathrm{MeV}/c^2)$		4039(fixed)	
$\Gamma_1(\mathrm{MeV})$		80(fixed)	
$\Gamma_1^{e^+e^-}\mathcal{B}r_1$ (eV)	1.5 ± 0.3	1.4 ± 0.3	7.0 ± 0.6
ϕ_1 (rad)	3.3 ± 0.3	3.1 ± 0.3	4.5 ± 0.2
$M_2(\mathrm{MeV}/c^2)$		4218.6 ± 3.8	
$\Gamma_2(\mathrm{MeV})$		82.0 ± 5.7	
$\Gamma_2^{e^+e^-}\mathcal{B}r_2$ (eV)	8.0 ± 1.7	4.8 ± 1.0	7.0 ± 1.5
ϕ_2 (rad)	4.2 ± 0.4	3.6 ± 0.3	2.9 ± 0.3
$M_3(\mathrm{MeV}/c^2)$		4382.0 ± 13.3	
$\Gamma_3(\mathrm{MeV})$		135.8 ± 60.8	
$\Gamma_3^{e^+e^-}\mathcal{B}r_3$ (eV)	3.4 ± 2.2	1.5 ± 1.0	1.7 ± 1.1
ϕ_3 (rad)	2.8 ± 0.4	3.3 ± 0.4	3.0 ± 0.4

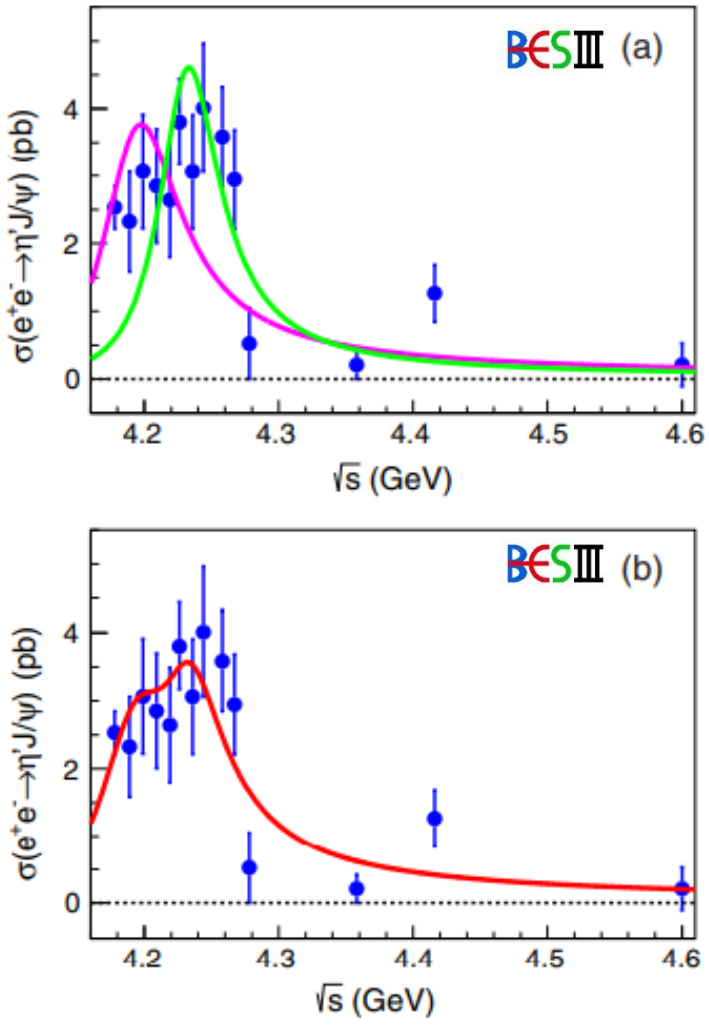
Phys. Rev. D 102, 031101(R) (2020)



- The new study of $e^+e^- \to \eta J/\psi$
- $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ channels are used for reconstruction
- Simultaneous fit is performed to the XYZ data and scan data
- The Y(4220) and Y(4390) are observed for the first time in the $\eta J/\psi$ final states

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

Phys. Rev. D 101, 012008 (2020)

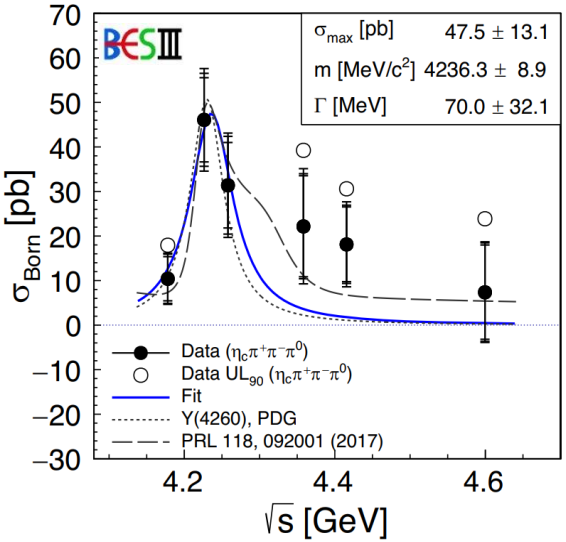


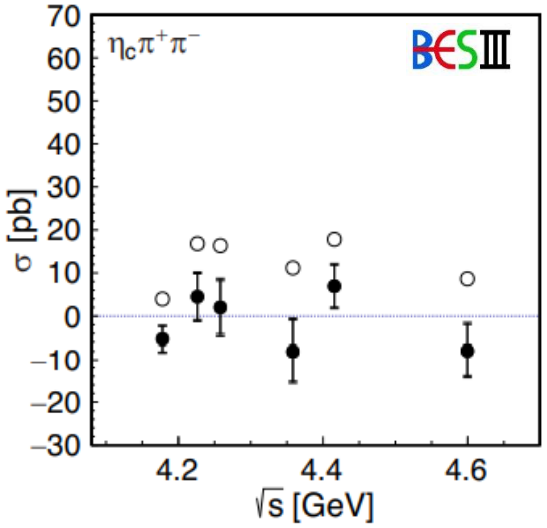
Parameter	Solution I	Solution II
$\Gamma_{ee}^{\psi(4160)}\mathcal{B}(\psi(4160) \to \eta' J/\psi)$ (eV)	0.17 ± 0.04	1.07 ± 0.09
$\Gamma_{ee}^{\psi(4260)}\mathcal{B}(\psi(4260) \to \eta' J/\psi)$ (eV)	0.06 ± 0.03	1.38 ± 0.11
ϕ (rad)	-0.03 ± 0.44	2.54 ± 0.04

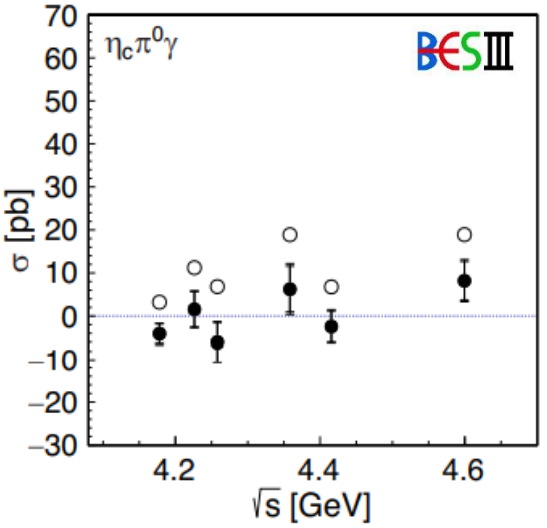
- The reconstruction of η':
  $\eta' \to \gamma\pi^+\pi^- / \eta\pi^+\pi^-, \eta \to \gamma\gamma$
- The cross section line shape shows an enhancement around 4.2 GeV
- Can't describe by a single $\psi(4160)$ or $\psi(4260)$ (Fixed mass and width)
- A coherent sum of $\psi(4160)$ or Y(4260) provides a reasonable description of data
- The significance of $\psi(4160)$ and Y(4260) are 6.3σ and 4.0σ, respectively

Process $e^+e^- \to \eta_c\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-$ and $\eta_c\pi^0\gamma$

Phys. Rev. D 103, 032006 (2021)







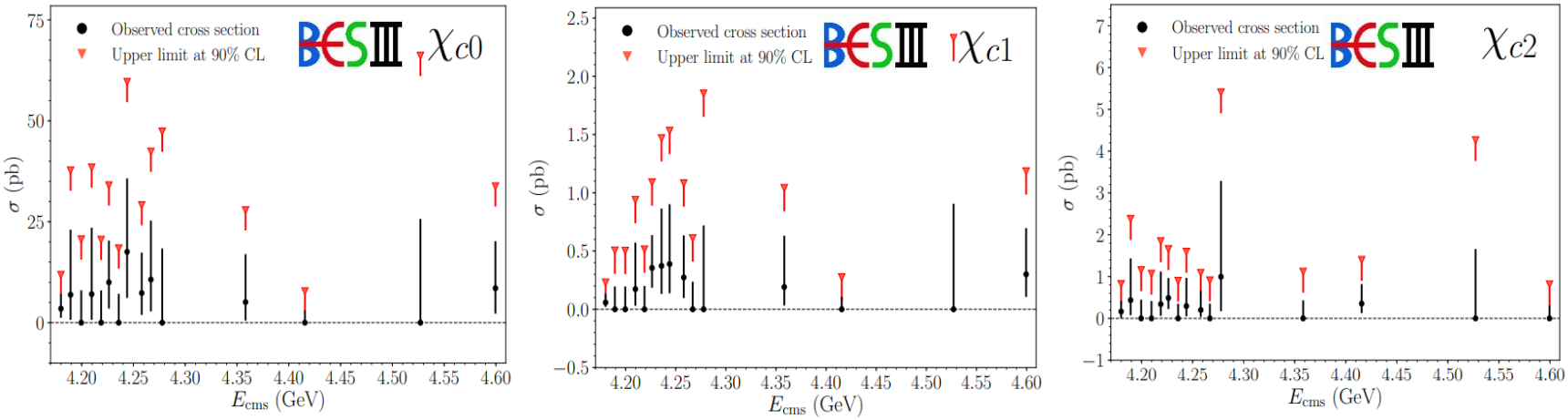
$M = (4236.3 \pm 8.9)\text{MeV}/c^2 \quad \Gamma = (70.0 \pm 32.1)\text{MeV}$

- The process $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ is observed for the first time (5.1σ @ 4.23 GeV)
- The cross sections of $e^+e^- \to \eta_c\pi^+\pi^-$ and $e^+e^- \to \eta_c\pi^0\gamma$ are found to be consistent with zero
- The Born cross section is consistent with the production via the intermediate Y(4260)

Decay	$\mathcal{B}_i$[%] [39]	Mode No. i
$3(\pi^+\pi^-)$	1.8 ± 0.4	01
$2(\pi^+\pi^-\pi^0)$	17.4 ± 3.3	02
$\pi^+\pi^-\pi^0\pi^0$	4.7 ± 1.0	03
$2(\pi^+\pi^-)$	0.97 ± 0.12	04
$K_S^0K^+\pi^-$	2.43 ± 0.17	05
$K^+K^-\pi^+\pi^-$	0.69 ± 0.11	06
$K^+K^-\pi^0$	1.21 ± 0.83	07
$K_S^0K^+\pi^-\pi^+\pi^-$	2.75 ± 0.74	08
$2(\pi^+\pi^-)\eta$	4.4 ± 1.3	09
$\pi^+\pi^-\eta$	1.7 ± 0.5	10
$K^+K^-\eta$	1.35 ± 0.16	11
$K^+K^-K^+K^-$	0.146 ± 0.030	12
$K^+K^-2(\pi^+\pi^-)$	0.75 ± 0.24	13
$p\bar{p}$	0.150 ± 0.016	14
$p\bar{p}\pi^+\pi^-$	0.53 ± 0.18	15
$p\bar{p}\pi^0$	0.36 ± 0.13	16
Summed up	$\sum_i \mathcal{B}_i = 41.34 \pm 3.93$	

Process $e^+e^- \to \pi^+\pi^-\chi_{cJ}$

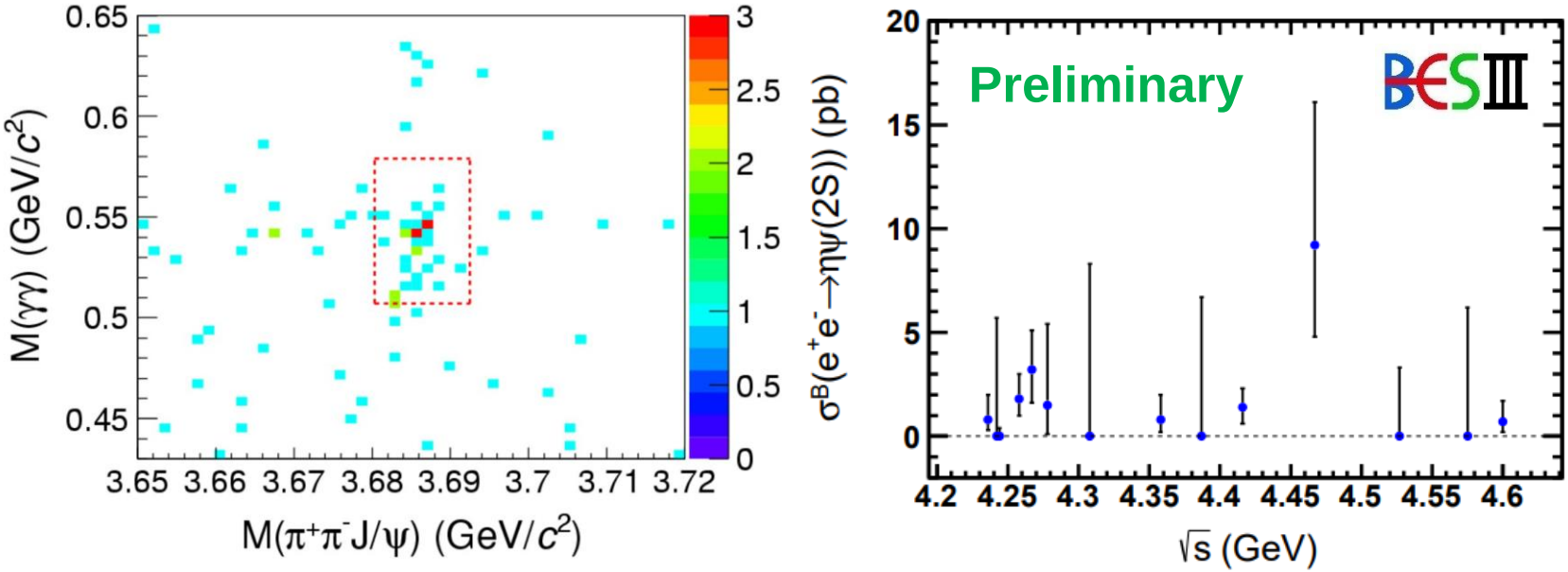
Phys. Rev. D 103, 052010(2021)



- The measured cross sections and corresponding upper limits of $e^+e^- \to \pi^+\pi^-\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi$ are given
- No significant signal has been observed, despite the hint of an slight enhancement at center-of-mass energies between 4.18 GeV and 4.26 GeV

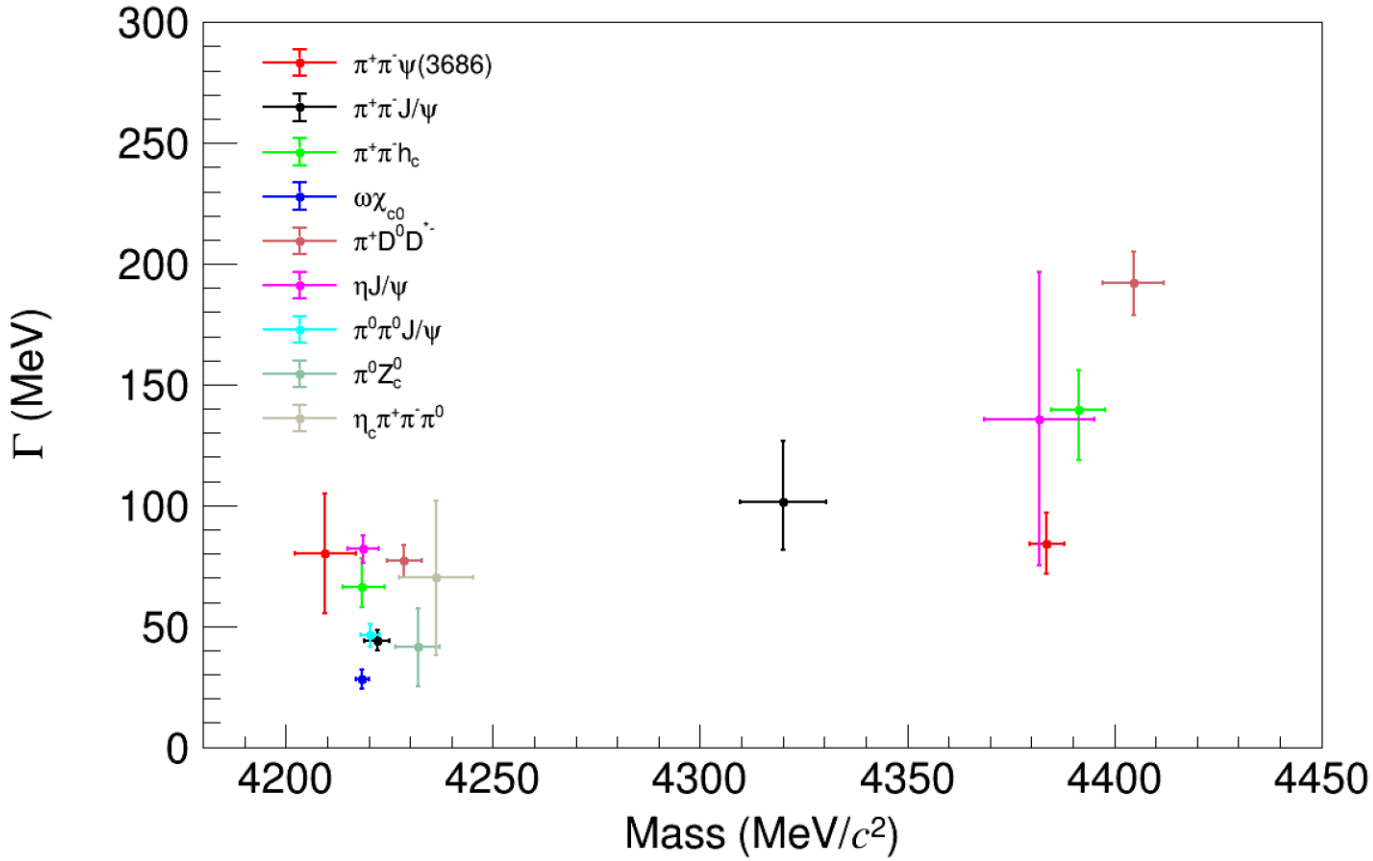
Process $e^+e^- \to \eta\,\psi(2S)$

arXiv:2103.01480



- The $e^+e^- \to \eta\,\psi(2S)$ process is observed for the first time(5σ for 14 data points)
- Impossible to extract the Y state due to limitation of statistics
- Further experimental studies with higher statistics are needed to draw a clear conclusion on the structure

Summary


300
250
200
150
100
50
0
Γ (MeV)
4200
4250
4300
4350
4400
4450
Mass (MeV/c^2)
$\pi^+\pi^-\psi(3686)$
$\pi^+\pi^-J/\psi$
$\pi^+\pi^-h_c$
$\omega\chi_{c0}$
$\pi^+D^0D^{*-}$
$\eta J/\psi$
$\pi^0\pi^0J/\psi$
$\pi^0Z_c^0$
$\eta_c\pi^+\pi^-\pi^0$

Summary

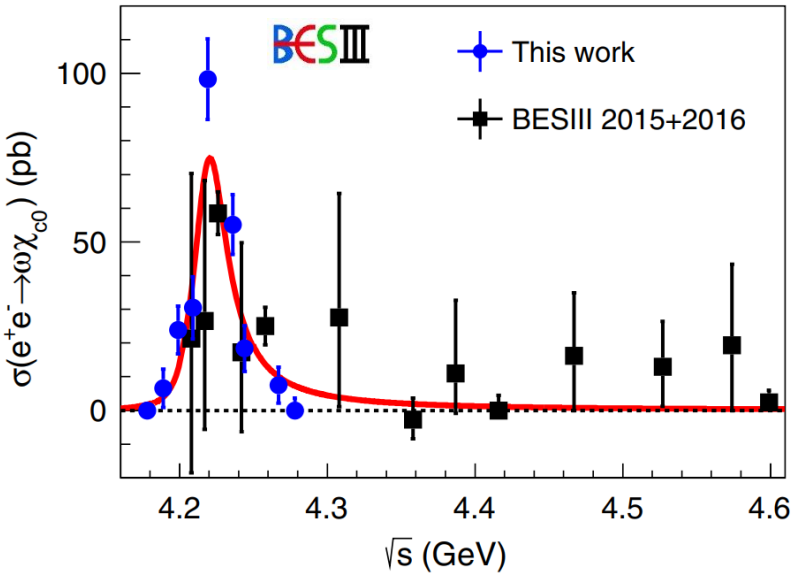
- With the data collected by BESIII, lots of progress in study Y states are made:
  - Y(4220) and Y(4320) in $e^+e^- \to \pi^{+/0}\pi^{-/0}J/\psi$
  - Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^- h_c$
  - Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^-\psi(2S)$
  - Y(4220) in $e^+e^- \to \omega\chi_{c0}$
  - Y(4220) in $e^+e^- \to \pi^+ D^0 D^{*-}$
  - Y(4390) in $e^+e^- \to \eta\, J/\psi$
  - New reactions are studied to search Y states:
    $e^+e^- \to \pi^+\pi^- D^+D^-, \pi^+\pi^- D^0D^0, \eta'\, J/\psi, \eta_c\pi^+\pi^-\pi^0,$
    $\pi^+\pi^-\chi_{cJ}, \eta\, \psi(2S),$

- More results for Y states study are coming soon

BACKUP

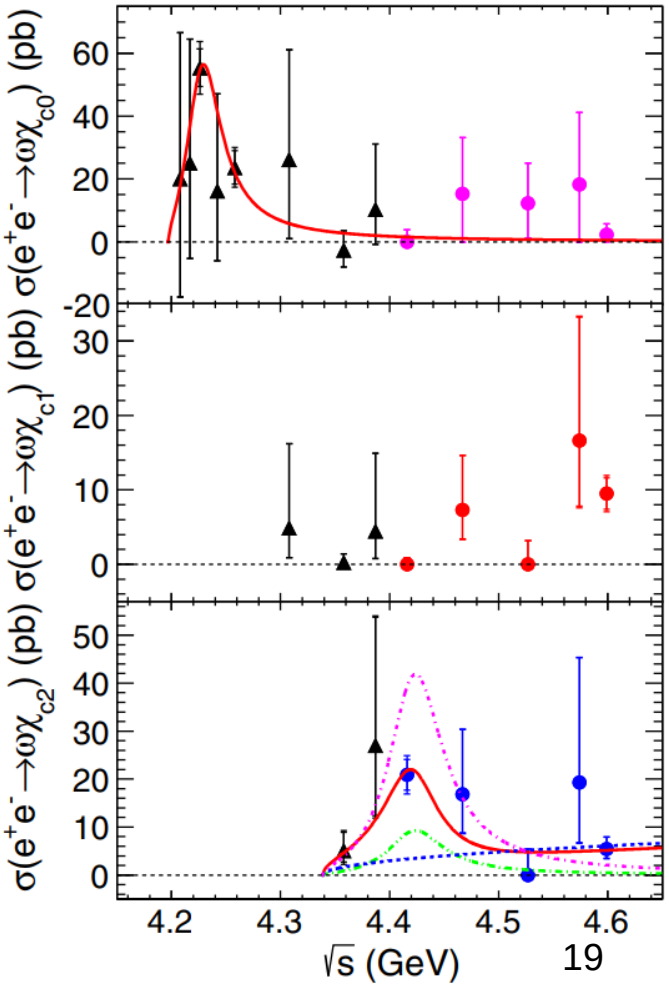
Process $e^+e^- \to \omega\chi_{cJ}$

Phys. Rev. D 99, 091103(R) (2019)



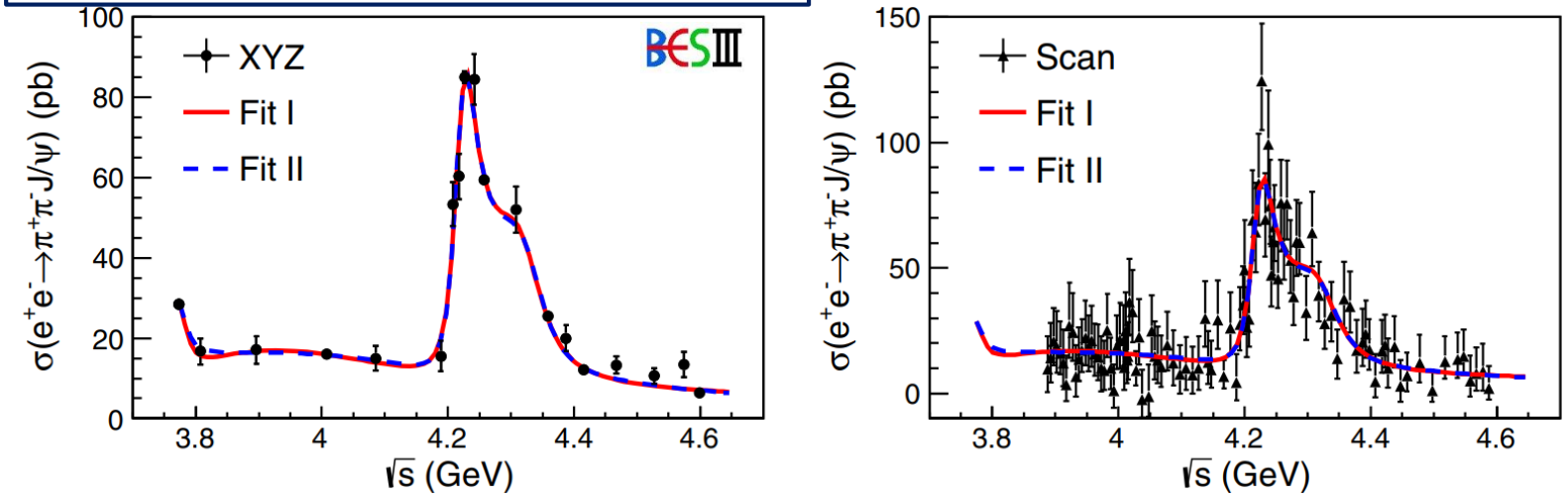
- The study of $e^+e^- \to \omega\chi_{cJ}$ (J=0,1,2)
- $\chi_{c0} \to \pi^+\pi^-/K^+K^-, \omega \to \pi^+\pi^-\pi^0$
- A resonant structures are observed in the fit to the cross section
  - $M = (4218.5 \pm 1.6 \pm 4.0)\mathrm{MeV}/c^2$, $\Gamma = (28.2 \pm 3.9 \pm 1.6)\mathrm{MeV}$
- The clear Y(4220) can be seen

Phys. Rev. Lett. 114, 092003 (2015)
Phys. Rev. D 93, 011102(R) (2016)



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

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

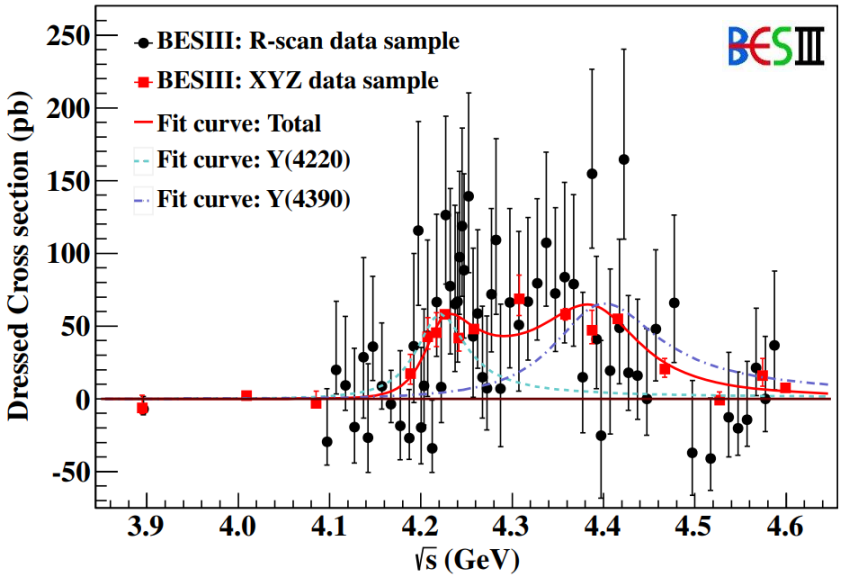


- Simultaneous fit to XYZ data(left) and R-scan data (right)
- Two resonant structures are observed in the fit to the cross section
  - $M = (4222.0 \pm 3.1 \pm 1.4)\mathrm{MeV}/c^2$, $\Gamma = (44.1 \pm 4.3 \pm 2.0)\mathrm{MeV}$
  - $M = (4320.0 \pm 10.4 \pm 7.0)\mathrm{MeV}/c^2$, $\Gamma = \left(101.4^{+25.3}_{-19.7} \pm 10.2\right)\mathrm{MeV}$
- The significance of the second resonance is 7.6σ
- The Y(4220) agrees with the Y(4260)
- The Y(4320) agrees with the Y(4360)

Y(4260) -> Y(4220) + Y(4360) ?

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

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



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

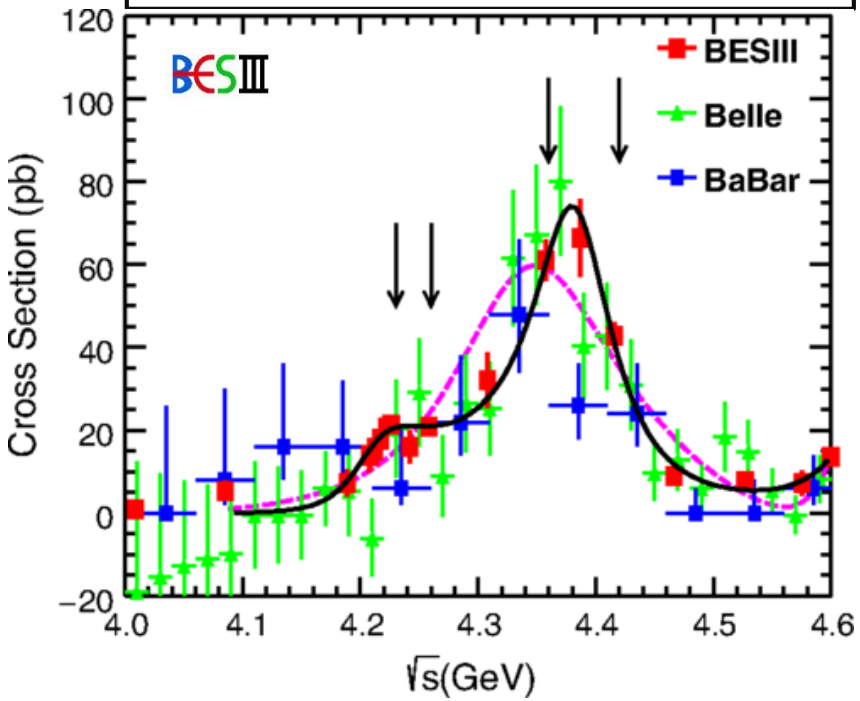
TABLE I. $e^+e^- \to \pi^+\pi^- h_c$ cross sections (or upper limits at the 90% confidence level). The third errors are from the uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$ [11].

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$n^{\rm obs}_{h_c}$	$\sigma(e^+e^- \to \pi^+\pi^- h_c)$ (pb)
3.900	52.8	<2.3	<8.3
4.009	482.0	<13	<5.0
4.090	51.0	<6.0	<13
4.190	43.0	8.8 ± 4.9	$17.7 \pm 9.8 \pm 1.6 \pm 2.8$
4.210	54.7	21.7 ± 5.9	$34.8 \pm 9.5 \pm 3.2 \pm 5.5$
4.220	54.6	26.6 ± 6.8	$41.9 \pm 10.7 \pm 3.8 \pm 6.6$
4.230	1090.0	646 ± 33	$50.2 \pm 2.7 \pm 4.6 \pm 7.9$
4.245	56.0	22.6 ± 7.1	$32.7 \pm 10.3 \pm 3.0 \pm 5.1$
4.260	826.8	416 ± 28	$41.0 \pm 2.8 \pm 3.7 \pm 6.4$
4.310	44.9	34.6 ± 7.2	$61.9 \pm 12.9 \pm 5.6 \pm 9.7$
4.360	544.5	357 ± 25	$52.3 \pm 3.7 \pm 4.8 \pm 8.2$
4.390	55.1	30.0 ± 7.8	$41.8 \pm 10.8 \pm 3.8 \pm 6.6$
4.420	44.7	29.1 ± 7.3	$49.4 \pm 12.4 \pm 4.5 \pm 7.6$

- h_c is reconstructed by $h_c \to \gamma\eta_c$, η_c is reconstructed by 16 exclusive hadronic final states
- The cross sections are found to be of the same order of magnitude as those of $e^+e^- \to \pi^+\pi^- J/\psi$
- Two resonant structures are observed in the fit to the cross section
  - $M = \left(4218.4^{+5.5}_{-4.5} \pm 0.9\right)\mathrm{MeV}/c^2, \Gamma = \left(66.0^{+12.3}_{-8.3} \pm 0.4\right)\mathrm{MeV}$
  - $M = \left(4391.5^{+6.3}_{-6.8} \pm 1.0\right)\mathrm{MeV}/c^2, \Gamma = \left(139.5^{+16.2}_{-20.6} \pm 0.6\right)\mathrm{MeV}$
- The Y(4220) here is consistent with state in $\pi^+\pi^- J/\psi$
- The Y(4390) is different from Y(4360) and $\psi(4415)$

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

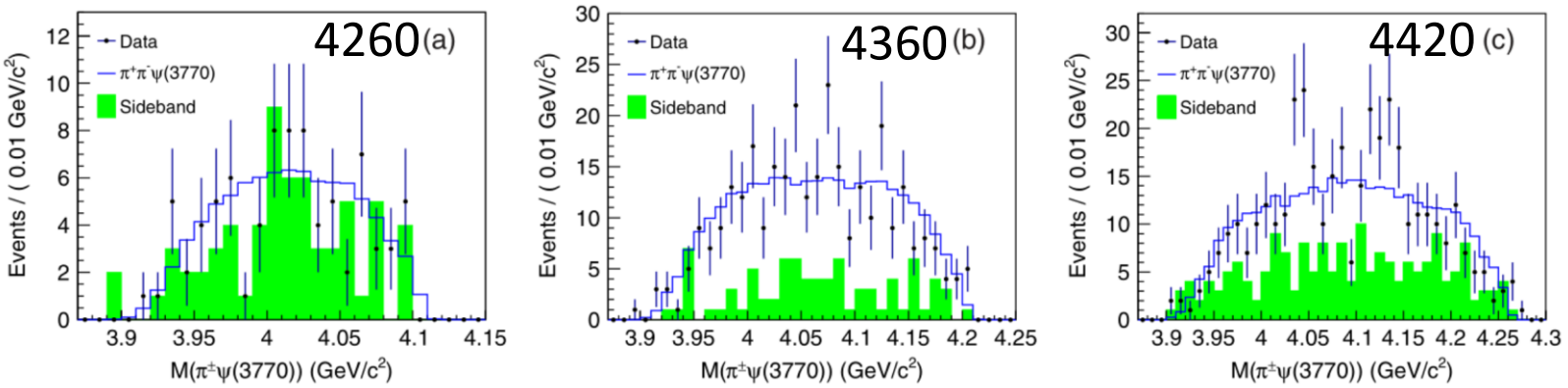
Phys. Rev. D 96, 032004 (2017)



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)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

- The fit to the cross section shows contributions from two structures, Y(4220)+Y(4390)
- The Y(4360) observed by Belle and BaBar consists of two structure.

Process $e^+e^- \to \pi^+\pi^- D^+ D^- \& \pi^+\pi^- D^0 \bar{D}^0$



- The $\pi^\pm\psi(3770)$ invariant mass distribution