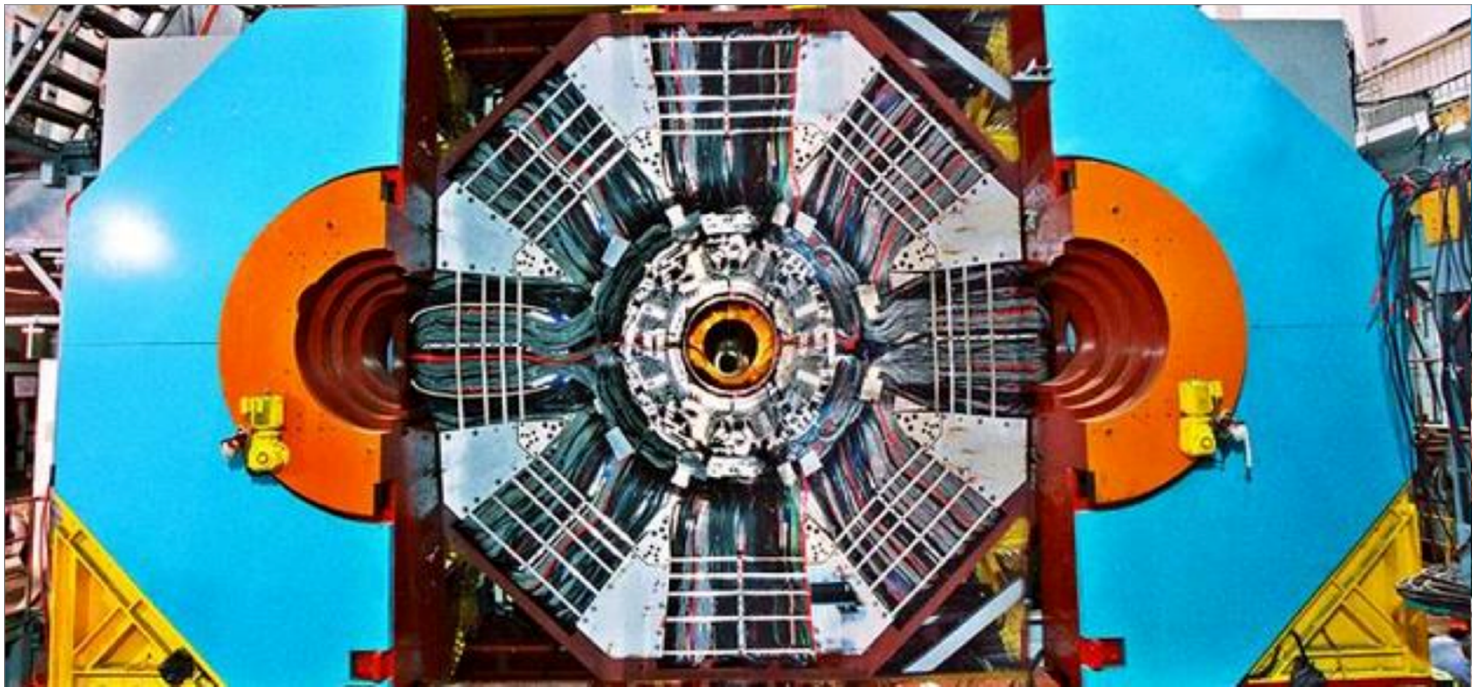


Recent results on the Y states

Xiao-Rui Lyu (吕晓睿)
中国科学院大学
(On behalf of the BESIII collaboration)

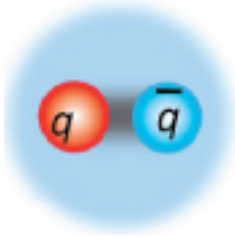
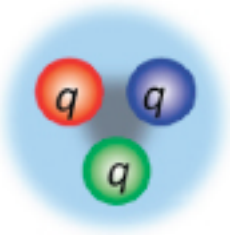
Outline

- Introduction
- Status of BESIII
- The Y states
- Prospects
- Summary

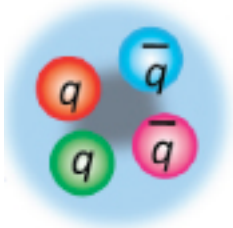
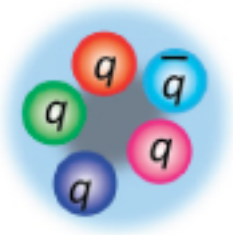
New forms of hadrons

- **Conventional hadrons consist of 2 or 3 quarks：**

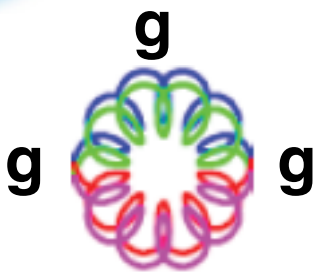
  Naive Quark Model：

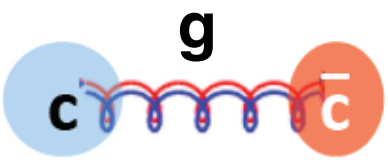
  meson   baryon

- **QCD predicts the new forms of hadrons:**
  - **Multi-quark states： Number of quarks >＝ 4**

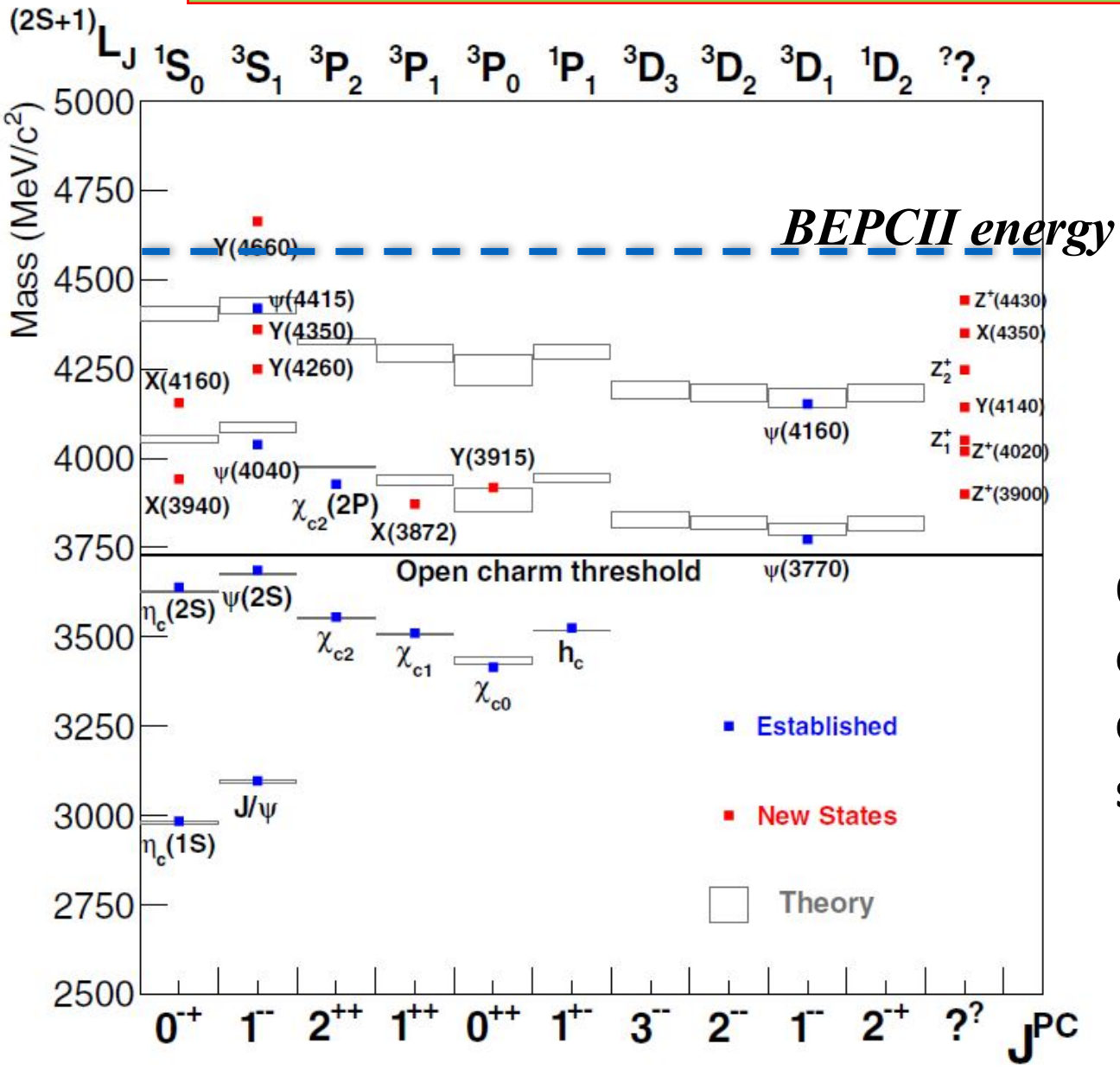
  - **Hybrids： $q\bar{q}g$， $qqqg$ …**
  - **Glueballs： gg， ggg …**

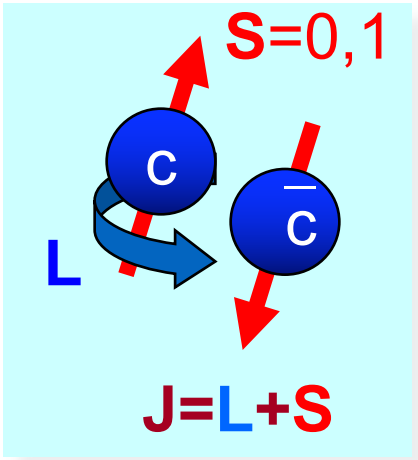




None of the new forms of hadrons is settled !

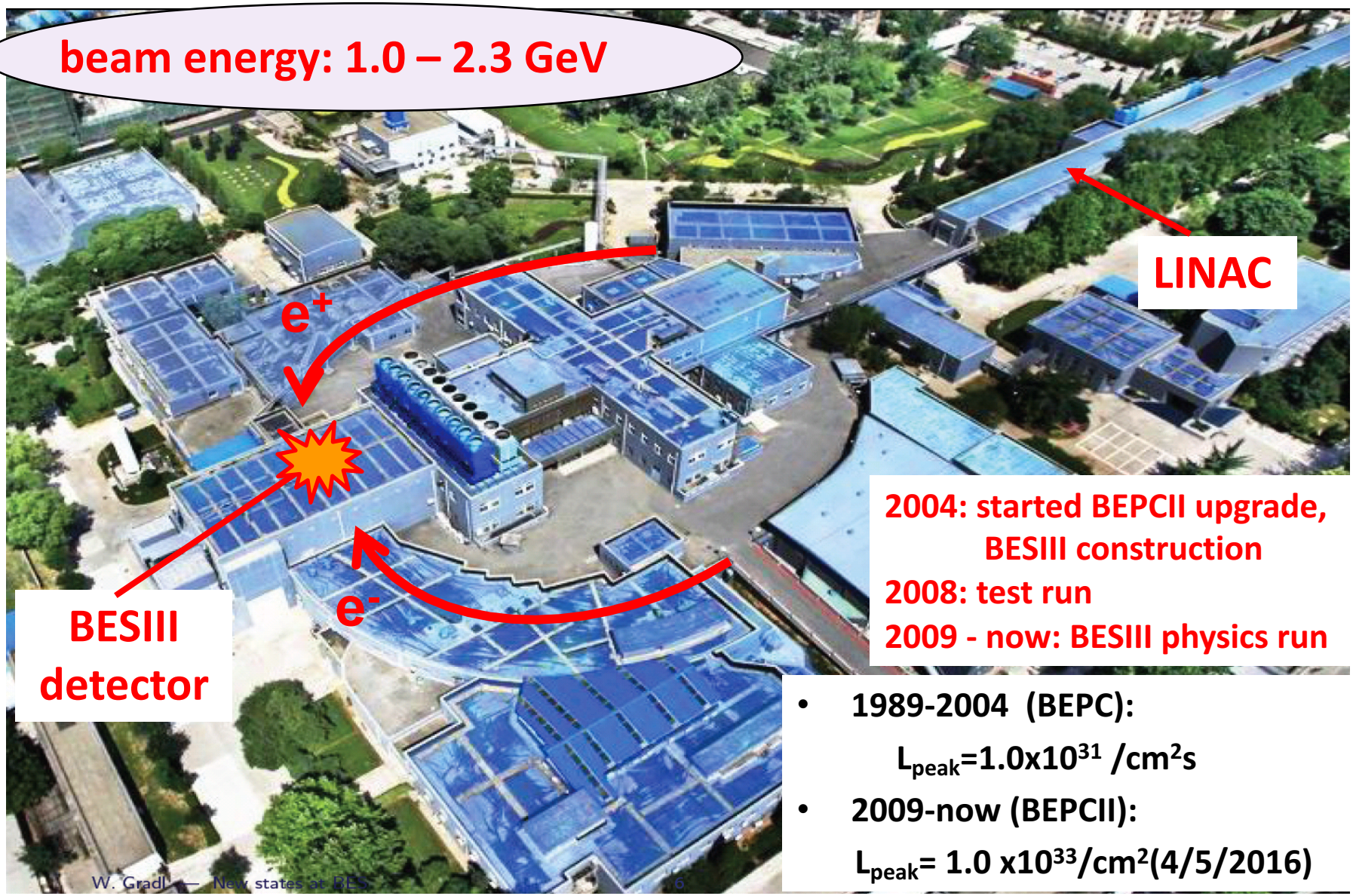
Charmonium Spectrum





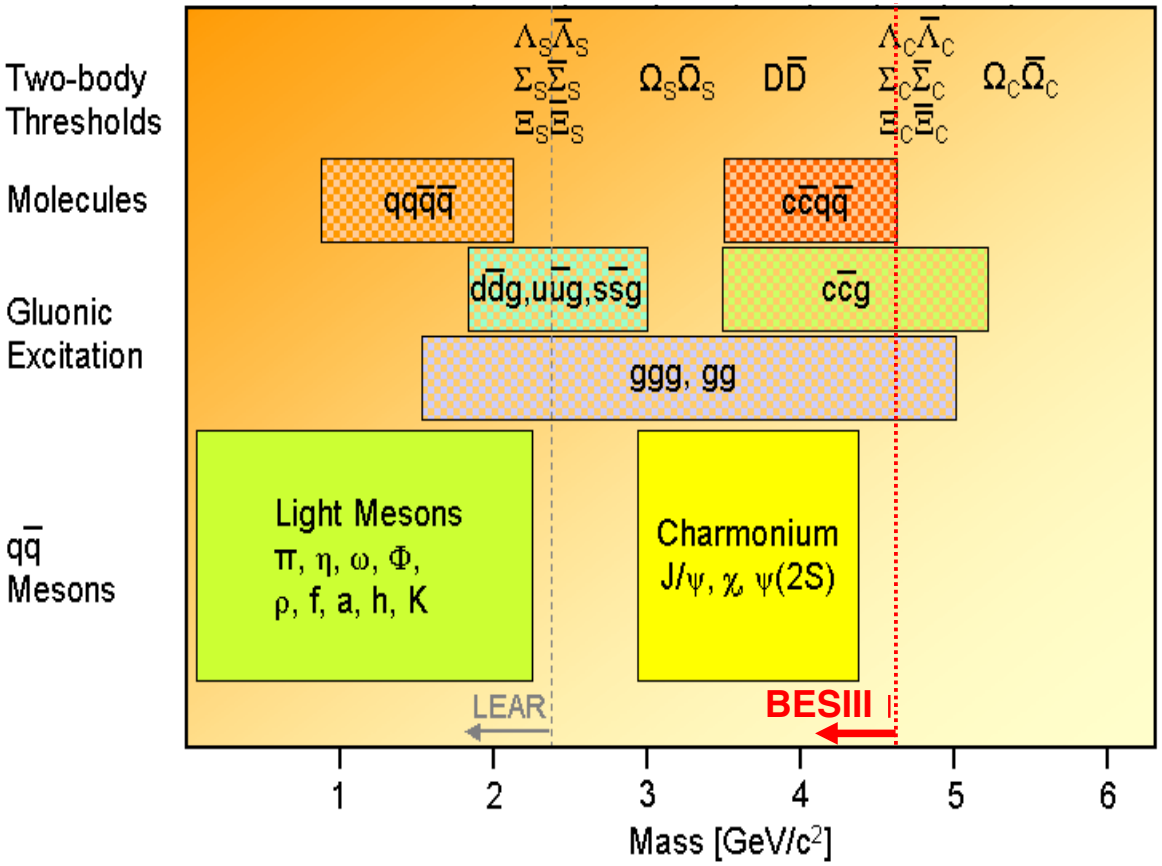
Overpopulated observed new charmonium-like states, i.e. "XYZ".

Beijing Electron Positron Collider (BEPC)



- 1989-2004 (BEPC):
  $L_{peak}=1.0x10^{31}$ /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

Hadron Landscape



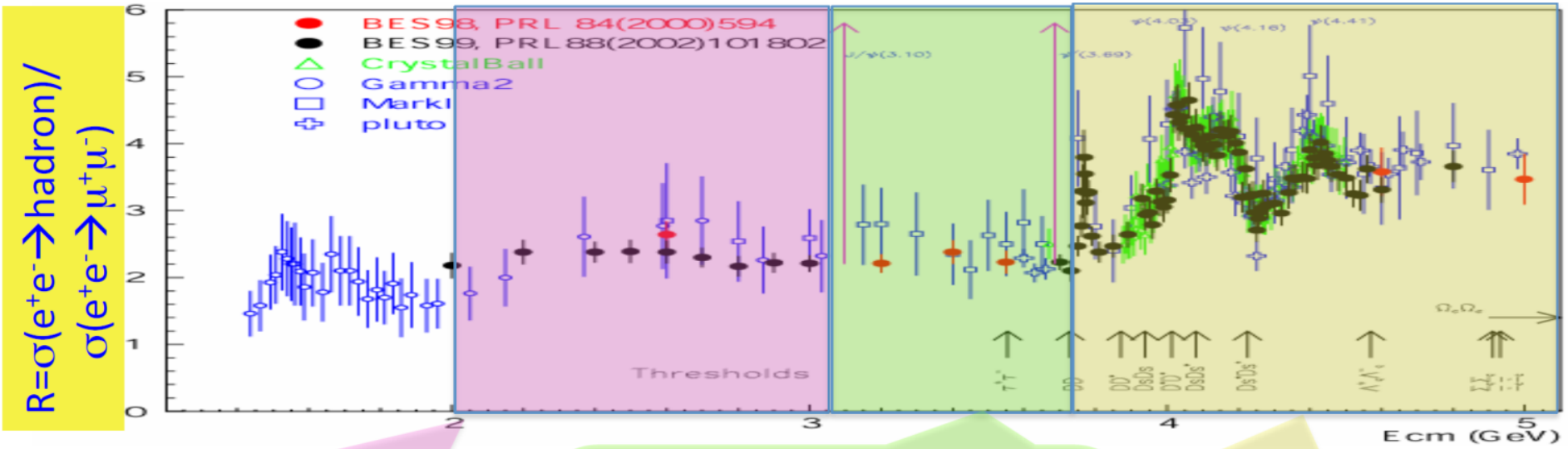
Hadron-physics challenges:

- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter)
- Heavy hadrons: direct production, radiative and hadronic transitions

Physics at tau-charm Energy Region

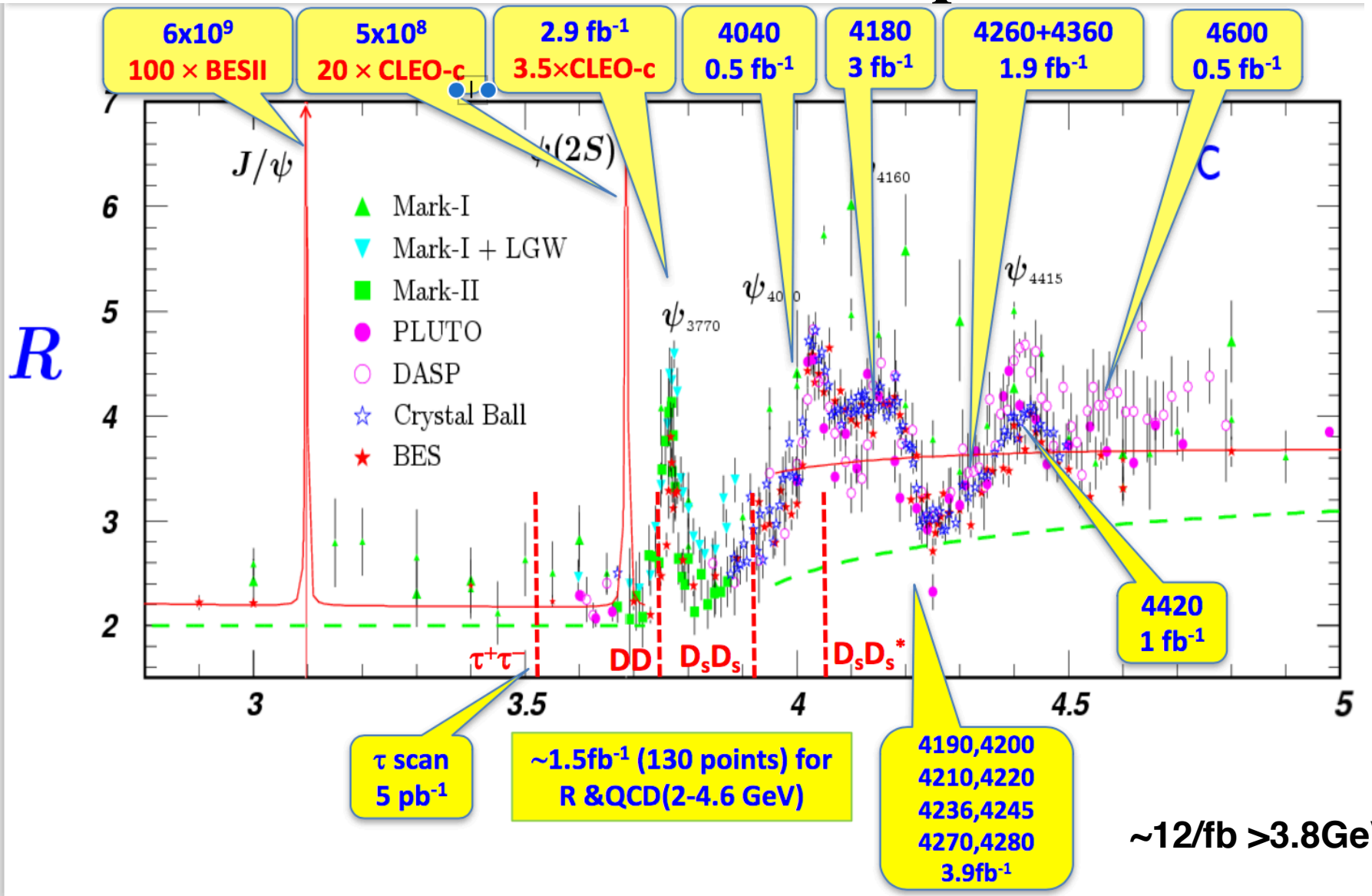


- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

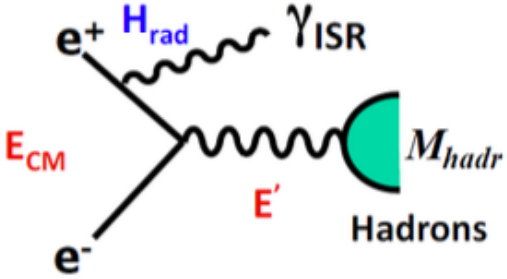
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-$\bar{D}_0$ mixing
- Charm baryons

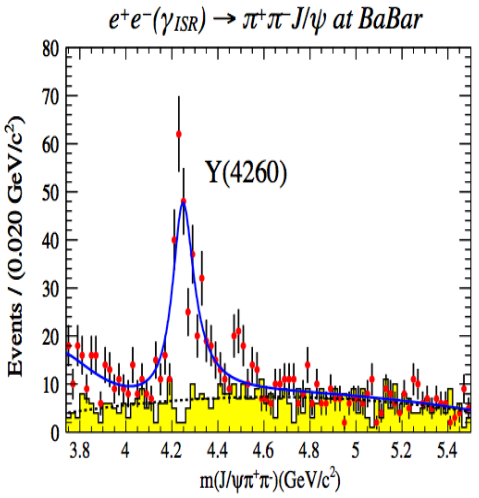
BESIII data samples



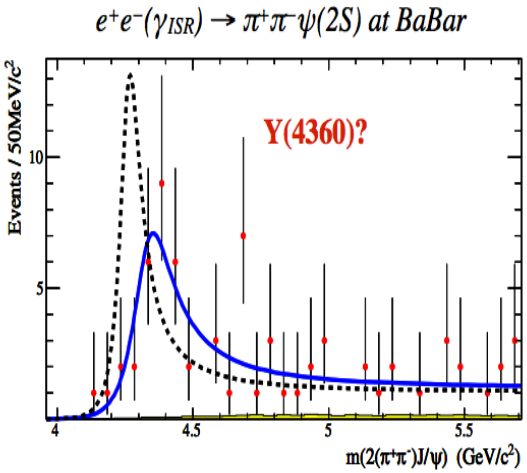
The Y states



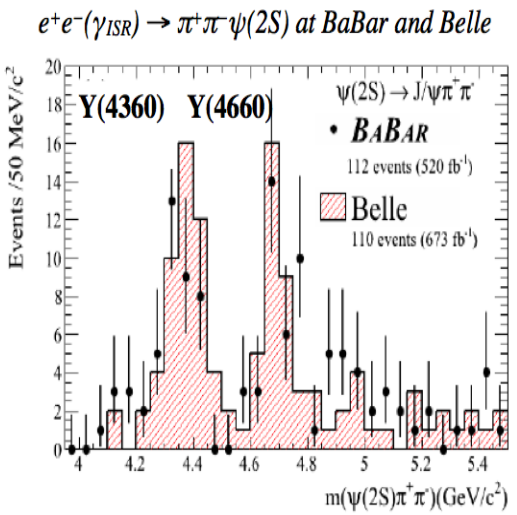
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e+e- annihilation or initial state radiation (ISR).



PRD 86, 051102(R) (2012)



PRL 98, 212001 (2007)



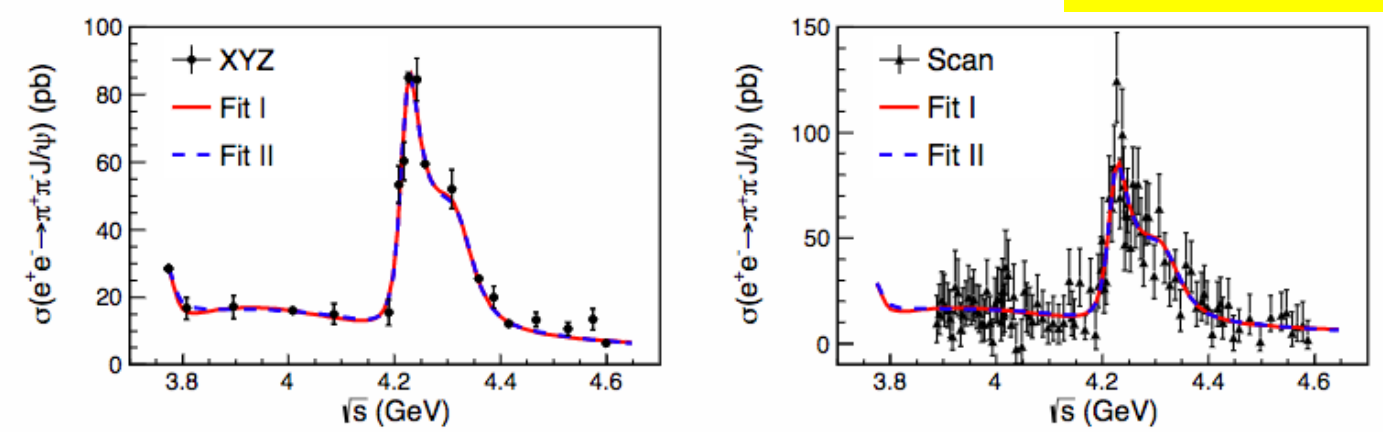
arXiv:1211.6271 and CHARM 2012

Cross sections of $e^+e^-\to\pi^+\pi^- J/\psi$

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)

Inconsistent with a single BW of Y(4260)

PRL118, 092001 (2017)



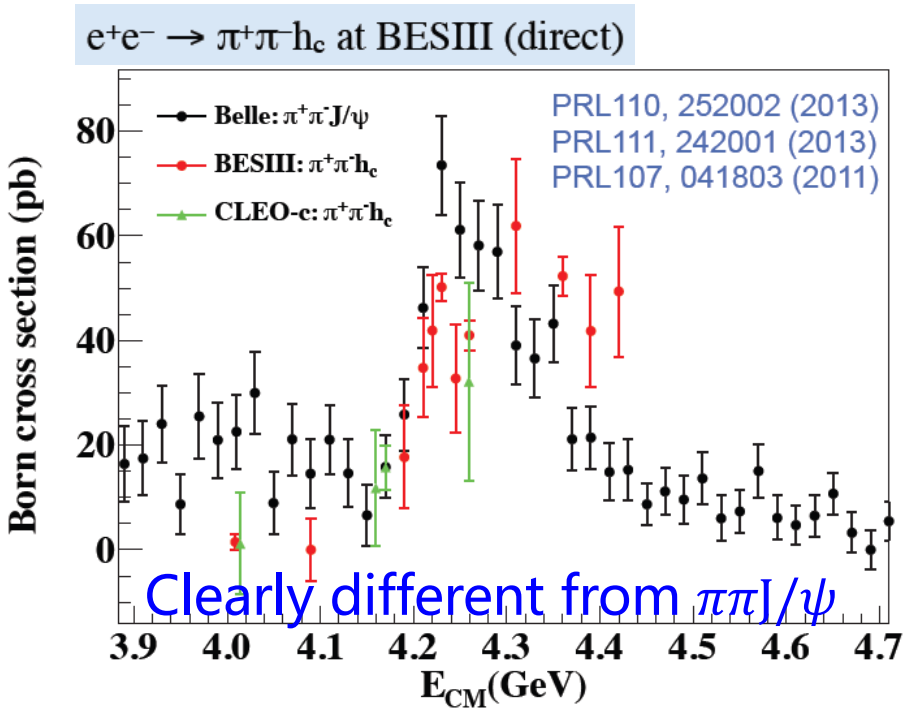
Parameters	Fit result
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$ $(\cdots)$
$\Gamma_{\rm tot}(R_1)$	$476.9^{+78.4}_{-64.8}$ $(\cdots)$
$M(R_2)$	4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma_{\rm tot}(R_2)$	44.1 ± 4.3 (44.1 ± 3.8)
$M(R_3)$	4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma_{\rm tot}(R_3)$	$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$

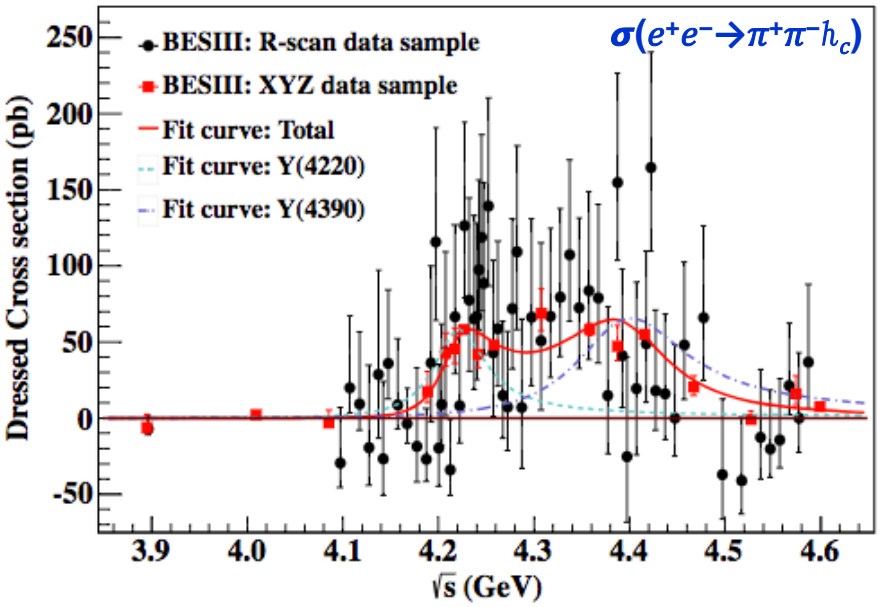
Structure at 4260 is not a simple BW, but rather two:

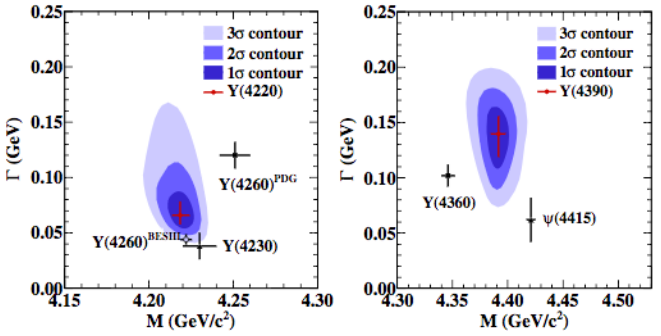
- Significance > 7.6σ
- R_2: consistent with the Y(4260), however narrower
- R_3: comparable to the Y(4360)

Cross sections of $e^+e^-\to\pi^+\pi^- h_c$

PRL118, 092002 (2017)

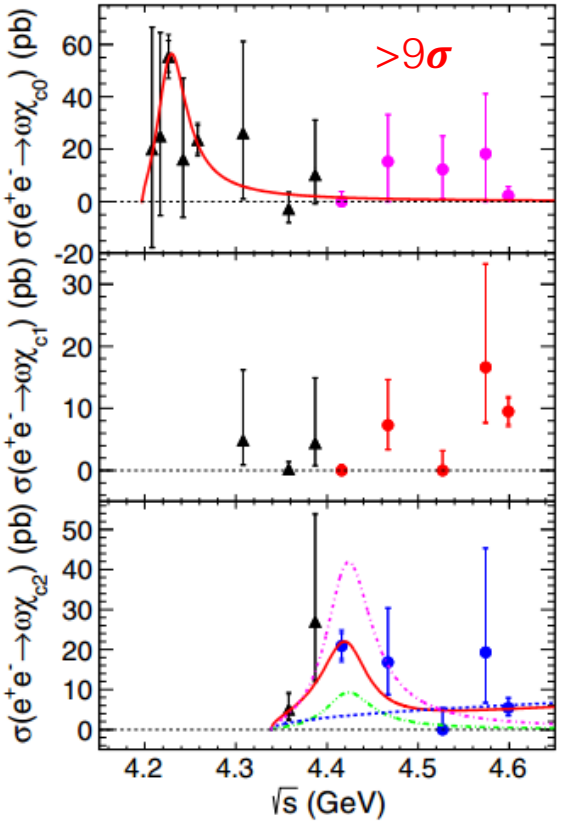






- h_c reconstructed in $h_c \to \gamma\eta_c$, $\eta_c \to$ 16 exclusive hadronic final states
- Coherent sum of two BWs
  - $M_1 = (4218.4^{+5.5}_{-4.5} \pm 0.9)$ MeV, $\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 0.4)$ MeV
    $M_2 = (4391.5^{+6.3}_{-6.8} \pm 1.0)$ MeV, $\Gamma_2 = (139.5^{+16.2}_{-20.6} \pm 0.6)$ MeV
- First one has consistent mass with $\pi^+\pi^- J/\psi$ state at 4222 MeV
- Significance of double BW vs. single BW is 10 σ

Cross sections of $e^+e^- \to \omega/\phi\chi_{cJ}$ (J=0,1,2)



The triangle black data points are from

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

Other data points are from

Phys. Rev. D 93, 011102 (2016)

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

Fit with a single BW

Mass = $4226 \pm 8 \pm 6$ MeV

Width = $39 \pm 12 \pm 2$ MeV

Significance $> 9\sigma$

$e^+e^- \to \omega\chi_{c2}$:

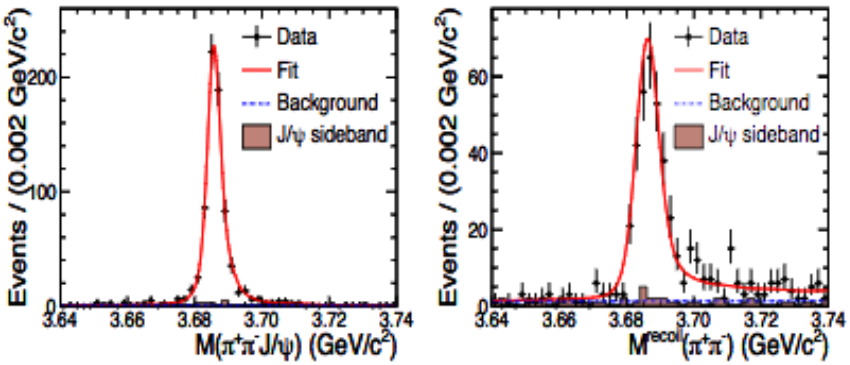
Agree with from $\psi(4415)$ with BR=$(1.4 \pm 0.5) \times 10^{-3}$ (sol. I), or BR=$(6 \pm 1) \times 10^{-3}$ (sol. II)

While BESIII measures $e^+e^- \to \phi\chi_{cJ}$ at 4.6GeV *PRD97, 032008 (2018)*

- $\sigma\,(e^+e^- \to \phi\chi_{c0}) < 5.4$ pb
- $\sigma\,(e^+e^- \to \phi\chi_{c1}) < (4.2^{+1.7}_{-1.0} \pm 0.3)$ pb
- $\sigma\,(e^+e^- \to \phi\chi_{c2}) < (6.7^{+3.4}_{-1.7} \pm 0.5)$ pb

Need data beyond 4.6 GeV to check structure in $\omega\chi_{c1}$ and $\phi\chi_{cJ}$

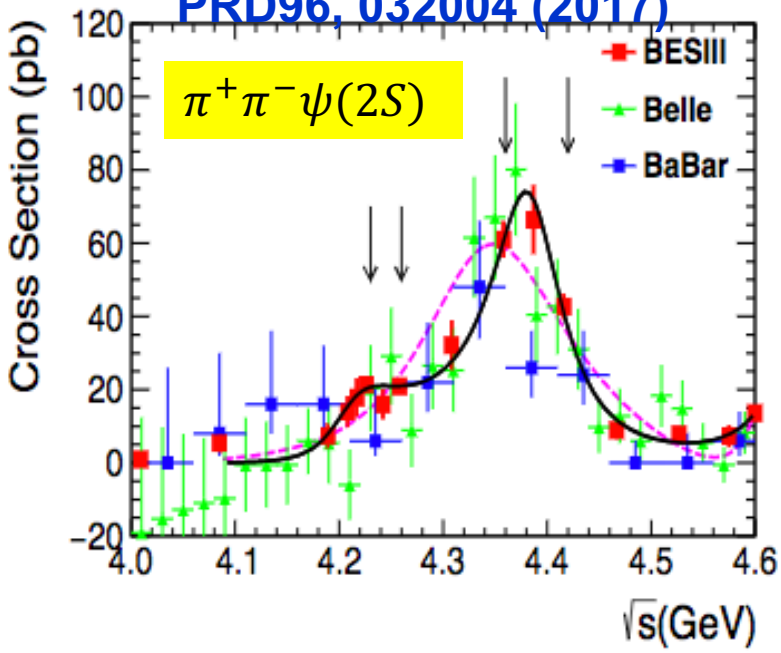
Cross sections of $e^+e^-\to\pi\pi\psi(2S)$



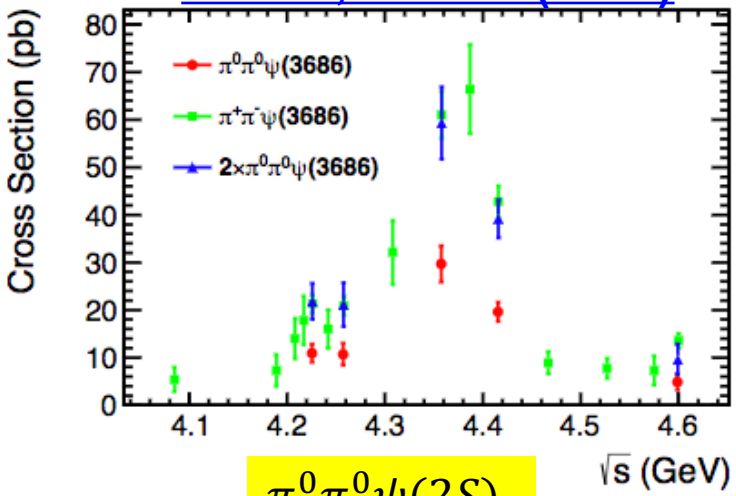
Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

- Confirm the lineshape of the Y(4360)
- Y(4220) and Y(4390) are confirmed

PRD96, 032004 (2017)



PRD97, 052001 (2018)

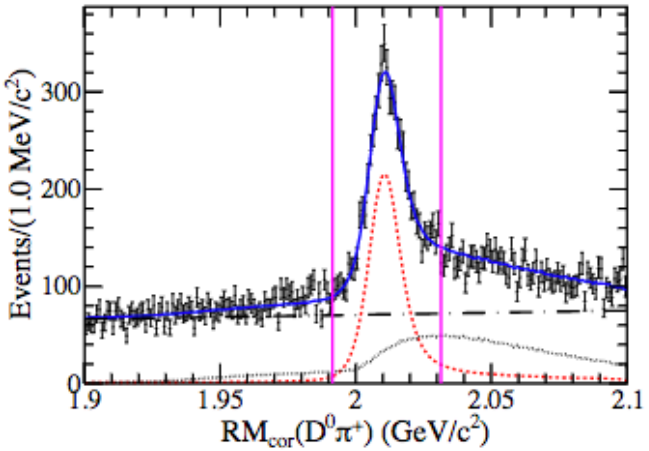


$\pi^0\pi^0\psi(2S)$

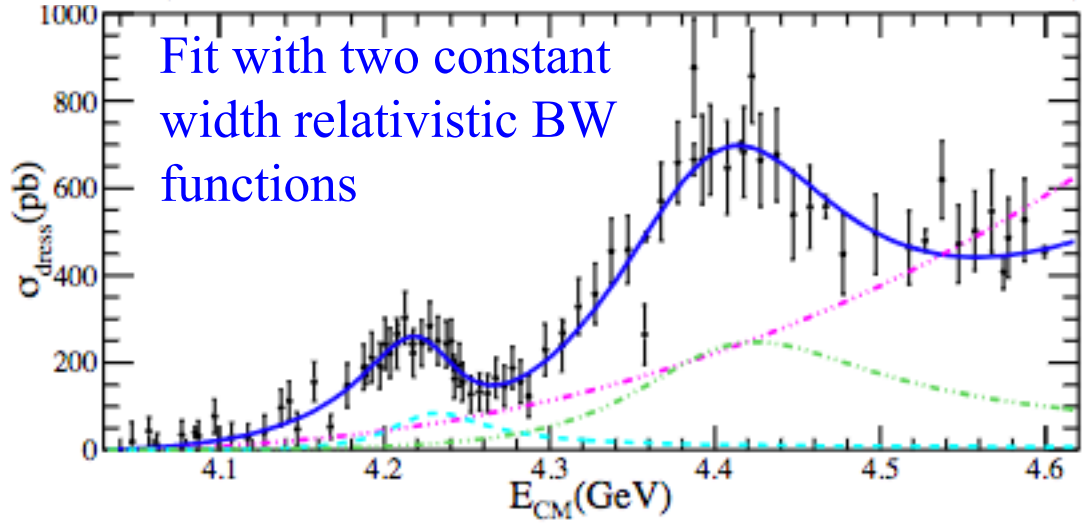
$e^+e^- \to \pi^+ D^0 D^{*-}$ cross section

arXiv:1808.02847

- Detect $D^0 \to K^-\pi^+$ and bachelor π^+, and reconstruct D^{*-} in the missing mass spectrum



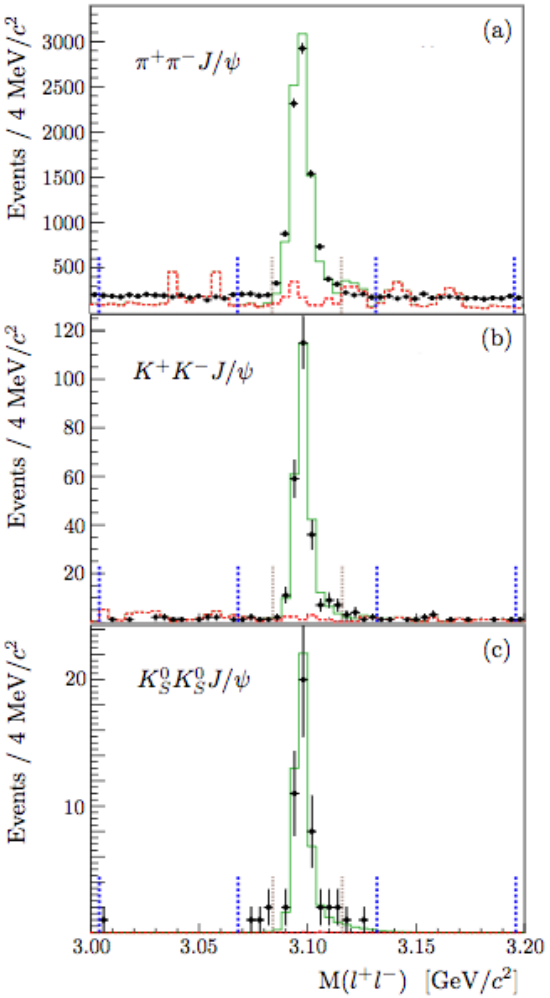
$$\sigma_{\rm dress}(m) = \left| c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m) \sqrt{P(m)/P(M_1)} + e^{i\phi_2} B_2(m) \sqrt{P(m)/P(M_2)} \right|^2$$

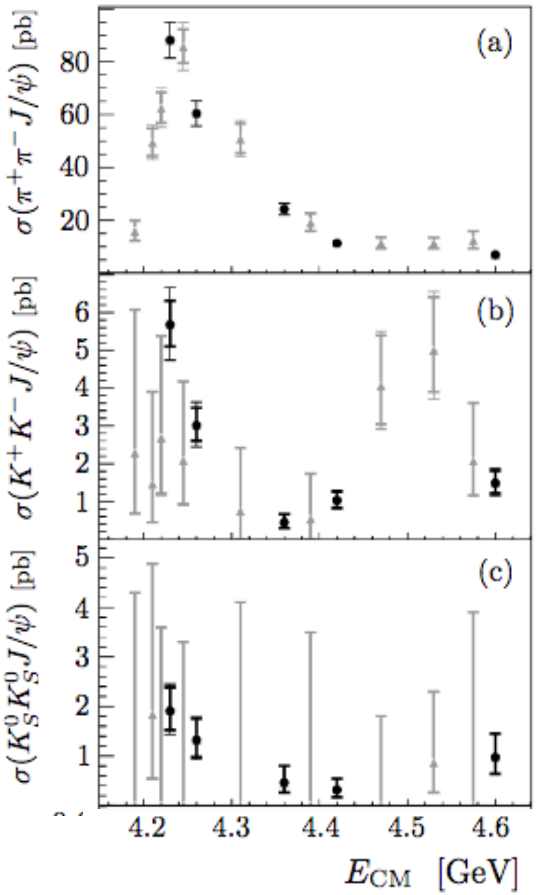


- Two enhancements are evident
- Many ψ and Y states are adopted to fit the bumps
- The lower bump consistently corresponds to the Y(4220)
  $M = (4228.6 \pm 4.1 \pm 5.9)$ MeV
  $\Gamma = (77.1 \pm 6.8 \pm 6.9)$ MeV
- The higher bump around 4.4GeV can not be described by either single resonance of the Y(4260), Y(4320), Y(4360) or $\psi(4415)$. Further more data set is required to better understand this.

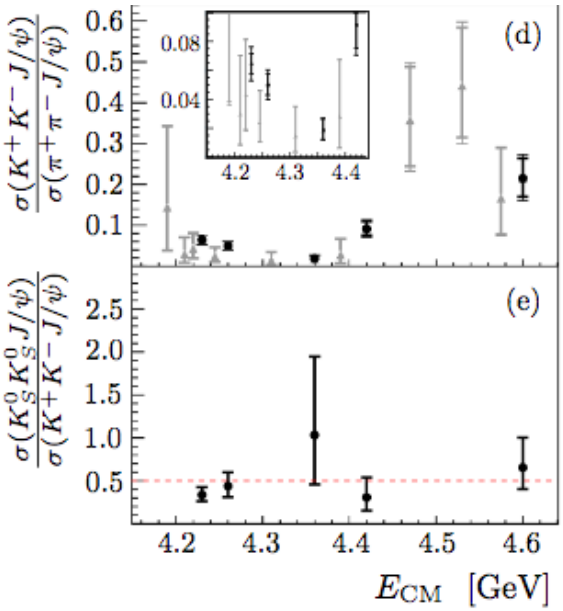
First observation of the Y(4260) decays to open charm states

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



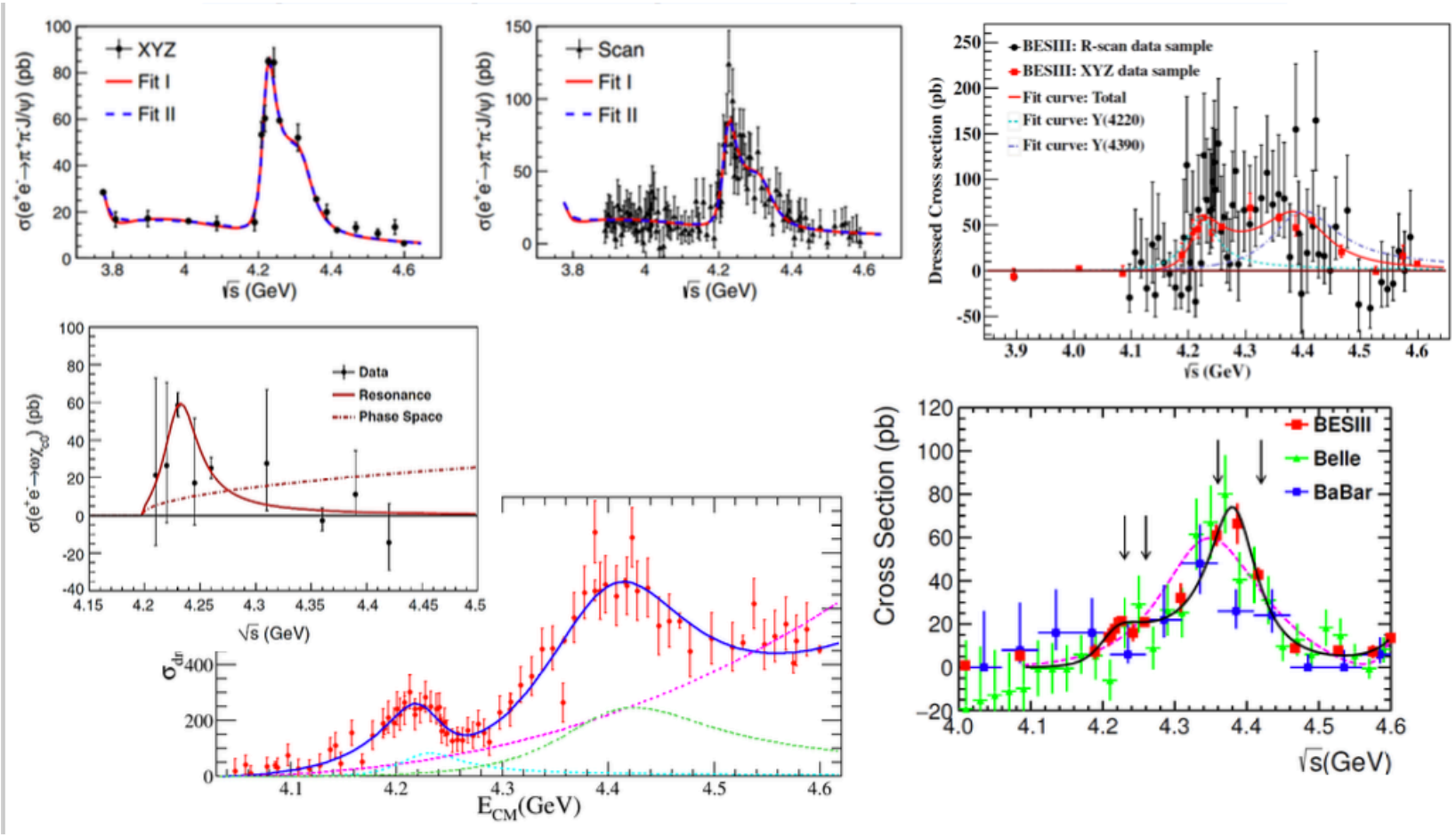


[PRD 97, 071101 (2018)]



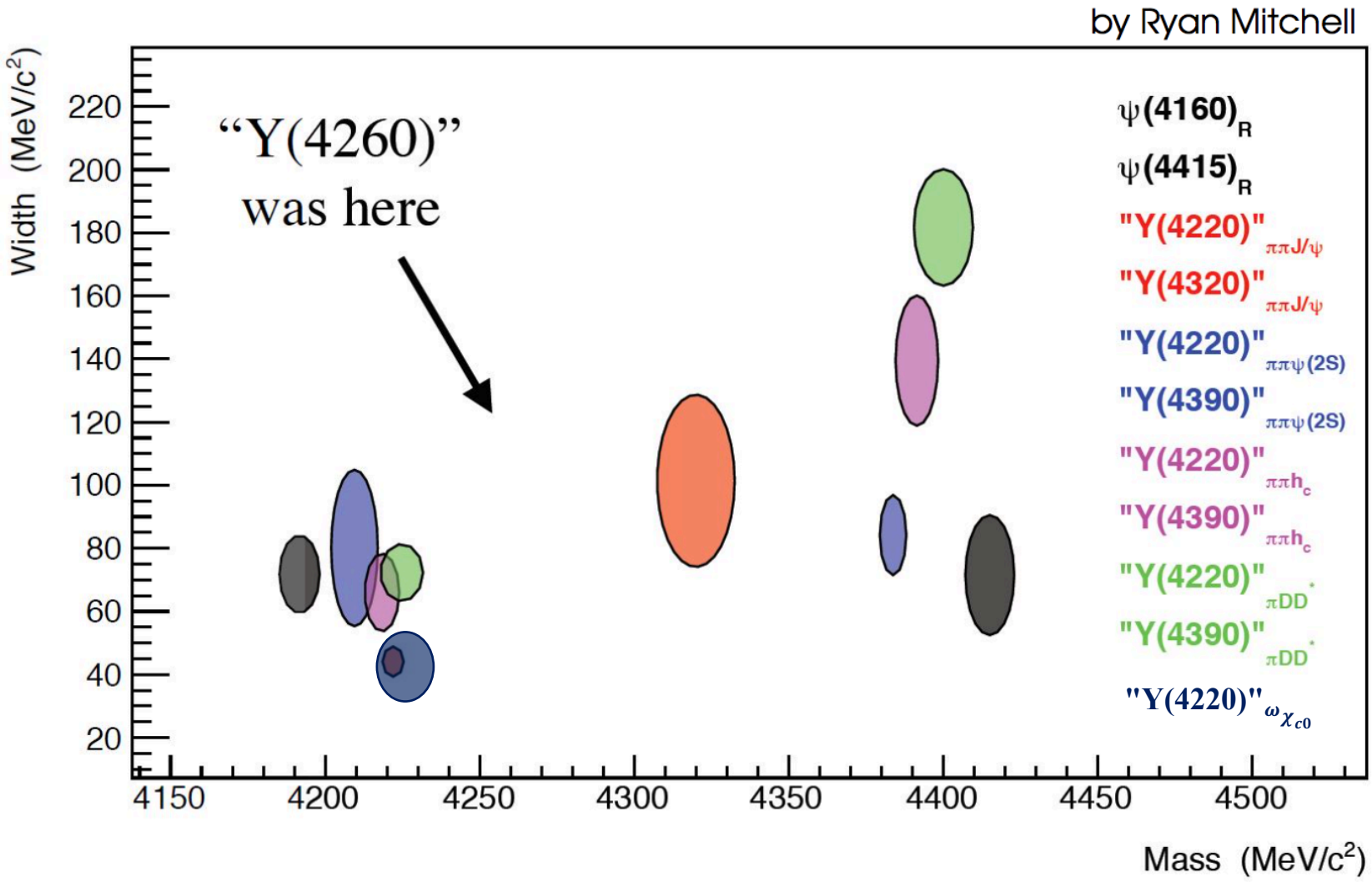
- $\sigma\,(KKJ/\psi)$ lineshape is quite different from $\sigma\,(\pi^+\pi^- J/\psi)$ around Y(4220)/Y(4260)
- Higher bump around 4.5GeV is clear and need further investigation

Y(4260) ➔ Y(4220)



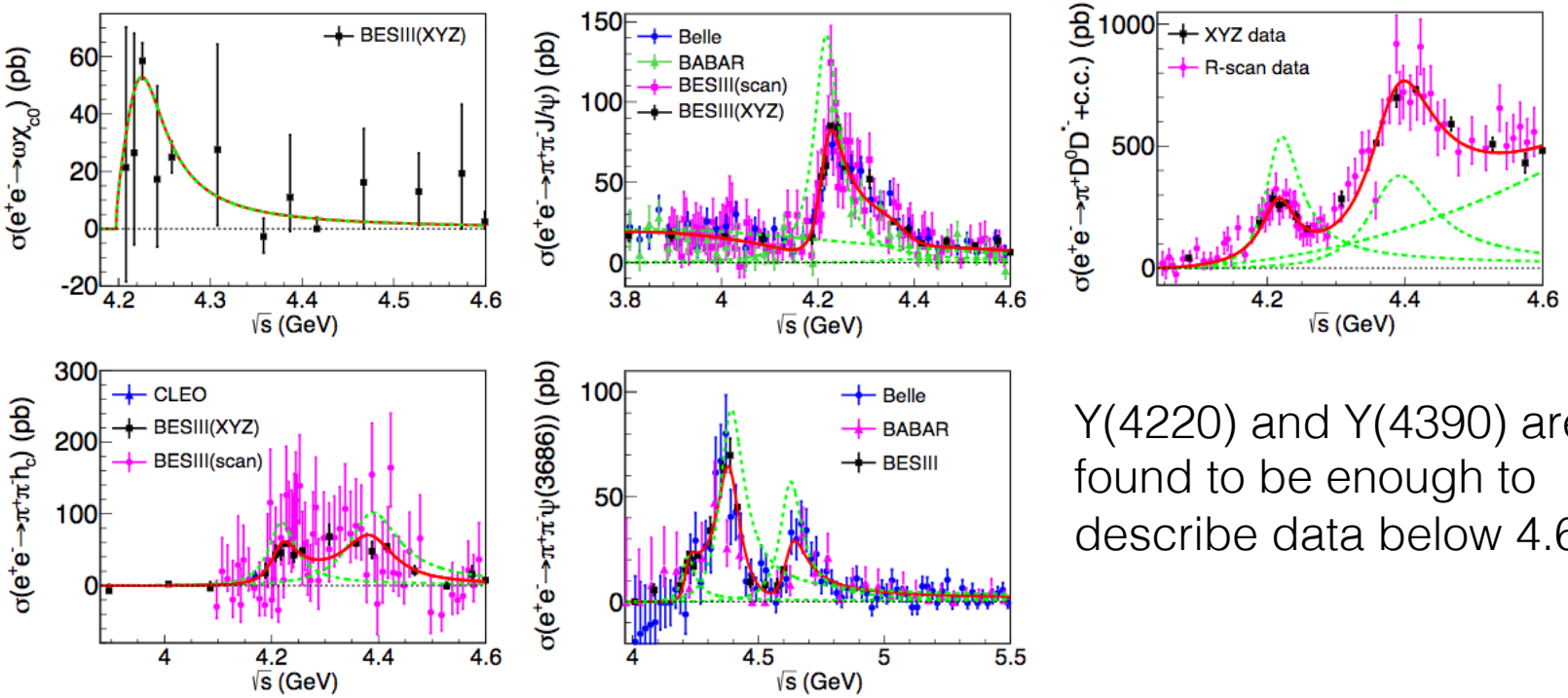
Mass~4220 MeV, Width~ 60 MeV!

Y(4220) and the new Y's



A combined fit

J. L. Zhang et al., arXiv:1805.03565



Y(4220) and Y(4390) are found to be enough to describe data below 4.6 GeV

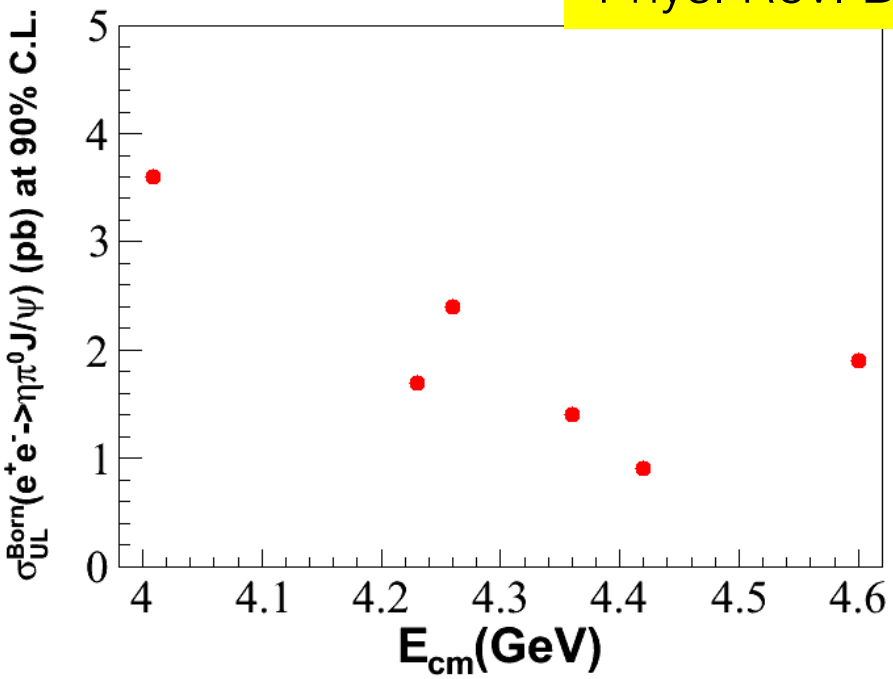
Parameter	$Y(4220)$	$Y(4390)$	$Y(4660)$
M (MeV/c^2)	$4216.5 \pm 1.4 \pm 3.2$	$4383.5 \pm 1.9 \pm 6.0$	$4623.4 \pm 10.5 \pm 16.1$
Γ (MeV)	$61.1 \pm 2.3 \pm 3.1$	$114.5 \pm 5.4 \pm 9.9$	$106.1 \pm 16.2 \pm 17.5$

Y(4220) appears in $\omega\chi_{c0}$, $\pi^+\pi^- J/\mathrm{psi}$, $\pi^+\pi^-\psi'$, $\pi^+\pi^- h_c$, $D^0 D^{*-}\pi^+$ modes

$\Gamma_{ee}^{Y(4220)} > (36.4 \pm 2.0 \pm 4.2)$ eV $\Gamma_{ee}^{Y(4390)} > (123.8 \pm 6.5 \pm 9.0)$ eV

Search for the isospin violating decay $Y(4260) \rightarrow J/\psi\eta\pi^0$

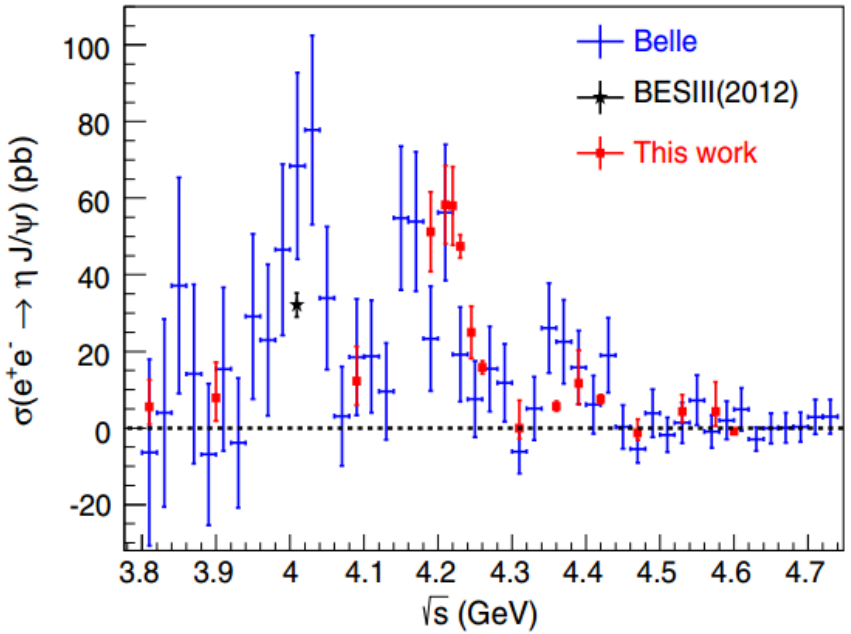
Phys. Rev. D 92, 012008 (2015)



- Considerable decay width expected in hadro-charmonium model and tetraquark model of Y(4260) [PRD 86 034013, PRD 87 111102]
- Measured upper limit is well above the prediction of D_1D molecule model (0.05 pb at 4.260 GeV) [PRD 89, 054038]

Cross sections of $e^+e^-\rightarrow\eta/\eta'J/\psi$

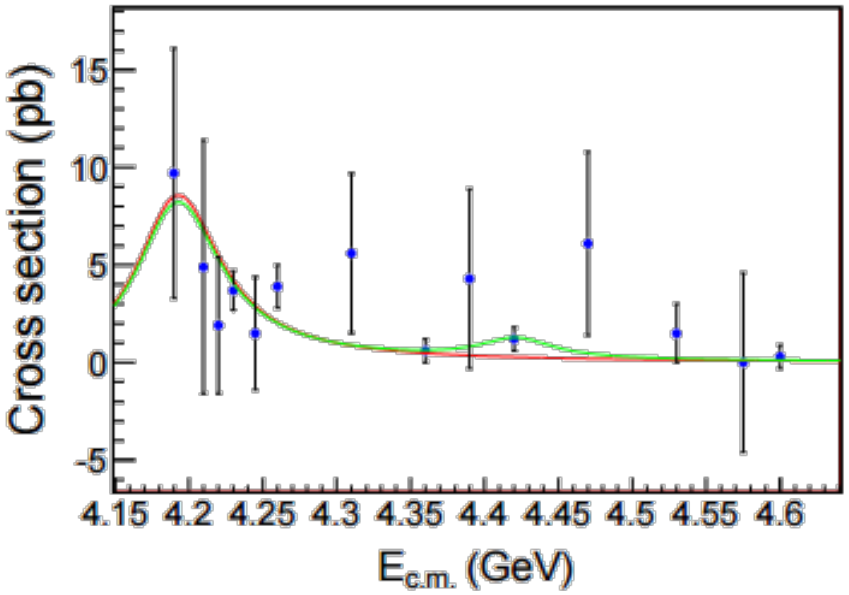
$\boldsymbol{\sigma}(e^+e^-\rightarrow \eta J/\psi)$



Phys. Rev. D 91, 112005 (2015)

- Agree with previous results with improved precision
- Structure around 4.2GeV possible from $\psi(4160)\rightarrow\eta\, J/\psi$?

$\boldsymbol{\sigma}(e^+e^-\rightarrow \eta' J/\psi)$



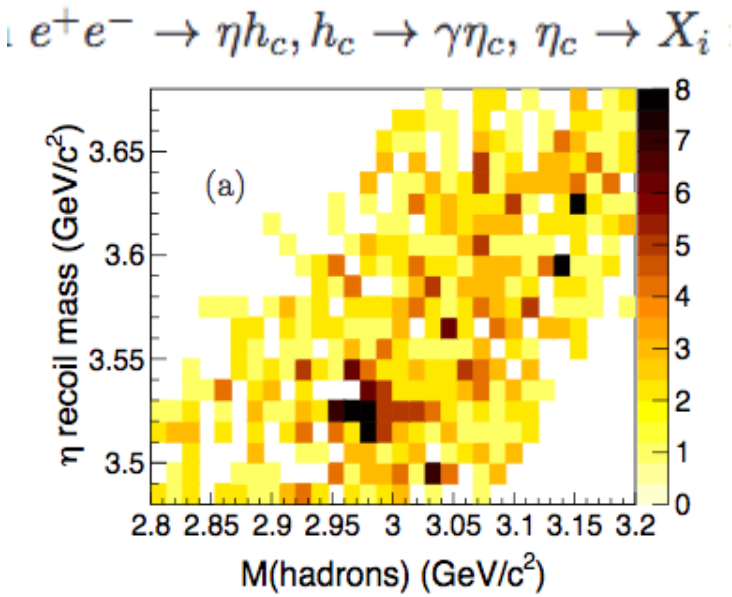
Phys. Rev. D 94, 032009 (2016)

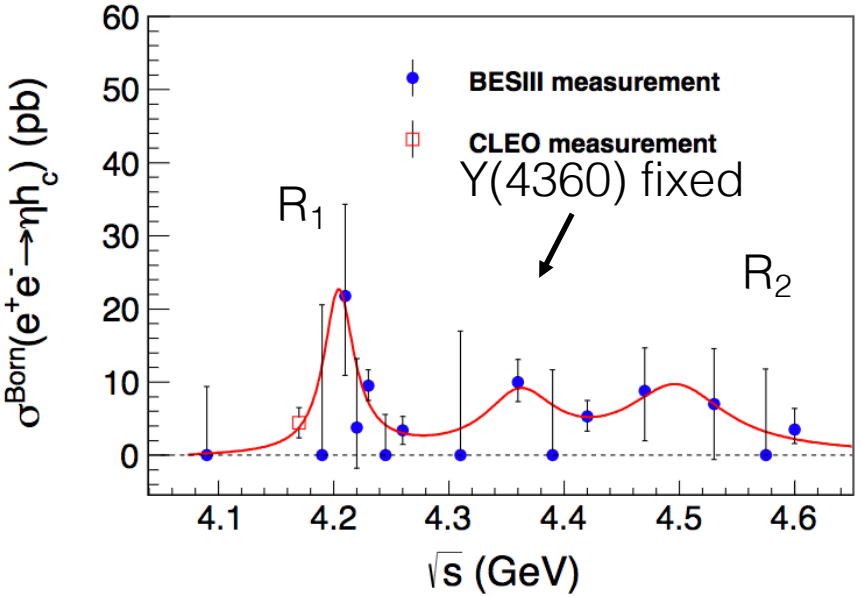
- Fit with the ψ(4160) and ψ(4415) resonances
  ➔The ψ(4415) is not significant
- $\sigma(\eta' J/\psi)$ much lower than $\sigma(\eta\, J/\psi)$, lower than NRQCD calculation

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

PRD96, 012001 (2017)

- **Search for new Y decays to spin-singlet $c\bar{c}$ final state**





Fitting curve with3 coherent BW's

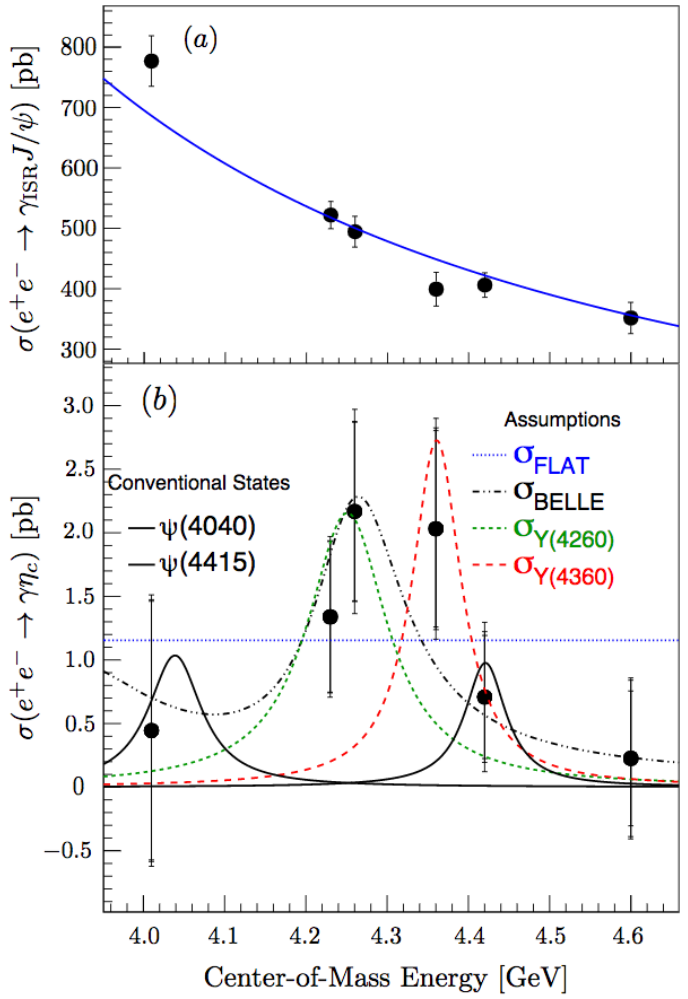
- Clear signals of $e^+e^- \to \eta h_c$ only at 4.226 GeV and evidence at 4.358 GeV

- $M_1 = (4204 \pm 6)$ MeV
- $\Gamma_1 = (33 \pm 22)$ MeV
- $M_2 = (4496 \pm 26)$ MeV
- $\Gamma_2 = (104 \pm 69)$ MeV

$e^+e^- \to \gamma\eta_c$

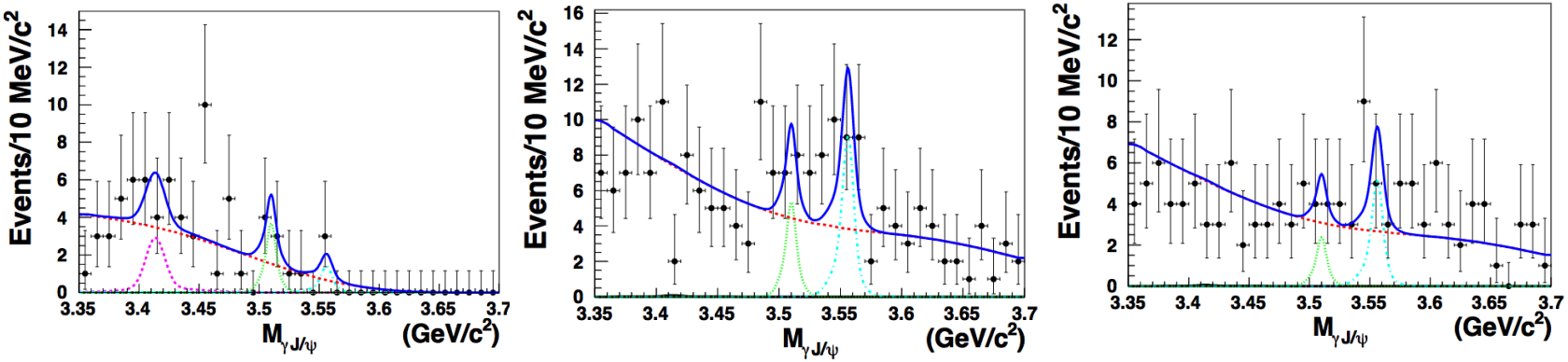
PRD 96, 051101 (2017)

- Search for radiative decay of the Y to the spin-singlet state of η_c
- Lattice QCD predicts that Hybrid model of the Y(4260) would enhance the ratio $\frac{\Gamma(Y\to\gamma\eta_c)}{\Gamma(Y\to\gamma\chi_{c0})}$, while for conventional charmonium state $\frac{\Gamma(Y\to\gamma\eta_c)}{\Gamma(Y\to\gamma\chi_{c0})} \sim \frac{1}{30}$
- The over significance is above 3σ by combing all data set
- Under current statistics, no firm conclusions can be made about the involved resonance structures.
- However, the Y(4260) is better than conventional ψ states: ψ(4040), ψ(4160), and ψ(4415) to describe the cross sections.



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

Chin. Phys. C39, 041001 (2015)

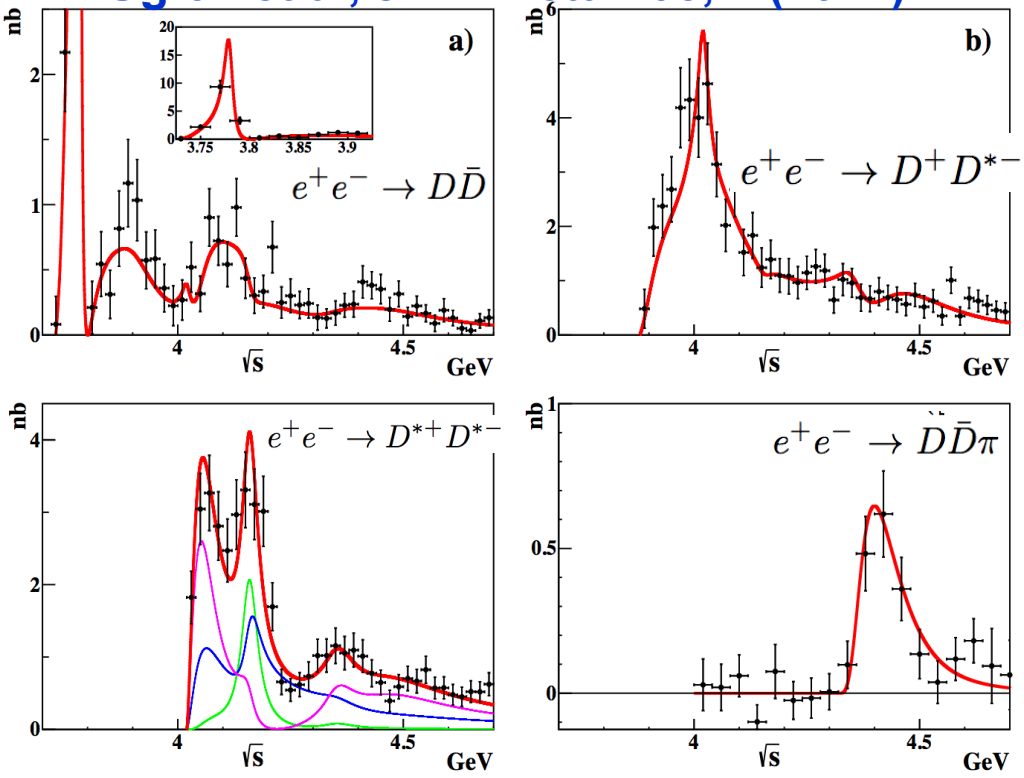


$\sqrt{s}$ (GeV)		N^{obs}	significance (σ)	N^{UP}	ϵ (%)	$1+\delta^r$	$1+\delta^v$	σ^{UP} (pb)	σ^B (pb)
4.009	χ_{c0}	7.0±6.6	1.6	18	36.4±0.2	0.738	1.04	182	65.0±61.3±5.3
	χ_{c1}	4.4±2.6	2.2	9	23.4±0.1			5.3	2.4±1.4±0.2
	χ_{c2}	1.8±1.7	1.5	6	8.7±0.1			18	4.7±4.4±0.6
4.230	χ_{c0}	0.2±2.3	0.0	7	37.2±0.2	0.840	1.06	26	0.7±8.0±0.1
	χ_{c1}	6.7±4.3	1.9	14	44.4±0.2			1.7	0.7±0.5±0.1
	χ_{c2}	13.3±5.2	2.9	22	42.0±0.2			5.0	2.7±1.1±0.3
4.260	χ_{c0}	0.1±1.9	0.0	5	36.7±0.2	0.842	1.06	26	0.5±8.8±0.1
	χ_{c1}	3.0±3.0	1.1	7	42.7±0.2			1.1	0.4±0.4±0.1
	χ_{c2}	7.5±3.9	2.3	14	41.7±0.2			4.2	2.0±1.1±0.2
4.360	χ_{c0}	0.1±0.7	0.0	3	32.4±0.2	0.943	1.05	23	0.7±5.0±0.1
	χ_{c1}	5.2±4.9	2.4	10	31.7±0.2			2.9	1.4±1.3±0.1
	χ_{c2}	4.4±4.5	2.0	9	30.3±0.2			5.0	2.3±2.3±0.2

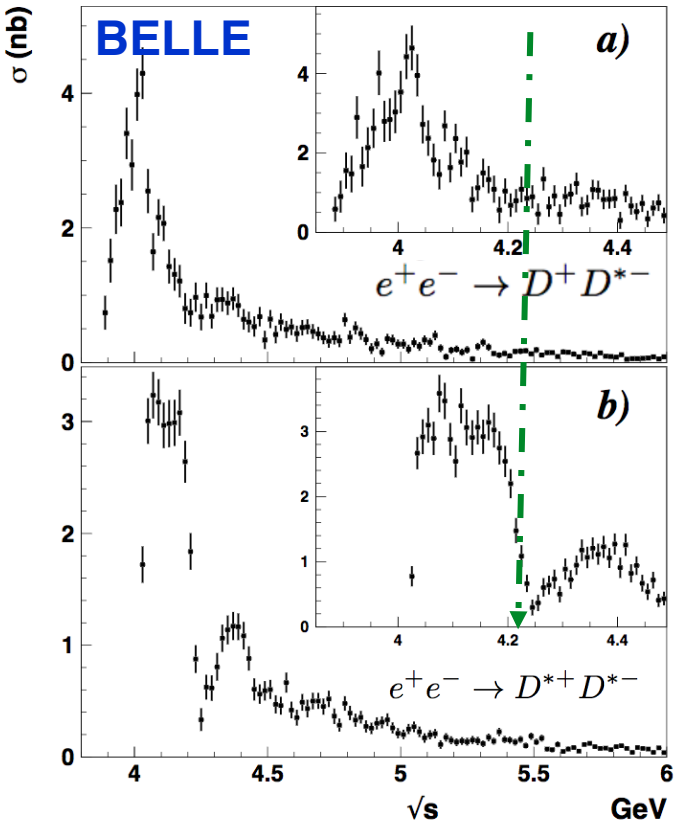
Low statistics of signal yields and no firm conclusions can be drawn

Y searches in other exclusive open charm decays

Uglov et al, JETP Lett. 105, 1 (2017)



PRD97. 012002 (2018)



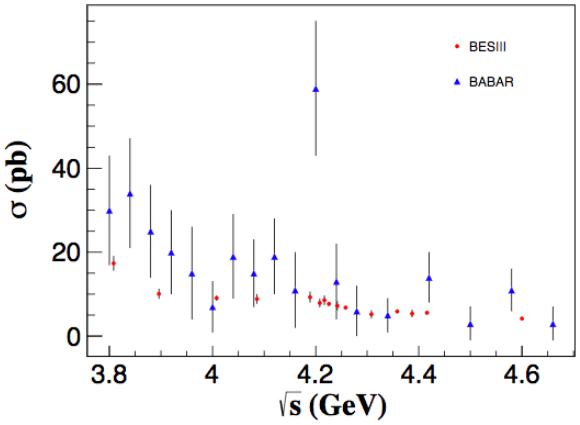
Updated $\sigma(e^+e^- \to D^{*+}D^{(*)-})$

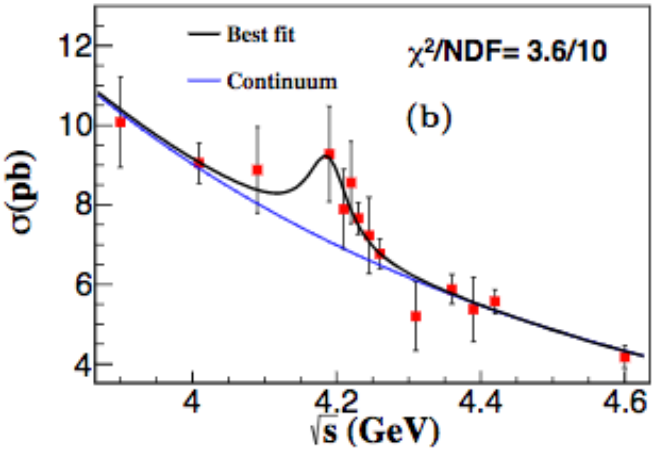
- An attempt of coupled channel fit to data points from BELLE using K-matrix amplitude
- Five vector charmonium resonances ($\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$,) can describe data fairly well
- More data and channels are required to extend the analysis

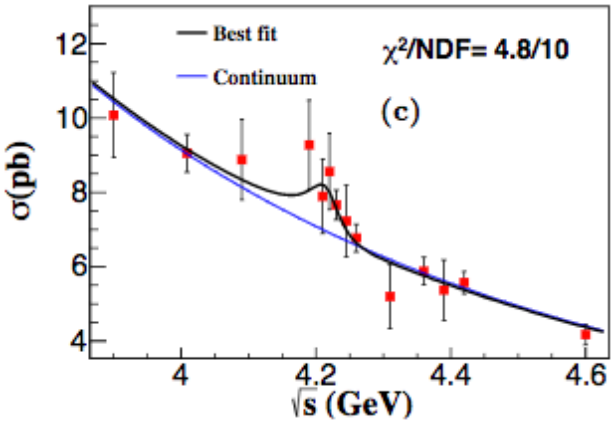
$e^+e^- \to K_s K^+ \pi^-$

arXiv:1808.08733

- The light mesonic decays of the Y state help to under its nature
- BaBar reported possible enhancement around 4.2 GeV







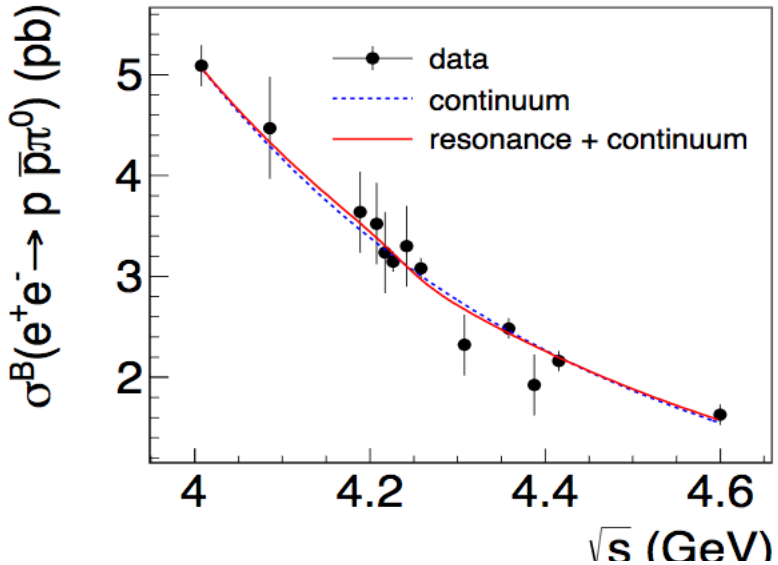
	$\psi(4160)$		$Y(4220)$	
	Solution I	Solution II	Solution I	Solution II
$\Gamma_{ee} \times B_{K^0_S K^+\pi^-}$ (eV)	2.71±0.13	0.0118±0.0098	2.03±0.05	0.0038±0.0029
ϕ (rad)	-1.60±0.03	1.71±0.38	-1.61±0.02	2.11±0.43
Significance	2.8σ		2.6σ	

- Basically agree with BaBar results
- Evidence of $\psi(4160) \to KsK\pi$ and Y(4220) $\to KsK\pi$
- Precisions will be improved using 2017 data set

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

PLB771, 45, (2017)

The Y state decay to baryonic final states?



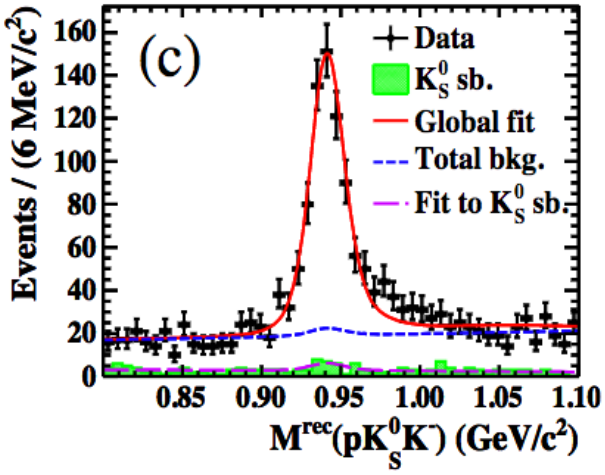
$$\sigma(s) = \left| \sqrt{\sigma_{\rm con}} + \sqrt{\sigma_Y} \frac{m\Gamma}{s - m^2 + im\Gamma} \exp(i\phi) \right|^2$$

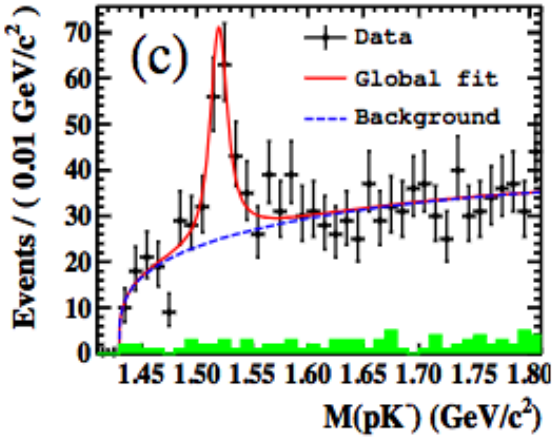
$\sigma(e^+e^- \to Y(4260) \to p\bar{p}\pi^0) < 0.1\,pb$ at 90 C.L.

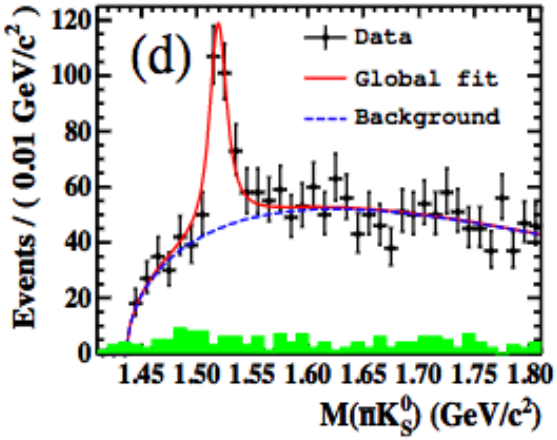
$e^+e^- \to pK_s\bar{n}K^-$

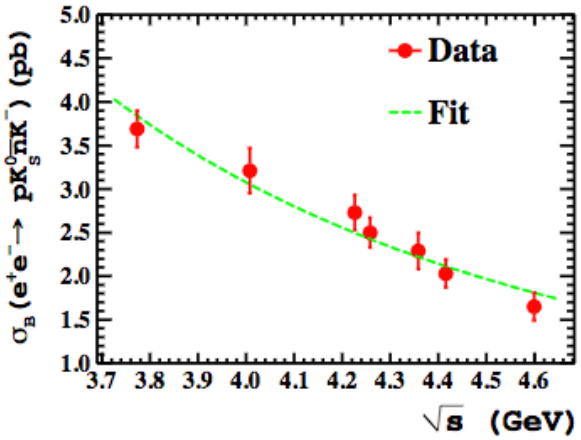
arXiv:1807.03468

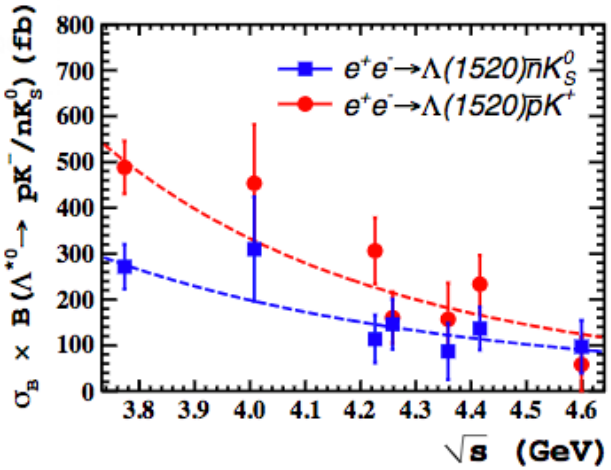
Neutron is not directly detected, but inferred from the missing-mass spectrum







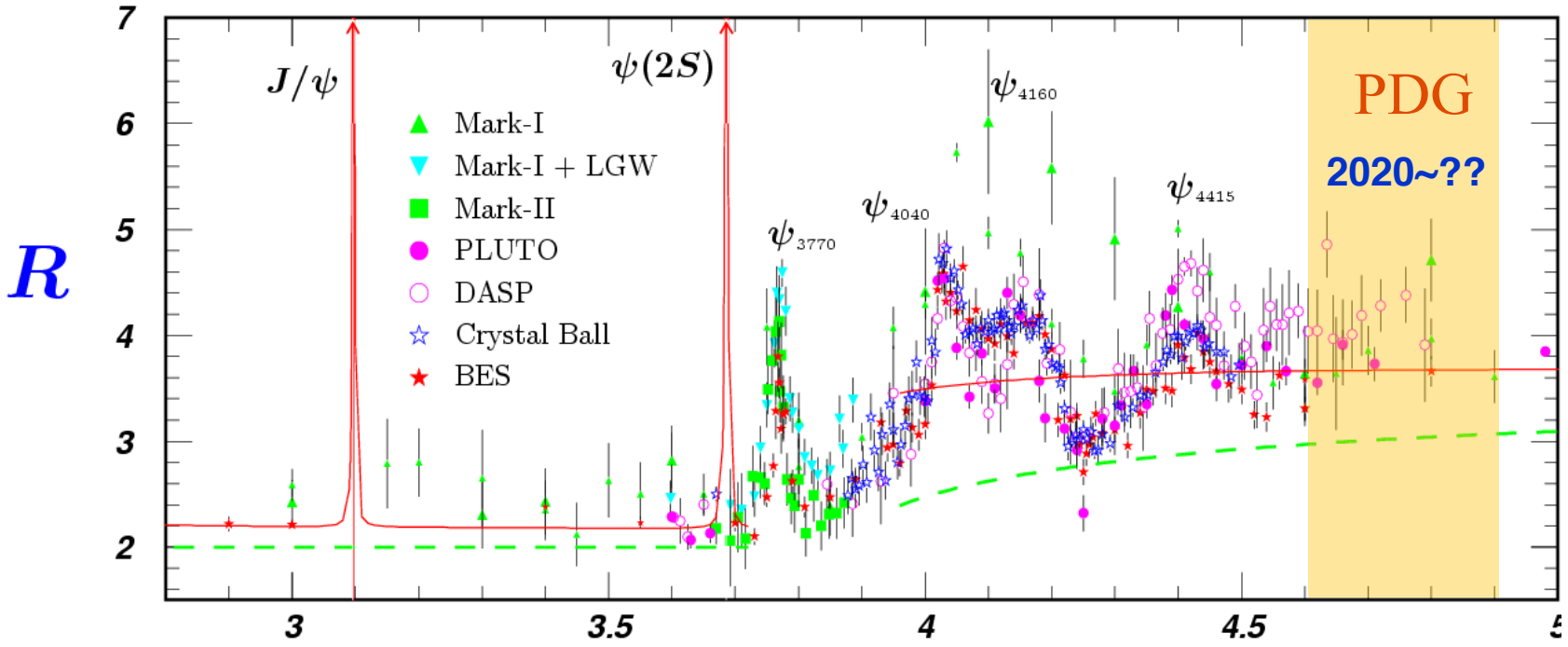




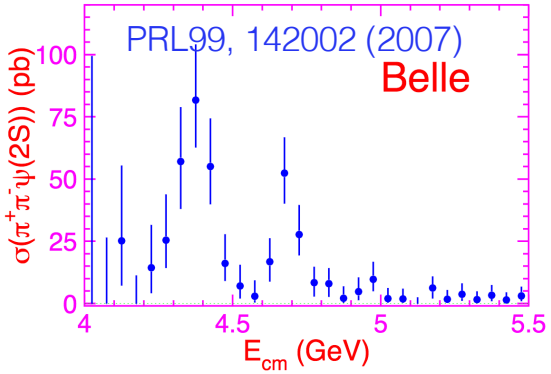
No Y states are evident

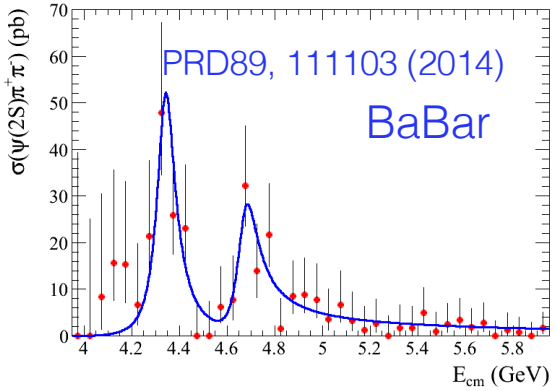
BEPCII upgrade

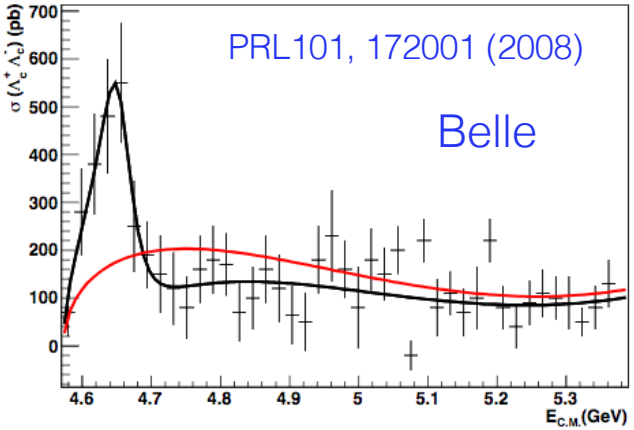
- Increase of beam energy 2.30→2.35→2.45 GeV
  - ➔ 2.35 GeV in 2018 summer (done)
  - ➔ 2.45 GeV in 2020-21, change ISPB (Interaction region SePtum Bending) magnet
- Top-up injection
  - Data taking efficiency increases by 20~30%

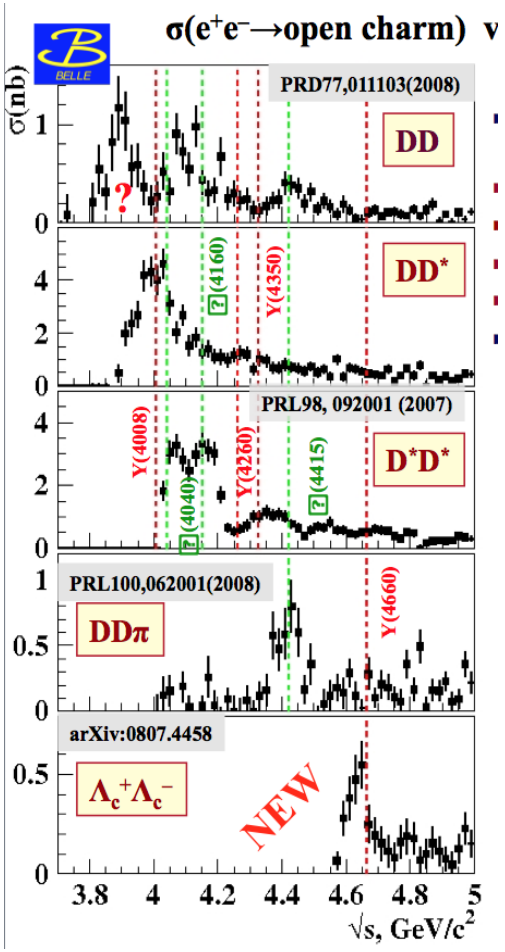


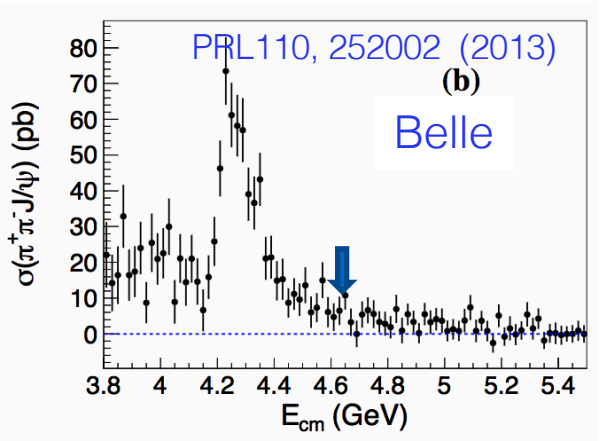
The Y(4630)/Y(4660)











$$\frac{\mathcal{B}(Y_B \to \Lambda_c\bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7,$$

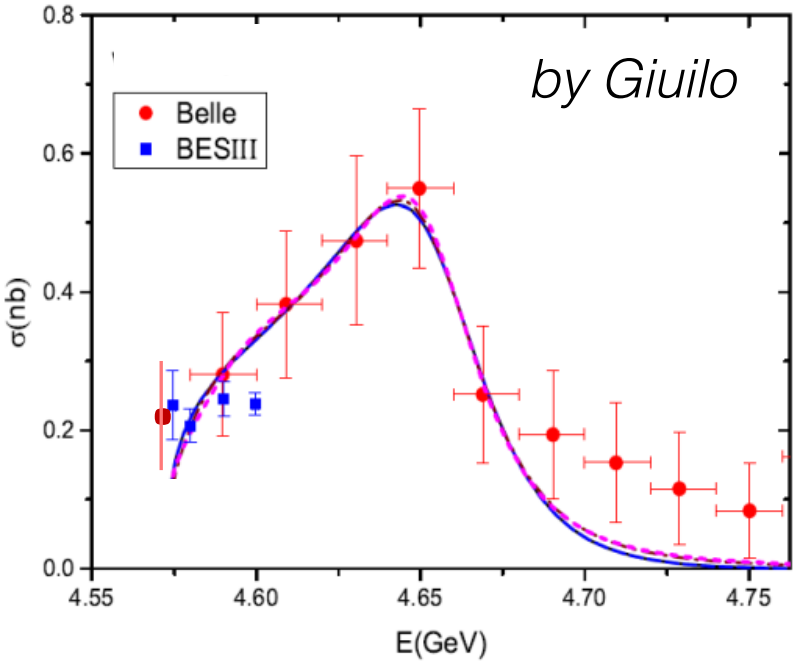
Phys.Rev.Lett. 104 (2010) 132005

$$\frac{B(Y_B \to D^0 D^{*-}\pi^+)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} < 10$$

PDG

- Y(4660) baryonic coupling $\geq$ 10 mesonic coupling (unexpected!)
- Another missing large mesonic decay? Or Y(4660) is a charmed baryonium?

Lineshape of $e^+e^- \to \Lambda_c^+\Lambda_c^-$

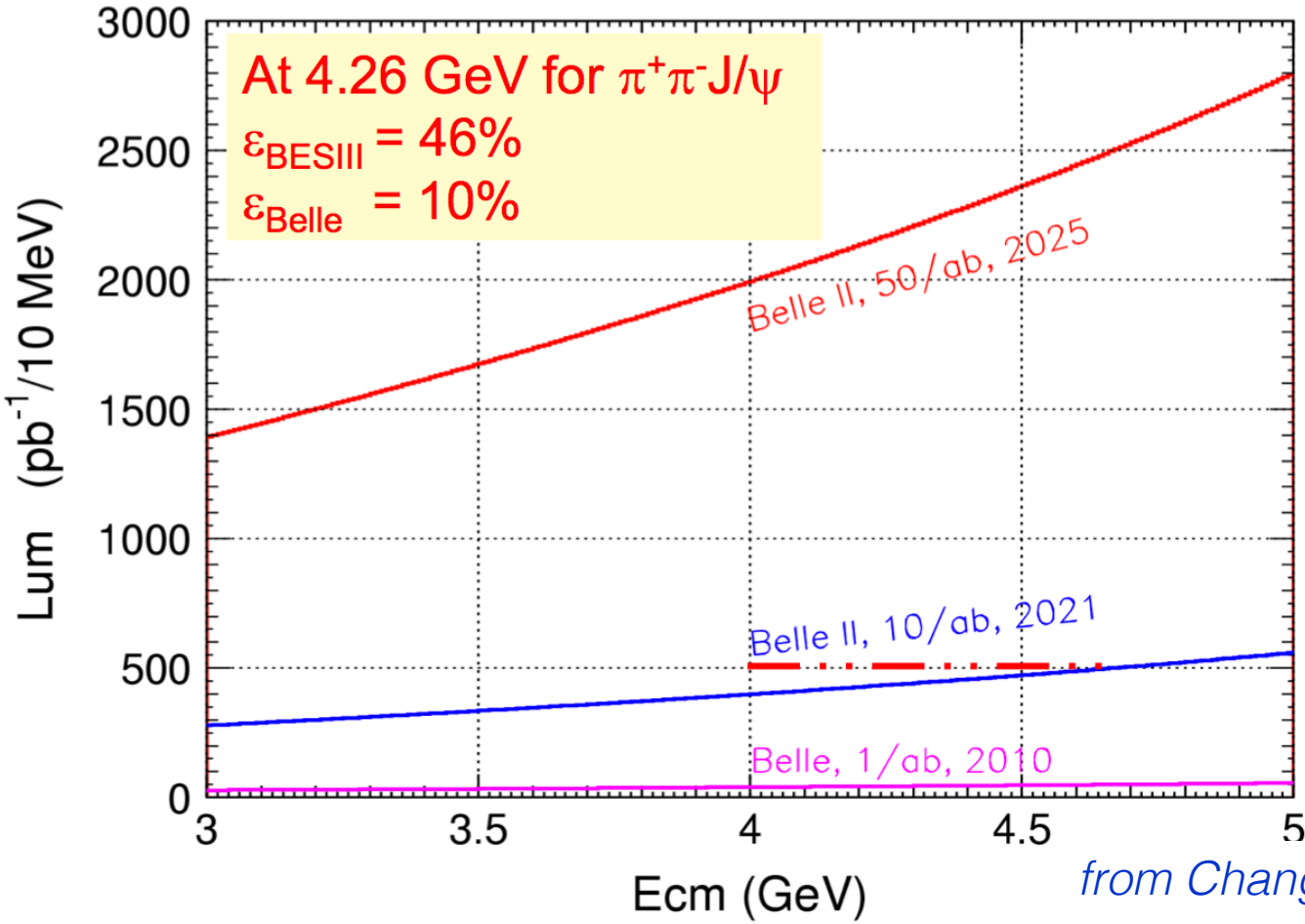


Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)

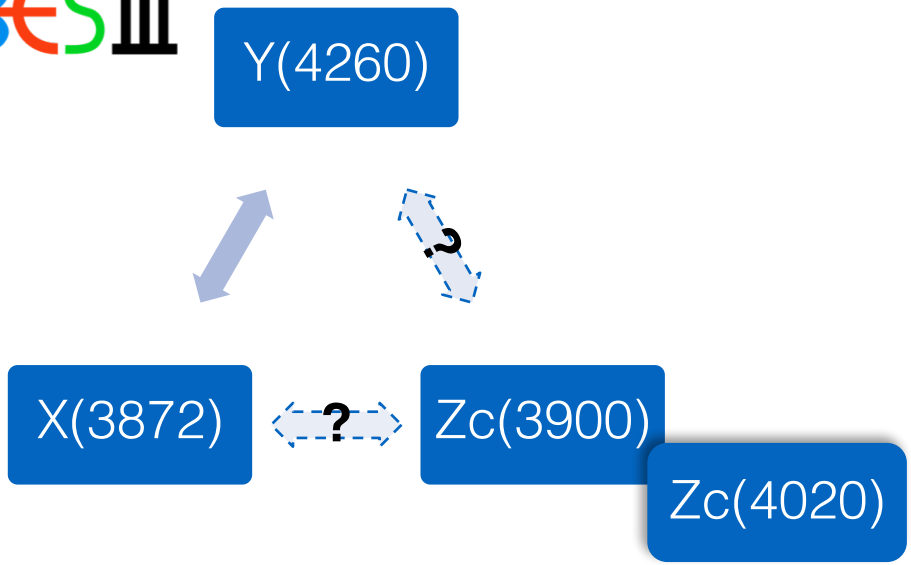
- Some tension between BELLE and BESIII data on $e^+e^- \to \Lambda_c^+\Lambda_c^-$
- BESIII future data above 4.6 GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold?

BELLE-II versus BESIII

ISR produces events at all CM energies BESIII can reach



from Changzheng



Multiquark
Hybrid
Hadrocharmonium

Molecule
Threshold effects
Cusps

… **States or/and interactions**

What is the role of threshold

--Many new observations near thresholds: D*D,D*D*, D_1D, …

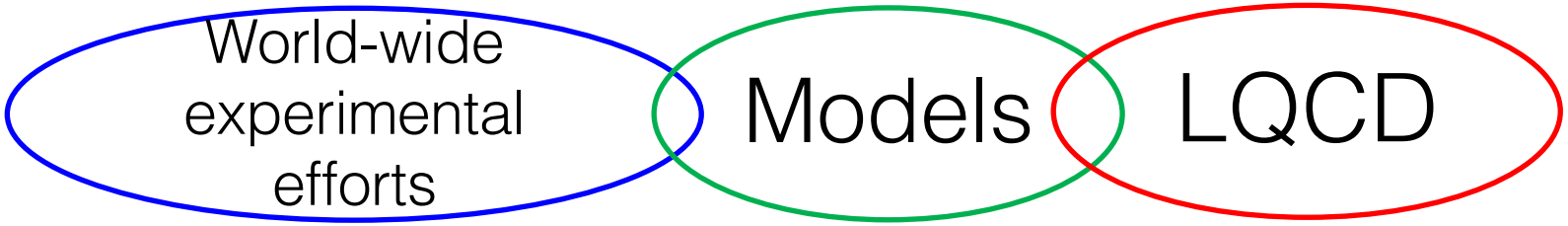
* Phase variations appear in many process: not unique for resonance

To have a complete picture, more investigations are desired, e.g., the consistency among direction productions and B hadron decays $B \to KY, Y \to X$

- **Energy-dependence**
- **Patterns in productions and decays**

Pole properties

For XYZ, the picture is still unclear



Summary

- BESIII is now overwhelmingly dominating the studies on the Y states
- Improved understanding of the previous reported state Y(4260)
  - ✓ Now Y(4260)➔ Y(4220)
  - ✓ New observation of decays to open charm final states
  - ✓ Exhaustive studies on the decays to various hidden charm final states
  - ✓ Searches for decays to the light meson and baryon final states
  - ✓ …
- Continuously, more data set will be recorded and new analyses will be publicized …
- Future BEPCII energy upgrade enable us to study the Y(4360)/Y(4660) states
- BELLE-II and (HL)-LHCb: searches for the Y's in direct production and the *B* decays

Thank you!

谢谢!