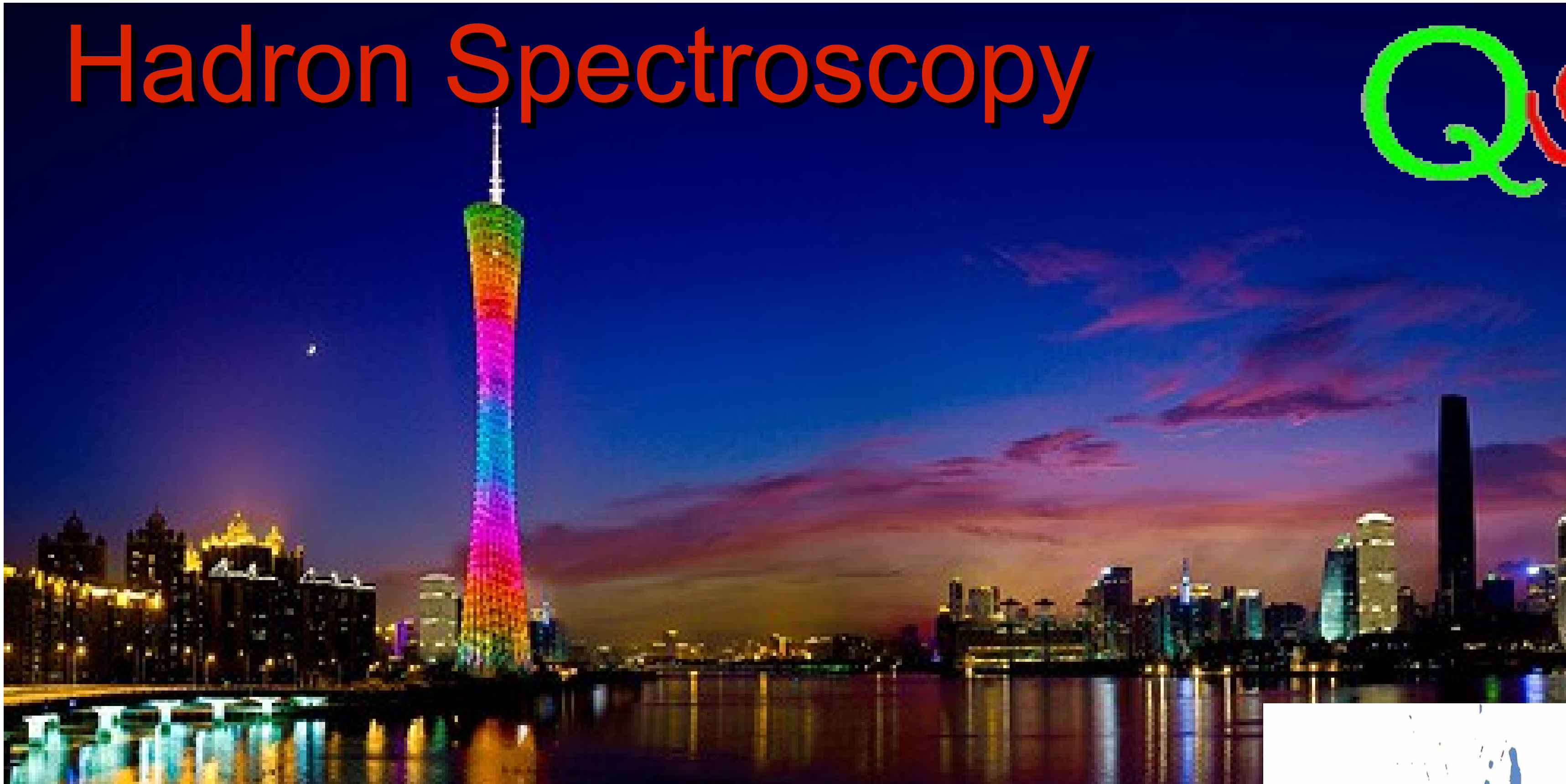
Hadron Spectroscopy



Heavy Quarkonia

XYZ states and tetraquarks

Heavy Mesons and Baryons

Roberto Mussa

INFN TORINO

LEPTON PHOTON 2017

Workshops in China

Topical Seminar School on

Heavy Quarkonia at Accelerators: New Theoretical Tools and Experimental Techniques

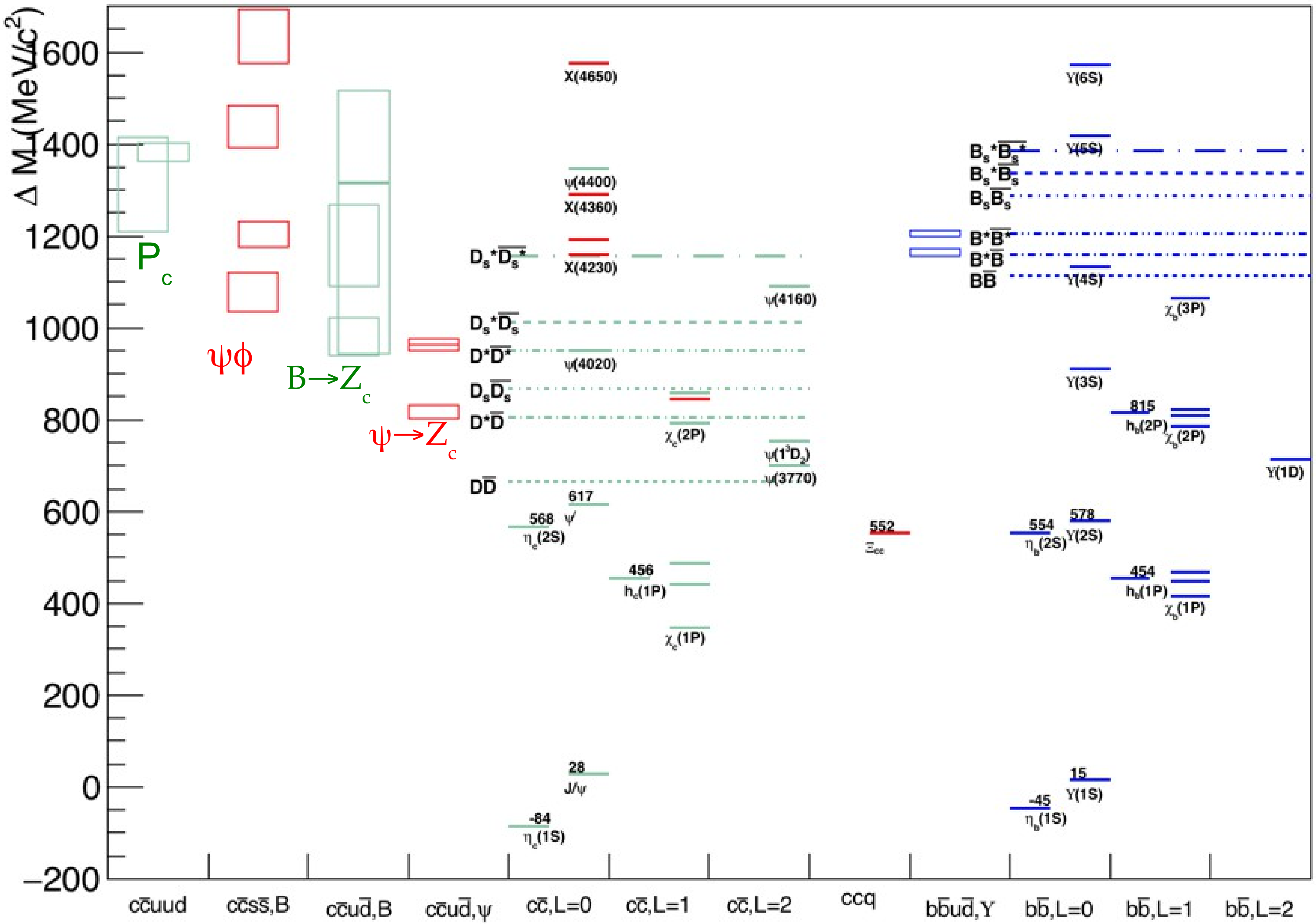
October 8-11, 2004 , ITP Beijing

October 12-15, 2004 , IHEP Beijing

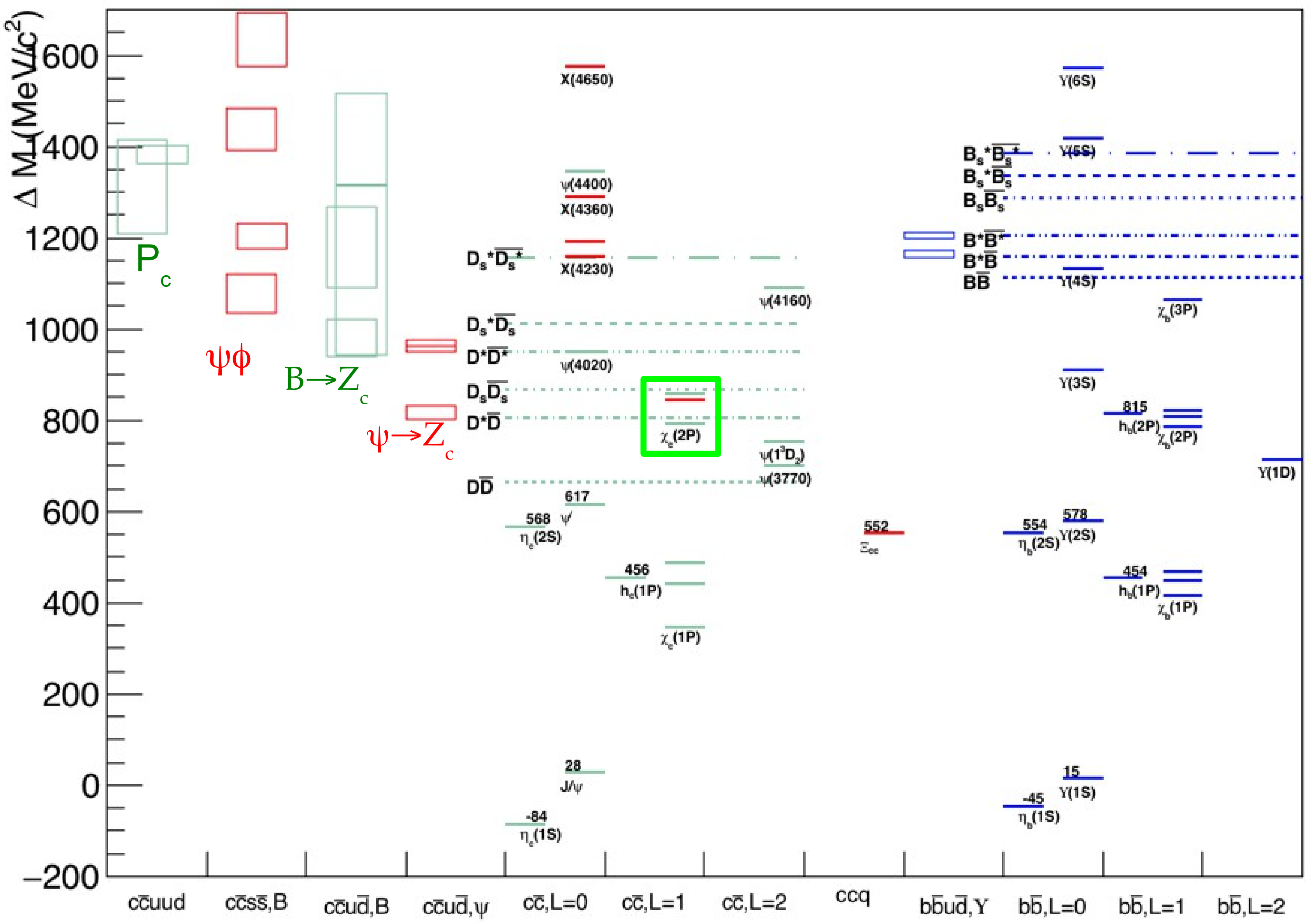
3rd International Workshop on Heavy Quarkonia

Organized by the Quarkonium Working Group

Charmonium(like) Bottomonium(like)



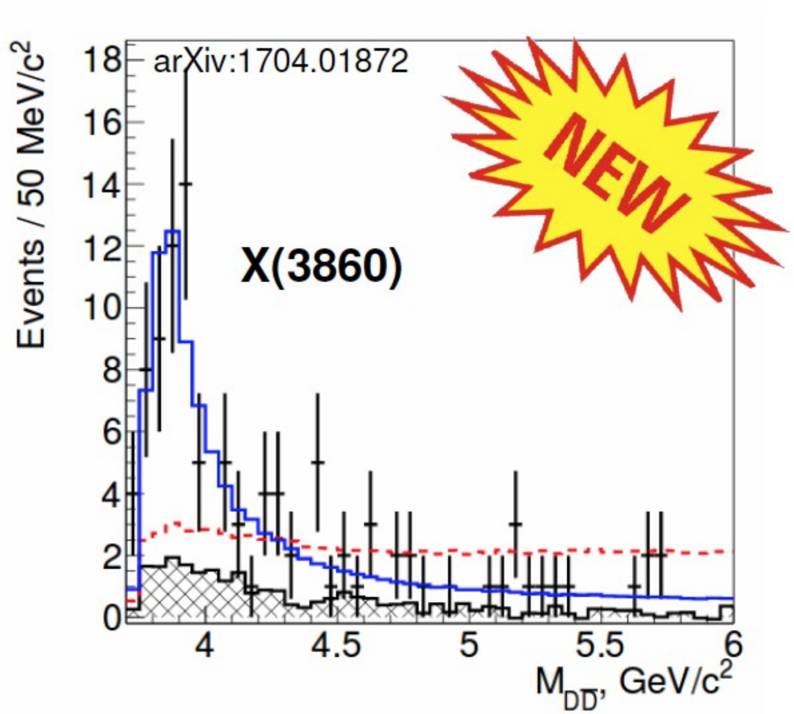
Charmonium(like) Bottomonium(like)

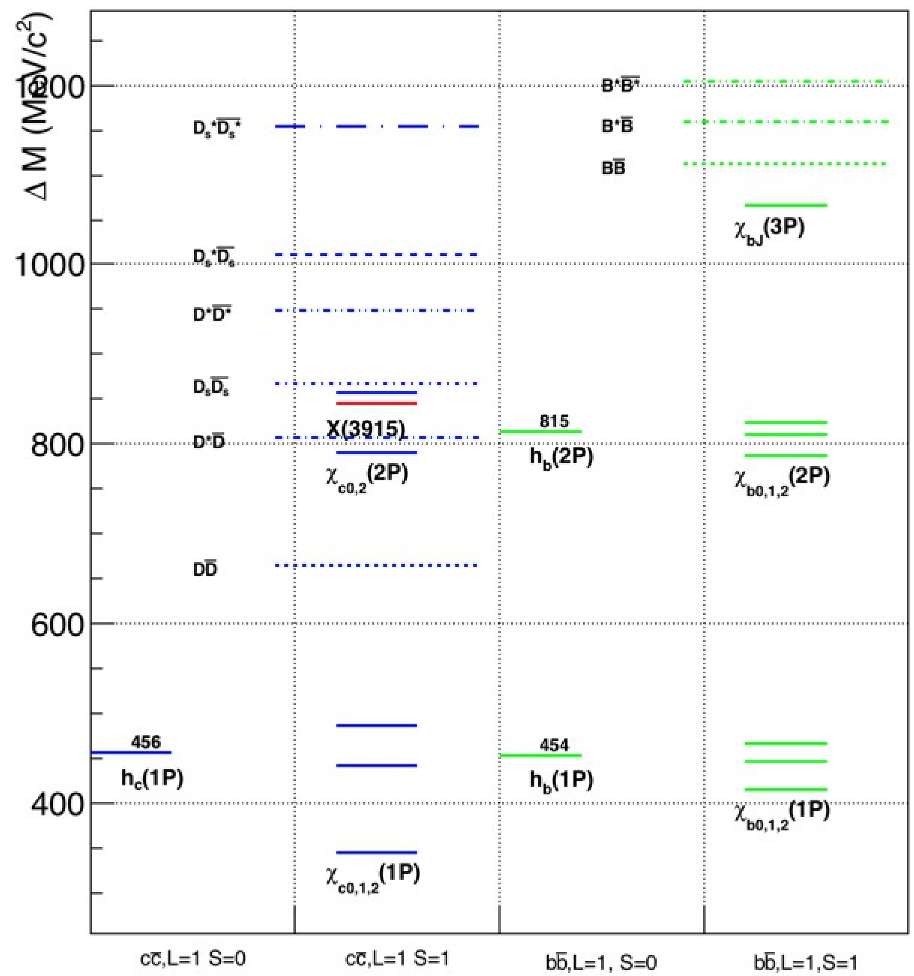


Observation of the 'real' $\chi_{c0}(2P)$?

Phys.Rev. D95 (2017) 112003

Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\overline{D}^0$: **X(3860)**



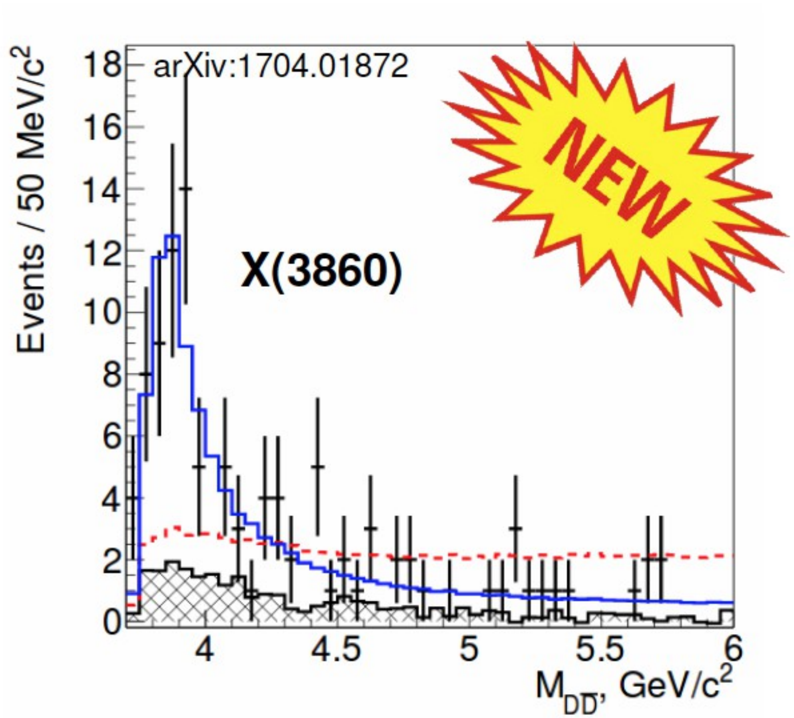


$\chi_{cJ0}(2P)$ ***should have:***	X(3915)	X(3860)
1) Dominant decay to $D^0\overline{D}^0$	✗	✓
2) Be 80-120 MeV below $\chi_{cJ2}(2P)$	✗	✓
3) $\mathcal{B}(\chi'_{c0} \to \omega J/\psi) < 7.8\%$.	✗	✓

$\chi_{c0}(2P)$

Phys.Rev. D95 (2017) 112003

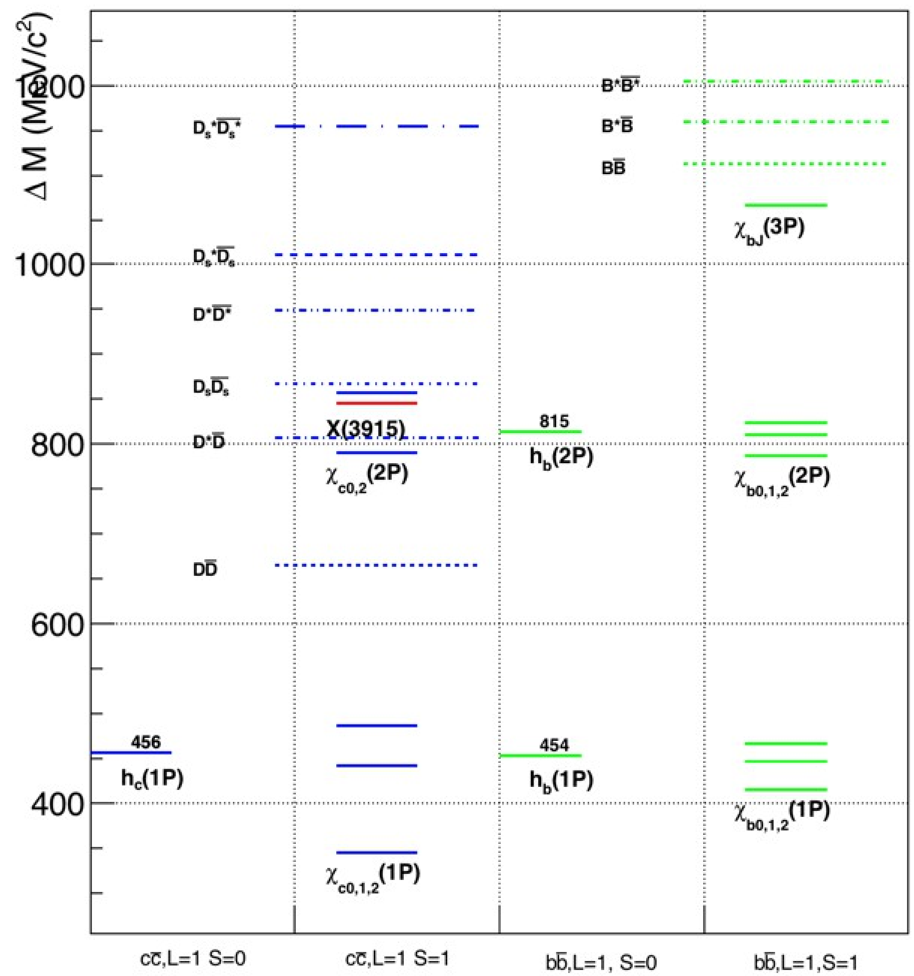
Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\overline{D}^0$: **X(3860)**



$$M = 3862^{+26+40}_{-32\,-13}\ MeV/c^2 \quad \Gamma = 201^{+154+88}_{-67\,-84}\ MeV$$

$$r_c = \frac{m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}}{m_{\chi_{c2}(1P)} - m_{\chi_{c0}(1P)}}$$

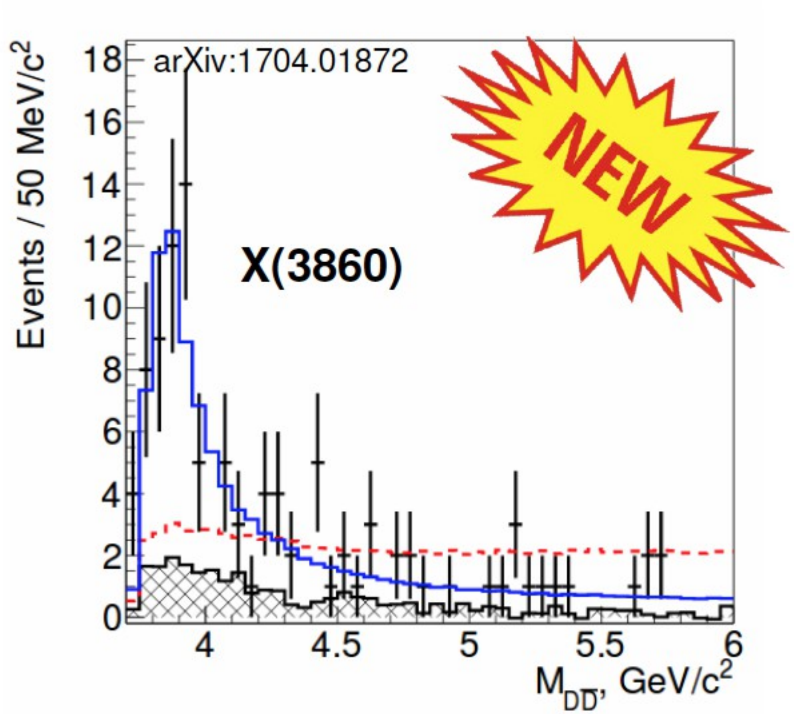
$$r_c = 0.46\ ^{+0.25}_{-0.34} \qquad r_b = 0.69 \pm 0.01$$



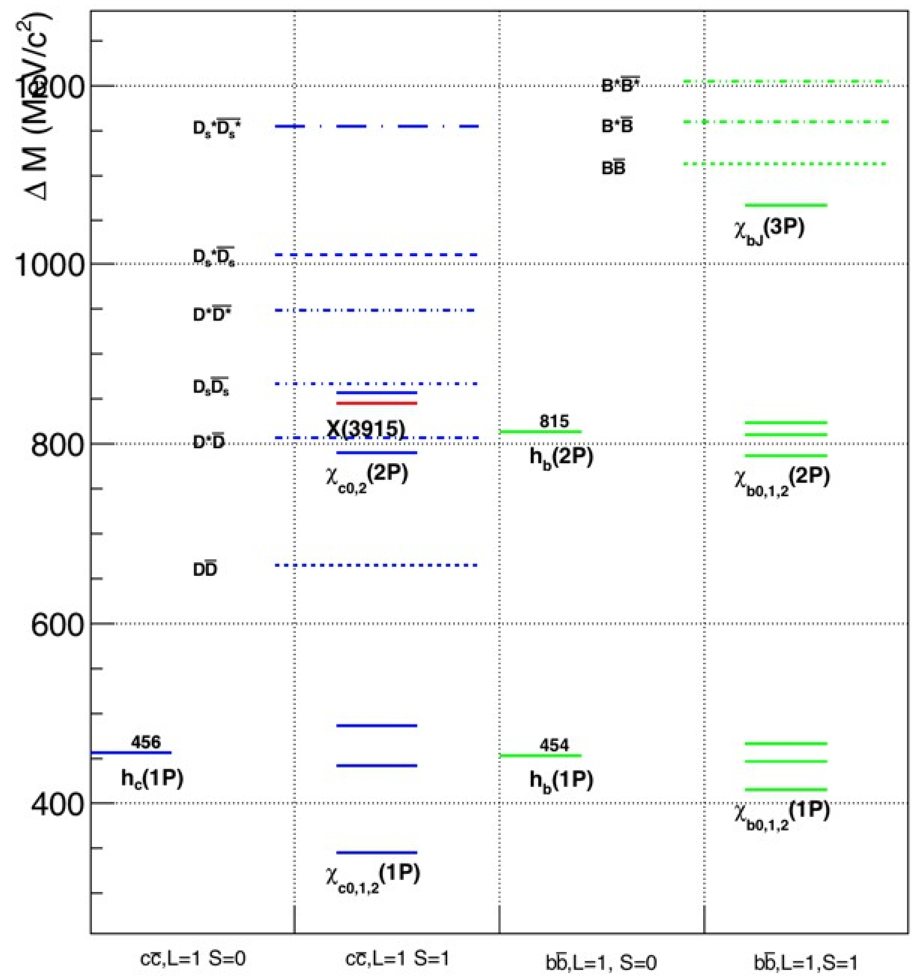
$\chi_{c0}(2P)$

Phys.Rev. D95 (2017) 112003

Belle 2017: New analysis of $e^+e^- \to J/\psi\, D^0\bar{D}^0$: **X(3860)**



$M = 3862^{+26+40}_{-32\ -13}\ MeV/c^2 \quad \Gamma = 201^{+154+88}_{-67\ -84}\ MeV$

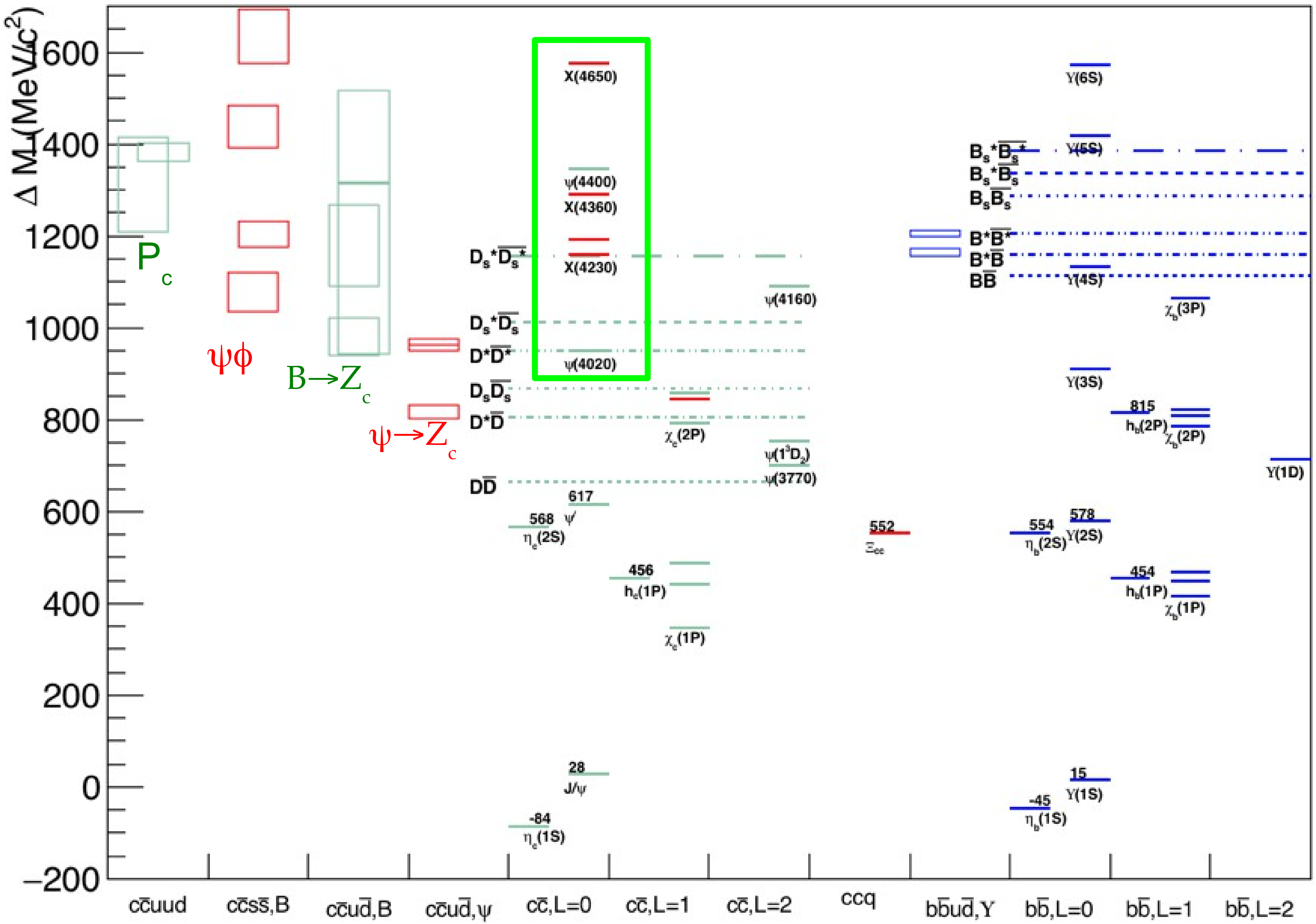


Open problems:

- **what is the X(3915) , then?**
- **where is the J=1 state?**

(X3872 is NOT a simple $c\bar{c}$)

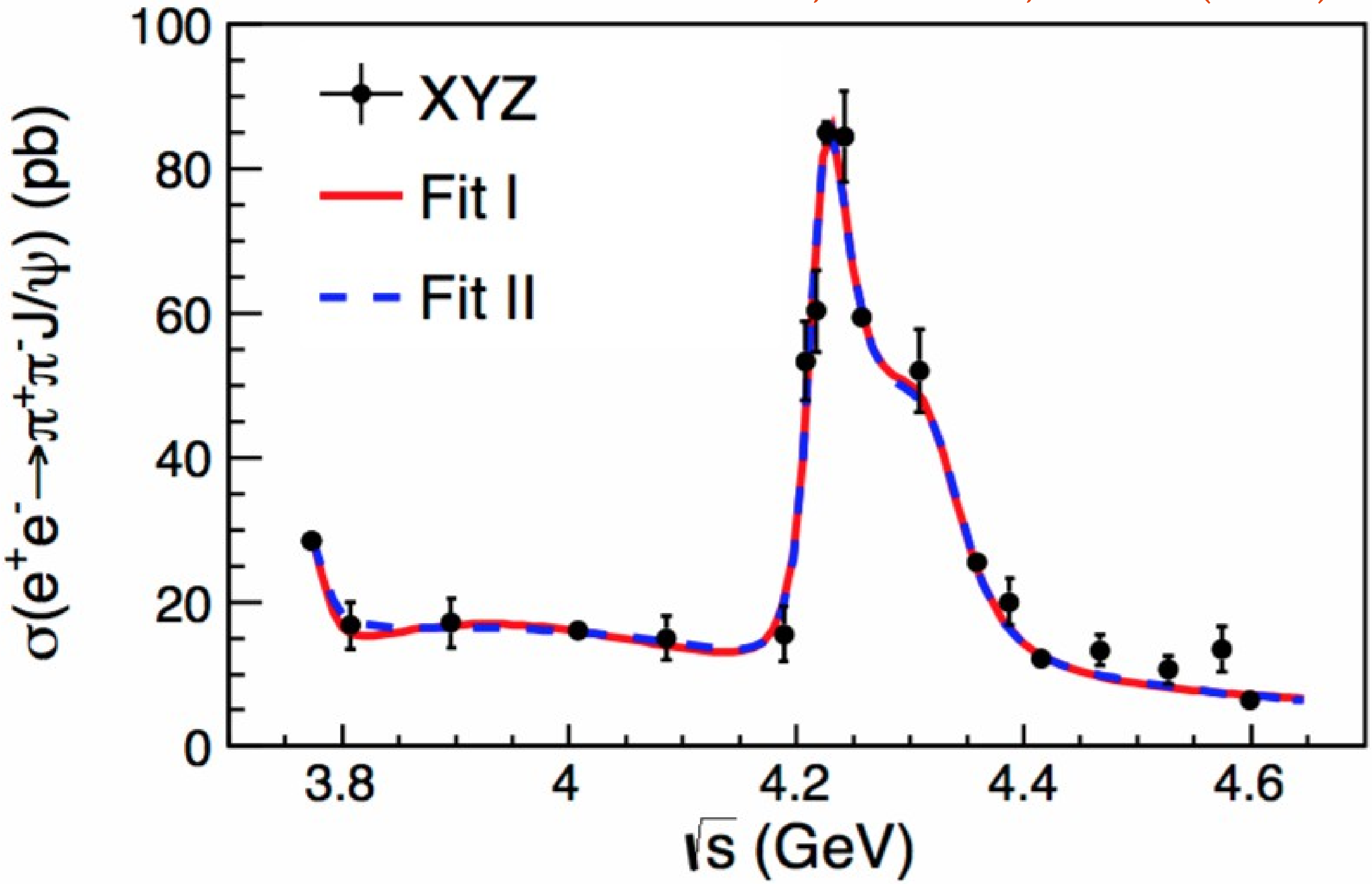
Charmonium(like) Bottomonium(like)



BESIII: XYZ scan
- $e^+e^- \to J/\psi\, \pi\pi$

Y(4260) : PDG2016: M = 4251± 9 , Γ = 120±12

BESIII, PRL 118,092001(2017)



Y(4220) decay modes:
- $\pi^+\pi^- J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\, J/\psi$
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

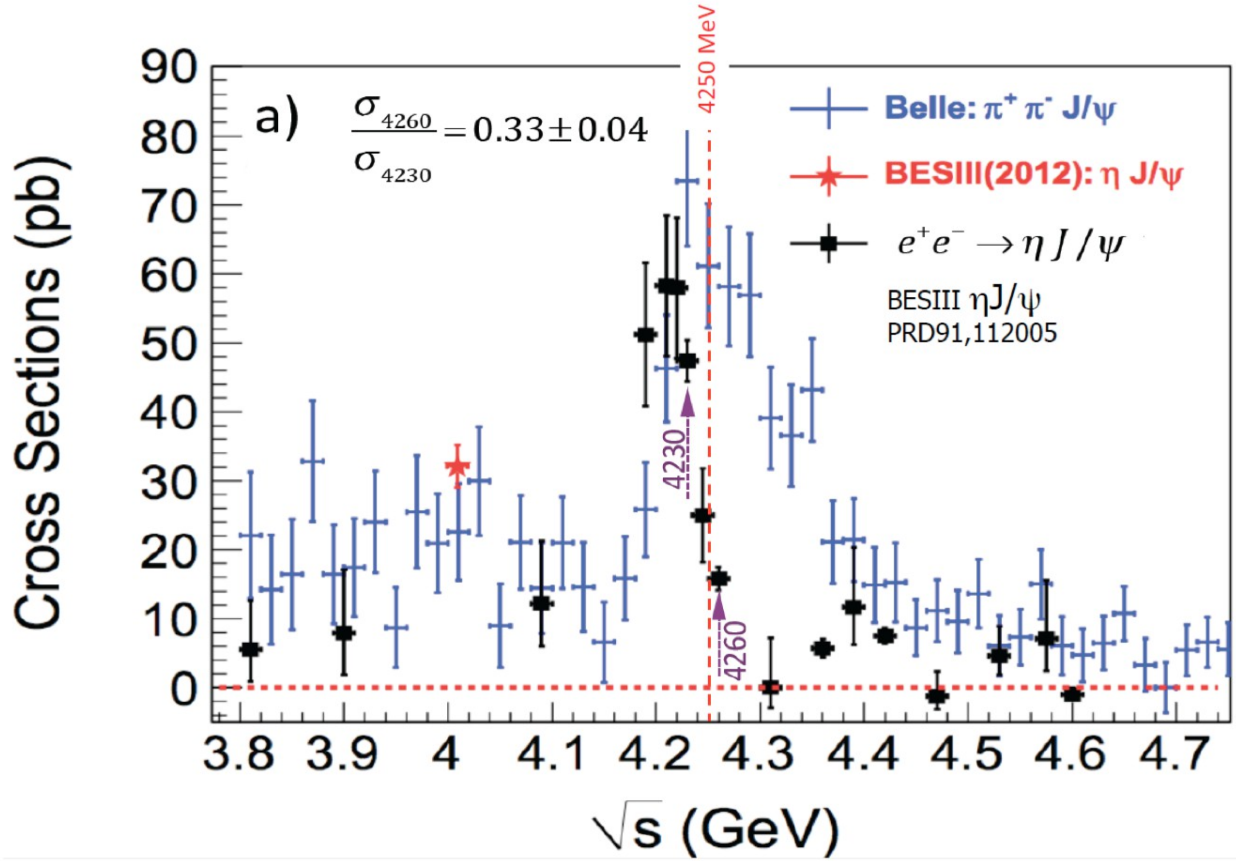
Y(4320) decay modes:
- $\pi^+\pi^- J/\psi$
- $\pi^+\pi^- \psi'$

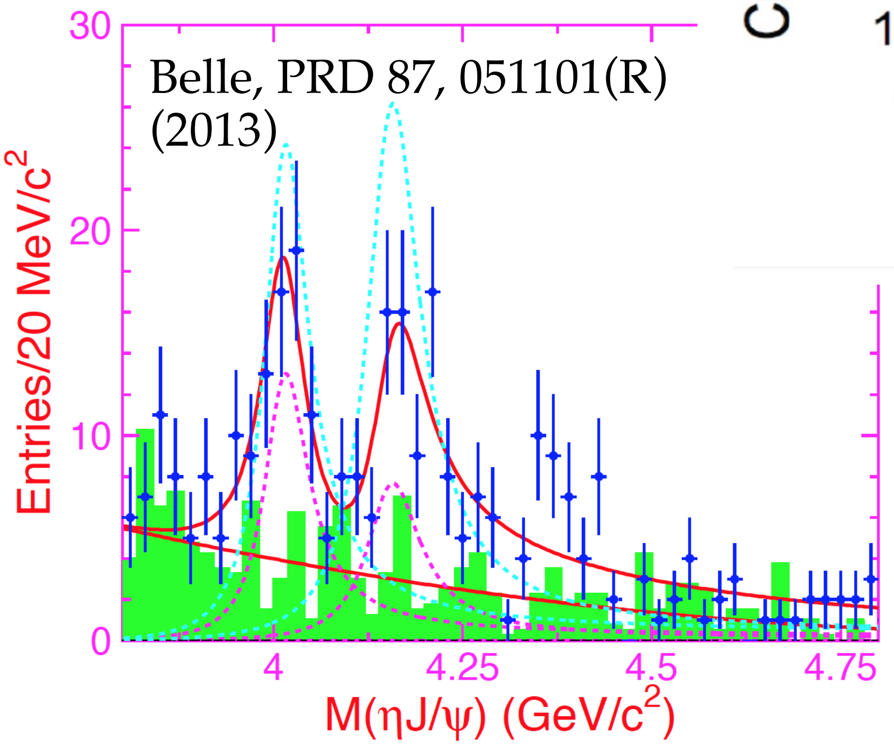
From the simultaneous fit of XYZ data (40 pb^{-1}/pt), and Rscan data (7-9 pb^{-1}/pt), BESIII shows that Y(4260) is made of *at least* two Breit- Wigners:

Y(4220) M=4222.0± 3.1 ±1.4 , Γ =44.1±4.3 ±2.0

Y(4320) M=4320.0±10.4±7.0 , $\Gamma = 101.4^{+25.3}_{-19.7} \pm 10.2$

BESIII: XYZ scan
- $e^+e^- \to \eta J/\psi$

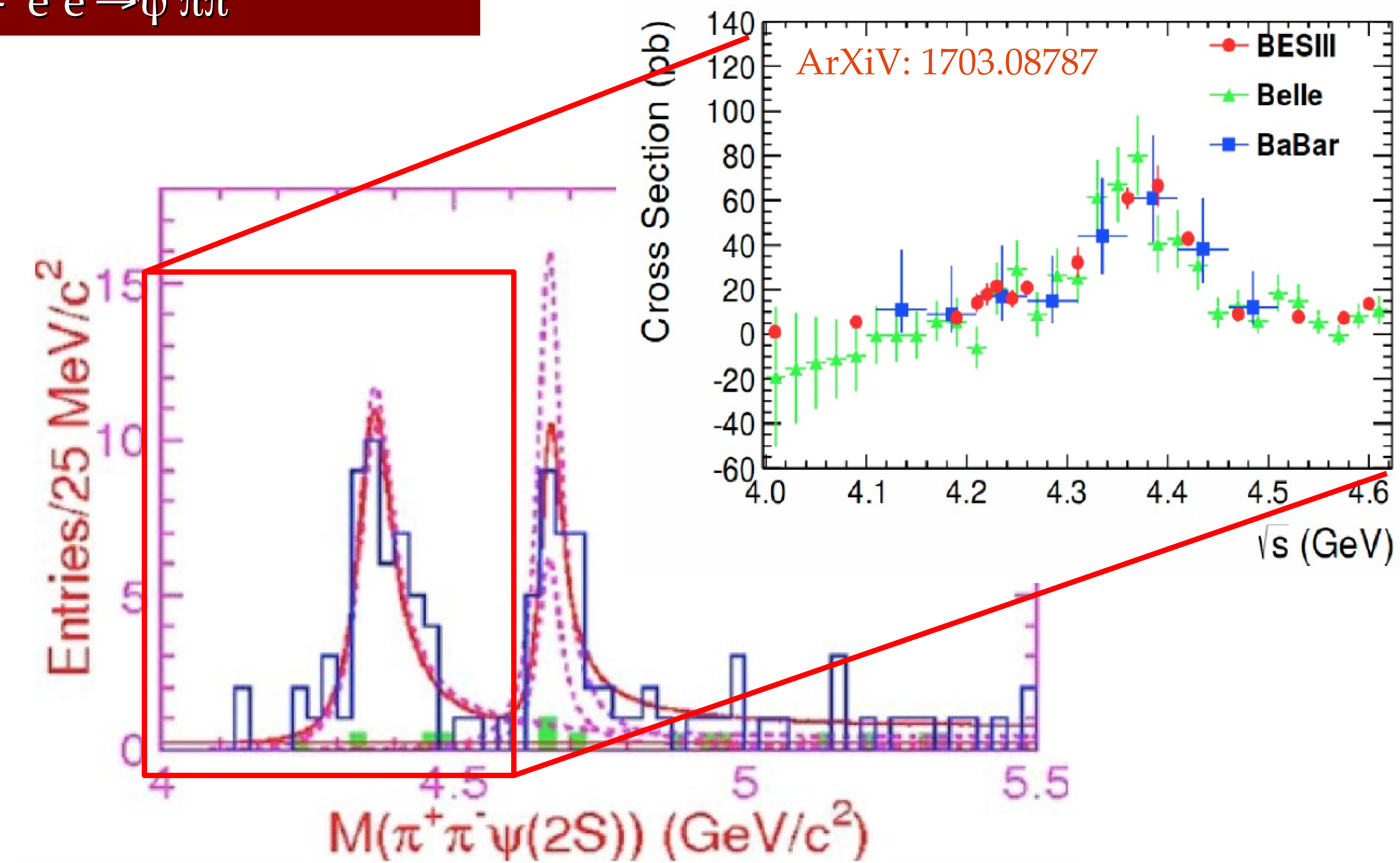




Belle found an additional peak at 4 GeV, smaller in BESIII. Size and width of the peak at 4220 are consistent with what observed in psi pi pi.

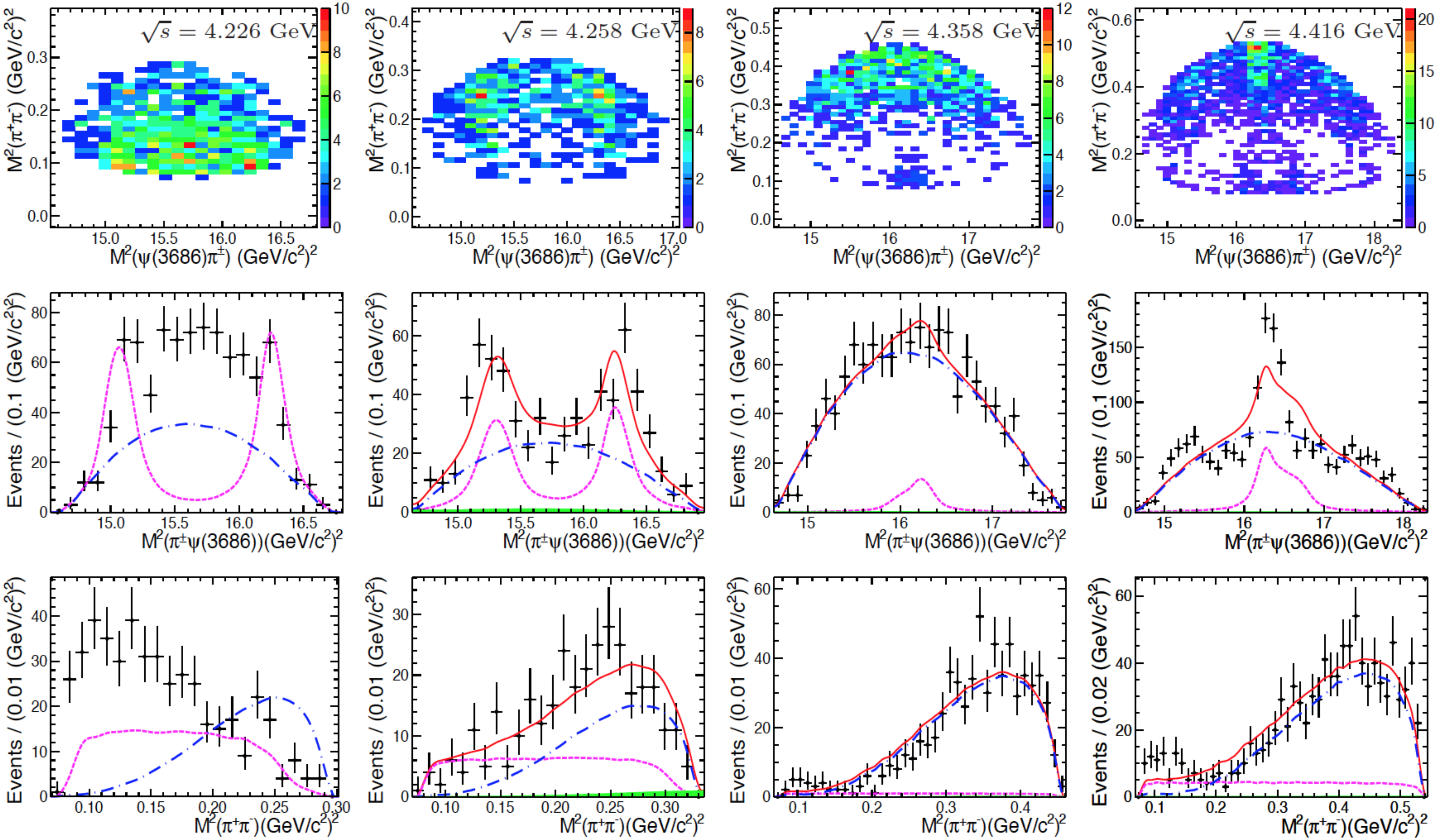
BESIII: XYZ scan

- $e^+e^- \to \psi'\pi\pi$



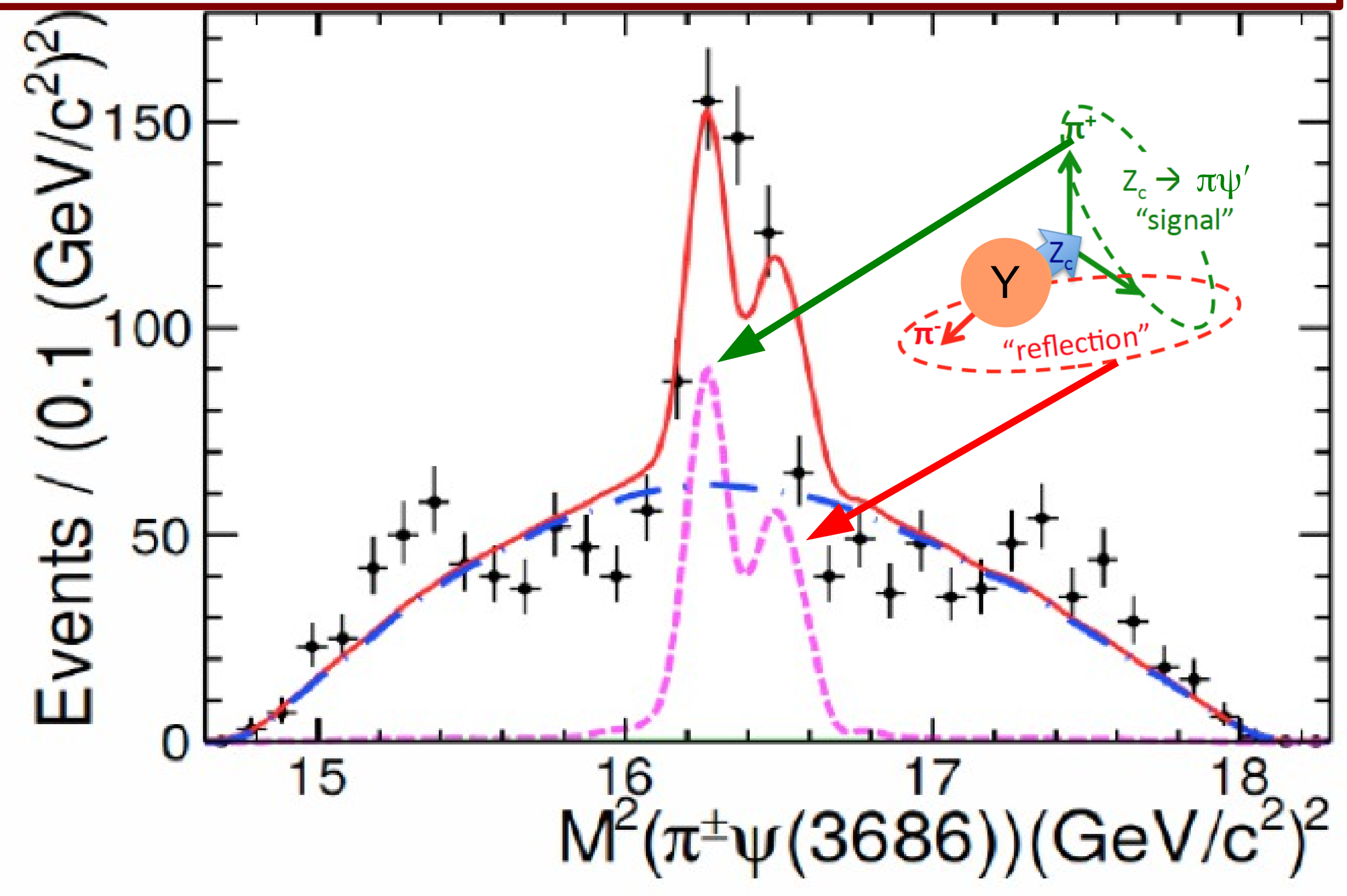
BESIII: XYZ scan
- $e^+e^- \to \psi' \pi\pi$

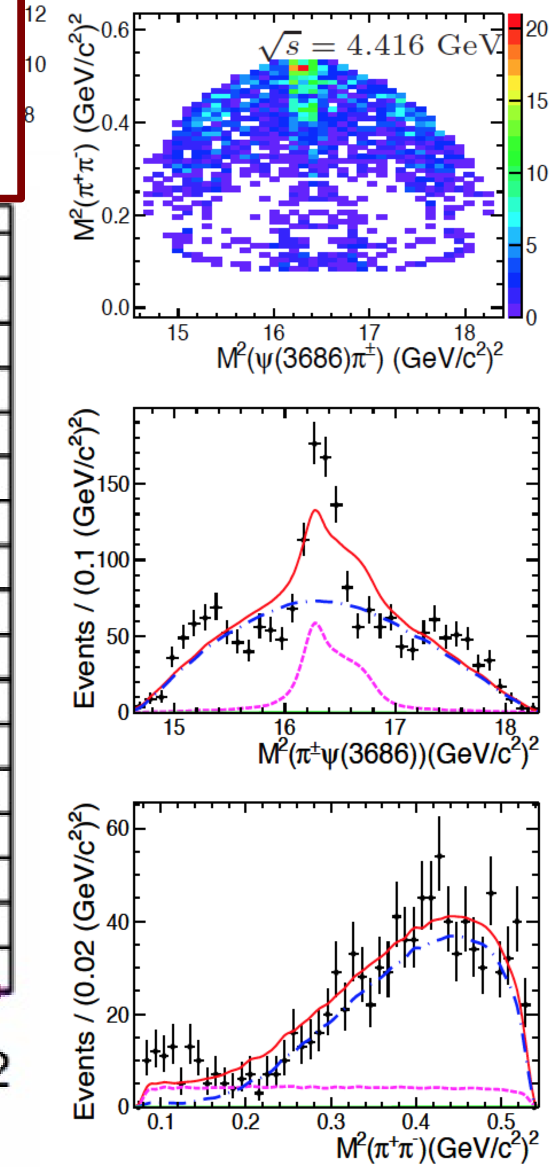
The very fast change of the Dalitz Plot from 4.23 to 4.26 GeV suggests that the region is populated by at least two states.



BESIII: XYZ scan
- $e^+e^- \to \psi'\pi\pi$

The double peak structure can be interpreted as a single Zc state:
with mass M = 4032.1±2.4 MeV/c^2
and total width Γ = 26.1 ± 5.3 MeV

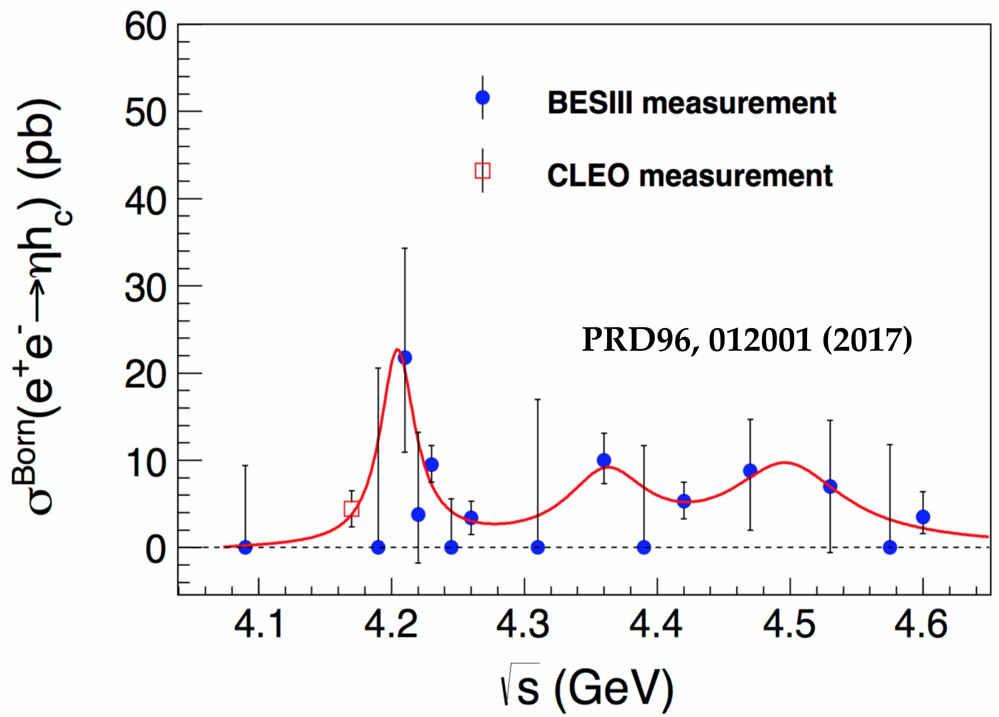


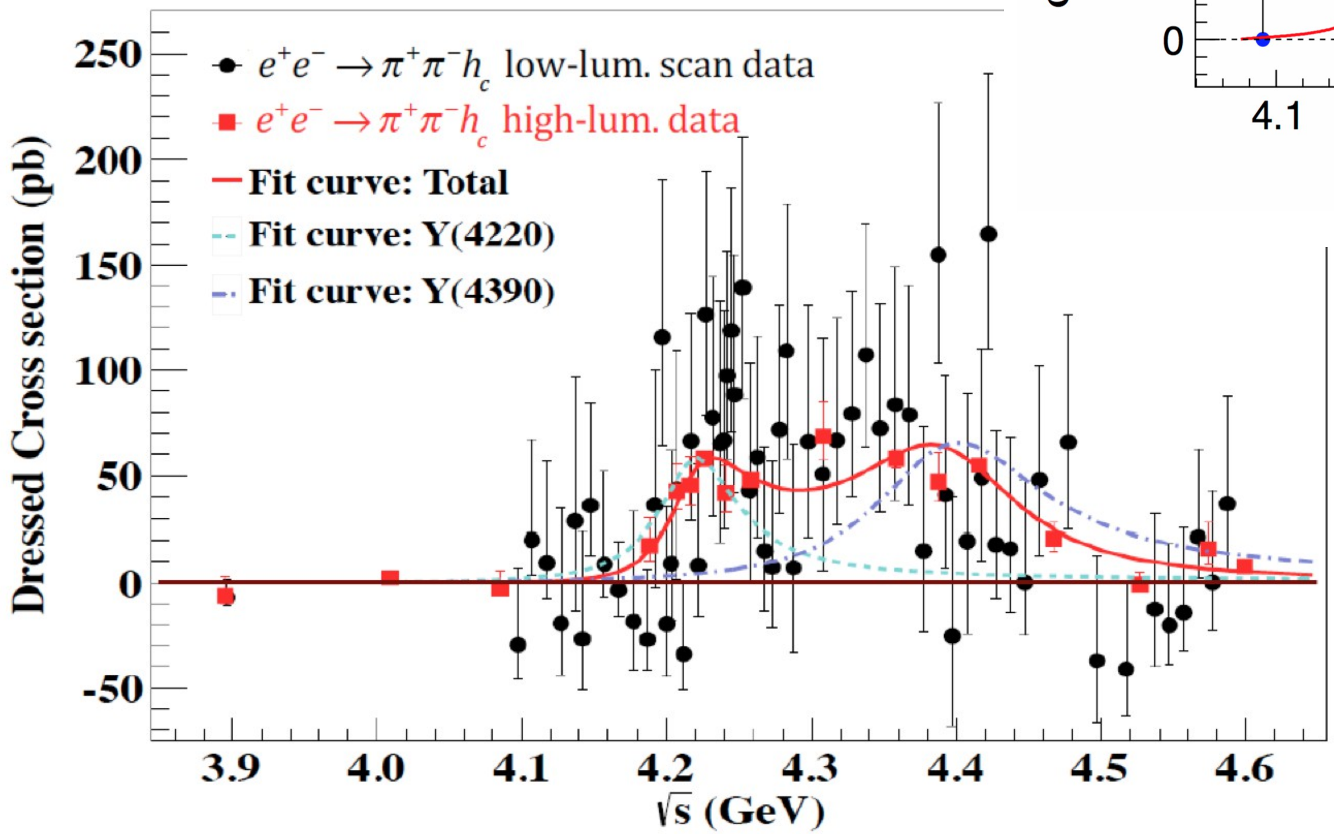


BESIII: XYZ scan
- $e^+e^- \to \eta h_c$, $\pi\pi h_c$

At least two peaks are needed to describe the dipion transition.
More statistics is needed to understand the structure of $e^+e^- \to \eta h_c$

Very different from bottomonium where on the Y(4S) peak $e^+e^- \to \eta h_b$ is dominant

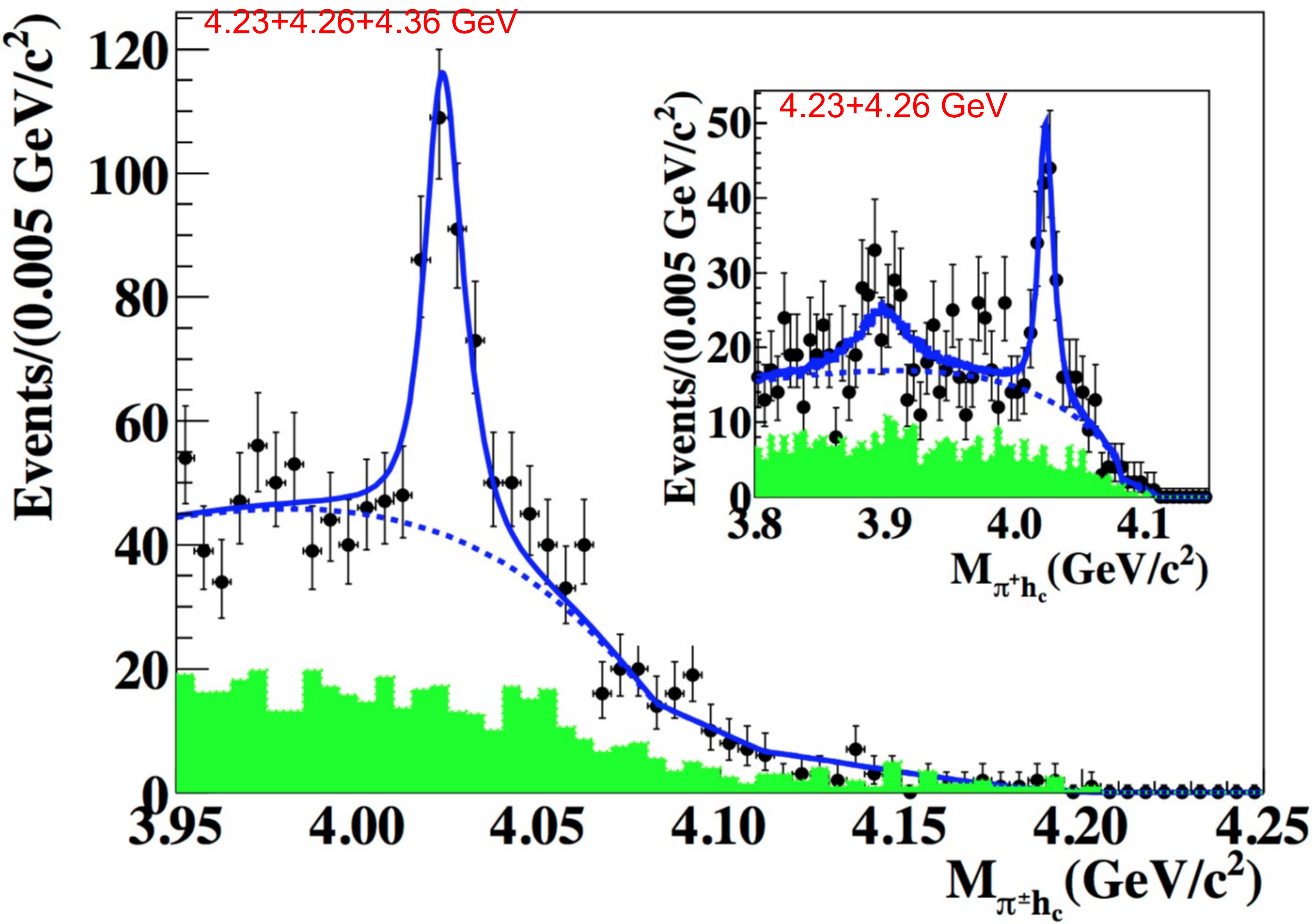




BESIII: XYZ scan
- $Z_c(3900,4020) \rightarrow \pi h_c$

Two Zc are observed in the πh_c final state

$Z_c(3900)$	M = 3886.2±2.4 MeV/c^2	Γ = 28.1±2.6 MeV
$Z_c(4020)$	M = 4024.0±1.9 MeV/c^2	Γ = 13 ± 5 MeV



Belle: $e^+e^- \to$ Υ(1,2,3S) ππ

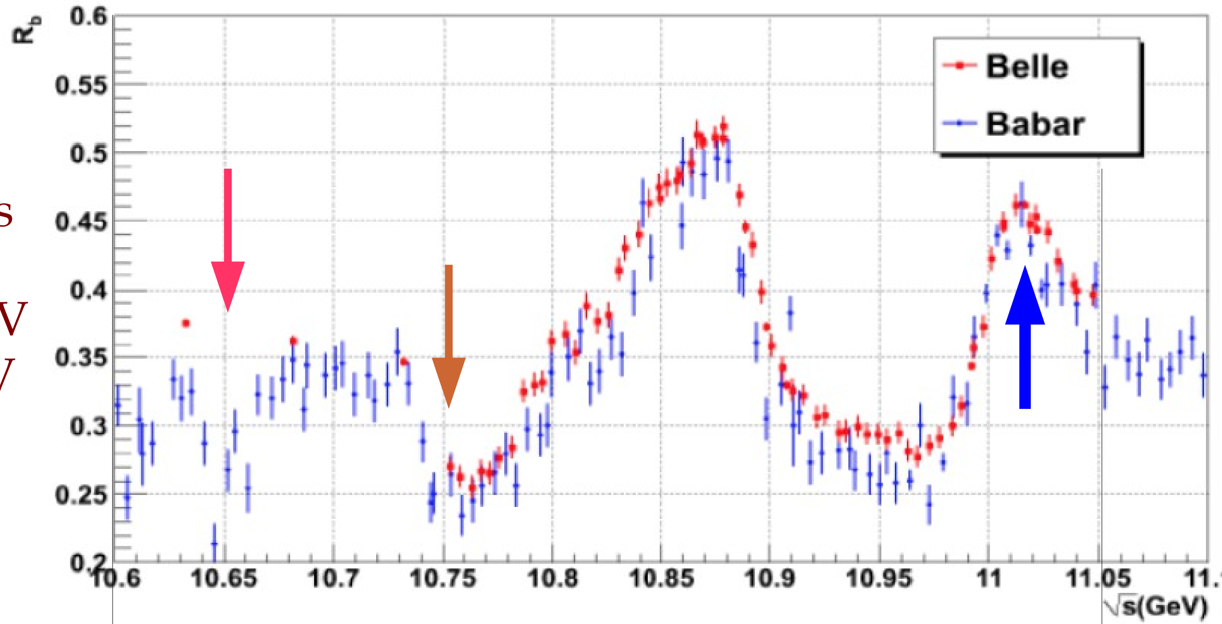
Data samples:
- 121.4 fb^{-1} on Υ(5S) nominal peak, at √s = 10865 GeV
- 61 points, 50 pb^{-1}, √s = 10.75-11.05 GeV
- 16 points, 1 fb^{-1} , √s = 10.63-11.02 GeV
- continuum data at √s = 10520 GeV

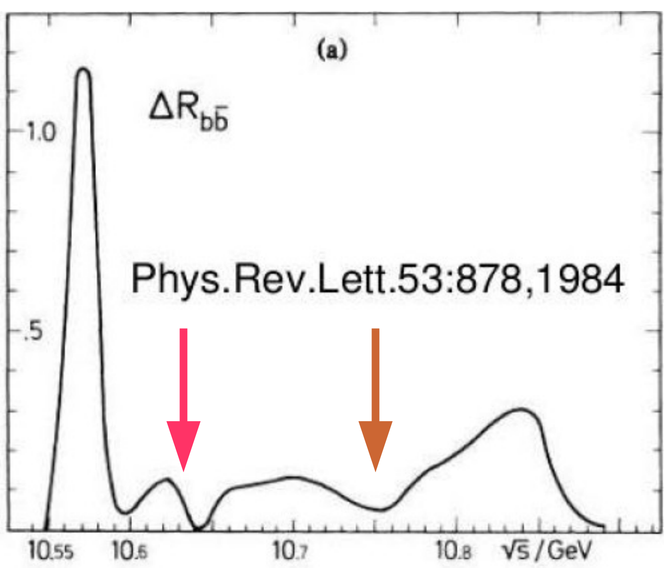
$R_b = \sigma(b\bar{b}+X)/\sigma(\mu\mu)$

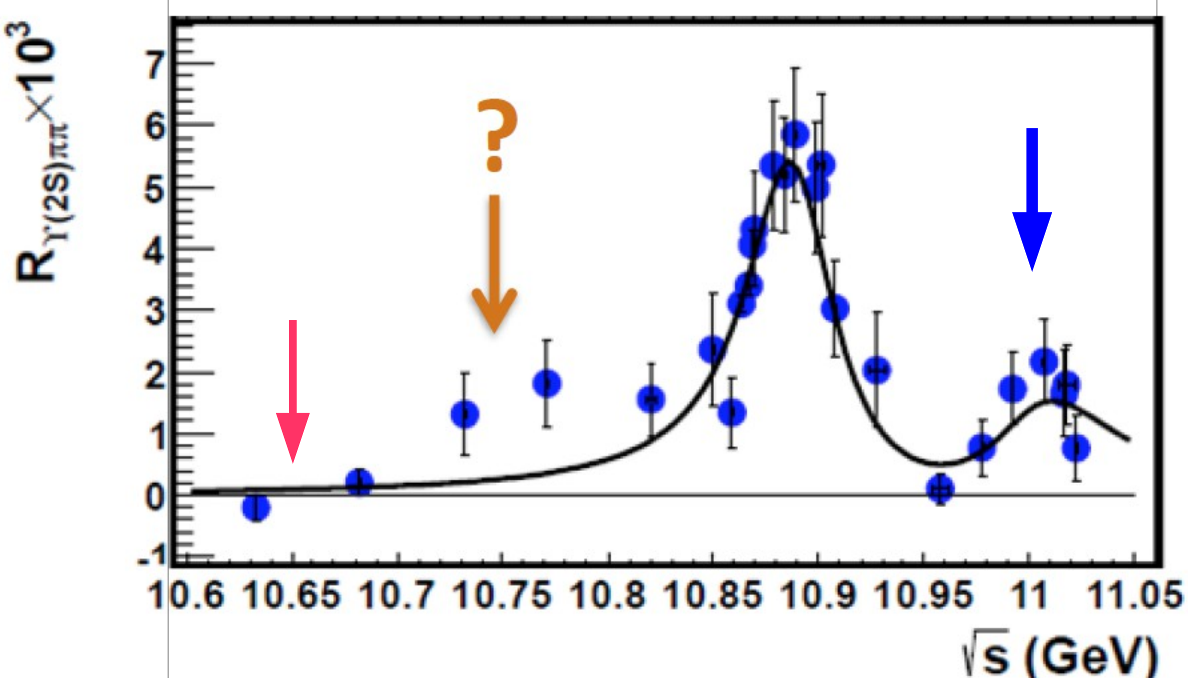
Peaks at 10.86, 11 GeV

$R_{\Upsilon\pi\pi} = \sigma(\Upsilon\pi\pi)/\sigma(\mu\mu)$

Peaks at 10.89, 11; bump at 10.75?

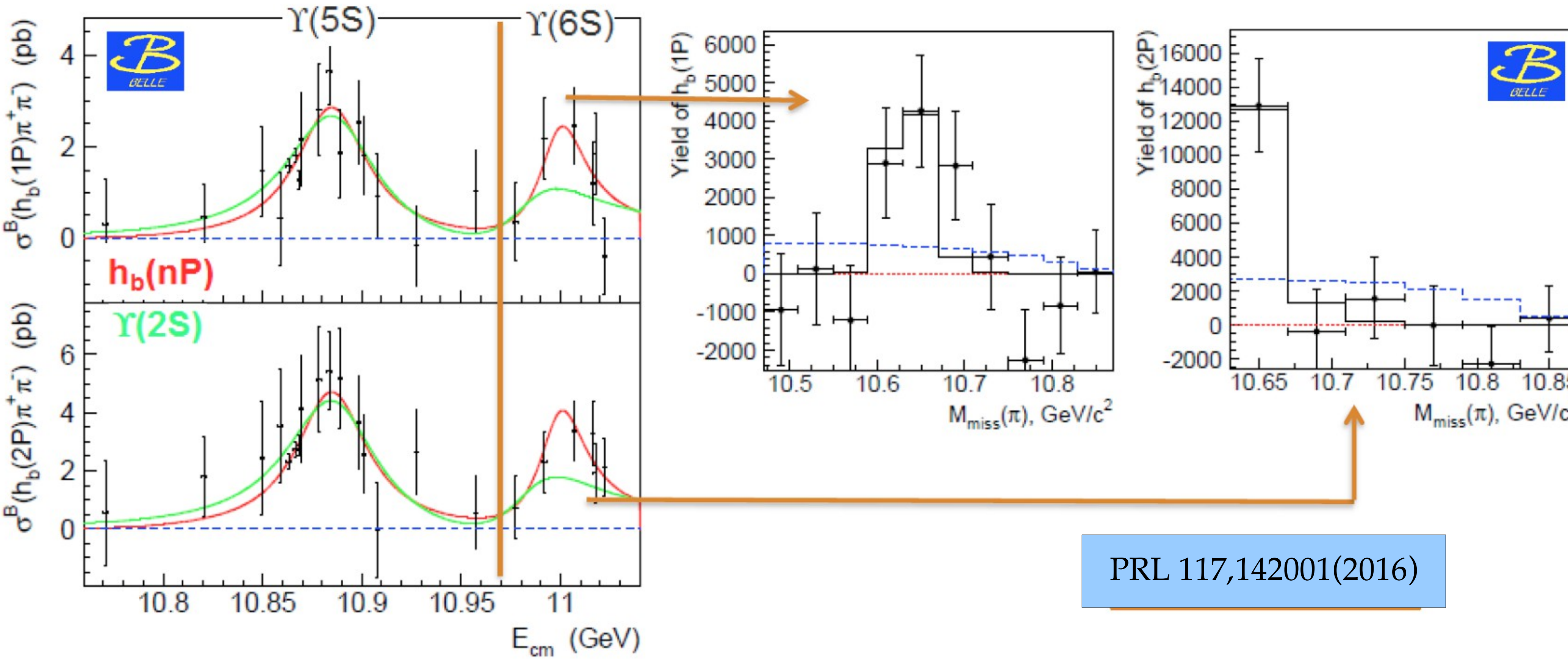






Belle: $e^+e^- \to h_b(1,2P)\,\pi\pi$

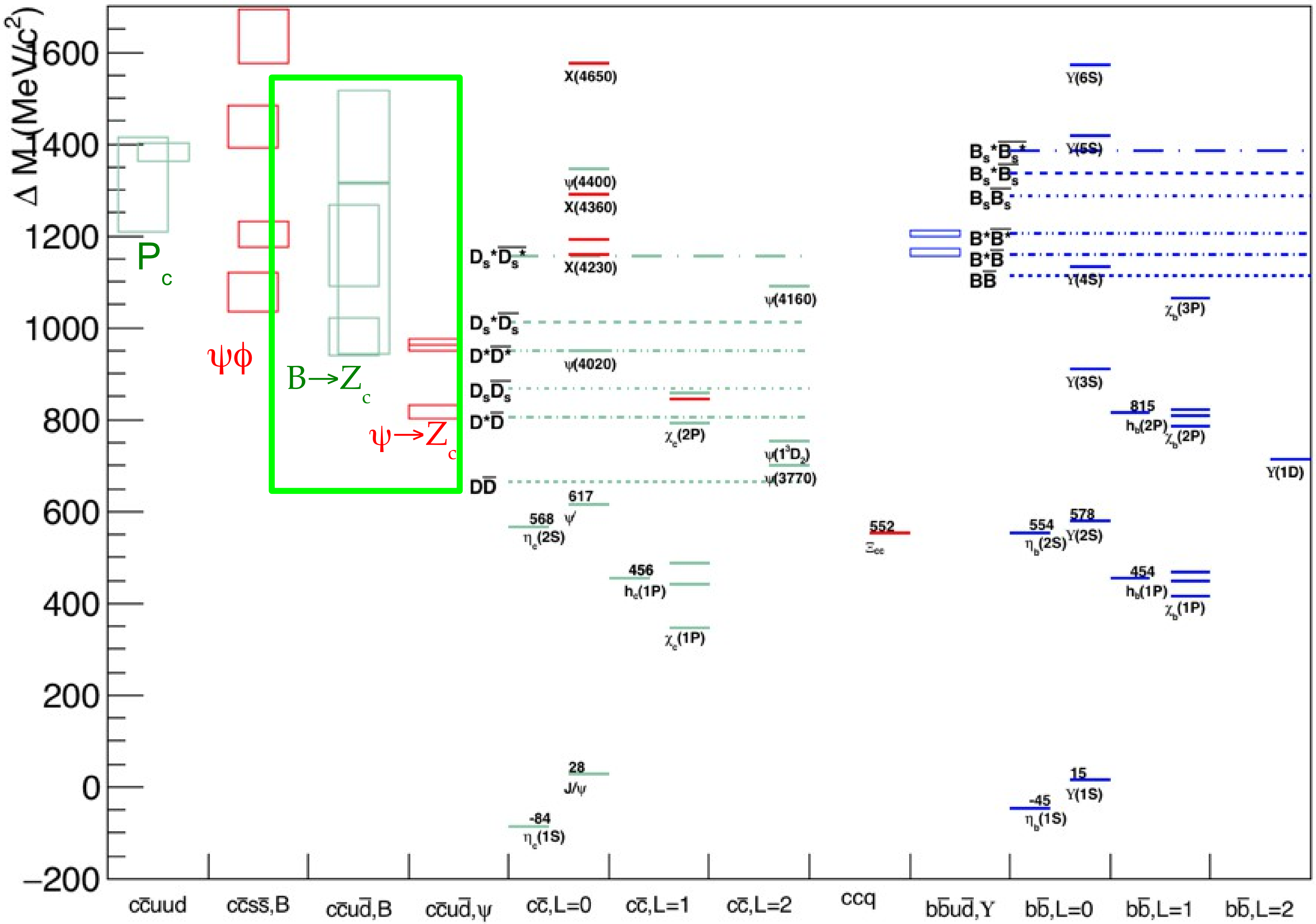
The analysis of the 6 points (1 fb^{-1} each) in the proximity of the Y(6S) show a clear evidence of dipion transitions to both the h_b states. The small statistics does not allow to quantify the fractions decaying via Zb(10610) and Zb(10650) .



PRL 117,142001(2016)

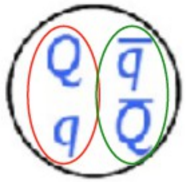
Belle-II is planning to take more data at Y(6S) during the first or second year of data taking

Charmonium(like) Bottomonium(like)



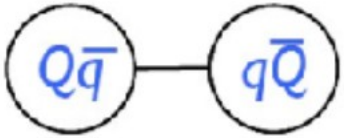
Quarkonium Tetraquarks

- compact tetraquark



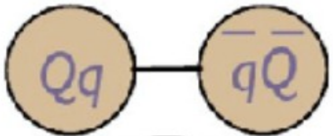
L. Maiani, A. Polosa, V. Riquer, F, Piccinini, Phys. Rev. D **89**, 114010 (2014) and reffs therein

- meson molecule



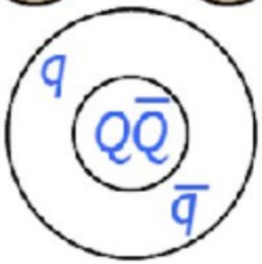
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



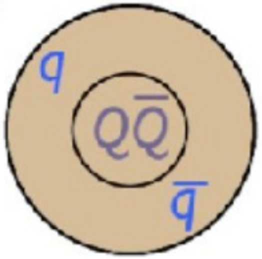
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



X.Li, M.B.Voloshin, Mod. Phys. Lett. **29**(2014) 12, 1450060 and refs. therein

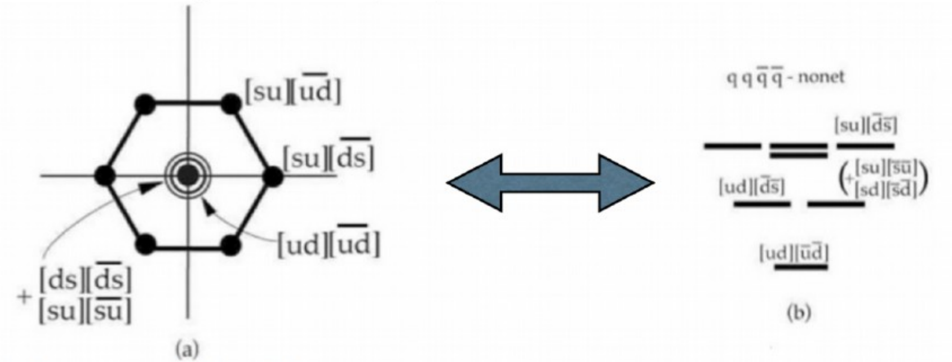
- quarkonium adjoint meson



Tetraquarks

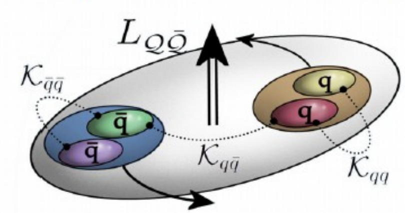
The tetraquark idea was meant to sort all the states in the scalar meson multiplet. Later on, it was used to explain the nature of the excited Ds mesons and of the X(3872).

Maiani et al, Phys.Rev.Lett. 93 (2004) 212002
t'Hooft et al, Phys.Lett. B662 (2008) 424-430



$$\sigma^{[0]} = [ud][\bar{u}\bar{d}]$$
$$\kappa = [su][\bar{u}\bar{d}];\ [sd][\bar{u}\bar{d}]\ (+\text{ conjugate doublet})$$
$$f_0^{[0]} = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$
$$a_0 = [su][\bar{s}\bar{d}];\ \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}};\ [sd][\bar{s}\bar{u}]$$

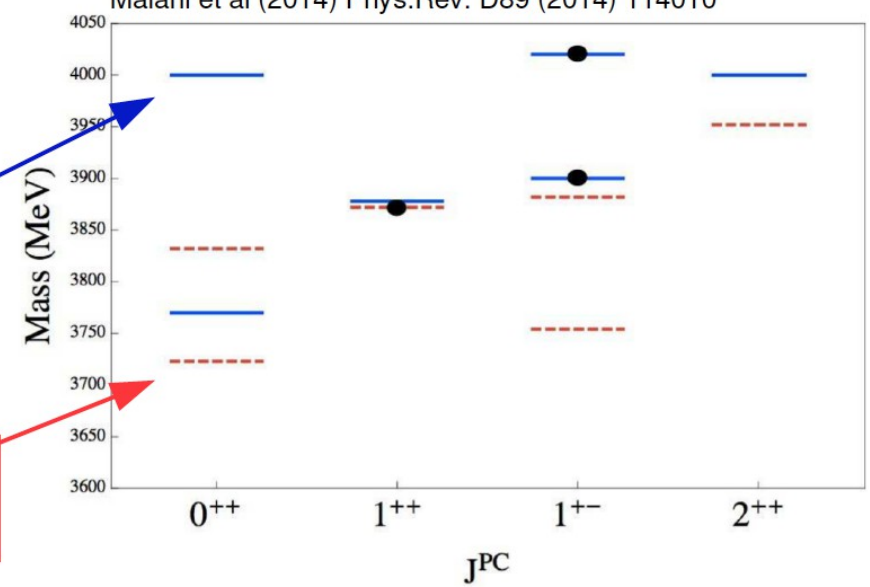
Tetraquark in the heavy sector



Interaction within di-quark dominates
$H \sim 2\kappa_{qc}(s_q.s_c + s_{\bar{q}}.s_{\bar{c}})$

Interaction across di-quarks dominates
$H \sim 2\kappa_{q\bar{q}}s_{q\bar{q}}(s_{q\bar{q}} + 1)$

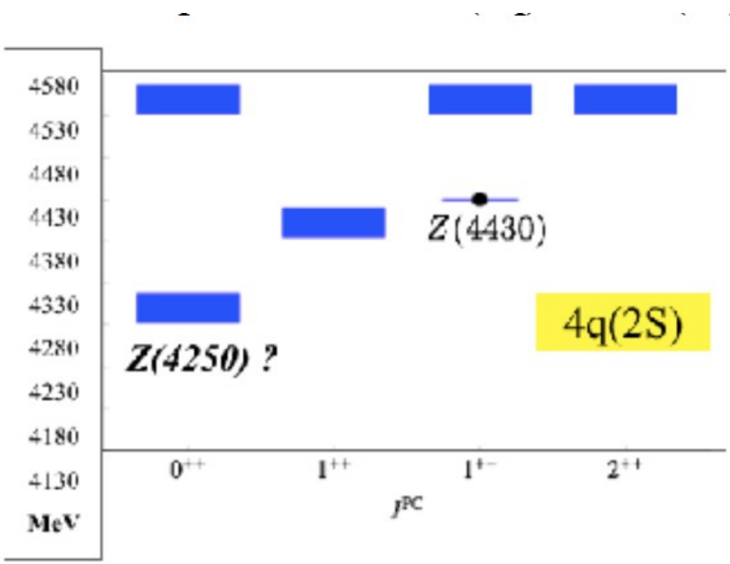
Maiani et al (2014) Phys.Rev. D89 (2014) 114010



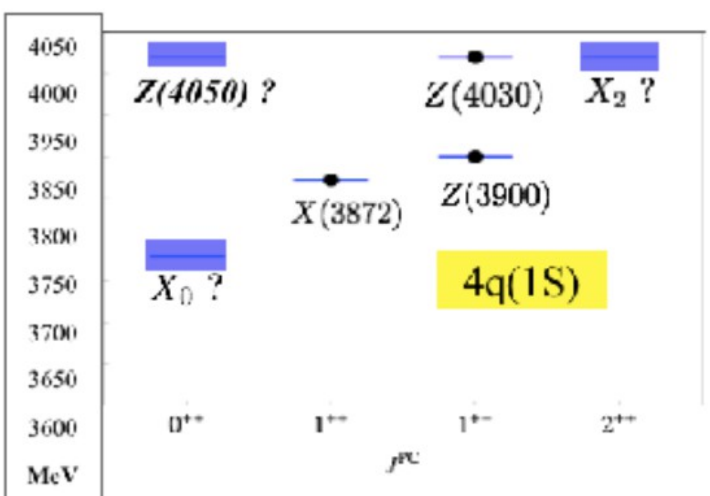
Kqc fixed by mass difference between Z(3900) and Z(4430)

Kqq fixed by mass difference baryons

XYZ as Tetraquarks

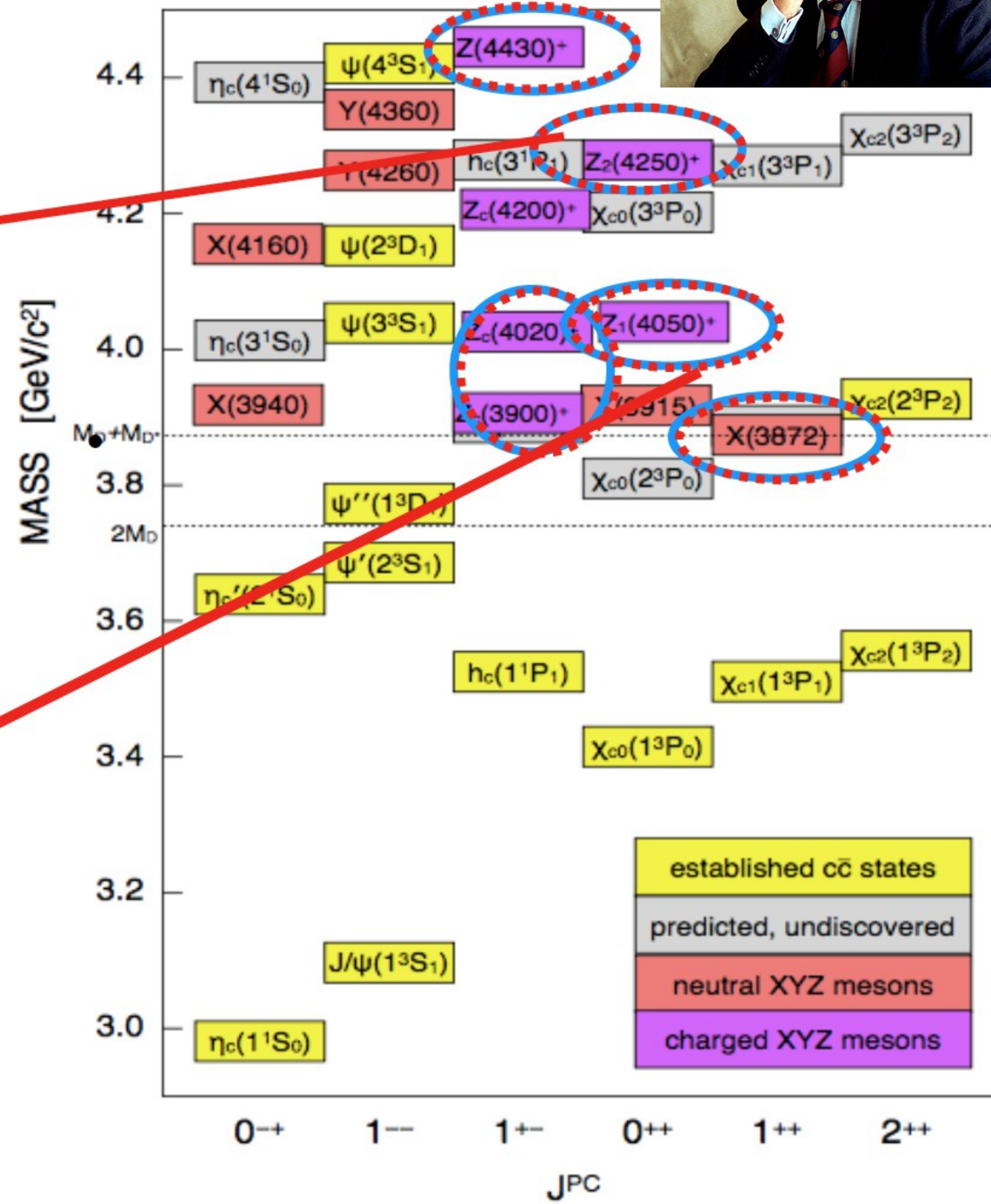


$\Delta E_r(cq) = 530$ MeV

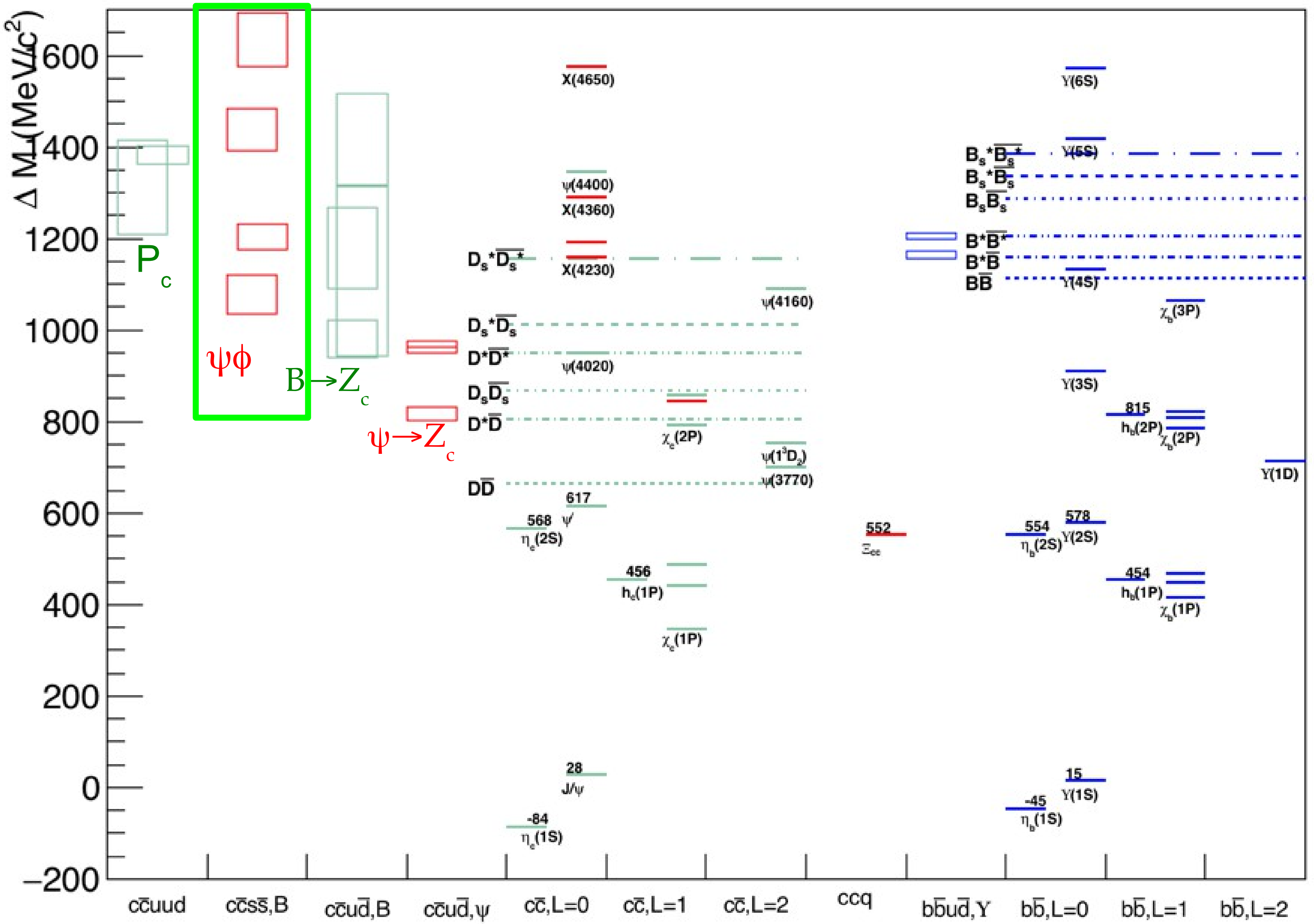


$m_{[cq]} = 1980$ MeV

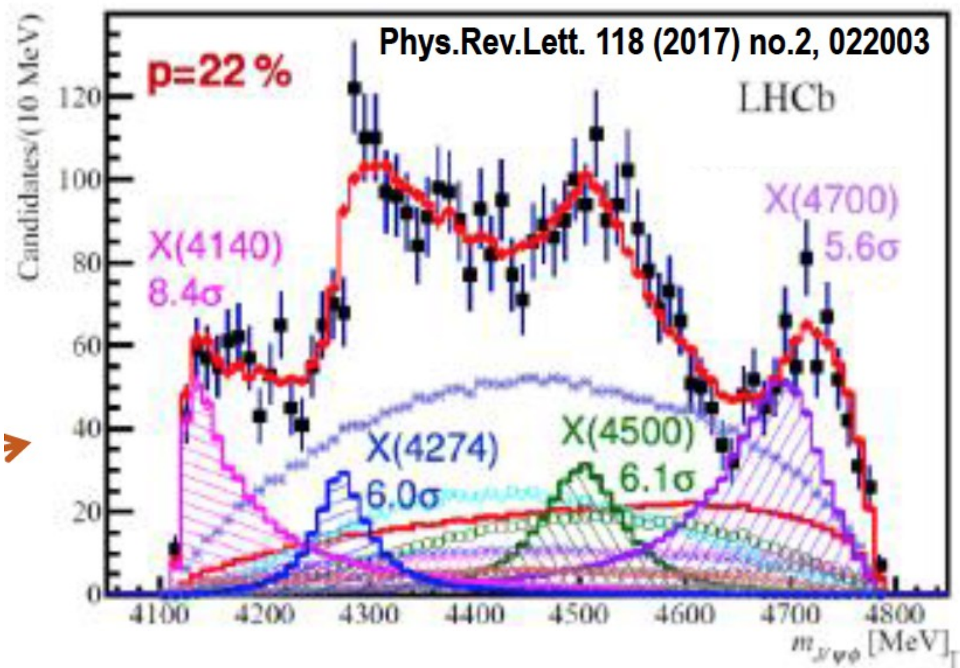
$\kappa_{cq} = 67$ MeV

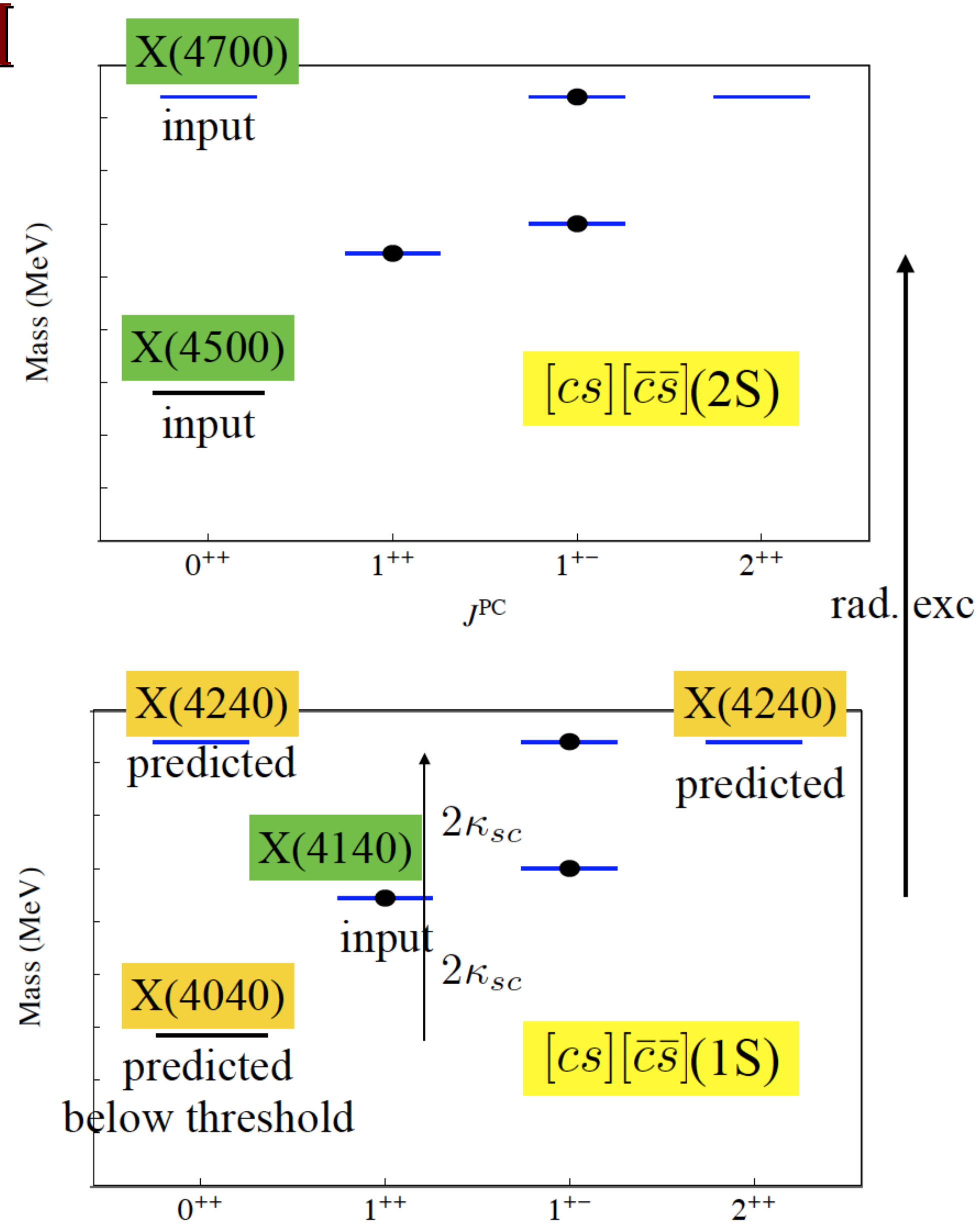


Charmonium(like) Bottomonium(like)



Tetraquark picture for charmonium-like states observed by LHCb in B → φψ ∏



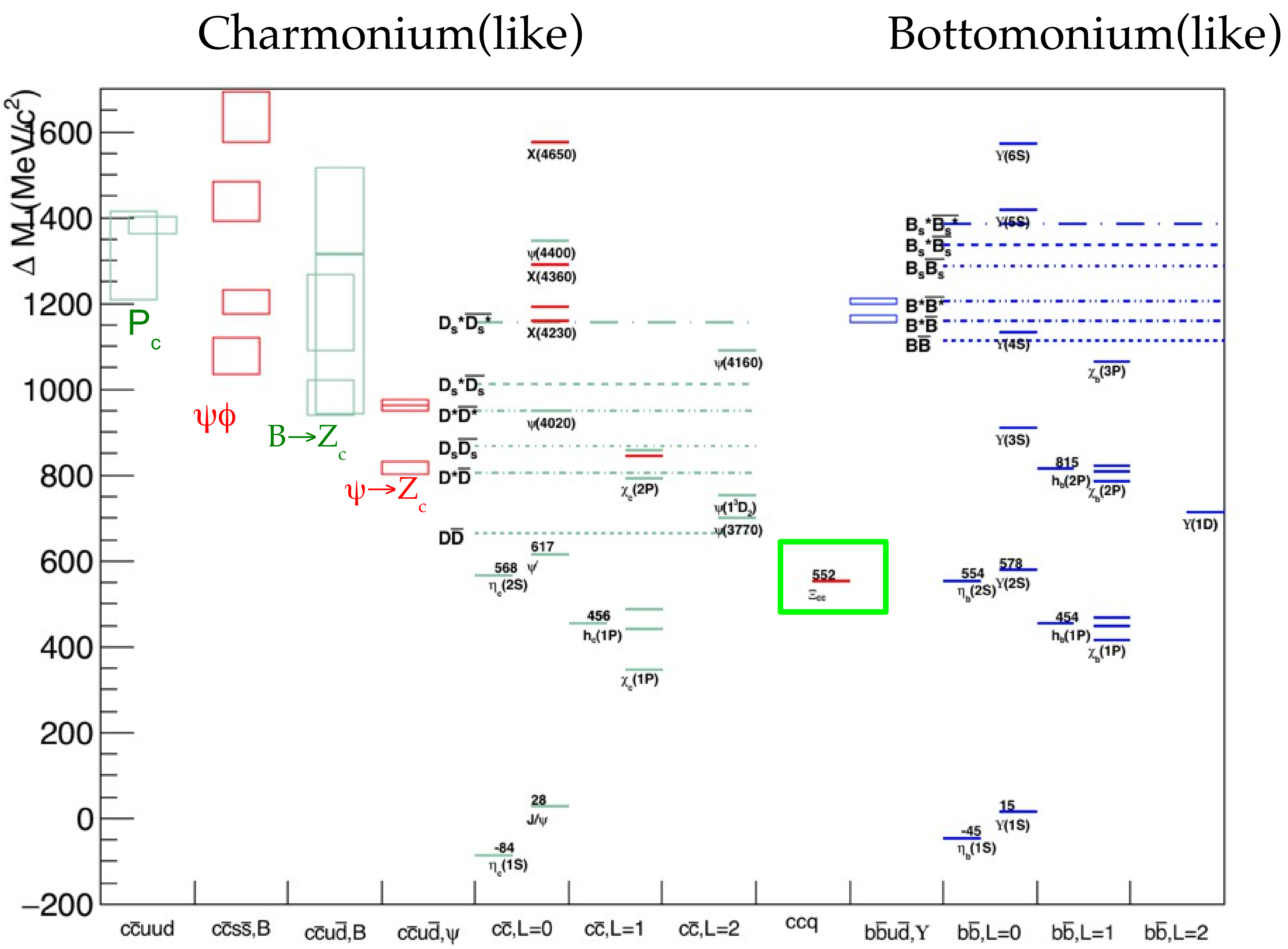


$$\Delta m = m_{cs} - m_{cq} = 129 \text{ MeV};$$

$$\kappa_{sc} = 50 \text{ MeV } (\kappa_{qc} = 67 \text{ MeV})$$

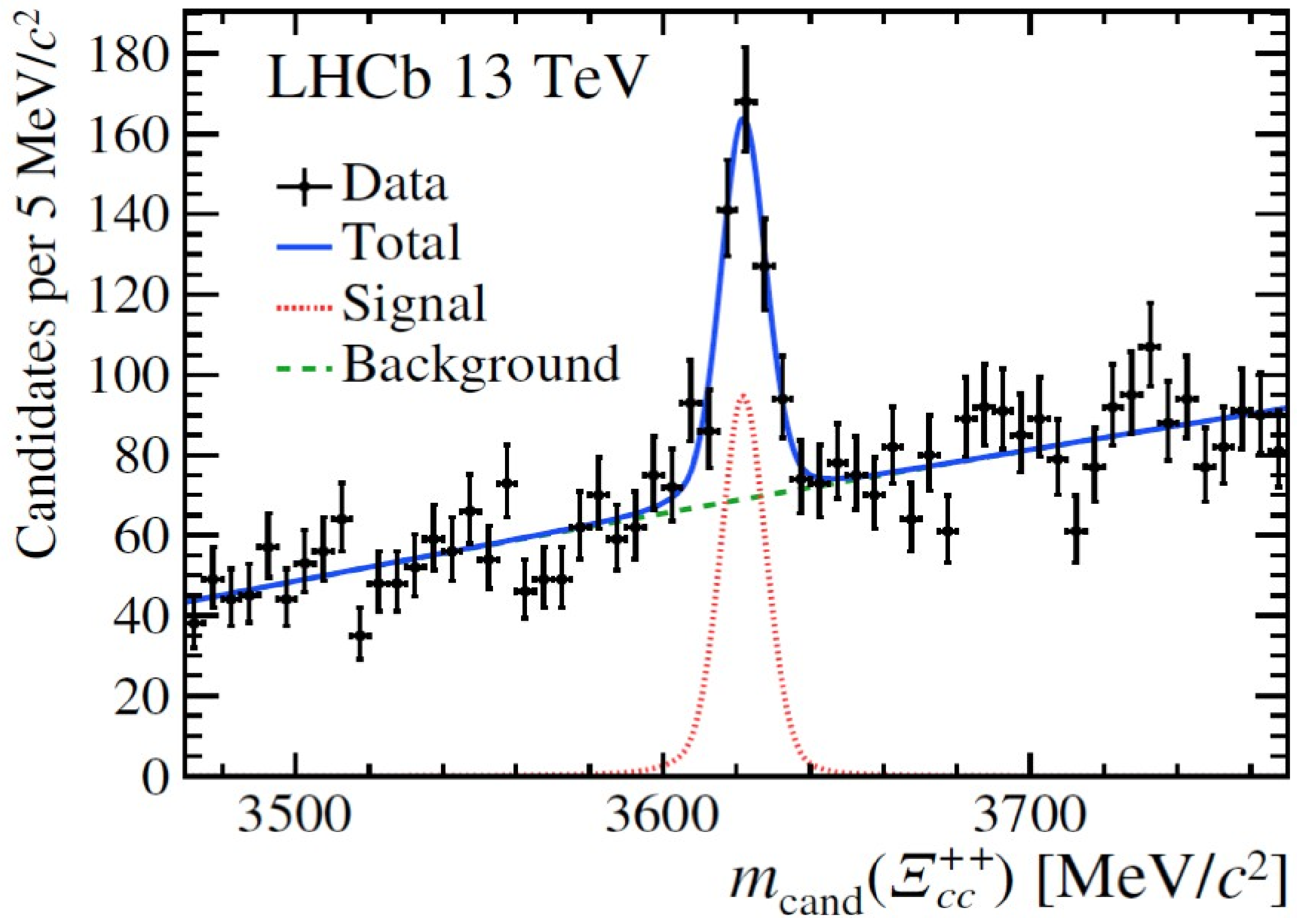
$$\text{radial excit.} = 460 \text{ MeV}$$

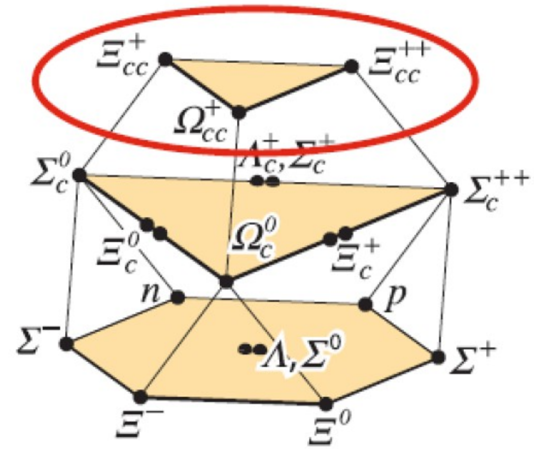
$$[Z(4430) - Z(3900) = 530 \text{ MeV}]$$


Charmonium(like)
Bottomonium(like)
Δ M (MeV/c²)
Pc
ψφ
B→Zc
ψ→Zc
X(4650)
ψ(4400)
X(4360)
X(4230)
Ds*Ds*
Ds*Ds
D*D*
DsDs
D*D
DD
ψ(4020)
ψ(4160)
χc(2P)
ψ(1³D₂)
ψ(3770)
617
ψ'
568
ηc(2S)
456
hc(1P)
χc(1P)
28
J/ψ
-84
ηc(1S)
552
Ξcc
Bs*Bs*
Bs*Bs
BsBs
B*B*
B*B
BB
Υ(6S)
Υ(5S)
Υ(4S)
χb(3P)
Υ(3S)
815
hb(2P)
χb(2P)
Υ(1D)
554
ηb(2S)
578
Υ(2S)
454
hb(1P)
χb(1P)
15
Υ(1S)
-45
ηb(1S)
ccuud
ccss,B
ccud,B
ccud,ψ
cc,L=0
cc,L=1
cc,L=2
ccq
bbud,Υ
bb,L=0
bb,L=1
bb,L=2

Discovery of Double Charm Baryons

As announced in Gao's talk this morning....





Narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum.

Significant displacement consistent with a weakly decaying particle.

Observed in two LHCb data sets.

Consistent with Ξ_{cc}^{++} (ccu).

Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\,\text{MeV}$

CQM rules!

PHYSICAL REVIEW D **90,** 094007 (2014)

Baryons with two heavy quarks: Masses, production, decays, and detection

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(Received 5 September 2014; published 10 November 2014)

The large number of B_c mesons observed by LHCb suggests a sizable cross section for producing doubly heavy baryons in the same experiment. Motivated by this, we estimate masses of the doubly heavy $J = 1/2$ baryons Ξ_{cc}, Ξ_{bb}, and Ξ_{bc}, and their $J = 3/2$ hyperfine partners, using a method which accurately predicts the masses of ground-state baryons with a single heavy quark. We obtain $M(\Xi_{cc}) = 3627 \pm 12$ MeV, $M(\Xi_{cc}^*) = 3690 \pm 12$ MeV, $M(\Xi_{bb}) = 10162 \pm 12$ MeV, $M(\Xi_{bb}^*) = 10184 \pm 12$ MeV, $M(\Xi_{bc}) = 6914 \pm 13$ MeV, $M(\Xi'_{bc}) = 6933 \pm 12$ MeV, and $M(\Xi_{bc}^*) = 6969 \pm 14$ MeV. As a byproduct, we estimate the hyperfine splitting between B_c^* and B_c mesons to be 68 ± 8 MeV. We discuss P-wave excitations, production mechanisms, decay modes, lifetimes, and prospects for detection of the doubly heavy baryons.

DOI: 10.1103/PhysRevD.90.094007 PACS numbers: 14.20.Lq, 14.20.Mr, 12.40.Yx

Double beauty Tetraquark

ArXiV:1707.07666

Discovery of doubly-charmed Ξ_{cc} baryon implies a stable $bb\bar{u}\bar{d}$ tetraquark

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Raymond and Beverly Sackler Faculty of Exact Sciences
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University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637, USA

ArXiV:1707.09575

FERMILAB–PUB–17/289–T

Heavy-quark symmetry implies stable heavy tetraquark mesons $Q_iQ_j\bar{q}_k\bar{q}_l$

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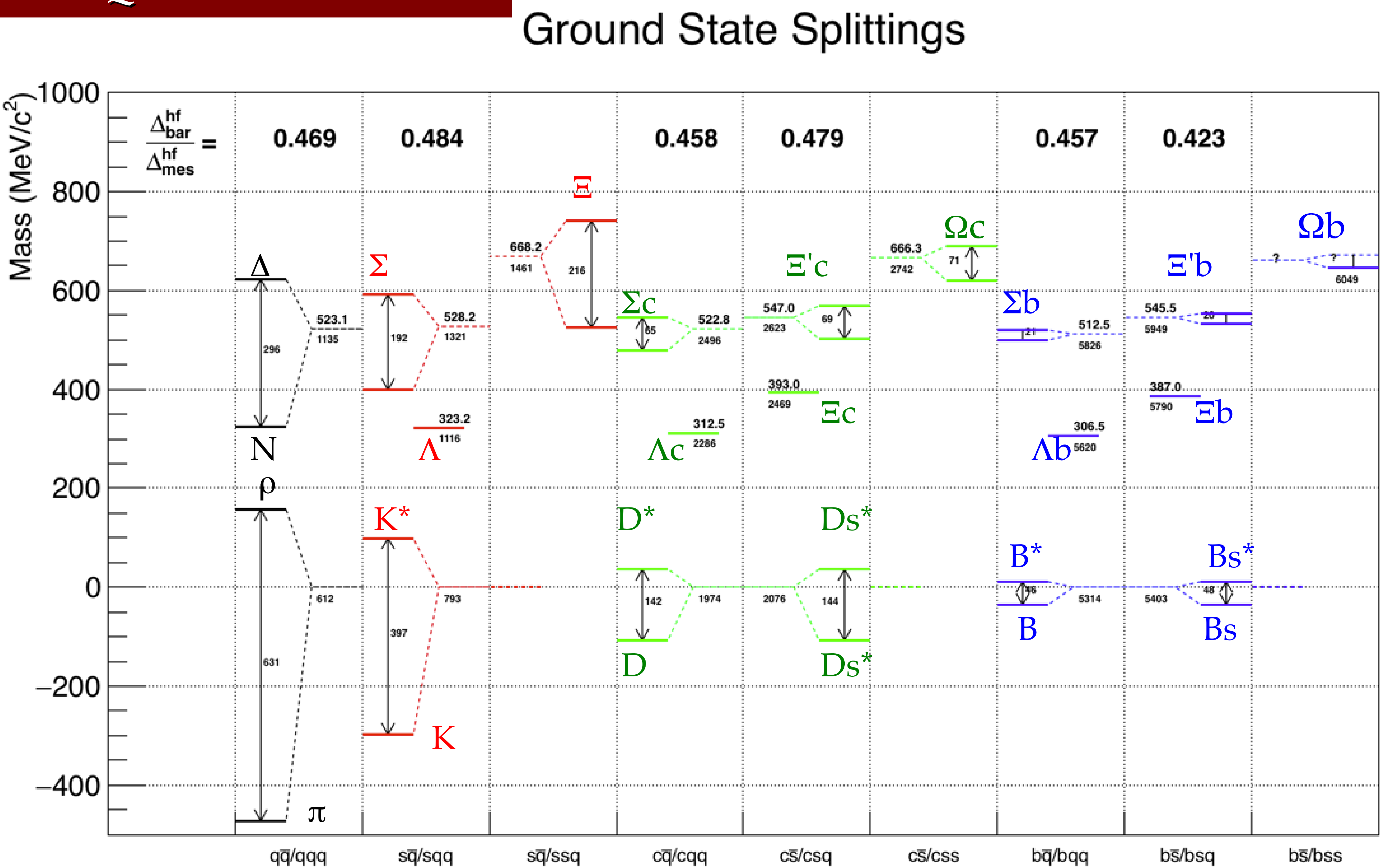
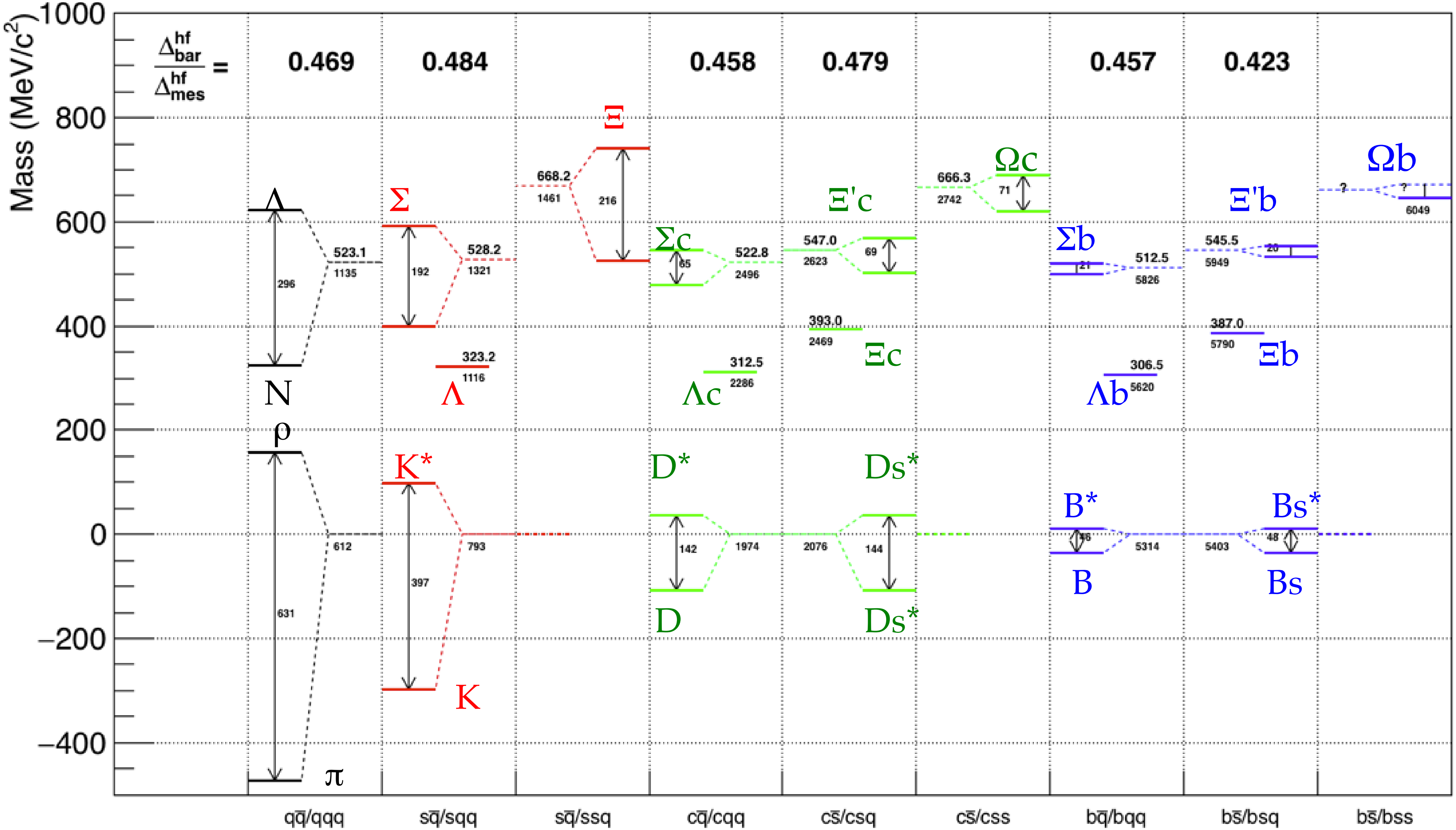
(Dated: August 1, 2017)

CQM rules! Part 2



AdS / CFT?

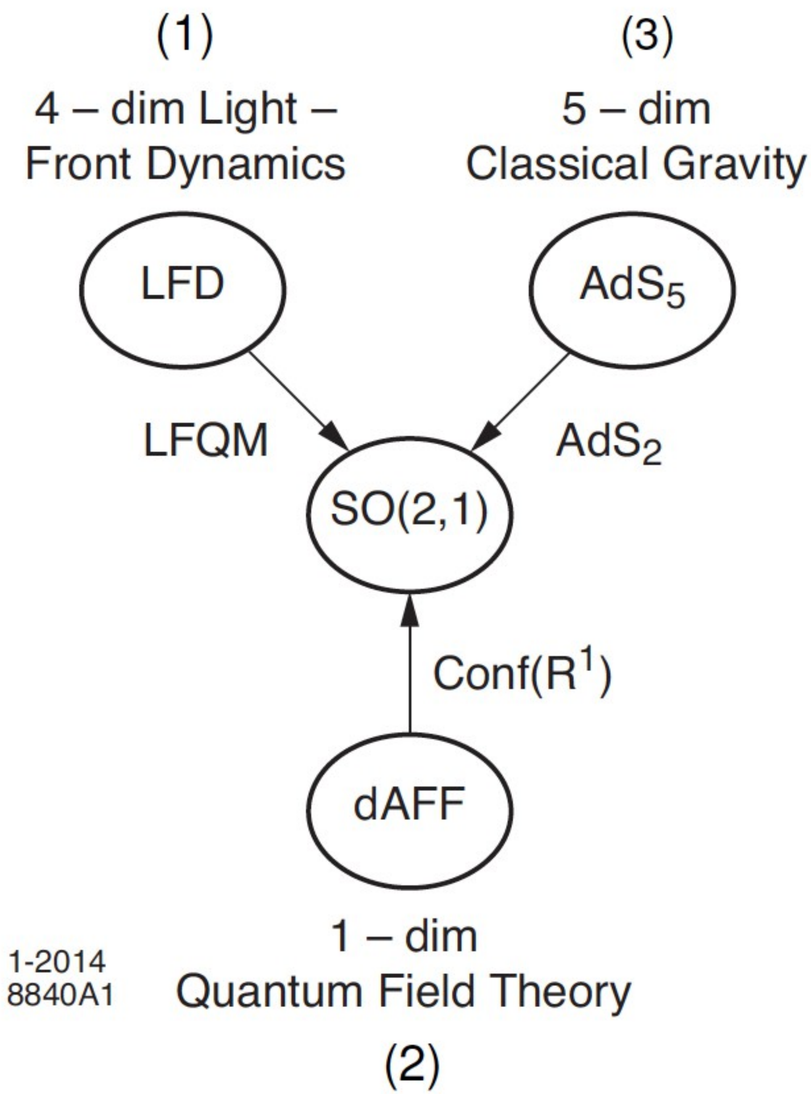
Ground State Splittings



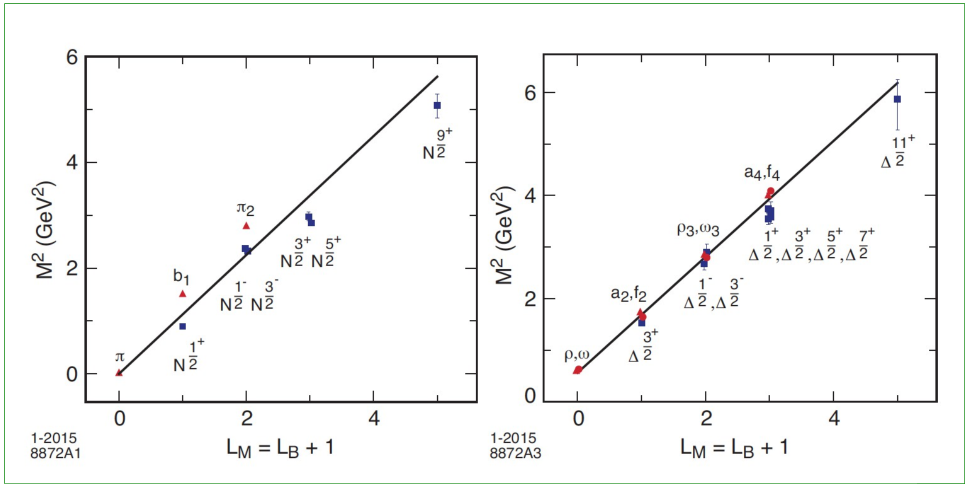
Brodsky, Dosch, De Teramond: “Superconformal QM at work!”

Brodsky, Dosch, De Teramond: ArXiV 1504.05112

Hadronic triality: Baryons and Baryon-Meson SUSY



From light hadrons...



Superconformal Quantum Mechanics [Fubini and Rabinovici (1984)]

Isomorphism *Conf* $(R^1) \sim SO(2,1) \sim \mathrm{AdS}_2$

Brodsky, Dosch, De Teramond: ArXiV 1504.05112

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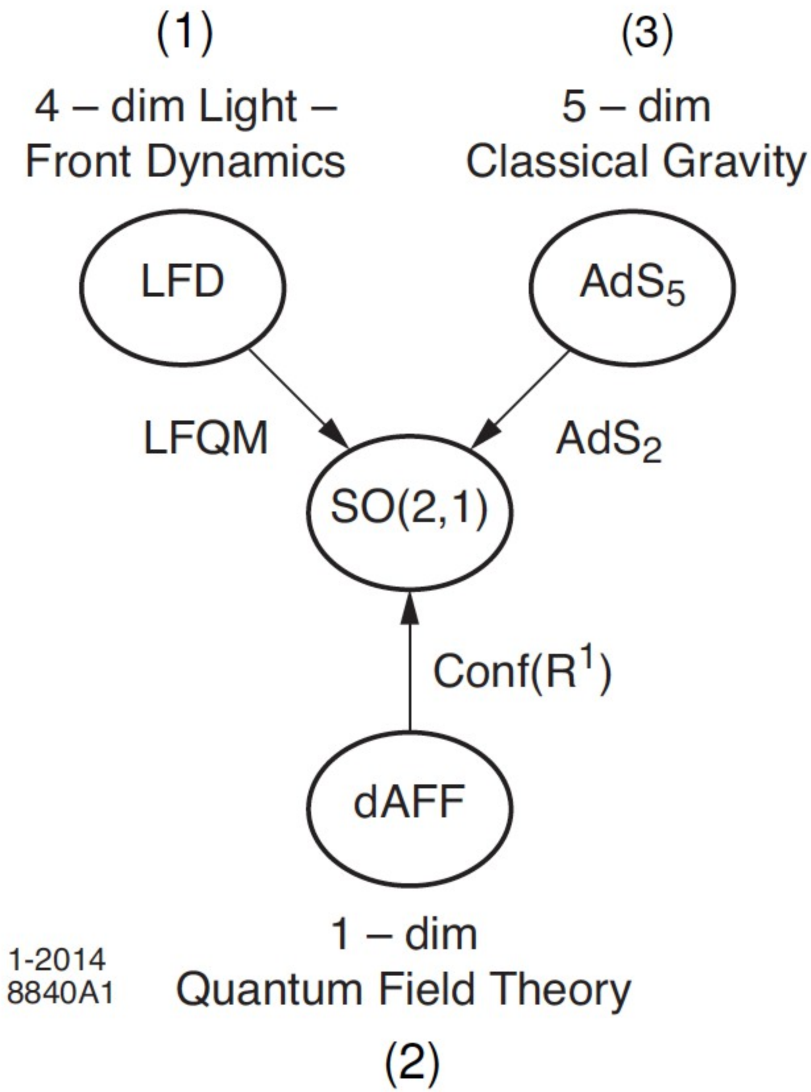

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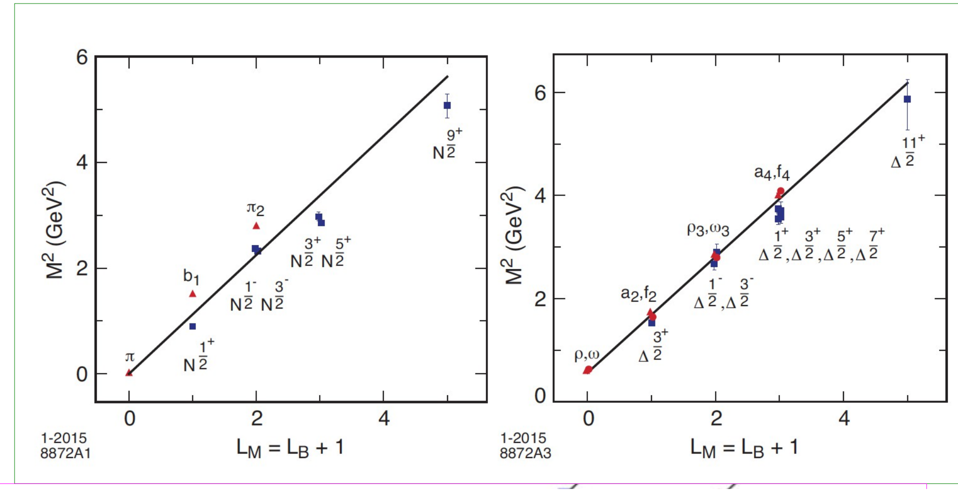

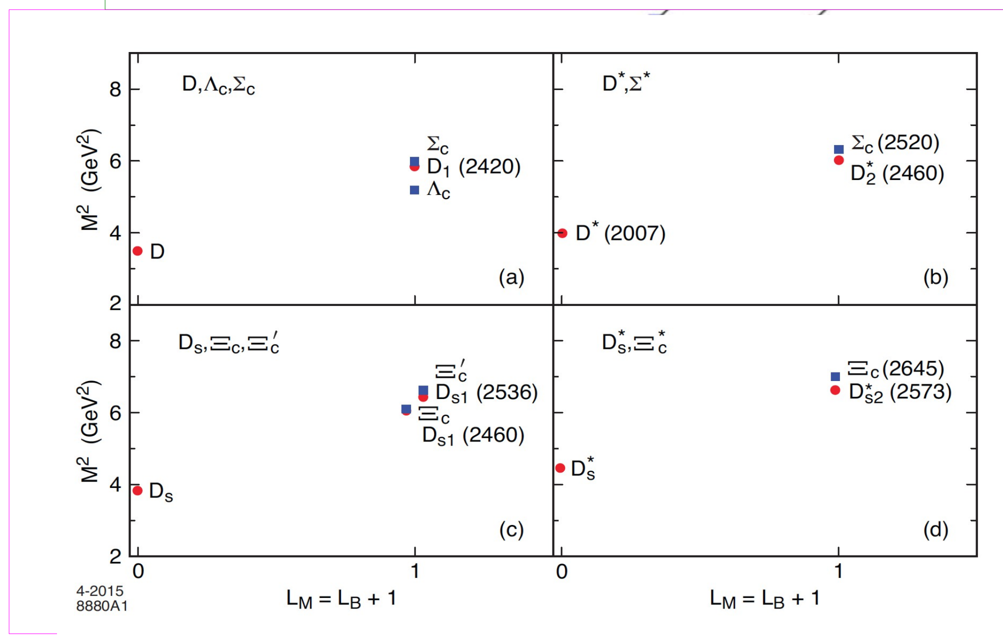

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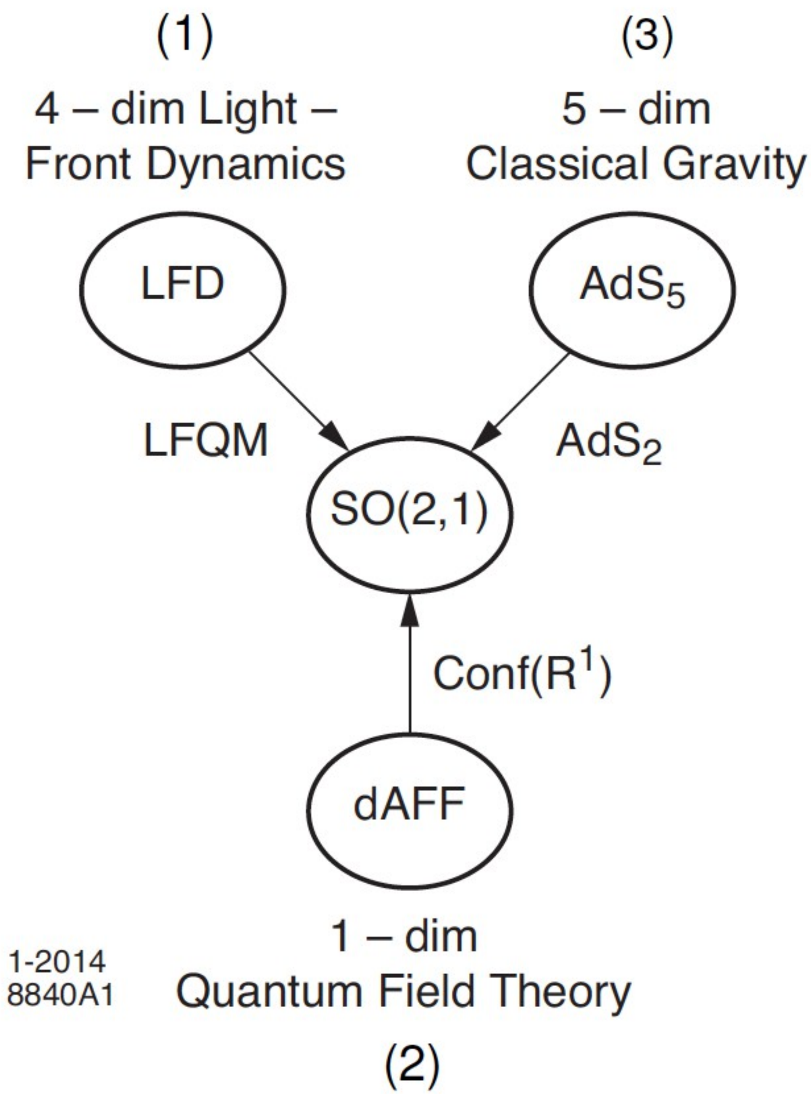

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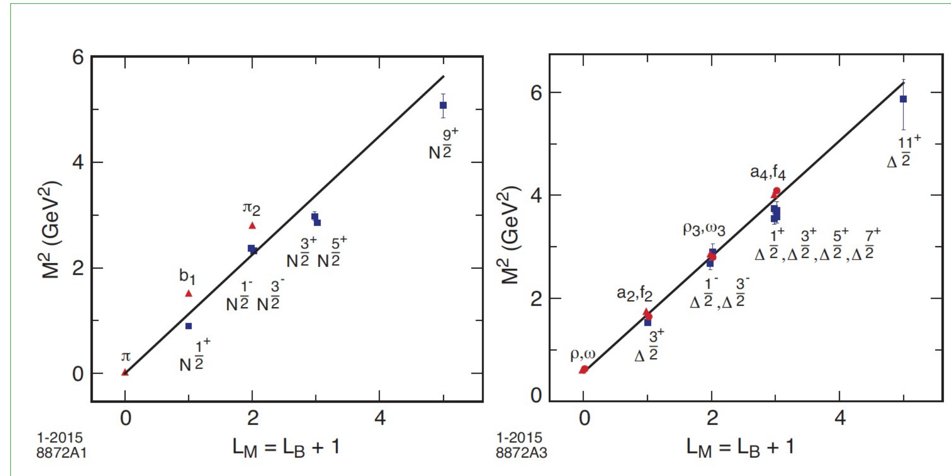
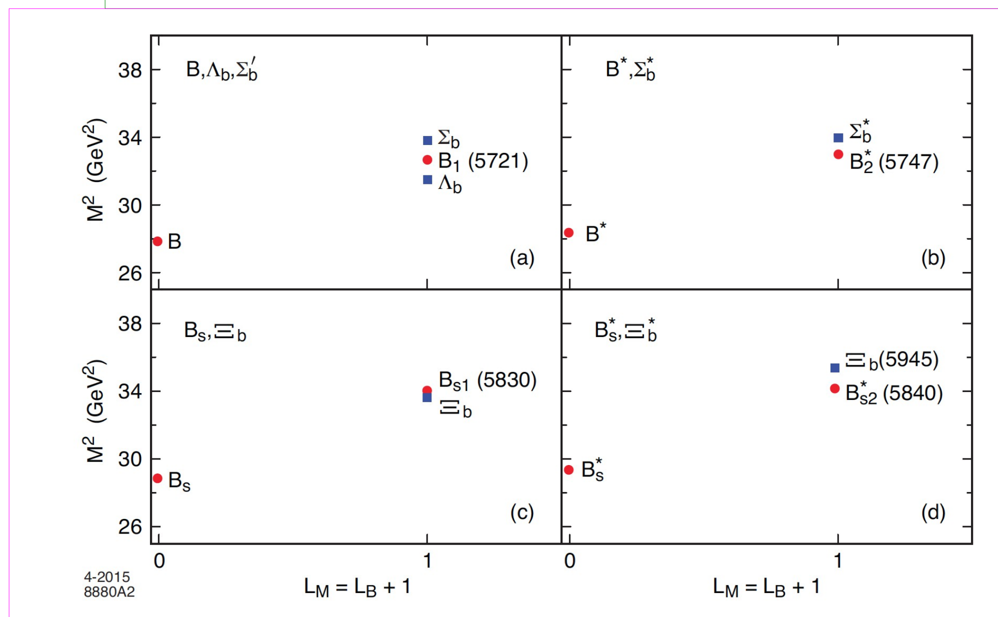




Superconformal Quantum Mechanics [Fubini and Rabinovici (1984)]

... To heavy ones

Isomorphism *Conf* $(R^1) \sim SO(2,1) \sim \mathrm{AdS}_2$

Λ_c excited states

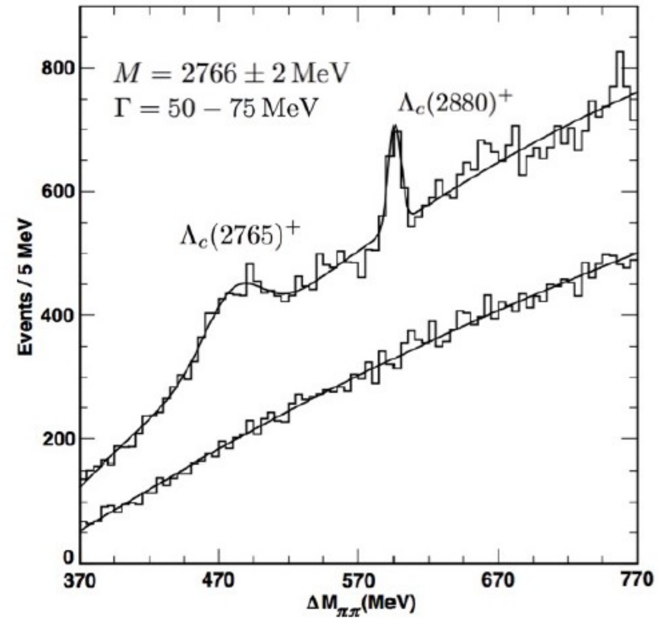
The ground state is made of a qq 'good diquark' (j_{qq}=0) and a c quark.

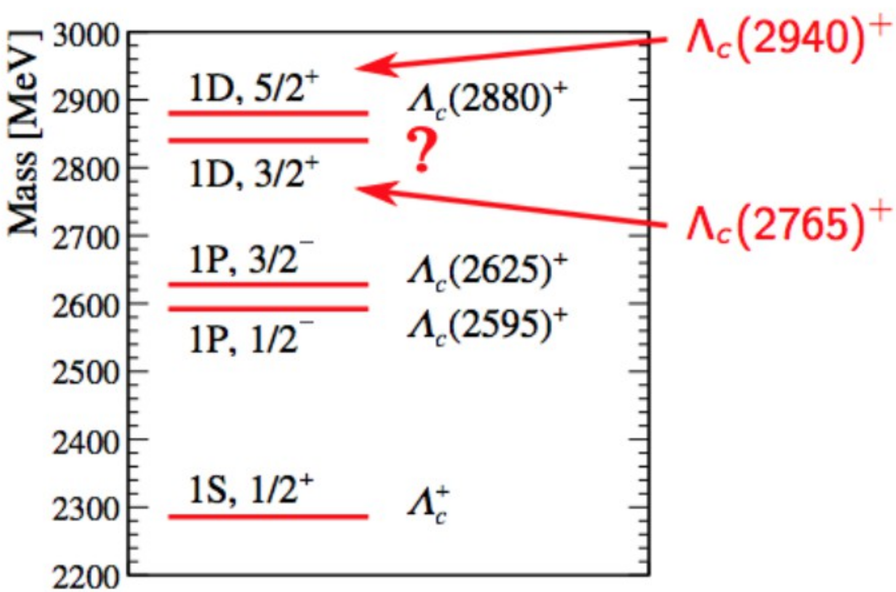
Spin/parity of the excited states will be $\mathbf{J=L+s_c}$; $P=(-1)^L$

Studied by CLEO, Babar and Belle.

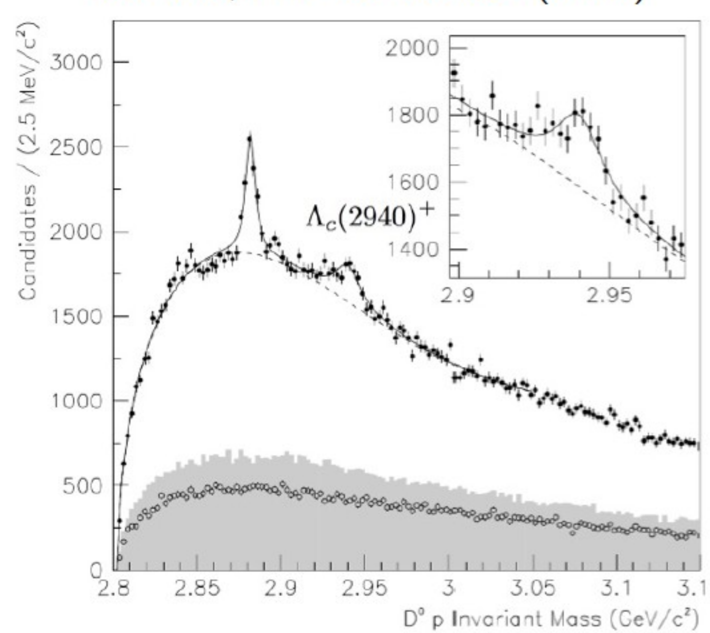
Open problem: D-wave state with $J=3/2^+$ missing.

CLEO, PRL86 4479 (2001)





BABAR, PRL 98 012001 (2007)

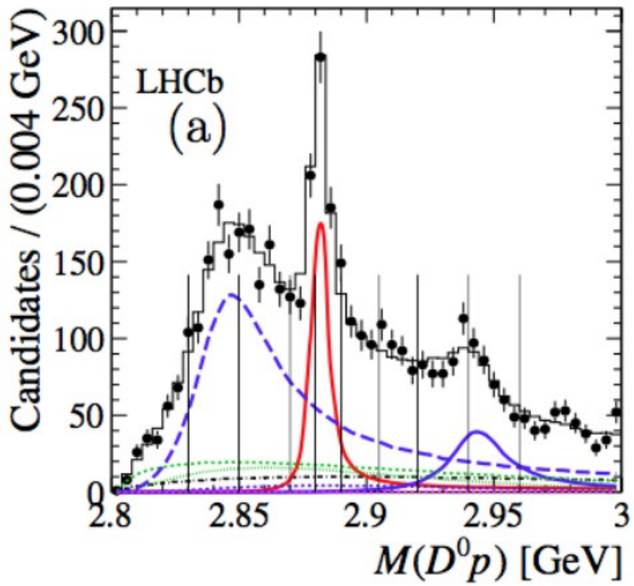


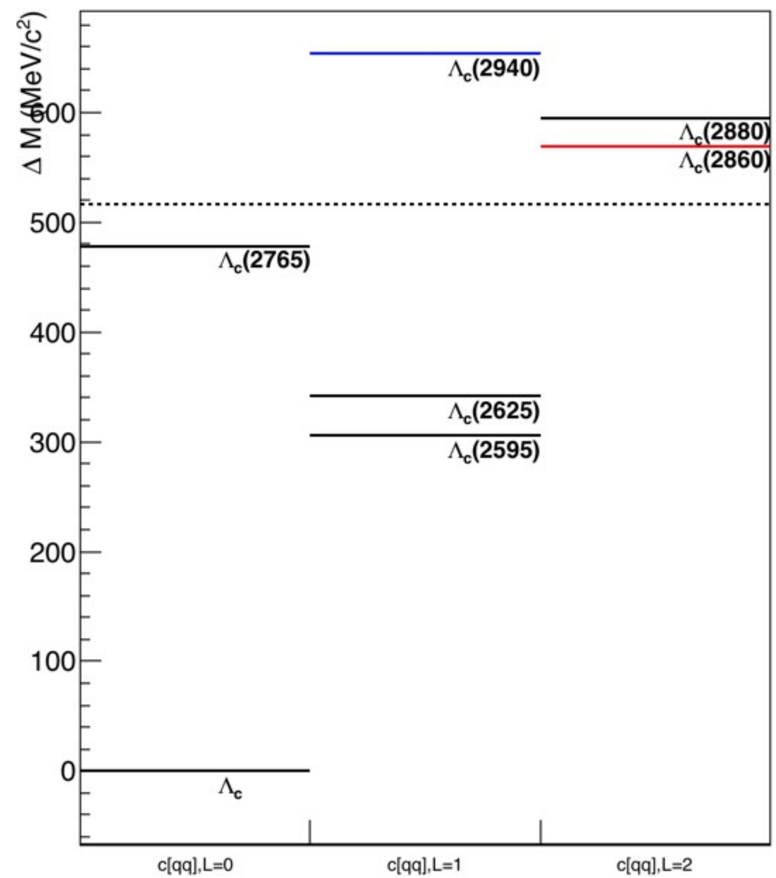
Λ_c excited states

LHCb, ArXiv:1701.07873

LHCB: search for $\Lambda_c/$ in $\Lambda_b \rightarrow (pD^0)K^+$

Sample : 11k Λ_b





$J^P = 3/2^+$

$$M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(syst)^{+1.1}_{-5.6}(model)\ \mathrm{MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(syst)^{+5.9}_{-20.0}(model)\ \mathrm{MeV}$$

preferred $J^P = 3/2^-$

$$M(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4(syst)^{+0.1}_{-4.6}(model)\ \mathrm{MeV}$$

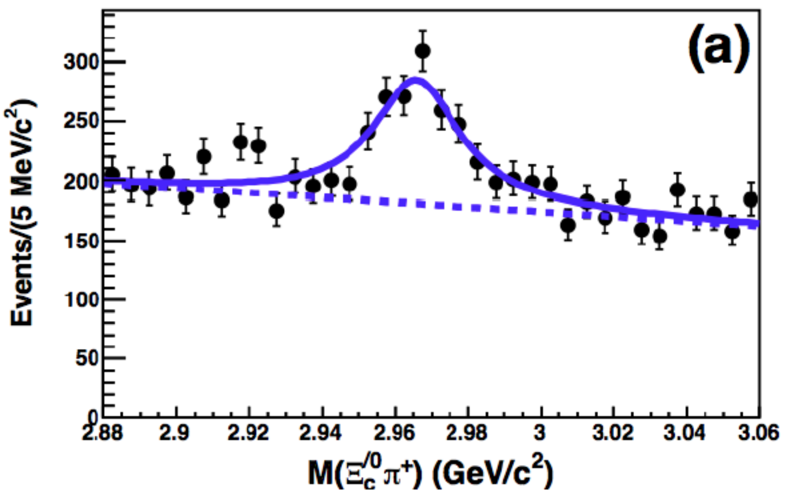
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9(syst)^{+5.2}_{-10.4}(model)\ \mathrm{MeV}$$

Ξ_c excited states

BELLE, PRD94, 032002 (2016)

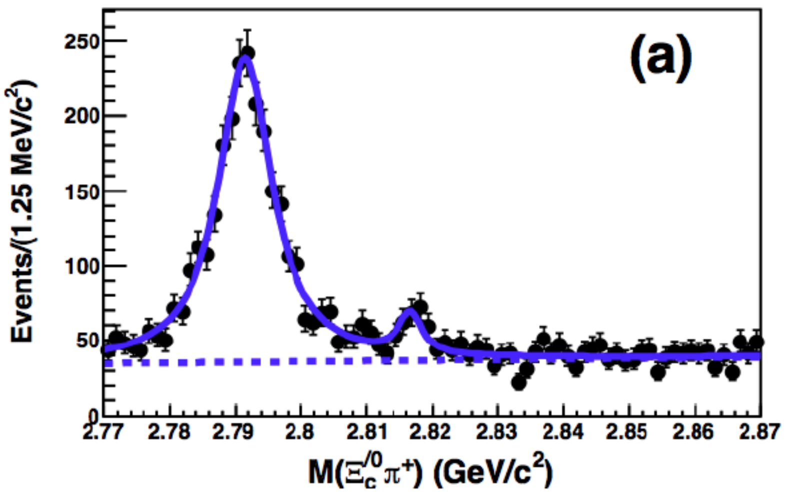
- Study of 5 different Ξ_c states:
  $\Xi_c^{'}$ $(J^P = 1/2^+)$,
  $\Xi_c^{'}(2646)$ $(J^P = 3/2^+)$,
  $\Xi_c(2790)$ $(J^P = 1/2^-)$,
  $\Xi_c(2815)$ $(J^P = ?)$
  using several decay modes
- Measurements of masses and widths
- All measured values significantly more precise than PDG: to investigate hadron mass models including isospin splittings
- Good agreement with theoretical expectations, modest disagreement for the $\Xi_c(2980)$ state wrt previous measurements

$\Xi_c(2980) \rightarrow \Xi_c^{'}\pi^+$



$\Xi_c(2790) \rightarrow \Xi_c^{'}\pi^+$

$\Xi_c(2815) \rightarrow \Xi_c^{'}\pi^+$

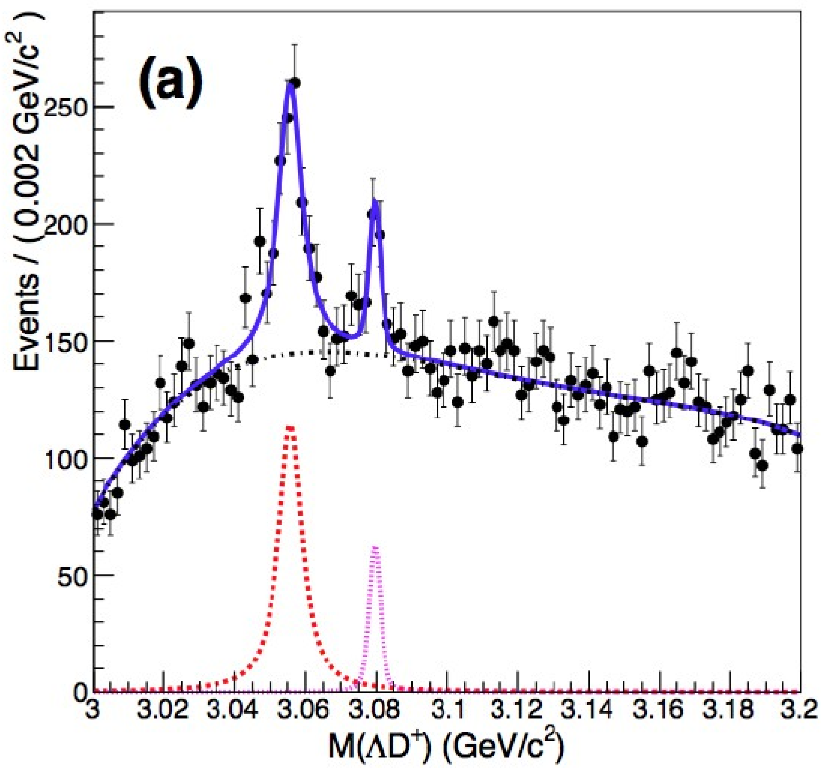


Ξ_c excited states

BELLE, PRD94, 052011 (2016)

- Study of Ξ_c^* decaying to ΛD^+ and ΛD^0 states
- First observation of the $\Xi_c(3055)^0$ with 8.6σ
  $M(\Xi_c(3055)^0) = 3059.0 \pm 0.5 \pm 0.6$
  $\Gamma(\Xi_c(3055)^0) = 6.4 \pm 2.1 \pm 1.1$
- Combined analysis coomparing ΛD^+ with $\Sigma_c^{++} K^-$ and $\Sigma_c^{*++} K^-$

$\Xi_c^+(3055)$, $\Xi_c^+(3080)$



$$\mathcal{B}(\Xi_c(3055)^+ \to \Lambda D^+)/\mathcal{B}(\Xi_c(3055)^+ \to \Sigma_c^{++} K^-) = 5.09 \pm 1.01 \pm 0.76$$
$$\mathcal{B}(\Xi_c(3080)^+ \to \Lambda D^+)/\mathcal{B}(\Xi_c(3080)^+ \to \Sigma_c^{++} K^-) = 1.29 \pm 0.30 \pm 0.15$$
$$\mathcal{B}(\Xi_c(3080)^+ \to \Sigma_c^{++}(2520) K^-)/\mathcal{B}(\Xi_c(3080)^+ \to \Sigma_c^{++} K^-) = 1.07 \pm 1.01 \pm 0.76$$

- Contradictions with expectations from theory

Ξ_c excited states

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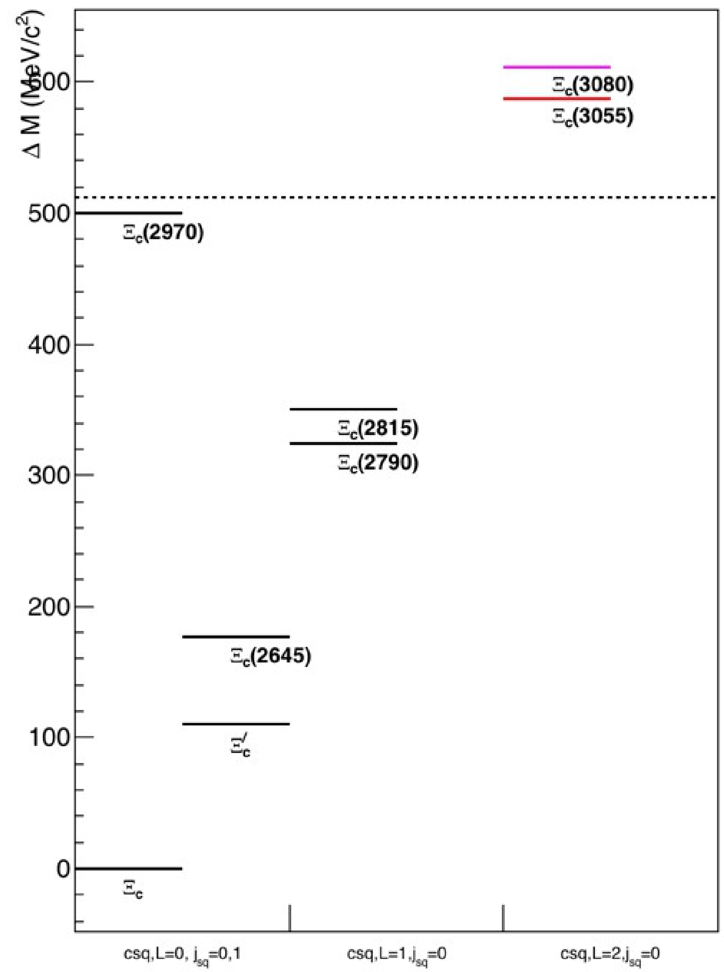

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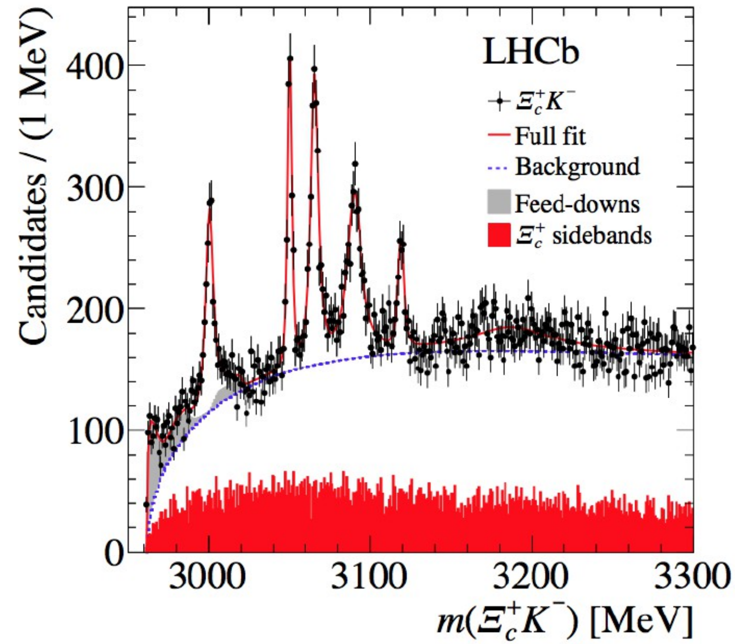
- Contradictions with expectations from theory

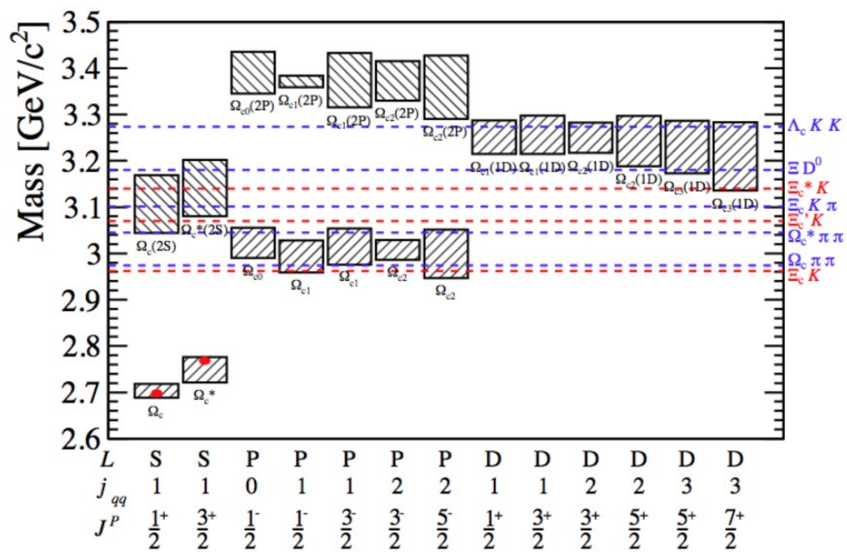
Ω_c excited states

LHCb, PRL 118 (2017) 182001

- Observation of 5 new excited Ω_c states with significances greater than 5σ
- The broad state ($\Omega_c(3188)$) could be a superposition of several states
- The largest systematic uncertainty is due to possible interference and due to the Ξ_c^+ mass knowledge

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2\,\text{MeV}, 95\%\ \text{CL}$	$970 \pm 60 \pm 20$	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6\,\text{MeV}, 95\%\ \text{CL}$	$480 \pm 70 \pm 30$	10.4
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	





Karliner-Rosner (ArXiV: 1703.07774): narrow width suggests that the ss diquark is very tightly bound, and the decay:

$c(ss) \rightarrow q(ss)\, c\bar{q} = \Xi D^0$

is kinematically forbidden.

In conclusion …

Neutral bottomonium and charmonium bound state spectroscopy is approaching completion: recent progress was made on charmonium 2P wave

Above the thresholds, analogies and differences are still not completely understood:
- Zb and Zc exhibit different BR patterns
- BES-III is discovering a much richer phenomenology between 4.2 and 4.4 GeV

Heavy meson and baryon spectroscopy are tightly bound

LHC-b is showing its huge potential in heavy hadron spectroscopy
- confirmation of the Zc(4430) tetraquark
- observation of 4 tetraquark states in psi phi
- observation of the first pentaquark
- discovery of many excited heavy baryons
- discovery of the first double heavy baryon

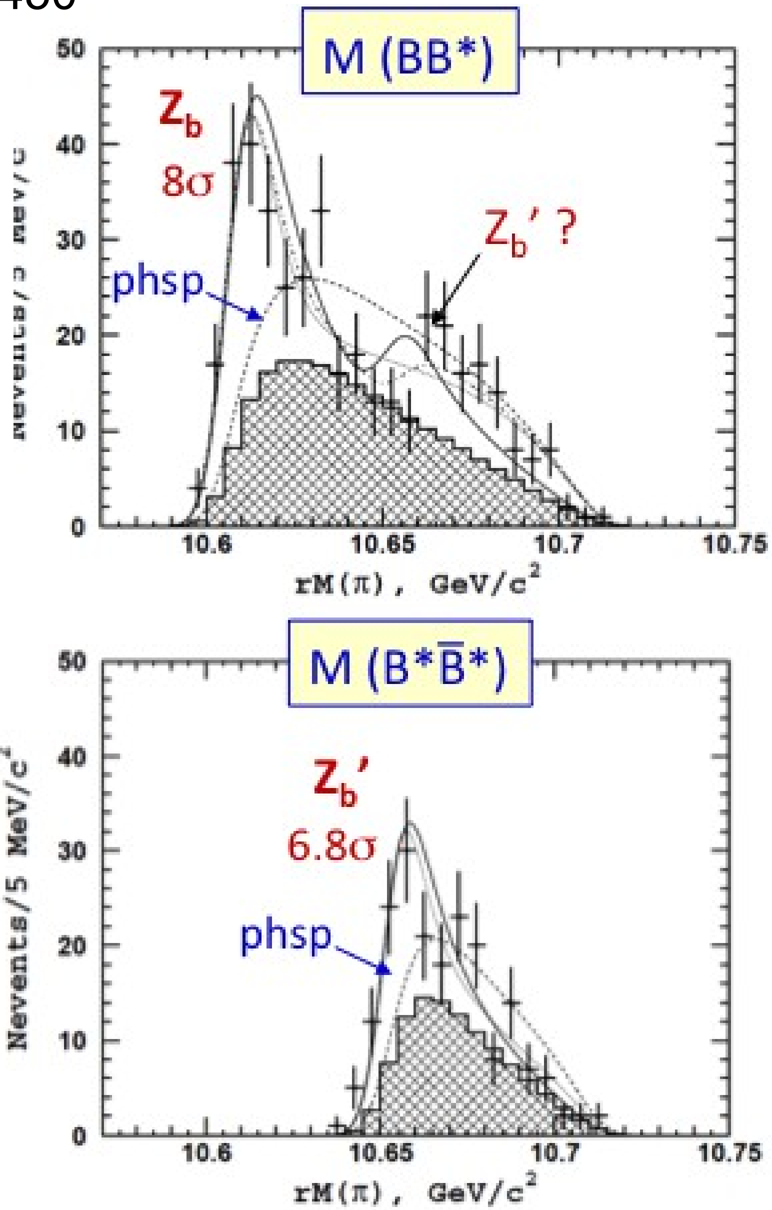
LHCB, BES-III and Belle-II future data taking promise new and even more exciting results

$Z_b \rightarrow \bar{B}B^* + B\bar{B}^*,\ B^*\bar{B}^*$

ArXiV:1209.6450

BF[$\Upsilon(5S) \rightarrow B^{(*)}\bar{B}^{(*)}\pi$]	preliminary Belle 121.4 fb^{-1}	significance
$B\bar{B}$	<0.60 % at 90% C.L.	
$B\bar{B}^* + B\bar{B}^*$	(4.25 ± 0.44 ± 0.69) %	9.3σ
$B^*\bar{B}^*$	(2.12 ± 0.29 ± 0.36) %	5.7σ

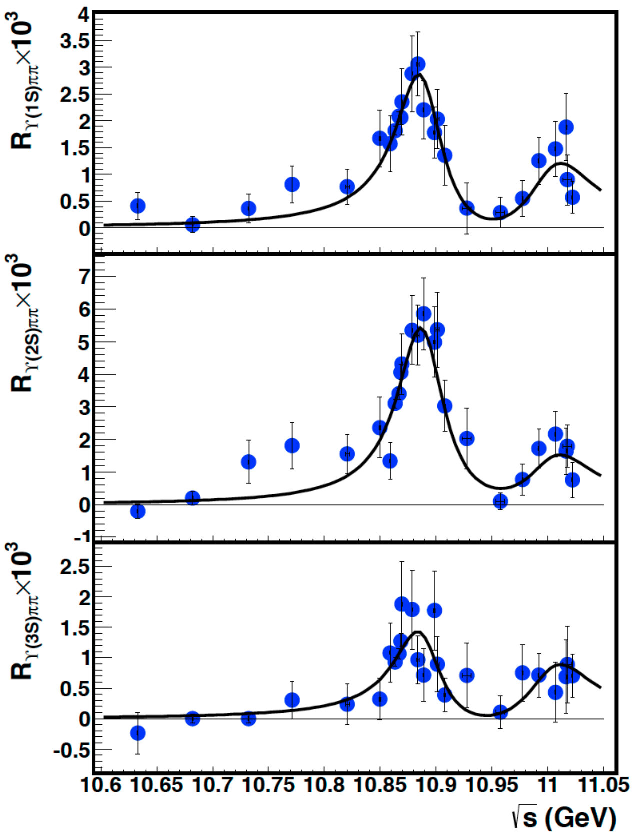
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

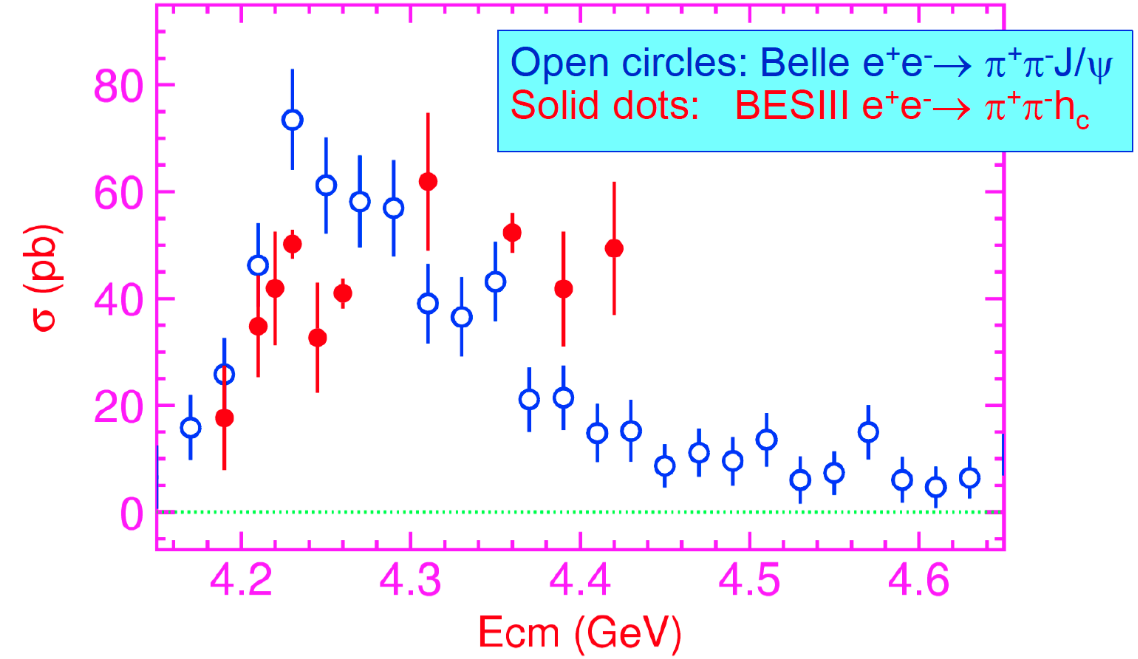


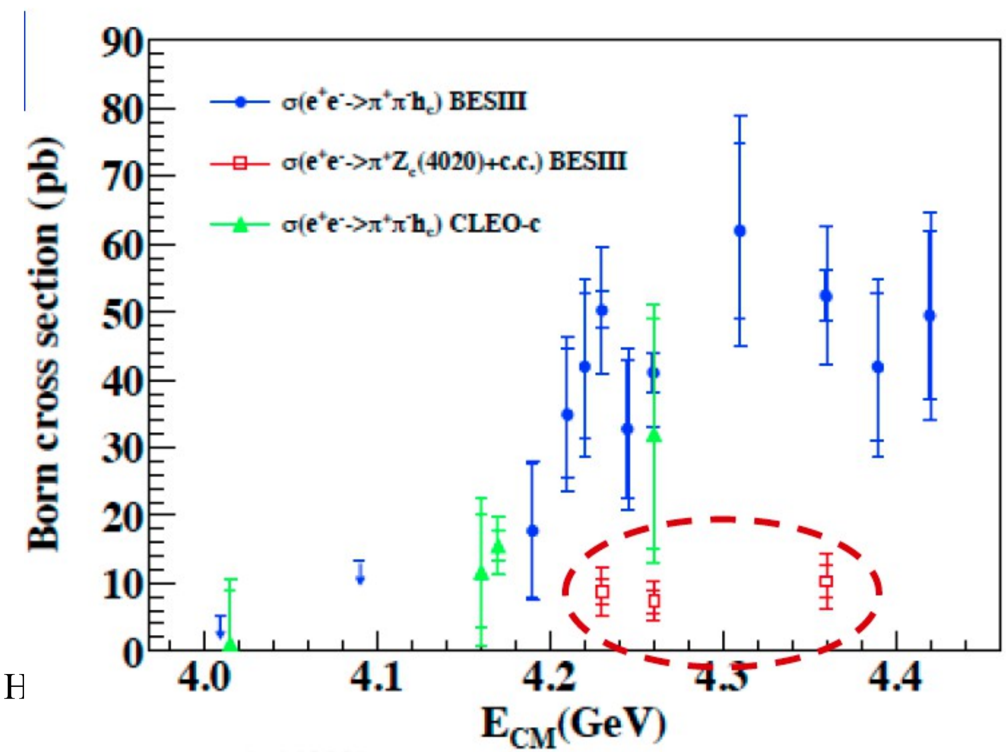
High energy scans: $b\bar{b}$ vs $c\bar{c}$

Differences:
- Υ(5,6S) peaks are well resolved, Y(4.26,4.36) are NOT

- Transitions to h_b dominated by Z_b, While only 20% of h_c is reached via Z_c







BESIII/BEPCII physics reach: