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Heavy Hadron Spectroscopy

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Heavy hadrons – theoretical description is simplified because heavy quark is approximately static.

Outline

Observation of doubly charmed baryon

LHCb

Observation of six excited Ω_c baryons

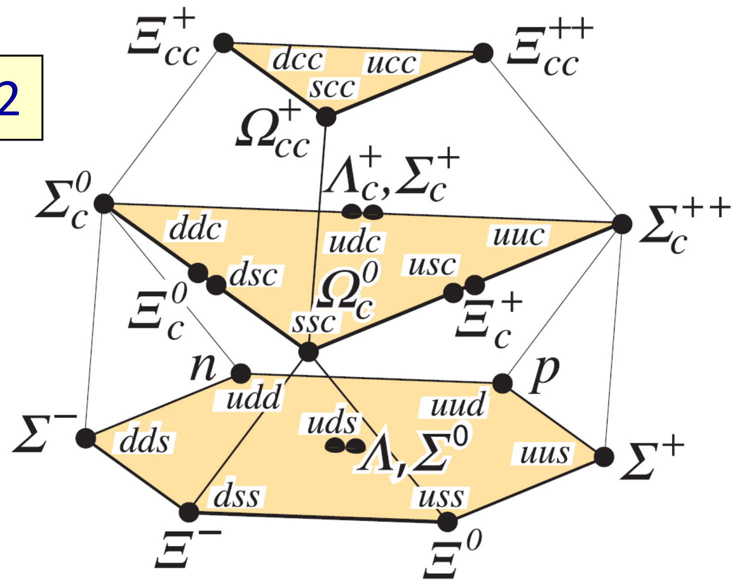
Heavy quarkonium:

Observation of $\chi_{c0}(2P)$ Belle

Observation of Y(4220), Y(4390) BESIII

Doubly charmed baryons

J=1/2



Quark Model, HQET, Lattice ⇒

$m(\Xi_{cc}) \sim 3500–3700$ MeV

weakly decaying

$\tau(\Xi_{cc}^{++}) \sim 200–700$ fs

$\tau(\Xi_{cc}^{+}) \sim 50–250$ fs

SELEX: 600 GeV hyperon beam on nuclear target

PRL89,112001(2002)

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^- \pi^+$ (6.3σ), pD^+K^- (4.8σ)

$m(\Xi_{cc}^{+}) = 3519 \pm 2$ MeV

Issues:

lifetime <33 fs

20% of Λ_c are produced via Ξ_{cc}^{+}

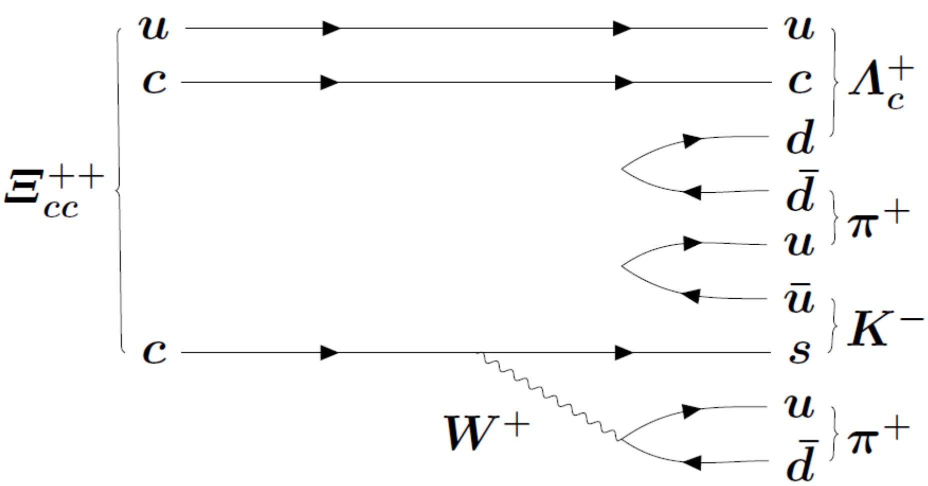
null results: Belle, BaBar (e+e- E_{cm}~10 GeV), COMPASS (γN E_γ~170 GeV)

PRL97,162001(2006), PRD74,011103(2006)

N.B. Observation of Ξ_{cc} at different mass will disprove SELEX result

only ground state is weakly decaying!

Lifetime of Ξ_{cc}

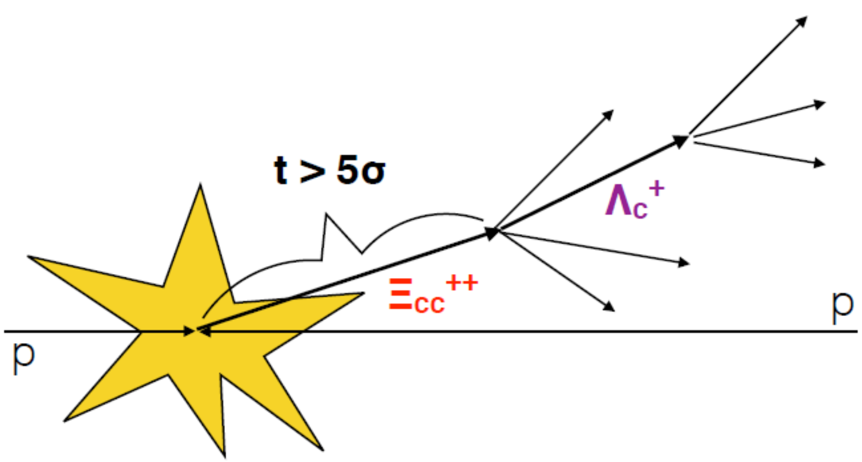


Pauli interference of decay products, $W^{\pm}$ exchange between quarks $\Rightarrow$

Ξ_{cc}^{++} : 200–700 fs
Ξ_{cc}^{+} : 50 – 250 fs

Reconstruction at LHCb

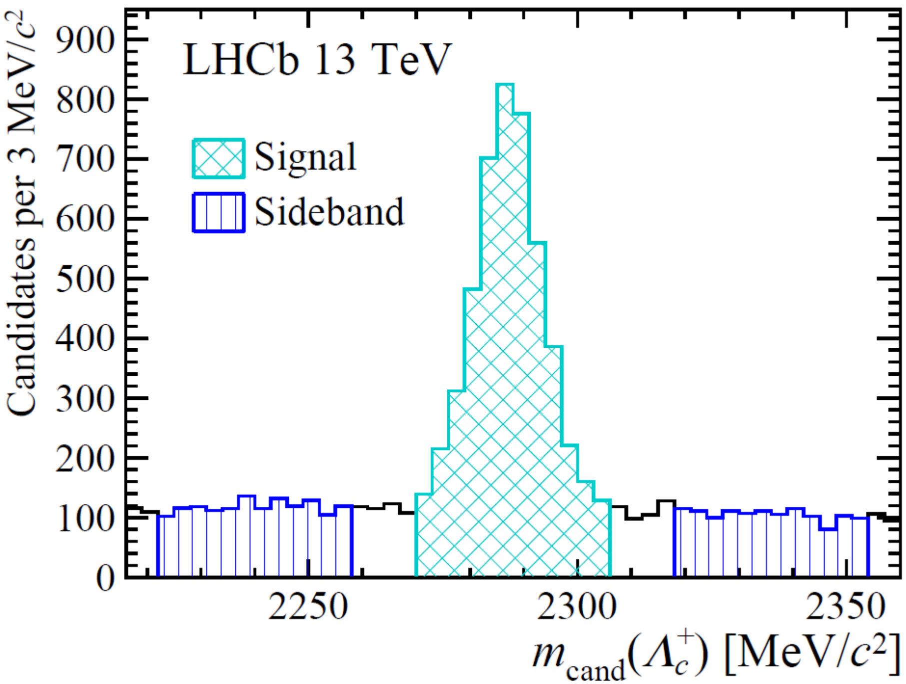
PRL119,112001(2017)

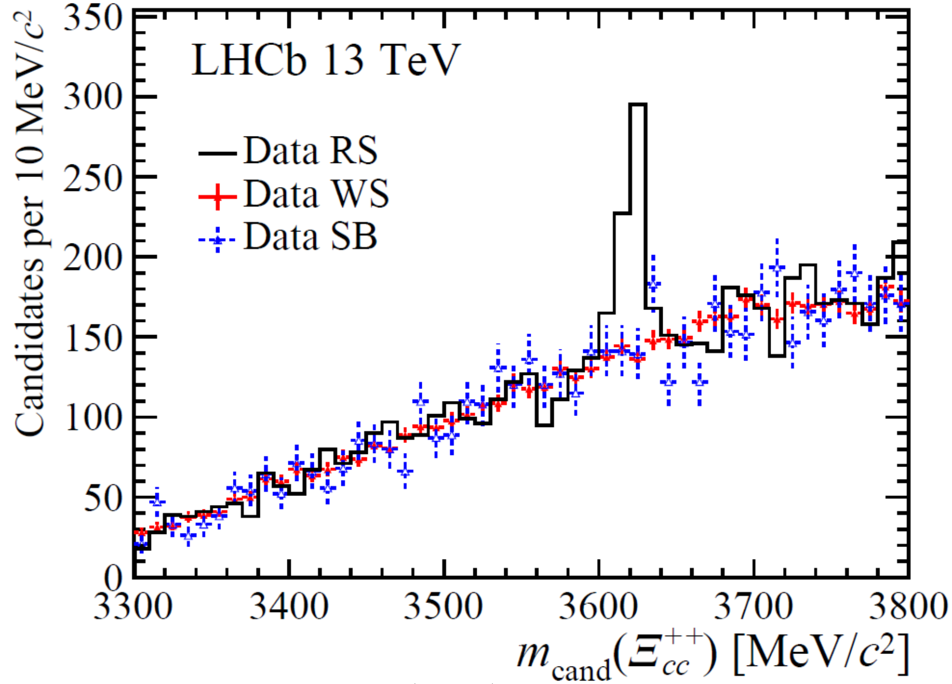


$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ \, K^- \, \pi^+ \, \pi^+$$

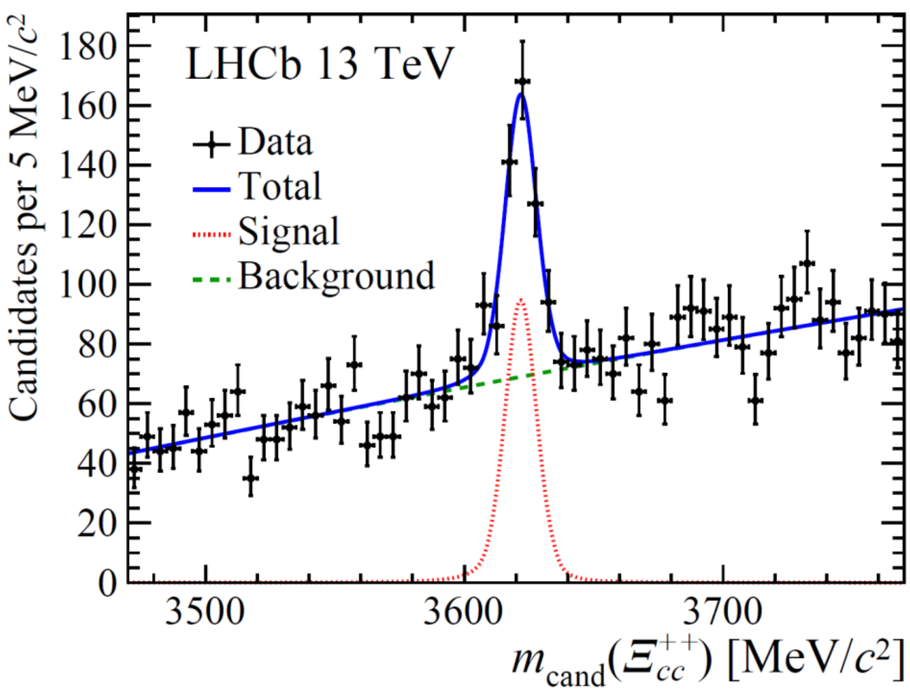
$$\Lambda_c^+ \rightarrow p \, K^- \, \pi^+$$

Large lifetime is useful for efficient triggering.





PRL119,112001(2017)



m =

3621.40 ± 0.72 ± 0.72 ± 0.14 MeV

Λ_c

Significance >12σ

significant signal with $t/\sigma_t > 5$

⇒ weakly decaying particle

⇒ Observation of Ξ_{cc}^{++}

Implications

Ξ_{cc} mass is consistent with most theoretical expectations.

Implies large binding energy B(cc)=129 MeV   Karliner, Rosner arXiv:1707.07666

$\approx \frac{1}{2}$ B($c\bar{c}$) – expected for one-gluon exchange

$\Rightarrow$ in non-perturbative regime heavy quark potential factorizes into color-dependent part and space-dependent part

$\Rightarrow$ space-dependent part is the same for quark-quark and quark-antiquark

Prediction of stable tetraquark $bb\bar{u}\bar{d}$ with $J^P=1^+$

215 MeV below B^+B^{*0} threshold, weakly decaying

Compact $c\bar{c}u\bar{d}$ and $b\bar{b}u\bar{d}$ tetraquarks should be unstable.

Observation of five Ω_c baryons

Ω_c baryons

Ω_c^0 : css spin$_{ss}$ = 1 $\Rightarrow$ ground states J^P=1/2$^+$, J^P = 3/2$^+$

Pauli exclusion principle

both are observed

no excited states were known

PRL118,182001(2017)

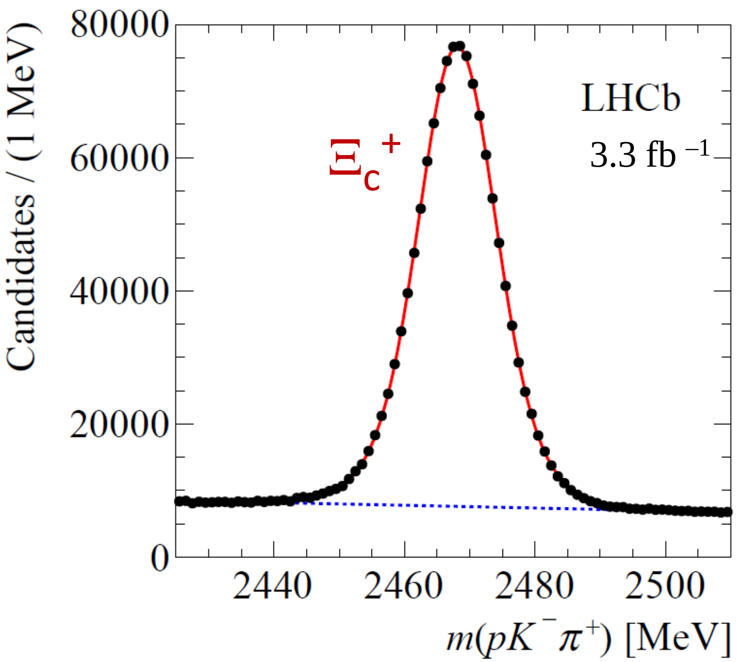
LHCb : search for $\Omega_c \rightarrow \Xi_c^+ K^-$ $\Xi_c^+ \rightarrow p\, K^- \pi^+$

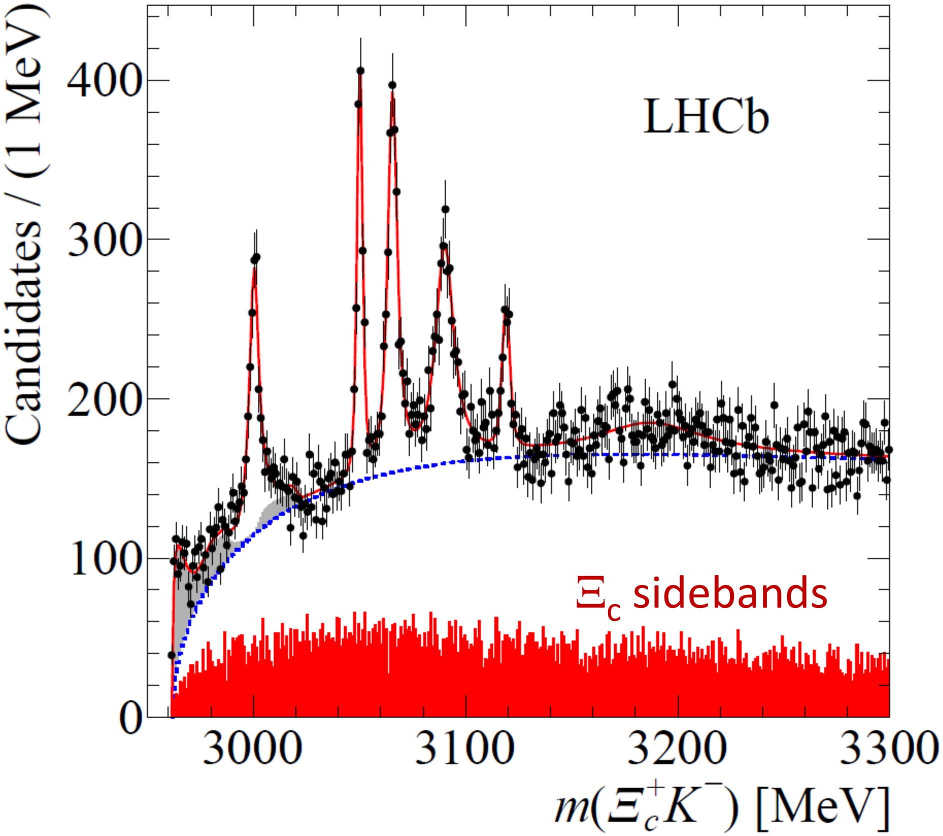
csu Cabibbo suppressed decay

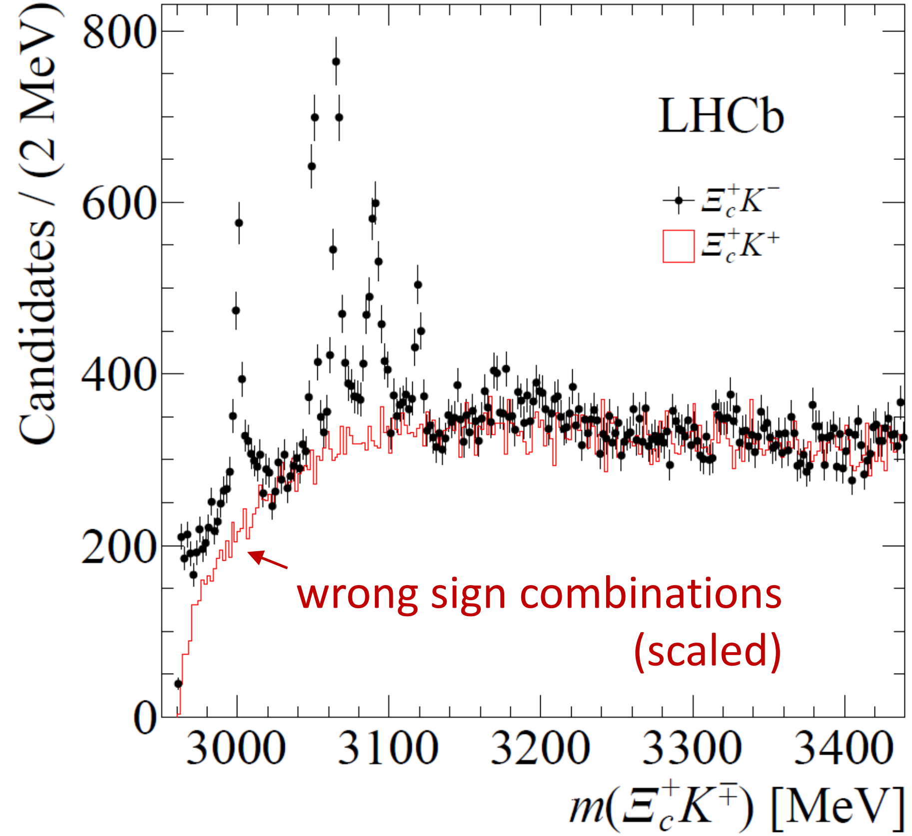
Multivariate analysis

– detached Ξ_c, Ω_c vertices

– particle identification



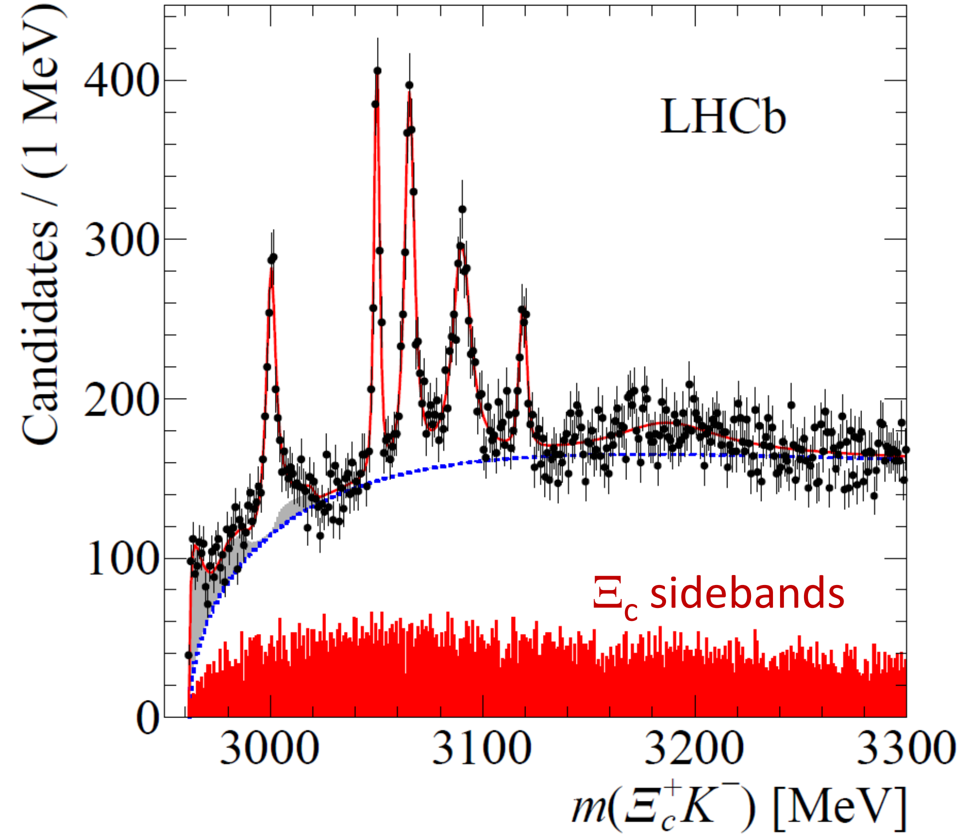


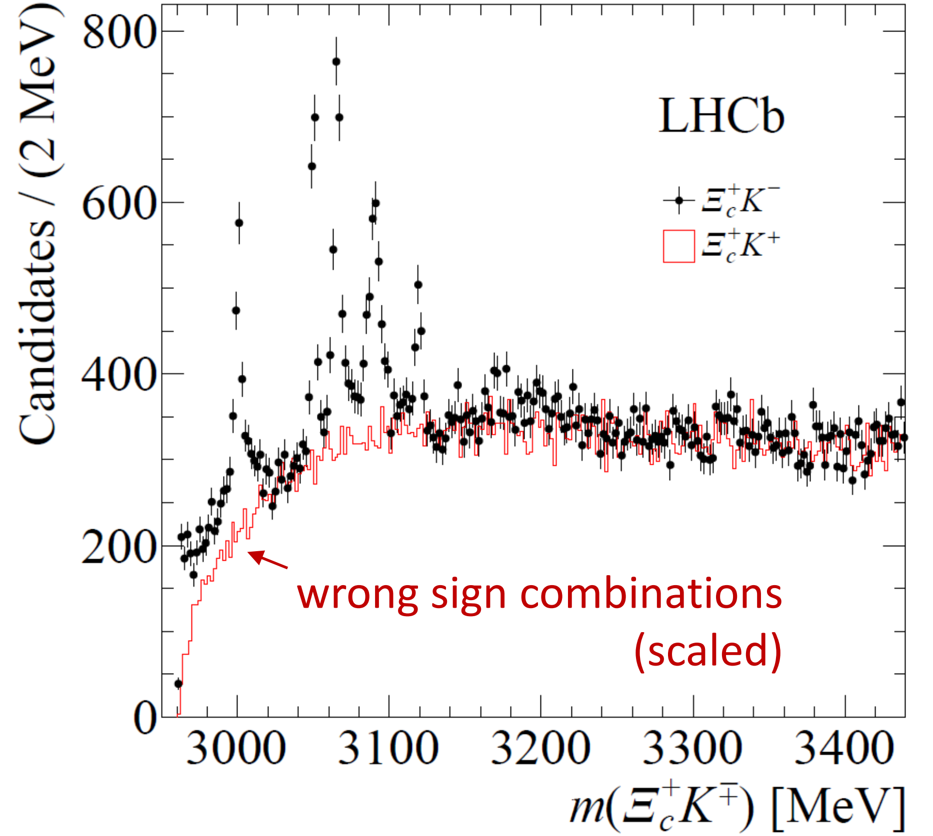


PRL118,182001(2017)

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
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		< 1.2 MeV, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	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
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
	Ξ_c	< 2.6 MeV, 95% CL		

Observations!

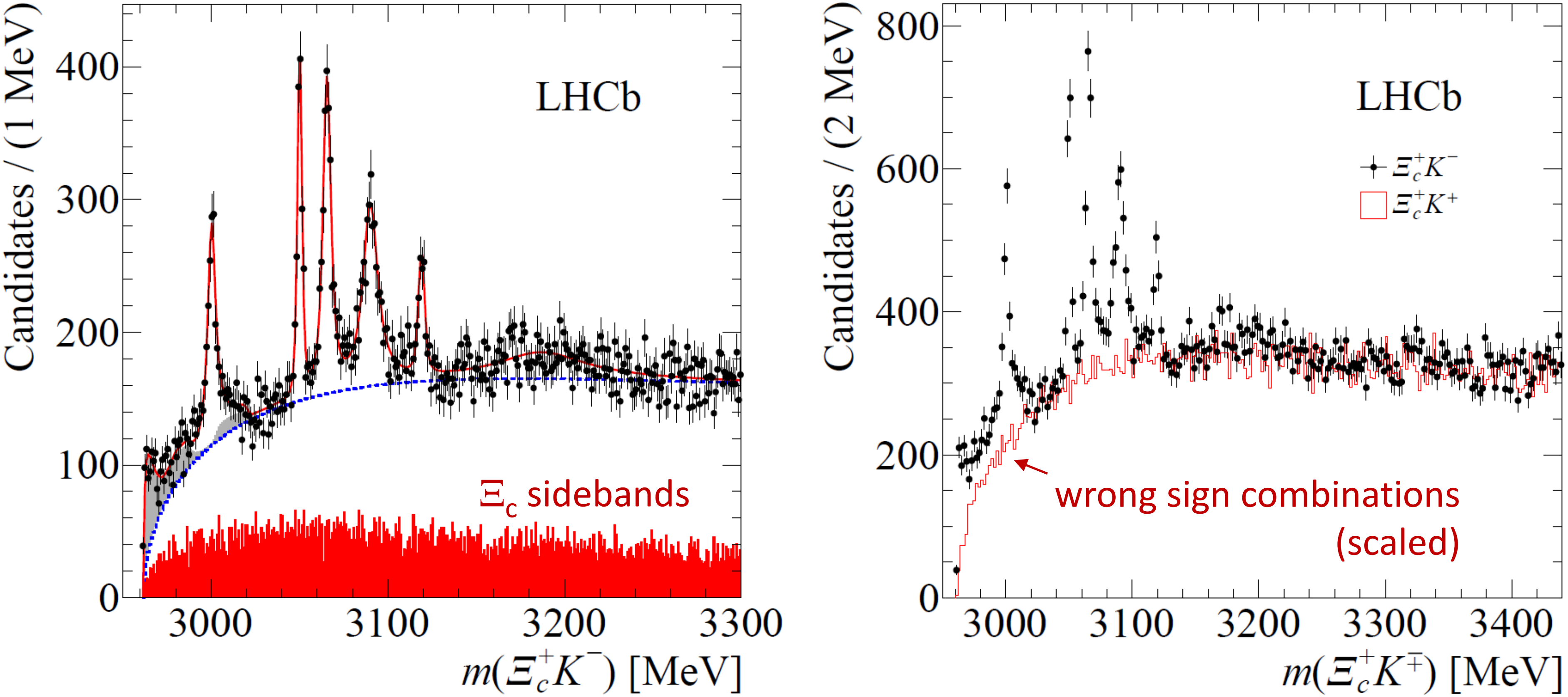




Threshold enhancements: feed-down from $\Omega_c \rightarrow \Xi_c' K \rightarrow \Xi_c \gamma K$

Resonance	Mass (MeV)	Γ (MeV)	Yield
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$

Decays $\Omega_c(3066,3090,3119) \rightarrow \Xi_c' K$ are established via feed-down.



Broad Breit-Wigner at 3188 MeV :

Resonance	Mass (MeV)	Γ (MeV)	Yield
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$

Single resonance, superposition of resonances, feed down?

Interpretation of new Ω_c

Inclusive production and two body decay $\Rightarrow$ no sensitivity to J^P.

Need three-body decays or reconstruction in b-baryon decays.

Karliner, Rosner PRD95,114012(2017)

State	Mass (MeV)[a]	Width (MeV)	Proposed J^P
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1$	$4.5 \pm 0.6 \pm 0.3$	$1/2^-$ $(3/2^-)$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1$	$0.8 \pm 0.2 \pm 0.1$	$1/2^-$ $(3/2^-)$
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3$	$3.5 \pm 0.4 \pm 0.2$	$3/2^-$ $(5/2^-)$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5$	$8.7 \pm 1.0 \pm 0.8$	$3/2^-$ $(1/2^+)$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9$	$1.1 \pm 0.8 \pm 0.4$	$5/2^-$ $(3/2^+)$
		< 2.6 MeV, 95% CL	

radial

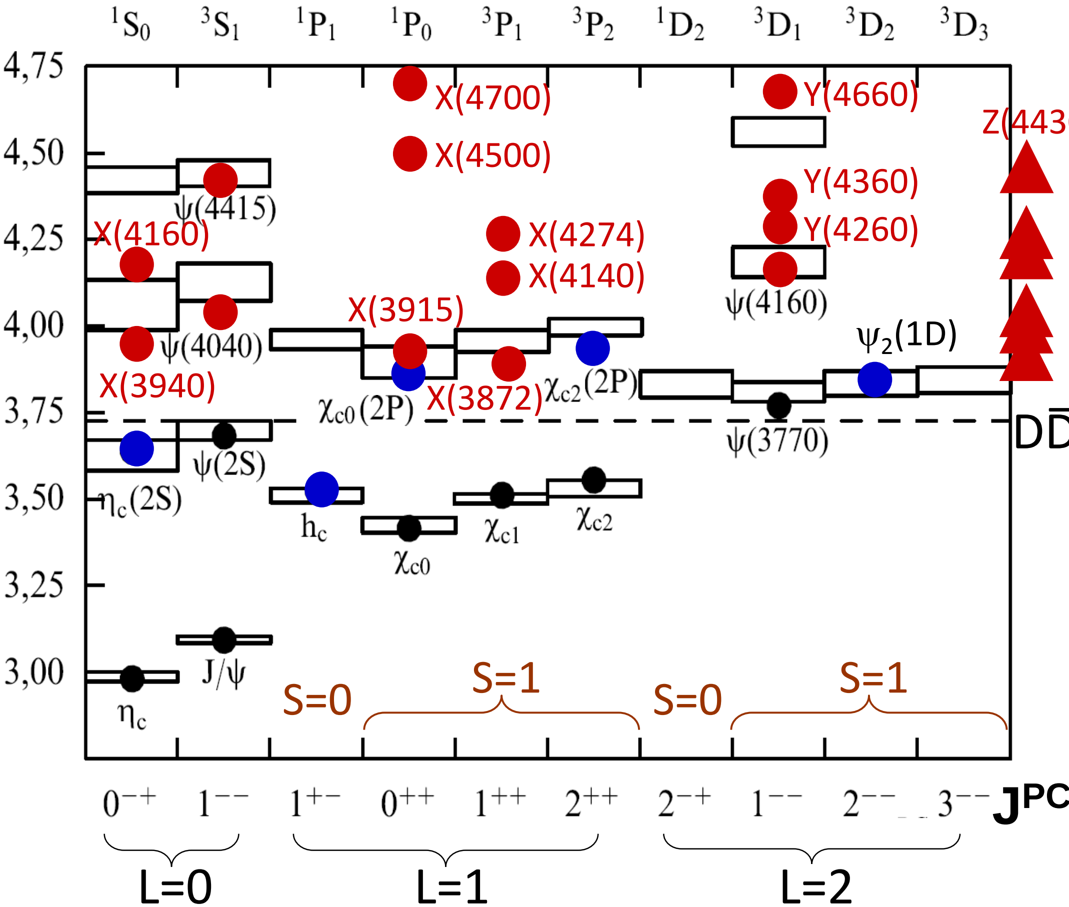
P-wave

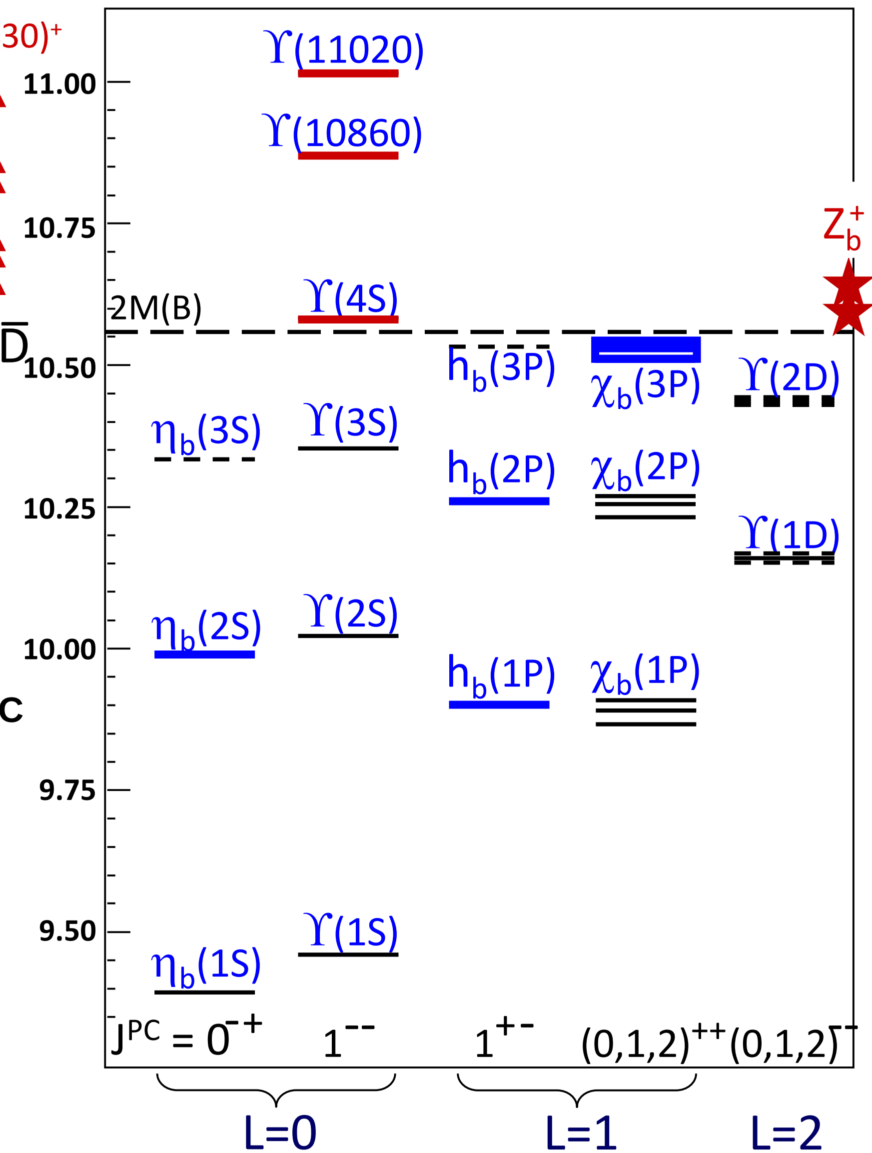
Mass range of P-wave or radial excitations.

Heavy quarkonium

Charmonium

Bottomonium





Almost all hadrons with cc and bb
above open flavor threshold
have properties
unexpected for pure quarkonium

Observation of $\chi_{c0}(2P)$ candidate

$\chi_{c0}(2P)$ charmonium level

2^3P_0 : radial excitation, L=1, S=1, $J^{PC} = 0^{++}$

$\chi_{c0}(2P)$ candidate is already known: X(3915)

$B \to (J/\psi\ \omega)\ K$
$\gamma\gamma \to (J/\psi\ \omega)$

BaBar: angular analysis in $\gamma\gamma$ process $\Rightarrow$ $J^P = 0^+$ is favored

PRD86,072002(2012)

Difficulties:

tiny width: 20 MeV, expect >100 MeV (190 MeV above S-wave threshold)
$D\bar{D}$ not seen $\Rightarrow$ $\Gamma(J/\psi\ \omega) > 0.6\ \Gamma(D\bar{D})$
tiny 2^3P_2-2^3P_0 splitting: 8.8 ± 3.2 MeV (expect ~80 MeV)

Olsen PRD91,057501(2015)

Belle: search for $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi\ (D\bar{D})$

PRD95,112003(2017)

$\Leftarrow$ double charmonium production, already seen:
$J/\psi\ \eta_c$, $J/\psi\ \eta_c(2S)$, $J/\psi\ \chi_{c0}$, J/ψ X(3940) , J/ψ X(4160)

Reconstruction

$e^+e^- \to J/\psi\,(D\bar{D})$ ← $M_{rec} = \sqrt{[\underline{p}(e^+e^-) - \underline{p}(J/\psi) - \underline{p}(D)]^2}$

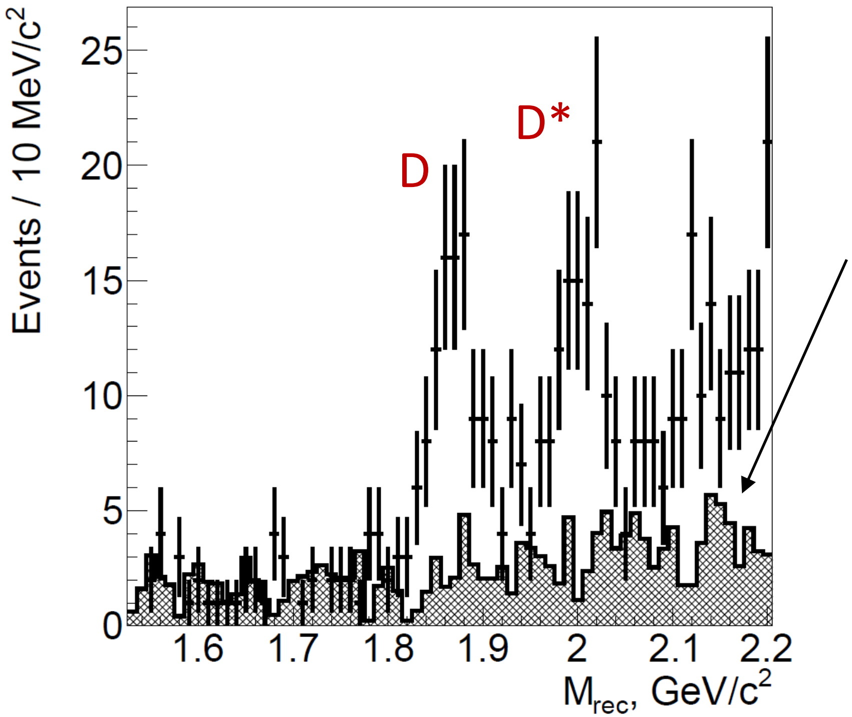
not reconstructed

$J/\psi \to \mu^+\mu^-$, e^+e^-

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^-$

$D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+$, $K_S\pi^+$, $K_S\pi^+\pi^0$, $K_S\pi^+\pi^+\pi^-$

Neural Networks. Requirements on $M(J/\psi)$, $M(D)$, M_{rec} and NN output are chosen individually for each channel.



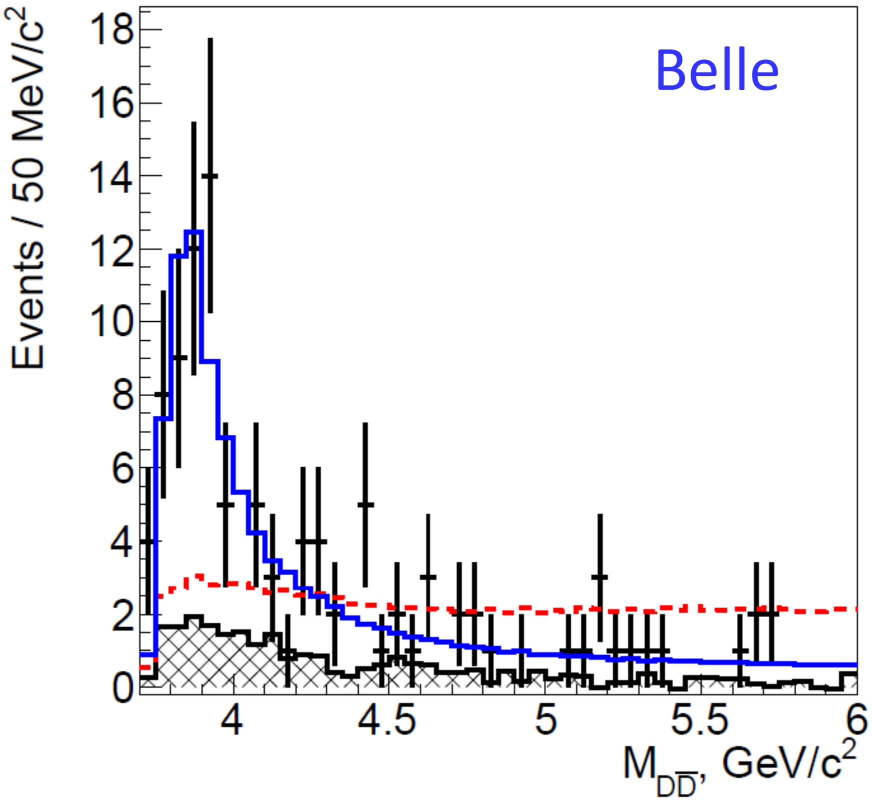
2D sidebands in $M(J/\psi)$, $M(D)$ describe background level well.

⇒ 103 events in signal region

25 ± 2 background events

Amplitude analysis

PRD95,112003(2017)



in 6D phase space

Model: X* + non-resonant contribution

$$M = (3862^{+26}_{-32}{}^{+40}_{-13})\ \mathrm{MeV}/c^2$$

$$\Gamma = (201^{+154}_{-67}{}^{+88}_{-82})\ \mathrm{MeV}$$

Significance 6.5σ including systematics and "look-elsewhere" effect

⇒ X*(3860)

$e^+e^- \to J/\psi\ (D\bar{D})$

$J^{PC} = 0^{++}$, ~~1^{--}~~, 2^{++}, ~~3^{--}~~, …

C-parity too high

0^{++} is favored over 2^{++} at 3.8σ

… at 2.5σ including systematics

Discussion

X*(3860)

$\Rightarrow$ good $\chi_{c0}(2P)$ candidate

$M = (3862^{+26}_{-32}{}^{+40}_{-13})\ \mathrm{MeV}/c^2$

$\Gamma = (201^{+154}_{-67}{}^{+88}_{-82})\ \mathrm{MeV}$

$J^{PC} = 0^{++}$ favored

Seen in $D\bar{D}$

What is X(3915) ? $\Rightarrow$ Unlikely $\chi_{c0}(2P)$.

No more 0^{++} charmonia nearby are expected $\Rightarrow$ exotics.

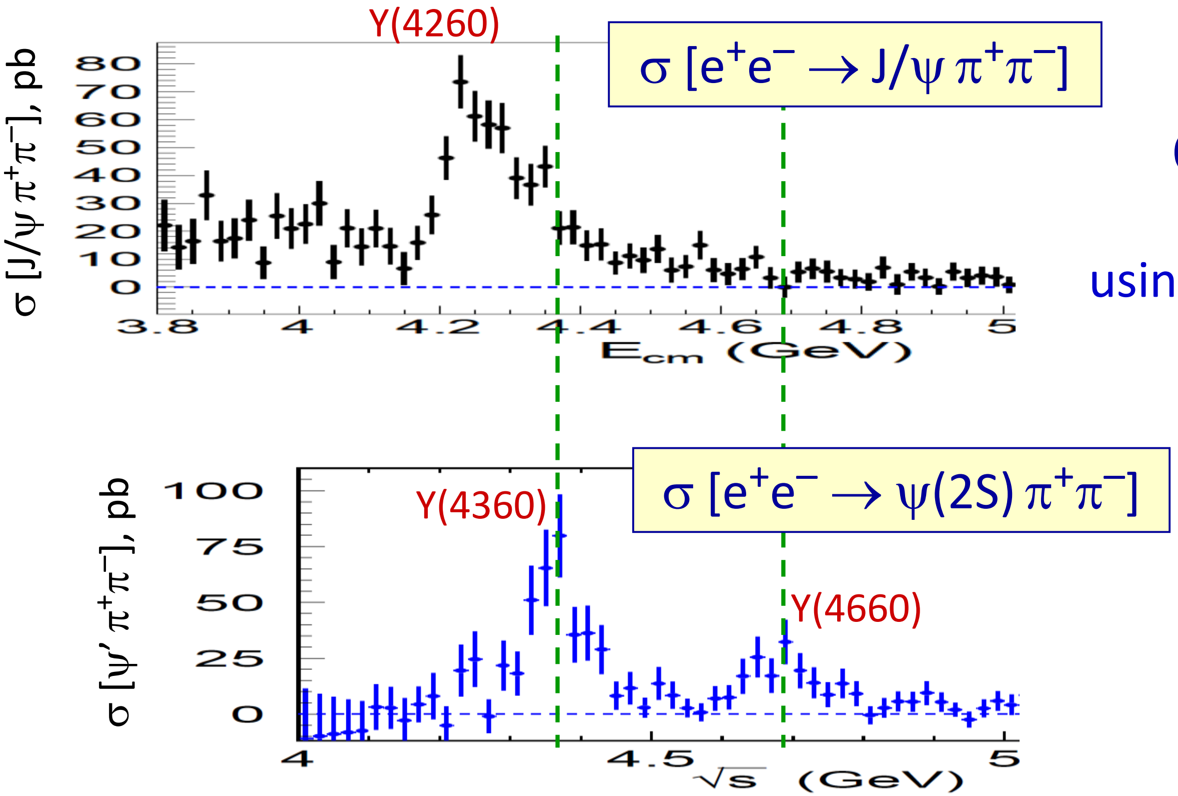
Zhou, Xiao, Zhou PRL115,022001(2015)

J^P measurement by BaBar is model dependent, X(3915) could be $\chi_{c2}(2P)$.

Need full amplitude analysis of $B \to J/\psi\, \omega\, K$, $\gamma\gamma \to J/\psi\, \omega$ to measure J^P of X(3915).

Observation of Y(4220), Y(4390)

Cross-sections in charmonium region



using ISR

BaBar PRD86,051102R(2012)
Belle PRL110,252002(2013)

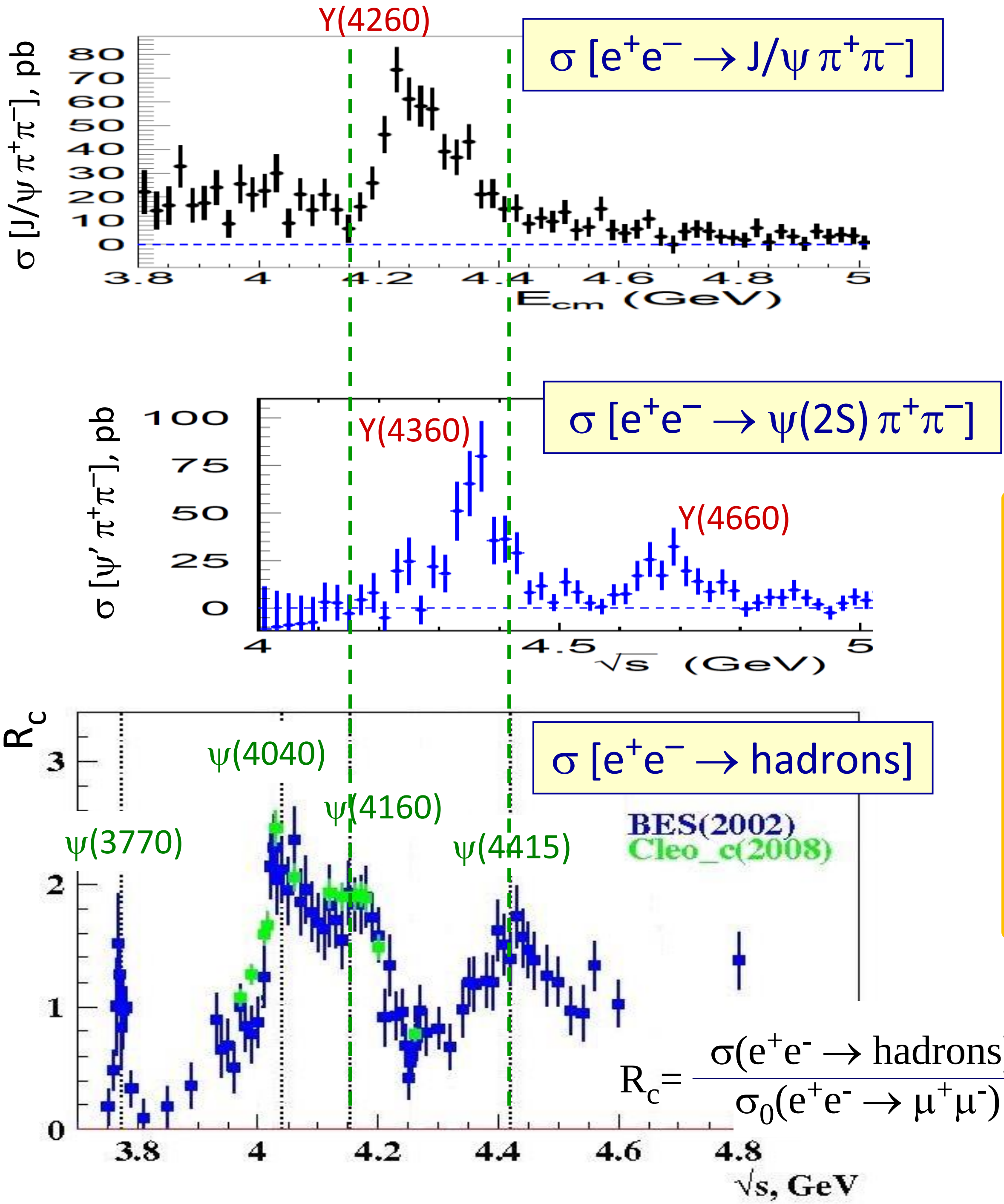
BaBar PRD89,111103(2014)
Belle PRD91,112007(2015)

Puzzles:

1. Each Y state decays to one channel only.

Cross-sections in charmonium region

BaBar PRD86,051102R(2012)
Belle PRL110,252002(2013)
BaBar PRD89,111103(2014)
Belle PRD91,112007(2015)

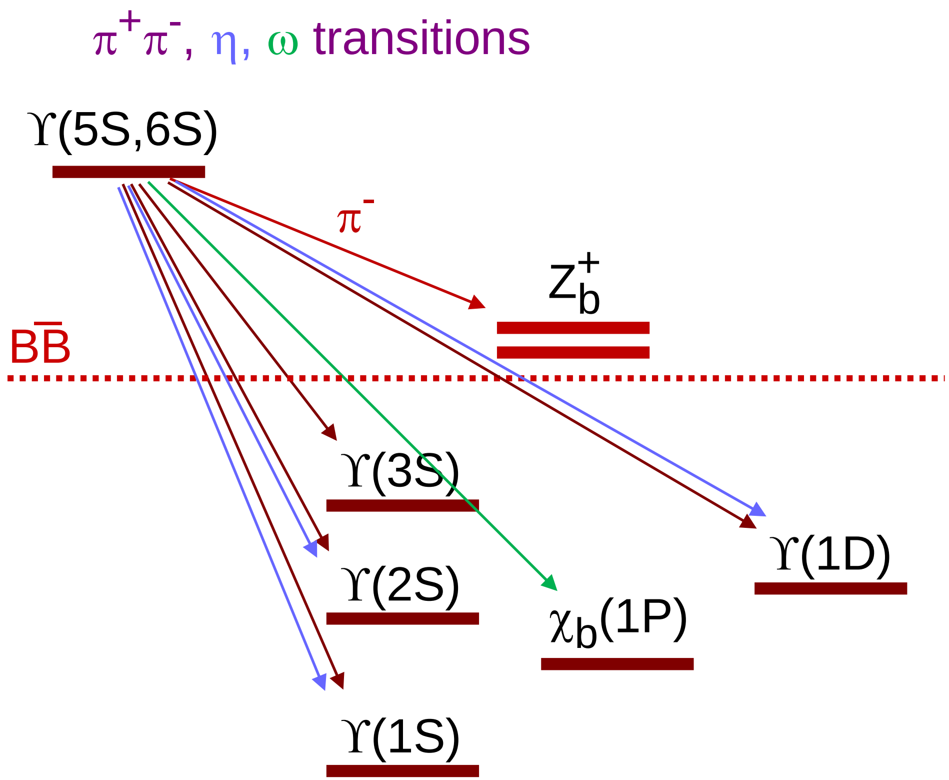


$$R_c = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)} - R_{uds}$$

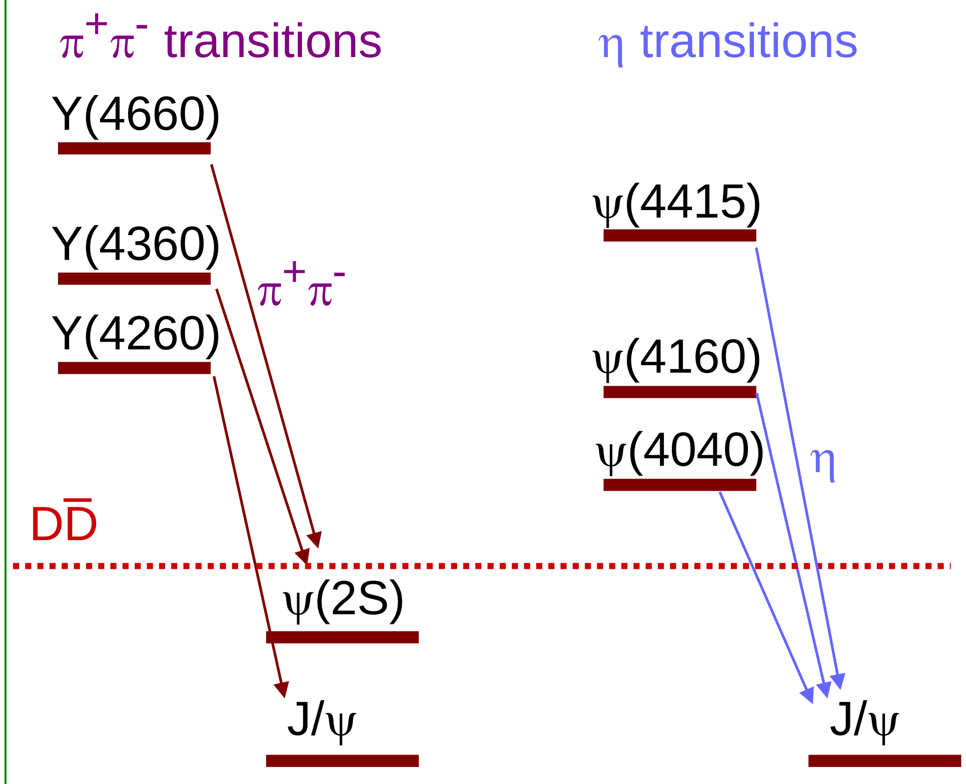
Puzzles:

1. Each Y state decays to one channel only.
2. Y states are not seen in total cross section scan.

Bottomonium



Charmonium



Bottomonium with molecular admixture:

$$\Upsilon(5S,6S) = |b\bar{b}\rangle + |B^{(*)}\bar{B}^{(*)}\rangle$$

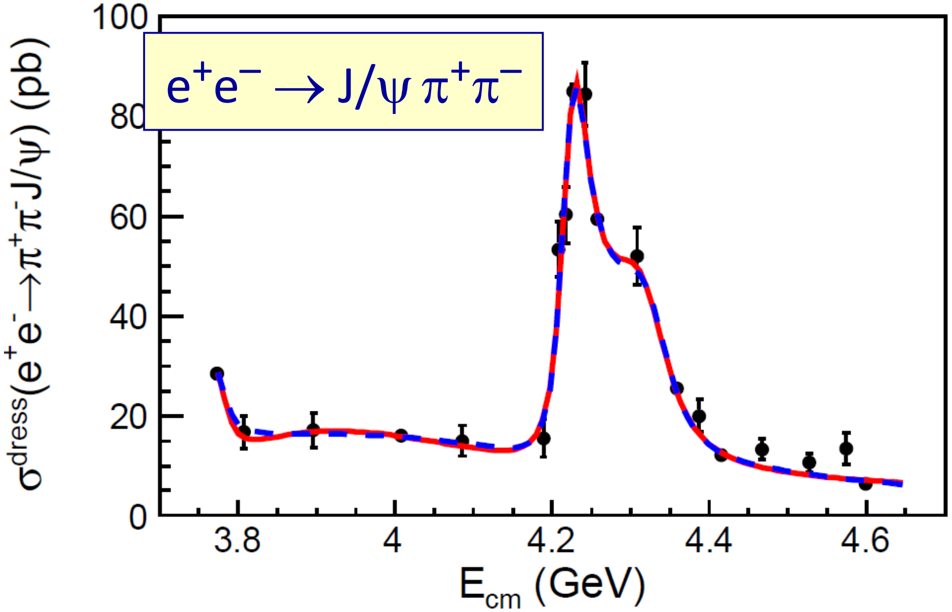
Hadrocharmonium

charmonium in a cloud of light meson;
should decay into constituents

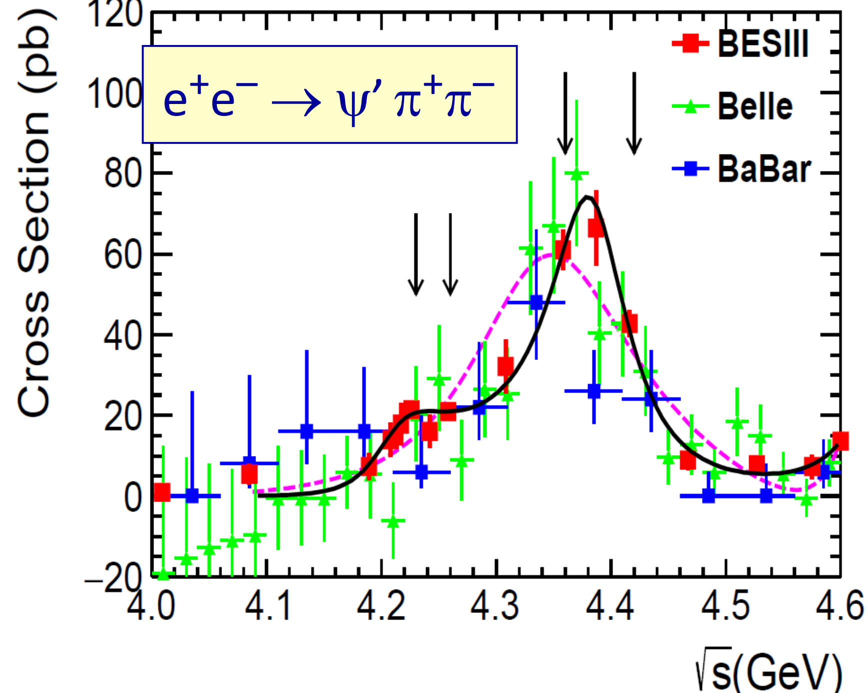
Why qualitative difference btw charmonium and bottomonium?

BESIII energy scan results

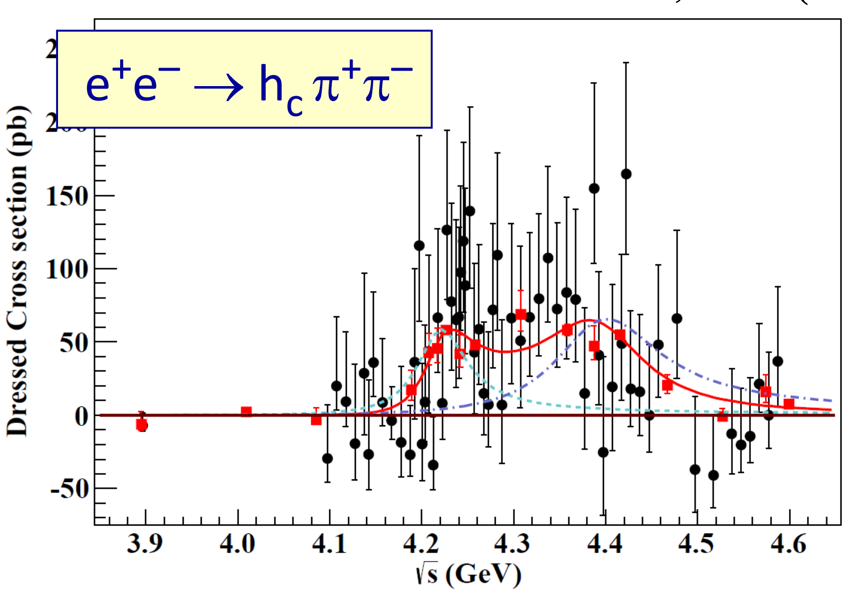
PRL118,092001(2017)

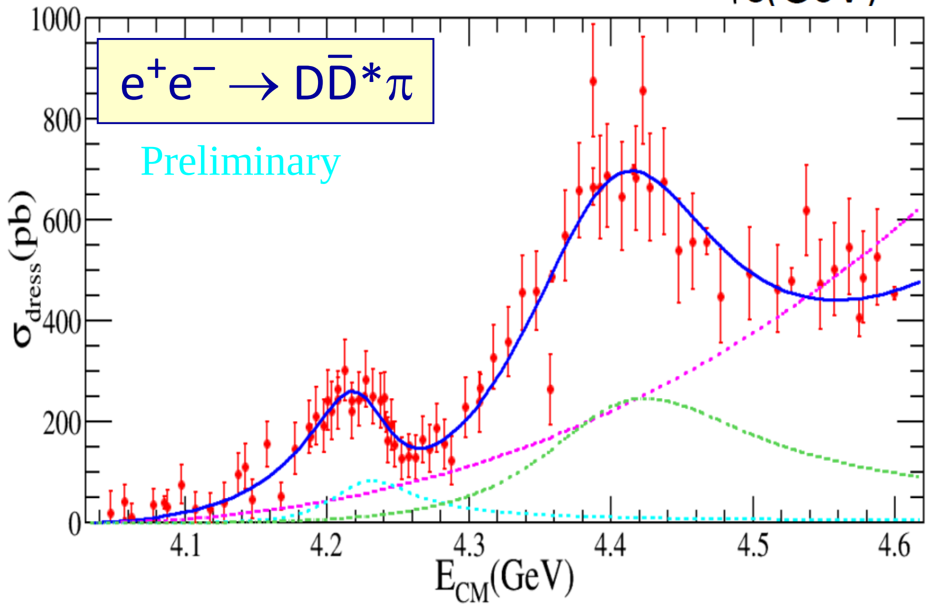


PRD96,032004(2017)



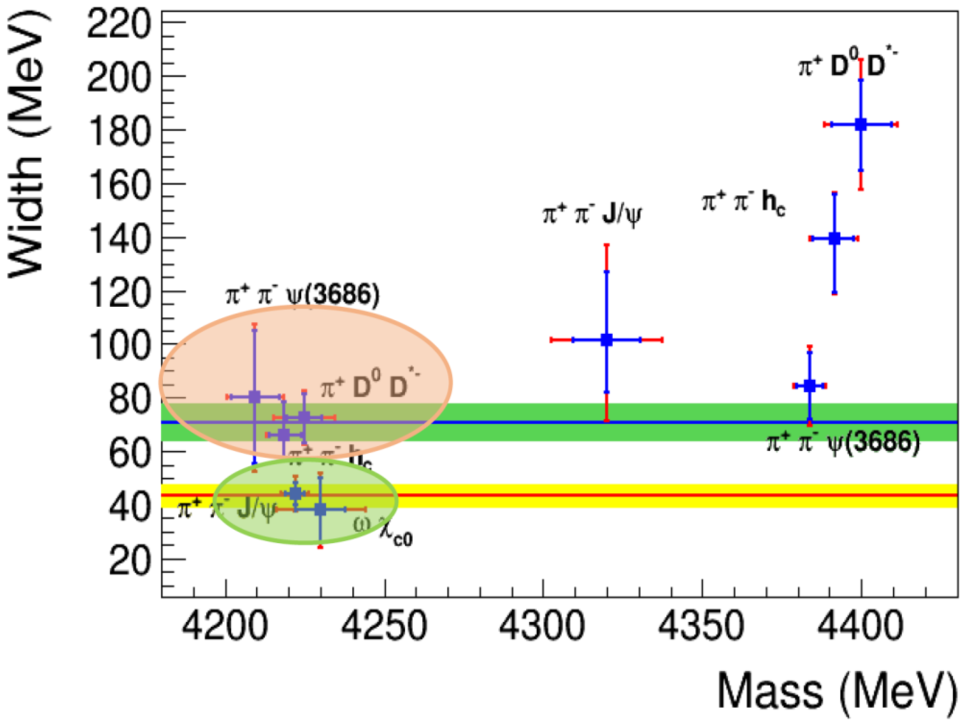
PRL118,092002(2017)

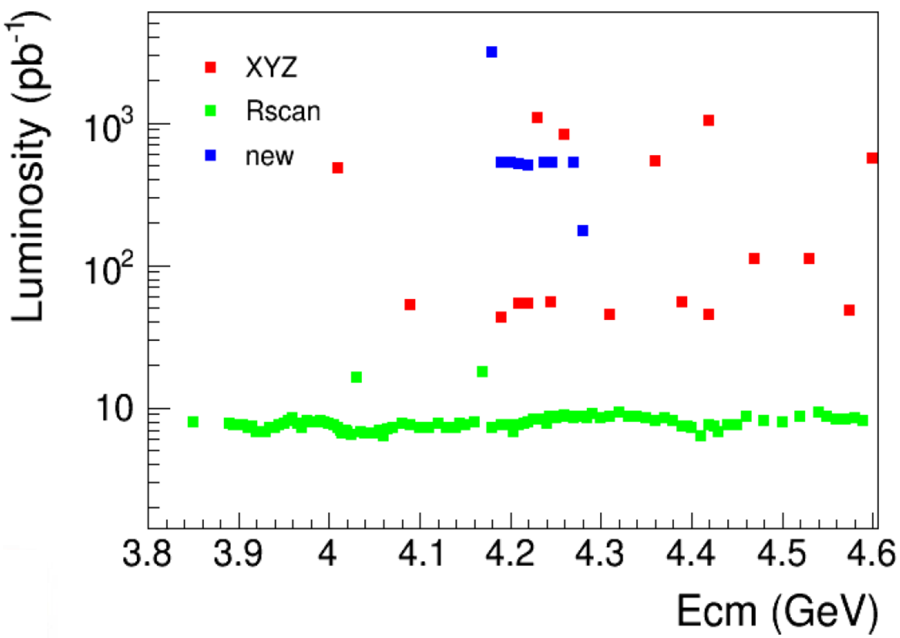




How many states?

Ke Li, Hadron 2017





Only two states in all channels? BESIII collected more data to clarify.

Y(4260), Y(4360) are gone. Instead, Y(4220), Y(4390) are observed.
New states decay to several channels, including open flavor.
Expected for hadronic molecules or states with molecular admixture.

Conclusions

Last year was very fruitful in heavy hadron spectroscopy

Highlights:

- Observation of Ξ_{cc}^{++}
- Observation of five narrow Ω_c states
- Observation of charmonium state $\chi_{c0}(2P)$
- Observation of Y(4220,4390) decaying to several final states

Many on-going studies, very active field.