Charmonium and charm spectroscopy

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(on behalf of the BESIII Collaboration)

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Outline

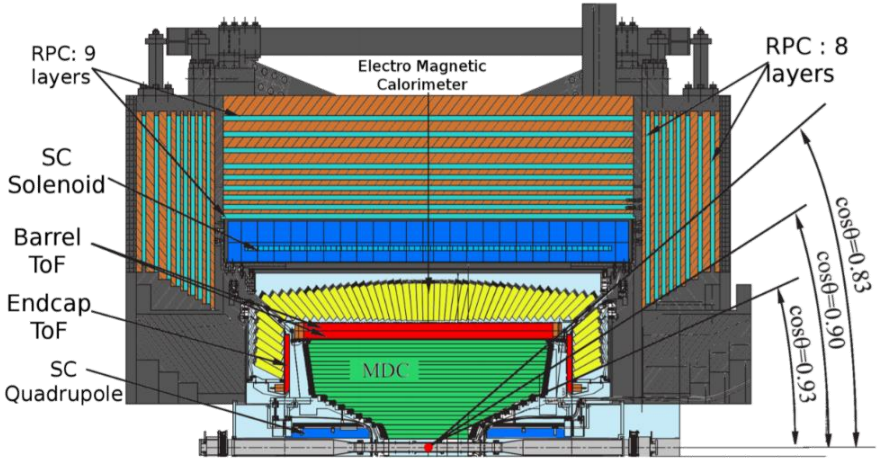
- Main Experiments
- Charmonium spectroscopy
- Charm spectroscopy
  - The charm meson
  - The charm baryon
- Summary

Main Experiments

BESIII @ BEPC II

e^+e^- : 2 - 4.6 GeV

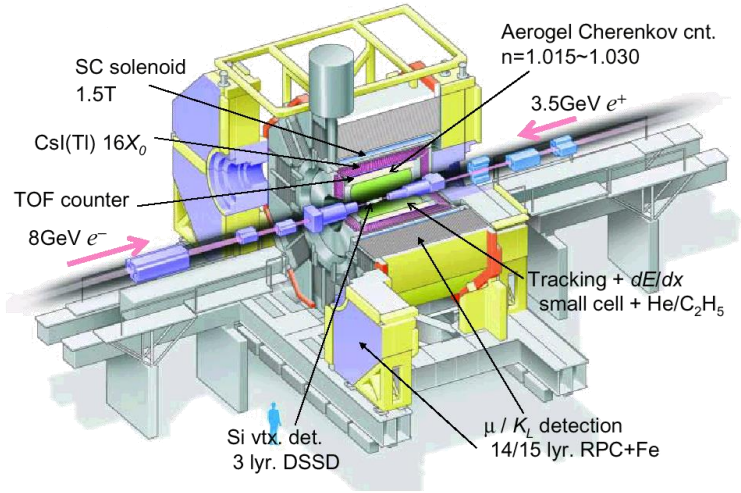
$\mathcal{L}_{\text{peak}} = 1 \times 10^{33} cm^{-2} s^{-1}$



Belle @ KEKB

e^+e^- : ~10.6 GeV ($\Upsilon(4S)$)

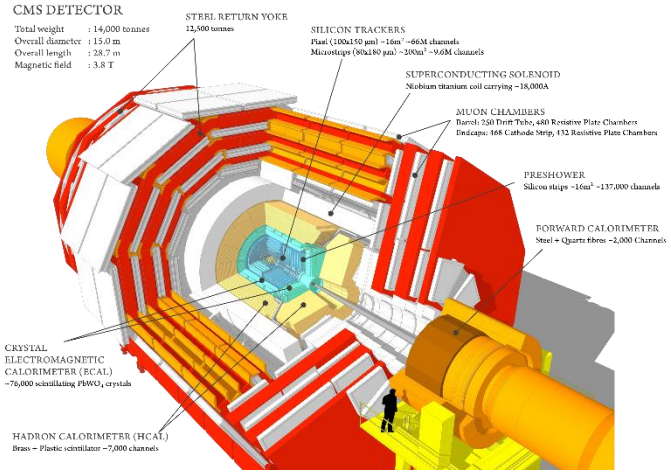
$\mathcal{L}_{\text{peak}} = 2 \times 10^{34} cm^{-2} s^{-1}$



CMS @ LHC

$p\bar{p}$: 7-13 TeV

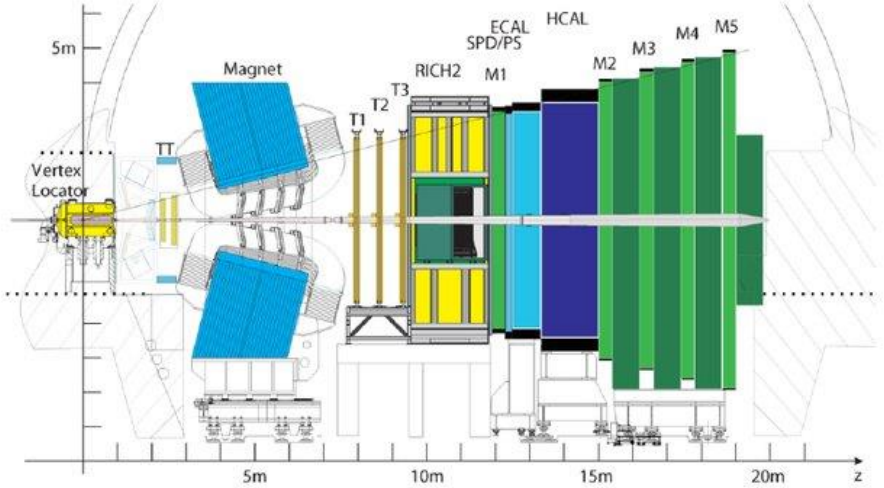
$\mathcal{L}_{\text{peak}} = 1 \times 10^{34} cm^{-2} s^{-1}$



LHCb @ LHC

$p\bar{p}$: 7-13 TeV

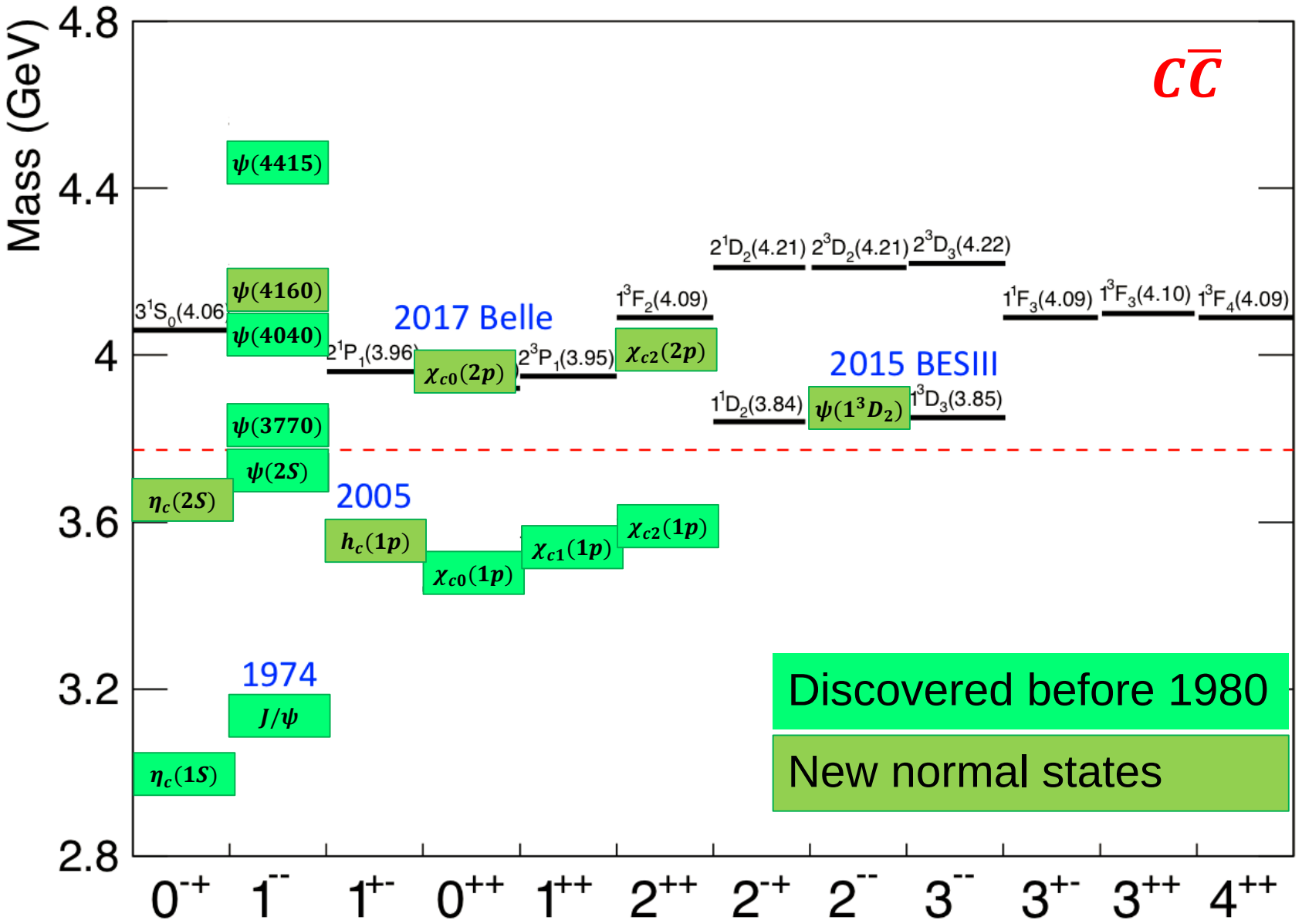
$\mathcal{L}_{\text{peak}} = 1 \times 10^{34} cm^{-2} s^{-1}$



Charmonium spectroscopy

- Precise $\chi_{c1,2}$ parameters using $\chi_{c1,2} \to J/\psi\mu^+\mu^-$
- Measurement of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$
- Charmonia from $B^+ \to p\bar{p}K^+$
- Charmonia from $B^+ \to \phi\phi + X$
- Near-threshold $D\bar{D}$ spectroscopy
- Alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$

Charmonium Spectroscopy



$n^{2S+1}L_J$

n radial quantum number
S total spin of c & $\bar{c}$
L orbital angular mom.
(L = 0, 1, 2 ... S, P, D, … states)
J = S + L
$P = (-1)^{L+1}$ parity
$C = (-1)^{L+S}$ charge conj.

$2M(D)$

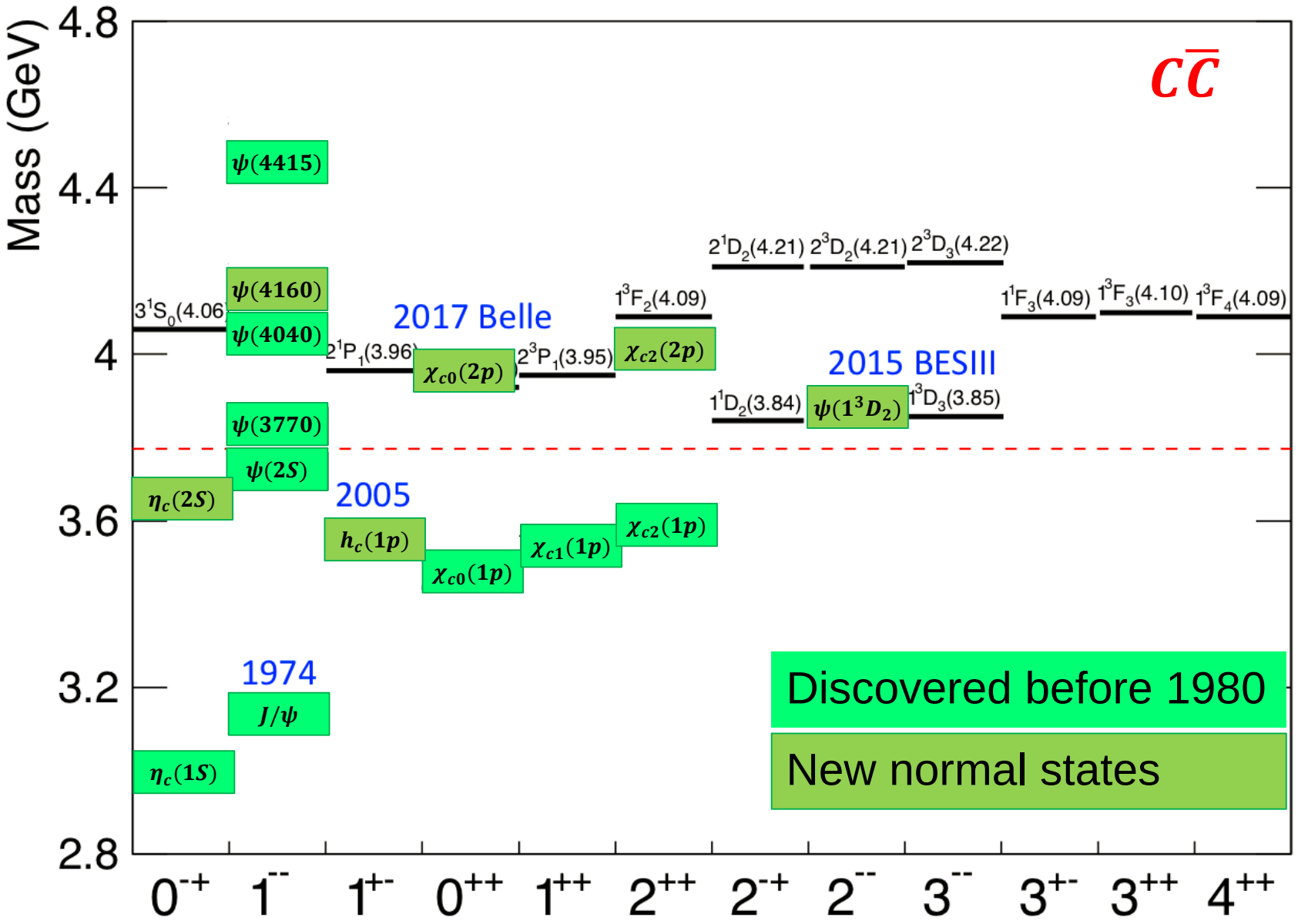
Below the $D\bar{D}$ threshold:

- States are narrow
- All states observed
- Match with prediction

well measured

recently observed

Charmonium Spectroscopy



$n^{2S+1}L_J$

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J = S + L
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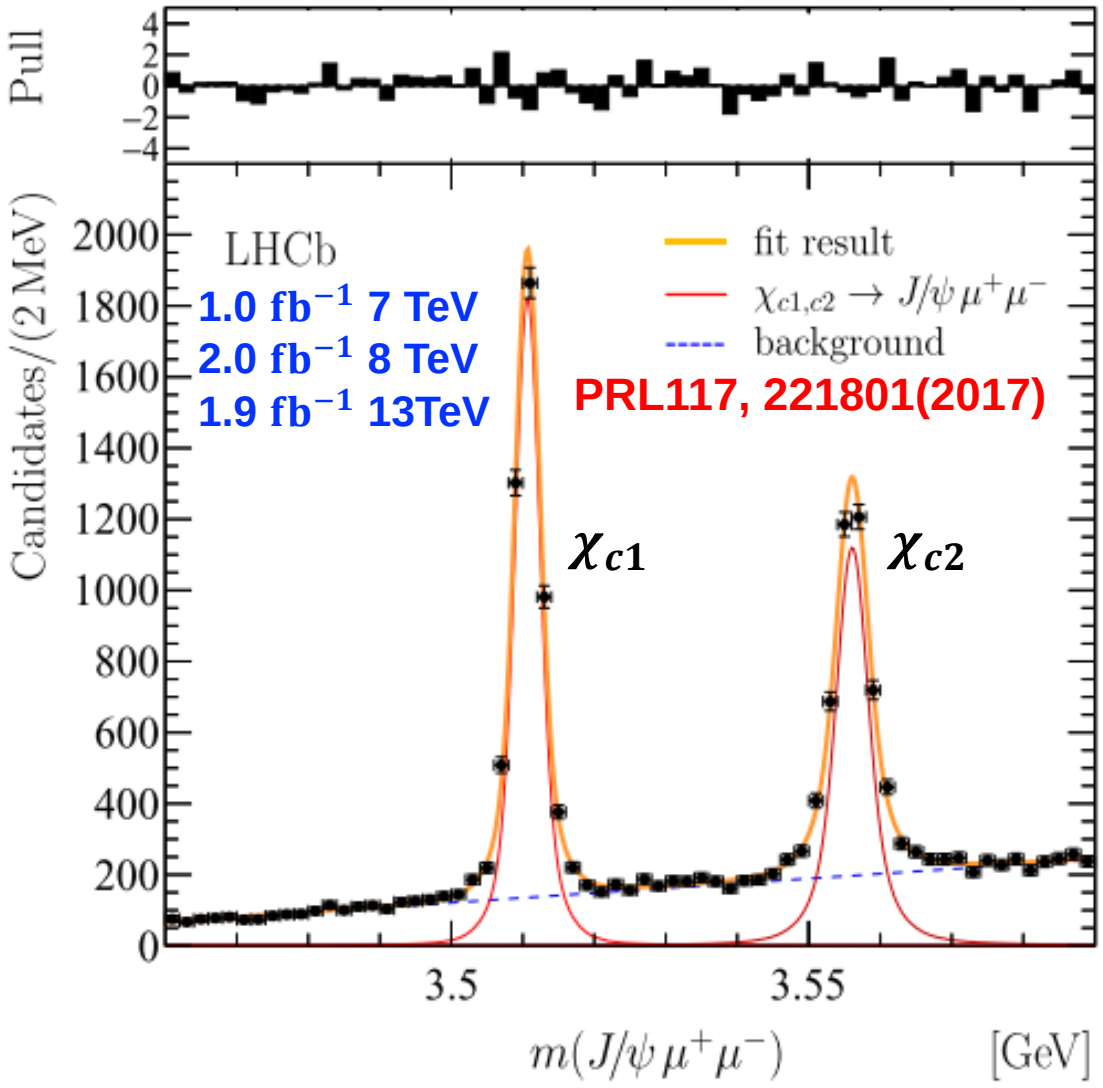
$2M(D)$

Above the $D\bar{D}$ threshold:

- States expected to be wide
- Only few states measured and identified
- Many candidates available
  - Such as X(3872)

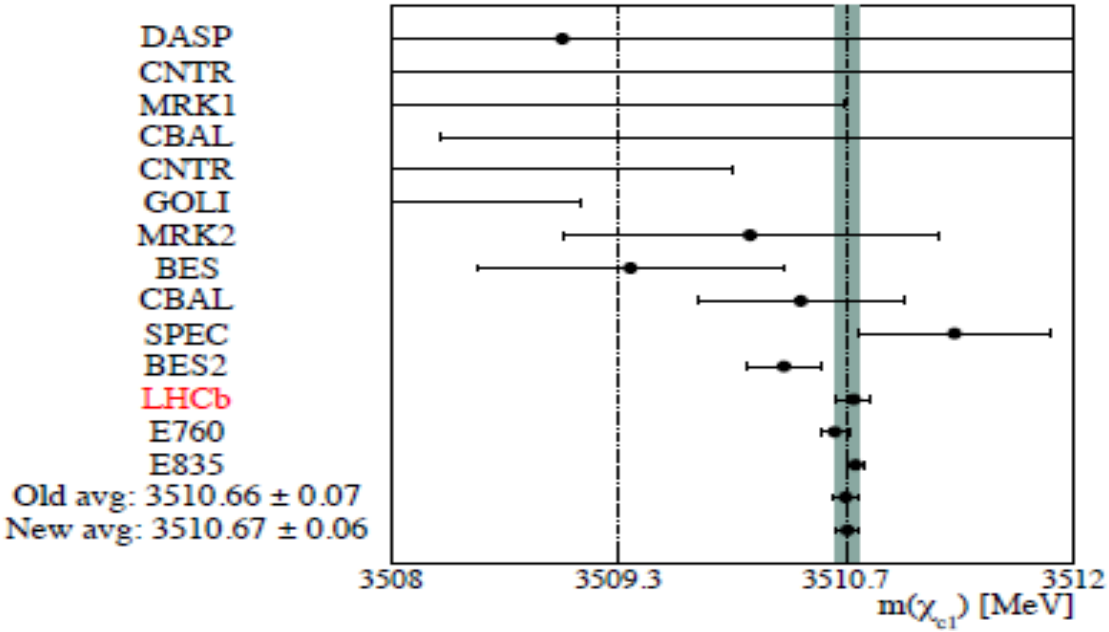
Precise $\chi_{c1,2}$ parameters using $\chi_{c1,2} \to J/\psi\mu^+\mu^-$

- First observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$.



- Fit $m(J/\psi\mu^+\mu^-)$ with a relativistic Breit-Wigner convolved with double-Gaussian.

$$\mathrm{M}(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09 \text{ MeV}$$
$$\mathrm{M}(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11 \text{ MeV}$$
$$\mathrm{M}(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03 \text{ MeV}$$
$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20 \pm 0.02 \text{ MeV}$$



- Comparable to world's best precision.

Measurement of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$ with BESIII

- Via the process $\psi(3686) \to \gamma\chi_{cJ},\ \chi_{cJ} \to J/\psi\mu^+\mu^-$.
- Branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$ and $J/\psi \to ll$ from PDG.
- Absolute branching fractions $\mathcal{B}(\chi_{cJ} \to J/\psi\mu^+\mu^-)$ and ratios $\frac{\mathcal{B}(\chi_{cJ}\to J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{cJ}\to J/\psi e^+e^-)}$:

χ_{c0}:

$\mathcal{B} < 2.0 \times 10^{-5}$ @ 90% C.L.

$R < 0.14$ @ 90% C.L.

χ_{c1}:

$\mathcal{B} = (2.51 \pm 0.18 \pm 0.20) \times 10^{-4}$

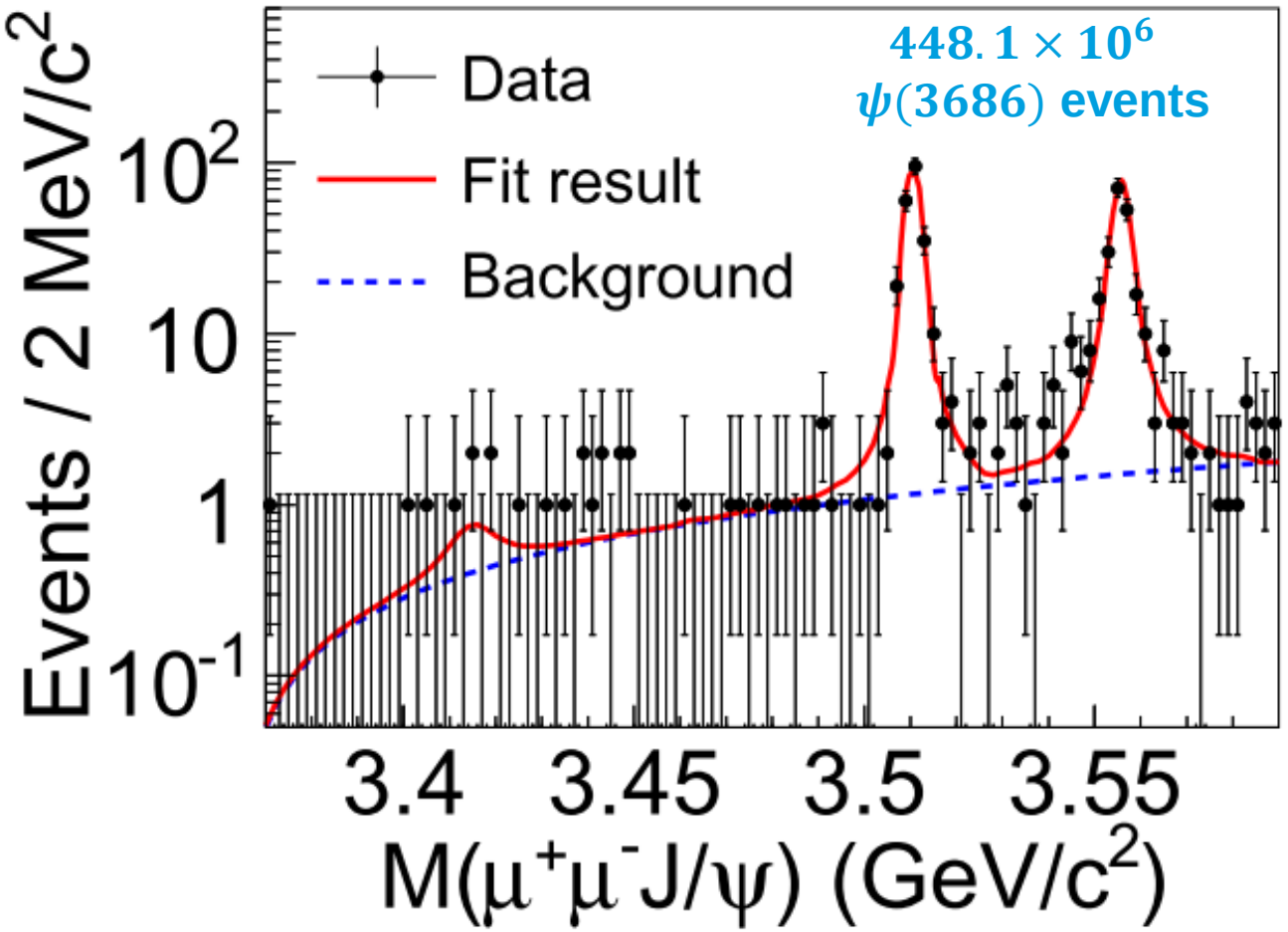
$R = (6.73 \pm 0.51 \pm 0.50) \times 10^{-2}$

χ_{c2}:

$\mathcal{B} = (2.33 \pm 0.18 \pm 0.29) \times 10^{-4}$

$R = (9.40 \pm 0.79 \pm 1.15) \times 10^{-2}$

PRD 99, 051101 (2019)



Charmonia from $B^+ \to p\bar{p}K^+$

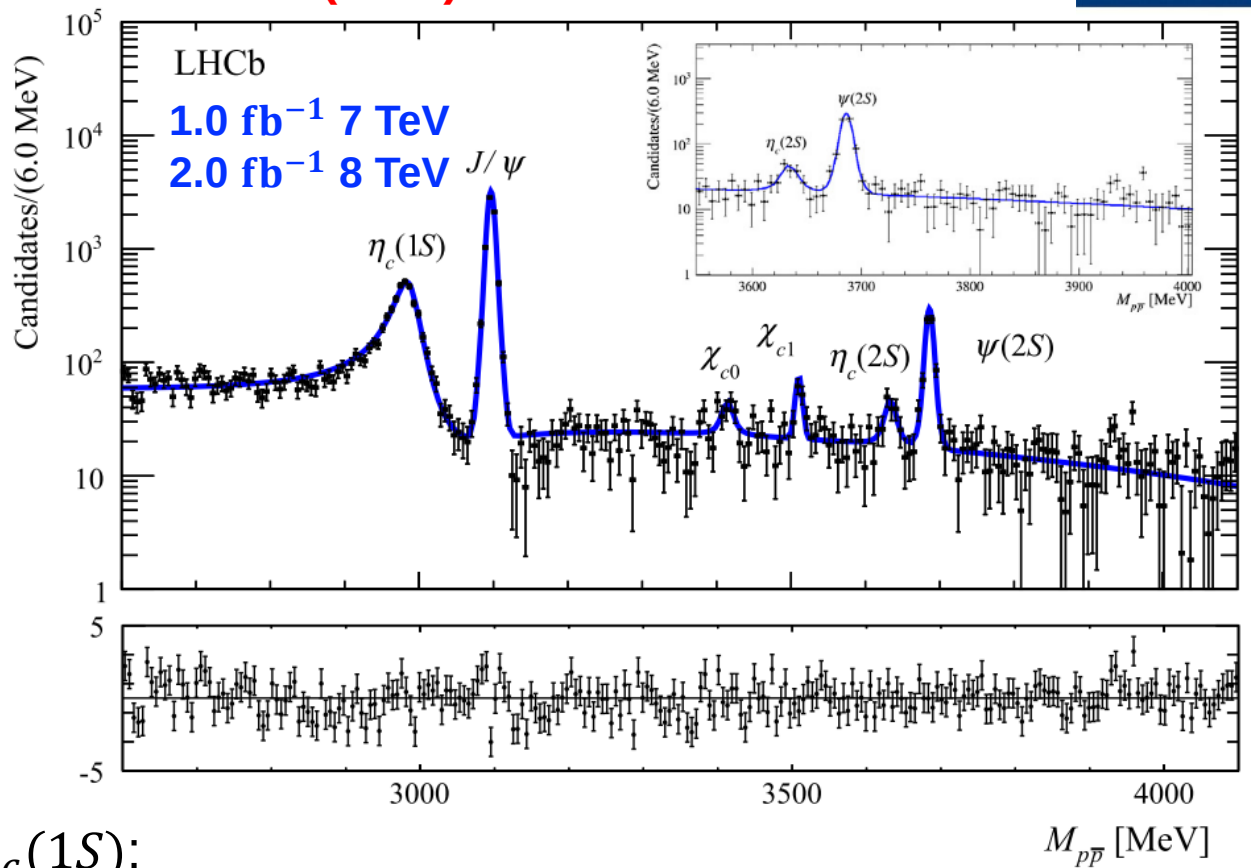
PLB 769(2017) 305-313

- Exclusive reconstruction: clean sample, better control of background and resolution effects.
- First observe $\eta_c(2S) \to p\bar{p}$ (**6.0σ**), relative branching fraction:

$$\mathcal{R}_{\eta_c(2S)} \equiv \frac{\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} = (1.58 \pm 0.33 \pm 0.09) \times 10^{-2}$$

$$\mathcal{R}_{\psi(3770)} < 9\,(10) \times 10^{-2},$$

$$\mathcal{R}_{X(3872)} < 0.20\,(0.25) \times 10^{-2}$$



- The mass differences and natural width of the $\eta_c(1S)$:

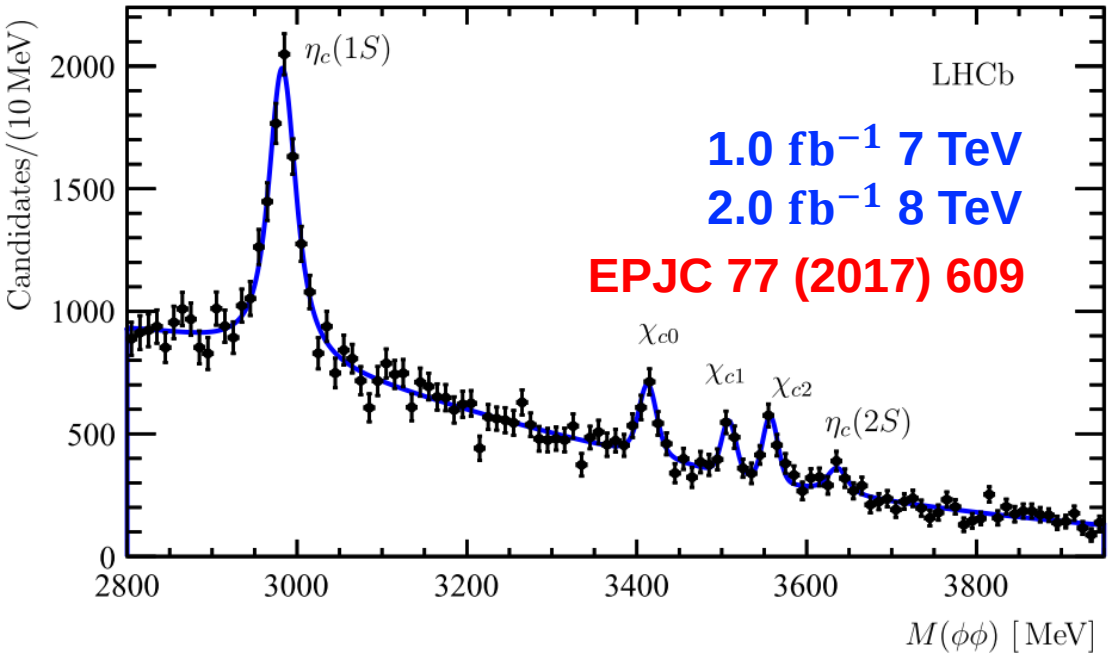
$$M_{J/\psi} - M_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\ \text{MeV},$$

$$M_{\psi(2S)} - M_{\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6\ \text{MeV}$$

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\ \text{MeV}$$

Not depend on knowledge of the magnetic dipole transition line shapes in contrast to radiative decays method.

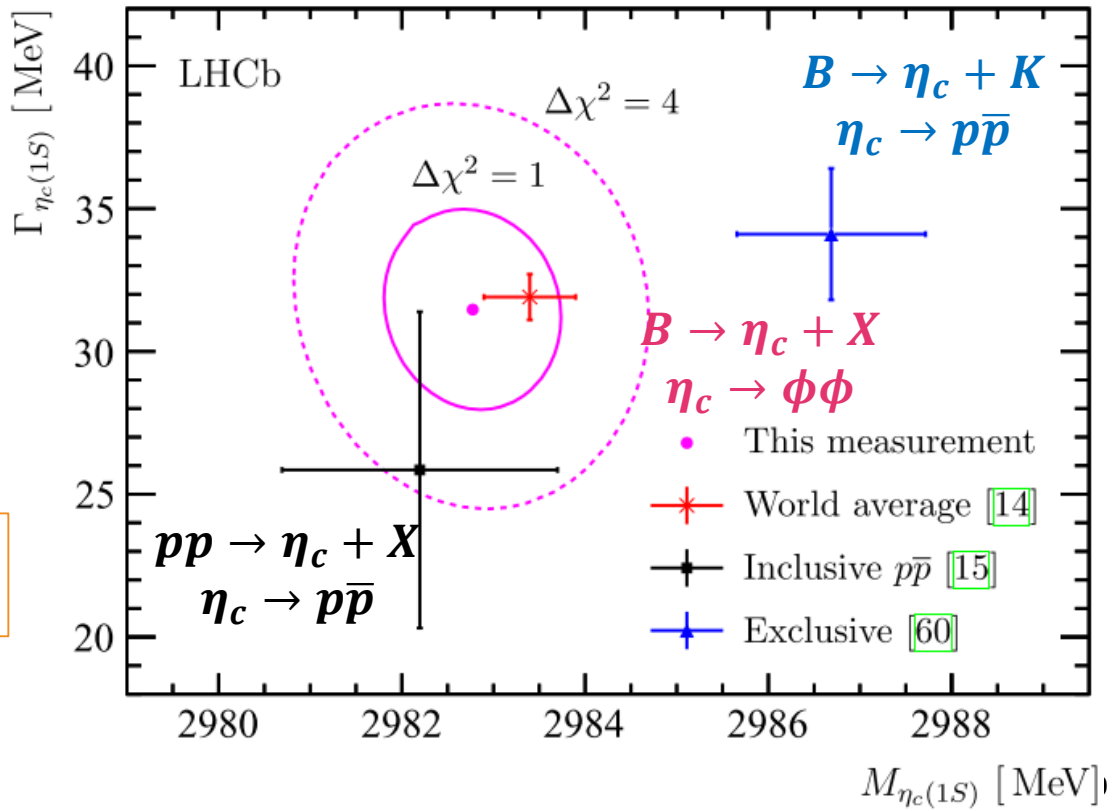
Charmonia from $B^+ \to \phi\phi + X$



	Measured value	World average [14]
$M_{\eta_c(1S)}$	$2982.8 \pm 1.0 \pm 0.5$	2983.4 ± 0.5
$M_{\chi_{c0}}$	$3413.0 \pm 1.9 \pm 0.6$	3414.75 ± 0.31
$M_{\chi_{c1}}$	$3508.4 \pm 1.9 \pm 0.7$	3510.66 ± 0.07
$M_{\chi_{c2}}$	$3557.3 \pm 1.7 \pm 0.7$	3556.20 ± 0.09
$M_{\eta_c(2S)}$	$3636.4 \pm 4.1 \pm 0.7$	3639.2 ± 1.2
$\Gamma_{\eta_c(1S)}$	$31.4 \pm 3.5 \pm 2.0$	31.8 ± 0.8
$\Gamma_{\eta_c(2S)}$	–	$11.3\ ^{+\ 3.2}_{-\ 2.9}$

In MeV

- Inclusive production of charmonium in b-hadron decays, decays to ϕ meson pairs.
- First observe $\eta_c(2S) \to \phi\phi$.
- Competitive measurements of masses of width.

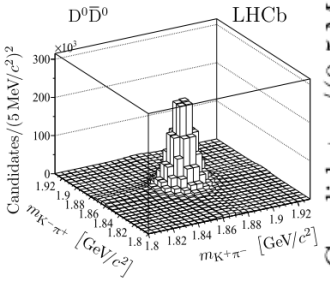


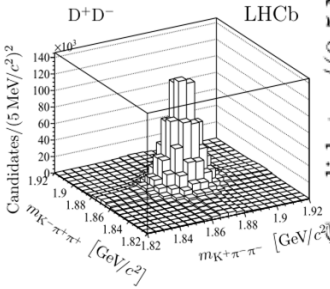
Near-threshold $D\bar{D}$ spectroscopy

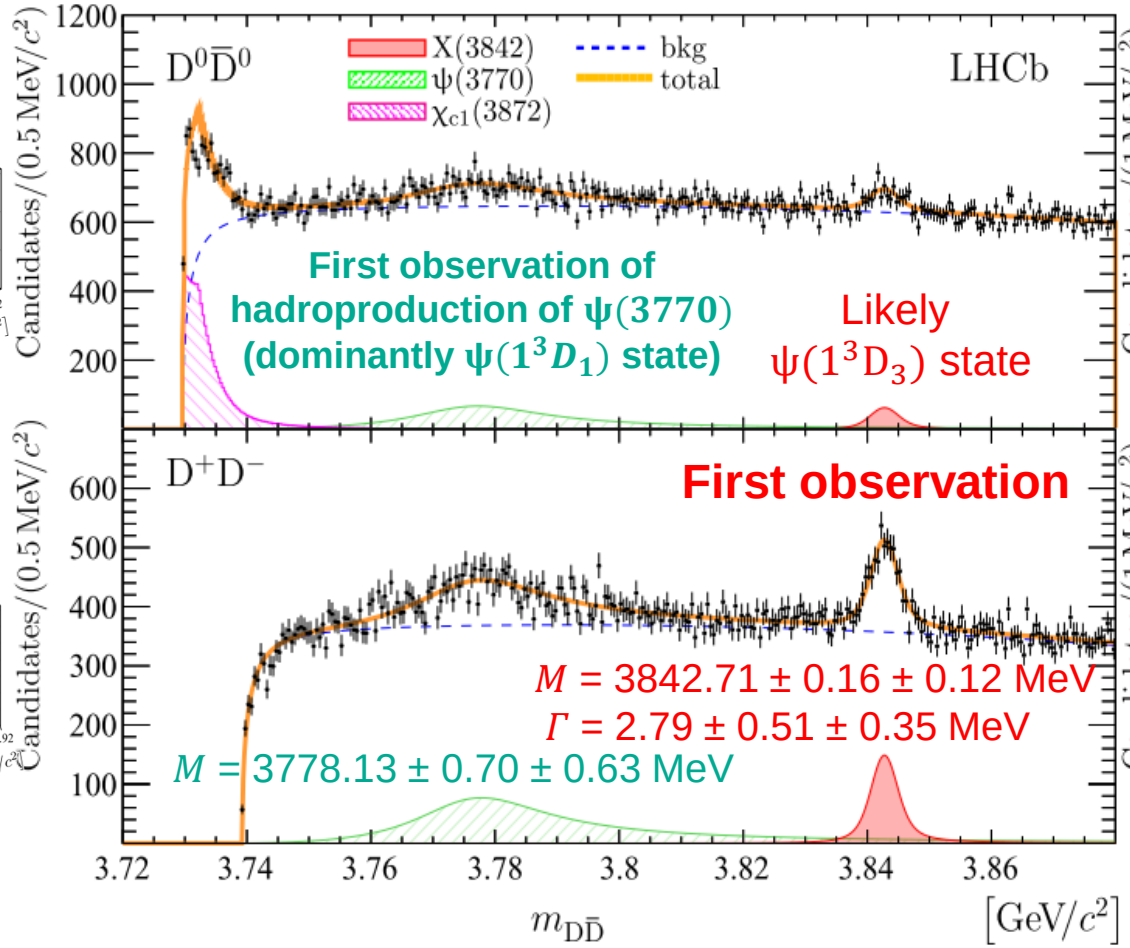
- First LHCb result with full Run 1 + Run 2 data.
- Promptly produced $D\bar{D}$ candidates selected.
- Fit performed in 3 overlapping mass regions to better model background.

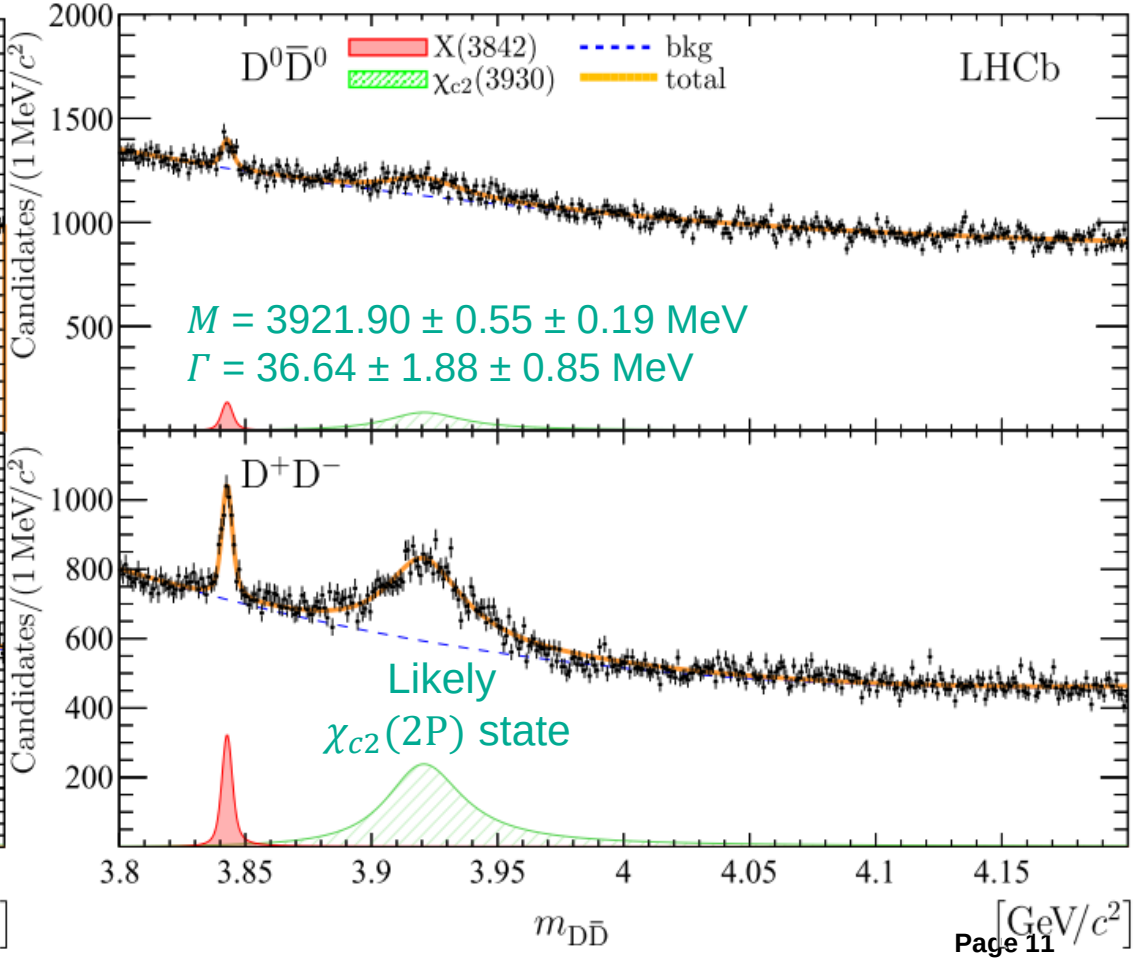
[LHCb-PAPER-2019-005]
arXiv:1903.12240

Run 1 + Run 2 9 fb^{-1}





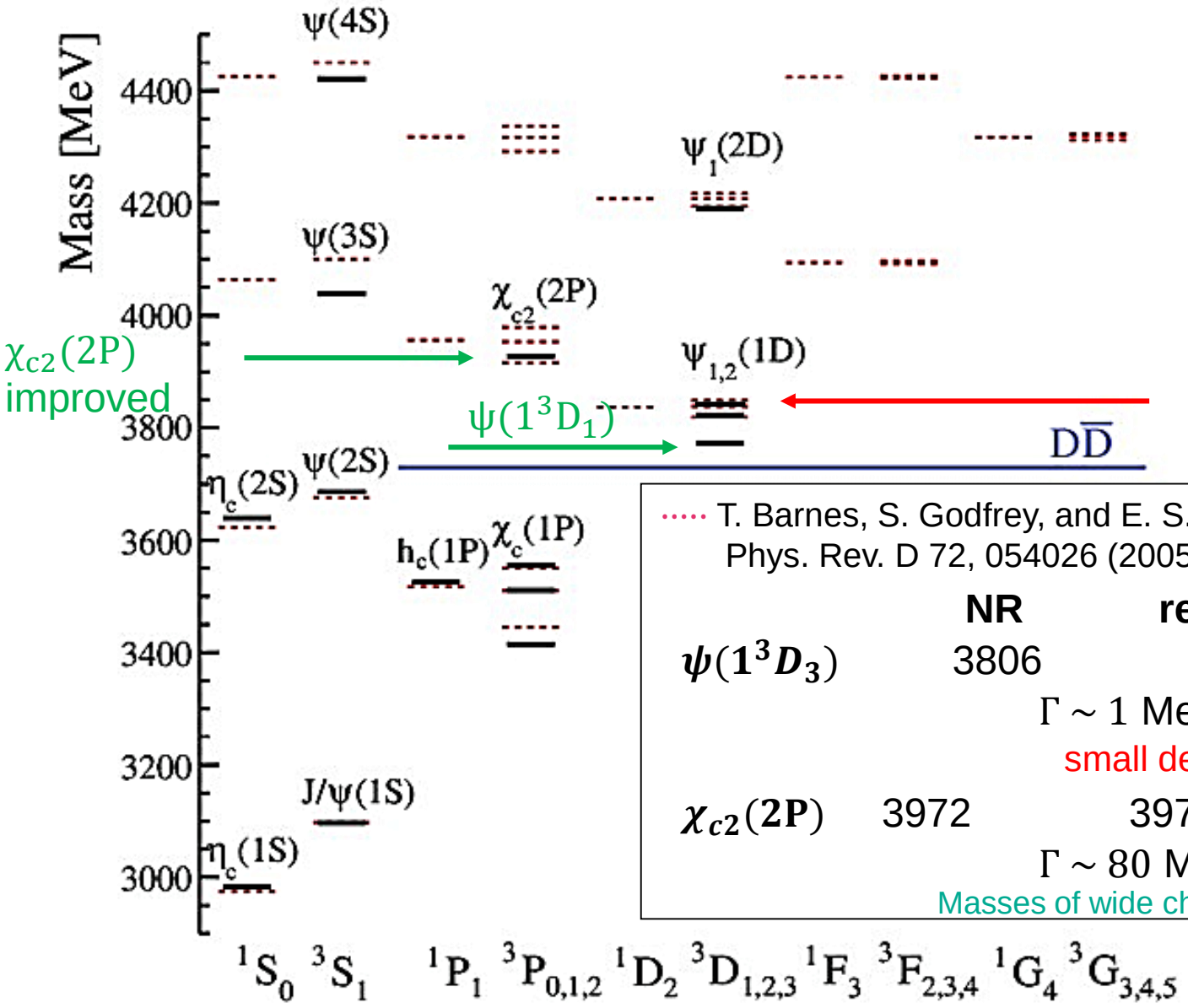




Near-threshold $D\bar{D}$ spectroscopy

$C\bar{C}$

[LHCb-PAPER-2019-005]
arXiv:1903.12240



····· T. Barnes, S. Godfrey, and E. S. Swanson
Phys. Rev. D 72, 054026 (2005):

	NR	relativized	this work
$\psi(1^3D_3)$	3806	3849	3842.71 ± 0.16 ± 0.12 MeV
	Γ ~ 1 MeV		2.79 ± 0.51 ± 0.35 MeV
	small decay phase-space and L=3 centrifugal barrier!		
$\chi_{c2}(2P)$	3972	3979	3921.90 ± 0.55 ± 0.19 MeV
	Γ ~ 80 MeV		36.64 ± 1.88 ± 0.85 MeV
	Masses of wide charmonium states are overestimated in potential approaches.		

Alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$

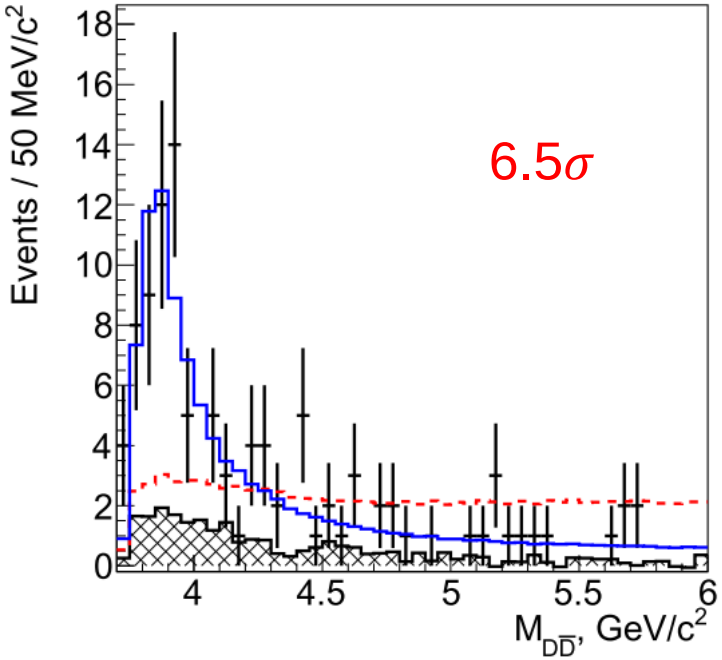
X(3915) → Observed by Belle, confirmed by BaBar in $B \to (J/\psi\omega)K$

X(3915) → Observed by both Belle and BaBar in $\gamma\gamma \to J/\psi\omega$

BaBar: $J^P = 0^+ \Longrightarrow \chi_{c0}(2P)$ candidate(PRD 86, 072002(2012))

Difficulties:

- Too narrow: 20 MeV (measured) versus >100 MeV(expected)
- Not seen in $D\bar{D}$ (expected $\Gamma > 100$ MeV!)
- Unnaturally small $2^3P_2 - 2^3P_1$ mass splitting

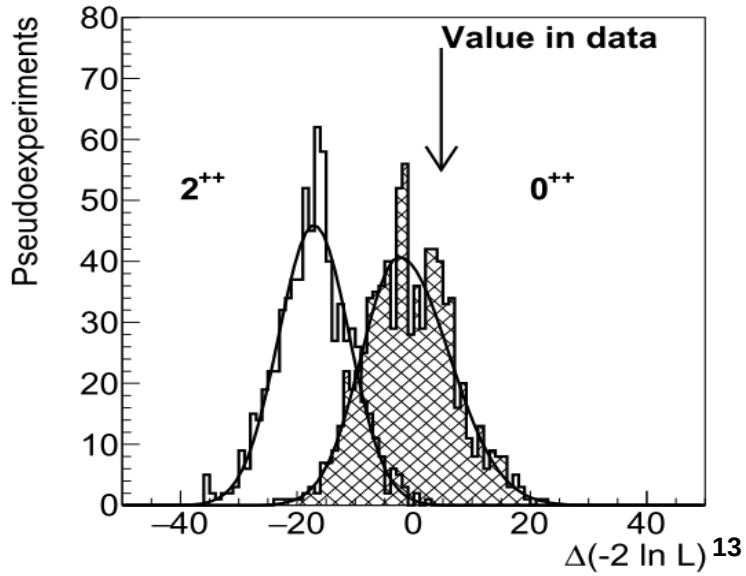


- Belle search for alternative $\chi_{c0}(2P)$ via double-charmonium production in association with the J/ψ.
- Full amplitude analysis of $e^+e^- \to J/\psi D\bar{D}$.

M = 3862^{+26+40}_{-32-13} MeV/c²

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

Consistent with potential model expectations for $\chi_{c0}(2P)$



- The $J^{PC} = 0^{++}$ hypothesis is favored over 2^{++} with 2.5σ (from MC pseudo-experiments).
- Better candidate for the $\chi_{c0}(2P)$ charmonium.

Charm spectroscopy

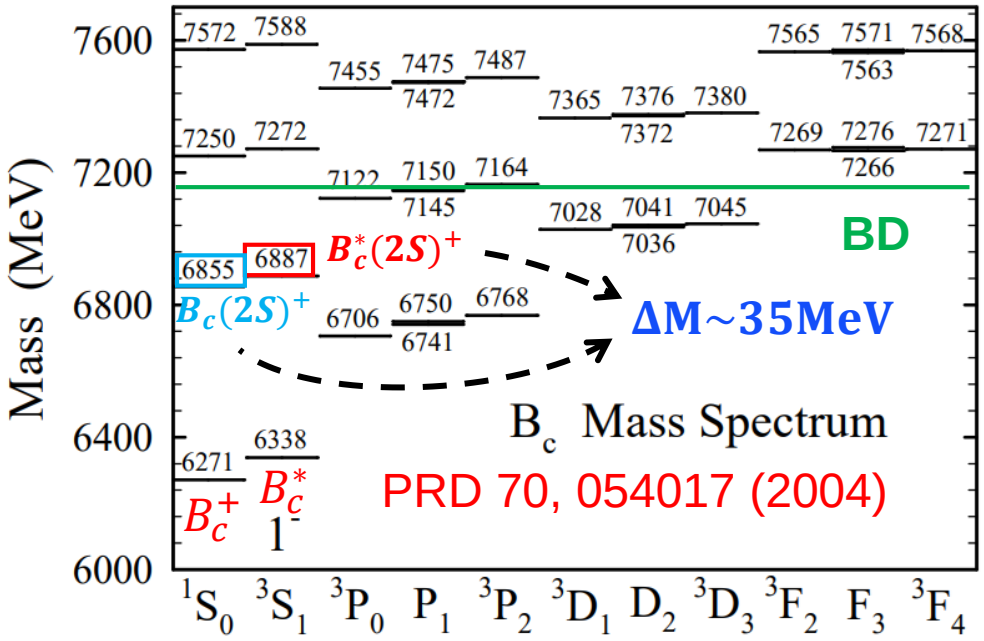
- B_c spectroscopy
- Charmed baryons
  - Λ_c^* states in $\Lambda_b^0 \to D^0 p \pi^-$
  - $\Xi_c(2930)^0$ and $\Xi_c(2930)^+$
  - Observation of exited Ω_c states
  - Observation of the doubly charmed baryon

B_c spectroscopy

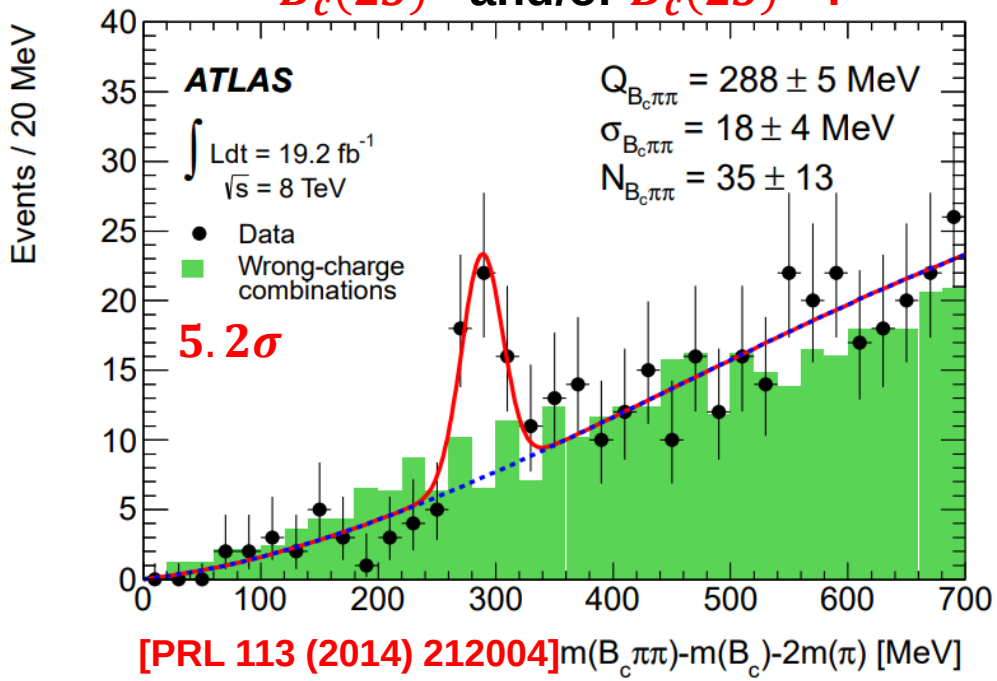
- Unique system of two heavy quarks in a bound state.
- Expected rich spectrum predicted by QCD potential models and Lattice QCD.
- Less explored due to small production rate.
- States below BD threshold can only undergo radiative or pionic transitions to the ground state B_c^+.

In 2014, ATLAS reported a new resonance in the $B_c^+(J/\psi\pi^+)\pi^-\pi^+$ mass spectrum with mass:

$$M = 6842 \pm 4 \pm 5\ \mathrm{MeV/c^2}$$



$B_c(2S)^+$ and/or $B_c^*(2S)^+$?



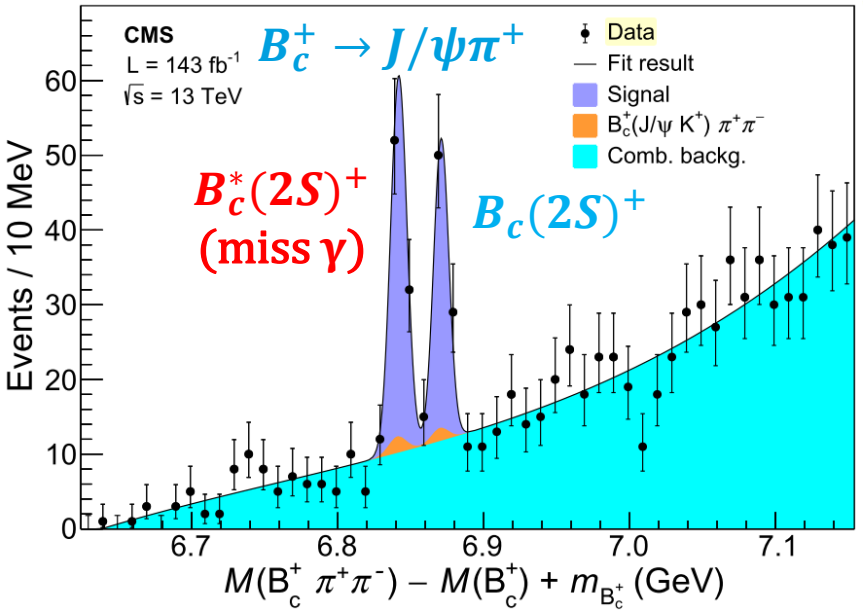
Observation of excited B_c

$B_c^{(*)}(2S)^+$ at CMS

[PRL 122 (2019) 132001]

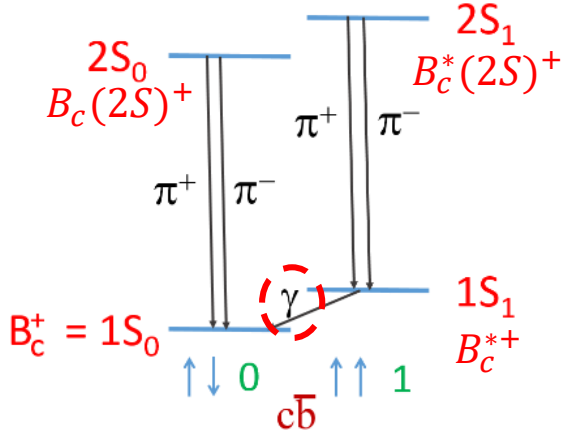
- $B_c^*(2S)^+$ and $B_c(2S)^+$ resolved for the first time with significance $> 5\sigma$.

$$\mathrm{M}(B_c(2S)^+) = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8(B_c^+)\ \mathrm{MeV}/c^2$$
$$\mathrm{M}(B_c(2S)^+) - \mathrm{M}(B_c^*(2S)^+)_{rec} = 29.0 \pm 1.5 \pm 0.7\ \mathrm{MeV}/c^2$$
$$\mathrm{M}(B_c^*(2S)^+) - \mathrm{M}(B_c^{*+}) = 567.1 \pm 1.1\ \mathrm{MeV}/c^2$$

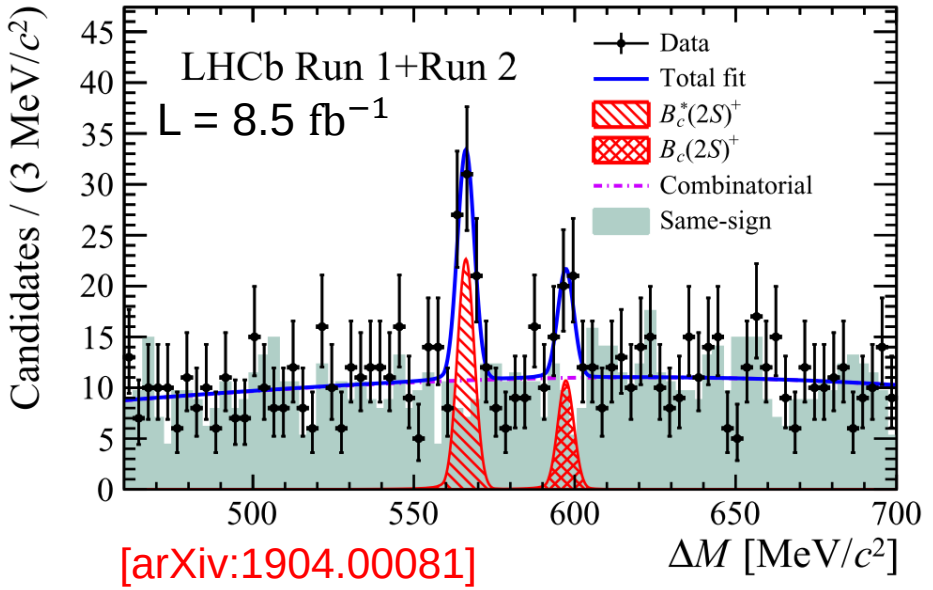


$B_c^{(*)}(2S)^+$ at LHCb

- $B_c^*(2S)^+$ observed with sig. $> 5\sigma$.
- Hint for $B_c(2S)^+$ with global (local) sig. of $2.2(3.2)\sigma$.



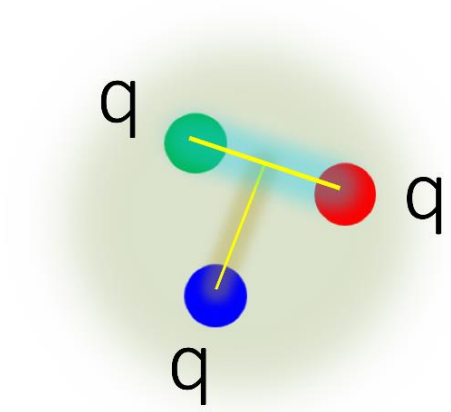
$$\mathrm{M}(B_c(2S)^+) = 6872.1 \pm 1.3 \pm 0.1 \pm 0.8(B_c^+)\ \mathrm{MeV}/c^2$$
$$\mathrm{M}(B_c(2S)^+) - \mathrm{M}(B_c^*(2S)^+)_{rec} = 31.0 \pm 1.4\ \mathrm{MeV}/c^2$$
$$\mathrm{M}(B_c^*(2S)^+)_{rec} = 6841.2 \pm 0.6 \pm 0.1 \pm 0.8(B_c^+)\ \mathrm{MeV}/c^2$$



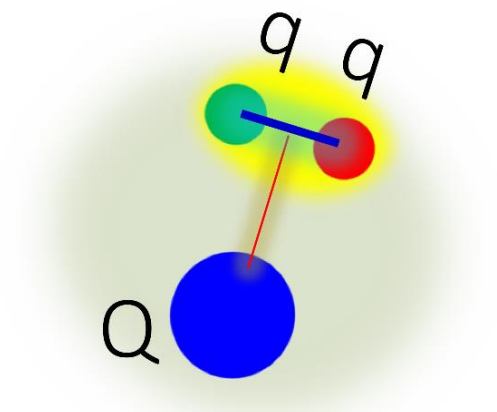
[arXiv:1904.00081]

Charmed baryons

Nucleon / Strange baryons



Charmed baryon

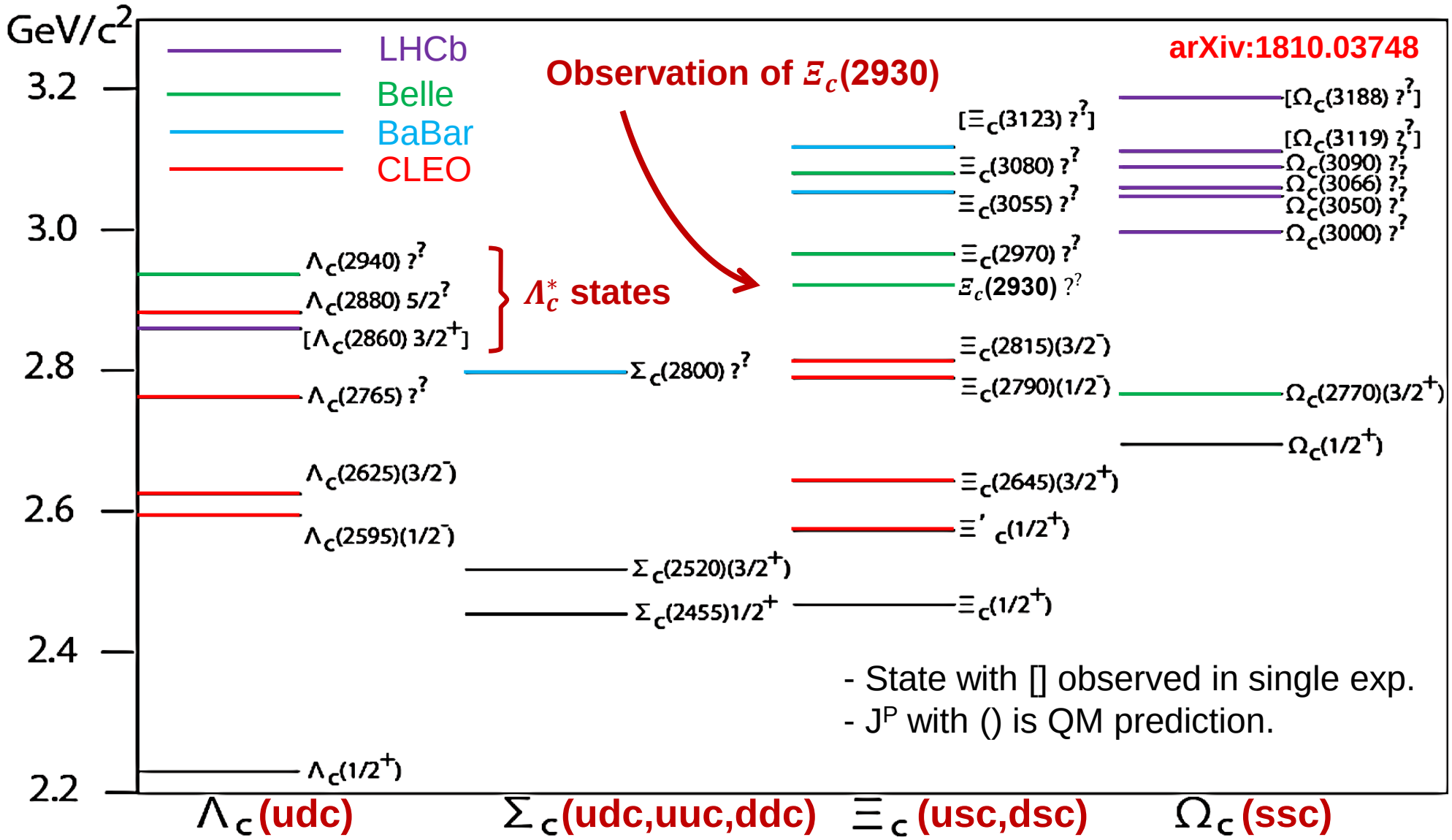


- Charmed baryons consist of one heavy charm quark and two light (u, d, s) quarks.
- Large mass difference provides a natural way to classify these states using HQET.
  - Di-quark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark.
  - Di-quark as new degree of freedom.

Symbol	I	Content
$N(p,n)$	$1/2$	udq
Δ	$3/2$	qqq
Λ	0	sud
Σ	1	sqq
Ξ	$1/2$	ssq
Ω	0	sss
Λ_c	0	cud
Σ_c	1	cqq
Ξ_c	$1/2$	csq
Ω_c	0	css
Ξ_{cc}	$1/2$	ccq
Ω_{cc}	0	ccs
Ω_{ccc}	0	ccc

Not well studied.

Currently observed charmed baryons



✓**Some predicted states unobserved!**

✓**Many missing J^P measurements!**

Study of Ξ_{cc}

Λ_c^* states in $\Lambda_b^0 \to D^0 p\pi^-$

- Amplitude analysis (5D) of the angular distributions of the $\Lambda_b^0 \to D^0 p\pi^-$ decay.
- Detailed study of $D^0 p$ amplitude.
- **$\Lambda_c(2880)^+$ preferred spin $J = \frac{5}{2}$.**

  $M = 2881.75 \pm 0.29 \pm 0.07^{+0.14}_{-0.20}$(model) MeV

  $\Gamma = 5.43^{+0.77}_{-0.71} \pm 0.29^{+0.75}_{-0.00}$(model) MeV

- **$\Lambda_c(2940)^+$ preferred $J^P = \frac{3}{2}^-$, but $\frac{1}{2}$ and $\frac{7}{2}$ not ruled out. First analysis constraining JP for this state.**

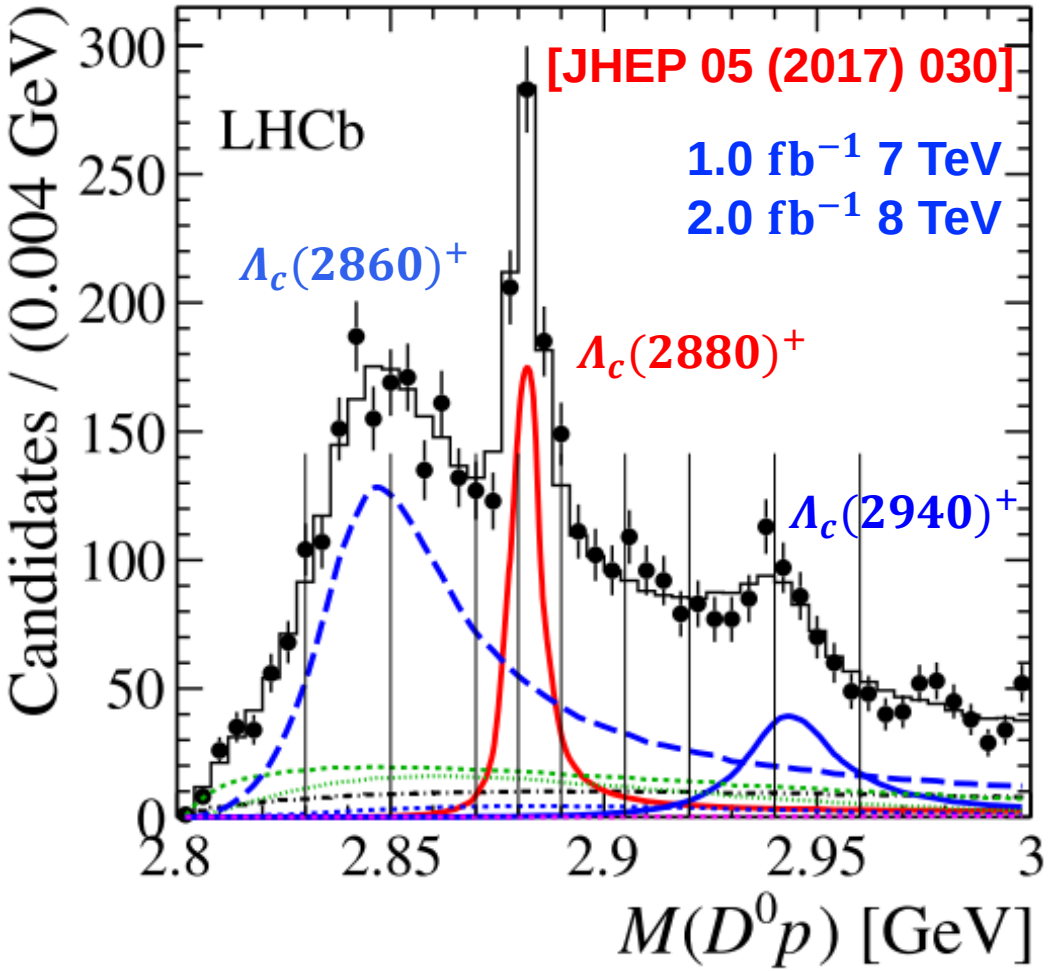
  $M = 2944.8^{+3.5}_{-2.5} \pm 0.4^{+0.1}_{-4.6}$(model) MeV

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

- **New resonance at threshold, designated as $\Lambda_c(2860)^+$, preferred $J^P = \frac{3}{2}^+$.**

  $M = 2856.1^{+2.0}_{-1.7} \pm 0.5^{+1.1}_{-4.6}$(model) MeV

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



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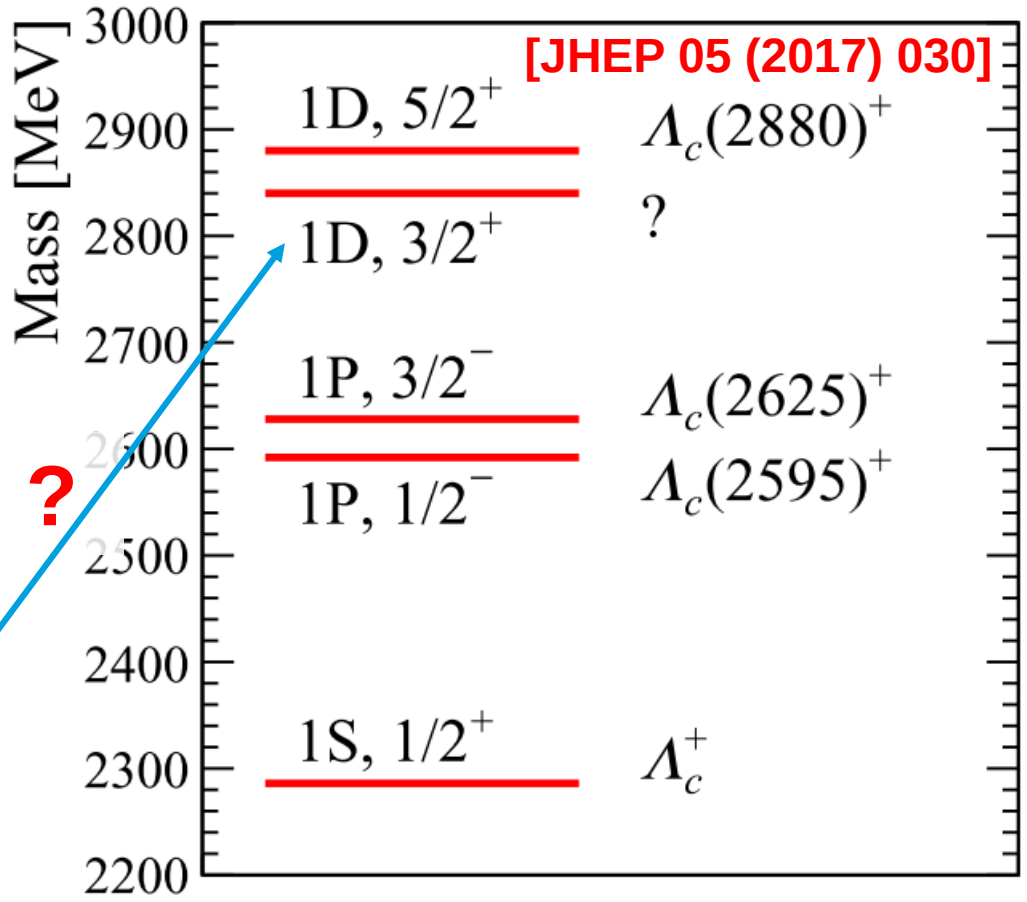
  $M = 2856.1^{+2.0}_{-1.7} \pm 0.5^{+1.1}_{-4.6}$(model) MeV

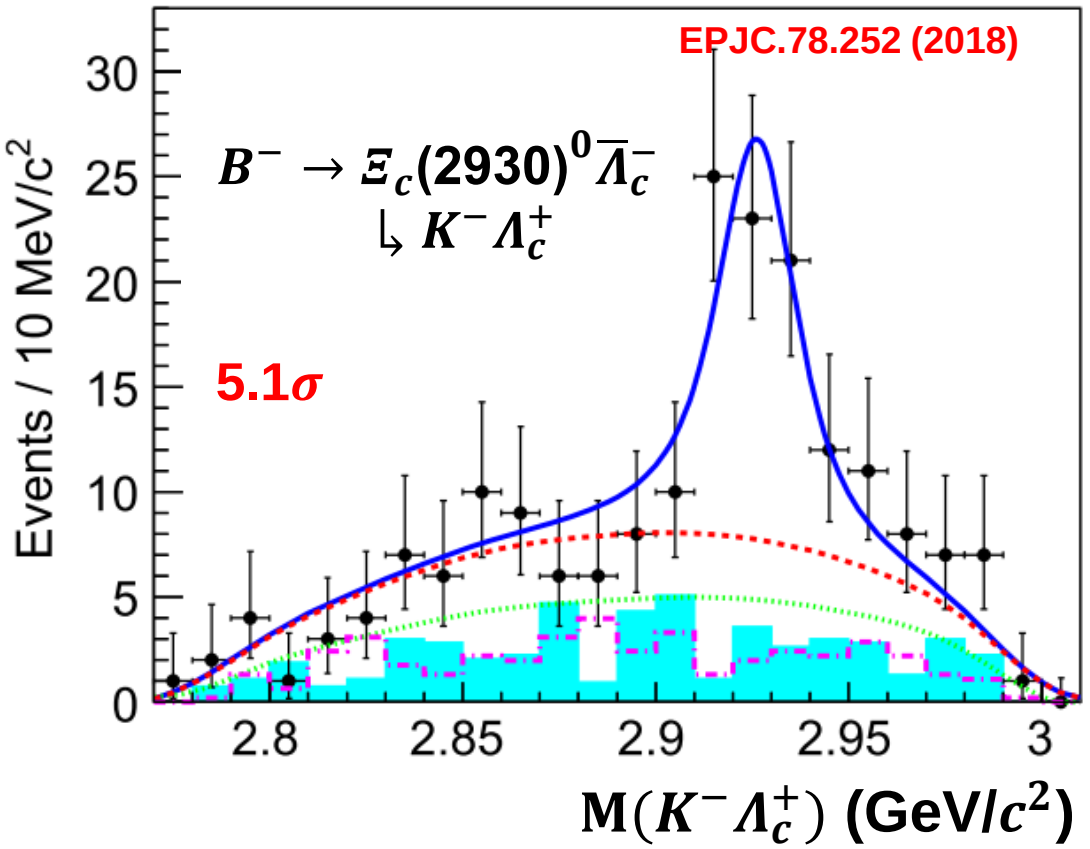
  $\Gamma = 67.6^{+10.1}_{-8.1} \pm 1.4^{+5.9}_{-20.0}$(model) MeV

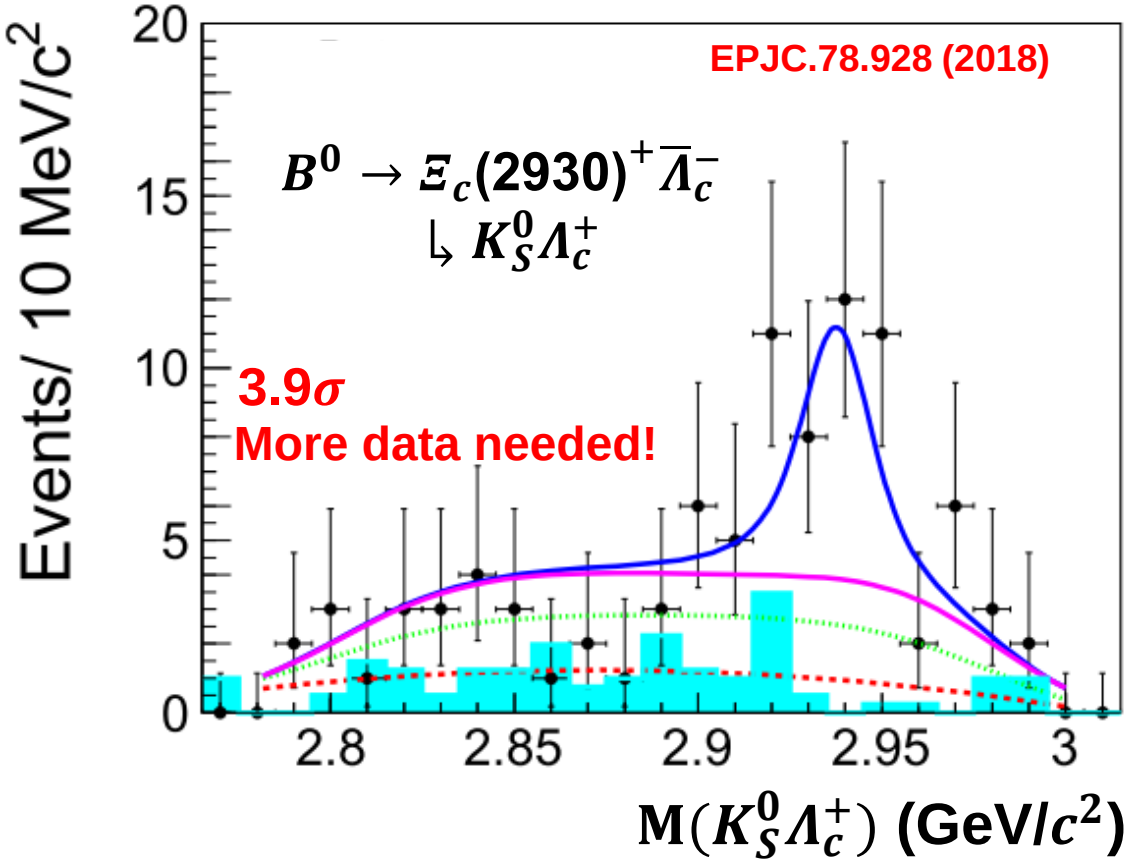


Consistent with recent predictions for the D-wave Λ_c^* with $3/2^+$.

Observation of $\Xi_c(2930)^0$ and evidence of $\Xi_c(2930)^+$

- First reported by Babar, now confirmed by Belle (711 fb^{-1} of data at the $\Upsilon(4S)$ resonance):





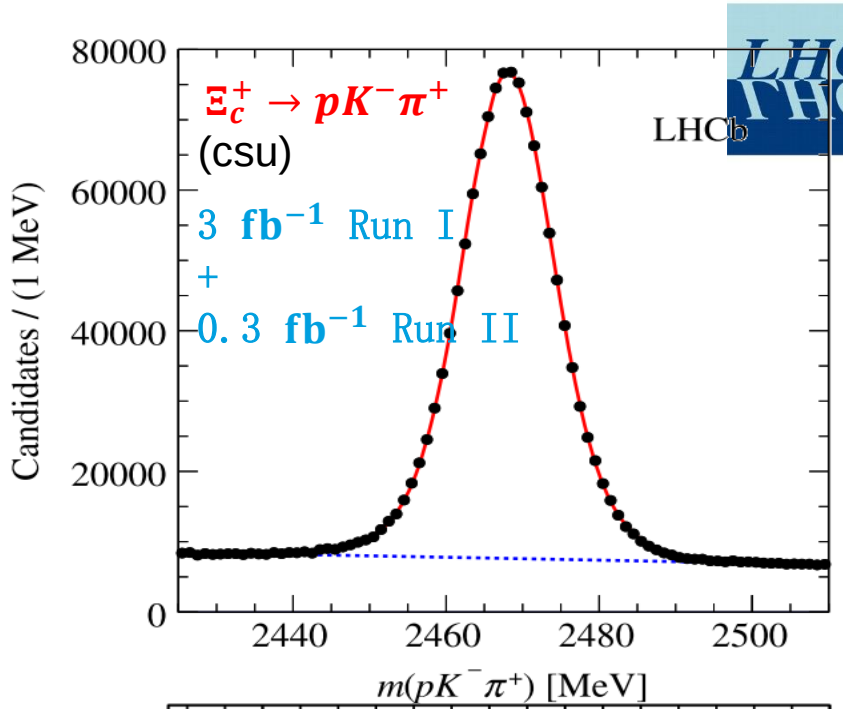
$\mathrm{M} = 2928 \pm 3.0(\mathrm{stat.})^{+0.9}_{-12.0}(\mathrm{syst.})$ MeV
$\Gamma = 19.5 \pm 8.4(\mathrm{stat.})^{+5.9}_{-7.9}(\mathrm{syst.})$ MeV

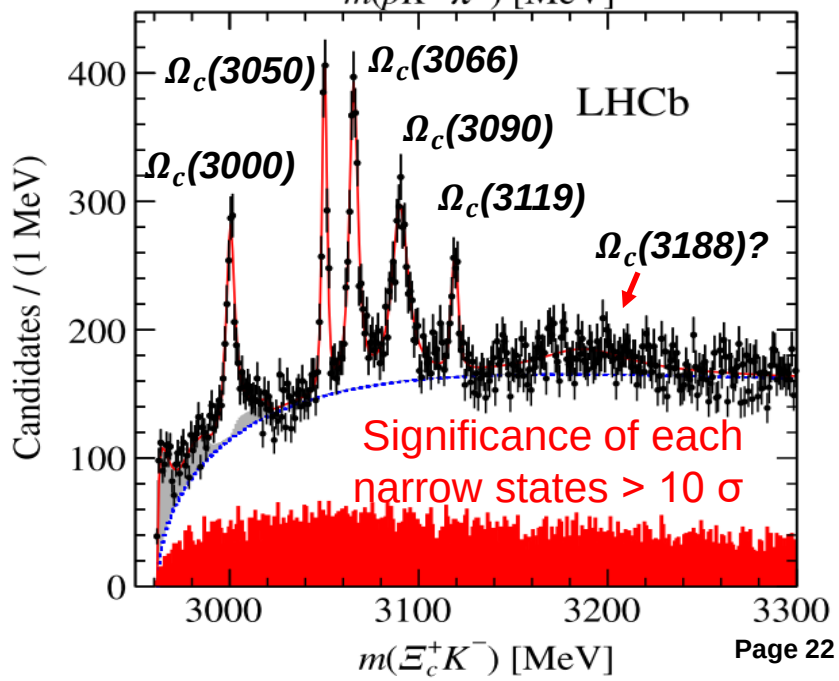
$\mathrm{M} = 2942 \pm 4.4(\mathrm{stat.}) \pm 1.5(\mathrm{syst.})$ MeV
$\Gamma = 19.5 \pm 8.4(\mathrm{stat.}) \pm 2.5(\mathrm{syst.})$ MeV

Observation of exited Ω_c states

- Excited $\Lambda_c^+, \Sigma_c, \Xi_c$ states have been reported but no excited Ω_c^0 states were observed before LHCb.
- Search via decay: $\Omega_c^{*0} \to \Xi_c^+ K^-$, $\Xi_c^+ \to pK^-\pi^+$.
- Cabibbo suppressed c → d weak decay, but much higher reconstruction efficiency and purity.
- 5 narrow states & evidence for 6th broader state at high mass.

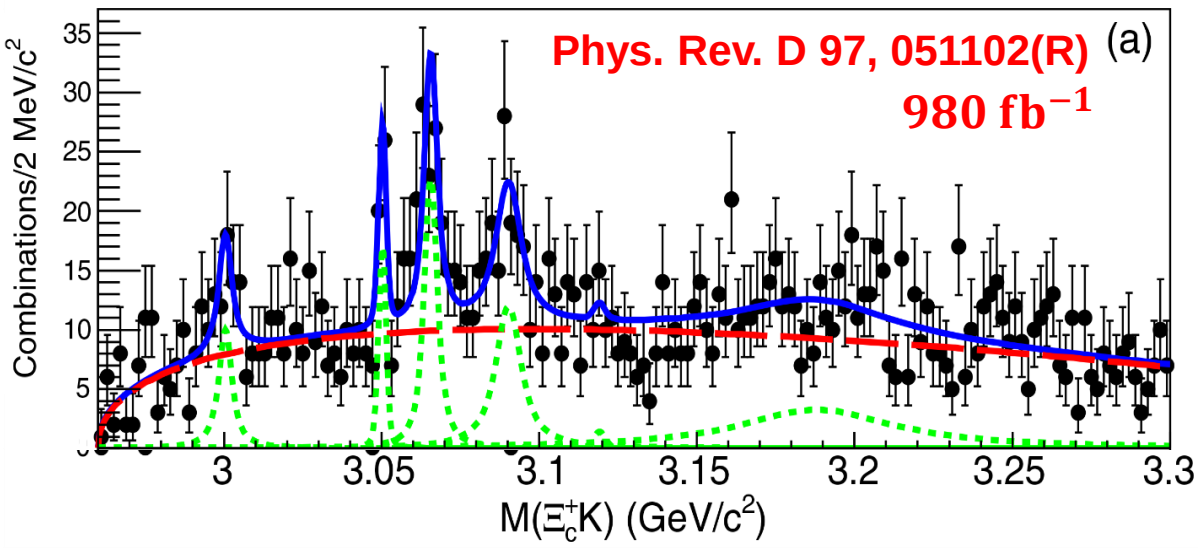
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$





PRL 118 (2017) 182001

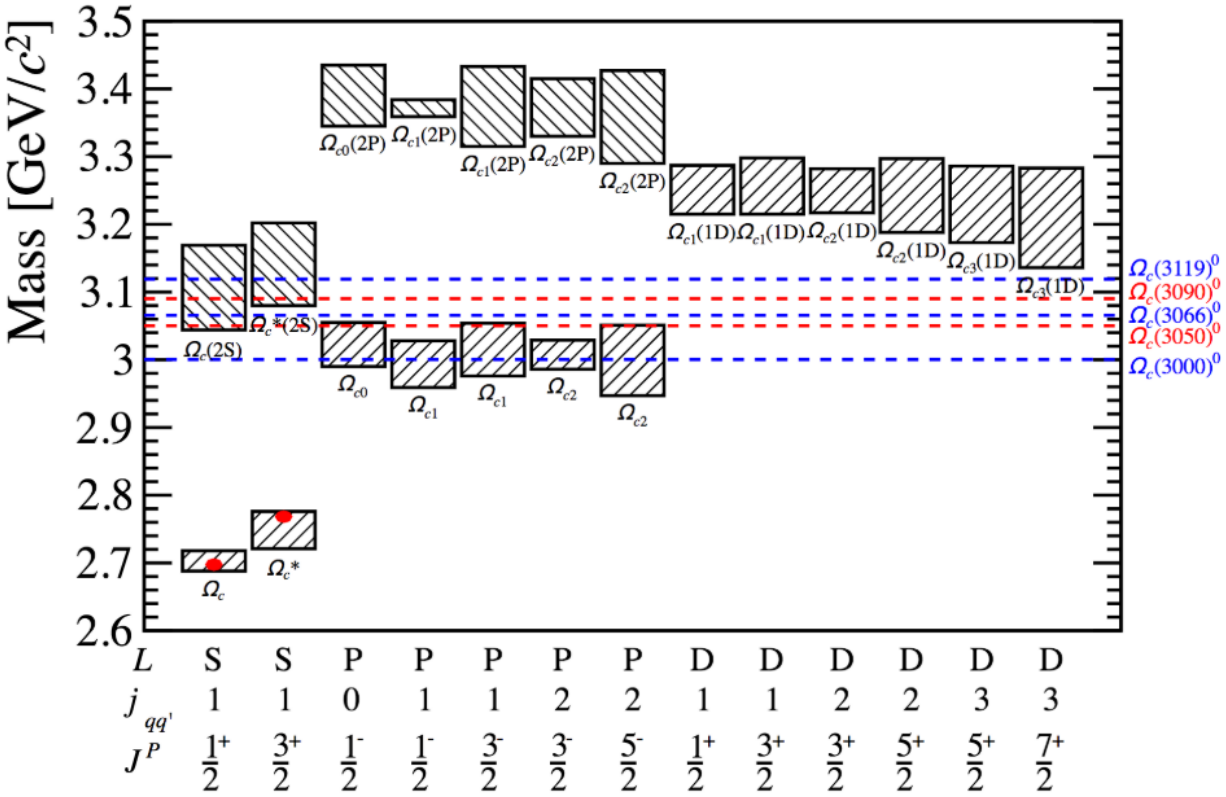
Confirmation by Belle



	LHCb	Belle
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$3000.7 \pm 1.0 \pm 0.2 (3.9\sigma)$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$3050.2 \pm 0.4 \pm 0.2 (4.6\sigma)$
$\Omega_c(3066)^0$	$3065.5 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3064.9 \pm 0.6 \pm 0.2 (7.2\sigma)$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$3089.3 \pm 1.2 \pm 0.2 (5.7\sigma)$
$\Omega_c(3119)^0$	$3119 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	- (0.4σ)
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$3199 \pm 9 \pm 4 (2.4\sigma)$

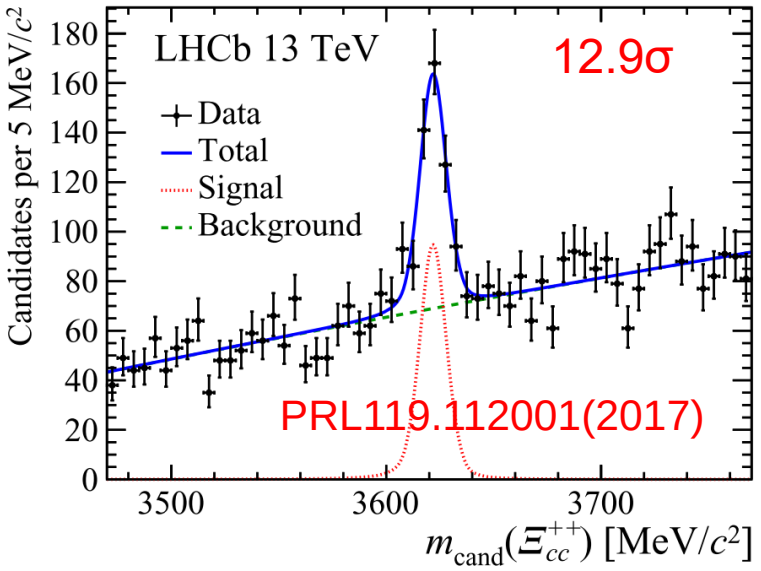
- Belle also measured $\Omega_c^{*0} \to \Xi_c^+ K^-$, $\Xi_c^+ \to pK^-\pi^+$
- Ω_c^{*0} width fixed with the value from LHCb.
- All the Ω_c^{*0} except $\Omega_c(3119)^0$ confirmed.

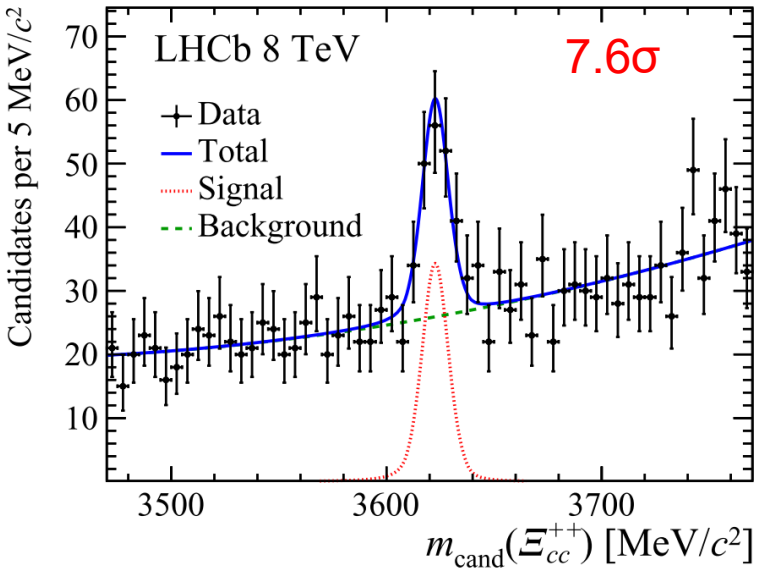
- Matching between observed peaks and predictions requires spin parity information.

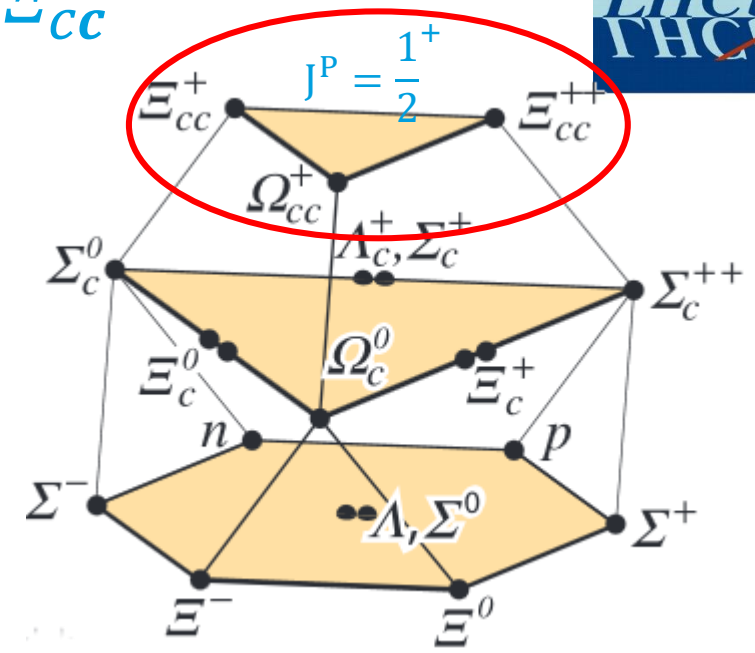


Observation of the doubly charmed baryon Ξ_{cc}^{++}

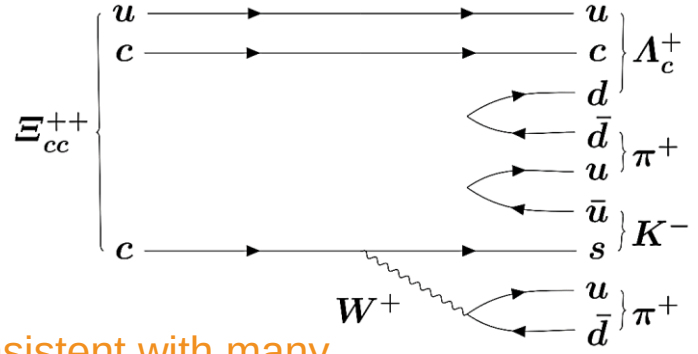
- Existence of doubly charmed baryons predicted by quark model.
- Observation of Ξ_{cc}^{++} claimed by SELEX [PLB 628 (2005) 18-24].
- No evidence observed by BaBar, FOCUS, Belle and LHCb.
- Search in LHCb for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ (most promising channel).
- Data sample: 2.0 (8 TeV) + 1.7 (13 TeV) fb^{-1}.







Lattice QCD calculations
$\text{m}(\Xi_{cc}^{++}) = 3606 \pm 11 \pm 8\ MeV/c^2$
[arXiv: 1704.02647]



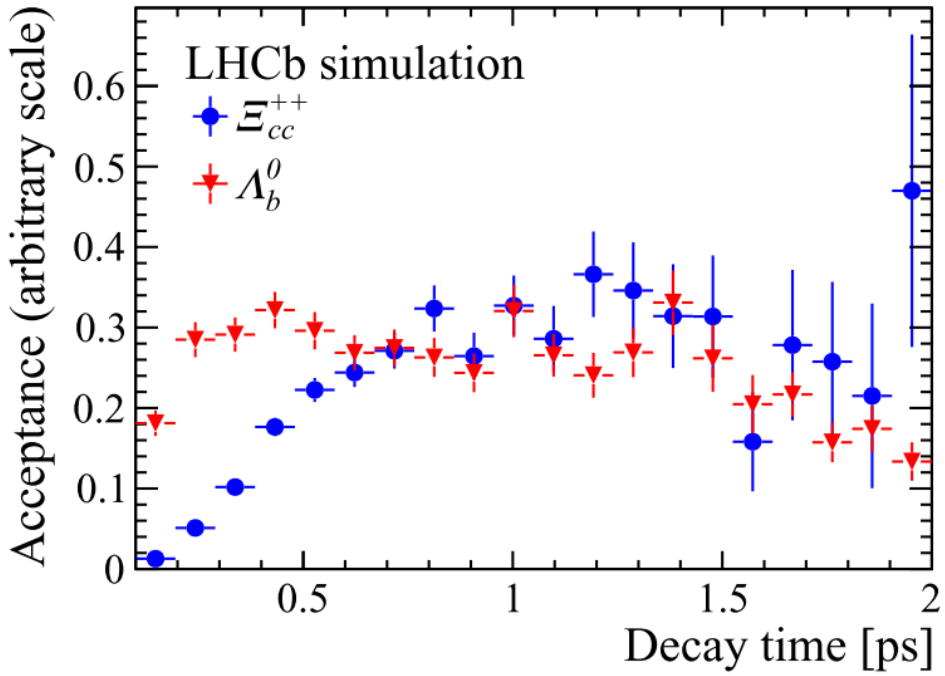
- The mass is measured with the 2016 (13 TeV) sample:

$$m(\Xi_{cc}^{++}) = 3621 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

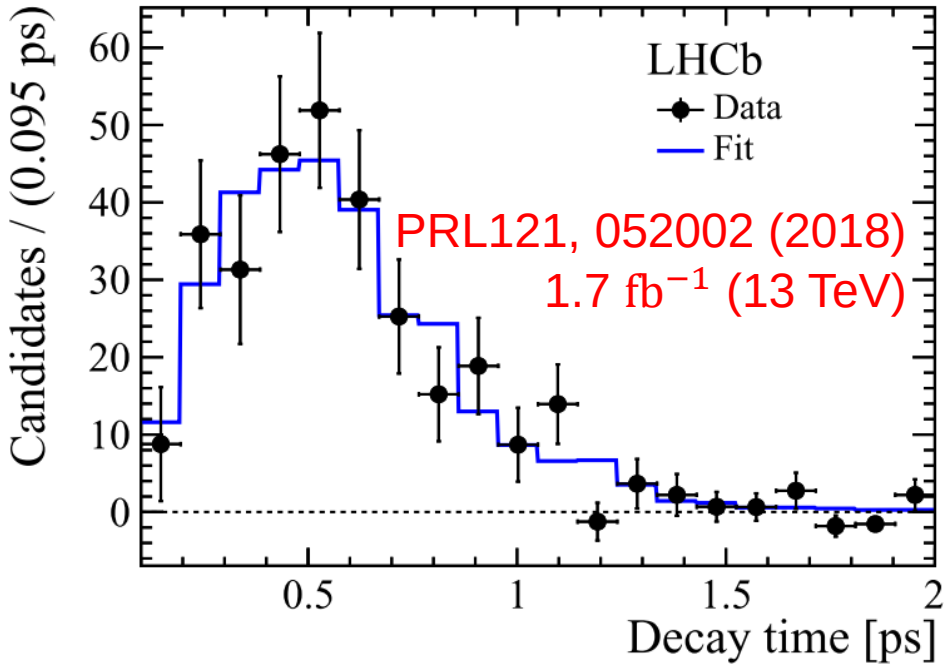
Consistent with many theoretical calculations

Measurement of Ξ_{cc}^{++} lifetime

- Same data as $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ analysis with extra trigger requirement.
- Decay-time distribution measured relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$.
  - Same selection criteria, common systematic effects largely cancel.
  - Lifetime acceptances taken from simulation.



Ξ_{cc}^{++} background subtracted data



- Result from fit to data:

$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst}) \text{ ps}$$

Establishes the weakly decaying nature of Ξ_{cc}^{++}!

Summary

- Wide range of interesting charmonium and charm spectroscopy results: only a small selection of recent results.
- Measurements of resonance parameters improved.
- New states have been just observed and fit the expectations.
  - Candidates for $\psi(1^3D_3)$ and $\chi_{c0}(2P)$.
  - Excited B_c states, excited Λ_c, Ξ_c, Ω_c states, and doubly charmed baryon Ξ_{cc}^{++}.
- BESIII will keep taking data in the region of charmonium. Belle II just started Phase III data taking. With the upgrade, LHCb will get much more data.
- Look forward to more exciting news!

Thanks for your attention!