

Hadron spectroscopy at LHCb

Recent results (2018-2019)

Anton Poluektov
on behalf of LHCb collaboration

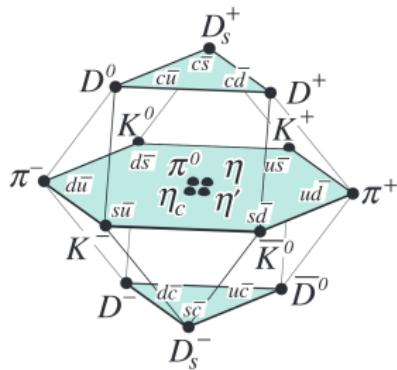
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

1 October 2019

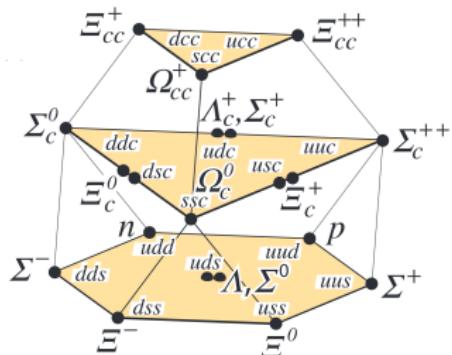


Heavy flavour spectroscopy

- No free quarks, held together by strong interaction. Form colourless objects, most simple ones: mesons ($q\bar{q}$) and baryons (qqq)
- Angular, spin and radial excitations \Rightarrow spectroscopy
- Perturbative QCD calculations have limited applicability: phenomenological models (e.g. non-relativistic potential), lattice QCD.



$SU(4)$ meson multiplets with
 $S = 1/2$



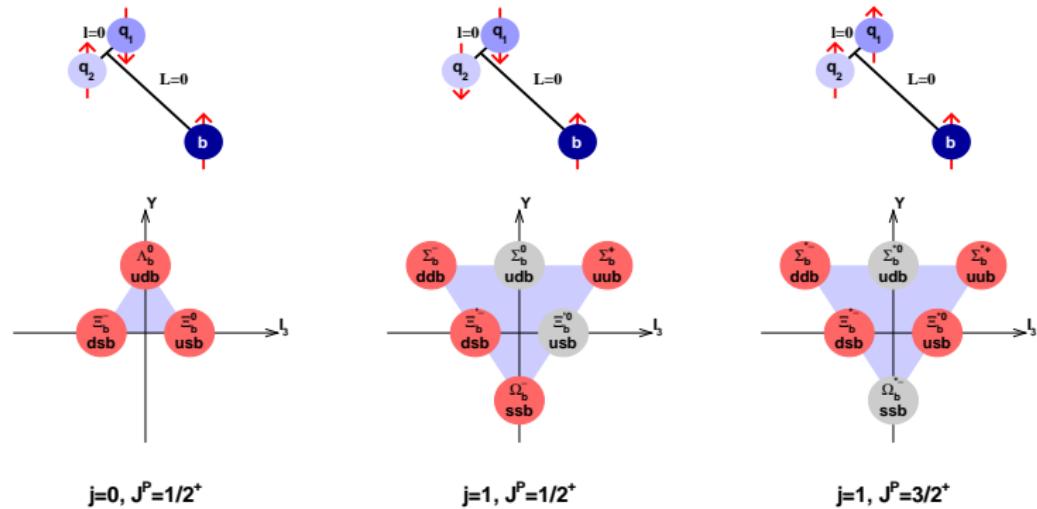
$SU(4)$ baryon multiplets with
 $S = 1/2$

- Exotic spectroscopy: beyond 2- and 3-quark systems:
tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$)

Conventional states: b -baryons

Ground-state baryons

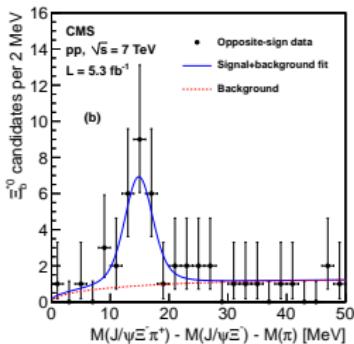
- - observed
- - unobserved



Three of them discovered recently at LHC:

- Ξ_b^{*0} : CMS [PRL 108 (2012) 252002]
- $\Xi_b^{'-}$, Ξ_b^{*-} : LHCb [PRL 114 (2015) 062004]

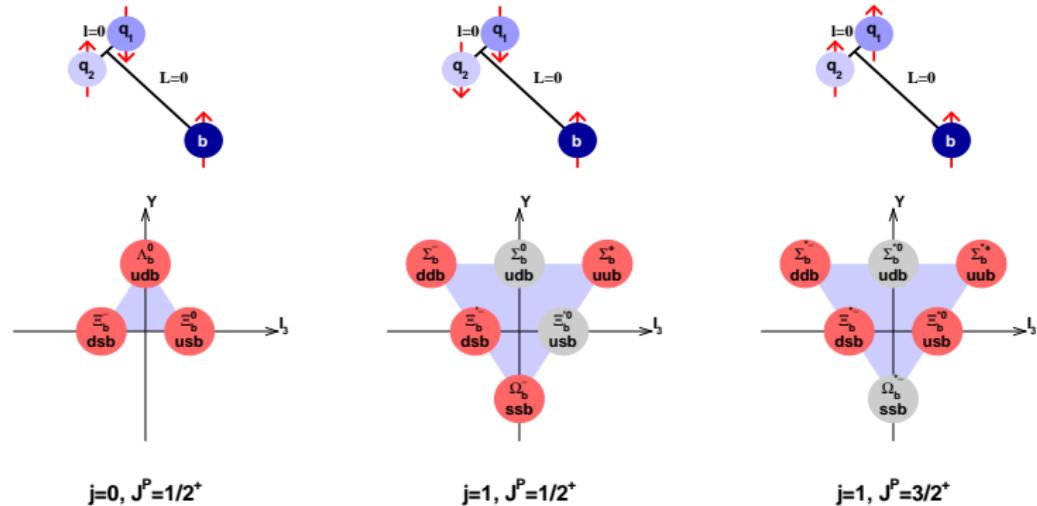
Four still hiding (Σ_b^0 , Σ_b^{*0} , $\Xi_b^{'0}$, Ω_b^{*-})
(final state involves soft neutral particles)



Conventional states: b -baryons

Ground-state baryons

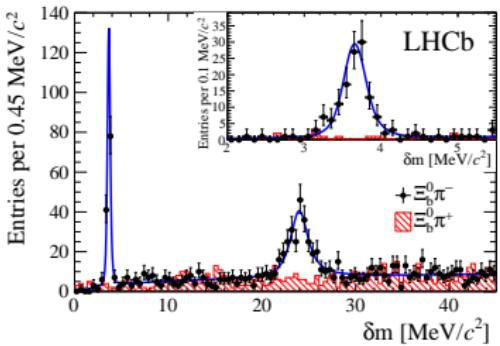
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Four still hiding (Σ_b^0 , Σ_b^{*0} , Ξ_b^{*0} , Ω_b^{*-})
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Excited Λ_b^0 and Σ_b states

Large number of excitations. Strong decays to $\Lambda_b^0\pi$, $\Lambda_b^0\gamma$, $\Lambda_b^0\pi^+\pi^-$

Baryon	State	J^P	Experiment [29]	Ref. [10]	Ref. [11]	Ref. [12]	Ref. [13]
Λ_b^0	1S	1/2 ⁺	5619.60 ± 0.17	5619	5620	5612	5585
	1P	1/2 ⁻	5912.20 ± 0.21	5911	5930	5939	5912
		3/2 ⁻	5919.92 ± 0.19	5920	5942	5941	5920
	2S	1/2 ⁺			6089	6107	6045
	1D	3/2 ⁺		6147	6190	6181	6145
		5/2 ⁺		6153	6196	6183	6165
	2P	1/2 ⁻			6326	6180	6100
		3/2 ⁻			6333	6191	6185
	1S	1/2 ⁺	$\sim 5810^\dagger$		5808	5833	5795
Σ_b^0		3/2 ⁺	$\sim 5830^\dagger$		5834	5858	5805
	1P	1/2 ⁻			6101	6099	6070
		3/2 ⁻			6096	6101	6070
		5/2 ⁻			6084	6172	6090
	2S	1/2 ⁺			6213	6294	6200
		3/2 ⁺			6226	6308	6250
	1D	1/2 ⁺			6311		
		3/2 ⁺			6326		
		3/2 ⁺			6285		
		5/2 ⁺			6284	6325	6325
		5/2 ⁺			6270	6328	

[10] B. Chen, K.-W. Wei, and A. Zhang, *Investigation of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture*, Eur. Phys. J. **A51** (2015) 82, arXiv:1406.6561.

[11] D. Ebert, R. N. Faustov, and V. O. Galkin, *Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture*, Phys. Rev. **D84** (2011) 014025, arXiv:1105.0583.

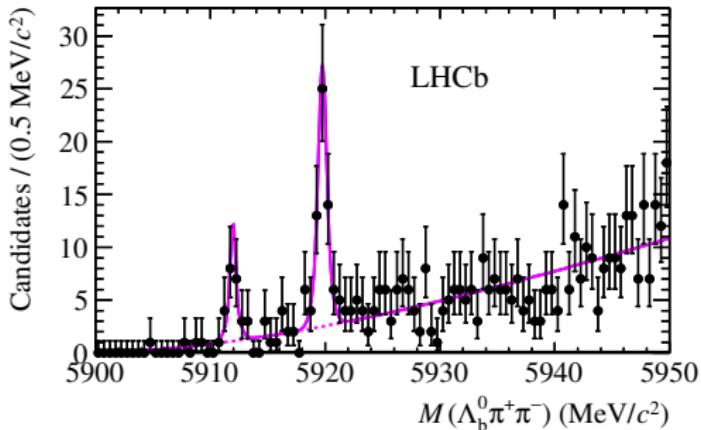
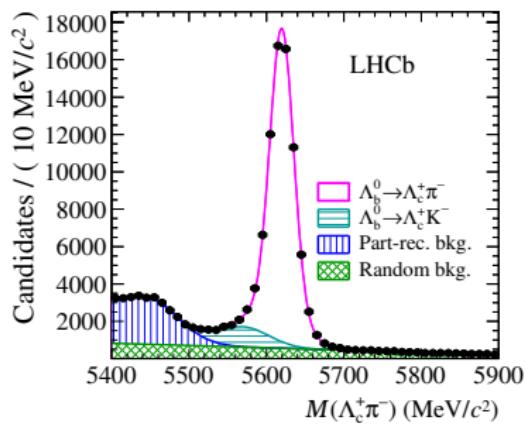
[12] W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

[13] S. Capstick and N. Isgur, *Baryons in a relativized quark model with chromodynamics*, Phys. Rev. **D34** (1986) 2809.

Excited Λ_b^0 states

[PRL 109 (2012) 172003]

$$\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi^+ \pi^-, \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ \rightarrow p K^- \pi^+$$



$$m(\Lambda_b^0(5912)^0) = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66 \text{ MeV}$$

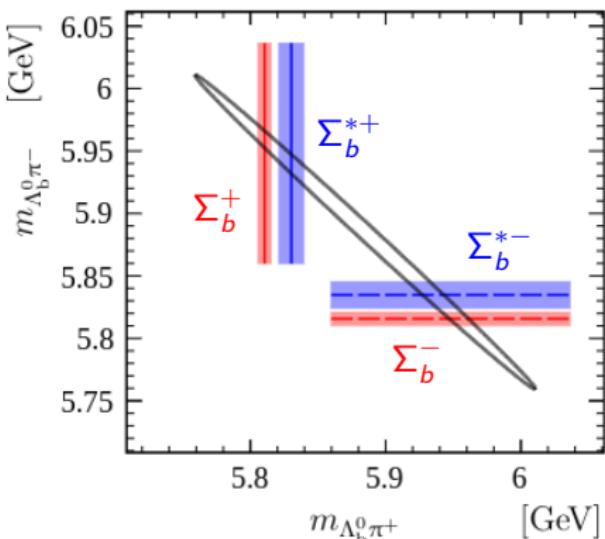
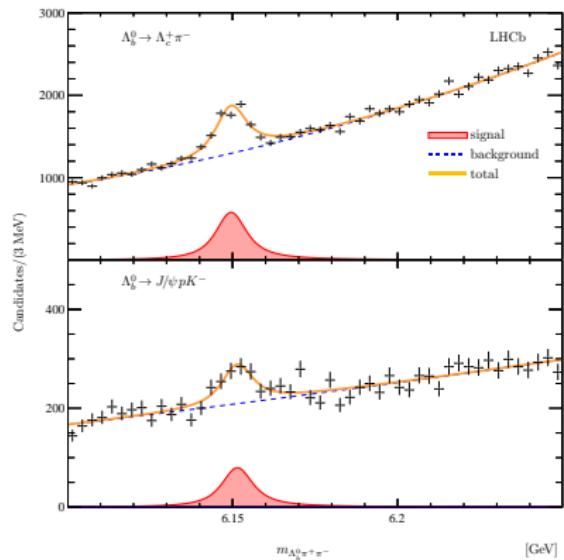
$$\Gamma(\Lambda_b^0(5912)^0) < 0.66 \text{ MeV}$$

$$m(\Lambda_b^0(5920)^0) = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66 \text{ MeV}$$

$$\Gamma(\Lambda_b^0(5920)^0) < 0.63 \text{ MeV}$$

Interpretation: doublet of orbitally-excited $\Lambda_b^0(1P)$ states ($J^P = 1/2^-, 3/2^-$)

Spectrum of higher $\Lambda_b^0\pi^+\pi^-$ masses (above $\Sigma_b\pi$ threshold)



Relative rates with intermediate Σ_b ($1/2^+$) and Σ_b^{*+} ($3/2^+$) can constrain quantum numbers \Rightarrow

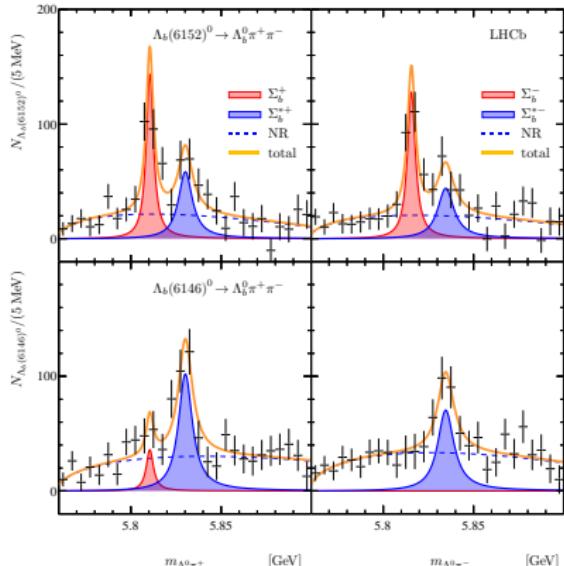
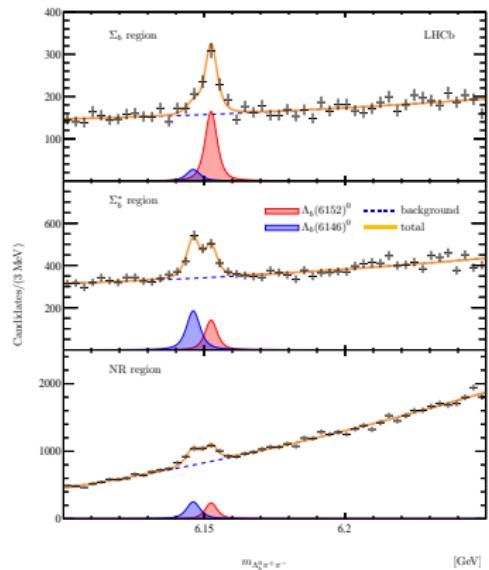
Investigate $m(\Lambda_b^0\pi^+\pi^-)$ in 3 regions: $\Sigma_b\pi$, $\Sigma_b^*\pi$ and “non-resonant” (the rest)

Discovery of new Λ_b^0 doublet

New!

[arXiv:1907.13598]

Two peaks! Higher-mass \rightarrow both $\Sigma_b^{(*)}$, lower only to Σ_b^*



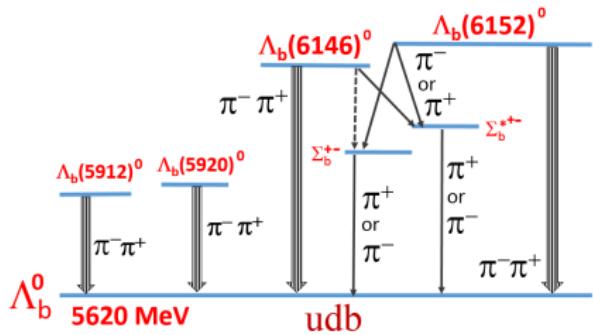
$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$

$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$

$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$

$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

New $\Lambda_b^0\pi^+\pi^-$ doublet: interpretation



Possible interpretation:
 $\Lambda_b^0(1D)$ states with $J^P = 3/2^+, 5/2^+$.

$3/2^+ \rightarrow 1/2^+ + 0^-$: *P-wave*.

$3/2^+ \rightarrow 3/2^+ + 0^-$: *P-wave*.

$5/2^+ \rightarrow 1/2^+ + 0^-$: *F-wave*.

$5/2^+ \rightarrow 3/2^+ + 0^-$: *P-wave*.

In this interpretation, $m(\Lambda_b^0(3/2^+)) > m(\Lambda_b^0(5/2^+))$!

Other possible interpretations in the given mass range ($\Lambda_b(2S)$, $\Sigma_b(2S)$, $\Sigma_b(1P)$) are less likely.

[W. Liang, Q.-F. Lu, X.-H. Zhong, PRD 100, 054013 (2019)]

Study of $\Sigma_b^{(*)}$ states

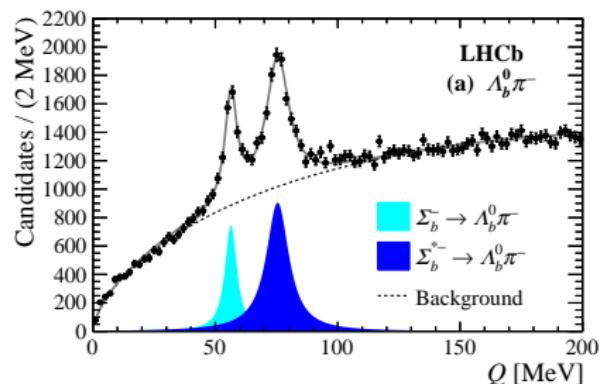
[PRL 122(2019) 012001]

Ground-state Σ_b , Σ_b^* states near $\Lambda_b^0\pi$ threshold.

Discovered by CDF

[PRL 99 (2007) 202001]

LHCb measurement: $\sim \times 5$ better precision

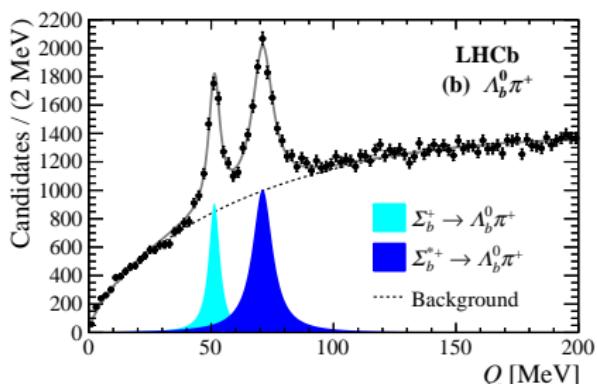


$$m(\Sigma_b^-) = 5815.64 \pm 0.14 \pm 0.24 \text{ MeV}$$

$$\Gamma(\Sigma_b^-) = 5.33 \pm 0.42 \pm 0.37 \text{ MeV}$$

$$m(\Sigma_b^{*-}) = 5834.73 \pm 0.17 \pm 0.25 \text{ MeV}$$

$$\Gamma(\Sigma_b^{*-}) = 10.68 \pm 0.60 \pm 0.33 \text{ MeV}$$



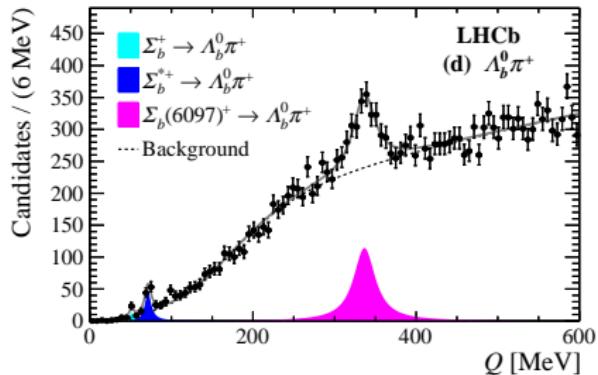
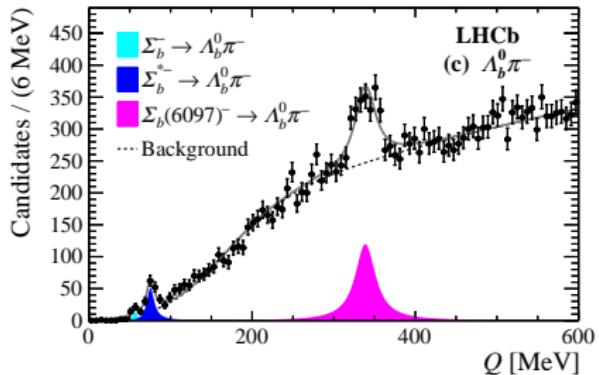
$$m(\Sigma_b^+) = 5810.55 \pm 0.11 \pm 0.23 \text{ MeV}$$

$$\Gamma(\Sigma_b^+) = 4.83 \pm 0.31 \pm 0.37 \text{ MeV}$$

$$m(\Sigma_b^{*+}) = 5830.28 \pm 0.14 \pm 0.24 \text{ MeV}$$

$$\Gamma(\Sigma_b^{*+}) = 9.34 \pm 0.47 \pm 0.26 \text{ MeV}$$

Wider $m(\Lambda_b^0\pi)$ region:



$$m(\Sigma_b(6097)^-) = 6098.0 \pm 1.7 \pm 0.5 \text{ MeV}$$

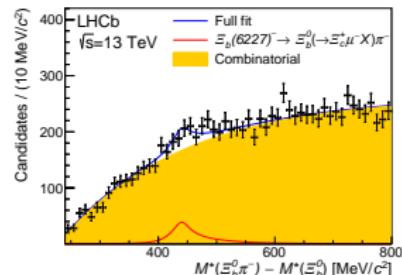
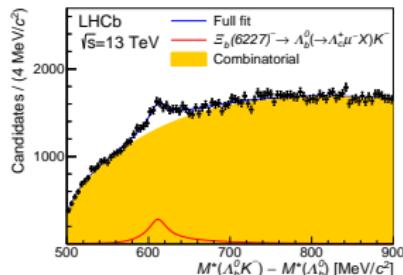
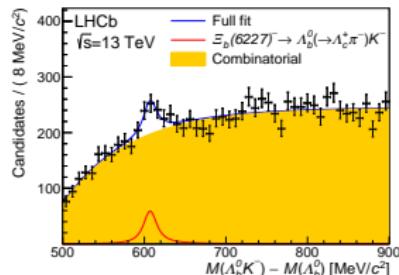
$$\Gamma(\Sigma_b(6097)^-) = 28.9 \pm 4.2 \pm 0.9 \text{ MeV}$$

$$m(\Sigma_b(6097)^+) = 6095.8 \pm 1.7 \pm 0.4 \text{ MeV}$$

$$\Gamma(\Sigma_b(6097)^+) = 31.0 \pm 5.5 \pm 0.7 \text{ MeV}$$

Several $\Sigma_b(1P)$ states ($J^P = 1/2^-, 3/2^-, 5/2^-$) are expected in 6100 MeV region. Could be one of them or a superposition.

Orbitally or radially excited state, decaying to $\Xi_b^0 \pi^-$ and $\Lambda_b^0 K^-$



Partially reconstructed $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$, $\Xi_b^0 \rightarrow \Xi_c^+ \mu^- \nu_\mu$ decays;
reasonable resolution in mass difference

$$m(\Xi_b(6227)^-) = 6226.9 \pm 2.0 \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0) \text{ MeV}$$

$$\Gamma(\Xi_b(6227)^-) = 18.1 \pm 5.4 \pm 1.8 \text{ MeV}$$

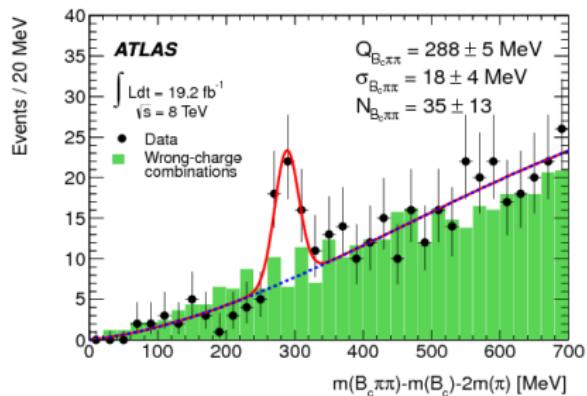
Interpretation: $\Xi_b(1P)$ or $\Xi_b(2S)$ state (or a superposition of several states).

Excited B_c^+ mesons

Excitations in B_c^+ system: $B_c^+\gamma$, $B_c^+\pi^+\pi^-$, $B\bar{D}$

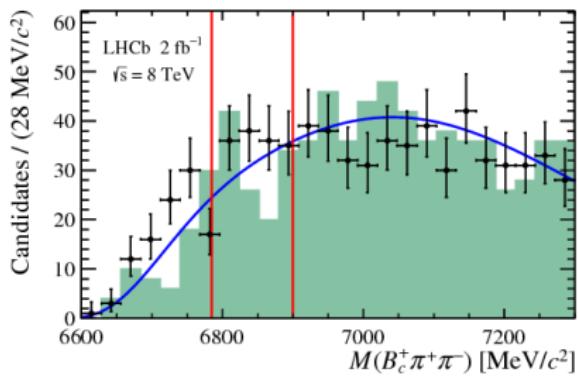
$B_c^* \rightarrow B_c^+\pi^+\pi^-$, $B_c^+ \rightarrow J/\psi\pi$, well suited for GPDs

[ATLAS, PRL 113 (2014) 212004]



$$m = 6842 \pm 4 \pm 5 \text{ MeV}$$

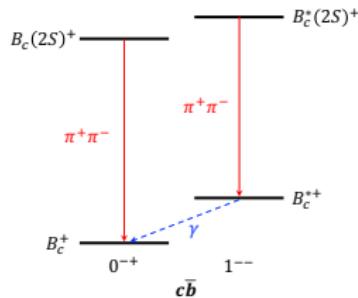
[LHCb, JHEP (2018) 2018:138]



No evidence found

Observation of excited B_c^+ mesons

[CMS, PRL 122 (2019) 132001]

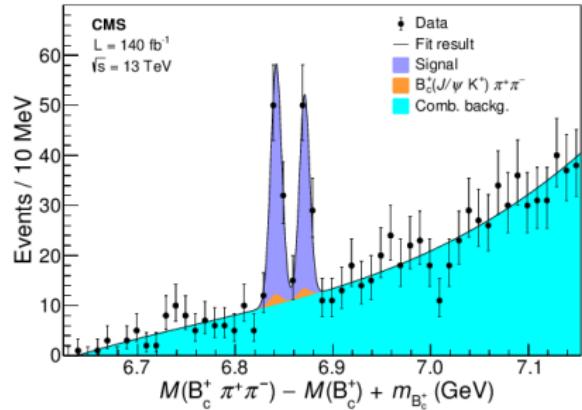


Both $B_c(1S)^+$ and $B_c(2S)^+$ have spin-excited vector partners, B_c^{*+}

$B_c^{*+} \rightarrow B_c^+ \gamma$ with mass difference
20 – 50 MeV

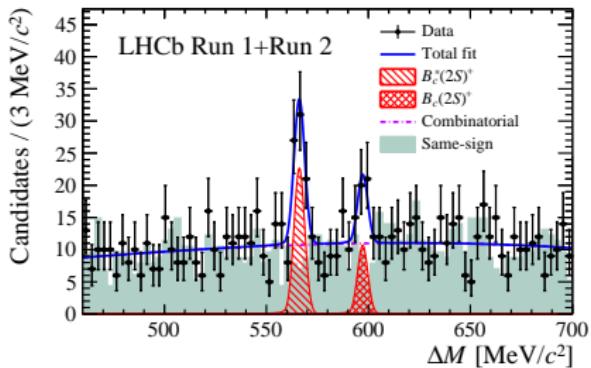
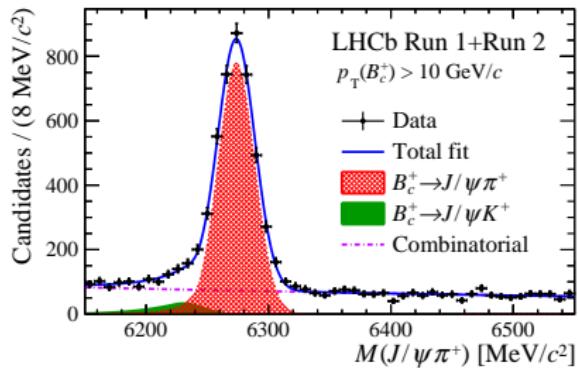
$$m(B_c(2S)^+) = 6871.0 \pm 1.2 \pm 0.8(\text{syst}) \pm 0.8(B_c^+) \text{ MeV}$$

$$\Delta m = 29.1 \pm 1.5 \pm 0.7(\text{syst}) \text{ MeV}$$



Observation of excited B_c^+ mesons

[PRL 122 (2019) 232001]



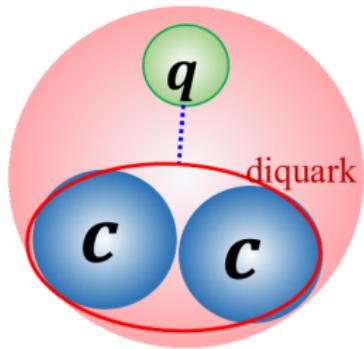
$$m_1 = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+) \text{ MeV} , \text{ } 6.3\sigma \text{ global}$$

$$m_2 = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+) \text{ MeV} , \text{ } 2.2\sigma \text{ global}$$

$$\Delta m = 31.0 \pm 1.4 \pm 0.0(\text{syst}) \text{ MeV}$$

Doubly heavy states

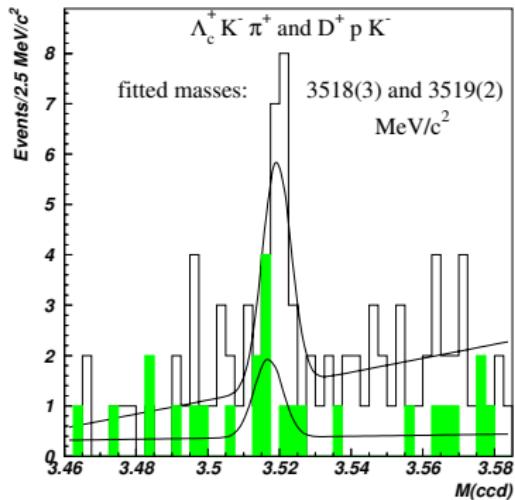
- Double heavy quarks have been seen for a long time in mesons: $\psi(c\bar{c})$, $\Upsilon(b\bar{b})$, $B_c^+(\bar{b}c)$.
- Expect three doubly-charmed states: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ccu) and Ω_{cc}^+ (ccs)
- A different system: cc as a heavy diquark; similar to heavy mesons Qq .
- Many theoretical models (relativistic and non-relativistic QCD potential, triple harmonic oscillator, sum rules, bag model etc.), lattice results.
- Ξ_{cc}^+ and Ξ_{cc}^{++} expected to have small mass difference.
- Lifetime $\tau(\Xi_{cc}^{++}) > \tau(\Xi_{cc}^+)$ due to different interference pattern of spectator and exchange diagrams



Searches for doubly-charmed states: “SELEX particle”

SELEX collaboration (Fermilab E781) seen a peak in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$ spectra

[PRL 89 (2002) 112001, PLB 628 (2005) 18]



Combined mass:

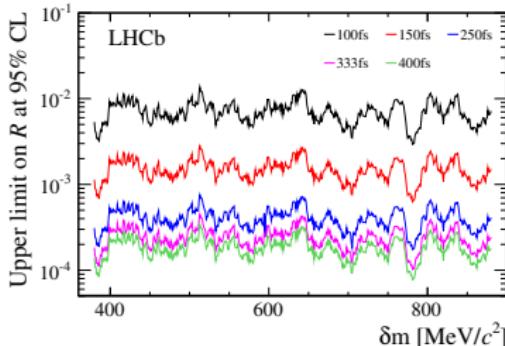
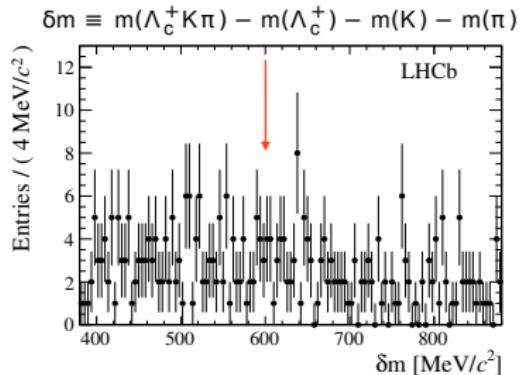
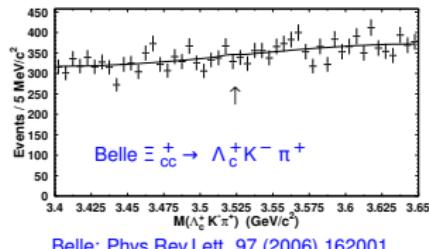
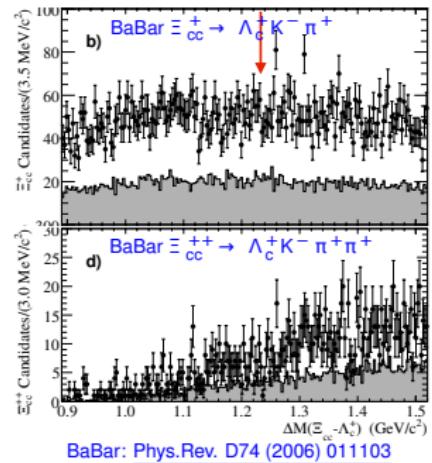
$$M(\Xi_{cc}^+) = 3518.7 \pm 1.7 \text{ MeV}$$

Questions:

- Weakly decaying, but very short lifetime ($\tau(\Xi_{cc}^+) < 33$ fs 90% CL)
- Large production ratio (20% of Λ_c^+ rate through Ξ_{cc}^+)

Searches for doubly-charmed states: “SELEX particle”

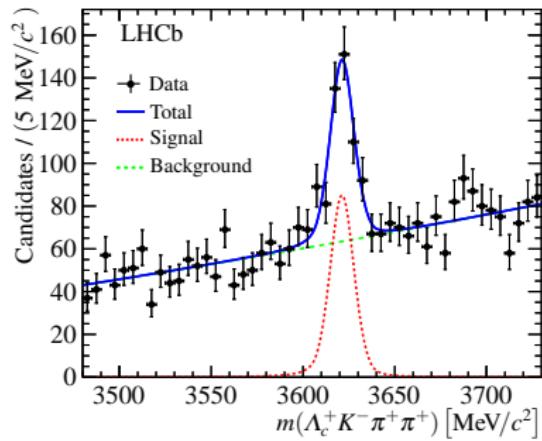
Not confirmed by other experiments:



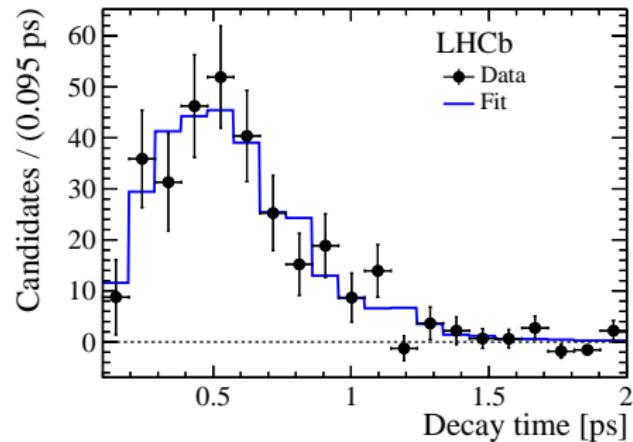
[LHCb, JHEP 12 (2013) 090] (0.65 fb^{-1})

Discovery of doubly-charmed baryon Ξ_{cc}^{++}

[PRL 119 (2017) 112001]



[PRL 121 (2018) 052002]



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

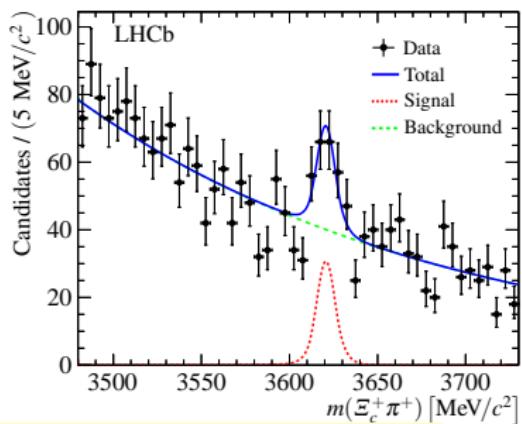
Lifetime measurement

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

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

Doubly-charmed baryon Ξ_{cc}^{++} : other decay channels

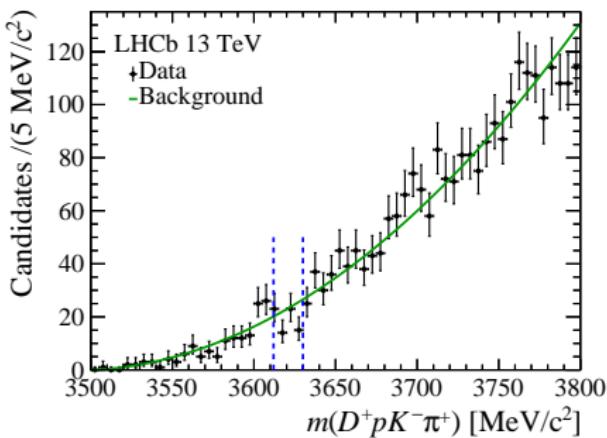
[PRL 121 (2018) 162002]



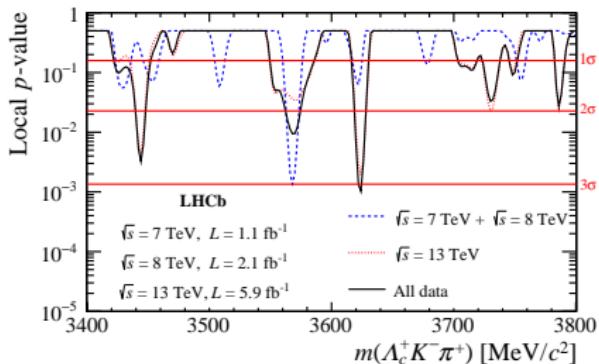
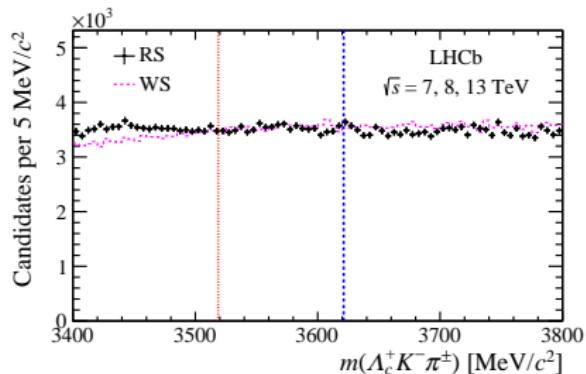
$$\mathcal{R} = 0.035 \pm 0.009 \pm 0.003$$

$$m(\Xi_{cc}^{++}) = 3620.6 \pm 1.5 \pm 0.4(\text{syst}) \pm 0.3(\Xi_c) \text{ MeV}$$

[arXiv:1905.02421]

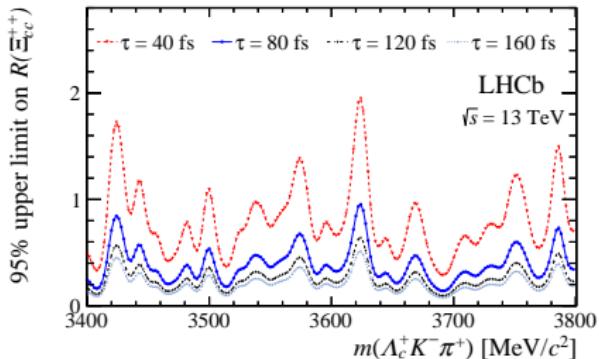
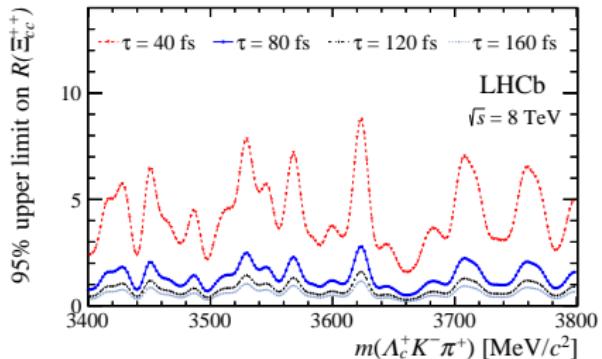


$$\mathcal{R} < 1.7 \text{ (90\% CL)}$$



Set upper limits on $\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^+) \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}$ for four lifetime hypotheses

Largest local significance of 3.1σ (1.7σ global) at 3620 MeV .



Set upper limits on $\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^+) \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} \text{ for four lifetime hypotheses}$

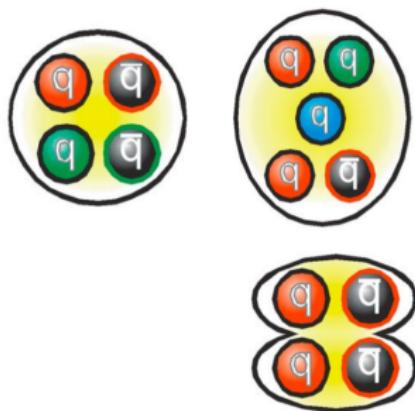
Largest local significance of 3.1σ (1.7σ global) at 3620 MeV.

Exotic states and interpretations

Exotic hadrons: hadrons with quark content other than well-established $q\bar{q}$ (mesons) and qqq (baryon) states.

- Tightly-bound **multiquark states**:

- $qq\bar{q}\bar{q}$: tetraquarks
- $qqqq\bar{q}$: pentaquarks

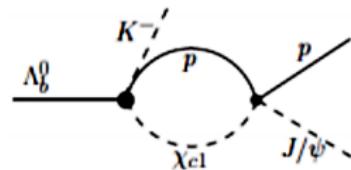


- Loosely-bound **molecules** (meson-meson, meson-baryon, baryon-baryon)

Strong evidence from many analyses for the existence of such states.

However, kinematical effects in rescattering can lead to structures that can resemble resonances

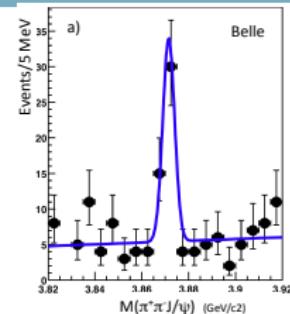
- Cusps**: rescattering without binding.



$X(3872)$

Discovered by Belle in 2003 [PRL 91 262001 (2003)]

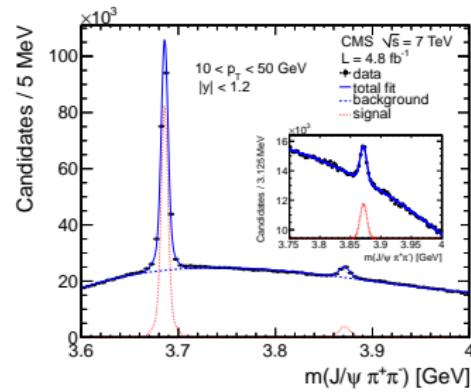
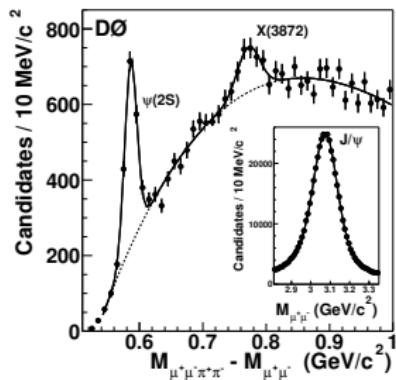
- $B^+ \rightarrow X(3972)K^+$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
- Mass close to $D^0 \bar{D}^{*0}$ [PRD 91 (2015), 011102]
 $m(D^0 \bar{D}^{*0}) - m(X(3872)) = 3 \pm 192 \text{ keV}$ (sic!)
- Small width ($\Gamma < 1.2 \text{ MeV}$)



Hadron machines are also active in studies of $X(3872)$ production

D0, [PRL 93:162002, 2004]

CMS, 7 TeV [JHEP 04 (2013) 154]



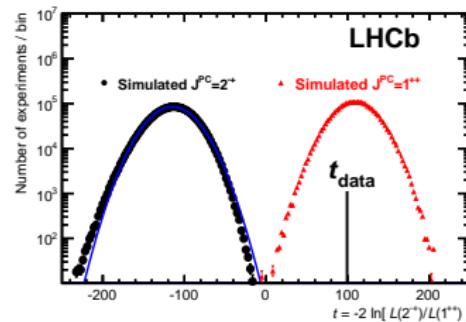
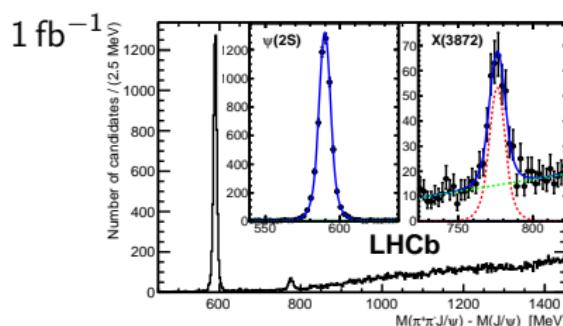
$X(3872)$ results from LHCb

Observation of prompt $X(3872)$ in pp collisions and mass measurement:

$M(X(3872)) = 3871.95 \pm 0.48 \pm 0.12 \text{ MeV}$ with 35 pb^{-1} [EPJC 72 (2012) 1972]

Quantum numbers: $J^{PC} = 1^{++}$ ($> 8\sigma$ over 2^{-+})

[PRL 110, 222001 (2013)]



D -wave decay could invalidate 1^{++} , constrained $< 4\%$ [PRD 92 (2015) 011102]

Branching ratio to $c\bar{c}\gamma$:

[Nucl.Phys. B886 (2014) 665-680]

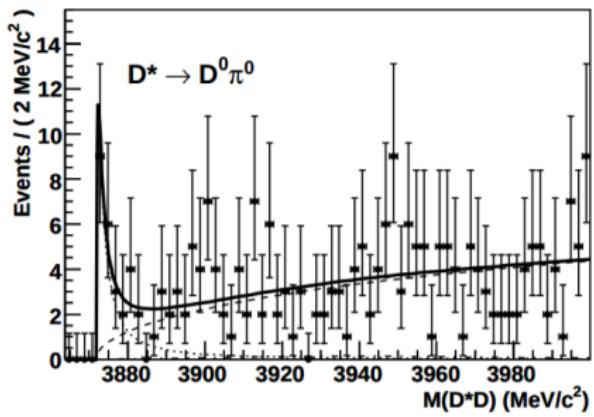
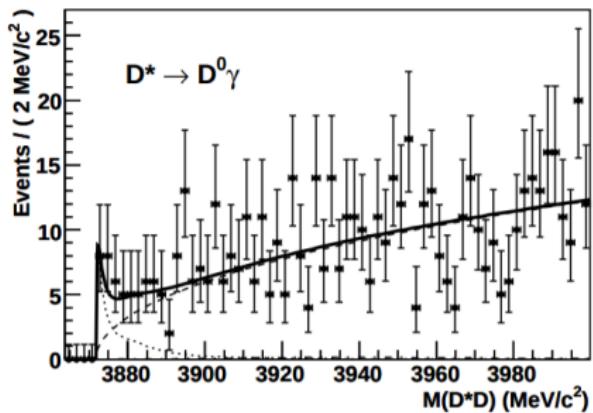
$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

Rules out purely molecular interpretation ($R_{\psi\gamma} \ll 1$)

$X(3872)$ coupling to $D\bar{D}^*$

[Belle, PRD 81 (2010) 031103] [BaBar PRD 77 111101]

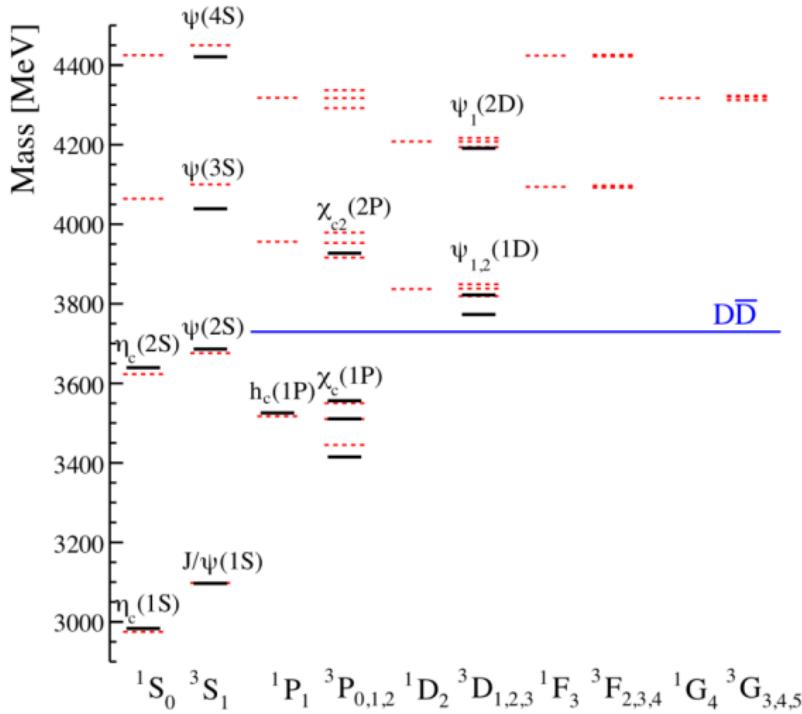
$$B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow D\bar{D}^*$$



"Strong coupling to $D\bar{D}^*$ and low binding energy imply unambiguously either a molecule ($E < 0$) or a virtual $D\bar{D}^*$ state ($E > 0$). "

[Braaten, Lu, PRD 76 094028]

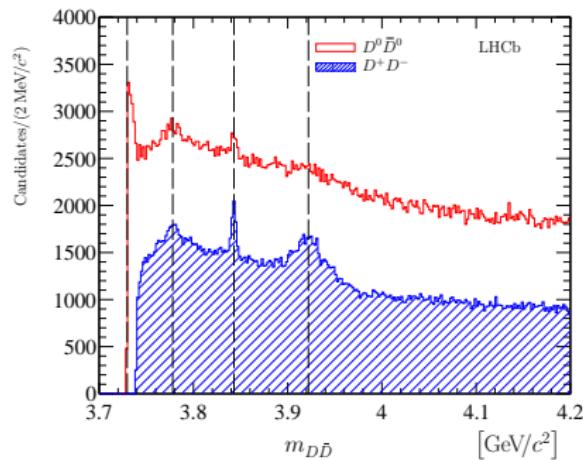
“Conventional” charminium spectrum



Rev.Mod.Phys. 90 (2018) no.1, 015003

Study charmonium states above $D\bar{D}$ threshold.

Reconstruct two D from the same PV



- Known $\psi(3770)$, $\chi_{c2}(3930)$
- New narrow peak at 3842 MeV
- Threshold enhancement in $D^0\bar{D}^0$: partially-reconstructed $X(3872)$

Measure parameters of the $X(3842)$ state

$$m(X(3842)) = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}$$

$$\Gamma(X(3842)) = 2.79 \pm 0.51 \pm 0.35 \text{ MeV}$$

Likely interpretation: $J^{PC} = 3^{--}$ charmonium state $\psi_3(1^3D_3)$

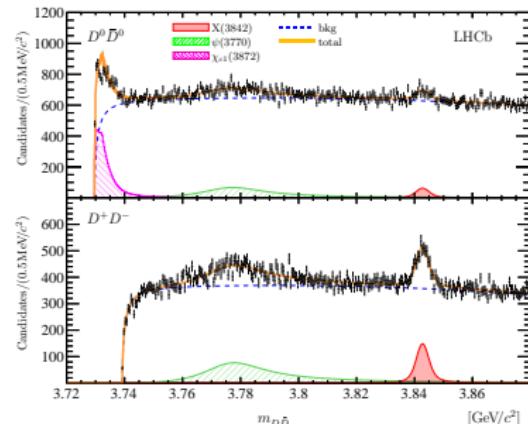
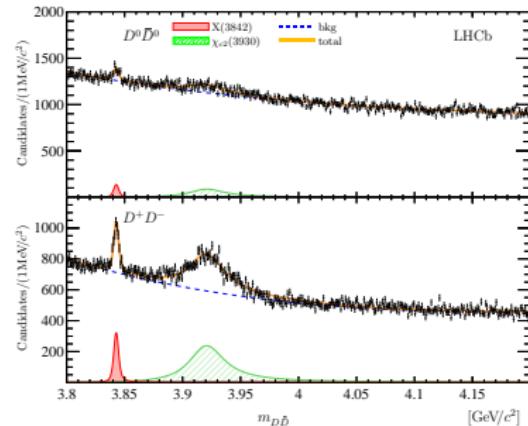
Parameters of the $\chi_{c2}(3930)$:

$$m(\chi_{c2}(3930)) = 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}$$

$$\Gamma(\chi_{c2}(3930)) = 36.6 \pm 1.9 \pm 0.9 \text{ MeV}$$

Potential to measure $X(3872)$ lineshape?

- Excellent mass resolution at threshold
- But high background \Rightarrow go for $D\bar{D}$ from B decays?

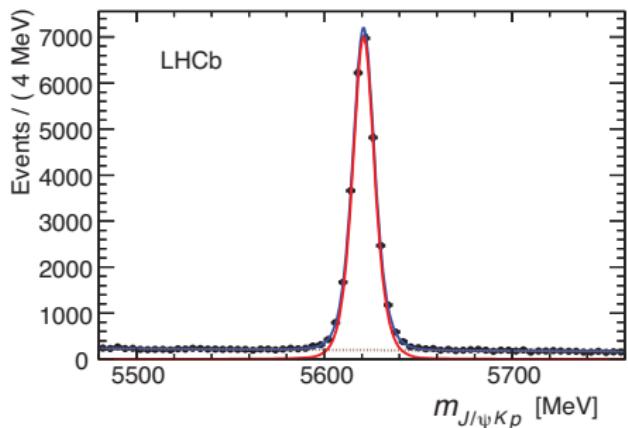


Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

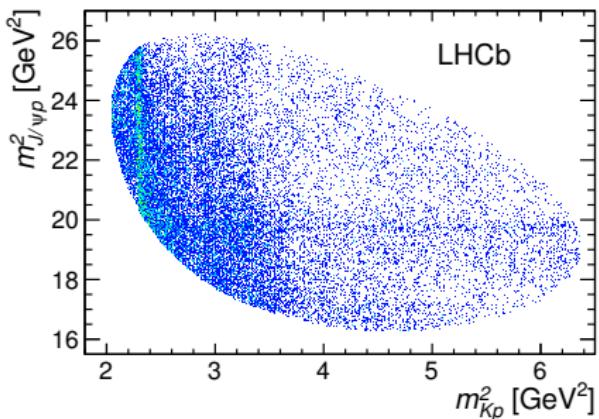
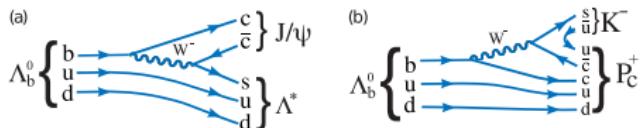
$\Lambda_b^0 \rightarrow J/\psi p K^-$ decay

[PRL 115 (2015) 072001]

Conventional contributions only in pK^- spectrum (Λ^* states).



Event yield: 26007 ± 166 events
Low background (5.4%)



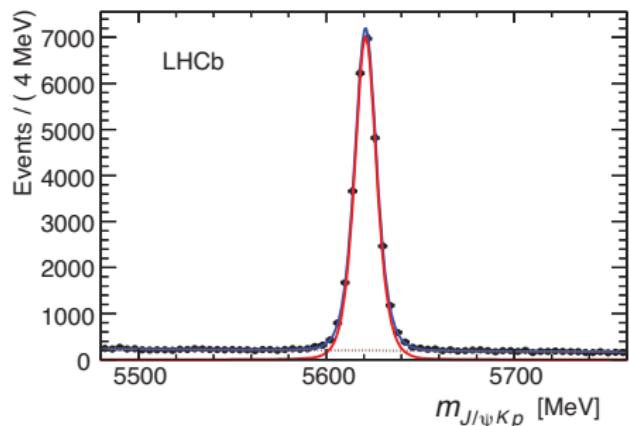
Dalitz distribution shows a narrow feature in $J/\psi p$ mass.

Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

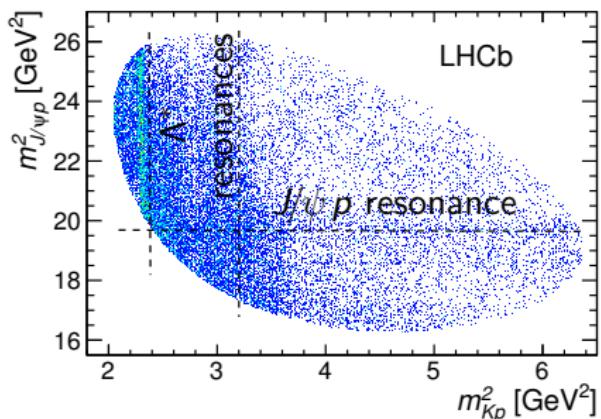
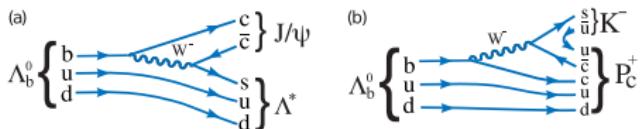
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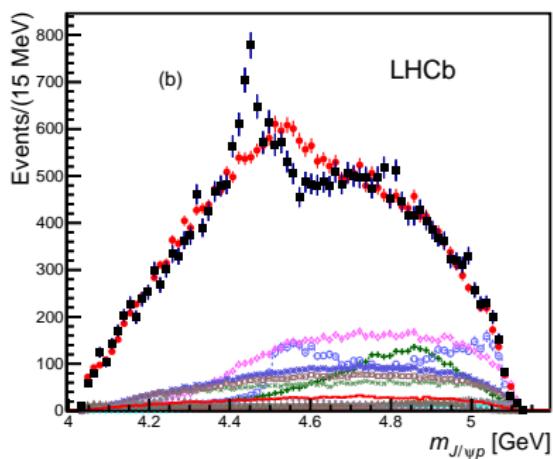
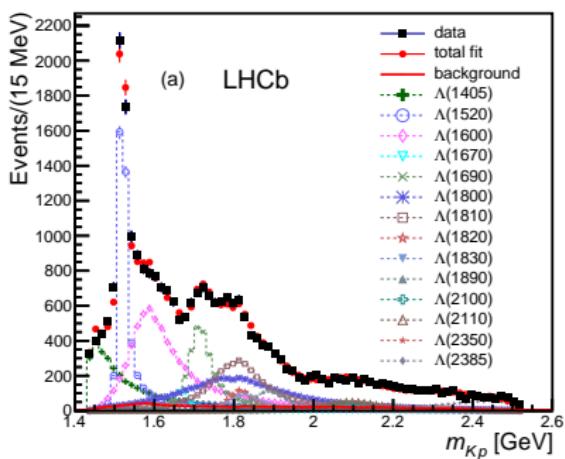
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Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$



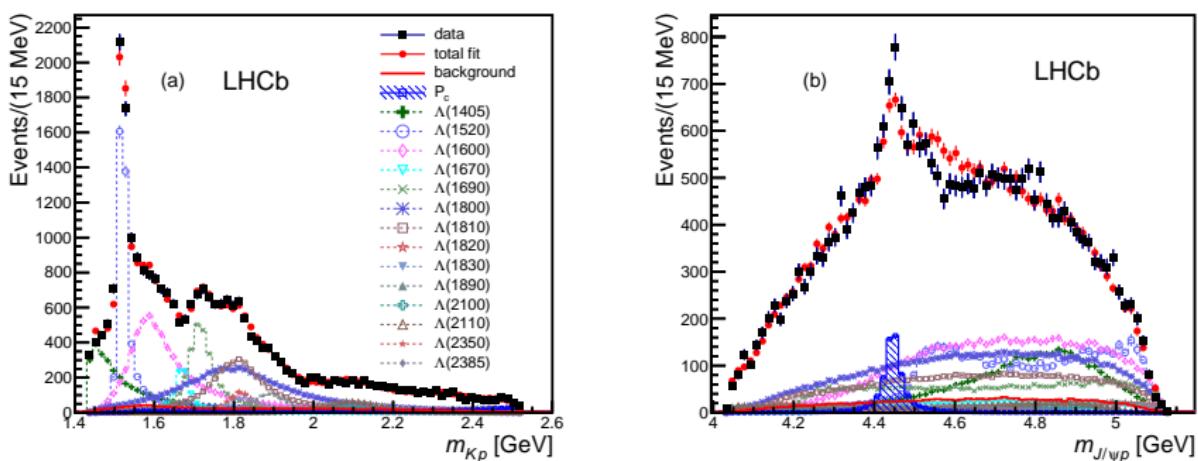
Admixture of all known Λ^* states does not reproduce the peak observed at $m_{J/\psi p} = 4450$ MeV.

Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay to understand its dynamics.

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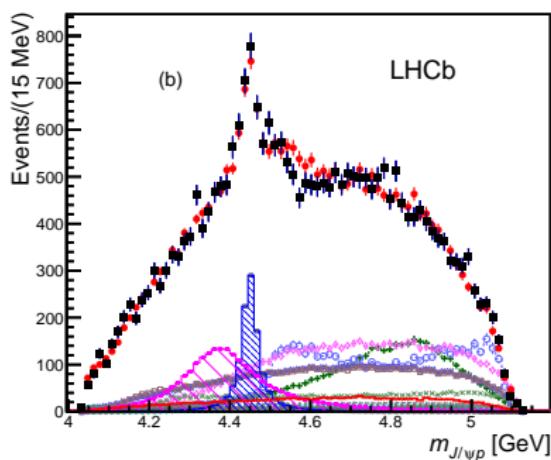
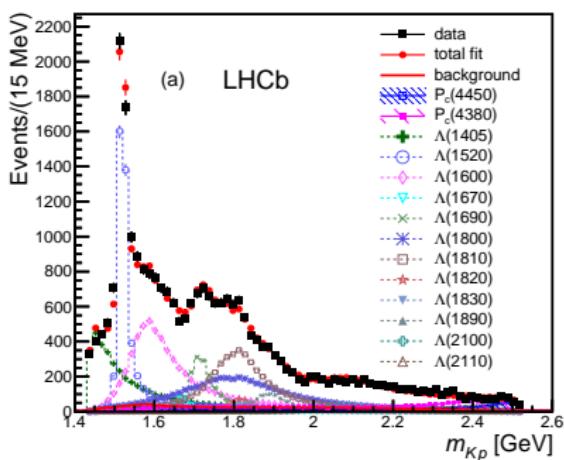
Inclusion of the exotic $J/\psi p$ state improves the fit, best $J^P = 5/2^\pm$

Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$

PRL 115, 072001 (2015),

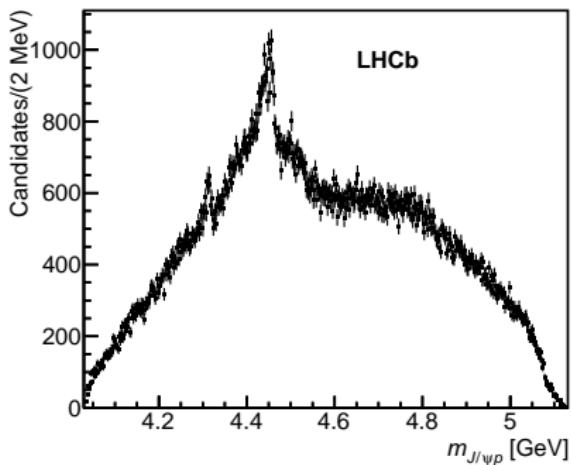
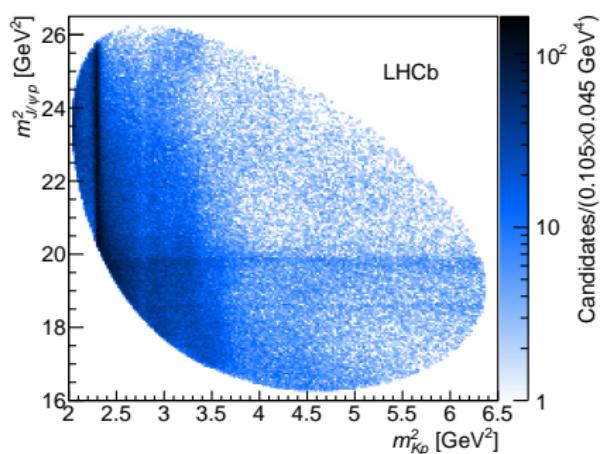
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Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$



Two $J/\psi p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities

Update with Run 1+2, improved selection: 246×10^3 candidates
($\sim \times 10$ wrt. Run 1 analysis)

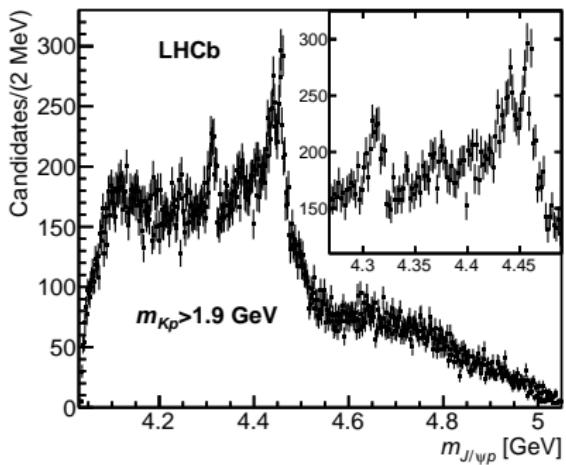
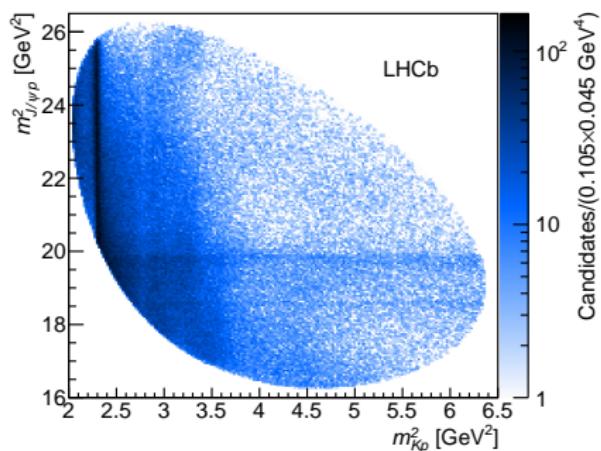


New narrow peak around $m(J/\psi p) = 4312 \text{ MeV}$!

Double peak at $m(J/\psi p) = 4450 \text{ MeV}$!

Narrow states \Rightarrow 1D $m(J/\psi p)$ fit is sufficient.

Update with Run 1+2, improved selection: 246×10^3 candidates
 $(\sim \times 10$ wrt. Run 1 analysis)



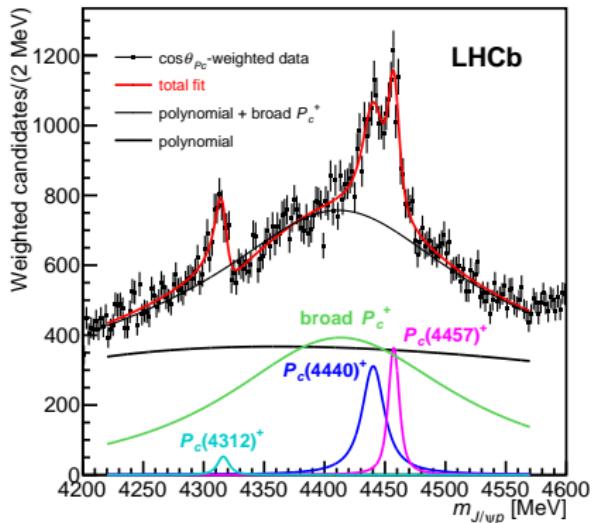
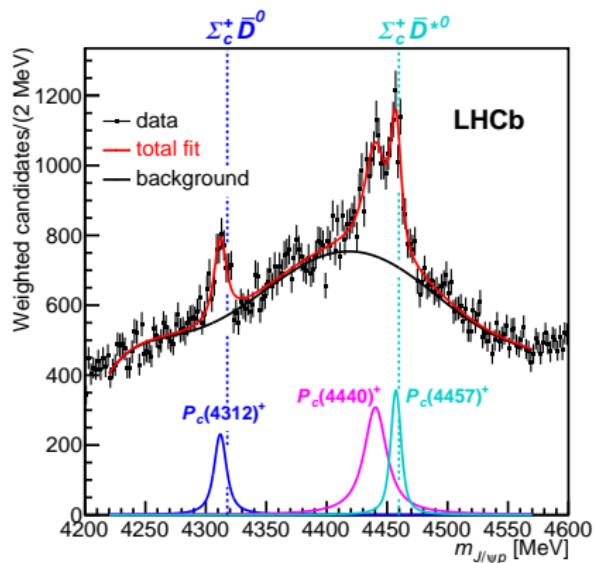
New narrow peak around $m(J/\psi p) = 4312$ MeV!

Double peak at $m(J/\psi p) = 4450$ MeV!

Narrow states \Rightarrow 1D $m(J/\psi p)$ fit is sufficient.

New pentaquarks in $\Lambda_b^0 \rightarrow J/\psi pK^-$

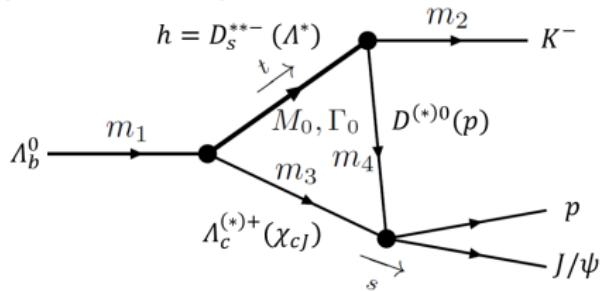
[PRL 122 (2019) 222001]



State	M [MeV]	Γ [MeV]	(95% CL)	\mathcal{R} [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

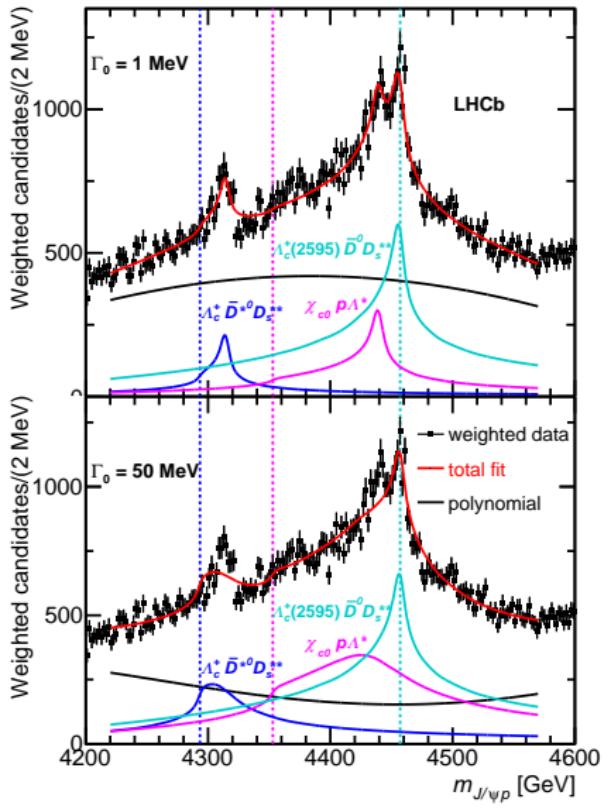
$P_c(4312)^+$ and $P_c(4457)^+$: loosely bound $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ molecules?

Possible interpretation of the three peaks as “cusps”:



Good fit only after significant fine-tuning of M_0 and $\Gamma_0 \rightarrow 0$

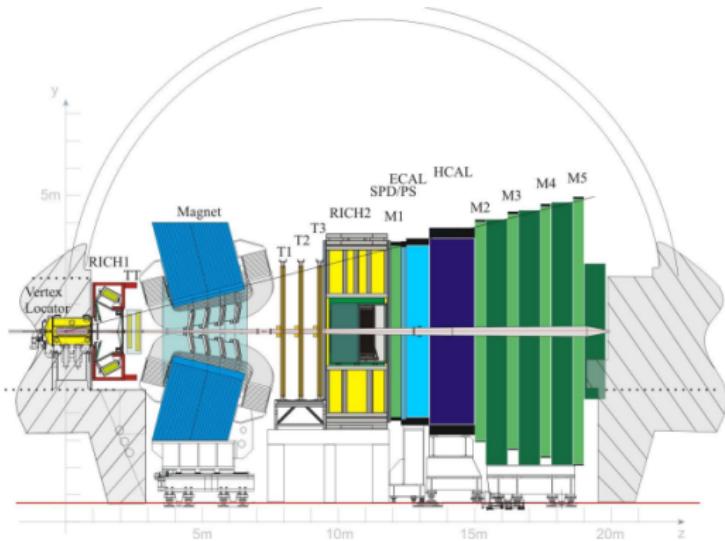
Reasonable $\Gamma_0 \simeq 50$ MeV:
fair description of $P_c(4457)^+$ state,
but not the others.



Conclusion

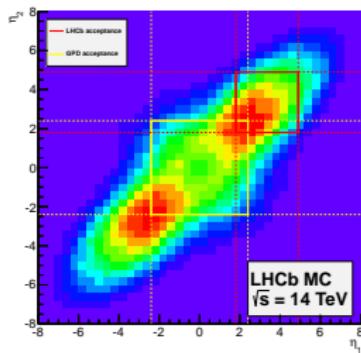
- Experimental hadron spectroscopy is a very dynamic and exciting field now.
- In many areas, LHCb is a unique facility, e.g. heavy b -hadrons.
- Competition with B -factories and BES-III in charm and charmonium spectroscopy.
- ATLAS, CMS: huge datasets (where they can trigger).
- Post-upgrade LHCb: expect enormous amounts of data.
 - Converted photons in radiative decays
 - Open-charm decays of charmonia
 - More amplitude analyses of B decays
 - bc , bb doubly heavy states
 - ...

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



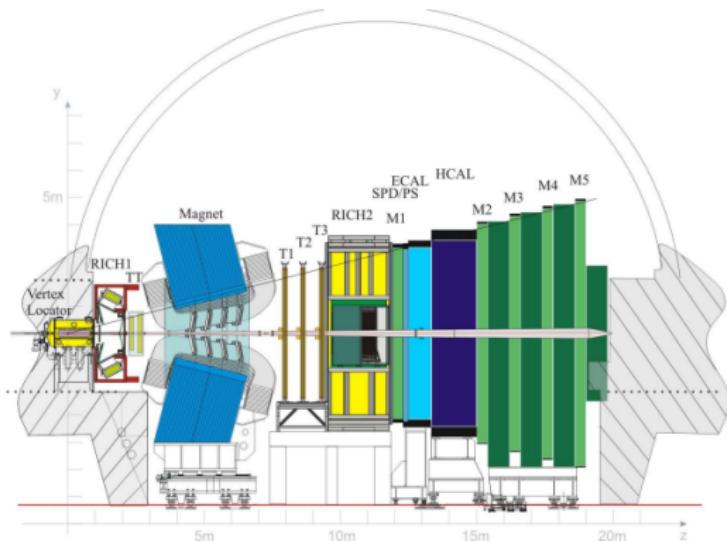
Rapidity coverage

$$2 < \eta < 5$$



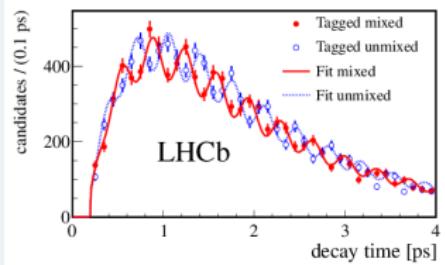
- Covers forward region (maximum of c and b production)

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Vertexing

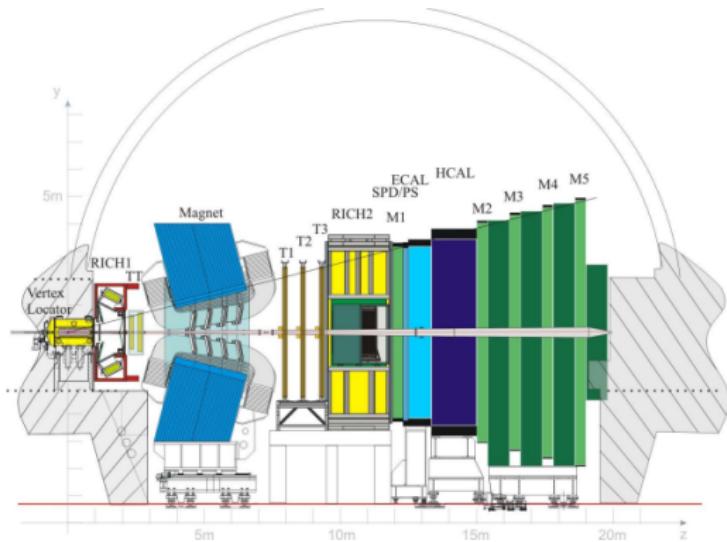
B_s^0 oscillations with $B_s^0 \rightarrow D_s\pi$



[New J. Phys. 15 (2013) 053021]

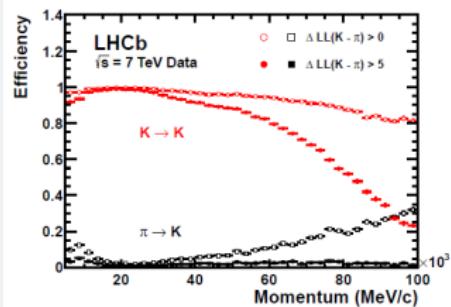
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



PID

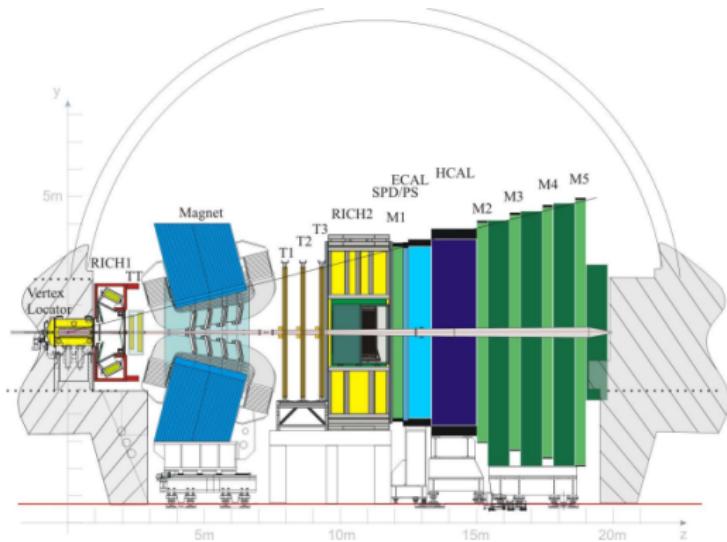
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

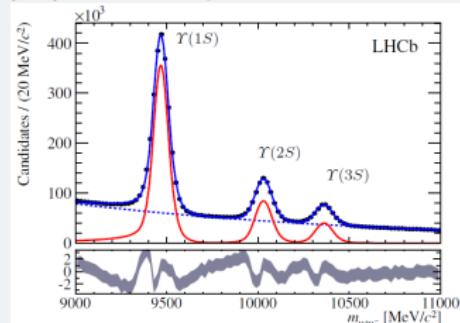
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Tracking

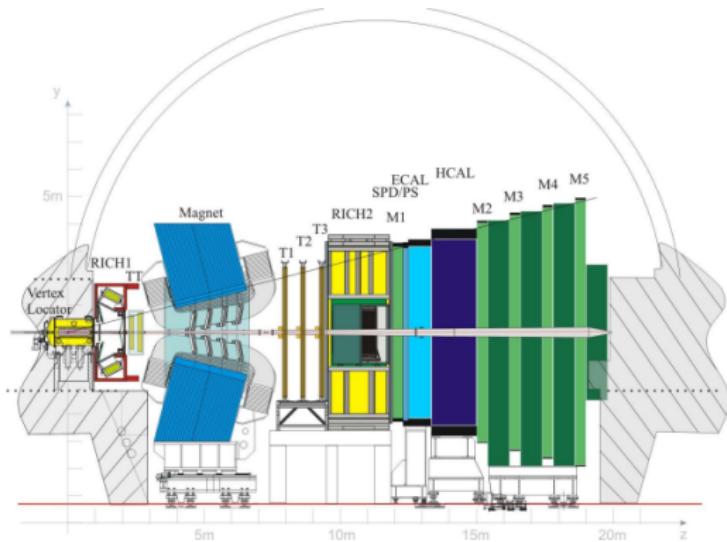
$\mu^+ \mu^-$ mass spectrum



[PRL 111 (2013) 101805]

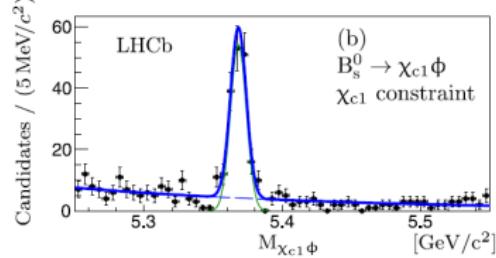
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

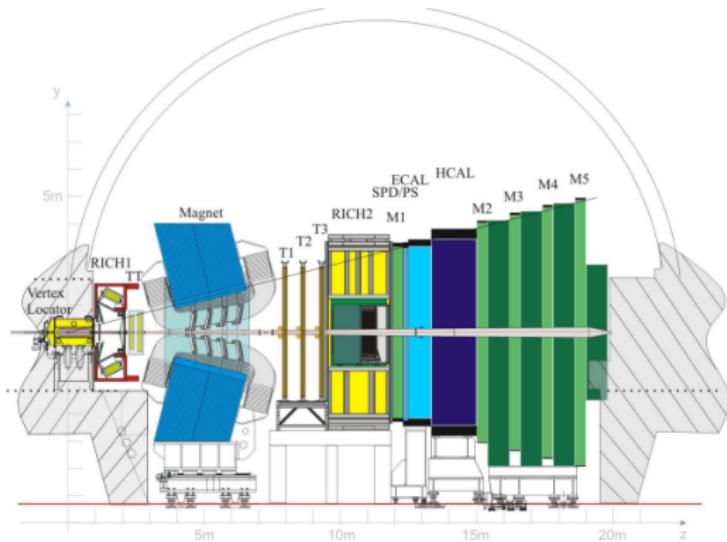
$$B_s^0 \rightarrow \chi_{c1}\phi, \chi_{c1} \rightarrow J/\psi\gamma$$



[Nucl. Phys. B874 (2013) 663]

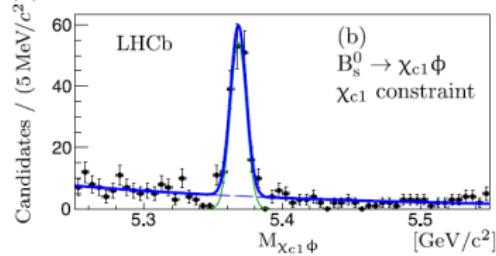
- Covers forward region (maximum of c and b production)
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- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

$$B_s^0 \rightarrow \chi_{c1}\phi, \chi_{c1} \rightarrow J/\psi\gamma$$



[Nucl. Phys. B874 (2013) 663]

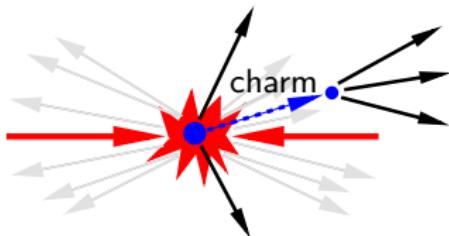
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state
- Efficient trigger, including fully hadronic modes

Production mechanisms and properties

Conventional and exotic charm states are studied at LHCb in two production regimes:

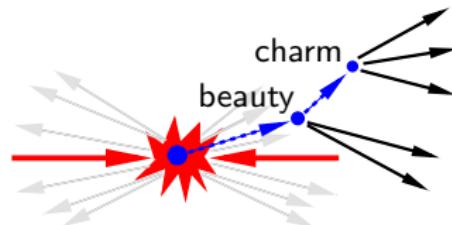
- **Prompt production** in pp collisions

- High statistics
- High combinatorial background



- **Weak decays** of beauty hadrons (fully or partially reconstructed)

- Low background
- Well-defined initial state, determination of quantum numbers
- Kinematic constraints



Properties of exotic states which can be determined and tested against theory models

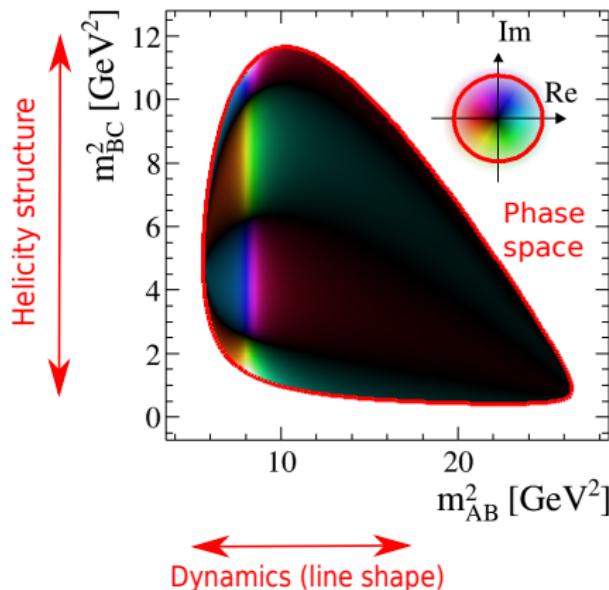
- Mass and width
- Production and decay channels, branching ratios
- Quantum numbers: spin, parity
- Line shape

Amplitude analyses

Many of LHCb exotic measurements use amplitude analysis technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \rightarrow ABC$: two kinematic variables M_{AB}^2, M_{BC}^2 (Dalitz plot)
- Add angular variables if initial/final state not scalar



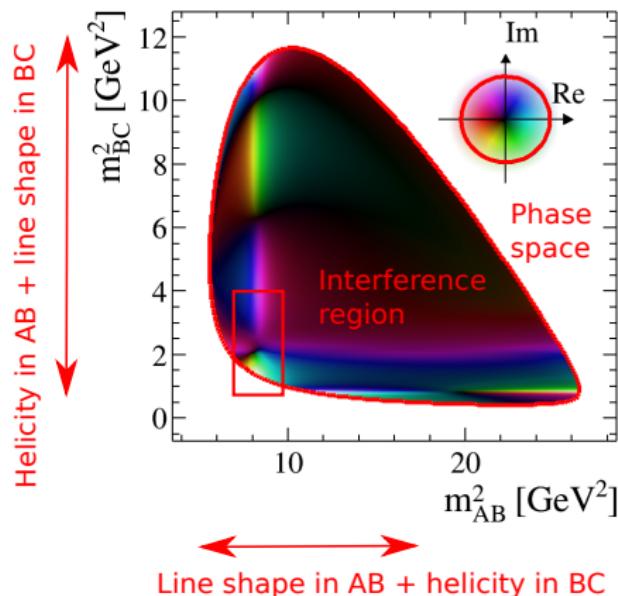
- Both lineshape parameters and spin can be extracted.
- Complex phases of components can be accessed through interference with other structures.

Amplitude analyses

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