Heavy flavour production and spectroscopy

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for the ALICE, ATLAS, CMS, LHCb collaborations

Presented at LHCP 2021

Outline

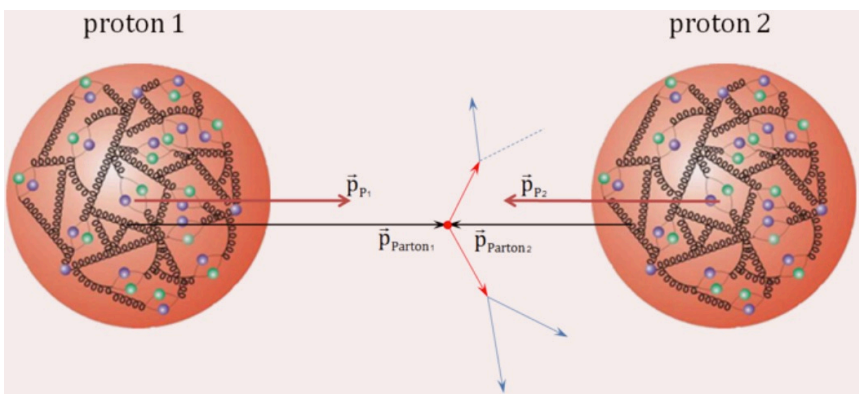
- Introduction
- Heavy flavour production
  - $D, \Lambda_c^+, \Xi_c, \Lambda_b^0, B_c(2S)^+, \ldots$
- Heavy flavour spectroscopy
  - $D_{s0}(2590)^+$, excited $\Xi_b, Z_{cs}^+, X(6900), P_{cs}^+, \ldots$
- Summary

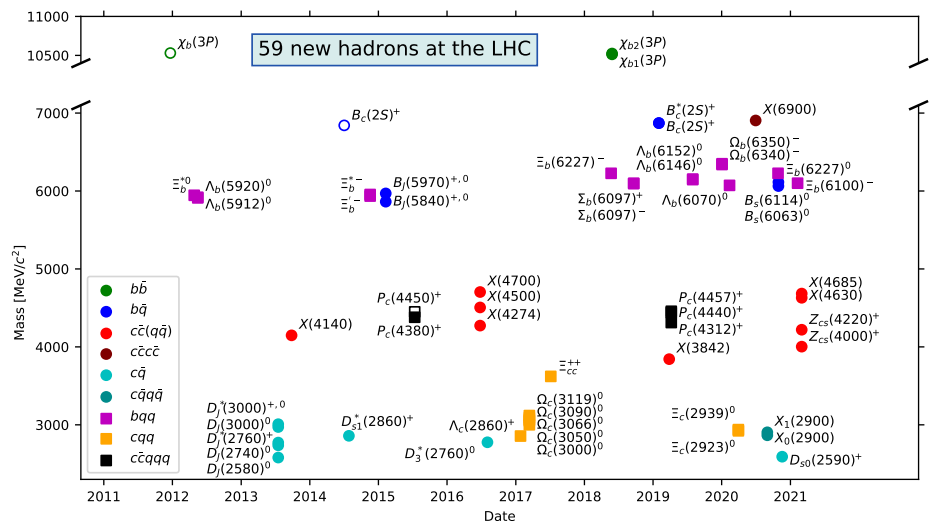
* Focus on recent results since LHCP2020, sorry if I miss your favourite

[ALICE]	Open charm/beauty production in pp at 5.02 TeV		JHEP 05 (2021) 220
[LHCb]	Precise measurement of f_s/f_d		arXiv:2103.06810
[ALICE]	Λ_c^+ production in pp at 5.02 TeV		arXiv:2011.06708
[ALICE]	Ξ_c^0, Ξ_c^+ production in pp at 13 TeV		arXiv:2105.05187
[ALICE]	Charm fragmentation fractions in pp collision		arXiv:2105.06335
[LHCb]	Λ_b^0 production asymmetry	(New)	LHCb-Paper-2021-016
[CMS]	$B_c(2S)^+$ production		PRD 102 (2020) 092007
[LHCb]	Observation of a new excited D_s^+ state		PRL 126 (2021) 122002
[LHCb]	Ω_c^{**0} states in Ω_b^- decay		LHCb-Paper-2021-012
[LHCb]	Observation of new excited B_s^0 states		arXiv:2010.15931
[CMS]	Observation of $\Xi_b(6100)^-$		arXiv:2012.04524
[LHCb]	Observation of $\Xi_b(6227)^0$		PRD 103 (2021) 012004
[LHCb]	Search for Ξ_{cc}^+		LHCb-Paper-2021-019
[LHCb]	Search for Ω_{cc}^+		arXiv:2105.06841
[LHCb]	Search for Ξ_{bc}^0		JHEP 11 (2020) 095
[LHCb]	Search for Ω_{bc}^0		arXiv:2104.04759
[LHCb]	Observation of $X(2900) \to D^-K^+$		PRL 125 (2020) 242001
[LHCb]	Observation of $Z_{cs}^+ \to J/\psi K^+$		arXiv:2103.01803
[LHCb]	Observation of structure in Di-J/ψ		Sci. Bull. 65 (2020) 032
[LHCb]	Evidence of $P_{cs} \to J/\psi\Lambda$		arXiv:2012.10380
[LHCb]	Evidence of new Pentaquark in $B_s^0 \to J/\psi p\bar{p}$	(New)	LHCb-Paper-2021-018
[LHCb]	Measurement of Ξ_c^0, Ω_c^0 lifetimes		LHCb-Paper-2021-019

Introduction

- Heavy flavour production
  - Test QCD: PDF, hard scattering, fragmentation
  - New physics search: Background; f_s
  - pp collisions, reference for pPb, PbPb
- Spectroscopy
  - Quark model

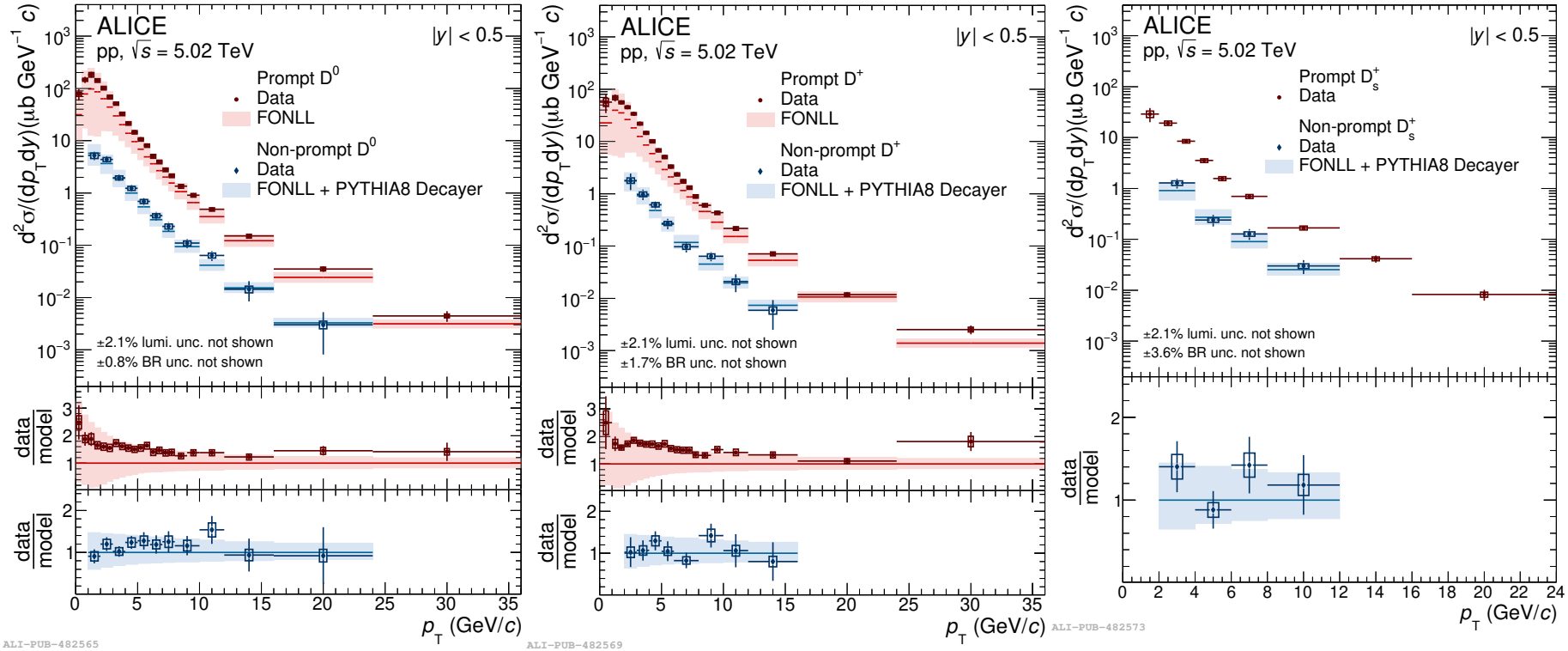




Open charm/beauty production

- Well described by pQCD calculations (FONLL) with fragmentation function from e^+e^-

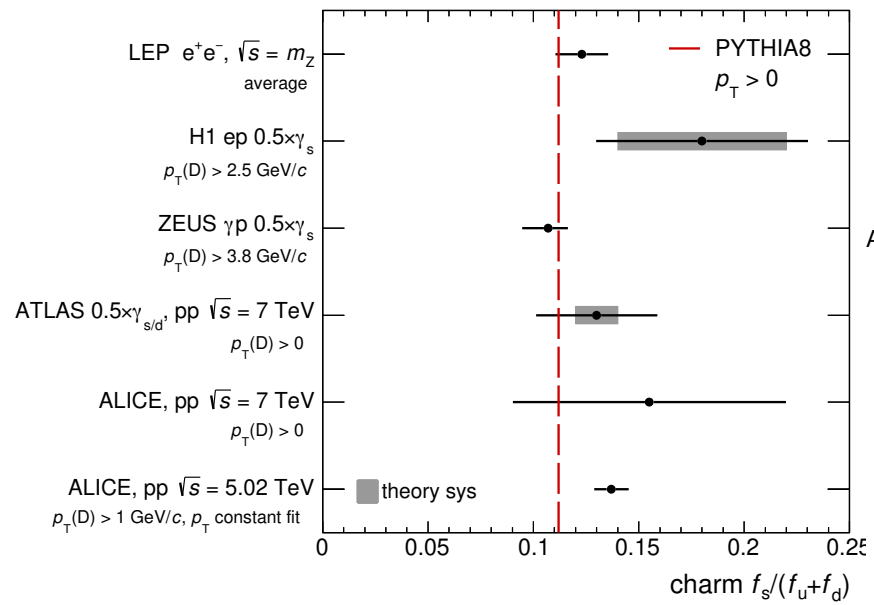
[JHEP 05 (2021) 220]

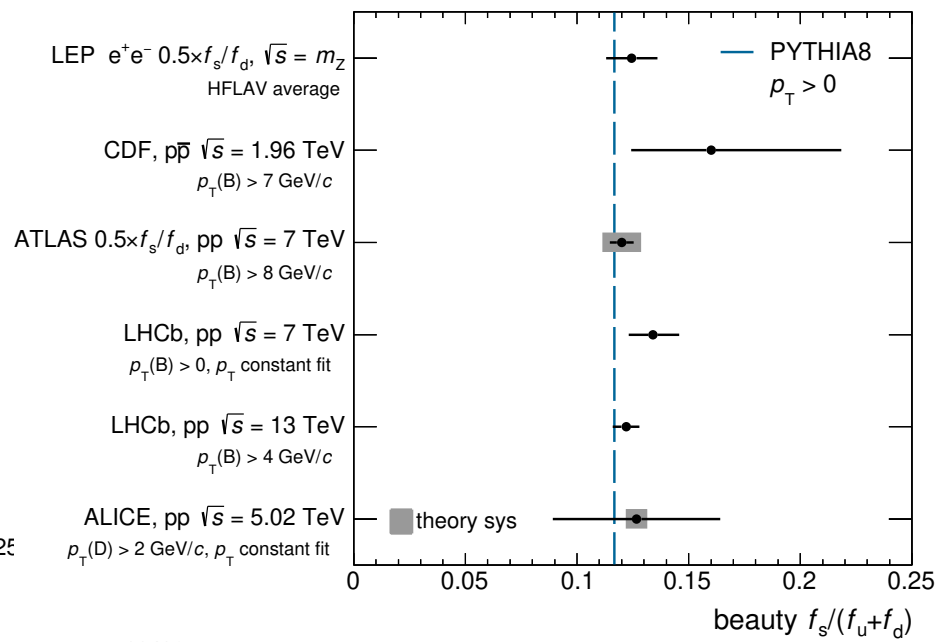


$f_s/(f_u + f_d)$ in B/D system

- Similar for charm and beauty
- No significant dependence on energy and collision system with the current precision

[JHEP 05 (2021) 220]

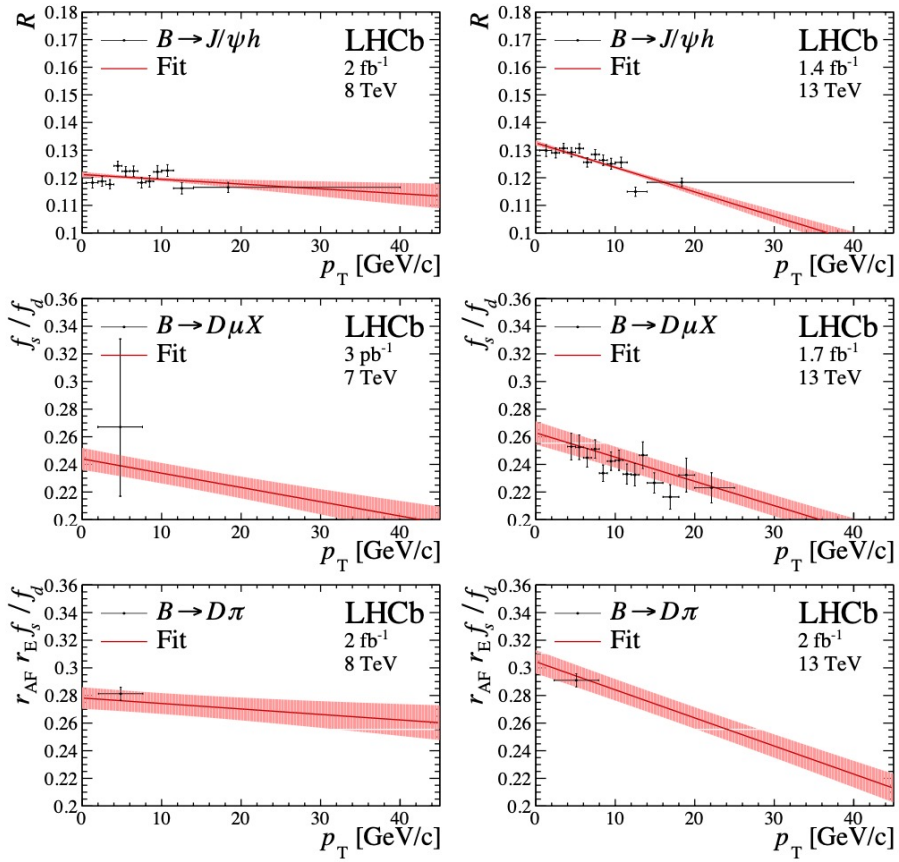


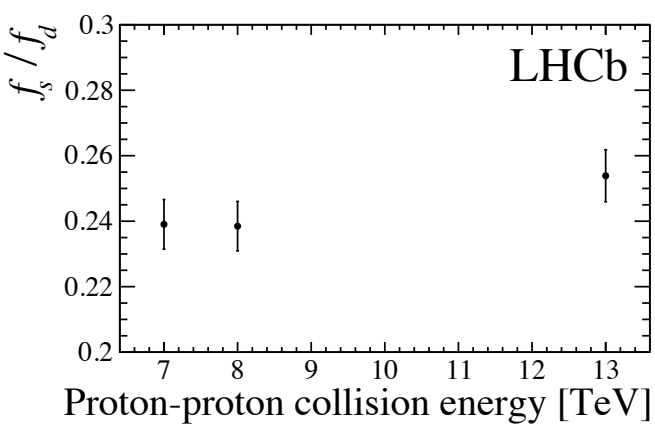


f_s/f_d in beauty system

- Combined analysis of different decay modes. BR of B_s^0 updated
  - $\mathcal{B}(B_s^0 \to J/\psi\phi)$ and $\mathcal{B}(B_s^0 \to D_s^- \pi^+)$ improved by a factor of 2

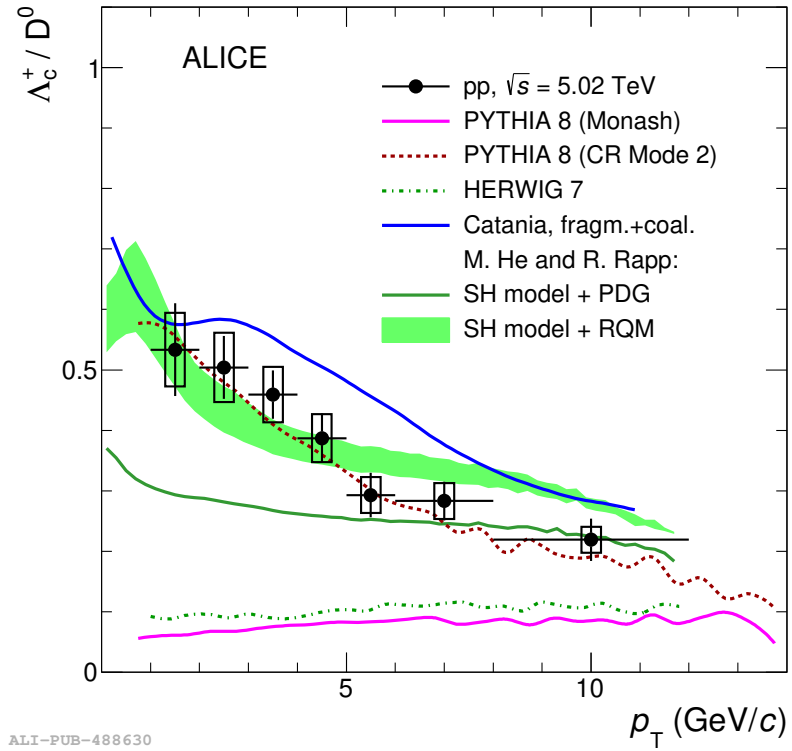
[arXiv:2103.06810]



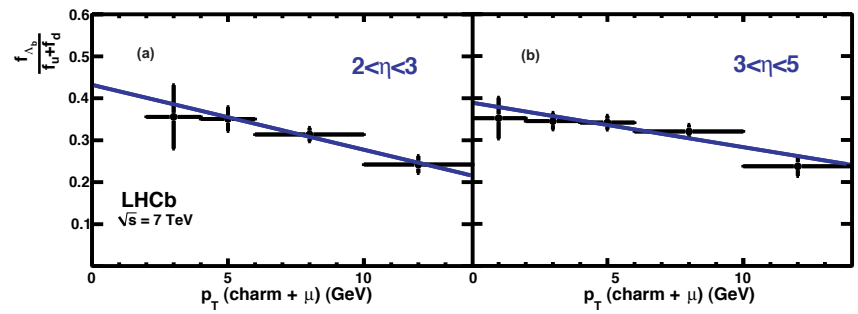


$$f_s/f_d \quad (p_T, 7\,\text{TeV}) = (0.244 \pm 0.008) + ((-10.3 \pm 2.7) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 8\,\text{TeV}) = (0.240 \pm 0.008) + ((-\ 3.4 \pm 2.3) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 13\,\text{TeV}) = (0.263 \pm 0.008) + ((-17.6 \pm 2.1) \times 10^{-4}) \cdot p_T$$

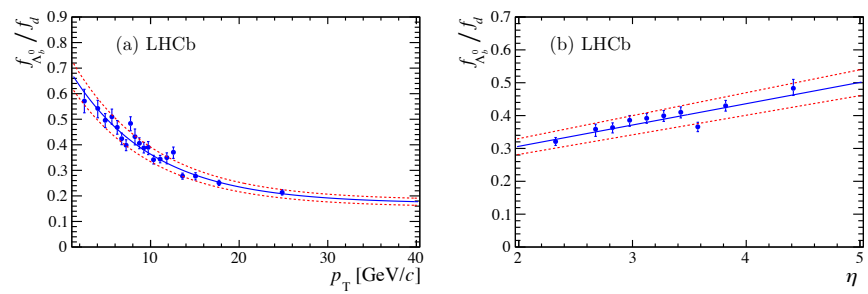
Baryon-to-meson ratio



[arXiv:2011.06708]



[PRD 85 (2012) 032008]

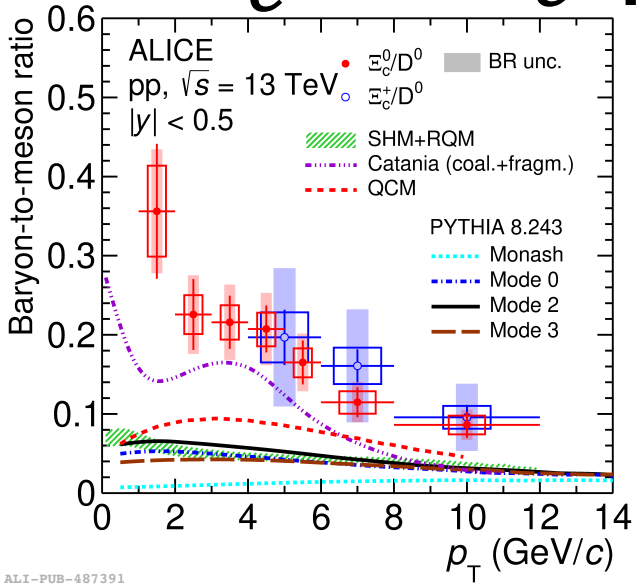


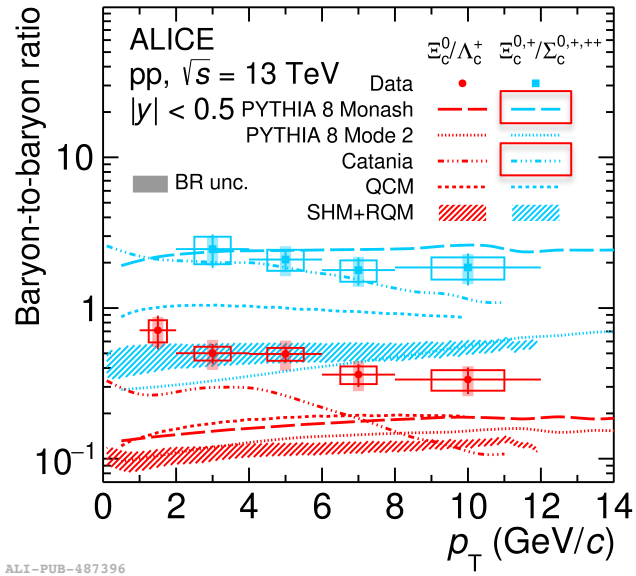
[JHEP 08 (2014) 143]

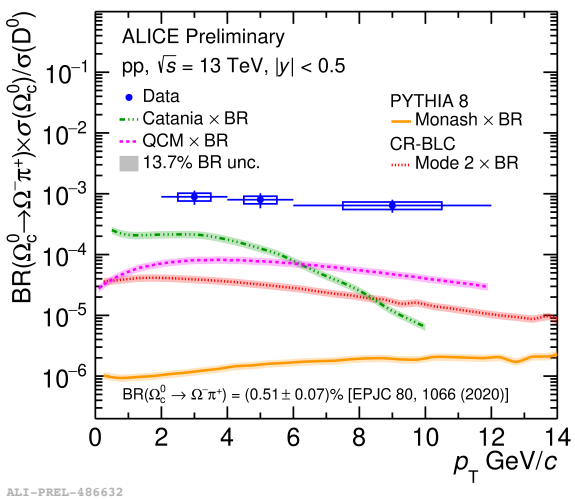
- Clear trend as function of p_T, well decribed by, e.g.,
  - Pythia8 + New Colour-Reconnection (CR) mode
  - Statistical Hadronisation (SH) including additional excited charm baryons predicted by Relativistic Quark Model (RQM)
  - Catania, hadronisation via coalescence + fragmentation

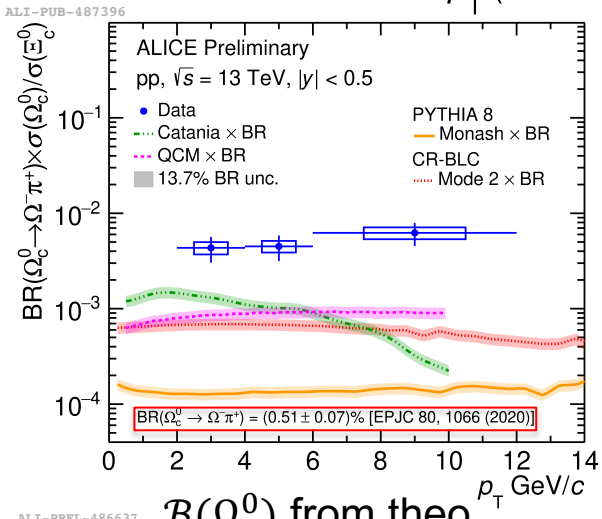
$\Xi_c^{0/+}, \Omega_c^0$ production

[arXiv:2105.05187]







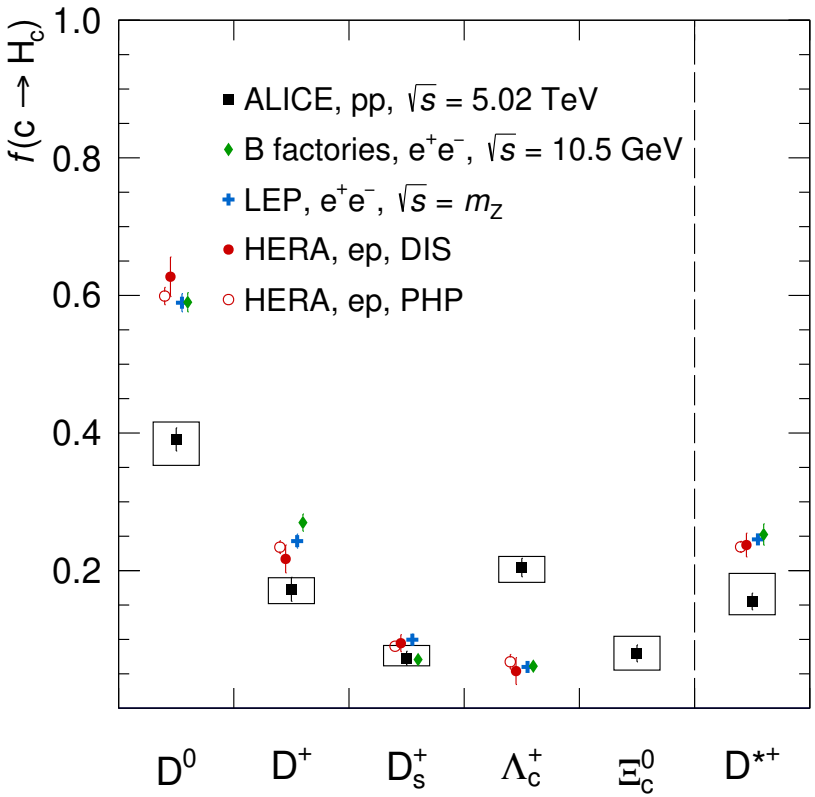


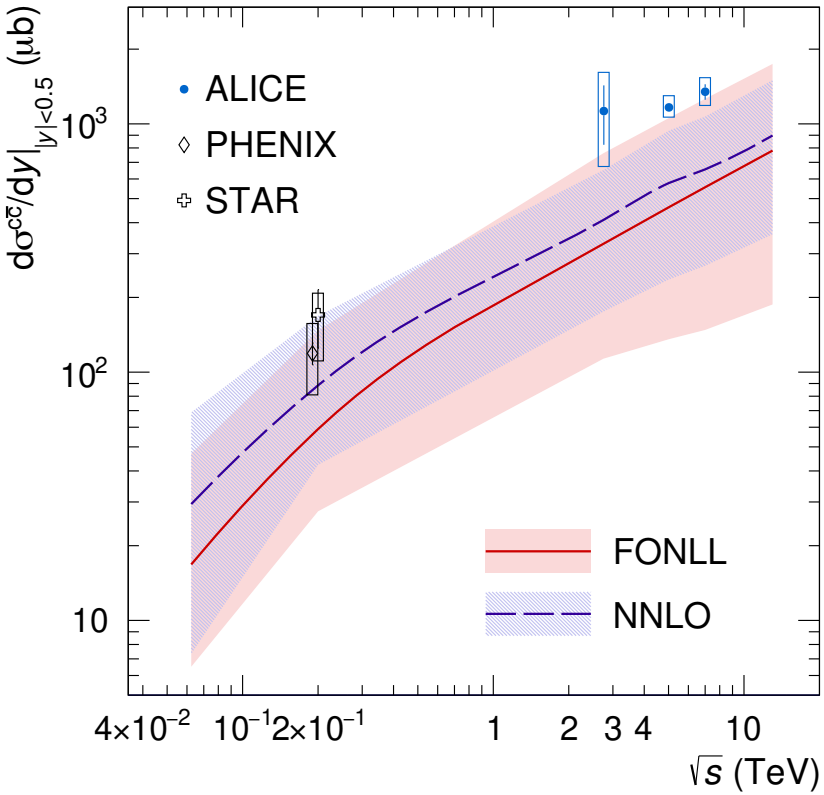
$\mathcal{B}(\Omega_c^0)$ from theo.

Charm FF & cross-section

- Fragmentation fraction not universal
- Cross-section at the upper edge of FONLL/NNLO

[arXiv:2105.06335]



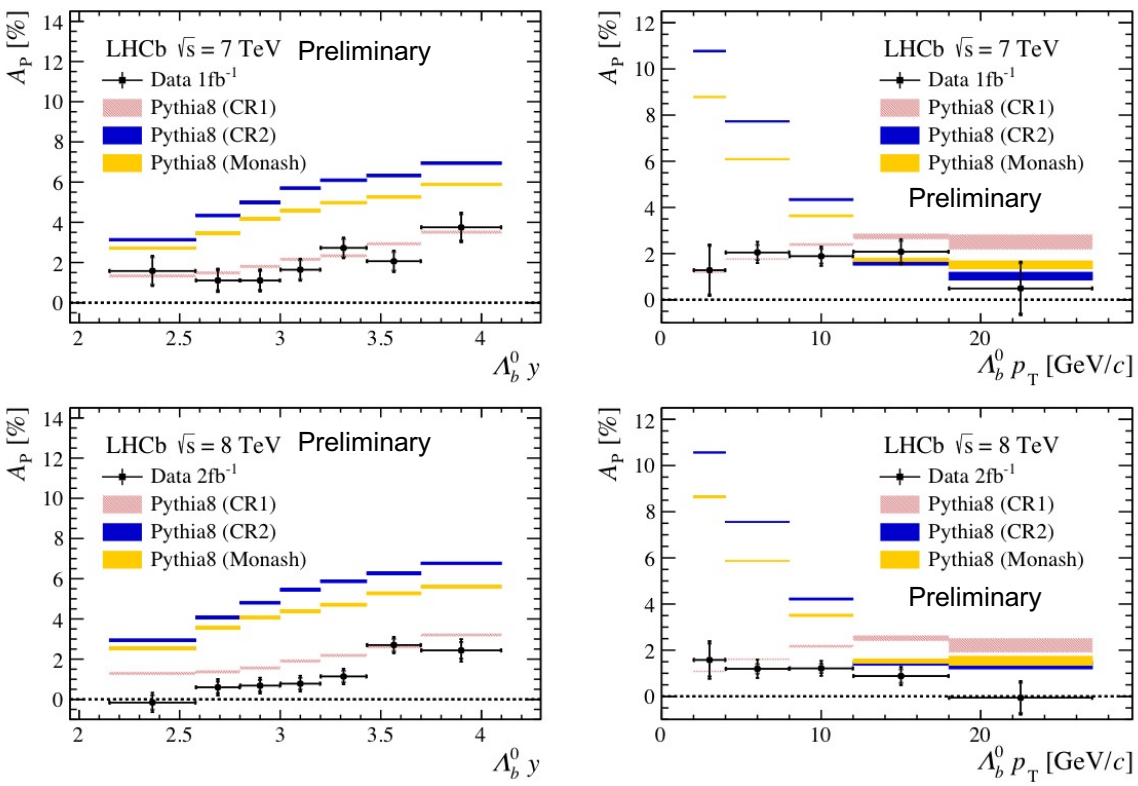


New

Λ_b^0 production asymmetry

- Using $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu X$, 7/8 TeV pp data
- First observation of *b*-hadron prod. asym.

[LHCb-Paper-2021-016]



$B_c^{(*)}(2S)^+$ production

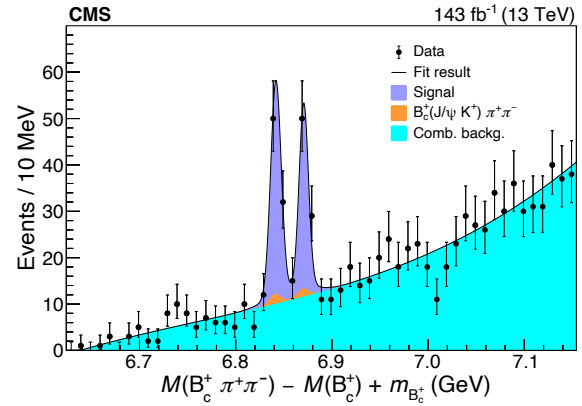
- Measured relative to B_c^+

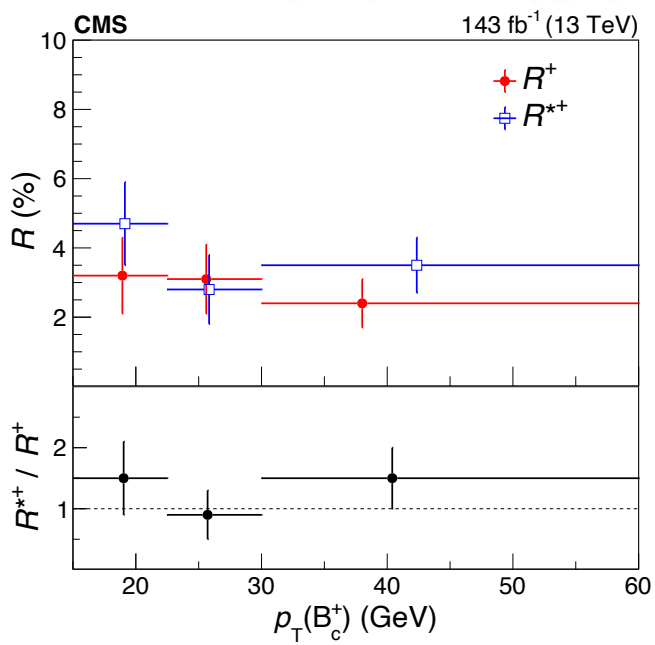
$$R^{(*)+} \equiv \frac{\sigma\left(B_c^{(*)}(2S)^+\right)}{\sigma(B_c^+)} \mathcal{B}\left(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-\right)$$

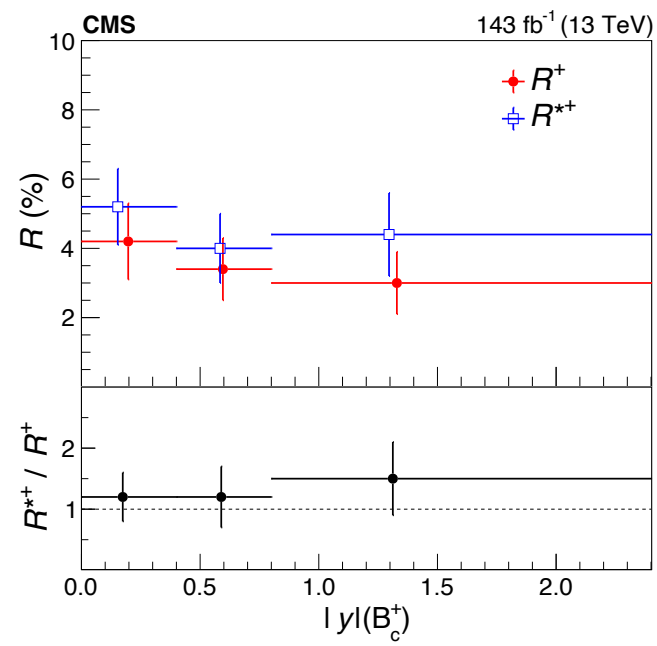
$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$

$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$

$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$







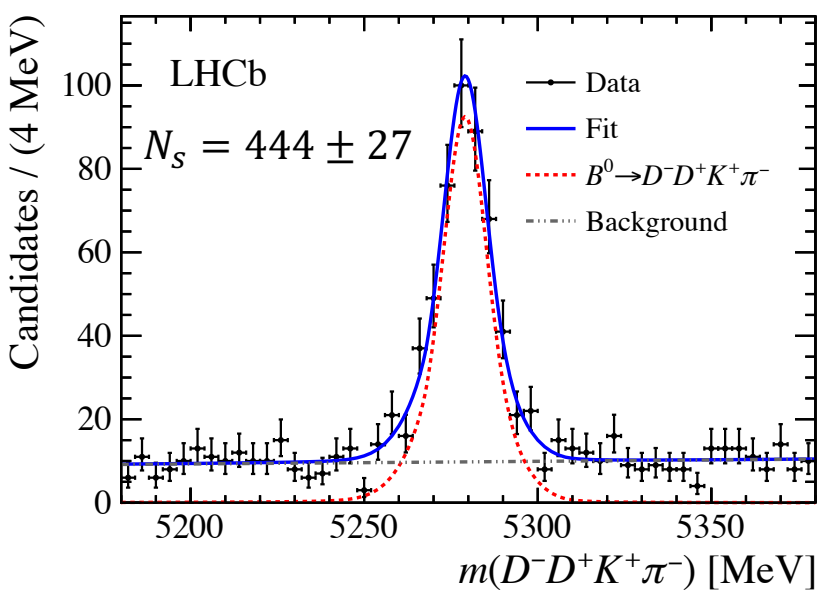
[PRD 102 (2020) 092007]

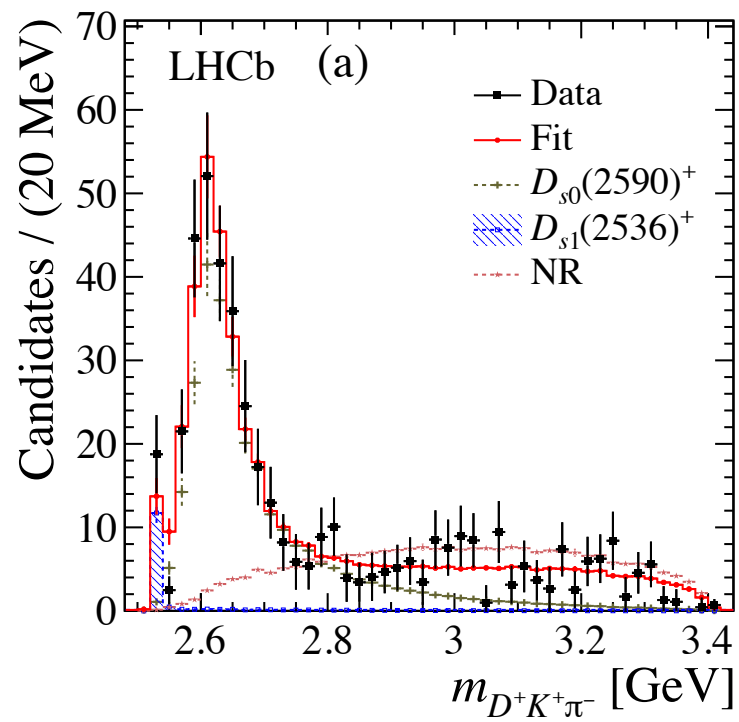
New excited D_s^+ state $(c\bar{s})$

- $D_{s0}(2590)^+$, observed in $B^0 \to D^- D^+ K^+ \pi^-$
  - Candidate for $D_s(2^1S_0)^+$, radial excitation

$m = 2591 \pm 6 \pm 7$ MeV
$\Gamma = 89 \pm 16 \pm 12$ MeV
$J^P = 0^-$

[PRL 126 (2021) 122002]



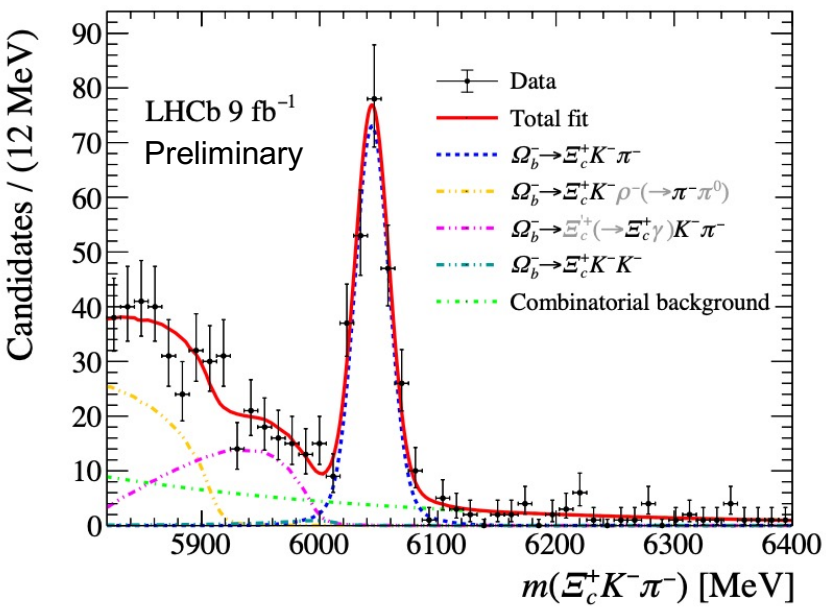


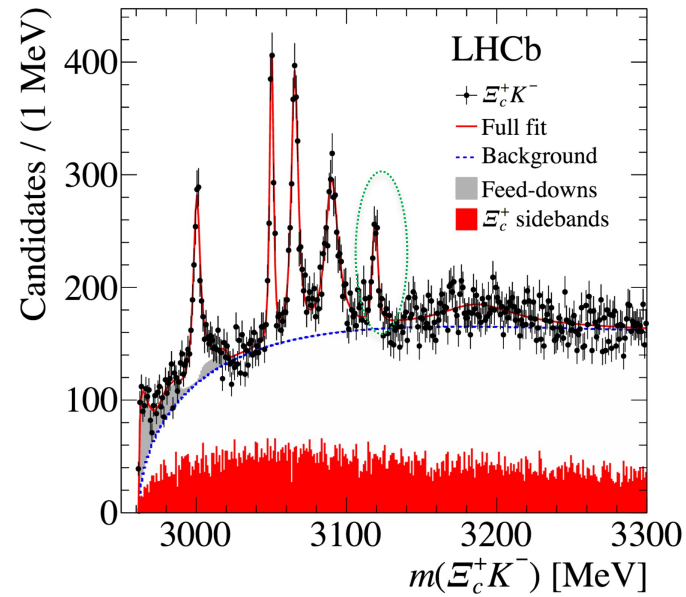
Ω_c^{**0} in Ω_b^- decay

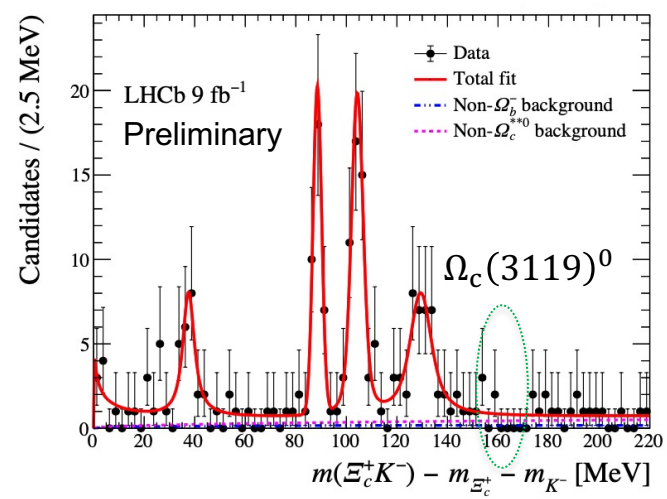
(css)

- $\Omega_b^- \to \Xi_c^+ K^- \pi^-$
  - Same four peaks observed, except $\Omega_c(3119)^0$
  - Structure at threshold (4.3σ)

[LHCb-Paper-2021-012]



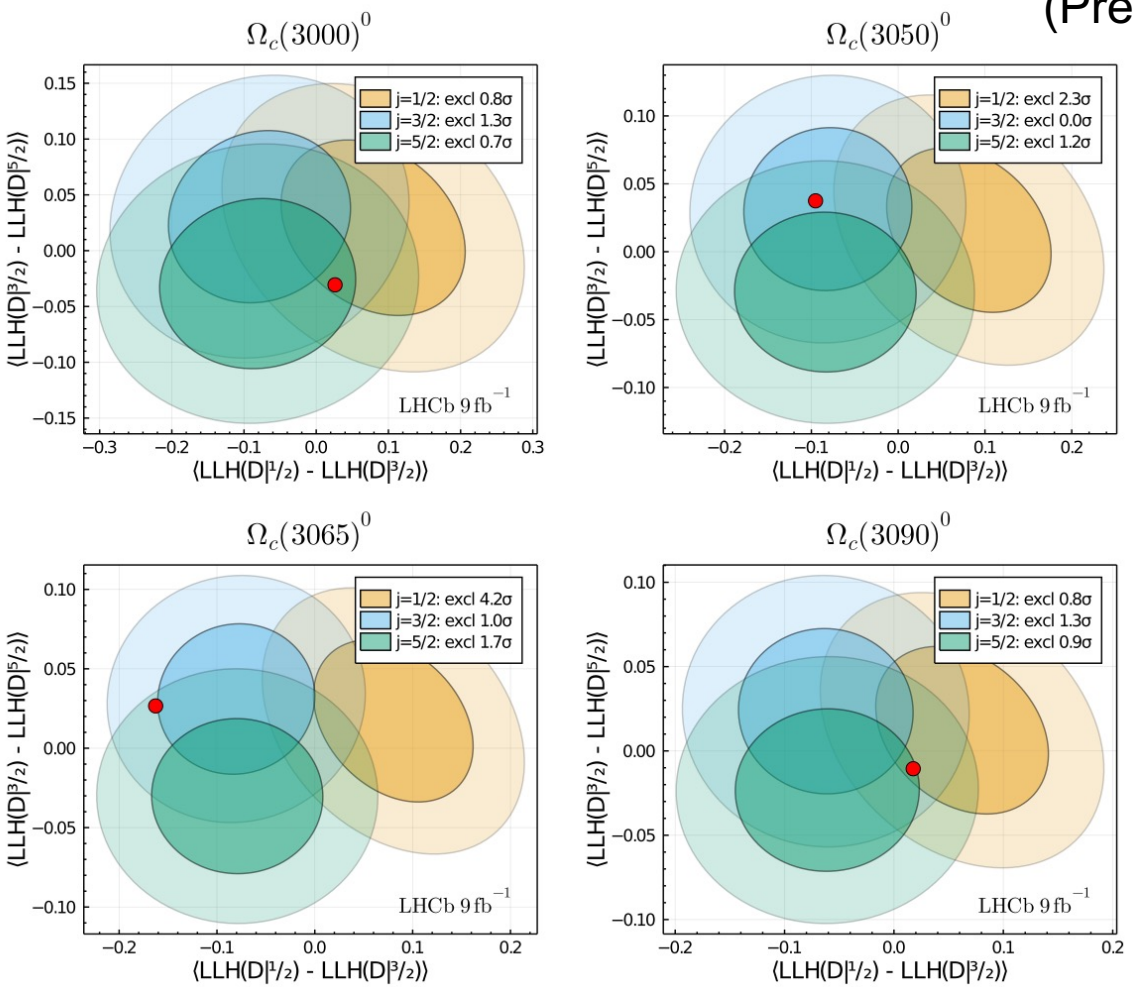




- Spin of Ω_c^{**0} probed, not conclusive yet
  - Assignment of (1/2, 1/2, 3/2, 3/2) rejected by 3.5σ

(Preliminary)

[LHCb-Paper-2021-012]

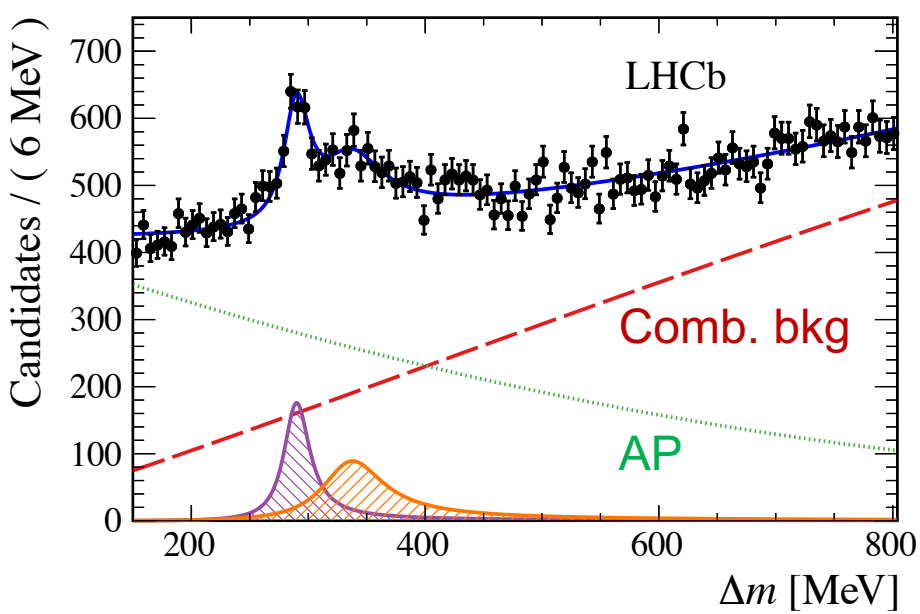


New excited B_s^0 states $(\bar{b}s)$

- Observed in $m(B^+K^-)$
  - directly to B^+K^-
  - through $B^{*+}K^-$

$$m_1 = 6063.5 \pm 1.2\ (\text{stat}) \pm 0.8\ (\text{syst})\ \text{MeV},$$
$$\Gamma_1 = 26 \pm 4\ (\text{stat}) \pm 4\ (\text{syst})\ \text{MeV},$$
$$m_2 = 6114 \pm 3\ (\text{stat}) \pm 5\ (\text{syst})\ \text{MeV},$$
$$\Gamma_2 = 66 \pm 18\ (\text{stat}) \pm 21\ (\text{syst})\ \text{MeV},$$
$$f_1 = 0.47 \pm 0.11\ (\text{stat}) \pm 0.15\ (\text{syst}),$$

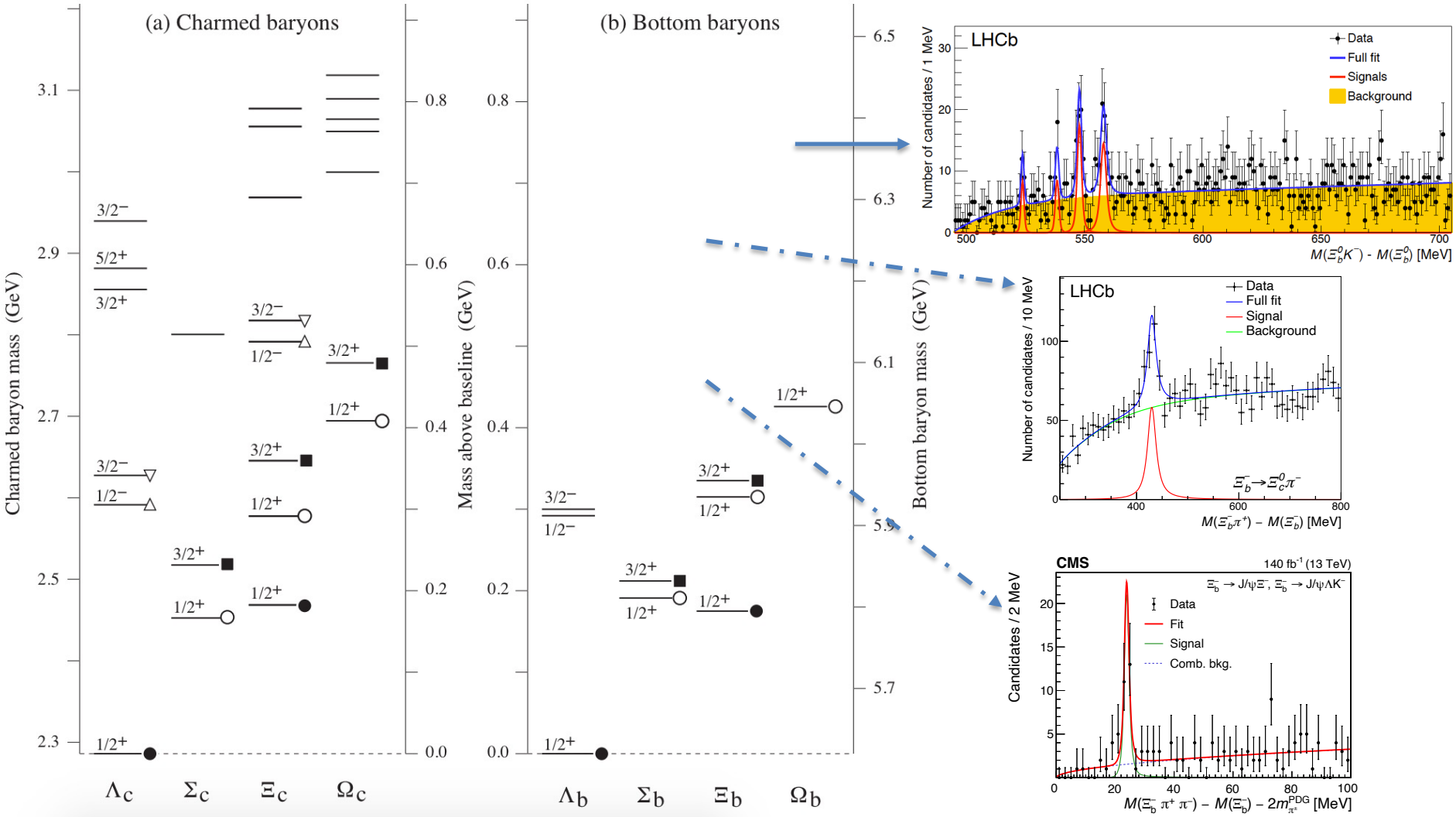
[arXiv:2010.15931]



if through $B^{*+}K^-, B^{*+} \to B^+\gamma$

$$m_1 = 6108.8 \pm 1.1\ (\text{stat}) \pm 0.7\ (\text{syst})\ \text{MeV},$$
$$\Gamma_1 = 22 \pm 5\ (\text{stat}) \pm 4\ (\text{syst})\ \text{MeV},$$
$$m_2 = 6158 \pm 4\ (\text{stat}) \pm 5\ (\text{syst})\ \text{MeV},$$
$$\Gamma_2 = 72 \pm 18\ (\text{stat.}) \pm 25\ (\text{syst})\ \text{MeV},$$
$$f_1 = 0.42 \pm 0.11\ (\text{stat}) \pm 0.16\ (\text{syst}).$$

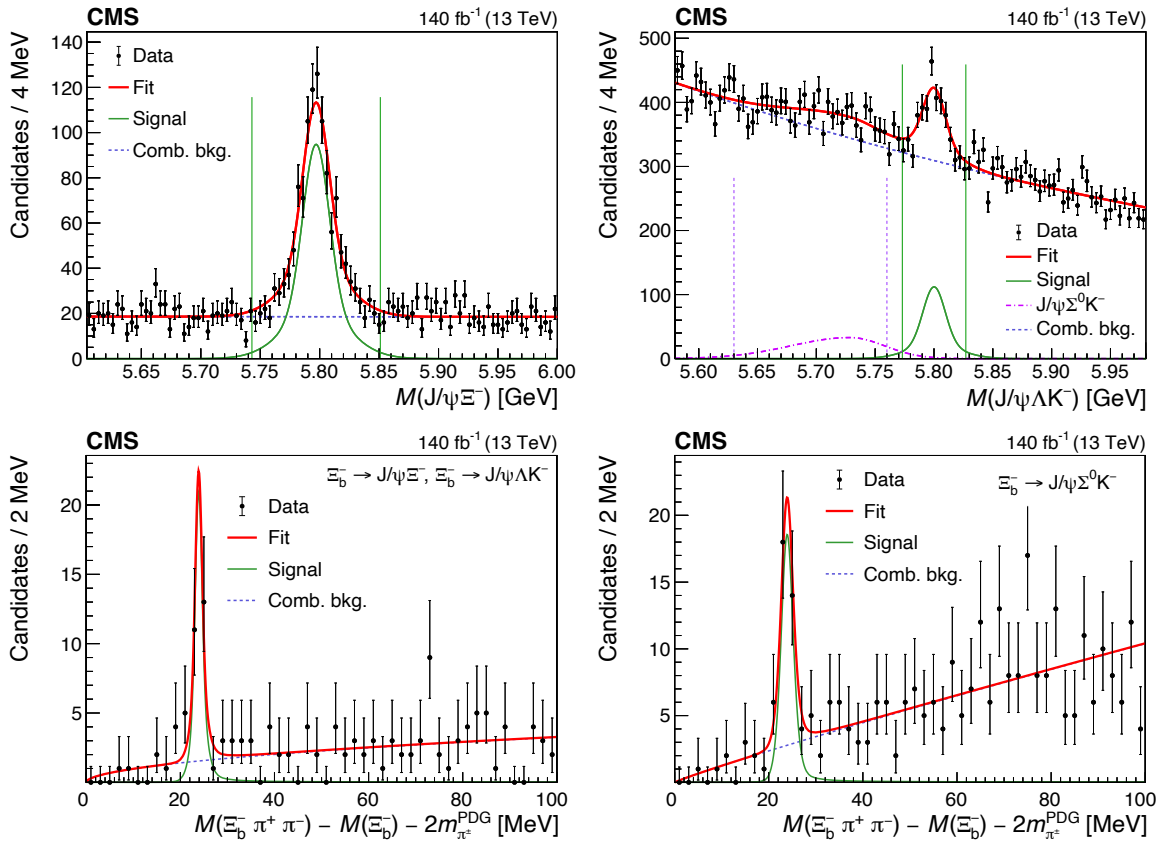
Beauty baryons



Observation of $\Xi_b(6100)^-$ (bsd)

- $\Xi_b(6100)^-$ with $\Xi_b^-\pi^+\pi^-$

[arXiv:2102.04524]

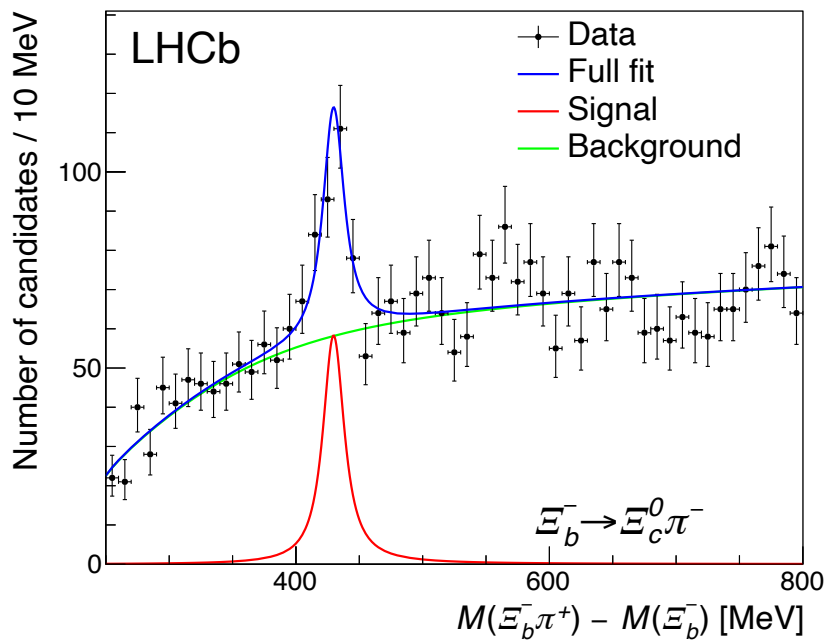


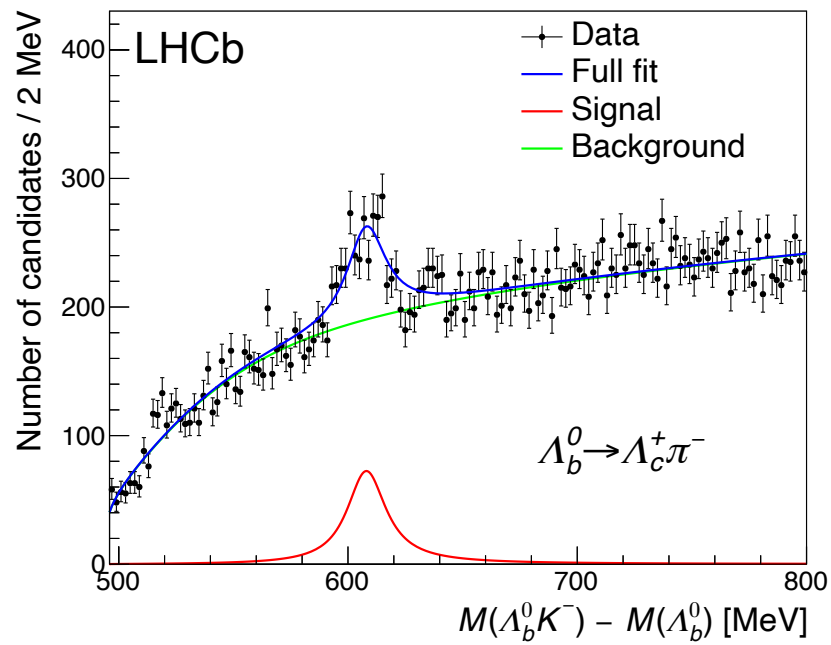
$m = 6100.3 \pm 0.2 \pm 0.1$ MeV, $\Gamma < 1.9$ MeV at 95% CL

Observation of $\Xi_b(6227)^0$ (bsu)

- Neutral $\Xi_b(6227)$ with $\Xi_b^- \pi^+, \Xi_b^- \to \Xi_c^0 \pi^-$

[PRD 103 (2021) 012004]

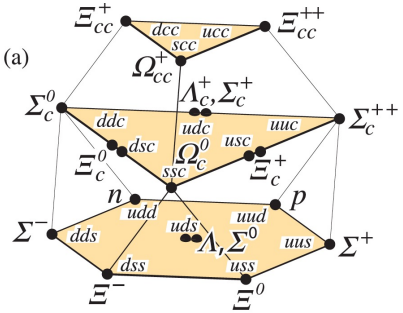




$$\delta m_\pi^{\text{peak}} = 429.8\,^{+1.4}_{-1.5} \pm 0.3\,\text{MeV},$$
$$m(\Xi_b(6227)^0) = 6227.1\,^{+1.4}_{-1.5} \pm 0.5\,\text{MeV},$$
$$\Gamma(\Xi_b(6227)^0) = 18.6\,^{+5.0}_{-4.1} \pm 1.4\,\text{MeV},$$

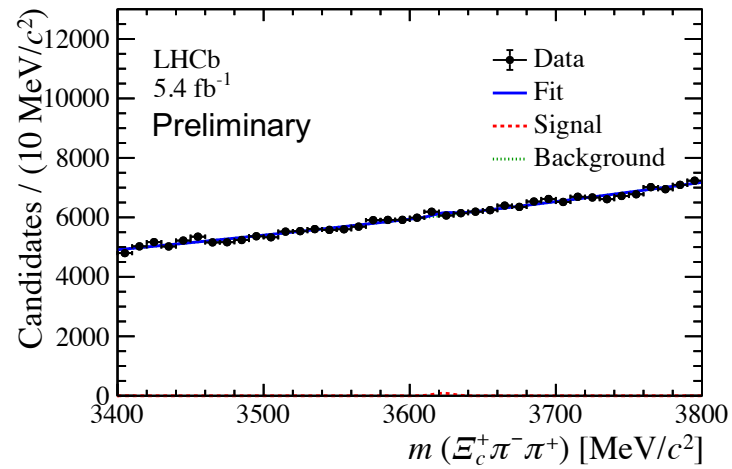
$$\delta m_K^{\text{peak}} = 608.3 \pm 0.8 \pm 0.4\,\text{MeV},$$
$$m(\Xi_b(6227)^-) = 6227.9 \pm 0.8 \pm 0.5\,\text{MeV},$$
$$\Gamma(\Xi_b(6227)^-) = 19.9 \pm 2.1 \pm 1.5\,\text{MeV},$$

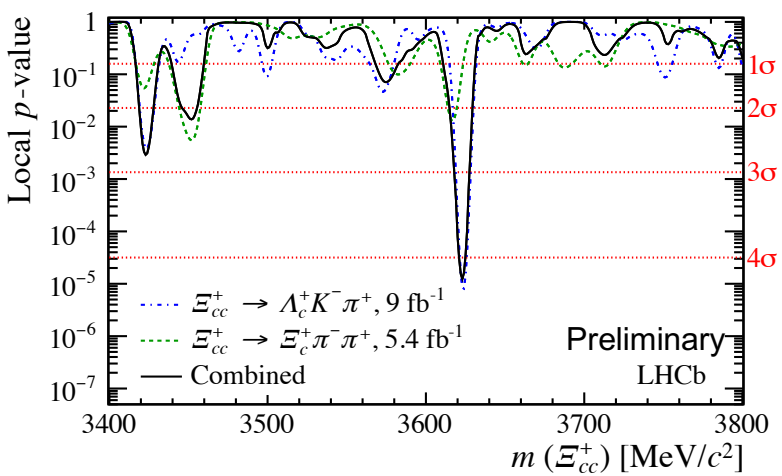
Search for Ξ_{cc}^{+}

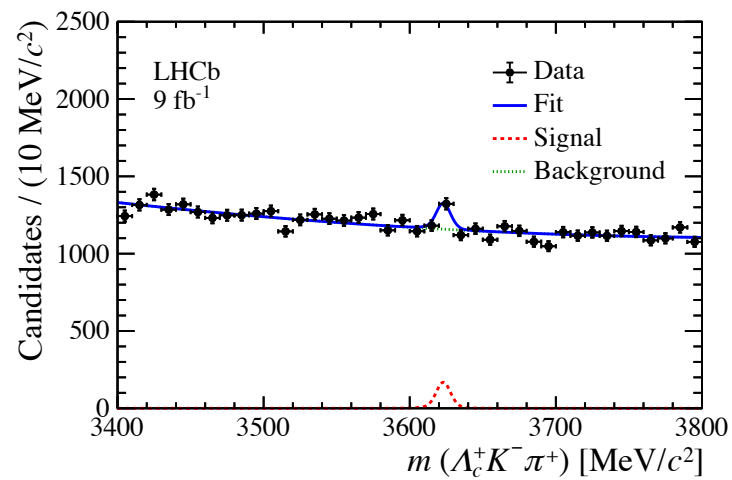


- $\Xi_{cc}^{+} \to \Xi_c^{+}\pi^{+}\pi^{-}$, no significant signal, combined with $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$
  - Local (global) significance 4σ (2.9σ)
  - $m = 3623.0 \pm 1.4_{\text{stat}}$ MeV

c.f. $m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30$ MeV





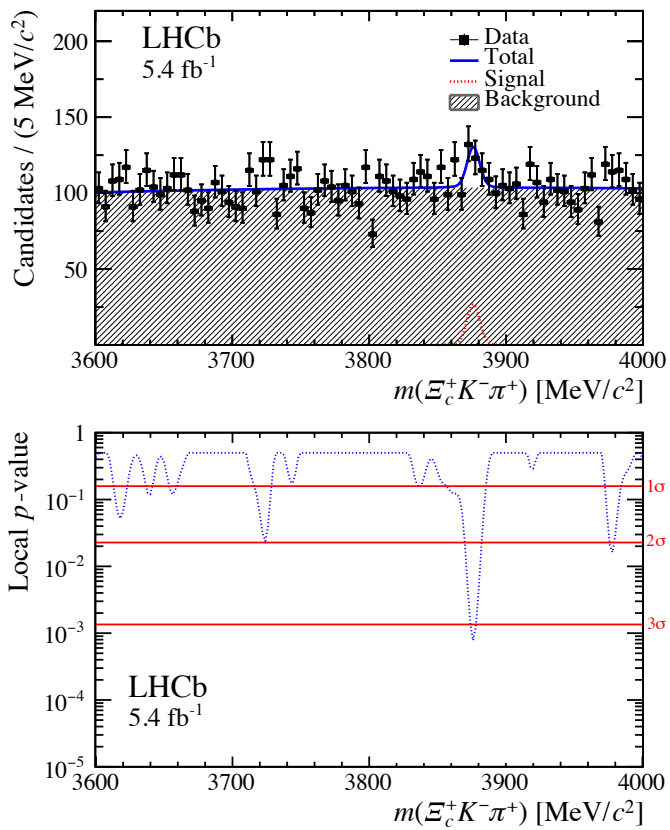


[LHCb-Paper-2021-019]

First search for Ω_{cc}^{+} (ccs)

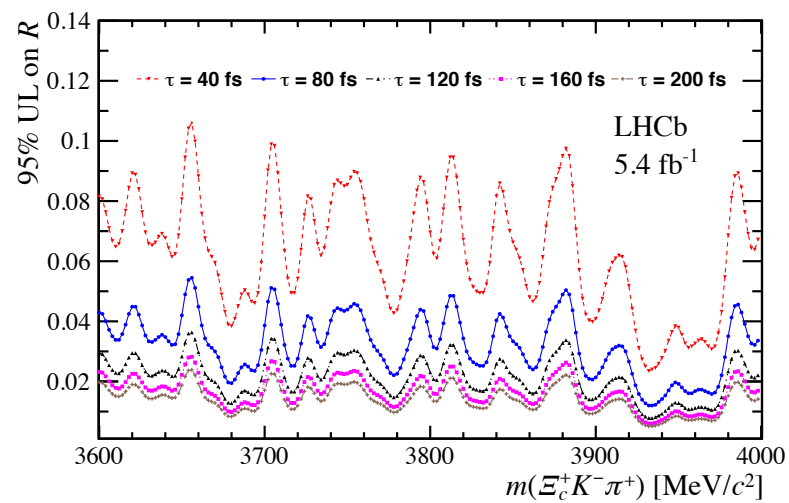
- $\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$, bump at 3876 MeV, with local (global) significance 3.2σ (1.8σ)

[arXiv:2105.06841]



- Upper limit on

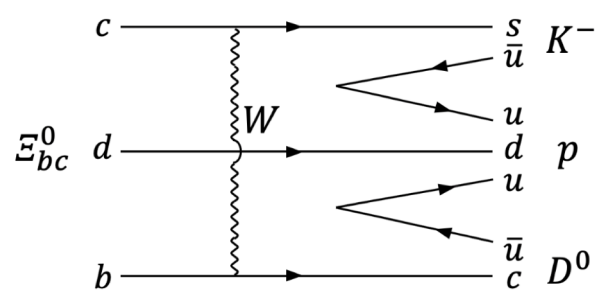
$$R = \frac{\sigma(\Omega_{cc}^{+}) \cdot \mathcal{B}_{\text{total}}(\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+})}{\sigma(\Xi_{cc}^{++}) \cdot \mathcal{B}_{\text{total}}(\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+})}$$

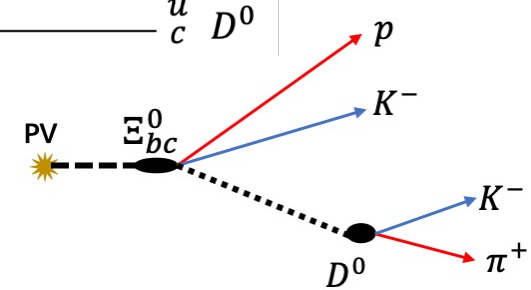


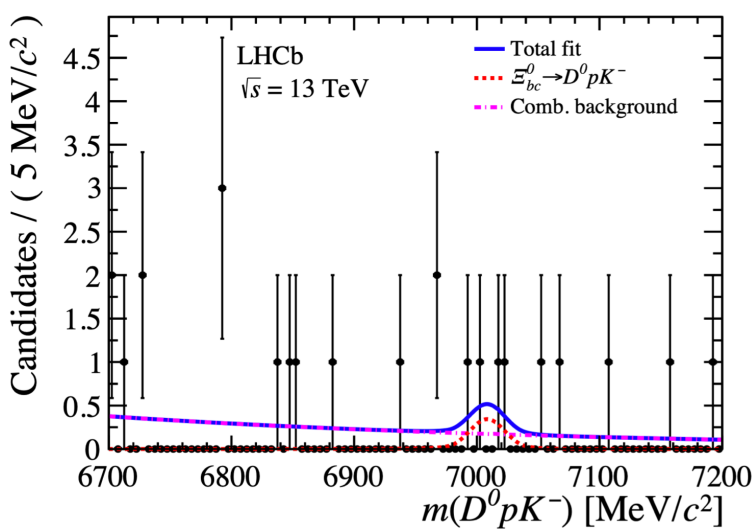
First search for Ξ_{bc}^0 (bcd)

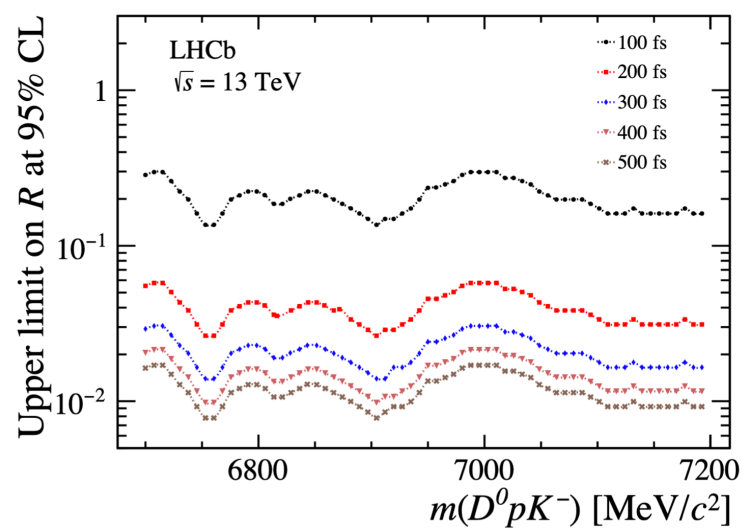
- $\Xi_{bc}^0 \to D^0 p K^-$
- No obvious signal, UL as function of m/τ on

$$R = \frac{\sigma(\Xi_{bc}^0) \cdot \mathcal{B}(\Xi_{bc}^0 \to D^0 p K^-)}{\sigma(\Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \to D^0 p K^-)}$$







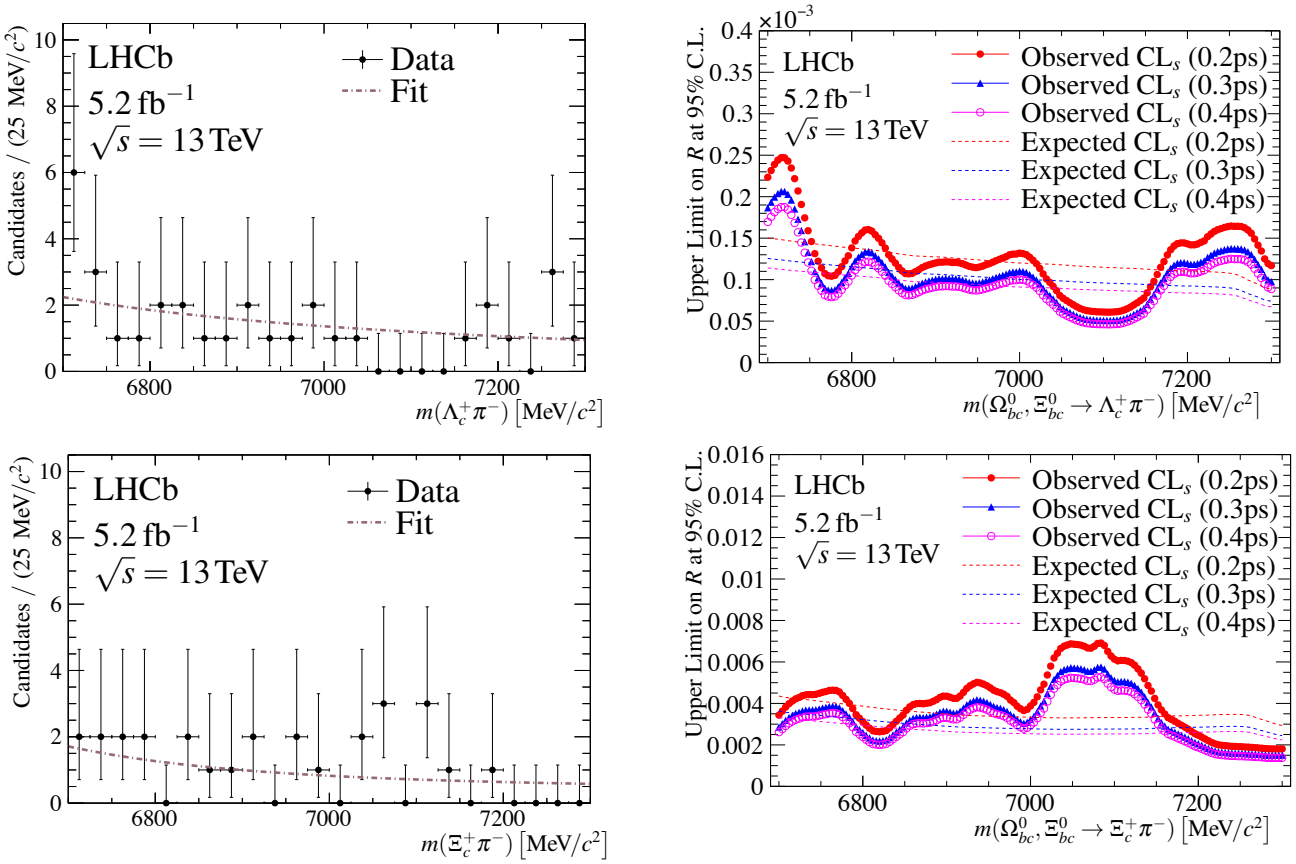


[JHEP 11 (2020) 095]

First search for Ω_{bc}^0 (bcs)

- $\Omega_{bc}^0, \Xi_{bc}^0 \to \Lambda_c^+(\Xi_c^+)\pi^-$. No obvious signal, UL as function of m/τ on $R = \frac{\sigma(H_{bc}^0)\cdot\mathcal{B}(H_{bc}^0 \to H_c^+\pi^-)}{\sigma(H_b^0)\cdot\mathcal{B}(H_b^0 \to H_c^+\pi^-)}$

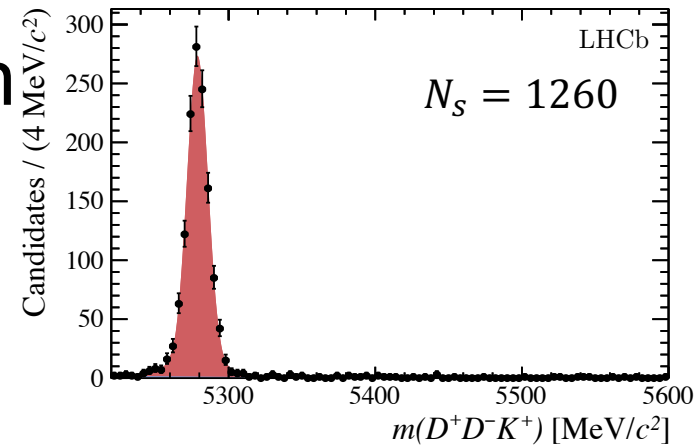
[arXiv:2104.04759]

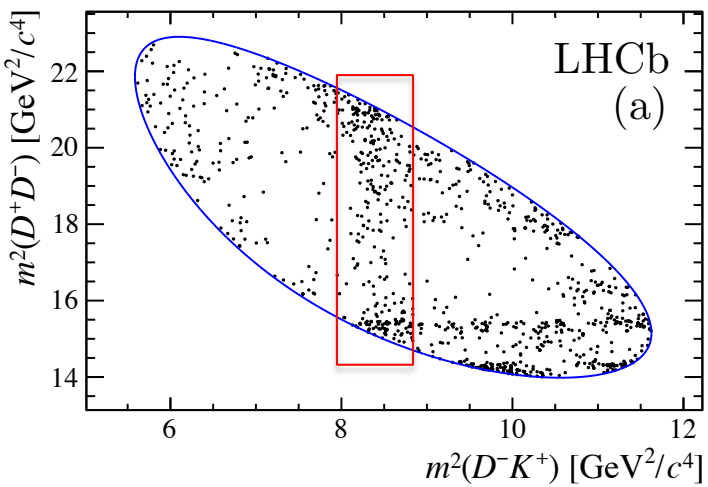


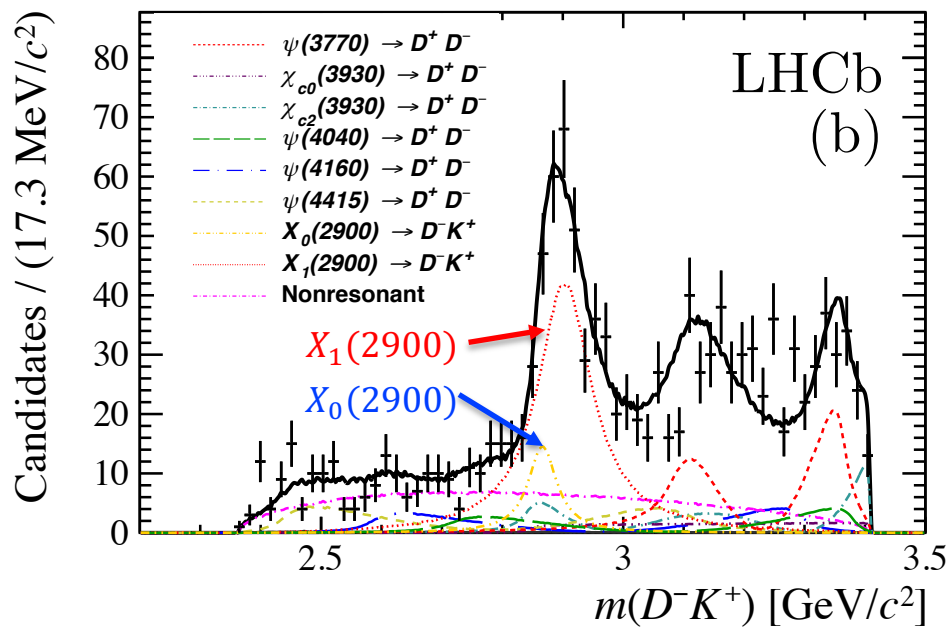
Observation of $X(2900) \to D^- K^+$ $(\bar{c}du\bar{s})$

[PRL 125 (2020) 242001, PRD 102 (2020) 112003]

- Using $B^+ \to D^+ D^- K^+$, both model-independent study & amplitude analysis





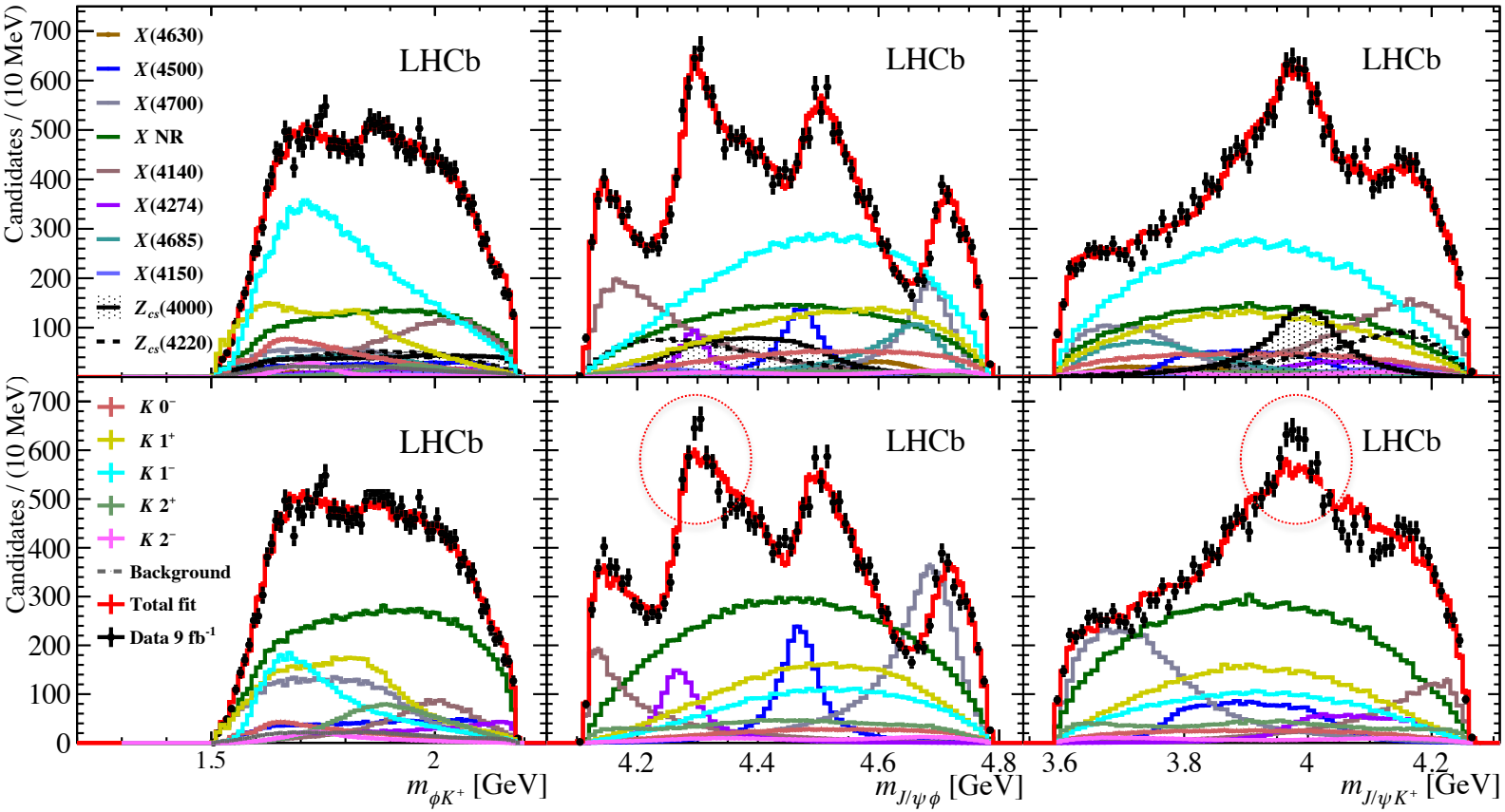


$X_0(2900)$: $m = 2866 \pm 7 \pm 2$ MeV
$\Gamma = 57 \pm 12 \pm 4$ MeV
$X_1(2900)$: $m = 2904 \pm 5 \pm 1$ MeV
$\Gamma = 110 \pm 11 \pm 4$ MeV

Observation of $Z_{cs}^{+} \to J/\psi K^{+}$ $(c\bar{c}u\bar{s})$

- Amplitude analysis with $B^{+} \to J/\psi \phi K^{+}$

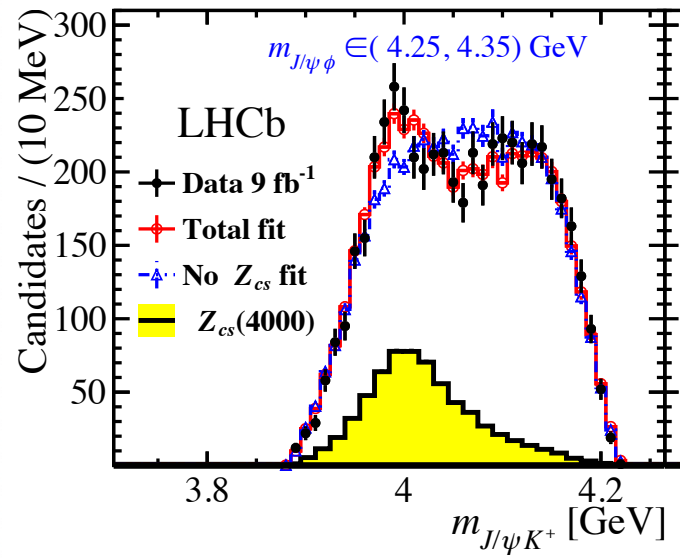
[arXiv:2103.01803]



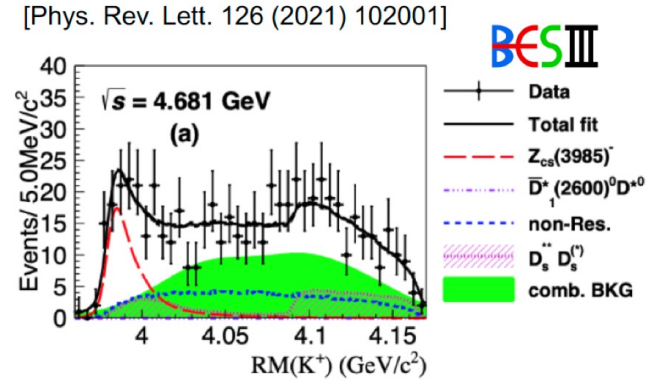
Run1
Model

[arXiv:2103.01803]

	Contribution	Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4^{+6}_{-15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
	All $K(2^-)$				$2.1 \pm 0.4^{+2.0}_{-1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4^{+10}_{-19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
	All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
	All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
	$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
	$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$



[Phys. Rev. Lett. 126 (2021) 102001]



Unlikely to be the same one as seen by BESIII:

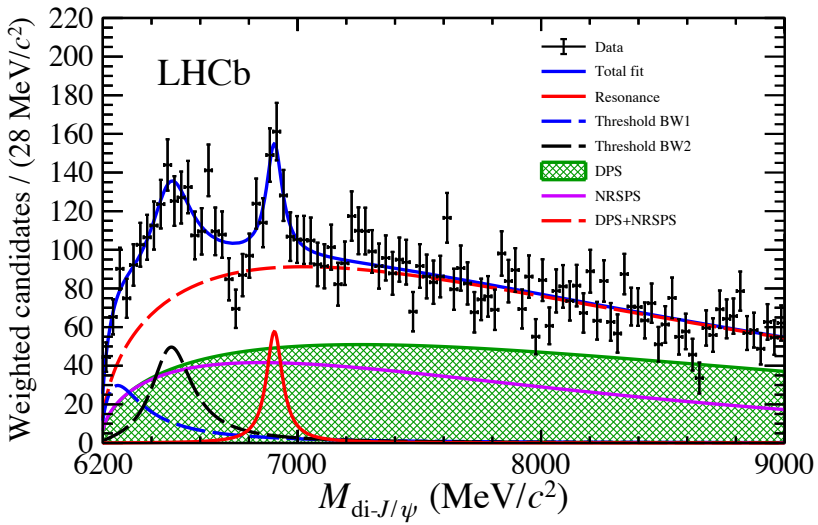
$m = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV

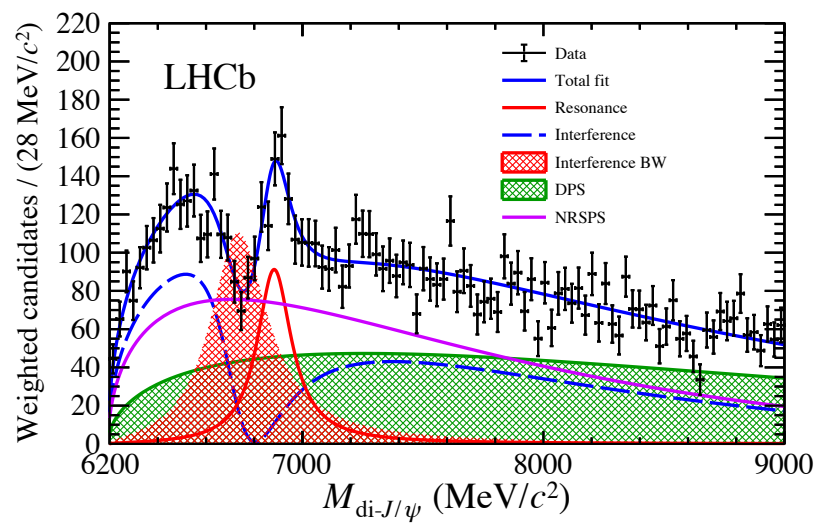
$\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

$X(6900)$ in Di-J/ψ system $(c\bar{c}c\bar{c})$

- Structure observed in Di-J/ψ mass
  - Two models, both with significance $> 5\sigma$
- First candidate for $T_{c\bar{c}c\bar{c}}$

[Sci. Bull. 65 (2020) 032]





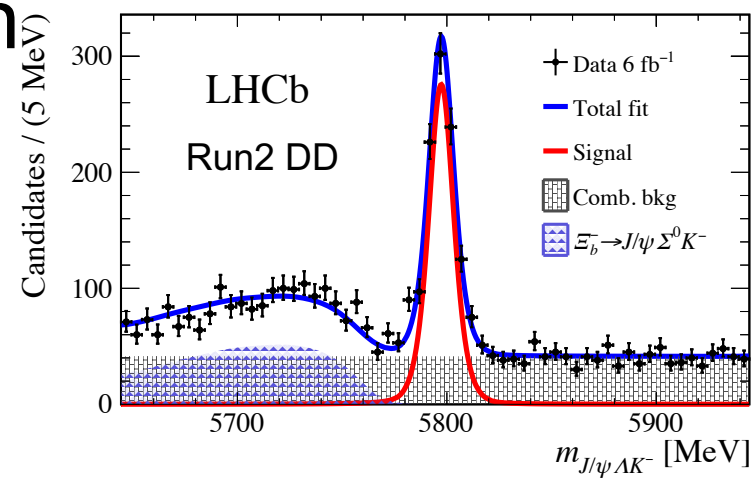
No interfence, using Breit-Wigner
$m = 6905 \pm 11 \pm 7$ MeV
$\Gamma = 80 \pm 19 \pm 33$ MeV

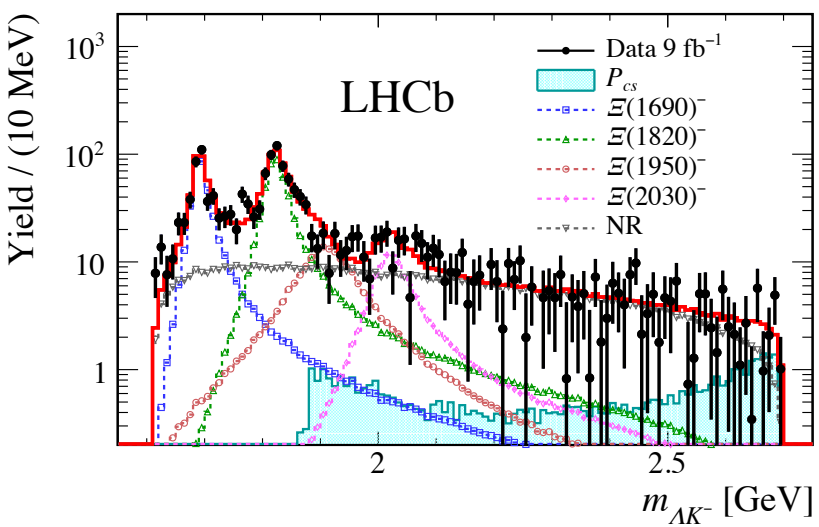
NRSPS interfence w/ broad structure
$m = 6886 \pm 11 \pm 11$ MeV
$\Gamma = 168 \pm 33 \pm 69$ MeV

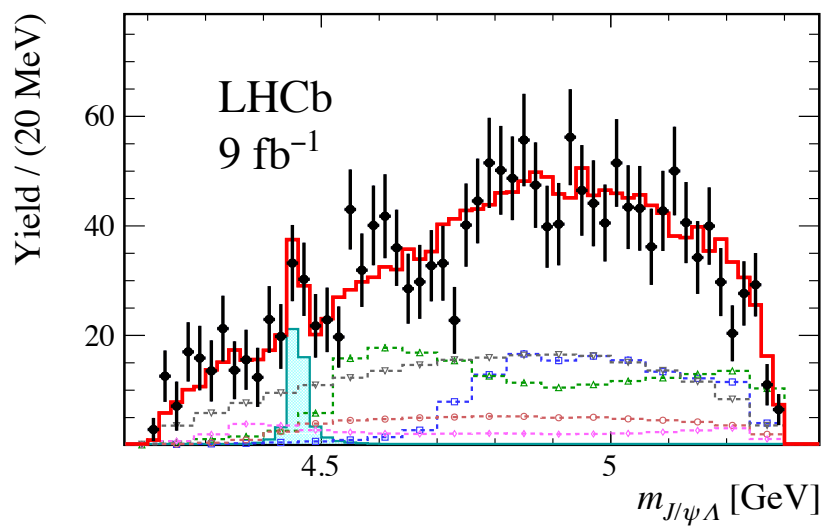
Evidence of $P_{cs}^0 \to J/\psi\Lambda$ $(c\bar{c}uds)$

- Amplitude analysis with $\Xi_b^- \to J/\psi\Lambda K^-$
  - 1750 signals
- P_{cs}^0 evidence $\Xi(1690)^-, \Xi(1820)^-$

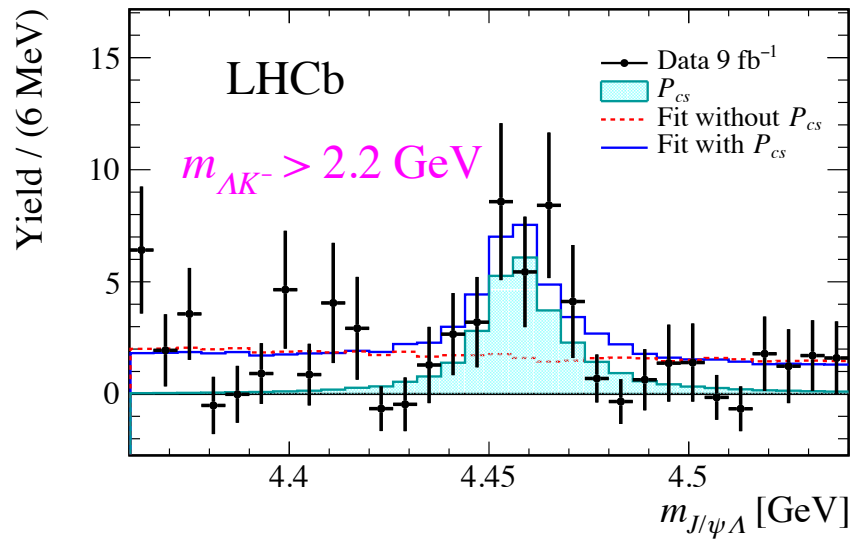
[arXiv:2012.10380]







- P_{cs}^{+}
  - $4.3\sigma \rightarrow 3.1\sigma$ including systematics
  - Statistics not enough to determine J^P
  - 19 MeV below $\Xi_c^0 \bar{D}^{*0}$ threshold



[arXiv:2012.10380]

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8+49.9}_{-3.5-\ \ 9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8+3.8}_{-1.8-4.1}$
NR	–	–	$35.8\,^{+4.6+10.3}_{-6.4-11.2}$

New

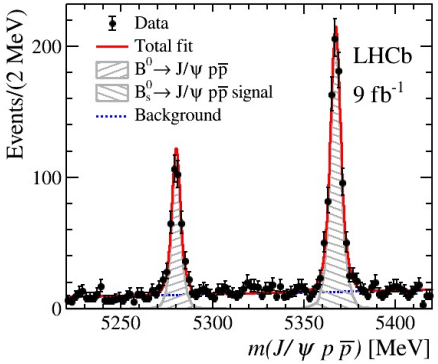
New structure in $J/\psi p$ $(c\bar{c}uud)$

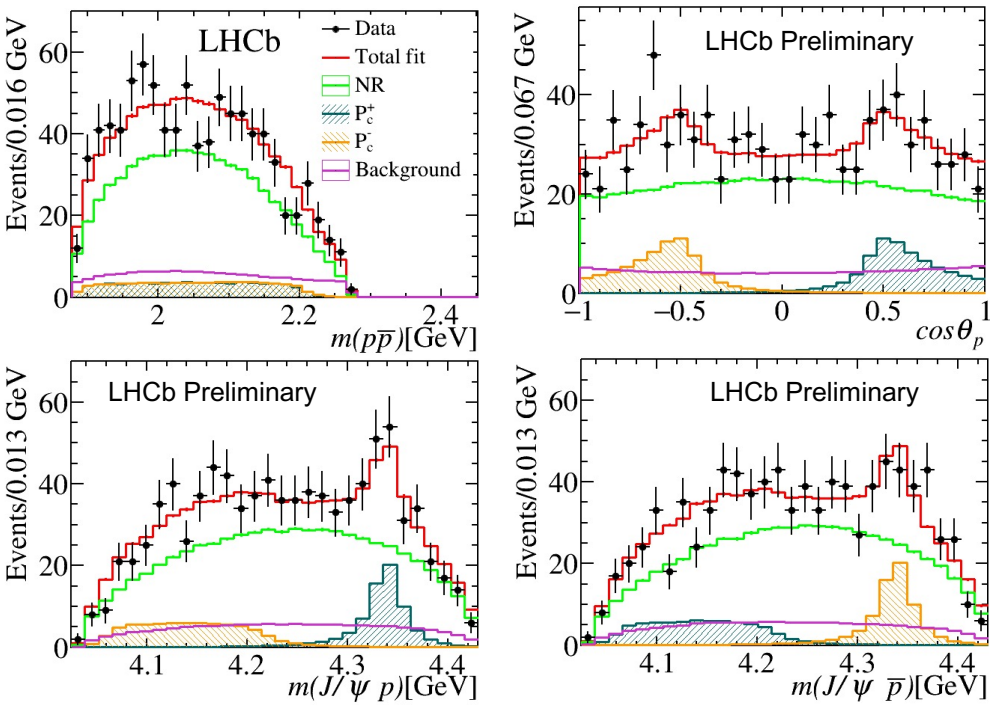
- Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$
  - 800 signals
  - P_c^+ state, 3.1 – 3.7σ depending on J^P, $1/2^+$ used in nominal fit

$m = 4337^{+7}_{-4}\,(\text{stat})^{+2}_{-2}(\text{syst})$ MeV
$\Gamma = 29^{+26}_{-12}\,(\text{stat})^{+14}_{-14}(\text{syst})$ MeV

10 MeV below $\chi_{c0}(1P)p$ threshold

More in E. Spadaro Norella's talk in Flavour Physics: Session 3



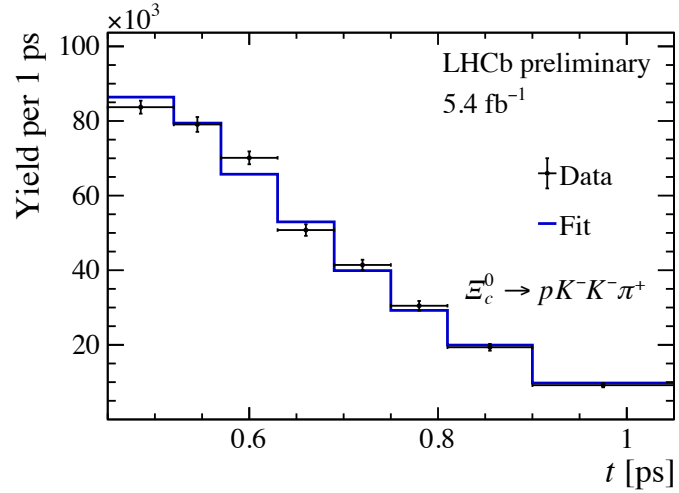


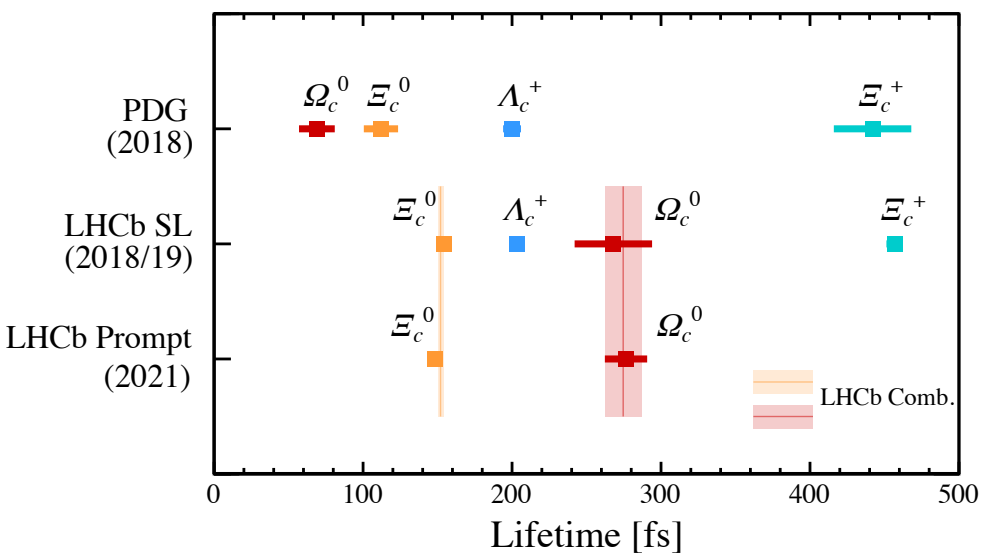
[LHCb-Paper-2021-018]

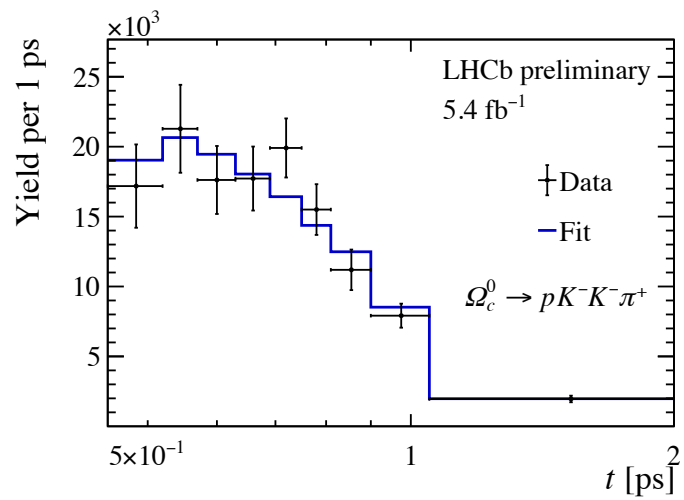
Ξ_c^0, Ω_c^0 lifetimes

- Measured with prompt Ξ_c^0, Ω_c^0 relative to D^0, confirming those using b-decay

$$\tau(\Xi_c^0) = (148.0 \pm 2.3 \pm 2.2 \pm 0.2)\ \text{fs}$$
$$\tau(\Omega_c^0) = (276.5 \pm 13.4 \pm 4.3 \pm 0.7)\ \text{fs}$$







[LHCb-Paper-2021-021]

Summary

- Many results on heavy flavour production and spectroscopy since last LHCP
  - Production, $D, \Lambda_c^+, \Xi_c, \Lambda_b^0, B_c(2S)^+, \ldots$
  - Spectroscopy, $D_{s0}(2590)^+$, excited Ξ_b states, $X(2900), Z_{cs}^+, X(6900), P_{cs}^+, \ldots$
  - Lifetime, Ξ_c^0, Ω_c^0
- Upgrade of LHC experiments ongoing, many results on their way, stay tuned