Non-leptonic hadron decays at the LHC

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on behalf of the ATLAS, CMS and LHCb collaborations

FPCP 2023, Lyon
May 29, 2023

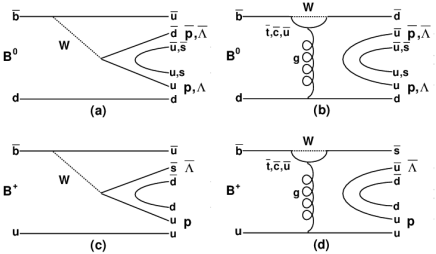
Outline

- $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ ..... arXiv:2206.06673 [hep-ex]
- $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$ ..... arXiv:2211.08847 [hep-ex]
- $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$ ..... Eur. Phys. J. C 82 (2022) 499
- $B_c^+ \to J/\psi D_s^{(*)+}$ ..... JHEP 08 (2022) 087
- $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios ..... Phys. Rev. D 102 (2020) 092007
- Charmonium decays in $B \to (K_s^0 K\pi)K$ ..... arXiv:2304.14891 [hep-ex]
- $\Xi_b^-\pi^+\pi^-$ decay studies ..... Phys. Rev. Lett. 126 (2021) 252003
- Prompt open-charm production cross sections ..... JHEP 11 (2021) 225

$B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ (1/2)

arXiv:2206.06673 [hep-ex]

- Differences in the way B mesons decay to baryonic versus purely mesonic final states have been found since the first experimental measurements
- To date, only three charmless two-body baryonic decays have been observed, namely the $B^+ \to p\bar{\Lambda}(1520)$, $B^+ \to p\bar{\Lambda}$ and $B^0 \to p\bar{p}$
- Some theoretical predictions allow a yield $\mathcal{B}(B_s^0 \to pp) \sim 10^{-8}$ that is experimentally accessible[1]
- **LHCb** performed a search for the rare hadronic decay $B_s^0 \to p\bar{p}$ with integrated luminosity of $6\,\text{fb}^{-1}$
- Valuable information on the role of exchange and annihilation diagrams in baryonic B decays



[1] Y. K. Hsiao, S.-Y. Tsai, C.-C. Lih, and E. Rodrigues, Testing the W-exchange mechanism with two-body baryonic B decays, JHEP 04 (2020) 035, arXiv:1906.01805

$B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ (2/2)

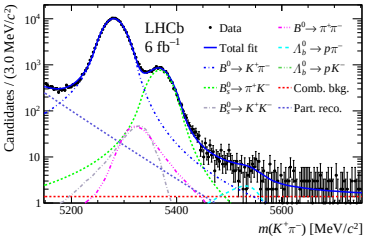
arXiv:2206.06673 [hep-ex]

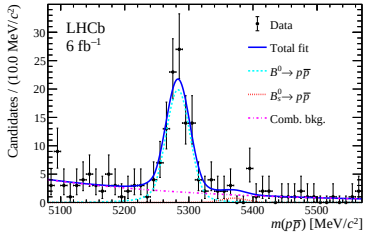
- The yields of $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ are normalized to the $B^0 \to K^+\pi^-$ decays (Similar topology and a precisely measured branching fraction)
- $B^0 \to K^+\pi^-$ has multiple contributions from other decays treated as systematic effects
- The shape of the partially reconstructed background component is determined from a mixture of simulated samples
- The significances following Wilk's theorem[1] extracted from the fit to the $p\bar{p}$ data are 16.2σ and 0.9σ
- No significant evidence for $B_s^0 \to p\bar{p}$ was observed

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4(5.1) \times 10^{-9} \text{at } 90\% \ (95\%) \text{ CL}$$

[1] S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, Ann. Math. Stat. 9 (1938) 60. link

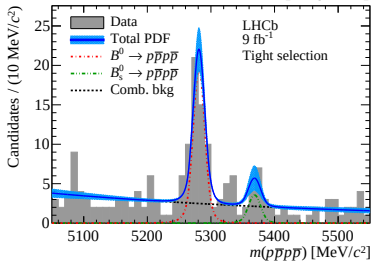




$B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$ (1/1)

arXiv:2211.08847 [hep-ex]

- The four-body decays are not as suppressed relative to the corresponding two-body decays
- Multi-body baryonic decay modes may be significantly increased due to a threshold enhancement effect in the baryon-antibaryon invariant mass spectrum
- The branching fraction for $p\bar{p}K^+K^-$ is $(4.5 \pm 0.5) \times 10^{-6}$, $p\bar{p}K^+\pi^-$ is $(1.4 \pm 0.3) \times 10^{-6}$ and $p\bar{p}\pi^+\pi^-$ is $(4.3 \pm 2.0) \times 10^{-7}$
- Neither the fully baryonic decay $B^0 \to p\bar{p}p\bar{p}$ nor $B_s^0 \to p\bar{p}p\bar{p}$ have been observed previously



- **LHCb** performed a search for these decays using a dataset with integrated luminosity of 9 fb^{-1}
- Significances of 9.3σ and 4.0σ, including statistical and systematic uncertainties were observed
- The normalization channels $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ were used
- The branching fractions are measured to be

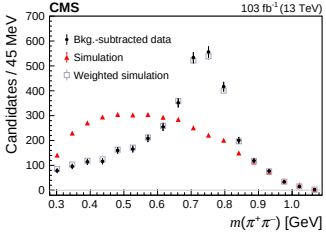
$$B^0 \to p\bar{p}p\bar{p} = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$$

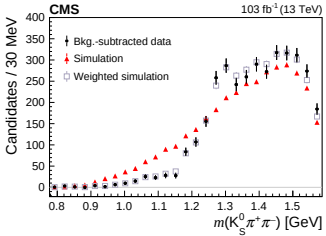
$$B_s^0 \to p\bar{p}p\bar{p} = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$

$B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_s$ (1/2)

Eur. Phys. J. C 82 (2022) 499

- Studies involving K^0_s are very challenging in the LHC environment
- $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_s$ decays can potentially be used for CP asymmetry measurements
- The $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ can be used to search for intermediate exotic resonances
- **CMS** performed an analysis of these decays using data from 2017 and 2018 with total integrated luminosity of 103 fb^{-1}
- The $B^0 \to \psi(2S)K^0_s$ decay was chosen as the normalization channel
- The $K^0_s \to \pi^+\pi^-$ candidates are formed from displaced two-prong vertices
- Simulation does not take into account the intermediate resonance structure (re-weighting applied)





$B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_s$ (2/2)

Eur. Phys. J. C 82 (2022) 499

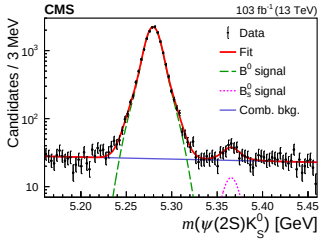
- Decays are observed with significances exceeding 5 standard deviations ($B^0_s \to \psi(2S)K^0_s \sim 5.2\sigma$, $B^0 \to \psi(2S)K^0_s\pi^+\pi^- > 30\sigma$)
- The resulting branching fraction ratios, measured for the first time

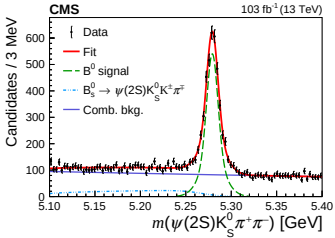
$$R_s = \frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_s)}{\mathcal{B}(B^0 \to \psi(2S)K^0_s)} = (0.69 \pm 0.14(\text{stat.}) \pm 0.11(\text{syst.}) \pm 0.34(f_s/f_d)) \times 10^{-2}$$

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S)K^0_s\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^0_s)} = 0.480 \pm 0.013(\text{stat.}) \pm 0.032(\text{syst.})$$

- The fragmentation fraction ratio $f_s/f_d = 0.208 \pm 0.021$ was used

- No significant exotic narrow structures were observed
- Further studies with more data will be needed to investigate more precisely the internal dynamics of the $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ decay

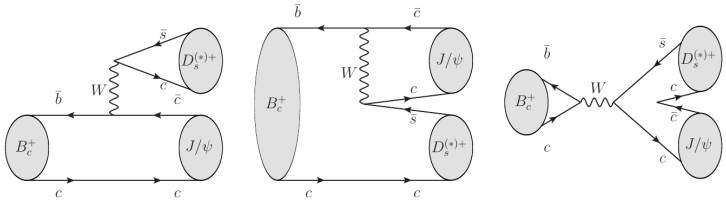




$B_c^+ \to J/\psi D_s^{(*)+}$ (1/3)

JHEP 08 (2022) 087

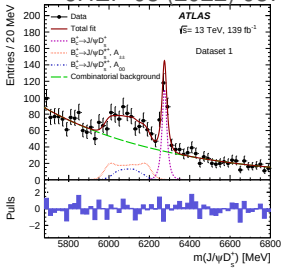
- Operating LHC experiments at a centre-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ opens new opportunities to measure the properties of the B_c meson precisely
- Previous studies were limited by the low B_c production cross-section
- These statistics allow measurement of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$
- These decays were studied at **ATLAS** using $139\,\text{fb}^{-1}$ of integrated luminosity
- In this channel, B_c decays can occur through a weak transition of either heavy quark (a,b) as well as through a weak annihilation (c)

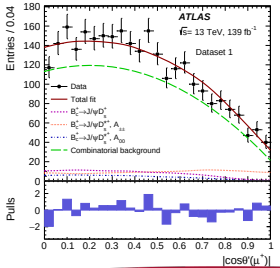


$B_c^+ \to J/\psi D_s^{(*)+}$ (2/3)

JHEP 08 (2022) 087

- J/ψ meson is reconstructed via its decay into a muon pair
- D_s^+ meson is reconstructed via the $D_s^+ \to \phi\pi^+$ decay, with the ϕ meson decaying into pairs of charged kaons
- D_s^{*+} meson decays into a D_s^+ meson and a soft photon or π^0 which is not reconstructed in the analysis
- The mass difference between D_s^+ and D_s^{*+} is sufficient for the two decay signals to be resolved as two distinct structures in the reconstructed mass of the $J/\psi D_s^+$ system
- $B_c^+ \to J/\psi D_s^{*+}$ decay is a pseudoscalar meson into two vector states (can be described in terms of three helicity amplitudes: A_{--}, A_{++} and A_{00})
- To suppress the combinatorial background, a BDT is employed
- The extended unbinned maximum-likelihood fit to the two-dimensional distribution of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ is performed





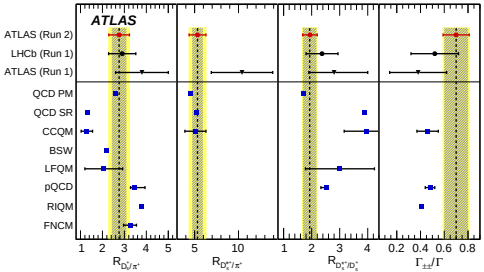
$B_c^+ \to J/\psi D_s^{(*)+}$ (3/3)

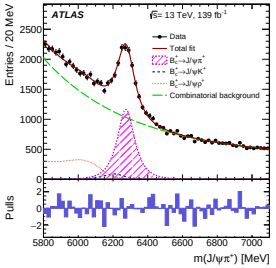
JHEP 08 (2022) 087

- $B_c^+ \to J/\psi\pi^+$ decay is used as a reference to measure the branching fractions such as:

$$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- $\Gamma_{\pm\pm}/\Gamma$ is the transverse polarization fraction in the $B_c^{*+} \to J/\psi D_s^{*+}$ decays





- All results are consistent with the earlier measurements by ATLAS[1] and LHCb[2]
- Results compared with the theory predictions
- A QCD (PM) relativistic potential model agrees well

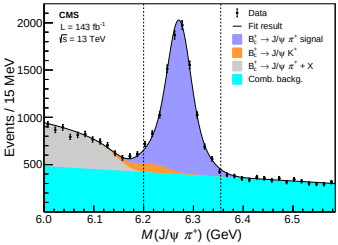
[1] ATLAS Collaboration: Eur. Phys. J. C 76 (2016) 4

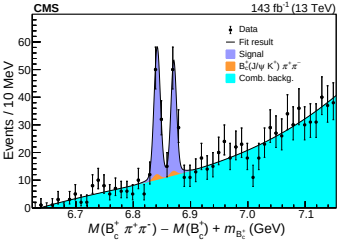
[2] LHCb Collaboration: Phys. Rev. D 87 (2013) 112012, [Addendum: Phys. Rev. D 89 (2014) 019901]

$B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios (1/2)

Phys. Rev. D 102 (2020) 092007

- $B_c(2S)^+$ and $B_c^*(2S)^+$ were observed by ATLAS and were analysed by LHCb and CMS as well
- The masses of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states are found to be consistent with theoretical predictions[1−3]
- These results stimulated new theoretical studies aimed at reaching a better understanding of the B_c^+ quarkonium family
- The latest results are by **CMS** who analyzed the full Run2 with 143 fb^{-1} of data
- The $B_c^{(*)}(2S) \to B_c^{(*)+}\pi^+\pi^-$ is followed by $B_c^+ \to J/\psi\pi^+$ decay
- The B_c^* decay into a B_c and soft photon that is not reconstructed
- The fit was performed for the distribution $\mathcal{M}(B_c^+\pi^+\pi^-) - \mathcal{M}(B_c^+) + m_{B_c^+}$ (This variable was used since it provides better resolution)





[1] E. B. Gregory et al. Phys. Rev. Lett. 104 (2010) 022001
[2] R. J. Dowdall et al. Phys. Rev. D 86 (2012) 094510
[3] N. Mathur et al. Phys. Rev. Lett. 121 (2018) 202002

$B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios (2/2)

Phys. Rev. D 102 (2020) 092007

- The main challenge in this cross-section measurement was evaluation of the corresponding (relative) detection efficiencies
- 'Pions' reflects the uncertainty in the reconstruction efficiency of the two pions emitted in decays

	Central	Stat.	Spread	Pions
$\epsilon(B_c(2S)^+)/\epsilon(B_c^+)$	0.196	1.1%	1.8%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c^+)$	0.187	1.0%	1.6%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c(2S)^+)$	0.955	1.4%	0.9%	—

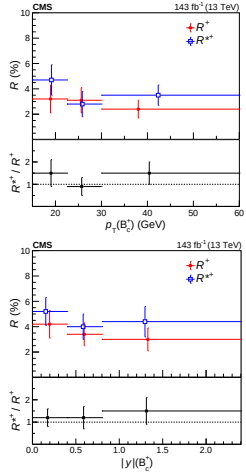
- The ratios of the $B_c^{(*)}(2S)^+ \to B_c^+$ and $B_c^*(2S)^+ \to B_c(2S)^+$ cross sections, R^{*+}, R^+ , and R^{*+}/R^+ were measured

$$R^+ = (3.47 \pm 0.63(stat) \pm 0.33(syst))\%$$

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

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

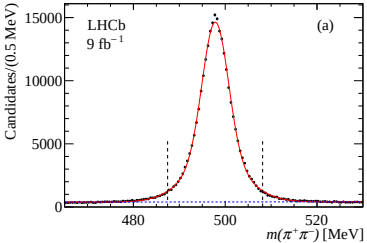
- The dependencies on the transverse momentum p_T and rapidity were studied

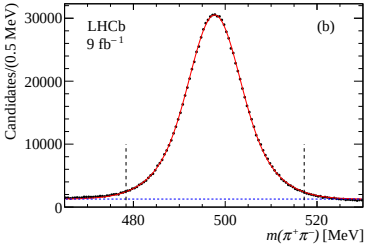


Charmonium decays in $B \to (K^0_s K\pi)K$ (1/3)

arXiv:2304.14891 [hep-ex]

- The $B^+ \to K^0_s K^+ K^- \pi^+$ and $B^+ \to K^0_s K^+ K^+ \pi^-$ decays are studied since $K^0_S K\pi$ invariant mass spectra from both decay modes reveal a rich content of charmonium resonances
- A simple factorization method used to describe these events is incomplete since it fails to describe the $B \to \chi_{c0} K$ mode
- **LHCb** performed a study using Run1 and Run2 datasets with combined integrated luminosity of $9\,\text{fb}^{-1}$ focusing on the precise measurement of charmonium parameters
- $K^0_s \to \pi^+\pi^-$ reconstruction in two categories: the first involving K^0_s mesons that decay early enough for the pions to be reconstructed inside the VELO (K^0_{SLL}), and the second containing K^0_s mesons that decay later such that track segments from the pions are outside the VELO (K^0_{SDD})
- K^0_{SLL} has better mass, momentum and vertex resolution
- Both of these categories were used to reconstruct the B meson





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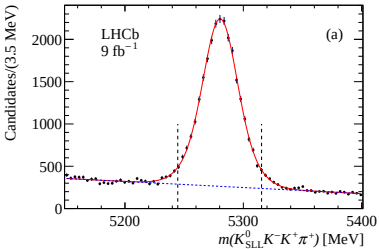
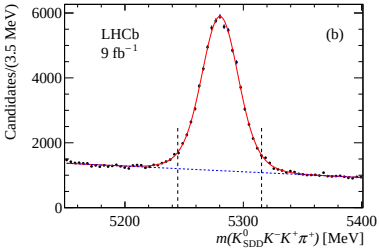
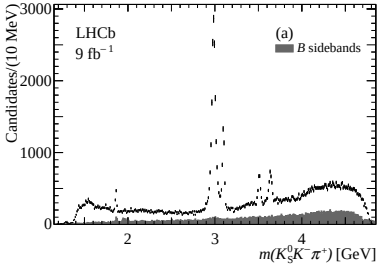




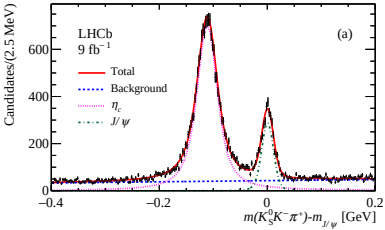
Charmonium decays in $B \to (K^0_s K\pi)K$ (2/3)

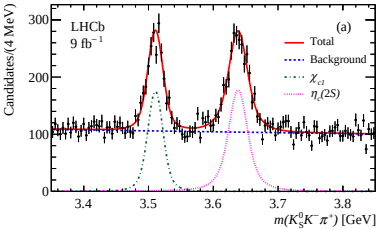
arXiv:2304.14891 [hep-ex]

- The $K^0_S K\pi$ invariant-mass spectra for events in the B^+ signal region, summed over the K^0_{SLL} and K^0_{SDD} datasets
- We can see a broad spectrum of resonances such as η_c, J/ψ, χ_{c1} and $\eta_c(2S)$



- The measurements of charmonium-resonance parameters such as mass, width and branching ratio are performed with binned fits to the $K^0_S K\pi$ invariant-mass spectra separately in the $\eta_c - J/\psi$ and the $\chi_{c1} - \eta_c(2S)$ mass regions
- Best determinations from a single measurement



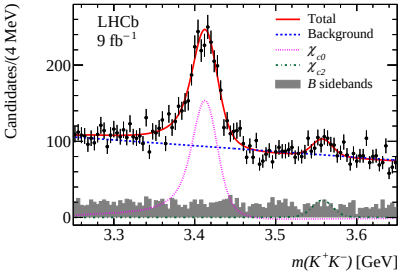


Charmonium decays in $B \to (K^0_s K\pi)K$ (3/3)

arXiv:2304.14891 [hep-ex]

- Looking at the K^+K^- invariant mass spectrum from the $B \to K^0_s K^+K^-\pi^+$ decays we can see the $\chi_{c0} - \chi_{c2}$ region
- First observation of branching fraction of $B^+ \to \chi_{c0} K^0_S \pi^+$ is reported
- Evidence of $B^+ \to \chi_{c2} K^0_S \pi^+$
- Measured branching fractions using (top) the η_c and (bottom) the J/ψ resonance as reference for $B^+ \to K^0_s K^+K^-\pi^+$ data

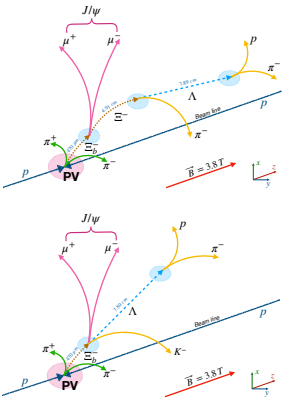
Final state	$\mathcal{B}_\infty$ $(\times 10^{-3})$	PDG $(\times 10^{-3})$
$B^+ \to \chi_{c0} K^0 \pi^+$	$1.38 \pm 0.07 \pm 0.11 \pm 0.32$	
$B^+ \to \chi_{c2} K^0 \pi^+$	$0.87 \pm 0.20 \pm 0.08 \pm 0.20$	0.116 ± 0.025
Final state	$\mathcal{B}_\epsilon$ $(\times 10^{-3})$	
$B^+ \to \chi_{c0} K^0 \pi^+$	$1.45 \pm 0.08 \pm 0.11 \pm 0.16$	
$B^+ \to \chi_{c2} K^0 \pi^+$	$0.92 \pm 0.21 \pm 0.08 \pm 0.10$	



$\Xi_b^- \pi^+ \pi^-$ decay studies (1/2)

Phys. Rev. Lett. 126 (2021) 252003

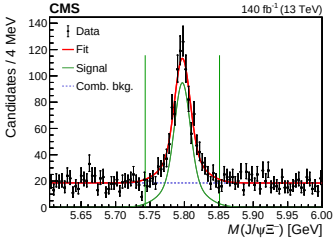
- The Ξ baryon family consists of isodoublet states composed of bsq ($q = u||d$) quarks
- Various theoretical models and calculations predict a spectrum of excited Ξ_b
- Three of the four excited states with $j_{qs} = 1$ were observed in $\Xi_b^- \pi^+$ and $\Xi_b^0 \pi^-$ decays
- **CMS** focused on the search for the Ξ_b^- excited states in the $\Xi_b^- \pi^+ \pi^-$ invariant mass spectrum using a dataset with integrated luminosity of 140 fb^{-1}
- The ground state Ξ_b is reconstructed via its decays to $J/\psi \Xi^-$ and $J/\psi \Lambda K^-$, followed by the decays $\Xi^- \to \Lambda \pi^-$ and $\Lambda \to p\pi^-$

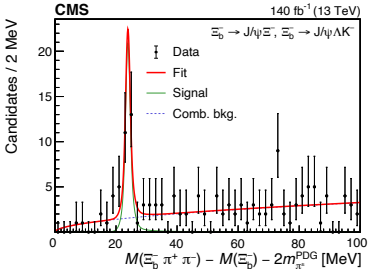


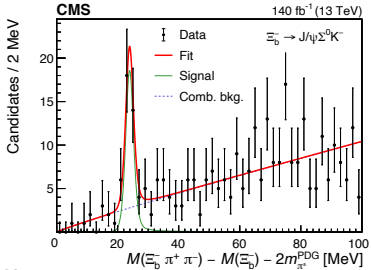
$\Xi_b^- \pi^+ \pi^-$ decay studies (2/2)

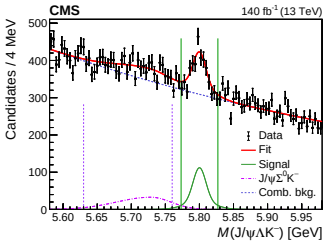
Phys. Rev. Lett. 126 (2021) 252003

- Partially reconstructed $\Xi_b^- \to J/\psi \Sigma^0 K^-$ events were included with the shape parameters fixed from simulation studies
- Independent unbinned extended maximum-likelihood fits were applied to the mass difference variable ΔM
- A new resonance was observed with $\Delta M_{\Xi_b(6100)^-} = 24.14 \pm 0.22\,\mathrm{MeV}$ and upper limit on the width of $\Gamma(\Xi_b(6100)^-) < 1.9\,\mathrm{MeV}$
- The significance varies between 6.2σ and 6.7σ





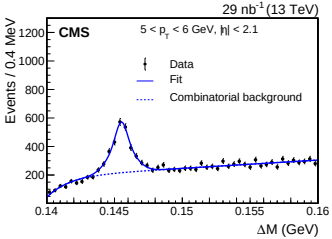


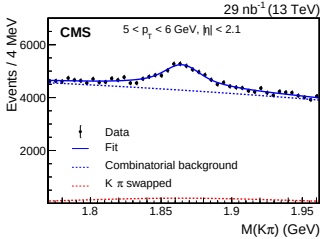


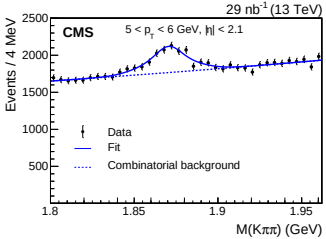
Prompt open-charm production cross sections (1/2)

JHEP 11 (2021) 225

- Cross-section measurement of open-charm mesons is an important test of QCD
- **CMS** studied the cross sections for the prompt production of D^{*+} , D^0 , and D^+ mesons using 29 nb^{-1} of pp collisions at 13 TeV collected in year 2016 (unbiased trigger with high prescale)
  - $pp \to D^{*+}X \to D^0\pi_s^+X \to K^-\pi^+\pi_s^+X$
  - $pp \to D^0X \to K^-\pi^+X$
  - $pp \to D^+X \to K^-\pi^+\pi^+X$
- π_s^+ "slow" pion has significantly lower momentum than K
- The mass distributions were fitted in bins of p_T and rapidity for $\Delta M = M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$, $M(K\pi)$ and $M(K\pi\pi)$







Prompt open-charm production cross sections (2/2)

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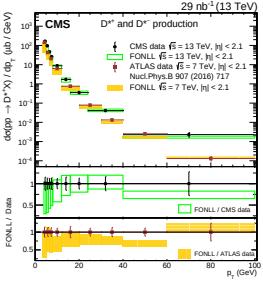
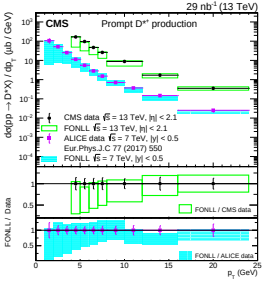
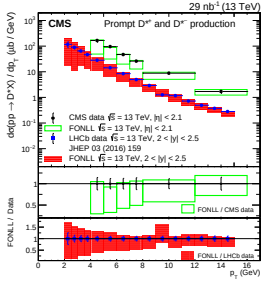
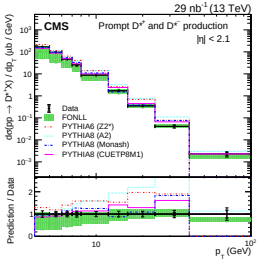
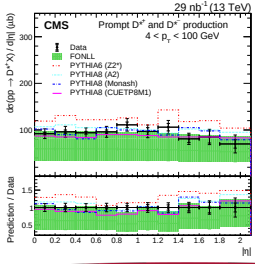
- Measured production cross-sections were compared with theoretical predictions using the FONLL[1] and various Pythia models[2]
- The agreement with the different predictions is fair in the wide kinematic range analyzed
- The cross-sections were also compared with the other measurements from ATLAS, ALICE and LHCb and also with *PbPb* data measured by CMS











[1] M. Cacciari et.al. JHEP 05 (1998) 007 and Eur. Phys. J. C 75 (2015) 610

[2] T. Sjostrand et.al. JHEP 05 (2006) 026 and Comput. Phys. Commun. 191 (2015) 159

Summary

- The non-leptonic decays contain a broad spectrum of interesting physics that can be studied in the various channels
- The main goal is to understand the production dynamics of the hadronic decays and precisely describe their parameters
- With a large sample of LHC data at $\sqrt{s} = 13\,\text{TeV}$ the rare processes are experimentally accessible
- New results help to improve the theoretical models

LYON

Stay tuned for new results!