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Recent results on heavy flavor production and spectroscopy with LHCb

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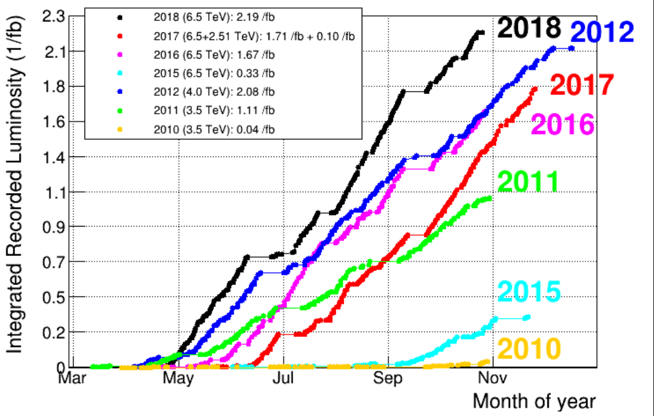
Outline

- LHCb is an extraordinary gym for "standard" and "exotic" spectroscopy
- High cross section allows high yields of heavy hadrons
  - 10^{11} $b\bar{b}$/year
  - 20x for $c\bar{c}$/year



- Heavy flavor production and spectroscopy is a broad topic
- I will cover only a selection of very recent results by LHCb
- Nice results are now appearing using full Run1+Run2 dataset!

Shopping list

- **Observation of a narrow pentaquark state, $Pc(4312)^+$, and of two-peak structure of the $Pc(4450)^+$**
  PAPER-2019-014 arXiv:1904.03947, now accepted by PRL
- **Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state**
  PAPER-2019-005 arXiv:1903.12240
- **Observation of an excited Bc^+ state**
  PAPER-2019-007 arXiv:1904.00081
- **A search for $\Xi cc^{++} \rightarrow D^+pK^-\pi$ decays**
  PAPER-2019-011 arXiv:1905.02421 New

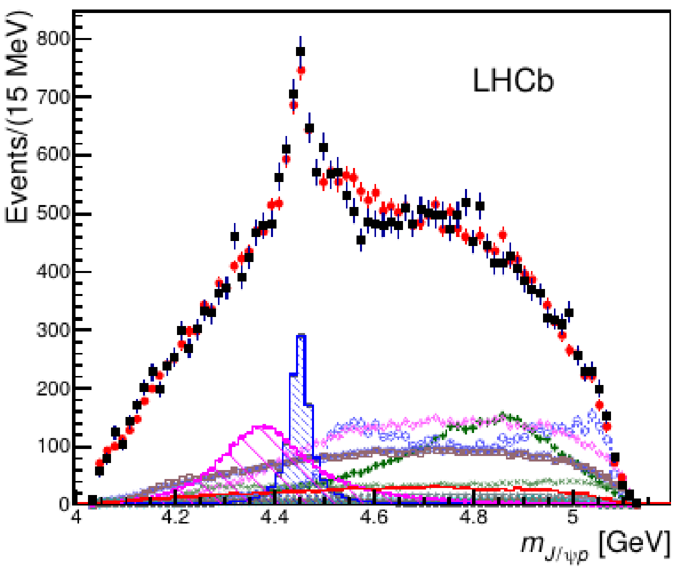
Experimental history of pentaquarks

- History so far
  - In 2015 LHCb reported the observation of 2 pentaquark candidates [PRL117(2016)082002]
  - Analysis performed with Run1 data 3fb^{-1} using $\Lambda_b \rightarrow J/\Psi\ p\ K$ final state
  - 26k signal candidates with 5.4% background
  - Dalitz plot analysis (6D amplitude fit) confirmed 2 new states
  - Followed by a model independent analysis to exclude reflections from Λ^* resonances

- Two exotic states with opposite parities

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

[PRL 115 (2015) 072001, PRL 117 (2016) 082002]



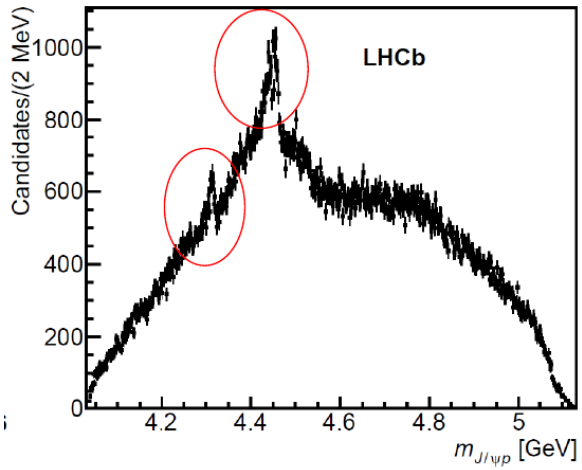
Narrow $P_c(4312)^+$ & two-peak structure

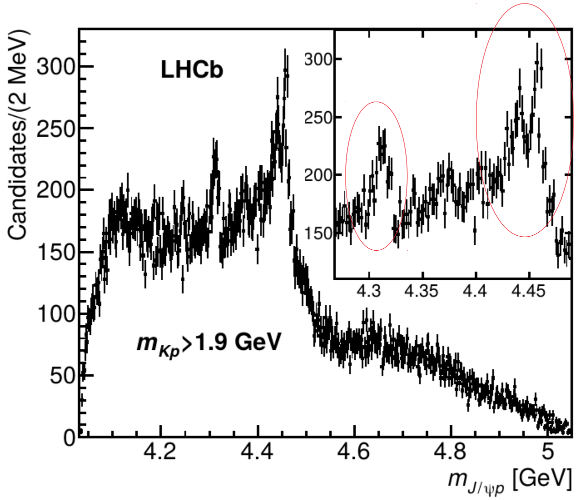
PAPER-2019-014 arXiv:1904.03947

- Update of the analysis with full Run1+Run2 dataset
- 246k signal events of nice $\Lambda_b \rightarrow J/\Psi\, p\, K$
- That's more than 9x statistics used by previous analysis
- 6D amplitude fit (2015 model) to check consistency between Run1 and Run2

- More statistics → finer binning
- Reveals more complicate structures in the $J/\Psi\, p$ system
- They were not resolvable in the Run1 analysis

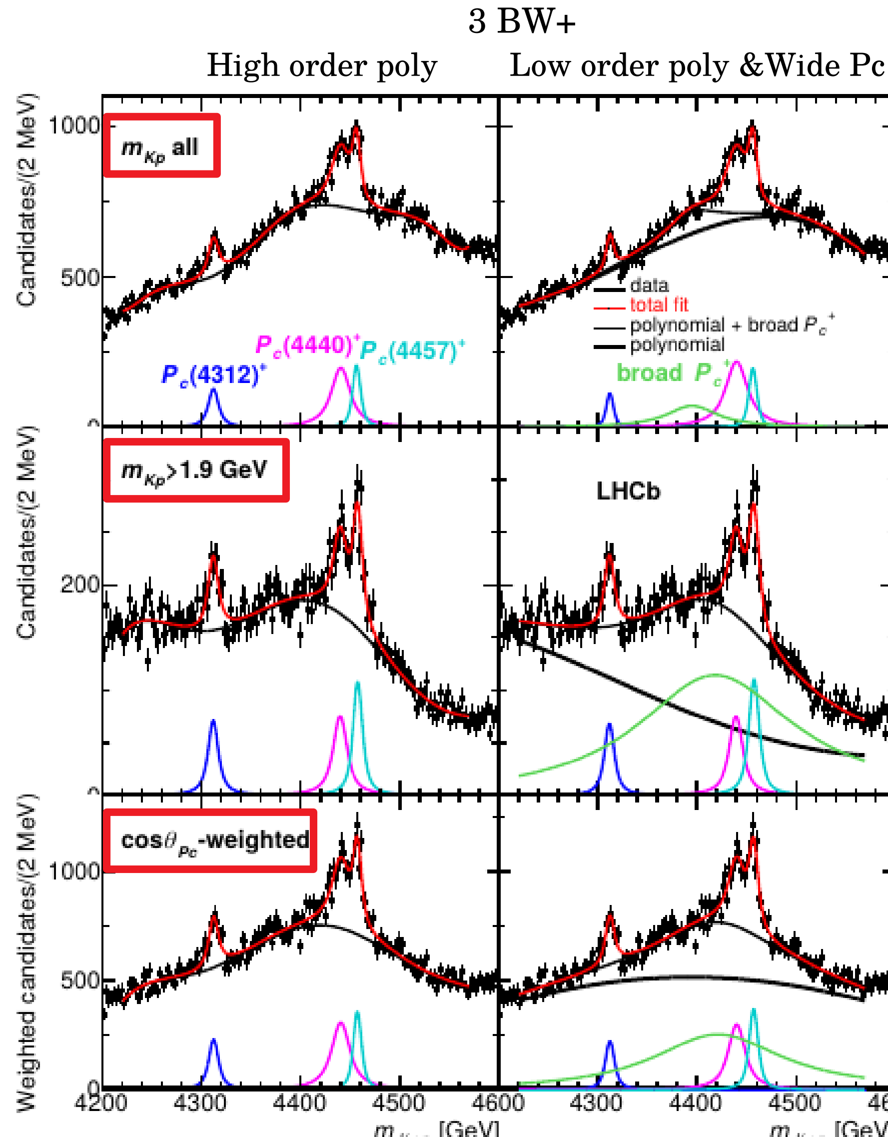
- **Summary of findings:**
  - Narrow peak at 4312 MeV with a width comparable with experimental resolution (2-3 MeV)
  - The structure at 4450 MeV now resolved in two narrow peaks at 4440 MeV and 4457 MeV, respectively
  - All statistical significances are well above 5σ





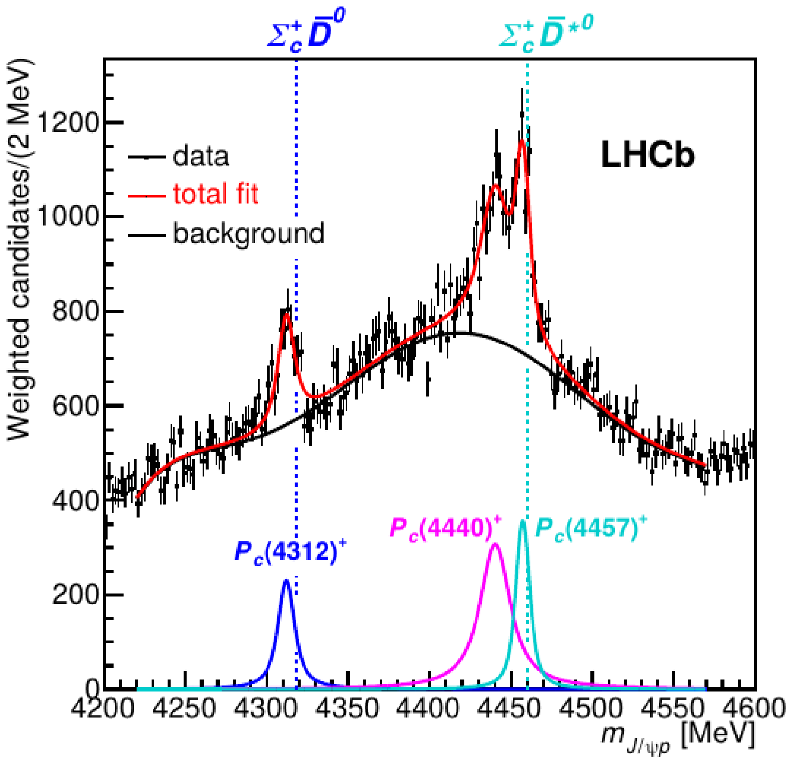
Narrow $P_c(4312)^+$ & two-peak structure

- Amplitude analysis is challenging due to
  - size of sample
  - amplitude model
  - mass resolution
- Can reduce the contribution of Λ* reflections with PT cuts on Λ*
- Other cross checks performed
- For narrow peaks perform 1D fit to mass



Narrow $P_c(4312)^+$ & two-peak structure

PAPER-2019-014 arXiv:1904.03947



A few considerations

- Wide P_c does not perturbate the fit to the lower mass states
- $P_c(4312)^+$, $P_c(4440)^+$ are not near triangle diagram thresholds
- $P_c(4457)^+$ close to threshold
- Data are described better by BW than triangle-diagram terms
- Narrow widths and masses close to thresholds points toward baryon-meson bound states interpretation

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

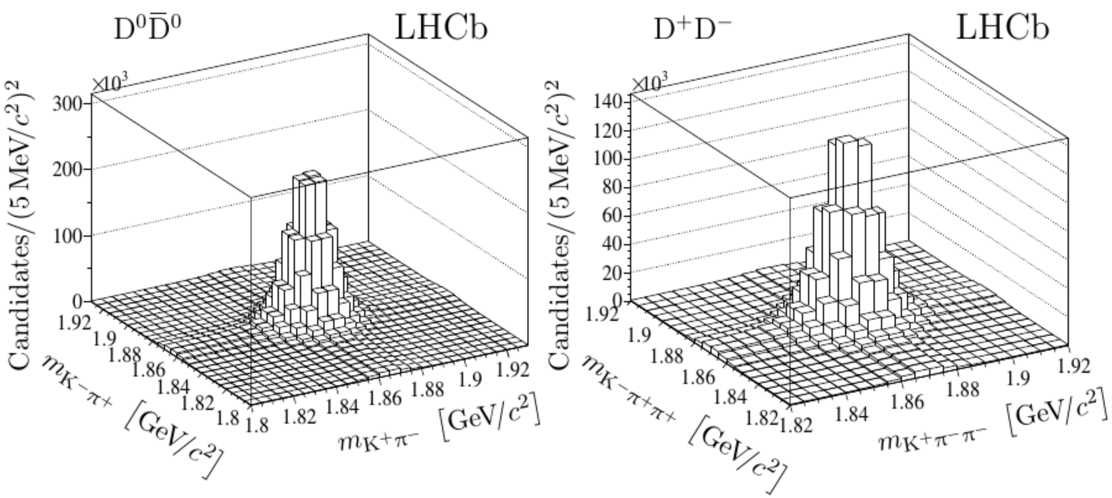
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

New charmonium state in $D\bar{D}$

- This is the first LHCb analysis using Run1+Run2 data: $9fb^{-1}$
- Combined analysis of prompt D^+D^- and $D^0\bar{D}^0$ combinations
- Scan wide region of Q value above threshold

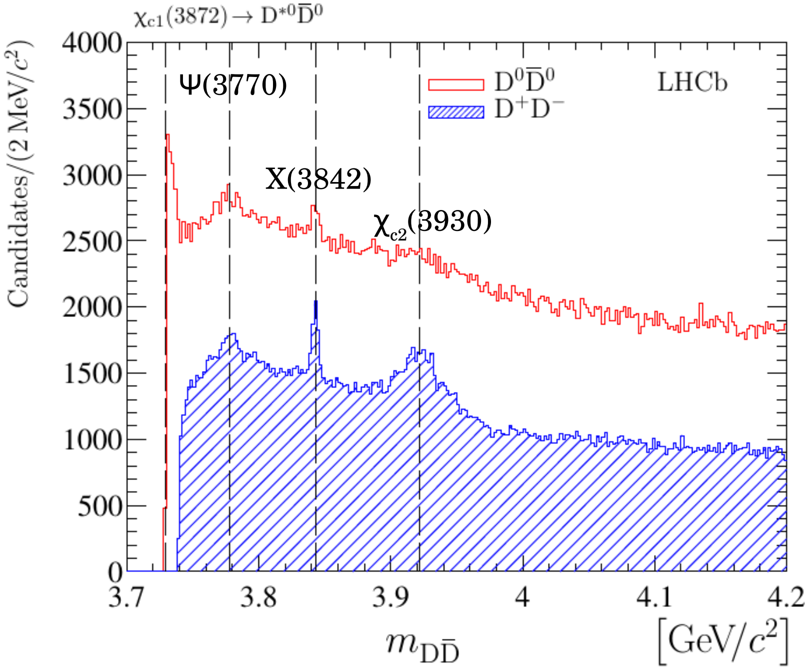
PAPER-2019-005 arXiv:1903.12240

- **Analysis strategy**
  - Reduce combinatoric background exploiting D lifetime
  - Tight ±20 MeV mass cuts
  - D mass constrained to known values
  - Fits performed in different mass regions for better paramerisation of background components
  - Below: nice correlations of D mass distributions



New charmonium state in $D\bar{D}$

PAPER-2019-005 arXiv:1903.12240



- Narrow charmonium state **X(3842)** clearly visible in both channels
- Interpretation as the unobserved $\Psi_3(1^3D_3)$ with $J^{PC} = 3^{--}$ $\quad n\,^{2s+1}\ell_J \quad J^{PC}$
- Properties:

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}$$

- First observations of prompt hadroproduction of Ψ(3770) and $\chi_{c2}(3930)$

New charmonium state in $D\bar{D}$

PAPER-2019-005 arXiv:1903.12240

	$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis	$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

	$m_{\psi(3770)}$ [MeV/c^2]
Shamov and Todyshev	3779.8 ± 0.6
PDG average	3778.1 ± 1.2
PDG fit	3773.13 ± 0.35
This analysis	$3778.1 \pm 0.7 \pm 0.6$

- The mass of $\chi_{c2}(3930)$ is 2σ lower than current world average
- The width of $\chi_{c2}(3930)$ is 2σ higher than current world average
- Mass value is in the middle between mass of this state and for the X(3915)
- Question: are they two distinct $c\bar{c}$ states or only one? [PRL115(2015)0220001]

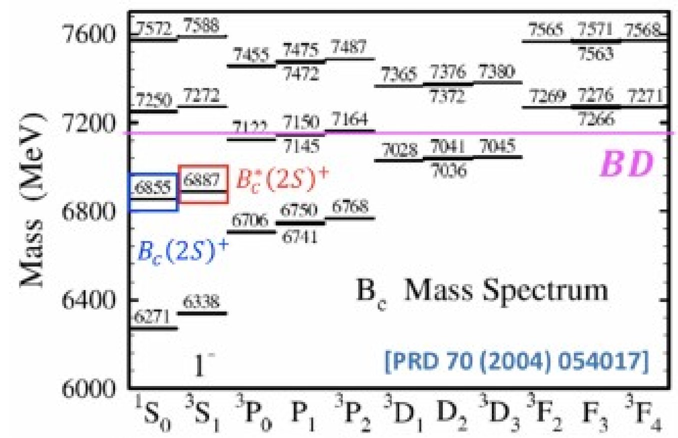
Observation of an excited B_c^+ state

- Bc system is extremely interesting
- Composed by 2 heavy quarks
- Unique feature (until the discovery of the Ξ_{cc})

- Ground state discovered by CDF in 1998
- Predictions on a very rich spectrum of excitations have been published
- Final states below BD threshold can undergo:
    - "radiative"
    - "2pion" transitions

- But… experimental challenges due to
    - low production cross-section
    - reconstruction of photon (if present)

PAPER-2019-007 arXiv:1904.00081



State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P_1'+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8

*. Gouz, Phys.Atom.Nucl.67(2004) 1559
† Godfrey, PRD 70 (2004) 054017

Observation of an excited B_c^+ state

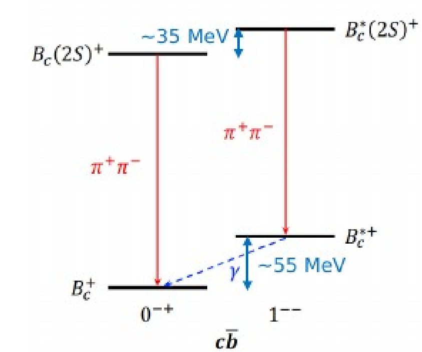
PAPER-2019-007 arXiv:1904.00081

- Look for ππ transitions
- Main decay modes:

$$B_c(2S) \to B_c\pi^+\pi^-$$
$$B_c^*(2S) \to B_c^*(\to B_c\gamma)\pi^+\pi^-$$

- Low energy photon (not reconstructed)
- Look at $B_c\pi\pi$ spectrum

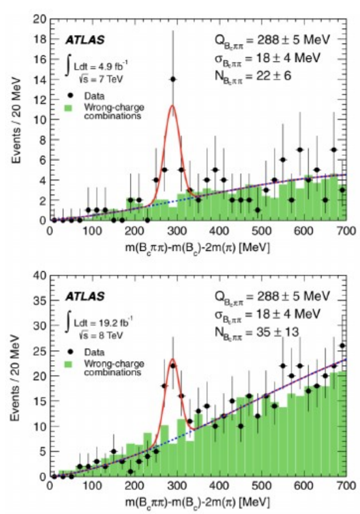
$$M(B_c^+(2S))_{\rm rec} = M(B_c^+(2S)) - M(B_c^{*+}) - M(B_c^+)$$



When considering ΔM, expect $B_c^*(2S)$ to give peak lower than $B_c(2S)$ by 10-55 MeV

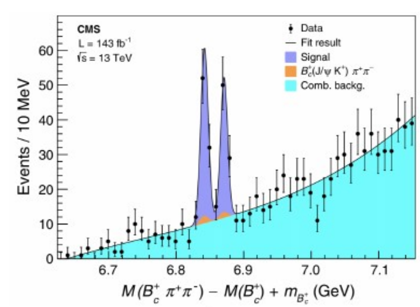
- 2014: Observed by ATLAS with Run1 data
- No discrimination between $B_c^+(2S)$ and $B_c^{+*}(2S)$
- Two peaks unresolved

PRL 113 (2014) 12004



- 2019: Observed by CMS
- Uses full Run2 data
- Two peaks well resolved

[arXiv:1902.00571, submitted to PRL]

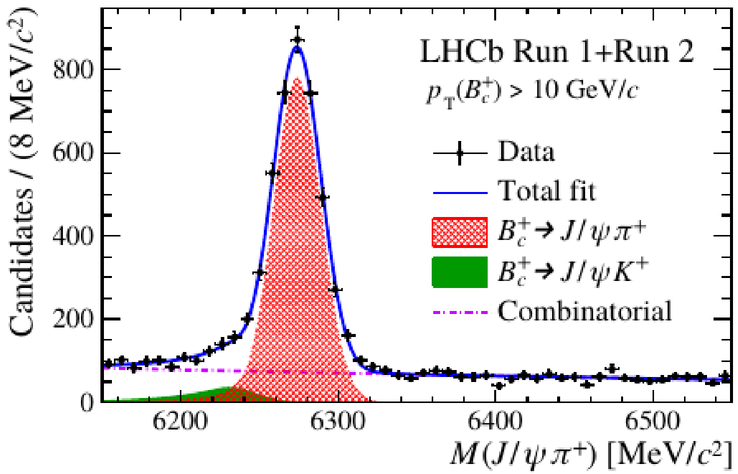


$$N(B_c^*(2S)^+) = 67 \pm 10$$
$$N(B_c(2S)^+) = 51 \pm 10$$

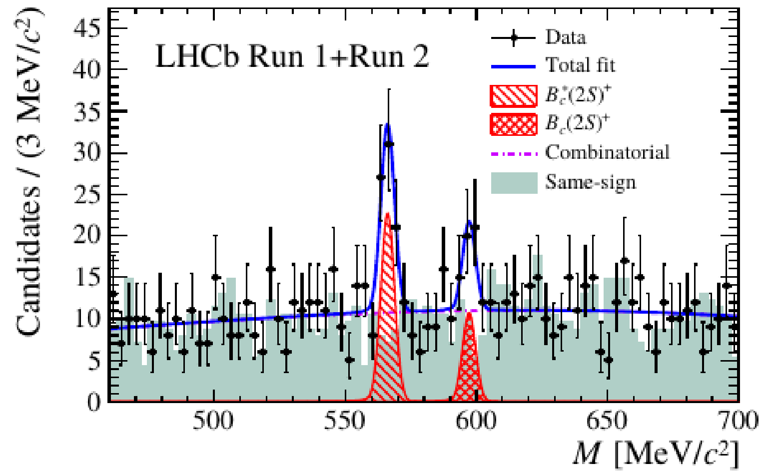
Observation of an excited B_c^+ state

PAPER-2019-007 arXiv:1904.00081

- Run1 + Run2 data
- Requirement on PT(B_c) > 10 GeV and PT(π) > 300 MeV
- $B_c^*(2S)^+$ observed with significance > 5σ
- Hint for $B_c(2S)^+$ with global (local) significance of 2.2 (3.2)σ



$$N(B_c) = 3785 \pm 73$$



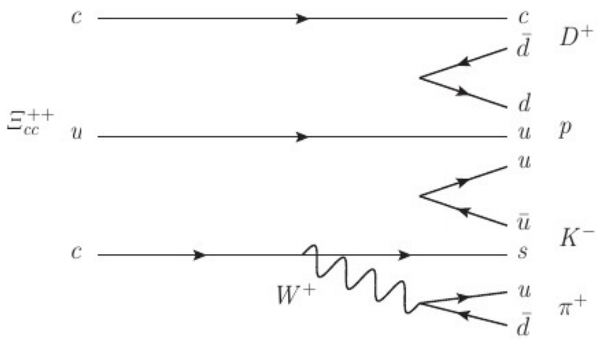
$$N(B_c^*(2S)^+) = 51 \pm 10$$
$$N(B_c(2S)^+) = 24 \pm 9$$

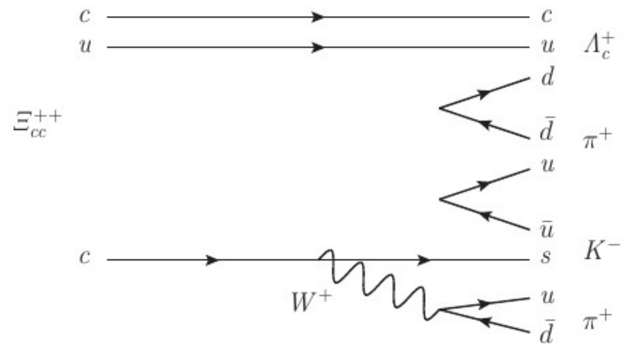
$$M(B_c^*(2S)^+)_{\rm rec} = 6841.2 \pm 0.6(stat) \pm 0.1(syst) \pm 0.8(B_c^+)\ \text{MeV}$$
$$M(B_c(2S)^+) = 6872.1 \pm 1.3(stat) \pm 0.1(syst) \pm 0.8(B_c^+)\ \text{MeV}$$
$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} = 31.0 \pm 1.4(stat)\ \text{MeV}$$

A search for $\Xi_{cc}^{++} \to D^+pK^-\pi$ decay

New

PAPER-2019-011 arXiv:1905.02421





- First observation of double charmed baryon triggered a lot of theoretical attention
- Ξ_{cc}^{++} was observed in $\Xi_{cc}^{++} \to \Lambda_c K^-\pi^+\pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$
- A measurement of lifetime was also performed

$$3621.24 \pm 0.65(\text{stat}) \pm 0.31 (\text{syst})\ \text{MeV}/c^2$$
$$0.256^{+0.024}_{-0.022}\ (\text{stat}) \pm 0.014\ (\text{syst})\ \text{ps}$$

LHCb collaboration, R. Aaij *et al.*, *Observation of the doubly charmed baryon Ξ_{cc}^{++}*, Phys. Rev. Lett. **119** (2017) 112001, arXiv:1707.01621.

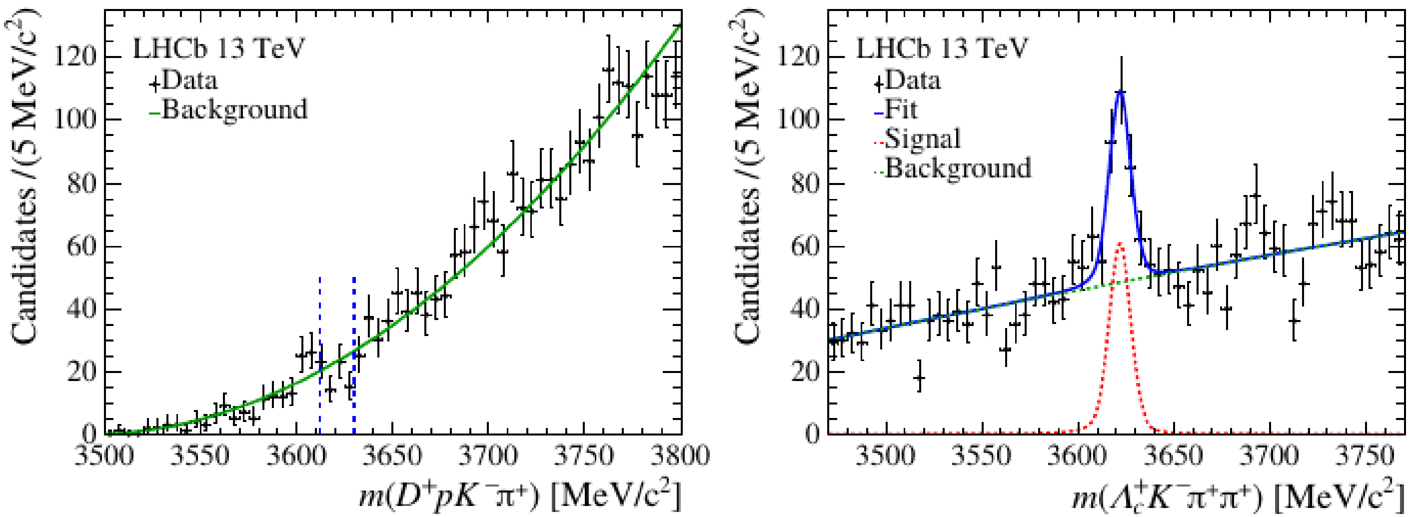
LHCb collaboration, R. Aaij *et al.*, *First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$*, Phys. Rev. Lett. **121** (2018) 162002, arXiv:1807.01919.

- The analysis relies on:
  - Sample corresponding to integrated luminosity of 1.7fb^{-1}
  - Very efficient trigger from the D
  - Multivariate selection

A search for Ξcc⁺⁺ → D⁺pK⁻π decay

New

PAPER-2019-011 arXiv:1905.02421



- No significant signal is found in the mass range 3300-3800 MeV
- Upper limit on ratio of Bfs: R<1.7 (2.1) 10^{-2} at 90%(95%)

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$

Summary

- Here, I presented only a short list of the latest results from LHCb
- The first analyses using the full Run1+Run2 dataset are now appearing
- Expect many updates in the future
- Many Dalitz analyses become feasible

- **Upgrade has now started → expect to collect more luminosity from 2021!**
- **You can follow our progress on our page (weekly updates and videos)!**

Stay Tuned!