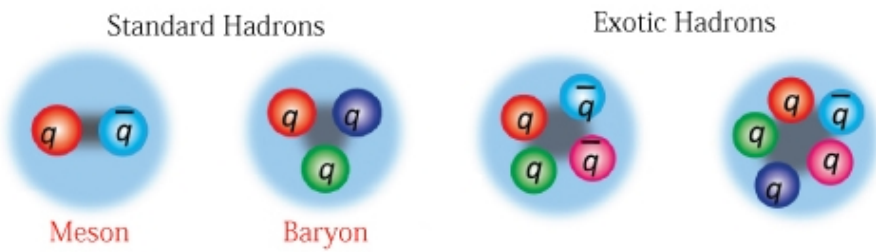
# Heavy flavour spectroscopy at the LHC

**Liupan An**
On behalf of the LHCb, CMS and ATLAS collaborations
Sezione INFN di Firenze

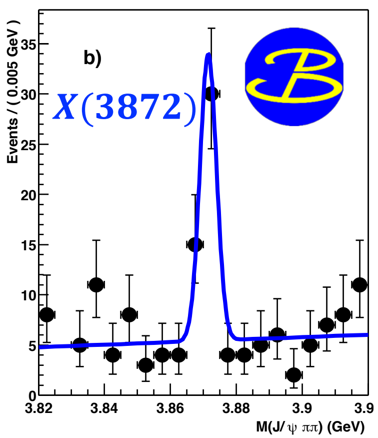
@ La Thuile 2019, Mar 12th 2019

# Introduction

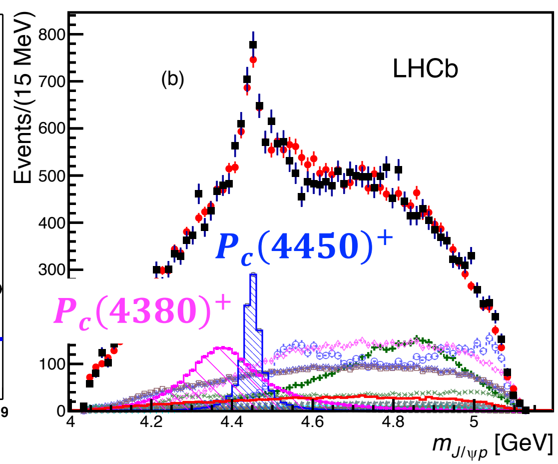
- Quark model proposed by M. Gell-mann and G. Zweig in 1964



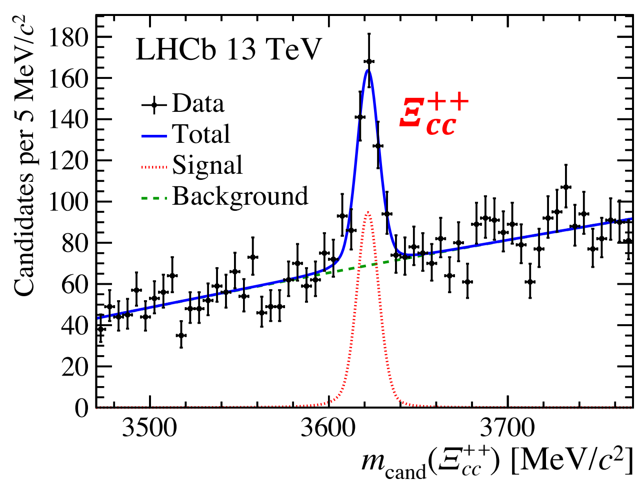

- Heavy spectroscopy provides primary tests and inputs to QCD models
- Striking news keep emerging in recent years, e.g.
  - ✓ $X(3872)$
  - ✓ Pentaquarks
  - ✓ $\Xi_{cc}^{++}$
  - ✓ …




[PRL 91 (2003) 262001]



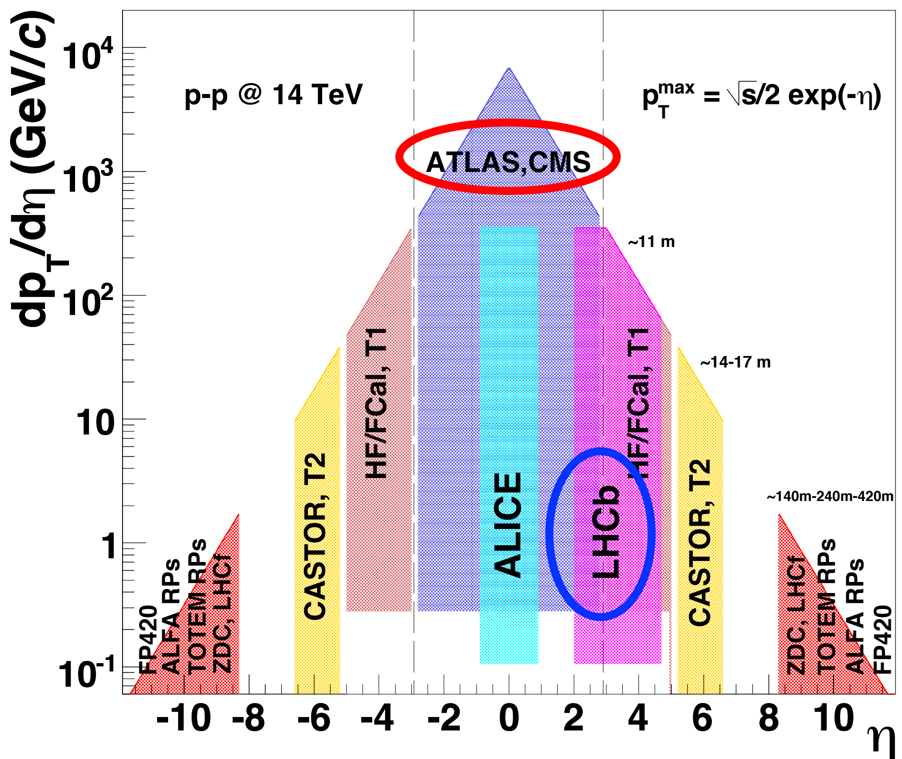

[PRL 115 (2015) 072001]




[PRL 119 (2017) 112001]

# LHCb, CMS and ATLAS experiments

- Major LHC detectors complementary to each other in spectroscopy
  - ✓CMS and ATLAS cover high $p_{\mathrm{T}}$ and low $y$ region
  - ✓LHCb covers low $p_{\mathrm{T}}$ and higher $y$ region:
    excellent **vertexing** and **particle identification** capabilities
    ⇒ dedicated heavy flavor experiment!




[arXiv: 0708.0551]

# Incomplete list of recent results

- Mesons
  - ✓Observation of new charmonium in near threshold $D\overline{D}$ spectroscopy [LHCb-PAPER-2019-005] (in preparation)
  - ✓Studies of $B_{s2}^{*}(5840)^0$ and $B_{s1}(5830)^0$ mesons [EPJC 78 (2018) 939]
  - ✓Observation of $B_{(s)}^0 \to J/\psi p\bar{p}$ and mass measurements of $B_{(s)}^0$ [arxiv: 1902.05588]
  - ✓Observation of excited $B_c^+$ states [arxiv: 1902.00571] [LHCb-PAPER-2019-007] (in preparation)
  - ✓Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ [PRL 121 (2018) 092002]
- Baryons
  - ✓Lifetime measurement of $\Omega_c^0$ [PRL 121 (2018) 092003]
  - ✓Observation of a new $\Xi_b^-$ resonance [PRL 121 (2018) 072002]
  - ✓Observation of two resonances in $\Lambda_b^0\pi^{\pm}$ system [PRL 122 (2019) 012001]
  - ✓Mass and production measurement of $\Xi_b^-$ baryons [arxiv: 1901.07075]

*$\Xi_{cc}$ covered in ***Murdo Traill***'s talk on Wednesday

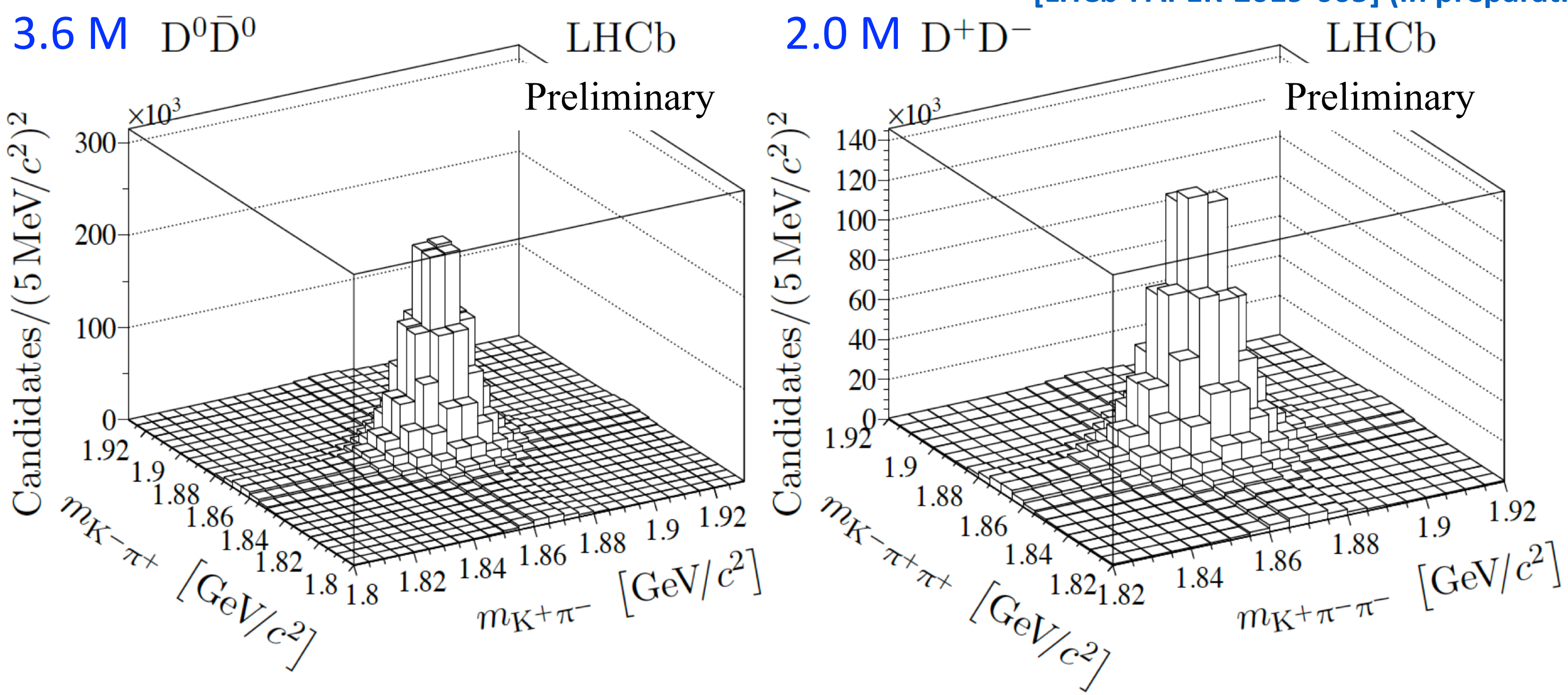
- Exotic states
  - ✓Exotic contributions to $B^0 \to J/\psi K^+\pi^-$ [arxiv: 1901.05745]
  - ✓Evidence for an $\eta_c(1S)\pi^-$ resonance [EPJC 78 (2018) 1019]
  - ✓Search for beautiful tetraquarks in $\Upsilon(1S)\mu^+\mu^-$ [JHEP 10 (2018) 086]

* This talk will focus on the most recent ones. Sorry for not being able to cover all results!

# New charmonium in $D\bar{D}$ spectroscopy (I)

- Study of conventional $c\bar{c}$ states is critical to understand the nature of exotic $c\bar{c}$ states
- **First LHCb result** with **full Run 1 + Run 2 data** corresponding to $9\ \mathrm{fb}^{-1}$
- Promptly produced $D^+D^-$ and $D^0\bar{D}^0$ candidates selected
- Exploit the long decay time of $D$ mesons to suppress background

[LHCb-PAPER-2019-005] (in preparation)

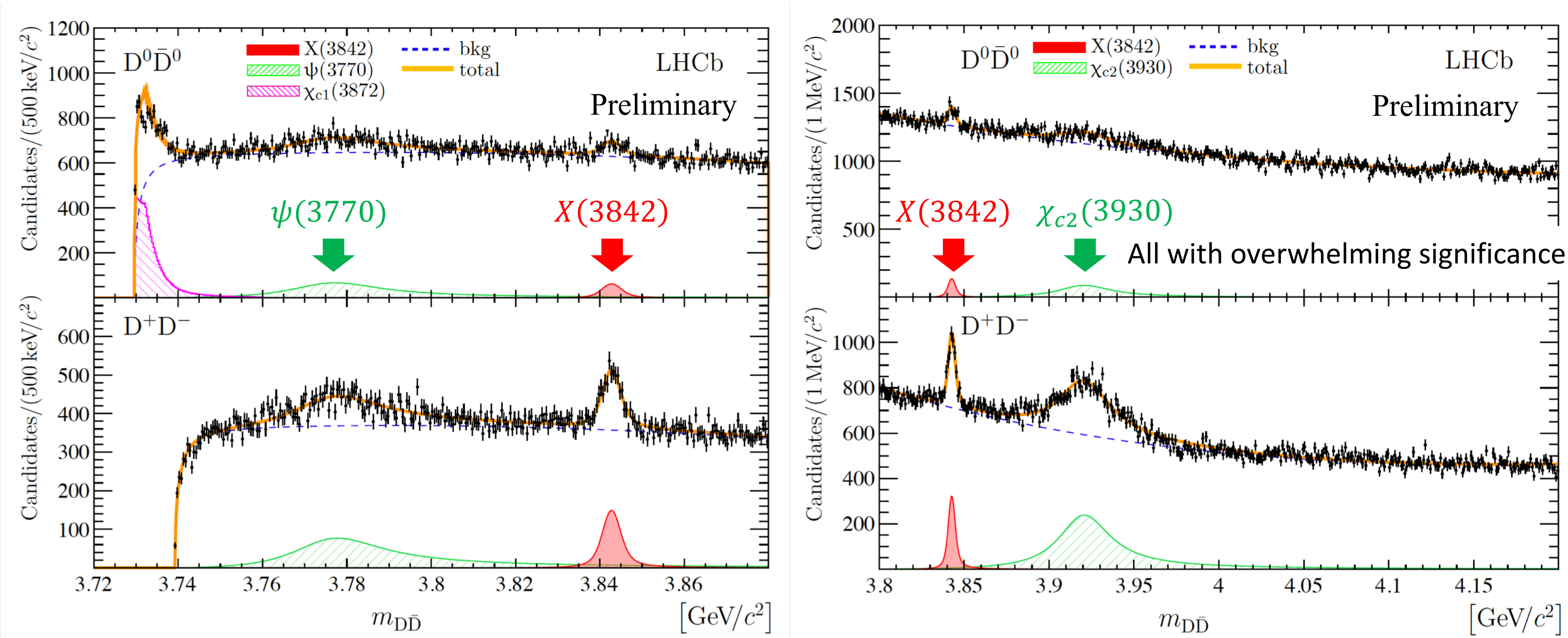



- Only $D$ mesons within $\pm 20\ \mathrm{MeV}/c^2$ of the known masses are selected

# New charmonium in $D\bar{D}$ spectroscopy (II)

[LHCb-PAPER-2019-005] (in preparation)

- Fit performed in 3 overlapping mass regions to better model background




- First observation of $X(3842)$; possible interpretation: $\psi_3(1^3D_3)$ with $J^{PC} = 3^{--}$

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

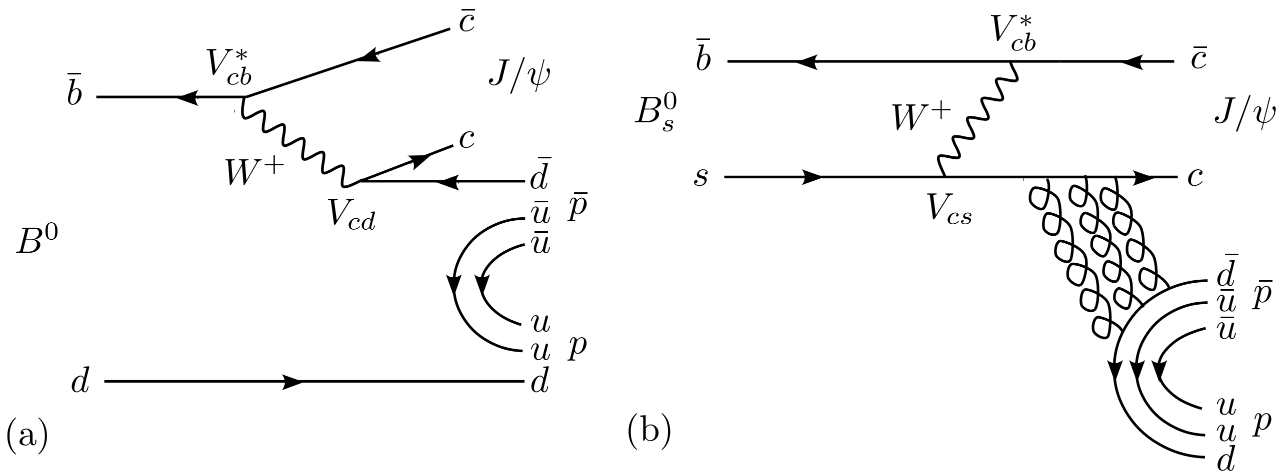
- Prompt hadroproduction of $\psi(3770)$ and $\chi_{c2}(3930)$ seen for the first time

$$\mu_{\psi(3770)} = 3778.13 \pm 0.70 \pm 0.63\ \mathrm{MeV}/c^2$$

$$\mu_{\chi_{c2}(3930)} = 3921.90 \pm 0.55 \pm 0.19\ \mathrm{MeV}/c^2,\ \Gamma_{\chi_{c2}(3930)} = 36.64 \pm 1.88 \pm 0.85\ \mathrm{MeV}/c^2$$

# $B^0_{(s)} \to J/\psi p\bar{p}$ (I)

- $B^0_{(s)} \to J/\psi p\bar{p}$ are sensitive to pentaquark in $J/\psi p(\bar{p})$ and glueball in $p\bar{p}$
- The $B^0_{(s)} \to J/\psi p\bar{p}$ decays are Cabibbo or OZI suppressed and have limited phase space

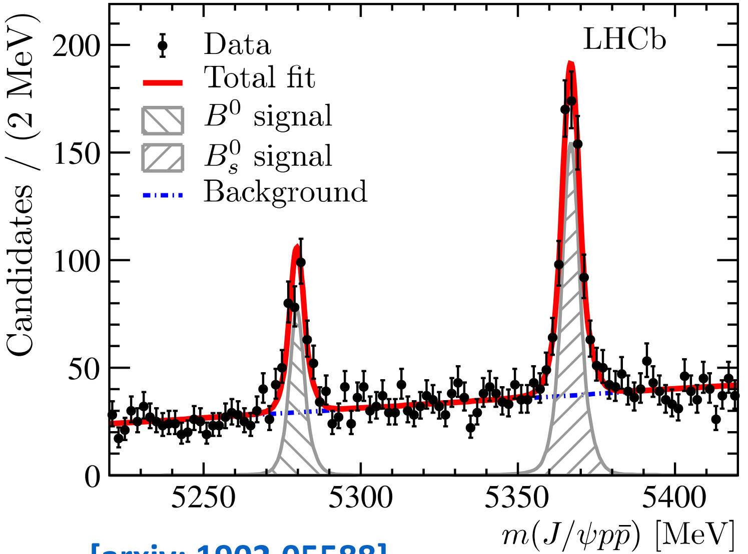



- $\mathcal{B}(B_s^0 \to J/\psi p\bar{p})$ is predicted to be $\mathcal{O}(10^{-9})$, but can be enhanced by pentaquark and glueball contributions [EPJC 75 (2015) 101]

- Searched with 2011-2016 data corresponding to 1, 2 and 2.2 $\text{fb}^{-1}$ at $\sqrt{s} = 7, 8$ and 13 TeV

# $B^0_{(s)} \to J/\psi p\bar{p}$ (II)

- Event selection relies on excellent vertexing and charged PID capabilities of LHCb
- First observation of the decays $B^0_{(s)} \to J/\psi p\bar{p}$




[arxiv: 1902.05588]

- $B^0 \to J/\psi p\bar{p}$: $256 \pm 22$
- $B^0_s \to J/\psi p\bar{p}$: $609 \pm 31$

✓ Most precise determination of
$m_{B^0} = 5279.74 \pm 0.30(\text{stat}) \pm 0.10(\text{syst})\ \text{MeV}/c^2$
$m_{B^0_s} = 5366.85 \pm 0.19(\text{stat}) \pm 0.13(\text{syst})\ \text{MeV}/c^2$

- $\mathcal{B}(B^0 \to J/\psi p\bar{p}) = \left(4.51 \pm 0.40(\text{stat}) \pm 0.44(\text{syst})\right)\times 10^{-7}$
  - ✓Consistent with theoretical prediction
- $\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = \left(3.58 \pm 0.19(\text{stat}) \pm 0.33(\text{syst})\right)\times 10^{-6}$
  - ✓Enhanced by two orders of magnitude w.r.t predictions without resonances

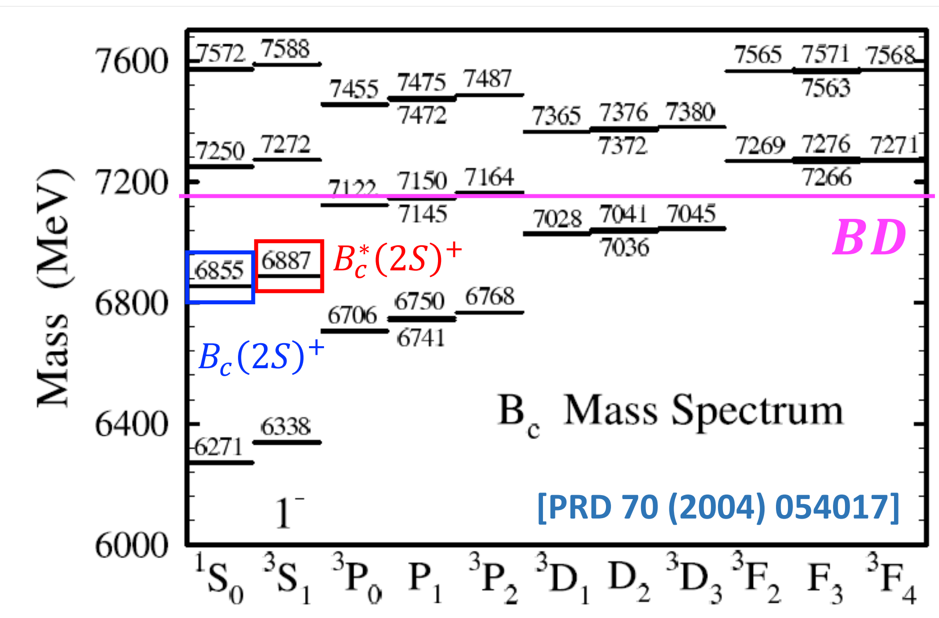
[EPJC 75 (2015) 101]

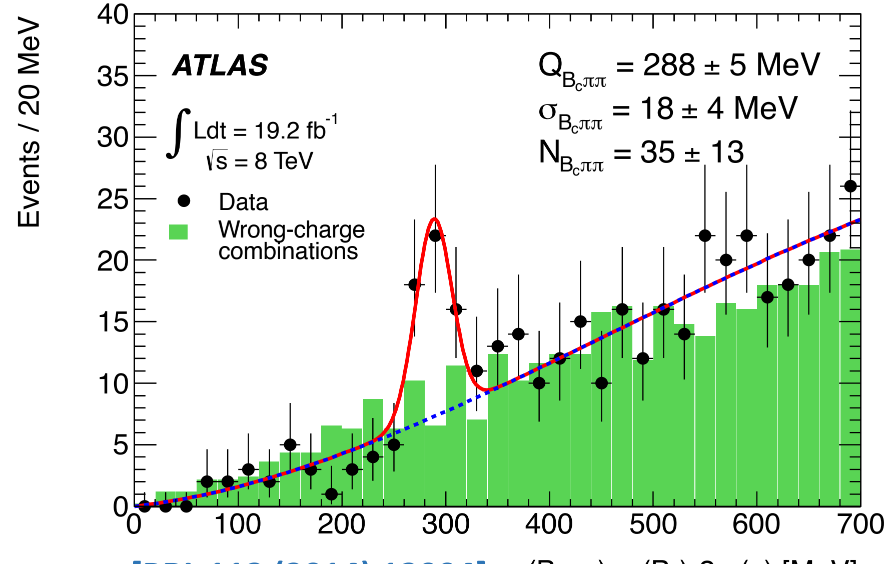
# Excited $B_c^+$ states

- $B_c$ has a rich spectroscopy
  - ✓ Can provide tests of QCD models successfully applied to quarkonium
  - ✓ Less explored due to limited statistics
  - ✓ States below $BD$ threshold can only undergo radiative or pionic transitions to the ground state $B_c^+$ which decays weakly
- In 2014, ATLAS observed a state consistent with $B_c^{(*)}(2S)^+$ in $B_c^+\pi^+\pi^-$ spectrum

$$M\left(B_c^{(*)}(2S)^+\right) = 6842 \pm 4(\text{stat}) \pm 5(\text{syst})\ \text{MeV}/c^2$$

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

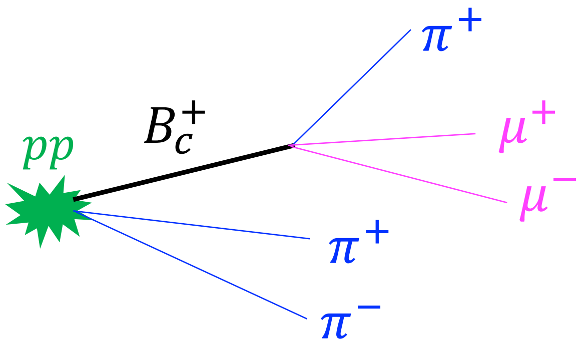


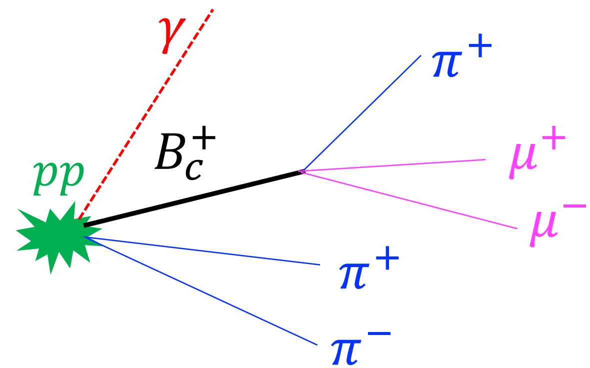

[PRL 113 (2014) 12004]

# $B_c^{(*)}(2S)^+$ in $B_c^+\pi^+\pi^-$

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




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




- With the low-energy photon not reconstructed, the $B_c^*(2S)^+$ peak remains with

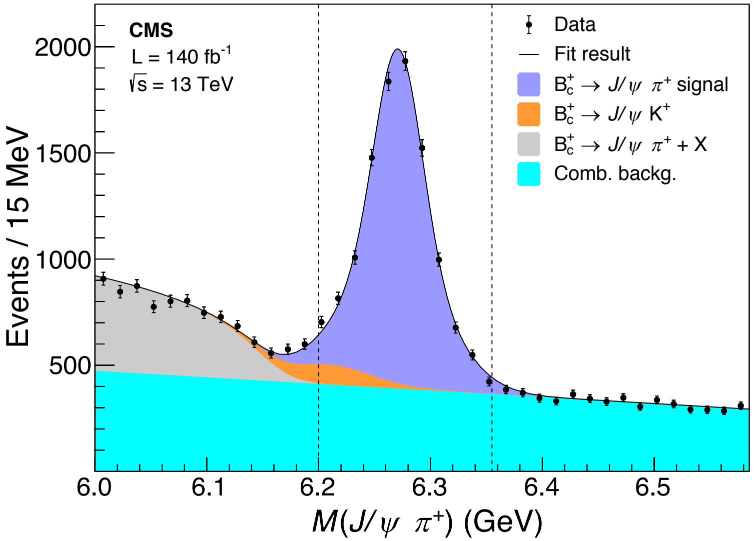
$$M(B_c^*(2S)^+)_{\rm rec} = M(B_c^*(2S)^+) - \Delta M(1S) = M(B_c^*(2S)^+) - (M(B_c^{*+}) - M(B_c^+))$$

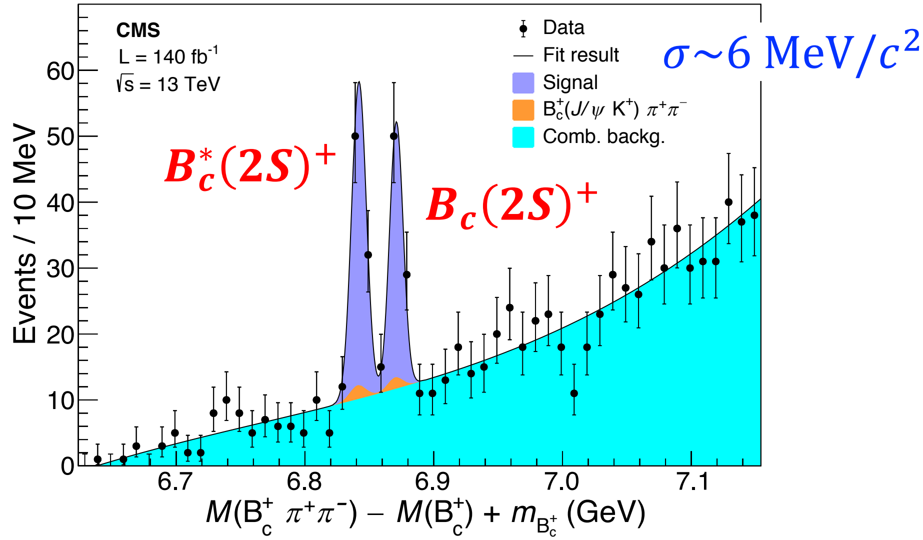
$$\begin{aligned} M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} &= \Delta M(1S) - \Delta M(2S) \\ &= \left(M(B_c^{*+}) - M(B_c^+)\right) - \left(M(B_c^*(2S)^+) - M(B_c(2S)^+)\right) \end{aligned}$$

- Most predictions give $M(B_c(2S)^+) > M(B_c^*(2S)^+)_{\rm rec}$

# $B_c^{(*)}(2S)^+$ at CMS [arxiv: 1902.00571]

- CMS performed the search with the full 140 $\text{fb}^{-1}$ Run 2 data
- Selection criterion designed based on the event topology
- Kinematic requirements: $p_\text{T}(B_c^+) > 15$ GeV/$c$, one pion $p_\text{T} > 800$ MeV/$c$, the other pion $p_\text{T} > 600$ MeV/$c$
- $B_c^*(2S)^+$ and $B_c(2S)^+$ resolved for the first time with significance $> 5\,\sigma$




$7495 \pm 225$ $B_c^+$ signals

**66 ± 10** $B_c^*(2S)^+$; **51 ± 10** $B_c(2S)^+$

$$M(B_c(2S)^+) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_\text{rec} = 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}/c^2$$

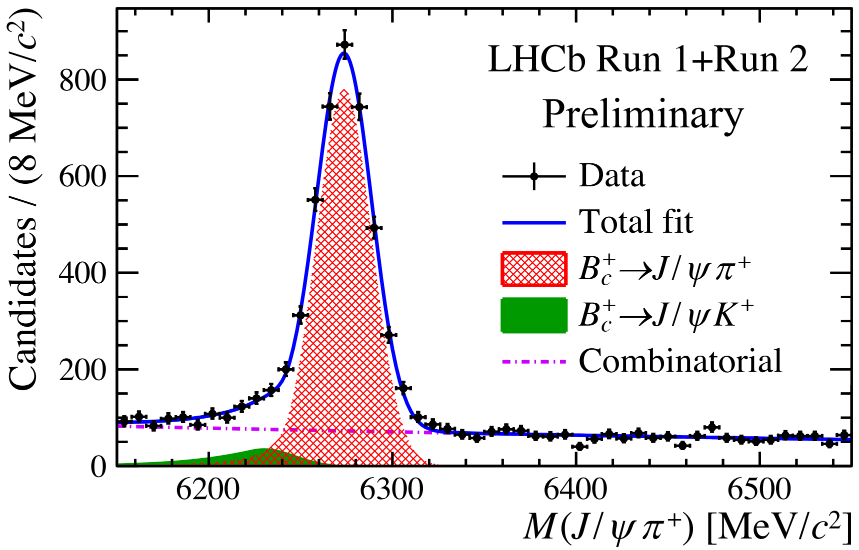
$$M(B_c^*(2S)^+) - M(B_c^{*+}) = 567.1 \pm 1.0(\text{stat})\ \text{MeV}/c^2$$

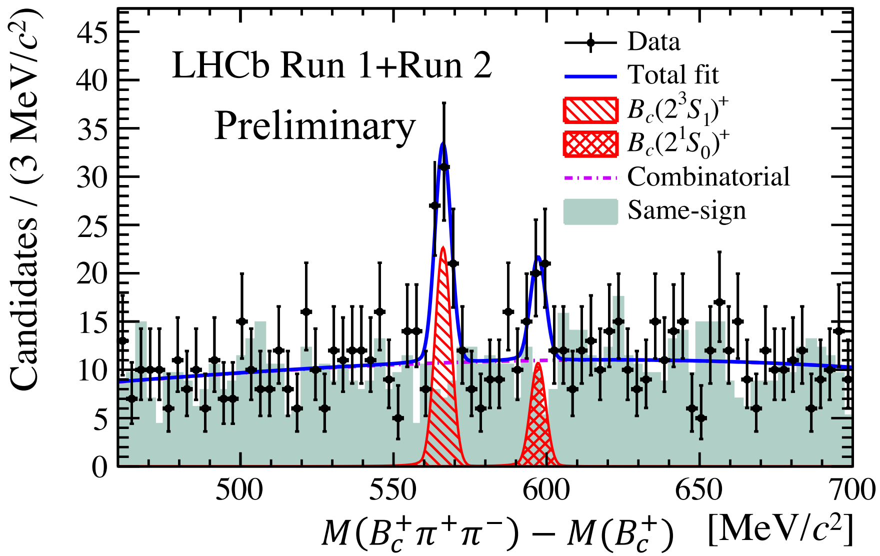
# $B_c^{(*)}(2S)^+$ at LHCb

[LHCb-PAPER-2019-007] (in preparation)

- LHCb performed the search with 8.5 $\text{fb}^{-1}$ Run 1 + Run 2 data
- Kinematic requirements: $p_\text{T}(B_c^+) > 10$ GeV/$c$, $p_\text{T}(\pi^\pm) > 300$ MeV/$c$
- $B_c^*(2S)^+$ observed with significance $> 5\ \sigma$
- Hint for $B_c(2S)^+$ with global (local) significance of 2.2 (3.2) $\sigma$

$\sigma \sim 2.5$ MeV/$c^2$




3785 $\pm$ 73 $B_c^+$ signals

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

$$M(B_c^*(2S)^+)_\text{rec} = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_\text{rec} = 31.0 \pm 1.4(\text{stat})\ \text{MeV}/c^2$$

# Mass and production of $\Xi_b^-$ (I)

- No complete measurement of $b$-hadron fragmentation functions at LHC yet

$$f_u + f_d + f_s + f_{\text{baryon}} = 1$$

$$f_{\text{baryon}} = f_{\Lambda_b^0} + f_{\Xi_b^0} + f_{\Xi_b^-} + f_{\Omega_b^-} = f_{\Lambda_b^0} \cdot \left(1 + 2\times\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} + \frac{f_{\Omega_b^-}}{f_{\Lambda_b^0}}\right)$$

- Using *SU(3)* flavor symmetry

$$\frac{\Gamma(\Xi_b^- \to J/\psi\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda)} = \frac{3}{2}$$ **[PLB 751 (2015) 127-130]**

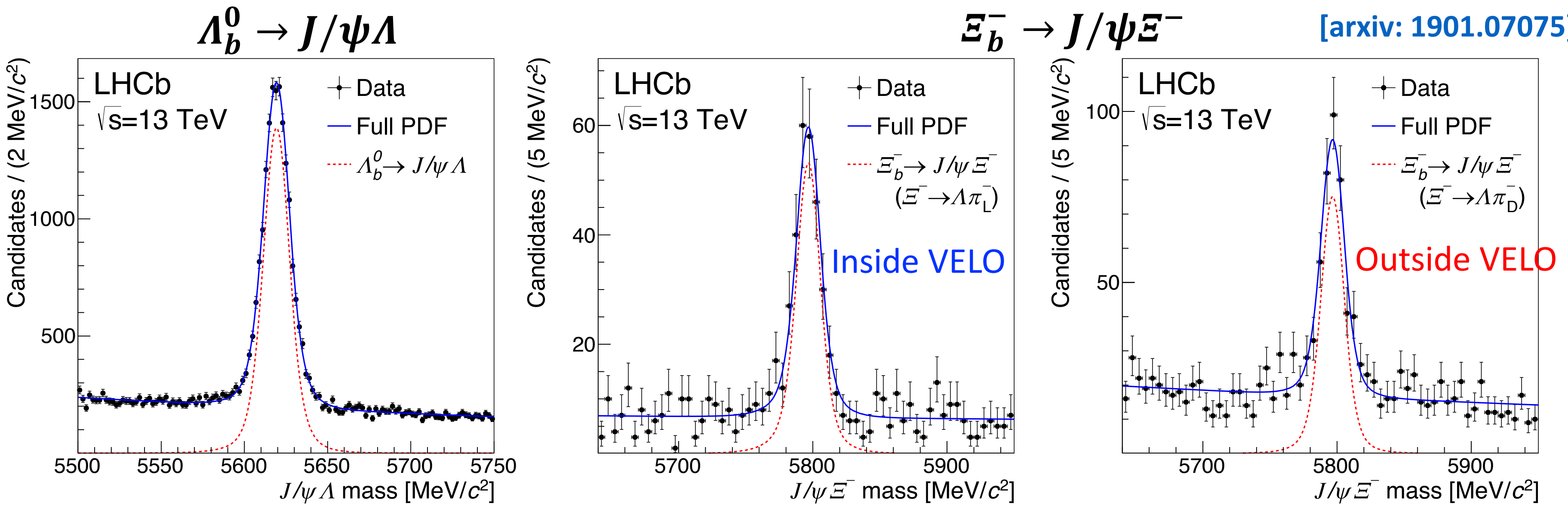
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\frac{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\frac{\Gamma(\Xi_b^- \to J/\psi\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda)}\frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}} = \frac{N(\Xi_b^- \to J/\psi\Xi^-)}{N(\Lambda_b^0 \to J/\psi\Lambda)}\frac{\varepsilon_{\Lambda_b^0}}{\varepsilon_{\Xi_b^-}}$$

Known — Measurable

- Using 2011-2016 data corresponding to 1, 2 and 1.6 $\text{fb}^{-1}$ at $\sqrt{s} = 7, 8$ and 13 TeV
- First measurement of $\Xi_b^-$ production rate in $pp$ collisions

# Mass and production of $\Xi_b^-$ (II)

- $\Xi^- \to \Lambda\pi^-$ occurs either inside or outside the vertex locator (VELO)



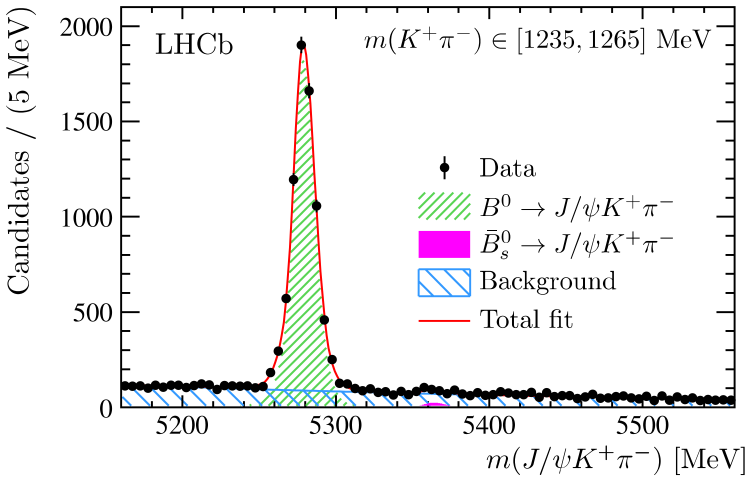

- Most precise measurement of $m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17\ \mathrm{MeV}/c^2$
- $\Xi_b^-$ production asymmetry consistent with zero
- $$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = \begin{matrix} (6.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \pm 2.0(SU(3)\ \text{breaking}))\times 10^{-2}\ @\ \sqrt{s} = 7,8\ \text{TeV} \\ (8.2 \pm 0.7(\text{stat}) \pm 0.6(\text{syst}) \pm 2.4(SU(3)\ \text{breaking}))\times 10^{-2}\ @\ \sqrt{s} = 13\ \text{TeV} \end{matrix}$$

No significant dependence on centre-of-mass energy in 7 to 13 TeV range

# Exotics in $B^0 \to J/\psi K^+\pi^-$ (I)

[PRD 90 (2014) 112009] [PRD 79 (2009) 112001]

- Exotic state $Z_c(4200)^- \to J/\psi\pi^-$ reported by Belle, but not seen by Babar
- LHCb performed angular analysis of $B^0 \to J/\psi K^+\pi^-$ using 3 fb$^{-1}$ Run 1 data




$554{,}500 \pm 800$ signals in $m(K^+\pi^-) \in [745{,}1545]$ MeV/$c^2$

[arxiv: 1901.05745]

- Signal statistics ×20 larger than Belle and ×40 larger than Babar
- Poor understanding of $K^*$ leads to large systematics in $Z_c^-$ searches

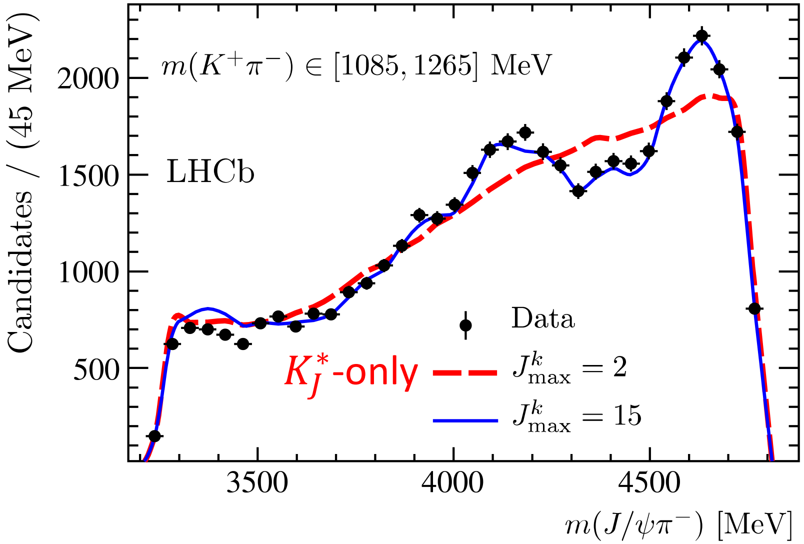
⇒a **model-independent 4D** analysis, which gives significantly better sensitivity

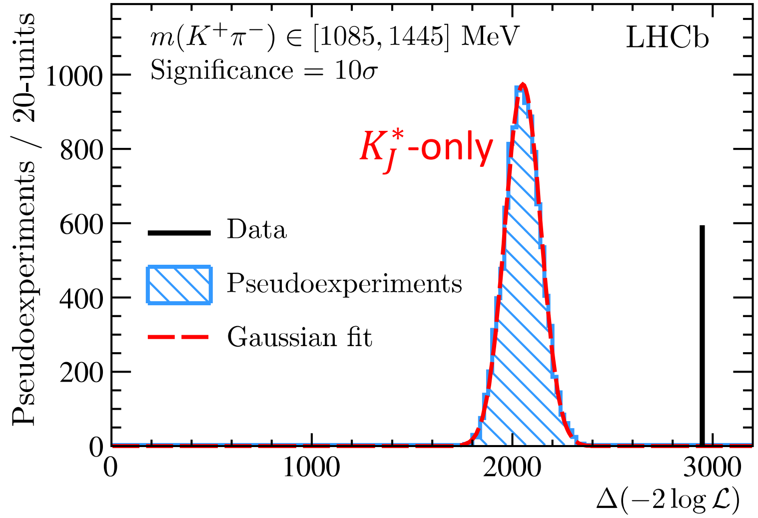
- ✓Divide the data into fine bins of $m(K^+\pi^-)$
- ✓In each bin, check if the 3D angular distribution can be described with reflections from conventional $K_J^*[K\pi]$ without exotic $Z_c^-[\psi\pi]$ component
- ✓Requiring only the knowledge of the highest spin $J_{\max}$ of $K_J^*$

# Exotics in $B^0 \to J/\psi K^+ \pi^-$ (II)

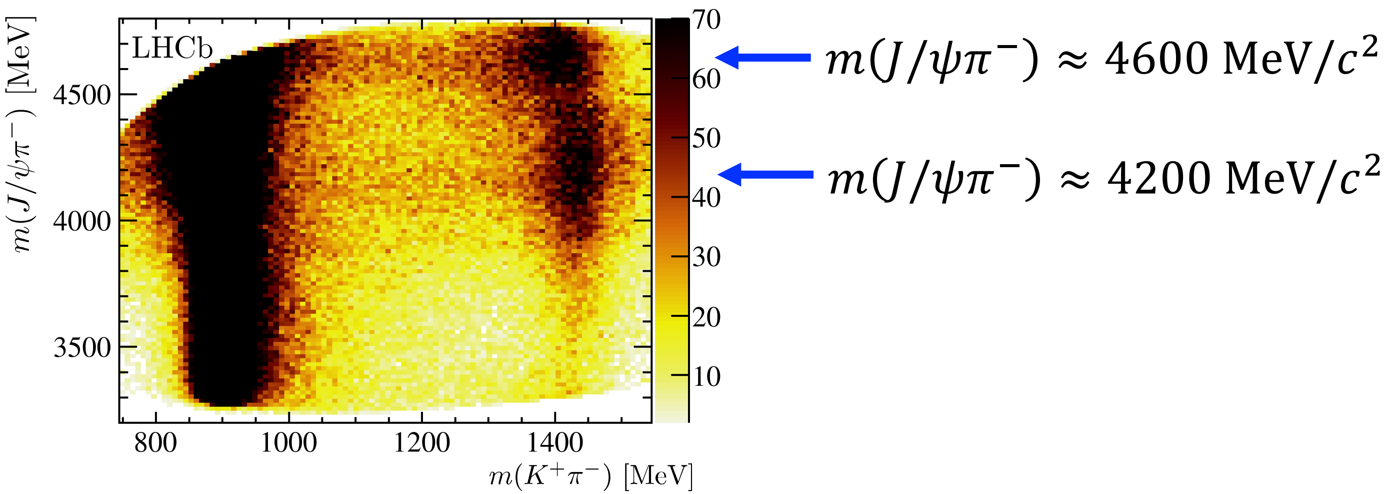
- ➢ $K_J^*$-only hypothesis rejected with significance = $10\,\sigma$

[arxiv: 1901.05745]




- ➢ Structures visible in $\left(m(J/\psi\pi^-), m(K^+\pi^-)\right)$ 2D plot



# Summary

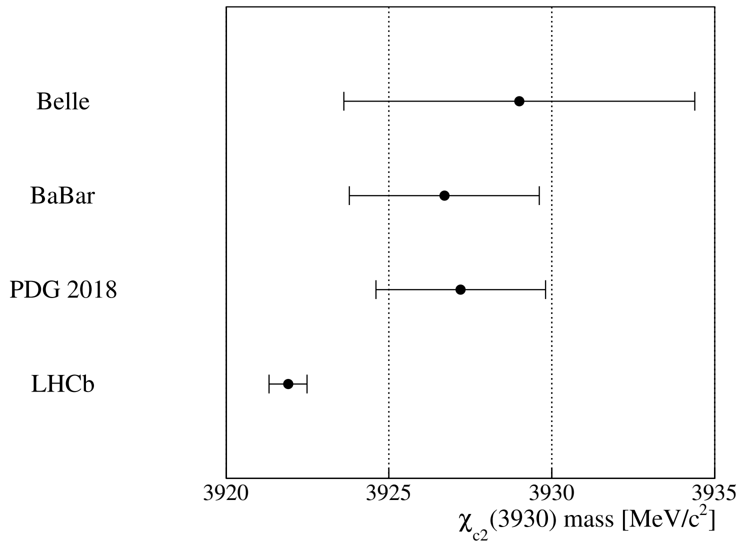
- A wide range of interesting spectroscopy results
  - ✓ Observation of new charmonium in near threshold $D\overline{D}$ spectroscopy [LHCb-PAPER-2019-005] (in preparation)
  - ✓ Observation of $B^0_{(s)} \to J/\psi p\bar{p}$ and mass measurements of $B^0_{(s)}$ [arxiv: 1902.05588]
  - ✓ Observation of excited $B_c^+$ states [arxiv: 1902.00571] [LHCb-PAPER-2019-007] (in preparation)
  - ✓ Mass and production measurement of $\Xi_b^-$ baryons [arxiv: 1901.07075]
  - ✓ Exotic contributions to $B^0 \to J/\psi K^+\pi^-$ [arxiv: 1901.05745]
  - ✓ ……

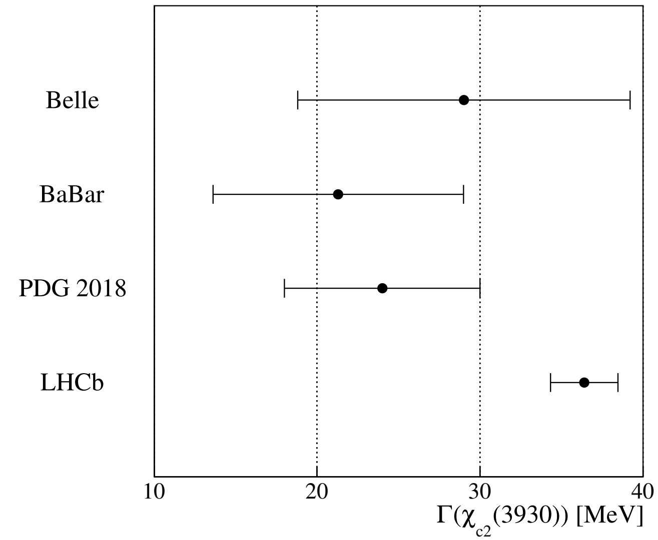
- The usage of Run 2 data opens new possibilities
- The LHCb, CMS and ATLAS experiments each shows its own strength in spectroscopy studies

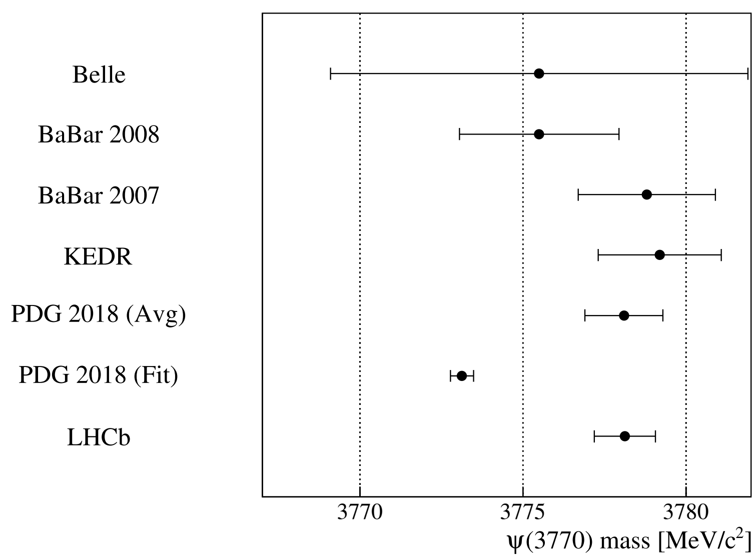
- Look forward to more exciting news!

# Back up

# Charmonium states in $D\bar{D}$ spectroscopy

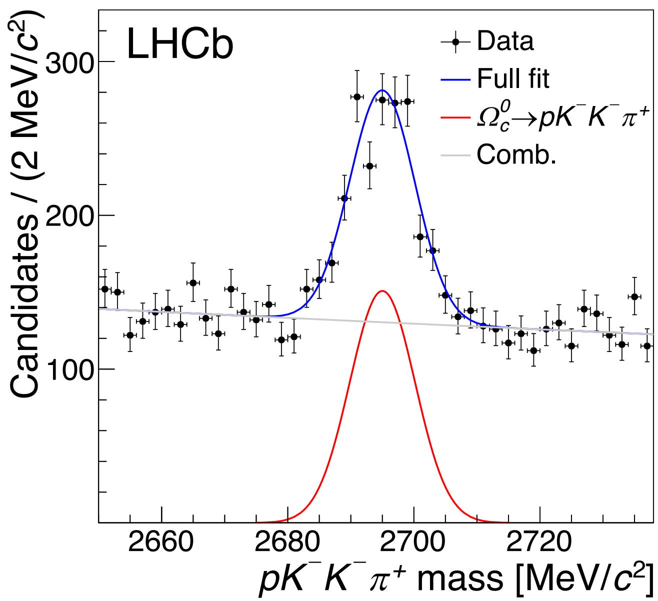


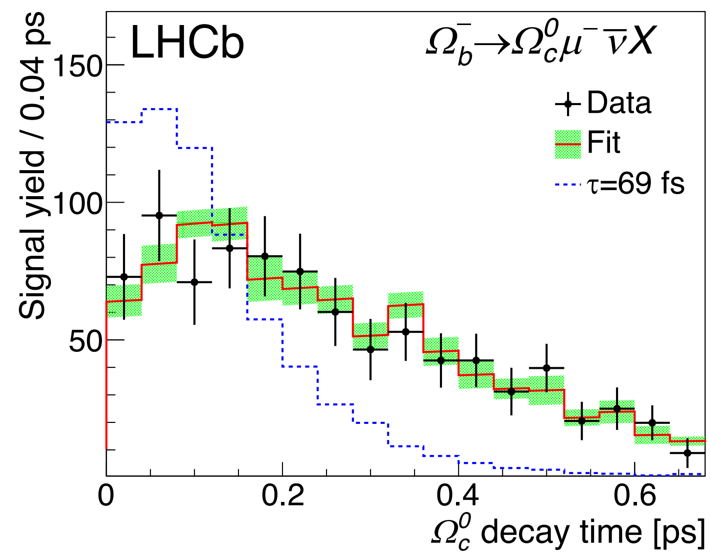



# $\Omega_c^0$ lifetime measurement [PRL 121 (2018) 092003]

- The $c$-baryon lifetime hierarchy was considered to be $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$
- Using data corresponding to 3 $fb^{-1}$ at $\sqrt{s} = 7$ and 8 TeV
- Sample of $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$ used to measure $r_{\Omega_c^0} \equiv \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$, taking $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$ as reference to reduce systematic uncertainty




- $\tau_{\Omega_c^0} = \mathbf{268 \pm 24 \pm 10 \pm 2}$ **fs**, ~4 times larger than world average $69 \pm 12$ fs
- New $c$-baryon lifetime hierarchy: $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$