Measurements of heavy-flavor production at CMS

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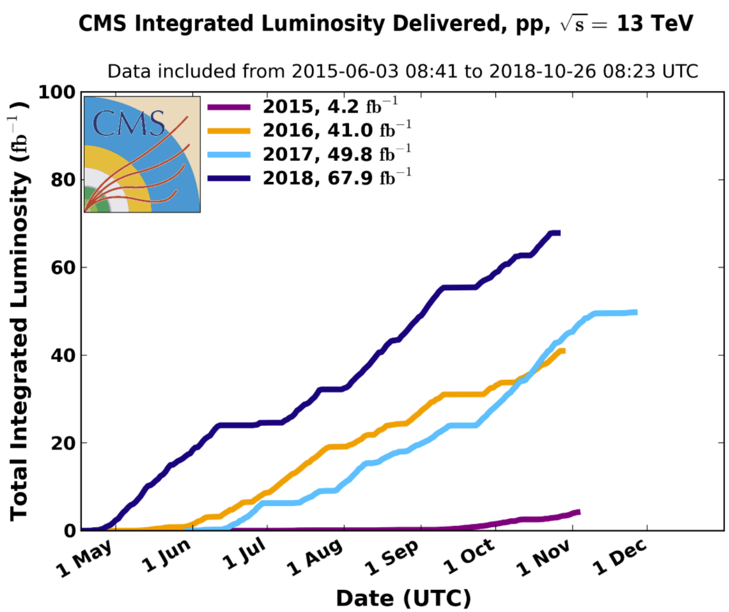
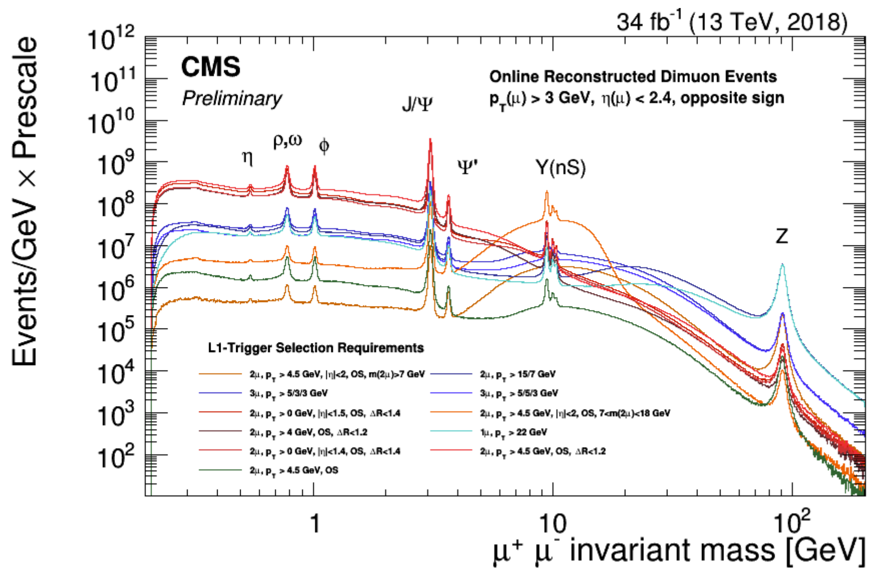
Introduction

Heavy-flavor production studies are very important to improve understanding of QCD.
These studies are becoming more feasible at CMS because of:

- Efficient and very flexible set of dimuon triggers
- Good resolution in p_T ~1% for central region tracker
- Remarkable vertexing efficiency
- Over 140 fb^{-1} of data is recorded for physics data analysis during Run 2





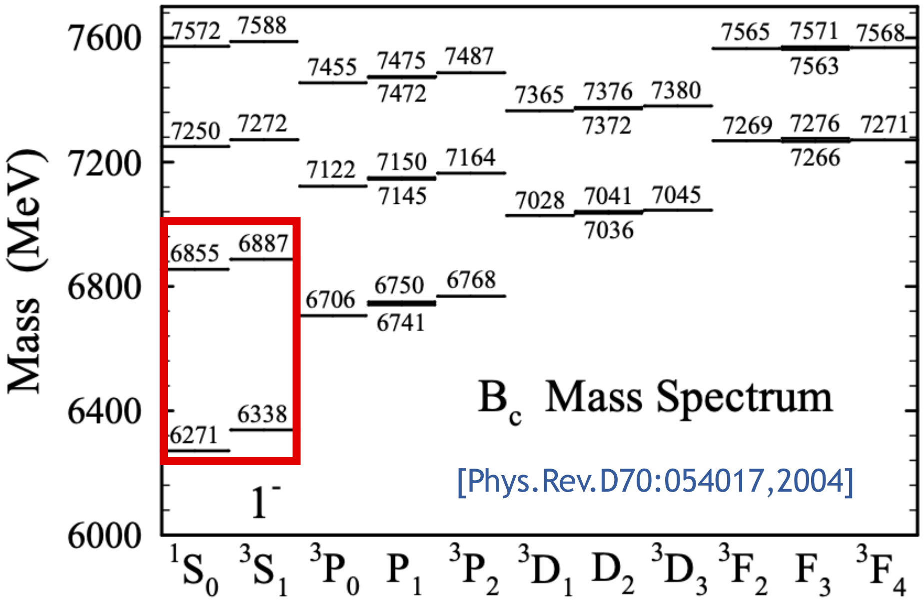
Recent results in heavy-flavor sector from CMS

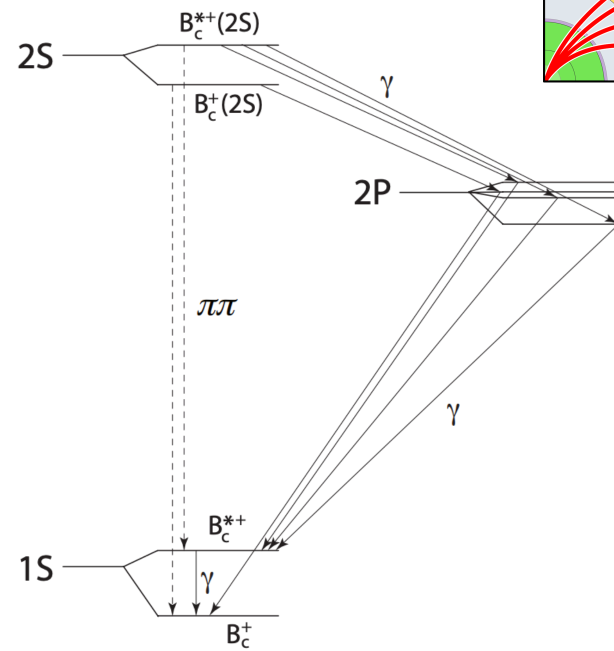
- Run 2 results:
  - Observation of two excited B_c^+ states and measurement of $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV. (PRL 122 (2019) 132001)
- Run 1 results:
  - Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV. (CMS-PAS-BPH-18-005)
  - Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions. (CMS-PAS-BPH-15-003)

Observation of two excited B_c^+ states and measurement of $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

[PRL 122 (2019) 132001]

S-wave B_c spectroscopy





Study focuses on $B_C^+(2S)$ and $B_C^*(2S)^+$ states.

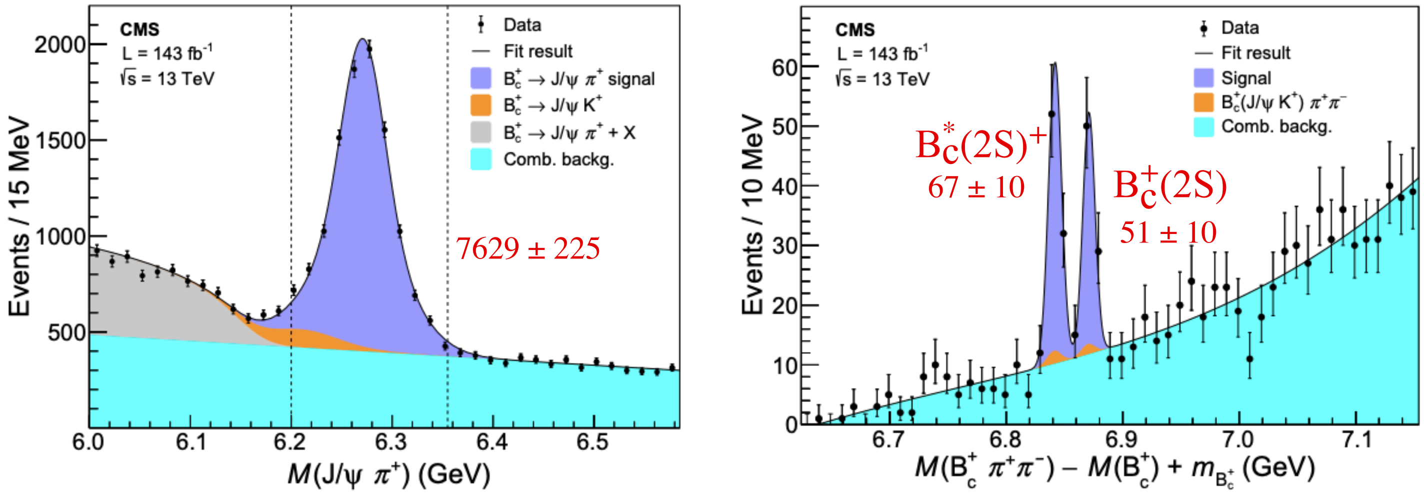
- Decay modes are: $B_C^+(2S) \to B_C^+\pi^+\pi^-$ and $B_C^{+*}(2S) \to B_C^{+*}\pi^+\pi^- \to B_C^+\pi^+\pi^-\gamma$, with a lost photon in the final state. Both $B_C^+(2S)$ and $B_C^{*+}(2S)$ can be observed in the same mass distribution.
- Theoretical input: [Phys.Rev.D70:054017,2004]

  $\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S))] \approx 20$ MeV

  $B_C^*(2S)^+$ state will be observed at lower reconstructed mass because the ground states splitting is expected to be greater than for 2S states

Observation of two excited B_c^+ states and measurement of $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

Full Run 2 dataset analysis.

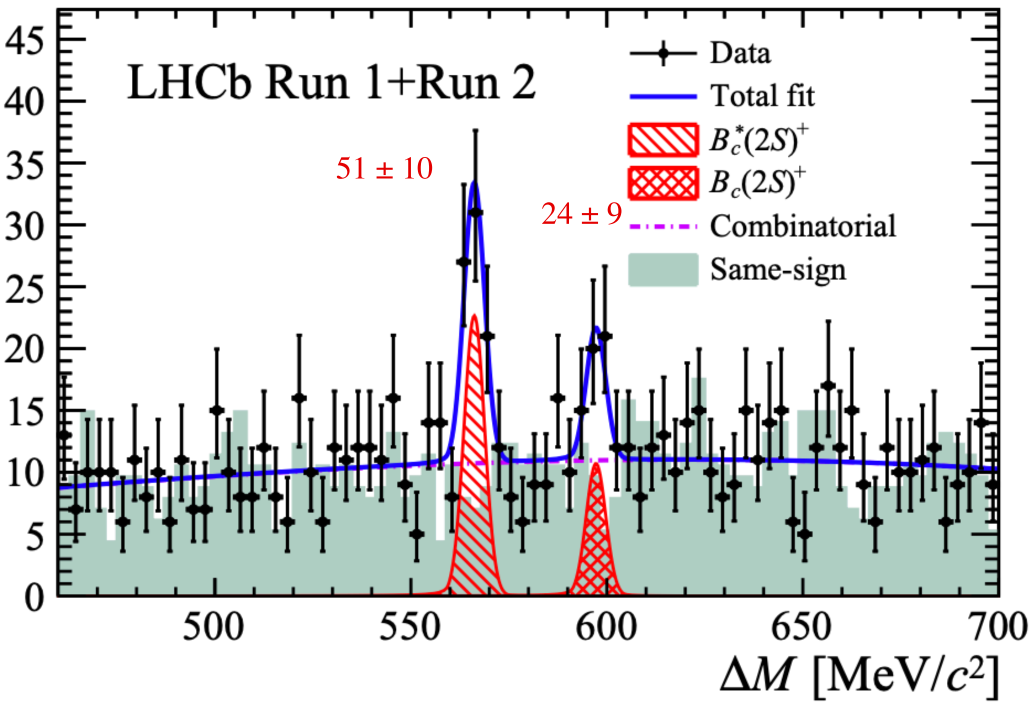


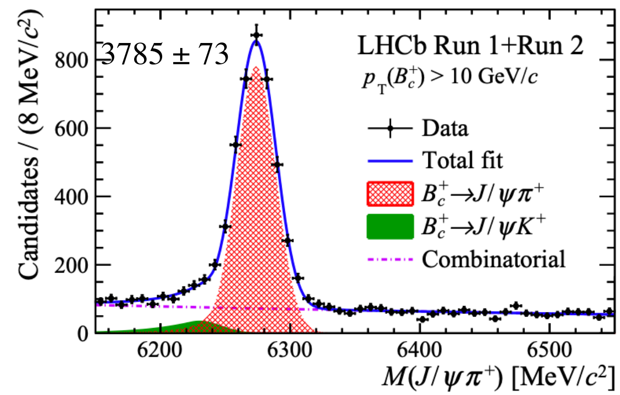
- First observation of well-separated $B_c^+(2S)$ and $B_c^{+*}(2S)$ states, resolved at > 5σ level
- $M(B_c^+(2S)) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV
- $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV

Latest LHCb results on Run1+Run2 data

[Phys. Rev. Lett. 122, 232001 (2019)]

CMS results were recently confirmed by LHCb collaboration:





	$B_c^*(2S)^+$	$B_c(2S)^+$
Signal yield	51 ± 10	24 ± 9
Peak ΔM value (MeV/c^2)	566.2 ± 0.6	597.2 ± 1.3
Resolution (MeV/c^2)	2.5 ± 0.5	2.5 ± 1.0
Local significance	$6.8\,\sigma$	$3.2\,\sigma$
Global significance	$6.3\,\sigma$	$2.2\,\sigma$

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

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

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

Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

[CMS-PAS-BPH-15-003]

Models to describe J/ψ production

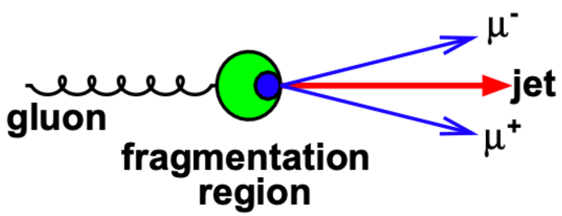
The mechanism of colorless $c\bar{c}$ state production from hadronic collisions has been a subject of extensive studies since 1974.

Overview:

- The original approach using the color-singlet (CS) model predicted J/ψ cross-sections significantly smaller than the Tevatron measurements
- NRQCD approach (color-singlet+color-octet amplitudes) was able to describe the Tevatron data
- NRQCD describes J/ψ production at LHC for $p_T > 10$ GeV

NRQCD and Fragmentation Jet Function (FJF) approach:

- J/ψ mesons are not produced directly but from high-p_T jet fragmentation
- The fragmentation function is decomposed in terms of NRQCD amplitudes and long-distance matrix elements (LDMEs). Depends on L and color configuration of $c\bar{c}$ pre-resonance state.
- LDME terms: ${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^3P_J^{(8)}$, ${}^3S_1^{(1)}$
- Feature: J/ψ mesons are not isolated

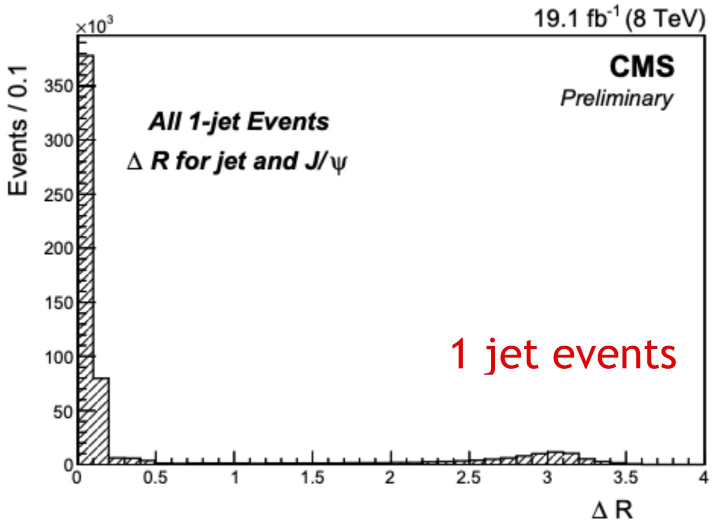


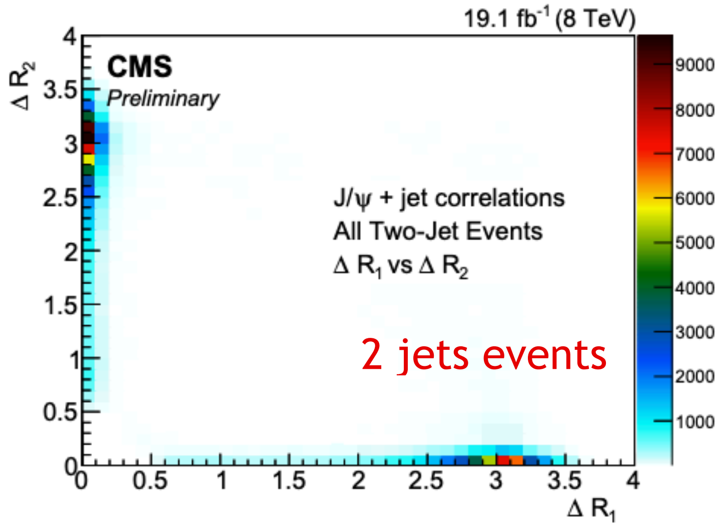
Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

1. What fraction of J/ψ production is a result jet fragmentation?

$$\Delta R = \sqrt{(\eta_{jet} - \eta_{\mu\mu})^2 + (\phi_{jet} - \phi_{\mu\mu})^2}$$

Fragmentation is assumed if: $\Delta R < 0.5$ and muons are required to constitute jets





Results:

For events with 1 jet 84% of J/ψ with E>15 GeV and |y|<1 are fragments of jets produced in $|\eta| < 1$. When unobserved jets (p_T< 25 GeV) are taken into account → jet fragmentation is a source of >80% of J/ψ mesons

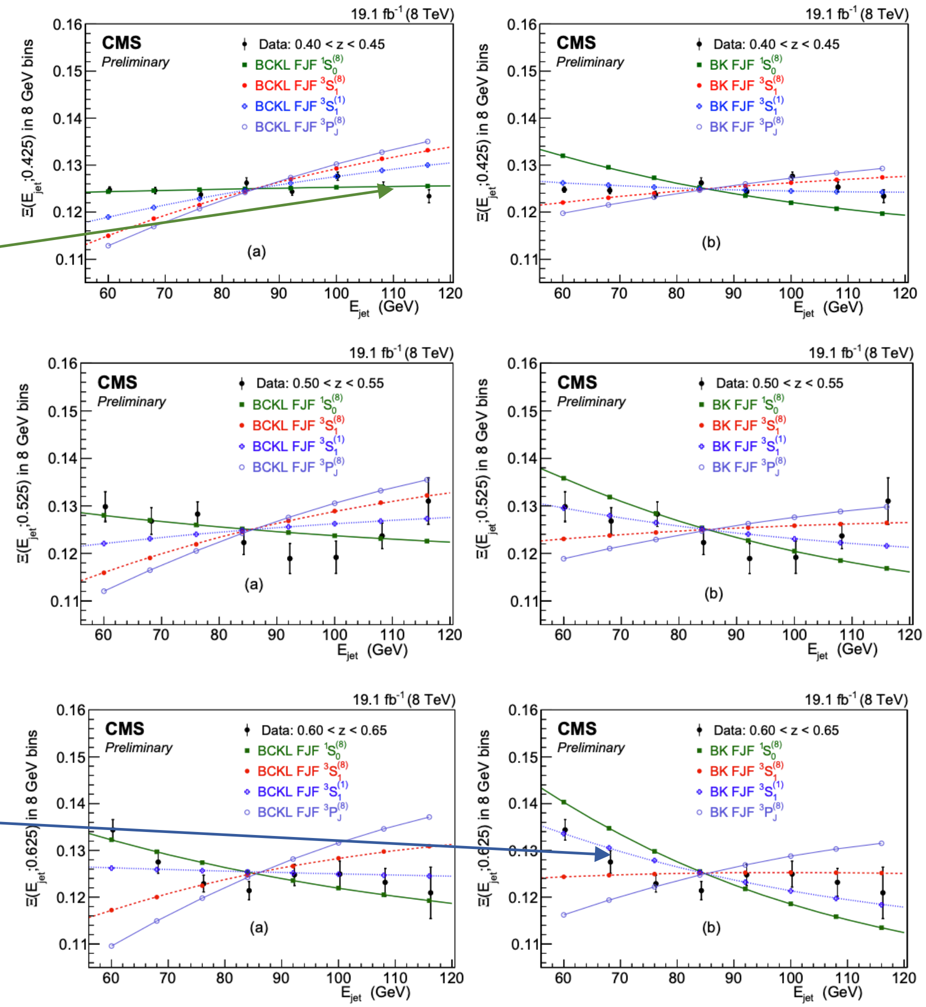
Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

2. Matching data with FJF predictions.

$z = E_{J/\psi}/E_{jet}$

- Unfolded data are compared with BCKL and BK predictions in three z ranges: 0.40-0.45; 0.50-0.55; 0.60-0.65;
- Only one NRQCD term $^1S_0^{(8)}$ using BCKL parameters is able to describe data for 3 measured ranges
- For z>0.5 $^3S_1^{(1)}$ BK might play a role, but introduces polarization
- Further studies might eliminate ambiguity between $^3S_1^{(1)}$ BK and $^1S_0^{(8)}$ BCKL

BK and BCKL FJF - [Phys. Rev. D 96, 036020 (2017)]



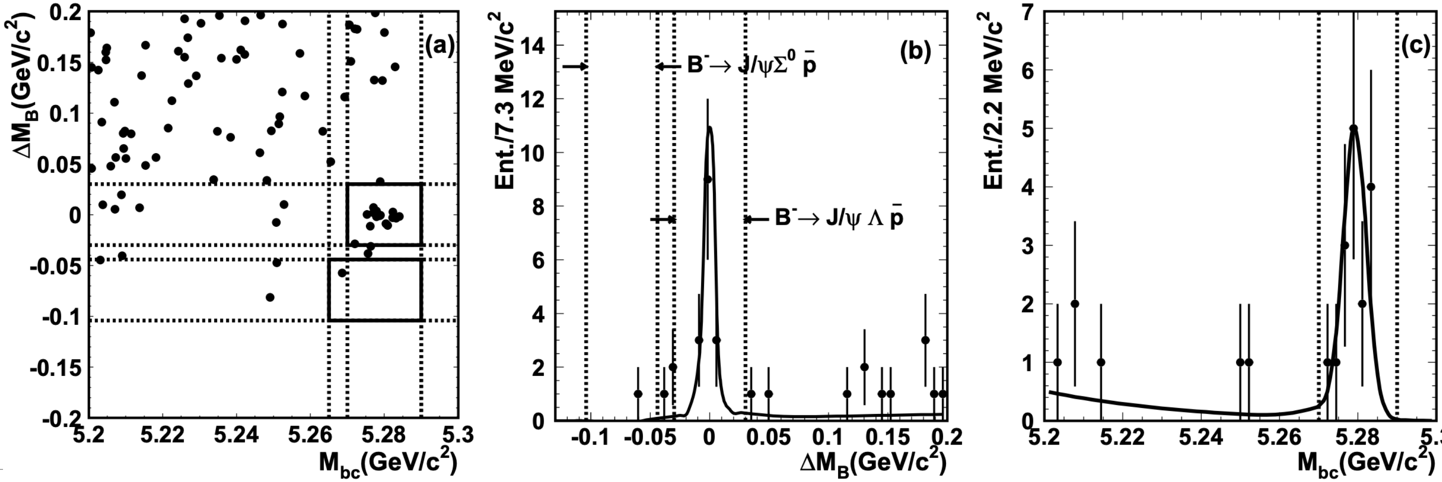
Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV

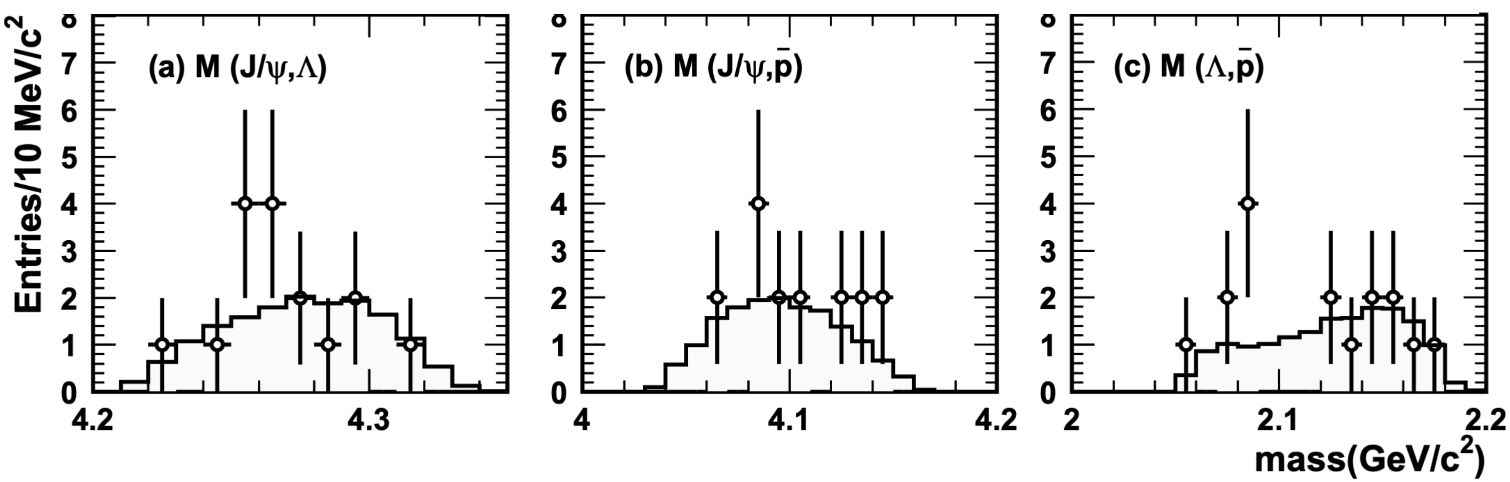
[CMS-PAS-BPH-18-005]

Previous results on $B^+ \to J/\psi\bar{\Lambda}p$ decay

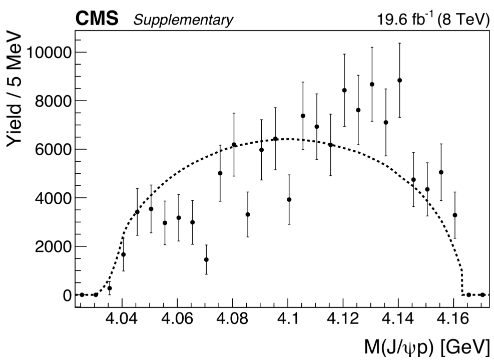
The Belle Collaboration reported the observation of this decay in 2005 [Phys.Rev.D72:051105,2005]

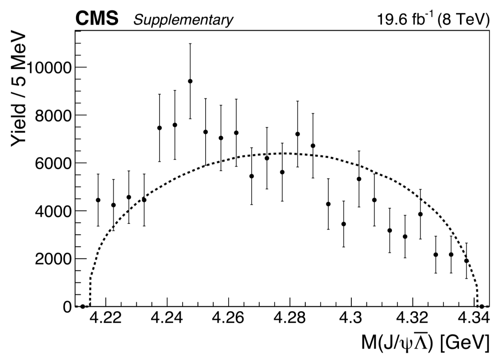
mode	Y	b	n_0	$\epsilon(\%)$	Y_{90}	$\mathcal{B}$
$B^- \to J/\psi\Lambda\bar{p}$	17.2 ± 4.1	$0.41 \pm 0.09(\text{stat.})$	16	$7.2^{+1.1}_{-1.4}$	–	$11.6 \pm 2.8(\text{stat.})^{+1.8}_{-2.3}(\text{sys.}) \times 10^{-6}$

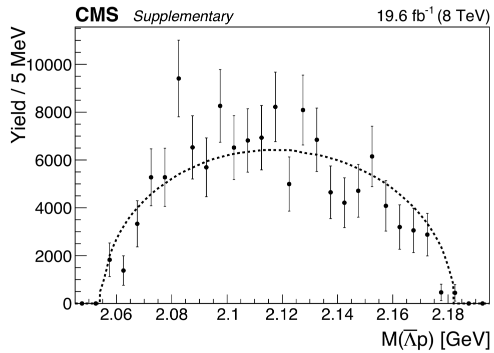


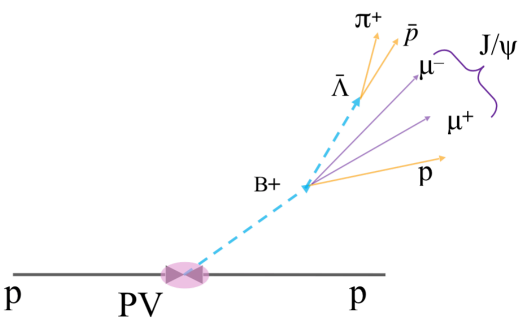


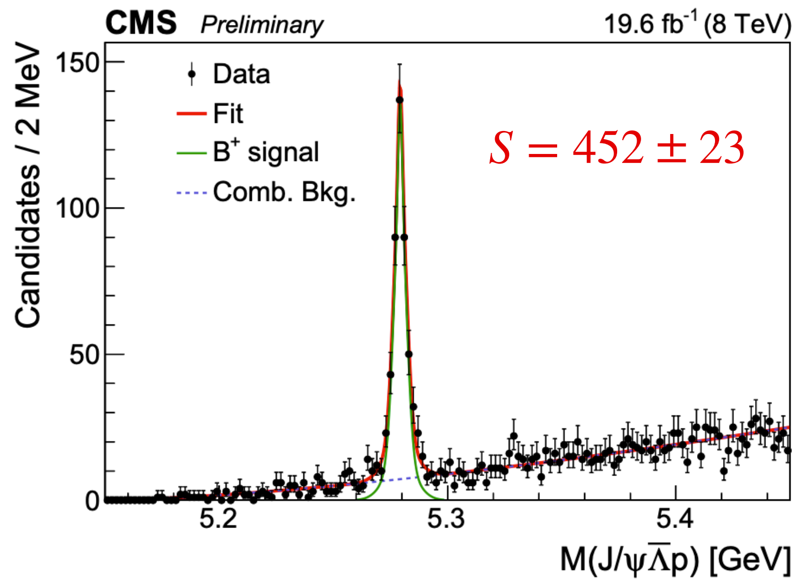
Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay











- Using $B^+ \to J/\psi K^{*+}$ decay as the normalisation channel with a similar topology:
- $\mathscr{B}(B^+ \to J/\psi\bar{\Lambda}p) = (15.07 \pm 0.81(\text{stat}) \pm 0.40(\text{syst}) \pm 0.86(\text{br.})) \times 10^{-6}$
- **The most precise result to date and compatible with previous results:**
- PDG: $\mathscr{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$
- Belle: $\mathscr{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$
- Allows to study intermediate invariant masses of J/ψ + baryon system
- The masses are found to be inconsistent with pure 3-body PS with a significance > 6.1, 5.5 and 3.4 for $J/\psi p$, $J/\psi\bar{\Lambda}$ and $\bar{p}\Lambda$, respectively, including systematics

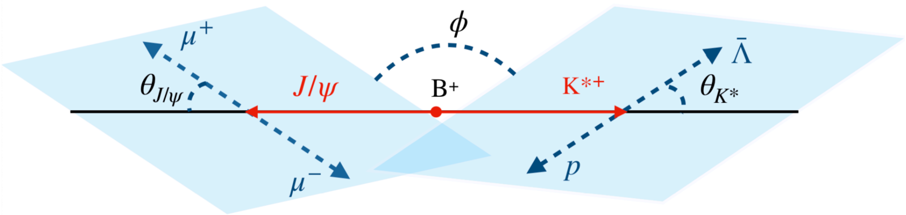
Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay. Model-independent approach

- Introduced by BaBar [Phys.Rev.D79:112001,2009] used by LHCb [Phys. Rev. D 92, 112009 (2015)]
- K* resonances decaying to $p\bar{\Lambda}$ final states can contribute and alter 2-body invariant mass distributions
- Their possible contributions is taken into account by measuring $\cos\theta_{K*}$ distribution in each $M(p\bar{\Lambda})$ bin on data

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

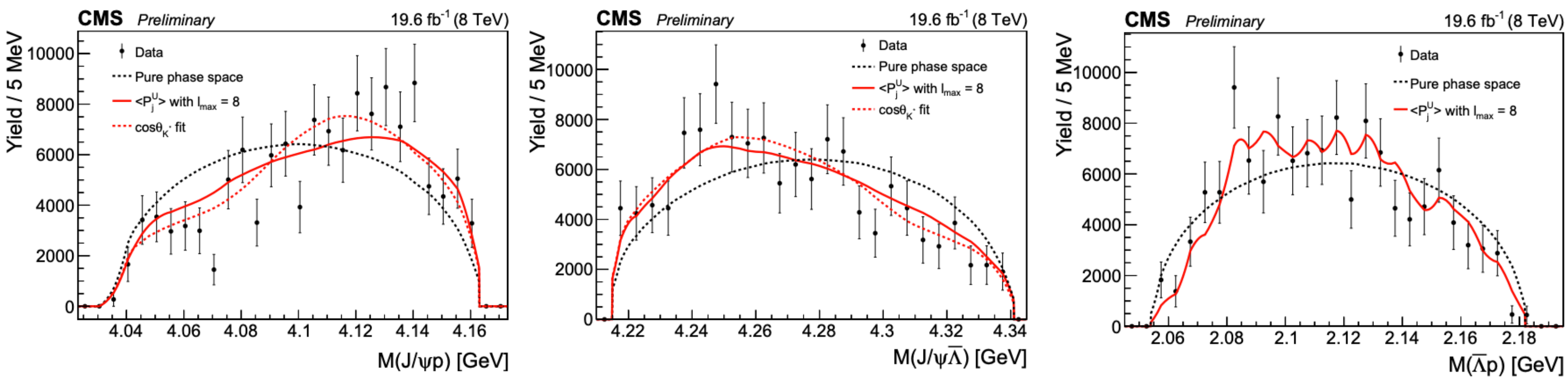
- and reweighting pure 3-body phase space accordingly

$$w^i = 1 + \sum_{j=1}^{l_{max}} < P_j^N > P_j(cos\theta^i_{K*}) \qquad l_{max} = 8,\ s \leq 4$$



Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay. Model-independent approach



PS - - - - - -

8 moments in $\cos\theta_{K*}$ – ——

1D $\cos\theta_{K*}$ reweighting – - - - - -

The model-independent method is used to check the non-exotic hypothesis originated by the contributions of K* resonances to $p\bar{\Lambda}$ system.

The inclusion of first eight moments corresponding to already known resonances decaying to $p\bar{\Lambda}$ improved the description of the data in J/ψp and $J/\psi\bar{\Lambda}$ systems , the significance of incompatibility is less than 2.8 standard deviations.

→No need for additional exotic resonances

Conclusion

Presented results which demonstrate high potential of upcoming studies using full Run 2 data:

- Observation of two excited B_c^+ states and measurement of $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV
  - ➡ Well-resolved $B_c^+(2S)$ and $B_c^{+*}(2S)$ states

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

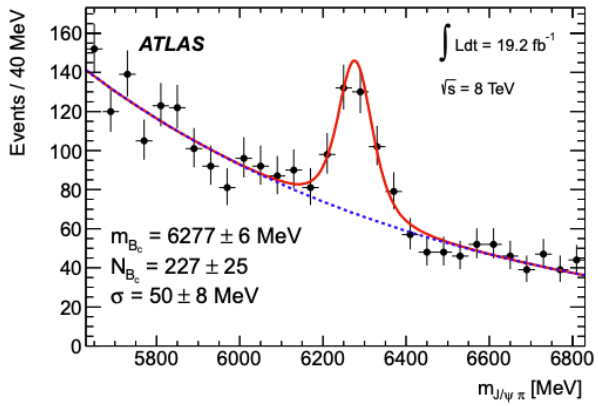
    $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV
- Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions
  - ➡ Concluded that more than 80% of J/ψ mesons are produced by jet fragmentation in the central region
  - ➡ Shown that NRQCD term ${}^1S_0^{(8)}$ using BCKL can describe the data for three different z regions
- Study of the $B^+ \rightarrow J/\psi\bar{\Lambda}p$ decay
  - ➡ The most precise measurement of branching fraction
  - ➡ Study of potentially exotic intermediate states shows that no additional resonances are needed

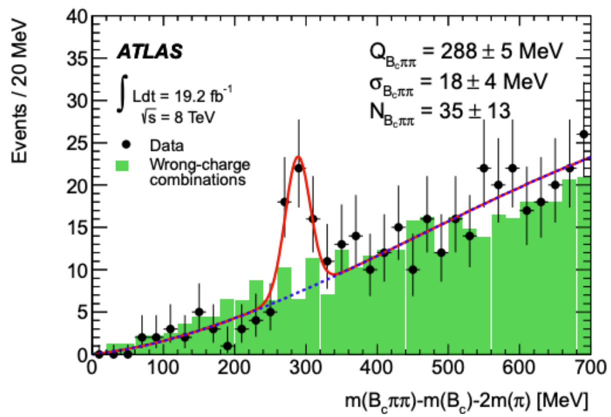
Backup

S-wave B_c spectroscopy (before CMS results)

ATLAS

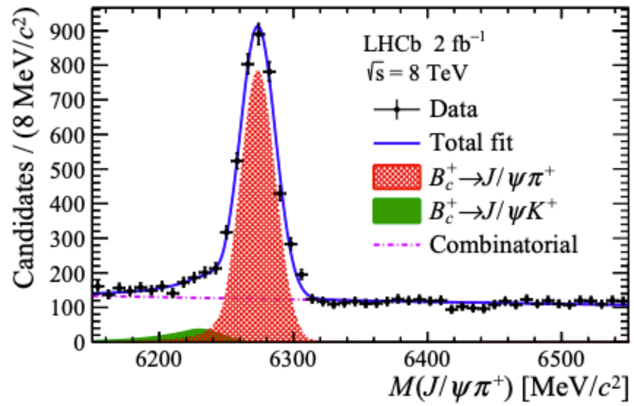
[Phys. Rev. Lett. 113, 212004 (2014)]

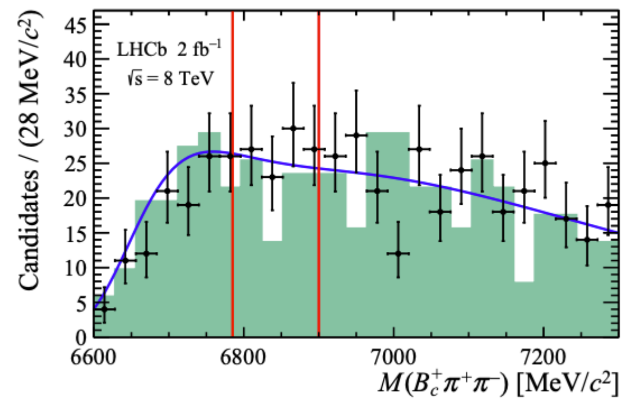




LHCb Collaboration

[J. High Energ. Phys. (2018) 2018: 138]





	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ATLAS	$(0.22 \pm 0.08\,(\text{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\text{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

2. Matching data with FJF predictions

Set of variables:

- Theory uses E_{jet} and $z = E_{J/\psi}/E_{jet}$ as independent variables
- FJF differential cross section for each LDME term: z<0.8

$$d\tilde{\sigma}_i(E;z_1) = \frac{d\sigma_i}{dE}|_{z_1} / \Sigma_{i=1}^{4} \int_{.3}^{.8} \frac{d\sigma_i(E;\zeta)}{dE} \, d\zeta$$

- Experimentally, a ratio function is used:

$$\Xi(E_1, z_1) \equiv \frac{N(E_1, z_1)}{\int_{0.3}^{0.8} N(E_1, z)dz} \equiv \frac{d\tilde{\sigma}}{dEdz}|_{E_1, z_1},$$

$\mathcal{N}_{corr}(E; z_1)$ is the number of events in $\pm\Delta z = 0.25$ about z_1.

$\mathcal{R}_{corr}(E; .3 - .8)$ is the number of events .3-.8 excluding $\mathcal{N}_{corr}(E; z_1)$.

Two different LDMEs sets from Bodwin, Chung, Kim and Lee (BCKL) [Phys. Rev. Lett. 113, 022001 (2014)] and Butenschoen and Kniehl (BK) [Phys. Rev. Lett. 108, 242004 (2012)] are used to compare with data (differ in production mechanisms)