ATLAS and CMS measurements on spectroscopy

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Observation of an Excited $B_c$ Meson State with the ATLAS Detector.

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

Search for a Structure in the $B_s^0\pi$ Invariant Mass Spectrum with the ATLAS Experiment.

Study of the $B\rightarrow J/\psi\Lambda p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV.
CMS-PAS-BPH-18-005
Exceeding the original integrated luminosity projections, 150 fb\(^{-1}\) has been delivered by the LHC in Run 2 (2015–2018).

Congratulations LHC, for a great performance!

ATLAS/CMS has accumulated over 140 fb\(^{-1}\) at 13 TeV of data for physics.
Observation of an Excited $B_c$ Meson State with the ATLAS Detector.

Introduction

The $B_c$ meson was discovered in 1998 by CDF. **PRL 81 (1998) 2432**
It is the lowest-mass bound state of the family of mesons composed of a charm quark and a bottom anti-quark.

Experimental information is limited by rare production rate, $\alpha_s^4$: $qq\bar{q}$, $gg \rightarrow (c\bar{b}b\bar{c}) b\bar{c}$.

Given the different heavy quark flavors, the only allowed transitions are through photons or pion pairs

<table>
<thead>
<tr>
<th>Particle</th>
<th>Predicted M(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_c$</td>
<td>6247-6286</td>
</tr>
<tr>
<td>$B_c^*$</td>
<td>6308-6341</td>
</tr>
<tr>
<td>$B_c(2S)$</td>
<td>6835-6882</td>
</tr>
<tr>
<td>$B_c(2S)^*$</td>
<td>6881-6914</td>
</tr>
</tbody>
</table>

Observation of an Excited Bc Meson at ATLAS

- Ground state: $B_c \rightarrow J/\Psi(\mu\mu)\pi$

- The $B_c$ selection criteria for the events are optimized separately for 7 and 8 TeV:
  $p_T(B_c) > 15$ GeV (7 TeV) and $p_T(B_c) > 15$ GeV (8 TeV)

- Extended unbinned maximum likelihood fit, with a Gaussian function modeling the signal and an exponential modeling the background shape.

More details in the next slides.
Observation of an Excited B\(c\) Meson at ATLAS

- Select B\(c\) ground state candidates within 3\(\sigma\) of the fitted mass value.
  - The three tracks from the secondary vertex and the two tracks from the primary vertex are refitted simultaneously.
  - Momentum of B\(c\) candidate must point to the pions vertex.

- Extended unbinned maximum likelihood fit. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure.

- To improve the resolution, peaks are sought in the distribution of the variable:
  \[ Q = m(B_{c\pi\pi}) - m(B_c) - 2m(\pi) \]
Observation of an Excited $B_c$ Meson at ATLAS

- A new state is observed at $Q = 288.3 \pm 3.5 \text{ stat} \pm 4.1 \text{ syst MeV}$

  Corresponding to a mass of $6842 \pm 4 \text{ stat} \pm 5 \text{ syst MeV}$

- The significance of the observation is $5.2\sigma$

- The observed structure is consistent with the predicted mass of the $B_c(2S)$ excited state.

- This analysis "open the door" to more studies and results in this sector.
Observation of two excited $B_c$ states and measurement of the $B_c(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

PRL 122 (2019) 132001
They report the observation of a new state whose mass is consistent with predictions for the $B_c(2S)$. The $B_c(2S)$ is reconstructed from the decay $B_c \pi \pi$ followed by $B_c \to J/\psi \pi$, with a local significance of 5.4 $\sigma$.

With 3325 ± 73 $B_c$ events: “No significant signal is found” in the search for the excited states $B_c(2S)$ and $B_c(2S)^*$ in 8 TeV data.
Reconstruction of the $B_c \pi \pi$

The $B_c(2S)^*$ decays to the $B_c$ ground state through the emission of two pions and a soft photon (around 55 MeV in rest frame):

$$B_c(2S)^* \rightarrow B_c^* \pi^+ \pi^- \text{ followed by } B_c^* \rightarrow B_c \gamma_{\text{lost}}$$

Since the photon is not detected, we end up seeing

$$B_c(2S)^* \rightarrow B_c \pi^+ \pi^- \text{ plus “missing energy’}}$$

Same final state as

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

So, we see a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, with the $B_c(2S)^*$ peak at a mass shifted by

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

which is predicted to be around 20 MeV.

One have to notice:

$$[M(B_c(1S)^*) - M(B_c(1S))] > [M(B_c(2S)^*) - M(B_c(2S))]$$
Event selection criteria

- $B_c$ meson momentum required to point to the PV in the $xy$ plane
- The PV is re-fitted excluding the three $B_c$ decay tracks (two muons and one pion ($\pi_1$))
- $\pi_2$ and $\pi_3$ are tracks in that PV, e.g. they are prompt tracks, which are combined with $B_c$
- Tracks and muons satisfy high-quality requirements
- When multiple $B_c \pi \pi$ candidates are found in the same event, we only keep the one with the highest $p_T$ value
Reconstruction of $B_c$ in data: 2015 + 2016 + 2017 + 2018

Fit details:
Unbinned ML; the signal is modeled using a double Gaussian with common mean and the background as a polynomial. Additional background contributions from $B_c \rightarrow J/\psi \ K^+$ decay is modeled from the simulated sample, while the partially reconstructed $B_c \rightarrow J/\psi \ \pi^+ X$ decays are modeled with an ARGUS function convolved with a Gaussian.

7629 ± 225 candidates
33.5 ± 2.5 MeV mass resolution
Event selection

kinematic requirements

\[ p_T(\pi_1) > 3.5 \text{ GeV} \]
\[ B_c \text{ prob(vtx)} > 0.1 \]
\[ p_T(B_c) > 15 \text{ GeV} \]
\[ B_c \text{ decay length} > 0.01 \text{ cm} \]

\[ 6.2 < M(B_c) < 6.35 \text{ GeV} \]
\[ B_c \pi \pi \text{ prob(vtx)} > 0.1 \]
\[ p_T(\pi_2) > 0.8, \ p_T(\pi_3) > 0.6 \text{ GeV} \]

Event display of reconstructed candidate
The mass difference between the two states in the $B_c \pi^+ \pi^-$ mass distribution is predicted to be $M(B_c(2S)) - \Delta M$, where

$$\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c(2S)^*) - M(B_c(2S))] \rightarrow ~ 20 \text{ MeV}$$

Mass distribution fitted with Gaussian functions for the peaks and a 3rd order polynomial for the background.

Mass resolution agrees with MC expectations $\sim 6 \text{ MeV}$

Two-peak structure observed (well resolved):

$$\Delta M = 29.1 \pm 1.5 \text{ (stat) MeV}$$

Local significance exceeding six $\sigma$ for observing two peaks rather than one, evaluated through the ratio of likelihoods (including syst.). Each of them above five $\sigma$.

Mass of $B_c(2S)$ measured to be:

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

Natural widths: (50-90 keV predicted)

measurements consistent with zero, e.g. smaller than the resolution.
Systematic uncertainty evaluation

The systematic uncertainties come from: \( B_c(2S) \) fit modeling, \( J/\psi K \) uncertainties, partially reconstructed decays, and alignment of the detector.

Fit modeling:
alternative functions for the signal and the backgrounds
signal peaks: changed from two Gaussians to two Breit-Wigner functions
background: changed from a polynomial to a threshold function used in previous CMS analyses
observed differences in \( M \) and \( \Delta M \) are quoted as systematic uncertainties: 0.8 and 0.7 MeV respectively

\( J/\psi K \) background contamination:
difference seen when its yield is varied by 10% (PDG BFs uncertainty): the difference is negligible

Alignment of the detector:
the possible misalignment of the detector biases the measured masses, however for studies with major detector changes (2016 vs 2017), was found to be negligible

Partially-reconstructed decays:
the low-mass edge of the signal mass window was varied from 6.2 to 6.1 GeV, to increase (by 8%) this contamination;
the variations in the results are smaller than the uncorrelated stat. uncertainty: no systematic uncertainty is considered

In summary, the total systematic uncertainty is 0.8 MeV for \( M \) and 0.7 MeV for \( \Delta M \), fully determined by the choice of the fitting model for the signal peaks
Now LHCb has also confirmed the two peaks!

Observation of an excited Bc state
arXiv:1904.00081
CERN-EP-2017-333:

Search for a Structure in the $B_s^0 \pi$ Invariant Mass Spectrum with the ATLAS Experiment.

PRL 120 (2018) 202007
D0 observed an unexpected narrow structure, named X(5568), in the $B_s^0\pi$ system.

State w/ 4 different flavors of quarks

Given the large difference between $M_X$ and the $B^0 K^{\pm}$ mass threshold, a molecular hypothesis is unlikely.

If confirmed, Tetraquark interpretation would be favored. However, Theory predicts more states.


$M_X = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV

$\Gamma_X = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV

Strong decay!

$N_X = 133 \pm 31 \pm 15$ cand.

If $X(5568)^- \to B_s^0\pi^-$ then $J^P = 0^+$

If $X(5617)^- \to B_{s0}^{*}\pi^-$ then $J^P = 1^+$

Not confirmed by LHCb
Not confirmed by CMS
Not confirmed by CDF
Search for $X^+(5568) \rightarrow B_s^0 \pi^+$: ATLAS

- ATLAS has recollected several thousands of $B_s \rightarrow J/\psi \phi$ decays on what to look for.

Model:
- 2 gaussians for signal.
- An exponential for Bkg.

Two regions of interest are defined with $\sigma_{\text{eff}} \sim 14$ MeV:
- **Signal region.** Keep events in $[5346.6, 5386.6]$ MeV range for further investigation.
  \[ N_{B_s^0} = 52750 \pm 280 \]
- **SideBands.**
  $5150 < m(J/\psi KK) < 5210$ MeV and $5510 < m(J/\psi KK) < 5650$ MeV
The $B_s\pi^+$ candidates are constructed by combining each of the tracks forming the selected PV with the selected $B_s$ candidate.

- Mass variable:
  
  $$m(J/\Psi KK\pi) - m(J/\Psi KK) + m_{fit}(B_s)$$

  where, $m_{fit}(B_s) = 5366.6$ MeV

- Following other experiments extended unbinned maximum likelihood fits are performed for two subsets of $B_s^{0}\pi^+$ candidates: $p_T(B_s^{0}) > 10$ GeV and $p_T(B_s^{0}) > 15$ GeV
No significant signal is observed

95%CL upper limits

\[ N(X) < 382 \ (p_T(B) > 10 \text{ GeV}) \]
\[ N(X) < 356 \ (p_T(B) > 15 \text{ GeV}) \]

Systematic uncertainties affecting these limits are included in the determination of N(X)

Efficiency

\[ \epsilon_{\text{rel}}(X) = \epsilon(X) / \epsilon(B^0_{s}) \]

In the ratio, the acceptance of the Bs decay cancels, so the value to be determined is the pion reconstruction efficiency

<table>
<thead>
<tr>
<th>N\text{gevol}(B^0_{s})/10^3</th>
<th>p_T(B^0_{s}) &gt; 10 \text{ GeV}</th>
<th>52.75 \pm 0.28</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p_T(B^0_{s}) &gt; 15 \text{ GeV}</td>
<td>43.46 \pm 0.24</td>
</tr>
<tr>
<td>N(X)</td>
<td>p_T(B^0_{s}) &gt; 10 \text{ GeV}</td>
<td>60 \pm 140</td>
</tr>
<tr>
<td></td>
<td>p_T(B^0_{s}) &gt; 15 \text{ GeV}</td>
<td>-30 \pm 150</td>
</tr>
<tr>
<td>\epsilon_{\text{rel}}(X)</td>
<td>p_T(B^0_{s}) &gt; 10 \text{ GeV}</td>
<td>0.53 \pm 0.09</td>
</tr>
<tr>
<td></td>
<td>p_T(B^0_{s}) &gt; 15 \text{ GeV}</td>
<td>0.60 \pm 0.10</td>
</tr>
</tbody>
</table>
Search for \( X^+(5568) \rightarrow B^+_s \pi^+ \): ATLAS

- Extract 95% CL upper limits on production rate

\[
\rho_X \equiv \frac{\sigma(pp \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B^0_s \pi^\pm)}{\sigma(pp \rightarrow B^0_s + \text{anything})} = \frac{N(X)}{N(B^0_s)} \times \frac{1}{\epsilon_{\text{rel}}(X)}
\]

- Signal: Breit-Wigner (assuming a resonant state as described by D0 observation).

- Systematic uncertainties affecting these limits are included.

- Scan range 5550 - 5700 MeV every 5 MeV
CMS-PAS-BPH-18-005:

Study of the $B \rightarrow J/\psi \Lambda p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV.
First example of a B meson decay into baryons

Observed in 2005 by Belle with very low yield (17.2 ± 4.1 events)

\[ \beta(B \rightarrow J/\psi \Lambda p) = (11.6 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6} \]

Recently, the LHCb Collaboration reported the first observation of the baryonic \( B_c \rightarrow J/\psi pp \). 10.1103/PhysRevLett.113.152003

Motivation to study this decay is to search for new intermediate resonances in the \( J/\psi \Lambda, J/\psi p \) and \( \Lambda p \) systems.

Such a study in the \( \Lambda b \rightarrow J/\psi pK \) decay resulted in the observation by the LHCb Collaboration of new multiquark states consistent with pentaquarks. 10.1103/PhysRevLett.115.072001, arXiv:1904.00081 (2019)
B → J/ψΛp production at CMS

- Using data collected at 8 TeV, corresponding to an integrated luminosity of 19.6 fb\(^{-1}\)

- The decay B→J/ψK\(^+\)(K\(^+\)→K\(_s\)\(^0\)π\(^+\)) is chosen as the normalization channel, as it is measured with high precision and has a similar decay topology.

  The ratio of branching fractions is measured to be

  \[
  (15.07 \pm 0.81 \text{ (stat)} \pm 0.40 \text{ (syst)} \pm 0.86(\beta )) \times 10^{-6}
  \]

  This measurement is the most precise to date & consistent with previous Belle measurement
J/ψΛ, J/ψp and Λp systems

- Large signal yield allowed CMS to conduct a search for new exotic multiquark states in the two-body systems

- The three two-body systems show incompatibility with the phase space hypothesis
Model-independent approach: method of moments

- First introduced by the BaBar [PRD 79 112001(2009)] and later used by the LHCb [PRD 92,112009 (2015), PRL 117, 082002 (2016)].
- There are at least three known $K^*$ resonances that can decay to $\Lambda p$. So, these broad excited kaon states can contribute to the two-body invariant mass distributions.
- In each $M(\Lambda p)$ bin, the $\cos(\theta K^*)$ distribution can be expressed as an expansion in terms of Legendre polynomials:

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

$\cos(\theta K^*)$ helicity angle defined as the angle between $\Lambda$ momentum and $B^+$ momentum in the $\Lambda p$ rest frame.

$L_{\text{max}}$ equal to twice the spin of the highest-spin resonance can describe all the resonances and their interferences. From table $L_{\text{max}} = 2*4=8$.

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<tbody>
<tr>
<td>$K_4^+(2045)^+$</td>
<td>$2045 \pm 9$</td>
<td>$198 \pm 30$</td>
<td>$4^+$</td>
</tr>
<tr>
<td>$K_2^+(2250)^+$</td>
<td>$2247 \pm 17$</td>
<td>$180 \pm 30$</td>
<td>$2^-$</td>
</tr>
<tr>
<td>$K_3^+(2320)^+$</td>
<td>$2324 \pm 24$</td>
<td>$150 \pm 30$</td>
<td>$3^+$</td>
</tr>
</tbody>
</table>
Simulation reweighting according to the observed angular structure in the $\Lambda p$ system.

It is evident that the description of the $M(J/\psi \Lambda)$ and $M(J/\psi p)$ data distributions is improved after accounting for the angular and invariant mass structure in the $\Lambda p$ system in simulation.

Compatibility with data eliminating the need for new resonances!
Considerable LHC data sets collected in Run 2 by ATLAS and CMS offers future opportunities in searches for new resonances.

For both experimentally and theoretically point of view, Heavy-flavor spectroscopy continues to be very fruitful.

Using full Run 1 data (7 TeV and 8 TeV), a $B_c$ meson excited state was observed at ATLAS.

Signals consistent with the $B_c(2S)$ and $B_c(2S)^*$ states have been separately observed for the first time by investigating the $B_c \pi \pi$ invariant mass spectrum measured by CMS. The analysis is based on the full Run 2 data (13 TeV), corresponding to a total integrated luminosity of 143 fb-1.

ATLAS has searched for the new structure reported by D0, so called $X(5568)$. No significant signal observed, upper limits was set.

The ratio of branching fractions $\frac{B(B^+\to J/\psi \Lambda p)}{B(B^+\to J/\psi K^{*+})}$ is measured. This measurement is the most precise to date. The study of two-body invariant mass distributions of the $B\to J/\psi \Lambda p$ decay products was performed. A model Independent approach was used to conclude that no new resonances are needed.
THANKS for listening!