Spectroscopy and exotica of HF states in ATLAS

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On behalf of the ATLAS collaboration

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HQL2018
Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum in the ATLAS

Observation of an excited state of $B_c^\pm$ consistent with predictions for $B_c^\pm(2S)$
In December 2016, D∅ published the evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \rightarrow B_s^0 \pi^\pm$, $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-)\phi(K^+ K^-)$


$X(5568)$ is a tetraquark candidate, composed of two quarks and two antiquarks of four different flavors: $b, s, u, d$
Fixed background shape

- a) opening angle ($B_s^0 - \pi^\pm$) cut $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$:

  \[
  m = 5567.8 \pm 2.9 \text{ (stat)} \pm 0.9 \text{ (syst)} \text{ MeV}/c^2, \\
  \Gamma = 21.9 \pm 6.4 \text{ (stat)} \pm 5.0 \text{ (syst)} \text{ MeV}/c^2,
  \]

  significance $5.1\sigma$, and number of signal events $N = 133 \pm 31$

- b) without $\Delta R$ cut (but with the mass, natural width, and background shape fixed to default values): $N = 106 \pm 23$, significance $3.9\sigma$
$B_{s}^{0}\pi^{\pm}$: DØ Semileptonic Result
Phys. Rev. D 97 no 9 (2018), 092004

- $p\bar{p}$ data 10.4 fb$^{-1}$
- Significance including systematic uncertainty:
  - a) with cone cut $\sigma = 3.2$
  - b) without cone cut $\sigma = 3.4$
$B^0_s \pi^\pm$: Results from other experiments

**LHCb:**
(Phys. Rev. Lett. 117 (2016) no.15, 152003)

\[
\rho^{LHCb}_X (p_T(B^0_s) > 5 \text{ GeV}) < 0.012, \\
\rho^{LHCb}_X (p_T(B^0_s) > 10 \text{ GeV}) < 0.024, \\
\rho^{LHCb}_X (p_T(B^0_s) > 15 \text{ GeV}) < 0.020
\]

**CMS:**
(Phys. Rev. Lett. 120 (2018) no. 20, 202005)

\[
\rho^{CMS}_X (p_T(B^0_s) > 10 \text{ GeV}) < 0.011 \\
\rho^{CMS}_X (p_T(B^0_s) > 15 \text{ GeV}) < 0.010
\]

**CDF:**

\[
f_{B^0_s}/\chi(5568) < 0.067
\]
**$B^0_s\pi^\pm$: Data and Selection**

**$B^0_s$ candidate**

Data of $pp$ collisions: 4.9 fb$^{-1}$ (2011 7 TeV) + 19.5 fb$^{-1}$ (2012 8 TeV)

**$B^0_s$ candidate selection:**

- Jpsi has been reconstructed by fitting muon pairs into common vertex
- $m(KK) \in 1008.5\text{ MeV} - 1030.5\text{ MeV}$
- $p_T(K) > 1\text{ GeV}$
- Only using the best $\chi^2/NDF$ candidate from each event
- $p_T(B_s) > 10\text{ GeV}$
- $\tau(B_s) > 0.2\text{ ps}$

**$B^0_s\pi^\pm$ candidate selection:**

- $m(B_s) \in 5346.6\text{ MeV} - 5386.6\text{ MeV}$
- $p_T(\pi^\pm) > 500\text{ MeV}$
- $m(B^0_s\pi^\pm) < 5900\text{ MeV}$
- All $B^0_s\pi^\pm$ candidates in the event are taken
\(B_{s}^{0}\pi^{\pm}\): Fit to the Data

- \(B_{s}^{0}\pi^{\pm}\) candidates from RUN1 data with combined integrated luminosity of 24.3 \(fb^{-1}\) are fitted using an unbinned maximum-likelihood fit.

- The signal mass and Breit-Wigner width (BW) are fixed according to the central values obtained by the D\(\phi\) collaboration, i.e. \(M_{X} = 5567.8\) MeV and \(\Gamma_{X} = 21.9\) MeV.

- The fits are performed for two subsets of the \(B_{s}^{0}\pi^{\pm}\) candidates: \(p_T(B_{s}^{0}) > 10\) GeV (left) and \(p_T(B_{s}^{0}) > 15\) GeV (right).

- No significant signal corresponding to the properties of the D\(\phi\) resonance is observed.
No significant signal corresponding to the properties of the $D\emptyset$ resonance is observed.

CLs formalism is used to establish the upper limits for the number of expected $B_s^0\pi^\pm$ signals $N(X)$ and for the relative production rate $\rho_X$ at 95% CL:

$$\rho_X \equiv \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow B_s^0\pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon_{\text{rel}}(X)},$$

Systematics for $N(X)$:

- alternative Background PDF Chebyshev of 7th order - replacing default PDF
- P-wave BW for Signal replacing the default S-wave
- Tripple-Gaus for detector Bsmpi mass resolution determined by MC - replacing the per-candidate resolution model of the default fit.
- Uncertainty on $D\emptyset$ parameters
The upper limit for $\rho_X$ is established in the same way as for $N(X)$ including in addition the systematic effects from determination of number of $B_s^0$ signal events and of the relative efficiency $\epsilon^{rel}$ as gaussian constraints.

The highest upper limits are extracted by including all systematics and give

<table>
<thead>
<tr>
<th>$p_T(B_s^0)&gt;10$ GeV</th>
<th>$p_T(B_s^0)&gt;15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(X)$</td>
<td>382</td>
</tr>
<tr>
<td>$\rho_X$</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>356</td>
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<td>0.016</td>
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These results are consistent with LHCb and CMS measurements.
$B^0_s\pi^\pm$: Mass scan

- BW width fixed to $D\phi$ value + uncertainty on $D\phi$ value
- Scanning with the mean resonance masses from 5550 MeV to 5700 MeV, in steps of 5 MeV using 10 GeV $p_T$ cut
- All systematics are included

![Graph showing observed and expected 95% CL limits for $\rho_\pi$ versus $m_X$ in MeV.](image)
A search for a new state $X(5568)$ decaying to $B_s^0 \pi^\pm$ was performed by ATLAS, using RUN1 $pp$ data.

No significant signal has been found.

The upper limit on the production rate of the $X(5568)$ decaying to $B_s^0 \pi^\pm$ state relative to $B_s^0$ mesons produced in ATLAS volume has been determined at 95 % CL.

ATLAS results are published at Phys. Rev. Lett. 120 (2018) 202007 and are consistent with CMS and LHCb measurements.
The $B_c^{\pm}(1S)$ meson was first observed by the CDF experiment in the semileptonic decay mode.

The spectrum and properties of $B_c^{\pm}$ family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations.

The search for first excited state $B_c^{\pm}(2S)$ was performed in the decay sequence $B_c^{\pm}(2S) \rightarrow B_c^{\pm}(1S)\pi^+\pi^-$. 
The analysis uses 7 TeV and 8 TeV pp collisions data

- 4.9 fb$^{-1}$ and 19.2 fb$^{-1}$, respectively

Selection optimised using MC

- Optimization performed separately for 7 TeV and 8 TeV data
**$B_c^\pm(1S)$ selection and fit**

$B_c^\pm(1S)$ selection for 2011 (2012) data

- $p_T(\mu_1, \mu_2) > 4, 6$ GeV
- $\chi^2/n.d.f.(J/\psi) < 15$
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal ($\sigma$ depending on the rapidity range)

- $\chi^2/n.d.f.(B_c^\pm) < 2.0 (1.5)$
- $p_T(B_c^\pm) > 15$ GeV (18 GeV)
- $d^0_{xy}/\sigma(d^0_{xy})(\pi^+) > 5 (4.5)$

Extended unbinned fit of the mass distribution

- **Signal**: Gaussian with per-candidate errors
- **Background**: exponential
\( B_c^{\pm}(2S) \) selection and fit

**Selection of \( B_c^{\pm}(2S) \to B_c^{\pm}(1S)\pi^+\pi^- \) candidates**
- \( B_c^{\pm}(1S) \) candidates within \( \pm 3\sigma \) of the fitted mass
- \( p_T(\pi^+, \pi^-) > 400 \) MeV

- for several candidates in event, the one with the best cascade fit \( \chi^2 \) is kept

**Extended unbinned fit of Q-value distribution**

\[
Q_{B_c^{\pm}\pi\pi} = m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2m(\pi^+)
\]

- **Signal**: Gaussian
- **Background**: 3rd order polynomial

Wrong charge combination (same-sign \( \pi \)) used for background control
Significance of the observed signal calculated with toy studies accounting for a "look elsewhere effect"

- $3.7\sigma$ in 7 TeV data
- $4.5\sigma$ in 8 TeV data
- Combined significance is $5.2\sigma$
- (local significance is $5.4\sigma$)

A new state observed at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (error-weighted mean of 7 and 8 TeV values)

Corresponds to a mass $6842\pm 4 \pm 5$ MeV, that is consistent with the predicted mass of $B_c^\pm(2S)$ with no $B_c^*(2S)$ hypothesis
$B_c^{\pm}(2S)$: Conclusions

- $B_c^{\pm}(2S)$ Highlights:
- First and so far the only observation of an excited state of $B_c$
  - LHCb published upper limits on the observation of this state (J. High Energ. Phys. (2018) 2018: 138) and awaiting results from CMS.
- ATLAS is continuing $B_c^{\pm}$ program in RUN2 with special attention to $B_c^{\pm}(2S)$

Stay tuned.