ATLAS: Spectroscopy and exotic states

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on behalf on the ATLAS collaboration

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Outline

• The ATLAS detector
• $B_c(2S)$ observation
• Search for tetraquarks in $B^0_s$ decays
• conclusion
The ATLAS detector

- Important subsystems for B-physics:
  - Inner Detector (ID)
    - tracking, momentum measurement and vertexing
  - Muon spectrometers
    - trigger and muon identification
Datasets and triggers

- **Datasets:**
  - 4.9 fb⁻¹ @ 7 TeV
  - 20.6 fb⁻¹ @ 8 TeV

- **ATLAS B-physics analyses based on (di-)muon triggers**
  - different thresholds available

**Entries / 50 MeV**

- Trigger 
  - **EF_2mu4_DiMu**
  - **EF_2mu4_Jpsimumu**
  - **EF_2mu4_Bmumu**
  - **EF_2mu4_Upsimumu**
  - **EF_mu4mu6_Jpsimumu**
  - **EF_mu4mu6_Bmumu**
  - **EF_mu4mu6_Upsimumu**
  - **EF_mu20**

**ψ(2S), ψ(1S), Υ(2S), Υ(3S)**

- **relevant di-muon triggers for this talk:**
  - \( p_T(\mu_1) > 4 \) GeV & \( p_T(\mu_2) > 4 \) GeV
  - \( p_T(\mu_1) > 6 \) GeV & \( p_T(\mu_2) > 4 \) GeV
  - \( p_T(\mu_1) > 6 \) GeV & \( p_T(\mu_2) > 6 \) GeV

- **final states containing J/Ψ**
  - \( M(\mu\mu) \) in [2.5,4.3] GeV
  - common vertex

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**Graphical representation**

- \( \sqrt{s} = 7 \) TeV
- \( \int L dt \approx 2.3 \) fb⁻¹
- **ATLAS Preliminary**
B_c(2S) theoretical predictions

- B_c is a unique system
  - composed of two distinct heavy quarks
  - valuable inputs to lattice and perturbative QCD models

- several theoretical predictions on B_c production and excited states

- a search for an excited B_c state was performed in ATLAS

Phys.Rev.D70:054017,2004
B_c(2S) observation at ATLAS

- ground state: B_c → J/ψ(μμ)π
- peak searched in mass difference distribution
  \[ Q = m(B_c(2S)) - m(B_c) - 2m(\pi) \]

\[ \begin{align*}
\int Ldt &= 4.9 \text{ fb}^{-1} \\
\sqrt{s} &= 7 \text{ TeV} \\
m_{B_c} &= 6282 \pm 8 \text{ MeV} \\
N_{B_c} &= 100 \pm 23 \\
\sigma &= 49 \pm 12 \text{ MeV}
\end{align*} \]

- selection optimised differently for 7 TeV and 8 TeV data
- extended unbinned maximum likelihood fit to get number of \( B_c^\pm \)
**B_c(2S) observation at ATLAS**

- select B_c candidates ±3 sigma from centre of the Gaussian peak

- B_c(2S) candidate:
  - 3 tracks from B_c and two tracks (2\pi) fitted simultaneously
  - must intersect in two different vertices
  - momentum of B_c candidate must point to the pions vertex

- extended unbinned maximum likelihood fit in mass difference spectrum to extract number of B_c(2S)
B_c(2S) observation at ATLAS

- peak at $Q = 288.3 \pm 3.5_{\text{stat}} \pm 4.1_{\text{syst}}$ MeV
- corresponds to mass $m(B_c(2S)) = 6842 \pm 4_{\text{stat}} \pm 5_{\text{syst}}$ MeV
  - no $B_c^*(2S)$ hypothesis
  - consistent with theory [6835,6917] MeV
- significance:
  - 5.2 sigma combining 7 and 8 TeV
  - first observation of $B_c$ excited state
- similar analysis recently performed by LHCb (arXiv:1712.04094)
  - no evidence found
- further studies underway
Search for a structure in $B^0_s \pi^\pm$ spectrum

- D0 published evidence of $X(5568)$ state in the $B^0_s \pi^\pm$ spectrum via:
  - $B^0_s \to J/\Psi (\mu \mu) \phi (K K)$
  - $B^0_s \to \mu^+ D^+_s (\phi [KK] \pi^-) X$
    - $X = $ neutrino

- $m = 5567.8^{+2.9}_{-1.9} \text{ stat} +^{0.9}_{-1.9} \text{ MeV}$
- $\Gamma = 21.9^{+6.4}_{-2.5} \text{ stat} +^{5.0}_{-2.5} \text{ MeV}$
- significance 5.1$\sigma$

- interpreted as a tetraquark made of 4 different quarks ($b, s, u, d$)

arXiv:1712.10176
tetraquark search at ATLAS

• Search for tetraquarks in $B^0_s \pi^{\pm}$ decays in ATLAS

• exploit well know $B^0_s$ decay
  • $B^0_s \rightarrow J/\Psi(\mu\mu)\phi(KK)$

• Paper accepted by PRL. E-print: https://arxiv.org/abs/1802.01840
**tetraquark search at ATLAS**

- unbinned extended maximum likelihood fit on $B^0_s \rightarrow J/\Psi \phi$
  - $m_{fit}(B^0_s) = 5366.6 \pm 0.1_{stat} \text{ MeV}$

- fit model
  - sig: double gaussian
  - bkg: exponential

- keep events in $[5346.6, 5386.6] \text{ MeV}$ range for further investigation
  - fit: $N(B^0_s) = 52750 \pm 280_{stat}$
tetraquark search at ATLAS

- combine $B_0^s$ with tracks from same PV
  - pion hypothesis

- mass variable
  $m(J/\Psi K K \pi) - m(J/\Psi KK) + m_{\text{fit}}(B_0^s)$
  - $m_{\text{fit}}(B_0^s) = 5366.6$ MeV

- extended unbinned maximum likelihood fit on mass difference distribution
  - two fits $p_T(B) > 10$ GeV, $p_T(B) > 15$ GeV
  - as performed by other experiments
tetraquark search at ATLAS

- no significant $X(5568)$ signal observed

- fitted $X(5568)$ yield:
  - $N(X) = 60 \pm 140$ ($p_T(B) > 10$ GeV)
  - $N(X) = -30 \pm 150$ ($p_T(B) > 15$ GeV)
  - stat only

95%CL upper limits
- $N(X) < 382$ ($p_T(B) > 10$ GeV)
- $N(X) < 356$ ($p_T(B) > 15$ GeV)
- stat + syst

ATLAS
- $\sqrt{s} = 7$ TeV, $4.9$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $19.5$ fb$^{-1}$
- $p_T(B) > 10$ GeV
- $D_0$ peak

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tetraquark search at ATLAS

- extract 95% CL upper limits on production rate
- Measure relative to $B^0_s$, for $p_T(B) > 10$ GeV:

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

- Signal: Breit-Wigner (D0 observation)
- scan range 5550 - 5700 MeV every 5 MeV
- systematic uncertainties included
tetraquark search at other experiments

- X(5568) has been searched also by other collider experiments

X(5568) signal observed


CDF

D0

ATLAS

CMS

LHCb

CDF

LHCb $p_T(B^0_s) > 10$ GeV

no significant X(5568) signal observed

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\rho_X$</th>
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<tbody>
<tr>
<td>D0</td>
<td>$(8.6\pm1.9\pm1.4)%$</td>
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<tr>
<td>ATLAS</td>
<td>&lt; 0.015</td>
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<tr>
<td>CMS</td>
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<td>LHCb</td>
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<tr>
<td>CDF</td>
<td>&lt; 0.067</td>
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</table>
conclusions

• $B_c$ meson excited state $B_c(2S)$ observed at ATLAS
  • process: $B^\pm_c(2S) \rightarrow B^\pm_c (J/\Psi[\mu\mu] \pi^\pm) \pi\pi$
  • more studies on this new state underway

• ATLAS has searched for the new structure reported by D0
  • called $X(5568)$
  • exploit $X(5568) \rightarrow B^0_s (J/\Psi [\mu \mu] \phi[K K]) \pi^\pm$ channel
  • no significant signal observed
  • upper limits set
BACKUP
B_{c}(2S) observation at ATLAS
event selection

• selection optimised separately for the two datasets because of:
  • change in center of mass energy
  • change in pile-up conditions
• differences between the cuts applied on the datasets:

7 TeV dataset

• pion from B_{c} decay
  • d_{0}/\sigma(d_{0}) > 5
• PV identification:
  • PV with highest \Sigma p_{T}^{2}
• J/\Psi vertex fit:
  • \chi^{2}/NDOF < 2

8 TeV dataset

• pion from B_{c} decay
  • d_{0}/\sigma(d_{0}) > 4.5
• PV identification:
  • closest PV in 3D from reconstructed B_{c} decay vertex
• J/\Psi vertex fit:
  • \chi^{2}/NDOF < 1.5