Heavy flavour studies with the ATLAS detector

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ATLAS detector

Inner Detector: tracking, momentum and vertex measurement
- $|\eta| < 2.5$, $d_0$ resolution $\sim 10 \ \mu m$

Muon Spectrometer: trigger and muon identification
- $|\eta| < 2.7$

Mass resolution $\sigma(m_{J/\psi}) = 60 \pm 1 \ \text{MeV}$

\[ \int \mathcal{L} \ dt = 0.24 \ \text{fb}^{-1} \]

\[ N_{J/\psi} = (2.208 \pm 0.002) \times 10^6 \]
\[ m_{J/\psi} = 3.094 \pm 0.003 \ \text{GeV} \]
\[ \sigma_{m_{J/\psi}} = 60 \pm 1 \ \text{MeV} \]
Trigger and dataset

B-physics trigger:
- muons, di-muon decays ($J/\psi$, $\Upsilon$)
- L1: single and di-muon triggers (threshold from $p_T = 4\text{GeV}$)
- L2 and EF: muons from common vertex, opposite charge
- invariant mass window of $J/\psi$, $B$ and $\Upsilon$ un-prescaled in 2011
- 2012: added barrel-only triggers to keep a larger fraction of data

Datasets for analyses shown here:
- 2011 dataset at $\sqrt{s} = 7\text{ TeV}$, recorded $\int L = 5.08\text{ fb}^{-1}$
- 2012 dataset at $\sqrt{s} = 8\text{ TeV}$, recorded $\int L = 21.3\text{ fb}^{-1}$
- presenting selected recent results only, all results on https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
Associated production of prompt and non-prompt $J/\psi$ mesons and $Z$ boson
Associated production of quarkonia with additional objects on LHC:
- single parton scattering (SPS)
- double parton scattering (DPS)

Event selection: \( J/\psi \rightarrow \mu^+\mu^- \), \( Z \rightarrow e^+e^- \) or \( \mu^+\mu^- \)
- \( Z \): muons \( p_T > 24 \) GeV or electrons \( p_T > 15 \) GeV, isolation requirement on leptons and trigger match for at least 1 lepton
- \( m(Z_{\text{cand}}) = m(Z_{\text{PDG}}) \pm 10 \) GeV
- \( J/\psi \): \( p_T > 8.5 \) GeV, \( |\eta| < 2.1 \), leading muon \( p_T > 4 \) GeV,
- dataset 2012, 20.3 \( fb^{-1} \)
Associated production of $J/\psi$ and $Z$

Fit $J/\psi$ mass and pseudo-proper time:

Prompt $J/\psi + Z$:
- $56 \pm 10 \pm 3$ events
- significance $> 5\sigma$

Non-prompt $J/\psi + Z$:
- $95 \pm 12 \pm 8$ events
- significance $> 9\sigma$

Azimuthal angle between $J/\psi$ and $Z$:
- DPS expecting flat
- SPS peaking at high $\Delta \phi$
Associated production of $J/\psi$ and $Z$

- normalised to the inclusive $Z$ cross-section
- fiducial, inclusive (SPS+DPS) and DPS-subtracted cross-section
- compared to theoretical predictions (LO colour-singlet mechanism, NLO colour singlet and colour octet)
- models underestimate the SPS contribution

![Graph](https://via.placeholder.com/150)

**ATLAS, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$**

$pp \rightarrow$ prompt $J/\psi + Z : pp \rightarrow Z$

$|y_{J/\psi}| < 2.1, 8.5 < p_T^{J/\psi} < 100$ GeV

Data

- Spin-alignment uncertainty

- NLO NRQCD CS
- NLO NRQCD CO
- NLO NRQCD CO+CS
- LO CSM

![Graph](https://via.placeholder.com/150)

**ATLAS, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$**

$pp \rightarrow$ non-prompt $J/\psi + Z : pp \rightarrow Z$

$|y_{J/\psi}| < 2.1, 8.5 < p_T^{J/\psi} < 100$ GeV

Data

- Spin-alignment uncertainty

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Associated production of $J/\psi$ and $Z$

Measured differential production cross-section as a function of $p_T$ (again normalised to the inclusive $Z$ cross-section)

![Graph 1: $J/\psi + Z$ production](image1)

![Graph 2: $J/\psi + Z$ production](image2)

**ATLAS**, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

$pp \rightarrow$ prompt $J/\psi+Z : pp \rightarrow Z$

$pp \rightarrow$ non-prompt $J/\psi+Z : pp \rightarrow Z$

Data
Spin-alignment uncert.
Total theoretical uncert.
NLO NRQCD CO
NLO NRQCD CS
DPS uncert.
Estimated DPS contrib.

$B(J/\psi \rightarrow \mu\mu) \times \frac{1}{\sigma(Z)}$

$p_T^{J/\psi}$ [GeV]

$B(J/\psi \rightarrow \mu\mu) \times \frac{1}{\sigma(Z)}$

$p_T^{J/\psi}$ [GeV]

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Associated production of $J/\psi$ and $Z$

- can set upper limit on DPS contribution (assuming independent hard scattering in DPS)
- that gives lower limit on effective cross-section of DPS

$$\sigma_{\text{eff}} > 5.3 \ (3.7) \ \text{mb at 68 (95)}\% \ \text{C.L.}$$
Parity-violating asymmetry parameter $\alpha_b$ and helicity amplitudes of $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
$\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-) \Lambda^0(p\pi^-)$ helicity

Selection:
- $J/\psi$: $2.8 \text{ GeV} < m_{\mu\mu} < 3.4 \text{ GeV}$
- $\Lambda^0$: $1.08 \text{ GeV} < m_{hh} < 1.15 \text{ GeV}$
- $\Lambda_b^0$: $5.56 \text{ GeV} < m_{J/\psi^0} < 5.68 \text{ GeV}$
- cascade topology: $\chi^2/N_{dof} < 3$, $L_{xy} > 10 \text{ mm}$, $\tau_{\Lambda_b} > 0.35 \text{ ps}$
- $1400 \Lambda_b^0$ and $\bar{\Lambda}_b^0$ in 2011 dataset

Analysis:
- decay described by 4 helicity amplitudes
- parity violating asymmetry parameter
  $$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$
- full angular PDF
- used method of moments $F_i$
- lifetime and mass measurement in Phys. Rev. D87 (2013) 032002
Check fit: compared $F_i$ for data with weighted signal+background MC

Results:

\[
|a_+| = 0.17^{+0.12}_{-0.17}\text{(stat)} \pm 0.09\text{(syst)}
\]

\[
|a_-| = 0.59^{+0.06}_{-0.07}\text{(stat)} \pm 0.03\text{(syst)}
\]

\[
|b_+| = 0.79^{+0.04}_{-0.05}\text{(stat)} \pm 0.02\text{(syst)}
\]

\[
|b_-| = 0.08^{+0.13}_{-0.08}\text{(stat)} \pm 0.06\text{(syst)}
\]

\[
\alpha_b = 0.30 \pm 0.16\text{(stat)} \pm 0.06\text{(syst)}
\]

- $\Lambda^0$ and $J/\psi$ are highly polarized in direction of their momenta
- $\alpha_b$ value consistent with LHCb:
  \[0.05\pm0.17\text{(stat)}\pm0.07\text{(syst)}\]
- inconsistent with pQCD
  $\alpha_b=\left(-0.17,-0.14\right)$ and HQET $\alpha_b=0.78$
  at a level of 2.6 and 2.8$\sigma$
Study of the $B_{c}^{+} \rightarrow J/\psi D_{s}^{+}$ and $B_{c}^{+} \rightarrow J/\psi D_{s}^{*+}$ decays
$B^+_c \rightarrow J/\psi D^+_s$ and $B^+_c \rightarrow J/\psi D^{*+}_s$ decays

$B^\pm_c$ is an interesting object with two different heavy-flavour quarks

- decay $B^\pm_c \rightarrow J/\psi (\mu^+ \mu^-) \pi^\pm$ observed in 2011 data (ATLAS-CONF-2012-028)
- process $\bar{b} \rightarrow \bar{c} c \bar{s}$ allows $B^+_c$ decay to charmonium and $D^{(*)}_s$
- subsequent $D^{*+}_s \rightarrow D^+_s (\gamma/\pi^0)$ and $D^+_s \rightarrow \phi (K^+ K^-) \pi^+$
- $B^+_c \rightarrow J/\psi D^{*+}_s$ helicity amplitudes: $A_{++}$, $A_{--}$ and $A_{00}$
$B_c^+ \rightarrow J/\psi(\mu^+\mu^-)D_s^+(K^+K^-\pi^+) \text{ event selection}$

**$J/\psi$:**
- 2 muons $p_T > 3$ GeV
- $\chi^2$/n.d.f($J/\psi$) < 15
- $m(J/\psi)$ in 2800–3400 MeV

**$D_s^+$:**
- 3 tracks fitted to common vertex
- tracks $p_T > 1$ GeV
- $\chi^2$/n.d.f < 8
- $m(K^+K^-)$ within $\pm$ 7 MeV from $m_{PDG}$
- $m(K^+K^-\pi^+) = 1930$–2010 MeV
- 0.15 mm < $L_{xy}$ < 10 mm
- pion pointing angle: $\cos \theta^* < 0.8$
- $|\cos^3 \theta(K\pi)| > 0.15$ in c.m.s ($\phi$)

**$B_c^+$: fitting cascade decay**
- constraining $J/\psi$ and $D_s^+$ masses to PDG values
- $\chi^2$/n.d.f < 3
- $p_T > 15$ GeV
- $d_0 < 0.1$ mm; $z_0 \cdot \sin \theta < 0.5$ mm
- 0.1 mm < $L_{xy}$ < 10 mm
- $D_s^+$ pointing: $\cos \theta^* > -0.8$
- 1547 $J/\psi D_s^+$ candidates selected
\[ B^+_c \rightarrow J/\psi D_{s}^{(*)+} \text{ fit} \]

2D unbinned maximum likelihood fit of mass and helicity angle \( \theta'(\mu^{+}) \):
- \( B^+_c \rightarrow J/\psi D_s^+ \) signal
- \( B^+_c \rightarrow J/\psi D_{s}^{*+} \) with \( A_{\pm\pm} \)
- \( B^+_c \rightarrow J/\psi D_{s}^{*+} \) with \( A_{00} \)
- background

Measured transverse polarisation fraction of \( B^+_c \rightarrow J/\psi D_{s}^{*+} \)

\[ \Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23 \text{ (stat) } ^{+0.06}_{-0.07} \text{ (syst)} \]
$B_c^+ \rightarrow J/\psi D_s^{(*)+}$ branching fraction ratios

Ratios of branching fractions with $B_c^+ \rightarrow J/\psi \pi^+$ as reference decay:

$$\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 3.8 \pm 1.1 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.2 (\mathcal{B}_{D_s})$$

$$\mathcal{R}_{D_{s^*}^+/\pi^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 10.3 \pm 3.1 \text{ (stat)} \pm 0.8 \text{ (syst)} \pm 0.6 (\mathcal{B}_{D_s})$$

Ratio of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ branching fractions:

$$\mathcal{R}_{D_{s^*}^+/D_s^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.7 \pm 1.1 \text{ (stat)} \pm 0.4 \text{ (syst)}$$
Observation of an excited $B^\pm_c$ meson state
Excited states of $B_c^{\pm}$ are predicted by NRQCD, pQCD and Lattice:

- 1S and 2S states have a mass splitting for $0^+$ and $0^-$ components
- ATLAS not sensitive enough to distinguish them: missing soft gamma, mass resolution
\( B_c^{\pm}(1S) \rightarrow J/\psi(\mu^+\mu^-)\pi^{\pm}: \) selection and fit

\( B_c^{\pm}(1S) \) selection optimised separately for 2011 (2012) dataset:
- \( p_T(\mu) > 4 \) and 6 GeV
- \( \chi^2/\text{n.d.f} (J/\psi) < 15 \)
- \( m(J/\psi) \) 3\( \sigma \) from nominal mass
- \( \chi^2/\text{n.d.f} (B_c) < 2.0 \) (1.5)
- \( p_T(B_c) > 15 \) (18) GeV
- \( d_{xy}^0/\sigma(d_{xy}^0)(\pi^+) > 5 \) (4.5)

Unbinned fit of mass distribution:
- Gaussian with per-candidate error
- exponential background

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

Candidate selection:
- $B_c^{\pm}(1S)$ within $3\sigma$ from fitted mass
- $p_T(\pi^{\pm}) > 400$ MeV
- if several candidates per event, select the one with the best cascade fit $\chi^2$

Extended unbinned fit of $Q$-value:

$$Q_{B_c^{\pm}\pi\pi} = m(B_c^{\pm}\pi\pi) - m(B_c^{\pm}) - 2m(\pi)$$

- Gaussian signal
- 3rd order polynomial for background
Observation of an excited $B_c^\pm$ state

Significance calculated using toy studies to account for "look elsewhere effect"
- $3.7\sigma$ in 7 TeV data
- $4.5\sigma$ in 8 TeV data
- combined significance is $5.2\sigma$

Observed new state at

$$Q = 288.3 \pm 3.5 \text{ (stat)} \pm 4.1 \text{ (syst)} \text{ MeV}$$

corresponding to a mass

$$m = 6842 \pm 4 \text{ (stat)} \pm 5 \text{ (syst)} \text{ MeV}$$

consistent value of 6835–6917 MeV predicted by various theories
Search for $X_b$ and other hidden-beauty states using $\pi^+\pi^- \Upsilon(1S)$ channel
Search for $X_b$

Heavy-quark symmetry suggests existence of $X_b$ analogous to $X(3872)$ observed by Belle in $B^+ \rightarrow K^+ X(3872)$ with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ (Phys. Rev. Lett. 91 (2003) 262001)

- search for $X_b$ in $\Upsilon(nS)\pi^+\pi^-$
- mass predictions around 10.5 GeV

Data and selection:
- selected by di-muon trigger with $p_T > 4$ GeV, $m(\mu\mu) = 8$-12 GeV
- 16.2 fb$^{-1}$ at 8 TeV
- reconstructed 6 million $\Upsilon(1S)$ and 0.2 million $\Upsilon(2S)$ candidates

Expected number of $X_b$ events

$$N = N_{2S} \cdot R \cdot \frac{A}{A_{2S}} \cdot \frac{\varepsilon}{2\varepsilon_{2S}}$$

where $R \equiv (\sigma B)/(\sigma B)_{2S}$ is production rate relative to $\Upsilon(2S)$
bin data according to $S/B$ in $p_T$ and $\cos(\theta)$

$\Upsilon(1S) \pi^+ \pi^-$ mass distribution for most sensitive bin – $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks

invariant mass fits for $\Upsilon(2S)$ (barrel, endcap) and $\Upsilon(3S)$:
no evidence for $X_b$ found

considered also different spin alignments for $X_b$

upper limits 0.8-4% (depending on mass) - currently the best limits

no evidence for production of $\Upsilon(1^3D_J)$ triplet, $\Upsilon(10860)$ or $\Upsilon(11020)$
B-physics programme will follow the Run 1 approach:
- precision measurements of rare processes, focus on potential beyond-SM effects
- heavy flavour production at 13 TeV
- searches for new and exotic states and decay modes

Detector upgrades during long shutdowns:
- already installed IBL, additional muon chambers, consolidation
  – improved tracking, impact parameter and decay time resolution
- study potential for CPV measurements, e.g. $B_s^0 \rightarrow J/\psi \phi$

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<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2015-17</th>
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<tbody>
<tr>
<td>Detector</td>
<td>current</td>
<td>current</td>
<td>IBL</td>
</tr>
<tr>
<td>Average interactions per BX $&lt;\mu&gt;$</td>
<td>6-12</td>
<td>21</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity, fb$^{-1}$</td>
<td>4.9</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Di-$\mu$ trigger $p_T$ thresholds, GeV</td>
<td>4 - 4(6)</td>
<td>4 - 6</td>
<td>6 - 6</td>
</tr>
<tr>
<td>Signal events per fb$^{-1}$</td>
<td>4 400</td>
<td>4 320</td>
<td>3 280</td>
</tr>
<tr>
<td>Signal events</td>
<td>22 000</td>
<td>86 400</td>
<td>327 900</td>
</tr>
<tr>
<td>Total events in analysis</td>
<td>130 000</td>
<td>550 000</td>
<td>1 874 000</td>
</tr>
<tr>
<td>MC $\sigma(\phi_s)$ (stat.), rad</td>
<td>0.25</td>
<td>0.12</td>
<td>0.054</td>
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The large amount of Heavy Flavour data collected by ATLAS is potentially sensitive to New Physics. Presented analyses:

- associated production of $J/\psi$ and $Z$
- asymmetry parameter and helicity amplitudes of $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
- $B^+_c \rightarrow J/\psi D_s^{*-}$
- $B^\pm_c$ (2S) observation
- search for $X_b \rightarrow \Upsilon(nS)\pi^+\pi^-$

Few more measurements and searches from Run1 dataset to be completed soon and we are collecting first data from Run2.

Thank you for your attention.
Backup slides
Associated production of $W$ and prompt $J/\psi$

Probes quarkonium production mechanism, sensitive to multiple parton interactions.

Selection:
- prompt $J/\psi$ via mass and pseudo-proper time
- $W^{\pm}$ muon trigger, identified by $\mu$ and missing $p_T$
- fit $W^{\pm}$ transverse mass with multijet background
- 29 events with $W^{\pm}$ $J/\psi$
Associated production of $W$ and prompt $J/\psi$

- double parton scattering estimate $\sim 40\%$ from
  \[ d\sigma_{J/\psi|W} = \sigma_W \otimes \sigma_{J/\psi}/\sigma_{\text{eff}} \]
- extract inclusive (SPS+DPS) cross-section ratio
- comparison with theory: measured rate underestimated (but large uncertainties of data)

![Graph showing ATLAS preliminary data for $W + \text{prompt J}/\psi$](image)

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30.6.2015
$B^0_s \rightarrow J/\psi\phi$ analysis

- tagged analysis using 2011 data (4.9 fb$^{-1}$)
- measured

$$\phi_s = 0.12 \pm 0.25 \text{ (stat)} \pm 0.05 \text{ (syst) rad}$$

$$\Delta \Gamma_s = 0.053 \pm 0.021 \text{ (stat)} \pm 0.010 \text{ (syst) ps}^{-1}$$

- about to release analysis using 2012 data