RECENT RESULTS ON HADRON SPECTROSCOPY AND STRUCTURE FROM ATLAS

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Presentation Outline

- The ATLAS Experiment overview
- Recent run 1 results
  - Associated production of $J/\psi$ and vector boson
  - Measurements of properties of $B_c$, $B_s$, and $B_d$ mesons
    - Branching fractions and polarization of $B_c \rightarrow J/\psi D_s$ and $B_c \rightarrow J/\psi D_s^*$
    - Observation of an excited $B_c$ meson state
    - $\phi_s$ and $\Delta \Gamma_s$ from flavor-tagged time-angular analysis of $B_s \rightarrow J/\psi \phi$
    - Measurement of b-quark fragmentation fraction ratio $f_s / f_d$
  - Baryon studies
    - Measurement of the $\Lambda^0$ polarization
    - Observation and branching fraction of $\Lambda_b \rightarrow \psi(2S) \Lambda$ decay
    - Search for a hidden beauty using $\Upsilon(1S) \pi \pi$ final state
    - Differential prompt and non-prompt $J/\psi$ and $\psi(1S)$ cross-section
- Run 2 results: $J/\psi$ relative cross-section at 13 TeV
- Summary and conclusions
ATLAS Experiment

- Muon reconstruction from **Muon Spectrometer** and **Inner Detector** tracking
- ID tracks (from muons) provides **precision momentum** and **lifetime** measurements

### Muon Spectrometer

<table>
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<tr>
<th>Toroid B-Field, average</th>
<th>0.5 T</th>
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<td>$</td>
<td>\eta</td>
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<td>Track momentum resolution</td>
<td>$\sigma/p &lt; 10%$ up to 1 TeV</td>
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### Inner Detector

- **Axial Magnetic field**
  - 2 T
- **Track momentum resolution**
  - $\sigma/pT^2$ [GeV]$^{-1}$
  - $\sim 0.05p_T + 0.015$
- **Lifetime resolution**
  - $<100 \text{ fs} \Rightarrow 50 \text{ fs}$
The ATLAS Experiment

Run 1 and 2 trigger

- 3 level trigger system
- Trigger rate reduction: 20MHz → 200Hz (~1kHz for run 2)
- Primary B-phys triggers: \( J/\psi(\mu\mu) \) and \( \Upsilon(\mu\mu) \)
  - Two muons @ level 1
  - Confirmed at level 2 and 3
  - Vertexing & inv. mass selection (but no lifetime cut)
- Typical thresholds:
  - Run 1: \( p_T(\mu) > 4 \) GeV or 6 & 4 GeV
  - Run 2: \( p_T(\mu) > 6 \) GeV plus additional selection @ level 1

ID run 2 upgrade

- Insertable b-layer
- Expected improvement in impact parameter resolution

ATLAS simulation
Preliminary

https://cds.cern.ch/record/1604429
Analyses overview
Associated production

- Measurements of production of $J/\psi$ and vector boson:
  - Prompt $J/\psi + W$ [JHEP 04 (2014) 172]

- Tests of QCD at the perturbative boundary

- Prompt color octet & color singlet production contributions uncertain

- Double parton scattering (DPS) contribution – $J/\psi$ and VB from two parton interaction
Associated production: $J/\psi + W$

- **DPS contribution** (rate estimated from $\sigma_{\text{eff}}$ value from $W+2j$):
  - Assuming independence of the two scatters
  - Assuming universality of $\sigma_{\text{eff}}$
- **SPS** theory **CS and CO** contributions both underestimated
  - Higher-order corrections may be needed
  - DPS contribution may need to be modified
Associated production: $J/\psi + Z$

- Observation of $Z + J/\psi$ in both prompt ($5\sigma$) and non-prompt ($9\sigma$) modes
- **Differential** relative cross-section measured v. $p_T(J/\psi)$
- DPS contributes to both prompt and non-prompt modes
- For prompt mode both CO and CS predictions underestimate data
  - Higher-order corrections may be needed
  - DPS contribution may need to be modified
Branching fractions of $B_c \rightarrow J/\psi \, D_s^{(*)}$

- $B_c$ consists of two heavy quarks that decay weakly
- Its decay to $J/\psi \, D_s$ offers test of various theoretical predictions
- Reconstruction: $B_c \rightarrow J/\psi \, D_s^{(*)}$ with $D_s^{(*)} \rightarrow \phi(KK) \, \pi$ ($+\text{soft} \, \pi^0 \text{or} \, \gamma \text{undetected}$)
- Measured relative branching ratios & transverse polarization of $D_s^{(*)}$
The polarization is found to be well described by the available theoretical approaches.

The measured ratios of the branching fractions are generally well described by pQCD, sum rules and relativistic quark models.

Results agree with the measurement by the LHCb.
Excited $B_c$ meson

- Reconstruction of $B_c(J/\psi \pi) + \pi \pi$ final state
- Observation ($5.2\sigma$) of new structure with the invariant mass $m(B_c\pi\pi) = 6842 \pm 4$ (stat) $\pm 5$ (syst) MeV
- Consistent with prediction of $B_c(2S)$ meson
CPV phase with $B_s \to J/\psi \phi$

- **Mixing** between $B_s$ and anti-$B_s$ → two mass eigenstates
- **Interference** between mixing and direct decay → CP violation
- CPV depends on weak phase $\phi_s$
- In SM: $\phi_s^{(SM)} \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ rad
- Phase is sensitive to BSM physics
- Reconstruction of $B_s \to J/\psi(\mu\mu) \phi(KK)$
  - 3 decay angles
  - Time dependent analysis to distinguish CP-odd and even eigenstates
  - Flavor tagged analysis to identify flavor at the point of production

\[ V_{us} V_{ub}^{*} \left| \frac{V_{ts} V_{tb}^{*}}{V_{cs} V_{cb}^{*}} \right| \sim 1 \]

\[ (0,0) \sim (\rho, \eta) \]
CPV phase with $B_s \rightarrow J/\psi \phi$

- Unbinned likelihood function: 9 physics parameters
- Observables: $m(J/\psi KK)$, $t$, $\sigma(t)$, 3 angles, and $P_{\text{tag}}$
- Using 14.3 fb$^{-1}$ of 8 TeV data statistically combined with 4.9 fb$^{-1}$ of 7 TeV data
- Preliminary result:
  \[ \phi_s = -0.094 \pm 0.083 \pm 0.033 \text{ rad} \]
  \[ \Delta \Gamma = 0.082 \pm 0.011 \pm 0.007 \]

- Consistent with other experiments and SM prediction

\[ \varphi_s^{(\text{SM})} = -0.0363^{+16}_{-15} \text{ rad.} \]
\[ \Delta \Gamma_s^{(\text{SM})} = 0.087 \pm 0.021 \text{ ps}^{-1} \]
Fragmentation function ratio $f_s / f_d$ 

- Integrated fragmentation functions needed for studies like $B_s \rightarrow \mu\mu$
- Measured using decays $B_s \rightarrow J/\psi \phi$ and $B_d \rightarrow J/\psi K^*$
- Branching fractions $BR(B_s \rightarrow J/\psi \phi) / BR(B_d \rightarrow J/\psi K^*)$ obtained from arXiv:1309.0313v2 [PRD 89 (2014) 094010]
- Result: $f_s / f_d * BR(B_s) / BR(B_d) = 0.199 \pm 0.004({\text{stat}}) \pm 0.010({\text{sys}})$
  
  $$f_s / f_d = 0.240 \pm 0.004({\text{stat}}) \pm 0.013({\text{syst}}) \pm 0.017({\text{th}})$$
- No evident $p_T$ and $\eta$ dependence
**Λ^0 polarization**

- **Polarization** of inclusively produced hyperons not yet understood
- **Measurement:**
  - Reconstructing decays $Λ \to p \pi$ in the 7 TeV minimum bias sample (760 µb^{-1})
  - **Transverse polarization** of $Λ^0$ measured as a function of $p_T$ and $x_F = p_z / p_{beam}$
- Measured polarization consistent with 0 – in agreement with expectations from extrapolation of the previous experiments
Observation of $\Lambda_b \rightarrow \psi(2S) \Lambda$

- First observation of $\Lambda_b \rightarrow \psi(2S) \Lambda$ decay with
  - $\psi(2S) \rightarrow \mu\mu$
  - $\Lambda \rightarrow \rho\pi$
- **Reference** channel: $\Lambda_b \rightarrow J/\psi \Lambda$
- Using 20 fb$^{-1}$ of 8 TeV data
- Kinematic range $p_T(\Lambda_b) > 10$ GeV and $|\eta(\Lambda_b)| < 2.1$

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**Graphs:**
- **Left graph:**
  - ATLAS
  - $\sqrt{s} = 8$ TeV, 20.6 fb$^{-1}$
  - $\Lambda_b^0 + \bar{\Lambda}_b^0$
  - $N_{\text{sig}} = 724 \pm 45$
  - Data, Fitted model, $\psi(2S)$ signal, Background

- **Right graph:**
  - ATLAS
  - $\sqrt{s} = 8$ TeV, 20.6 fb$^{-1}$
  - $\Lambda_b^0 \rightarrow \psi(2S) \Lambda^0$
  - $N_{\text{sig}} = 702 \pm 38$
  - Data, Fitted model, $\Lambda^0$ signal, Background
Observation of $\Lambda_b \rightarrow \psi(2S) \Lambda$

- **Result:**

$$\frac{\Gamma[\Lambda_b \rightarrow \psi(2S) \Lambda]}{\Gamma(\Lambda_b \rightarrow J/\psi \Lambda)} = 0.501 \pm 0.033\text{(stat)} \pm 0.016\text{(syst)} \pm 0.011\text{(br)}$$

- **Consistent** with ratios from other $B$ decays $\approx 0.5 - 0.8$

- **Comparable** with theoretical prediction $\approx 0.8$
Hidden Beauty in $\Upsilon(1S) \pi \pi$

- **Looking for signal in** $\Upsilon(1S) \pi \pi$ **final state with** $\Upsilon \to \mu\mu$
  - Known bottomonium resonances $\Upsilon(2S)$ and $\Upsilon(3S)$ – excluded from the signal region
  - **Search for** $X_b$, an analogue to $X(3872)$ – which is still a mystery
  - Search for higher-mass bottomonium resonances $\Upsilon(1^3D_J)$, $\Upsilon(10860)$ and $\Upsilon(11020)$

- Analysis using 16.2 fb$^{-1}$ of 8 TeV data
- **Observable**: cross-section ratio relative to $\Upsilon(2S)$

\[
R = \frac{\sigma \cdot B}{\sigma_{2S} \cdot B_{2S}}
\]
Hidden Beauty in $\Upsilon(1S) \pi \pi$

- **Search strategy:**
  - Hypothesis tests with $m_{\text{hypo}}$ in 10 MeV steps in range 10 – 11 GeV
  - Mass window $m_{\text{hypo}} \pm 8\sigma$
  - Simultaneous fit in 8 regions of $|y|$, $p_T$, and $\cos\theta^*$

- **Most sensitive production search** in mass range $m > 10.1$ GeV
- **Limits** on $R$ of 0.8 – 4% at 95% CLs. Excludes $X_b$ analogous to $X(3872)$
- **No evidence** for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances
- Isotropic angular distribution hypothesis – shifts for alternative polarization scenarios indicated
Measurement of quarkonia provides insight into QCD at the boundary of perturbative regime

Production modes – separated using proper decay time
- **Prompt** – directly at the interaction point (QCD)
- **Non-prompt** – from $b$ decays

Previous measurements with 7 and 8 TeV data (2.5 fb$^{-1}$ and 11.4 fb$^{-1}$):
- prompt and non-prompt differential cross-sections of $J/\psi$ and $\psi(2S)$ in the dimuon decay mode
  - $\psi(2S)$: no significant feed-down – possibility to study $J^{PC}=1^{--}$ states
  - $J/\psi$: contributions from $1^{--}$ and $J^{++}$ in comparable amounts
- Prompt production shows fair agreement with NLO NRQCD
- Non-prompt production generally good agreement
  - Theory predicts slightly harder $p_T$ spectrum for $J/\psi$
  - Theory predicts slightly larger yields for $\psi(2S)$
- Overall good agreement over several orders of magnitude of cross-section
Prompt $J/\psi$ cross-section

**Cross-section**

**Data / NRQCD prediction**

*ATLAS Preliminary*

$s=8$ TeV, 11.4 fb$^{-1}$

Prompt $J/\psi$

$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \frac{d^2\sigma}{dy}$ (nb GeV$^{-1}$)

- data $x 10^7$, $y=2.00$
- data $x 10^6$, $y<1.75$
- data $x 10^5$, $y<1.50$
- data $x 10^4$, $y<1.25$
- data $x 10^3$, $y<1.00$
- data $x 10^2$, $y<0.75$
- data $x 10^1$, $y<0.50$
- data $x 10^0$, $y<0.25$
- NRQCD Prediction

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Prompt $\psi(2S)$ cross-section

Cross-section

Data / NRQCD prediction
Non-prompt $J/\psi$ cross-section

Cross-section

Data / NRQCD prediction
$J/\psi$ non-prompt fraction @ 13 TeV

- Measured **fraction of non-prompt** $J/\psi$'s relative to the prompt ones
- Analyzed 6.5 pb$^{-1}$ of **13 TeV data**, $\mu \approx 27$
- **No significant change** in fraction with rapidity or between 7 and 13 TeV
- Measurement of the non-prompt fraction between 2.76 – 13 TeV from a single experiment
Summary and Conclusions

- Significant contribution of Run 1 b-physics program
  - Observation and search for new states
  - Precise mass, lifetime and branching fractions measurements
  - Search for new physics using rare decays and CPV

- Quarkonium sector explored in variety of decay modes and production processes

- Run 2 detector upgrade
  - Insertable B layer offers potential for much improved tracking
  - Upgrade to trigger system provides reduced background rates through topological constraints on B-Physics signatures allowing for lower kinematic thresholds than otherwise possible

- No significant deviations from SM expectations observed