Inclusive production of quarkonium in ATLAS

Konstantin Toms
on behalf of the ATLAS Collaboration

University of New Mexico
Outline

• The ATLAS detector @ LHC

• Recent ATLAS results covered in this talk:
  – b-hadron pair production cross-section @ 8 TeV
  – quarkonium production in p-Pb and pp @ 5.02 TeV

• Conclusions
The ATLAS detector @ LHC

- Subsystems essential for B-physics: Inner detector and Muon spectrometer.
- Inner detector: tracking, momentum and vertexing, $|\eta|<2.5$, $d_0$ resolution $\sim 10\mu m$.
- Muon spectrometer: trigger and muon identification, $|\eta|<2.7$.
- $J/\psi$ mass resolution: $60\pm1$ MeV, $\Upsilon(1S)$: $119\pm1$ MeV (depend on $\eta$).
b-hadron pair production cross-section

- **JHEP 11 (2017) 062**
- 11.4 fb\(^{-1}\) @ 8 TeV, luminosity uncertainty 1.9%
- **Motivation:**
  - test of QCD predictions
  - disagreements among theoretical predictions and between predictions and data
  - important background for Higgs production \((H \rightarrow b\bar{b})\) with association of a vector boson
Analysis overview (1)

• Search for $1^{st}$ $b \rightarrow J/\psi(\mu\mu)+X$, $2^{nd}$ $b \rightarrow \mu+X$
• Dimuon trigger, $p_T(\mu_1,\mu_2)>4$ GeV, $2.5<m(\mu\mu)<4.3$ GeV
• Primary vertex of at least two tracks with $p_T>400$ MeV
• Muon candidates are “dressed” by adding four-momenta of nearby photons ($\Delta R<0.1$)
• $J/\psi$ candidates are formed from oppositely charged muons, $p_T(\mu)>6$ GeV, $|\eta|<2.3$, $2.6<m(J/\psi)<3.5$
• In case of multiple $J/\psi$ candidates per event the one with the mass closest to the world average is chosen
• Third muon: the one with the highest $p_T$ which is not included in the $J/\psi$ reconstruction
• The $J/\psi$ and the third $\mu$ may come from feed-down or cascade decay
Analysis overview (2)

• $J/\psi$ candidates are required to be separated from the primary vertex

• Requirement on the pseudo-proper lifetime $\tau$, $\tau > 0.25$ mm/c ($\tau = L_{xy} m(J/\psi_{PDG})/p_T(\mu\mu)$)

• Simultaneous maximum likelihood fit is performed to the invariant mass of the muon pair and the pseudo-proper lifetime

• Various MC-based corrections:
  – trigger efficiency (including spatial resolution of the dimuon trigger and vertexing)
  – muon reconstruction efficiency (including “fake” muons from kaon/pion decays/punch-throughs
Results (1)

• Measured total cross-section in the fiducial region:
  \[ \sigma(B(\rightarrow J/\psi(\mu\mu)+X)B(\rightarrow \mu+X)) = 17.7 \pm 0.1^{\text{stat}} \pm 0.2^{\text{syst}} \ \text{nb} \]

• Various differential cross-sections compared to MC-generators output
  – separation between the J/\psi and the third \mu in the azimuth-rapidity plane (\Delta \phi(J/\psi, \mu), see next slide)
  – mass of the J/\psi\mu system
  – azimuthal separation \Delta \varphi between the J/\psi and the third \mu
  – transverse momentum \( p_T \) of the 3-muon system
  – rapidity separation \Delta y between the J/\psi and the third \mu
  – magnitude \( y_{\text{boost}} \) of the average rapidity of the J/\psi and the third \mu
  – ratio of the \( p_T \) to the invariant mass of the 3-muon system
  – ratio of the invariant mass of the 3-muon system to its \( p_T \)
Results (2)

• Comparison with Pythia 8: a set of production options for the $g \rightarrow b\bar{b}$ splitting kernel which dominates small-angle quarkonium production

• The shape of the angular distributions is not accurately predicted by any of the production options
• Comparison with HERWIG++, SHERPA, and MadGraph5_aMC@NLOv2.2 + PYTHIA8.186 parton shower model

• HERWIG++ has the best correspondence with data for ΔR and Δφ

• 4 massless flavours model has a better correspondence than 5 one for ΔR and Δφ

• $\Delta y$ distribution is well described by MADGraph and Sherpa

• 5-massless flavor MadGraph models low mass distribution better than 4,

• But 4-massless flavor MadGraph models high $p_T/m$ best.
Results (4)

• Among all of the distributions, the 4-massless flavour model gives the best correspondence with the data (MadGraph5_aMC@NLO +Pythia8)

• HERWIG++ and Pythia8 demonstrate compatible agreement with the data

• Among the various Pythia8 production options the $p_T$-based splitting kernel is the best one (option 4b)
Quarkonium production in p-Pb and pp

- 28 nb$^{-1}$ (p-Pb) and 25 pb$^{-1}$ (pp) @ 5.02 TeV
- Motivation:
  - QGP (quark-gluon plasma) is not expected to occur in p-Pb collisions, so one can study the effects of CNM (cold nuclear matter)
  - compare the production of $J/\psi$, $\psi(2S)$, $\Upsilon(1S,2S,3S)$
  - understand the background to QGP effects
Analysis overview (1)

• The double-differential cross section multiplied by the dimuon decay branching fraction is calculated for each measurement interval as:

\[
\frac{d^2 \sigma_{\Omega(nS)}}{dp_T dy^*} \times B(\Omega(nS) \rightarrow \mu^+ \mu^-) = \frac{N_{\Omega(nS)}}{\Delta p_T \times \Delta y \times L}
\]

• The \(y^*\) here is the center-of-mass p-Pb rapidity, which is shifted by \(\Delta y=0.465\) with respect to \(y\) in the laboratory rest frame
Analysis overview (2)

• Dimuon trigger: $p_T(\mu_1,\mu_2) > 4$ GeV
• Primary vertex is formed with at least 4 tracks, at least 2 muons with common vertex
• All muons with $|\eta| < 2.4$ are considered as quarkonium candidates
• $p$-Pb events are divided into “centrality class” – more participating nucleons leads to more transverse energy
• MC corrections for acceptance calculation: final state radiation, $p_T$, $\eta$, trigger and reconstruction efficiency
Analysis overview (3)

- Reconstruction and trigger efficiencies are taken from $J/\psi \rightarrow \mu \mu$ data
- Pseudo-proper lifetime is used to separate prompt and non-prompt quarkonium candidates
- Simultaneous maximum likelihood fit to the $\mu \mu$ invariant mass and pseudo-proper lifetime is performed to extract the number of charmonium candidates
- Separate fits in every $p_T$, rapidity, and centrality bins
Analysis overview (4)

- For the bottomonium the acceptance is recalculated in order to take into account peak overlaps
- Systematics include: acceptance, muon reconstruction efficiency, trigger effects, fit model, bin-to-bin migration, luminosity
Results (1)

- The differential non-prompt $J/\psi$ and $\psi(2S)$ production cross-section is compared to FONLL theory predictions for three intervals of rapidity.
- Non-prompt $J/\psi$ and $\psi(2S)$ production in pp is in a good agreement with FONLL.
- Prompt charmonium production is compatible with NRQCD.
- The error bands in the prediction correspond to the combined factorisation scale, quark mass and parton distribution functions uncertainties.
• Bottomonium production is not in a good agreement with NRQCD
Results (3)

- Nuclear modification factors are calculated as functions of $p_T$ and rapidity for prompt and non-prompt production.
- Bars on the plots represent statistical uncertainty, boxes – uncorrelated systematical ones, and the gray boxes – correlated systematics.
Results (4)

• Double ratio of nuclear modifications factors versus centrality:

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\[
\frac{\psi^{(2S)}}{J/\psi} \quad p+p, \sqrt{s_{NN}} = 5.02\text{ TeV}, L = 28 \text{ nb}^{-1}
\]

\[
\frac{\psi^{(2S)}}{\gamma^{(1S)}} \quad p+p, \sqrt{s} = 5.02\text{ TeV}, L = 25 \text{ pb}^{-1}
\]

\[
\frac{\gamma^{(nS)}}{\gamma^{(1S)}} \quad p+p, \sqrt{s} = 5.02\text{ TeV}, L = 25 \text{ pb}^{-1}
\]
Results (5)

• Prompt charmonium $\rho$ decreases slightly from backward (Pb-side) to forward (p-side)
• Prompt $\psi(2S)$ suppressed with retard to prompt $J/\psi$ at the one-sigma level
• Prompt $\psi(2S)/J/\psi$ and prompt $\Upsilon(2S)/\Upsilon(1S)$ are suppressed in central collisions at the one-sigma level
• $\Upsilon(nS)/\Upsilon(1S)$ suppressed for $p_T < 40$ GeV and $-2 < y^* < 1.5$ at the two-sigma level
Conclusions

• ATLAS has studied b-hadron pair production with 8 TeV pp collisions data
  – Various production options of several MC generators are compared to the data
  – Allowing better tuning of the corresponding underlying models

• ATLAS has performed a study of quarkonium production in p-Pb and pp collisions data
  – Number of observations on the production of prompt and non-prompt quarkonium, comparison with theoretical predictions
  – Constraints on CNM models
BACKUP
B-physics starts with single or di-muon triggers with various thresholds:

- $p_T(\mu) > 6$ GeV
- $p_T(\mu) > 18$ GeV
- $p_T(\mu_1) > 4$ 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

Di-muon mass range: $m(\mu\mu) \in [2.5; 4.3]$ GeV (final states containing $J/\psi$) and $m(\mu\mu) \in [4.0; 8.5]$ GeV (B to $\mu$ transitions).