Recent ATLAS Results in Charmonium Production

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on behalf of the ATLAS collaboration
ATLAS B-Physics Programme

- ATLAS B-physics program includes:
  - Precision measurements:
    - rare decays
    - b-hadron decay properties, CPV
  - Heavy flavour production:
    - b-hadrons, (associated) quarkonia production
  - Spectroscopy:
    - new states and decay modes
  - Mostly in fully reconstructable exclusive decays with single/di-/multi-muon final states, which allows to trigger low-\(p_T\) objects

- Outline of the talk (charmonium production):
  - Production of J/\(\psi\) and \(\psi(2S)\) in 7 & 8 TeV pp collisions
  - Quarkonium production in 5.02 TeV pp & pPb collisions

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J/ψ and ψ(2S) Production at 7&8 TeV

- Quarkonia production at LHC offers unique windows on understanding strong interactions

Two distinct charmonium production mechanisms at LHC:

- **Prompt**: produced directly in the pp interaction or through feed-down decays of heavier states
  - Theory: Non-relativistic QCD (arXiv:1009.3655), NRQCD
    - pQCD cc production, soft evolution into quarkonium (data derived)
  - Non-prompt: produced in decays of b-hadrons, can be separated experimentally due to the “long” b-hadron lifetime
      - perturbative b̅b production, data driven fragmentation and b-hadron decay model

- Around 35% of prompt J/ψ come from feed-down, prompt ψ(2S) almost all produced directly
Measurement Method

- Data (2.1 fb\(^{-1}\) @ 7 TeV and 11.4 fb\(^{-1}\) @ 8 TeV) collected using di-muon triggers
- Basic di-muon selection (\(p_T(\mu_1,\mu_2) > 4\) GeV, \(|\eta(\mu_1,\mu_2)| < 2.3\)), di-muon tracks vertex fit
- Weights to correct for trigger efficiency, muon identification and reconstruction and geometrical acceptance
  - probe various spin-alignment scenarios (not yet measured at ATLAS)
- Corrected prompt and non-prompt J/\(\psi\) and \(\psi(2S)\) yields determined from an unbinned fit to the 2D di-muon mass and pseudo-propertime distribution
  - in 22 \(p_T\) x 8 rapidity bins
J/ψ and ψ(2S) Prod. at 7&8 TeV: Results

- Prompt J/ψ compared to NRQCD – good agreement across range of $p_T$, no $y$-dependence
- Prompt ψ(2S) (no significant feed-down) compared to NRQCD – mostly well describing data, some deterioration at high-$p_T$
- Non-prompt compared to FONLL – predicts slightly harder $p_T$ spectra
- Ratio of prompt ψ(2S) / J/ψ flat across the whole $p_T$ range
- Prompt J/ψ fraction dominates at low-$p_T$, but non-prompt exceeds prompt at around 20 GeV
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![Prompt ratio of ψ(2S) to J/ψ](image-url)
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Fraction of Non-Prompt J/ψ at 13 TeV

- Early data sample 6.4 pb$^{-1}$ collected with di-muon triggers

- Yields extracted from an un-weighted and unbinned fit to 2D di-muon mass and proper decay time

- Efficiencies and acceptance cancels to a good approximation in the non-prompt fraction

- Interesting trends in dependence on $\sqrt{s}$, though little change between 7 and 13 TeV
J/ψ, ψ(2S) and χ(ns) Production in p+p, p+Pb collisions at 5.02 TeV
Quarkonium Production in A/p+A Collisions

- Probe deconfined quark-gluon plasma in A+A collisions
  - Suppression (=melting) could provide info about temperature and deg. of deconfinement
  - Enhancement could also appear; at low-$p_T$ => new quarkonium formation mechanism (recombination of $c\bar{c}$ from the medium)
  - Non-prompt allows studying b-quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (color screening)

- Collisions of p+A to disentangle cold nuclear matter effects (CNM)

- Suppression of charmonium production relative to pp collisions
  - $J/\psi$ suppressions in p+Pb seen at low $p_T$ and high $y$ (LHCb, ALICE), but not at ATLAS/CMS

- Suppression of relative production of the (1S) and (nS) charmonium states in p+A (and A+A) vs. the pp coll.
  - $\psi(2S) / J/\psi$ suppression at PHENIX, ALICE
  - $\Upsilon(nS) / \Upsilon(1S)$ suppression at CMS
  - Detector effects cancel, easy experiments comparison
  - Only final-state CNM effects (initial-states effects cancel)
  - Centrality dependence

\[
R_{p\text{Pb}} = \frac{1}{208} \frac{\sigma_{p+\text{Pb}}^{O(nS)}}{\sigma_{pp}^{O(nS)}} \rho \frac{O(nS)/O(1S)}{R_{p\text{Pb}}(O(nS)) / R_{p\text{Pb}}(O(1S))}
\]
Measurement Method

- Data (25 pb\(^{-1}\) pp, 28 nb\(^{-1}\) pPb @ 5.02 TeV) collected using di-muon triggers
- Basic di-muon selection: \(p_T(\mu_1,\mu_2) > 2\) GeV (pPb) or 4 GeV (pp)
- Assuming unpolarized quarkonia
- Candidate extraction method using mass pseudo-lifetime fits; for \(\Upsilon(nS)\) mass fit only
Quarkonium Production in p+Pb: Results

- Prompt charmonium production in $p_T$ 8-40 GeV x-section compatible with NRQCD, bottomonium only at $p_T > 15$ GeV
- Non-prompt charmonium consistent with FONLL calculations
- R-factors of prompt and non-prompt $J/\psi$ consistent with unity (no $p_T$ and $y^*$ dependence)
  - Weak modification of $J/\psi$ production due to CNM effects
- R-factors of $\Upsilon(1S)$ below 1 at $p_T < 15$ GeV, compatible with 1 above; no $y^*$ dependence
  - Nuclear parton distribution functions modified relative to of nucleon (nPDF shadowing)
Quarkonium Production in p+Pb: Results

- Production of ratios of prompt and non-prompt J/ψ to Z constant vs. centrality

- Linear correlation trend in self-normalized yields of ground states vs. self-normalized event activity (2σ at deviation at the highest event activity)
  - Self-normalized event activity not robust enough scale param.?

- Double ratios in p+Pb:
  - Charmonium suppression increases with rapidity (1σ),
  - Υ suppression by 2σ in $p_T < 40$ and $-2 < y^* < 1.5$
  - Both more suppressed with more central collisions (1σ)

- Stronger CNM effect in excited quarkonium w.r.t. ground states
  - ground states follow Z-boson behavior
Summary

• Presented latest ATLAS results on charmonium production
  - Production of J/ψ and ψ(2S) in 7 & 8 TeV p+p collisions
  - Production of J/ψ, ψ(2S) and γ(nS) in 5.02 TeV p+p and p+Pb collisions

• ATLAS shall continue its B-physics program in the Run 2,3 and the HL-LHC era, continue focusing on precision measurements, rare decays and heavy flavour production and spectroscopy
  - Detector upgrades (namely in tracking and muon system) and new trigger strategies and tools will help to cope with the high-luminosity environment
  - See talk of Wolfgang Walkowiak on Friday 11:30
Backup
B-Physics at the ATLAS Experiment

- Triggering $|\eta| < 2.4$
- Precision Tracking $|\eta| < 2.7$

**Muon Spectrometer**

- Toroid Magnets
- Precision $\mu$ tracking:
  - MDT (Monitored Drift Tubes)
  - CSC (Cathode Strip Chambers)
- Trigger:
  - RPC (Resistive Plate Chamber)
  - TGC (Thin Gas Chamber)

**Inner Detector (ID)**

- $p_T > 0.4$ GeV, $|\eta| < 2.5$
- **New for Run2: Insertable B-Layer (IBL):** an additional inner-most pixel layer ($r = 33$mm)
  => ~30% more precise secondary vertex reconstruction

**Calorimeter System**

- EM and Hadronic energy
- LAr EM barrel and EC
- LAr Had. Barrel
- Tile Calorimeter (Fe-Scin.) hadron barrel

- Resolution in $m_{\mu^+\mu^-}$: around 50 MeV for $J/\psi$ and 150 MeV for $\Upsilon$(nS)
- Resolution in b-hadron proper decay time around 100 fs
  (no IBL, ~30% improvement expected)
**B-Physics Trigger**

- **Datasets (pp):**
  - 7 TeV data, 5.08 fb$^{-1}$
  - 50ns, $3.7 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
  - 8 TeV, 21.3 fb$^{-1}$
  - 50ns, $7.7 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
  - 13 TeV, 3.9+35.6 fb$^{-1}$
  - 50/25ns, $13.8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

- **20/40 MHz collision rate → ~400 Hz recording**

- **B-physics concentrates on low-\(p_T\) di-muon signatures:**
  - Quarkonia: \(J/\psi \rightarrow \mu\mu, \Upsilon \rightarrow \mu\mu\), etc.
  - Exclusive \(B \rightarrow J/\psi(\mu\mu)X\) decays
  - Rare and semi-rare \(B \rightarrow \mu\mu(X)\) decays

- **Trigger on low-\(p_T\) (4,6 GeV) di-muon**
  - 2 muons at L1 (HW-based)
  - Confirmed at HLT
  - Track vertex fit and mass cuts at HLT

- **8 TeV data: low-\(p_T\) maintained introducing barrel triggers**

- **13 TeV data: low-\(p_T\) maintained using barrel triggers, introduce coarse topological cuts (HW, opening angle, inv. mass) in 2016**
Measurements in p+p, p+Pb and Pb+Pb

- Measured Quantities
  - Cross-sections
  - Charmonium suppression: nuclear modification factor $R_{pPb}$
  - Higher states suppression: double-ratios
  - Prompt / non-prompt charmonium
  - $p_T$, rapidity and centrality dependences

- Rapidity $y^*$ and centrality definition
  - In p+Pb collisions, the CMS $y^*$ rapidity has shift of 0.465 w.r.t. rapidity $y$ in lab-frame
  - After 60% of data recorded, p and Pb beams were reversed
Measurements in Run-2 and Beyond

- New pixel layer (IBL, 32-38 mm) + small radius Be beam pipe
- Topological L1 trigger

- New small muon wheel
- Fast tracking trigger (FTK) at LVL 1.5; available in Run-2

- Completely new Si based tracker (ITK)