Spectroscopy and production of quarkonia and heavy flavour at ATLAS

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ψ(2S) and X(3872) production at $\sqrt{s} = 8$ TeV – JHEP 1701 (2017) 117


## ATLAS detector and trigger

### ATLAS Detector

- **Muon chambers**
- **Tiled magnets**
- **LAr hadronic end-cap and forward calorimeters**
- **Pixel detector**
- **Transition radiation tracker**
- **Solenoid magnet**
- **Semiconductor tracker**

### ATLAS Preliminary Data 2018

**Data 2018**

- **ISR = 13 TeV**
- **58.45 fb⁻¹**

### Dimuon triggers:

- **ATLAS** Preliminary

**Entries / 10 MeV**

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<th>$m_{\mu\mu}$ [GeV]</th>
<th>$N$</th>
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### Entries / 50 MeV

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### Entries (low-m)

- **$\psi(2S)$**
- **$\psi(1S)$**
- **$\Upsilon(2S)$**
- **$\Upsilon(3S)$**

### Triggering:

- **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) and X(3872) production

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- X(3872) was observed by Belle in 2003, later confirmed by others, $J^{PC} = 1^{++}$
- No clear theoretical picture yet
  - Loosely bound $D^0 \bar{D}^{*0}$ molecule
  - $\chi_{c1}(2P)$ state, or the mixture with $D^0 \bar{D}^{*0}$
  - Tetraquark (diquark + diquark)
- ATLAS measurement can help to answer some of the questions
  - Measure in $J/\psi \pi^+ \pi^-$ mode, together with well known $\psi(2S)$ state
    - helps to reduce systematics in ratios
  - Use 11.4 fb$^{-1}$ @ 8 TeV data
    - Limit to $|y| < 0.75$ for the best mass resolution
  - Measure differential cross-sections over 5 $p_T$ bins
  - Use 4 bins of pseudo proper lifetime to extract prompt/non-prompt components
X(3872) lifetime hypotheses

- Measure the $X(3872)/\psi(2S)$ ratio
  \[ R_B = \frac{B(B \to X(3872) + \text{any})B(X(3872) \to J/\psi \pi^+ \pi^-)}{B(B \to \psi(2S) + \text{any})B(\psi(2S) \to J/\psi \pi^+ \pi^-)} \]

- **Single lifetime hypothesis**
  - Assume non-prompt $\psi(2S)$ and $X(3872)$ produced from the same mix of parent $b$ hadrons
  - same lifetime for $\psi(2S)$ and $X(3872)$ in each $p_T$ bin
  - $R_B^{1L} = (3.95 \pm 0.32(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-2}$
  - $X(3872)$ lifetime shorter in low-$p_T$ bins
  - Possible $B_c$ contribution?

- **Double lifetime hypothesis**: long-lived (LL) and short-lived (SL) components
  - $\tau_{LL}$ determined from $\psi(2S)$ fits, allowing for some SL contribution
  - $\tau_{SL}$ from simulation, varying $B_c$ lifetime
  - Calculate $X(3872)$ fraction from $B_c$
    \[ \frac{\sigma(pp \to B_c + \text{any})B(B_c \to X(3872) + \text{any})}{\sigma(pp \to \text{non-prompt } X(3872) + \text{any})} = (25 \pm 13(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{spin}))\% \]
**X(3872) production cross-section**

- Prompt production described well by NRQCD
  - $X(3872)$ considered as a mixture of $\chi_c(2P)$ and $D^0\bar{D}^{*0}$ molecule
- Non-prompt compared to FONLL calculations
  - Predictions for $\psi(2S)$ recalculated using kinematic template of $X(3872)/\psi(2S)$
  - $B_s$ estimated from CDF data
  - Factor 4–8 above the data, larger discrepancy at high $p_T$
- Non-prompt production fraction: no $p_T$ dependence, agreement with CMS data
Prompt charmonium pair production

- Two principal possibilities to produce two objects in a \textit{pp} collision:
- Single Parton Scattering (\textit{SPS})
  - Dominated by gluon–gluon fusion
  - Theoretical description has a long history and still far from final
    - generally sensitive to higher-order QCD corrections
    - CS vs. CO models
    - needs to properly account for feed-downs from higher states
  - None of the models gives a perfect description of data
    - pair quarkonia production can help in understanding, interpretation of the measured cross-section can be simpler
- Double Parton Scattering (\textit{DPS})
  - effective cross-section $\sigma_{\text{eff}}$ accounting for probability of the two processes to happen in a single \textit{pp} collision: $\sigma_{\text{DPS}} = \frac{1}{2} \frac{\sigma(J/\psi)^2}{\sigma_{\text{eff}}}$
  - $\sigma_{\text{eff}}$ is assumed to be universal across processes and energy scales
  - 12–20 mb values obtained earlier; however, indication of lower values from pair charmonia/bottommonia production questions the universality of $\sigma_{\text{eff}}$
Measure production of prompt $J/\psi$ pairs

- Use 11.4 fb$^{-1}$ at $\sqrt{s} = 8$ TeV
- Kinematic range: $p_T(J/\psi) > 8.5$ GeV, $|\eta(J/\psi)| < 2.1$

Per-event corrections
- Efficiency of trigger and reconstruction
- Muon acceptance

Backgrounds
- Non-$J/\psi$ background separated by 2D mass fits
- Non-prompt $J/\psi$ contribution separated by 2D $L_{xy}$ fits
  - per-event weights as a function of $L_{xy}$
- (Small) pile-up background separated by 1D fit to $d_z$ vertex distance

Due to different resolution, the measurement is done separately in central ($|y(J/\psi)| < 1.05$) and forward ($1.05 < |y(J/\psi)| < 2$) regions

DPS and SPS contributions are distinguished with a data-driven approach
Data-driven extraction of DPS contribution

- Templates for DPS and SPS contribution in
  \( \Delta \phi(J/\psi J/\psi) \times \Delta y(J/\psi J/\psi) \)
- DPS template – event mixing
  - combine \( J/\psi \)'s from random different events, assuming their independent kinematics
  - normalize to \( \Delta y > 1.8, \Delta \phi > \pi/2 \) region
- SPS contribution
  - obtained by subtracting the DPS from data
- Per-event weights \( w_{\text{DPS}}(\Delta \phi, \Delta y), w_{\text{SPS}}(\Delta \phi, \Delta y) \)
  assigned to study the DPS/SPS spectra
Results: cross-sections (1)

- **Fiducial cross-section in** $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, $p_T(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$, $p_T(\mu) > 4$ GeV for two trigger muons

  $15.6 \pm 1.3$ (stat) $\pm 1.2$ (syst) $\pm 0.2$ (BF) $\pm 0.3$ (lumi) pb, for $|y| < 1.05$, $13.5 \pm 1.3$ (stat) $\pm 1.1$ (syst) $\pm 0.2$ (BF) $\pm 0.3$ (lumi) pb, for $1.05 \leq |y| < 2.1$

- **Total cross-section in the $J/\psi$ kinematic volume**

  $82.2 \pm 8.3$ (stat) $\pm 6.3$ (syst) $\pm 0.9$ (BF) $\pm 1.6$ (lumi) pb, for $|y| < 1.05$, $78.3 \pm 9.2$ (stat) $\pm 6.6$ (syst) $\pm 0.9$ (BF) $\pm 1.5$ (lumi) pb, for $1.05 \leq |y| < 2.1$

  - assume unpolarized production
  - **Two peaks in** $p_T(J/\psi J/\psi)$
    - near zero – away topology, back-to-back
    - near higher $p_T$ – towards topology
      - back-to-back to another gluon
      - NLO effect
Results: cross-sections (2)

- Differential SPS/DPS cross-sections measured in the muon fiducial volume
- DPS: scaled to measured $f_{DPS}$ – only shape comparison
- SPS
  - Scaled by $\times 1.85$ to allow for feed-down
Results: cross-sections (2)

- Overall good agreement for DPS contribution
- Some discrepancies in total cross-section for away topology
- Significant fraction of events with towards topology $\rightarrow$ LO predictions alone not enough to describe it
Results: DPS measurements

- $\sigma_{\text{eff}}$ can be measured as
  $$\sigma_{\text{eff}} = \frac{1}{2} f_{\text{DPS}} \times \sigma(J/\psi J/\psi)$$
- $\sigma(J/\psi)$ from the ATLAS measurement Eur. Phys. J. C 76 (2016) 283
- $f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat.}) \pm 0.5(\text{syst.}))\%$
- $\sigma_{\text{DPS}} = 14.8 \pm 3.5(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.2(\text{BF}) \pm 0.3(\text{lumi.}) \text{ pb}$
- $\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi.}) \text{ mb}$
- LHC results with quarkonia are close to each other and to those of D0, but lower than measurements with other probes
  - Questions the assumption of $\sigma_{\text{eff}}$ universality
  - $\text{di-J/}\psi, J/\psi-\Upsilon, 4$-jet processes are dominated by $gg$ interactions → probe gluon distributions in proton

ATLAS

CMS ($\sqrt{s} = 8 \text{ TeV}, \ U(1S) + U(1S), 2016$)
LHCb ($\sqrt{s} = 13 \text{ TeV}, J/\psi + J/\psi, 2017$)
CMS + Lunsberg, Shao ($\sqrt{s} = 7 \text{ TeV}, J/\psi + J/\psi, 2014$)

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$\sigma_{\text{eff}}$ [mb]

LHC results with quarkonia are close to each other and to those of D0, but lower than measurements with other probes

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Charmonia production in Pb + Pb, p + Pb

- Probe deconfined quark-gluon plasma in A + A collisions
  - Suppression (melting) could provide info about temperature of deconfinement
  - Enhancement could also appear; at low-$p_T$ → new quarkonium formation mechanism (recombination of $c\bar{c}$ from the medium)
  - Non-prompt charmonia allows studying $b$ quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (colour screening)
- ATLAS measurement for $J/\psi$ and $\psi(2S)$ production in Pb + Pb with 0.42 nb$^{-1}$ @ $\sqrt{s_{NN}} = 5.02$ TeV: arXiv:1805.04077

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

- Suppression of charmonia production versus pp collisions, $R_{pPb} = \frac{1}{208} \frac{\sigma^{O(nS)}_{pPb}}{\sigma^{O(nS)}_{pp}}$
  - Seen in $p + Pb$ at low $p_T$ (ALICE) and high $y$ (LHCb), but not at ATLAS or CMS
- Suppression of relative production of the 1S and nS states in $p + Pb$ vs. pp,
  $\rho_{pPb}^{O(nS)/O(1S)} = \frac{R_{pPb}(O(nS))}{R_{pPb}(O(1S))}$
  - Seen at ALICE, PHOENIX for $\psi(2S)$ and $J/\psi$; at CMS for $\Upsilon(nS)$
  - Detector uncertainties mostly cancel
- ATLAS measurement for $J/\psi$, $\psi(2S)$, and $\Upsilon(nS)$ production in $p + Pb$ with 28 nb$^{-1}$ @ $\sqrt{s} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 171, see below
Charmonia in $p + p$ (reference): cross-sections

- Prompt $J/\psi$ and $\psi(2S)$ production compatible with NRQCD;
- Non-prompt charmonia consistent with FONLL calculations;
- $\Upsilon$ production described well by NRQCD above $p_T > 15$ GeV;
- LDMEs extracted from fitting high-$p_T$ data, not quite applicable to lower $p_T$.

![Graphs showing charm production cross-sections and comparisons with theory.](image-url)
Charmonia in $p + $ Pb: $R$ factors

- $R_{pPb}$ factors for prompt and non-prompt $J/\psi$ consistent with unity
  - no $p_T$ or $y^*$ dependence
  - weak modification for $J/\psi$ production due to CNM effects
- $R_{pPb} < 1$ for $\Upsilon(1S)$ below 15 GeV
  - stronger nPDF shadowing for small $x$?
Charmonia in Pb + Pb: $R_{AA}$ factors

- $J/\psi$ production strongly suppressed in central collisions
  - very similar for prompt and non-prompt
  - not quite expected, as the two cases have different origins
- $R_{AA}$ increases at high $p_T > 12$ GeV for prompt $J/\psi$, flat for non-prompt
Charmonia in \( p + \text{Pb} \): \((nS)\) suppression

- Double ratios \( \rho_p^{O(nS)/O(1S)} \) in \( p + \text{Pb} \)
  - Relative \( \psi(2S) \) suppression increases with centre-of-mass rapidity, \( 1\sigma \) significance trend
  - \( \Upsilon(nS) \) suppression by \( 2\sigma \) in the full \( p_T < 40 \text{ GeV} \) and \( -2 < y^* < 1.5 \) region
  - Both more suppressed with more central collisions

![Diagrams showing double ratios for \( \psi(2S) \) and \( \Upsilon(nS) \)]
Charmonia in Pb + Pb: \((nS)\) suppression

- Expect \(\rho_{\text{PbPb}}^{O(nS)/O(1S)} = 1\) for non-prompt charmonia
  - originate from \(b\) quark loosing energy in the medium and hadronizing outside
- The double ratio indeed consistent with unity for non-prompt, and < 1 for prompt
  - consistent with the interpretation that the tighter bound \(J/\psi\) survives in the hot and dense medium with higher probability than more loosely bound \(\psi(2S)\)

\[\text{ATLAS} \quad \text{Pb+Pb, } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV, } 0.42 \text{ nb}^{-1} \]
\[\text{pp, } \sqrt{s} = 5.02 \text{ TeV, } 25 \text{ pb}^{-1} \]
\[9 < p_T < 40 \text{ GeV, } |y| < 2 \]

\(\text{Npart} \quad \text{Npart} \)
A selection of ATLAS results on heavy flavour production was presented

- Exotic states: $X(3872)$ measurement
- Associated production: prompt $J/\psi$ pairs
- Heavy flavours in media: onia production in $p$Pb and PbPb

Many interesting results not covered, e.g.

- $b$ hadron pair production at $\sqrt{s} = 8$ TeV – JHEP 1711 (2017) 062
- $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 7, 8$ TeV – Eur. Phys. J. C 76 (2016) 283
- $D$ mesons production at $\sqrt{s} = 7$ TeV – Nucl. Phys. B 907 (2016) 717
- Search for resonances in $B_s^0\pi\pm$ system – Phys. Rev. Lett. 120 (2018) 202007

Full Run-2 dataset is still be be fully exploited – stay tuned for many new results!
Backup slides
Non-prompt $J/\psi$ fraction at $\sqrt{s} = 13$ TeV

- Analyse early sample of $6.4 \text{ pb}^{-1}$ collected with di-muon triggers
- Very similar shape to $\sqrt{s} = 7$ TeV, but certain change compared to lower energies
  - The NP fraction grows steadily from 0.25 to 0.65 between 8 and 40 GeV
  - No sizeable dependence on rapidity
$m(\pi^+\pi^-)$ spectrum disfavours the phase space distribution, preferring higher masses.
Studying associated production

- Multiple possibilities to produce two objects $A, B$ in a $pp$ collision
  - Single Parton Scattering ($SPS$)
    - described by specific process cross-section $\sigma_{AB}^{SPS}$ – higher-order "real" associated production
  - Double Parton Scattering ($DPS$)
    - individual process cross-sections $\sigma_A, \sigma_B$
    - effective cross-section $\sigma_{eff}$ accounting for probability of the two processes to happen in a single $pp$ collision
      
      $$\sigma_{AB} = \sigma_{AB}^{SPS} + \sigma_{AB}^{DPS} = \sigma_{AB}^{SPS} + \frac{\sigma_A\sigma_B}{\sigma_{eff}} \times \frac{1}{1 + \delta_{AB}}$$

- DPS/SPS separation is intrinsically uncertain
  - Limited knowledge of $\sigma_{eff}$
  - Higher-order SPS contributions can undermine assumptions
  - Experimentally one can measure $N_A, N_B, N_{AB}$, with different efficiencies, lumi etc

$$f_{DPS} = \frac{\sigma_{AB}^{DPS}}{\sigma_{AB}} = \frac{\sigma_A\sigma_B}{\sigma_{AB}\sigma_{eff}} \times \frac{1}{1 + \delta_{AB}} \sim \frac{1}{\sigma_{eff}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1 + \delta_{AB}}$$
Di-$J/\psi$: 2D mass fit

- Projections of the fit
  - $J/\psi_1 =$ higher-$p_T$
  - $J/\psi_2 =$ lower-$p_T$

- The peak is described with *Crystal Ball*, its parameters are obtained from fitting inclusive $J/\psi$ sample
Di-$J/\psi$: prompt–prompt component extraction

- 1D projections of 2D fits to $L_{xy}$
  - $L_{xy}$ resolution function determined from inclusive $J/\psi$ sample
- Prompt–prompt fraction $f_{PP}$ extracted in 4 fits, based on $y$ region of each $J/\psi$
  - Per-event weights assigned as a function of $L_{xy}$
  - Corrected for the biases in differential distributions

![Graphs showing data and fits for $L_{xy}$ distributions](image1)

![Graphs showing reconstructed $f_{PP}$ distributions](image2)
Di-$J/\psi$: pile-up contribution

- To subtract $J/\psi$ pairs from multiple collisions in a bunch crossing
- Fit to $d_z$
  - two gaussians for signal and background
  - determined from inclusive $J/\psi$ sample
- Pile-up fraction found to be $< 1\%$
- Subtraction done using template from PU-enriched $d_z > 2.0 \text{ mm region}$

![ATLAS Data](image1)

- $\sqrt{s} = 8 \text{ TeV, 11.4 fb}^{-1}$
- $|y(J/\psi)| < 1.05$
- $|d_z| = 1.2 \text{ mm}$
**$B_c$ excited states**

- No excited states of $B_c$ reported previously
- The spectrum and properties of $B_c$ family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- Measurements of the ground and excited states → test of these predictions
  - 2S states are experimentally easy to search
  - Both 1S and 2S have pseudoscalar and vector components

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**Bc(2S) observation**


- Search in $B_c \pi^+ \pi^-$ final state, $B_c$ in $J/\psi \pi^+$ mode
  - Study the spectrum of $Q = m(B_c \pi^+ \pi^-) - m(B_c) - 2m(\pi^+)$
- A new state observed at $Q = 288.3 \pm 3.5\text{(stat.)} \pm 4.1\text{(syst.)}$ MeV (error-weighted mean of 7 and 8 TeV values)
  - Corresponds to a mass $6842 \pm 4\text{(stat.)} \pm 5\text{(syst.)}$ MeV, consistent with the predicted mass of $B_c(2S)$
  - Combined significance is $5.2\sigma$
- Possible interpretations:
  - $B_c[2^3S_1] \to B_c^*(1S)(\to B_c \gamma)\pi^+ \pi^-$
  - $B_c[2^1S_0] \to B_c(1S)\pi^+ \pi^-$
- Similar analysis recently reported by LHCb (arXiv:1712.04094, JHEP 1801 (2018) 138)
  - no evidence, upper limits set
- Further study underway
A number of recent measurement of $b$ production highlighted certain disagreements between models and data.

Especially $b\bar{b}$ production at small open angles is sensitive to the details of various calculations, but only loosely constrained experimentally.

Studies of $H \rightarrow b\bar{b}$ much rely on modelling of $b\bar{b}$ production in this region.

Use $11.5 \ fb^{-1}$ at $\sqrt{s} = 8 \ TeV$.

Measure $b\bar{b}$ pair production.

- one $b$ is identified via $H_b \rightarrow J/\psi + X$ decay.
- the other via $H_b \rightarrow \mu + X$.

Differential cross-sections are measured in 10 kinematic observables.

Various predictions compared to data.

- different ME, PS models, 4-/5-flavour treatment; $g$ splitting kernels.

New test of QCD, motivate the choice of calculations used to model $b$ hadron production and their further tuning.
\[ \sigma(B(\rightarrow J/\psi[\rightarrow \mu^+\mu^-] + X)B(\rightarrow \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}) \text{ nb.} \]

- Full fiducial cross-section:

- Test various gluon splitting kernels in Pythia 8:

Pythia generally does not describe these shapes

\[ p_T \]-based scale splitting kernels behave better for close-by \( b\bar{b} \)

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JINR
Comparison with other generator predictions:

- **HERWIG++**
- **MADGRAPH_aMC@NLOv2.2.2** interfaced to **PYTHIA 8**, 5- and 4-FNS
- **SHERPA 2.1.1** (5-FNS)

- **HERWIG++** reproduces $\Delta R$ and $\Delta \phi$ best
- 4-FNS works better for $\Delta R$ and $\Delta \phi$ than 5-FNS (on either sides VS data)
Comparison with other generator predictions:

- **HERWIG++**
- **MadGraph_aMC@NLOv2.2.2** interfaced to **Pythia 8**, 5- and 4-FNS
- **Sherpa 2.1.1** (5-FNS)

- MG and **Sherpa** has better agreement in $\Delta y$, $y_{\text{boost}}$
- Overall, 4-FNS provides better description of data; **Pythia** and **HERWIG++** are comparable and further tuning may improve