Production of quarkonia and heavy flavor states in ATLAS and CMS

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On behalf on the ATLAS and CMS Collaborations
Outline

- Introduction
  - Data sets and general features on Heavy Flavor Physics with ATLAS and CMS
- Quarkonia production
  - $J/\psi, \psi(2S), \Upsilon$ at 5.02 and 8 TeV in pp, pPb, PbPb collisions
  - Associated production of $J/\psi$ and $\Upsilon(1S)$ pairs
- Open Beauty
  - $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ angular analysis
  - $B^+ \rightarrow K^+\mu^+\mu^-$ angular analysis
  - Search for $X^{\pm}(5568) \rightarrow B^0_s\pi^{\pm}$ resonance
  - $B_c^+$ ground and excited states
- Observation of $Z \rightarrow J/\psi \mu^+\mu^-$ decay

Selected recent results among the many published by the two Collaborations.
Quarkonia and HF at ATLAS & CMS

- Based on low $p_T$ muon trigger and track reconstruction in the Inner Detector
- Wide rapidity and $p_T$ regions
- Wide $\sqrt{s}$ range: 5.02, 7, 8, 13 TeV
- $pp$, $pA$; AA collisions

$\Delta p_T/p_T \sim O(1-5\%)$ for low-momentum tracks
Quarkonia and HF at ATLAS & CMS

- Heavy Flavor production characterized by
  - $M(\mu^+\mu^-)$
  - $\tau(\mu^+\mu^-)$
  - Prompt vs Non-Prompt (B decays in flight) production

![Graphs and plots showing data and fits for quarkonia and heavy flavor production at ATLAS and CMS.]
Quarkonia production

- Heavy quarkonium bound states
  - pp collisions: comparison with QCD models, different from prompt and non-prompt production
  - AA collisions: study the deconfined quark-gluon plasma (QGP)
  - pA collision: disentangling the effects from cold nuclear matter (CNM) interactions

Reference

Cold Nuclear Matter

Quark-Gluon Plasma

- Observables
  - Differential cross-section
  - Nuclear Modification Factor in pA
  - Nuclear Modification Factor in AA

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

\[O(nS) = J/\psi, \, \psi(2S), \text{ and } \Upsilon(nS) \ (n = 1, 2, 3)\]

\[
R_{AA} = \frac{N_{AA}}{< T_{AA} > \times \sigma_{pp}}
\]

\(< T_{AA} >: \text{mean nuclear thickness function}\)

ATLAS: 28 nb\(^{-1}\) at 5.02 TeV pPb and 25 pb\(^{-1}\) at 5.02 TeV pp
CMS: ~2.5 fb\(^{-1}\) at 7 TeV pp

10.04.19

P. IENGO - Quarkonia & HF with ATLAS & CMS
Prompt J/ψ and ψ(2S) in pp

- Good description of the data by NLO NRQCD (prompt) calculations in the full $p_T$ range (same at 7 and 8 TeV)
Good description of the data by FONLL (non-prompt) calculations in the full $p_T$ range.
Good description of the data by NLO NRQCD for $p_T>20$ GeV; discrepancies for $p_T<15$ GeV
J/ψ, Ψ(2S) production in pPb 5.02 TeV

- **Prompt and non-prompt J/ψ**
  - ATLAS
  - $p+\text{Pb}$ $\sqrt{s_{\text{NN}}}=5.02$ TeV, $L=28$ nb$^{-1}$
  - $-2.0 < y^* < 1.5$
  - Prompt J/ψ
  - Non-prompt J/ψ

- **Prompt and non-prompt Ψ(2S)**
  - ATLAS
  - $p+\text{Pb}$ $\sqrt{s_{\text{NN}}}=5.02$ TeV, $L=28$ nb$^{-1}$
  - $-2.0 < y^* < 1.5$
  - Prompt Ψ(2S)
  - Non-prompt Ψ(2S)

- **pPb:** improved measurements consistent with previous results
Y production in pPb at 5.02 TeV

- Difficult to separate Y(2S) and Y(3S) at forward and backward $y^*$ intervals in pPb collisions → combined

Comparison with CMS: good agreement

Comparison with ALICE: central vs forward
Nuclear Modification Factors: J/ψ and Υ

Prompt J/ψ: $R_{pPb} \sim 1$ in the full kinematic range → CNM effects are small for prompt and non-prompt J/ψ production

Non-prompt J/ψ

$\Upsilon$(1S): Production suppressed at low $p_T$ (<15 GeV) and increases with $p_T$ → CNM effects are relevant for $\Upsilon$(1S)

No significant dependency on rapidity observed
Nuclear Modification Factors

- Comparison between $R_{pPb}$ and $R_{PbPb}$ for prompt and non-prompt $J/\psi$
  - Very strong suppression of charmonia production in PbPb collisions
  - Similar for prompt and non-prompt $J/\psi$ production

- $R_{AA}$ vs $N_{jets}$ in PbPb collisions
(Prompt $J/\psi$)

- Many other interesting measurements and results in PbPb collisions not included here, see e.g.
  - Measurement of suppression and azimuthal anisotropy of muon from heavy-flavor decays in Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV with the ATLAS detector (Phys. Rev. C 98 (2018) 044905)
Quarkonia associated production

- Associated production of two objects in the same pp collision

- Single Parton Scattering (SPS)
  - Two quarkonia produced in a single interaction between partons

- Double Parton Scattering (SPS)
  - Simultaneous, independent and uncorrelated interactions of two pairs of partons, each interaction producing a quarkonium
  - Cross-section sensitive to spatial distribution of gluons in the proton

\[ f_{DPS} = \text{fraction of DPS events} \]
\[ \sigma_{\text{eff}} \sim (2-20) \text{ mb assumed to be independent of the scattering process and } \sqrt{s}; \text{ related to the spatial separation between partons inside the proton} \]

Large uncertainties on DPS due to possible higher-order SPS contributions, feed-down and limited knowledge of the proton’s transverse profile
Di-J/ψ production at 8 TeV

- Two prompt J/ψ → μμ decays from the same pp collision
  - Invariant mass fit
  - Pseudo-proper decay time fits → prompt-prompt
  - Vertex $d_{z}$ fit → two J/ψ from the same vertex (pileup-removal)
- Data driven SPS contribution
- Analysis in two regions according to sub-leading J/ψ$_2$ rapidity

\[ |y^{*}_{J/\psi_{2}}| < 1.05 \quad 1.05 < |y^{*}_{J/\psi_{2}}| < 2.1 \]

\[ N_{J/\psi_{2}/J/\psi} = 3310 \pm 330 \quad N_{J/\psi_{2}/J/\psi} = 3140 \pm 370 \]

Cross—section in fiducial region

\[
s_{\text{Fid}}(pp \rightarrow J/\psi J/\psi + X) = \begin{cases} 
15.6 \pm 1.3 \text{ (stat)} \pm 1.2 \text{ (syst)} \pm 0.2 \text{ (BF)} \pm 0.3 \text{ (lumi)} \text{ pb, for } |y| < 1.05, \\
13.5 \pm 1.3 \text{ (stat)} \pm 1.1 \text{ (syst)} \pm 0.2 \text{ (BF)} \pm 0.3 \text{ (lumi)} \text{ pb, for } 1.05 \leq |y| < 2.1 
\end{cases}
\]

Extrapolating to the full acceptance (assuming unpolarized J/ψ):

\[
s(pp \rightarrow J/\psi J/\psi + X) = \begin{cases} 
82.2 \pm 8.3 \text{ (stat)} \pm 6.3 \text{ (syst)} \pm 0.9 \text{ (BF)} \pm 1.6 \text{ (lumi)} \text{ pb, for } |y| < 1.05, \\
78.3 \pm 9.2 \text{ (stat)} \pm 6.6 \text{ (syst)} \pm 0.9 \text{ (BF)} \pm 1.5 \text{ (lumi)} \text{ pb, for } 1.05 \leq |y| < 2.1 
\end{cases}
\]

ATLAS: 11.4 fb$^{-1}$ at 8 TeV pp
Di-J/ψ production at 8 TeV

- DPS vs SPS undistinguishable on event-by-event base
- Different overall kinematics → angular correlation: Δy and Δφ (bin event re-weighting)

General agreement with NLO* SPS (with feed-down correction factor) + LO DPS (normalised to measurements)

\[ f_{\text{DPS}} = (9.2 \pm 2.1 \text{ (stat)} \pm 0.5 \text{ (syst)})\% \]

Effective cross-section of DPS

\[ \sigma_{\text{eff}} = 6.3 \pm 1.6 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.1 \text{ (lumi) mb} \]
Y(1S) pair production at 8 TeV

- Y(1S)Y(1S) → 4μ decay
- Kinematic fit to oppositely charged muon pair and then on the four muons with common vertex

\[ p_T(\mu) > 2.5 \text{GeV} \]
\[ |\eta(\mu)| < 2.4 \]
\[ |y_X| < 2.0 \]

Fiducial region

\[ N_{\text{signa}}(Y(1S)Y(1S)) = 38 \pm 7 \]

Very limited statistic!

\[ \sigma_{\text{fid}} = 68.8 \pm 12.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 2.8 \text{ (B)} \text{ pb} \]

Assuming both mesons decaying isotropically (polarisation effects: up to ~40% variation)

CMS: 20.7 fb\(^{-1}\) at 8 TeV pp

\[ \sigma_{\text{eff}} \approx 2.2 - 6.6 \text{ mb} \]
Quarkonia associated production

- Summary of experimental results (including older ATLAS results on J/ψ associated production with vector bosons)

- $\sigma_{\text{eff}}$ generally lower from prompt di-J/ψ and di-Υ wrt other final states
Quarkonia associated production

- Summary of experimental results (including older ATLAS results on J/ψ associated production with vector bosons)

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- Quarkonium final states dominantly produced from gluon-gluon interactions; jet-related channels by quark-antiquark and quark-gluon parton interactions

- Average transverse distance between gluons in the proton smaller than between quarks, or between quarks and gluons?
Heavy Flavor: Open Beauty
B^0 \rightarrow K^{*0}\mu^+\mu^- angular analysis

- B^0 \rightarrow K^{*0}\mu^+\mu^- \rightarrow K^{\mp}\mu^+\mu^- is a FCNC process
- The process can be fully described by the three angles (\theta_L, \theta_K, \phi) and the dimuon invariant mass squared q^2
- New physics entering the loop can be detected by looking at the angular distributions of the decay
Angular differential decay rate expressed with S coefficients that may be represented by helicity or transversity amplitudes:

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left\{ \frac{3(1 - F_L)}{4} \sin^2\theta_K + F_L \cos^2\theta_K \right. + \left. \frac{1 - F_L}{4} \sin^2\theta_K \cos 2\theta_L \right. \\
- F_L \cos^2\theta_K \cos 2\theta_L + S_3 \sin^2\theta_K \sin^2\theta_L \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_5 \sin 2\theta_K \sin \theta_L \cos \phi \\
+ S_6 \sin^2\theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_L \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_L \sin 2\phi \right\}.
\] (1)

\[A_{FB} = \frac{3S_6}{4}\]

Forward-backward Asymmetry
\[F_L = \text{fraction of longitudinally polarised K}^*\]
\[F_S = \text{s-wave fraction}\]

- Generally written in terms of P and P' observables as they are less sensitive to theoretical uncertainties at LO
- LHCb measured a >3\sigma discrepancy with model on P'\(_5\)

ATLAS and CMS analysis uses ~20 fb\(^{-1}\) of 8 TeV pp data taken in 2012
ATLAS extracts P\(_1\) and P'\(_1\) (i=4,5,6,8); CMS extracts P\(_1\) and P'\(_5\)
B^0 \rightarrow K^{*0} \mu^+ \mu^- angular analysis

- **ATLAS**: fit signal and background
  - Four different fits, 3 free parameters each
  - FL, S3 common to each fit
  - S4, S5, S7, S8 fitted parameters

- Signal PDF folded to reduce the number of free parameters and improve fit convergence

- **ATLAS**: fit signal and background
  - P1, P1' extracted from fit parameters
  - S-wave component (non-resonant K\pi) neglected and included as systematics
  - 340 events in 3 q^2 bins

Statistically limited

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B^0 \rightarrow K^{*0}\mu^+\mu^- angular analysis

- CMS: fit signal, mistag signal and bkg
  - Fs, As, F_L fixed from previous measurements
  - P1, P5' fitted parameters
- Signal PDF folded to reduce the number of free parameters and improve fit convergence

Statistically limited
B⁰ → K*⁰μ⁺μ⁻ angular analysis

- **Theory:**
  - DHMV/JC: QCD factorization, hadronic uncertainties from calculations
  - HEP t/CFFMP SV t: hadronic charm contributions fitted from LHCb data

- ATLAS generally in good agreement with SM, except a ~2.5σ deviation from DHMV for P₄', P₅' in one bin
  - LHCb sees a >3σ discrepancy on P₅'}
B^0 \rightarrow K^{*0}\mu^+\mu^-\text{ angular analysis}

- **Theory:**
  - DHMV/JC: QCD factorization, hadronic uncertainties from calculations
  - HEP t/CFFMPSV t: hadronic charm contributions fitted from LHCb data

- ATLAS generally in good agreement with SM, except a ~2.5\sigma deviation from DHMV for P_4', P_5' in one bin
  - LHCb sees a >3\sigma discrepancy on P_5'

- CMS data compatible with SM predictions in the whole range and favoring DHMV at low q^2
B$^+ \rightarrow K^+\mu^+\mu^-$ angular analysis

- Decay rate depends on angle between the directions of $\mu^-$ and $K^+$ in the di-muon rest frame $\theta_L$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_L} = \frac{3}{4}(1 - F_H)(1 - \cos^2 \theta_L) + \frac{1}{2} F_H + A_{FB} \cos \theta_L$$

$A_{FB} = $ Forward-backward Asymmetry
$F_H =$ contribution from the pseudoscalar, scalar, and tensor amplitudes to the decay width

- Angular analysis in 7 $q^2$ bins (1< $q^2$<22 GeV$^2$)
- 2D unbinned max-likelihood fit: $m(K\mu\mu)$ and $\cos \theta_L$
- $N(B \rightarrow K\mu\mu) = 2286 \pm 73$

Results compatible with SM prediction and consistent with previous measurements

Search for $X^{\pm} \rightarrow B_0^s \pi^{\pm}$ resonance

- D0 published evidence of a (tetraquark) state $X(5568)$ in the $B_s \pi^{\pm}$ spectrum via $B_s^0 \rightarrow J/\psi \, \phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$
- Also seen in semi-leptonic decays: $X^{\pm}(5568) \rightarrow B_0^s \pi^{\pm}$ where $B_0^s \rightarrow \mu^\pm D_\pm^s X$, $D_\pm^s \rightarrow \phi \pi^{\pm}$
- Not seen by LHCb, nor CDF
- ATLAS and CMS have enough statistic to observe a signal or set precise limits on production cross-section

ATLAS uses 4.9 fb$^{-1}$ at 7 TeV + 19.5 fb$^{-1}$ at 8 TeV data $\Rightarrow N(B_0^s) = 52750 \pm 280$
CMS uses 19.7 fb$^{-1}$ at 8 TeV data $\Rightarrow N(B_0^s) = 49277 \pm 278$
Search for $X^\pm \rightarrow B_{s}^{0}\pi^{\pm}$ resonance

- $B_{s}^{0}\pi^{\pm}$ candidates selected by requiring a charged track, with $p_{T}>500$ MeV + track quality cuts, from the same PV as the $B_{s}^{0}$
- Analysis repeated for $p_{T}(B_{s}^{0})>10$ GeV and for $p_{T}(B_{s}^{0})>15$ GeV
- Invariant mass of the $B_{s}^{0}\pi^{\pm}$ candidates (re)defined as (improving mass resolution):

$$M^{A}(B_{s}^{0}\pi^{\pm}) = M(J/\psi K^{+}K^{-}\pi^{\pm}) - M(J/\psi K^{+}K^{-}) + m_{B_{s}^{0}}$$

Number of $X^\pm$ candidates from unbinned max-likelihood fit

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$p_{T}(B_{s}^{0}) &gt; 10$ GeV</th>
<th>$p_{T}(B_{s}^{0}) &gt; 15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>60±140</td>
<td>30±150</td>
</tr>
<tr>
<td>CMS</td>
<td>-85±160</td>
<td>-103±122</td>
</tr>
</tbody>
</table>

No signal evidence
Both experiments can set upper limits
Search for $X^{\pm} \rightarrow B_0^{*+} \pi^{\pm}$ resonance

- Upper limits set to $\rho X$, the cross-section ratio of $X(5568)$ to $B_0^s$

$$\rho_X \equiv \frac{\sigma(pp \rightarrow X + \text{anything}) \mathcal{B}(X \rightarrow B_0^{*+} \pi^\pm)}{\sigma(pp \rightarrow B_0^s + \text{anything})} = \frac{N_X}{\epsilon_{rel} N_{B_0^s}}$$

- Asymptotic CLs method

$\rho_X < 1.5\%$ at 95\% CL for $p_T(B_0^s) > 10$ GeV

$\rho_X < 1.6\%$ at 95\% CL for $p_T(B_0^s) > 15$ GeV

$\rho_X < 1.1\%$ at 95\% CL for $p_T(B_0^s) > 10$ GeV

$\rho_X < 1.0\%$ at 95\% CL for $p_T(B_0^s) > 15$ GeV
- Weakly decaying particle consisting of two heavy quarks
- 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

- In 2016 ATLAS published the first observation of state $B_c^+(2S)$ state at a mass:
  \[ M = 6842 \pm 4 \text{(stat)} \pm 5 \text{(syst)} \text{ MeV} \]
  - Consistent with the prediction
  - $5.2\sigma$ including 7 and 8 TeV data
  - Not resolving the two $B_c^+(2S)$ and $B_c^{*+}(2S)$ states
- New evidence from LHCb
- New results from CMS
  - Observation of two excited $B_c^+$ states
  - Measurement of $B_c^+(2S)$ mass

**B_c^+** excited states

- Observation of signals consistent with **B_c^+(2S)** and **B_c^*(2S)** in the decay channel
  
  \[ B_c^+(2S) \rightarrow B_c^+ \pi^+ \pi^- \rightarrow J/\psi \pi^+ \pi^+ \pi^- \]
  
  \[ B_c^{(*)+}(2S) \rightarrow B_c^+ \pi^+ \pi^- \rightarrow B_c^+(\gamma) \pi^+ \pi^- \rightarrow J/\psi \pi^+(\gamma) \pi^+ \pi^- \]
  
  - **B_c^+** reconstruction: di-muon constrained to J/\psi mass + high purity charged track as \( \pi \)
  
  - **B_c^+(2S) and B_c^{*+}(2S)** reconstruction: kinematic fit of **B_c^+** with 2 oppositely charged particles from the same vertex

- Low energetic \( \gamma \) from **B_c^* \rightarrow B_c^+ \gamma** difficult to detect
  
  \( \rightarrow B_c^{*+}(2S)\) peak in the **B_c^+\pi^+\pi^-** mass spectrum seen at a mass lower than \( M(B_c^+(2S)) \rightarrow \)** double peak structure

- Good separation of the two states

- \( N(B_c^+(2S))=67\pm10; \)
  
  \( N(B_c^{*+}(2S))=51\pm10; \)
  
  \( \Delta M=29.1\pm1.5 \) MeV

**First measurement of**

\[ M(B_c^+(2S)) = 6871.0\pm1.2(\text{stat})\pm0.8(\text{syst})\pm0.8(B_c^+) \) MeV
Observation of $Z \rightarrow J/\psi \ell^+\ell^-$ decay

- Valuable measurement for calculation of the fragmentation function for a virtual photon to split into a $J/\psi$
- Background for $H \rightarrow \text{quarkonia}$ decays accessible in future
- Analysis in $e$ and $\mu$ channels ($\ell\ell = ee$ or $\mu\mu$)

Fiducial region

$$40 < m_{\ell^+\ell^-} < 80 \text{ GeV}$$
$$|\eta| < 2.5, \quad |\eta(\text{muons})| < 2.4$$
$$p_T(\ell_1, \ell_2, \mu, \mu) > (30, 15, 3.5, 3.5) \text{ GeV}$$

Signal: $p_T^{J/\psi} > 8.5 \text{ GeV}$

Reference channel: $4 < m(\mu^+\mu^-) < 80 \text{ GeV}$

Ratio of exclusive $Z \rightarrow J/\psi \ell^+\ell^-$ decay to inclusive $Z \rightarrow 4\mu$ (partial cancellation of systematics)

$$\mathcal{R}_{J/\psi \ell^+\ell^-} = \frac{\mathcal{B}(Z \rightarrow J/\psi \ell^+\ell^-)}{\mathcal{B}(Z \rightarrow \mu^+\mu^-\mu^+\mu^-)}$$

CMS: 35.9 fb$^{-1}$ at 13 TeV data

Observation of $Z \rightarrow J/\psi l^+l^-$ decay

Yields from fits:
N($Z \rightarrow \psi \mu\mu$) = 13.0±3.9
N($Z \rightarrow \psi ee$) = 11.2±3.4

\[ \mathcal{R}_{J/\psi \ell^+\ell^-} = 0.67 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

Assumption of unpolarised J/\psi (full polarisation change the result by <25%)

\[ \mathcal{B}(Z \rightarrow J/\psi \ell^+\ell^-) \approx 8 \times 10^{-7} \]

Consistent with predictions (6.7±0.7×10^{-7} and 7.7×10^{-7})

Summary

- ATLAS and CMS have a rich physics program for studies of heavy flavor physics

- Selection of recent results on:
  - Quarkonia production
    - Good general agreement with predictions
    - Measurement of Nuclear Modification Factors in pPb and PbPb collisions → CNM effects relevant for Y in low p_T region
    - \( \sigma_{\text{eff}} \) generally lower from prompt di-J/\( \psi \) and di-Y wrt other final states
  - \( B^0 \rightarrow K^+\pi\mu^+\mu^- \) angular analysis:
    - CMS compatible with expectations; ATLAS has tension of \( \sim 2.5\sigma \) in \( q^2 \) bins for \( P'_4 \) and \( P'_5 \)
  - \( B^+ \rightarrow K^+\mu^+\mu^- \) angular analysis
    - Compatible with SM predictions
  - Search for \( X^\pm(5568) \rightarrow B^0_s\pi^\pm \) resonance
    - No evidence; strong limits set on cross-section
  - \( B_{c}^+ \) ground and excited states
    - First measurement of \( M(B_{c}^+(2S)) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(\text{B}_{c}^+) \) MeV
  - Observation of \( Z \rightarrow J/\psi \ l^+l^- \) decay

Many more studies ongoing; more results to come in the next months
Additional Material
Data set

- LHC runs
  - Run1 (2009-2012)
  - Run2 (2015-2018)
- Excellent data taking performance
  - ~160 fb$^{-1}$ data at pp collisions collected by each experiments at 13 TeV
  - 7 and 8 TeV data in Run1
  - pPb and PbPb runs

General purpose experiment with very good potential for Heavy Flavor physics
Non-prompt $J/\psi$ and $\psi(2S)$ in $pp$

- Good description of the data by FONLL (non-prompt) calculations in the full $p_T$ range
Good description of the data by FONLL calculations in the full pT range
### ATLAS

<table>
<thead>
<tr>
<th>Collision type</th>
<th>Sources</th>
<th>Ground-state yield [%]</th>
<th>Excited-state yield [%]</th>
<th>Ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>p+Pb collisions</strong></td>
<td>Luminosity</td>
<td>2.7</td>
<td>2.7</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Acceptance</td>
<td>1–4</td>
<td>1–4</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Muon reco.</td>
<td>1–2</td>
<td>1–2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td>Muon trigger</td>
<td>4–5</td>
<td>4–5</td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td>Charmonium fit</td>
<td>2–5</td>
<td>4–10</td>
<td>7–15</td>
</tr>
<tr>
<td></td>
<td>Bottomonium fit</td>
<td>2–15</td>
<td>2–15</td>
<td>5–12</td>
</tr>
</tbody>
</table>

| **pp collisions** | Luminosity       | 5.4                    | 5.4                     | –         |
|                  | Acceptance       | 1–4                    | 1–4                     | –         |
|                  | Muon reco.       | 1–5                    | 1–5                     | < 1       |
|                  | Muon trigger     | 5–7                    | 5–7                     | < 1       |
|                  | Charmonium fit   | 2–7                    | 4–10                    | 7–11      |
|                  | Bottomonium fit  | 1–15                   | 2–15                    | 5–12      |

### CMS

- **Lumi**: 2.3%
- **Acceptance**: 3.0%
- **Muon eff (J/ψ, ψ(2S))**: 2.5%
- **Muon eff (Y(nS))**: 1.8%
- **Muon trigger**: 3%
- **Fit model**: 2.0%
Nuclear Modification Factors

- Comparison with ALICE (J/psi) and ALICE and LHCb (Y): pPb collisions
  - Very strong suppression of charmonia production in PbPb collisions
  - Similar for prompt and non-prompt J/ψ production
  - Suggests a common dependence on $y^*$

- Comparison between $R_{pPb}$ and $R_{PbPb}$ for prompt and non-prompt J/ψ
  - Small increase of $R_{AA}$ with $p_T$ in prompt J/ψ production
  - $R_{AA}$ for non-prompt J/ψ production ~constant

- $R_{AA}$ vs $N_{jets}$ in PbPb collisions
  - Suppression decreases going from central to peripheral collisions
Di-J/ψ production at 8 TeV

- Two prompt J/ψ → μμ decays from the same pp collision
  - Invariant mass fit
  - Pseudo-proper decay time fits → prompt-prompt
  - Vertex $d_z$ fit → two J/ψ from the same vertex (pileup-removal)
- Data driven SPS contribution
- Analysis in two regions according to sub-leading J/ψ$_2$ rapidity

ATLAS: 11.4 fb$^{-1}$ at 8 TeV pp

\[ N_{J/\psi J/\psi} = (3310 \pm 330) \]

\[ 1.05 < |y^{*}_{J/\psi_2}| < 2.1 \]

\[ |y^{*}_{J/\psi_2}| < 1.05 \]

\[ N_{J/\psi J/\psi} = (3140 \pm 370) \]
Di-\(J/\psi\) production at 8 TeV

- DPS vs SPS undistinguishable on event-by-event base
- Different overall kinematics \(\rightarrow\) angular correlation \((\Delta y \text{ and } \Delta \phi)\)
- Events re-weighted according to \(\Delta y-\Delta \phi\) bin
Di-\(J/\psi\) production at 8 TeV

- Theory plots for inclusive acceptance, not for fiducial one (scale factor \(~6\) )
Di-J/ψ production at 8 TeV

- Systematics

| Source                        | $|y(J/ψ)| < 1.05$ | $1.05 ≤ |y(J/ψ)| < 2.1$ |
|-------------------------------|-------------|-------------|
| Trigger                       | ±7.5        | ±8.3        |
| Muon reconstruction           | ±1.1        | ±1.3        |
| Kinematic acceptance          | ±0.4        | ±1.1        |
| Mass model                    | ±0.1        | ±0.1        |
| Mass bias                     | ±0.2        | ±0.2        |
| Prompt–prompt model           | ±0.2        | ±0.01       |
| Differential $f_{pp}$ corr.   | ±0.6        | ±0.3        |
| Pile-up                       | ±0.03       | ±0.4        |
| Total                         | ±7.7        | ±8.5        |

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>±0.7</td>
</tr>
<tr>
<td>Muon reconstruction</td>
<td>±0.1</td>
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<tr>
<td>Mass model</td>
<td>±0.01</td>
</tr>
<tr>
<td>Mass bias</td>
<td>±0.02</td>
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<tr>
<td>Prompt–prompt model</td>
<td>±0.1</td>
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<tr>
<td>Differential $f_{pp}$ corr.</td>
<td>±0.1</td>
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<tr>
<td>Pile-up</td>
<td>±0.8</td>
</tr>
<tr>
<td>DPS model</td>
<td>±5.6</td>
</tr>
<tr>
<td>Total</td>
<td>±5.7</td>
</tr>
</tbody>
</table>
Di-$J/\psi$ production at 8 TeV

- **Spin-alignment**

| Scenario                  | $|y(J/\psi_2)| \leq 1.05$ | $1.05 \leq |y(J/\psi_2)| < 2.1$ |
|---------------------------|-----------------|-----------------|
| Longitudinal              | -47%            | -45%            |
| Transverse positive       | +68%            | +82%            |
| Transverse negative       | +39%            | +28%            |
| Transverse zero           | +51%            | +47%            |

| Scenario                  | $|y(J/\psi_2)| \leq 1.05$ | $1.05 \leq |y(J/\psi_2)| < 2.1$ |
|---------------------------|-----------------|-----------------|
| Longitudinal              | -47%            | -45%            |
| Transverse positive       | +79%            | +65%            |
| Transverse negative       | +35%            | +35%            |
| Transverse zero           | +54%            | +48%            |
Y(1S) pair production at 8 TeV

- Systematics

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty (%)</th>
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<tbody>
<tr>
<td>Resonance shape</td>
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<tr>
<td>Simulation</td>
<td>4.9</td>
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<tr>
<td>Efficiency</td>
<td>3.7</td>
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<tr>
<td>Acceptance</td>
<td>2.8</td>
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<tr>
<td>Integrated luminosity</td>
<td>2.6</td>
</tr>
<tr>
<td>Total</td>
<td>10.7</td>
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</tbody>
</table>

Effects of polarisation

<table>
<thead>
<tr>
<th>$\lambda_{\theta_1}$</th>
<th>$\lambda_{\theta_2}$</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>+1</td>
<td>+0.5</td>
</tr>
<tr>
<td>+1</td>
<td>+0.5</td>
<td>+0.5</td>
</tr>
<tr>
<td>+0.5</td>
<td>+0.5</td>
<td>+0.5</td>
</tr>
<tr>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-0.5</td>
</tr>
<tr>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-0.5</td>
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<tr>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-0.5</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Change (%)</th>
<th>+36</th>
<th>+26</th>
<th>+18</th>
<th>-2</th>
<th>-3</th>
<th>-9</th>
<th>-9</th>
<th>-19</th>
<th>-29</th>
<th>-38</th>
</tr>
</thead>
</table>
B⁰ \rightarrow K^{*0}\mu^+\mu^- angular analysis

- B⁰ \rightarrow K^{*0}\mu^+\mu^- \rightarrow K^+\pi^-\mu^+\mu^- is a FCNC process
- The process can be fully described by the three angles (\theta_L, \theta_K, \phi) and the dimuon invariant mass squared q^2
- New physics entering the loop can be detected by looking at the angular distributions of the decay
- Angular differential decay rate expressed with S coefficients that may be represented by helicity or transversity amplitudes:

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3(1-F_L)}{4} \sin^2\theta_K \cos\theta_K + \frac{1-F_L}{4} \sin^2\theta_K \cos 2\theta_L \right.
- F_L \cos^2\theta_K \cos 2\theta_L + S_3 \sin^2\theta_K \sin 2\theta_L \cos 2\phi
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_5 \sin 2\theta_K \sin \theta_L \cos \phi
+ S_6 \sin^2\theta_K \cos\theta_L + S_7 \sin 2\theta_K \sin\theta_L \sin\phi
\left. + S_8 \sin 2\theta_K \sin 2\theta_L \sin\phi + S_9 \sin^2\theta_K \sin^2\theta_L \sin 2\phi \right].
\]

A_{FB} = 3S_6/4  
Forward-backward Asymmetry  
F_L = fraction of longitudinally polarised K*  
F_S = s-wave fraction

- Generally written in terms of P and P' observables as they are less sensitive to theoretical uncertainties at LO
- LHCb measured a >3\sigma discrepancy with model on P'_5

ATLAS and CMS analysis uses \sim20 fb\(^{-1}\) of 8 TeV pp data taken in 2012  
ATLAS extracts P_1 and P'_i (i=4,5,6,8); CMS extracts P_1 and P'_5
B^0 \rightarrow K^{*0}\mu^+\mu^- \text{ angular analysis}

- **Systematics**

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$F_L(10^{-3})$</th>
<th>$A_{FB}(10^{-3})$</th>
<th>$d\mathcal{B}/dq^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–17</td>
<td>0–37</td>
<td>1.0–5.5</td>
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<tr>
<td>Fit bias</td>
<td>0–34</td>
<td>2–42</td>
<td>—</td>
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<tr>
<td>MC statistical uncertainty</td>
<td>3–10</td>
<td>5–18</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>34</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>$K\pi$ mistagging</td>
<td>1–4</td>
<td>0–7</td>
<td>0.1–4.1</td>
</tr>
<tr>
<td>Background distribution</td>
<td>20–36</td>
<td>12–31</td>
<td>0.0–1.2</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>3</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>0–27</td>
<td>0–5</td>
<td>0.0–4.0</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>6–24</td>
<td>0–5</td>
<td>0.2–2.1</td>
</tr>
<tr>
<td>Normalization to $B^0 \rightarrow J/\psi K^{*0}$</td>
<td>—</td>
<td>—</td>
<td>4.6</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>41–65</td>
<td>18–74</td>
<td>6.4–8.6</td>
</tr>
</tbody>
</table>

- **Diff. cross-section**
The D0 Collaboration obtains a significance above five standard deviations for the X(5568) state only when an upper limit on $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ between $B^0_s$ and $\pi^\pm$ imposed ($\Delta R < 0.3$).
Observation of signals consistent with $B_c^+(2S)$ and $B_c^{*+}(2S)$ in the decay channel:

$B_c^+(2S) \rightarrow B_c^{+}\pi^+\pi^- \rightarrow J/\psi \pi^+\pi^+\pi^-$

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

$\rightarrow J/\psi \pi^+(\gamma) \pi^+\pi^-$

$B_c^+$ reconstruction: di-muon constrained to $J/\psi$ mass + high purity charged track as $\pi$

Selection cuts on $B_c^+$ reconstructed candidates:

- $p_T(B_c^+)>15$ GeV
- $|y^*(B_c^+)|<2.4$
- $l(B_c^+)>100$ $\mu$m
- Vertex $\chi^2$ prob. $>10\%$

CMS: 143 fb$^{-1}$ at 13 TeV data

$B_c^+$ signal yield:

$N(B_c^+) = 7629 \pm 226$

$M(B_c^+) = 6271.1 \pm 0.5$ MeV

B$_c^+$ excited states

- B$_c^+(2S)$ and B$_c^{*+}(2S)$ reconstruction: kinematic fit of B$_c^+$ with 2 oppositely charged particles from the same vertex
- Low energetic $\gamma$ from B$^*_c \rightarrow B_c^+\gamma$ difficult to detect $\rightarrow$ B$_c^{*+}(2S)$ peak in the B$_c^+\pi^+\pi^-$ mass spectrum seen at a mass lower than M(B$_c^+(2S)) \rightarrow$ double peak structure

Selection cuts on B$_c^+$ reconstructed candidates

- $p_T(\pi_1) > 0.8$ GeV
- $p_T(\pi_2) > 0.6$ GeV
- $|y^*(B_c^{*+}\pi^+\pi^-)| < 2.4$
- Vertex $\chi^2$ prob. $> 10\%$

Mass variable defined as (higher resolution):

$$M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$$

- Good separation of the two states
- N(B$_c^+(2S)) = 67 \pm 10$;
- N(B$_c^{*+}(2S)) = 51 \pm 10$;
- $\Delta M = 29.1 \pm 1.5$ MeV

First measurement of

M(B$_c^+(2S)) = 6871.0 \pm 1.2$(stat)$\pm 0.8$(syst)$\pm 0.8$(B$_c^+$) MeV