Production and spectroscopy of quarkonia states at the ATLAS experiment

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Naïvely a ‘simple’ system: quark and anti-quark of same flavour in a bound state:

No calculational approach currently able to simultaneously describe production rates and other observables

- Tests of QCD calculations at the perturbative / non-perturbative boundary
- Standard candles for Heavy Ions, B-meson production, backgrounds to SM/BSM processes
- Test multiple parton scattering effects, parton density functions
- Search for rare decays and probes of new physics
Understanding of quarkonium production requires discrimination and understanding of the various modes of production.
Today, I will discuss three of the most recent quarkonium results from ATLAS:

- **Measurement of the production cross-section of** $\psi(2S) \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \pi^+ \pi^-$ **in** $pp$ **collisions at** $\sqrt{s} = 7$ **TeV at ATLAS**
  
  ATLAS-CONF-2013-094, to be submitted to JHEP

- **Measurement of** $\chi_{c1}$ **and** $\chi_{c2}$ **production with** $\sqrt{s}=7$ **TeV** $pp$ **collisions at ATLAS**
  
  Submitted to JHEP, arXiv:1404.7035

- **Measurement of the production cross section of prompt** $J/\psi$ **mesons in association with a** $W^{\pm}$ **boson in** $pp$ **collisions at** $\sqrt{s} = 7$ **TeV with the ATLAS detector**
  
Measurement with 2.1 fb$^{-1}$ pp data at 7 TeV
Muon $p_T > 4$ GeV, pion candidate tracks $p_T > 0.5$ GeV

- Use unbinned mass-lifetime maximum likelihood fit to separate prompt and non-prompt production sources
- Baseline channel for study of X(3872)
- Extend $p_T$ range probed to 100 GeV
High precision wide reach prompt production cross-section in $\psi(2S)\rightarrow J/\psi \pi\pi$.

- Agreement with NRQCD, overestimate at highest $p_T$ never before explored
- $k_T$-factorisation model does not describe data well
- Colour Singlet NNLO* predictions undershoot at highest scales

$\psi(2S)\rightarrow J/\psi \pi\pi$ production

![Graph showing production cross-sections](image-url)
Previous measurements by CMS hinted at tension with previously well-understood non-prompt production (a proxy for B-production).

A possible exception to the generally good agreement is the observation, made by CMS in [63], that the experimental cross section for non-prompt $J/\psi$ and $\psi(2S)$ production tends to fall off at large transverse momentum slightly faster than the FONLL prediction. More data at even larger $p_T$ will help clarify this issue.
Non-prompt $\psi(2S) \rightarrow J/\psi \pi \pi$ production

Good agreement with NLO and FONLL predictions at low $p_T$, but discrepancies observed in both at larger $p_T$ (more prevalent for NLO, without resummation)

- High $p_T$ B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.
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- Discrepancy not seen reconstruction of full B meson decay (using same efficiency corrections and methodology)
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- Energy fraction in decay of $B \to J/\psi (2S)+X$ not being appropriately shared.?  

This is an input parameter for theory from B-factories (largely low $p_T$ and different species) … *a flaw in applicability revealed by this data?*
$\chi_c \rightarrow J/\Psi(\rightarrow \mu\mu)\gamma(\rightarrow ee)$

P-wave charmonium production theoretically and experimentally(!) tricky to determine.

Important to understand this production channel to get a complete picture of quarkonium production.

Experimentally challenging:
- low $p_T$ muons
- precise reconstruction of soft ($p_T \sim 5$ GeV) photon through conversions – low efficiencies

Perform unbinned maximum likelihood fit on acceptance and efficiency corrected mass and lifetime.

Extract prompt and non-prompt production of the $\chi_c$ states
Fraction of prompt $J/\psi$ produced in $\chi_c$ feed-down (right) 

Data show that between 20–30% of prompt $J/\psi$ are produced in $\chi_c$ decays.

Prompt $\chi_c$ cross-section ratio $\leftarrow$ (left)

Data show more $\chi_{c1}$ than $\chi_{c2}$

Ratio sensitive to presence of possible colour octet contributions in NRQCD.
Absolute $\chi_c$ production rates

First absolute prompt (right) and non-prompt (below) $\chi_{c1}$ and $\chi_{c2}$ differential cross sections, compared to predictions.

NRQCD / FONLL able to describe the data, hints at high-$p_T$ excess in latter?
Branching fraction measurement
Using same $\chi_c$ data sample and selections, can extract measurement of $\text{Br}(B^\pm \to \chi_{c1}K^\pm)$

Use precisely-known $B^\pm \to J/\psi K^\pm$ decay as control.

$$B\left(B^\pm \to \chi_{c1}K^\pm\right) = A_B \cdot \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \cdot \frac{B(B^\pm \to J/\psi K^\pm)}{B(\chi_{c1} \to J/\psi \gamma)}$$

Hadron collider measurement not far from best B-factory results; prospects for improvements!
Extend quarkonium studies into new horizons:
Search for associated production of a W boson and prompt $J/\psi$ production for first time (7 TeV, 4.6 fb$^{-1}$ data)

- Probe new production modes of quarkonium, new ways to test theory
- Background to SM processes like WW scattering, $H \rightarrow WW$
- Search channel for new physics phenomena

Unbinned maximum likelihood fit to $J/\psi$ mass and lifetime, extract prompt component from data – background-only hypothesis rejected at 5.1 $\sigma$ level

Background contributions assessed from: pileup (multiple pp collisions in bunch crossing), $Z+jets$, top pair production, $W+b$-quark, $B_c \rightarrow J/\psi + \mu \nu + X$, heavy quark jets.
Double parton scattering can contribute to prompt signal cross-section. Estimate using the following standard/simple ansatz:

\[
d\sigma^{DPS}_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{\text{eff}}}
\]

Measured directly in this analysis

From ATLAS measurement
\(W+2\text{jets}\) arXiv:1301.6872

From ATLAS measurement
prompt \(J/\psi\) arXiv:1104.3038
Present cross-sections **before and after** estimation of double parton scattering component

- DPS consistency with ATLAS $W+2\text{jet}$ measurement
- DPS-subtracted data in disagreement with colour octet NLO, consistent with colour singlet

Measured relative to inclusive $W$ production with rates below $10^{-6}$ – this is one of the rarest processes measured at the LHC!
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Extensions with 2012/Run-2 data:
- DPS measurements
- Sensitivity to rare (unobserved) 3-body decay $W \rightarrow l + \nu + J/\psi$
- Light scalar mixing with SM Higgs
- Rare Higgs decay channel in $Z$ (SM and BSM)
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With the excellent performance of the LHC detectors and the large data samples we are able to make high precision measurements. New discrepancies and puzzling results in both prompt and non-prompt production Quarkonia measurements can provide input to wide range of physics:

- Tests of QCD modelling at perturbative/non-perturbative boundary
- Searches for exotic quarkonium states
- Competitive branching fraction measurements
- Probe the proton structure through numerous final states (DPS, $k_T$-dependent PDFs)
- Sensitivity to rare W boson decays

Unique opportunities to study rare Higgs decays / couplings and searches for extensions to the Standard Model in novel final states.

Thanks for your attention! 😊
Reconstructing and separating quarkonia

Separate two classes of production:

1) From B-decays “non-prompt”
2) Direct QCD production “prompt”

Use lifetime of B hadrons to distinguish

\[ l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T} \]
Measurement of spin-alignment (or ‘polarisation’) of quarkonia has historically proven to be a challenging observable to correctly predict.

\[
\frac{dN}{d\Omega} = 1 + \lambda_{\theta*} \cos^2 \theta^* + \lambda_{\phi*} \sin^2 \theta^* \cos 2\phi^* + \lambda_{\theta*\phi*} \sin 2\theta^* \cos \phi^*
\]

Transverse polarisation: \( \frac{dN}{d\Omega} \propto 1 + \cos^2 \theta^* \)

Longitudinal polarisation: \( \frac{dN}{d\Omega} \propto 1 - \cos^2 \theta^* \)
J/$\psi$ candidate $p_T = 9.4$ GeV
Pseudo proper time = -0.1 ps

W boson $p_T = 42$ GeV

Muons from J/$\psi$ candidate decay

Muon from W boson decay

Missing E$_T$ vector