Recent Results from ATLAS on Heavy Flavour and Vector Boson Physics

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Plans for the seminar

1) My own (recent) ATLAS measurements:

2) Other related analyses, but:
3) Other ATLAS physics, but:

- **SEARCH FOR THE MAGNETIC MONOPOLE AT ATLAS**
- **Graviton** searches using the ATLAS detector
- **PROBING THE HIGGS PROPERTIES AT ATLAS**
- **Peaky blinders: searches for \(t\bar{t}\) resonances**

→Updated plan for the seminar

- An assortment of recent ATLAS heavy flavour results
- Some overlap with previous seminars
- Not everyone will have heard those / been awake / remember anything...
Heavy flavour physics in ATLAS

- Many methods developed for b-jet and c-jet tagging in ATLAS
  - Particularly important for Standard Model processes, e.g. top, Higgs, flavour-tagged analyses
  - Also for heavy flavour cross-sections and related measurements
    - I will cover one of those today

- Majority of ATLAS heavy flavour results involve quarkonium (J/ψ, Υ)
  - Use muon decays
  - Easy for reconstruction and triggering
The ATLAS detector for b,c physics

**Inner detector**
- Covers $|\eta|<2.5$
- Solenoidal B-field, 2T
- Precise tracking chambers and trigger chambers
- Toroidal B-field, ~0.5T

**Muon system**
- Transition radiation tracker
  - Particle ID, pattern recognition
- Silicon strips
  - Momenta
- Silicon pixels
  - Secondary vertices

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Calorimeters

- Electromagnetic and hadronic calorimeters
- Covers $|\eta|<4.9$
- For jets, electrons, photons and missing $E_T$
Performance

- Most analyses presented today use 2011 data; 2012 analyses in preparation
- Events predominantly selected in muon or di-muon decay channels (e.g. J/ψ or Υ)
- Single-muon triggers supplemented by di-muon triggers:
  - invariant mass windows in the regions of the J/ψ, B and Υ
  - largely unprescaled
Muon and quarkonium reconstruction

- **Muon reconstruction**
  - **Combined muons**: match inner detector and muon tracks
  - **Tagged muons**: match inner detector tracks to muon segments (low $p_T$)
- Require $\geq 1$ combined muon for $J/\psi$, 2 for $\Upsilon$
Charmonium spectroscopy \((\bar{c}c)\)

**ATLAS measurements in red**

- Mass (MeV)
  - \(4700\)
  - \(4500\)
  - \(4300\)
  - \(4100\)
  - \(3900\)
  - \(3700\)
  - \(3500\)
  - \(3300\)
  - \(3100\)
  - \(2900\)

**Thresholds:**
- \(D_s^* D_s^*\)
- \(D_s^* D_s\)
- \(D^* D^*\)
- \(D_s D_s\)
- \(D D^*\)

- \(\eta_c (2S)\)
- \(\psi (2S)\)
- \(\psi (3770)\)
- \(\psi (4160)\)
- \(\psi (4415)\)
- \(X(4260)\)
- \(X(4360)\)
- \(X(4660)\)

- \(\eta_c (1S)\)

- \(J/\psi (1S)\)

- \(\pi \pi\)

- \(\pi^+ \pi^-\)

- \(\mu^+ \mu^-\)

- \(\gamma\)

- \(\chi_{c2} (2P)\)
- \(\chi_{c1} (1P)\)
- \(\chi_{c0} (1P)\)

- \(J^{PC} = 0^{-+}\)
- \(1^{--}\)
- \(1^{+-}\)
- \(0^{++}\)
- \(1^{++}\)
- \(2^{++}\)
Bottomonium spectroscopy \((b\bar{b})\)

ATLAS measurements in red
Quarkonium production

- Production mechanism for quarkonium states not fully understood
- Colour singlet (CS) mechanism cannot describe all measurements
- Colour octet (CO) model
  - Initial coloured state decays into a singlet quarkonium bound state
- Non-Relativistic QCD (NRQCD) includes CO+CS+non-perturbative effects, with matrix elements tuned to data
- Quarkonium production at the LHC offers
  - Numerous tests of perturbative QCD in a new energy regime
  - Higher transverse momenta
  - A wider rapidity range
Classifying quarkonia

- **Prompt**: Produced directly in the pp interaction or produced through feed-down decays from higher charmonium states (no displaced decay vertex)
- **Non-prompt**: Produced in the decay chains of b-hadrons (decay vertex can be displaced from primary pp vertex)

\[ \text{e.g. } B \rightarrow J/\psi \, K_s \]
Quarkonium measurements

Introduction: inclusive J/$\psi$

$\psi$(2S)

$\chi_c$

$\Upsilon$(nS)

Other measurements
Inclusive J/ψ cross-section: method

\[
\frac{d^2\sigma(J/\psi)}{dp_T \, dy} \cdot Br(J/\psi \rightarrow \mu^+ \mu^-) = \frac{N_{corr}}{L \cdot \Delta p_T \Delta y}
\]

\[N_{corr} = \sum w^{-1} \cdot N_{reco}\]

Event weight: \[w^{-1} = A \cdot M \cdot \epsilon_{trk}^2 \cdot \epsilon_{\mu}(p_T^+, \eta^+) \cdot \epsilon_{\mu}(p_T^-, \eta^-) \cdot \epsilon_{\text{trig}}\]

- **Detector Acceptance**: with generator level MC
- **Bin migration correction**: due to finite detector resolution
- **Reconstruction efficiencies**: with tag-and-probe method using data
- **Trigger efficiency**: determined from MC and reweighted to data

- **Result with 2.2 pb\(^{-1}\)**
- **Example of one rapidity bin (4 in total)**
  - □: variation due to 5 extreme spin alignment scenarios
- **Agreement with CMS**

T. Matsushita (Kobe)  
PLHC2012
Prompt and non-prompt $J/\psi$: method

pseudo-proper time

$$\tau = \frac{L_{xy} \cdot m(J/\psi)}{p_T(J/\psi)}$$

- $x$-$y$ displacement of $J/\psi$ from PV
- Invariant mass of $J/\psi$
- $p_T$ of $J/\psi$

- Prompt $J/\psi$ have $\sim$ zero $\tau$ while non-prompt $J/\psi$ have positive $\tau$
- Simultaneous fit to mass and $\tau$
- Good agreement with CDF
- Fraction is $p_T$ dependent

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PLHC2012
**ψ(2S) measurement**

- Measured in $\psi(2S) \rightarrow J/\psi \pi\pi$ mode
- 2.1 fb$^{-1}$ at 7 TeV
- No significant feed-down from higher charmonium states
- Additional pion efficiency and acceptance corrections

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Uncorrected $\psi(2S)$
**ψ(2S) cross-section compared to other results**

- Agree well with other LHC results
- $p_T$ range extended

Spin-alignment of $ψ(2S)$ was assumed to be isotropic for central results. Variations for a number of extreme spin-alignment scenarios detailed separately.
\( \psi(2S) \) cross-section compared to theory

**Prompt cross-section**

- (N)LO NRQCD in good agreement, except for highest \( p_T \)
- Matrix element retuning possible
- \( k_T \) factorisation underestimates data
  (parton-level colour singlet+\( k_T \)-dependent parton distributions)

**Non-prompt cross-section**

- NLO and FONLL (Fixed Order Next-to-Leading Logarithm) have a harder \( p_T \) spectrum than data
- FONLL: \( b \)-hadron production spectrum \( \otimes \) momentum distribution of the \( \psi(2S) \)
Measurement of $\chi_{c1}$ and $\chi_{c2}$ production

- Using 4.5 fb-1 at 7 TeV (2011)
- P-wave states of the charmonium system: triplet $\chi_{cJ}(1P)$, with $J=0,1,2$
  - Complementary to S-wave $J/\psi$ and $\psi(2S)$
  - Radiative decays into $J/\psi \gamma$
  - Photon reconstructed from $\gamma \rightarrow e^+e^-$ conversions in inner tracking detectors
- Large branching fractions for $J=1,2$
- Yield of $\chi_{c0}$ is too low for reliable measurement
- Additional photon efficiency corrections
$\chi_{c1,2}$ prompt cross-section

- Measured for $|y_{J/\psi}| < 0.75$ as function of $p_T^{J/\psi}$ and $p_T^{\chi_c}$

- Compare to the predictions of
  - NLO NRQCD: matrix elements from experimental data
    Good agreement
  - LO colour singlet + potential model
    Low: higher orders important?
  - $k_T$ factorisation: colour singlet + longitudinal/transverse gluon distribution
    Overestimates data

Plots for isotropic decay angular distributions (unpolarised)
\( \chi_{c1,2} \) non-prompt cross-section and ratios

Non-prompt cross-section

- First measurement at LHC
- Fixed-order next-to-leading log (FONLL) describes data
- FONLL: b-hadron production combined with momentum distributions of \( \chi_{c1} \) and \( \chi_{c2} \)

Prompt \( \chi_{c2}/\chi_{c1} \)

- Sensitive to possible colour octet contributions, NLO NRQCD in good agreement (esp. low \( p_T \))

Plots for isotropic decay angular distributions (unpolarised)

- 20-30\% of prompt J/\( \psi \) originate from \( \chi_c \)
Bottomonium: $Y(nS)$

- Updated: $Y(nS)$, $n=1,3$ using 1.8 fb$^{-1}$ at 7 TeV

- Fit dimuon invariant mass spectra in finely binned $p_T$ and rapidity intervals
- Correct each event for detector efficiencies and acceptances: extract production cross-sections
$\Upsilon(nS)$ Corrected differential cross-sections

- Corrected for muon fiducial acceptance cuts
- $|y(\Upsilon)| < 2.25$, $p_T(\Upsilon) < 70$ GeV

Acceptance depends on spin-alignment, i.e. angular distributions of muons

Shown here for unpolarised (isotropic) muon angular distributions
Comparison with theory: $\Upsilon(1S)$

- Compare differential cross-sections with models:
  - NNLO* Colour Singlet Model (direct $\Upsilon$ production only)
  - Phenomenological Colour Evaporation Model (inclusive)

Models fail to describe shape & normalisation of data

Better at $p_T < 20$ GeV (Tevatron region), new contributions at high $p_T$ not accounted for by CSM

Also for $\Upsilon(2S,3S)$

Note: high $p_T$ has negligible spin-alignment uncertainty $\rightarrow$ very precise measurements

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Y(3S)/Y(1S) and Y(2S)/Y(1S)

- Production ratios sensitive to feed-down contributions
- Rise in production rates of higher Y states as function of $p_T$ (c.f. CMS)
- Indication of saturation at 30-40 GeV: direct production dominates over decays of excited states?
- Ratio sensitive to $\chi_b(nP)$ contributions
Other measurements involving quarkonium decays

- A few examples

**Exclusive decays e.g.** $B_c \rightarrow \psi \pi$

$\Lambda_b \rightarrow J/\psi \Lambda$

Mass, lifetime and helicity amplitudes

$B_s \rightarrow J/\psi \phi$

Mixing parameters

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Heavy flavour cross-sections

Overview

B\(^+\) cross-section
Earlier heavy flavour production measurements

- **$D^{(*)}$ meson production cross sections**
  ATLAS-CONF-2011-017

- **Inclusive and dijet cross-sections of b-jets**

- **$D^{*+/-}$ production in jets**

- **Inclusive production of electrons and muons (b/c cross section)**

- **Flavour composition of dijet events**

**Graphs and Data:**

- ATLAS, FONLL, NLO, PowHeq+Pythia, PowHeq+Herwig

**Equation:**

$$R(p_T,dz)$$

**Diagram:**

- $D^{(*)}$ meson production cross sections plotted against $p_T$.
- Flavour composition of dijet events shown with histograms and data points.
B\(^+\) cross-section

- 2.4 fb\(^{-1}\) data at 7 TeV; select B\(^+\) → J/\(\psi\) K\(^+\)
- Start from J/\(\psi\) candidates in mass window [2.7, 3.5] GeV
- Fit to common vertex with additional charged track of p\(_T\) > 1 GeV
- Retain B\(^\pm\) candidates with p\(_T\) > 9 GeV and |\(\eta\)| < 2.3

- Resonant backgrounds J/\(\psi\) π, J/\(\psi\) Kπ
- Combinatorial background J/\(\psi\)+X
- Extract differential cross-section:

\[
\frac{d^2\sigma(pp \to B^+ X)}{dp_T dy} \cdot \mathcal{B} = \frac{N_{B^+}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}
\]

\[
N_{B^+} = \frac{1}{A e^{B^+} + e^{B^-}}
\]

Luminosity
Branching ratio
Acceptance, efficiencies

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**B^+ double differential cross-section**

- **POWHEG + Pythia**: Good agreement with data throughout
- **MC@NLO+Herwig**: lower cross-section at low $p_T$, softer $p_T$ spectrum for $|y| < 1$; harder for $|y| > 1$
B$^+$ cross-section vs. $p_T$

- Comparison with CMS and FONLL prediction with
  \[ f_{b \rightarrow B^+} = 0.401 \pm 0.008 \]

- FONLL (Fixed-Order-Next-to-Leading-Logarithm) describes dependence in $p_T$ and rapidity

- Theoretical uncertainties from scale and $b$-quark mass

\[ \sigma(pp \rightarrow B^+ X) = 10.6 \pm 0.3 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.2 \text{ (lumi.)} \pm 0.4 (\mathcal{B}) \text{ \(\mu\)b} \]
Heavy flavour with vector bosons

$W + \text{prompt } J/\psi$

$W + \text{charm}$
Will concentrate on $W+J/\psi$ and $W+c$ today
W candidates

- Selected in $W \rightarrow e\nu, \mu\nu$ modes
- General selection:
  - Single lepton trigger
  - $p_T, |\eta|$ cuts on lepton
  - Significant missing $E_T$
  - Significant transverse mass, $M_T$
  - Isolated lepton: check track or cluster activity in a cone around the lepton to remove leptons in jets

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$$

$$M_T = \sqrt{2E_T^{\mu}E_T^{\nu,\text{miss}}(1 - \cos \Delta \phi_{e,\text{miss}})}$$
W+prompt $J/\psi$ measurement

- Search for associated production of $W(\rightarrow\mu\nu)$ and prompt $J/\psi (\rightarrow\mu\mu)$
- Probes quarkonium production mechanism
- Sensitive to multiple parton interactions
- Use 4.6 fb$^{-1}$ at 7 TeV (2011)
- Include double parton scattering (DPS) in signal, and estimate contribution

Events triggered on W muon (single lepton trigger)

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Prompt $J/\psi$ fits and $W$ verification

- Unbinned maximum likelihood fit to $J/\psi$ mass and pseudo-proper time $\rightarrow$ extract prompt signal
- Fit weighted $m_T(W)$ distribution for prompt candidates: $W$ signal and multi-jet background
- Jet bkd. $0.1 \pm 4.6$ events

Observe $\sim 29$ $W+prompt J/\psi$ events

Background-only hypothesis rejected at $5.3\sigma$ level
Muons from J/$\psi$ candidate
\( p_T (J/\psi) = 9.3 \text{ GeV}, \) pseudo-proper time = 0.0 ps

Muon from W candidate
\( p_T (\mu) = 39 \text{ GeV} \)
SPS and DPS contributions

- Measure \((W^± + J/ψ)\) production cross-section relative to inclusive \(W^±\) cross-section
- Estimate DPS contribution from:
  - \(dσ(W+J/ψ) = dσ(W) \otimes dσ(J/ψ) / σ_{eff}\)

  Measured in this analysis
  - From ATLAS prompt \(J/ψ\) arXiv:1104.3038
  - From ATLAS \(W+2\)jets arXiv:1301.6872

- Note: this is a phenomenological approximation
- DPS estimate \(~40\%\)
- Expect peak towards \(Δφ = π\) for SPS contribution
Prompt $J/\psi+W$ compared to theory

- Summary of fiducial, corrected and DPS-subtracted cross-section ratios
- Colour singlet model (CS): LO, includes feed-down from $\psi(2S)$ and $\chi_c$
- Colour octet model (CO): NLO
- Rate appears to be dominated by CS contributions (but could have large corrections to CO, or modified DPS formalism)
- Both compatible with measurement at $2\sigma$

CS: arXiv:1303.5327
CO: arXiv:1012.3798
Heavy flavour with vector bosons

$W + \text{prompt } J/\psi$

$W + \text{charm}$
W + charm quarks

- W boson + single charm quark is produced in LO by quark-gluon scattering with a down-type quark (d, s, b).

- Contribution of quark flavours determined by PDFs and by CKM Matrix (Vcd, Vcs and Vcb)

- At LHC energy and M_w:
  - gs and gs̄ initial states dominant, d-quark contributes about 10%
  - Directly sensitive to the s-quark PDF

- Constrained only by neutrino-nucleon DIS, sensitive to the modeling of c-quark fragmentation and nuclear corrections

- Some PDF analyses suggest s-quark sea is suppressed w/r to d-quark sea

ATLAS W/Z analysis indicated SU(3) flavour symmetric sea

Kristin Lohwasser
Measurement overview

- 4.6 fb\(^{-1}\) of data collected in 2011 at \(\sqrt{s} = 7\) TeV
- W boson selected via muon or electron decays
- Charm is tagged using either:
  - Semi-leptonic decays inside a jet (soft muons)
  - D(*) decays
- Charge correlation between W boson and charm quark
  - Signal has opposite sign (OS)
  - Most backgrounds are charge symmetric (SS)
- OS-SS enables isolation of the W + c final state from W + c\(\bar{c}\), b\(\bar{b}\)
W + D analysis

- Select samples of $W^+ + D^\pm$ and $W^+ + D^{*\pm}$ by reconstructing $D^{(*)\pm}$ decays in the inner detector:
  - $D^- \rightarrow K^+ \pi^- \pi^-$
  - $D^{*+} \rightarrow D^0 \pi^+$ with
    - $D^0 \rightarrow K^- \pi^+$
    - $D^0 \rightarrow K^- \pi^+ \pi^0$
    - $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$

- Form OS-SS distributions of $m(K\pi\pi)$ for $D^\pm$ and $\Delta m = m(D^*) - m(D^0)$ and fit

W+light jets background: functional form
Data-driven correction for peaking heavy flavour background
W + c-jet analysis

- Select a sample of jets containing soft muons
  - Anti-\(k_t\) jets, \(R=0.4\)
  - Muons \(\Delta R < 0.5\) from jet axis, \(p_T > 4\) GeV
- Discriminate using muon momentum relative to jet axis, \(p_T^{\text{rel}}\)
Fiducial $W+c$ cross-sections

- Compare fiducial cross-sections with aMC@NLO plus various PDF sets
- Predicted values vary by $\sim 25\%$

- Data consistent with wide range of predictions
- Favour symmetric light-quark sea at $x\sim 0.01$

\[\int L dt = 4.6 \text{ fb}^{-1} \quad s = 7 \text{ TeV} \]

$W^+c$-jet

\begin{align*}
\text{Data} & : 23.6 \pm 0.9 \pm 1.8 \text{ [pb]} \\
\text{Stat} & : \quad \text{Stat+syst}
\end{align*}

$s$-quark suppressed cf. $d$-quark

$s$-quark $\sim d$-quark

$W^+D$

\begin{align*}
\text{Data} & : 17.8 \pm 1.9 \pm 0.8 \text{ [pb]} \\
\text{Stat} & : \quad \text{Stat+syst}
\end{align*}

Data

$s$-quark suppressed cf. $d$-quark

$s$-quark $\sim d$-quark

$W^+D^*$

\begin{align*}
\text{Data} & : 21.2 \pm 0.9 \pm 1.0 \text{ [pb]} \\
\text{Stat} & : \quad \text{Stat+syst}
\end{align*}

Favour symmetric light-quark sea at $x\sim 0.01$
Ratio of strange-to-down sea quarks

- Ratio of strange to down sea quarks is regulated in HERA PDF by a single parameter (PDF eigenvector: $f_s$)
- Free fit of strange to down sea content of proton in ATLAS data (within this model)

$$r_s = \frac{0.5(s+\bar{s})}{d} = \frac{f_s}{1-f_s} = 0.96^{+0.16+0.21}_{-0.18-0.24}$$

- Results compatible with the ATLAS-epWZPDF which includes ATLAS W/Z data
- Consistent with SU(3) flavour symmetry in the proton

Default: s-quark suppressed cf. d-quark
Cross-section ratio +/-

\[ R_c^\pm = \frac{W^+ + \bar{c}}{W^- + c} \]

- Ratio \( W^+ / W^- \) is smaller than 1 due to valence down contribution
- Deviation of predicted value might be due to strange sea asymmetry \( s : \bar{s} \)
- Take CT10 prediction (no asymmetry) \( \rightarrow \) estimate of sensitivity

\[ A_{s\bar{s}} = (2 \pm 3)\% \]

- \( W^+c \) analysis is dominated by statistical uncertainties: 2012 data will help
Summary

- Many interesting results from the first years of ATLAS

  - Heavy flavour production measurements
    - Absolute cross-section measurements
    - Detailed comparisons with NLO and NLO+NLL predictions
    - Associated production of $W + \text{charm quarks}$: probes s-quark PDFs

  - Quarkonium physics
    - Production of charmonium and bottomonium; comparison with theory
    - First observation of associated $W + \text{prompt J}/\psi$
    - Confronting data with colour-singlet, -octet and -evaporation models
    - Future vector boson+onia measurements will provide input to multiple parton scattering studies

- Updates and new analyses with more data are in progress