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

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University of Birmingham Particle Physics Seminar
21st January 2014
1. Theoretical Motivation
   • Standard Model of Particle Physics
   • J/ψ production
   • Double Parton Scattering

2. Experimental Apparatus
   • Large Hadron Collider
   • A Toroidal LHC Apparatus

3. Analysis
   • Strategy
   • Background sources
   • Fit procedure

4. Results
   • Observation of W+J/ψ process
   • Measurement of cross-section ratio W+J/ψ : W
   • Double Parton Scattering
   • Uncertainties

5. Conclusions
   • Significance
   • Next steps

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Standard Model of Particle Physics

http://www.isgtw.org
Standard Model of Particle Physics

http://www.isgtw.org
### J/ψ meson

**CHARM QUARK**
Heavier than a strange quark, but not as heavy as a bottom quark, the CHARM QUARK was discovered in 1974. Particles that contain charm and anticharm quarks are called "charmed matter."

*Acrylic felt/fleece with a mix of poly beads and gravel for medium-heavy mass.*

**ANTICHARM QUARK**
Acrylic felt with a mix of poly beads and gravel for medium-heavy mass.

| Property         | Value/Description                                      |
|------------------|--------------------------------------------------------|
| Mass             | $3.096916 \pm 0.000011$ GeV/c$^2$                       |
| Decay width      | $91.0 \pm 3.2$ keV                                      |
| Decays           | 88% hadrons, 6% $e^+e^-$, 6% $\mu^+\mu^-$              |
| Quantum properties | Spin=1, Angular Momentum=0, Odd parity, Odd charge conjugation |

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Charmonium

Phys. Lett. B 592 1 (2004)

- **Mass**: $3.096916 \pm 0.000011$ GeV/c$^2$
- **Decay width**: $91.0 \pm 3.2$ keV
- **Decays**: 88% hadrons, 6% e$^+e^-$, 6% $\mu^+\mu^-$
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\[ J^{PC} = \begin{cases} 0^{-+} & \text{hadrons} \\ 1^{-+} & \text{hadrons} \\ 0^{++} & \gamma^* \text{ radiative} \\ 1^{++} & \text{hadrons} \\ 1^{--} & \text{hadrons} \\ 2^{++} & \chi_{c2}(1P) \end{cases} \]
**J/ψ production**

**Nucl. Phys. B 850 (2011) 387-444**

- J/ψ production poorly understood
- Models (Colour Singlet, Colour Octet, Colour Evaporation) cannot predict transverse momentum ($p_T$) spectrum, or polarization profile, or both

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J/ψ production

- QCD factorization theorem
- Colour Singlet:
  - creation of two heavy quarks: pQCD
  - binding: wave function
  - assume colour and spin of qq pair do not change during binding
  - two gluons
- Colour Octet:
  - NRQCD
  - short distance: pQCD
  - hadronization of qq: non-perturbative
  - colours can be different
  - one gluon
**W+J/ψ production**

- **W+J/ψ** is quark-initiated process (Colour Singlet and Colour Octet)
- Differs from mostly gluon fusion inclusive J/ψ
- Only previous similar search from CDF, W+Υ, set limits
- Another contribution to **W+J/ψ** can come from Double Parton Scattering

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Double Parton Scattering

- Products of collisions coming from different partons in the protons
- Probes structure of proton (correlations of partons)
- Background for some rare processes
- Need to measure to probe universality
- $\sigma_{\text{eff}}$ measured in different experiments and energies
Double Parton Scattering

Single Parton Interaction

Jet more collinear to each other
Jet differs in transverse momentum
Jet associated directly with W production

Double Parton Interaction

Jet back-to-back
Jet balanced in transverse momentum
Independent W and dijet production

ATL-PHYS-SLIDE-2013-267
Use normalized jet pair transverse momentum imbalance as discriminating factor

- template A = SPI-like events
- template B = DPI-like events

- fraction of DPI events = \(0.076 \pm 0.013\) (stat) \(\pm 0.018\) (syst)

- Measured ATLAS result \(\sigma_{\text{eff}} = 15 \pm 3\) (stat) \(^{+5}_{-3}\) (syst) mb
Cross-section ratio $W+J/\psi : W$

Measurement of cross-section ratio provides input to theorists who study $J/\psi$ and $W+J/\psi$ production.
Cross-section ratio \( W + J/\psi : W \)

- Measurement of cross-section ratio provides input to theorists who study \( J/\psi \) and \( W + J/\psi \) production.
- Ratio reduces or cancels systematic uncertainties associated with luminosity and \( W \) boson.

\[
\frac{\sigma(pp \rightarrow W + \text{prompt } J/\psi)}{\sigma(pp \rightarrow W)} = \frac{N_{W+J/\psi} \epsilon_{J/\psi} \alpha_{J/\psi} \epsilon_{W} \mathcal{L}}{N_W \epsilon_W \mathcal{L}}
\]
Large Hadron Collider
Large Hadron Collider
Large Hadron Collider
A Toroidal LHC Apparatus
Data collection

- LHC delivered 5.5 fb\(^{-1}\) of data in 2011 with pp collisions at \(\sqrt{s}=7\) TeV
- ATLAS recorded 5.1 fb\(^{-1}\)
- 4.6 fb\(^{-1}\) of data were deemed to be good for physics
Trigger

- Decisions on which data to save for further analysis
- Fast, efficient

- Select events with muon with high transverse momentum ($p_T>18$ GeV)

- 4.5 fb$^{-1}$ data selected by our trigger

Bunch crossing rate 40 MHz

HLT

Event Builder

Full Event Buffers

~300 MB/s

~200 Hz

Storage & offline processing

Event Builder

EF 1800 PCs
$t>4s$

Readout Buffers

~3kHz

Calo, Muon, Specialized Detectors

Tracking

Front End Pipelines

<75 kHz

L2 500 PCs
$t>40ms$

L1 Fast Custom Electronics
$t<2.5\mu s$

Requested Data in Roll

Eur. Phys. J. C72 (2012) 1849
Muon reconstruction

$W^\pm \rightarrow \mu^\pm \nu_\mu$

$J/\psi \rightarrow \mu^+\mu^-$

- Tracks in inner detector
- Minimum ionization in calorimeters
- Hits and tracks in muon detectors

Low transverse momentum muons may not escape calorimeter
Muon efficiency

CB = combined
ST = segment-tagged
ST more efficient at low transverse momentum

ATLAS Preliminary
Data 2011 $\sqrt{s} = 7$ TeV
$<\mu> = 11.6$
Missing transverse energy

\[ W^\pm \rightarrow \mu^\pm \nu_\mu \]

\[ J/\psi \rightarrow \mu^+\mu^- \]

- Neutrinos cannot be detected at ATLAS
- Principle of energy-momentum conservation
- Initial transverse momentum is 0
Missing transverse energy

ATLAS-CONF-2012-101

Missing transverse energy well described by simulation
W observation

ATLAS-CONF-2010-044

• W boson observed in ATLAS already with 33 pb$^{-1}$ of data

• W transverse mass $M_T(W)$ combines $\mu$ and $\nu$ in the transverse plane

$$M_T(W) = \sqrt{2E_T^{\text{miss}} p_T(\ell)(1 - \cos \Delta \phi(\ell, E_T^{\text{miss}}))}$$
J/ψ observation

- J/ψ meson observed in ATLAS already with 2.2 pb^{-1} of data
- Invariant mass of two oppositely-charged muons peaks at 3.1 GeV for J/ψ
- ψ at 3.7 GeV
- Background combinatorics
- Rapidity y is measure of angle at which particle is traveling

\[ y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c} \]

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**J/ψ pseudo-proper time**

\[ \tau = \frac{L_{xy} m_{J/\psi}^{\text{PDG}}}{p_T} \]

- Measure of distance travelled by J/ψ before its decay
- J/ψ pseudo-proper time to separate prompt from non-prompt J/ψ production (B-decays)

Prompt centered at 0 ps

Non-prompt exponential tail

**ATLAS**

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ L \, dt = 2.3 \text{ pb}^{-1} \]

Events / (0.15 ps)

Prompt centered at 0 ps

Non-prompt exponential tail

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## Analysis strategy

1. **Select W+J/ψ candidates**
   - High pT μ and high E_T^{miss}
   - Two oppositely charged muons

2. **Fit W+J/ψ spectra**
   - Simultaneously fit mass and pseudo-proper time distributions to get prompt J/ψ component

3. **W+J/ψ observation**
   - Evaluate backgrounds
   - Evaluate significance

4. **W+J/ψ:W ratio**
   - Subtract backgrounds
   - Evaluate uncertainties
   - Measure ratio

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**January 21st 2014**
W+J/ψ pre-selection

Requiring:
- Trigger (µ p_T>18 GeV)
- µ (from W) p_T > 25 GeV
- strict isolation for µ from W
- E_T^{miss} > 20 GeV
- M_T(W) > 40 GeV
- Two oppositely-charged muons
- µ (from J/ψ) p_T > 2.5 GeV
Background sources

\[ t \rightarrow Wb \]

\[ b \overset{\text{fragmentation}}{\rightarrow} B^{\pm/0} \]

\[ B^+ \rightarrow J/\psi K^+ \]

\[ B^0 \rightarrow J/\psi K^0 \]

\[ B^+ \rightarrow J/\psi K^* (892)^+ \]

\[ B^0 \rightarrow J/\psi K^* (892)^0 \]

\[ B_s^0 \rightarrow J/\psi \phi (1020) \]

- top decays predominantly to W+bottom
- bottom fragmentation can result to B meson
- B meson can decay to J/\psi
Background sources

| Background        | Rejection         |
|-------------------|-------------------|
| top-antitop pair  | non-prompt        |
| W+bottom          | non-prompt        |

\[ \sqrt{s} = 7 \text{ TeV}, \quad \int L \, dt = 2.3 \text{ pb}^{-1} \]

- \( J/\psi \) from bottom or top decays tend to be non-prompt, since b is long-lived
- Would be incorporated in the exponential tail in the fit

*Nucl. Phys. B 850 (2011) 387-344*
Background sources

| Background     | Rejection           |
|----------------|---------------------|
| top-antitop pair | non-prompt          |
| W+bottom       | non-prompt          |
| multi-jet      | fit $M_T(W)$ distribution |

- multi-jets can mimic W
- “ABCD” method, based on isolation cut
- C is signal region, B is multi-jet enriched region
- kinematically-independent multi-jet fake-factor $(AxD)/B$ to derive templates
Background sources

- Data-driven templates for multi-jets and W shapes in W transverse mass $M_{T}(W)$
- Fit data to determine multi-jet yield

| Background            | Rejection            |
|-----------------------|----------------------|
| top-antitop pair      | non-prompt           |
| W+bottom              | non-prompt           |
| multi-jet             | fit $M_{T}(W)$ distribution |
Background sources

Extra interactions from other proton-proton collisions during the same event are called “pileup”

| Background             | Rejection                    |
|------------------------|------------------------------|
| top-antitop pair       | non-prompt                   |
| W+bottom               | non-prompt                   |
| multi-jet              | fit $M_T(W)$ distribution    |
| pileup                 | independent estimate         |
Background sources

\[ P_{J/\psi} = \frac{\sigma_{J/\psi}^{\text{bin}}}{\sigma_{\text{inel}}} = \frac{1}{\sigma_{\text{inel}}} \int_{\text{bin}} \frac{d^2\sigma(pp \rightarrow J/\psi X)}{dy \, dp_T} dy \, dp_T \]

\[ N_{\text{extra}} = 0.81 \pm 0.08 \]

\[ N_{\text{pileup}} = N_{\text{extra}} P_{J/\psi} \mathcal{L} \sigma_{W}^{\pm} \]

- Multiply rate of W production with probability for additional J/\psi
- Estimate using \( \sigma_{\text{inel}} = 71.5 \text{ mb} \), measured J/\psi cross-section and mean number of extra vertices in data
- Estimated yield 1.8 ± 0.2 events, subtract from result
Background sources

- Same experimental signature as $W + J/\psi$: $B_c^\pm \rightarrow J/\psi \, \mu^\pm \, \nu_\mu \, X$
- Inspect sPlot of invariant mass of three muons
- No events found with mass less than 6.3 GeV ($B_c$ mass)

- Combining $\mu$ from $W$ and oppositely-charged $\mu$ from $J/\psi$
- Reject events with invariant mass within 10 GeV of $Z$ mass
- No $Z$+jets events remain

| Background          | Rejection                  |
|---------------------|----------------------------|
| top-antitop pair    | non-prompt                 |
| $W$+bottom          | non-prompt                 |
| multi-jet           | fit $M_T(W)$ distribution  |
| pileup              | independent estimate       |
| $B_c$               | invariant mass             |
| $Z$+jets            | rejected by cut            |

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Fit procedure

- Simultaneously fit dimuon mass and pseudoproper time
- Extract prompt $J/\psi$, non-prompt $J/\psi$, prompt combinatorics and non-prompt combinatorics yields
- Nuisance parameters from inclusive $J/\psi$ fit due to better statistics

\[ M_{J/\psi}(m_{\mu+\mu-}) = G(m_{\mu+\mu-}; m_{J/\psi}^{\text{PDG}}, \sigma_m) \]
\[ T_{\text{prompt } J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left( (1-a) \delta(\tau) + aC_0 e^{-|\tau|/\tau_0} \right) \]
\[ T_{\text{non-prompt } J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left( C_1 \theta(\tau) e^{-\tau/\tau_1} \right) \]
\[ M_{\text{prompt bkg}}(m_{\mu+\mu-}) = C_2 e^{-m_{\mu+\mu-}/k_0} \]
\[ M_{\text{non-prompt bkg}}(m_{\mu+\mu-}) = C_3 e^{-m_{\mu+\mu-}/k_1} \]
\[ T_{\text{prompt bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left( (1-b) \delta(\tau) + bC_4 e^{-|\tau|/\tau_0} \right) \]
\[ T_{\text{non-prompt bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left( C_5 \theta(\tau) e^{-\tau/\tau_2} \right) \]
**W + J/ψ fit**  Whole region $0 < |y| < 2.1$

**J/ψ**: gaussian  
Combinatorics: exponential

**prompt**: gaussian + 2-sided exponential
**non-prompt**: 1-sided exponential
Confirming the $W$

- $\chi^2$ fit with $W$ and multi-jet templates on weighted data
- multi-jet yield < 0.3 events at 95% credibility

$ATLAS, \sqrt{s} = 7$ TeV, $\int L\, dt = 4.5$ fb$^{-1}$

[Graphs showing normalized yield and weighted events vs. W transverse mass for $W$ and multi-jets hypotheses]
• Maximum likelihood method to determine yields
• Different regions in rapidity to take advantage of resolution
Yields

| Process                        | Barrel   | Endcap   | Total    |
|-------------------------------|----------|----------|----------|
| Prompt $J/\psi$               | $10.0^{+4.7}_{-4.0}$ | $19.2^{+5.8}_{-5.1}$ | $29.2^{+7.5}_{-6.5}$ (*) |
| Non-prompt $J/\psi$           | $27.9^{+6.5}_{-5.8}$  | $13.9^{+5.3}_{-4.5}$ | $41.8^{+8.4}_{-7.3}$   |
| Prompt background              | $20.4^{+5.9}_{-5.1}$  | $18.8^{+6.3}_{-5.3}$ | $39.2^{+8.6}_{-7.3}$   |
| Non-prompt background          | $19.8^{+5.8}_{-4.9}$  | $19.2^{+6.1}_{-5.1}$ | $39.0^{+8.4}_{-7.1}$   |
| $p$-value                     | $8.0 \times 10^{-3}$ | $1.4 \times 10^{-6}$ | $2.1 \times 10^{-7}$   |
| Significance ($\sigma$)       | 2.4      | 4.7      | 5.1      |

(*) of which $1.8 \pm 0.2$ originate from pileup

*p-value evaluated with pseudo-experiments with B-only hypothesis to determine how often it fluctuates to S+B hypothesis*
Double Parton Scattering

- Multiply rate of $W$ production with probability for additional $J/\psi$
- Estimate using $\sigma_{\text{eff}} = 15 \text{ mb}$ and measured $J/\psi$ cross-section
- Estimated yield 10.8 +/- 4.2 events

\[
P_{J/\psi | W^\pm} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}}.
\]

\[
N_{W+J/\psi}^{\text{DPS}} = P_{J/\psi | W^\pm} \times \sigma_W
\]
Double Parton Scattering

- Azimuthal $\Delta \phi(W,J/\psi)$ expected to be flat for Double Parton Scattering (DPS), peak at $\pi$ for Single Parton Scattering (SPS)
- Both contributions present in sample
Cross-section ratio $W+J/\psi:W$

Measurement of cross-section ratio provides input to theorists who study $J/\psi$ and $W+J/\psi$ production.

Ratio reduces or cancels systematic uncertainties associated with luminosity and $W$ boson.

We have measured: $N(W)$, $N(W+J/\psi)$.

Only unknowns are: efficiency $\varepsilon(J/\psi)$, acceptance $\alpha(J/\psi)$.
Efficiencies (J/ψ muons)

Muon efficiencies $\varepsilon(J/\psi)$ calculated using J/ψ “tag-and-probe” method, in bins of muon $p_T$ and charged pseudorapidity.
Spin-alignment - Acceptance

- $J/\psi$ spin-alignment is not known
- Decay muons can follow different paths, depending on the spin-alignment
- The efficiency for these muons to fall in the fiducial region of the detector is called acceptance $\alpha(J/\psi)$, in bins of $J/\psi$ $p_T$ and rapidity
Different spin-alignment assumptions lead to different acceptance
Report isotropic scenario as central value, and range of results
Fiducial cross-section ratio

Fiducial: ratio before the acceptance corrections

\[ \frac{d^2\sigma(W+J/\psi)}{dy dp_T} \times \frac{BR(J/\psi \rightarrow \mu\mu)}{\sigma(W)} \]

\[ pp \rightarrow \text{prompt } J/\psi + W : pp \rightarrow W, \text{ Fiducial} \]

ATLAS Preliminary, \( \sqrt{s} = 7 \, \text{TeV}, \int L \, dt = 4.5 \, \text{fb}^{-1} \]

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Inclusive cross-section ratio

**Graph:**

- **Title:** $d^2\sigma(W+J/\psi)\over d\eta dp_T$
- **Y-axis:** $BR(J/\psi \rightarrow \mu\mu)$ x $\sigma(W)^{-1}$
- **X-axis:** $J/\psi$ Transverse Momentum [GeV]

- **Data Points:**
  - Data
  - Spin-alignment uncertainty
  - Estimated DPS contribution
  - DPS uncertainty

**Equation:**

$pp \rightarrow \text{prompt } J/\psi + W : pp \rightarrow W$

**Legend:**

- **Variables:** $\sqrt{s} = 7\ \text{TeV}$, $\int L\ dt = 4.5\ \text{fb}^{-1}$

**Discussion:**

Inclusive: ratio after the acceptance corrections
Uncertainties

| Source                                | Barrel  | Endcap   |
|---------------------------------------|---------|----------|
| $J/\psi$ muon efficiency              | (3–5)\%| (3–5)\% |
| $W^{\pm}$ boson kinematics           | 2\%     | 5\%      |
| Fit procedure                         | $^{+3}\%_{-2}\%$ | $^{+2}\%_{-1}\%$ |
| Choice of fit nuisance parameters     | 1\%     | 1\%      |
| Choice of fit functional forms        | 4\%     | 4\%      |
| Muon momentum scale                   | negligible |
| $J/\psi$ spin-alignment               | $^{+36}\%_{-25}\%$ | $^{+27}\%_{-13}\%$ |
| Statistical                           | $^{+47}\%_{-40}\%$ | $^{+30}\%_{-27}\%$ |

- Muon efficiency: Difference between data-driven and Monte Carlo efficiencies
- $W$ boson kinematics: Difference between several MC simulations
- Fit: Tried different functional forms, nuisance parameters
- Dominated by statistical uncertainties
Comparison with theoretical predictions

• Comparing DPS-subtracted measurement to theoretical predictions
• Leading-order Colour Singlet (CSM) contributions include $\chi \rightarrow J/\psi$ feeddown: $(10-32) \times 10^{-8}$
• Next-to-leading order Colour Octet (COM) contributions below CSM: $(4.6-6.2) \times 10^{-8}$
Summary - Outlook

Set out to search for $W+J/\psi$ associated production

- First observation of Charmonium+Vector boson production
- Measurement of cross-section ratio $W+J/\psi : W$
- Provide input to theorists who study $J/\psi$ and $W+J/\psi$ production
- Dominated by statistical uncertainties
- Measurement compatible with theoretical predictions within $2\sigma$

Next steps:
- Higher energy: $W+J/\psi$ at 8/14 TeV, differential cross-section
- New undetected signatures: $Z+J/\psi$, $W/Z+\Upsilon$
- Better understanding of $J/\psi$ production

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sPlot weights

\[ \mathcal{L} = \sum_{e=1}^{N} \ln \left\{ \sum_{i=1}^{N_s} N_i f_i(y_e) \right\} - \sum_{i=1}^{N_s} N_i \]

- Sophisticated method of background subtraction
- Each event attributed a signal or background weight according to likelihood fit
- No cuts are made, all events contribute to the projection
- We use sPlot to inspect prompt J/ψ candidates using all pre-selected events