

# Associated production of $J/\psi$ and $W$ in ATLAS

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on behalf of ATLAS

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IN PRAGUE



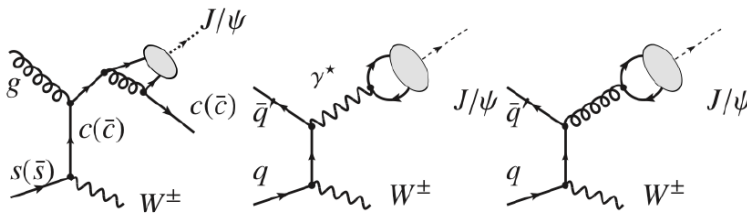


- $J/\psi$  meson: bound state of  $c\bar{c}$  quarks (charmonium)
- Production mechanism **not well understood**
- Competing production **models** (most popular):
  - **Color singlet**:  $c\bar{c}$  already produced in a color singlet state in the hard process and directly couple to the final meson
  - **Color octet**:  $c\bar{c}$  produced in a color octet state, converting to the final meson through a low-energy non-pQCD matrix element



- **Experimental measurements** sensitive to the CS and CO production mechanisms:
  - **Inclusive quarkonia cross section** measurement: current CS model not enough to describe **experimental results**
  - Measurement of quarkonia **polarization** ( $J/\psi$ ,  $\Upsilon$ ):
    - CS and CO models produce mesons with different **spin alignment** (polarization)
    - $J/\psi$  polarization from CMS & Tevatron **disagree** with both **CS and CO models**
  - Associated production of **prompt quarkonia + vector boson** (this talk)
    - **CDF**: limit on  $\Upsilon$  + vector boson production
- **ATLAS: first evidence** of the  $J/\psi + W$  vector boson production!

## Associated production of $J/\psi + W$ boson



- **Different production mechanisms** than for inclusive  $J/\psi$
- **Lowest-order** production processes:
  - $s(\bar{s}) + g \rightarrow J/\psi + W + c(\bar{c})$  (color singlet state)
  - $q\bar{q} \rightarrow \gamma^* + W \rightarrow J/\psi + W$  (color singlet state)
  - $q\bar{q} \rightarrow W^\pm g \rightarrow W^\pm Q\bar{Q}$  (color octet state)

## Pileup contamination and double parton scattering

- **Pileup contamination:**  $J/\psi$  and  $W$  from different  $pp$  collisions
- **Double parton scattering:**  $J/\psi$  and  $W$  in two different parton interactions in the colliding protons



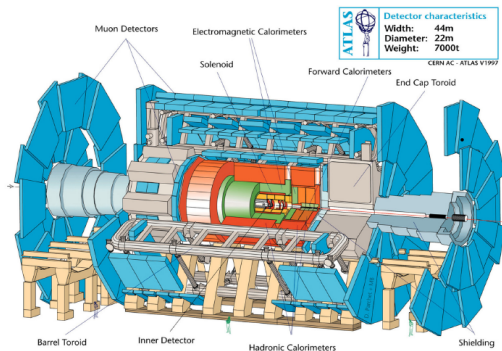
- **Theoretical predictions** made only for a **single parton** scattering processes
- $\Rightarrow$  The pileup and double parton scattering contributions must be **subtracted** for the results to be comparable to the predictions

## Experimental measurement

- Two ATLAS measurements: ATLAS-CONF-2013-042
  - 1 **First evidence** of the associated  $J/\psi + W$  production
  - 2 Measurement of the **cross-section ratio** of the prompt  $J/\psi + W$  and inclusive  $W$ :

$$R = BR(J/\psi \rightarrow \mu^+ \mu^-) \frac{1}{\sigma(pp \rightarrow W)} \frac{d^2 \sigma(pp \rightarrow J/\psi + W)}{dp_T dy}$$

- **Decay channels:**  $J/\psi \rightarrow \mu^+ \mu^-$  and  $W \rightarrow \mu \nu$
- **Physics signatures:** 2 opposite-charged muons ( $J/\psi$ ) + 1 isolated muon (from  $W$ ) + missing transverse energy,  $E_T^{miss}$  (neutrino)



- **General purpose detector** at the LHC
- **Dimensions:** 44 m (length)  $\times$  22 m (height)

- Close to  $4\pi$  coverage
- Sub-detectors
  - **Inner detector:** momentum of charged particles, vertex location
  - **EM calorimeter:** identification and energy of electrons and photons
  - **Hadronic Calorimeter:** energy of particle jets, tau leptons, missing energy
  - **Muon spectrometer:** identification and momentum of muons



- Using **ATLAS 2011 data** selected by a **single-muon trigger** ( $p_T^\mu \gtrsim 18$  GeV)
- **Integrated luminosity** of the selected data:  $4.6 \text{ fb}^{-1}$

## W selection

- One **isolated muon** (calorimeter and track isolation)
- **Fiducial volume**:  $p_T^\mu > 25$  GeV and  $|\eta^\mu| < 2.4$
- **Transverse missing energy**:  $E_T^{\text{miss}} > 20$  GeV
- **W transverse mass**:  $M_T^W > 40$  GeV

## J/ψ selection

- Two **oppositely charged muons**
- Muon momenta **re-fitted** with a common **vertex** constraint
- **Invariant mass** close to the nominal J/ψ mass:  $1.5 < m_{\mu\mu} < 3.5$  GeV
- **Fiducial volume**:  $8.5 < p_T < 30$  GeV and  $|y| < 2.1$
- **Pileup suppression**: impact parameter of muons  $z_0 < 1$  cm



## (2+1)-dimensional fit:

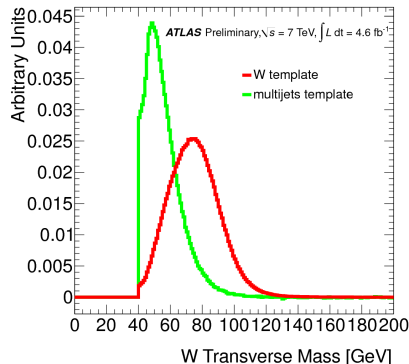
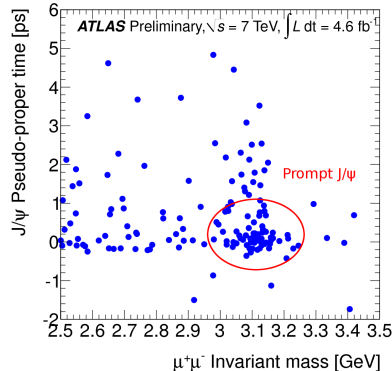
- $J/\psi$  yield** determined using a **2D maximum likelihood fit** in the invariant mass and pseudo-proper decay time:

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T}$$

Pseudo-proper decay time used to **distinguish prompt  $J/\psi$**  and  $J/\psi$  from  **$b$ -decays**

- $W + J/\psi$  yield** determined using a **template fit** to the  **$W$  transverse mass**

- $W$  template from MC simulation
- Background template: data-driven (ABCD method)



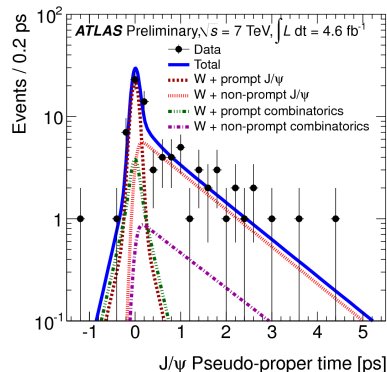
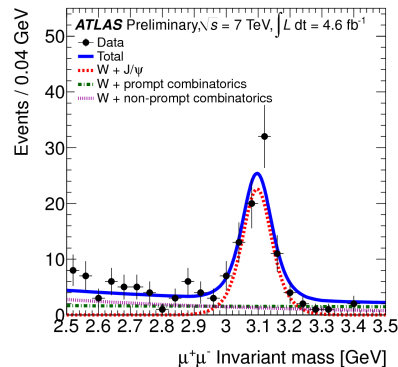


## Background for $J/\psi$

- 1 Combinatorial background
- 2 Non-prompt  $J/\psi$  background

## Maximum likelihood fit

- 1 Fit performed on a high statistics **inclusive  $J/\psi$  sample** and **values and uncertainties of the nuisance parameters** (e.g. resolution, effective bkg. lifetimes, etc.) are determined
- 2 Fit performed on  **$J/\psi + W$  sample**, where **gaussian constraints** are applied on the **nuisance parameters**
- 3 Using the *sPlot* procedure, **weights for the prompt  $J/\psi$  hypothesis** are determined for all events





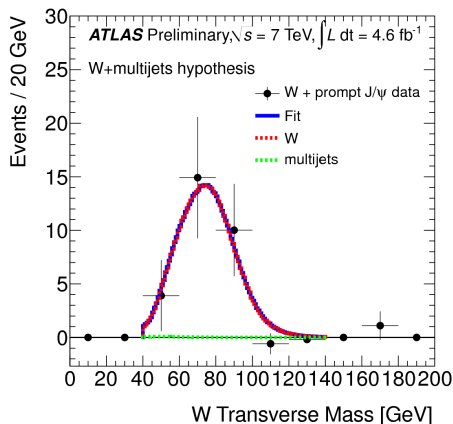
## Background for $W$

- **Multijet QCD**: data driven estimate (ABCD method)
- **$t\bar{t}$ ,  $Z + \text{jets}$  and diboson ( $WW$ ,  $WZ$ ,  $WZ$ )**: MC simulation

## $W$ template fit

- Template fit to the  $W$  transverse mass
- **Inclusive  $W$  sample**: determination of the inclusive  $W$  cross-section
- **$J/\psi + W$  sample**: events weighted using the  $sPlot$  weights to get the  $W$  transverse mass spectrum for the prompt  $J/\psi$  hypothesis

- Template fit to weighted events:  $J/\psi + W$  yield
- Estimated  $0.1 \pm 4.6$  background events in the sample





## Pileup subtraction

- Pileup contribution estimated using the inclusive  $J/\psi$  cross section, total inelastic cross section and the beam parameters
- **Pileup** contribution **subtracted** from the  $J/\psi + W$  yield

## Double parton scattering contribution

- Estimated using the the inclusive prompt  $J/\psi$  cross section and effective area parameter measured using the  $pp \rightarrow W(l\nu) + jj$  events<sup>1</sup>
- The total number of **DPS** events estimated  **$10.8 \pm 4.2$**

## Systematic uncertainties

- **Fit uncertainties:** background modeling and nuisance parameters
- **Spin alignment:**  $J/\psi$  acceptance depends on the spin alignment
- **W kinematics:** different kinematics for inclusive  $W$  and  $J/\psi + W$
- Uncertainty of **muon efficiency** and **momentum scale**

<sup>1</sup>New J. Phys. 15 (2013) 033038



## Evidence of the $J/\psi + W$ production

- The  $J/\psi$  significance and  $p$ -value estimated using comparison of the **bkg.-only and signal+bkg. fits** to the background-only samples generated in many **pseudo-experiments** and the **real data**
- $J/\psi$  **Yield:  $29.2_{-5.1}^{+5.8}$**  ( $p$ -value =  $4.4 \times 10^{-8}$  and **sig. = 5.3**)
- Using fits to the  $sPlot$  weighted  $W$  transverse mass, the multijet **background fraction** was estimated less than **0.31 at 95% CL**

## $J/\psi + W$ and inclusive $W$ cross section ratio

- Measurement of the **cross section ratio**:

$$R = BR(J/\psi \rightarrow \mu\mu)\sigma(pp \rightarrow J/\psi + W)/\sigma(pp \rightarrow W)$$

- 1 Cross section in the **fiducial volume**
- 2 Cross section **corrected** for the fiducial acceptance
- 3 Cross section with the **DPS** contribution **subtracted**

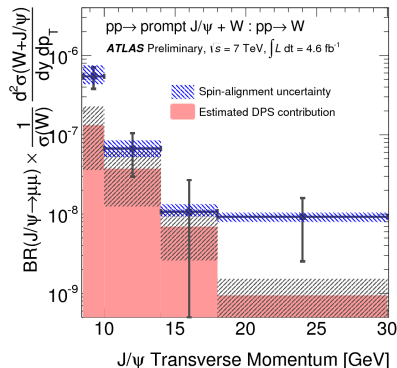
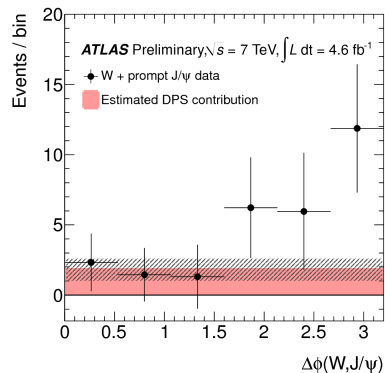


## SPS vs DPS contribution

- **Different** distribution of the **azimuthal angle** ( $\Delta\phi$ ) between  $J/\psi$  and  $W$ 
  - **SPS**: back-to-back topology
  - **DPS**: assuming uniform distribution
- **Top Figure**: comparison of the DPS template **normalized to the DPS rate** estimated **from  $W + jj$  measurement** (New J. Phys. 15 033038) and data
- **Good agreement** with the DPS+SPS hypothesis!

## Differential cross section

- Inclusive differential cross-section
- DPS contribution estimated
- SPS dominates low  $J/\psi$   $p_T$  production rate





## DPS-subtracted ratio vs. theoretical predictions

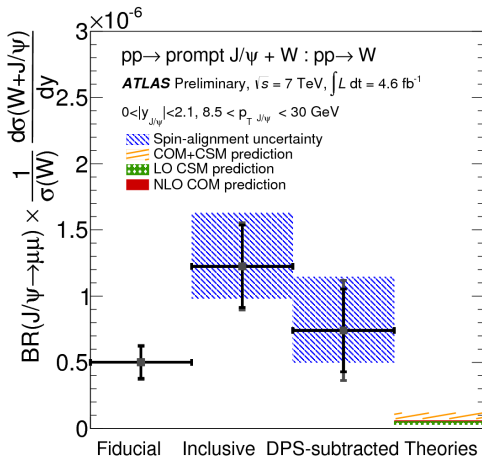
- Theory underestimates the measured value
- Possible explanations:
  - Large additional contributions to CO or CS predictions
  - Charm content of the proton
  - Underestimation of the DPS contribution
  - ...

- Still, agreement within  $2\text{-}\sigma$ !

$$R^{fid} = [50 \pm 12(stat) \pm 4(syst)] \times 10^{-8}$$

$$R^{incl} = [123 \pm 31(stat) \pm 10(syst) {}^{+40}_{-24}(spin)] \times 10^{-8}$$

$$R^{DPS-sub} = [74 \pm 31(stat) \pm 21(syst) {}^{+40}_{-24}(spin)] \times 10^{-8}$$





- **Observation** of the associated **production of  $J/\psi + W$**  with significance of  $5.3\sigma$  was made
- The **ratio** of the fiducial **cross section** of prompt  $J/\psi + W$  and the inclusive  $W$  was measured
- In addition, the cross-section ratio was **corrected for acceptance** and the **DPS contribution** was estimated
- Study of **angular separation of  $J/\psi$  and  $W$**  which is **sensitive** to the **SPS and DPS** contributions was performed. It confirms that **DPS** forms a **large contribution** to the  $J/\psi + W$  production (further studies needed to directly measure DPS contribution from the angular distribution)
- **Comparison** of the **DPS-subtracted cross section measurement** and current **CS and CO** model **predictions** was made
- The **prediction underestimates** the production rate, however, it **agrees with the measurement** within  $2\text{-}\sigma$