Measurement of the W + prompt J/ψ production cross section in pp collisions at √s = 7 TeV with the ATLAS detector

[JHEP 04 (2014) 172]

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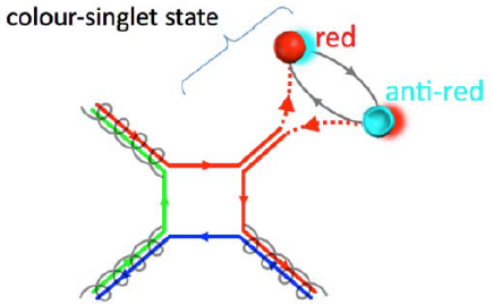
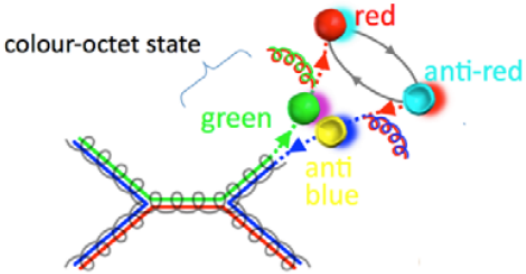
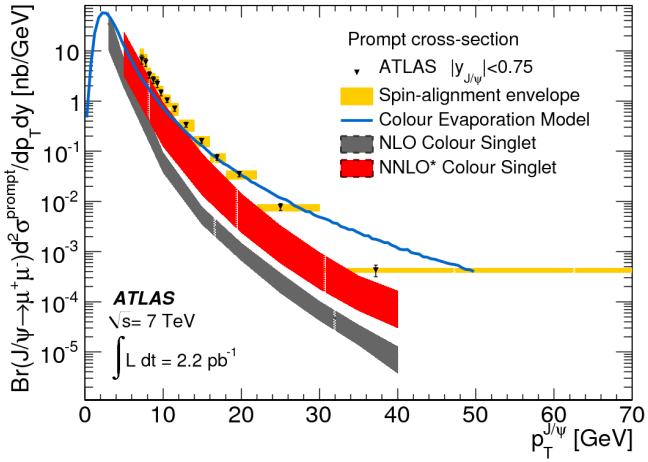
Heavy Quarkonium (QQbar) Production

- *Production of heavy charmonium (ccbar) in pp and ppbar collisions*
  - *Hard to calculate due to small charm quark mass*
  - *Phenomenological models fail to describe properties ($d\sigma/dp_T$, ccbar polarization, etc.)*
- *Models*
  - *Color singlet process (CS): charmonium quantum numbers determined by original quarks*
  - *Color octet process (CO): charmonium quantum numbers determined when ccbar system evolves into quarkonium state through radiation of soft gluons*
- *ATLAS measurements of QQbar production*
  - *$\psi(2S)$ cross section [1407.5532]*
  - *χ_{cJ} production [JHEP 07 (2014) 154]*
  - *Incl. Y(nS) diff. cross sections and ratios [PRD 87 (2013) 052004]*
  - *Y(1S) fiducial production cross section [PLB 703 (2011) 428]*
  - *differential cross sections of inclusive, prompt and non-prompt J/ψ production [NPB 850 (2011) 387]*
- *Measurement of W + prompt J/ψ production could shed further light on heavy quarkonium production mechanisms*





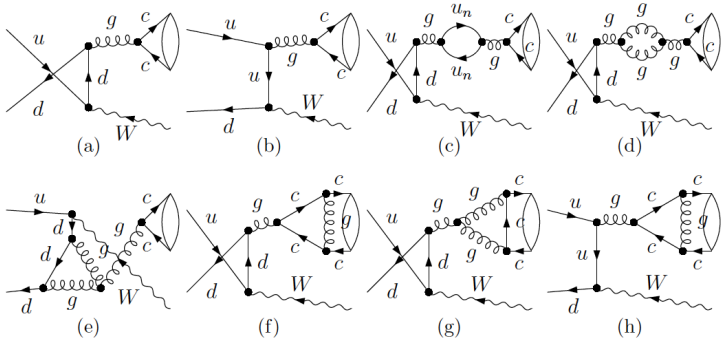
ATLAS, NPB 850 (2011) 387



Single and Double Parton Scattering (SPS & DPS)

- *Single Parton Scattering (SPS)*
  - *SPS involves a single parton from each proton*
- *Double Parton Scattering (DPS)*
  - *Mechanism with two hard scattering processes (A and B) in a single pp collision*
  - *The W is produced in one hard scatter and the J/ψ in the other*

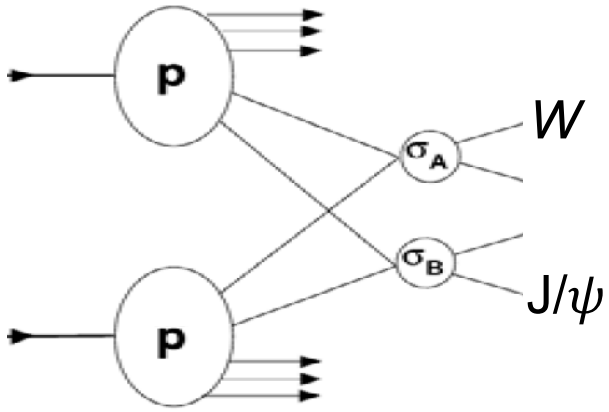
Some low-order Feynman diagrams for SPS production of W + prompt charmonium [Song, Zhang, Ma, PRD 83 (2011) 014001]



SPS and DPS contributions to W + prompt J/ψ production could (in principle) be distinguished statistically based on event topology

- *Pile up (background)*
  - *W and J/psi are produced in different pp collisions in the same bunch crossing*

Double Parton Production



Event Selection

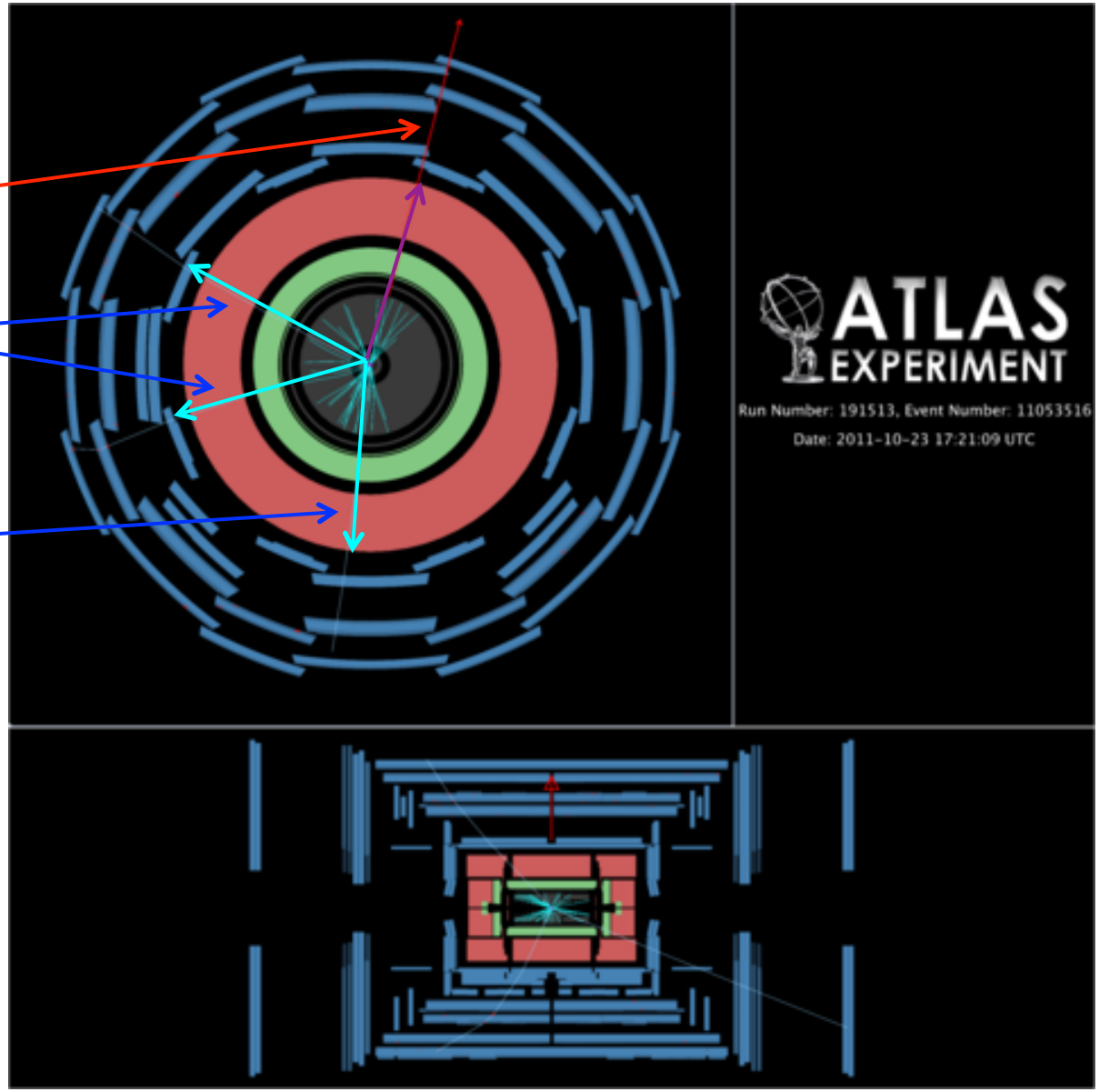
- *2011 ATLAS data set*
  - *4.5 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 TeV*
- *Single muon trigger p_T > 18 GeV*
- *$W \rightarrow \mu\nu$*
  - *Isolated muon p_T > 25 GeV and $|\eta| < 2.4$*
  - *Missing transverse energy > 20 GeV*
  - *Transverse mass of W m_T^W > 40 GeV*
  - *μ consistent with primary vertex*
- *$J/\psi \rightarrow \mu\mu$*
  - *p_T^μ > 3.5 (2.5) GeV with $|\eta^\mu| < 1.3$ ($|\eta^\mu| > 1.3$)*
  - *Di-muon pair consistent with common vertex (z_0 within 10 mm of PV)*
  - *$2.5 < m_{\mu\mu} < 3.5$ GeV*
  - *$8.5 < p_T^{J/\psi} < 30$ GeV and $|y_{J/\psi}| < 2.1$*
- *Z veto*
  - *Events with a di-muon mass within 10 GeV of Z mass are removed*

W + prompt J/ψ Candidate Event

Missing transverse momentum direction (associated with ν from W)

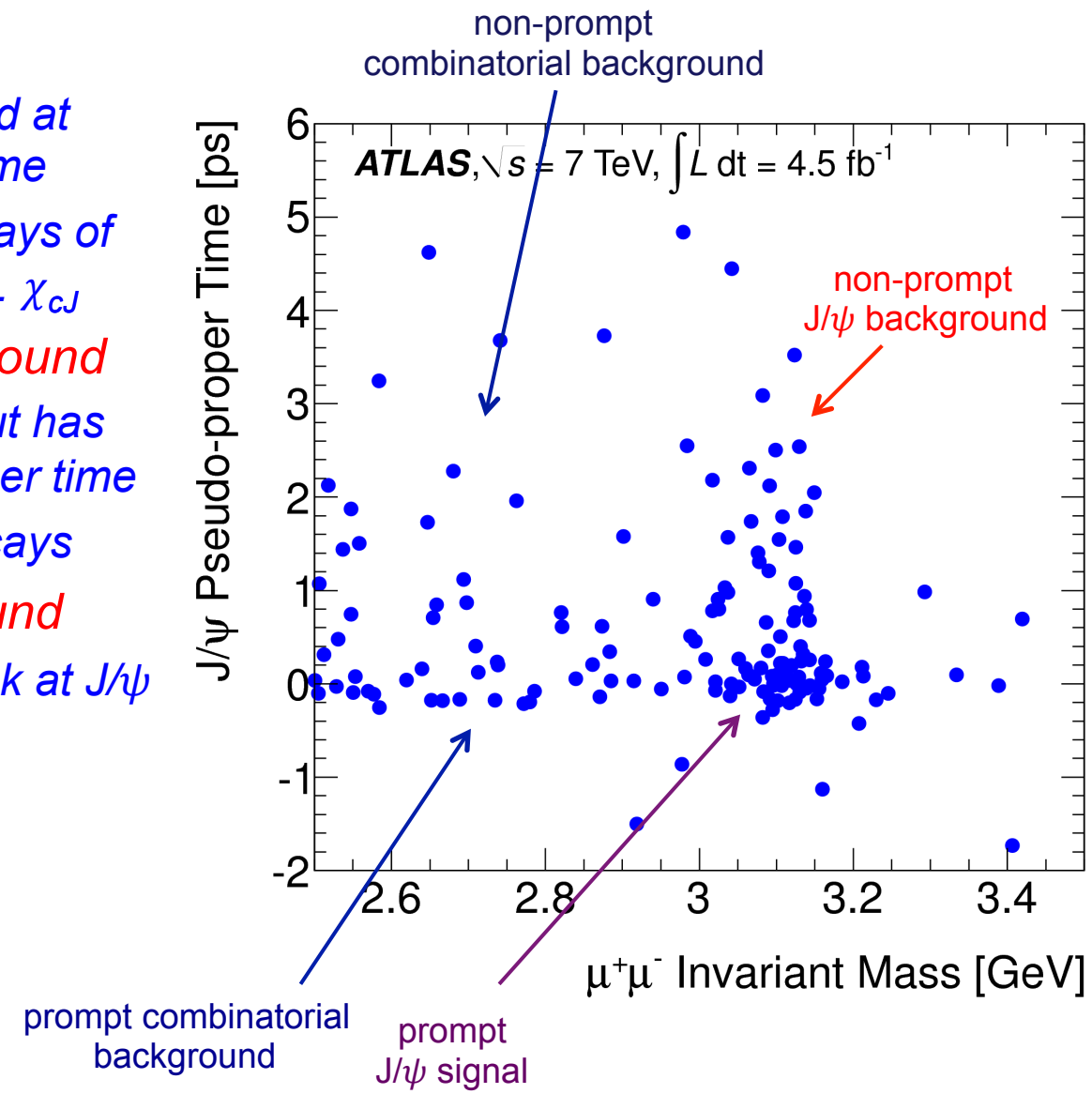
J/ψ → μμ

μ (from W)



J/ψ Candidates

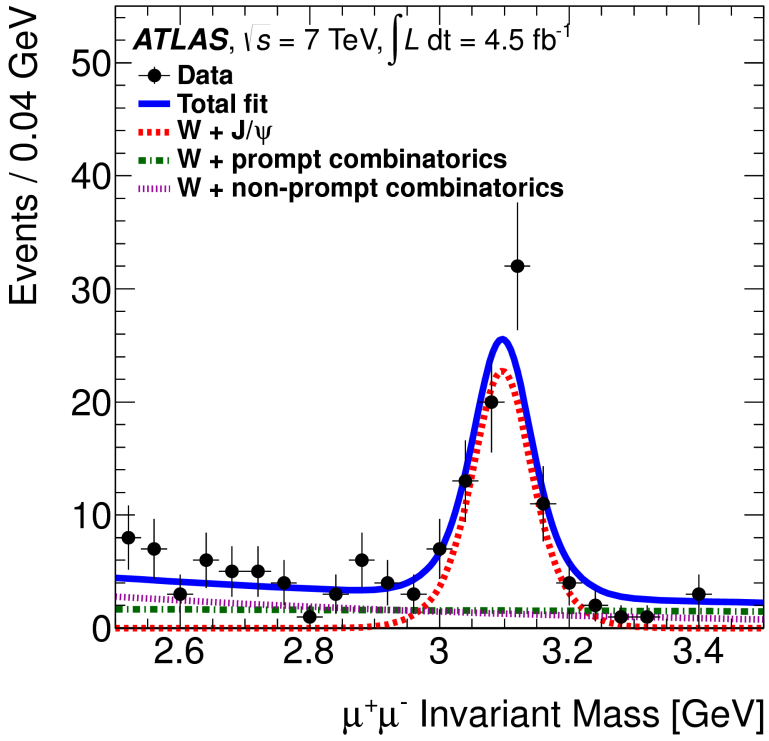
- *Prompt J/ψ signal*
  - *Peaks at J/ψ mass and at zero pseudo-proper time*
  - *Includes J/ψ from decays of excited charmonia e.g. χ_{cJ}*
- *Non-prompt J/ψ background*
  - *Peaks at J/ψ mass, but has non-zero pseudo-proper time*
  - *J/ψ from b hadron decays*
- *Combinatorial background*
  - *μμ mass does not peak at J/ψ mass*

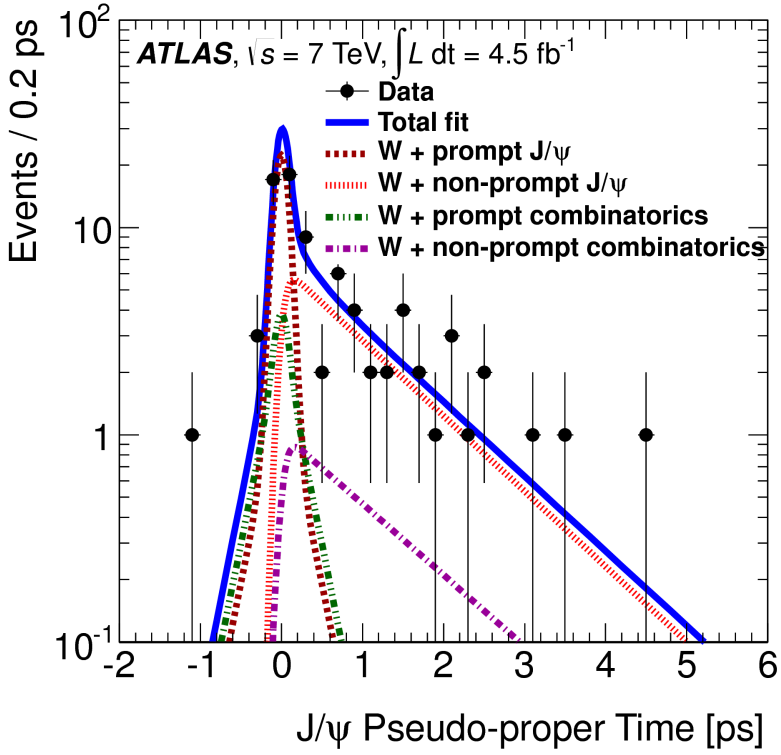


Extraction of prompt J/ψ Component

- *Two-dimensional maximum likelihood fit in μμ invariant mass and pseudo-proper time*
  - *Mass PDFs*
    - *Signal: Gaussian*
    - *Combinatorial background: Exponential*
  - *Pseudo-proper time PDFs*
    - *Prompt: Gaussian ⊗ (δ function + double-sided Exponential)*
    - *Non-prompt: Gaussian ⊗ Exponential*

Probability Density Function (PDF) shape parameters determined with a large inclusive J/ψ data sample





W + Prompt J/ψ Signal and Background Yields

Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
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	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

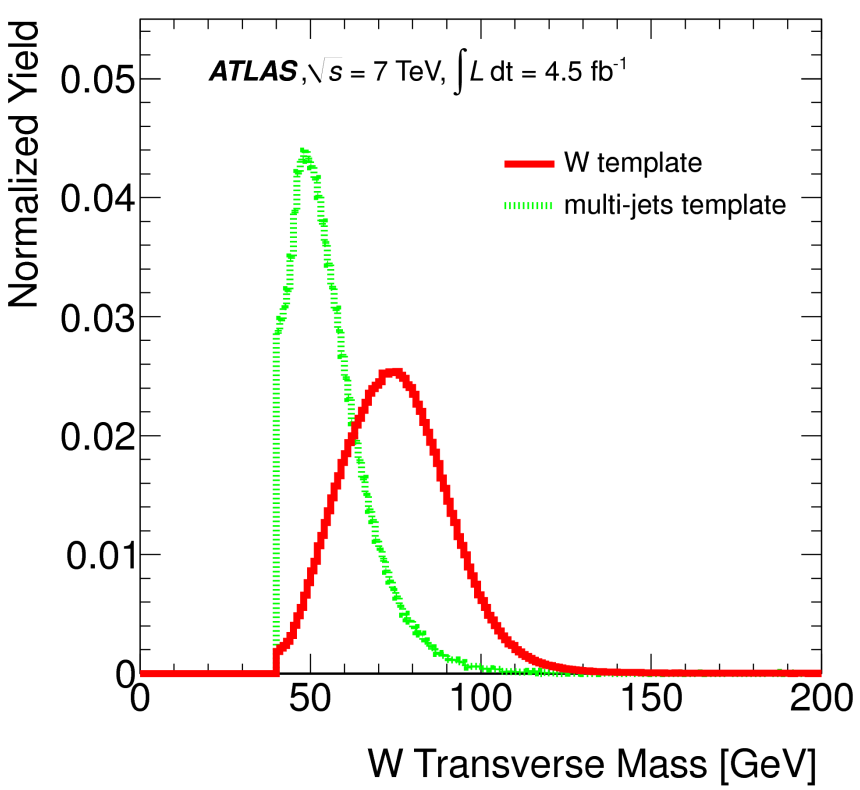
(*) of which 1.8 ± 0.2 originate from pileup

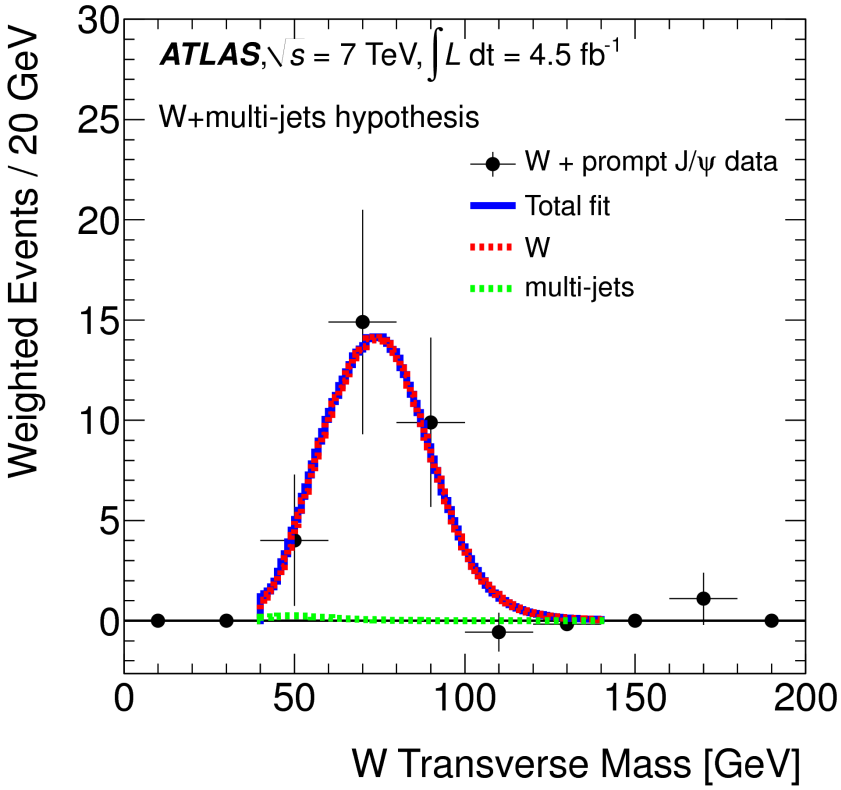
First observation

- *p-value and significance of W+ prompt J/ψ signal determined from probability that (S+B)/B likelihood ratio in background-only pseudo-experiments fluctuates up to observed value in data or higher*

Prompt J/ψ + Non-W Multi-jet Background Yields

- *Extract m_T^W from prompt J/ψ signal using $_s$Plot*
- *Fit m_T^W distribution to*
  - *W signal template*
  - *Data-driven multi-jet template*
- *0.1 ± 4.6 multi-jet events; multi-jet fraction < 0.31 at 95% C.L.*





Other Backgrounds

- *W + b*
  - *Rejected as non-prompt from likelihood fit*
- *$B_c \rightarrow J/\psi\ \mu\ \nu\ X$*
  - *All candidate events have 3-μ mass above 12 GeV [$m(B_c) = 6.28$ GeV]*
- *Z + jets*
  - *Require for all oppositely-charged muon pairs $|m_{\mu\mu} - m_Z| > 10$ GeV*
- *Pile-up*

$$N_{pileup} = N_{extra} \times P_{J/\psi} \times L \times \sigma_{pp \to W} = 1.8 \pm 0.2$$

  - *N_{extra} = extra pp collisions per event close enough to primary vertex to pass selection*
  - *$P_{J/\psi}$ = probability to produce a J/ψ in given $y^{J/\psi}$ and $p_T^{J/\psi}$ range*

Double Parton Scattering

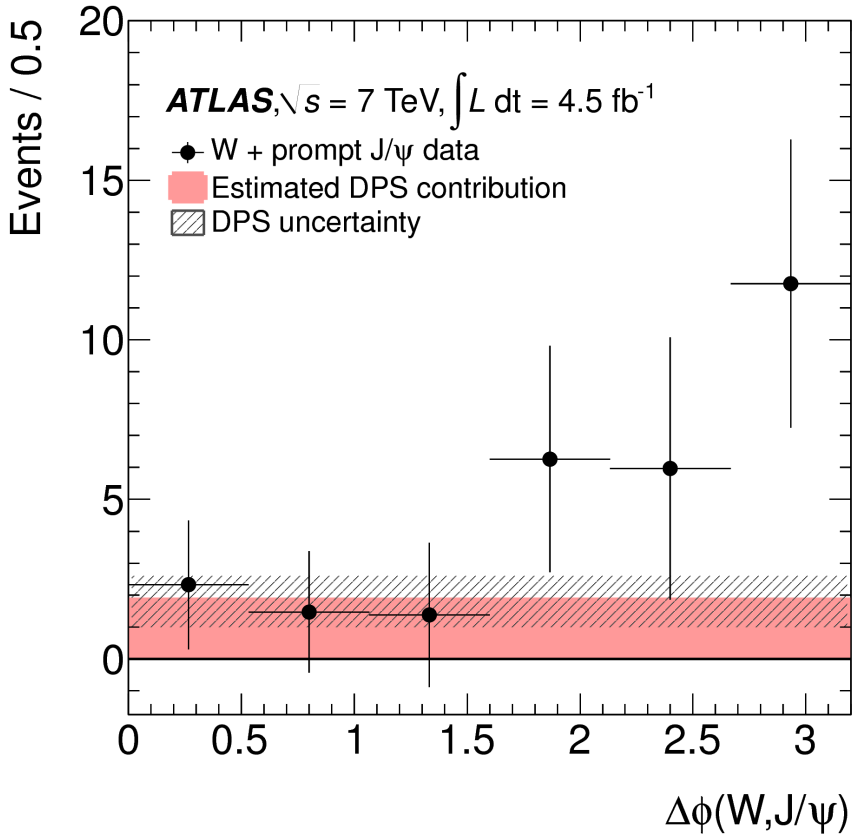
- *W and J/ψ originate from different parton interactions in the same pp collision*
  - *Estimate DPS W + prompt J/ψ yield from W yield and probability that a second scattering produces a J/ψ*

$$N_{DPS} = P_{J/\psi|W} \times N_W$$

  - *$P_{J/\psi|W}$ calculated from incl. J/ψ cross section and effective cross section for a second hard scattering*

$$P_{J/\psi|W} = \sigma_{J/\psi} / \sigma_{eff}$$

  - *σ_{eff} assumed independent of scattering process and calculated from W (➛ l ν) + 2-jet events [ATLAS, NJP 15 (2013) 033038]*
    - *$\sigma_{eff} = (15 \pm 3\ ^{+5}_{-3})$ mb*
  - *DPS events account for 10.8 ± 4.2 events in the signal yield*



Δϕ (between W and J/ψ) distribution consistent with DPS estimate (expect DPS flat in Δϕ, and SPS to peak near π)

W + prompt J/ψ Cross Section

- *Measure ratio $R_{J/\psi}$ of W + prompt J/ψ cross section to incl. W cross section*

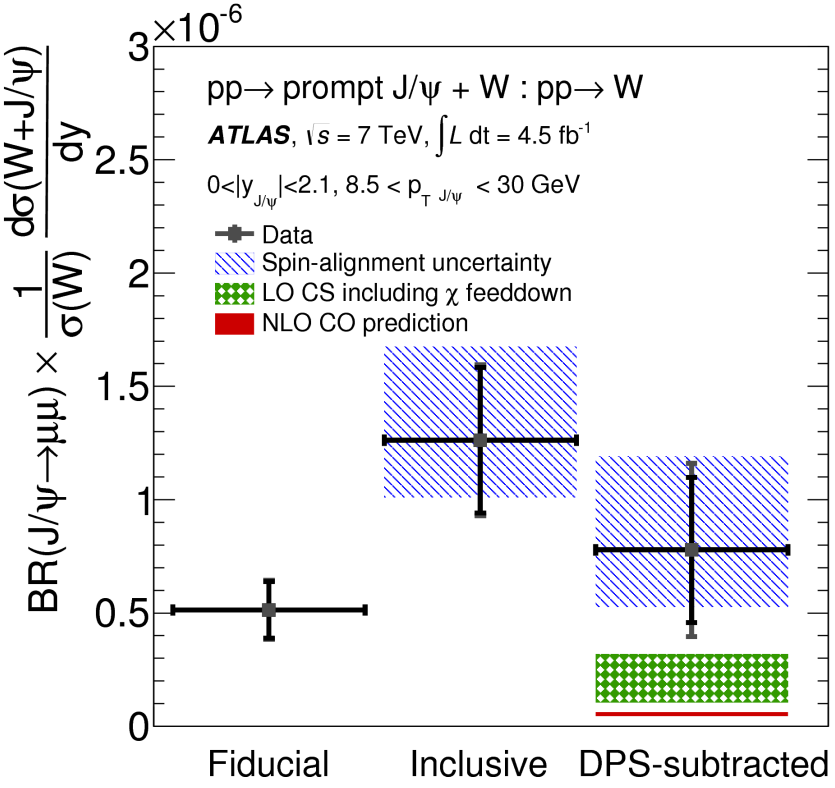
$$R_{J/\psi}^{fid} = \frac{BR(J/\psi \to \mu\mu)}{\sigma_{fid}(pp \to W)} \times \frac{d\sigma_{fid}(pp \to W + J/\psi)}{dy^{J/\psi}}$$

  - $R_{J/\psi}^{fid} = (51 \pm 13 \pm 4) \times 10^{-8}$
  - $R_{J/\psi}^{incl} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$
  - $R_{J/\psi}^{DPS\ sub} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

  [$|y^{J/\psi}| < 2.1$, $8.5 < p_T^{J/\psi} < 30$ GeV; third error is due to uncertainties in J/ψ spin alignment]

- *Comparison with predictions*
  - $R_{J/\psi}^{SPS\ LO\ CS} = (10\text{–}32) \times 10^{-8}$
  - $R_{J/\psi}^{SPS\ NLO\ CO} = (4.6\text{–}6.2) \times 10^{-8}$

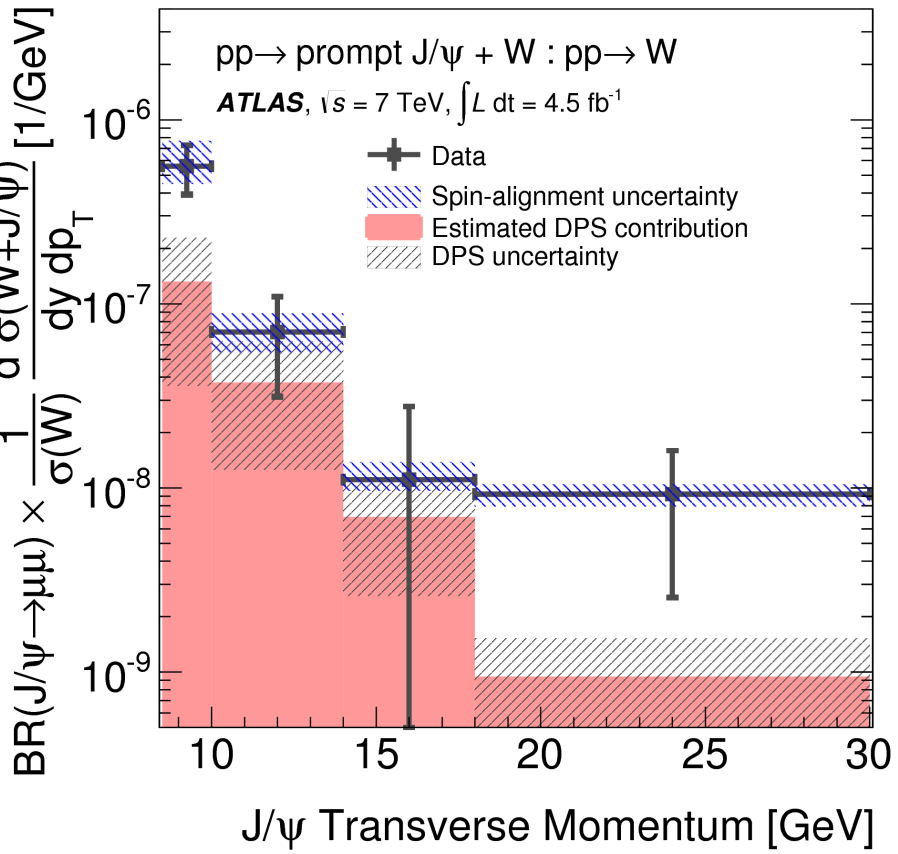
- *Discrepancy with CO prediction could be due to large higher-order contributions or possible breakdown of NRQCD universality*



CS [PLB 726 (218) 2013]
CO [PRD 83 (014001) 2011]

$p_T^{J/\psi}$ Dependence of Cross Section Ratio

- *Dependence of $R_{J/\psi}^{incl}$ and $R_{J/\psi}^{DPS}$ are shown as function of $p_T^{J/\psi}$*
  - *SPS appears to be dominant contribution at low $p_T^{J/\psi}$*



Conclusions

- *The associated W + J/ψ production measurement [ATLAS, JHEP 04 (2014) 172] is the latest in a series of ATLAS measurements of the production of heavy quarkonium in pp collisions*
  - *First observation of associated W + J/ψ production*
  - *DPS scattering process estimated to contribute at the level of 40% to the signal yield*
  - *Measured inclusive SPS contribution larger than LO CSM and NLO CO predictions, but consistent at the 2σ level*
- *ATLAS will publish a few more heavy quarkonium measurements on Run 1 data (at 7 and 8 TeV)*