Multiple charmonia production at LHC

Semen Turchikhin[1]

on behalf of ATLAS, CMS, and LHCb Collaborations

[1]Joint Institute for Nuclear Research

The 9th International Workshop on Charm Physics
Novosibirsk, Russia
21–25 May 2018

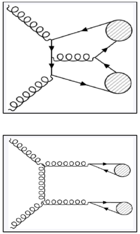
Studying associated production

- Multiple possibilities to produce two objects A, B in a pp collision
  - Single Parton Scattering (*SPS*)
    - described by specific process cross-section σ_{AB}^{SPS} – higher-order *"real"* associated production
  - Double Parton Scattering (*DPS*)
    - individual process cross-sections σ_A, σ_B
    - effective cross-section σ_{eff} accounting for probability of the two processes to happen in a single pp collision

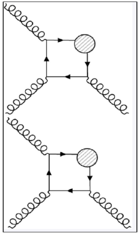
$$\sigma_{AB} = \sigma_{AB}^{\text{SPS}} + \sigma_{AB}^{\text{DPS}} = \sigma_{AB}^{\text{SPS}} + \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}}$$

- DPS/SPS separation is intrinsically uncertain
  - Limited knowledge of σ_{eff}
  - Higher-order SPS contributions can undermine assumptions
  - Experimentally one can measure N_A, N_B, and N_{AB}, with different efficiencies, lumi etc

$$f_{\text{DPS}} = \frac{\sigma_{AB}^{\text{DPS}}}{\sigma_{AB}} = \frac{\sigma_A \sigma_B}{\sigma_{AB}\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}} \sim \frac{1}{\sigma_{\text{eff}}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1+\delta_{AB}}$$



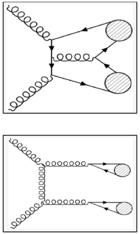
SPS



DPS

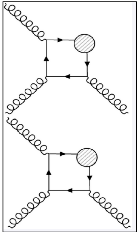
Prompt charmonium pair production

- SPS
  - Dominated by gluon–gluon fusion
  - Theoretical description has a long history and still far from final
    - generally sensitive to higher-order QCD corrections
    - CS vs. CO models
    - needs to properly account for feed-downs from higher states
  - None of the models gives a perfect description of data
    - pair quarkonia production can help in understanding, interpretation of the measured cross-section can be simpler



SPS

- DPS
  - $$\sigma_{\text{DPS}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\text{eff}}}$$
  - 1/2 accounts for two identical particles in final state
  - σ_{eff} is assumed to be universal across processes and energy scales
  - 12–20 mb values obtained earlier; however, indication of lower values from pair charmonia/bottommonia production questions the universality of σ_{eff}



DPS

What's on the market?

- DPS was probed via many types of
  - Hidden charm: $J/\psi + Z$, $J/\psi + W \dots$
  - Open charm
    - Reconstructed either via D meson decays or c jet tagging
    - $W + D$, $Z + D$, $\gamma + c$-jet
- This talk focuses on double charmonia production
  - **ATLAS:** prompt J/ψ pair production at $\sqrt{s} = 8$TeV Eur. Phys. J. C 77 (2017) 76
  - **CMS:** prompt J/ψ pair production at $\sqrt{s} = 7$TeV JHEP 09 (2014) 094
  - **LHCb:** prompt J/ψ pair production at $\sqrt{s} = 13$TeV JHEP 06 (2017) 047

  - I will describe the ATLAS analysis procedure in some details, and present the results of all three analyses

The measurements in a nutshell

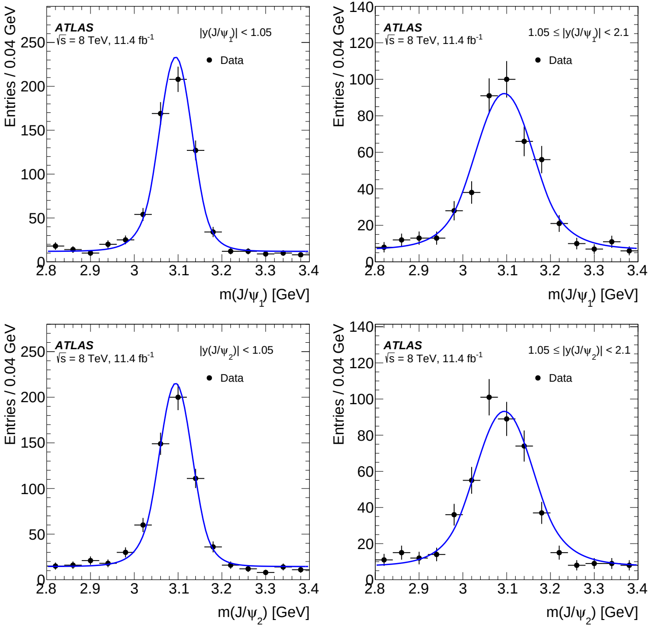
ATLAS EXPERIMENT	CMS	LHCb
11.4 fb^{-1} @ 8 TeV	4.7 fb^{-1} @ 7 TeV	279 pb^{-1} @ 13 TeV
$p_T(J/\psi) > 8.5$ GeV	$p_T(J/\psi) > 4.5 \div 6.5$ GeV	$p_T(J/\psi) < 10$ GeV
$\lvert y(J/\psi)\rvert < 2.1$	$\lvert y(J/\psi)\rvert < 2.1$	$2.0 < \lvert y(J/\psi)\rvert < 4.5$
$n_{\text{sig}} = 1160 \pm 70$	$n_{\text{sig}} = 443 \pm 23$	$n_{\text{sig}} = 1050 \pm 50$
fiducial x-sec	fiducial x-sec	fiducial x-sec
differential x-secs	differential x-secs	differential x-secs
data-driven f_{DPS}	–	f_{DPS} for different models
σ_{eff}	–	σ_{eff}
–	search for $\eta_b \to J/\psi J/\psi$	–

ATLAS analysis overview

- Muon kinematic requirements
  - $p_{\mathrm{T}}(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$
  - $p_{\mathrm{T}}(\mu) > 4$ GeV for one J/ψ firing the dimuon trigger
- (both) J/ψ requirements
  - $2.8 < m(\mu\mu) < 3.4$ GeV
  - $p_{\mathrm{T}}(\mu) > 8.5$ GeV, $|y(\mu)| < 2.1$
  - separation between two J/ψ vertices $d_z < 1.2$ mm
    - to suppress pile-up contribution
- Per-event corrections
  - Efficiency of trigger and reconstruction
  - Muon acceptance
- Signal extraction
  - Non-J/ψ background separated by 2D mass fits
  - Non-prompt J/ψ contribution separated by 2D L_{xy} fits
  - (Small) pile-up background separated by 1D fit to d_z vertex distance
- Due to different resolution, the measurement is done separately in central ($|y(J/\psi)| < 1.05$) and forward ($1.05 < |y(J/\psi)| < 2$) regions

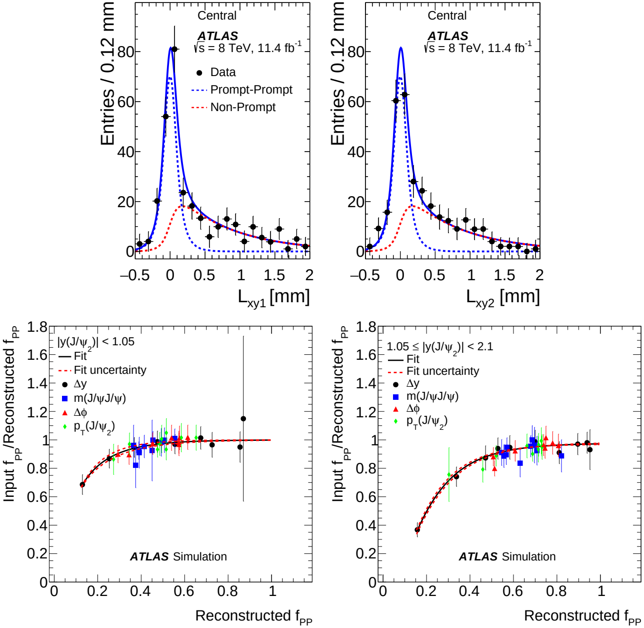
2D mass fit

- Projections of the fit
  - J/ψ_1 = higher-p_T
  - J/ψ_2 = lower-p_T
- The peak is described with *Crystal Ball*, its parameters are obtained from fitting inclusive J/ψ sample



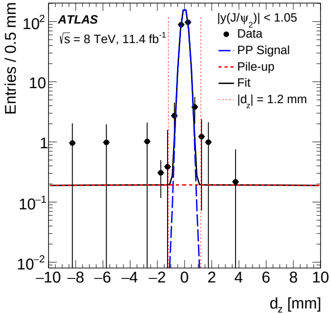
Prompt–prompt component extraction

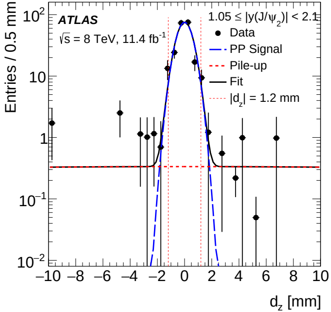
- 1D projections of 2D fits to L_{xy}
  - L_{xy} resolution function determined from inclusive J/ψ sample
- Prompt–prompt fraction f_{PP} extracted in 4 fits, based on y region of each J/ψ
  - Per-event weights assigned as a function of L_{xy}
  - Corrected for the biases in differential distributions



Pile-up contribution

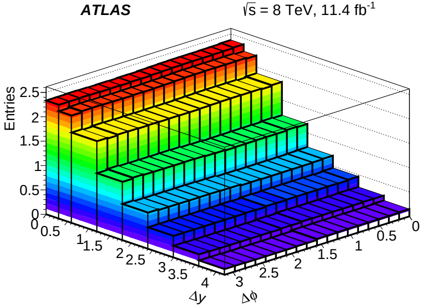
- To subtract J/ψ pairs from multiple collisions in a bunch crossing
- Fit to d_z
  - two gaussians for signal and background
  - determined from inclusive J/ψ sample
- Pile-up fraction found to be $< 1\%$
- Subtraction done using template from PU-enriched $d_z > 2.0$ mm region

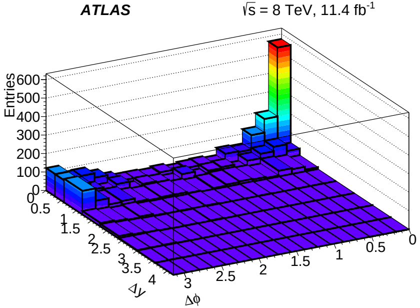




Data-driven extraction of DPS contribution

- Templates for DPS and SPS contribution in $\Delta\phi(J/\psi J/\psi) \times \Delta y(J/\psi J/\psi)$
- DPS template – event mixing
  - combine J/ψ's from random different events, assuming their independent kinematics
  - normalize to $\Delta y > 1.8$, $\Delta\phi > \pi/2$ region
- SPS contribution
  - obtained by subtracting the DPS from data
- Per-event weights $w_{\text{DPS}}(\Delta\phi, \Delta y)$, $w_{\text{SPS}}(\Delta\phi, \Delta y)$ assigned to study the DPS/SPS spectra





ATLAS results: cross-sections

- Fiducial cross-section in $p_{\mathrm{T}}(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, $p_{\mathrm{T}}(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$, $p_{\mathrm{T}}(\mu) > 4$ GeV for two trigger muons

  $15.6 \pm 1.3\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.2\,(\text{BF}) \pm 0.3\,(\text{lumi})$ pb, for $|y| < 1.05$,

  $13.5 \pm 1.3\,(\text{stat}) \pm 1.1\,(\text{syst}) \pm 0.2\,(\text{BF}) \pm 0.3\,(\text{lumi})$ pb, for $1.05 \leq |y| < 2.1$

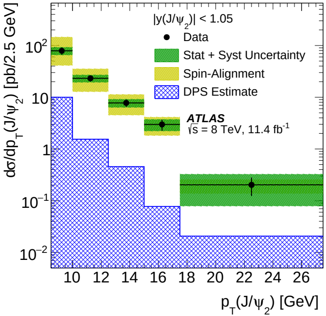
- Total cross-section

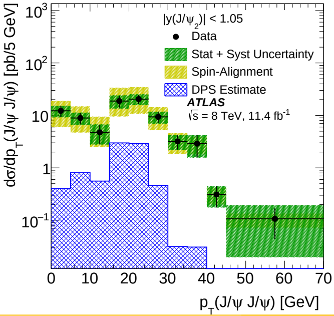
  $82.2 \pm 8.3\,(\text{stat}) \pm 6.3\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.6\,(\text{lumi})$ pb, for $|y| < 1.05$,

  $78.3 \pm 9.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.5\,(\text{lumi})$ pb, for $1.05 \leq |y| < 2.1$

  - assume unpolarized production

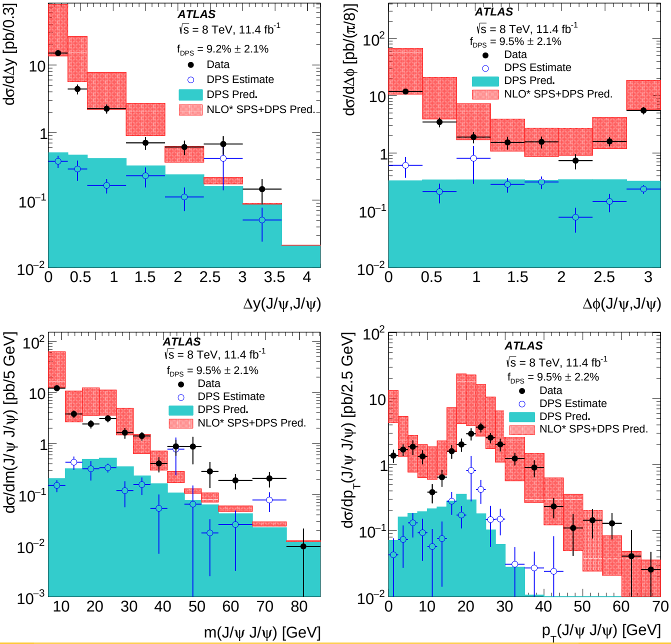
- Two peaks in $p_{\mathrm{T}}(J/\psi J/\psi)$
  - near zero – away topology, back-to-back
  - near higher p_{T} – towards topology
    - back-to-back to another gluon
    - NLO effect





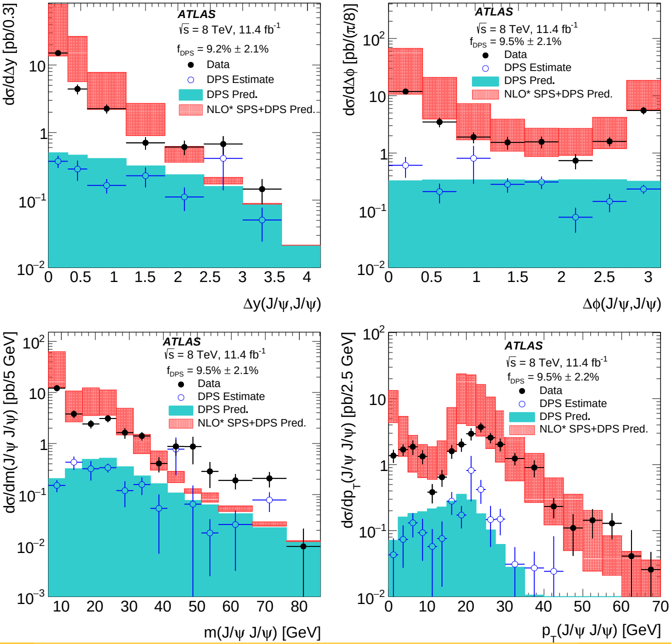
ATLAS results: cross-sections

- Differential SPS/DPS cross-sections measured in the muon fiducial volume
- DPS: scaled to measured f_{DPS} – only shape comparison
  - LO predictions based on Phys. Rev. D 95 (2017) 034029
- SPS
  - Colour-Singlet NRQCD w/o loops (NLO*) Phys. Lett. B 751 (2015) 479, Phys. Rev. Lett. 111 (2013) 122001
  - Scaled by $\times 1.85$ to allow for feed-down



ATLAS results: cross-sections

- Overall good agreement for DPS contribution
- Some discrepancies in total cross-section for away topology
- Significant fraction of events with towards topology → LO predictions alone not enough to describe it



ATLAS results: DPS measurements

- σ_{eff} can be measured as

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{f_{\text{DPS}} \times \sigma(J/\psi J/\psi)}$$

  - $\sigma_{J/\psi}$ from the ATLAS measurement Eur. Phys. J. C 76 (2016) 283
  - f_{DPS}, $\sigma(J/\psi J/\psi)$ from this analysis
- $f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat.}) \pm 0.5(\text{syst.}))\%$
- $\sigma_{\text{DPS}} = 14.8 \pm 3.5(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.2(\text{BF}) \pm 0.3(\text{lumi.})$ pb
- $\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi.})$ mb

CMS analysis results

- Reach softer region than ATLAS

  $p_T^{J/\psi} > 6.5$ GeV $\quad |y^{J/\psi}| < 1.2$

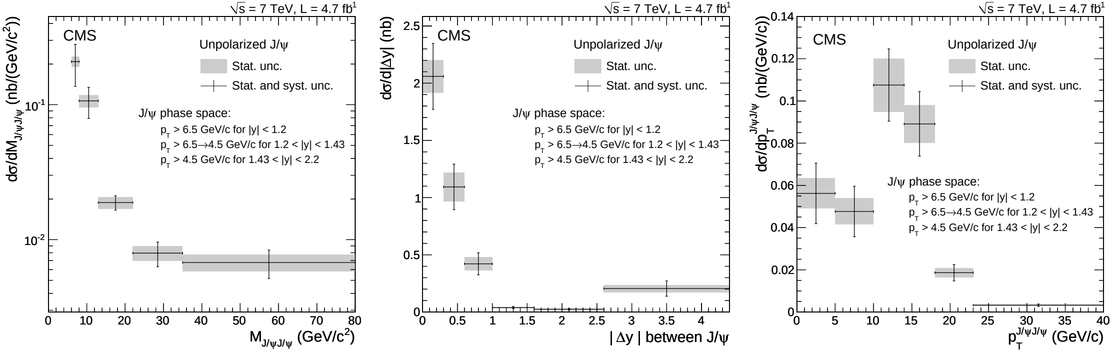
  $p_T^{J/\psi} (6.5 - 4.5)$ GeV $\quad 1.2 < |y^{J/\psi}| < 1.43$

  $p_T^{J/\psi} > 4.5$ GeV $\quad 1.43 < |y^{J/\psi}| < 2.2$

- Total cross-section

  $\sigma(J/\psi J/\psi) = 1.49 \pm 0.07 \pm 0.13$ nb

- Fit (done by *Lansberg et al* *Phys. Lett. B 751 (2015) 479*) yields $\sigma_{\text{eff}} = 8.2 \pm 2.2$ mb
- Also searches for $\eta_b \to J/\psi J/\psi$ contribution
  - 15 ± 4 events expected in [9.16, 9.64] GeV from the sidebands
  - 15 events observed $\to$ no evidence for signal



LHCb results: total cross-section

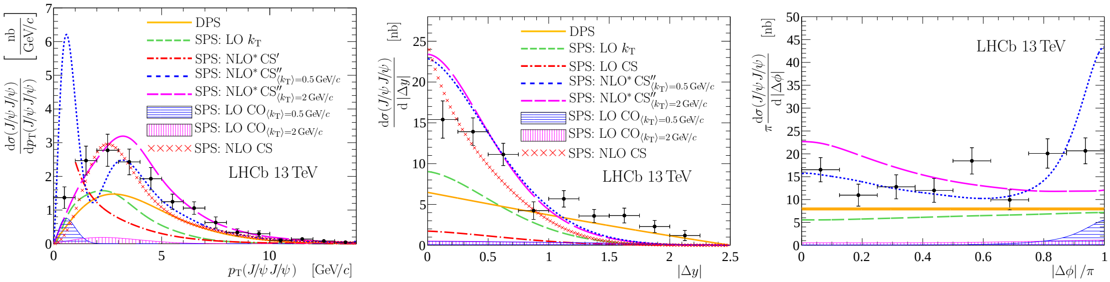
- LHCb probes different fiducial volume:
  - $p_T(J/\psi) < 10$ GeV, $2.0 < |y(J/\psi)| < 4.5$
  - Run 2 energy $\sqrt{s} = 13$ TeV
- Total cross-section (assuming unpolarized production)
  - $\sigma(J/\psi J/\psi) = 15.2 \pm 1.0(\text{stat.}) \pm 0.9(\text{syst.})$ nb
- Compared to a rather comprehensive set of predictions (and DPS assuming $\sigma_{\text{eff}} = 14.5$ mb)
  - Integral cross-sections mostly suffer from high PDF and scale uncertainties
  - Shapes are more stable against them

	$\sigma(J/\psi\, J/\psi)$ [nb]		
	no p_T cut	$p_T > 1\,\text{GeV}/c$	$p_T > 3\,\text{GeV}/c$
LO CS [92]	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
LO CO [95, 96]	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
LO k_T [102]	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
NLO* CS′ [92]	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$
NLO* CS″ [70, 93–96]	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
NLO CS [39]	$11.9^{+4.6}_{-3.2}$	—	—
DPS [44, 85, 91]	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$
Data	$15.2 \pm 1.0 \pm 0.9$	$13.5 \pm 0.9 \pm 0.9$	$8.3 \pm 0.6 \pm 0.5$

LHCb results: shapes

- Away topology of SPS not as visible as in ATLAS/CMS, due to kinematics
  - Clearly larger DPS contribution than in ATLAS/CMS
- Neither the DPS or any SPS model can describe the data simultaneously
  - Sum of them can
  - Perform a fit of each variable v distribution with DPS + any of the SPS models:

$$\frac{d\sigma}{dv} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$$



LHCb results: f_{DPS}

- All fits indicate dominant DPS contribution
  - Including CO contribution does not change much f_{DPS} and is much smaller than the CS
- The $\sigma_{\mathrm{SPS}} = (1 - f_{\mathrm{DPS}})\sigma(J/\psi J/\psi)$ determined from the fits
  - Roughly agrees with NLO* CS' model (CS NLO w/o loops, using simple cut-off on $p_{\mathrm{T}}(J/\psi J/\psi)$) and LO k_{t}-factorization based calculations
  - Smaller than NLO CS and NLO* CS" (cut-off on any light parton pair mass)

<table>
<tr><th rowspan="2">Variable</th><th rowspan="2">LO CS</th><th rowspan="2">LO k_{T}</th><th rowspan="2">NLO* CS$'$</th><th colspan="2">NLO* CS$''$</th><th rowspan="2">NLO CS</th></tr>
<tr><th>$\langle k_{\mathrm{T}}\rangle = 2\,\mathrm{GeV}/c$</th><th>$\langle k_{\mathrm{T}}\rangle = 0.5\,\mathrm{GeV}/c$</th></tr>
<tr><td colspan="7">no $p_{\mathrm{T}}(J/\psi\,J/\psi)$ cut</td></tr>
<tr><td>$p_{\mathrm{T}}(J/\psi\,J/\psi)$</td><td>—</td><td>$78 \pm 2$</td><td>—</td><td>$86 \pm 55$</td><td>$81 \pm 7$</td><td>—</td></tr>
<tr><td>$y(J/\psi\,J/\psi)$</td><td>83 ± 39</td><td>—</td><td>—</td><td>75 ± 37</td><td>68 ± 34</td><td>—</td></tr>
<tr><td>$m(J/\psi\,J/\psi)$</td><td>76 ± 7</td><td>74 ± 7</td><td>—</td><td colspan="2">78 ± 7</td><td>77 ± 7</td></tr>
<tr><td>$\lvert\Delta y\rvert$</td><td>59 ± 21</td><td>61 ± 18</td><td>—</td><td>63 ± 18</td><td>61 ± 18</td><td>69 ± 16</td></tr>
<tr><td colspan="7">$p_{\mathrm{T}}(J/\psi\,J/\psi) > 1\,\mathrm{GeV}/c$</td></tr>
<tr><td>$y(J/\psi\,J/\psi)$</td><td>—</td><td>—</td><td>75 ± 24</td><td>71 ± 38</td><td>68 ± 34</td><td>—</td></tr>
<tr><td>$m(J/\psi\,J/\psi)$</td><td>—</td><td>73 ± 8</td><td>76 ± 7</td><td colspan="2">88 ± 1</td><td>—</td></tr>
<tr><td>$\lvert\Delta y\rvert$</td><td>—</td><td>57 ± 20</td><td>59 ± 19</td><td>60 ± 18</td><td>60 ± 19</td><td>—</td></tr>
</table>

LHCb results: σ_{eff}

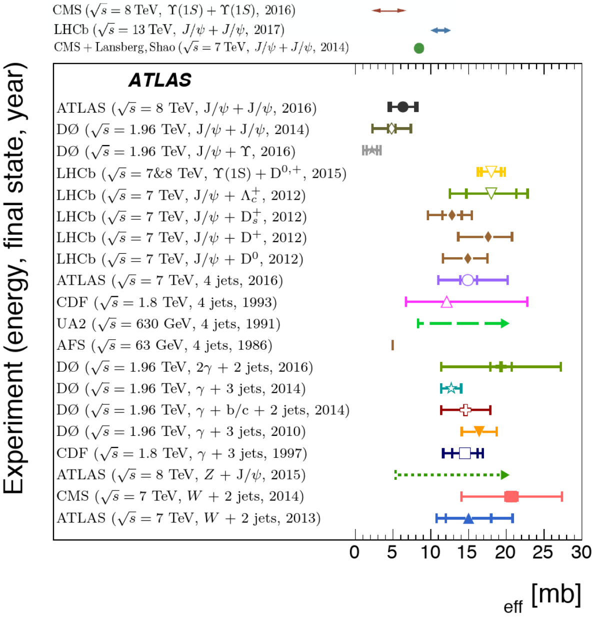
- Using σ_{DPS} from the fits yields values **8.8–12.5 mb**
  - Slightly higher than ATLAS result and that derived from the CMS measurement
  - Larger than D0 results from $J/\psi + J/\psi$ and $J/\psi + \Upsilon$
  - Smaller than LHCb measurements of onia + open charm

Variable	LO k_{T}	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 2\,\mathrm{GeV}/c$	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 0.5\,\mathrm{GeV}/c$	NLO CS
$p_{\mathrm{T}}(J/\psi\, J/\psi)$	9.7 ± 0.5	8.8 ± 5.6	9.3 ± 1.0	—
$y(J/\psi\, J/\psi)$	—	11.9 ± 7.5	10.0 ± 5.0	—
$m(J/\psi\, J/\psi)$	10.6 ± 1.1	10.2 ± 1.0		10.4 ± 1.0
$\lvert\Delta y\rvert$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

- Rough assumption that all di-J/ψ come from DPS gives $7.3 \pm 0.5(\text{stat.}) \pm 1.0(\text{syst.})$ mb

DPS results comparison

- Generally, the LHC di-J/ψ results are close to the D0 measurements with quarkonia
- Lower than the other measurements
- Questions the assumption of σ_{eff} universality
- di-J/ψ, J/ψ–Υ, 4-jet processes are dominated by gg interactions $\to$ probe gluon distributions in proton



Summary

- Three experiment di-J/ψ production measurements are reviewed
  - All allow differential cross-section measurements and DPS contribution estimate
- Overall reasonable description of both DPS and SPS contributions measured in data
  - Still room for improvement towards more complete theoretical picture
- Some indication of non-universality of σ_{eff}, motivates more studies

Backup slides

ATLAS systematics

Systematic uncertainty: di-J/ψ cross-section [%]		
Source	$\lvert y(J/\psi_2)\rvert < 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Trigger	± 7.5	± 8.3
Muon reconstruction	± 1.1	± 1.3
Kinematic acceptance	± 0.4	± 1.1
Mass model	± 0.1	± 0.1
Mass bias	± 0.2	± 0.2
Prompt–prompt model	± 0.2	± 0.01
Differential f_{PP} corr.	± 0.6	± 0.3
Pile-up	± 0.03	± 0.4
Total	$\pm$ 7.7	$\pm$ 8.5
Branching fraction	± 1.1	
Luminosity	± 1.9	

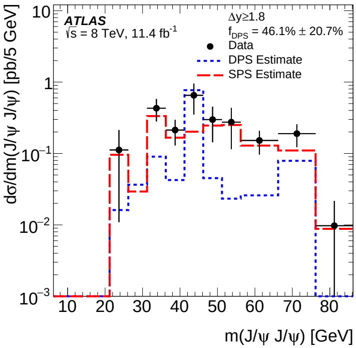
Systematic uncertainty: f_{DPS} [%]	
Source	Relative uncertainty [%]
Trigger	± 0.7
Muon reconstruction	± 0.1
Mass model	± 0.01
Mass bias	± 0.02
Prompt–prompt model	± 0.1
Differential f_{PP} corr.	± 0.1
Pile-up	± 0.8
DPS model	± 5.6
Total	$\pm$ 5.7

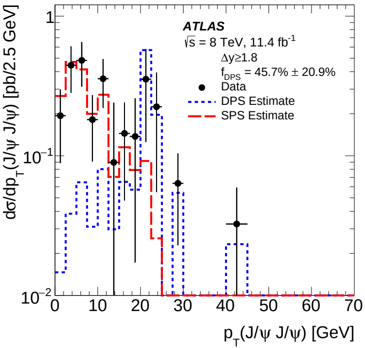
ATLAS polarization corrections

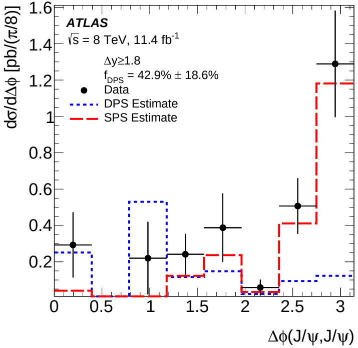
Maximum spin-alignment scenarios: di-J/ψ cross-section		
Scenario	$\lvert y(J/\psi_2)\rvert \leq 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Longitudinal	-47%	-45%
Transverse positive	+68%	+82%
Transverse negative	+39%	+28%
Transverse zero	+51%	+47%

Maximum spin-alignment scenarios: di-J/ψ DPS cross-section		
Scenario	$\lvert y(J/\psi_2)\rvert \leq 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Longitudinal	-47%	-45%
Transverse positive	+79%	+65%
Transverse negative	+35%	+35%
Transverse zero	+54%	+48%

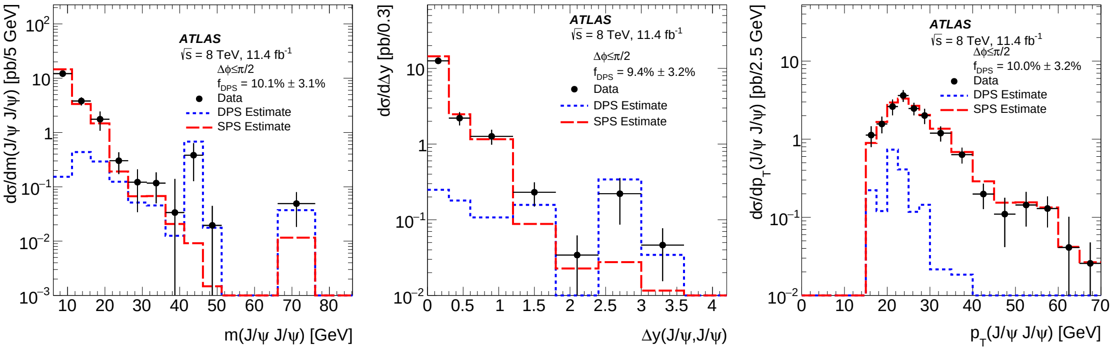
ATLAS di-J/ψ plots for $\Delta y > 1.8$







ATLAS di-J/ψ plots for $\Delta\phi < \pi/2$



$\Upsilon(1S)$ pair production at CMS

- $20.7\ \text{fb}^{-1}$ @ $\sqrt{s} = 8$ TeV
- Fiducial region $|y^{\Upsilon}| < 2.0$
- $\sigma_{\text{fid}} = 68.8 \pm 12.7(\text{stat.}) \pm 7.4(\text{syst.}) \pm 2.8(\text{BF})$ pb
  - $\sigma_{\text{eff}} = 6.6$mb assuming expectation for $f_{\text{DPS}} = 10\%$
  - $\sigma_{\text{eff}} = 2.2$mb assuming expectation for $\sigma_{\text{SPS}} = 48$ pb