Double Parton Scattering with the ATLAS Experiment

Sandro Palestini, CERN
on behalf of the ATLAS Collaboration

MPI@LHC, 11-15 Dec. 2017,

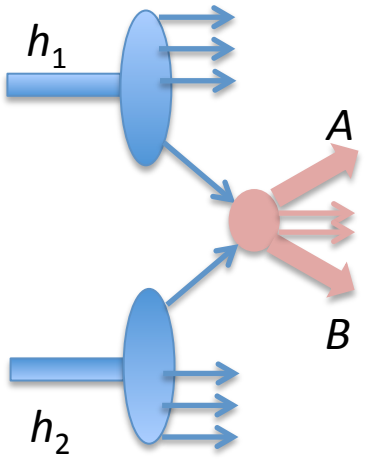
Shimla, India

Introduction: associated production: SPS and DPS

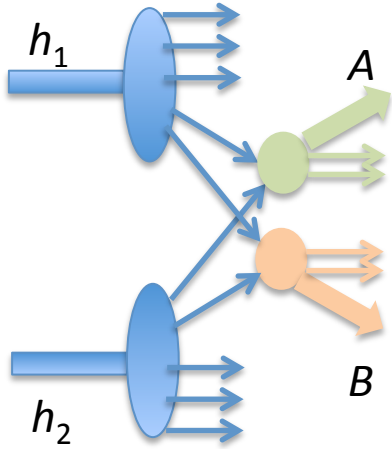
Two components in the associated inclusive production $h_1\, h_2$ -> $A\, B$ X :

$$\sigma_{AB} = \sigma_{AB}^{SPS} + \sigma_{AB}^{DPS}$$

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



Single Parton Scattering



Double Parton Scattering

- The *effective cross-section* σ_{eff} accounts for the size of the hadrons and for and for transverse parton correlations, and is usually assumed to be approximately independent of the choice of *A* and *B.*
- The parameter δ_{AB} corrects for double counting, and ranges from 0 ($A \neq B$) to 1 ($A=B$, measured in the same phase-space).

Introduction continued

- Experimentally,

$$\sigma_{eff} = \frac{N_A \times N_B}{f_{DPS} \times N_{AB}} \times \frac{C_{AB}}{C_A \times C_B} \times \frac{1}{1+\delta_{AB}}$$

with event counts, DPS fraction ($\sigma_{AB}^{DPS}/\sigma_{AB}$), and factors $C_X = \varepsilon_X / L_X$ that include efficiency, detector effects, integrated luminosity. Systematic uncertainties may reduce in the combination of C_X factors.

- We'll review results presented by ATLAS In the last few years:
  - starting with analyses that supported the presence of DPS,
  - and going into more detail in those that resulted in a determination of the effective area parameter σ_{eff},
  - the two most recent ones in particular, including the implications that were left about σ_{eff}.

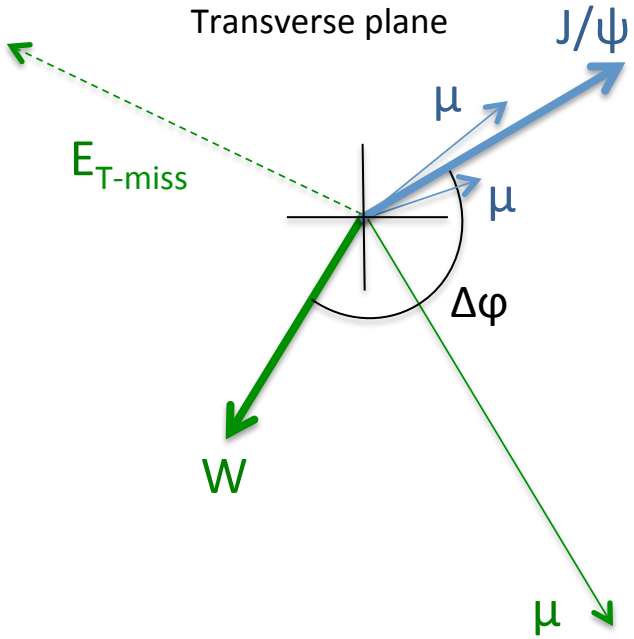
1) SPS and DPS in J/ψ + W production

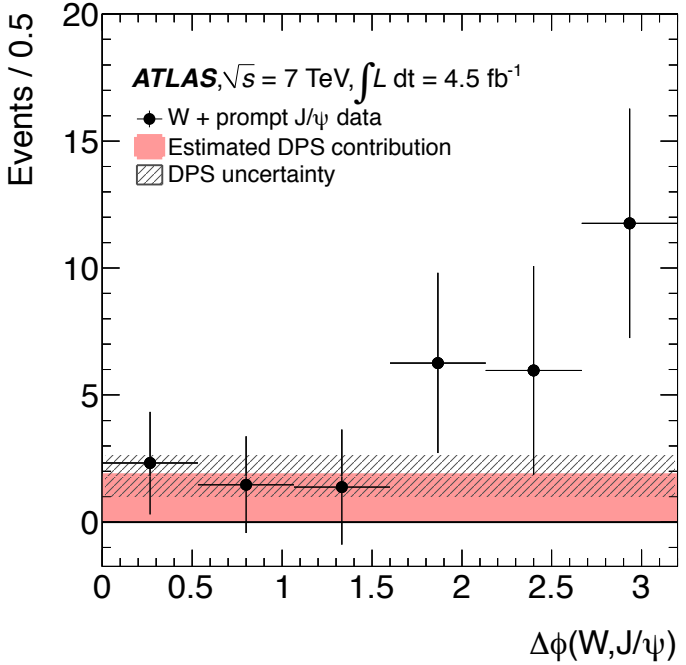
First study by ATLAS, based on the data collected at 7 TeV (4.5 fb^{-1}):

- Look for prompt J/ψ (->μ+μ-) in events selected as W(->μ ν)
  - p_T(μ/W) > 18 GeV at trigger level, p_T(μ/J/ψ) > 3.5 or 2.5 GeV (forward region), |η|<2.5 , E_T^{miss}> 20 GeV, M_T^W > 40 GeV,
  - 27+-7 events with $p_T^{J/\psi}$ > 8.5 GeV , $|y^{J/\psi}|$<2.1 , with negligible background (W+b, tt, multi-jets J/ψ, etc., 1.8+-0.2 pile-up events subtracted) .

p_T balance between W and J/ψ:

- data with Δφ < π/2 are compatible with DPS at the level of ≈10 events for σ_{eff} ≈15 mb (value from other measurements)
- σ_{AB}^{SPS} higher than predicted.



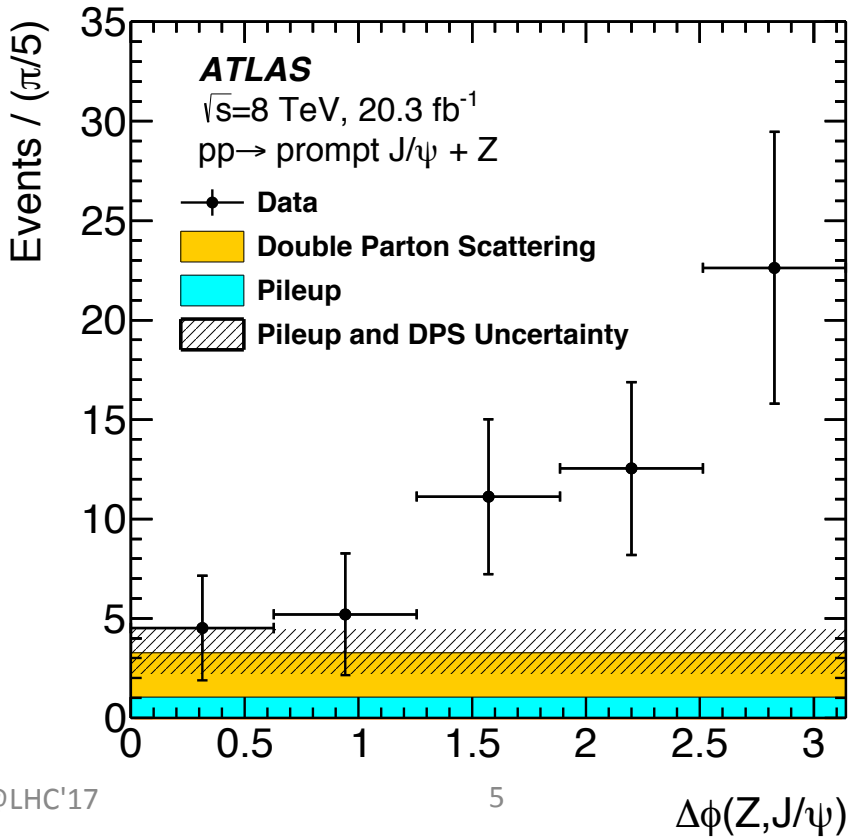


2. Associated production of J/ψ and Z

8 TeV data (20.3fb^{-1}), Z -> μ+μ- and Z -> e+e-

- Online selection based on Z->l+l- (one lepton with p_T > 24 GeV, offline requirements of p_T> 15 GeV on the other, |η|<2.5 on both).
- Muons from J/ψ are required p_T > 4 and p_T > 3.5 GeV or 2.5 GeV (forward region).
- About 60 (100) events with prompt (non-prompt) J/ψ. $p_T^{J/\psi}$ > 8.5 GeV , $|y^{J/\psi}|$<2.1

- Non-prompt: B hadron decays, cross section large, DPS fraction negligible.
- Prompt: DPS component not isolated: compatible with σ_{eff} ≈15 mb,
- Under the assumption that in the bin 0–π/5 contains only DPS, the limit σ_{eff} > 5.3 mb (3.7 mb) at 1σ (2σ) level.
- SPS (prompt) component higher than predicted

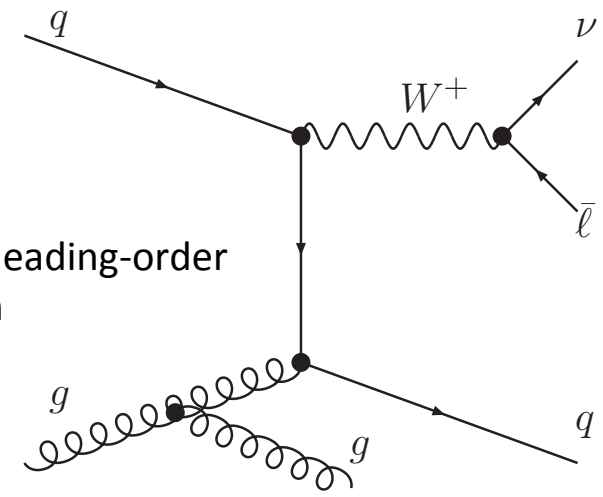


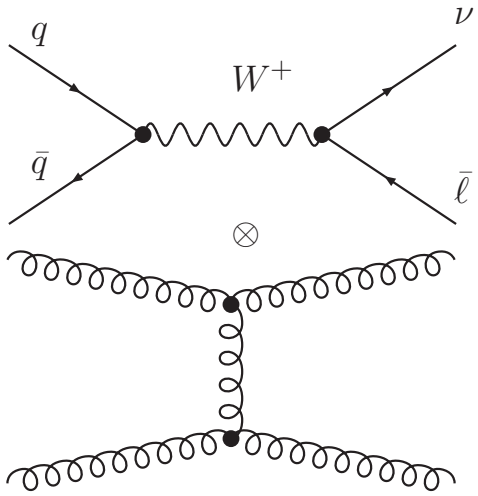
3. DPS in W(->lυ)+2 jets

Based on 36 pb^{-1} collected at 7 TeV: early data, less than one interaction per LHC bunch crossing

- Trigger on lepton from W; reference 2-jets cross section from minimum-bias data
- Lepton $p_T > 20$ GeV, $|\eta|<2.4$; $E_T^{miss} > 25$ GeV, $M_T^W > 40$ GeV
- Jets with $p_T > 20$ GeV, $|y|<2.8$
- The physics processes are modeled with ALPGEN+HERWIG+JIMMY (AHJ), with JIMMY adding DPS, and SHERPA for comparison.

Example of leading-order SPS diagram





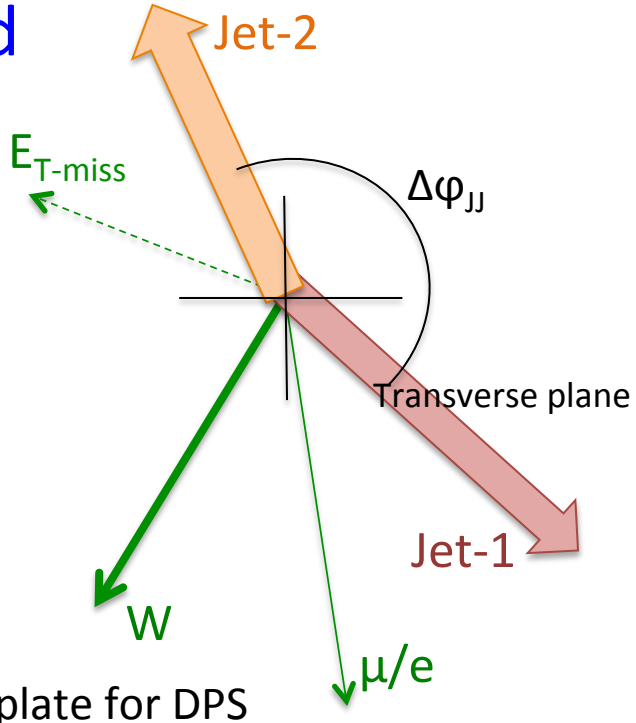
Example of leading-order DPS diagrams

W + 2 jets continued

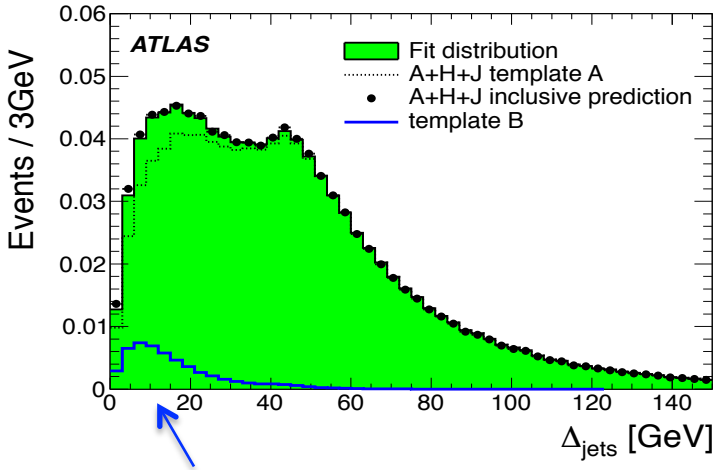
- In DPS, p_T balance occurs between the two jets, and the variables:

$$\Delta_{\text{jets}} = |\vec{p}_{\text{T}}^{J_1} + \vec{p}_{\text{T}}^{J_2}|, \quad \Delta_{\text{jets}}^{\text{n}} = \frac{|\vec{p}_{\text{T}}^{J_1} + \vec{p}_{\text{T}}^{J_2}|}{|\vec{p}_{\text{T}}^{J_1}| + |\vec{p}_{\text{T}}^{J_2}|}$$

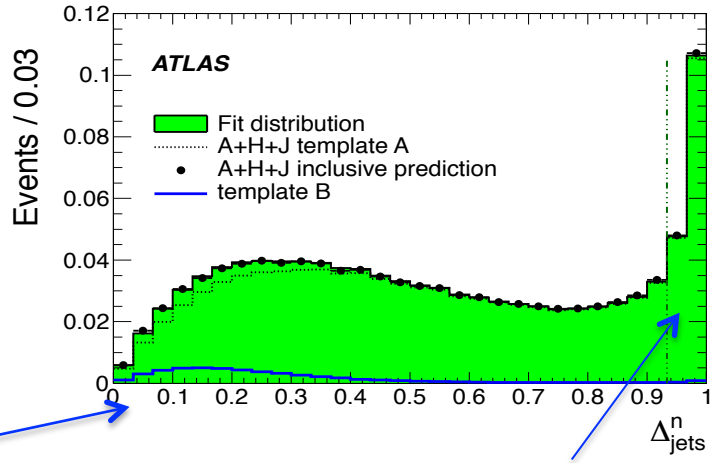
are used to separate the two components.



Simulation (AHJ) and data-driven template for DPS



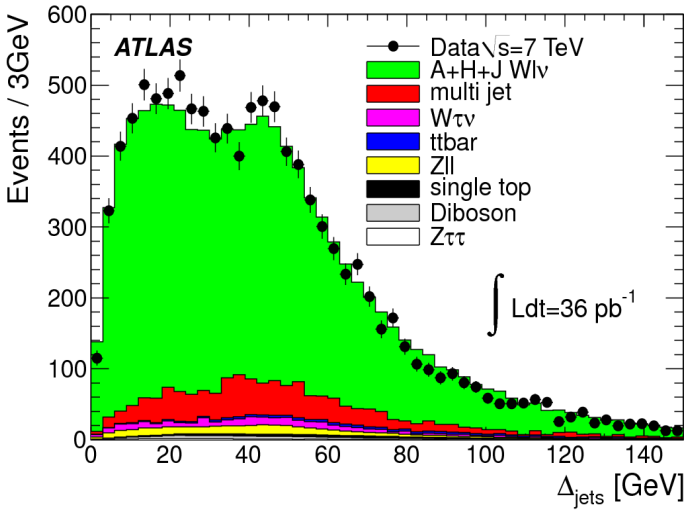
SPS contribution at low values of Δ's distributions.

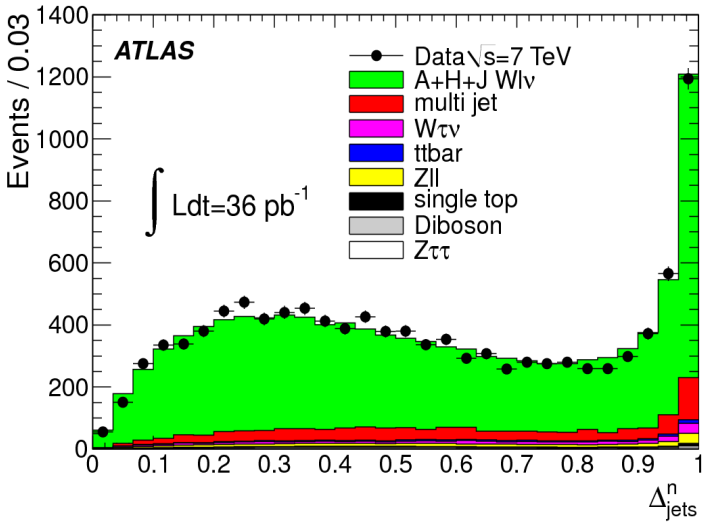


Jacobian accumulation

W + 2 jets continued

Data compared to simulation and to physics backgrounds





ATLAS: Eur.Phys.J. C75 (2015) no.5, 229

- The result of the fit to the data is:

$f_{DP} = 0.08 \pm 0.01(\text{stat.}) \pm 0.02\ (\text{sys.}),$

$\sigma_{eff} = 15 \pm 3(\text{stat.})\ {}^{+5}_{-3}(\text{sys.})\ \text{mb}$

- In the systematic uncertainty: pile-up, bkg. modeling & detector response, jet energy scale, and theory, each of them in the range of 1-1.5 mb

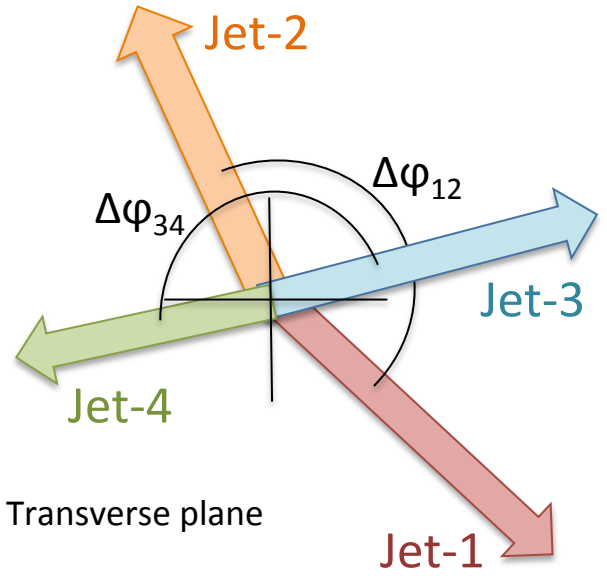
4. DPS in 4 jets events

Based on 37pb^{-1} collected at 7 TeV, with small instantaneous luminosity.

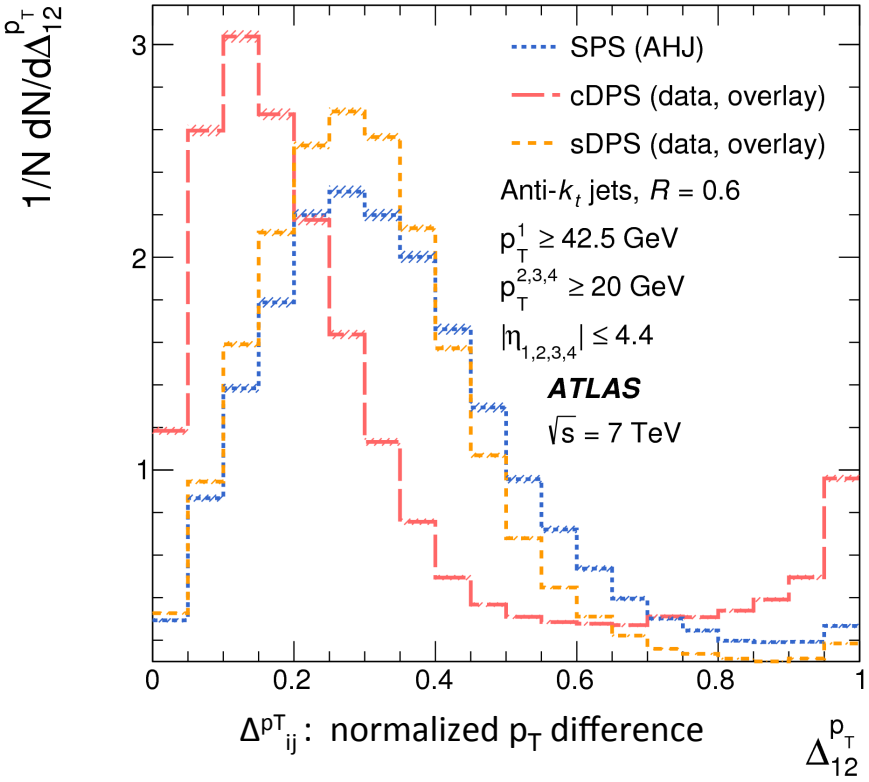
- The selection for 4-jets events required one jet with $p_T > 42.5$ GeV, and three with $p_T > 20$ GeV, all with $|\eta| < 4.4$.
- For the 2-jet samples needed for σ_{eff} , threshold of 42.5, 20 GeV were placed for one sample, and 20 GeV on both jets for the second sample.
- Partial overlap between the two processes: $\delta_{AB} = 0.069$

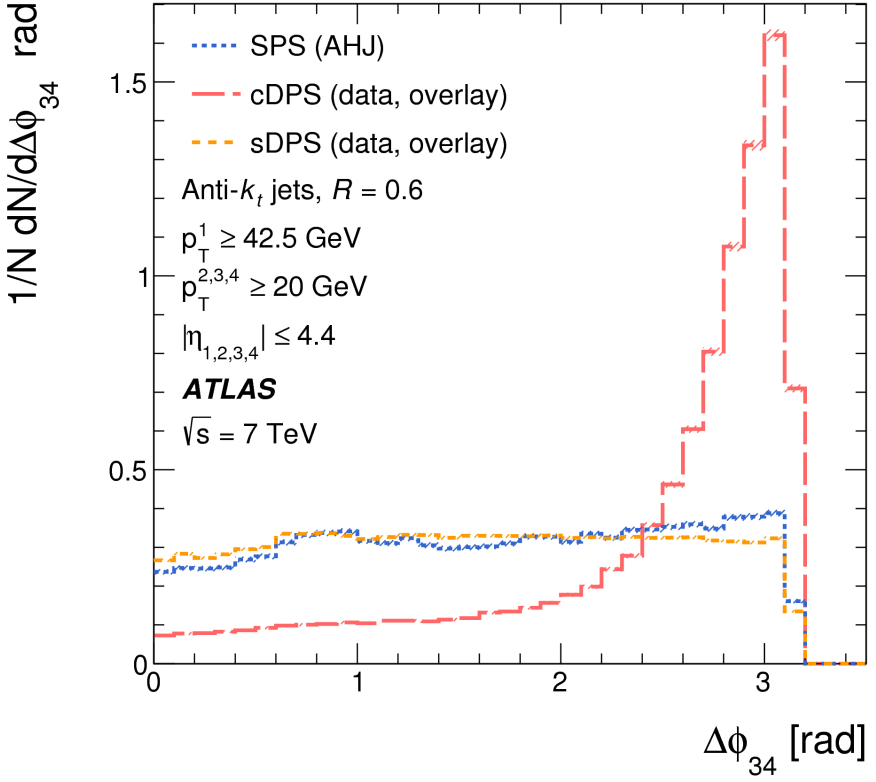
Here DPS contributes with two topologies:

- *complete*-DPS (cDPS): superposition of two 2-jets events.
- *semi*-DPS (sDPS): one 3-jet event plus a single jet event (with additional softer or merged jet(s)).



4 jets continued

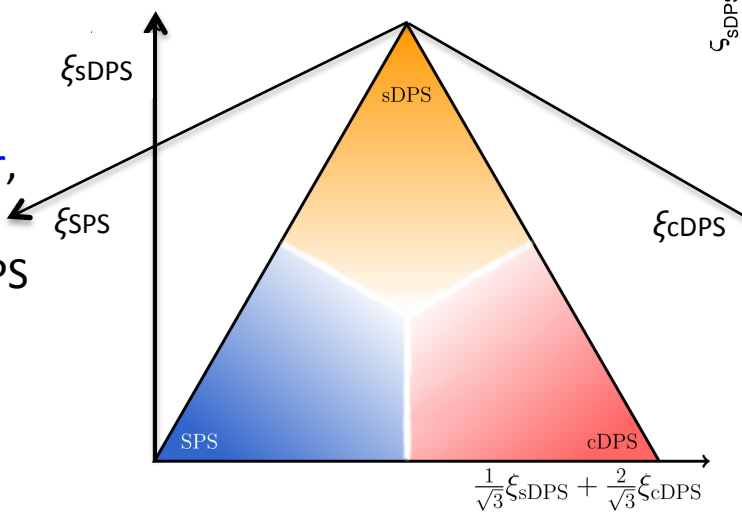




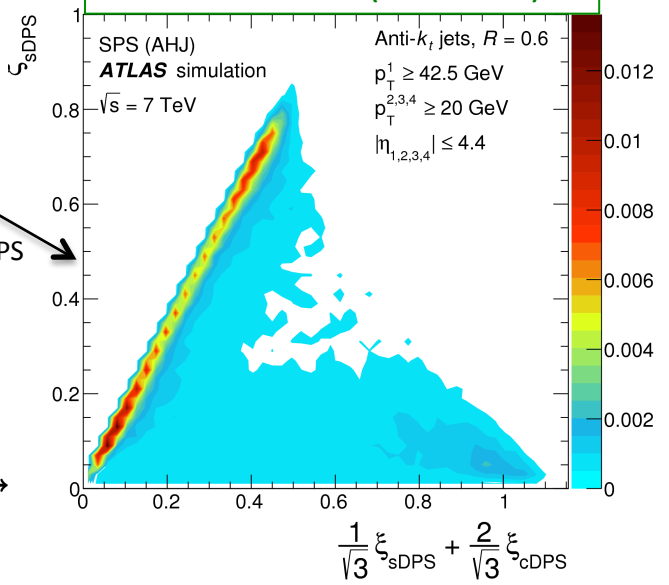
- In cDPS, the jets are back-to-back both in pair-1 (containing the jet with highest p_T) and in pair-2.
- In SPS, pair-1 is less balanced, and jet-3, jet-4 are scarcely correlated, but tend to be closer to another jet.
- In sDPS, jet-3 and jet-4 are even less correlated.

4 jets continued

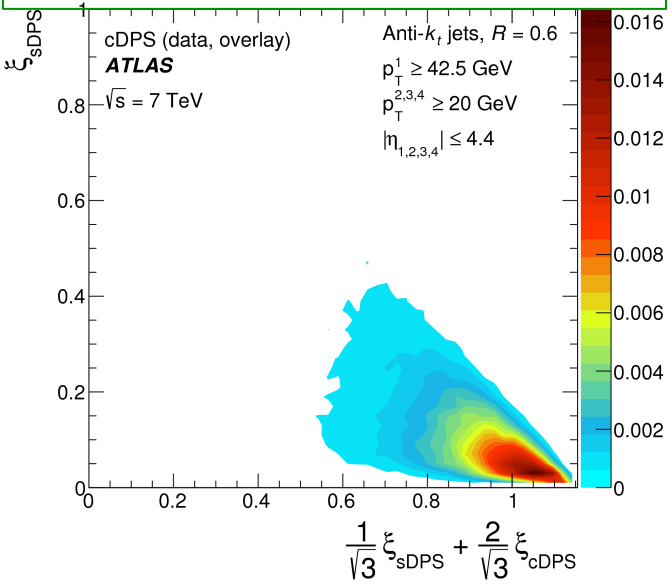
p_T balance, azimuthal and rapidity differences are used in a neural network classifier, providing the (normalized) *probabilities* for the SPS, cDPS and sDPS hypotheses (ξ_{SPS}, ξ_{cDPS}, ξ_{sDPS} respectively).



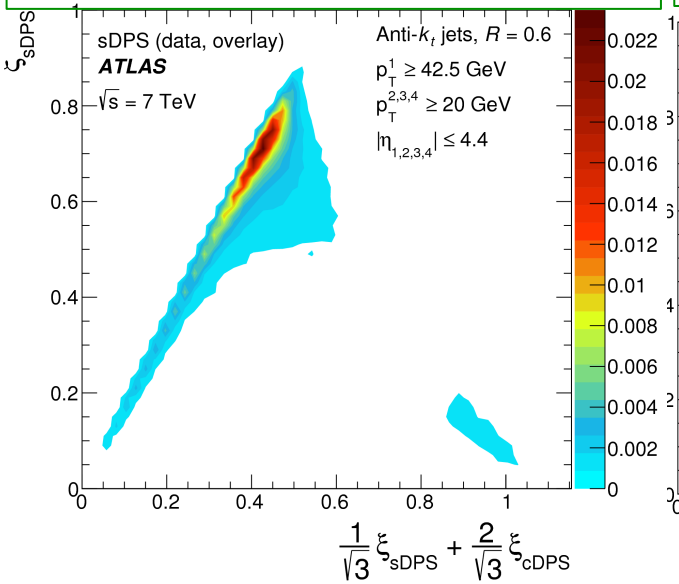
SIMULATION (SPS+DPS)



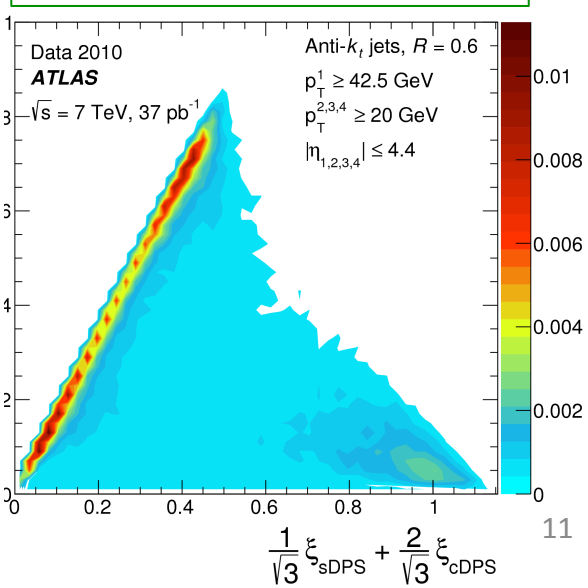
DATA RANDOM OVERLAY FOR cDPS



DATA RANDOM OVERLAY FOR sDPS



FITTED DATA



4 jets continued

- Result of the fit:

$$f_{\mathrm{DPS}} = 0.092\ ^{+0.005}_{-0.011}\ (\mathrm{stat.})\ ^{+0.033}_{-0.037}\ (\mathrm{syst.})$$

with sDPS contributing for about 40% of the total DPS,

$$\sigma_{eff} = 14.9\ ^{+1.2}_{-1.0}\ (\mathrm{stat.})\ ^{+5.1}_{-3.8}\ (\mathrm{syst.})\ \mathrm{mb}$$

The systematic uncertainty is dominated by the detector uncertainty in the jet energy scale.

ATLAS: JHEP 11 (2016) 110

5. J/ψ+J/ψ associated production

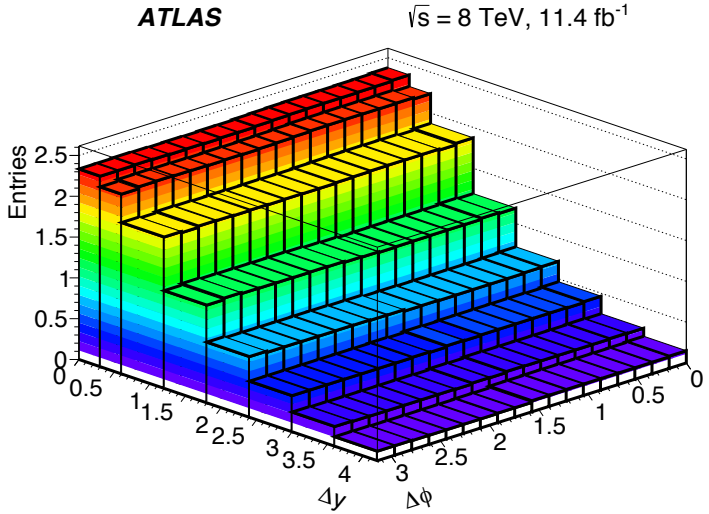
Based on 11.4 fb^{-1} collected at 8 TeV.

- J/ψ's selected in 4 muons events, requiring two with $p_T > 4$ GeV and two with $p_T > 2.5$ GeV.
- About 1200 J/ψ+J/ψ events with prompt J/ψ's, $p_T^{J/\psi} > 8.5$ GeV , $|y^{J/\psi}| < 2.1$.

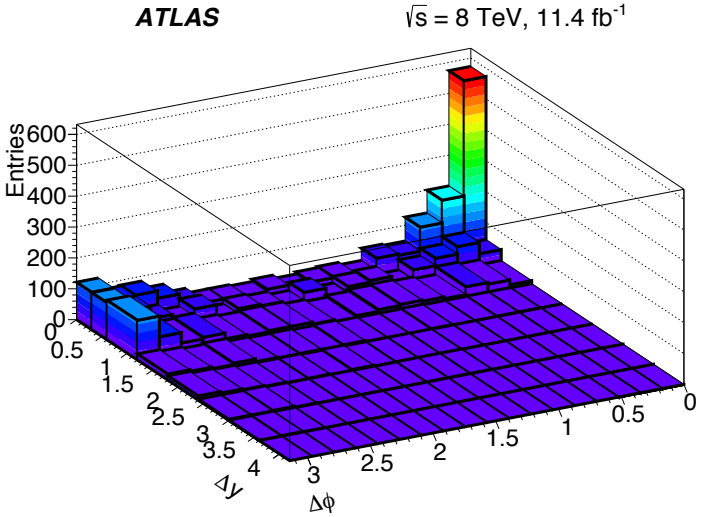
- Since the two J/ψ's are measured on the same fiducial volume, in the expression for σ_{eff} we have $\delta_{AB} = 1$.

- SPS and DPS components are distinguished studying the separation between the two J/ψ's in azimuthal angle and rapidity.

J/ψ+J/ψ continued



DPS TEMPLATE FROM
RANDOM OVERLAY OF DATA



DATA AFTER SUBTRACTION
OF DPS CONTRBUTION

- DPS J/ψ's have no correlation in φ, and loose correlation in *y* (driven mainly by acceptance/fiducial volume)
- SPS J/ψ's are produced in two modes:
  - Back-to-back in φ, with $\Delta y \approx 1$
  - Nearby both in φ ($\Delta\varphi \approx 0.15$) and *y* ($\Delta y \approx 0.5$)

  The subtraction of the DPS component is normalized in the region $\Delta y > 1.8$, $\Delta\varphi < \pi/2$.

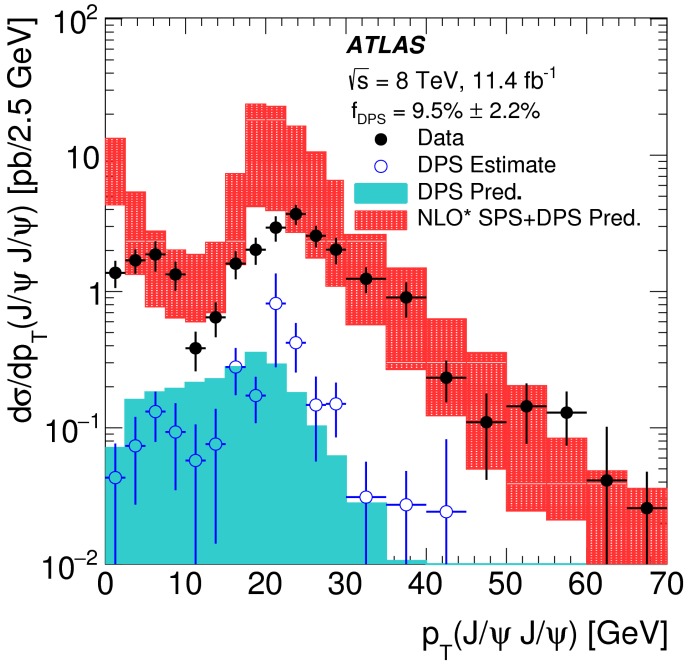
J/ψ+J/ψ continued

Result of the fit to DPS and SPS components:

$$f_{\mathrm{DPS}} = (9.2 \pm 2.1\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst}))\%.$$

$$\sigma_{\mathrm{DPS}}^{J/\psi,J/\psi} = 14.8 \pm 3.5\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}) \pm 0.2\ (\mathrm{BF}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb}.$$

$$\sigma_{\mathrm{eff}} = 6.3 \pm 1.6\ (\mathrm{stat}) \pm 1.0\ (\mathrm{syst}) \pm 0.1\ (\mathrm{BF}) \pm 0.1\ (\mathrm{lumi})\ \mathrm{mb}.$$



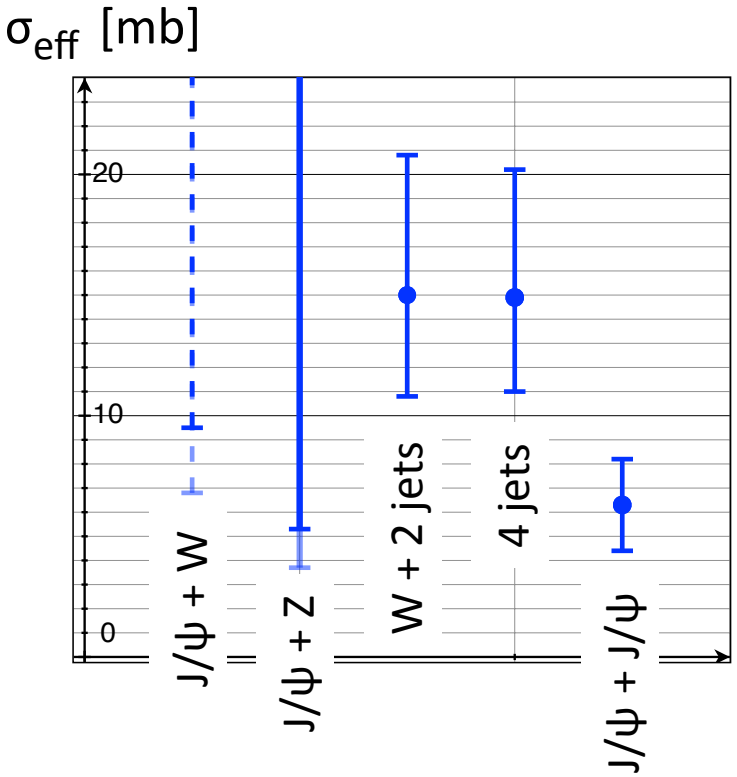
Note the *small* value of σ_{eff}

The differential cross section vs. $p_T^{J/\psi\ J/\psi}$ shows a component at low p_T (back-to-back J/ψ's) and a component at high p_T (nearby J/ψ's)

ATLAS: Eur.Phys.J. C77 (2017) no.2, 76

Theory: LO DPS: Borschensky and Kulesza (2015)
NLO* SPS: Lansberg and Shao (2015)

Summary of ATLAS results for σ_{eff}



The recent result on J/ψ pairs shows a larger DPS contribution, that is a smaller value of σ_{eff} , than expected.

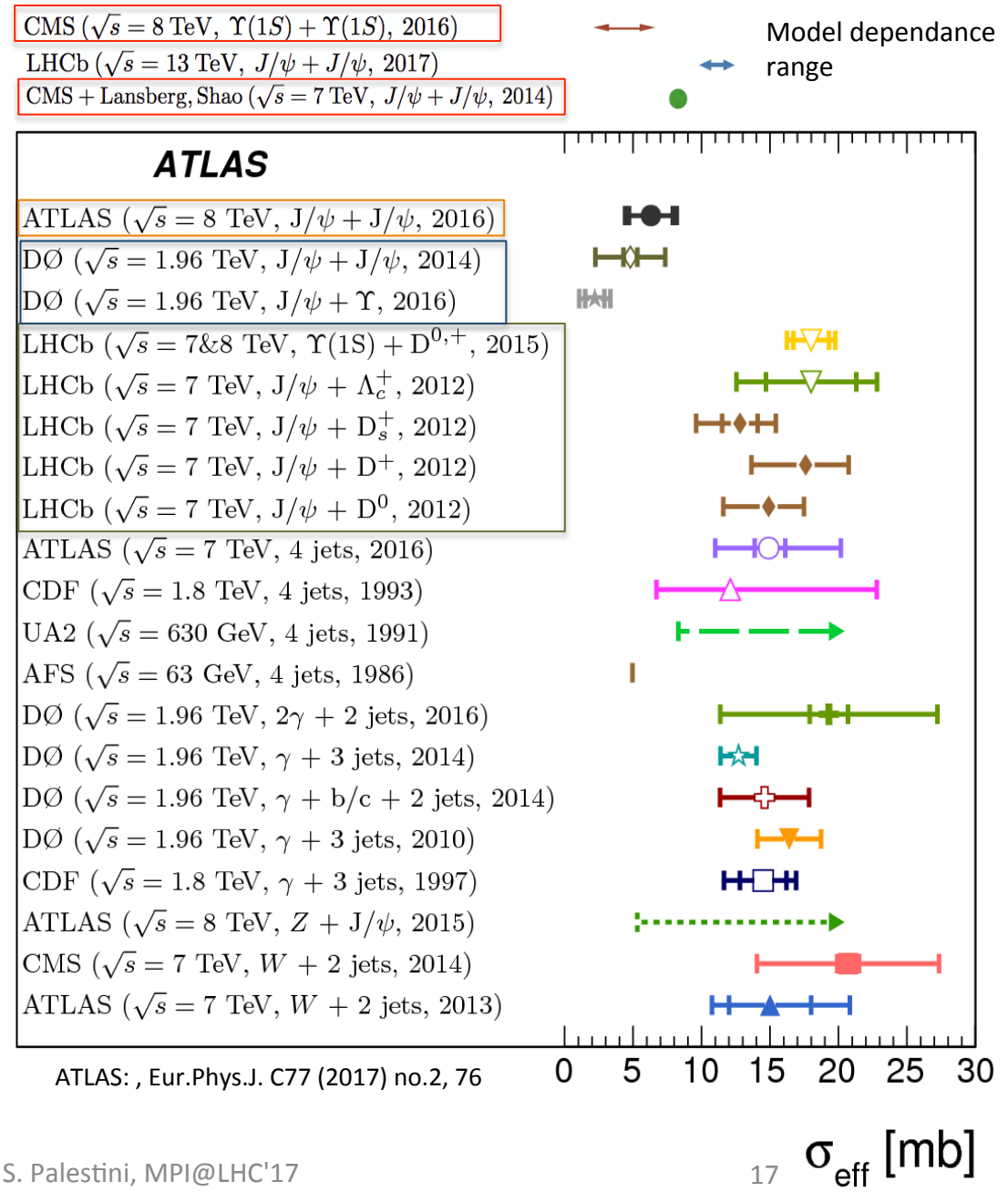
It is interesting to compare these results with others.

σ_{eff} measurements

The ATLAS J/ψ+J/ψ result is in line with *low* values of σ_{eff} in J/ψ+J/ψ and J/ψ+Y found earlier by D0, and also hinted in CMS data.

However measurements of J/ψ+charm, Y+charm made by LHCb are in line with the larger values of σ_{eff} observed with jets.

Do we have here indication of the dependence of σ_{eff} on the process? maybe related to the constituents involved and the p_T, y ranges?



ATLAS: , Eur.Phys.J. C77 (2017) no.2, 76

Conclusions

- Data collected at LHC have allowed for the study of associated production which have confirmed the contribution of double parton scattering.
- ATLAS has performed measurements with jets, W, Z and J/ψ's
- The results are relevant for both DPS and SPS components.
  - Concerning DPS, there are indications of *non-universality* of σ_{eff}, certainly worth additional studies.

- The programme of studies continues, next expected results on
  - associated production of J/ψ+W in the larger samples of data collected at 8 and 13 TeV,
  - DPS in Z+Z (4 leptons).

References

1. *Measurement of the production cross section of prompt J/ψ mesons in association with a W boson in pp collisions at √s=7 TeV with the ATLAS detector,* JHEP 1404 (2014) 172, http://dx.doi.org/10.1007/JHEP04(2014)172 http://arxiv.org/abs/arXiv:1401.2831
2. Theory references used in ref. 1 for SPS:
   - color singlet: J.-Ph. Lansberg and C. Lorce, *Reassessing the importance of the colour-singlet contributions to direct J/psi+W production at the LHC and the Tevatron,* Phys.Lett.B726:218-222,2013, http://dx.doi.org/10.1016/j.physletb.2014.10.015 http://xxx.lanl.gov/abs/1303.5327 ;
   - NRQCD: G. Li, M. Song, R.-Y. Zhang and W.-G. Ma, *QCD corrections to J/ψ production in association with a W-boson at the LHC*, Phys.Rev.D83:014001,2011, http://dx.doi.org/10.1103/PhysRevD.83.014001 , http://xxx.lanl.gov/abs/1012.3798
3. *Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at √s=8 TeV with the ATLAS detector* , Eur.Phys.J. C75 (2015) no.5, 229, http://dx.doi.org/10.1140/epjc/s10052-015-3406-9, http://arxiv.org/abs/arXiv:1412.6428
4. Theory predictions used in ref. 3:
   - LO, NLO color singlet: B. Gong, J.-Ph. Lansberg, C. Lorce, J. Wang, *Next-to-leading-order QCD corrections to the yields and polarisations of J/Psi and Upsilon directly produced in association with a Z boson at the LHC*, JHEP 1303 (2013) 115, http://dx.doi.org/10.1007/JHEP03(2013)115 , https://arxiv.org/abs/1210.2430 ;

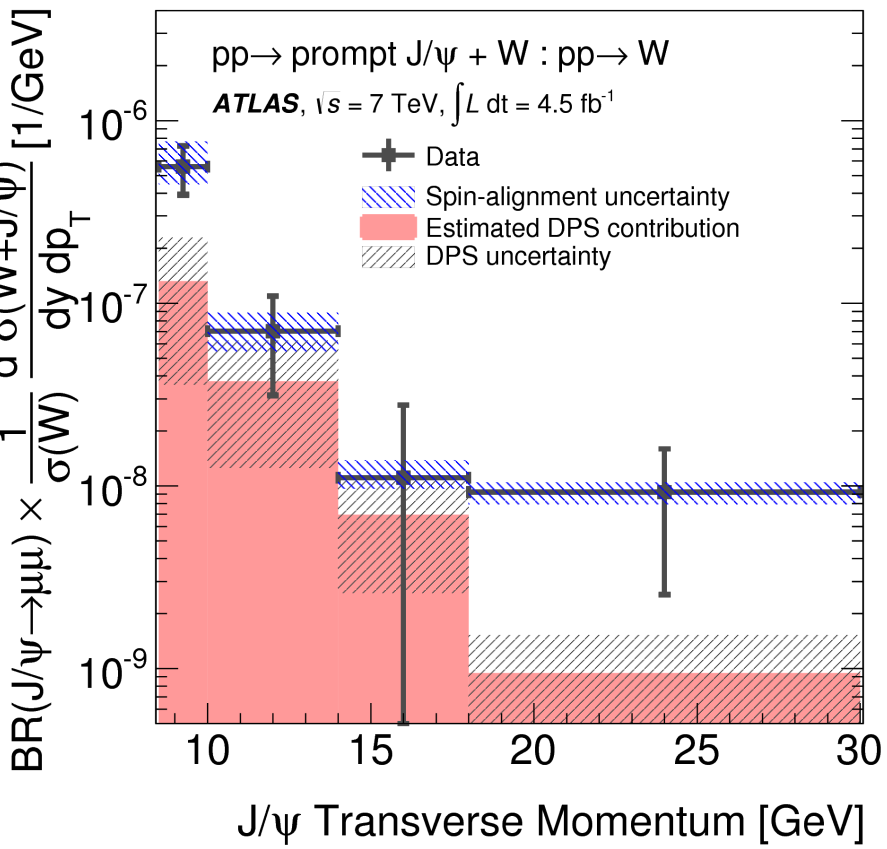
- NLO NRQCD: M. Song, W.-G. Ma, G. Li, R.-Y. Zhang and L. Guo, QCD corrections to J/ψ plus Z0-boson production at the LHC, JHEP 1102:071,2011, http://dx.doi.org/10.1007/JHEP02(2011)071 https://arxiv.org/abs/1102.0398

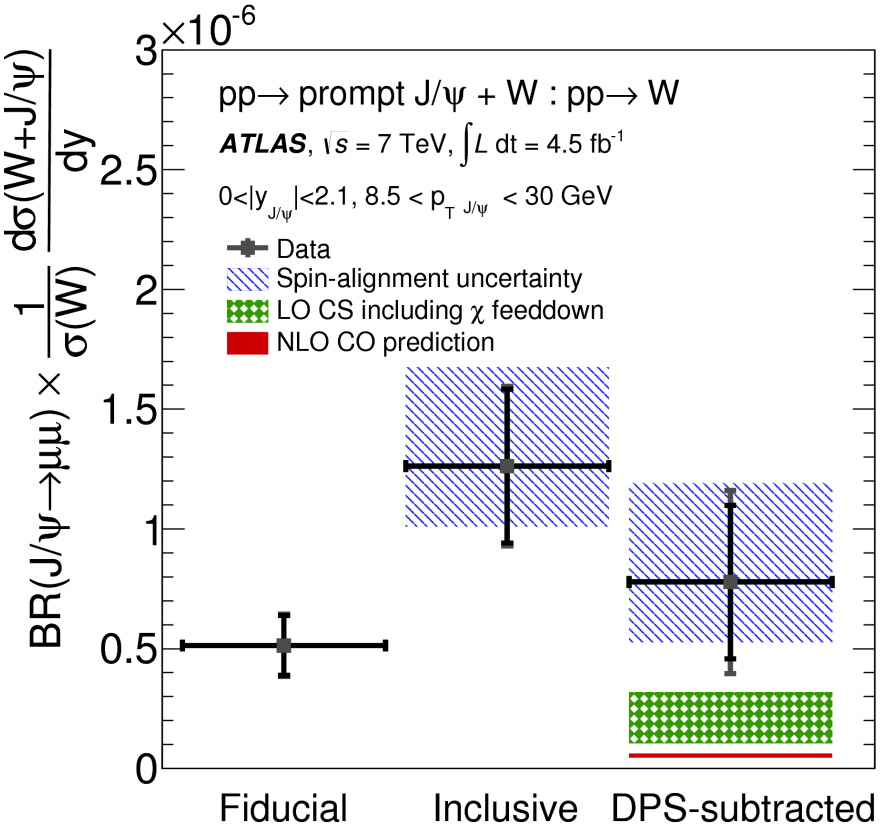
5. *Measurement of hard double-parton interactions in W->lv+ 2 jet events at √s=7 TeV with the ATLAS detector*, New J. Phys. 15 (2013) 033038, http://dx.doi.org/10.1088/1367-2630/15/3/033038 , http://arxiv.org/abs/arXiv:1301.6872
6. *Study of hard double-parton scattering in four-jet events in pp collisions at √s=7 TeV with the ATLAS experiment*, JHEP 11 (2016) 110, http://dx.doi.org/10.1007/JHEP11(2016)110 https://arxiv.org/abs/1608.01857
7. *Measurement of the prompt J/ψ pair production cross-section in pp collisions at √s=8 TeV with the ATLAS detector*, Eur.Phys.J. C77 (2017) no.2, 76, http://dx.doi.org/10.1140/epjc/s10052-017-4644-9 http://arxiv.org/abs/1612.02950
8. References for 7:
   - LO DPS: Ch. Borschensky and A. Kulesza, *Double parton scattering in pair-production of J/ψ mesons at the LHC revisited,* Phys.Rev. D95 (2017) no.3, 034029, http://dx.doi.org/10.1103/PhysRevD.95.034029 , http://arxiv.org/abs/arXiv:1610.00666 ;
   - NLO* SPS: J.-Ph. Lansberg and H.-S. Shao, *J/ψ-Pair Production at Large Momenta: Indications for Double-Parton Scatterings and Large α_S^5 Contributions,* Phys.Lett. B751 (2015) 479-486, http://dx.doi.org/10.1016/j.physletb.2015.10.083 , http://arxiv.org/abs/arXiv:1410.8822 .

9. References for added points to the figure in slide n. 10:

- CMS Collaboration, *Observation of Upsilon(1S) pair production in proton-proton collisions at √s = 8 TeV*, JHEP 05 (2017) 013 http://dx.doi.org/10.1007/JHEP05(2017)013 https://arxiv.org/abs/1610.07095
- LHCb Collaboration, *Measurement of the J/ψ pair production cross-section in pp collisions at √s=13TeV*, JHEP 1706 (2017) 047, ibid. 1710 (2017) 068 http://dx.doi.org/10.1007/JHEP06(2017)047 http://dx.doi.org/10.1007/JHEP10(2017)068 https://arxiv.org/abs/1612.07451
- J.-Ph. Lansberg and H.-S. Shao, *ibid.*

J/ψ + W continued



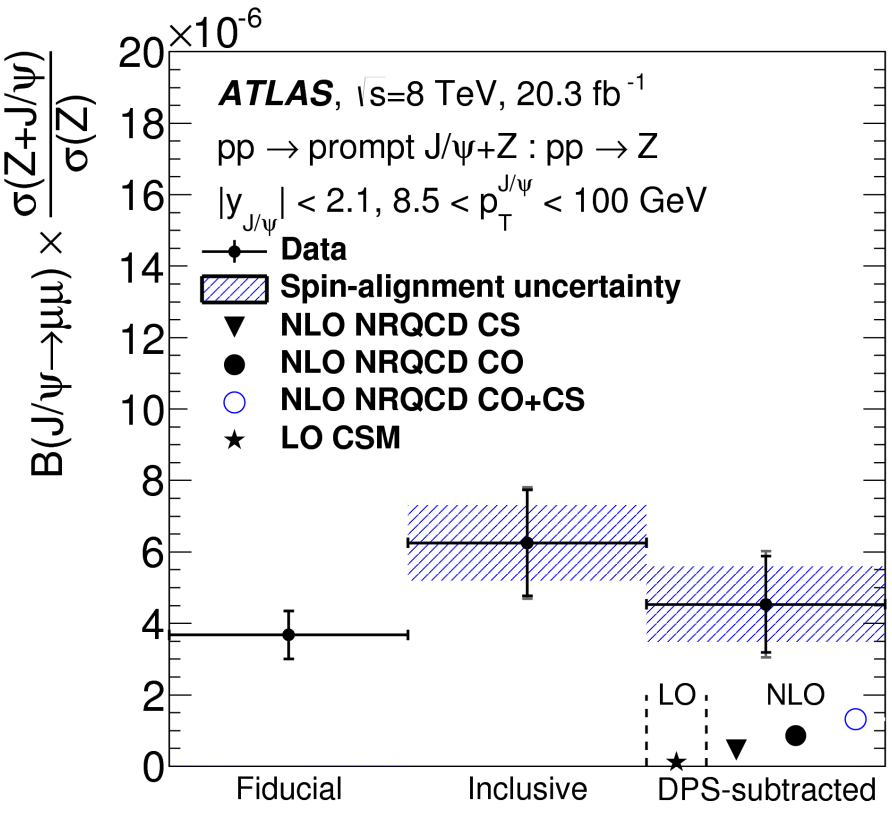


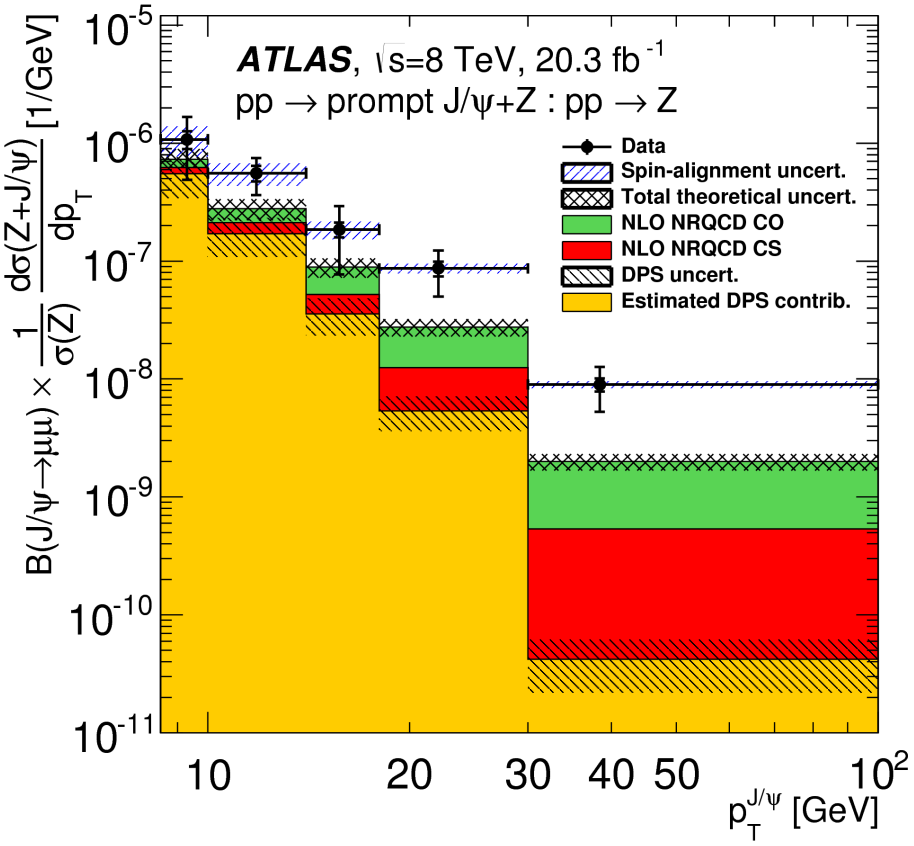
ATLAS: JHEP 1404 (2014) 172

Theory ref.s (SPS): color singlet: Lansberg and Lorce (2013)

color octet: Li, Song, Zhang and Ma (2011)

J/ψ + Z continued





ATLAS: Eur.Phys.J. C75 (2015) no.5, 229

Theory: color singlet: Gong, Lansberg, Lorce and Wang (2013)

color octet: Somg, Ma, Li, Zhang and Guo (2011)