Studies of associated production in ATLAS

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Motivation

- We don’t have a coherent and predictive HEP picture of quarkonium production in collisions
- More data can help:
  - We keep accumulating ‘data points’ from hadron colliders, several E_{CM} conditions
  - Other production mechanisms can complement and help clarify the picture
- Several examples of such new “observables” come from ‘associated production’:
  - Broader range of quarkonium states (ATLAS, CMS, LHCb...)
  - W and Z bosons + quarkonium
  - …more to come?

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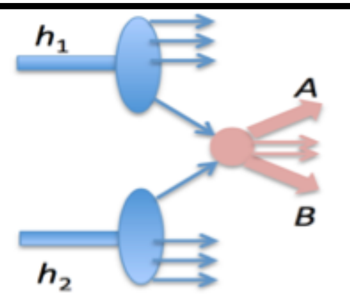
Associated Production, DPS, SPS

- Conceptually there are multiple possibilities to produce two objects in the same pp collision:
  - **Single Parton Scattering** (SPS):

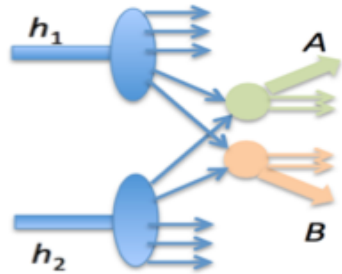
    Described by a specific process
    Cross-section $\boldsymbol{\sigma_{AB}^{SPS}}$

One single process produces the two objects



  - **Double Parton Scattering** (DPS):

Two separate processes produce one of the final objects each



Described by the individual process cross-sections $\boldsymbol{\sigma_A}$ $\boldsymbol{\sigma_B}$
And an effective cross section $\boldsymbol{\sigma_{eff}}$ accounting for the intrinsic probability of two processes happening simultaneously in the hadron collision

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

0÷1, accounting for interference etc.

Measuring DPS and SPS

- Cannot distinguish easily in a single collision
- Expect different kinematic properties e.g. A-B angular correlations
- DPS-SPS Separation is intrinsically uncertain:
  - Limited knowledge of $\boldsymbol{\sigma_{eff}}$
  - Higher order SPS processes can undermine assumptions
- Experimentally one can measure N_A, N_B and N_{AB}, with different efficiencies and integrated luminosities

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

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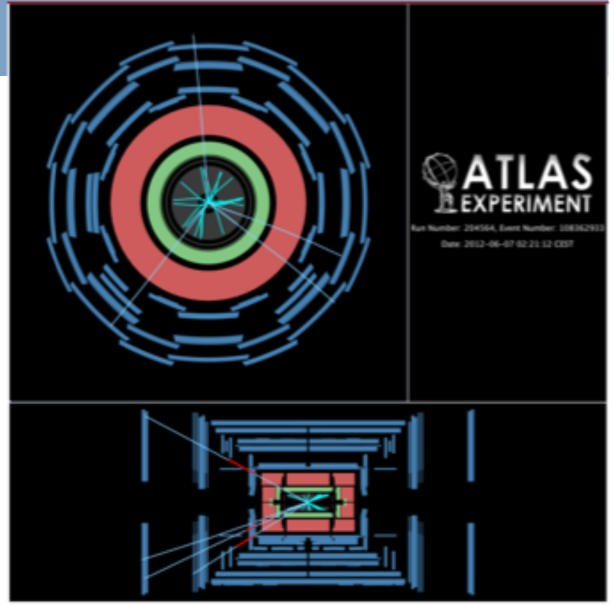
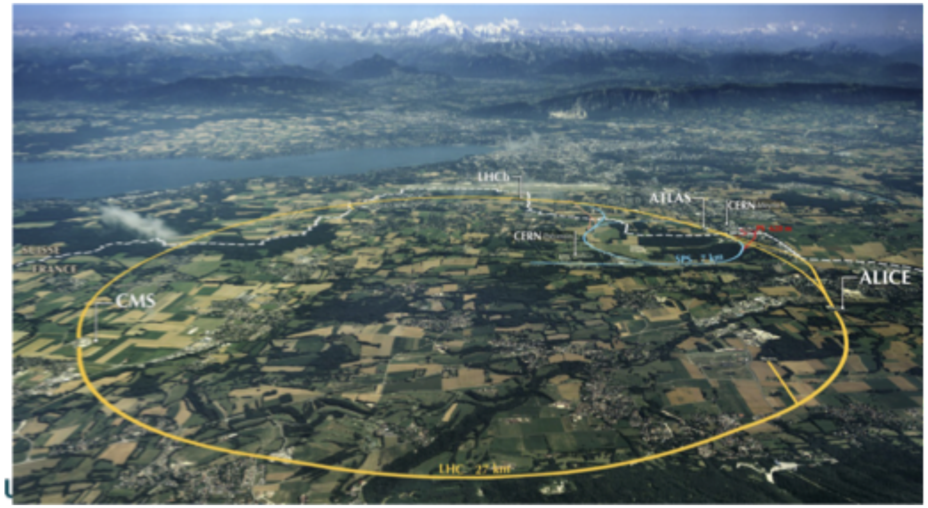
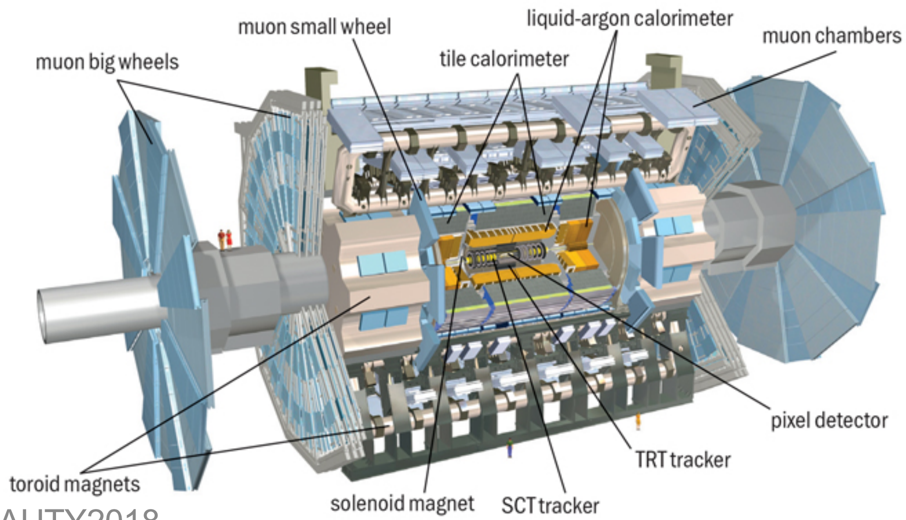
Associated Production Results from ATLAS

W+jj	NJP 15 (2013) 033038	arXiv:1301.6873
J/ψ+W$^{\pm}$	JHEP 04 (2014) 172	arXiv:1401.2831
J/ψ+Z^{0}	EPJ C75 (2015) 229	arXiv:1412.6428
4-jets	JHEP 11 (2016) 110	arXiv:1608.01857
J/ψ+J/ψ	EPJ C77 (2017) 76	arXiv:1612.02950



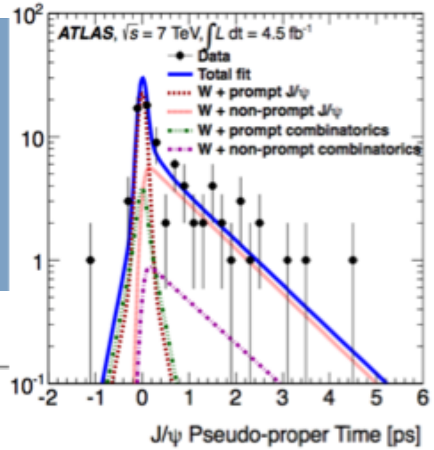
All results based on the excellent performance of the LHC and ATLAS detector

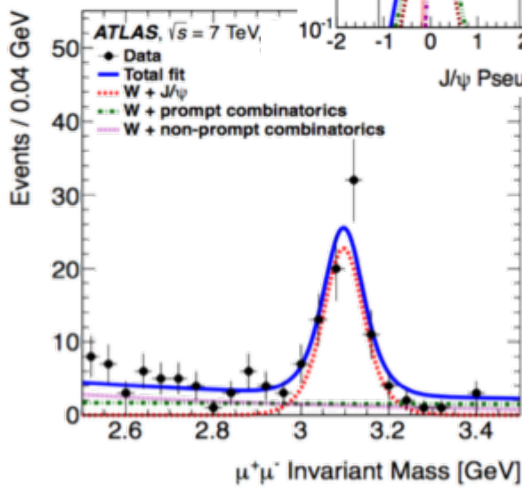


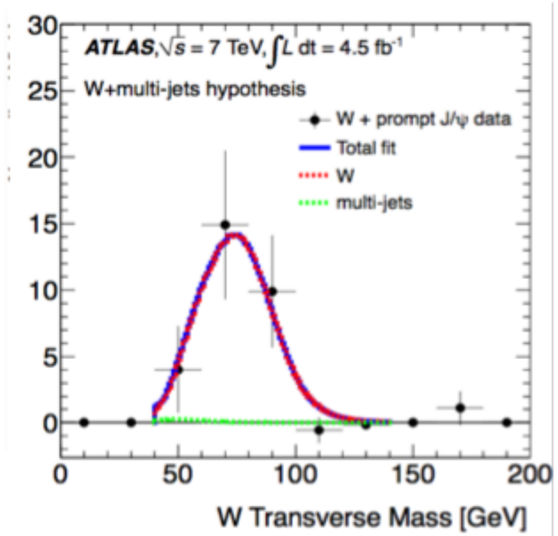


W+J/ψ

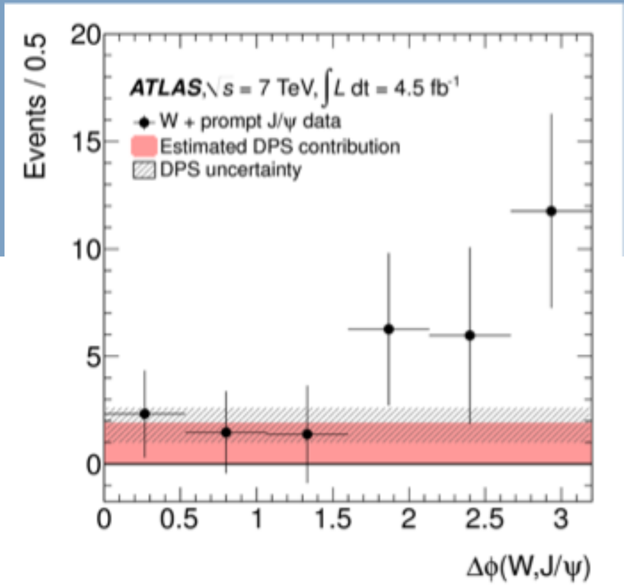
- Based on 4.5 fb^{-1} @ 7 TeV E_{CM}
  - Single-μ high-pT (>18 GeV) + E^T_{Miss} (>20 GeV) trigger, m_T(W)>40 GeV
    - Inclusive W sample (reference σ)
    - Two additional μ with p_T>3.5 GeV (2.5 GeV in fwd region)
  - p_T(J/ψ)> 8.5 GeV |y(J/ψ)|<2.1
  - Backgrounds: Wb, tt, Z+ E^T_{Miss}, etc. → removed with cuts or s-plot subtracted
  - Pile-up estimated to 1.8±0.2 events
- Fit signal and multi-jet m_T(W) templates to projected m_T(W): $29.2^{+7.5}_{-6.5}$ signal events
- DPS yield (using W+2j σ_{eff}): 10.8±4.2 events



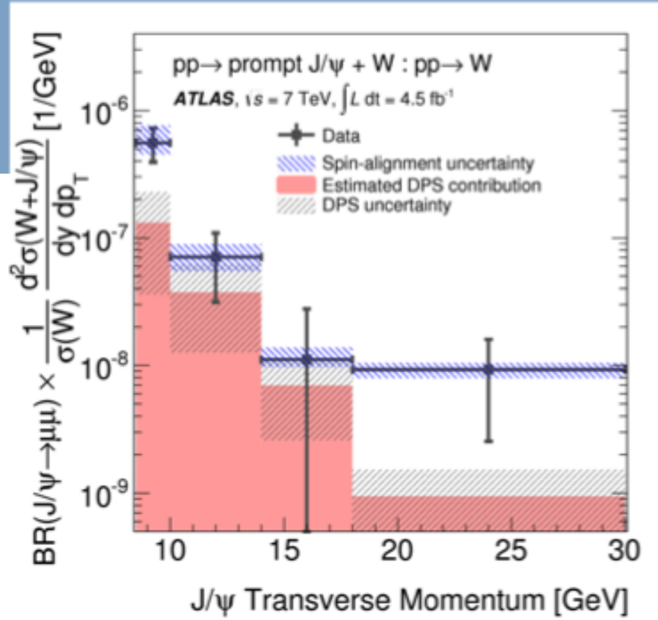




W+J/ψ



ΔΦ(W,J/ψ): Visible "SPS-like" behavior



- The fiducial volume (W+J/ψ) to inclusive W production ratio can be derived:

$$R^{\mathrm{fid}}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$$

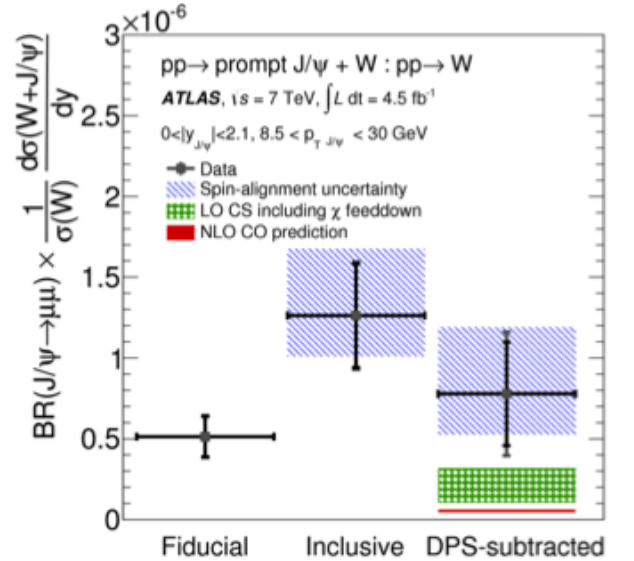
- And extrapolated/corrected to $p_T^{J/\psi} \in [8,30]$ GeV and $|\eta^{J/\psi}|<2.1$:

Spin Alig.

$$R^{\mathrm{incl}}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$

- With SPS obtained subtracting the estimated DPS contribution:

$$R^{\mathrm{DPS\ sub}}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$$



LO CS: Lansberg, arXiv:1303.532
NLO CO: Gavin, arXiv:1201.5896

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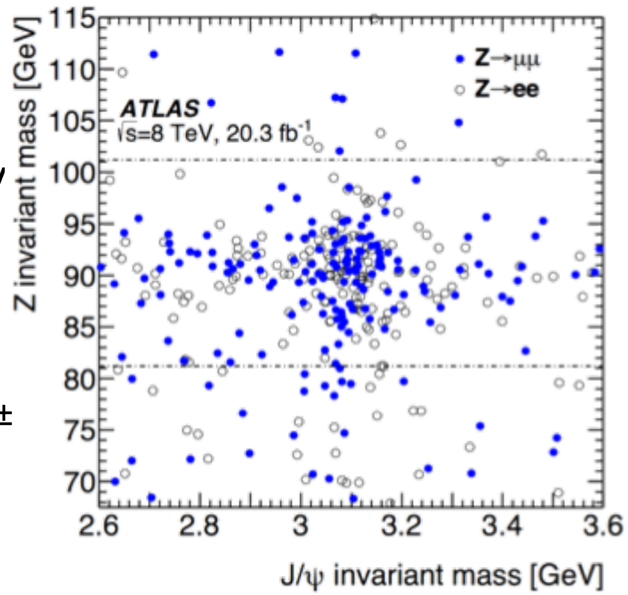
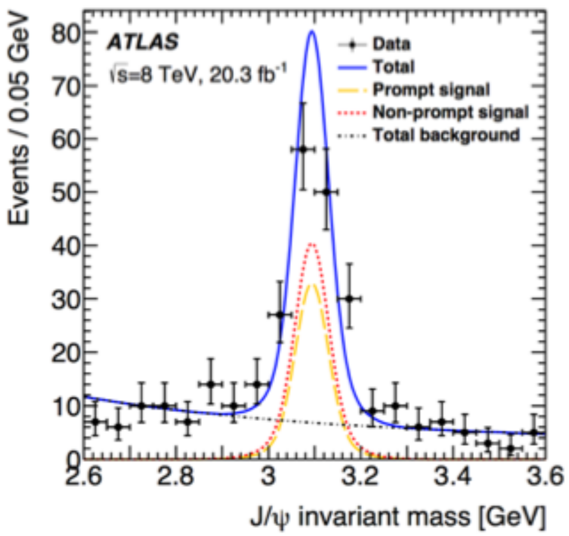
Z+J/ψ: Signal Extraction

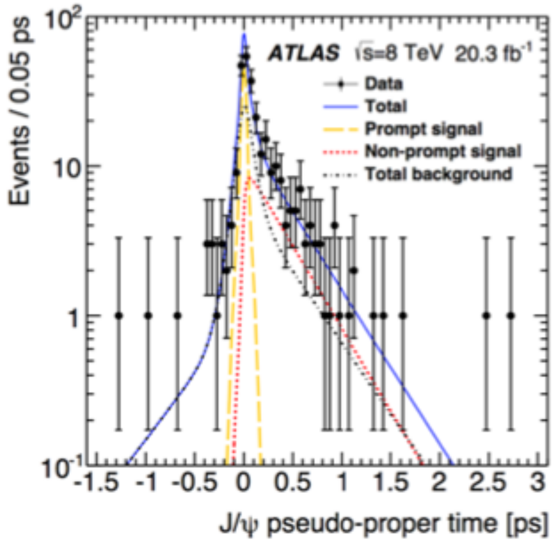
- Based on 20.3 fb^{-1} @ 8 TeV E_{CM}
  - Z→ℓℓ and J/ψ→μμ
    - Single-ℓ high-p_T (>24 GeV) +2x offline leptons p_T^{ℓ}>15 GeV
    - Two additional μ with p_T>3.5 GeV (2.5 GeV in fwd region)
      - One μ with p_T>4 GeV
    - p_T(J/ψ→μμ)> 8.5 GeV |y(J/ψ)|<2.1
  - Z leptons isolated to reject HF, conversions and fake e±



- Prompt/non-prompt components separated with s-plot weighting based on J/ψ mass-lifetime fit:

Prompt: 56±10±5 events
Non-Prompt: 95±12±8 events
Background: 138±17±9 events





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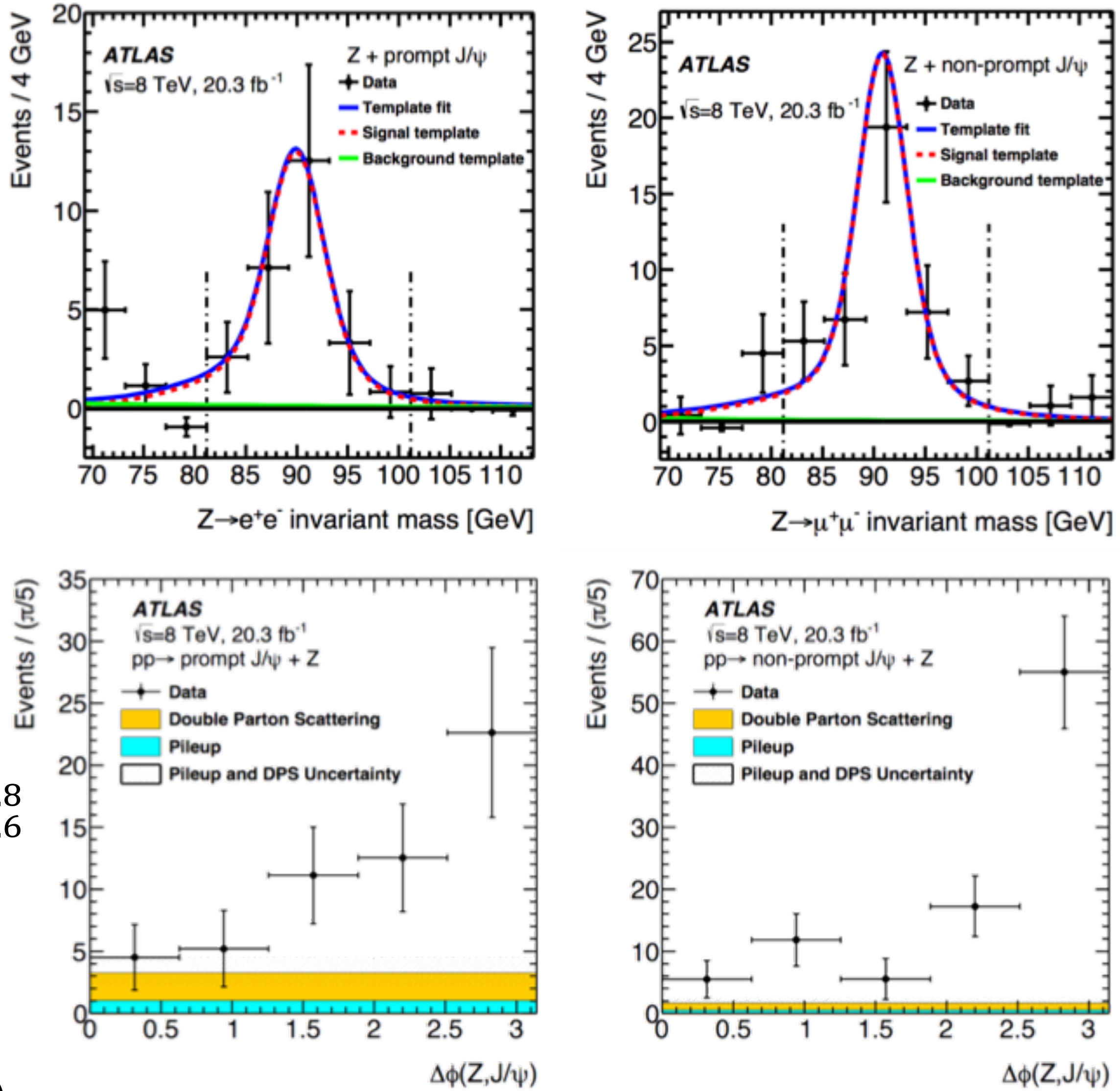
Z+J/ψ: DPS and SPS

- Z candidates can be projected with s-Plots
  - Signal region $m_Z \pm 10$ GeV contains consistent with 0 background events
  - Pile-up Z-J/ψ combinations estimated: ~5.2 (prompt) / 2.7 (non-prompt)
- Z-J/ψ azimuthal angle distinguishes DPS and SPS
  - Using W+2j σ_{eff}:
    - Prompt: $N_{DPS}^{Z+J/\psi} = 11^{+5.7}_{-5.0}$
    - Non-prompt: $N_{DPS}^{Z+J/\psi} = 5.8^{+2.8}_{-2.6}$



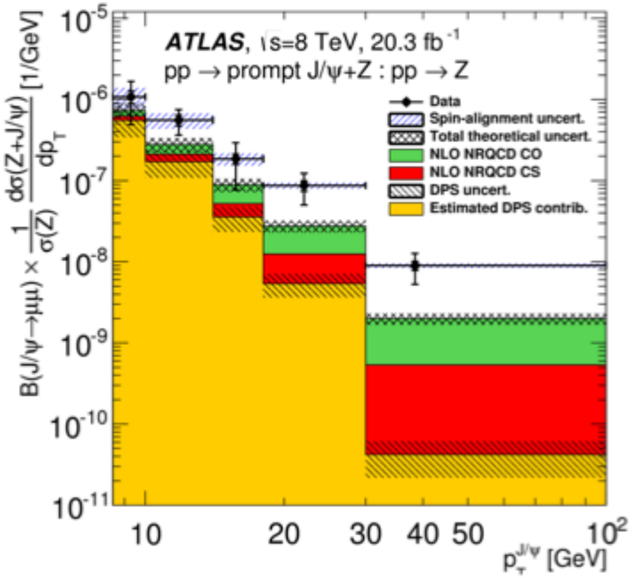
Can set a bound on σ_{eff} based on extrapolation from small ΔΦ:

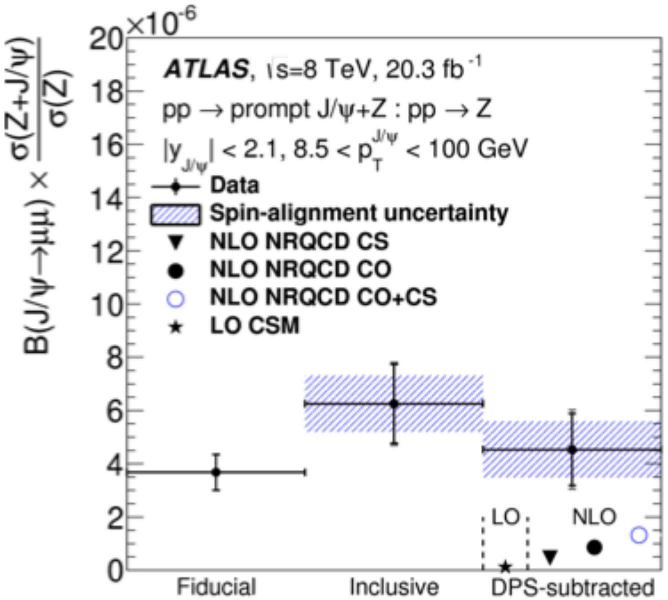
$\sigma_{eff} < 5.3\ (3.7)\ mb$ @ 68% (95%)

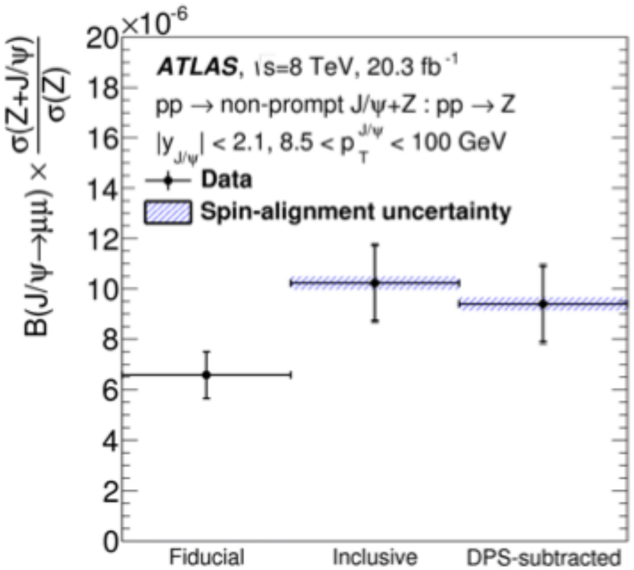
Z+J/ψ: f_{DPS} and $R_{J/\psi}$

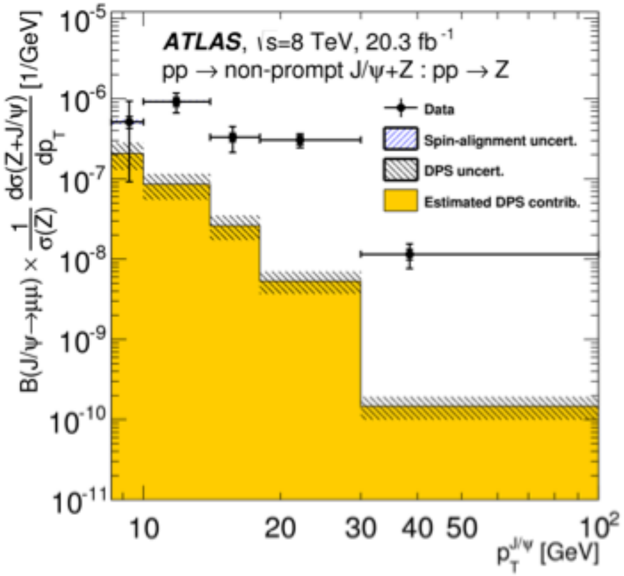
	prompt	non-prompt
fiducial	${}^{p}R^{fid}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$	${}^{np}R^{fid}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$
inclusive	${}^{p}R^{incl}_{Z+J/\psi} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7}$	${}^{np}R^{incl}_{Z+J/\psi} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS subtracted	${}^{p}R^{DPS\,sub}_{Z+J/\psi} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7}$	${}^{np}R^{DPS\,sub}_{Z+J/\psi} = (94 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS fraction	${}^{p}f_{DPS} = (29 \pm 9)\%$	${}^{np}f_{DPS} = (8 \pm 2)\%$

(using Wjj σ_{eff})

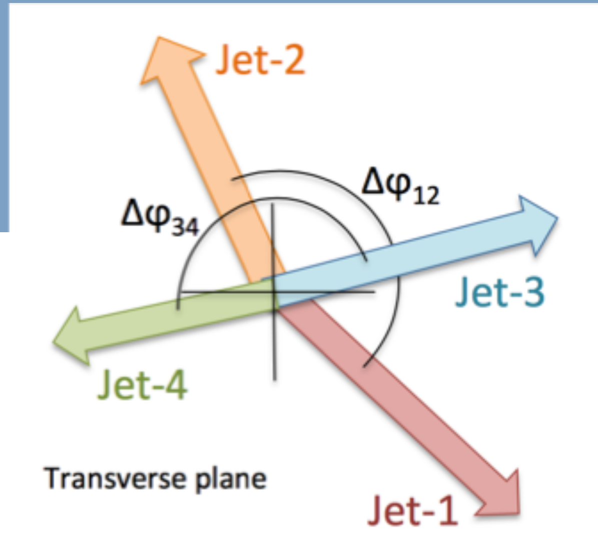




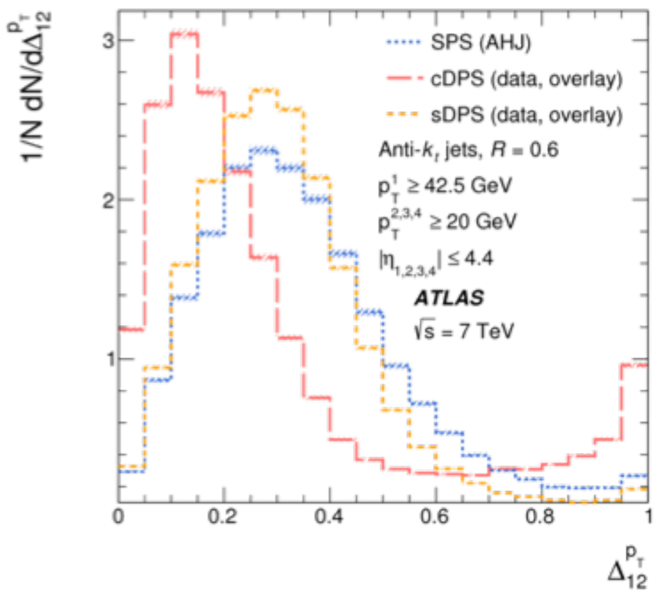


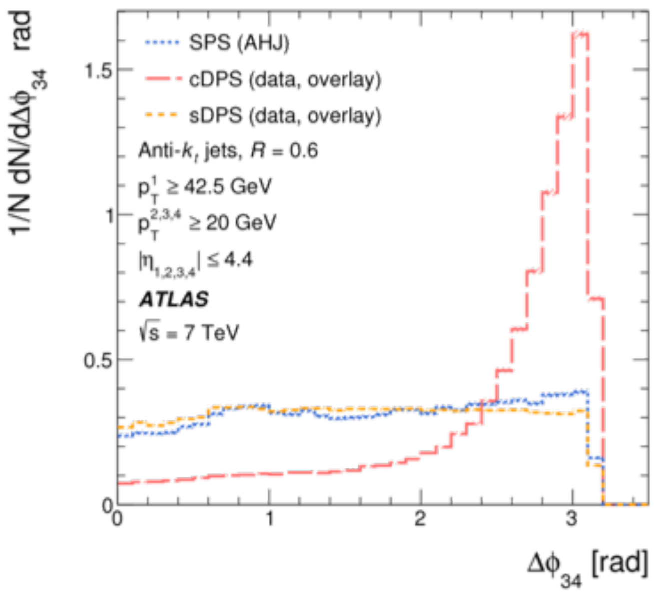


Four Jets



- $37pb^{-1}$@7 TeV, low L_{inst} to minimize pile-up
- Triggers:
  4j (42.5 GeV,3x20 GeV) and **2j** (42.5 GeV, 20 GeV) - (20 GeV,20 GeV)
- Two classes of DPS:
  - dijet-dijet (cDPS) → two pairs of "back-to-back" jets
  - trijet-single jet (sDPS) → less correlation in 1st pair, little/no correlation for 2nd pair
- Discriminate DPS/SPS using di-jet angular variables (ΔΦ, Φη, $\vec{p}_T^1 + \vec{p}_T^2$)





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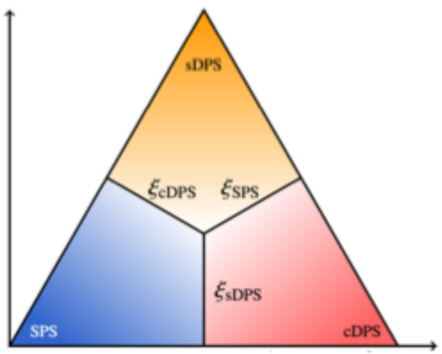
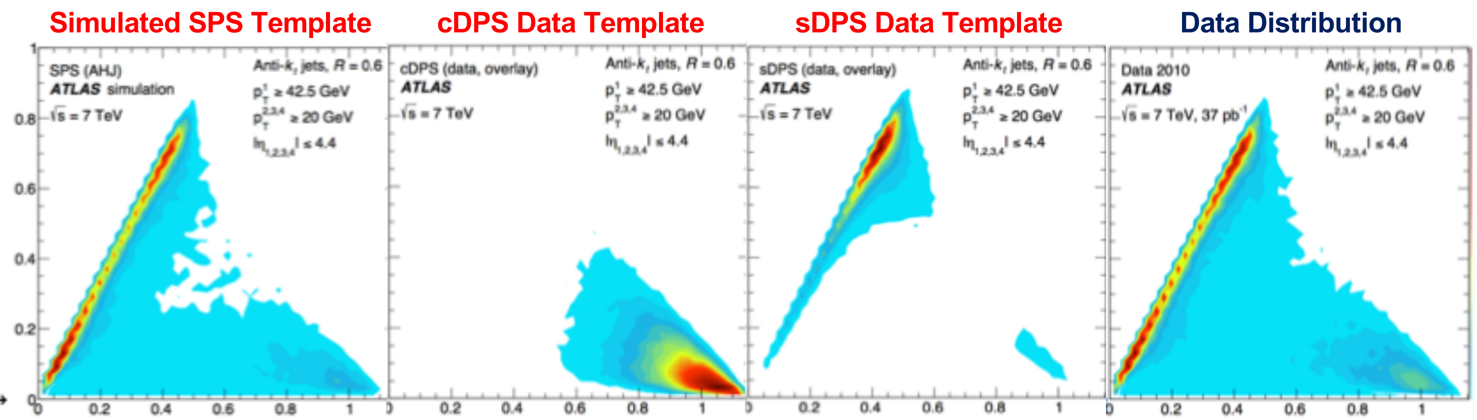
Four Jets: NN Fit





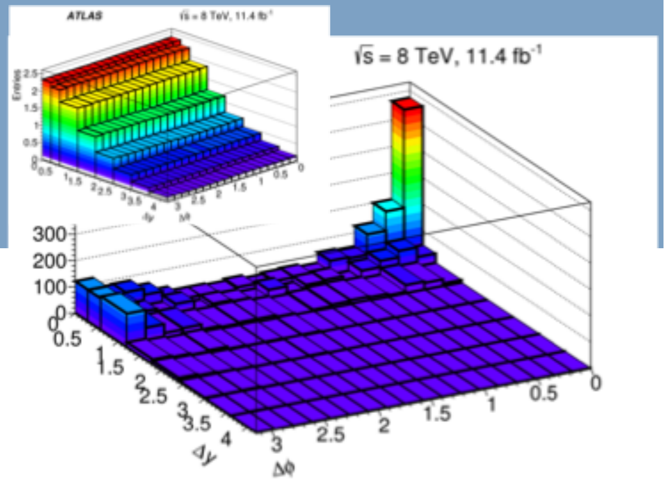
- Fit data using the three templates above:

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

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

Source of systematic uncertainty	$\Delta f_{\rm DPS}$	$\Delta\alpha^{4j}_{2j}$	$\Delta\sigma_{\rm eff}$
Luminosity			$\pm 3.5\,\%$
Model dependence for detector corrections		$\pm 2\,\%$	$\pm 2\,\%$
Reweighting of AHJ	$\pm 6\,\%$		$\pm 6\,\%$
Jet reconstruction efficiency			$\pm 0.1\,\%$
Single-vertex events selection			$\pm 0.1\,\%$
Jet energy and angular resolution	$\pm 15\,\%$	$\pm 3\,\%$	$\pm 15\,\%$
JES uncertainty	$^{+32}_{-37}\,\%$	$\pm 12\,\%$	$^{+31}_{-19}\,\%$
Total systematic uncertainty	$^{+36}_{-40}\,\%$	$\pm 13\,\%$	$^{+35}_{-25}\,\%$

Di-J/ψ



DPS subtracted Δy-$\Delta\Phi$ distribution

- 11.4 fb^{-1}@8 TeV
- 2x(p_T>4 GeV) and 2x(p_T>2.5 GeV) muons
- ~1200 di-J/ψ candidates $p_T(J/\psi)>8.5$ GeV $|y_{J/\psi}|<2.1$
    - Fiducial $\sigma_{J/\psi J/\psi}$ in two rapidity bins
    - Corrected (μ acceptance) $\sigma_{J/\psi J/\psi}$

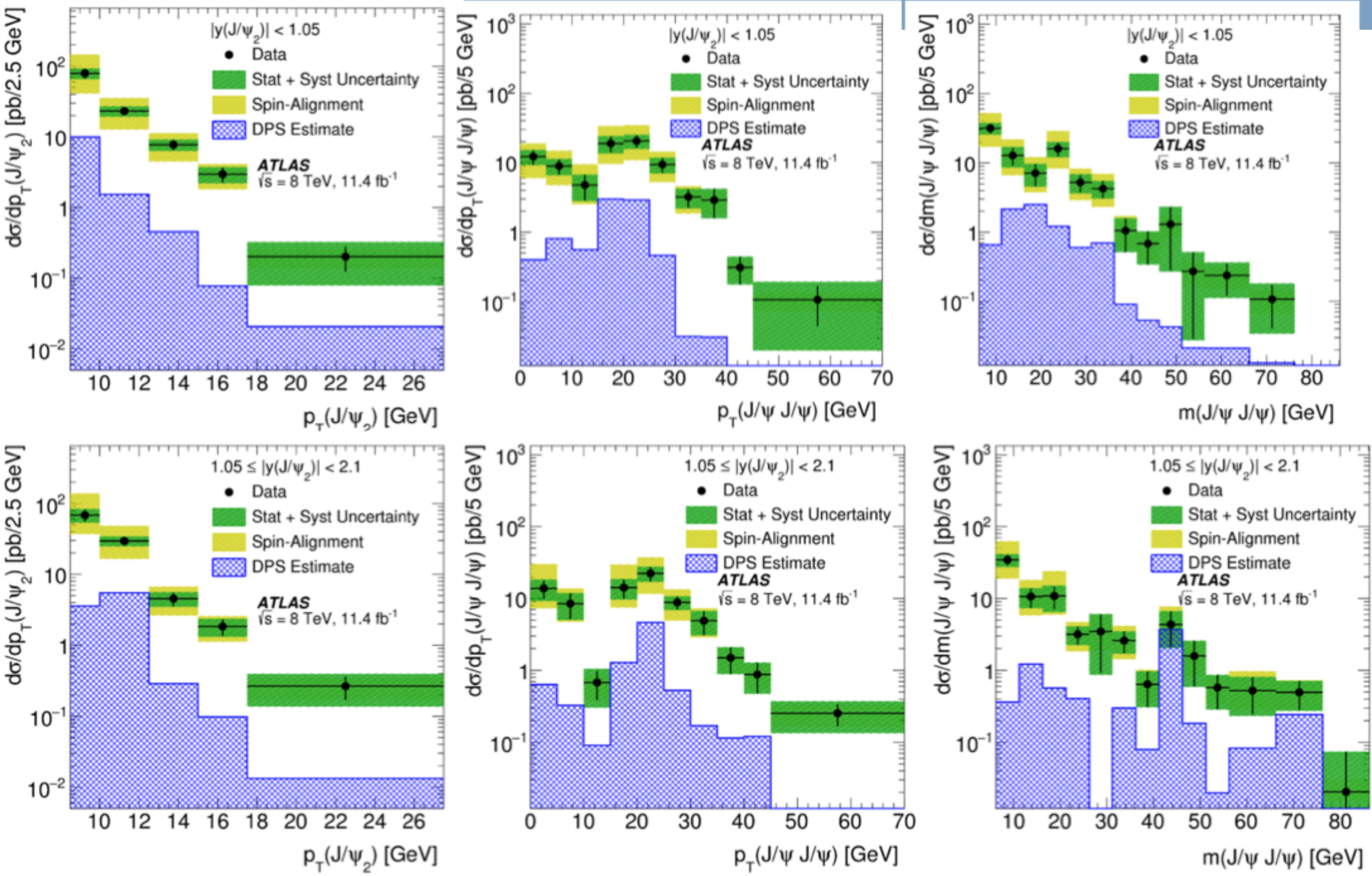
$$82.2 \pm 8.3\,(\text{stat}) \pm 6.3\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.6\,(\text{lumi})\,\text{pb}, \text{ for } |y| < 1.05,$$
$$78.3 \pm 9.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.5\,(\text{lumi})\,\text{pb}, \text{ for } 1.05 \leq |y| < 2.1$$

- DPS model: overlay of J/ψ from ≠ events, normalized to $\Delta y>1.8$ $\Delta\Phi<\pi/2$

$$f_{\text{DPS}} = (9.2 \pm 2.1\,(\text{stat}) \pm 0.5\,(\text{syst}))\%$$
$$\sigma^{J/\psi,J/\psi}_{\text{DPS}} = 14.8 \pm 3.5\,(\text{stat}) \pm 1.5\,(\text{syst}) \pm 0.2\,(\text{BF}) \pm 0.3\,(\text{lumi})\,\text{pb}$$
$$\sigma_{\text{eff}} = 6.3 \pm 1.6\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 0.1\,(\text{BF}) \pm 0.1\,(\text{lumi})\,\text{mb}.$$

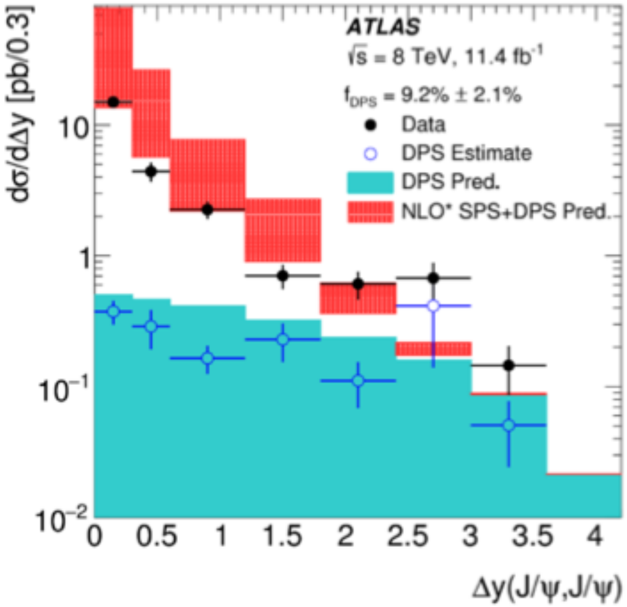
Cumulative and DPS-only crossection measured vs $p_T(J/\psi_2)$ $m(J/\psi\, J/\psi)$ $p_T(J/\psi\, J/\psi)$

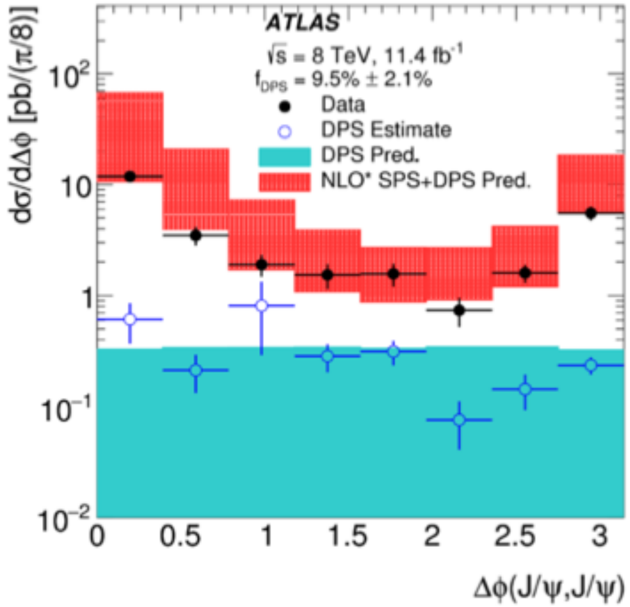
Di-J/ψ dσ/d…

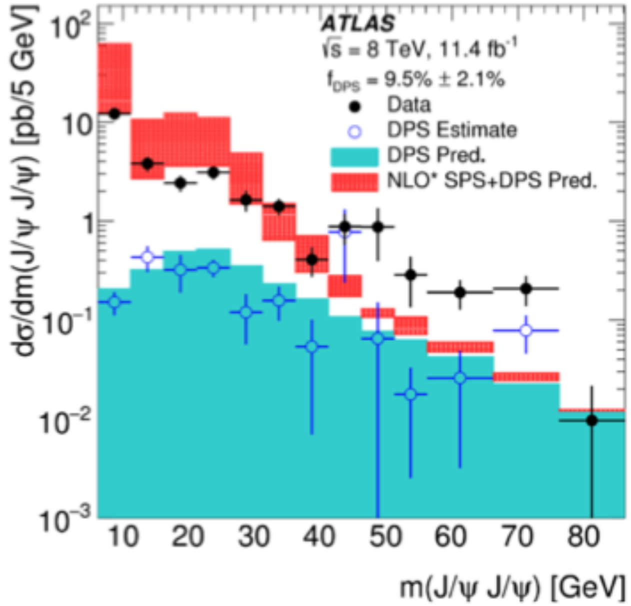


|y(J/ψ2)| < 1.05
Data
Stat + Syst Uncertainty
Spin-Alignment
DPS Estimate
ATLAS
√s = 8 TeV, 11.4 fb-1
dσ/dpT(J/ψ2) [pb/2.5 GeV]
pT(J/ψ2) [GeV]
dσ/dpT(J/ψ J/ψ) [pb/5 GeV]
pT(J/ψ J/ψ) [GeV]
dσ/dm(J/ψ J/ψ) [pb/5 GeV]
m(J/ψ J/ψ) [GeV]
1.05 ≤ |y(J/ψ2)| < 2.1

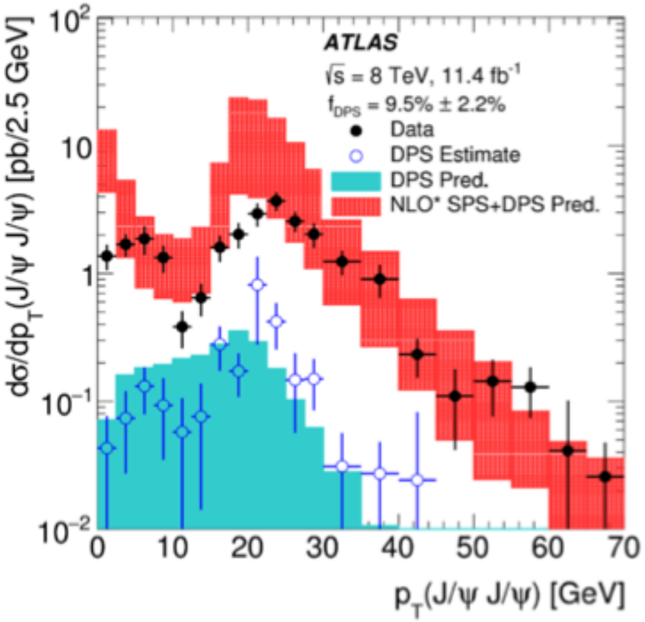
Comparison with Predictions







- Reasonable agreement of data with SPS(NLO)+DPS(LO) predictions except:
- Low pT, large m and large Δy
- More realistic predictions (Feed-down, parton transverse motion) needed



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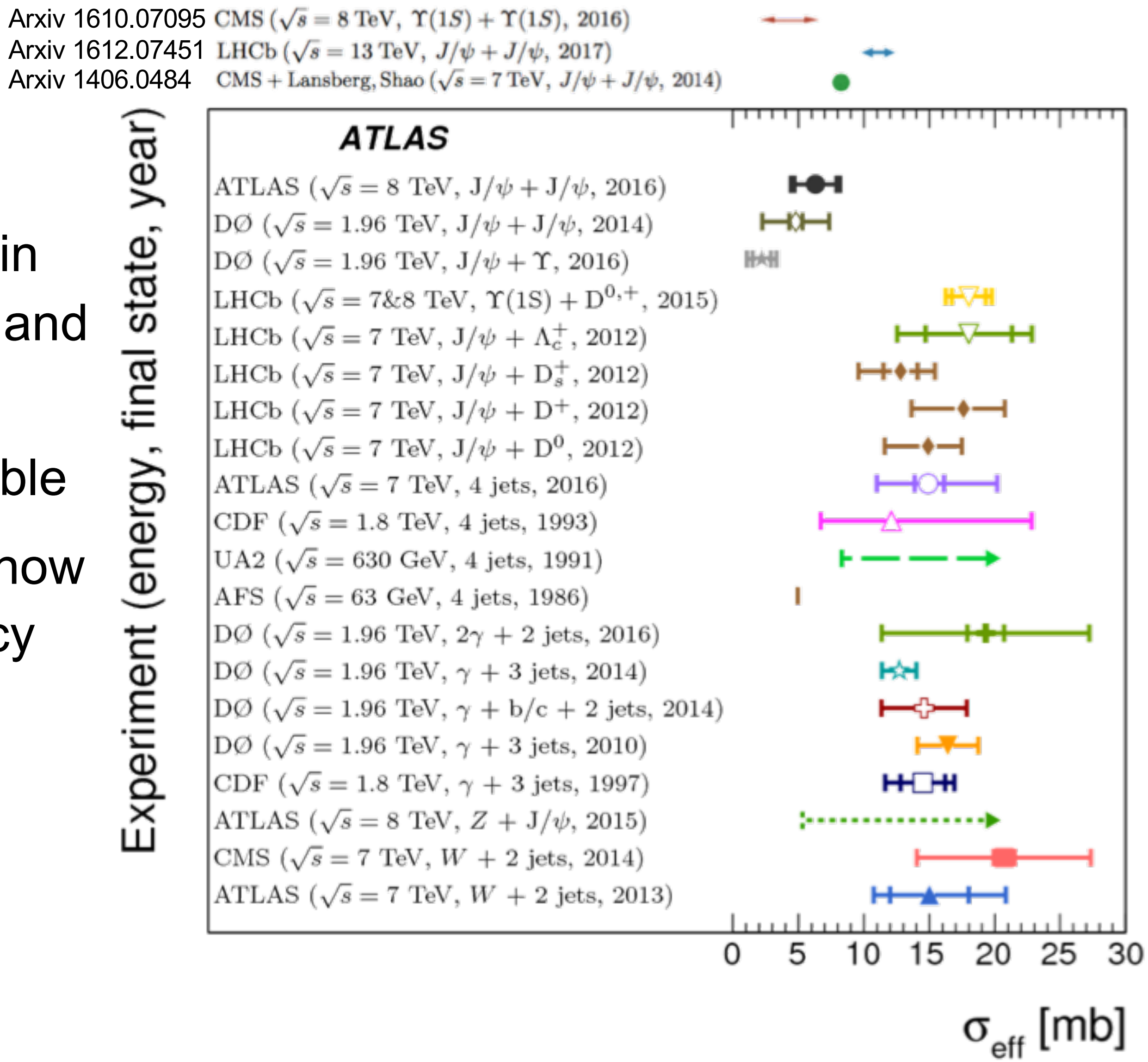
Conclusions

- LHC fertile ground for associated production measurements
- ATLAS measures effects in Wjj, jjjj, Z and W plus J/ψ and di-J/ψ
- DPS visible and measurable
- σ_{eff} measurements may show some process dependency
- More measurements to come:
  - Run 2 data for W+J/ψ
  - DPS in ZZ



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Backup

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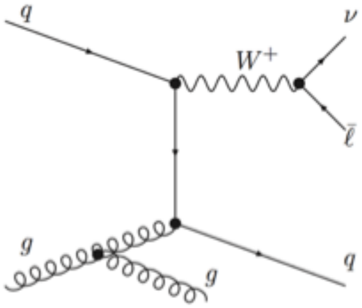
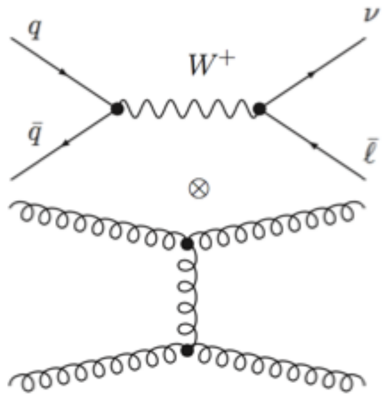


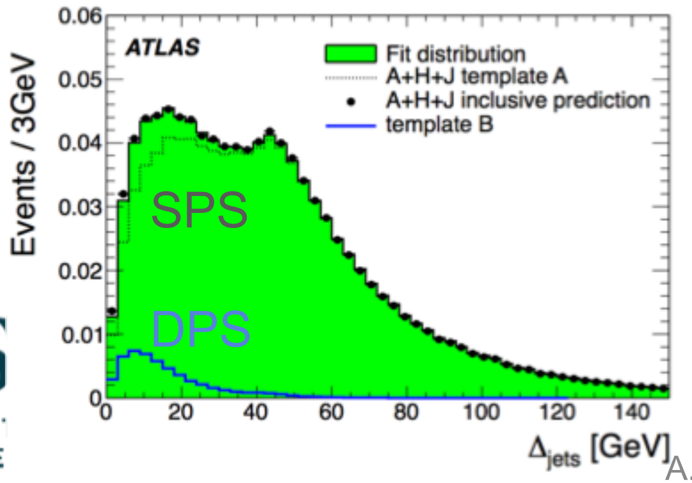
Wjj: early Run 1 Data

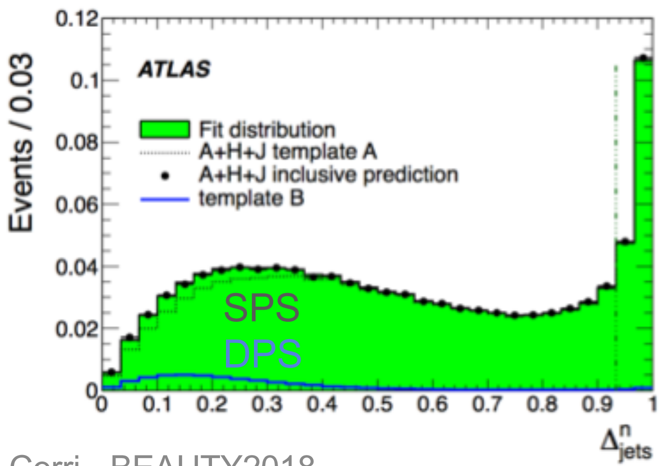


- Early data → low pile-up multiplicity n_{pu}
- Based on 36 pb^{-1} of data collected with $n_{pu}<1$
- Leptonic W decay (1ℓ [e,μ] trigger) and di-jet events from minimum bias data
- In DPI W and jj are very loosely correlated (only through parton PDF)
- Main discriminants related to jj balance:

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

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





Discriminants in Alpgen+Herwig+Jimmy simulation, compared to data-driven DPS template and MC AHJ template for SPS

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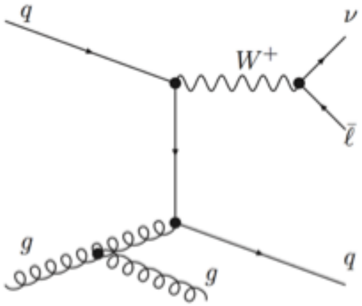

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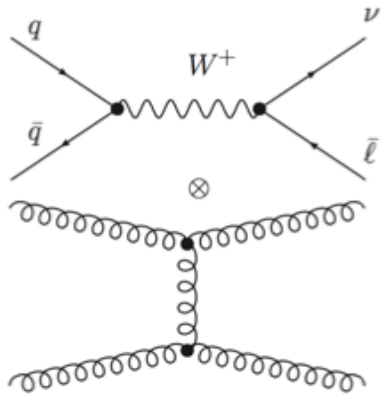
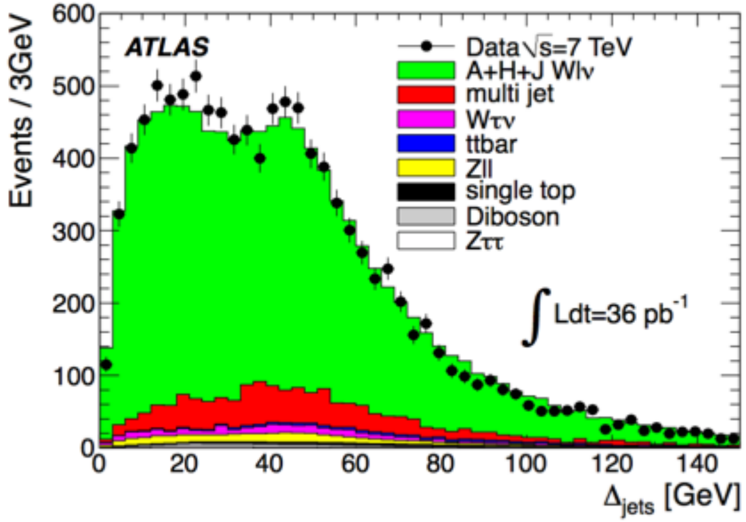
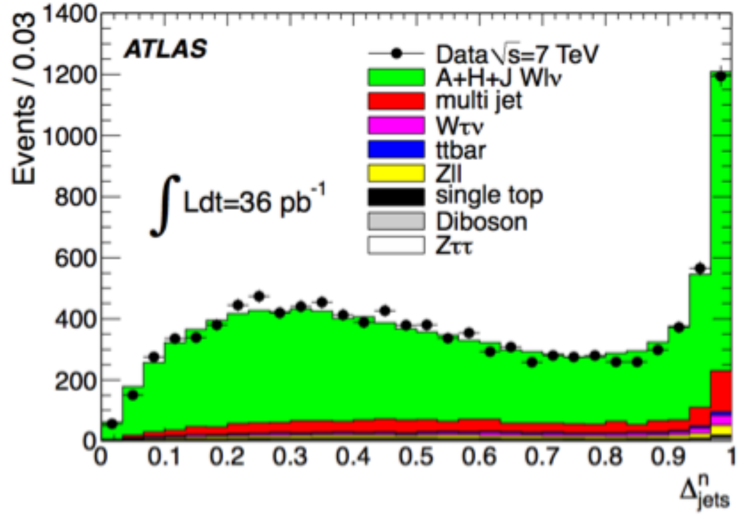


- Simulation of main physics backgrounds:





$$f_{\mathrm{DP}} = 0.076 \pm 0.013\ (\mathrm{stat.}) \pm 0.018\ (\mathrm{sys.})$$

Systematic source	Uncertainty [%]
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background modelling & lepton response	11
Total systematic	24
Total statistical	17

$$\sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\ (\mathrm{stat.})\ ^{+5}_{-3}\ (\mathrm{syst.})\ \mathrm{mb}$$

Systematic source	Uncertainty [%]
$f_{\mathrm{DP}}^{(\mathrm{D})}$	24
Background & lepton response	5
Luminosity	3
Total systematic	$^{+33}_{-20}$
Total statistical	17

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