Double Parton Scattering at ATLAS

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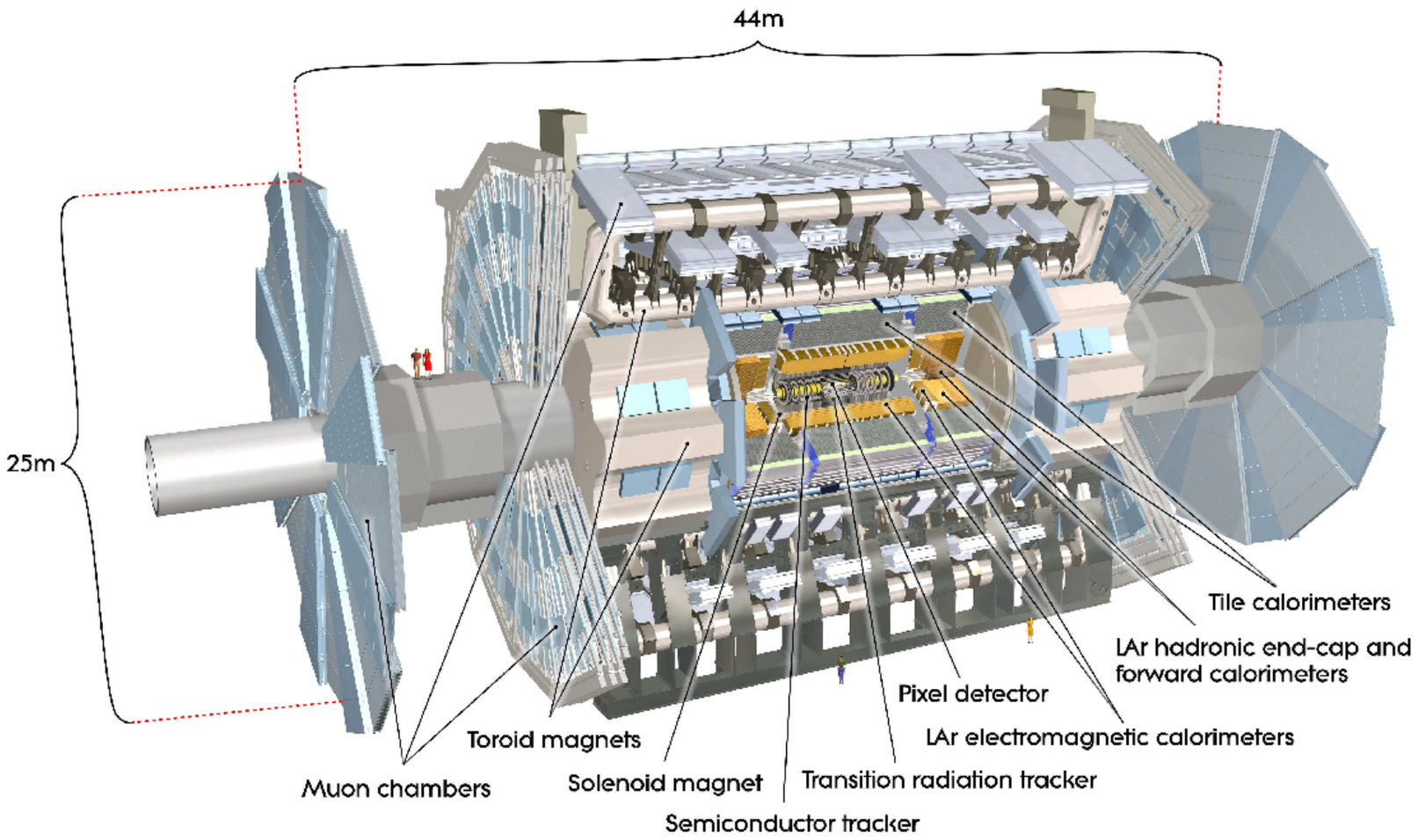
University of Washington

Workshop on Double Parton Scattering
and the 3D structure of hadrons

January 11-15, 2025

The ATLAS detector

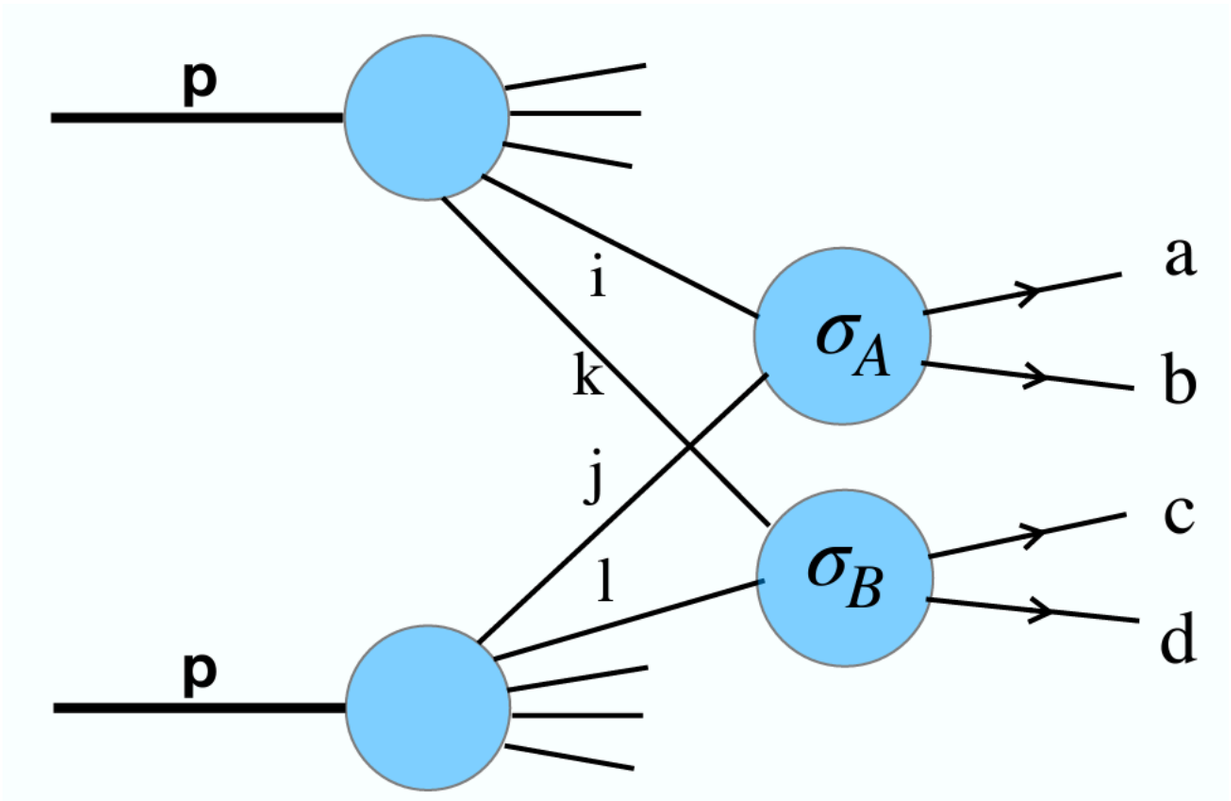


- ATLAS is one of the two general-purpose detectors at the LHC
- At 44 m long, 25 m high and 25 m wide, the 7000-tonne ATLAS detector is the largest volume particle detector ever constructed
- It's designed in layers to observe different types of particles

- Collected a large set of pp-collision data
  - Run 1 (2010-2013): 4.9 fb^{-1} at 7 TeV and 20.2 fb^{-1} at 8 TeV
  - Run 2 (2015-2018): 140 fb^{-1} at 13 TeV
  - Run3 (2022-): 183fb^{-1} at 13.6 TeV (recorded)

Double parton scattering

- Double parton scattering (DPS): two independent interactions in one pp collision



Cross section:

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

If A=B, $\delta_{AB} = 1$

Otherwise, $\delta_{AB} = 0$

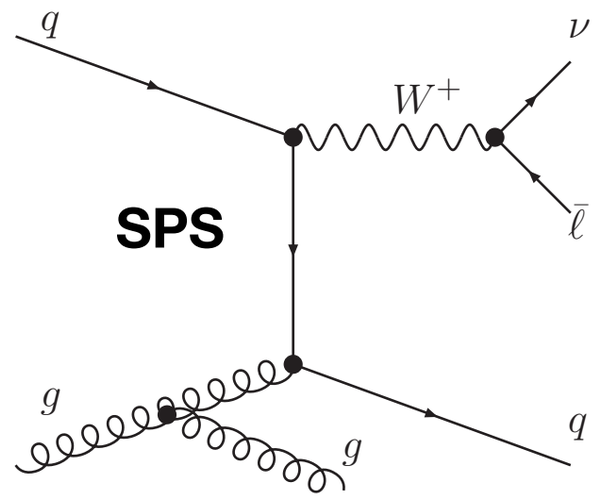
- σ_{eff} is the effective area parameter related to the overlap between the interacting hadrons, determining the overall size of DPS cross section
  - Assumed to be independent of process, cut and centre-of-mass energy
- Introduce DPS fraction f_{DPS}: $\sigma_{A+B}^{DPS} = f_{\text{DPS}} \cdot \sigma_{A+B}^{\text{tot}}$, where $\sigma_{A+B}^{\text{tot}}$ is the total cross section for A+B final state production, Thus, $\sigma_{\text{eff}} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{f_{\text{DPS}} \cdot \sigma_{A+B}^{\text{tot}}}$

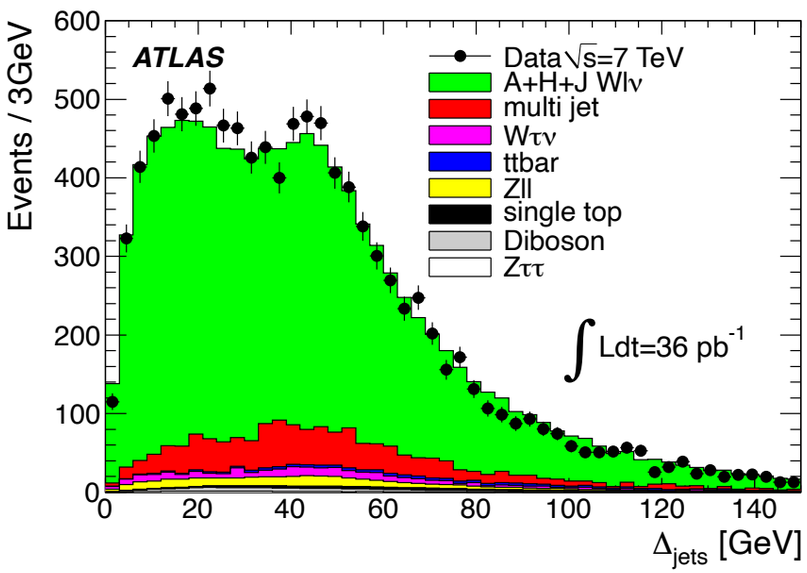
In this talk

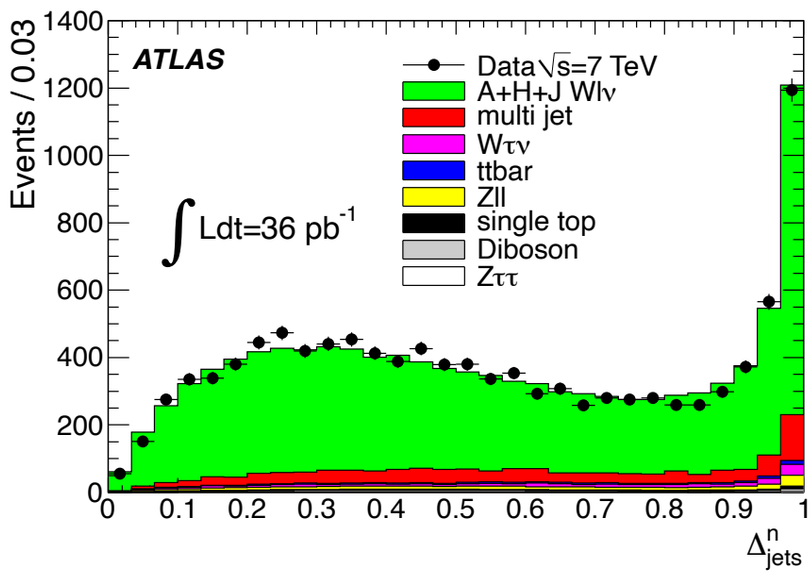
- Measurement of hard double-parton interactions in W($\rightarrow \ell\nu$) + 2-jet events @ 7 TeV New J. Phys. 15 (2013) 033038
- Study of hard double-parton scattering in four-jet events at 7 TeV JHEP 11 (2016) 110
- Study of the hard double-parton scattering contribution to inclusive four-lepton production @ 8 TeV Phys.Lett. B 790 (2019) 595
- Measurement of prompt J/ψ pair production cross-section @ 8 TeV Eur. Phys. J. C 77 (2017) 76
- Measurement of $Z + J/\psi$ (prompt and non-prompt) @ 8 TeV Eur. Phys. J. C 75 (2015) 229
- Measurement of $W + J/\psi$ (prompt) @ 8 TeV JHEP 01 (2020) 095

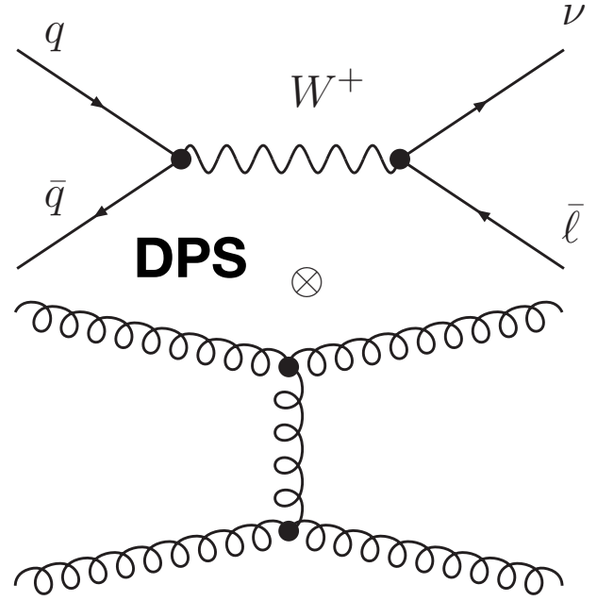
W($\rightarrow \ell\nu$) + 2-jet study

- Measure the hard DPS contribution with the W($\rightarrow \ell\nu$) + 2-jet events
- Dataset: 36 pb^{-1} @ 7 TeV collected in 2010, $< \mu > = 0.4$
- Selections:
  - Electron/muon: $p_T > 20$ GeV and $|\eta| < 2.47(2.4)$
  - $E_T^{\text{miss}} > 25$ GeV and $m_T > 40$ GeV ($m_T = \sqrt{2p_T^{\ell} E_T^{\text{miss}}(1 - cos\Delta\phi_{\ell, E_T^{\text{miss}}})}$)
  - Jets: $p_T > 20$ GeV and |y| < 2.8
- Observables: $\Delta_{\text{jets}} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$ and $\Delta^n_{\text{jets}} = \dfrac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$







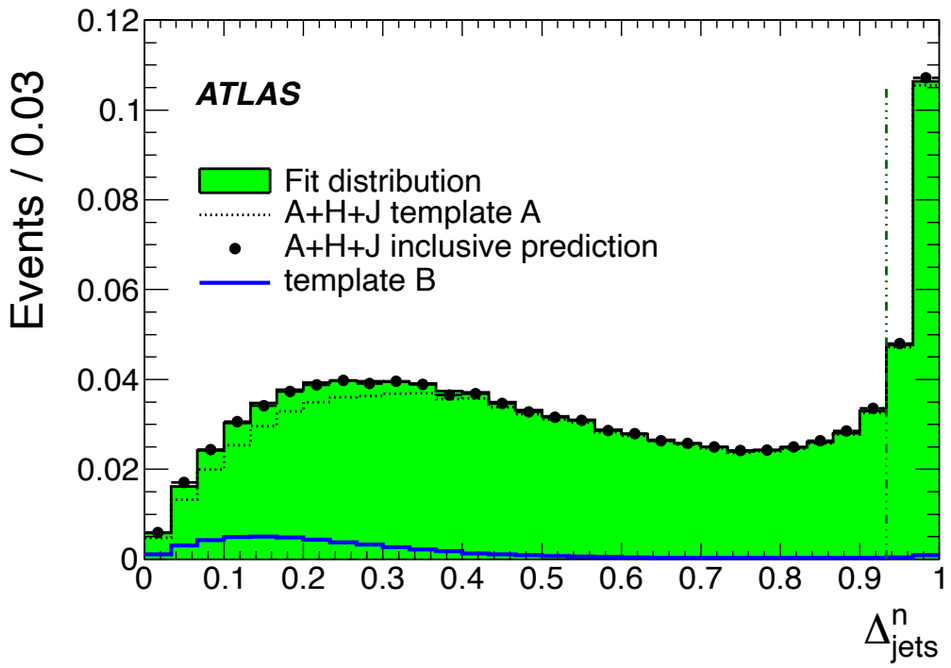


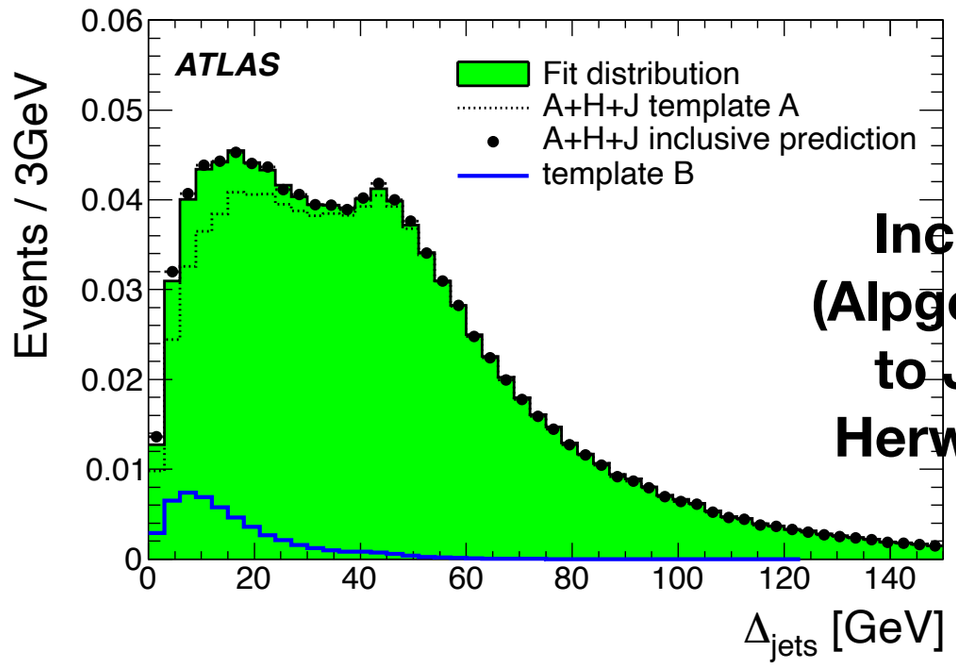
New J. Phys. 15 (2013) 033038

W($\rightarrow \ell\nu$) + 2-jet study

- To extract $f_{DP}^{(D)}$, a fit is performed by comparing the Δ_{jets}^{n} distribution at detector level in background-corrected data with two templates:
  - Template A “DPI-off”: two jets originate from a primary scatter (SPS). Constructed by removing hard MPI candidate events from generated sample
  - Template B “DPI-only”: both jets originate from a DPI scatter (DPS). Constructed by minimum bias dijet data

$$f = (1 - f_{DP}^{(D)}) \cdot A + f_{DP}^{(D)} \cdot B$$





Inclusive AHJ (Alpgen interfaced to Jimmy and Herwig) pseudo-data

New J. Phys. 15 (2013) 033038

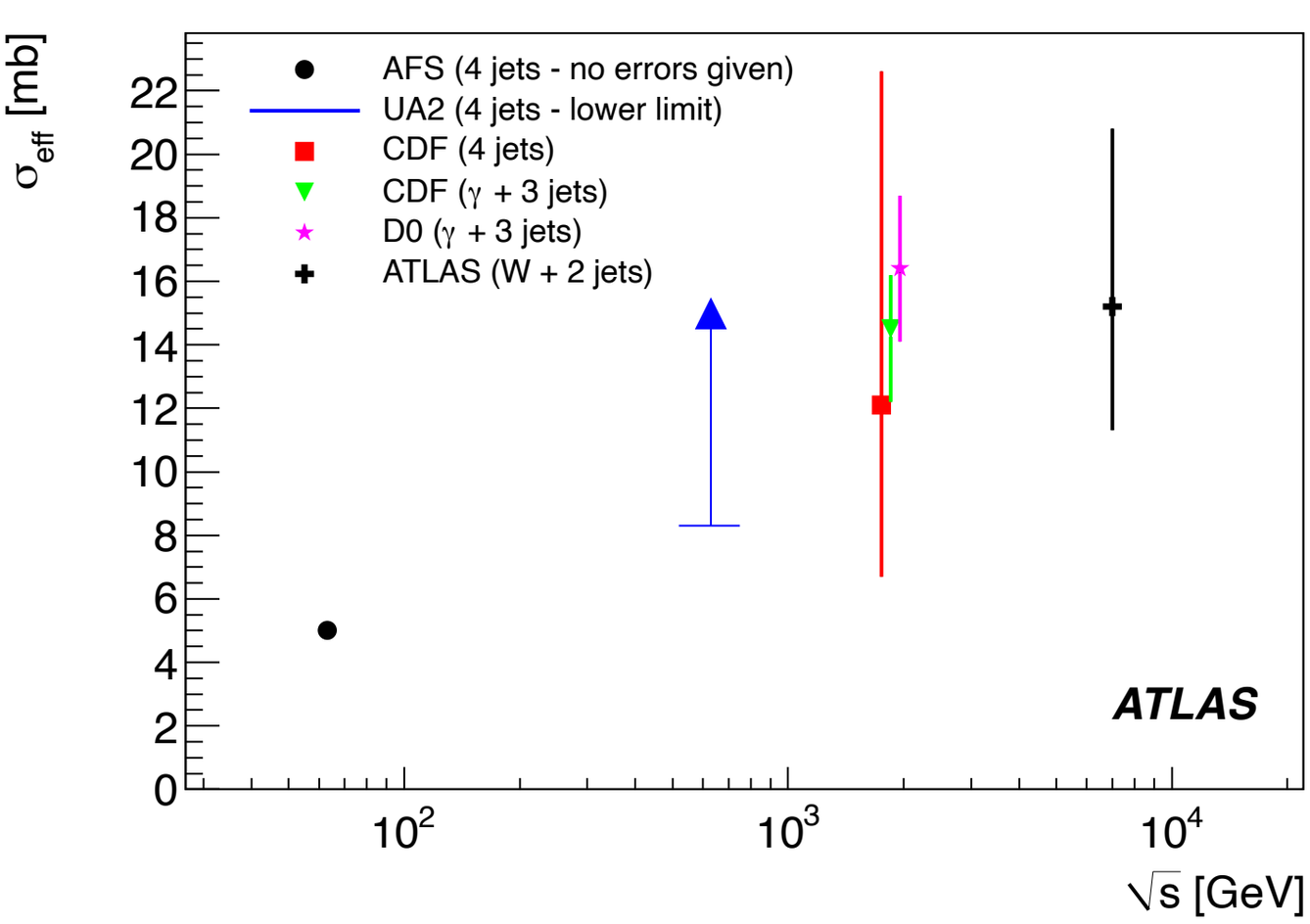
W($\rightarrow \ell\nu$) + 2-jet study

- For jets with $p_T > 20$ GeV and |y|<2.8, the double-parton interaction rate $f_{DP}^{(D)}$ is measured to be:

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

- The effective area parameter σ_{eff} extracted from data is:

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



- This value of σ_{eff} is consistent with values previously measured in other experiments at lower centre-of-mass energies

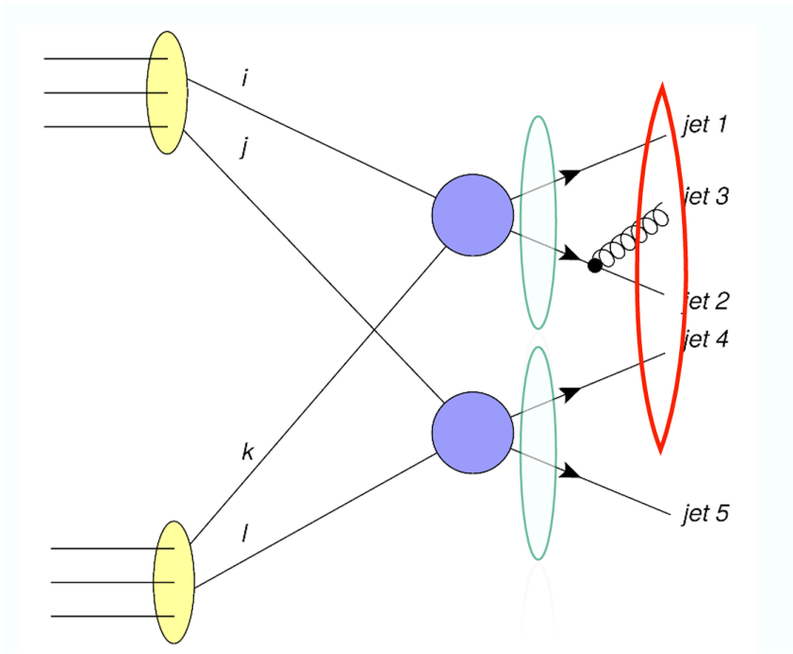
New J. Phys. 15 (2013) 033038

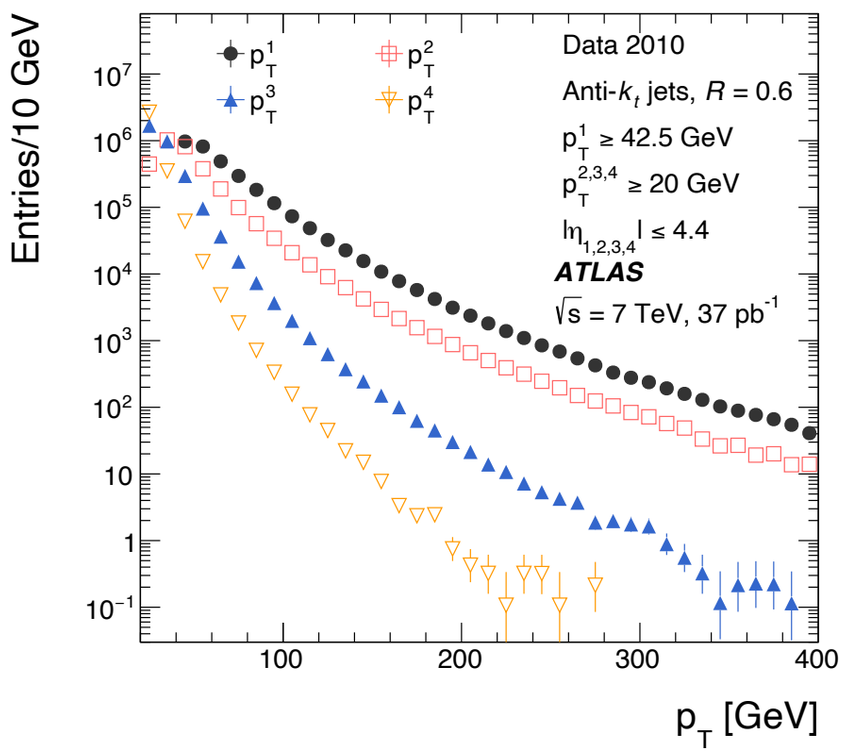
Four-jet study

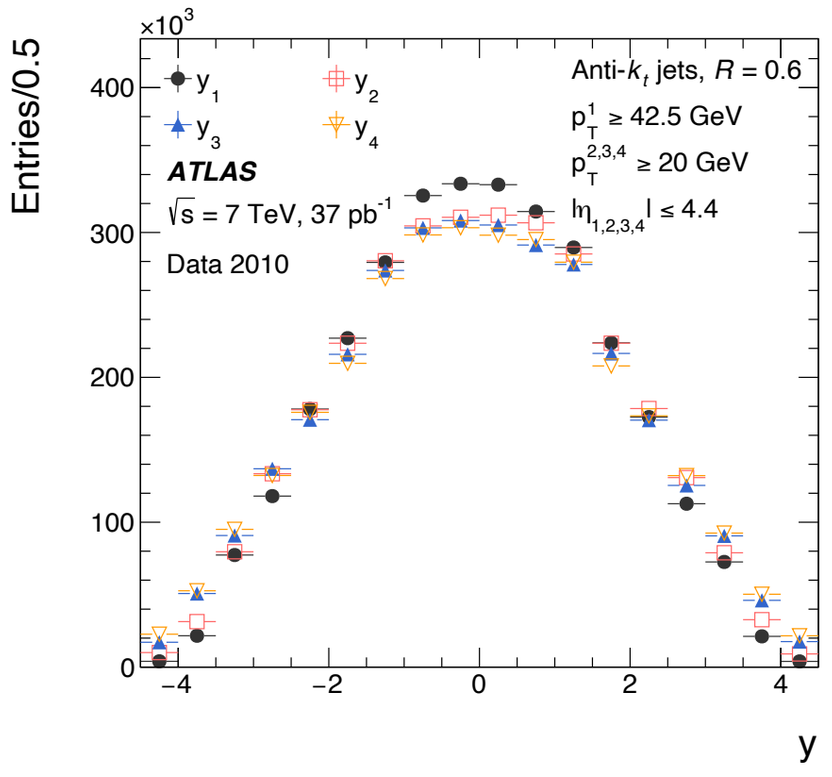
JHEP 11 (2016) 110

- Measure the hard DPS contribution with the inclusive 4-jet events
- Dataset: 36 pb^{-1} @ 7 TeV collected in 2010, $< \mu > = 0.4$
- Anti-kt jets with R = 0.6, $p_T > 20$ GeV and $|\eta| \leq 4.4$
- Event categories:
  - SPS: No jets matched to secondary scatter parton
  - sDPS: 1 jet matched to secondary scatter parton
  - cDPS: 2 jet matched to secondary scatter parton

$$f_{\mathbf{DPS}} = f_{\mathbf{sDPS}} + f_{\mathbf{cDPS}}$$



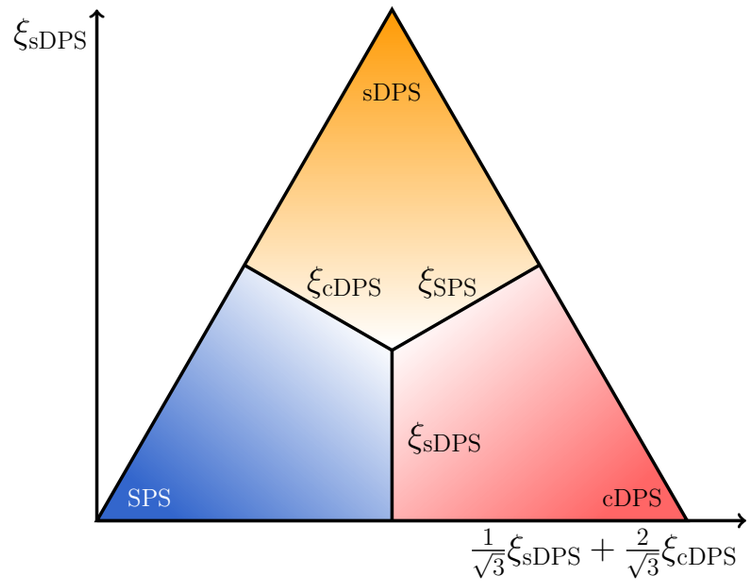


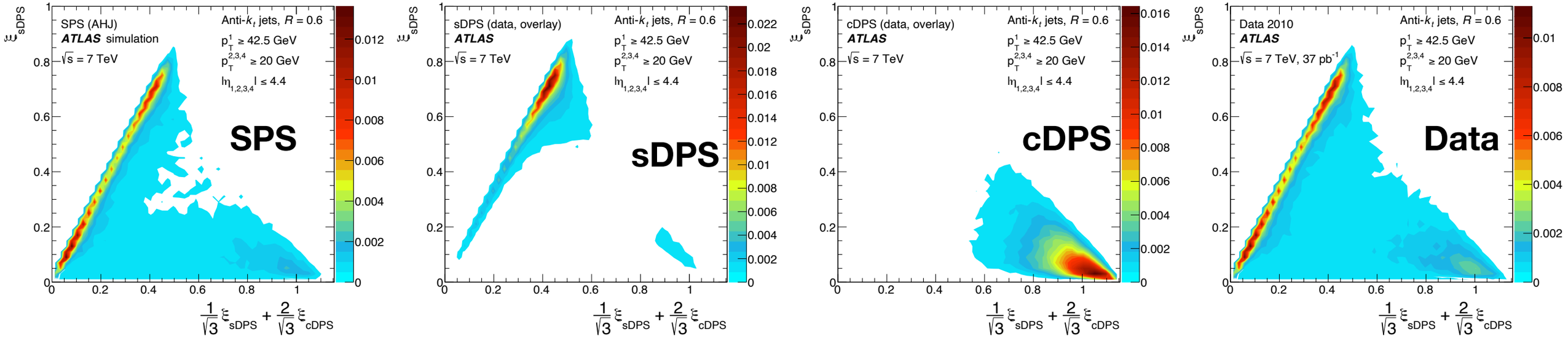


Four-jet study

JHEP 11 (2016) 110

- An artificial neutral network (NN) is trained to perfom event classification
  - Input: 21 variables consisting of all possible dijet combinations
  - Output: probabilities for an event to be more like SPS(δ_{SPS}), cDPS(δ_{sDPS}) or sDPS(δ_{cDPS}), with $\delta_{SPS} + \delta_{sDPS} + \delta_{cDPS} = 1$





- Good separation between event categories
  - The separation between SPS and sDPS is difficult
- Fit MC profiles to data: $D = (1 - f_{\mathrm{cDPS}} - f_{\mathrm{sDPS}})M_{\mathrm{SPS}} + f_{\mathrm{cDPS}}M_{\mathrm{cDPS}} + f_{\mathrm{sDPS}}M_{\mathrm{sDPS}}$

Four-jet study

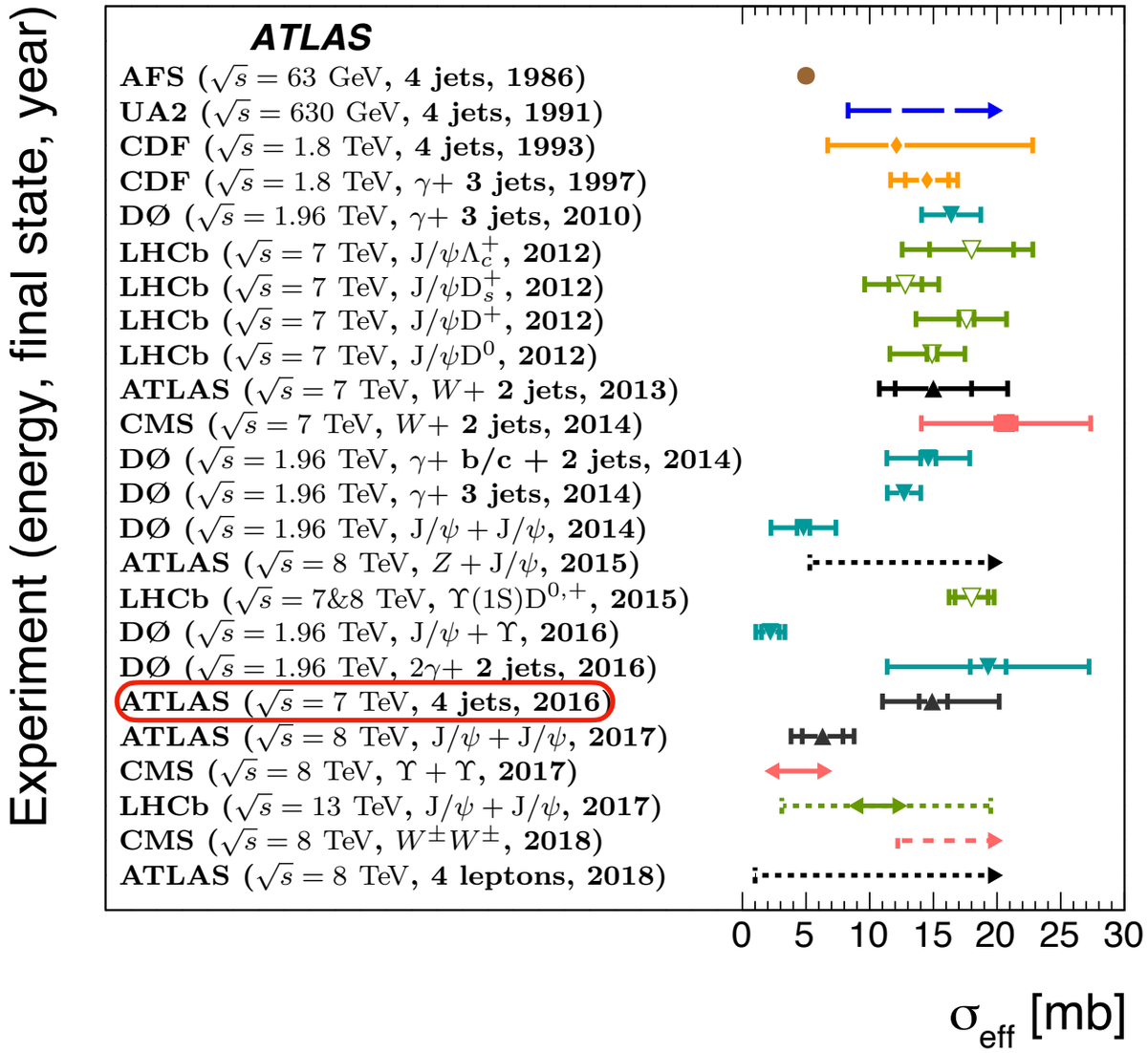
JHEP 11 (2016) 110

- The extracted f_{DPS} is $f_{\mathrm{DPS}} = 0.092^{+0.005}_{-0.011}(\mathrm{stat.})^{+0.033}_{-0.037}(\mathrm{syst.})$, with ~40% contribution from f_{sDPS}

- The measurements of the dijet and four-jet cross sections can be used to calculate the effective cross section:

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

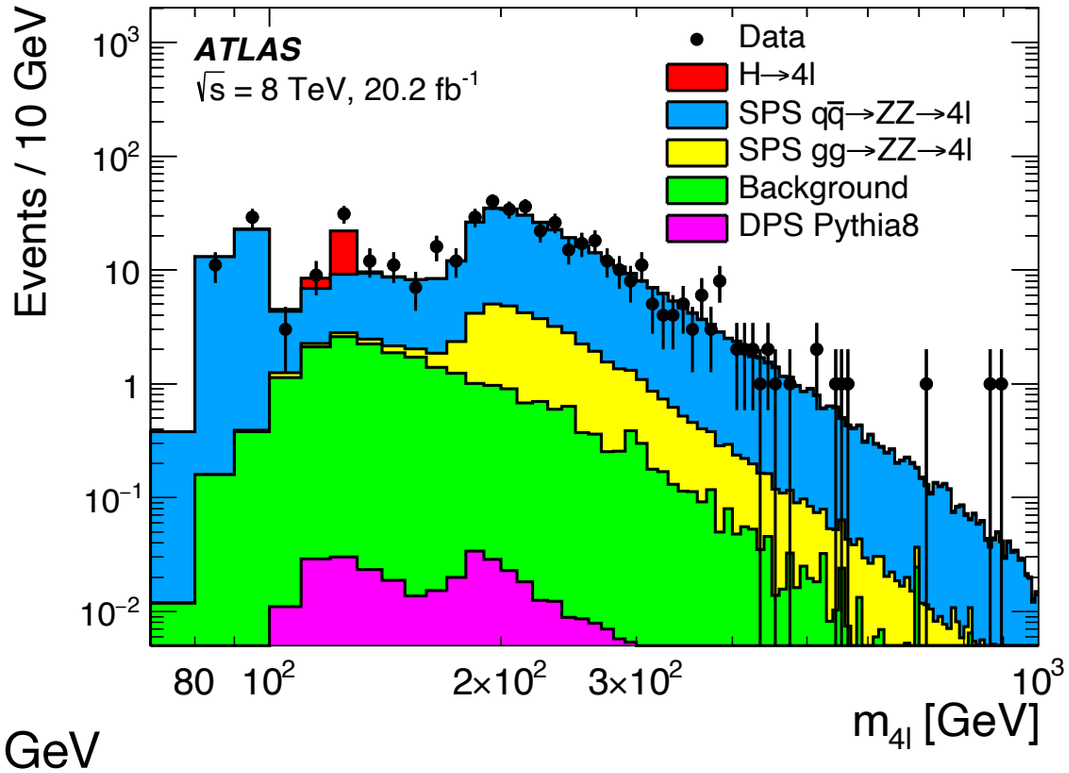
- It is consistent within the quoted uncertainties with previous measurements



Four-lepton study

- Measure the hard DPS contribution with the inclusive 4-lepton events
- Dataset: 20.2 fb^{-1} @ 8 TeV
- Events with at least four leptons (electrons or muons) which can form two same-flavor opposite-charge (SFOC) lepton pairs are selected

- **Pairing:**
  - Leading pair: SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$
  - Second pair: remaining SFOC with largest $m_{\ell\ell}$
- **Lepton selection:**
  - $p_T > 7$ (6 if muon) GeV, $|\eta| < 2.5$ (2.7 if muon)
- **Event selection:**
  - Lepton $p_T^{\ell_1,\ell_2,\ell_3,\ell_4}$: > 20, 15, 10 (8 if muon), 7 (6 if muon) GeV
  - Lepton pair mass: $50 < m_{\text{leading}} < 120$ GeV, $12 < m_{\text{sub-leading}} < 120$ GeV
  - Separation: $\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same (different) flavor leptons
  - J/ψ veto: $m(\ell_i^+, \ell_j^-) > 5$ GeV
  - Four-lepton mass: $80 < m_{4\ell} < 1000$ GeV



Phys.Lett. B 790 (2019) 595

Four-lepton study

- NN is applied to discriminate SPS and DPS
- Input: 21 variables with all the lepton combinations ($\Delta p_{T,ij}$, $\Delta\phi_{ij}$, Δy_{ij} and $\Delta_{ijkm} = |\phi_{i+j} - \phi_{k+m}|$)

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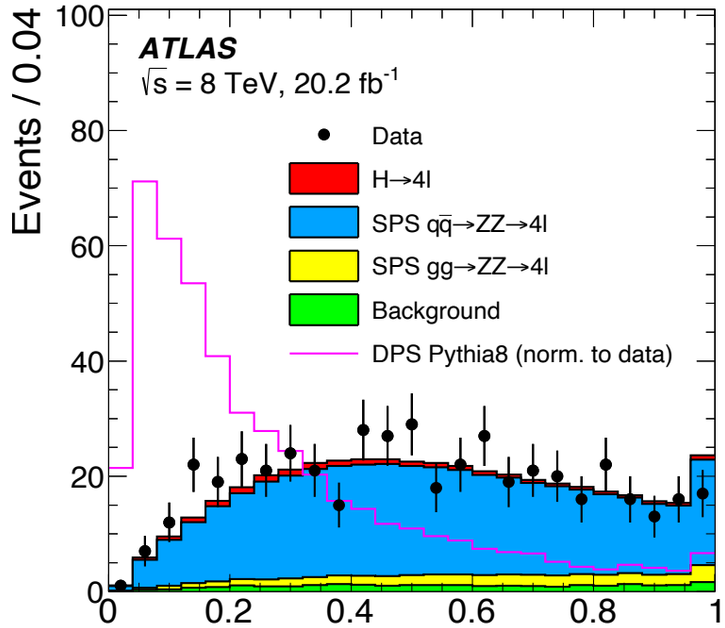
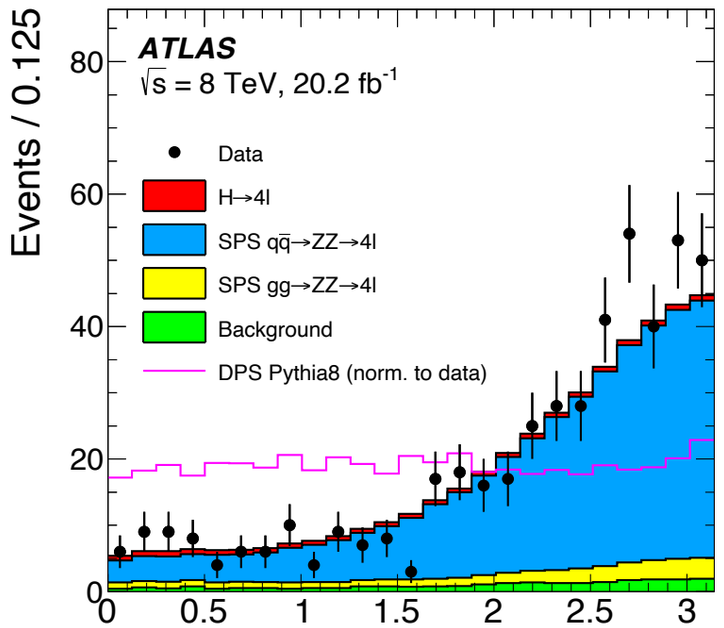
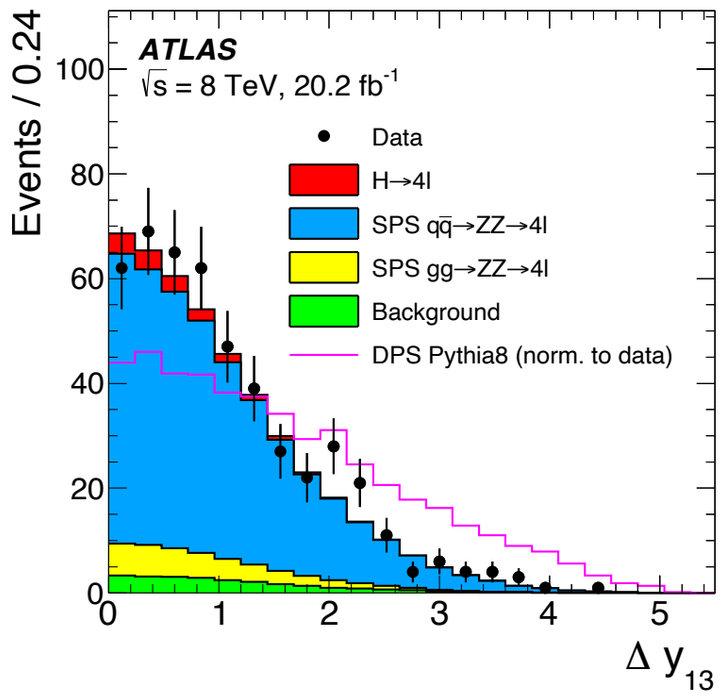
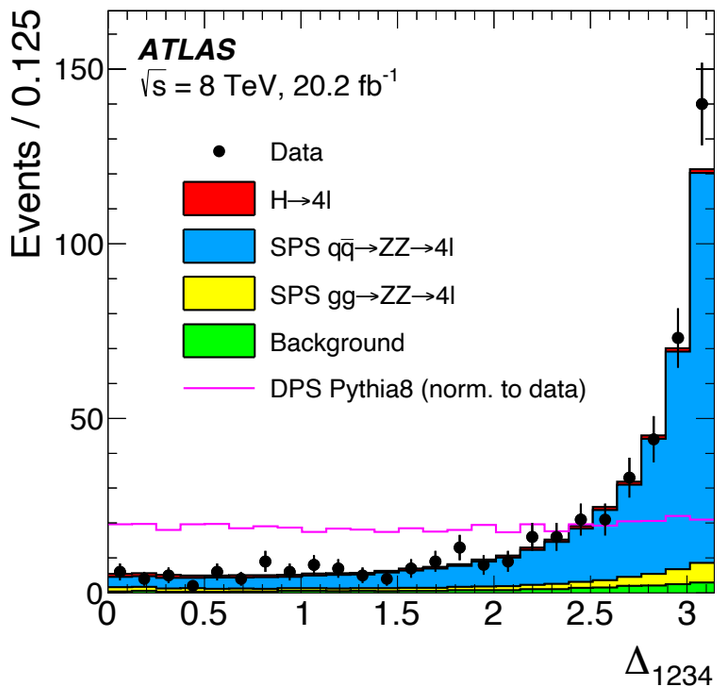




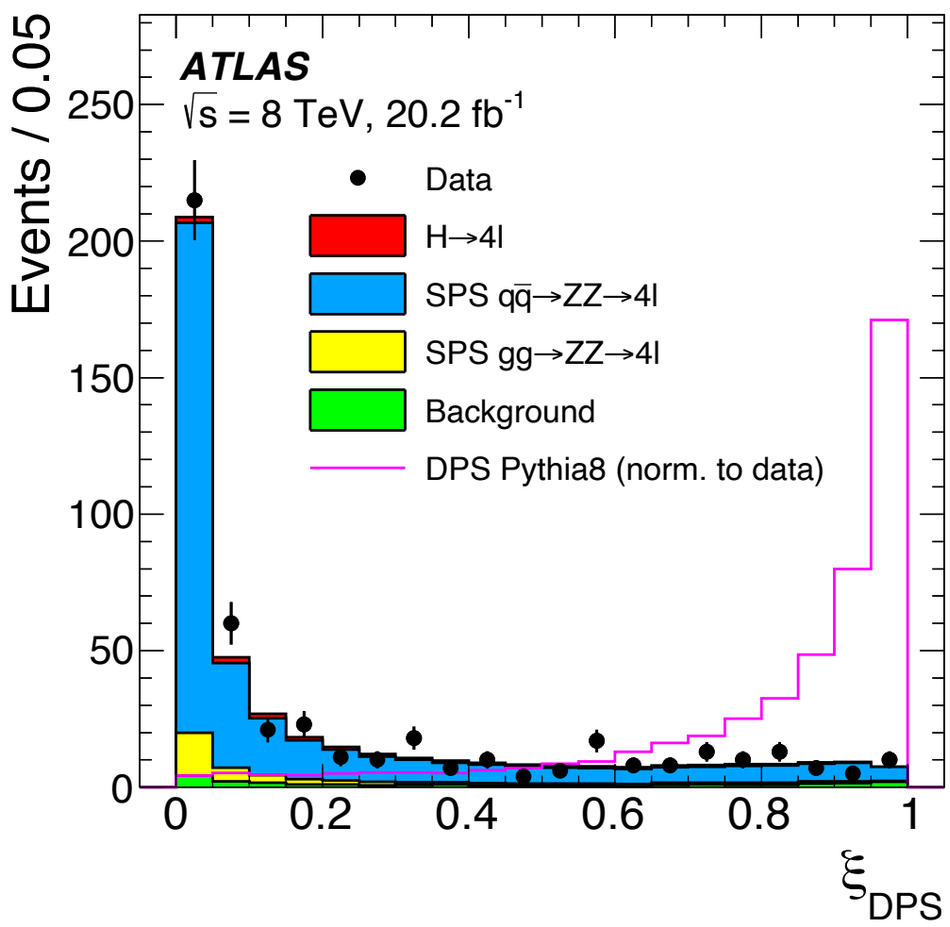


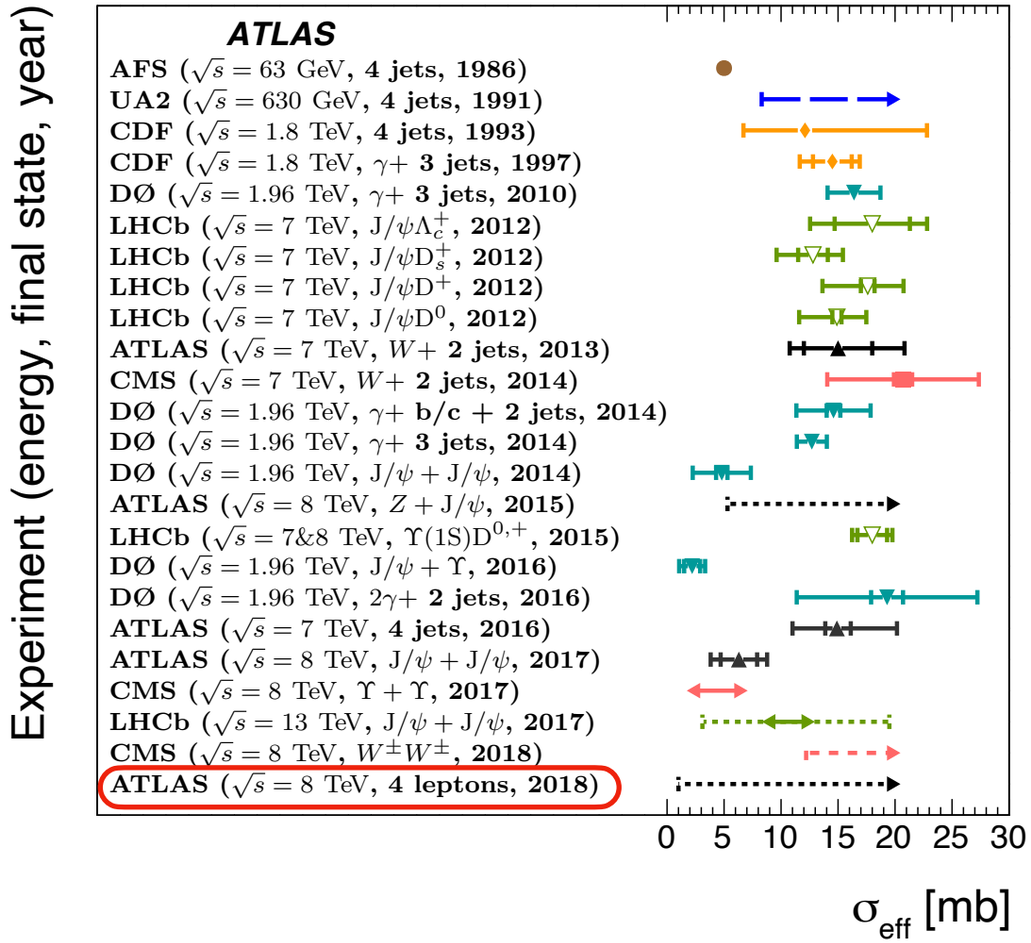


Four-lepton study

Phys.Lett. B 790 (2019) 595

- Perform fit on NN output variable ξ_{DPS} to determine DPS fraction
  $f_{\mathrm{DPS}} = -0.009 \pm 0.017(\mathrm{stat.}) \pm 0.003(\mathrm{sys.})$
- Translate into the upper limit $f_{\mathrm{DPS}} < 0.042$ at 95% CL
- The lower limit on σ_{eff} is extracted to be >1.0 mb at 95% CL

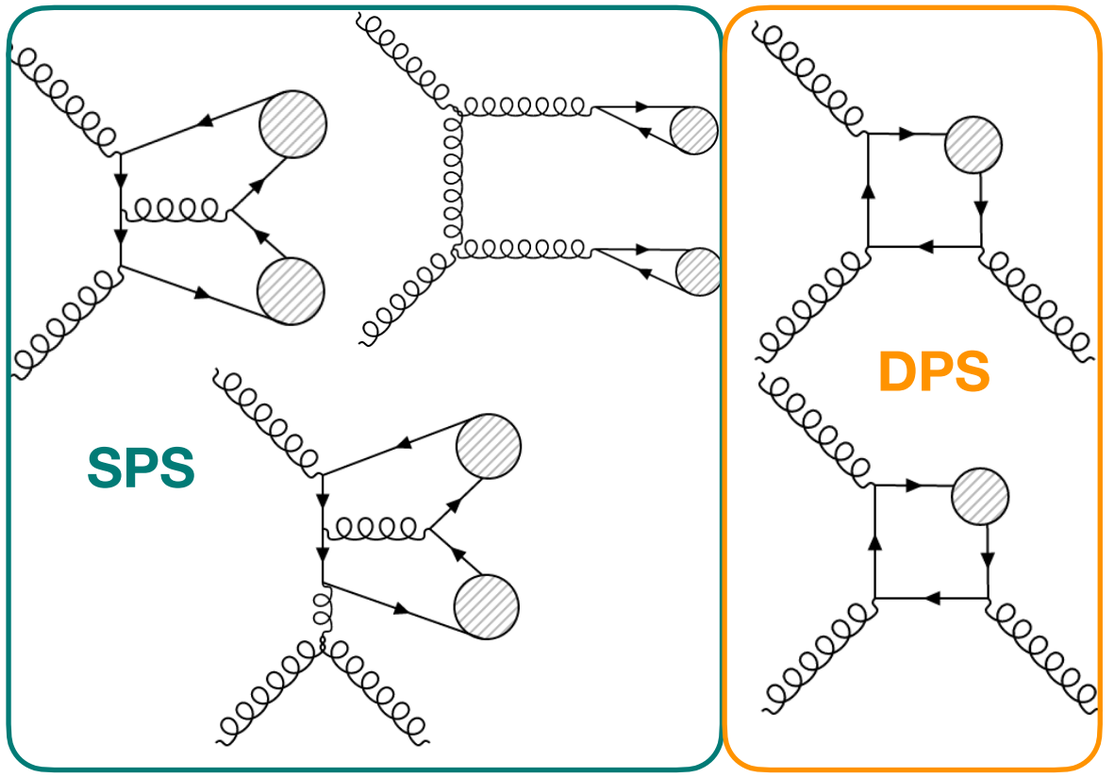




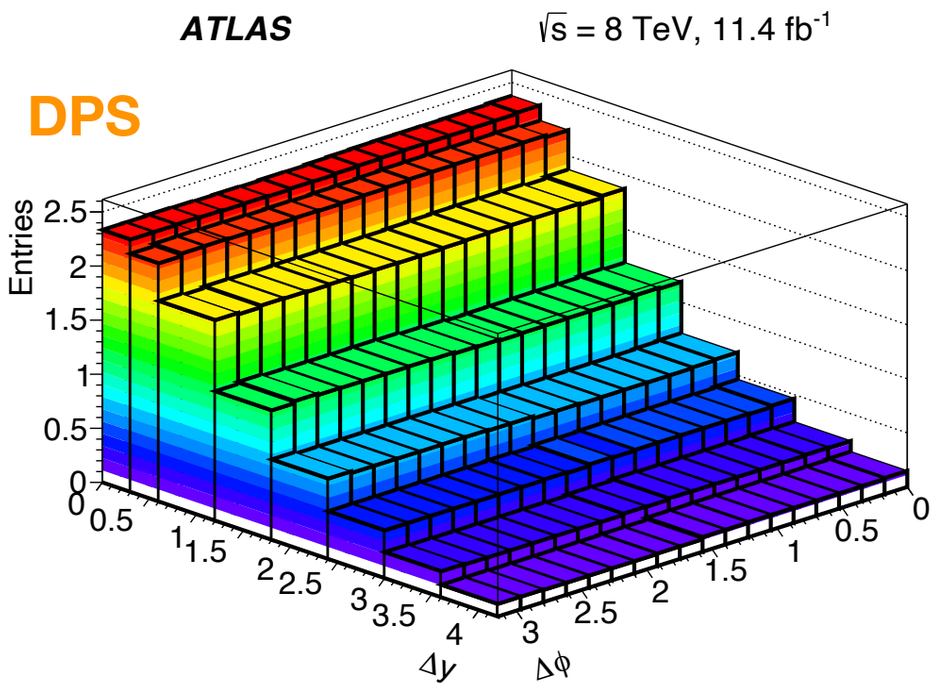
di-J/ψ study

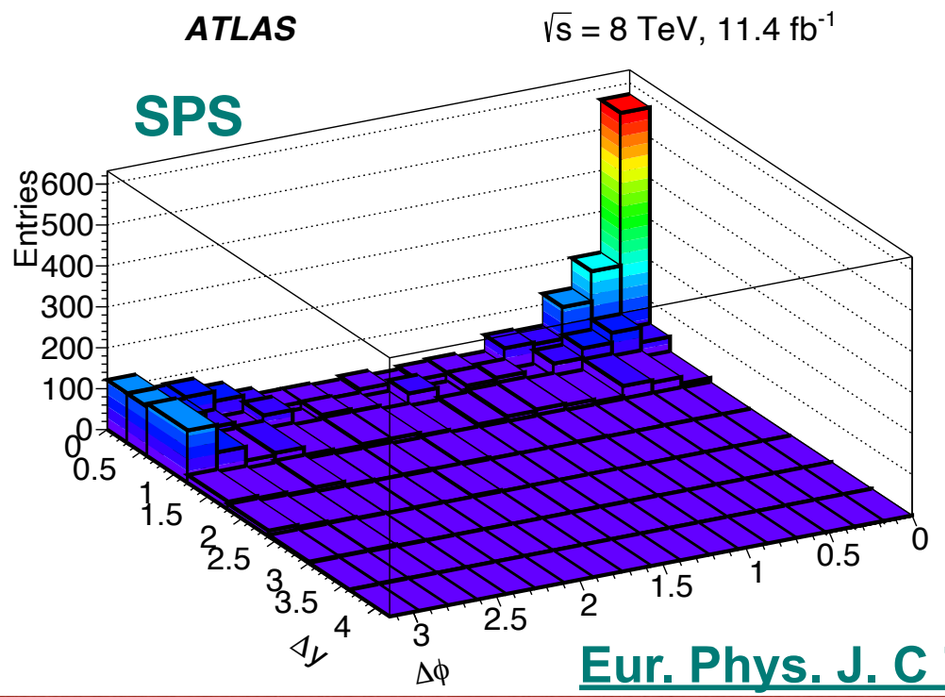
- Measure the hard DPS contribution with prompt di-J/ψ events
- Dataset: 11.4 fb^{-1} @ 8 TeV collected in 2012
- Selections:
  - J/ψ dimuon trigger with muon p_T threshold of 4GeV
  - $p_T^{\mu} > 2.5$ GeV and $|\eta^{\mu}| < 2.3$
  - $2.8 \leq m(\mu\mu) \leq 3.4$ GeV
  - $|y^{J/\psi}| < 2.1$ and $p_T^{J/\psi} > 8.5$ GeV
  - The distance between the two J/ψ decay vertices along the beam direction $|d_z| < 1.2$mm
  - L_{xy} uncertainty < 0.3 mm

$J/\psi \rightarrow \mu^+\mu^-$



- SPS and DPS event weights are derived with 2D data-driven templates of Δy and $\Delta\phi$ between the two J/ψ candidates

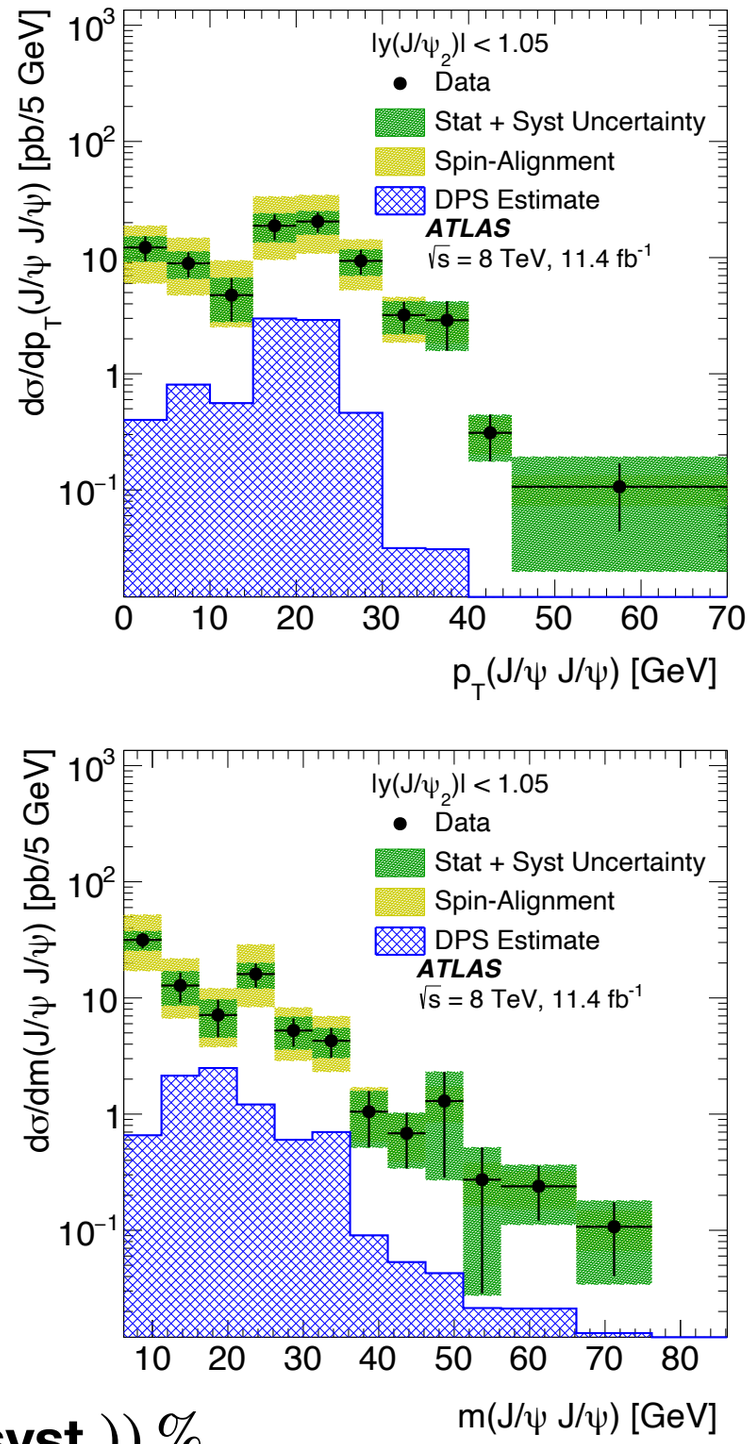


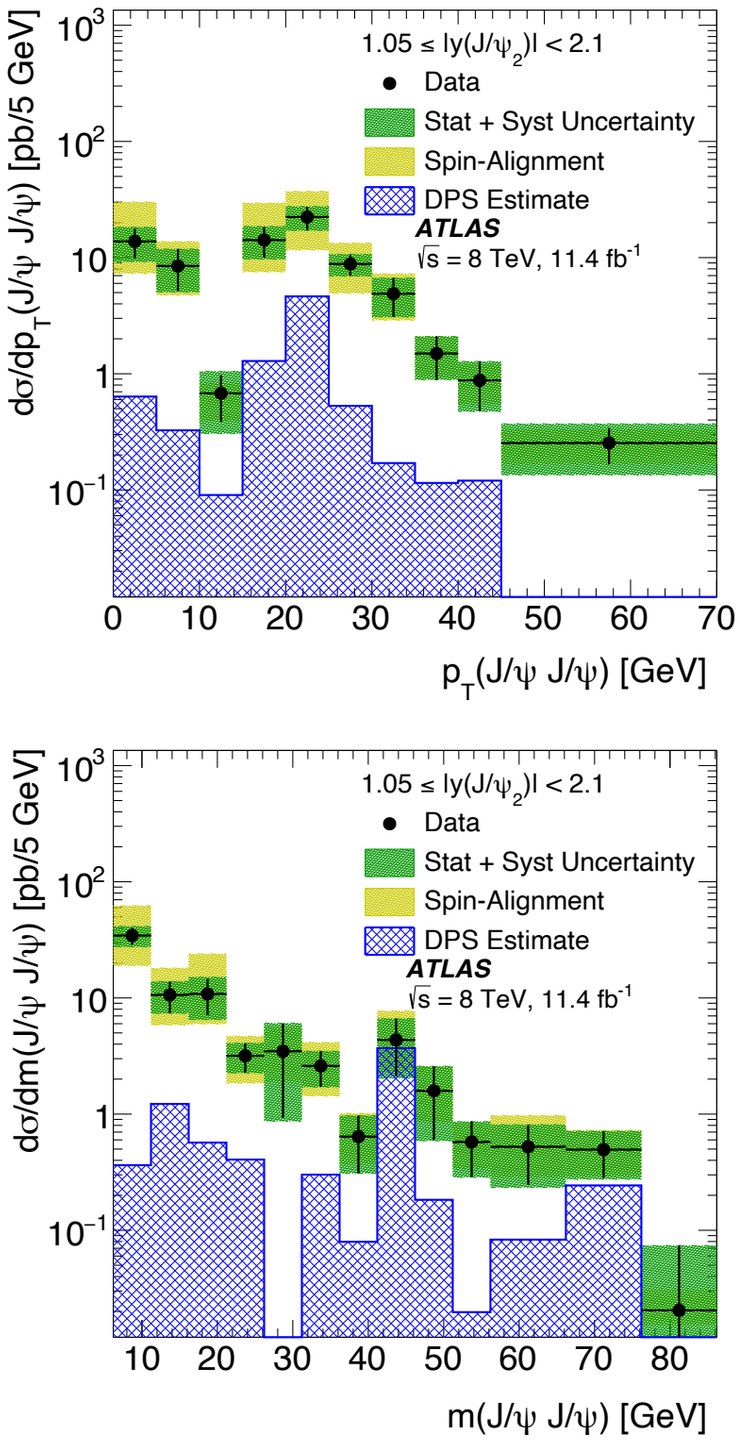


Eur. Phys. J. C 77 (2017) 76

di-J/ψ study

- The cross-section is measured in two rapidity regions as a function of the di-J/ψ p_T and invariant mass with assumption of unpolarised J/ψ mesons
- There are two peaks in the di-J/ψ p_T distribution
- Low p_T: two J/ψ are produced back-to-back in an away topology
- High p_T: two J/ψ are produced in the same direction in a towards topology





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

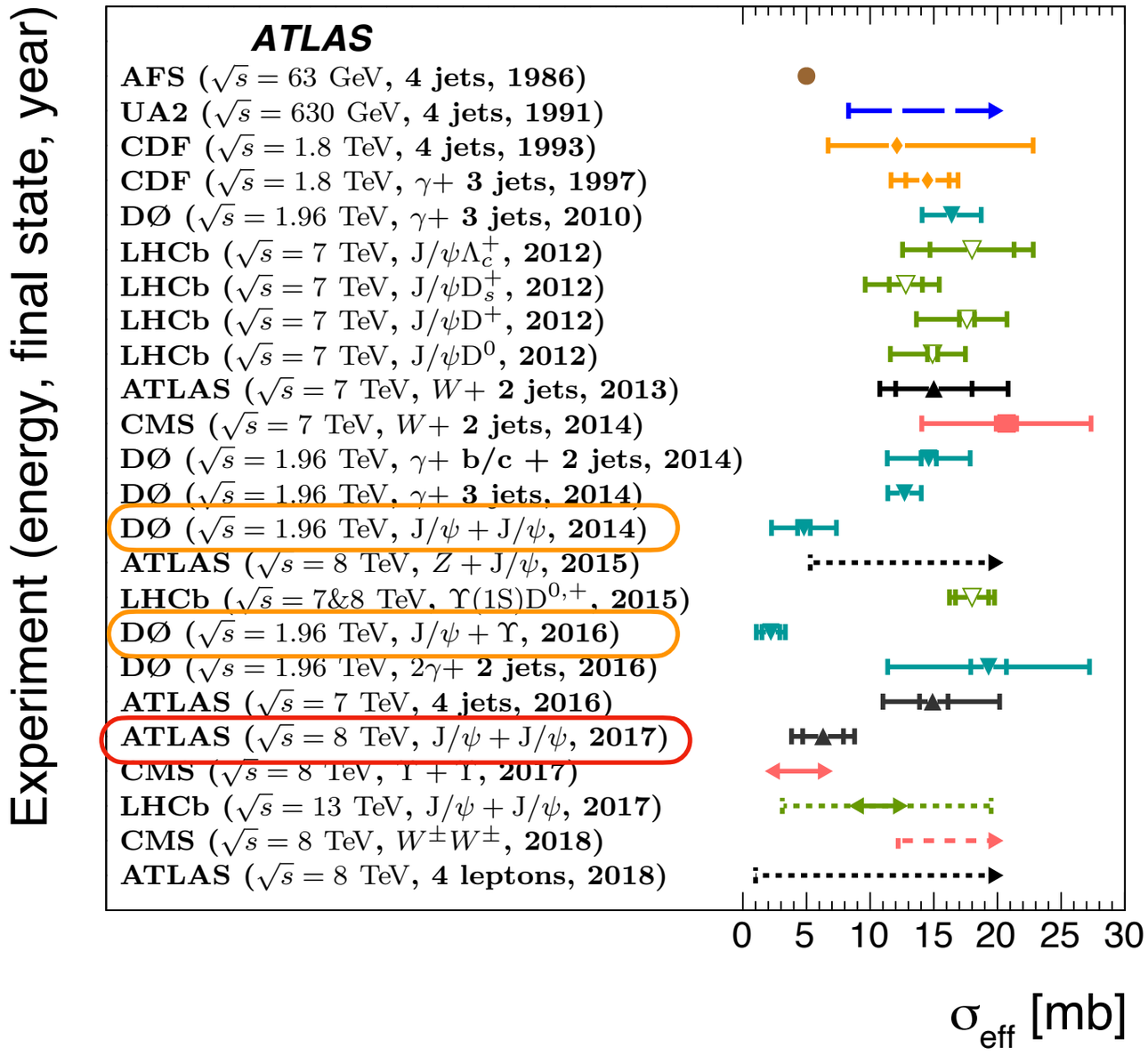
Eur. Phys. J. C 77 (2017) 76

di-J/ψ study

- With $\sigma_{J/\psi}$ obtained from ATLAS measurements (Eur. Phys. J. C 76 (2016) 283) and f_{DPS} as inputs, the effective cross-section is measured to be:

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

- Close to D0 results and lower than other measurements



Eur. Phys. J. C 77 (2017) 76

$Z + J/\psi$ study

Eur. Phys. J. C 75 (2015) 229

- Study DPS in the production of prompt and non-prompt J/ψ ($\rightarrow \mu^+\mu^-$) in association with a Z boson ($\rightarrow \ell^+\ell^-$)
- Dataset: 20.3 fb^{-1} @ 8 TeV

Event selections

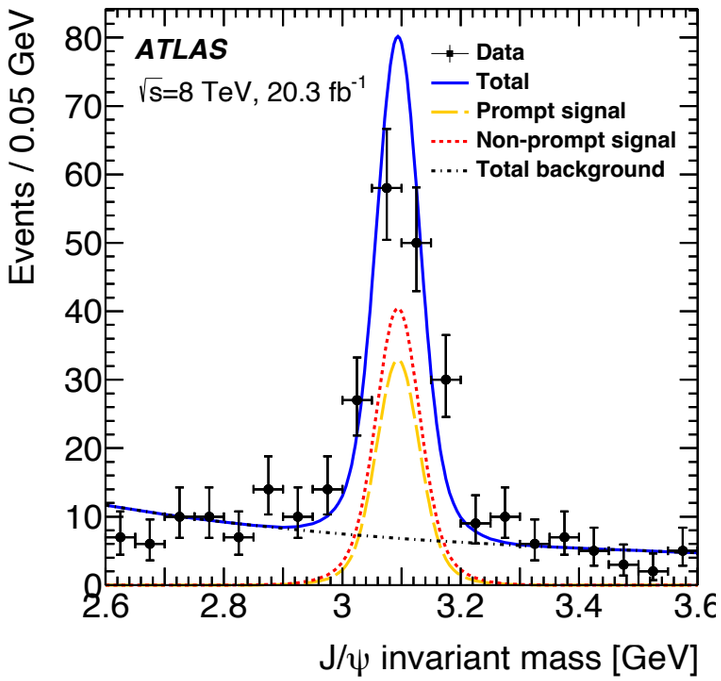
Z boson:

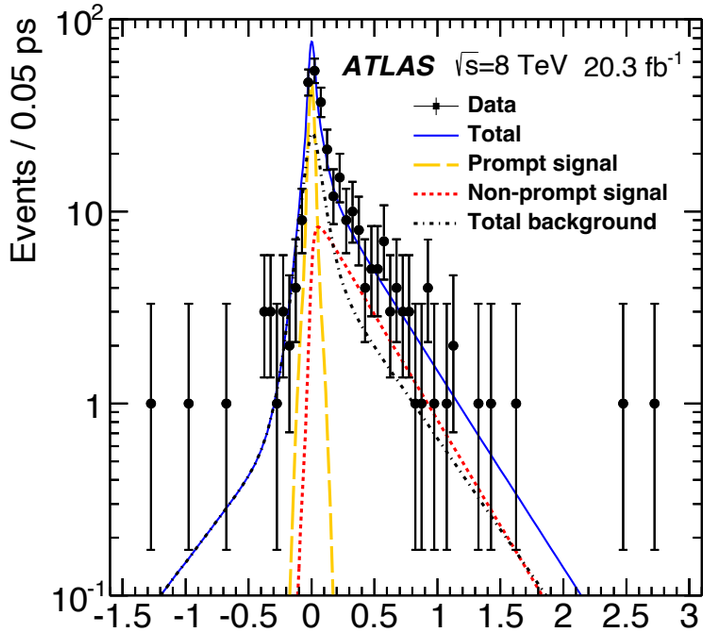
- $p_T^{\text{trigger } \ell} > 25$ GeV, $p_T^{\text{sub-leading } \ell} > 15$ GeV,
- $|\eta^{\ell}| < 2.5$, $|m^Z - 91.1876| < 10$ GeV

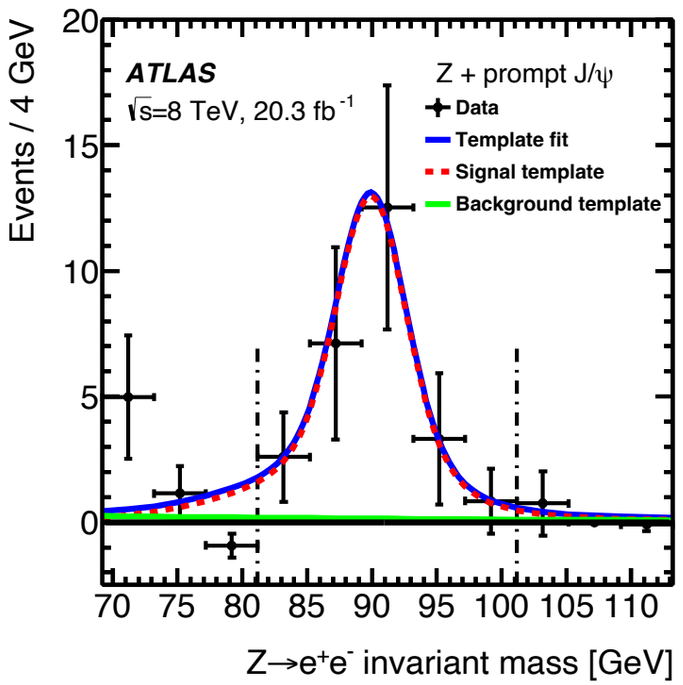
J/ψ:

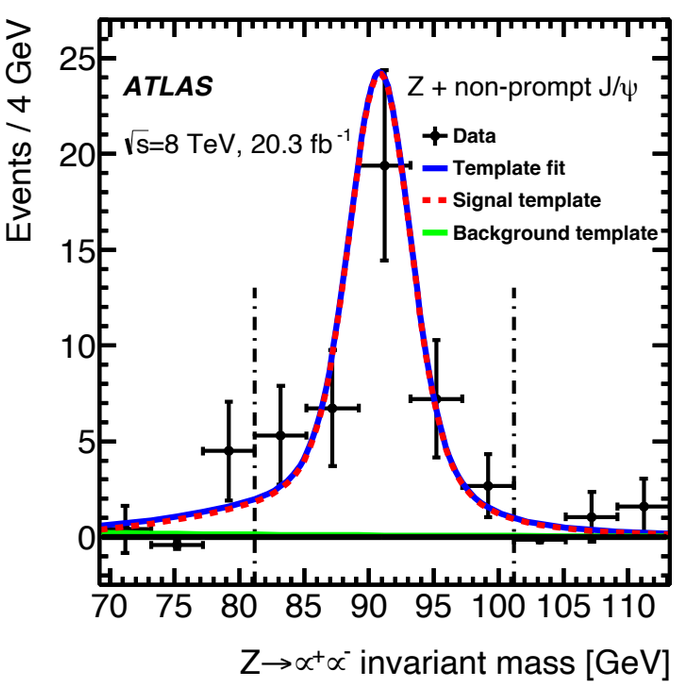
- $2.6 < m^{J/\psi} < 3.6$ GeV
- $8.5 < p_T^{J/\psi} < 100$ GeV, $|y_{J/\psi}| < 2.1$
- $p_T(\text{leading } \mu) > 4$ GeV, $|\eta(\text{leading } \mu)| < 2.5$
- Either $p_T(\text{sub-leading } \mu) > 2.5$ GeV, $1.3 \leq |\eta(\text{sub-leading } \mu)| < 2.5$
- Or $p_T(\text{sub-leading } \mu) > 3.5$ GeV, $|\eta(\text{sub-leading } \mu)| < 1.3$

Pseudo-proper time: $\tau = \dfrac{L_{xy} m^{J/\psi}}{p_T^{J/\psi}}$







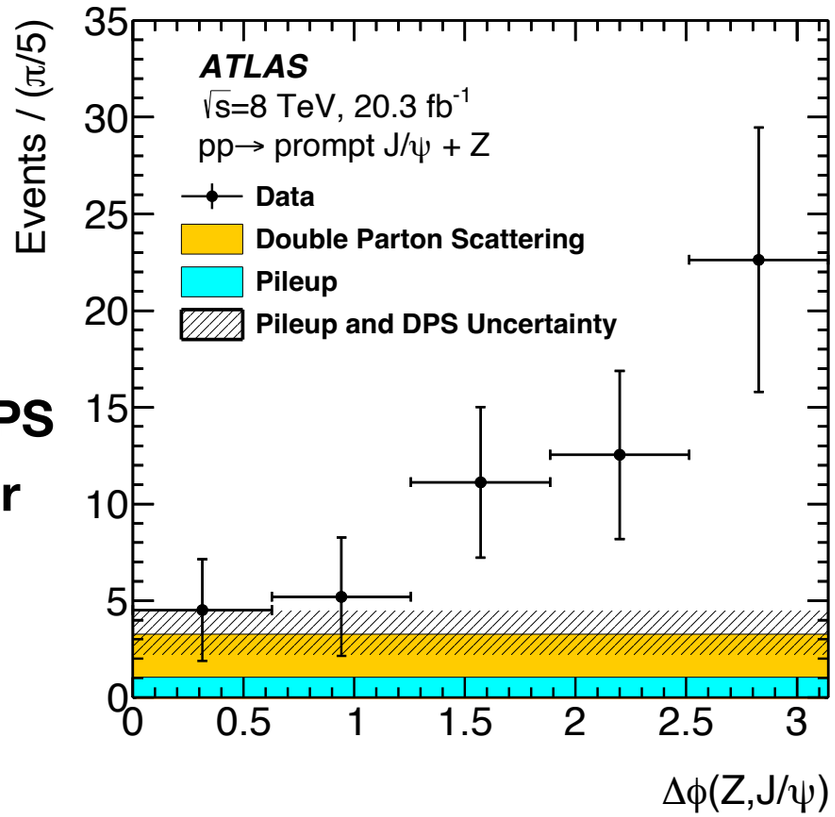


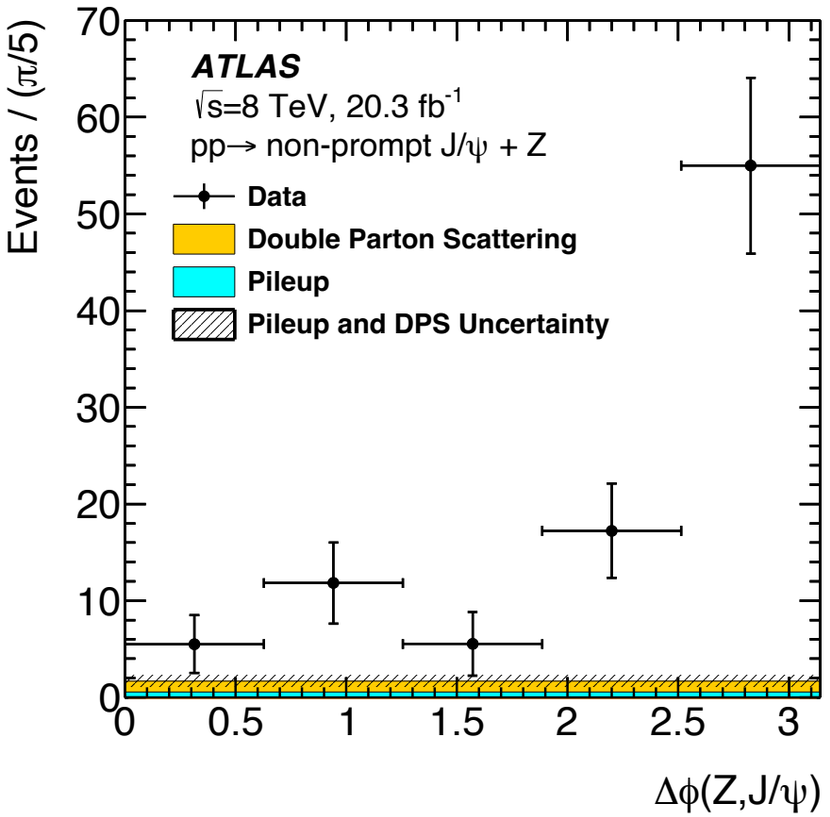
$Z + J/\psi$ study

Eur. Phys. J. C 75 (2015) 229

- For a collision where a Z boson is produced, the probability that a J/ψ is produced in addition due to a second hard process is $P_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{\text{eff}}$
  - $\sigma_{J/\psi}$ is taken from ATLAS J/ψ cross-section measurement
  - σ_{eff} is taken to be $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{sys.})$ mb according to ATLAS measurement in W+2-jet events

$11.1^{+5.7}_{-5.0}$ **DPS events for prompt**



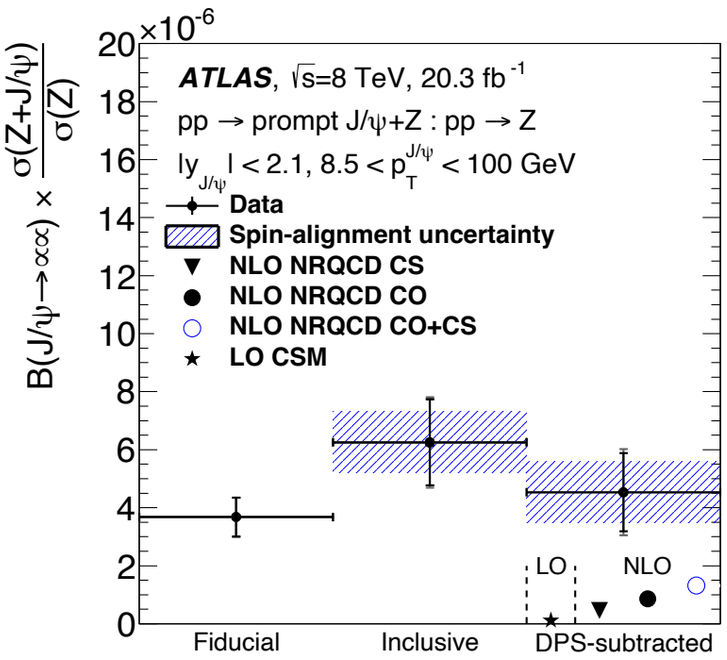


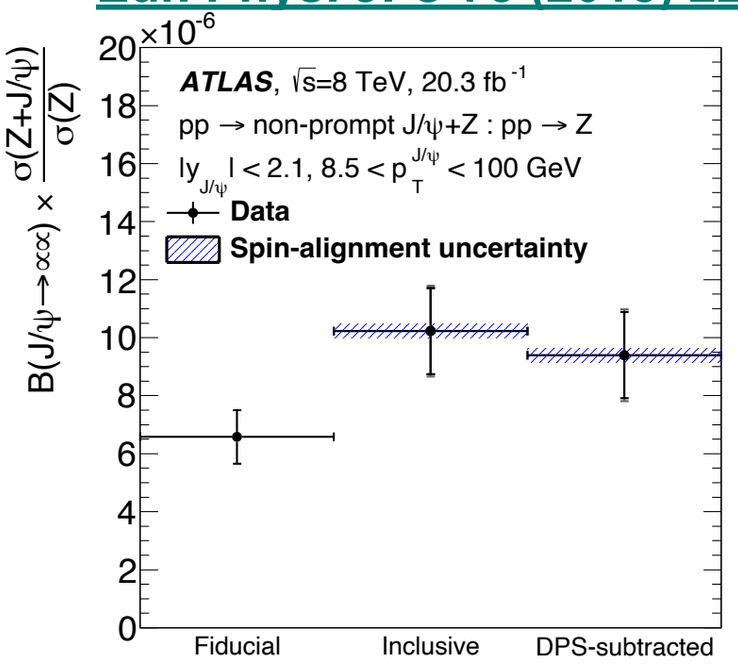
$5.8^{+2.8}_{-2.6}$ **DPS events for non-prompt**

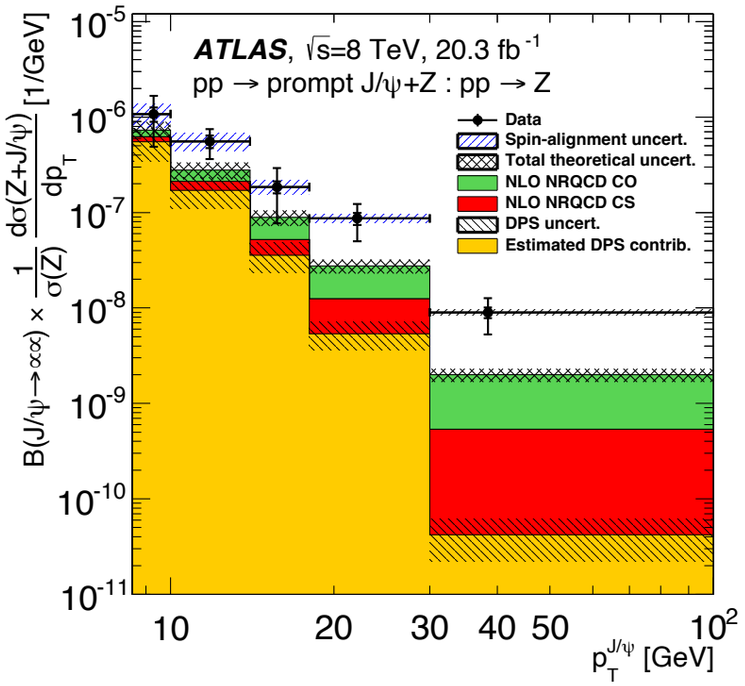
$Z + J/\psi$ study

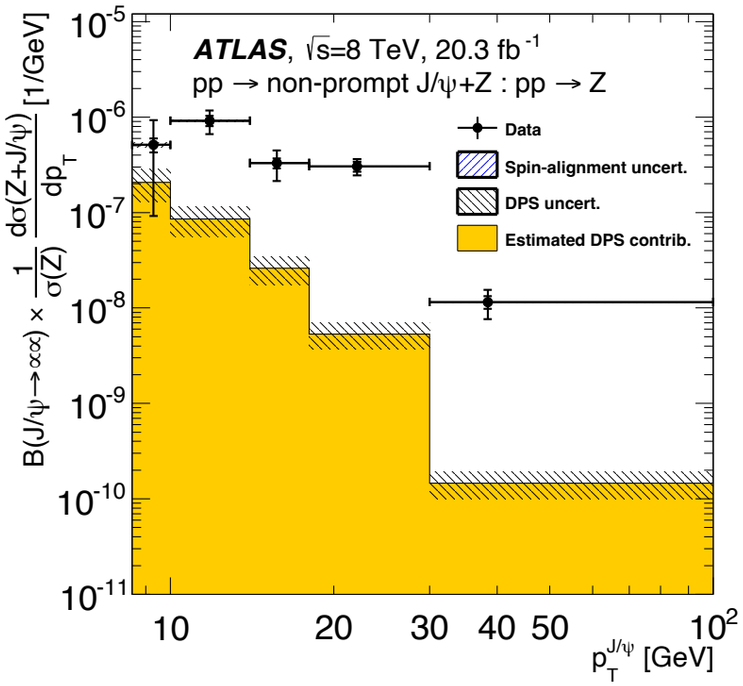
- For prompt and non-prompt production, the cross-section ratios were measured for $8.5 < p_T^{J/\psi} < 100$ GeV and $|y_{J/\psi}| < 2.1$
- Production of a $J/\psi \to \mu^+\mu^-$ meson in association with a Z boson occurs approximately 10 times per million Z boson
- The inclusive differential cross-section ratio is measured as a function of J/ψ p_T for both prompt and non-prompt
  - The observed p_T dependence is signifiantly harder than the inclusive J/ψ production [Nucl. Phys. B 850, 387–444 (2011)]
- For prompt, it's compared to NLO colour-singlet and colour-octet predictions
  - CO contribution is larger than CS by a factor of ~2, and becomes increasingly dominant for higher p_T

[Eur. Phys. J. C 75 (2015) 229]









$W + J/\psi$ study

JHEP 01 (2020) 095

- Study DPS in the production of prompt J/ψ ($\rightarrow \mu^+\mu^-$) in association with a W boson ($\rightarrow \mu\nu$)
- Dataset: 20.3 fb^{-1} @ 8 TeV collected

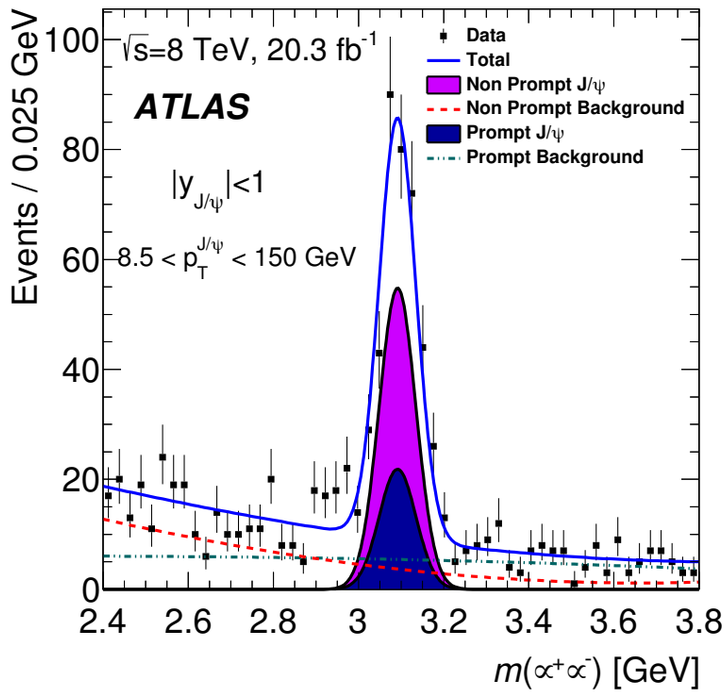
W boson

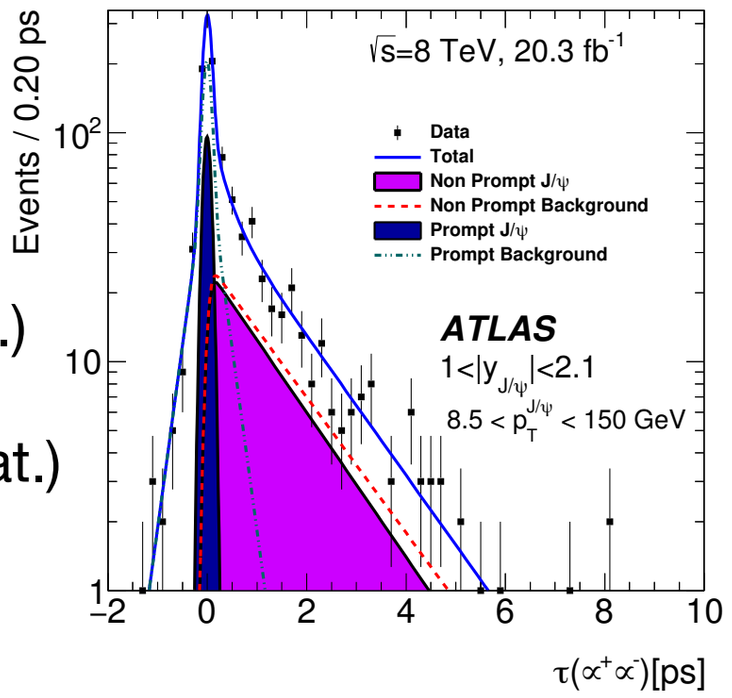
$W^{\pm}$ boson selection
At least one isolated muon that originates < 1 mm from primary vertex along z-axis
p_{T} (trigger muon) > 25 GeV
$\lvert\eta^{\mu}\rvert < 2.4$
Missing transverse momentum > 20 GeV
$m_{\mathrm{T}}(W^{\pm}) > 40$ GeV
$\lvert d_0\rvert/\sigma_{d_0} < 3$

J/ψ

J/ψ selection
$2.4 < m(\mu^+\mu^-) < 3.8$ GeV
$8.5 < p_{\mathrm{T}}^{J/\psi} < 150$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$
$p_{\mathrm{T}}^{\mu_1} > 4$ GeV, $\lvert\eta^{\mu_1}\rvert < 2.5$
either $p_{\mathrm{T}}^{\mu_2} > 2.5$ GeV, $1.3 \le \lvert\eta^{\mu_2}\rvert < 2.5$ or $p_{\mathrm{T}}^{\mu_2} > 3.5$ GeV, $\lvert\eta^{\mu_2}\rvert < 1.3$

- Prompt signal yields:
  - $\lvert y_{J/\psi}\rvert$<1: 91 ± 14 (stat.)
  - 1<$\lvert y_{J/\psi}\rvert$: 102 ± 17 (stat.)





$W + J/\psi$ study

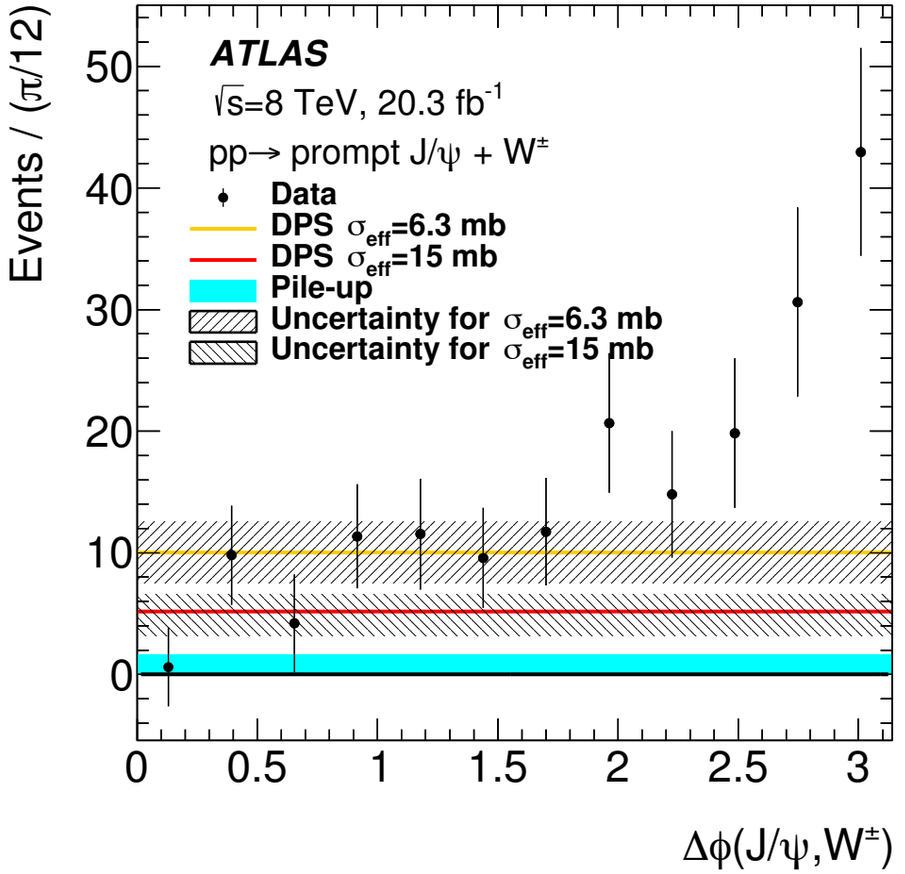
JHEP 01 (2020) 095

- Based on the assumption that the two hard scatters are uncorrelated, the probability that a J/ψ is produced by a second hard process in an event containing a W boson is:

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

- As it's unclear which σ_{eff} value to use, two values are chosen:
  - $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{sys.})$ mb from W+2-jet events
  - $\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{sys.})$ mb from prompt J/ψ pair production

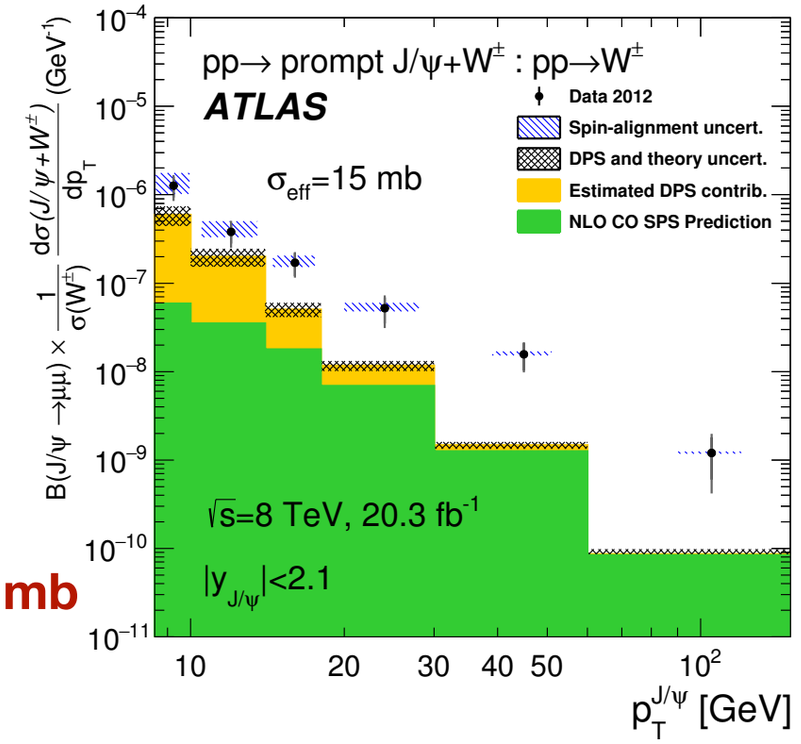
- The estimated DPS fraction among inclusive signal yield is between $(31^{+9}_{-12})\%$ ($\sigma_{\text{eff}} = 15$ mb) and $(75 \pm 23)\%$ ($\sigma_{\text{eff}} = 6.3$ mb)
- $\Delta\phi(J/\psi, W)$ distribution is measured with estimated DPS contribution
  - DPS component should almost be flat, while SPS events peak at $\Delta\phi \approx \pi$ due to momentum conservation
  - Both values of σ_{eff} are consistent with the data at low $\Delta\phi$



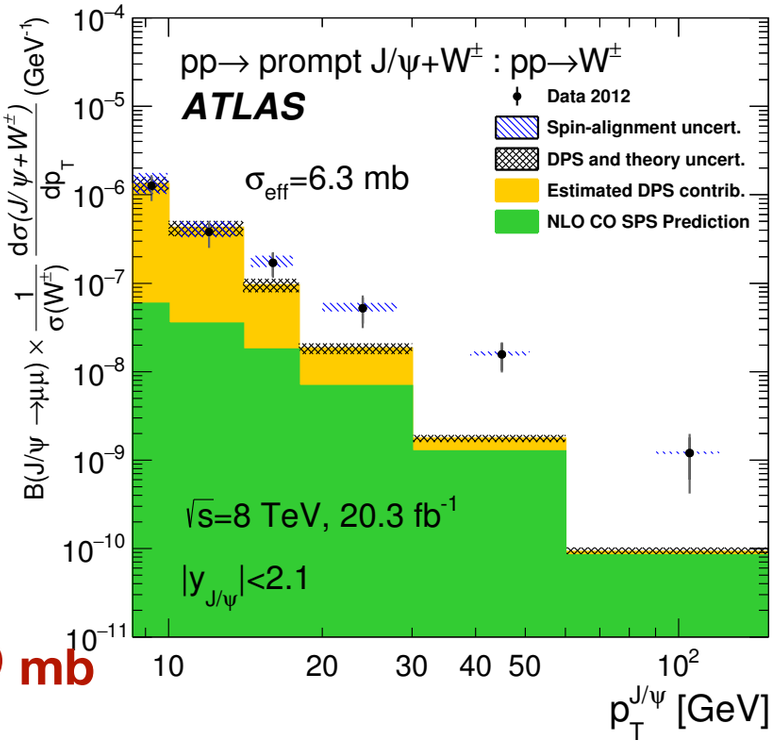
$W + J/\psi$ study

[JHEP 01 (2020) 095]

- Cross-section ratios ($R_{J/\psi}$) are measured in the region $8.5 < p_T^{J/\psi} < 150$ GeV and $|y_{J/\psi}|$<2.1
- **Fiducial** (in the J/ψ fiducial region):
  $R_{J/\psi}^{\text{fid}} = (2.2 \pm 0.3 \pm 0.7) \times 10^{-6}$
- **Inclusive** (with J/ψ acceptance and the unknown J/ψ spin-alignment taken into account):
  $R_{J/\psi}^{\text{incl}} = (5.3 \pm 0.7 \pm 0.8^{+1.5}_{-0.7}) \times 10^{-6}$
- **DPS subtracted**:
  - $R_{J/\psi}^{\text{DPSsub}} = (3.6 \pm 0.7^{+1.1\ +1.5}_{-1.0\ -0.7}) \times 10^{-6}$,
    $[\sigma_{\text{eff}} = 15^{+5.8}_{-4.2}$ mb$]$
  - $R_{J/\psi}^{\text{DPSsub}} = (1.3 \pm 0.7 \pm 1.5^{+1.5}_{-0.7}) \times 10^{-6}$,
    $[\sigma_{\text{eff}} = 6.3 \pm 1.9$ mb$]$
- Neither value of σ_{eff} is able to correctly model the J/ψ p_T dependence



$\sigma_{\text{eff}} = 15^{+5.8}_{-4.2}$ **mb**



$\sigma_{\text{eff}} = 6.3 \pm 1.9$ **mb**

Summary

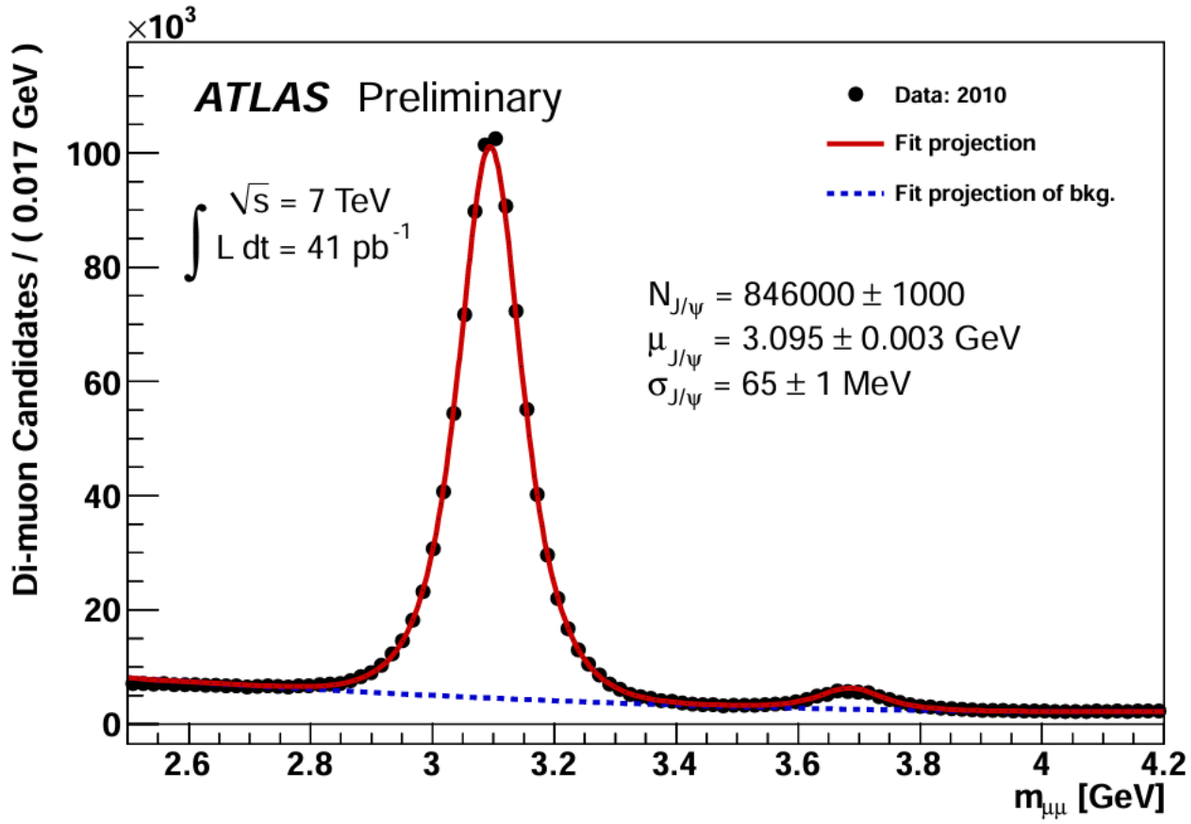
- DPS contribution with ATLAS Run 1 data are studied in various processes:
  - W($\rightarrow \ell\nu$) + 2-jet
  - Four-jet
  - Four-lepton
  - Prompt J/ψ pair
  - $Z + J/\psi$ (prompt and non-prompt)
  - $W + J/\psi$
- The measured values of σ_{eff} are consistent within uncertainties
- New measurements with Run 2 data are on-going: stay tuned!

Thanks

BACKUP

Bphys di-muon trigger

- Dimuon invariant mass around the J/ψ mass based on the full sample collected in 2010 using single- and di-muon triggers



W($\rightarrow \ell\nu$) + 2-jet study

Table 1. Summary of the fractional uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$.

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

- Various systematic sources are considered
  - The systematic uncertainty of pileup has the largest impact

New J. Phys. 15 (2013) 033038

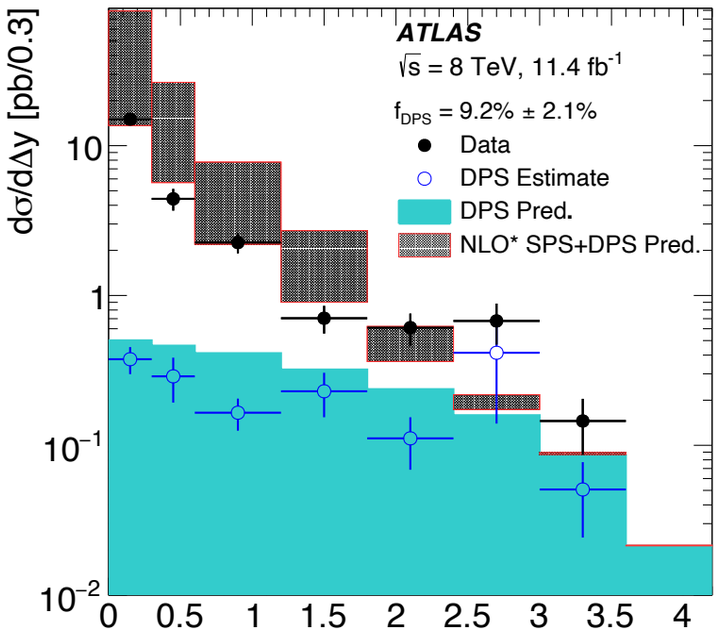
Four-jet study

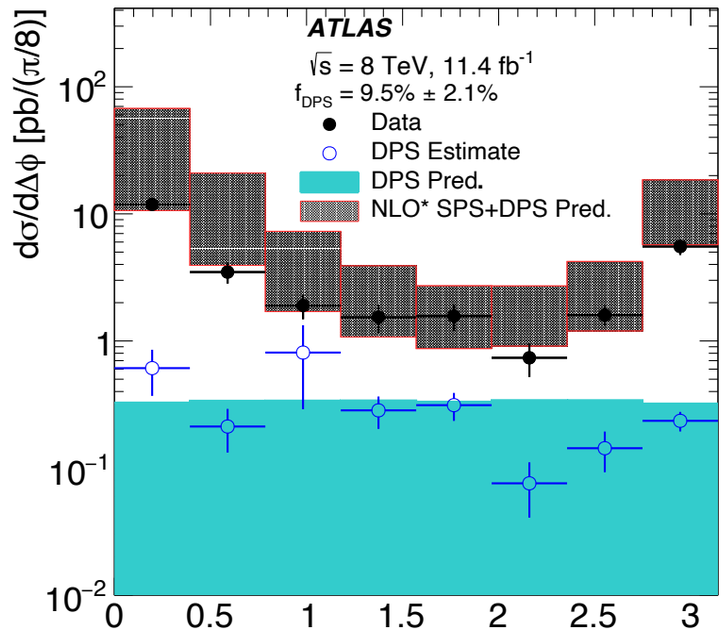
JHEP 11 (2016) 110

- Summary of the relative systematic uncertainties in f_{DPS}, α_{2j}^{4j} and σ_{eff}

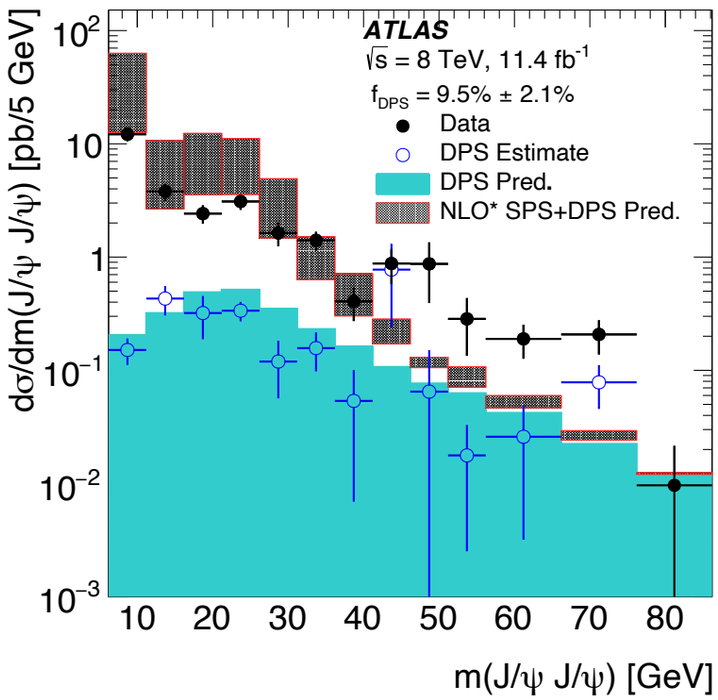
Source of systematic uncertainty	Δf_{DPS}	$\Delta\alpha_{2\mathrm{j}}^{4\mathrm{j}}$	$\Delta\sigma_{\mathrm{eff}}$
Luminosity			$\pm 3.5\,\%$
Model dependence for detector corrections		$\pm 2\,\%$	$\pm 2\,\%$
Reweighting of AHJ	$\pm 6\,\%$		$\pm 6\,\%$
Jet reconstruction efficiency			$\pm 0.1\,\%$
Single-vertex 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	$^{+36}_{-40}\,\%$	$\pm 13\,\%$	$^{+35}_{-25}\,\%$

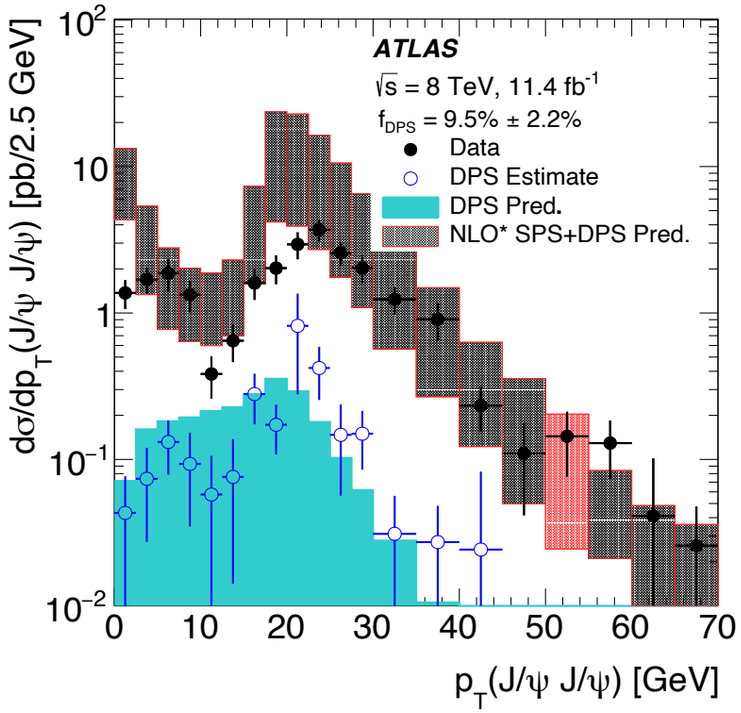
di-J/ψ study





- DPS predictions are normalised to measured f_{DPS}
- NLO SPS is scaled by 1.85 to account for feed-down





- Data deviates from NLO*SPS+DPS prediction at large Δy, large invariant mass and low p_T regions

Eur. Phys. J. C 77 (2017) 76

di-J/ψ study

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

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$Z + J/\psi$ study

Eur. Phys. J. C 75 (2015) 229

Source	Prompt		Non-prompt	
	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$
Fit procedure	3 %	3 %	4%	8%
Z boson kinematics	1%	1%	1%	1%
$\mu_{J/\psi}$ efficiency	1%	1%	1%	1%
Vertex separation	7%	16%	2%	15%

Process	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	Total	
			Events found	From pileup
Prompt signal	$24 \pm 6 \pm 2$	$32 \pm 8 \pm 5$	$56 \pm 10 \pm 5$	$5.2^{+1.8}_{-1.3}$
Non-prompt signal	$54 \pm 9 \pm 3$	$41 \pm 8 \pm 7$	$95 \pm 12 \pm 8$	$2.7^{+0.9}_{-0.6}$
Background	$61 \pm 11 \pm 6$	$77 \pm 13 \pm 7$	$138 \pm 17 \pm 9$	

$W + J/\psi$ study

JHEP 01 (2020) 095

Source of Uncertainty	Uncertainty [%]	
	$\lvert y_{J/\psi}\rvert < 1$	$1 < \lvert y_{J/\psi}\rvert < 2.1$
J/ψ mass fit	8.7	4.9
Vertex separation	12	15
$\mu_{J/\psi}$ efficiency	2.0	1.6
Pile-up	1.1	1.4
$J/\psi + Z$ and $J/\psi + W^{\pm}(\rightarrow \tau^{\pm}\nu)$	3.5	4.8
Efficiency correction	2.3	2.3