Studies of double parton scattering with the ATLAS detector

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Introduction

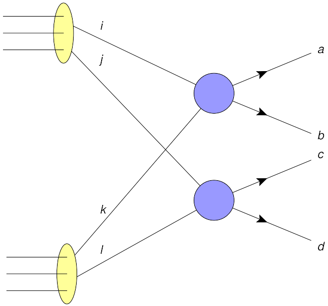
Four measurements performed in ATLAS:

Final state	Publication
$W^{\pm}$ + 2 jets	New J.Phys. 15 (2013) 033038
$W^{\pm} + J/\psi$ (prompt J/ψ production)	JHEP 1404 (2014) 172
$Z + J/\psi$ (prompt and non-prompt)	Eur.Phys.J. C75 (2015) 229
Four-jet	ATLAS-CONF-2015-058

Use phenomenological formula for DPS,

$$\hat{\sigma}^{\mathrm{DPS}}_{(\mathrm{A},\mathrm{B})} = \frac{1}{1+\delta_{\mathrm{AB}}} \frac{\hat{\sigma}_{\mathrm{A}} \hat{\sigma}_{\mathrm{B}}}{\sigma_{\mathrm{eff}}} ,$$

$$\Longrightarrow \quad \sigma_{\mathrm{eff}} = \frac{1}{1+\delta_{\mathrm{AB}}} \frac{\hat{\sigma}_{\mathrm{A}} \hat{\sigma}_{\mathrm{B}}}{f_{\mathrm{DPS}} \cdot \hat{\sigma}^{\mathrm{tot}}_{(\mathrm{A},\mathrm{B})}} .$$



The parameter σ_{eff} is,

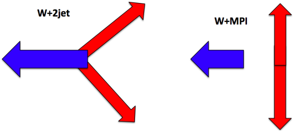
- ☞ a parton-level quantity;
- ☞ scaling parameter for the prob. of a hard secondary scatter;
- ☞ assumed to be process and cut independent;
- ☞ no dependence on $\sqrt{s}$ observed (considering uncertainties);
- ☞ Measured to be 20-30% of σ_{inel}.

DPS in $W^\pm + 2$j

New J.Phys. 15 (2013) 033038

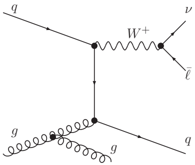
- Use data collected during 2010 ($\sqrt{s} = 7$ TeV, 36 pb^{-1}).
- **Jets selection:**
  - anti-$k_\perp$ jets ($R = 0.4$);
  - transverse momentum $p_\mathrm{T} > 20$ GeV, rapidity $|y| < 2.8$.
- $W^\pm$ **boson selection:**
  - 1 lepton (e, μ) with $p_\mathrm{T} > 20$ GeV, $|\eta| < 2.4$;
  - missing transverse energy, $E_\mathrm{T}^\mathrm{miss} > 25$ GeV;
  - transverse mass $m_\mathrm{T} > 40$ GeV.

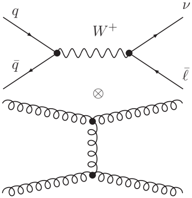
Schematic representation in the transverse plane



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

- Extract f_DPS by performing a fit to the distribution of $\Delta^\mathrm{n}_\mathrm{jets}$ in data of templates A and B of the form $(1 - f_\mathrm{DPS}) \cdot A + f_\mathrm{DPS} \cdot B$.
  - **Template *A* - no DPS:** ALPGEN + HERWIG + JIMMY (AHJ) sample of SPS $W^\pm + 2$ jets, $p_\mathrm{T}^\mathrm{max} = 15$ GeV.
  - **Template *B* - Dijets:** Dijet sample extracted from data.



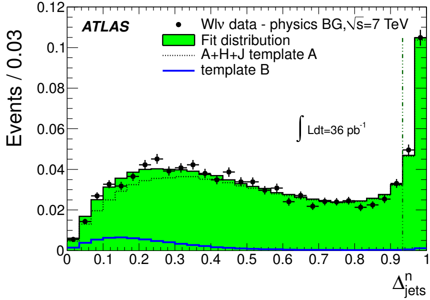


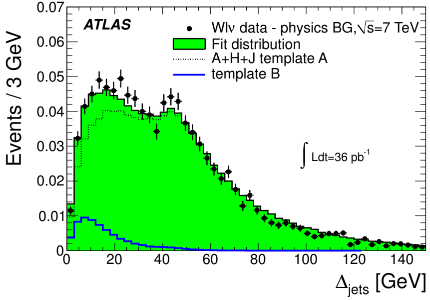
DPS in $W^{\pm} + 2j$

New J.Phys. 15 (2013) 033038

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

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





Systematic source	Δf_{DPS} [%]	$\Delta\sigma_{\text{eff}}$ [%]
Luminosity		3
Background & lepton	11	3
Theory	10	24
Pile-up	13	
Jet energy scale	12	
Jet energy resolution	8	
Total systematic	24	$^{+33}_{-20}$
Total statistical	17	17

Results

$$f_{\text{DPS}} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{syst.})$$

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

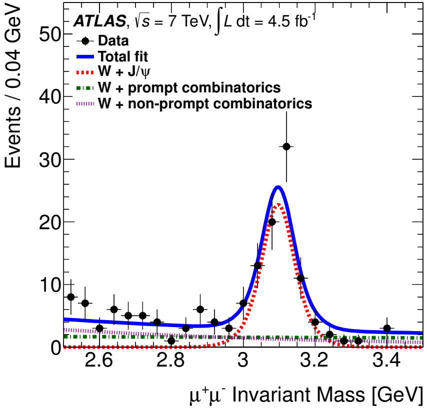
DPS in $W^{\pm} + J/\psi$

JHEP 1404 (2014) 172

First observation of $W^{\pm}$ $(\rightarrow \mu\nu_{\mu})$ + prompt J/ψ $(\rightarrow \mu^{+}\mu^{-})$ in hadronic collisions.

- Use data collected during 2011 ($\sqrt{s} = 7$ TeV, 4.5 fb^{-1}).
- Data collected using single-muon trigger $p_{\mathrm{T}} > 18$ GeV.
- **$W^{\pm}$ boson selection:**
  - 1 μ with $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.4$, matching trigger μ;
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $m_{\mathrm{T}} > 40$ GeV;

- **J/ψ selection:**
  - 2 oppositely charged μ;
  - $|\eta_{\mu}| < 2.5$;
  - $p_{\mathrm{T}}(\mu_1) > 4$ GeV;
  - $p_{\mathrm{T}}(\mu_2) > 3.5$ GeV for $|\eta(\mu_2)| < 1.3$;
  - $p_{\mathrm{T}}(\mu_2) > 2.5$ GeV for $|\eta(\mu_2)| > 1.3$;
  - $2.5 < m_{\mu^{+}\mu^{-}} < 3.5$ GeV;
  - $8.5 < p_{\mathrm{T}}^{J/\psi} < 30$ GeV;
  - $|y_{J/\psi}| < 2.1$;



Number of $W^{\pm}$ + prompt J/ψ events

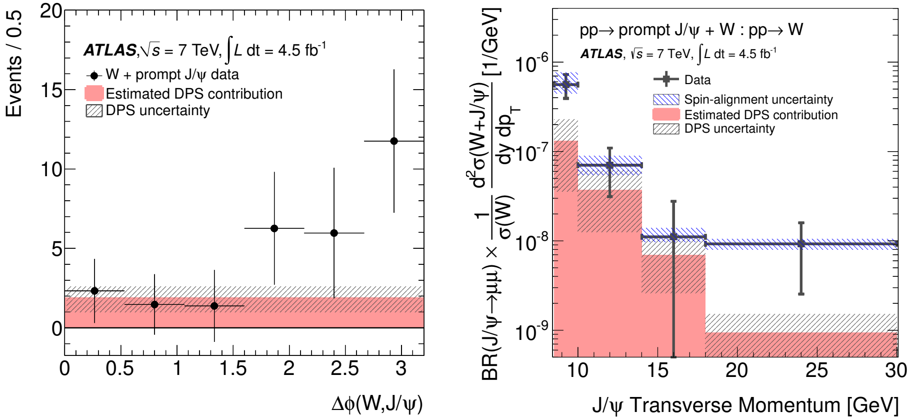
In total $N_{\mathrm{signal}} = 29.2^{+7.5}_{-6.5}$ (5.1σ)

DPS in $W^\pm + J/\psi$

JHEP 1404 (2014) 172

The final state $W^\pm + J/\psi$ can be produced in a DPS.

- Uniform $\Delta\phi(W, J/\psi)$ distribution expected for DPS.
- Following the usual ansatz, $\mathrm{P}_{J/\psi|W^\pm} = \sigma_{J/\psi}/\sigma_{\mathrm{eff}}$.
- Use σ_{eff} from $W^\pm + 2\mathrm{j}$ measurement to estimate DPS contribution $\Rightarrow 38^{+22}_{-20}\%$.



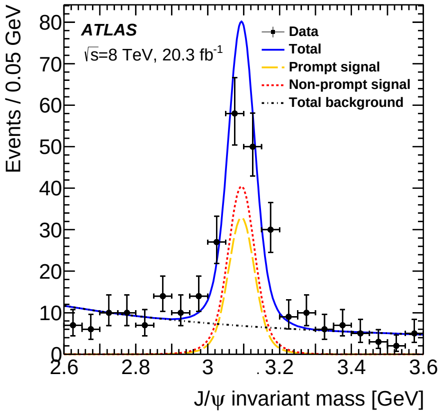
DPS in $Z + J/\psi$

Eur.Phys.J. C75 (2015) 229

First measurement of associated $Z + J/\psi$ production, prompt and non-prompt.

- Use data collected during 2012 ($\sqrt{s} = 8$ TeV, 20.3 fb^{-1}).
- Data collected using single-lepton trigger $p_T > 24$ GeV.
- **Z boson selection:**
  - 2 oppositely charged $\ell^{\pm}$ with $p_T > 15$ GeV, $|\eta| < 2.5$, one matching trigger $\ell^{\pm}$;
  - $m_{\ell^+\ell^-}$ within 10 GeV of m^Z_{PDG}.

- **J/ψ selection:**
  - 2 oppositely charged μ;
  - $|\eta_\mu| < 2.5$;
  - $p_T(\mu_1) > 4$ GeV;
  - $p_T(\mu_2) > 3.5$ GeV for $|\eta(\mu_2)| < 1.3$;
  - $p_T(\mu_2) > 2.5$ GeV for $|\eta(\mu_2)| > 1.3$;
  - $2.5 < m_{\mu^+\mu^-} < 3.5$ GeV;
  - $8.5 < p_T^{J/\psi} < 30$ GeV;
  - $|y_{J/\psi}| < 2.1$;

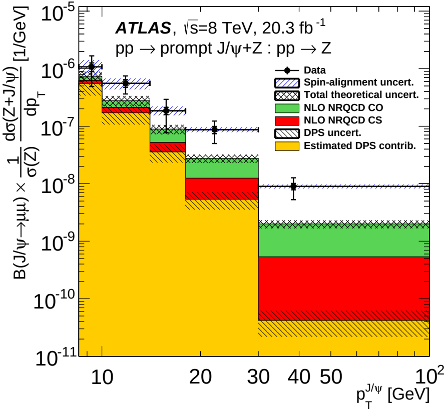


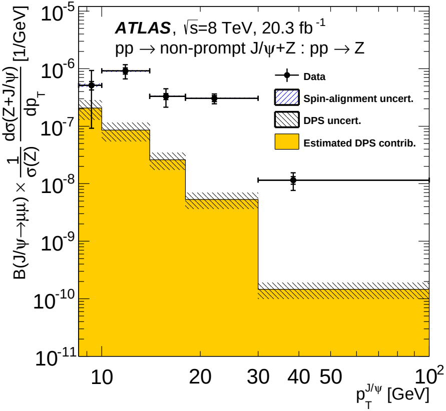
DPS in $Z + J/\psi$

Eur.Phys.J. C75 (2015) 229

The final state $Z + J/\psi$ can be produced in a DPS.

- Following the usual ansatz, $\mathrm{P}_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{\mathrm{eff}}$.
- Use σ_{eff} from $W^{\pm} + 2\mathrm{j}$ measurement to estimate DPS contribution
  $\Rightarrow (29 \pm 9)\%$ for prompt and $(8 \pm 2)\%$ for non-prompt.

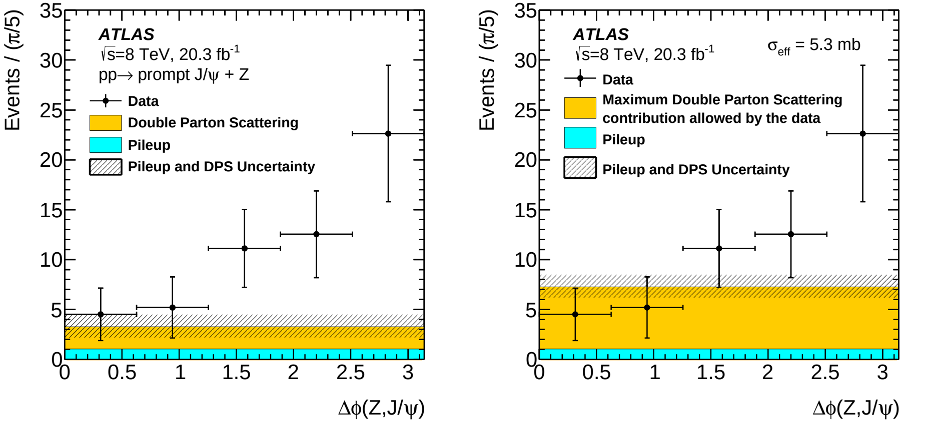




DPS in $Z + J/\psi$

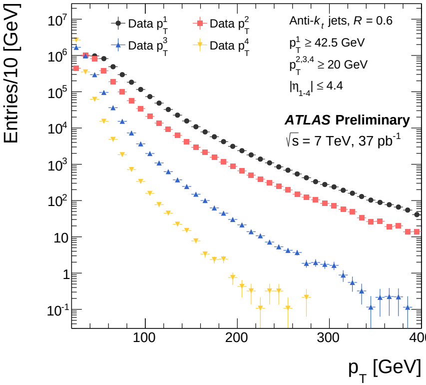
Eur.Phys.J. C75 (2015) 229

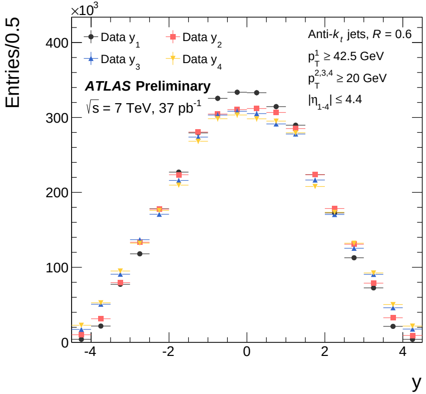
- Uniform $\Delta\phi(Z, J/\psi)$ distribution expected for DPS.
- Assume all observed signal in $\Delta\phi(Z, J/\psi) < \pi/5$ is due to DPS
  $\Rightarrow$ Extract lower limit for σ_{eff} from $\Delta\phi(Z, J/\psi)$ distribution - 5.3 mb at 68% CL.



DPS in four jet events

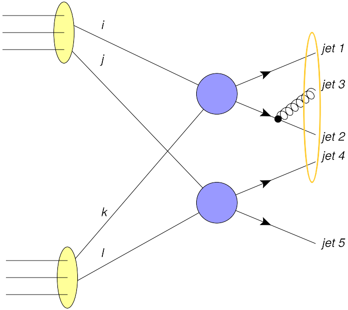
- Data collected during 2010, $\mathcal{L} = 37.3\ \mathrm{pb}^{-1}$ and $\langle\mu\rangle = 0.41$;
- single-vertex events ($N_{PV} = 1$);
- use anti-$k_\perp$, $R = 0.6$, jets in pseudo-rapidity range, $|\eta| \leq 4.4$;
- four-jet kinematic cuts, $p_T^1 \geq 42.5$, $p_T^{2,3,4} \geq 20\ \mathrm{GeV}$ (due to trigger conditions);
- different kinematic cuts for dijet samples to match four-jet cuts,
  - A - $p_T^{1,2} \geq 20\ \mathrm{GeV}$ ► B - $p_T^1 > 42.5$, $p_T^2 \geq 20\ \mathrm{GeV}$;





Classifying events in the MC - match jets to partons

- Template fit to determine f_{DPS} as in the $W^{\pm} + 2\mathrm{j}$ measurement.
- Use event record of AHJ to assign partons to primary or secondary interaction.
- Match jets to outgoing partons from the interactions.
- Jet matched to closest parton with $p_{\mathrm{T}}^{\mathrm{parton}} \geq 15\ \mathrm{GeV}$ and $\Delta R_{\mathrm{parton-jet}} \leq 1.0$.
- Take into account $\mathrm{semi\text{-}DPS}$ events $\Longrightarrow f_{\mathrm{DPS}} = f_{\mathrm{cDPS}} + f_{\mathrm{sDPS}}$.

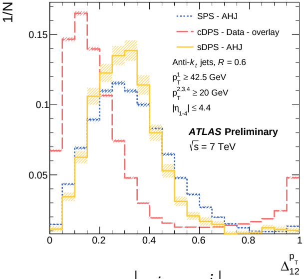


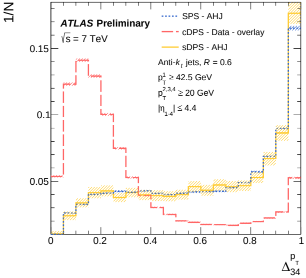
SPS	semi-DPS	complete-DPS
no jets match secondary-scatter parton.	**1** jet matches secondary-scatter parton.	**2** jets match secondary-scatter parton.

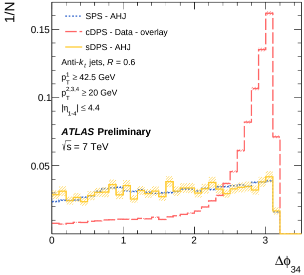
Differentiating variables

Look for differentiating variable,

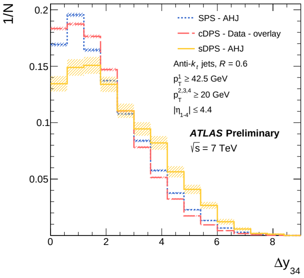
SPS - AHJ
cDPS - Data - overlay
sDPS - AHJ







- $\Delta_{ij}^{p_T} = \frac{\left|\vec{p}_T^{\,i} + \vec{p}_T^{\,j}\right|}{p_T^i + p_T^j}$, $\Delta\phi_{ij} = |\phi_i - \phi_j|$, $\Delta y_{ij} = |y_i - y_j|$.
- Strong correlations between the variables are observed.
- No variable differentiates between all three samples.
- Pairing can be ambiguous - all variables are important.



complete-DPS

- Overlaid dijet pairs from data.
- Require non-overlapping jets.

How to classify events in data?

We train a Neural Network to distinguish between SPS, cDPS and sDPS topologies using the following samples:

SPS

- Multi-jet events generated with AHJ.
- Match partons to jet to select SPS events.

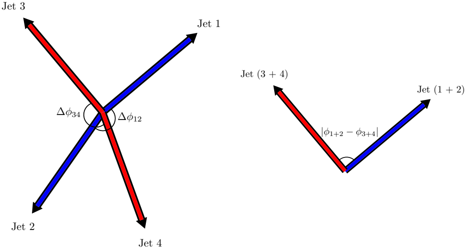
complete-DPS

- Overlaid dijet pairs from data.
- Require non-overlapping jets.

semi-DPS

- Multi-jet events generated with AHJ.
- Match partons to jet to select sDPS events.

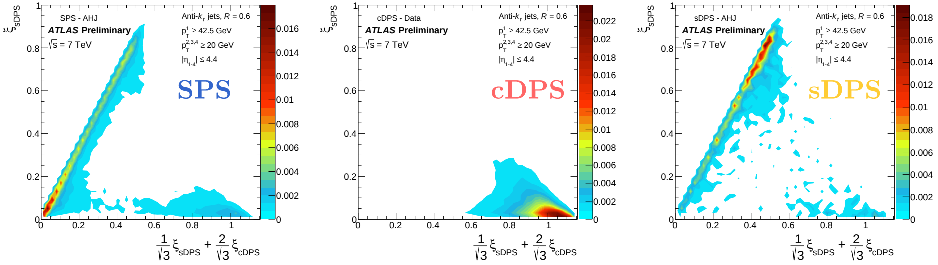
- Use 21 input variables in total (selected based on expected correlations and PCA):
  - $\Delta_{ij}^{p_{\mathrm{T}}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\,i} + \vec{p}_{\mathrm{T}}^{\,j}\right|}{p_{\mathrm{T}}^{i} + p_{\mathrm{T}}^{j}}$
  - $\Delta\phi_{ij} = |\phi_i - \phi_j|$
  - $\Delta y_{ij} = |y_i - y_j|$
  - $|\phi_{i+j} - \phi_{k+l}|$



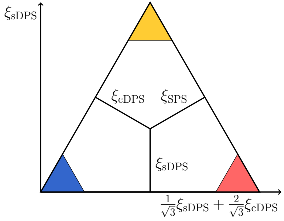
NN output in the SPS, cDPS and sDPS samples

NN provides three outputs ("probabilities") for each event, ξ_{SPS}, ξ_{cDPS} and ξ_{sDPS}.

$0 \leq \xi_i \leq 1$, $\xi_{\mathrm{SPS}} + \xi_{\mathrm{cDPS}} + \xi_{\mathrm{sDPS}} = 1 \Rightarrow$ plot on 2D Dalitz plot.

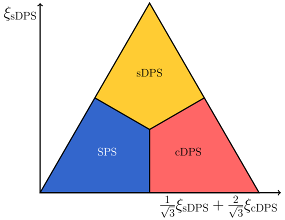


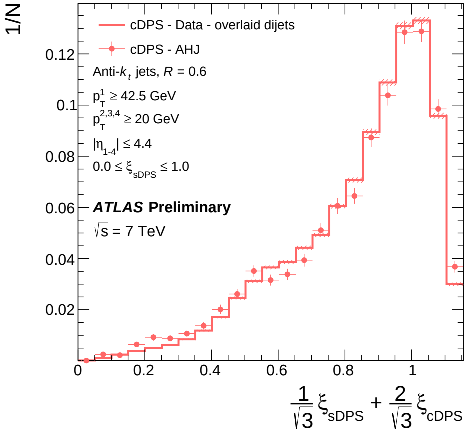
- The separation between cDPS and the others is quite good.
- Some overlap between SPS and cDPS is observed.
- Separation between SPS and sDPS is harder (expected).



Compare overlaid dijets and cDPS in AHJ

- Test the topology of overlaid dijets from data by comparing to cDPS events extracted from AHJ.
- Compare the NN output distribution (projected on x-axis) of both samples since it encompasses the topology of all four jets.
- Advantage of using overlaid dijets from data ⇒ smaller jet energy scale uncertainty.



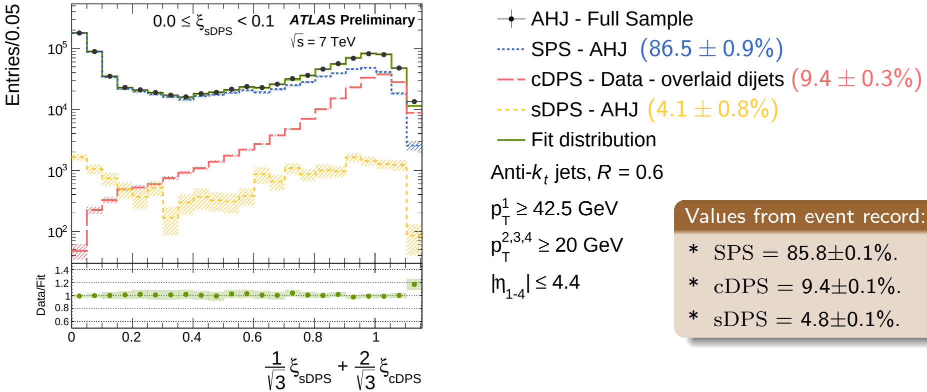


Overlaid dijets

- Resonable agreement observed.
- Topology well represented.

Validation

- Apply NN to the AHJ sample and perform a 2D fit of the form,
  $f_{\mathrm{cDPS}} \cdot H_{\mathrm{cDPS}} + f_{\mathrm{sDPS}} \cdot H_{\mathrm{sDPS}} + (1 - f_{\mathrm{cDPS}} - f_{\mathrm{sDPS}}) \cdot H_{\mathrm{SPS}}$.
- Visualize fit result by dividing the triangle into five slices (ξ_{sDPS} ranges).
- Compare extracted values of f_{cDPS} and f_{sDPS} to the fractions in AHJ extracted from the event record.



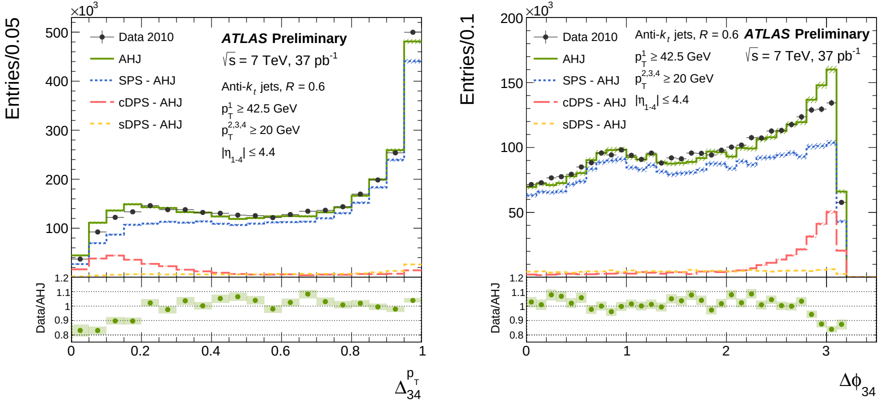
Values from event record:

* $\mathrm{SPS} = 85.8 \pm 0.1\%$.
* $\mathrm{cDPS} = 9.4 \pm 0.1\%$.
* $\mathrm{sDPS} = 4.8 \pm 0.1\%$.

Agreement with fractions in AHJ extracted from the event record is excellent.

Sub-leading dijet distributions in data and AHJ

Sizable discrepancy observed in sub-leading dijet distributions between data and AHJ.

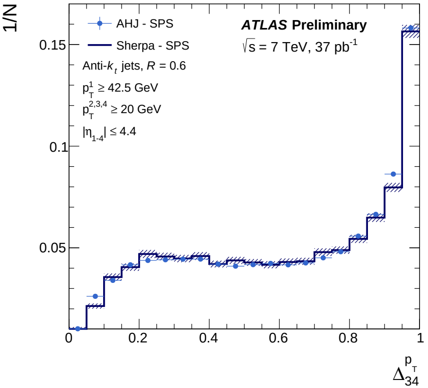


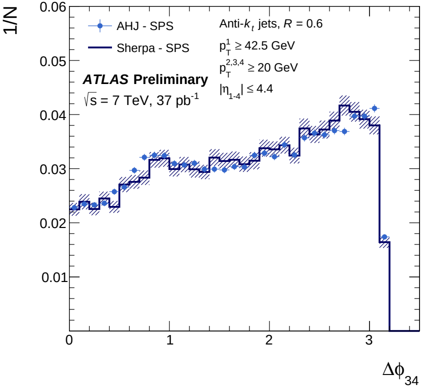
More back-to-back sub-leading dijets in AHJ than in the data. Two sources for this discrepancy are possible,

- a mis-modelling of SPS in AHJ, too many back-to-back dijets;
- the fraction of DPS in AHJ is higher than in the data.

Sub-leading dijet distributions

To test SPS modelling in AHJ, compare SPS from AHJ to SPS from SHERPA,

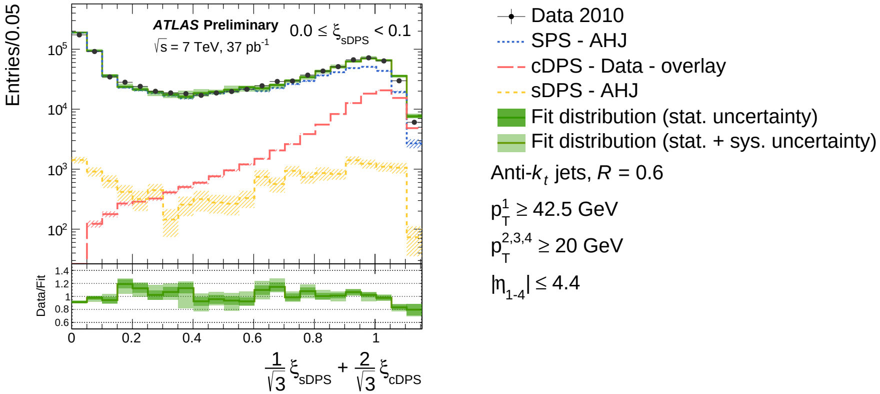




- Even though the SHERPA SPS sample is generated by turning off the MPI completely, the distributions mostly agree.
- This indicates that the second hypothesis, that the DPS fraction in AHJ is higher than in data, is correct.

Extract f_{cDPS} and f_{sDPS} in data

Perform 2D fit to extract the cDPS and sDPS fractions in data,



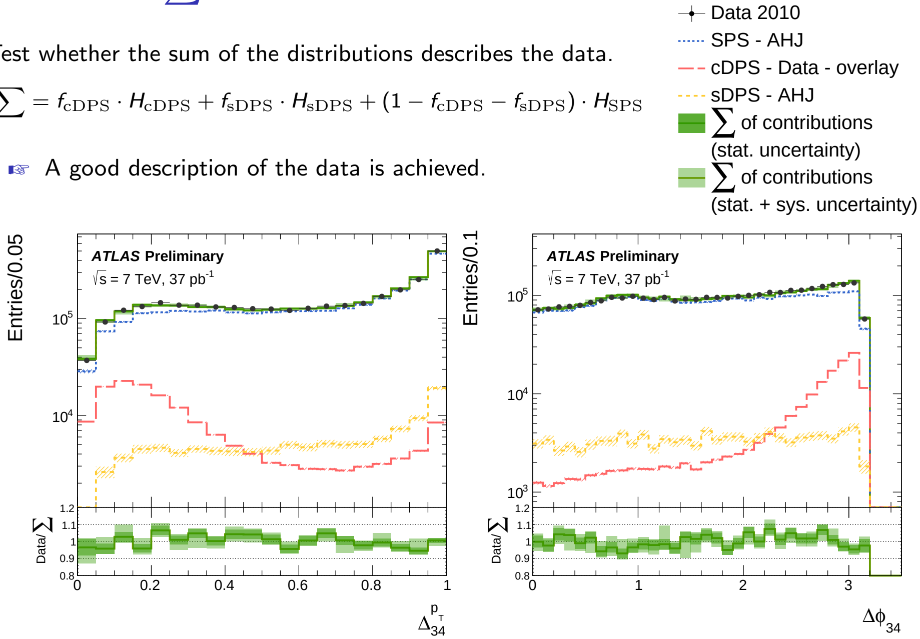
- Only statistical uncertainties participate in the fit.
- Most significant disagreement seen in SPS dominated bins $\Longrightarrow$ negligible effect on the measurement of DPS.
- See backup slides for the rest of the triangle slices.

Does the $\sum$ of contributions describe the data?

Test whether the sum of the distributions describes the data.

$$\sum = f_{\mathrm{cDPS}} \cdot H_{\mathrm{cDPS}} + f_{\mathrm{sDPS}} \cdot H_{\mathrm{sDPS}} + (1 - f_{\mathrm{cDPS}} - f_{\mathrm{sDPS}}) \cdot H_{\mathrm{SPS}}$$

☞ A good description of the data is achieved.



Results

The fractions obtained in data are,

$$f_{\rm cDPS} = 0.052\ ^{+0.002}_{-0.005}\ \text{(stat.)}, \qquad f_{\rm sDPS} = 0.032\ ^{+0.008}_{-0.01}\ \text{(stat.)}\,.$$

Detector corrections for dijet and four-jet events were determined with PYTHIA6 multi-dimensionally re-weighted to data,

$$\alpha^{4j}_{2j} = \frac{\mathcal{C}_{4j}}{\mathcal{C}^{A}_{2j}\mathcal{C}^{B}_{2j}} = 0.94 \pm 0.01\ \text{(stat.)}\ ^{+0.15}_{-0.14}\ \text{(syst.)}\,.$$

Adjust symmetry factor for partial overlap between σ^{A}_{2j} and σ^{B}_{2j},

$$\frac{1}{1+\delta_{AB}} = 1 - \frac{1}{2}\frac{\sigma^{B}_{2j}}{\sigma^{A}_{2j}} = 0.9353 \pm 0.0003\ \text{(stat.)}\,.$$

Insert all to the expression for $\sigma_{\rm eff}$,

$$\sigma_{\rm eff} = \frac{1}{1+\delta_{AB}}\,\frac{\alpha^{4j}_{2j}}{f_{\rm cDPS}+f_{\rm sDPS}}\,\frac{\sigma^{A}_{2j}\sigma^{B}_{2j}}{\sigma_{4j}}\,.$$

Largest sources of uncertainty

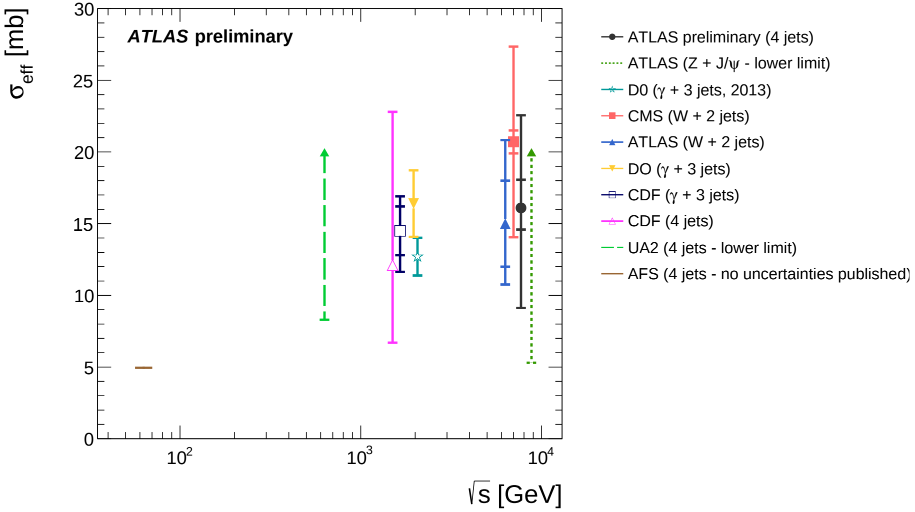
- Jet energy resolution - $\Delta\sigma_{\rm eff} = \pm 12\%$.
- Jet energy scale - $\Delta\sigma_{\rm eff} =^{+35}_{-39}\ \%$.

Result

$$\sigma_{\rm eff} = 16.1\ ^{+2.0}_{-1.5}\ \text{(stat.)}\ ^{+6.1}_{-6.8}\ \text{(syst.)}\ \rm mb$$

Results

Comparing result with previous measurements in different $\sqrt{s}$ and various final-states,



Within large uncertainties no indication of $\sqrt{s}$ dependence.

Conclusions

- Four measurements relating to DPS were released by ATLAS so far.
- Two provide measurements of σ_{eff} with large uncertainties.
- Sensitivity to DPS is shown in the $W^{\pm} + J/\psi$ final state.
- A lower limit extracted for σ_{eff} in the $Z + J/\psi$ final state.

Estimated fractions of DPS in the various final states

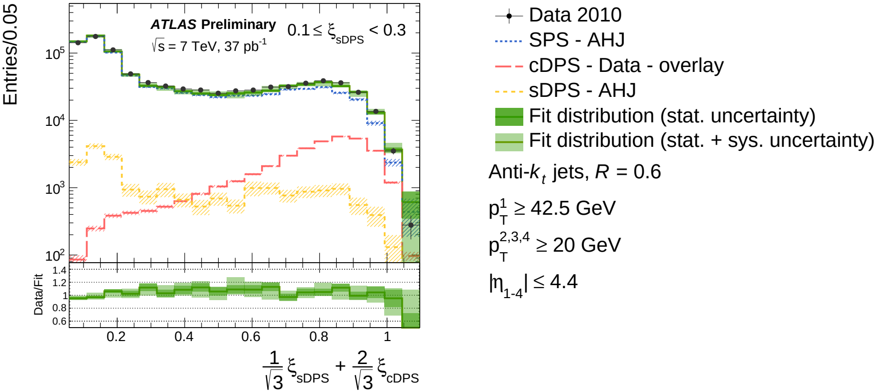
- High fractions in J/ψ final states.
- Leptonic final states easier experimentally.
- Few events available so far.
- Good candidates for Run II.

Final state	f_{DPS}
$W^{\pm} + 2\mathrm{j}$	8%
4j	8%
$W^{\pm} + J/\psi$	38%
$Z + J/\psi$	29%

Backup Slides

Extract f_{cDPS} and f_{sDPS} in data

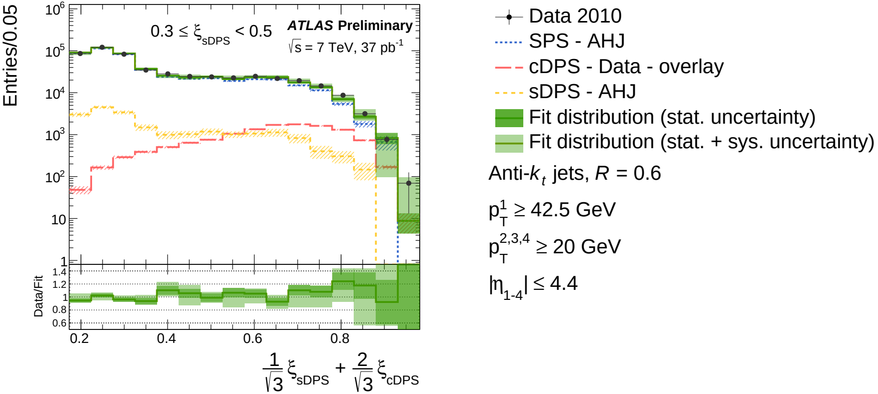
Perform 2D fit to extract the cDPS and sDPS fractions in data,



- Only statistical uncertainties participate in the fit.
- Reasonable description of the data is achieved.

Extract f_{cDPS} and f_{sDPS} in data

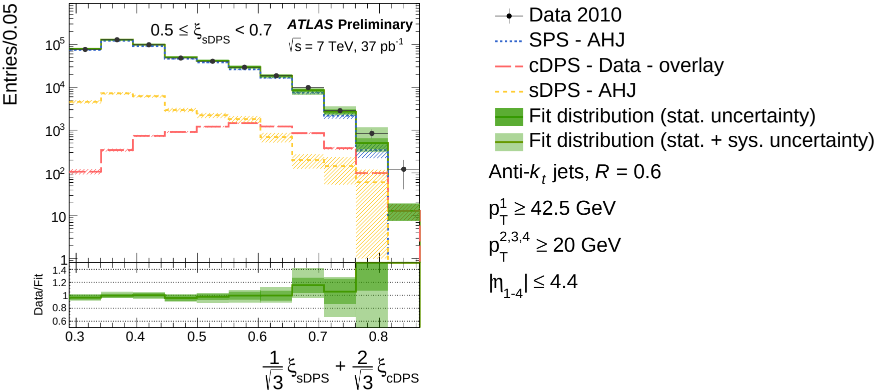
Perform 2D fit to extract the cDPS and sDPS fractions in data,



- Only statistical uncertainties participate in the fit.
- Reasonable description of the data is achieved.

Extract f_{cDPS} and f_{sDPS} in data

Perform 2D fit to extract the cDPS and sDPS fractions in data,



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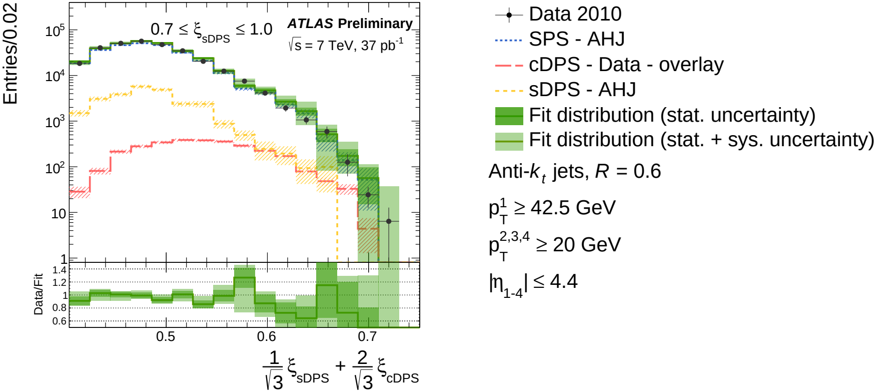
Extract f_{cDPS} and f_{sDPS} in data

Perform 2D fit to extract the cDPS and sDPS fractions in data,



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