Studies of double parton scattering with the ATLAS detector

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Introduction

Four measurements performed in ATLAS:

<table>
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<tr>
<th>Final state</th>
<th>Publication</th>
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<tbody>
<tr>
<td>$W^\pm + 2$ jets</td>
<td>New J.Phys. 15 (2013) 033038</td>
</tr>
<tr>
<td>$W^\pm + J/\psi$ (prompt $J/\psi$ production)</td>
<td>JHEP 1404 (2014) 172</td>
</tr>
<tr>
<td>Four-jet</td>
<td>ATLAS-CONF-2015-058</td>
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</tbody>
</table>

Use phenomenological formula for DPS,

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

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

The parameter $\sigma_{eff}$ 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 $\sigma_{inel}$.
DPS in $W^\pm + 2j$

- Use data collected during 2010 ($\sqrt{s} = 7$ TeV, 36 pb$^{-1}$).

- **Jets selection:**
  - anti-$k_\perp$ jets ($R = 0.4$);
  - transverse momentum $p_T > 20$ GeV, rapidity $|y| < 2.8$.

- $W^\pm$ boson selection:
  - 1 lepton ($e$, $\mu$) with $p_T > 20$ GeV, $|\eta| < 2.4$;
  - missing transverse energy, $E_T^{\text{miss}} > 25$ GeV;
  - transverse mass $m_T > 40$ GeV.

- Extract $f_{\text{DPS}}$ by performing a fit to the distribution of $\Delta_n^{\text{jets}}$ in data of templates $A$ and $B$ of the form $(1 - f_{\text{DPS}}) \cdot A + f_{\text{DPS}} \cdot B$.

  - **Template A - no DPS:** ALPGEN + HERWIG + JIMMY (AHJ) sample of SPS $W^\pm + 2$ jets, $p_T^{\text{max}} = 15$ GeV.
  - **Template B - Dijets:** Dijet sample extracted from data.

\[
\Delta_n^{\text{jets}} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}
\]
DPS in $W^{\pm} + 2j$

$$\Delta_{jets}^{n} = \frac{|\vec{p}_{T1}^{j} + \vec{p}_{T2}^{j}|}{|\vec{p}_{T1}^{j}| + |\vec{p}_{T2}^{j}|}$$

$$\Delta_{jets} = |\vec{p}_{T1}^{j} + \vec{p}_{T2}^{j}|$$

Results

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

$$\sigma_{\text{eff}} = 15 \pm 3 \text{ (stat.)}^{+5}_{-3} \text{ (syst.) \, mb}$$
**DPS in $W^\pm + J/\psi$**

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

- Use data collected during 2011 ($\sqrt{s} = 7$ TeV, $4.5$ fb$^{-1}$).
- Data collected using single-muon trigger $p_T > 18$ GeV.
- $W^\pm$ boson selection:
  - 1 $\mu$ with $p_T > 25$ GeV, $|\eta| < 2.4$, matching trigger $\mu$;
  - $E_T^{\text{miss}} > 20$ GeV, $m_T > 40$ GeV;

- $J/\psi$ selection:
  - 2 oppositely charged $\mu$;
  - $|\eta_\mu| < 2.5$;
  - $p_T(\mu_1) > 4$ 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;
  - $|y_{J/\psi}| < 2.1$;

**Number of $W^\pm +$ prompt $J/\psi$ events**

In total $N_{\text{signal}} = 29.2^{+7.5}_{-6.5}$ (5.1$\sigma$)
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, $P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{\text{eff}}$.
- Use $\sigma_{\text{eff}}$ from $W^{\pm} + 2j$ measurement to estimate DPS contribution $\Rightarrow 38^{+22}_{-20\%}$.
DPS in $Z + J/\psi$

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 $m_{\text{PDG}}^{Z}$.

- **$J/\psi$ selection:**
  - 2 oppositely charged $\mu$;
  - $|\eta_{\mu}| < 2.5$;
  - $p_T(\mu_1) > 4$ 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 $Z + J/\psi$

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

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

- 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 $\sigma_{\text{eff}}$ from $\Delta\phi(Z, J/\psi)$ distribution - 5.3 mb at 68% CL.

![Plot of $\Delta\phi(Z, J/\psi)$ vs. Events / ($\pi/5$) for ATLAS data, showing contributions from Double Parton Scattering, Pileup, and uncertainty. The effective cross-section $\sigma_{\text{eff}} = 5.3$ mb is indicated.](image)
DPS in four jet events

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

\begin{align*}
\text{Entries/10 [GeV]} & \\
\text{Entries/0.5} & \\
\text{Entries} & \\
\text{ Entries/10 [GeV]} & \\
\text{Entries/0.5} & \\
\text{Entries} & \\
\end{align*}
Classifying events in the MC - match jets to partons

- Template fit to determine $f_{\text{DPS}}$ as in the $W^\pm + 2j$ 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 $p_T^{\text{parton}} \geq 15 \text{ GeV}$ and $\Delta R_{\text{parton}-\text{jet}} \leq 1.0$.
- Take into account semi-DPS events $\Longrightarrow f_{\text{DPS}} = f_{c\text{DPS}} + f_{s\text{DPS}}$.

![Diagram of jet and parton matching]

**SPS**
- no jets match secondary-scatter parton.

**semi-DPS**
- 1 jet matches secondary-scatter parton.

**complete-DPS**
- 2 jets match secondary-scatter parton.
Differentiating variables

Look for differentiating variable,

\[
\Delta p_T^{ij} = \frac{|\vec{p}_T^i + \vec{p}_T^j|}{p_T^i + p_T^j}, \quad \Delta \phi_{ij} = |\phi_i - \phi_j|, \quad \Delta y_{ij} = |y_i - y_j|.
\]

- 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):

- \[ \Delta p_T^{ij} = \left| \frac{\vec{p}_T^i + \vec{p}_T^j}{p_T^i + p_T^j} \right| \]
- \[ \Delta \phi_{ij} = |\phi_i - \phi_j| \]
- \[ \Delta y_{ij} = |y_i - y_j| \]
- \[ |\phi_{i+j} - \phi_{k+l}| \]
NN output in the SPS, cDPS and sDPS samples

NN provides three outputs ("probabilities") for each event, $\xi_{\text{SPS}}$, $\xi_{\text{cDPS}}$ and $\xi_{\text{sDPS}}$.

$0 \leq \xi_i \leq 1$, $\xi_{\text{SPS}} + \xi_{\text{cDPS}} + \xi_{\text{sDPS}} = 1 \Rightarrow$ 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

- Reasonable agreement observed.
- Topology well represented.

\[ \frac{1}{\sqrt{3}} \xi_{sDPS} + \frac{2}{\sqrt{3}} \xi_{cDPS} \]

ATLAS Preliminary
\[ \sqrt{s} = 7 \text{ TeV} \]
Validation

- Apply NN to the AHJ sample and perform a 2D fit of the form, $f_{cDPS} \cdot H_{cDPS} + f_{sDPS} \cdot H_{sDPS} + (1 - f_{cDPS} - f_{sDPS}) \cdot H_{SPS}$.

- Visualize fit result by dividing the triangle into five slices ($\xi_{sDPS}$ ranges).

- Compare extracted values of $f_{cDPS}$ and $f_{sDPS}$ to the fractions in AHJ extracted from the event record.

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,

\[
\frac{1}{\sqrt{3}} \xi_{sDPS} + \frac{2}{\sqrt{3}} \xi_{cDPS}
\]

- Data 2010
- SPS - AHJ
- cDPS - Data - overlay
- sDPS - AHJ
- Fit distribution (stat. uncertainty)
- Fit distribution (stat. + sys. uncertainty)

Anti-\( k_t \) jets, \( R = 0.6 \)

\[
p_T^{1} \geq 42.5 \text{ GeV}
\]

\[
p_T^{2,3,4} \geq 20 \text{ GeV}
\]

\[
|\eta_{1-4}| \leq 4.4
\]

- Only statistical uncertainties participate in the fit.
- Most significant disagreement seen in SPS dominated bins \( \Rightarrow \) 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.

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

\( \sum \) of contributions

\( \sum \) of contributions (stat. uncertainty)

\( \sum \) of contributions (stat. + sys. uncertainty)

\( \sum \) of contributions

A good description of the data is achieved.
Results

The fractions obtained in data are,

\[ f_{c\text{DPS}} = 0.052 \pm 0.002^{+0.008}_{-0.005} \text{ (stat.)}, \quad f_{s\text{DPS}} = 0.032 \pm 0.01 \text{ (stat.)}. \]

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

\[ \alpha_{2j}^{4j} = \frac{C_{4j}}{C_{2j}^A C_{2j}^B} = 0.94 \pm 0.01 \text{ (stat.)} ^{+0.15}_{-0.14} \text{ (syst.)}. \]

Adjust symmetry factor for partial overlap between \( \sigma_{2j}^A \) and \( \sigma_{2j}^B \),

\[ \frac{1}{1 + \delta_{AB}} = 1 - \frac{1}{2} \frac{\sigma_{2j}^B}{\sigma_{2j}^A} = 0.9353 \pm 0.0003 \text{ (stat.)}. \]

Insert all to the expression for \( \sigma_{\text{eff}} \),

\[ \sigma_{\text{eff}} = \frac{1}{1 + \delta_{AB}} \frac{\alpha_{2j}^{4j}}{f_{c\text{DPS}} + f_{s\text{DPS}} \frac{\sigma_{2j}^A \sigma_{2j}^B}{\sigma_{4j}}} \].

Largest sources of uncertainty

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

Result

\[ \sigma_{\text{eff}} = 16.1 \pm 2.0^{+6.1}_{-6.8} \text{ (stat.)} +6.1^{+6.1}_{-6.8} \text{ (syst.) mb} \]
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 $\sigma_{\text{eff}}$ with large uncertainties.
- Sensitivity to DPS is shown in the $W^{\pm} + J/\psi$ final state.
- A lower limit extracted for $\sigma_{\text{eff}}$ in the $Z + J/\psi$ final state.

### Estimated fractions of DPS in the various final states

<table>
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<th>Final state</th>
<th>$f_{\text{DPS}}$</th>
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</thead>
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<tr>
<td>$W^{\pm} + 2j$</td>
<td>8%</td>
</tr>
<tr>
<td>4j</td>
<td>8%</td>
</tr>
<tr>
<td>$W^{\pm} + J/\psi$</td>
<td>38%</td>
</tr>
<tr>
<td>$Z + J/\psi$</td>
<td>29%</td>
</tr>
</tbody>
</table>

- High fractions in $J/\psi$ final states.
- Leptonic final states easier experimentally.
- Few events available so far.
- Good candidates for Run II.
Backup Slides
Extract $f_{cDPS}$ and $f_{sDPS}$ in data

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

\[
\frac{1}{\sqrt{3}} \xi_{sDPS} + \frac{2}{\sqrt{3}} \xi_{cDPS}
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Fit distribution (stat. uncertainty)
Fit distribution (stat. + sys. uncertainty)

Anti-$k_t$ jets, $R = 0.6$

$p_T^1 \geq 42.5$ GeV
$p_T^{2,3,4} \geq 20$ GeV
$|\eta_{1-4}| \leq 4.4$

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