Measurement of hard double-partonic interactions in $W \to l\nu + 2$ jet events using the ATLAS detector at the LHC

The ATLAS Collaboration

Abstract

The production of W bosons in association with two jets has been investigated using proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. The fraction of $W + 2$ jet events arising from double parton scattering was measured to be $f_{DP}^R = 0.16 \pm 0.01 \text{ (stat)} \pm 0.03 \text{ (sys)}$ for jets with transverse momentum $p_T > 20 \text{ GeV}$ and rapidity $|y| < 2.8$. This corresponds to an effective cross section for hard double partonic interactions of $\sigma_{\text{eff}} = 11 \pm 1 \text{ (stat)}^{+3}_{-2} \text{ (sys)} \text{ mb}$, which is consistent with previous measurements performed at lower centre-of-mass energies in different channels. This measurement was performed using data collected with the ATLAS detector corresponding to an integrated luminosity of 33 pb$^{-1}$.

1The full authorlist can be found at:
1 Introduction

Double Parton Interactions (DPI) in hadron-initiated processes have been discussed in theoretical studies since the first days of the parton model [1–3]. These studies have subsequently been refined and reformulated in the framework of perturbative QCD for a variety of processes, such as double Drell-Yan production of leptons, four-jet production, and $W$ production associated with two jets [4–10]. As a by-product, the existence of correlations in colour and spin space have been analysed [11] and evolution equations for multi-parton distribution functions have been presented [12].

A formalism to deal with double parton interactions has been established [7, 8] and can be summarised by

$$
\frac{d \sigma^{(\text{DPI})}_{Y+Z}(s)}{2 \sigma_{\text{eff}}(s)} = \frac{m}{\int dx_1 \, dy_1 \, dx_2 \, dy_2 \, f(x_1, y_1, \mu_F) f(x_2, y_2, \mu_F) \, d\hat{y}(x_1, x_2, s) \, d\hat{y}(y_1, y_2, s)},
$$

(1)

where $\sigma^{(\text{DPI})}_{Y+Z}$ is the double-parton scattering cross section for the inclusive production of a combined system $Y + Z$ at a given centre-of-mass energy, $\sqrt{s}$. The factor $m$ is equal to one if $Y = Z$ and equal to two if $Y \neq Z$. The integration over the momentum fractions $x$ and $y$ is constrained by energy conservation such that $x + y \leq 1$. The $f(x, y, \mu_F)$ are the double-parton distribution functions (DPDFs) evaluated at a specific factorisation scale, $\mu_F$. These DPDFs are typically expressed in terms of the conventional single parton distributions using a factorised ansatz [7, 8], namely

$$
f(x, y, \mu_F) = f(x, \mu_F) f(y, \mu_F) (1 - x - y) \Theta (1 - x - y).
$$

(2)

The quantity $\sigma_{\text{eff}}(s)$ is defined at the parton level and, in the formalism outlined here, is process- and cut-independent. Naively, it can be related to the geometrical size of the proton, leading to an estimate of about $\sigma_{\text{eff}} \approx \pi R^2_p \approx 50$ mb, where $R_p$ is the proton radius.1 Alternatively, $\sigma_{\text{eff}}$ can be connected to the inelastic cross section, which would lead to $\sigma_{\text{eff}} \approx \sigma_{\text{inel}} \approx 70$ mb at $\sqrt{s} = 7$ TeV [13, 14].

Up to now there have been a number of measurements of $\sigma_{\text{eff}}(s)$ at the hadron-level, namely

- by the AFS collaboration in multijet events from $pp$ collisions at a centre-of-mass energy of 63 GeV [16];
- by the UA2 collaboration in multijet events produced in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV [17];
- by the CDF collaboration in multijet events [18] and in $\gamma + 3$ jet events [19], both in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV; and
- by the DØ collaboration, also in $\gamma + 3$ jet events in $p\bar{p}$ collisions, but at $\sqrt{s} = 1.96$ TeV [20].

Broadly speaking, the energy dependence of the measured values yields an increase from about 5 mb at the lowest energy (63 GeV) to about 15 mb at Tevatron energies. Attempts to reconcile these numbers have used non-trivial correlations to explain the difference [21, 22]. Furthermore, it is noted that assuming a simple, Regge-physics inspired power law of the type $\sigma_{\text{eff}}(s) \propto s^\kappa$ yields a scaling behaviour of this parameter with $\kappa \approx 0.12$; a more careful analysis was presented in [23].

In the scientific programme of the LHC, issues related to double- and multi-parton interactions have attracted increasing interest, including

- general considerations concerning the form [24] and calculation [25] of the DPDFs;
- the structure of the emerging analytical expressions [26];

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1To compare the cross section for the production of four jets from direct and double parton scattering at the Tevatron [15], $\sigma_{\text{eff}} = 50$ mb has been used.
• correlations in multiparton interactions [27] and other phenomenological studies [28–38].

In this note, the parameter $\sigma_{\text{eff}}$ is determined in $W + 2$ jet events. A first theoretical study of double parton scattering in this process focused on the transverse momentum, $p_T$, distribution of the $W$-boson, which is calculated using the magnitude of the missing transverse momentum, $E_T^{\text{miss}}$ [10]. However, the $E_T^{\text{miss}}$ measured in ATLAS is calibrated using events that typically contain just a single partonic interaction. The corresponding $E_T^{\text{miss}}$ resolution in DPI is potentially different and inherently difficult to obtain. For this reason, a different approach is followed in this measurement, which does not rely on reconstructing the transverse momentum of the $W$ boson. This is discussed further in Section 6.

The outline of the note is as follows. In Section 2, an expression is given for the total cross-section to produce a combined system $Y + Z$ in hadron-hadron collisions. Conditions are discussed under which this parton-level expression can be transformed to an expression valid for reconstructed quantities. The emerging master equation is specified for $W + 2$ jet production at the LHC and the cross-section ratio for $W + 2$ jet production via double parton scattering, $f_{\text{DP}}$, is introduced. The ATLAS detector is briefly discussed in Section 3. The event selection and Monte Carlo event simulation is discussed in Sections 4 and 5, respectively. The comparison of data and MC for the variables of interest in this analysis is presented in Section 6. Finally, the extraction of $f_{\text{DP}}$ and evaluation of $\sigma_{\text{eff}}$ are presented in Sections 7 and 8, respectively.

2 Principle of the measurement

2.1 Theoretical background

As already noted in Section 1, $\sigma_{\text{eff}}$ parametrises the double parton-scattering part of the production cross section for a “composite” system $Y + Z$ in hadronic collisions. Assuming no correlations, the cross section $\hat{\sigma}^{(\text{tot})}_{Y+Z}$ for the production of $Y + Z$ consists of a direct part, $\hat{\sigma}^{(\text{dir})}_{Y+Z}$, and a double parton scattering contribution, $\hat{\sigma}^{(\text{DPI})}_{Y+Z}$:

$$d\hat{\sigma}^{(\text{tot})}_{Y+Z}(s) = d\hat{\sigma}^{(\text{dir})}_{Y+Z}(s) + d\hat{\sigma}^{(\text{DPI})}_{Y+Z}(s) = d\hat{\sigma}^{(\text{dir})}_{Y+Z}(s) + \frac{d\hat{\sigma}_{Y}(s) \times d\hat{\sigma}_{Z}(s)}{\sigma_{\text{eff}}(s)}.$$  (3)

In the following it is assumed that the proposed correlation in the PDFs, the factor $(1 - x - y)$ present in equation (2), is either absent or can be ignored. Each of the cross sections in equation (3) can then be written as

$$d\hat{\sigma}_{N}(s) = \frac{1}{2s} \sum_{1,2} dx_1 \ dx_2 \ d\Phi_N \ f_1(x_1, \mu_F) \ f_2(x_2, \mu_F) \ |M_{12\to N}(x_1 \ x_2 \ s, \Phi, \mu_F, \mu_R)|^2,$$  (4)

where $d\Phi_N$ is the phase space element for the $N$-body final state and $M_{12\to N}$ is the corresponding matrix element, which also depends on the factorisation scale $\mu_F$ and the renormalisation scale $\mu_R$. The individual cross sections on the r.h.s. of equation (3) can be calculated from first principles in the parton model. For the case of $W+2$ jet production discussed in this note, and at leading order, they can be related to Feynman diagrams such as those depicted in Figure 1. In practice some of the contributions could be either taken directly from data, see below, or they could be calculated at higher than tree-level accuracy.

If this simple factorisation picture is correct, then the same $\sigma_{\text{eff}}(s)$ should emerge for all possible cuts on the final state and for all combinations of $Y$ and $Z$. This is the reason why the cross sections above have been written in differential form. There will be some other effects which will eventually enforce a breakdown of this simple picture in some corners of phase space; for example total energy conservation, flavour conservation rules, or, more intricately, complicated final-state interactions. However, by choosing certain processes and cuts, such effects may turn out to be negligible.
Figure 1: Example leading order Feynman diagrams for the direct (left) and double parton-scatter (right) components in the production of a $W^+ + 2$ jet system. These contributions are defined in equation (3) with the identification $Y \rightarrow W^+$ and $Z \rightarrow jj$.

In order to account for some correlations, for example in the phase space of the combined system, the naive product of the two individual cross sections for producing the systems $Y$ and $Z$ has been replaced by the symbol $\otimes$. In integral form, more suitable for the analysis, equation (3) may be written symbolically as

$$\int_{\text{cuts}} \frac{d\hat{\sigma}^{\text{(tot)}}_{Y+Z}(s)}{d\hat{\sigma}^{\text{(tot)}}_{Y+Z}(s)} = \int_{\text{cuts}} \frac{d\hat{\sigma}^{\text{(dir)}}_{Y+Z}(s)}{d\hat{\sigma}^{\text{(dir)}}_{Y+Z}(s)} + \int_{\text{cut}(Y)} \frac{d\sigma_{Y}(s)}{d\sigma_{Y}(s)} \otimes \int_{\text{cut}(Z)} \frac{d\sigma_{Z}(s)}{d\sigma_{Z}(s)} . \quad (5)$$

In calculating a cross section $\hat{\sigma}_{Y}$, it should be noted that the calculation describes the cross section for the production of the system $Y$ plus any additional particles. In particular, when calculating the $W$ cross section, implicitly this also includes the production of additional jets; typically the phase space these jets can populate is constrained by $\mu_F$. Therefore, in order for the formalism to hold true, one would typically assume that the factorisation scale $\mu_F$ is of the order of the jet transverse momentum scale or below. In this note such effects are taken into account by

(a) realising that the rate for producing additional partons in the $p_T$ region of interest here – about or above 20 GeV – is typically of the order of 10%. This implies that when directly using data to describe the double parton scatter part of the $W$ production, the error is also typically of the order of 10%;

(b) restricting the event sample to those events with exactly two jets. This implies that, when using data to describe the dijet production part of the double parton scattering, one must use a two-jet exclusive data set.

However, solving equation (3) for $\sigma_{\text{eff}}$, and suppressing the argument $s$ by noting that this analysis has been carried out at a fixed centre of mass energy, $\sqrt{s} = 7$ TeV, yields

$$\sigma_{\text{eff}} = \frac{d\hat{\sigma}_{Y} \times d\hat{\sigma}_{Z}}{d\hat{\sigma}^{\text{(dir)}}_{Y+Z}} = \frac{d\hat{\sigma}_{Y} \times d\hat{\sigma}_{Z}}{d\hat{\sigma}^{\text{(tot)}}_{Y+Z} - d\hat{\sigma}^{\text{(dir)}}_{Y+Z}} . \quad (6)$$

In principle, all quantities in the above can be taken directly from data, with the exception of the direct component $\hat{\sigma}^{\text{(dir)}}_{Y+Z}$, for which theory input in the form of a Monte Carlo event generator would need to be employed. In such a case, and when referring to data, $\hat{\sigma}$ will be replaced by $\sigma$, and $\hat{\sigma}$ will be used for parton-level quantities only.
2.2 Strategy of the analysis

The aim of this analysis is to extract the fraction of $W + 2j$ events containing hard DPI produced in proton-proton collisions recorded by the ATLAS detector. The method of extraction is to fit over the distribution of a variable that has good discrimination between a $W$ boson produced in direct association with 2 jets ($W + 2j_D$) and a $W$ boson produced in association with zero jets in addition to a double-parton scatter resulting in two jets ($W_0 + 2j_{DPI}$).

The fraction of $W_0 + 2j_{DPI}$ events in the selected $W + 2j$ sample, $f^R_{DPI}$, is defined as

$$f^R_{DPI} = \frac{N_{W_0 + 2j_{DPI}}}{N_{W + 2j}},$$

(7)

where $N_{W_0 + 2j_{DPI}}$ is the number of $W_0 + 2j_{DPI}$ events passing $W + 2j$ selection, and $N_{W + 2j}$ is the total number of events passing $W + 2j$ selection. Although these quantities will be measured at detector level, it is shown in Section 7.3 that $f^R_{DPI}$ is closely related to its parton-level equivalent, $f^P_{DPI}$. Anticipating the equivalence of parton-level and detector-level cross sections in the ratio, equation (6) can be written as

$$\sigma_{eff} = \frac{\sigma_{W_0} \cdot \sigma_{2j}}{\sigma_{W_0 + 2j_{DPI}}},$$

(8)

where $\sigma_{W_0}$, $\sigma_{W_0 + 2j_{DPI}}$ and $\sigma_{2j}$ are the cross-sections of $W + 0j$, $W_0 + 2j_{DPI}$ and dijet (2j) events respectively. Each cross-section can be calculated using

$$\sigma = \frac{N}{A \cdot \epsilon \cdot \mathcal{L}},$$

(9)

where $N$ is the number of events, $A$ is the acceptance after reconstruction and unfolding corrections, $\epsilon$ is the trigger efficiency and $\mathcal{L}$ is the integrated luminosity. Equation (8) can therefore be rewritten as

$$\sigma_{eff} = \frac{1}{f^R_{DPI}} \cdot \frac{N_{W_0} N_{2j}}{N_{W + 2j}} \cdot \frac{A_{W_0 + 2j_{DPI}}}{A_{W_0} A_{2j}} \cdot \frac{\epsilon_{W_0 + 2j_{DPI}}}{\epsilon_{W_0} \epsilon_{2j}} \cdot \frac{\mathcal{L}_{W_0 + 2j_{DPI}}}{\mathcal{L}_{W_0} \mathcal{L}_{2j}}.$$  

(10)

In this analysis, a factorisation ansatz between the $W$ and the $2j$ systems is assumed. This leads to a number of conclusions regarding the quantities in equation (10). First, the kinematics of the $W$ do not influence the kinematic distributions of the DPI system. This implies that

$$A_{W_0 + 2j_{DPI}} = A_{W_0} \cdot A_{2j_{DPI}},$$

(11)

once corrections involving the impact of jets on $W$ reconstruction and vice versa have been made (discussed in detail in Section 7.4). Secondly, the kinematics of the jets in the DPI system may be modelled by the kinematics of single-scatter dijet events, which implies that

$$A_{2j_{DPI}} = A_{2j}.$$  

(12)

Finally, the $W_0 + 2j_{DPI}$ and $W_0$ events will be selected online using the same trigger selection. This results in luminosity and efficiency cancellations and equation (10) simplifies to

$$\sigma_{eff} = \frac{1}{f^R_{DPI}} \cdot \frac{N_{W_0} N_{2j}}{N_{W + 2j}} \cdot \frac{1}{\epsilon_{2j}} \cdot \frac{1}{\mathcal{L}_{2j}}.$$  

(13)

In this analysis the terms in equation (13) are determined as separate quantities allowing the evaluation of $\sigma_{eff}$ with its associated uncertainty.

$^2$W + nj will be used to denote processes in which W is produced in association with n-jets
3 The ATLAS detector

The ATLAS detector [39] comprises a superconducting solenoid surrounding the inner detector (ID) and a large superconducting toroid magnet system enclosing the calorimeters. The ID system is immersed in a 2T axial magnetic field and provides tracking information for charged particles in a pseudorapidity range matched by the precision measurements of the electromagnetic calorimeter. The silicon pixel and strip (SCT) tracking detectors cover the pseudorapidity\(^3\) range \(|\eta| < 2.5\). The transition radiation tracker (TRT), which surrounds the silicon detectors, enables tracking up to \(|\eta| = 2.0\) and contributes to electron identification.

The liquid argon (LAr) electromagnetic (EM) calorimeter is divided into one barrel (\(|\eta| < 1.475\)) and two end-cap components (1.375 < \(|\eta| < 3.2\)). It uses an accordion geometry to ensure fast and uniform response and fine segmentation for optimum reconstruction and identification of electrons and photons. The hadronic scintillator tile calorimeter consists of a barrel covering the region \(|\eta| < 1.0\), and two extended barrels in the range 0.8 < \(|\eta| < 1.7\). The LAr hadronic end-cap calorimeter (HEC) (1.5 < \(|\eta| < 3.2\)) is located behind the end-cap electromagnetic calorimeter. The forward calorimeter (FCal) covers the range 3.2 < \(|\eta| < 4.9\) and also uses LAr as the active material.

The muon spectrometer is based on three large superconducting toroids with coils arranged in an eight-fold symmetry around the calorimeters, covering a range of \(|\eta| < 2.7\). Over most of this range, precision measurements of the track coordinates in the principal bending direction of the magnetic field are provided by monitored drift tubes (MDTs). At large pseudorapidities (2.0 < \(|\eta| < 2.7\)), cathode strip chambers (CSCs) with higher granularity are used in the innermost station. The muon trigger detectors consist of resistive plate chambers (RPCs) in the barrel (\(|\eta| < 1.05\)) and thin gap chambers (TGCs) in the end-cap regions (1.05 < \(|\eta| < 2.4\), with a small overlap in the \(|\eta| ≈ 1.05\) region.

The ATLAS detector has a three-level trigger system consisting of level-1 (L1), level-2 (L2) and the event filter (EF). The L1 trigger rate at design luminosity is approximately 75 kHz. The L2 and EF triggers reduce the event rate to approximately 200 Hz.

4 Event selection

The measurement was performed using 33 \(\text{pb}^{-1}\) of data taken during 2010. Events were required to contain at least one primary vertex that was reconstructed within 200 mm of the interaction point and contained at least three tracks. Additional cuts were applied to reduce the contamination from noisy calorimeter cells, beam backgrounds and cosmic rays.

4.1 Selection of events containing a W-boson

The selection of the \(W \rightarrow \ell \nu\) signal was similar to that used in the \(W \rightarrow \ell \nu + \text{jets}\) cross-section analysis [40]. Dedicated single-electron and single-muon trigger selections were used to retain \(W \rightarrow e \nu\) and \(W \rightarrow \mu \nu\) events, respectively.

In the electron channel, events were required to contain one electron that satisfied the ‘tight’ identification criteria [41] with \(p_T > 20\ \text{GeV}\) and \(|\eta| < 2.47\). Electrons reconstructed in the transition region between the barrel and endcap calorimeters (1.37 < \(|\eta| < 1.52\) were excluded from the analysis. Additional requirements were applied to remove electrons falling into inactive regions of the calorimeter.

\(^3\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the \(z\)-axis along the beam pipe. The \(x\)-axis points from the IP to the centre of the LHC ring, and the \(y\)-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\). The rapidity of a particle with respect to the beam axis is defined as \(y = \frac{1}{2} \ln \frac{E + p_T}{E - p_T}\).
In the muon channel, events were required to contain a muon with $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$. The muon was reconstructed from information from both the muon spectrometer and the inner detector. Additional requirements were applied to the number of hits used to reconstruct the track in the inner detector. Furthermore, the $z$ coordinate of the muon impact parameter with respect to the primary vertex was required to be less than 10 mm in the $r - z$ plane. Isolation cuts were applied such that the summed transverse momentum of tracks within $\Delta R < 0.2$ of the muon was less than 10% of the muon $p_T$, where $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

In both channels, additional requirements were placed on $E_T^{\text{miss}}$ and transverse mass, $M_T$. The transverse mass is defined from the neutrino, $\nu$, and lepton, $l$, momentum components as $M_T = \sqrt{p_T^l p_T^\nu (1 - \cos(\phi^l - \phi^\nu))}$1/2. The neutrino components are inferred from the $E_T^{\text{miss}}$ vector. The $E_T^{\text{miss}}$ is calculated using the reconstructed physics objects, the remaining energy deposits in the calorimeter and the inner detector tracking information (details can be found in [40]). Events were required to have $E_T^{\text{miss}} > 25$ GeV and $M_T > 40$ GeV.

Jets are defined using the anti-$k_t$ algorithm with $R = 0.6$ and full four momentum recombination. The jets are reconstructed from electromagnetic scale topological clusters that are built from calorimeter cells. Each jet is subsequently corrected using $p_T$ and $\eta$ dependent jet energy scale (JES) calibration factors derived from simulated MC events [42]. JETS were required to have $p_T > 20$ GeV and $|y| < 2.8$. All jets within $\Delta R < 0.5$ of a reconstructed electron or muon were removed from the analysis. Jets originating from pile-up interactions were removed by applying a cut on the jet-vertex fraction (JVF), which was defined for each jet in the event. After associating tracks to jets with a matching in $\Delta R$(track, jet), requiring $\Delta R < 0.4$, the JVF was computed for each jet as the scalar sum $p_T$ of all matched tracks from the primary vertex divided by the total jet-matched track $p_T$ from all vertices. Jets were removed from the analysis if JVF < 0.75. The JVF cut was not applied to jets that lay outside the acceptance of the inner detector or those that had no matching tracks.

Events were subsequently divided into two orthogonal datasets. The first was a $W + 0j$ sample, in which no jets were reconstructed – in accordance with the definition above – in addition to the $W$ decay products. The second was the $W + 2j$ sample, in which exactly two additional jets were reconstructed. The $W + 0j$ sample is only used for the evaluation of $\sigma_{\text{eff}}$.

4.2 Selection of dijet events

Dijet events were selected online using a trigger selection derived from the Minimum Bias Trigger Scintillators and Zero Degree Calorimeters, which have been shown to be unbiased and fully efficient for jet-based measurements [42]. Dijet events were required to contain exactly two jets, reconstructed using the same algorithm, input objects and kinematic selection as in the previous section.

5 Monte Carlo simulation

Alpgen [43] was used to generate $W + nj$ signal events. MLM [46] matching was used, with the matching scale cut set at 20 GeV, to prevent any double counting caused by the parton shower. Alpgen is a matrix element generator that is interfaced to Herwig [44] v6.510, for parton showering and hadronisation, and to Jimmy [45] v4.31, for the underlying event. The event generator tune was AUET1 [47]. Sherpa [48] v1.3.1 was also used to generate an alternative sample of $W + nj$ signal events. Sherpa is a matrix element generator that uses CKKW [49] matching to prevent double counting from the parton shower. The Sherpa samples were generated with the default underlying event tune and the CKKW matching cut at 30 GeV. As a final comparison for signal events, Pythia6 [50] was used to generate inclusive $W$ events, with the AMBT1 tune [52] for the underlying event activity.
Table 1: Summary of Monte Carlo datasets that were used in the study.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Signal</th>
<th>Generator</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics signal estimation</td>
<td>$W \to \mu\nu$</td>
<td>ALPGEN+HERWIG+JIMMY</td>
<td>DEFAULT</td>
</tr>
<tr>
<td></td>
<td>$W \to e\nu$</td>
<td>ALPGEN+HERWIG+JIMMY</td>
<td>DEFAULT</td>
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<tr>
<td></td>
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<td>MI_HANDLER=ON</td>
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<tr>
<td></td>
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</tr>
<tr>
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<tr>
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<td></td>
<td>$W \to e\nu$</td>
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<td>MI_HANDLER=OFF</td>
</tr>
</tbody>
</table>

The $\tilde{t}\tilde{t}$ background events were generated at next-to-leading order accuracy using the MC@NLO [51] generator. MC@NLO was interfaced to HERWIG and JIMMY, and the AUET1 tune for the underlying event was used in the sample generation. Backgrounds from dijet and inclusive $Z$ production were simulated using PYTHIA6 with tune AMBT1 for the underlying event.

Each generated event was passed through the standard ATLAS detector simulation [53], which is based on Geant4 [54]. The MC events were reconstructed and analysed using the same chain as applied to the data. The Monte Carlo samples used in the analysis are summarised in Table 1.

5.1 Event generator samples without double parton scattering

In addition to the standard MC simulation, $W + 2j$ events with no multiple parton interactions were generated using SHERPA and ALPGEN+HERWIG+JIMMY. These samples model the jet-jet correlations in the non-DPI production of $W + 2j$ events and were used to extract $f_{\text{DP}}^R$ from the data. DPI was switched off in SHERPA using the MI_HANDLER switch. This prevents secondary parton-parton scattering with $p_T \gtrsim 5$ GeV. The initial/final state radiation from the incoming/outgoing legs of the leading-order matrix element is retained, in addition to the generation of intrinsic transverse momentum and fragmentation of beam remnants.

To create a corresponding ALPGEN+HERWIG+JIMMY sample with DPI switched off, the standard generation of $W + 2j$ was used, but events were rejected if the two jets were identified as originating from a non-primary parton-parton scatter. This jet-parton matching was performed using the HERWIG event record, by identifying the parton with status code 123/124 and $p_T > 3.5$ GeV that was closest to each jet.

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4^The threshold was chosen to be 3.5 GeV to approximately match the PTJIM parameter (3.86 GeV), which is used in JIMMY to set the transverse momentum scale of secondary scatters.
6 Characteristics of DPI events in data and MC

The goal of this study is to identify the fraction of $W + 2j$ events that are produced via double parton scattering. It is expected that the two partonic scatterings are independent and therefore the jets produced in DPI events will typically be produced back-to-back in azimuth. The independence of the two scatters can also be seen in variables that parameterise the transverse momentum imbalance between the jets, such as

$$\Delta_{\text{jets}} = |\vec{p}_{T,1} + \vec{p}_{T,2}| \quad \text{and} \quad \Delta_{\text{jets}}^n = \frac{|\vec{p}_{T,1} + \vec{p}_{T,2}|}{|\vec{p}_{T,1}| + |\vec{p}_{T,2}|},$$

where the indices 1 and 2 identify the two jets in the event.

The SHERPA and ALPGEN+HERWIG+JIMMY predictions for $\Delta_{\text{jets}}$ are shown in Figure 2, with and without the contribution from double parton scattering. The effect of including the DPI in each generator is an enhancement in the region $\Delta_{\text{jets}} \sim 10 \text{ GeV}$. It is concluded that this enhancement is related to the DPI contribution, for which the two jets are produced back-to-back in azimuth and with similar transverse momenta. The distribution of the $\Delta_{\text{jets}}^n$ variable is also shown in Figure 2. This variable is constructed such that the region close to $\Delta_{\text{jets}}^n = 1$ contains no DPI, and that near $\Delta_{\text{jets}}^n = 0$ contains a larger fraction of DPI. The $\Delta_{\text{jets}}^n$ variable is particularly useful because, as a ratio, it has reduced sensitivity to jet energy uncertainties whilst remaining sensitive to the presence of DPI.

The $\Delta_{\text{jets}}^n$ and $\Delta_{\text{jets}}$ distributions reconstructed in data are shown in Figure 3. The data is compared to the predictions from the SHERPA and ALPGEN+HERWIG+JIMMY generators, as well as the multijet, $t\bar{t}$, $Z$ and $W \to \tau \nu$ background processes. The ALPGEN+HERWIG+JIMMY sample produces the best description of the jet-jet correlations observed in the data. SHERPA predicts a smaller fraction of events with the two jets produced back-to-back than is observed in the data. One cause of this discrepancy may be that SHERPA predicts less $W + 2j_D$ events than ALPGEN+HERWIG+JIMMY in this region of phase space\(^5\) (Figure 2).

\(^5\)This may be due to the CKKW matching scale being set to 30 GeV in the default ATLAS production of the SHERPA samples.
Figure 3: Distribution of $\Delta n_{\text{jets}}$ (a,b) and $\Delta \text{jets}$ (c,d) in the data compared to expectations as predicted by Sherpa (a,c) and Alpgen+Herwig+Jimmy [A+H+J] (c,d) signal Monte Carlo including background after combined $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ selection. The sum of signal and background Monte Carlo is scaled to the number of events found in the data.

7 Extraction of $f_{\text{DP}}^R$

The extraction of $f_{\text{DP}}^R$ from the data was performed using a $\chi^2$ minimisation to the normalised $\Delta n_{\text{jets}}$ distribution of the form

$$(1 - f_{\text{DP}}^R) \cdot A + f_{\text{DP}}^R \cdot B,$$

where template $A$ is the normalised distribution for $W + 2j_D$ and template $B$ is the normalised distribution for $W_0 + 2j_{\text{DP}}$. The construction of these templates is discussed in Section 7.1. To minimise the dependence on near-collinear jets, the two bins covering $0.933 < \Delta n_{\text{jets}} < 1.0$ were not used in the fit.

7.1 Template construction

The model for the $W + 2j_D$ contribution (template A) was taken from the event generator predictions. The first model for this template was the Sherpa prediction with the MPI switched off. The second model was the Alpgen+Herwig+Jimmy prediction with the MPI removed. The procedure to switch off or remove MPI in the generators was discussed in Section 5. There is a small difference between the Sherpa and Alpgen+Herwig+Jimmy predictions, which will be used as a generator modelling uncertainty in the extraction of $f_{\text{DP}}^R$. This is discussed further in Section 7.3.
Figure 4: Comparison of $\Delta_{\text{jets}}^n$ distribution in the data with expectations after $\chi^2$ minimisation fits of the templates to data to extract $f_{\text{DP}}^R$. The result obtained using Sherpa for template A is shown in (a) and the result obtained using Alpgen+Herwig+Jimmy (A+H+J) for template A is shown in (b). The physics background (physics BG) is added to template A in the figure (dotted line). The fit region is the region to the left of the dotted line. Data and the overall fit were normalised to unity, template A to $1 - f_{\text{DP}}^R$, and template B to $f_{\text{DP}}^R$.

Template B, the model for $W_0 + 2j$ DPI kinematics, is constructed from dijet data using the selection outlined in Section 4. The fractional difference between the extracted value of $f_{\text{DP}}^R$ when using dijet MC in place of dijet data was found to be negligible.

7.2 Fit results

The result of fitting the templates to the data is shown in Figure 4. The fraction of DPI events was found to be $f_{\text{DP}}^R = 0.18$, using the Sherpa prediction for template A. The associated quality of the fit was $\chi^2/N_{\text{df}} = 1.4$ ($N_{\text{df}} = 27$). The fraction of DPI was observed to be $f_{\text{DP}}^R = 0.14$ using the Alpgen+Herwig+Jimmy prediction for template A, with a $\chi^2/N_{\text{df}}$ of 0.9. The final value of $f_{\text{DP}}^R$ was taken to be the average of these results ($f_{\text{DP}}^R = 0.16$). The statistical uncertainty was obtained by varying the $\chi^2$ by one unit and was found to be $\approx 0.07 f_{\text{DP}}^R$. The systematic uncertainties on the extracted value of $f_{\text{DP}}^R$ are discussed in Section 7.4.

The value $f_{\text{DP}}^R$ extracted from the fit to $\Delta_{\text{jets}}^n$ can be used to normalise appropriate templates for $\Delta_{\text{jets}}$. Figure 5 shows the distribution obtained in data compared to these normalised templates.

7.3 Transition of results from detector to parton level

In this section, the relationship between the parton-level, $f_{\text{DP}}^P$, and reconstruction level, $f_{\text{DP}}^R$, quantities is established. The fraction of events originating from double parton scattering is defined at parton-level by

$$f_{\text{DP}}^P = \frac{N_{W_0 + 2j + 2j}^P}{N_{W_0 + 2j + 2j}^P + N_{W + 2j}^P}.$$  \hspace{1cm} (16)

where $N_{W_0 + 2j + 2j}^P$ is the number of events generated with the two partons originating from DPI and $N_{W + 2j}^P$ is the number of events generated with the two partons produced directly from the $W + 2j$ matrix element. The partons are required to pass the same selection criteria as the reconstructed jets, $p_T > 20$ GeV and $|y| < 2.8$. The value of $f_{\text{DP}}^P$ was evaluated to be 0.18 in the nominal Alpgen+Herwig+Jimmy settings.
The relationship between $f_{\text{DP}}^P$ and $f_{\text{DP}}^R$ was evaluated using ALPGEN+HERWIG+JIMMY in the following way:

- the DPI component of the $W+2j$ sample was identified by matching the jets to hard-scatter partons in the event record, as described in section 5;

- a weighting factor, $x$, was applied to the DPI events before constructing the $\Delta_\text{jets}$ distribution. For the non-DPI events in the sample, a weighting factor of one was applied. The value of $f_{\text{DP}}^P$ can then be expressed as

$$f_{\text{DP}}^P = \frac{x \cdot N_{W+2j,\text{DPI}}^P}{x \cdot N_{W+2j}^P + N_{W+2j,\text{D}}^P},$$

(17)

- a $\chi^2$ minimisation fit to the ALPGEN+HERWIG+JIMMY sample obtained as above was performed, using expression (15) with the SHERPA prediction for template A and the dijet data for template B. The result of the fit yields an estimate of the fraction of DPI present in the detector level Monte Carlo, $f_{\text{DP}}^T$.

The result of the fit is shown in Figure 6(a) for $f_{\text{DP}}^P = 0.18$ ($x = 1$). The relationship between $f_{\text{DP}}^T$ and $f_{\text{DP}}^P$ is obtained by varying $x$ and is shown in Figure 6(b). In general, there is a strong correlation between the extracted value of $f_{\text{DP}}^T$ and the input value of $f_{\text{DP}}^P$. There is, however, a small bias of $f_{\text{DP}}^T$ at small values of $f_{\text{DP}}^P$. This bias arises from (i) modelling differences between the two generators and (ii) physics and detector effects present in the transition from parton-level to detector-level. As the fraction of DPI is increased, the fit result becomes increasingly insensitive to the details of template A and the extracted value of $f_{\text{DP}}^T$ converges towards the input value of $f_{\text{DP}}^P$.

### 7.4 Systematic uncertainty on $f_{\text{DP}}^R$

In Section 7.2, the final value of $f_{\text{DP}}^R = 0.16$ was determined using both the ALPGEN+HERWIG+JIMMY and SHERPA predictions for template A. In particular, the value of $f_{\text{DP}}^P$ was taken to be the average of the values extracted using the two event generators. The systematic uncertainty associated with the event
Figure 6: (a) Comparison of $\Delta_n^{\text{jets}}$ distribution predicted by the ALPGEN+HERWIG+JIMMY default ($x = 1$) with $\chi^2$ minimisation fits of templates $A$ (SHERPA) and $B$, to extract $f^T_{\text{DP}}$. The template construction and normalisation is the same as in Figure 4. (b) Extracted value of $f^R_{\text{DP}}$ as a function of $f^P_{\text{DP}}$. A one-to-one correspondence line (dashed line) and a linear fit (unbroken line) to the points are also shown. The data extracted value $f^R_{\text{DP}}$ (using the SHERPA prediction of template $A$) with its statistical uncertainty of 0.07 $f^R_{\text{DP}}$ is also shown extrapolated to the parton level using the linear fit.

generator modelling of $W+2j_D$ is taken to be the difference between this average and the generator-based predictions. This is the largest systematic uncertainty in the measurement and observed to be 0.12 $f^R_{\text{DP}}$. Furthermore, in Section 7.3, the shift between $f^P_{\text{DP}}$ and $f^T_{\text{DP}}$ at $f^T_{\text{DP}} = 0.16$ was observed to be 0.1 $f^R_{\text{DP}}$. This is taken to represent the systematic uncertainty in the use of reconstructed quantities to measure a quantity that is formally defined at the parton-level. It is noted that these estimates partially double count the effects of the modelling differences between SHERPA and ALPGEN+HERWIG+JIMMY.

Events in which $W + 1j_D$ is produced in conjunction with a DPI scatter were observed to have little impact on the analysis. At parton level, the shift in $f^P_{\text{DP}}$ was found to be negligible if these events were included. Furthermore, the addition of these events at reconstruction level did not significantly alter the shape of template $A$. It is therefore concluded that the systematic uncertainty due to such combinatoric events is negligible. The impact of physics modelling was observed to be negligible for the electroweak and $t\bar{t}$ backgrounds. For the QCD background, the normalisation uncertainty derived in [40] was included, resulting in a physics background modelling uncertainty of 1% on $f^R_{\text{DP}}$.

The systematic uncertainty on $f^R_{\text{DP}}$ due to jet energy scale calibration was found to be 0.1 $f^R_{\text{DP}}$. The systematic uncertainty due to the jet energy resolution was observed to be negligible. Both of these effects were calculated after varying the jet energy scale and resolution within the known uncertainties [42]. The impact of pileup was obtained by studying the fit results as a function of the number of primary vertices reconstructed in the event. The effect of removing the JVF selection criterion was studied, as an additional estimate of the uncertainty due to pile-up. The overall systematic uncertainty on $f^R_{\text{DP}}$ due to pileup was estimated to be 0.08 $f^R_{\text{DP}}$. The trigger used to select dijet events is 100% efficient in selecting dijet events and so should not bias their observed kinematics [42]. However, an additional uncertainty of 5% was included after studying the variation in the template $B$ shape when the calorimeter jet trigger was used to select the events.

The sources of systematic uncertainty discussed in this section are summed in quadrature to give an overall systematic uncertainty of 21% in the measurement of $f^R_{\text{DP}}$. The systematic uncertainties are summarised in Table 2.
7.5 Dependence of \( f_{DP}^R \) on phase space cuts

Figure 7 shows the values of \( f_{DP}^P \), \( f_{DP}^T \) and \( f_{DP}^R \) as a function of the minimum jet \( p_T \) requirement. The extracted values of \( f_{DP}^T \) and \( f_{DP}^R \) are presented only for phase space regions in which the jet energy scale is well understood and the measurement is statistically feasible. The decrease of \( f_{DP}^R \) with increasing jet \( p_T \) is consistent with the MC predictions for \( f_{DP}^P \) and \( f_{DP}^T \). This decrease reflects the fact that the partons originating from the additional scatters have a steeper \( p_T \) distribution than the partons from the primary scatter. The values of \( f_{DP}^{P,T,R} \) were observed to be only weakly correlated with the maximum rapidity requirement applied to the partons/jets and is not discussed further.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Method of evaluation</th>
<th>Fractional uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator modelling</td>
<td>ALPGEN+HERWIG+JIMMY VS SHERPA</td>
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</tr>
<tr>
<td>Transition to parton level</td>
<td>Monte Carlo studies</td>
<td>10%</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>Jet energy scale shift</td>
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</tr>
<tr>
<td>Pileup</td>
<td>Varying vertex number requirement</td>
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</tr>
<tr>
<td>Trigger bias</td>
<td>Comparison of data streams</td>
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<tr>
<td>Background modelling</td>
<td>Varying multi jet background normalisation</td>
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</tr>
<tr>
<td>Total systematic</td>
<td>Quadratic sum of the above</td>
<td>21%</td>
</tr>
<tr>
<td>Total statistical</td>
<td>( \chi^2 + 1 )</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 2: Summary of the uncertainties on the extraction of \( f_{DP}^R \).

8 Evaluation of \( \sigma_{\text{eff}} \)

The value of \( \sigma_{\text{eff}} \) was evaluated using equation 13. The fraction of events from double parton scattering was extracted from the data as discussed in the previous section. The exclusivity ratio, \( N_{W_1}/N_{W+2j} \), was obtained using the inclusive \( W \) dataset produced with the selection criteria outlined in Section 4. This ratio was observed to be 11, with an associated systematic uncertainty of 5% due to background
Figure 8: The centre-of-mass $\sqrt{s}$ dependence of $\sigma_{\text{eff}}$ extracted in different processes in different experiments, for an energy range between 63 GeV and 7 TeV.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Systematic source</th>
<th>Method of evaluation</th>
<th>Fractional uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{W_0}/N_{W_2} \cdot N_{jj}$</td>
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<td>Detector response studies</td>
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</tr>
<tr>
<td>$N_{W_0}/N_{W_2}$</td>
<td>Background modelling</td>
<td>Reference [40]</td>
<td>5%</td>
</tr>
<tr>
<td>$L_{jj}$</td>
<td>Luminosity</td>
<td>Beam parameters</td>
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</tr>
<tr>
<td>$f_{\text{DP}}^{R}$</td>
<td>Total</td>
<td>As in Table 2</td>
<td>21%</td>
</tr>
</tbody>
</table>

Table 3: Summary of the systematic uncertainties on $\sigma_{\text{eff}}$.

The statistical uncertainty was negligible. The number of (exclusive) dijet events was found to be 28820 following the event selection criteria outlined in Section 4.2. The integrated luminosity was $L = 184 \mu\text{b}^{-1}$, with a systematic uncertainty of 3.4% [61]. The trigger selection for dijet events is fully efficient ($\epsilon_{2j} = 1$).

The lepton-jet overlap removal was only applied to jets in the $W + 2j$ sample. A small correction was applied to account for any bias in the acceptance cancellation assumed in equation 11. This was derived in dijet data by, on an event-by-event basis, removing jets which fell within a cone defined by the lepton direction in a randomly chosen $W \rightarrow \mu\nu$ event. The correction factor was found to be 0.965. The effect of $E_{\text{miss}}^T$ resolution on the acceptance cancellation was found to be negligible. A summary of systematic uncertainties associated with $\sigma_{\text{eff}}$ is presented in Table 3.

The final result is $\sigma_{\text{eff}} (7 \text{ TeV}) = 11 \pm 1 \text{ (stat)} ^{+3}_{-2} \text{ (sys)} \text{ mb}$. This is compared to results from previous experiments [16–20] as a function of centre-of-mass energy in Figure 8. The value of $\sigma_{\text{eff}}$ obtained in this measurement is consistent with the Tevatron results assuming no energy dependence. However, given the quoted uncertainties on each measurement, a dependence on the centre-of-mass energy cannot be excluded.
9 Conclusion

The fraction of hard double parton scattering in $W + 2j$ events was extracted using data recorded by the ATLAS experiment. The $W$ candidate events were required to contain one lepton with $p_T > 25$ GeV and $|y| < 2.5$. These events were also required to satisfy $E_T^{\text{miss}} > 25$ GeV and $M_T > 40$ GeV. Jets were reconstructed using the anti-$k_t$ algorithm with $R = 0.6$ and required to have $p_T > 20$ GeV and $|y| < 2.8$.

The fraction of DPI is extracted from the $W + 2j$ events using templates derived from both MC event generators and data. The fraction of DPI was measured to be

$$f^R_{\text{DP}} = 0.16 \pm 0.01 \text{ (stat)} \pm 0.03 \text{ (sys)}.$$

This value was subsequently used to evaluate the parameter $\sigma_{\text{eff}}$ in $pp$-collisions at a centre-of-mass energy of 7 TeV. The value extracted from the data is

$$\sigma_{\text{eff}} \ (7 \text{ TeV}) = 11 \pm 1 \text{ (stat)} \pm^{+3}_{-2} \text{ (sys)} \text{ mb}.$$

This measurement is consistent with previous measurements performed in different channels at the Tevatron.
References


[33] E. Maina, “Multiple parton interactions, \( \bar{t} \) and \( W + 4j \) production at the LHC,” JHEP **0904** (2009) 098.

[34] E. Maina, “Multiple parton interactions in \( Z+4j, W^+W^- + 0/2j \) and \( W^+W^- + 2j \) production at the LHC,” JHEP **0909** (2009) 081.


[52] The ATLAS Collaboration, “Charged particle multiplicities in pp interactions at $\sqrt{s}=0.9$ at 7 TeV in a diffractive limited phase space measured with the ATLAS detector at the LHC and a new PYTHIA6 tune,” ATLAS-CONF-2010-031.


