Studies of double parton scattering with the ATLAS detector

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Interactions with more than one pair of incident partons in the same hadronic collision have been discussed on theoretical grounds since the introduction of the parton model to the description of particle production in collisions with hadronic initial states [1–3]. The simplest case of multi-parton interactions, referred to as double parton scattering (DPS), has been the focus of many phenomenological studies and experimental measurements [4]. For a process in which a final state $A + B$ is being produced, the simplified formalism of [5, 6] yields

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

(1)

where $\sigma_A$ ($\sigma_B$) is the cross-section for the final state $A$ ($B$). The quantity $\delta_{AB}$ is the Kronecker delta used to construct a symmetry factor such that for identical final states with identical phase space, the DPS cross-section is divided by two. The $\sigma_{\text{eff}}$ is a purely phenomenological parameter determining the overall size of DPS cross-sections. At values typical for hadronic cross-sections, it has been measured to range between 10 and 20 mb. Described here are four studies of ATLAS [7] in various final states [8–11].

The production of $W$ bosons in association with two jets in $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV has been analyzed for the presence of DPS using data corresponding to an integrated luminosity of 36 pb$^{-1}$ [8]. The fraction of events arising from DPS, $f_{DPS}$, has been measured through the normalized $p_T$ balance between the two jets, $\Delta_{\text{jets}}^n$,

$$
\Delta_{\text{jets}}^n = \frac{|p_T^{J_1} + p_T^{J_2}|}{|p_T^{J_1}| + |p_T^{J_2}|},
$$

(2)

which shows good differentiating power between the production of the $W + 2$ jets final state in a single parton scattering (SPS) and in a DPS. A fit was performed to the normalized, detector-level, background-corrected data distribution of $\Delta_{\text{jets}}^n$ using two normalized templates, denoted by A and B. The result of the fit of the form $(1 - f_{DPS}) A + f_{DPS} B$ is shown in Figure 1. Template A represents the expected contribution to the distribution of $\Delta_{\text{jets}}^n$ from SPS events and was selected from
events generated with the ALPGEN Monte Carlo generator, interfaced with HERWIG and JIMMY (AHJ). Template B represents the expected contribution from DPS events and was estimated from dijet events in data.

![Figure 1: Distribution of $\Delta_n^{\text{jets}}$ from background-subtracted data (dots) compared to the result from the best fit for $f_{\text{DPS}}$ [8]. The result of the fit is shown as the green histogram. The bins to the right of the vertical dash-dotted line were excluded from the fit. Data and the overall fit have been normalized to unity, Template A (dashed line) to $1 - f_{\text{DPS}}$ and Template B (blue solid line) to $f_{\text{DPS}}$.](image)

For jets with transverse momentum $p_T \geq 20$ GeV and rapidity $|y| \leq 2.8$, a central value of

$$f_{\text{DPS}} = 0.08 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (sys.)}$$  \hspace{1cm} (3)

was obtained. The result for $f_{\text{DPS}}$ was used to extract $\sigma_{\text{eff}}$,

$$\sigma_{\text{eff}}(7 \text{ TeV}) = 15 \pm 3 \text{ (stat.)} ^{+5}_{-3} \text{ (sys.)} \text{ mb.}$$  \hspace{1cm} (4)

The $W + J/\psi$ cross-section, corrected for the detector acceptance and the branching ratio of $J/\psi \to \mu^+\mu^-$, was measured relative to the inclusive $W$ boson cross-section ($R_{WJ/\psi}^{\text{incl}}$) using the 2011 ATLAS dataset of 4.5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV [9]. The value of $\sigma_{\text{eff}}$ measured in the $W + 2$ jets final state, together with the prompt $J/\psi$ cross-section from the ATLAS measurement [12], were then used to estimate the DPS contribution to the $W + J/\psi$ final state, $f_{\text{DPS}} = 0.38^{+0.22}_{-0.20} \text{ (tot.)}$. The distribution of $R_{WJ/\psi}^{\text{incl}}$ as a function of the $p_T$ of the $J/\psi$ is shown in Figure 2(a) together with the estimated DPS contribution.

The first measurement of associated $Z + J/\psi$ production was performed in ATLAS using 20.3 fb$^{-1}$ of data at $\sqrt{s} = 8$ TeV [10]. In DPS producing the $Z + J/\psi$ final state, the azimuthal angle between the $Z$ boson and the $J/\psi$ ($\Delta\phi(Z, J/\psi)$) is expected to be uniform, while in SPS producing the same final state the angle is expected to be $\sim \pi$ at leading-order. Assuming that all of the events with $\Delta\phi(Z, J/\psi) < \pi/5$ originate from DPS, a limit on the maximum DPS contribution to the observed $Z + J/\psi$ signal was obtained (see Figure 2(b)). The upper limit on $f_{\text{DPS}}$ was found to be $f_{\text{DPS}} < 0.29$ at 68% confidence level, corresponding to the lower limit on $\sigma_{\text{eff}}$,

$$\sigma_{\text{eff}}(8 \text{ TeV}) > 5 \text{ mb.}$$  \hspace{1cm} (5)
Figure 2: (a) The cross-section ratio $dR_{\text{incl}}^{J/\psi}/dp_T$ as a function of the $J/\psi$ transverse momentum [9]. The shaded uncertainty corresponds to the variations due to the various spin-alignment scenarios. The estimated contribution from DPS is overlaid with its uncertainty shown by a shaded region. (b) Distribution of the azimuthal angle between the $Z$ boson and the $J/\psi$ meson for prompt $J/\psi$ production, overlaid with the pileup contribution [10]. The maximum DPS contribution allowed by the data is shown as the yellow band. The hashed region shows the DPS and pileup uncertainties added in quadrature.

For the purpose of measuring $\sigma_{\text{eff}}$ in the four-jet final state [11], the 2010 ATLAS dataset, corresponding to 37 pb$^{-1}$ at $\sqrt{s} = 7$ TeV, was used to select three samples of events, two dijet samples and one four-jet sample. The former have at least two jets in the final state and the latter has at least four. Jets are required to have $p_T \geq 20$ GeV and $|\eta| \leq 4.4$. In each event, jets are sorted in decreasing order of their transverse momenta. Denoting $p_T^i$ the transverse momentum of the $i^{th}$ jet in an event, the jet with the highest-$p_T$, $p_T^1$, is referred to as the leading jet. The leading jet in four-jet events is required to have $p_T^1 \geq 42$ GeV to comply with the requirements of the available jet triggers.

Based on Monte Carlo studies, DPS contributes in two ways. In one contribution, the secondary scatter produces two of the four leading jets in the event; such events are classified as complete-DPS (cDPS). In the second contribution of DPS to four-jet production, three of the four leading jets are produced in the hardest scatter, and one jet is produced in the secondary scatter; such events are classified as semi-DPS (sDPS). The contribution of DPS to the four-jet final state was estimated using the expected topology of the jets in SPS, cDPS and sDPS events. The SPS and sDPS samples were extracted from a multi-jet sample generated with AHJ and the cDPS sample.
Figure 3: Comparison between the distribution of the variable $\Delta_{34}^{p_T}$, defined in Eq.(7), in four-jet events in data and the sum of the SPS, cDPS and sDPS contributions, as indicated in the legend [11]. The sum of the contributions is normalized to the cross-section measured in data and the various contributions are normalized to their respective fractions obtained from the fit. In the sum of contributions distribution, statistical uncertainties are shown as the dark shaded area and the light shaded area represents the sum in quadrature of the statistical and systematic uncertainties. The ratio of data to the sum distribution is shown in the bottom panels.

was constructed by overlaying dijet events from data. The kinematic relations between pairs of jets were then used as input in the training of an artificial neural network (NN). The fraction of DPS events was estimated with a template fit to the NN output distribution in data,

$$f_{\text{DPS}} = 0.084 \pm 0.009 \pm 0.054 \, \text{(stat.)} \pm 0.036 \, \text{(syst.)} \, . \quad (6)$$

The distribution of the variable

$$\Delta_{34}^{p_T} = \frac{|p_T^3 + p_T^4|}{p_T^3 + p_T^4} \, , \quad (7)$$

in data is compared to a combination of the distributions in the three samples, SPS, cDPS and sDPS in Figure 3. The latter three distributions are normalized to their respective fraction in the data as obtained by the fit. A good description of the data is achieved. The fraction in Eq.(6) was used to extract $\sigma_{\text{eff}}$, yielding

$$\sigma_{\text{eff}}(7 \, \text{TeV}) = 16.1 \, \pm 2.0 \, \pm 6.1 \, \text{mb} \, . \quad (8)$$

This value is consistent within the quoted uncertainties with previous measurements, performed in ATLAS and in other experiments [8,10,11,13–20], some of which are summarized in Figure 4. Within the large uncertainties, the measurements are consistent with no $\sqrt{s}$ dependence of $\sigma_{\text{eff}}$. 
Figure 4: The effective overlap area between the interacting hadrons, $\sigma_{\text{eff}}$, as a function of the center-of-mass energy, $\sqrt{s}$, for different processes and in different experiments [8, 10, 11, 13–20]. The inner error bars (where visible) correspond to the statistical uncertainties and the outer error bars represent the sum in quadrature of the statistical and systematic uncertainties. Dashed arrows indicate lower limits and the horizontal line represents the AFS measurement published without uncertainties. For clarity, measurements at identical center-of-mass energies are slightly offset in $\sqrt{s}$. Figure taken from Ref. [11].

References


