Measurements of $V+$jet production and MPI with ATLAS

Craig Sawyer

Oxford University

on behalf of the ATLAS Collaboration

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Outline

1. **V+jet Production**
   - Z + jets
   - W + jets
   - $R_{jets}$
   - $W + D$
   - $W + b$

2. **Multiple Parton Interactions**
   - $W + 2$ jets

3. **Conclusions**
**V+jet Production**

- Provides an important test of perturbative QCD
- Constrains parton distribution functions
- Constitutes non-negligible background to many searches for new phenomena
- Measurements reported in the past for lower jet multiplicities
- Large LHC dataset allows measurement of higher jet multiplicities and higher energy regimes
- Exclusive $V+$jets studies (e.g. $W+2$-jets) sensitive to Multiple Parton Interactions
Measurement of $Z$ boson production with associated jets from 4.6 fb$^{-1}$ of 2011 $pp$ collisions at $\sqrt{s} = 7$ TeV

Extension of a previous measurement up to seven jets

Results unfolded and extrapolated to a phase space defined by:

<table>
<thead>
<tr>
<th>Fiducial Phase Space</th>
</tr>
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<tbody>
<tr>
<td>$p_T^l &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>Opposite charge leptons</td>
</tr>
<tr>
<td>$66 \leq m_{ll} \leq 116$ GeV</td>
</tr>
<tr>
<td>$\Delta R^{ll} &gt; 0.2$</td>
</tr>
<tr>
<td>$p_T^{jet} &gt; 30$ GeV</td>
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<tr>
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</tr>
<tr>
<td>$\Delta R^{lj} &gt; 0.5$</td>
</tr>
</tbody>
</table>

Measurement compared to NLO predictions from BlackHat+Sherpa [1, 2, 3] and LO predictions from Alpgen [4] and Sherpa [5]
Jet Multiplicity Scaling

- Exclusive jet multiplicities expected to be described by two scaling patterns
  - 'Staircase scaling' - $R_{(n+1)/n}$ constant
  - 'Poisson scaling' - $R_{(n+1)/n}$ inversely proportional to $n$

- Standard $Z$ selection used to investigate staircase scaling (left)

- Large scale differences between the core $Z+1$-jet process and second leading jet $p_T$ enhance Poisson scaling (right)
- Staircase scaling well modelled
  - Flat staircase pattern provides acceptable description
- Poisson scaling well modelled
  - Described by $R_{(n+1)/n} = \frac{\bar{n}}{n}$
Jet Kinematics

- Jet $p_T$ and rapidity distributions presented for up to 4-jets
- When $p_T^{jet}$ exceeds scale of $Z$ mass $K$-factors large from QCD corrections
- Higher-order electroweak corrections expected to reduce cross section by 5-20% for $100 < p_T^l < 500$ GeV

- Fixed order NLO predictions are consistent for all jet multiplicities
- Alpgen predicts $p_T^{jet}$ for 2-4 jets well but leading jet $p_T$ too hard
- Sherpa characterised by 5-15% offset to the data
- BlackHat+Sherpa and Sherpa predict too wide rapidity spectra
Inclusive Distributions

- Previously seen large discrepancies between fixed order pQCD calculations and data in inclusive distributions such as $H_T$ the scalar $p_T$ sum of all objects (arXiv:1201.1276)
- Extends this observation to higher energy regime - significant deviations seen above 350 GeV

- Mean jet multiplicity exceeds two at $H_T \sim 350$ GeV
- Agreement improved by replacing fixed-order BlackHat+Sherpa estimate for $H_T$ with exclusive sum: $Z(+1 \text{ jet}) + Z(+ \geq 2 \text{ jets})$
**W + jet Production** (arXiv:1201.1276)

- Measurement of $W$ boson production with associated jets from 36 pb$^{-1}$ of 2010 $pp$ collisions at $\sqrt{s} = 7$ TeV
- Complementary to the $Z$+jets measurement
- Results are unfolded and extrapolated to a phase space defined by:

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<tr>
<td>$p_T &gt; 20$ GeV, $</td>
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<tr>
<td>$E_T^{\text{miss}} &gt; 25$ GeV</td>
</tr>
<tr>
<td>$m_T(W) &gt; 40$ GeV</td>
</tr>
<tr>
<td>$p_T^{\text{jet}} &gt; 30$ GeV</td>
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<td>$</td>
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- Measurement compared to NLO predictions from BlackHat+Sherpa and LO predictions from Alpgen and Sherpa
Results

- Leading jet $p_T$ and $H_T$ demonstrate similar effects as $Z+\text{jets}$
\( R_{\text{jets}} \) (arXiv:1108.4908)

- **Ratio measurement**
  \[
  R_{\text{jets}}(X) = \frac{W + \text{jets}(X)}{Z + \text{jets}(X)}
  \]

- **Similarity of** \( Z \) **and** \( W \) **production used to reduce systematics limitations of a** \( V + \text{jets} \) **measurement**

- **Performed using** 36pb\(^{-1} \) **of 2010** \( pp \) **collisions at** \( \sqrt{s} = 7 \) **TeV**

- **Function of jet** \( p_T \) **threshold in the exclusive 1-jet bin**

- **Comparison to LO (Pythia [6] & Alpgen) and NLO (MCFM [7]) predictions shows consistency with the measurement**
**W + D Production (ATLAS-CONF-2013-045)**

- $pp \rightarrow WcX$ measured at $\sqrt{s} = 7$ TeV from $4.6 fb^{-1}$ of 2011 $pp$ collisions
- Analysis (arXiv:1108.4908) of inclusive $W$ and $Z$ data from ATLAS and HERA data bolstered the case for an SU(3) symmetric sea at $x \sim 0.01$
- Large production rates provide the possibility of a measurement to directly constrain the $s$-quark PDF
- Sensitive to $s$-quark distribution at values of $x \sim M_W/\sqrt{s} \sim 0.01$
- Results unfolded to a common fiducial region

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<td>$p_T^l &gt; 20$ GeV, $</td>
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<tr>
<td>$p_T^\nu &gt; 25$ GeV</td>
</tr>
<tr>
<td>$m_W &gt; 40$ GeV</td>
</tr>
<tr>
<td>$p_T^D &gt; 8$ GeV, $</td>
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</tbody>
</table>
Extraction of Cross-sections

- Charge correlation between the lepton from $W$ and $D^{(*)}$ used to extract single-charm component
- Form opposite charge (OS) and same charge (SS) distributions
- OS-SS combination used for extraction
- Yield extracted by fitting the $D^\pm$ mass or $D^* - D^0$ mass difference
Differential Results

- Results presented differential in lepton $|\eta|$ and $p_T^D$

- Compared to aMC@NLO using 6 different PDF sets
  - 'Standard PDFs' with suppressed strangeness
  - epWZ from Hera and ATLAS WZ data with strangeness equal to $\bar{u}$ and $\bar{d}$
  - NNPDF2.3coll including only collider data which has even more enhanced strange than epWZ
Cross-section Results

- Shapes of the differential distributions agree well with NLO QCD predictions
- Normalisation strongly dependent on the PDF used
- \[ R_c^\pm = \frac{\sigma(W^+D^{(*)-})}{\sigma(W^-D^{(*)+})} \] sensitive to \[ \frac{s}{\bar{s}} \]

Results favour PDFs with enhanced strangeness
- Corroborates preference for an SU(3) symmetric sea
\( W + b \) (arXiv:1302.2929)

- Measurement of \( W \) boson production with associated \( b \)-quark jets from 4.6\( fb^{-1} \) of 2011 \( pp \) collisions at \( \sqrt{s} = 7 \) TeV
- Important test of perturbative QCD in the presence of heavy quarks
- \( W+b \)-jet events from top-quark decay not included in the primary signal definition
- Additional measurements performed including the contribution from single-top
Measurement Technique

- Measurement is defined in a restricted fiducial region at particle level

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Cut</th>
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<tbody>
<tr>
<td>Lepton transverse momentum</td>
<td>$p_T^l &gt; 25$ GeV</td>
</tr>
<tr>
<td>Lepton pseudorapidity</td>
<td>$</td>
</tr>
<tr>
<td>Neutrino transverse momentum</td>
<td>$p_T^{\nu} &gt; 25$ GeV</td>
</tr>
<tr>
<td>$W$ Transverse Mass</td>
<td>$m_T(W) &gt; 60$ GeV</td>
</tr>
<tr>
<td>Jet transverse momentum</td>
<td>$p_T^j &gt; 25$ GeV</td>
</tr>
<tr>
<td>Jet rapidity</td>
<td>$</td>
</tr>
<tr>
<td>Jet multiplicity</td>
<td>$n \leq 2$</td>
</tr>
<tr>
<td>$b$-jet multiplicity</td>
<td>$n_b = 1$ or $n_b = 2$</td>
</tr>
<tr>
<td>Jet-lepton separation</td>
<td>$\Delta R(l, \text{jet}) &gt; 0.5$</td>
</tr>
</tbody>
</table>

- The measurement performed using events with exactly one $b$-tagged jet and unfolded to this region
- This and 3rd jet veto reduce top-quark background
Fiducial Cross-section Results

- Results compared to NLO predictions from MCFM and Powheg [8, 9] and LO Alpgen predictions scaled to NNLO

- Measured results above both LO and NLO predictions
  - In 1-jet and 1+2-jet bins predictions are within $1.5\sigma$
**Differential Cross-section Results**

- Measure the differential cross-sections as a function of $p_T^{b\text{-jet}}$

- Data above predictions in both 1- and 2-jet bins
- Increased deviation at high $p_T$ but consistent within theoretical and experimental errors
**Effects of DPI**

- Neither MCFM or Powheg predictions include the contribution from DPI
- Additive correction is derived from Alpgen
- Represents a 25% effect on the total cross-section and is concentrated in lower momentum bins in the 1-jet region
- Compare the additive DPI correction to multiplicative non-perturbative correction
- DPI contribution consistent with direct DPI measurements

<table>
<thead>
<tr>
<th></th>
<th>1 jet</th>
<th>2 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{fid}}$</td>
<td>$5.0 \pm 0.5$ (stat) $\pm 1.2$ (syst)</td>
<td>$2.2 \pm 0.2$ (stat) $\pm 0.5$ (syst)</td>
</tr>
<tr>
<td>Non-perturbative DPI [pb]</td>
<td>$0.92 \pm 0.02$ (had.) $\pm 0.03$ (UE)</td>
<td>$0.96 \pm 0.05$ (had.) $\pm 0.03$ (UE)</td>
</tr>
<tr>
<td></td>
<td>$1.02 \pm 0.05$ (stat) $\pm 0.4_{0.29}$ (syst)</td>
<td>$0.32 \pm 0.02$ (stat) $\pm 0.12_{0.09}$ (syst)</td>
</tr>
</tbody>
</table>
Results including Single-Top

- Combining $W + b$-jet and single-top templates provides a complementary perspective
- Higher statistical precision
- Results are compared to $W + b$-jets as taken from Alpgen combined with single-top from AcerMC scaled to NLO
- Observe increase in data over prediction as $p_T$ increases
DOUBLE PARTON INTERACTIONS (DPI)

- DPI is characterised by the effective area parameter, $\sigma_{\text{eff}}(s)$, which is assumed to be independent of phase space and process
- Previously a number of measurements have been performed in $pp$ and $p\bar{p}$ collisions at $\sqrt{s} = 63$ GeV, 630 GeV, 1.8 TeV and 1.96 TeV
- Measured values range from 5mb at low energies up to 15mb at Tevatron energies
- Interest in DPI at the LHC due to
  - Higher centre-of-mass enhances parton densities so expect larger impact of DPI on many signatures
  - Higher energy and luminosity means multiple interactions occur at higher transverse momentum
$W + 2$ JETS (arXiv:1301.6872)

- Measurement of $\sigma_{\text{eff}}(s)$ in 36pb$^{-1}$ of 2010 $pp$ collisions at $\sqrt{s} = 7$ TeV using $W$+2-jet events

- Extract the fraction of $W$+2 jet events from DPI, $f_{\text{DP}}^{(D)}$

$$f_{\text{DP}}^{(D)} = \frac{N_{W2j+2j_{\text{DPI}}}}{N_{W2j+2j}} = \frac{N_{W2j+2j_{\text{DPI}}}}{N_{W2j} + N_{W2j+2j_{\text{DPI}}}}$$

- Used to extract $\sigma_{\text{eff}}$ via

$$\sigma_{\text{eff}} = \frac{\sigma_{W0j} \cdot \sigma_{2j}}{\sigma_{W2j+2j_{\text{DPI}}}} = \frac{N_{W0j} \cdot N_{2j}}{f_{\text{DP}}^{(D)} \cdot N_{W+2j}} \cdot \frac{1}{\epsilon_{2j}} \cdot \frac{1}{L_{2j}}$$

- $W$ boson and 2j system assumed to factorise
Sample Definitions

- 3 samples are constructed

**$W+0$-jet**
events passing $W$ selection but with no additional jets found

**$W+2$-jet**
events passing $W$ selection and with exactly two additional jets found

**dijet**
events with exactly two jets using minimum bias trigger taken from a sample with negligible pile-up corresponding to 184 $\mu$b$^{-1}$ of data
**RESULTS**

- Fit the variable $\Delta_{\text{jets}}^n$ to distinguish DPI and non-DPI events in $W + 2$-jet events
- Template A (DPI-off) taken from MC with hard MPI events removed
- Template B (DPI-only) taken from dijet sample
- $f_{\text{DP}}$ also evaluated at parton level in MC and after hadron level unfolding
  - Shown to be within 10% of $f_{\text{DP}}^{(D)}$
  - $f_{\text{DP}}^{(D)} = 0.076 \pm 0.013\,(\text{stat}) \pm 0.018\,(\text{sys})$
  - $\sigma_{\text{eff}} = 15 \pm 3\,(\text{stat}) \pm 5 \pm 3\,(\text{syst})\,\text{mb} $
Comparing DPI measurements

- ATLAS value is consistent with previous DPI measurements

![Graph showing DPI measurements for different experiments and ATLAS, with ATLAS (W + 2 jets) highlighted.](image)
Conclusions

- ATLAS has carried out pQCD constraining measurements of
  - $V + \text{light jet}$ production
  - $W + c$ production
  - $W + b$ production

- In many regions of the phase space experimental uncertainties are below theoretical uncertainties

- $W + c$ measurements give important information on $s$-quark PDFs

- ATLAS has also carried out measurements of DPI using $W + 2$-jet events and provided a measurement of $\sigma_{\text{eff}}$ consistent with previous measurements

- Many of these measurements will benefit from increased datasets and/or energy which will allow us to
  - Reduce errors
  - Extend measurements to more extreme phase spaces
  - Further constrain theoretical calculations and PDFs
REFERENCES


### Z + jet Event Selection

#### Electron Selection
- $p_T^e > 20$ GeV
- $|\eta| < 2.47$
  (excluding $1.37 < |\eta| < 1.52$)

#### Muon Selection
- $p_T^\mu > 20$ GeV
- $|\eta| < 2.4$

#### Z Selection
- exactly 2 opposite sign leptons
- $66 \leq m_\| \leq 116$ GeV
- $\Delta R_\| > 0.2$

#### Jet Selection
- anti-$k_t$ jets with $R = 0.4$
- $p_T > 30$ GeV
- $|y| < 4.4$
- jets within $\Delta R = 0.5$ of leptons are removed\(^a\)
- jets with $|JVF| < 0.75$ are rejected\(^b\)

\(^a\) $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$

\(^b\) JVF = $p_T$ weighted fraction of tracks in the jet coming from interaction vertex
# $W + D$ Event Selection

## Electron Selection
- $p_T^e > 25$ GeV
- $|\eta| < 2.47$
  - (excluding $1.37 < |\eta| < 1.52$)

## Muon Selection
- $p_T^\mu > 20$ GeV
- $|\eta| < 2.4$

## W Selection
- exactly 1 lepton
- $E_{T}^{\text{miss}} > 25$ GeV
- $m_T > 40$ GeV

## D Selection
- Tracking information used to reconstruct $D$ using the decays
  - $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^0 \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^+$
  - and conjugate processes

## Additional event vetos
- To improve background rejection events are rejected if
  - An additional lepton is found
  - Three or more $p_T > 25$ GeV, $|\eta| < 2.5$ jets, Anti-$k_t$, $R = 0.4$ jets are found
**W + 2-jets Event Selection**

**Electron Selection**
- $p_T^e > 20$ GeV
- $|\eta| < 2.47$
  (excluding $1.37 < |\eta| < 1.52$)

**Muon Selection**
- $p_T^\mu > 20$ GeV
- $|\eta| < 2.4$

**W Selection**
- exactly 1 lepton
- $E_T^{\text{miss}} > 25$ GeV
- $m_T > 40$ GeV

**Jet Selection**
- anti-$k_t$ jets with $R = 0.4$
- $p_T > 20$ GeV
- $|y| < 2.8$
- jets within $\Delta R = 0.5$ of leptons are removed$^a$
- jets with $|JVF| < 0.75$ are rejected$^b$

---

$^a \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$

$^b$ JVF = $p_T$ weighted fraction of tracks in the jet coming from interaction vertex
Strategy is to fit the variable $\Delta_{n_{\text{jets}}}^n$ to distinguish DPI and non-DPI events.

Fit is performed on $W+2$-jet events after background subtraction.

MC used to estimate $Z \rightarrow ll$, diboson, $W \rightarrow \tau \nu$, $t\bar{t}$ and single $t$ production.

Multi-jet background taken from data-driven method.
\( W+2\text{-jets} \) **Extracting** \( f_{\text{DP}}^{(D)} \) (II)

- Two templates derived for fitting
  - Template A (DPI-off) taken from MC with hard MPI events removed
  - Template B (DPI-only) taken from dijet sample
- fit yields result \( f_{\text{DP}}^{(D)} = 0.076 \pm 0.013\text{(stat)} \pm 0.018\text{(sys)} \)
- \( f_{\text{DP}} \) evaluated at parton level in MC and after hadron level unfolding shown to be within 10\% of \( f_{\text{DP}}^{(D)} \)

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Uncertainty [%]</th>
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<tbody>
<tr>
<td>Theory</td>
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<td>Pile-up</td>
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<td>Jet energy scale</td>
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<td>Jet energy resolution</td>
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<td>Background modelling</td>
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<tr>
<td>Lepton response</td>
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</tr>
<tr>
<td>Total systematic</td>
<td>24</td>
</tr>
<tr>
<td>Total statistical</td>
<td>17</td>
</tr>
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</table>
$W+2$-jets Extracting $\sigma_{\text{eff}}$

- We derive $\sigma_{\text{eff}}$ from $f_{\text{DP}}^{(D)}$
- Take the other necessary values from
  - $N_{W0j}/N_{W+2j}$ from event yields in the $W$ samples
  - $N_{2j}, \mathcal{L}_{2j} = 184 \mu b^{-1}$ and $\epsilon_{2j} = 1$ from dijet selection
  - A further correction to $N_{2j}$ for the lepton-jet overlap removal not applied in the dijet selection
- Gives a measured value of
  $$\sigma_{\text{eff}} = 15 \pm 3(\text{stat}) \pm_{-3}^{+5}(\text{syst}) \text{ mb}$$

Reminder

$$\sigma_{\text{eff}} = \frac{N_{W0j} N_{2j}}{f_{\text{DP}}^{(D)} \cdot N_{W+2j}} \cdot \frac{1}{\epsilon_{2j}} \cdot \frac{1}{\mathcal{L}_{2j}}$$

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<td>Lepton response</td>
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<tr>
<td>Luminosity</td>
<td>3</td>
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<tr>
<td>Total systematic</td>
<td>$+33$</td>
</tr>
<tr>
<td>Total statistical</td>
<td>$-20$</td>
</tr>
</tbody>
</table>
W + 2-jets at hadron level

ATLAS

- Wlv unfolded data, \( \sqrt{s} = 7 \) TeV
- Fit distribution
- A+H+J particle-level template A
- PYTHIA particle-level template B

\[ \int Ldt = 36 \text{ pb}^{-1} \]
**W + b Event Selection**

**Electron Selection**
- $p_T^e > 25$ GeV
- $|\eta| < 2.47$
  (excluding $1.37 < |\eta| < 1.52$)

**Muon Selection**
- $p_T^\mu > 25$ GeV
- $|\eta| < 2.4$

**W Selection**
- exactly 1 lepton
- $E_T^{\text{miss}} > 25$ GeV
- $m_T > 60$ GeV

**Jet Selection**
- 1 or 2 anti-$k_t$ jets with $R = 0.4$
- exactly one $b$-tagged jet
- $p_T > 25$ GeV
- $|y| < 2.1$
- jets within $\Delta R = 0.5$ of leptons are removed$^a$
- jets with $|JVF| < 0.75$ are rejected$^b$

$^a\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$

$^bJVF = p_T$ weighted fraction of tracks in the jet coming from interaction vertex
**W + b Background Estimation**

- Single-top, $t\bar{t}$ and multijet backgrounds are estimated from data.
- MC is used to extrapolate to signal regions for single-top and $t\bar{t}$ backgrounds.
- MC used to estimate $Z$ and diboson contributions.
- $W+b$-jets, $W+c$-jets and $W+$light-jets contributions are statistically separated using the different responses to the CombNN $b$ tagging algorithm and templates derived from MC.