Measurement of hard double-parton interactions with the ATLAS detector - New J.Phys. 15 (2013) 033038

Photon 2013 - Paris

THE UNIVERSITY OF WARWICK

Tim Martin

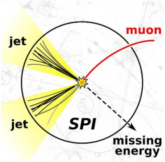
University of Warwick

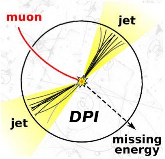
On behalf of the ATLAS Collaboration

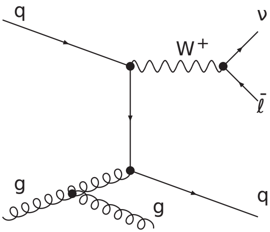
May 23, 2013

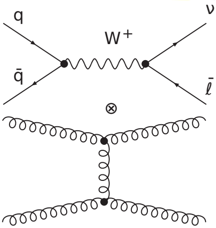
Introduction to Double Parton Interactions

- For di-jets systems produced in association with a W boson, the jets tend to display a greater degree of collinearity.
- Assuming no correlation between the systems, di-jet systems from DPI *balance each other in* p_{T} and are *independent of the primary scatter*.









$\sigma_{\text{eff}}(s)$

- Effective area parameter for double-parton interactions: $\sigma_{\text{eff}}(s)$

$$\sigma_{\text{eff}}(s) = \frac{\sigma_W(s).\sigma_{2\text{j}}(s)}{\sigma^{(\text{tot})}_{W+2\text{j}}(s) - \sigma^{(\text{SPI})}_{W+2\text{j}}(s)}$$

- Probability of second hard scatter, given that one has occurred, is proportional to the flux of the accompanying partons.
- Being bound in the hadron, their flux is inversely proportional to the proton cross-sectional area. σ_{eff} also includes longitudinal correlations.
- The effective cross section for DPI has little to do with the measured strength of the interaction.
- ATLAS W+b-jets [arXiv:1302.2929] cross section measurement has $^{+39}_{-28}$% uncertainty on its DPI correction.

Analysis Strategy

- Identify $W + 2\mathrm{jet}$ candidate events with the $W \rightarrow e\nu_e$ and $W \rightarrow \mu\nu_\mu$ modes.
- Using the ATLAS 2010 data set, $36\mathrm{pb}^{-1}$ of usable data at low pileup.
- Extract the fraction of the sample, $f_{\mathrm{DP}}^{\mathrm{Detector}}$ whose origin was from a secondary hard scatter.

$$f_{\mathrm{DP}}^{\mathrm{Detector}} = \frac{N_{W_{0\mathrm{j}}+2\mathrm{j}_{\mathrm{DPI}}}}{N_{W_{2\mathrm{j}}}+N_{W_{0\mathrm{j}}+2\mathrm{j}_{\mathrm{DPI}}}}$$

- $N_{W_{2\mathrm{j}}}$ is the number of events with the jets directly associated with the production of the W, $N_{W_{0\mathrm{j}}+2\mathrm{j}_{\mathrm{DPI}}}$ is the number of events where the jets originate from DPI.

Event Selection

- **Jets** were selected with the anti-k_t algorithm
  - Radius parameter $R = 0.4$.
  - $p_{\mathrm{T}} > 20$ GeV
  - $|y| < 2.8$.
- Additional requirements were placed on the Jet Vertex Fraction of associated tracks to reduce the effect of multiple pp collisions. Jets within $\Delta R < 0.5$ of a selected lepton were removed.
- Isolated **electron** candidates were selected with:
  - $p_{\mathrm{T}} > 20$ GeV
  - $|\eta| < 2.47$.
- Prompt **muon** candidates were selected using both inner detector tracking and outer muon spectroscopy.
  - $p_{\mathrm{T}} > 20$ GeV
  - $|\eta| < 2.4$

Event Selection

- Events with exactly one charged lepton were selected, these were further required to have:
  - Missing energy $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
  - Transverse mass from lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}} > 40$ GeV.

- Data samples with above selection:
  - $W + 0\mathrm{jet}$
  - $W + 2\mathrm{jet}$
  - di-jet. Events with exactly two jets, selected with fully unbiased and efficient trigger (Minimum Bias Trigger Scintillators and Zero Degree Calorimeter).

- *W* selection similar to "Study of jets produced in association with a W boson" ATLAS Collaboration, Phys. Rev. D 85, 092002 (2012)

Monte Carlo Samples

- W boson signal samples from Alpgen using the MLM matching scheme, interfaced with Herwig and Jimmy, using the AUET2 tune. Referred to as `A+H+J`
- W boson additionally simulated with Sherpa using CKWW merging and default underlying event tune.

Analysis Variables

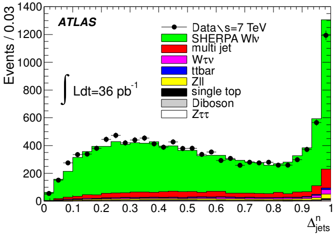
- The kinematics of the W and jets in DPI events are assumed uncorrelated.
- The momentum balance of such jets should be near zero in the transverse plane and is better than the azimuthal balance ($\Delta\phi^{\mathrm{j1j2}}$) which is more sensitive to the underlying event.
- In addition, the transverse momenta of the di-jet system normalised by the sum of individual jets is considered. This quantity is less affected by jet energy scale uncertainties.

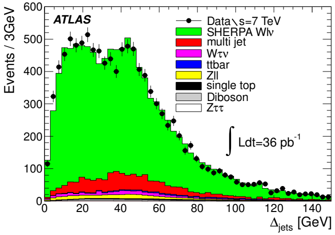
$$\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J1} + \vec{p}_{\mathrm{T}}^{J2}| \ , \qquad \Delta_{\mathrm{jets}}^{n} = \frac{|\vec{p}_{\mathrm{T}}^{J1} + \vec{p}_{\mathrm{T}}^{J2}|}{|\vec{p}_{\mathrm{T}}^{J1}| + |\vec{p}_{\mathrm{T}}^{J2}|}$$

$\Delta_{\mathrm{jets}}^{n}$ is used to obtain the main result.

Backgrounds

Pythia6: $Z \to ll$, Powheg: $t\bar{t}$, MC@NLO: single top plus di-boson.





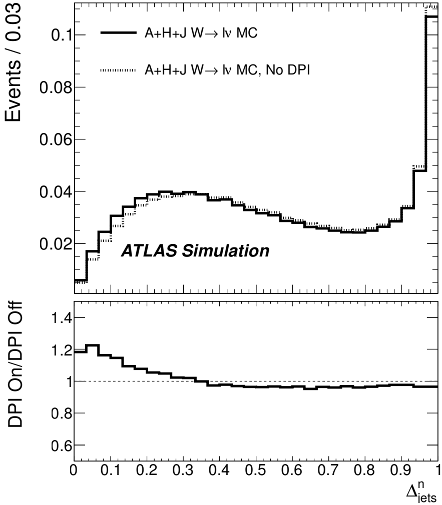
- A data-driven multi-jet background contamination was taken by reversing certain shower shape requirements,
- Backgrounds amount to:
  - **19%** of electron channel (dominantly multi-jet and $W \to \tau\nu_\tau$)
  - **14%** muon channel (dominantly multi-jet and $Z \to ll$).

DPI Fraction Extraction

- Additional parton-parton scatters result in additional hadronic activity or materialise as jets.
- A threshold $p_{\mathrm{T}}^{\mathrm{max}}$ is introduced to separate 'hard' and 'soft' scatters in MC.
- A template fit is performed on the $\Delta_{\mathrm{jets}}^{\mathrm{n}}$ distribution to extract $f_{\mathrm{DP}}^{\mathrm{Detector}}$ from background-corrected data.
- Template A: "DPI Off - $W_{2\mathrm{j}}$ Only"
  - Main sample from `A+H+J`. Hard MPI candidates removed by cutting events with two or more secondary partons above cut of scale $p_{\mathrm{T}}^{\mathrm{max}} = 15$ GeV.
  - Secondary sample from Sherpa with MPI switched off, no secondary pertubative scatters in range $p_{\mathrm{T}} > 3.5$ GeV.

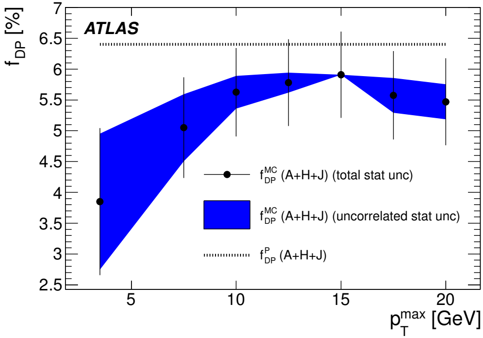
DPI Fraction Extraction

- Template B, "DPI Only"
- Sample in which both jets originate from DPI. Approximated using the data di-jet sample.
- Result difference using Pythia6 MC in place of data for this sample found to be well below the percent level.



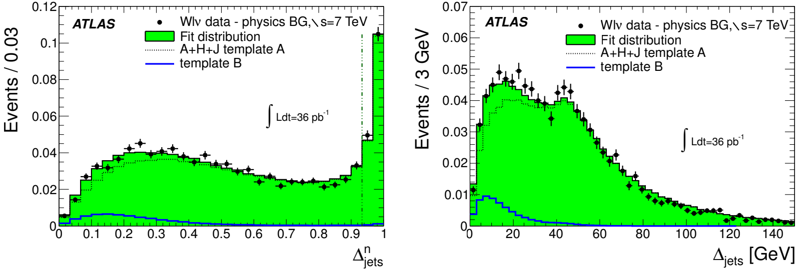
The Effect of $p_{\mathrm{T}}^{\max}$

- Choose $p_{\mathrm{T}}^{\max} = 15$ GeV, the value with best agreement between the MC extraction and the parton level value from the MC.
- The MC detector level is within 10% of the parton level, and can be interpreted as a result at the parton level to within this accuracy.



Detector Level Fits

- Background subtracted data are fit to the two templates in linear combination. Excluding last 2 bins of Δ^n_{jets}.
- A pileup correction is applied $(r_{\mathrm{pile-up}} = 1.17 \pm 0.15(\mathrm{stat.}))$.



Compatible results are obtained from both Δ^n_{jets} and Δ_{jets}.

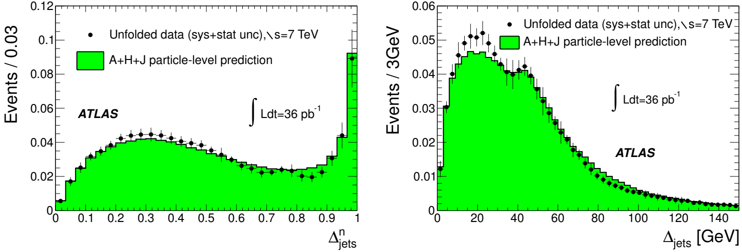
$$f^{\mathrm{Detector}}_{\mathrm{DP}}(\Delta^n_{\mathrm{jets}}) = 0.076 \pm 0.013(\mathrm{stat.}), \quad \chi^2/N_{\mathrm{dof}} = 37/28$$

Sources of Uncertainty

Source	**Uncertainty**
Theory	10%
Pile-up	13%
Jet Energy Scale	12%
Jet Energy Resolution	8%
Background Modelling & Lepton Response	11%
Total Systematic	**24%**
Total Statistical	**17%**

Correction to Hadron Level

- Key distributions are corrected for detector effects.
- Generator level definition matches detector level, however jet finding algorithms run over final state hadron-level particles.
- Data are corrected using a Bayesian unfolding approach.



These corrected data are available for use in MC tuning or alternative approaches for DPI extraction.

Determination of σ_{eff}

- σ_{eff} is calculated using the event yields along with $f_{\mathrm{DP}}^{\mathrm{Detector}}$.
- The obtained value agrees with the result obtained when fitting the data corrected to the hadron level to within 10%.

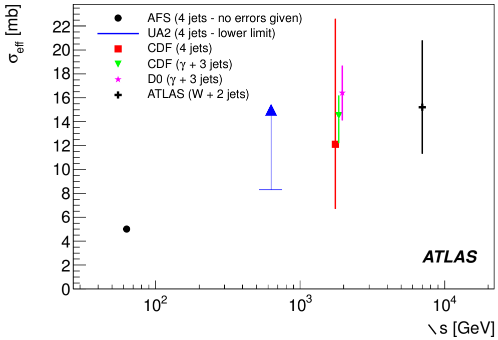
$$\sigma_{\mathrm{eff}} = \left(\frac{N}{\cancel{\mathcal{AC}}\,.\,\cancel{\epsilon\mathcal{L}}}\right)_{W+0\mathrm{j}} \cdot \left(\frac{N}{\cancel{\mathcal{AC}}\,.\,\epsilon\mathcal{L}}\right)_{2\mathrm{j}} \cdot \left(\frac{\cancel{\mathcal{AC}}\,.\,\cancel{\epsilon\mathcal{L}}}{f_{\mathrm{DP}}^{\mathrm{Detector}}.N}\right)_{W+2\mathrm{j}}^{\mathrm{DPI}}$$

- As $W_{0\mathrm{j}} + 2\mathrm{j}_{\mathrm{DPI}}$ and $W + 0\mathrm{j}$ events are taken with the same trigger, $\mathcal{L}$ and efficiency cancel.
- Assuming DPI as independent processes, correction & acceptance factors ($\mathcal{AC}$) cancel.
- The di-jet sample was fully efficient ($\epsilon_{2\mathrm{j}} = 1$).

$$\sigma_{\mathrm{eff}}(\sqrt{s} = 7\ \mathrm{TeV}) = 15 \pm 3(\mathrm{stat.})^{+5}_{-3}(\mathrm{syst.})\mathrm{mb.}$$

Determination of σ_{eff}

- The uncertainty on σ_{eff}:
  - **24%** dominant propagation from $f_{\text{DP}}^{\text{Detector}}$.
  - **3%** luminosity uncertainty
  - **5%** uncertainty on the response to leptons & background used to evaluate exclusivity ratio, $N_{W+0\text{j}}/N_{W+2\text{j}}^{\text{DPI}}$.



Conclusion

- The double-parton interaction rate, $f_{\mathrm{DP}}^{\mathrm{Detector}}$ in events with a W boson and exactly two jets has been extracted in pp collisions at $\sqrt{s} = 7$ TeV.
- The data are used to extract a value for the parameter σ_{eff} which is consistent with previous measurements at lower centre-of-mass energies.
- Unfolded distributions of Δ_{jets} and $\Delta^{n}_{\mathrm{jets}}$ are presented.

The Effect of $p_{\mathrm{T}}^{\max}$

- In Sherpa, the only option is to switch off secondary interactions to remove DPI ($p_{\mathrm{T}}^{\max} \sim 3.5$ GeV).
- In `A+H+J`, this can be steered through moving the $p_{\mathrm{T}}^{\max}$ cut.
- `A+H+J` with $p_{\mathrm{T}}^{\max} = 3.5$ GeV reproduces Sherpa result to within 10%.
- Optimal $p_{\mathrm{T}}^{\max}$ cut should retain soft interactions (present in the data di-jet sample, Template B).

However jets with $p_{\mathrm{T}} > 20$ GeV should not enter Template A.

Effects of Pile Up Interactions

- Use of only single interaction data not possible due to available statistics in the W sample.
- The fraction of DP was extracted from MC requiring exactly one interaction on both `A+J+H` pseudo-data, Template A and the data di-jet Template B.
- The ratio of the extracted fraction with and without the one-vertex requirement yields a correction factor $r_{\mathrm{pile-up}} = 1.17 \pm 0.15(\mathrm{stat.})$.
- The statistical uncertainty on $r_{\mathrm{pile-up}}$ is propagated as a systematic uncertainty where appropriate.