Direct measurement of double-parton scattering with ATLAS

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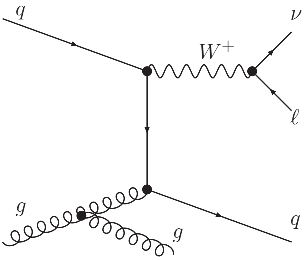
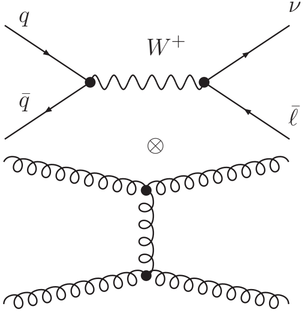
Introduction

- ▷ Hard double parton interactions (DPI) are measured in the $W + 2$ jets ($W + 2\text{j}$) channel with the ATLAS experiment.
- ▷ The kinematics of the jet system are used to extract the fraction of DPI events out of all $W + 2\text{j}$ final states.
- ▷ The DPI-fraction is used to compute σ_{eff} for detector-level DPI-jets with transverse momentum, $p_{\text{T}} > 20$ GeV, and rapidity, $|y| < 2.8$.
- ▷ Several improvements are included since the previous analysis (ATLAS-CONF-2011-160), including; ▷ ALPGEN, coupled to HERWIG and JIMMY, (AHJ) is now the primary MC used to define the DPI-off Template. ▷ Particle-level distributions are provided.





From theory to experiment

- General formalism for DPI:

$$d\sigma^{(\mathrm{DPI})}_{Y+Z}(s) = \frac{m}{2\sigma_{\mathrm{eff}}(s)} \int \mathrm{d}x_1\,\mathrm{d}y_1\,\mathrm{d}x_2\,\mathrm{d}y_2\,[f_{i_1 j_1}(x_1, y_1, \mu_F) f_{i_2 j_2}(x_2, y_2, \mu_F)\, \mathrm{d}\sigma_{i_1 i_2 \to Y}(x_1, x_2, s)\,\mathrm{d}\sigma_{j_1 j_2 \to Z}(y_1, y_2, s)]$$

Assuming $Y \neq Z$; factorization (no correlations) of the double-parton distribution functions, $f_{ij}(x, y, \mu_F)$; and integration of the cross sections over some phase-space:

$$\sigma^{(\mathrm{DPI})}_{Y+Z} = \frac{\sigma_Y \cdot \sigma_Z}{\sigma_{\mathrm{eff}}}$$

- For $W + 2\mathrm{j}$ (after some gymnastics) this gives:

$$\sigma_{\mathrm{eff}} = \frac{\sigma_{W_{0\mathrm{j}}} \cdot \sigma_{2\mathrm{j}}}{\sigma_{W_{0\mathrm{j}}+2\mathrm{j}_{\mathrm{DPI}}}} = \frac{\sigma_{W_{0\mathrm{j}}} \cdot \sigma_{2\mathrm{j}}}{f^{(\mathrm{D})}_{\mathrm{DP}}\,\sigma_{W_{0\mathrm{j}}+2\mathrm{j}}} = \frac{1}{f^{(\mathrm{D})}_{\mathrm{DP}}} \cdot \frac{N_{W_{0\mathrm{j}}}}{N_{W+2\mathrm{j}}} \cdot \frac{N_{2\mathrm{j}}}{\mathcal{L}_{2\mathrm{j}}}$$

$f^{(\mathrm{D})}_{\mathrm{DP}}$ - fraction of $W + 2\mathrm{j}$ DPI events; N_x - number of events of type x; $\mathcal{L}_{2\mathrm{j}}$ - luminosity.

Data/MC samples and data selection

- Jets reconstructed with the anti-$k_\perp$ algorithm ($R = 0.4$), defined as having transverse momentum, $p_T > 20$ GeV, and rapidity, $|y| < 2.8$.

Data samples	details
Data (W)	All 2010 data run (36 pb^{-1})
Data (jets)	All 2010 data run (and related subsets)

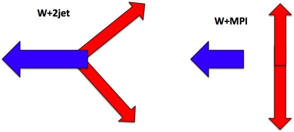
- $W + 0$j selection: ▹ All 2010 W data; ▹ collected with a single lepton trigger; ▹ 1 lepton (e, μ) with $p_T > 20$ GeV, $|\eta| < 2.4$; ▹ missing transverse energy, $E_T^{miss} > 25$ GeV, and mass $M_T > 40$ GeV; ▹ no jets.
- $W + 2$j selection: ▹ Selection as for $W + 0$j with the exception of ▹ exactly two jets.
- Dijet selection: ▹ Partial 2010 dataset (184 $\mu\mathrm{b}^{-1}$), collected with the Minimum bias trigger; ▹ exactly two jets.

MC Samples	details
AHJ (incl.)	MLM matching, JIMMY v4.31, AUET tune, HERWIG v6.510
SHERPA (incl.)	v1.3.1, default UE, CKKW matching scale is 15 GeV

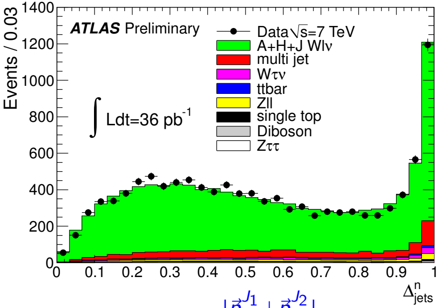
Strategy of the analysis

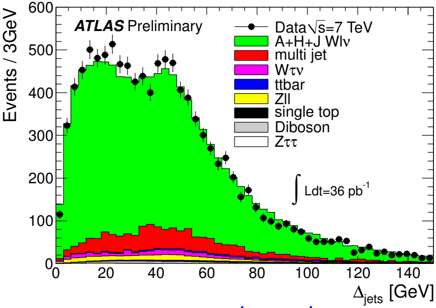
- Possible observables: ▷ Transverse momentum of the W (needs $E_{\mathrm{T}}^{\mathrm{miss}}$); ▷ p_{T} distributions of jets (significant jet energy scale uncertainties); ▷ Azimuthal correlation between jets (pile-up and underlying event affect it);

Schematic representation
in the transverse plain



- The normalized transverse momentum balance between the jets, $\Delta^{\mathrm{n}}_{\mathrm{jets}}$, is chosen. The balance without normalization, Δ_{jets}, is used for cross-checks.





$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$$

$$\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$$

Strategy of the analysis

$$f_{\mathrm{DP}}^{(\mathrm{D})} = \frac{N_{W_{0j}+2j_{\mathrm{DPI}}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{\mathrm{DPI}}}}{N_{W_{2j}} + N_{W_{0j}+2j_{\mathrm{DPI}}}}$$

- Estimate $f_{\mathrm{DP}}^{(\mathrm{D})}$ by fitting the data to a combination of two templates, $(1 - f_{\mathrm{DP}}^{(\mathrm{D})}) \cdot A + f_{\mathrm{DP}}^{(\mathrm{D})} \cdot B$.
  - **Template** A - **DPI-off:** AHJ (ALPGEN +HERWIG +JIMMY) based sample including a W and two jets.
  - **Template** B - **DPI-on:** Dijet sample extracted from data.

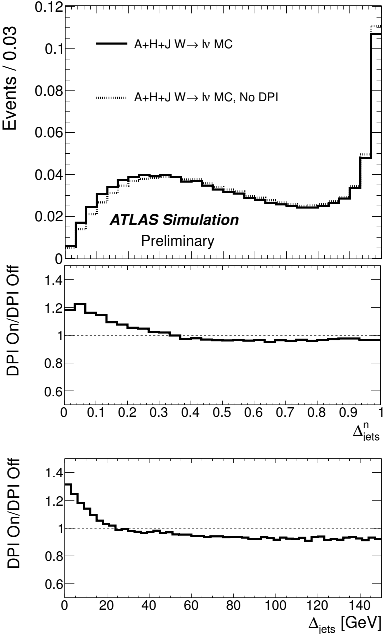
$$\sigma_{\mathrm{eff}} = \frac{1}{f_{\mathrm{DP}}^{(\mathrm{D})}} \cdot \frac{N_{W_{0j}}}{N_{W+2j}} \cdot \frac{N_{2j}}{\mathcal{L}_{2j}}$$

- Measure the dijet cross section (at detector-level, $N_{2j}/\mathcal{L}_{2j}$).
- Measure the number of $W+0j$ and $W+2j$ events.

MPI in AHJ

- ▷ MCs incorporate multiple-parton interactions (MPI) as part of the description of the underlying event. This mostly includes soft collisions.
- ▷ Hard MPI collisions can be regulated in AHJ by cutting on the parameter $p_{\mathrm{T}}^{\max}$(no MPI above chosen threshold).

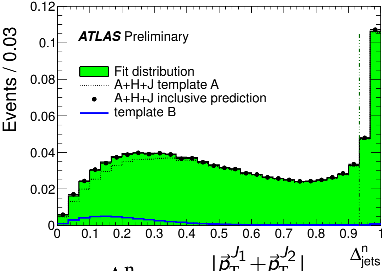
(Right ⟶) Plots show comparison of DPI-on/off in MC for $\Delta_{\mathrm{jets}}^{\mathrm{n}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$ (top) and $\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$ (bottom).
▷ The variance is due to the different cut on MPI-p_{T}.



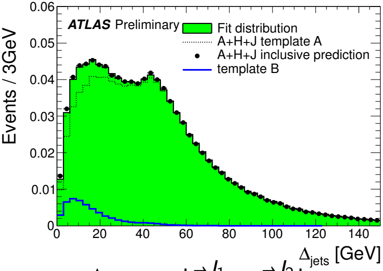
Improvements to the analysis since ATLAS-CONF-2011-160

- Anti-$k_\perp$ jets with size parameter $R = 0.4$ instead of 0.6 are used.
- SHERPA no longer used to derive the central value (it is used for systematic studies) → AHJ is used as the nominal MC.
- CKKW matching threshold in SHERPA is lowered from 30 GeV (increasing the jet correlation of the no-DPI SHERPA sample.)
- DPI-off sample of AHJ is defined by rejecting events which have partons with $p_{\mathrm{T}}^{\mathrm{max}} > 15$ GeV (instead of 3.5 GeV). Partons are not matched to reconstructed jets.
- Additional background samples are subtracted from data; single top, diboson and $Z \to \tau\tau$.
- Pile-up calibration to jets improved. In addition, a pileup correction factor, $r_{\mathrm{pile-up}} = 1.17 \pm 0.15\,(\mathrm{stat.})$, is incorporated into calculation of $f_{\mathrm{DP}}^{(\mathrm{D})}$.

Validation of the analysis strategy



$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$

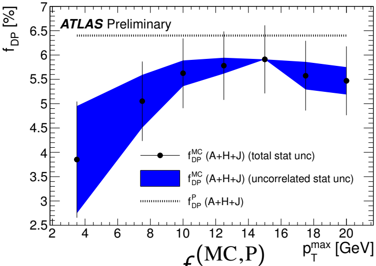


$$\Delta_{jets} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$$

(Up↑) Mimic the data by turning on MPI in AHJ, and use it to construct Template *B* (DPI-on).

Consistent results are achieved for $f_{DP}^{(MC)}$ (DPI fraction in MC) with Δ^{n}_{jets} and Δ_{jets}.

(Right →) Change the value of p_T^{max} and compare to the value of $f_{DP}^{(P)}$ (DPI fraction on the parton level.)



$f_{DP}^{(MC,P)}$

Uncertainties

- Uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$:
  - "Theoretical" uncertainty - due to generator model. Alternate between AHJ or SHERPA; change the value of $p_{\mathrm{T}}^{\max}$in AHJ.
  - Jet energy scale (JES) and Jet energy resolution (JER) - the value of calibrated jet energies is shifted up and down (JES) or smeared (JER).
  - Physics backgrounds and lepton response - estimated separately for the electron and muon channels, by varying the normalization and shape of the background.
  - Pile-up - a correction is used to estimate the effect of pile-up on $f_{\mathrm{DP}}^{(\mathrm{D})}$, using a scaling parameter, $r_{\mathrm{pile-up}} = 1.17 \pm 0.15\,(\mathrm{stat.})$. The uncertainty on this parameter is propagated.
  - Impact of $W+1$j events is found to be negligible on the DPI rate and on the modeling of Template A.
- Uncertainties on $\sigma_{\mathrm{eff}} = 1/f_{\mathrm{DP}}^{(\mathrm{D})} \cdot N_{W_{0\mathrm{j}}}/N_{W+2\mathrm{j}} \cdot N_{2\mathrm{j}}/\mathcal{L}_{2\mathrm{j}}$:
  - Uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$ are propagated.
  - Physics backgrounds and lepton response - in addition to those on $f_{\mathrm{DP}}^{(\mathrm{D})}$, the impact of the uncertainty on the ratio, $N_{W_{0\mathrm{j}}}/N_{W+2\mathrm{j}}$, are included.
  - Uncertainty on the luminosity is included.

Uncertainties

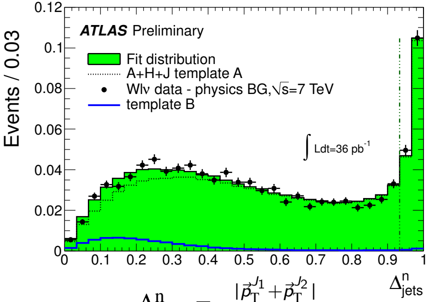
▷ Fractional uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$:

Systematic source	Unc [%]
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background & lepton	11
Total systematic	24
Total statistical	17

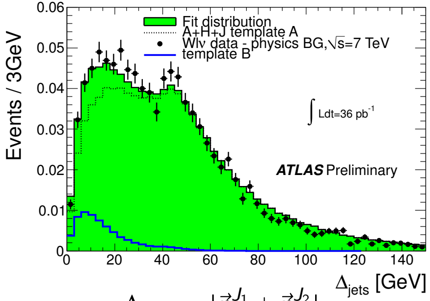
▷ Fractional systematic uncertainties on σ_{eff}:

Systematic source	Unc. [%]
$f_{\mathrm{DP}}^{(\mathrm{D})}$	24
Background & lepton response	3
Luminosity	3
Total systematic	25
Total statistical	17

Extraction of $f_{\mathrm{DP}}^{(\mathrm{D})}$ and the corresponding σ_{eff}



$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$$

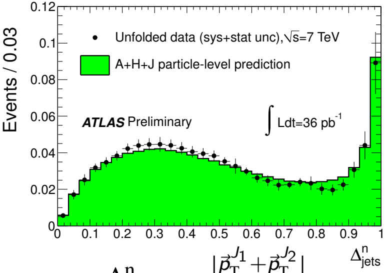


$$\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$$

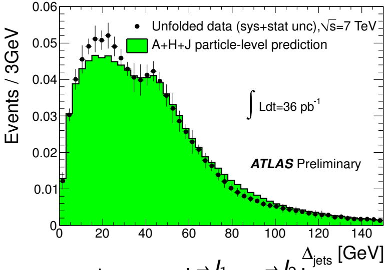
- Extract $f_{\mathrm{DP}}^{(\mathrm{D})}$ by a fit to the distribution of $\Delta^{\mathrm{n}}_{\mathrm{jets}}$ of Templates A and B using: $(1 - f_{\mathrm{DP}}^{(\mathrm{D})}) \cdot A + f_{\mathrm{DP}}^{(\mathrm{D})} \cdot B$.

$$f_{\mathrm{DP}}^{(\mathrm{D})} = 0.08 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{sys.})$$
$$\sigma_{\mathrm{eff}} = 15 \pm 3\,(\mathrm{stat.})\,^{+5}_{-3}\,(\mathrm{sys.})\ \mathrm{mb}$$

Particle-level distributions



$$\Delta^{n}_{\text{jets}} = \frac{|\vec{p}_{\text{T}}^{J_1} + \vec{p}_{\text{T}}^{J_2}|}{|\vec{p}_{\text{T}}^{J_1}| + |\vec{p}_{\text{T}}^{J_2}|}$$



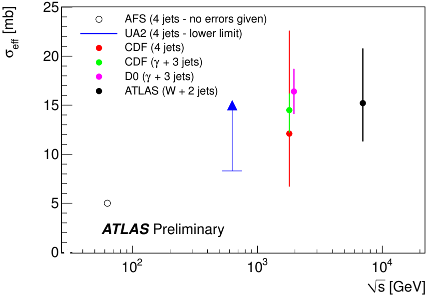
$$\Delta_{\text{jets}} = |\vec{p}_{\text{T}}^{J_1} + \vec{p}_{\text{T}}^{J_2}|$$

- ▷ Data are unfolded using a Bayesian unfolding algorithm implemented in the `RooUnfold` package.
- ▷ The unfolding response matrix is trained on AHJ, using two iterations.
- ▷ Here data is compared to the particle-level distributions directly from AHJ.

Summary

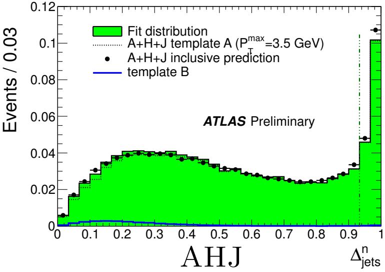
- The fraction of DPI events in the $W+2$j channel, $f_{\mathrm{DP}}^{(\mathrm{D})}$, is measured with the ATLAS experiment.
- $f_{\mathrm{DP}}^{(\mathrm{D})}$ is extracted from a fitted combination of two templates, DPI-off (based on AHJ) and DPI-on (dijet events from data).
- $f_{\mathrm{DP}}^{(\mathrm{D})}$ is used to compute σ_{eff}.
- Result for σ_{eff} consistent with previous measurements at lower energies. $\sqrt{s}$ dependence can not be confirmed or excluded.

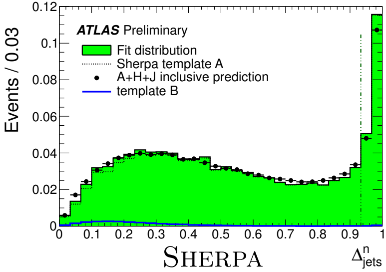
$$f_{\mathrm{DP}}^{(\mathrm{D})} = 0.08 \pm 0.01\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{sys.})$$
$$\sigma_{\mathrm{eff}} = 15 \pm 3\ (\mathrm{stat.})\ {}^{+5}_{-3}\ (\mathrm{sys.})\ \mathrm{mb}$$



Backup slides

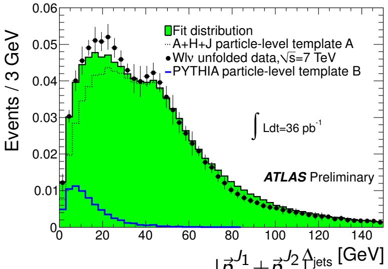
Validation of the analysis strategy



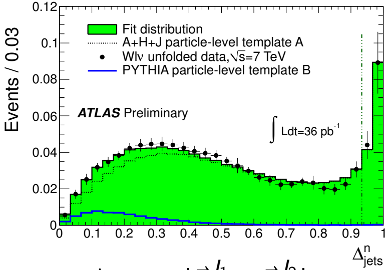


- Set $p_{\mathrm{T}}^{\mathrm{max}} = 3.5$ GeV in AHJ, which is then equivalent to the SHERPA cut in the no-MPI setting.
- Measure $\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$ and fit $f_{\mathrm{DP}}^{(\mathrm{MC})}$ in both AHJ and SHERPA. Do the same for Δ_{jets} (not shown here.)
- The values of $f_{\mathrm{DP}}^{(\mathrm{MC})}$ in AHJ and in SHERPA, respectively, $f_{\mathrm{DP}}^{(\mathrm{AHJ})} = 0.034 \pm 0.006$ and $f_{\mathrm{DP}}^{(\mathrm{S})} = 0.031 \pm 0.008$, are found to be consistent.

Particle-level distributions



$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|}{|\vec{p}_{\mathrm{T}}^{\,J_1}| + |\vec{p}_{\mathrm{T}}^{\,J_2}|}$$



$$\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|$$

- The fitted value of $f_{\mathrm{DP}}^{(\mathrm{D})}$ for the particle-level distributions is slightly different than that for the hadron-level distributions (due to differences in phase-space between the two.)
- The particle-level distributions are not used to extract $f_{\mathrm{DP}}^{(\mathrm{D})}$ and the corresponding σ_{eff} as the main results of the analysis. These distributions are given as reference for future studies.