Measurement of hard double-parton interactions in $W(\rightarrow \ell\nu) + 2$ jet events at $\sqrt{s} = 7$ TeV with the ATLAS detector

Orel Gueta

Tel-Aviv University

On behalf of the ATLAS Collaboration

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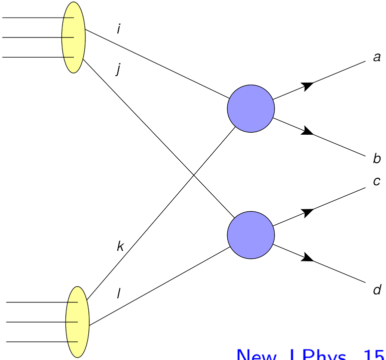
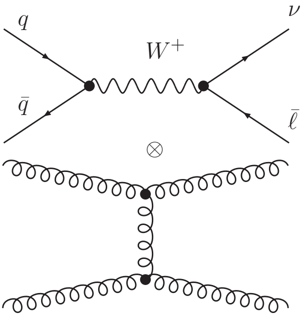
Introduction

- The rate of hard double-parton interactions (DPI) was measured in the $W + 2$ jets ($W + 2\text{j}$) channel with the ATLAS experiment.
- The kinematics of the jet system were used to extract the fraction of DPI events out of all $W + 2\text{j}$ final states.
- The DPI-fraction was used to compute σ_{eff}, a supposedly process-independent parameter related to the transverse size of the proton.





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Phenomenological background

The DPI phenomenology is based on the general expression for $\mathrm{d}\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s)$ in $pp \rightarrow Y + Z + (\mathrm{X})$,

$$\mathrm{d}\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s) = \frac{1}{1+\delta_{YZ}} \int \mathrm{d}x_{i_1}\, \mathrm{d}x_{j_1}\, \mathrm{d}x_{i_2}\, \mathrm{d}x_{j_2}\, d^2 r_\perp \, [A^2(r_\perp) f_{i_1 j_1}(x_{i1},\, x_{j_1},\, \mu_F) f_{i_2 j_2}(x_{i_2},\, x_{j_2},\, \mu_F) \\ \mathrm{d}\hat{\sigma}_{i_1 i_2 \rightarrow Y}(x_{i_1},\, x_{i_2},\, s)\, \mathrm{d}\hat{\sigma}_{j_1 j_2 \rightarrow Z}(x_{j_1},\, x_{j_2},\, s)]$$

For $W + 2$ jets,

- Assume independent interactions $\Rightarrow$ convolution of DPDFs and overlap function;
- factorization ansatz, $f_{ij}(x_i,\, x_j,\, \mu_F) = f_i(x_i,\, \mu_F)\, f_j(x_j,\, \mu_F)\, (1 - x_i - x_j)\, \Theta\, (1 - x_i - x_j)$;
- integrate over the phase space defined by selection cuts;
- define $\sigma_{\mathrm{eff}}(s)$ as the reciprocal of the integral of the overlap function,

$$\sigma_{\mathrm{eff}}(s) = \left[\int d^2 r_\perp A^2(r_\perp) \right]^{-1} \implies \hat{\sigma}^{(\mathrm{DPI})}_{Y+Z} = \frac{\hat{\sigma}_Y \cdot \hat{\sigma}_Z}{\sigma_{\mathrm{eff}}}.$$

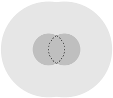
From theory to experiment

Measurements of $\sigma_{\rm eff}$,

Experiment	$\sqrt{s}$ (GeV)	Final state	$\sigma_{\rm eff}$
AFS (pp), 1986 [1]	63	4 jets	~5 mb
UA2 ($p\bar{p}$), 1991 [2]	630	4 jets	>8.3 mb (95% C.L)
CDF ($p\bar{p}$), 1993 [3]	1800	4 jets	$12.1^{+10.7}_{-5.4}$ mb
CDF ($p\bar{p}$), 1997 [4]	1800	$\gamma+$ 3-jets	$14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
DØ ($p\bar{p}$), 2010 [5]	1960	$\gamma+$ 3-jets	$16.4 \pm 0.3 \pm 2.3$ mb
CMS (pp), 2014 [6]	7000	$W+$ 2 jets	$20.7 \pm 0.8 \pm 6.6$ mb

The parameter $\sigma_{\rm eff}$ is,

- a parton level defined quantity;
- scaling parameter for the probability of a hard secondary scatter;
- assumed to be process and cut independent;
- no dependence on center-of-mass energy seen (considering uncertainties);
- related to the transverse size of the region where hard interactions are localized;
- measured results point to a proton size smaller than geometrical size ($\sigma_{\rm eff} \approx \pi R_p^2 \approx 50\ mb$).



A measurement of $\sigma_{\rm eff}$ may be performed through,

$$\sigma_{\rm eff}(s) = \frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{\hat{\sigma}^{\rm (tot)}_{Y+Z}(s) - \hat{\sigma}^{\rm (SPI)}_{Y+Z}(s)} = \frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{f^{\rm (D)}_{\rm DP}\cdot\hat{\sigma}^{\rm (tot)}_{Y+Z}(s)}.$$

From theory to experiment

The full expression for σ_{eff} in the W + 2 jets final state is

$$\sigma_{\text{eff}} = \frac{1}{f_{\text{DP}}^{(\text{D})}} \cdot \frac{N_{W_{0j}} N_{2j}}{N_{W+2j}} \cdot \frac{\mathcal{L}_{W_{0j}+2j_{\text{DPI}}}}{\mathcal{L}_{W_{0j}} \mathcal{L}_{2j}} \cdot \frac{\mathcal{A}_{W_{0j}+2j_{\text{DPI}}}}{\mathcal{A}_{W_{0j}} \mathcal{A}_{2j}} \cdot \frac{C_{W_{0j}+2j_{\text{DPI}}}}{C_{W_{0j}} C_{2j}} \cdot \frac{\varepsilon_{W_{0j}+2j_{\text{DPI}}}}{\varepsilon_{W_{0j}} \varepsilon_{2j}}.$$

- $f_{\text{DP}}^{(\text{D})}$ - fraction of $W + 2$j DPI events; ▸ N_x - number of events; ▸ $\mathcal{L}_x$ - luminosity.
- $\mathcal{A}$ - geometrical acceptance; ▸ C - unfolding corrections; ▸ ε - trigger efficiency.
- Take background into account.

This expression can be simplified using the following:

- The assumption of factorisation between the W boson and the 2j system leads to
  - $\mathcal{A}_{W_{0j}+2j_{\text{DPI}}} \cdot C_{W_{0j}+2j_{\text{DPI}}} = \mathcal{A}_{W_{0j}} \cdot C_{W_{0j}} \cdot \mathcal{A}_{2j} \cdot C_{2j}$
- $W_{0j} + 2j_{\text{DPI}}$ and W_{0j} events were collected using the same trigger selection
  - $\varepsilon_{W_{0j}+2j_{\text{DPI}}} = \varepsilon_{W_{0j}}$
- The minimum bias trigger was shown to be fully efficient in collecting dijets
  - $\varepsilon_{2j} = 1$

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

Main challenge is to measure $f_{\text{DP}}^{(\text{D})}$.

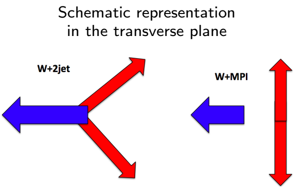
Data/MC samples and data selection

Sample	details
Data (W)	All 2010 data run (36 pb^{-1})
Data (jets)	All 2010 data run (and related subsets)
AHJ (incl.)	ALPGEN ME, JIMMY v4.31, AUET tune, HERWIG v6.510
SHERPA (incl.)	v1.3.1, default UE tune

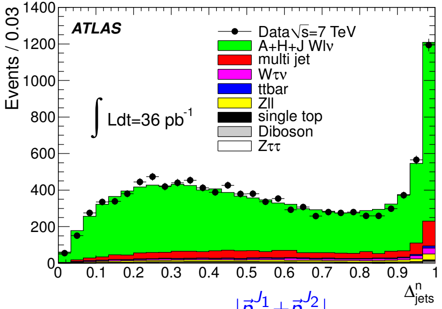
- Jets reconstructed with the anti-$k_\perp$ algorithm ($R = 0.4$), defined as having transverse momentum, $p_T > 20$ GeV, and rapidity, $|y| < 2.8$.
- $W + 0$j selection: ▶ All 2010 W data; ▶ collected with a single lepton trigger; ▶ 1 lepton (e, μ) with $p_T > 20$ GeV, $|\eta| < 2.4$; ▶ missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and mass $M_{\mathrm{T}} > 40$ GeV; ▶ no jets.
- $W + 2$j selection: ▶ Selection as for $W + 0$j with the exception of requiring exactly two jets.
- Dijet selection: ▶ Partial 2010 dataset (184 $\mu\mathrm{b}^{-1}$), collected with the minimum bias trigger; ▶ exactly two jets.

Strategy of the analysis

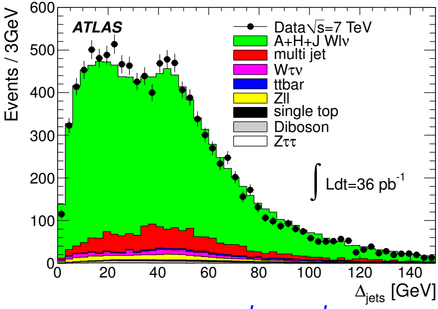
- Possible observables to measure $f_{\mathrm{DP}}^{(\mathrm{D})}$:
  - Transverse momentum of the W (requires $E_{\mathrm{T}}^{\mathrm{miss}}$);
  - p_T distributions of jets (significant JES uncertainties);
  - Azimuthal correlation between jets (pile-up and UE affect it);



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



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



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

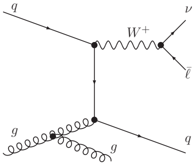
Strategy of the analysis

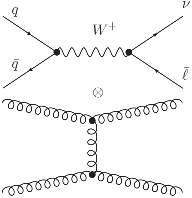
$$\sigma_{\text{eff}} = \frac{1}{f_{\text{DP}}^{(\text{D})}} \cdot \frac{N_{W_{0j}}}{N_{W+2j}} \cdot \frac{N_{2j}}{\mathcal{L}_{2j}} \qquad f_{\text{DP}}^{(\text{D})} = \frac{N_{W_{0j}+2j_{\text{DPI}}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{\text{DPI}}}}{N_{W_{2j}} + N_{W_{0j}+2j_{\text{DPI}}}}$$

- Estimate $f_{\text{DP}}^{(\text{D})}$ by fitting the data to a combination of two templates,

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

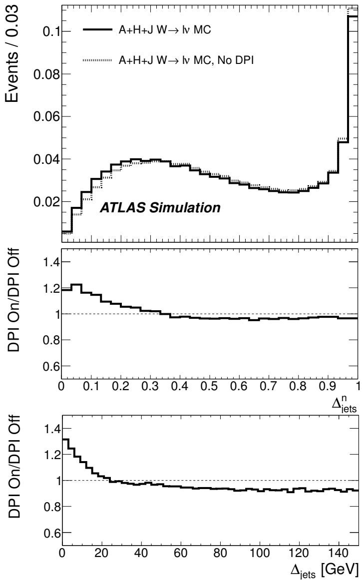
  - **Template A - DPI-off:** AHJ sample of SPI $W + 2$ jets.
  - **Template B - Dijets:** Dijet sample extracted from data.
- Measure the dijet cross section (at detector-level, $N_{2j}/\mathcal{L}_{2j}$), $N_{W_{0j}}$, and N_{W+2j}.
- Subtract background samples from data.
- Apply a pile-up correction factor to $f_{\text{DP}}^{(\text{D})}$.
- Contribution of the process $(W + 1j)_{\text{primary}} \oplus (1j)_{\text{secondary}}$ found negligible.
- Demonstrate relation between detector level, $f_{\text{DP}}^{(\text{D})}$, and parton level, $f_{\text{DP}}^{(\text{P})}$.



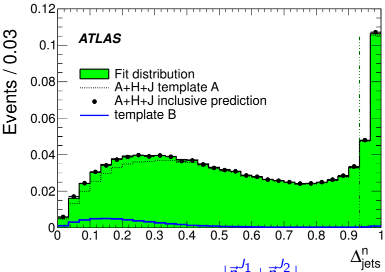


Multiple-parton interactions in AHJ

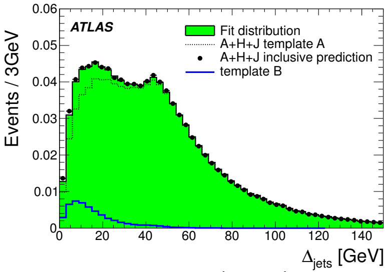
- MCs incorporate multiple-parton interactions (MPI) as part of the description of the underlying event. These mostly include soft interactions, but some may be hard and produce jets.
- Hard MPI can be regulated in AHJ by rejecting events with MPI partons with p_T above $p_{\mathrm{T}}^{\mathrm{max}} = 15\ \mathrm{GeV}$.
- Plots show comparison of DPI-on/off in AHJ for $\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$ (top) and $\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$ (bottom).
- The distributions show sensitivity to the effect of double-parton interactions, especially at low values of $\Delta^{\mathrm{n}}_{\mathrm{jets}}$ and Δ_{jets}, where more balanced dijet systems populate the histograms.



Validation of the analysis strategy



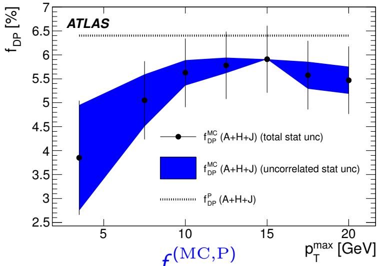
$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$



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

(Up↑) Mimic the data by replacing it with inclusive AHJ and fitting the templates to extract $f_{DP}^{(MC)}$ (DPI fraction in MC).
Consistent results are achieved for $f_{DP}^{(MC)}$ with Δ^{n}_{jets} and Δ_{jets}.

(Right →) Vary p_T^{max} and compare to the value of $f_{DP}^{(P)}$.
Agree within errors ⇒ detector-level measurement directly related to 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 as a systematic.
- 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 - apart from the effect on $f_{\mathrm{DP}}^{(\mathrm{D})}$, the impact of the uncertainty on the ratio $N_{W_{0\mathrm{j}}}/N_{W+2\mathrm{j}}$ is propagated.
  - Uncertainty on the luminosity is propagated.

Uncertainties

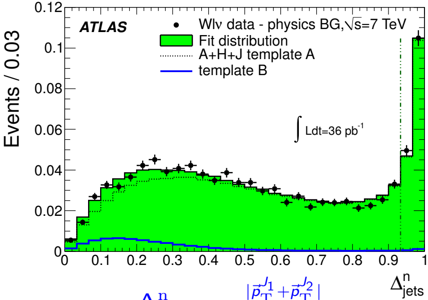
- Fractional uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$:

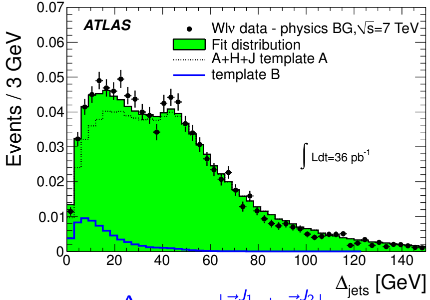
Systematic source	Unc [%]
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background & lepton	11
Total systematic	24
Total statistical	17

- Fractional systematic uncertainties on σ_{eff}:

Systematic source	Unc. [%]
$f_{\mathrm{DP}}^{(\mathrm{D})}$	24
Background & lepton response	3
Luminosity	3
Total systematic	$^{+33}_{-20}$
Total statistical	17

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



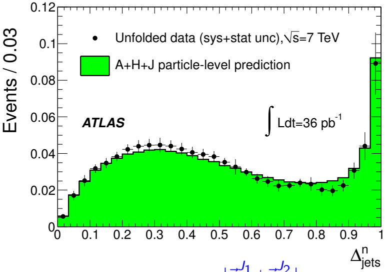


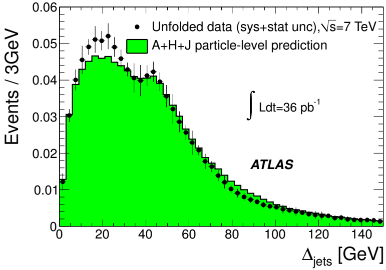
$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|} \qquad \Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$$

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

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

Particle-level distributions





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

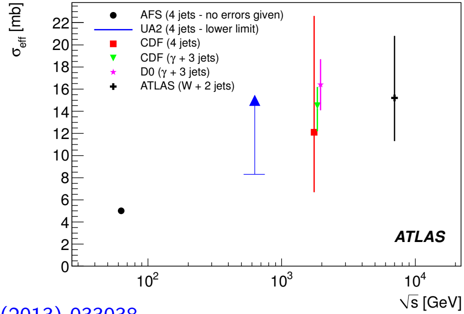
- To allow the results of this study to be used for comparisons with future MPI models, unfolded distributions of key observables are given.
- Unfolding performed using AHJ sample - event selection applied at particle level.
- Data are unfolded using a Bayesian unfolding algorithm, using two iterations, implemented in the `RooUnfold` package.
- Here the data are compared to the particle-level distributions from AHJ.
- The particle-level distributions are not used to extract the fraction of DPI events and the corresponding σ_{eff}.

Summary

- The fraction of DPI events in the $W + 2\mathrm{j}$ channel, $f_{\mathrm{DP}}^{(\mathrm{D})}$, was measured with the ATLAS experiment.
- $f_{\mathrm{DP}}^{(\mathrm{D})}$ was extracted from a fitted combination of two templates, DPI-off (based on AHJ) and DPI-on (dijet events from data) and σ_{eff} was extracted.
- Result for σ_{eff} are consistent with previous measurements at lower energies. Dependence on $\sqrt{s}$ can not be confirmed nor excluded.

- CMS measurement not in plot: $\sigma_{\mathrm{eff}}^{\mathrm{CMS}} = 20.7 \pm 0.8 \pm 6.6$ mb. Agree within errors, but the central value predicts ∼38% less DPI.

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



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Backup Slides

Event selection - more information

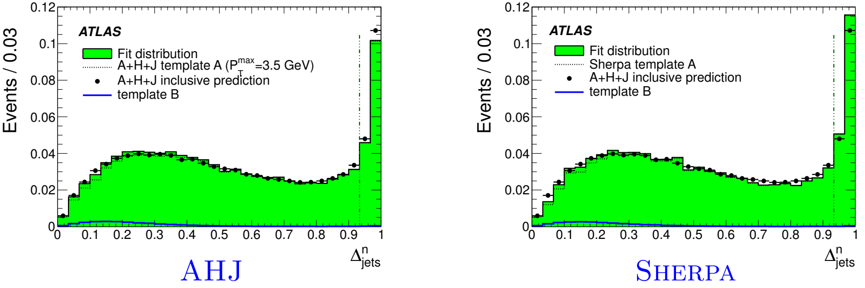
Object selection:

Objects	Selection
Electron	Isolation, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.47$, excluding $1.37 < \lvert\eta\rvert < 1.52$
Muon	Isolation, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$, cuts on track to ensure prompt muon
Jets	anti-$k_\perp$ jets, $R = 0.4$, $p_T > 20$ GeV, $\lvert y\rvert < 2.8$, $\mathrm{JVF} > 0.75$, $\Delta R(\mathrm{l},\mathrm{j}) > 0.5$

Background composition:

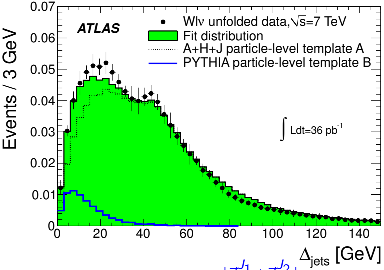
Channel	Source
QCD multi-jet	Data-driven, PYTHIA 6 ($\sim$ 14% e-channel, $\sim$ 6% μ-channel)
$W \to \tau\nu$	PYTHIA 6 ($\sim$ 2% for both e-channel and μ-channel)
$Z \to \mathrm{ll}$	PYTHIA 6 ($\sim$ 1% e-channel, $\sim$ 4% μ-channel)
Di-boson	MC@NLO + JIMMY + HERWIG ($\sim$ 1% for both channels)
Single top quark	MC@NLO + JIMMY + HERWIG ($\sim$ 0.5% for both channels)
$t\bar{t}$	Powheg + PYTHIA 6 ($\sim$ 1% for both both channels)

Validation of the analysis strategy

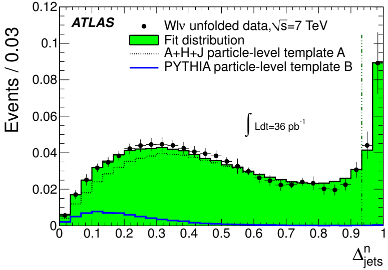


- Set $p_{\mathrm{T}}^{\max} = 3.5$ GeV in AHJ, which is then equivalent to the SHERPA cut in the no-MPI setting.
- Plot $\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$ and fit $f_{\mathrm{DP}}^{(\mathrm{MC})}$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

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 detector-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.