Measurement of hard double–parton interactions with the ATLAS detector

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On behalf of the ATLAS Collaboration

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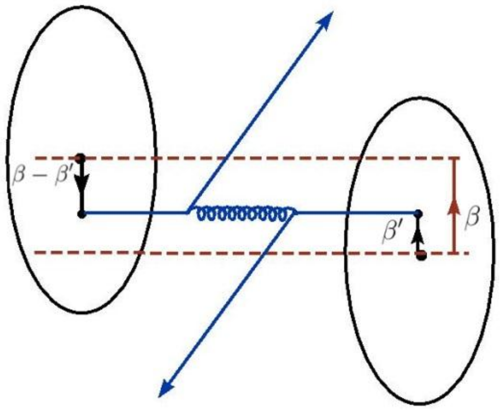
Introduction



- Single Parton Interaction (SPI)

$$\sigma_{SPI} = \sum_{i,j} \int dx_1 dx_2 \int d^2\beta f^i_{h_1}(x_1) f^j_{h_2}(x_2) A(\beta) \hat{\sigma}^{ij}$$

  - overlap $A(\beta)$ - function of impact parameter β

    - normalized to unity for SPI: $\int d^2\beta A(\beta) = 1$

- Double Parton Interactions (DPI)

  = two hard parton interactions in the same hadron-hadron collision

$$\sigma_{DPI} = \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' \int d^2\beta D^{ik}_{h_1}(x_1, x_1') D^{jl}_{h_2}(x_2, x_2') A^2(\beta) \hat{\sigma}^{ij}_a \hat{\sigma}^{kl}_b$$

  - Main assumption: independent interactions at given β

    → convolution of dPDF $D(x_1,x_2)$ and overlap $A(\beta)$

    At low x : dPDF = convolution of two (inclusive) standard PDF’s

Introduction – σ_{eff}

- Effective cross section (σ_{eff}):

$$\int d^2\beta (A(\beta))^2 = \frac{1}{\sigma_{eff}}$$

⇒

- Inclusive DPI cross section:

$$\sigma_{DPI} = \frac{1}{1+\delta_{ab}} \frac{\sigma_a \sigma_b}{\sigma_{eff}}$$

- σ_{eff} :
  - Quantifies the probability of hard secondary scatter
  - Parton-level defined quantity (!)
  - Process/energy/cut independent (?)
    - Naive expectation: σ_{eff} ~70 mb (= $\sigma_{\text{inelastic}}$ for pp @ 7 TeV)
    - Measured values: 5 to 16 mb ⟶ non-negligible effect of parton distribution

AFS	$(pp \ @\ 63\ \text{GeV} \rightarrow 4jets)$	$\sigma_{eff} \sim 5$
UA2	$(p\bar{p} \ @\ 630\ \text{GeV} \rightarrow 4jets)$	$\sigma_{eff} > 8.3$
CDF	$(p\bar{p} \ @\ 1.8\ \text{TeV} \rightarrow 4jets)$	$\sigma_{eff} = 12.1^{+10.7}_{-5.4}$
CDF	$(p\bar{p} \ @\ 1.8\ \text{TeV} \rightarrow \gamma + 3jets)$	$\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$
D0	$(p\bar{p} \ @\ 1.96\ \text{TeV} \rightarrow \gamma + 3jets)$	$\sigma_{eff} = 16.4 \pm 0.3 \pm 2.3$

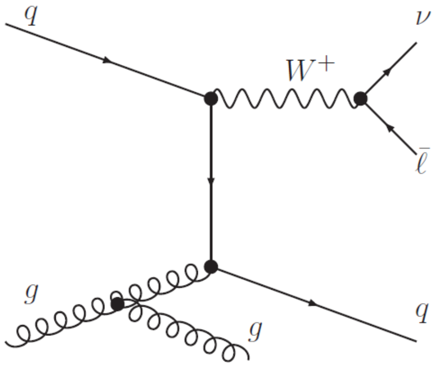
ATLAS measurement: W + 2 jets

- Process

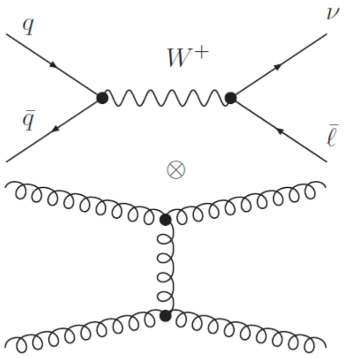
  $pp \rightarrow W (\rightarrow l\nu) + 2$ jets

  - Electron or muon W decay channel
  - Exactly 2 jets (above p_T cut)

[**New J.Phys. 15 (2013) 033038**]



SPI



DPI

- **DPI** production consists of two scatters:

  primary: W production associated with no jet

  secondary: di-jet production (exactly 2 jets)

- DPI of type $(W + 1 \text{ jet})_{\text{primary scatter}} \otimes (1 \text{ jet})_{\text{secondary scatter}}$
- Triple parton scattering ($W \otimes 1$ jet $\otimes 1$ jet)

} negligible

- Fraction of DPI events (**f_{DPI}**) is measured with respect to the leading mechanism:

  SPI production of W + 2 jets directly associated to the primary scatter

Goal: to evaluate $\boldsymbol{\sigma_{eff}}$ using $\mathbf{f_{DPI}}$

Discriminating variables

SPI / DPI event topology-sensitive variables (using MC)

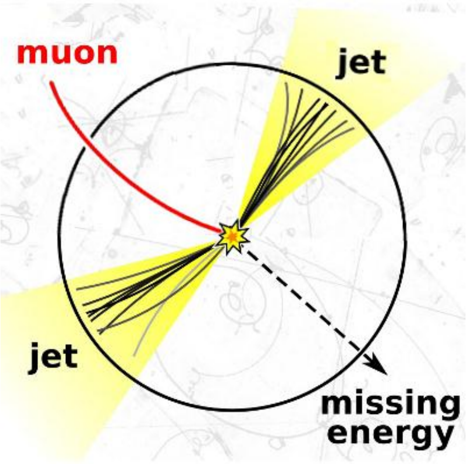
- Reconstruct **p_T of W** boson: p_T (l) + missing E_T
- **missing E_T**
- Azimuthal **angle between jets**
- **p_T of leading jet**
- **Di-jet p_T imbalance:** $\Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|$

Best: **normalized jet p_T imbalance:**

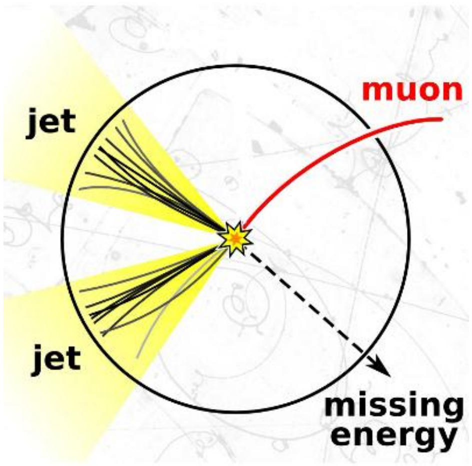
$$\boxed{\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}}$$

- DPI: independent processes → distribution of $\Delta^{\mathrm{n}}_{\mathrm{jets}}$ can be modeled using “2 jets” dataset

Transverse plane view:



DPI - like event

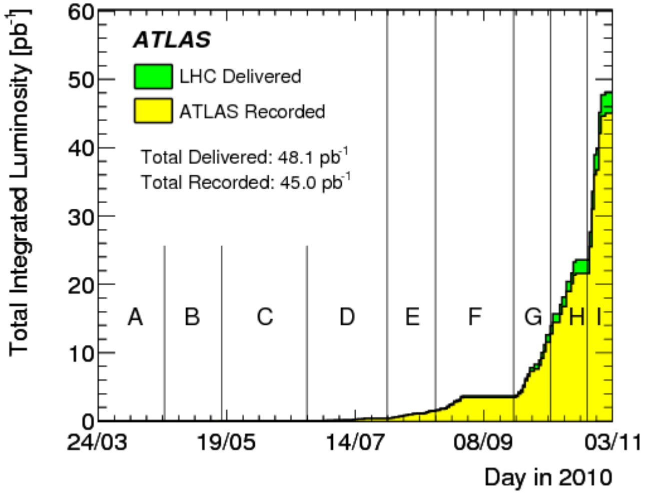


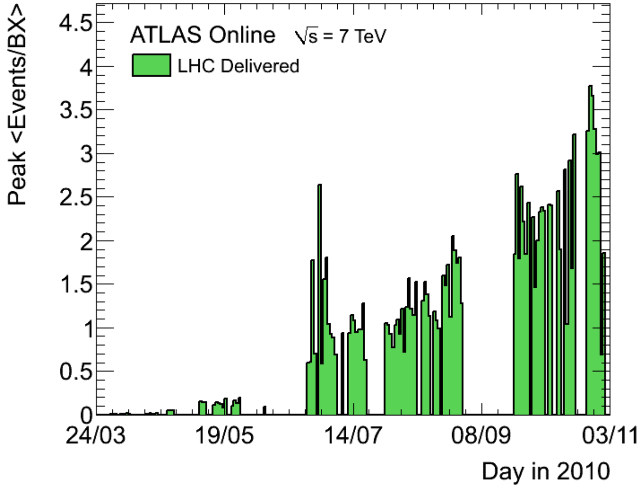
SPI - like event

Event selection

[Eur. Phys. J. C 72 (2012) 1849]

- 2010 ATLAS data, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 36\ \mathrm{pb}^{-1}$, $\langle n_{\text{pile-up}} \rangle \approx 2$
- **Objects:**
  - **Electrons:** $p_T > 20$ GeV, $|\eta| < 2.47$
  - **Muons:** $p_T > 20$ GeV, $|\eta| < 2.4$
  - **Anti-k_t jets**, R = 0.4: $p_T > 20$ GeV, $|y| < 2.8$, JVF > 0.75, $\Delta R(l,j) > 0.5$
- **Datasets:**
  - **W + 2 jets**: exactly one lepton (e or μ), exactly 2 jets missing $E_T > 25$ GeV, $m_T > 40$ GeV, 2 versions: exactly 1vtx / at least 1 vtx
  - **W + 0 jets**: same as W + 2 jets + zero jets required, exactly 1vtx required
  - **2 jets**: minimum bias trigger, exactly 2 jets
  - **2 jets** (no pile-up): subset of 2 jets – only Period A (184 μb^{-1})





Jet p_T imbalance; physics background

Sources of physics background:

- QCD multi-jet production (data-driven Pythia6)
  (~14% el-channel, ~6% muon channel)
- W → τ ν (~2% in both channels)
- Z → ll (~1% el., ~4% mu. channel)

Pythia6

- Di-boson
- Single top

MC@NLO

- ttbar (Powheg)

(!) backgrounds are subtracted from ATLAS data

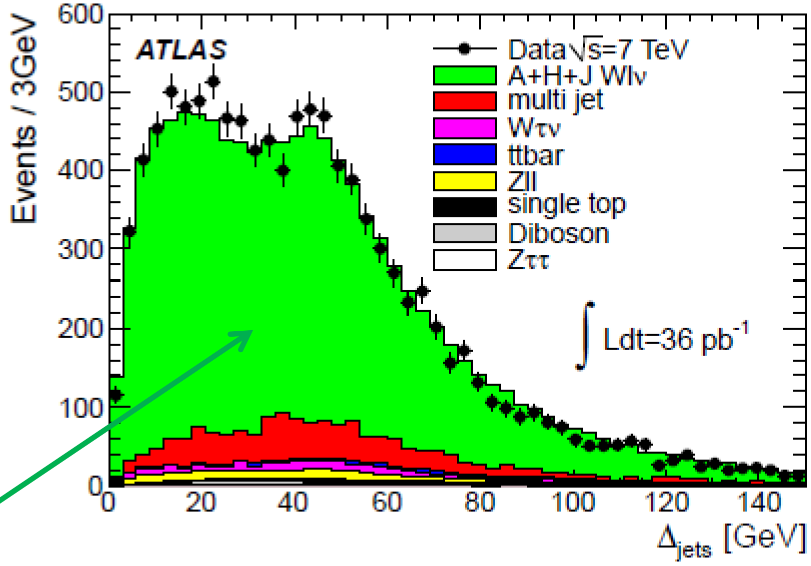
→ to study the main contribution:

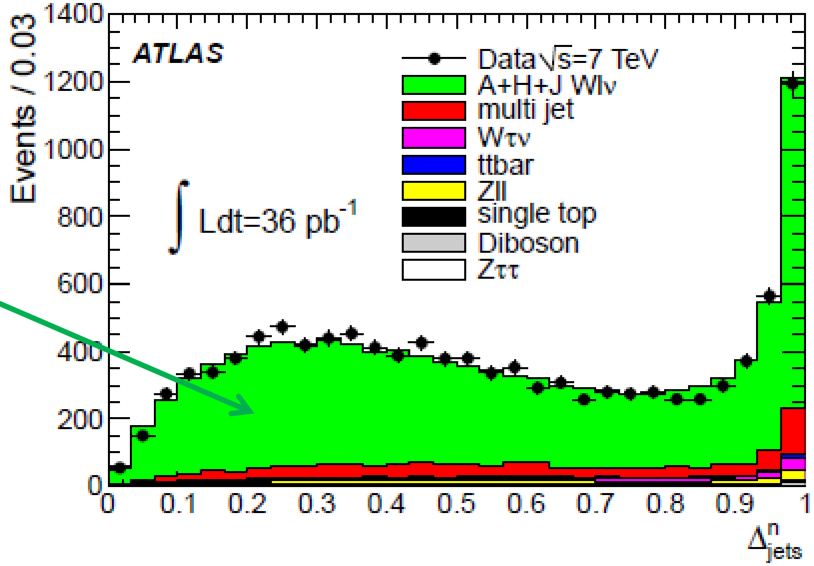
- **W (lν) + jets** production:

Alpgen + **Herwig** 6.510 + **Jimmy** 4.31 **(A+H+J)**

default settings of EU (MPI): AUET2 tune

(Alternative modeling: Sherpa 1.3.1)





Monte Carlo modeling

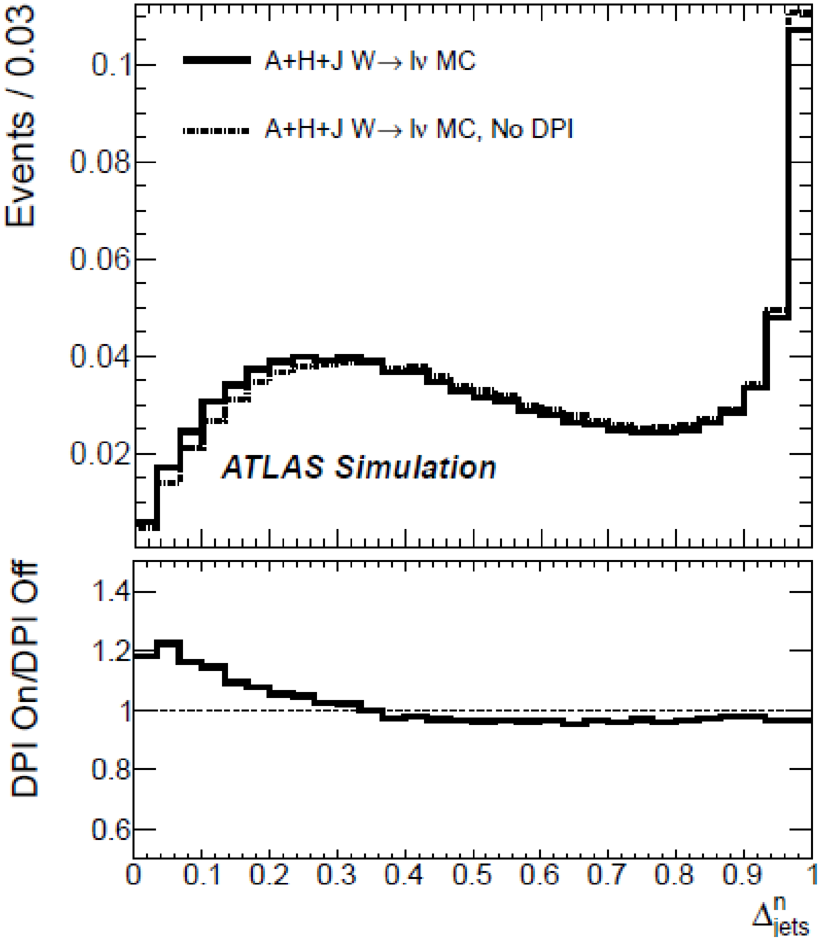
- **W (lν) + 2 jets generation in A+H+J (CTEQ6l1 PDF):**

– Alpgen (with MLM matching scheme) + Jimmy (additional QCD scattering)

– underlying event studied → to separate W + 2 jets events coming from SPI and DPI events

– **"No DPI" dataset:**

$p_T^{max} = 15$ GeV cut applied on partons from MPI to get exclusive SPI



Plot:
comparison between *inclusive* and *exclusive* SPI (No DPI) productions

DPI visible at low Δ^{n}_{jets}

σ_{eff} extraction – method

- Effective cross section
  - Theory:

$$\sigma_{eff} = \frac{\sigma_{(W+0j)}\sigma_{(2j)}}{\sigma^{DPI}_{(W+2j)}}$$

  - Experiment:

$$\sigma_{eff} = \left(\frac{N}{A\;C\;\epsilon\;\mathcal{L}}\right)_{(W+0j)} \left(\frac{N}{A\;C\;\epsilon\;\mathcal{L}}\right)_{(2j)} \left(\frac{A\;C\;\epsilon\;\mathcal{L}}{N}\right)^{DPI}_{(W+2j)}$$

- N = number of events
- A = geometrical acceptance
- C = correction factor for detector effects
- ε = trigger efficiency
- $\mathcal{L}$ = integrated luminosity

σ_{eff} extraction – method

- Effective cross section
  - Theory:

$$\sigma_{eff} = \frac{\sigma_{(W+0j)}\sigma_{(2j)}}{\sigma^{DPI}_{(W+2j)}}$$

The same online selection of data

  - Experiment:

$$\sigma_{eff} = \left(\frac{N}{\cancel{A\,C}\,\cancel{\epsilon\,\mathcal{L}}}\right)_{(W+0j)} \left(\frac{N}{\cancel{A\,C}\,\epsilon\,\mathcal{L}}\right)_{(2j)} \left(\frac{\cancel{A\,C}\,\cancel{\epsilon\,\mathcal{L}}}{N}\right)^{DPI}_{(W+2j)}$$

$$f_{DP}N^{tot}_{(W+2j)}$$

- N = number of events
- A = geometrical acceptance
- C = correction factor for detector effects
- ε = trigger efficiency
- $\mathcal{L}$ = integrated luminosity

DPI = (W+0j) + (2j)
Independent processes = correction factors multiply and cancel in ratio

σ_{eff} extraction – method

- Effective cross section

$$\boxed{\sigma_{eff} = \frac{1}{f_{DP}} \frac{N_{(W+0j)}}{N^{tot}_{(W+2j)}} \frac{N_{(2j)}}{\mathcal{L}_{(2j)}}}$$

- **Fraction of DPI events** in the W + 2 jets dataset:

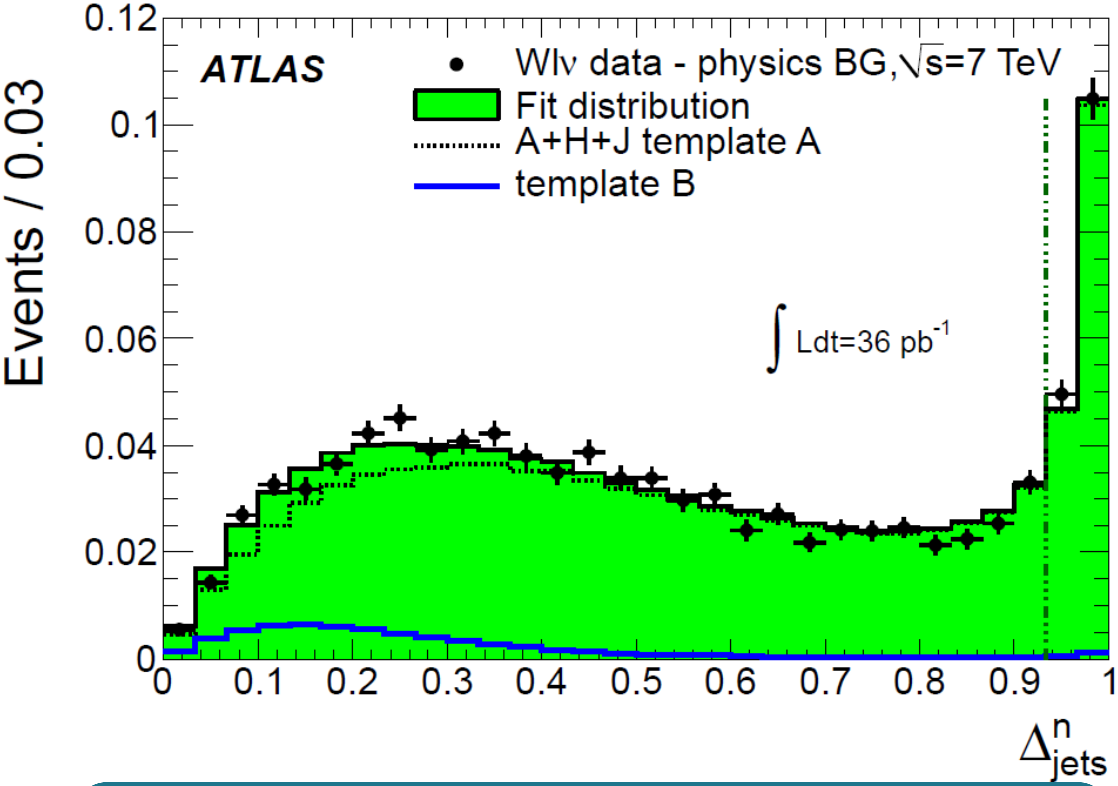
$$f_{DP} = \frac{N^{DPI}_{(W+2j)}}{N^{tot}_{(W+2j)}} \quad \text{where} \quad N^{tot}_{(W+2j)} = N^{SPI}_{(W+2j)} + N^{DPI}_{(W+2j)}$$

- **f_{DP} evaluation:** shape of Δ^{n}_{jets} distribution for W + 2 jets ATLAS data is compared to a linear combination of two normalized distributions A and B (templates) using χ^2 test

$$\text{overall distribution} = (1 - f_{DP}) \cdot A + f_{DP} \cdot B$$

template A: distribution for selected exclusive SPI (A+H+J) data - No DPI
template B: distribution for 2 jets dataset

Best fit – f_{DP} extraction from data



$$f^{(D)}_{DP} = 0.076 \pm 0.013 \text{ (stat.)}$$

Pile-up correction:

1) ATLAS data are replaced by A+H+J simulation

f_{DP} (all MC) = 0.051 ± 0.003 (stat.)

2) Only 1vtx A+H+J events

(template B: low luminosity 2 jets data)

f_{DP} (1vtx MC) = 0.059 ± 0.007(stat.)

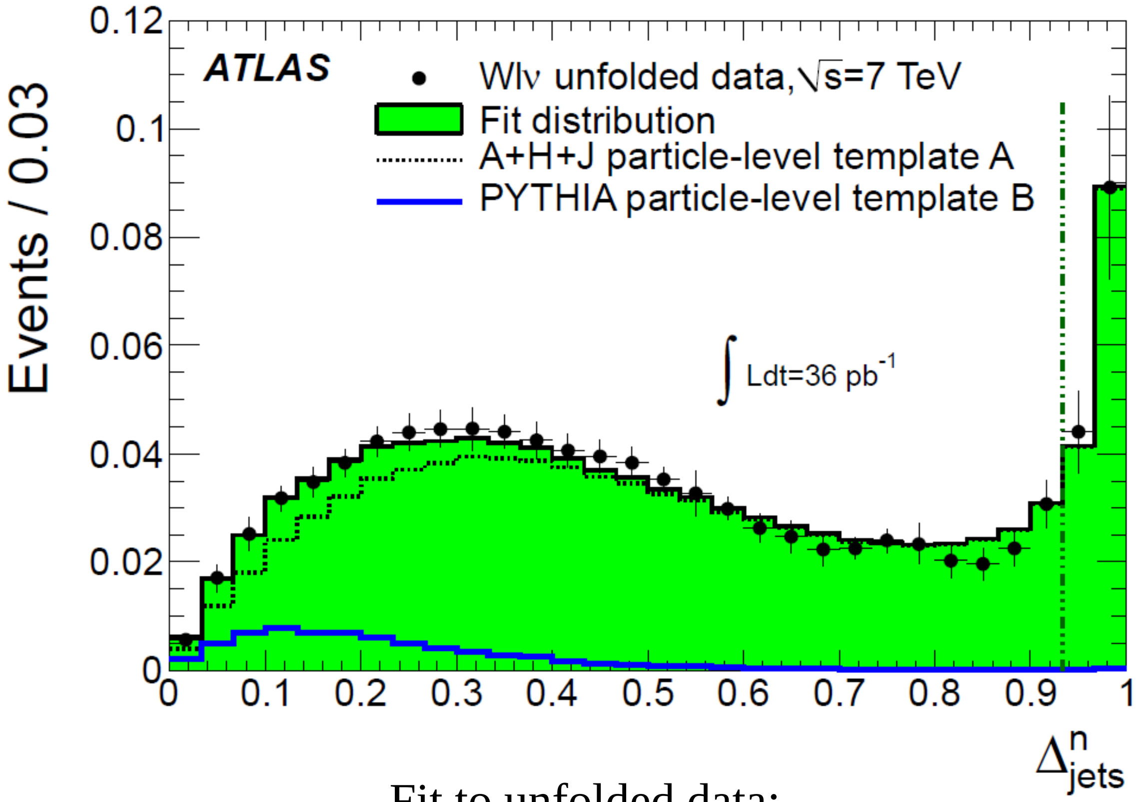
Ratio gives the correction factor:

$r_{pile\text{-}up}$ = 1.17 ± 0.15 (stat.)

- Fit is performed using full datasets (lack of 1 vtx data)
- pile-up correction (from MC) is applied
- two right bins are excluded from fit - too collinear jets

hadron-level: unfolded data

- Goals: 1) to provide an unfolded distribution for MC tunes
  2) to quantify the effect of detector resolution and efficiency on f_{DP} value



Unfolding:

- ATLAS data unfolded using A+H+J simulation,
- event selection applied at particle level
- Bayesian unfolding, two iterations performed
- Unfolding implicitly includes the correction for pile-up

Fit to unfolded data:

template A: A+H+J W + 2 jets SPI events

template B: Pythia6 di-jet events

best fit result for $f_{DP}^{(H)}$ is within 10 % from $f_{DP}^{(D)}$

Systematics (for detector-level f_{DP})

- **Pile-up:** 13%
  - statistical uncertainty of the $r_{\text{pile-up}}$ correction factor is propagated to systematics for f_{DP}
- Theoretical uncertainty: 10%
  - variation of p_T^{max} threshold in A+H+J
  - comparison of two models: A+H+J vs Sherpa
- Jet energy scale: 12%
- Jet energy resolution: 8%
  - variation of jet energy/resolution in Monte Carlo within the given uncertainties (applies to both jet energy scale and jet energy resolution)
- Physics background modeling and lepton response: 11%
  - f_{DP} obtained for electron and muon channels separately (difference < 1%)
  - variation of shapes and normalizations of distributions for background processes

Total systematics: 24% (statistical: 17%)

$$\boxed{f_{DP}^{(D)} = 0.076 \pm 0.013\ (\text{stat.}) \pm 0.018\ (\text{sys.})}$$

Effective cross section σ_{eff}

- DPI event fraction $\mathbf{f_{DP}}$ obtained using entire 2010 ATLAS dataset

  + correction for pile up
- **σ_{eff} is calculated:**

$$\sigma_{eff} = \frac{1}{f_{DP}} \frac{N_{(W+0j)}}{N^{tot}_{(W+2j)}} \frac{N_{(2j)}}{\mathcal{L}_{(2j)}}$$

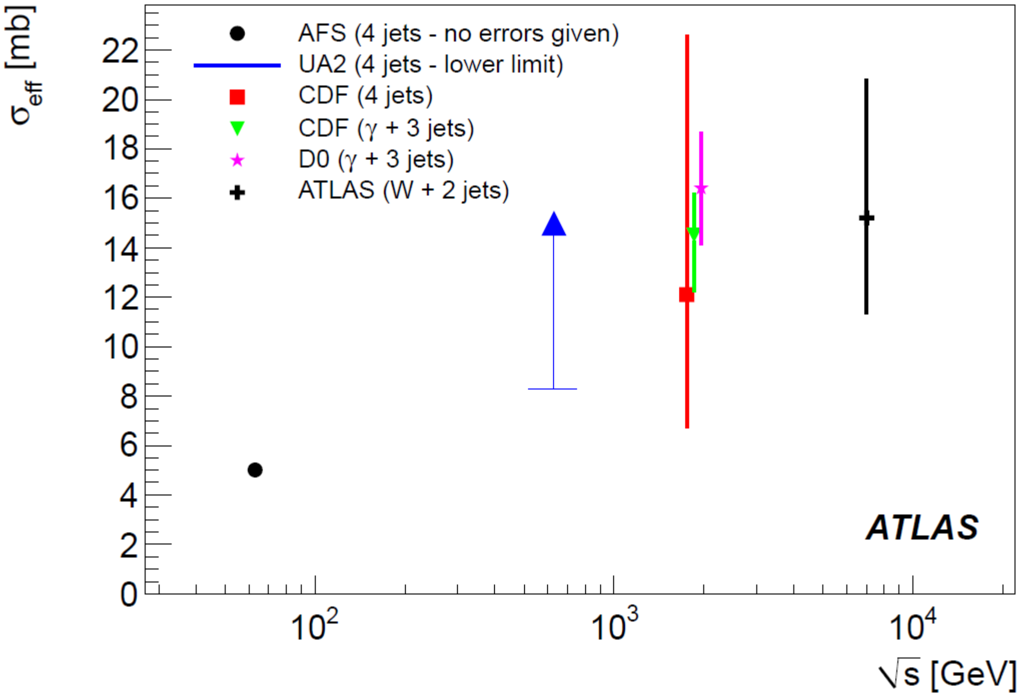
  - where 1 vtx datasets are used for calculating appropriate event numbers:

	Systematics:	
DPI exclusivity ratio $N_{(W+0j)} / N_{(W+2j)} = 23.0$	± 5%	
Number of 2 jets events $N_{(2j)} = 9488$	< 1%	
2 jets dataset: $\mathcal{L}_{(2j)} = 184\ \mu b^{-1}$	± 3%	Propagates asymmetrically to σ_{eff}
Remaining systematics is included in $\mathbf{f_{DP}}$	± 24 %	

$$\sigma_{eff} = 15 \pm 3\ (\text{stat.})\ {}^{+5}_{-3}\ (\text{sys.})\ \text{mb}$$

Summary

- 2010 ATLAS data (36 pb^{-1})
- Fraction of DPI events with respect to inclusive W+2jets events is found to be around 8%
- Uncertainty of the f_{DP} measurement high (~30%) – pile-up dominates => rather difficult measurement for high-luminosity data



- Effective cross section

$$\sigma_{eff} = 15 \pm 3 \text{ (stat.) } {}^{+5}_{-3} \text{ (sys.) mb}$$

- is consistent with previous measurements (AFS, UA2, CDF, D0)

- level of uncertainty still high - σ_{eff} energy-dependence not proven

Backup

parton–level f_{DP}

- σ_{eff} and f_{DP} are defined at parton level
- Can the detector-level quantity $f_{DP}^{(D)}$ be related to the parton-level $f_{DP}^{(P)}$?

- Important check using 1 vtx Monte Carlo data:

1) after **detector response simulation**

- 1 vtx event sub-selection of MC data (same as for pile-up correction)
- best fit result:

f_{DP} (1vtx MC) = 0.059 ± 0.007 (stat.)

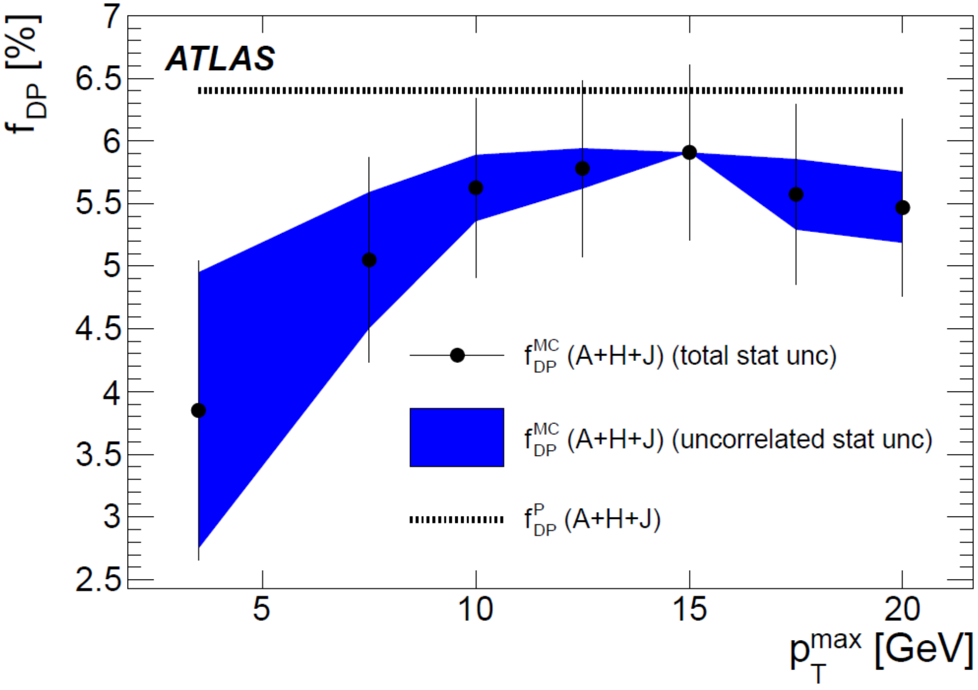
2) at parton level

- event selections applied on partons and leptons outgoing from the primary interaction
- DPI event fraction is directly counted:

$f_{DP}^{(P)} = 0.064 \pm 0.001$ (stat.)

→ difference is within 10 %

Theoretical uncertainty – p_T^{max}

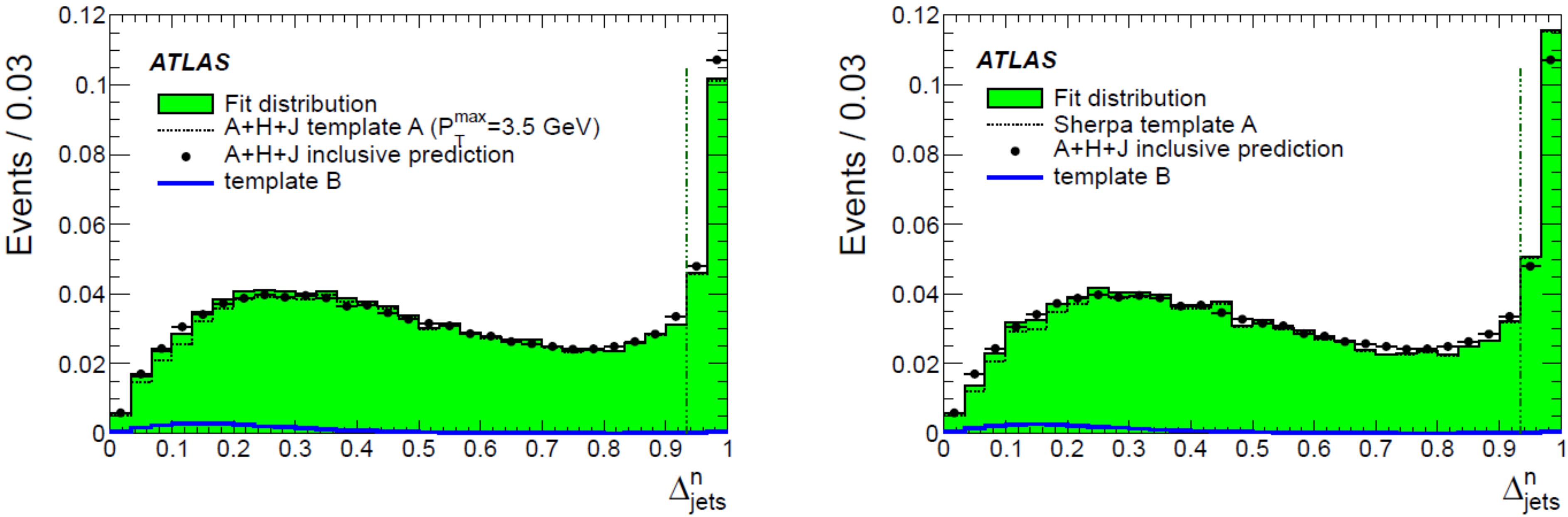


- Multiple parton interactions additional to the primary hard process contribute to the production of jets – form underlying event and decorrelate the direction of hard jets (p_T (jet) > 20 GeV)

- Central value of f_{DP} (1vtx MC) is for
  $p_T^{max} = 15$ GeV
  (the closest value to the "true" $f^{(P)}_{DP}$)

- Parton-level filtering of exclusive DPI events is studied by varying of p_T^{max} cut applied on template A:
  1 vtx A+H+J "NoMPI" W+2jets dataset

Theoretical uncertainty – MC modeling



- Modeling of template A (NoDPI) depends on Monte Carlo used:

  1) Sherpa 1.3.1 with MPI modeling switched off (right plot) - no hard MPI, only soft

$$f_{DP}^{(Sherpa)} = 0.031 \pm 0.008 \text{ (stat.)}$$

  2) A+H+J, p_T^{max} = 3.5 GeV in order to follow Sherpa:

$$f_{DP}^{(AHJ)} = 0.034 \pm 0.006 \text{ (stat.)}$$

- Difference is taken as systematic uncertainty + statistical uncertainty for Sherpa