ATL-PHYS-PUB-2015-019 → JHEP 03(2017)157

Studies of the underlying-event properties and of hard double parton scattering with the ATLAS detector

JHEP 11(2016)110

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on behalf of the ATLAS Collaboration

25th International Workshop on Deep Inelastic Scattering and Related Topics

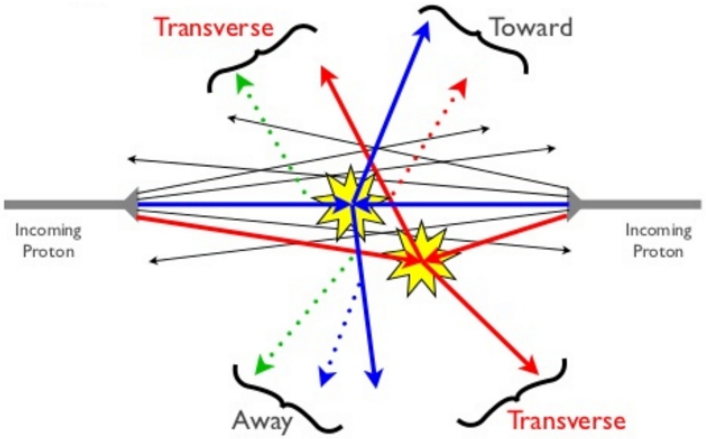
Birmingham, UK, 3-7 April 2017

Outline

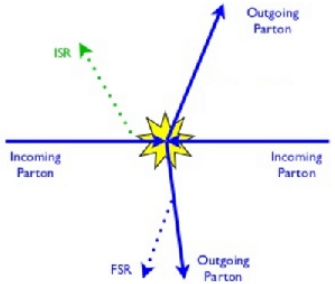
1. Leading Track Underlying Event
   - Data sample selection
   - Monte Carlo models & tunes
   - Distributions of UE parameters

2. Hard Double Parton Scattering with four jets
   - Data Sample
   - Events classification
   - Discriminating variables & neural network output
   - Fraction of DPS events in 4-jet sample
   - Effective proton cross section

Underlying Event

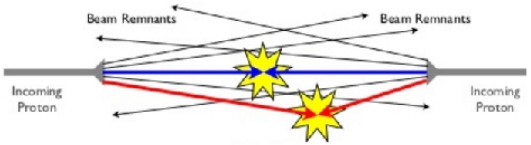


pp collision =



hard scattering

+



proton remnants

+

MPI + soft gluon emissions

Underlying Event (UE)

- **Refers to anything that accompanies the main hard scattering process:**
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Initial and Final State QCD Radiation

- It is not possible to derive properties of UE from first principles

  → Described by phenomenological Monte Carlo (MC) models including various tunes to experimental data

Leading Track Underlying Event at 13 TeV

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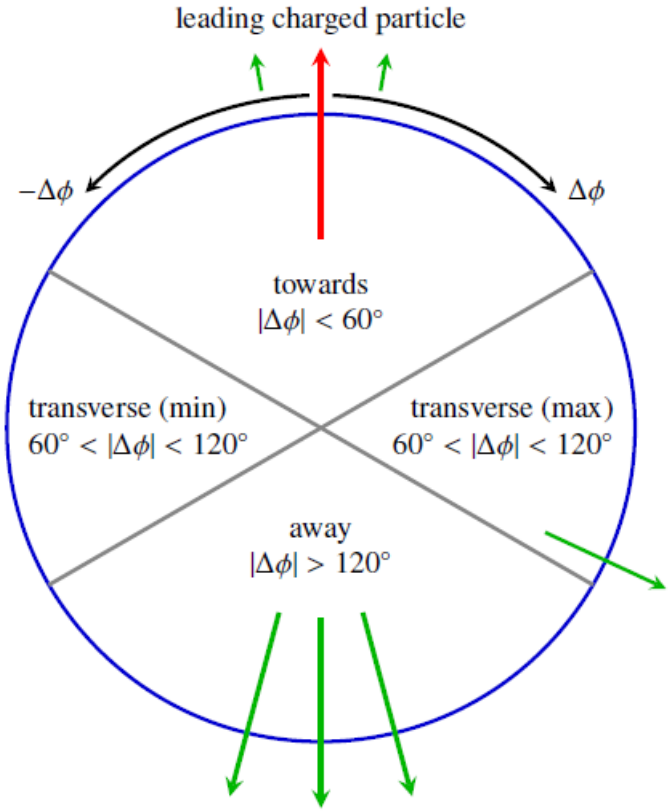


- 13 TeV, L = 1.6 nb^{-1}
- At least one hit in Minimum-Bias scintillators
- Presence of a leading track with p_T of at least 1 GeV → fully efficient trigger
- Presence of the primary vertex; no second vertex with four or more tracks
  → Contribution from tracks from additional interactions < 0.01%
  → Rate of background events from non-colliding beams < 0.01%
- Tracks selection: $p_T > 0.5$ GeV, $|\eta| < 2.5$ + quality cuts

- Divide phase space into three regions with respect to the leading track in the event
- Within the transverse region, identify side with the maximum sum of track pt's ("trans-max") – the opposite side ("trans-min") has maximum sensitivity to UE
  → **Study charged particle distributions in the tranfsverse region**

Monte Carlo Models & Tunes

- MC events were passed through the ATLAS detector simulation (Geant4)

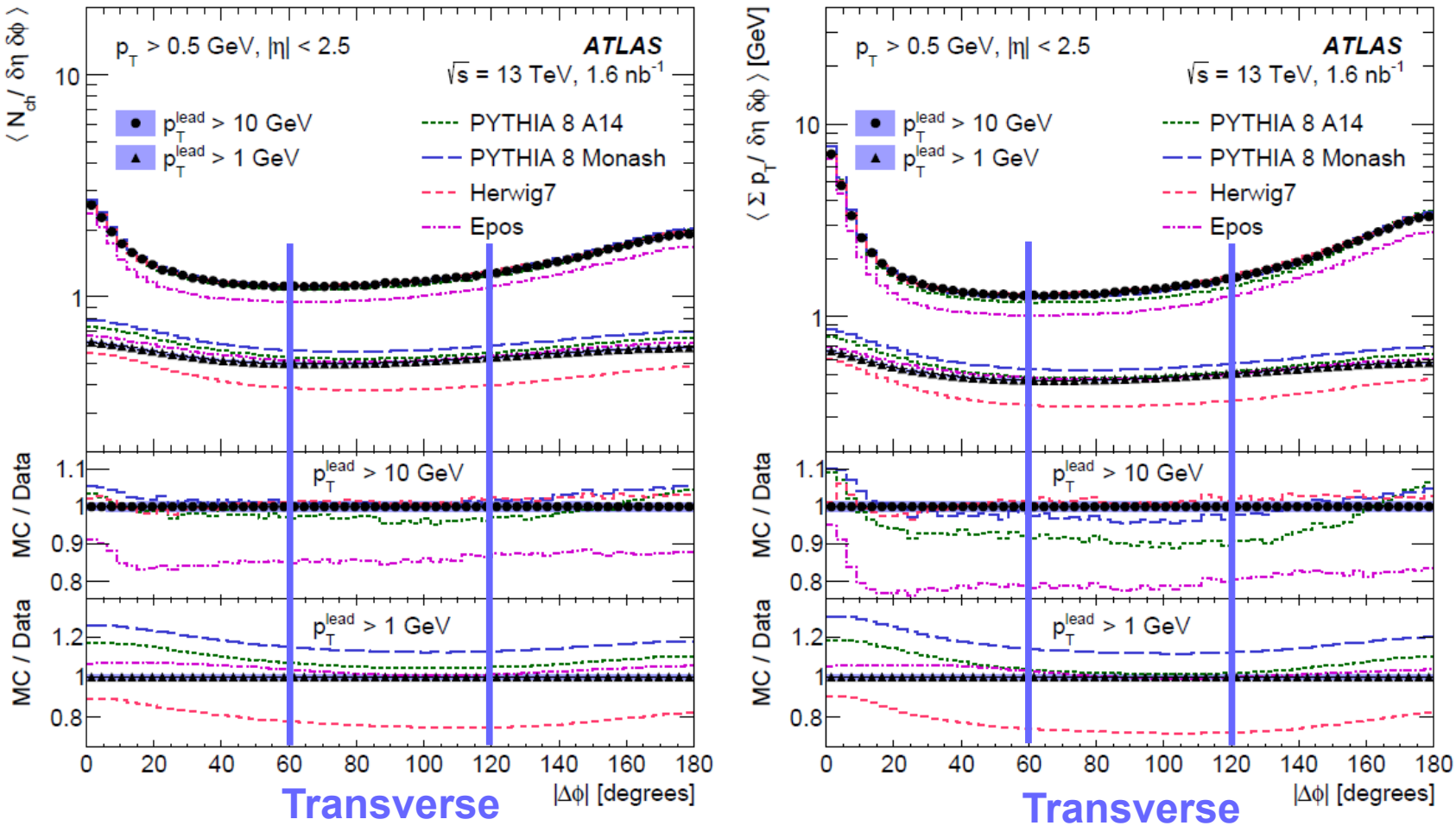
Generator	Version	Tune	PDF	Tuned to
Pythia8	8.153	A2	MSTW2008LO	UE/MB
Pythia8	8.186	A14	NNPDF2.3LO	UE/Jets
Pythia8	8.186	Monash	NNPDF2.3LO	MB/UE
Herwig++	2.7.1	UE-MMHT	MMHT2014LO	UE/DPS
Epos	3.1	LHC	---	MB

ATLAS tunes

Tunes by MC developers

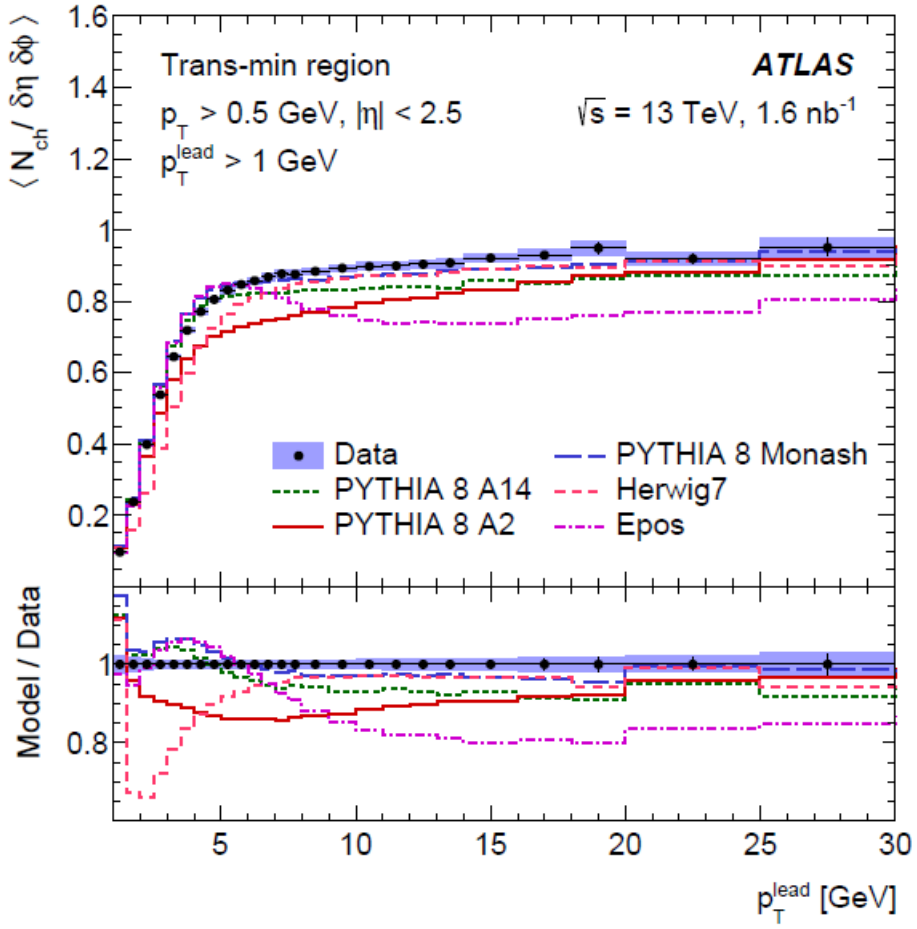
- Tunes use data from different experiments to constrain different processes
- Focused on describing the Minimum-Bias or Underlying Event distributions
- Performed by MC developers or by ATLAS
  → Pythia8 A14 is widely used in ATLAS for hard-process simulation

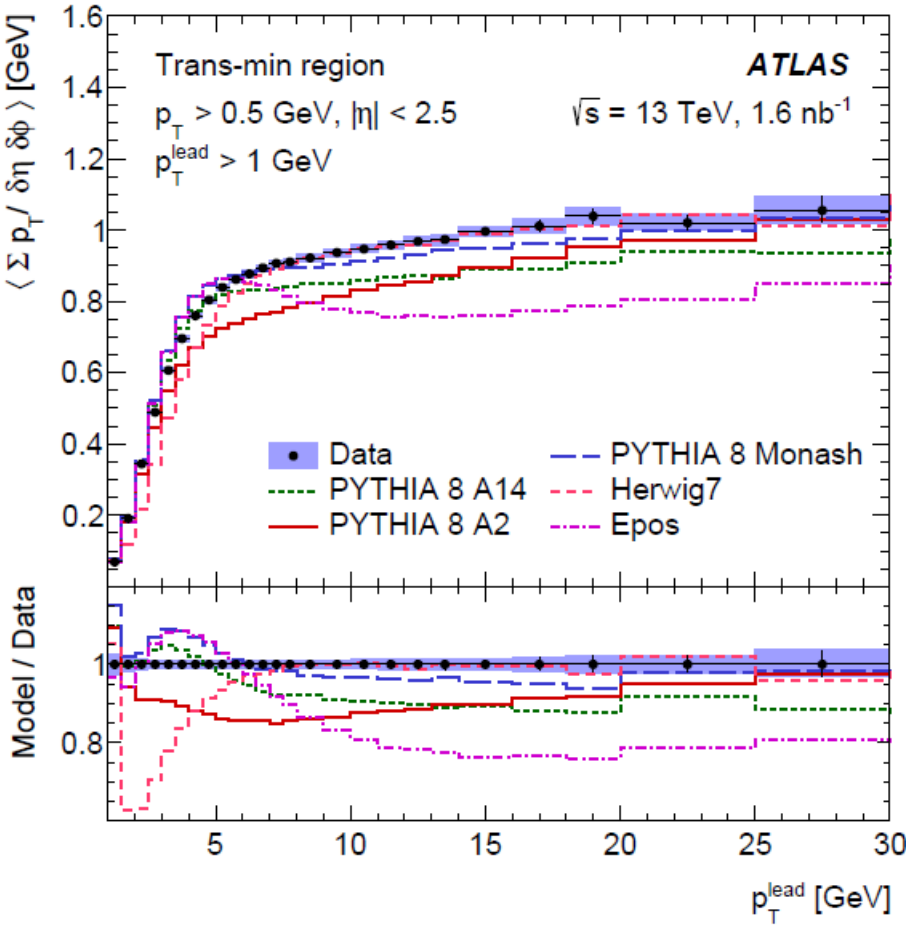
Average Number of Tracks and p_T sum per $\delta\eta\ \delta\varphi$



- p_T^{lead} > 1 GeV: Good description of the transverse region by EPOS, but EPOS is significantly off in the region p_T^{lead} > 10 GeV
- There is no single model describing well both N_{ch} and $\Sigma\ p_T$ in the same time

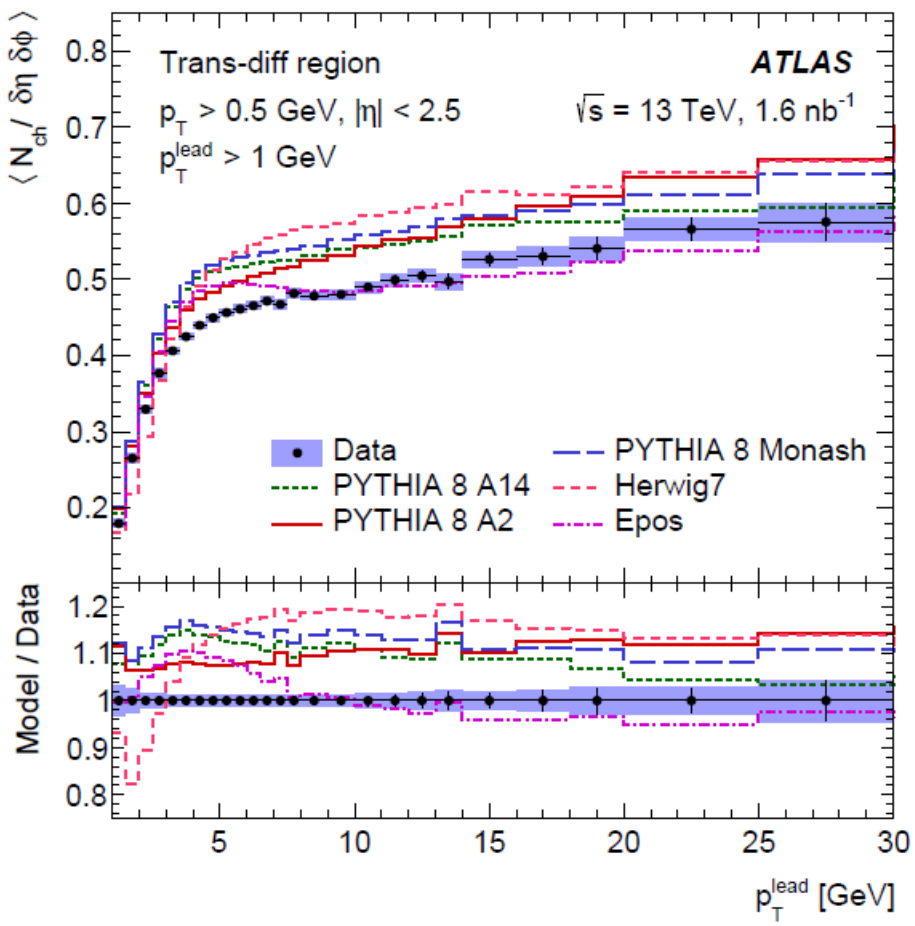
Transverse Region with Minimum Σ p_T

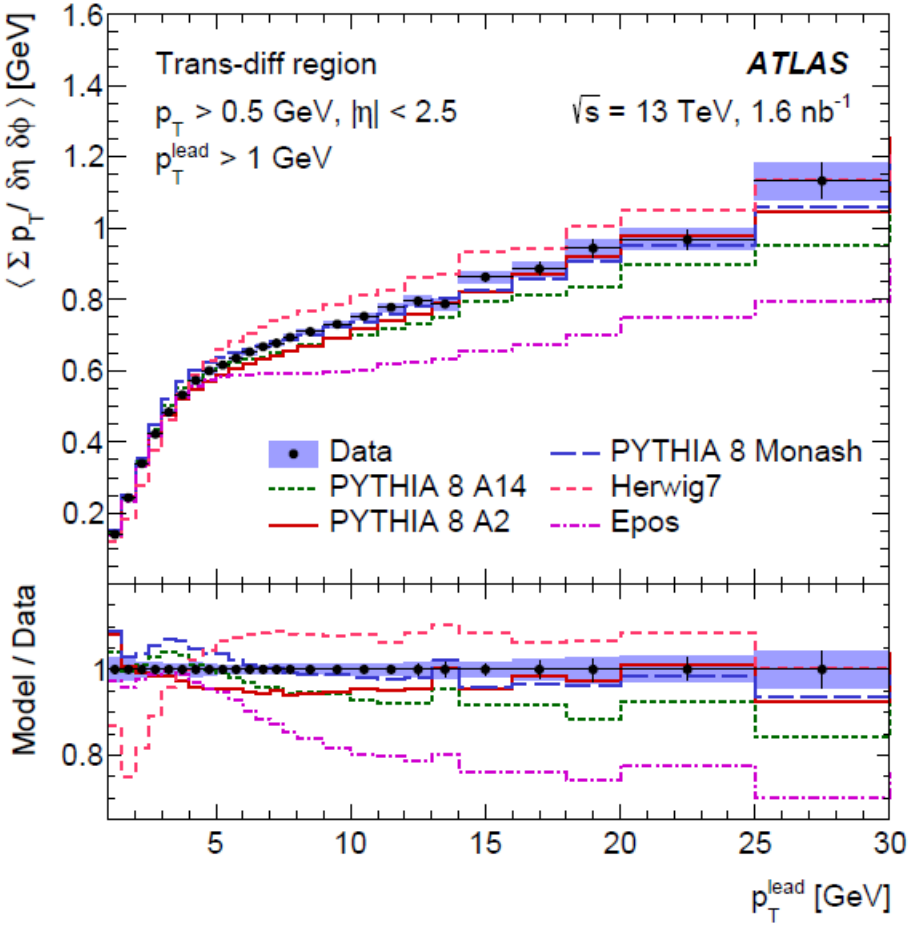




- Region with most sensitivity to Underlying Event
- Significant variation in performance between the models
- PYTHIA 8 Monash and Herwig7 give a good description in the plateau region
- None of models describe well the initial rise between 1 and 5 GeV

Transverse-diff

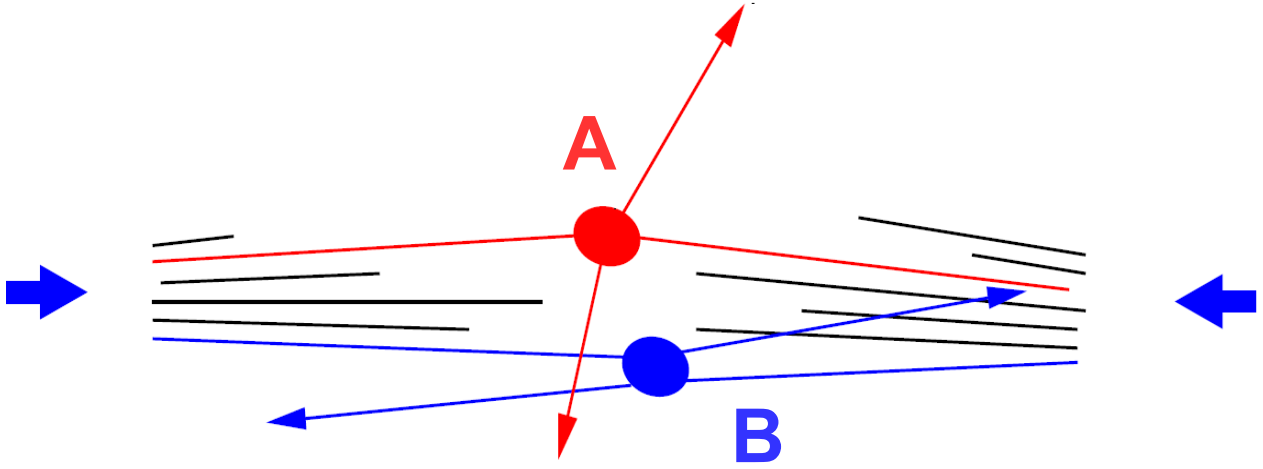




- Difference (per-event) between observables in trans-max and trans-min regions
  → The best sensitivity to contamination of hard-scattering in the transverse region
- Distribution shapes indicate systematic mismodelling by MC
  → Tunes to these new 13 TeV data would be of benefit for physics studies in Run 2

Hard Double Parton Scattering (DPS)

- Two hard parton interactions occur in the same hadron-hadron interaction



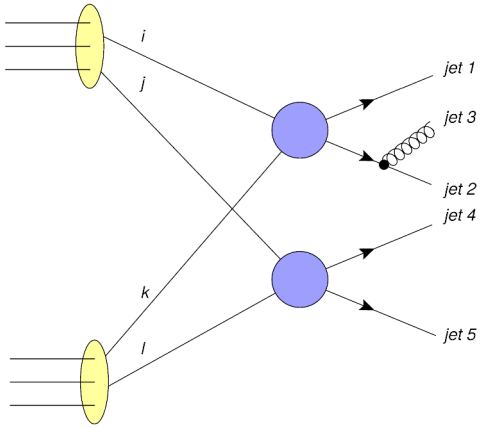
→ **Pocket formula:**

$$\sigma_{DPS}^{AB} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}} \quad \Rightarrow$$

$$\sigma_{eff} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{DPS}^{AB}} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{f_{DPS}\sigma_{tot}^{AB}}$$ (symmetry factor m = 1 if A = B, m = 2 if A ∩ B = ∅)

- $\sigma_{SPS}^{A(B)}$ is the **inclusive** cross section of **single** hard scattering A (B)
- σ_{eff} is a **universal parameter of the proton:**
  - Assumed to be process and cut independent
  - No dependence on sqrt s observed
  - Measured to be 20-30% of σ_{inel}

DPS in Four-Jet Events



- 7 TeV 2010 Data, L = 37.3 pb^{-1}, <μ> = 0.41
- Single-vertex events
- Anti-kt jets with R = 0.6
- Four-jet events: $p_T^1 > 42.5$ GeV, $p_T^{2,3,4} > 20$ GeV, $|\eta| < 4.4$
- Two dijet samples to match four-jet cuts: 1) $p_T^{1,2} > 20$ GeV, 2) $p_T^1 > 42.5$ GeV, $p_T^2 > 20$ GeV

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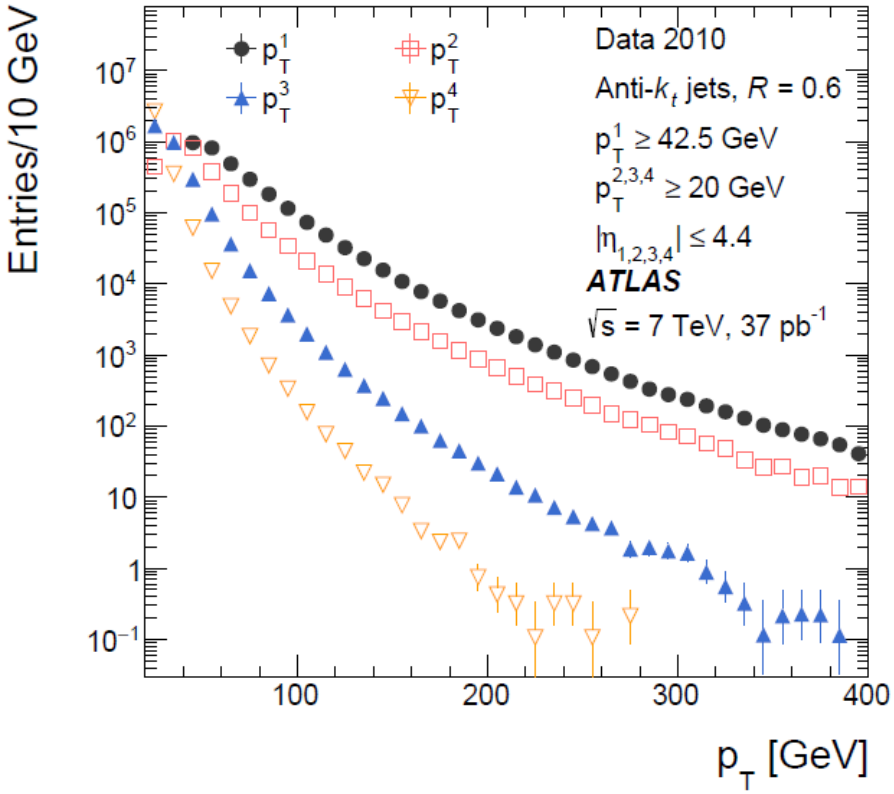
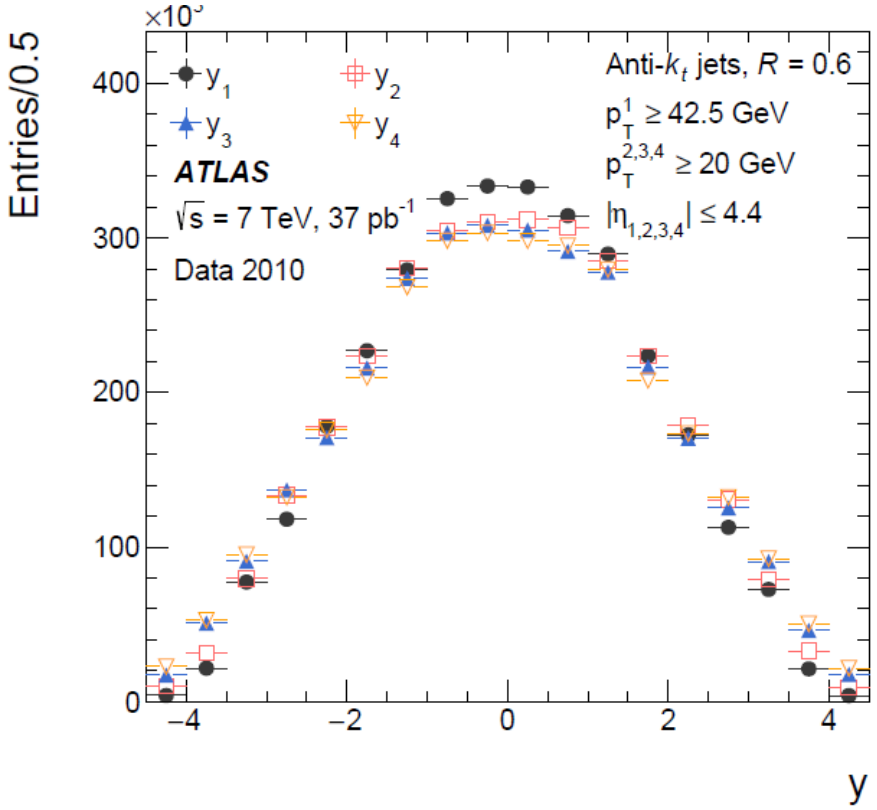


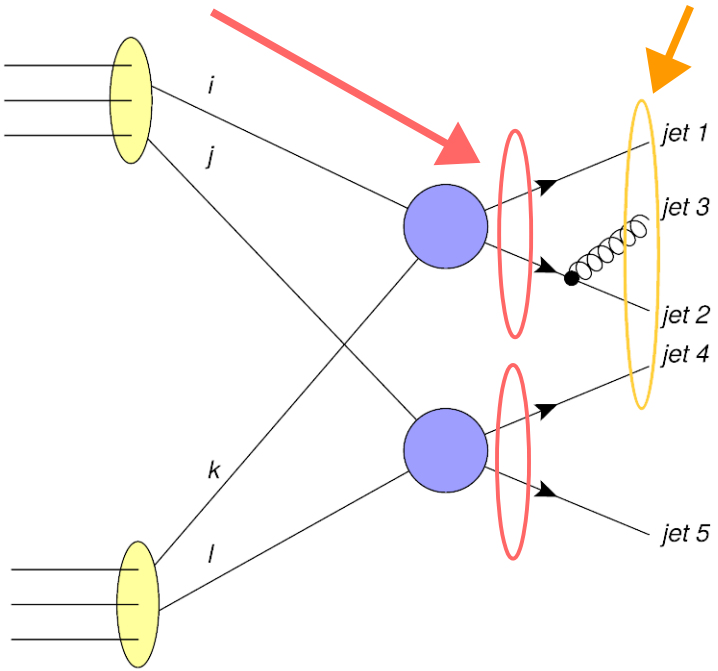


Event Classification

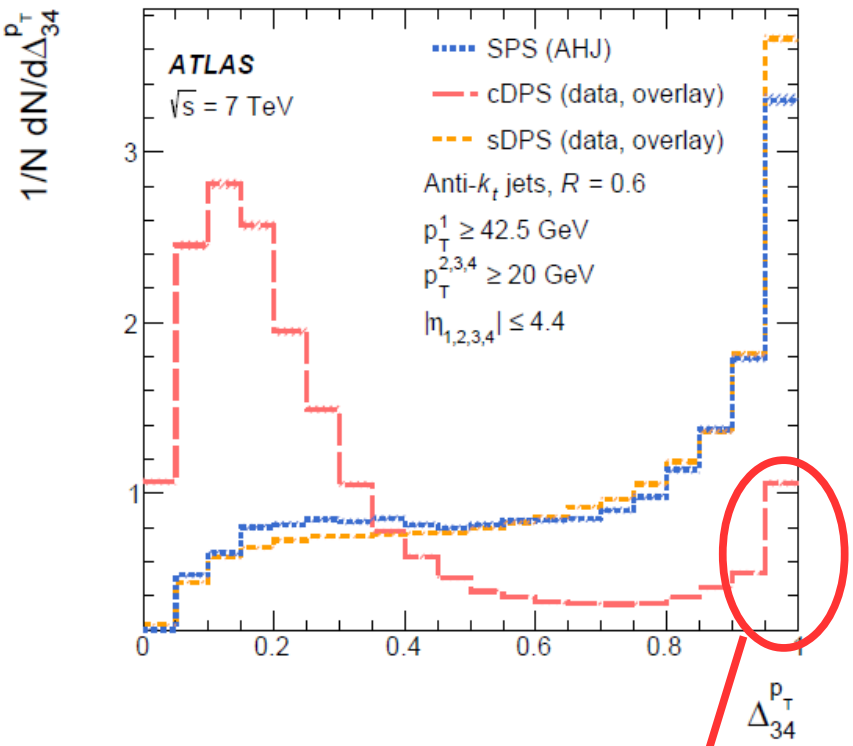
- Alpgen interfaced to Jimmy and Herwig (AHJ) for multi-jets
  - ➢ Event record is used to extract Single (SPS) and Double (DPS) parton scattering events
- Sherpa for SPS multi-jets
- Data events overlay for DPS events

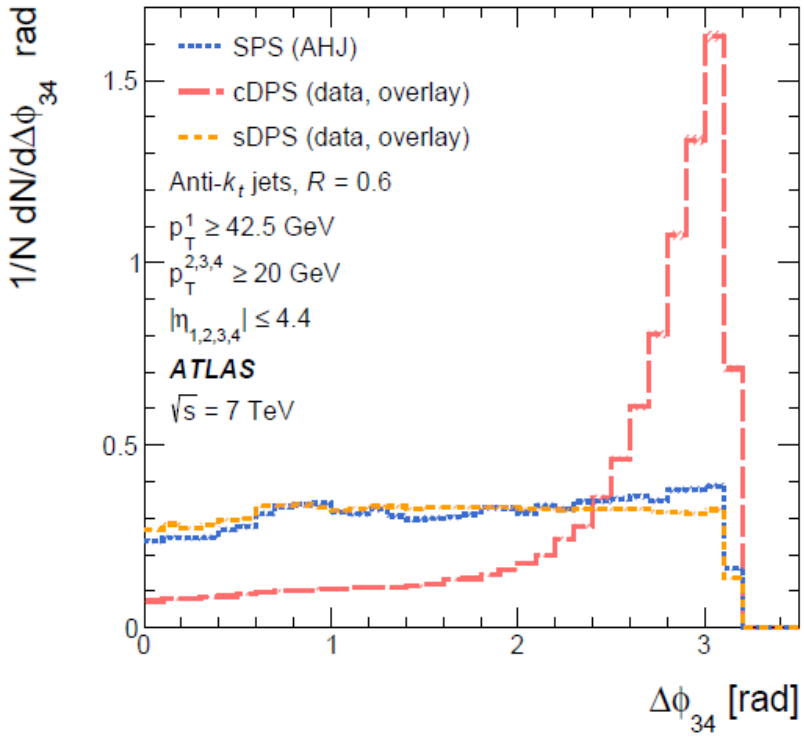
Process type	SPS	Complete-DPS	Semi-DPS
Number of jets matched to secondary-scatter partons	0	2	1
Modeled with	AHJ, Sherpa for validation	Overlaid data dijets, AHJ for validation	Overlaid data 3-jet + 1-jet events, AHJ for validation

- In MC, jets are matched to outgoing partons from primary and secondary interactions
- In data events overlay, require non-overlapping jets
- Jet match to closest parton with $p_T^{\text{parton}} > 15$ GeV and $\Delta R_{\text{parton-jet}} < 1$
- $f_{DPS} = f_{sDPS} + f_{cDPS}$



Discriminating Variables





- $\Delta p_{T,ij} = \frac{|\vec{p}_{T,i} + \vec{p}_{T,j}|}{|p_{T,i}| + |p_{T,j}|}$
- $\Delta \phi_{ij} = |\phi_i - \phi_j|$
- $\Delta y_{ij} = |y_i - y_j|$,

ij = 12, 13, 14, 23, 24, 34

- $|\phi_{i+j} - \phi_{k+m}|$,

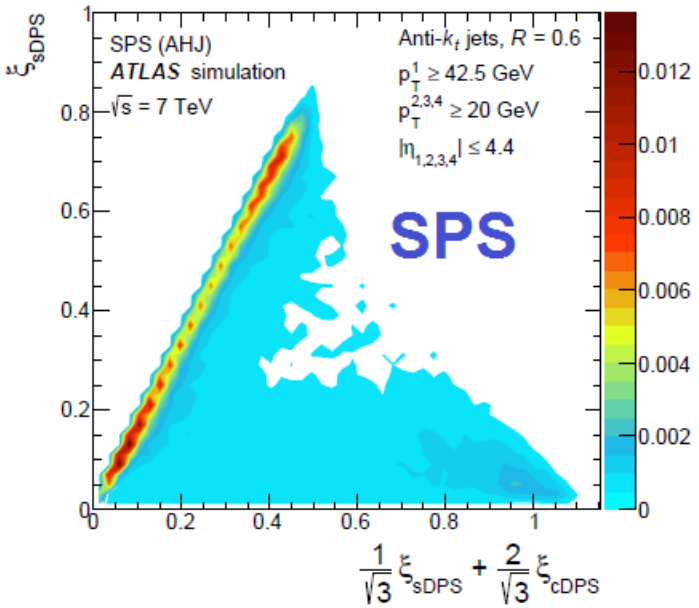
ijkm = 1234, 1324, 1423

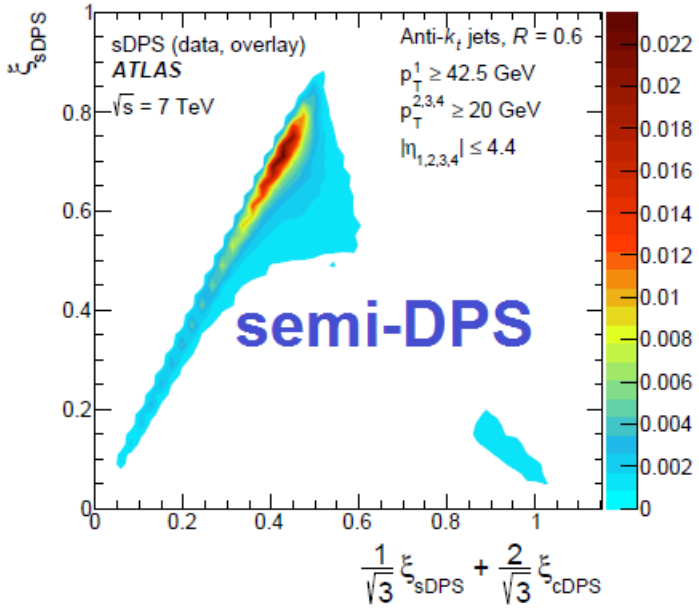
→ jets 1,2,3,4 are p_T-ordered

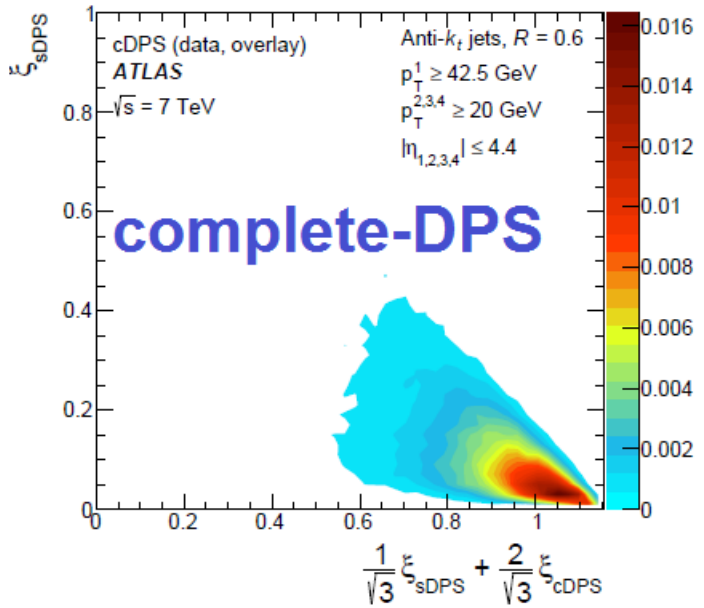
- Pairing can be ambiguous → use variables involving all possible jet combinations
- None of the variables provides clear separation between three classes
- The variables are correlated

  → **Use 21 variables for neural network training**

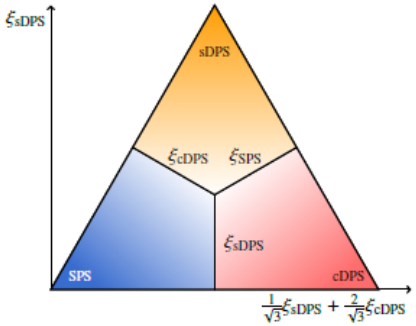
Neural Network Output

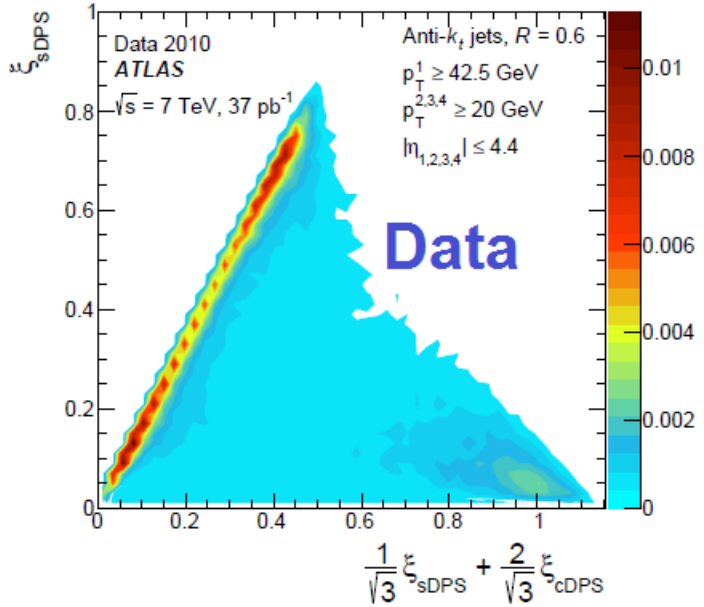






- NN output - "probabilities" for event to look like SPS, sDPS or cDPS:
  $0 < \xi_i < 1$, $\Sigma\, \xi_i = 1$





- Good separation between cDPS and others
- Separation between SPS and sDPS is difficult
- Fit sum of MC profiles to data:
  $D = (1 - f_{cDPS} - f_{sDPS})\, M_{SPS} + f_{cDPS}\, M_{cDPS} + f_{sDPS}\, M_{sDPS}$

Results: f_{DPS}

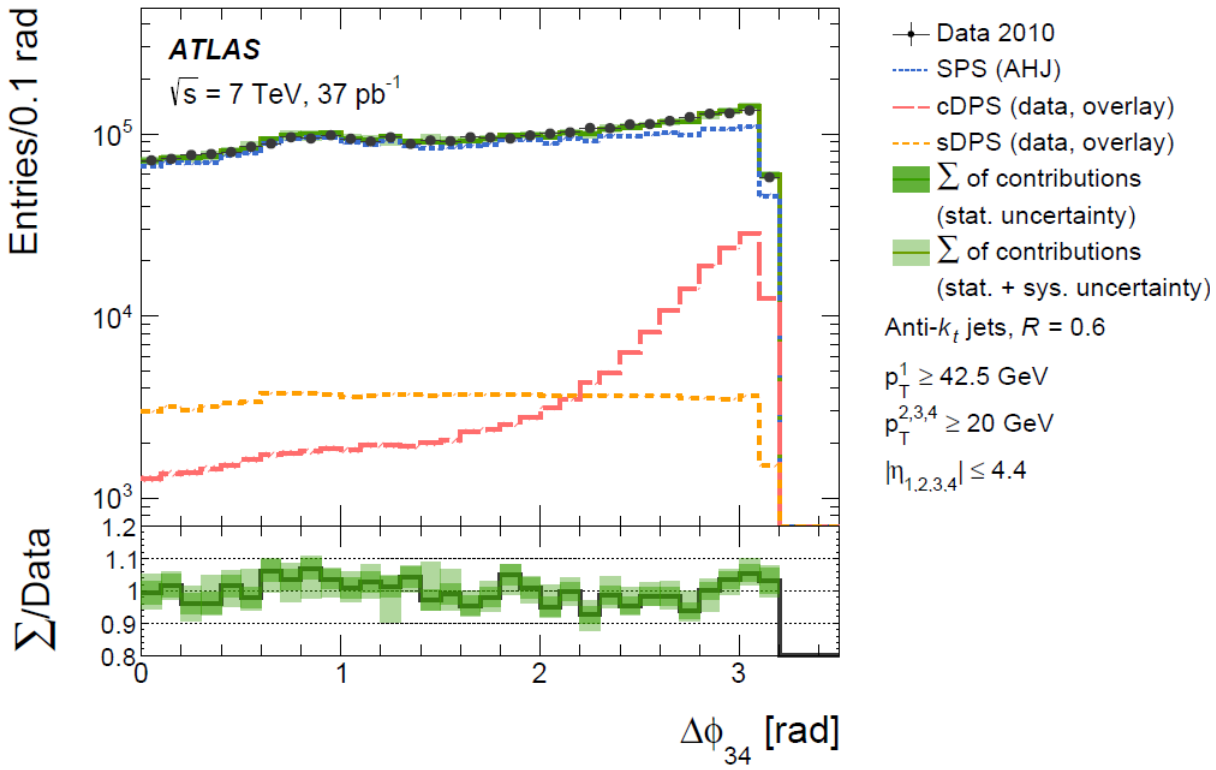
- f_{DPS}: fraction of DPS events in the inclusive 4-jet data sample

$$f_{\mathrm{DPS}} = 0.092\ ^{+0.005}_{-0.011}\ (\mathrm{stat.})\ ^{+0.033}_{-0.037}\ (\mathrm{syst.})$$

Sources of systematic uncertainties:

Source	Δf_{DPS}
Reweighting of AHJ	±6%
Jet energy and angular resolution	±15%
JES uncertainty	+32% -37%
Total syst. uncertainty	+36% -40%

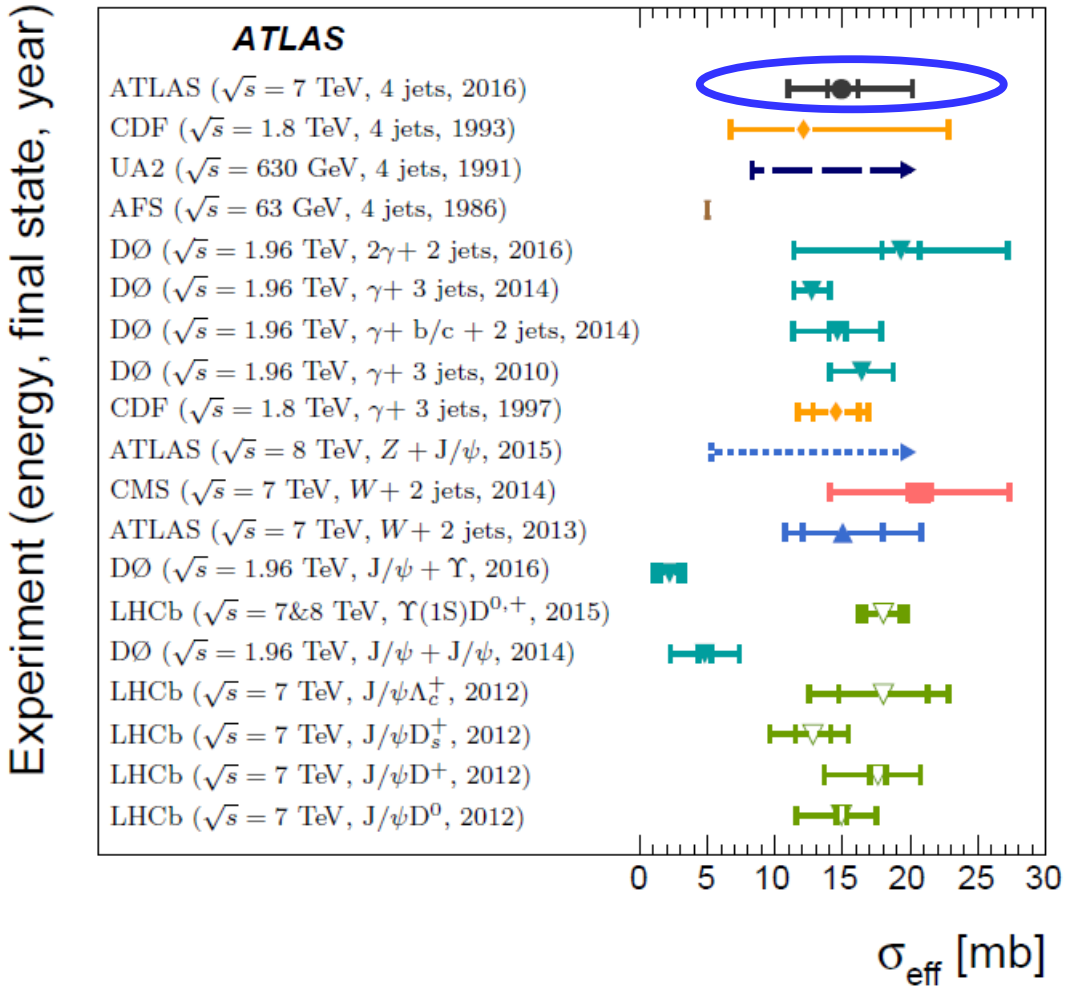
Post-fit distribution



(9±4)% of 4-jet events originate through Double Parton Scattering

→ uncertainty dominated by jet energy scale variations

Results: Effective Cross Section



$$\sigma_{\text{eff}} = 14.9\ ^{+1.2}_{-1.0}\ (\text{stat.})\ ^{+5.1}_{-3.8}\ (\text{syst.})\ \text{mb}$$

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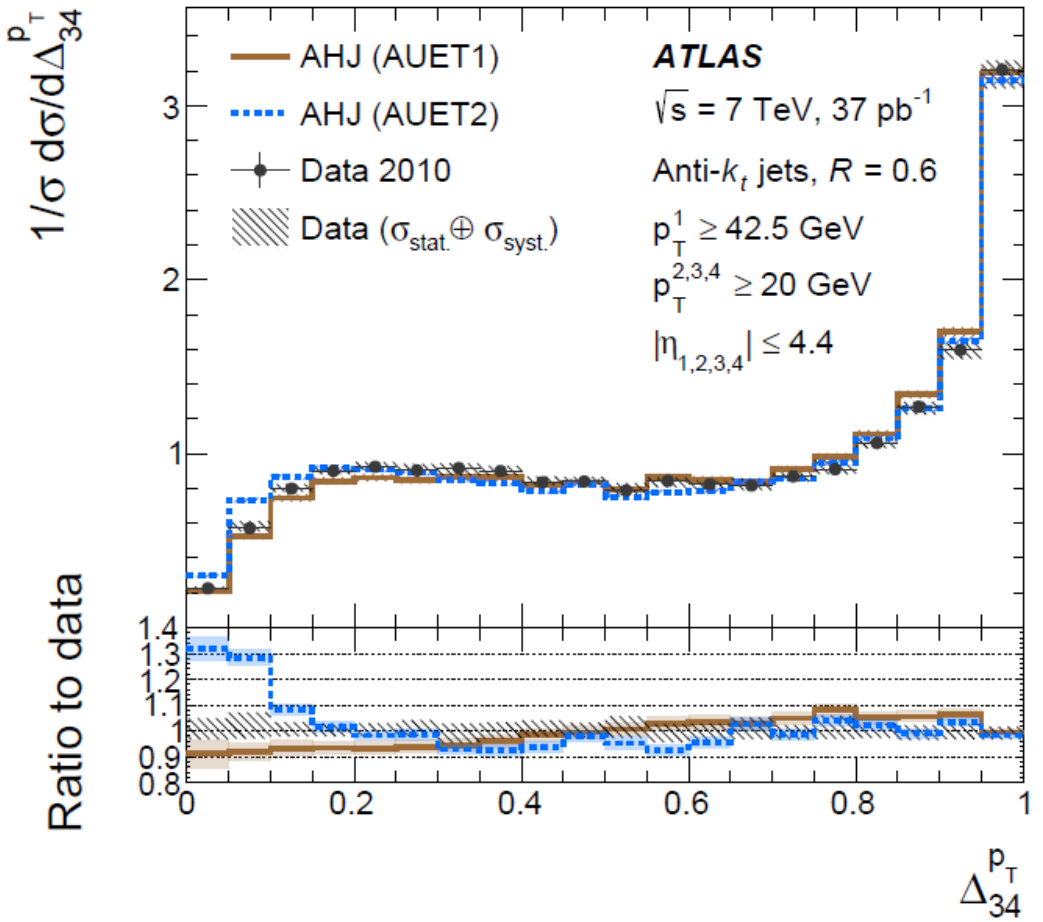
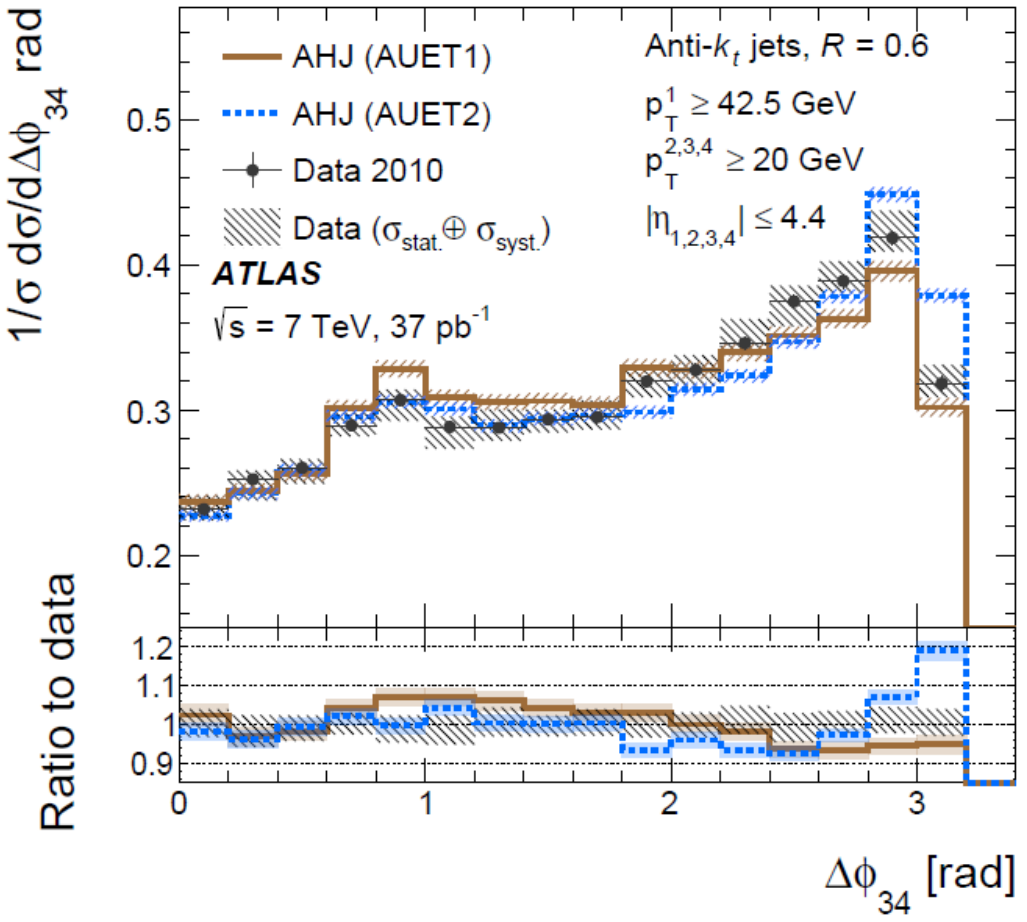
- Uncertainty is systematics dominated
  → Mostly due to jet energy scale uncertainty

- Compatible with most of previous measurements performed at different centre-of-mass energies and with different final states, except for two measurements with double heavy vector meson production by DØ

Unfolded Distributions





- Differential cross sections of variables sensitive to DPS are provided
- Gives a way to test various DPS MC models

Summary

Leading track underlying event: **JHEP 03 (2017) 157**

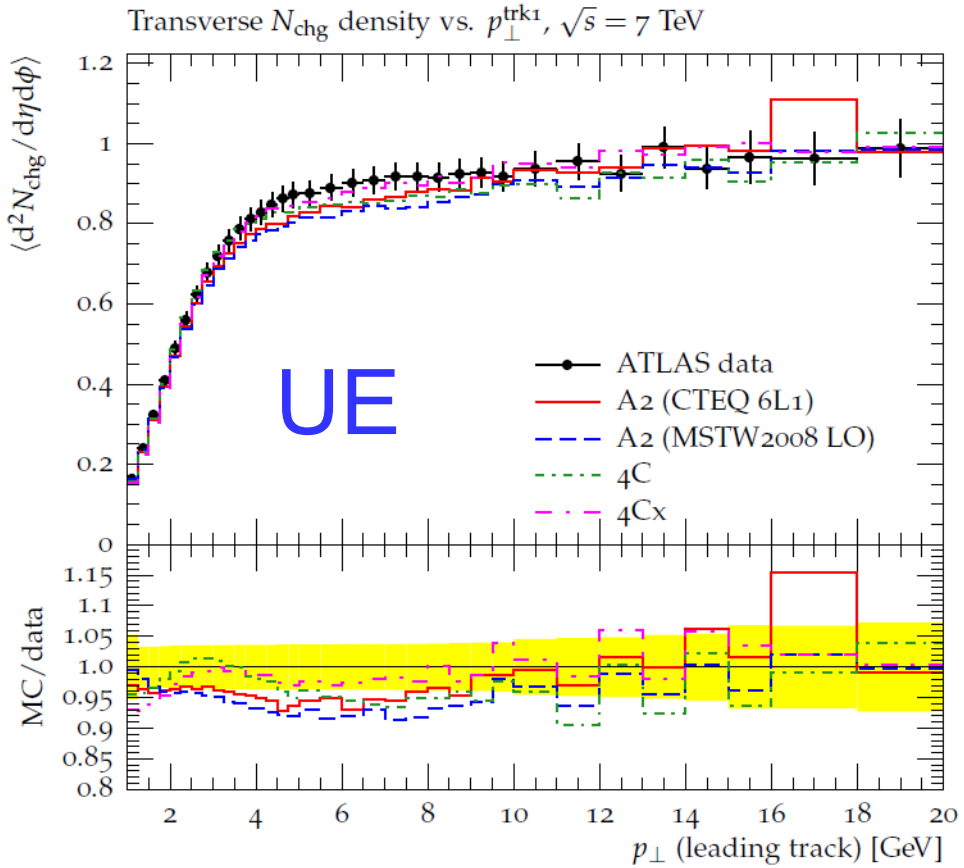
- Track distributions in transverse region relative to the leading track have a discriminating power between Monte Carlo models
- The understanding of track multiplicity & track p_T sum in events with low-p_T leading track is not complete
- Re-tuning using new 13 TeV data would be beneficial for Run-2 studies

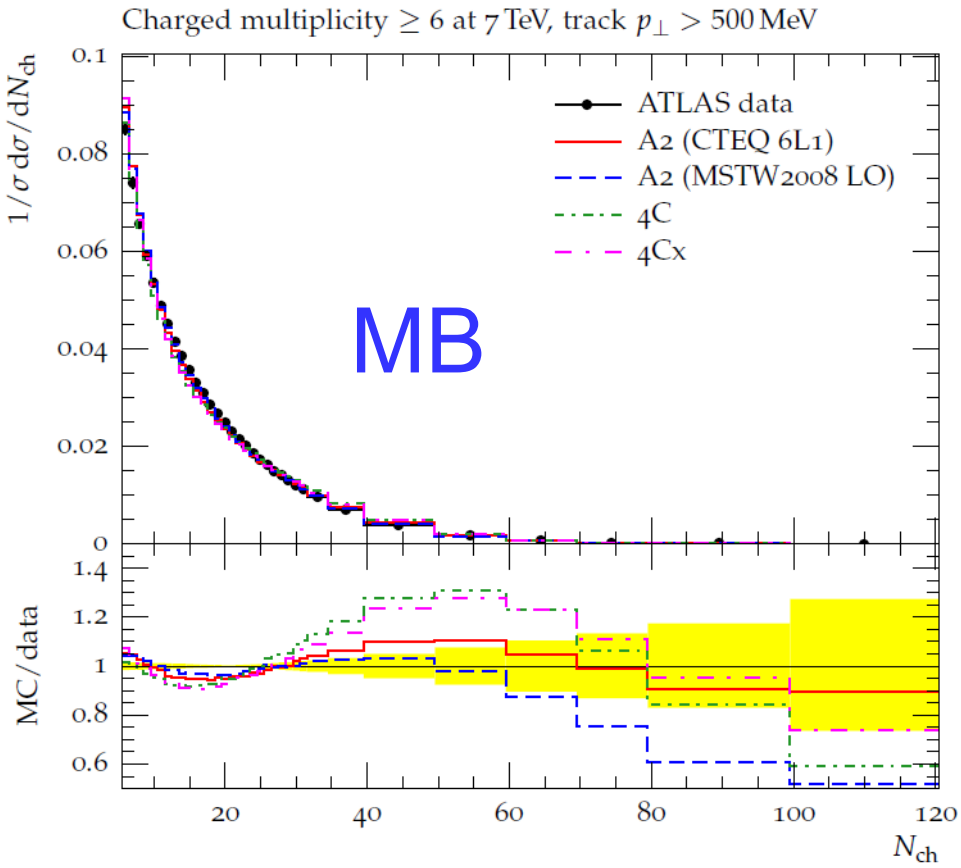
Hard double parton scattering with four jets: **JHEP 11 (2016) 110**

- Non-trivial due to different possibilities of four jet matching to primary and secondary partons
- (9±4)% of inclusive 4-jet events are due to DPS
- Extracted effective cross section of 15 mb suffers from systematic uncertainty (~30%), mostly due to jet energy scale uncertainty
- Paper provides unfolded distributions sensitive to DPS

Backup

Pytha A2





PDF	pT0Ref	ecomPow	a1	reconnectRange
CTEQ 6L1	2.18	0.22	0.06	1.55
MSTW2008 LO	1.90	0.30	0.03	2.28
CTEQ 6.6	1.73	0.16	0.03	5.12
CT10	1.70	0.16	0.10	4.67
MRST2007 LO*	2.39	0.24	0.01	1.76
MRST2007 LO**	2.57	0.23	0.01	1.47

Table 4: Tuned MPI parameters for the A2/AU2 Pythia 8 tunings.

- Tunes to ATLAS 7 TeV UE and MB data

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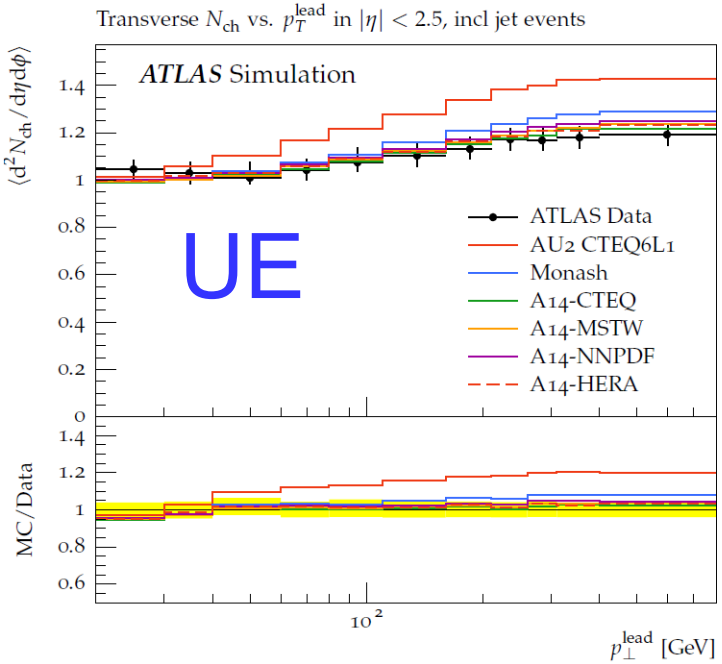
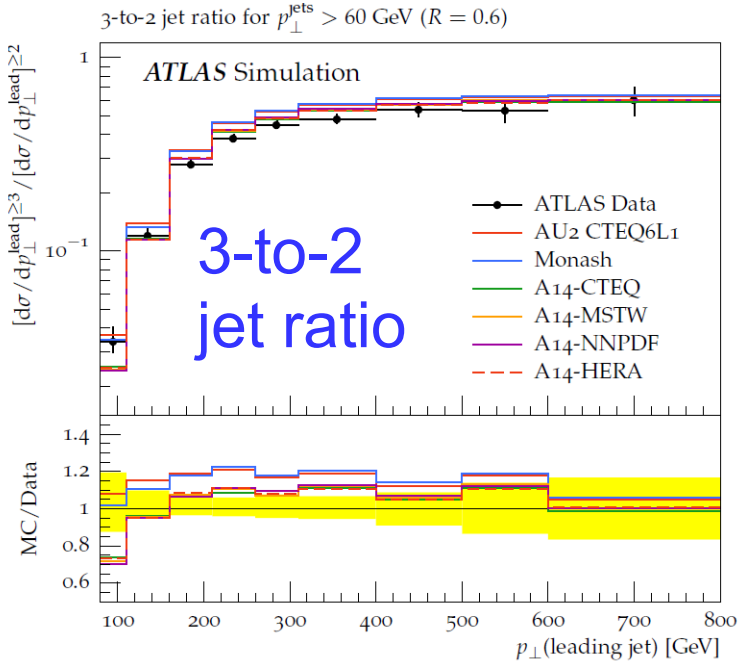
Pythia A14





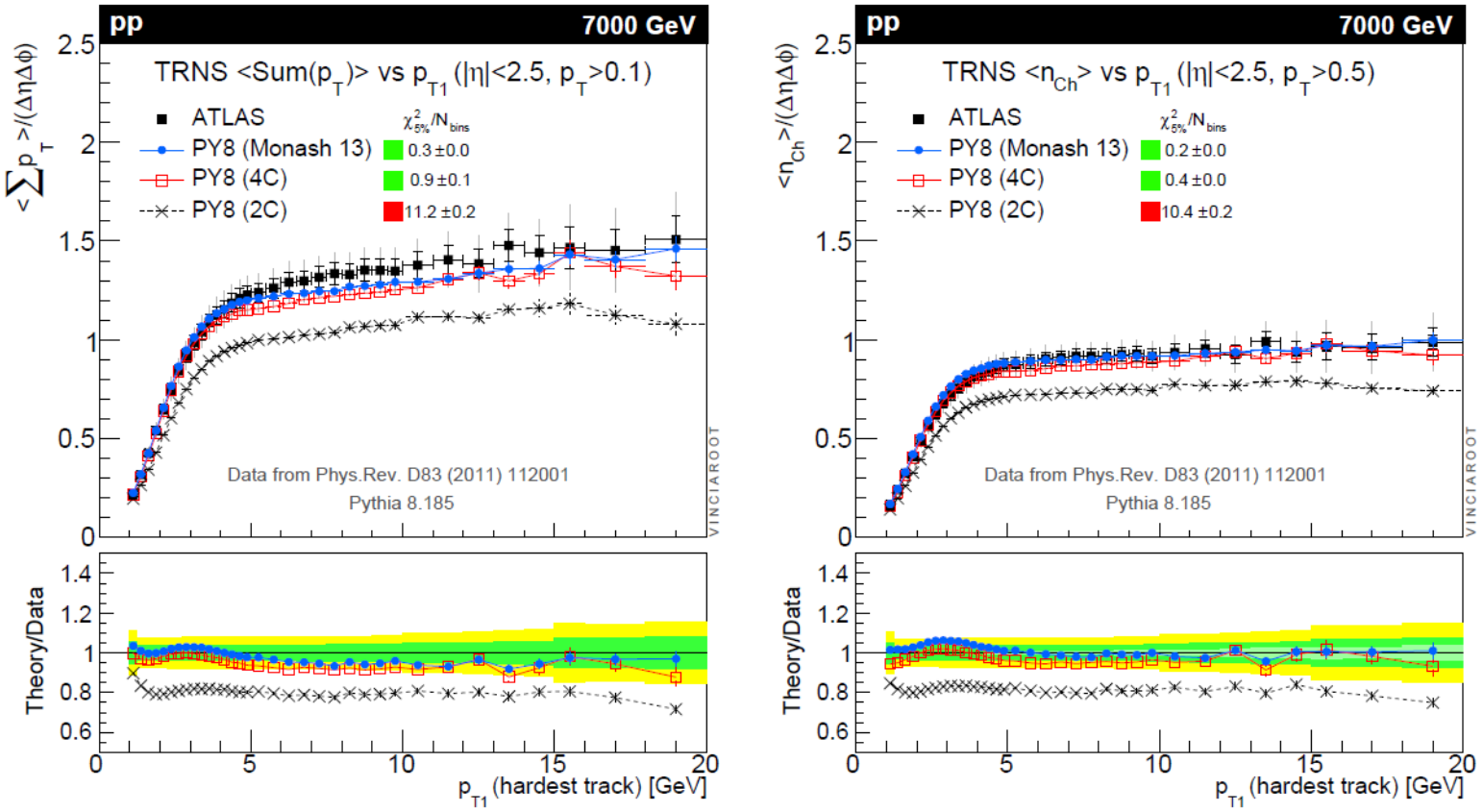
Param	CTEQ	MSTW	NNPDF	HERA
SigmaProcess:alphaSvalue	0.144	0.140	0.140	0.141
SpaceShower:pT0Ref	1.30	1.62	1.56	1.61
SpaceShower:pTmaxFudge	0.95	0.92	0.91	0.95
SpaceShower:pTdampFudge	1.21	1.14	1.05	1.10
SpaceShower:alphaSvalue	0.125	0.129	0.127	0.128
TimeShower:alphaSvalue	0.126	0.129	0.127	0.130
BeamRemnants:primordialKThard	1.72	1.82	1.88	1.83
MultipartonInteractions:pT0Ref	1.98	2.22	2.09	2.14
MultipartonInteractions:alphaSvalue	0.118	0.127	0.126	0.123
BeamRemnants:reconnectRange	2.08	1.87	1.71	1.78

Table 3: Tuned parameters for the A14 set of tunes

- Tunes to ATLAS Run-1 jet UE data, ttbar gap fractions and 3-to-2 jet ratios
- better description of UE distributions than for A2

ATL-PHYS-PUB-2014-021

Pythia Monash



- Tunes to LHC MB, UE and Drell-Yan data (to constrain ISR and MPI parameters) and to SPS + Tevatron data (for energy scale constraints)
- 1 (FSR) + 16 (String-breaking) + 3 (PDF + ME) + 5 (ISR + primordial kt) + 6 (MPI + colour reconnection + diffractive)

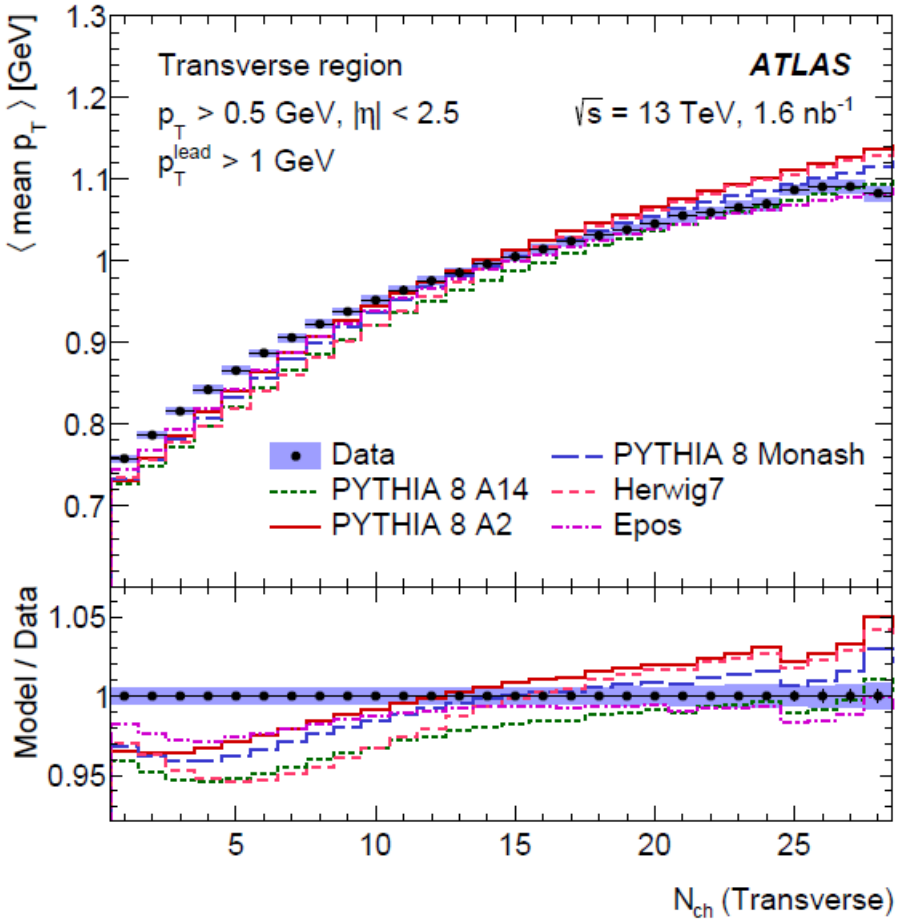
  → 31 parameter differs compared to default Pythia

EPOS LHC Tune

- EPOS: Soft-QCD/cosmic-ray air-shower MC generator
- Gribov-Regge theory (QCD inspired effective-field theory)
- Hydrodynamic flow modeling in high-density regions + string-based hadronisation
  - ➢ Doesn't use proton PDFs! (in the commonly used sense)

LHC Run-1 data used for the tune:

- Total, elastic and inelastic *pp* cross section by TOTEM
- Charged particle multiplicity in *pp* interactions with ALICE
- Charged particles pt distribution in *pp* with ATLAS and CMS
- Charged particles pt and eta distributions in PbPb and Pb-*p* collisions with ALICE, ATLAS and CMS



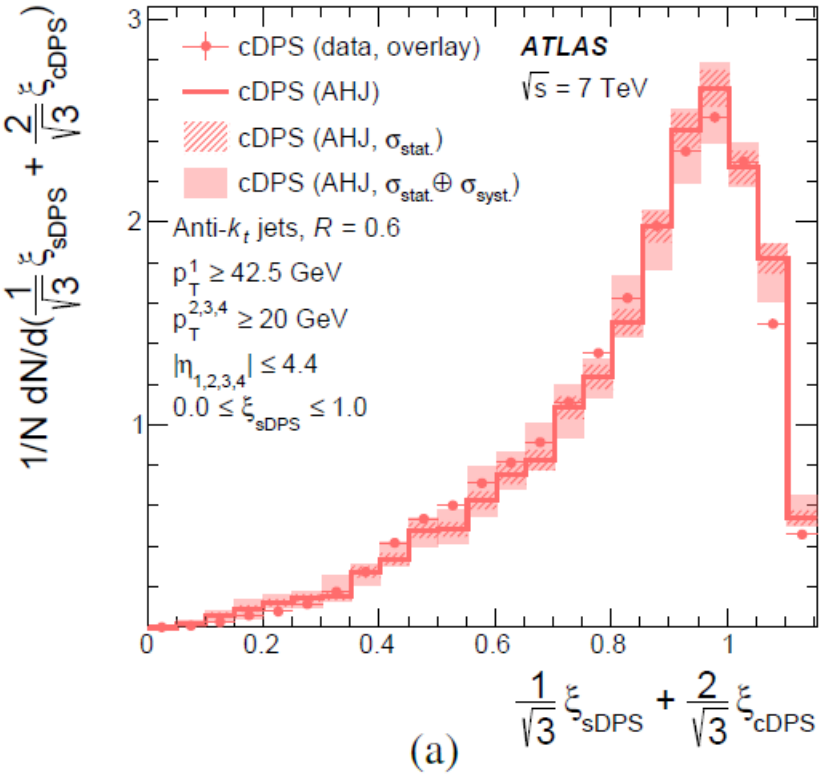
Leading Track Underlying Event: Systematic Uncertainties

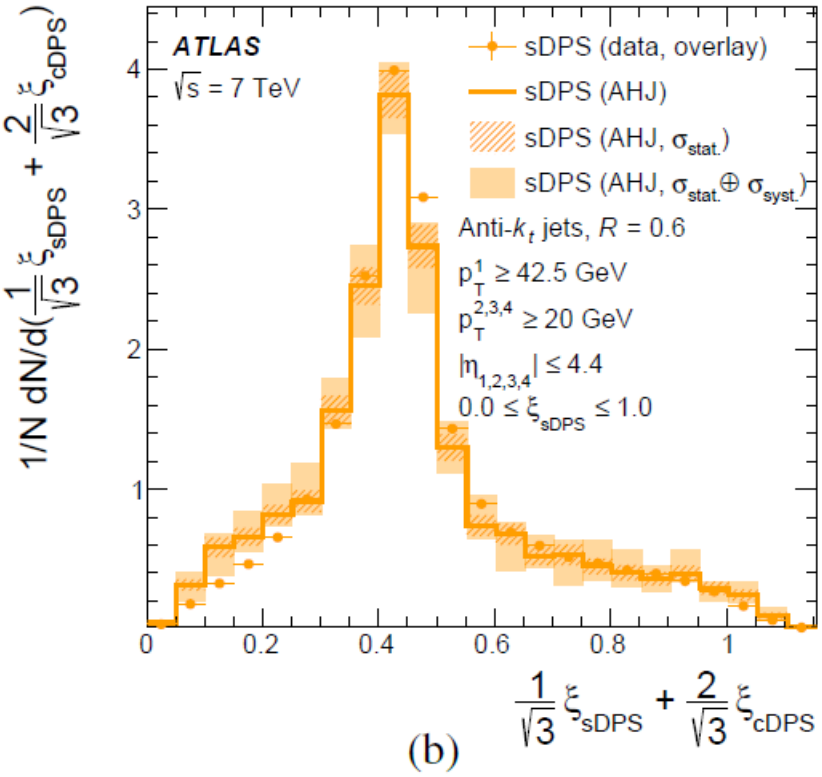
- Trigger and vertexing: systematic uncertainties found to be negligible

- Track reconstruction (uncertainty from imperfect knowledge of the material in inner detector)
- Expected fraction of non-primary particles (decay products, interaction with detector material)
- Unfolding (non-closure: non-reproduction of a known input; parameterisation: estimate the stability of the fit method)

	Range of values			
Observable	Material	Non-primaries	Non-closure	Parameterisation
N_{ch} or $\sum p_T$ vs. $\Delta\phi$	0.9%	0.6%	0–0.6%	0–0.4%
N_{ch} or $\sum p_T$ vs. p_T^{lead}	0.5–1.0%	0.3–0.6%	0–2.5%	0–0.4%
$\langle$mean $p_T\rangle$ vs. N_{ch}	0–0.5%	0–0.5%	— 0.5% (combined) —	
$\langle$mean $p_T\rangle$ vs. p_T^{lead}	0–0.4%	0–0.3%	— 0.5% (combined) —	

cDPS model validation





- The overlaid data dijet events were compared to DPS modelling by Alpgen + Herwig + Jimmy
- The DPS fraction was determined in the AHJ Monte Carlo using the same template fit technique and compared to the true value in the event record → a resonable agreement between the two was observed