Measurements of the event shapes and underlying event in pp collisions at 7 TeV

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Overview

1. Measurement of charged-particle EVENT SHAPE variables in inclusive $\sqrt{s} = 7\ \mathrm{TeV}$ proton-proton interactions with the ATLAS detector

   Phys. Rev. D 88, 032004 (2013) [arXiv:1207.6915]

   - Event Shape Definitions
   - Data Selection
   - Results

2. The UNDERLYING EVENT in jet events at $\sqrt{s} = 7\ \mathrm{TeV}$ with the ATLAS experiment

   ATLAS-CONF-2012-164

3. Summary

Motivation

- Soft interactions are not reliably calculable by theory - but important for quark confinement understanding

  $\Rightarrow$ described by phenomenological models, implemented in MC event generators

  $\Rightarrow$ contain many free parameters which are needed to be constrained by measurements.

Event Shapes = observables that describe the patterns, correlations, and origins of the energy flow in an interaction

- experimentally simply measured quantities
- enable detailed tests of the phenomenological models of QCD in leading order MC programs $\Rightarrow$ input for tuning MC generators

Event Shapes

- indirect probe of multi-jet topologies
- vanish in the limit of a pure $2 \rightarrow 2$ process
- increase to a maximum for uniformly distributed energy within a multi-jet event
- ratios of final state observables $\Rightarrow$ reduced sensitivity to theoretical and experimental uncertainties
- defined in terms of the transverse momentum, which is Lorentz-invariant under boosts along the beam axis
- *central event shapes*: include only particles from a restricted phase space in pseudorapidity η, in this analysis the range $|\eta| < 2.5$ is used

Transverse Thrust

$$T_{\perp} = \max_{\hat{\boldsymbol{n}}_{\perp}} \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_{\perp}|}{\sum_i p_{\mathrm{T}i}} \qquad \tau_{\perp} = 1 - T_{\perp}$$

- the sum over the $\boldsymbol{p}_{\mathrm{T}i}$ of all charged particles in the event
- $\hat{\boldsymbol{n}}_{\perp}$ - the unit vector of the *thrust axis* maximizing the ratio
- $T_{\perp} = 1$ - for a perfectly balanced, pencil-like, dijet topology
- $T_{\perp} = 2/\pi$ - for a circularly symmetric distribution of particles in the transverse plane

$\tau_{\perp}$ - complement to $T_{\perp}$ - matches the behavior of many event shape variables:

- vanishes in a balanced dijet topology
- large value of $\tau_{\perp}$ - a departure from a two-body system

Transverse Thrust Minor

Event Plane = defined by the thrust axis $\hat{\boldsymbol{n}}_\perp$ and beam axis $\hat{\boldsymbol{z}}$

$$T_{\mathrm{M}} = \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_m|}{\sum_i \boldsymbol{p}_{\mathrm{T}i}}, \qquad \hat{\boldsymbol{n}}_m = \hat{\boldsymbol{n}}_\perp \times \hat{\boldsymbol{z}}$$

The **transverse thrust minor** T_{M} quantifies the sum of all tranverse momenta out of the event plain

- $T_{\mathrm{M}} = 0$ - for a perfectly balanced, pencil-like, dijet topology
- $T_{\mathrm{M}} = 2/\pi$ - for an isotropic event (circularly symmetric distribution of particles in the transverse plane)

Transverse Sphericity

the **transverse sphericity S$_\perp$** is defined in terms of the transverse components only:

$$S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}$$

where $\lambda_1^{xy} > \lambda_2^{xy}$ are two eigenvalues of S^{xy}:

$$S^{xy} = \sum_i \frac{1}{|\mathbf{p}_{T,i}|^2} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{yi}p_{xi} & p_{yi}^2 \end{pmatrix}$$

- allowed range: $0 \leq S_\perp < 1$

Event and Track Selection

the data collected in April 2010 with a minimal prescale factor for the *minimum-bias trigger* (peak luminosity $\approx$ 1.9 $\times$ 10^{27} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

events rejected if they contain any other vertex with $\geq$ 4 tracks apart from the primary interaction vertex of the event

events required to contain at least 6 tracks fulfilling the criteria:

- $p_\mathrm{T} > 0.5$ GeV; $|\eta| < 2.5$
- a minimum of one pixel and 6 SCT hits;
- a hit in the innermost pixel layer, if the corresponding pixel module was active;
- transverse and longitudinal impact parameters wrt the primary vertex, $|\mathbf{d_0}| <$ **1.5 mm** and $|\mathbf{z_0}| \sin\theta <$ **1.5 mm**;
- a track-fit probability $\chi^2 > 0.01$ for tracks with $p_\mathrm{T} > 10$ GeV in order to remove mis-measured tracks.

Measured Distributions

I. Normalized distributions:

$$(1/N_{ev})dN_{ev}/d\tau_{\perp}^{ch} \quad (1/N_{ev})dN_{ev}/dT_{\mathrm{M}}^{ch} \quad (1/N_{ev})dN_{ev}/dS_{\perp}^{ch}$$

^{ch} in the event shape observables $\tau_{\perp}^{\mathrm{ch}}$, $T_{\mathrm{M}}^{\mathrm{ch}}$, $S_{\perp}^{\mathrm{ch}}$ indicating charged particles

studied separately for the following $p_{\mathrm{T}}^{\mathrm{lead}}$ regions:

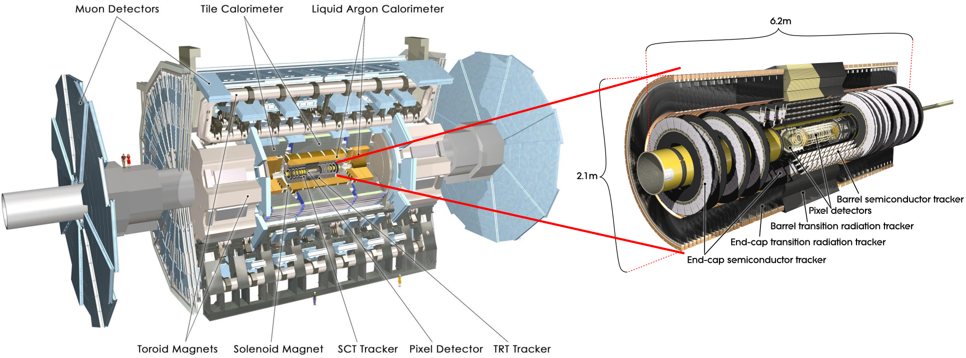
- $0.5 \text{ GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} < 2.5 \text{ GeV}$; $2.5 \text{ GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} < 5.0 \text{ GeV}$;
- $5.0 \text{ GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} < 7.5 \text{ GeV}$; $7.5 \text{ GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} < 10.0 \text{ GeV}$;
- $p_{\mathrm{T}}^{\mathrm{lead}} > 10.0 \text{ GeV}$

$p_{\mathrm{T}}^{\mathrm{lead}}$ - transverse momentum of the highest p_{T} (leading) charged particle

II. Average values: $\langle \tau_{\perp}^{ch} \rangle, \langle T_{\mathrm{M}}^{ch} \rangle, \langle S_{\perp}^{ch} \rangle$ as functions of N_{ch}, $\sum p_{\mathrm{T}}$

- N_{ev} - number of events with six or more charged particles within the selected kinematic range
- N_{ch} - number of charged particles in an event
- $\sum p_{\mathrm{T}}$ - scalar sum of transverse momenta of charged particles in the event

Atlas Detector



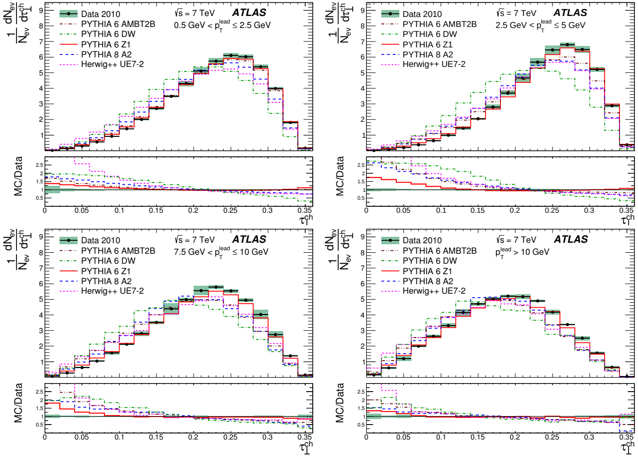
the ATLAS detector - almost full solid angle around the collision point coverage

tracking detectors - azimuthal angle ϕ: full coverage, pseudorapidity coverage: $\eta < 2.5$

- *pixel detector* (pixel); *semiconductor tracker* (SCT)
- for $|\eta| < 2.0$ *transition radiation tracker* (TRT)

Minimum Bias Trigger Scintillator (MBTS) - mounted at each end of the tracking detector at $z = \pm 3.56$ m segmented into 8 sectors in azimuth and two concentric rings in pseudorapidity $2.09 < |\eta| < 2.82$ and $2.82 < |\eta| < 3.84$

Complement of the Transverse Thrust Distributions



lower $p_{\mathrm{T}}^{\mathrm{lead}}$ ranges: spherical events prevalence

starting with $p_{\mathrm{T}}^{\mathrm{lead}} > 7.5\,\mathrm{GeV}$: shift to less spherical events & distribution broadening

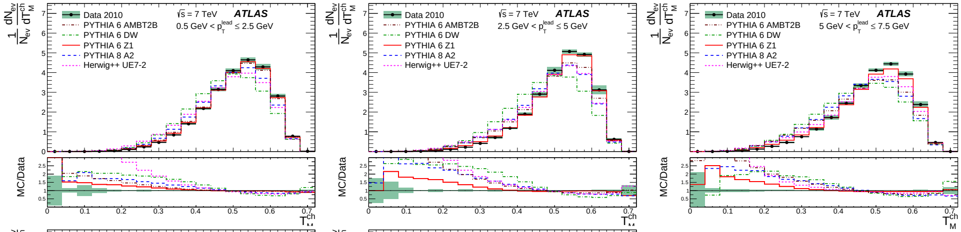
all models tend to better reproduce data selected with higher $p_{\mathrm{T}}^{\mathrm{lead}}$ ranges

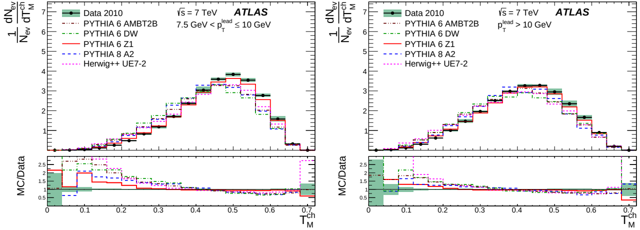
PYTHIA 6 tune Z1 tuned to UE at LHC agrees best; **PYTHIA 6 DW** is **furthest** from data

AMBT2B based on MB LHC data shows better agreement in the **lowest** $p_{\mathrm{T}}^{\mathrm{lead}}$ ranges

compared to AMBT2B, **PYTHIA 8** and **HERWIG++** agree better in **intermediate** $p_{\mathrm{T}}^{\mathrm{lead}}$

Transverse Thrust Minor Distributions





lower p_T^{lead} ranges: spherical events prevalence

starting with $p_T^{\text{lead}} > 7.5\,\text{GeV}$: shift to less spherical events & distribution broadening

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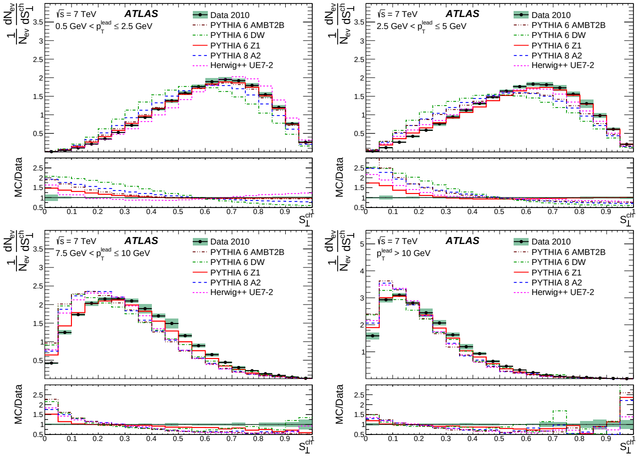
Transverse Sphericity Distributions



lower p_T^{lead} ranges: spherical events prevalence

more sensitive to p_T^{lead} incr.!

starting with $p_T^{lead} > 5$ GeV: shift to less spherical events & distribution broadening

all models tend to better reproduce data selected with higher p_T^{lead} ranges

PYTHIA 6 tune Z1 tuned to UE at LHC agrees best; **PYTHIA 6 DW similar** to other tunes

AMBT2B based on MB LHC data agrees better for the **lowest** p_T^{lead} ranges

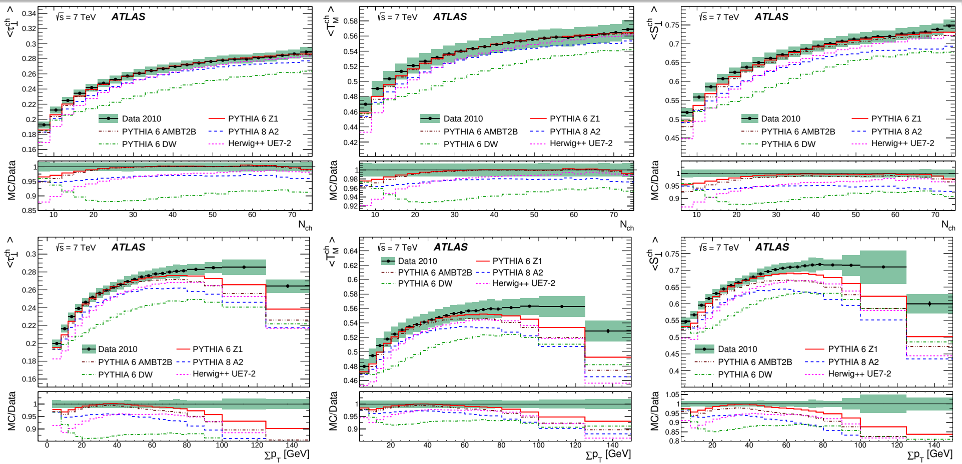
PYTHIA 8 A2 and **HERWIG++ UE7-2** agree better in the **intermediate** p_T^{lead} ranges

Average Values of the $\tau_{\perp}^{\mathrm{ch}}$, $T_{\mathrm{M}}^{\mathrm{ch}}$ and $S_{\perp}^{\mathrm{ch}}$ Distributions

$p_{\mathrm{T}}^{\mathrm{lead}}$ range	$\tau_{\perp}^{\mathrm{ch}}$	$T_{\mathrm{M}}^{\mathrm{ch}}$	$S_{\perp}^{\mathrm{ch}}$
$0.5\ \mathrm{GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} \leq 2.5\ \mathrm{GeV}$	0.227 ± 0.002	0.508 ± 0.002	0.618 ± 0.005
$2.5\ \mathrm{GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} \leq 5.0\ \mathrm{GeV}$	0.240 ± 0.006	0.514 ± 0.005	0.579 ± 0.013
$5.0\ \mathrm{GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} \leq 7.5\ \mathrm{GeV}$	0.227 ± 0.007	0.490 ± 0.006	0.449 ± 0.019
$7.5\ \mathrm{GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} \leq 10\ \mathrm{GeV}$	0.210 ± 0.010	0.459 ± 0.007	0.337 ± 0.017
$p_{\mathrm{T}}^{\mathrm{lead}} \leq 10\ \mathrm{GeV}$	0.185 ± 0.011	0.415 ± 0.010	0.230 ± 0.024

- mean values of $\tau_{\perp}^{\mathrm{ch}}$ and $T_{\mathrm{M}}^{\mathrm{ch}}$ initially rise with increasing $p_{\mathrm{T}}^{\mathrm{lead}}$ with their maximum value in the range $2.5\ \mathrm{GeV} < \mathrm{p}_{\mathrm{T}}^{\mathrm{lead}} \leq 5.0\ \mathrm{GeV}$, before decreasing
- similar trend observed by the ALICE Collaboration, transverse sphericity distribution, charged particles with $|\eta| < 0.8$ in inelastic 7 TeV *pp* collisions

Mean Values of $\tau_{\perp}^{ch}$, T_{M}^{ch}, $S_{\perp}^{ch}$ as Functions of N_{ch}, $\sum p_T$



- all observables increase with N_{ch}; increase is less marked at values of $N_{ch} > 30$
- similar trend for $\sum p_T$; for $\sum p_T > 100\,\mathrm{GeV}$ decrease again ⇒ events are more dijet-like
- MC models predict fewer high-sphericity events than seen in the data (similar by ALICE)
- N_{ch} behavior predicted by MC well; decrease in $\sum p_T$ happens before the data

Overview

1. Measurement of charged-particle EVENT SHAPE variables in inclusive $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector
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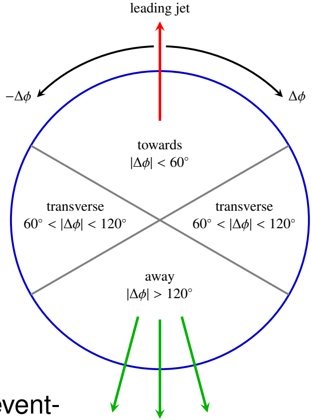
2. The UNDERLYING EVENT in jet events at $\sqrt{s} = 7$ TeV with the ATLAS experiment
   ATLAS-CONF-2012-164
   - Underlying Events Definition
   - Data Selection
   - Results

3. Summary

Measurement of Underlying Events

- **Underlying Events:**
  soft processes accompanying hard parton-parton interaction in proton-proton collisions
- η, φ plane divided into regions around leading (the highest p_T) object (track, calo. cluster, jet...):
  - $|\Delta\varphi| < 60°$ - **toward**
  - $60° < |\Delta\varphi| < 120°$ - **transverse**
  - $|\Delta\varphi| > 120°$ - **away**



further subdivision of the observables on an event-by-event basis depending on which side of the event is more activity:

- **trans-max**: observables in the more-active transverse region
- **trans-min**: observables in the less-active transverse region
- **trans-diff**: difference of trans-max and trans-min

UE - Using Neutral and Charged Particles

Topological clusters study:

- to extend the η coverage of the measurement beyond the ATLAS central tracker acceptance of $|\eta| < 2.5$. The cluster-based observables have been studied separately for the central region ($|\eta| < 2.5$) and for full η acceptance
- based on calorimeter three-dimensional energy deposit
- benefit of fine granularity:
  - electromagnetic calorimeter:
    - 4 longitudinal depths
    - $\Delta\eta \times \Delta\varphi$: $0.003 \times 0.1 - 0.05 \times 0.025$
  - hadronic calorimeter:
    - 3 longitudinal depths
    - $\Delta\eta \times \Delta\varphi$: 0.1×0.1 for $|\eta| < 2.5$
    - $\Delta\eta \times \Delta\varphi$: 0.2×0.2 for $2.5 < |\eta| < 3.2$
- sensitive to both neutral and charged particles
- complementary analyses to correspond. track based ones

  Phys. Rev. D 86 (2012) 072004 [arXiv:1208.0563]
  JHEP11(2012)033 [arXiv:1208.6256]

Data Selection

the full 2010 dataset of jet events in *pp* collisions at $\sqrt{s} = 7\ \mathrm{TeV}$ collected by the ATLAS, with jets of $p_T > 20\ \mathrm{GeV}$ and $|\eta| < 2.8$

429,000 (inclusive jet) and 99,000 (exclusive dijet) events selected - total luminosity: $37.3 \pm 1.2\ \mathrm{pb}^{-1}$

Triggers:
MBTS to select events with jets with $20 < p_T < 60\ \mathrm{GeV}$
the calorimeter-based jet trigger with tresholds over 60 GeV

Requirements:

- to remove cosmic ray muons and other background: at least one primary vertex and at least 5 associated tracks
- to reduce pile-up: events with more than one vertex with at least two associated tracks are removed
- additional req. for exclusive dijet selection: one and only one subleading jet with $p_{\mathrm{T}}^{\mathrm{sub}}/p_{\mathrm{T}}^{\mathrm{lead}} > 0.5$ and $|\Delta\phi| > 0.5$

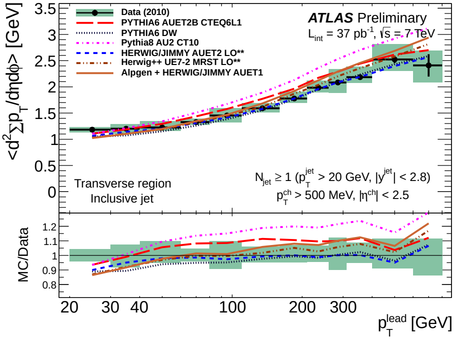
Measured Observables at Particle and Detector Level

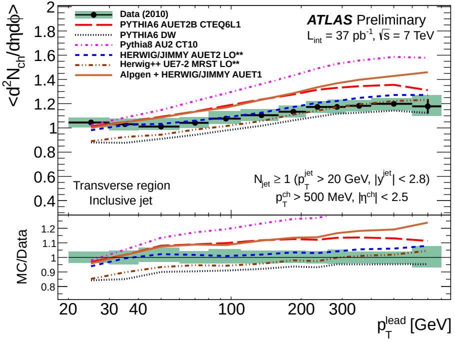
particle level:

- for momentum use only particles with $p_T > 0.5\ \mathrm{GeV}$
- for energy analysis:
  - $p > 0.5\ \mathrm{GeV}$ for charged particles
  - $p > 0.2\ \mathrm{GeV}$ for neutral particles

Observable	Particle level	Detector level
$p_{\mathrm{T}}^{\mathrm{lead}}$	Transverse momentum of the leading jet	
$d^2N_{ch}/d\eta d\phi$	Mean number of stable charged particles per unit $\eta - \phi$	Mean number of selected tracks per unit $\eta - \phi$
$d^2\Sigma p_{\mathrm{T}}/d\eta d\phi$	Mean scalar p_{T} sum of stable charged particles per unit $\eta - \phi$	Mean scalar p_{T} sum of selected tracks per unit $\eta - \phi$
$d^2\Sigma E_{\mathrm{T}}/d\eta d\phi$	Mean scalar E_T sum of stable charged and neutral particles per unit $\eta - \phi$	Mean scalar E_T sum of selected EM-scale topoclusters per unit $\eta - \phi$

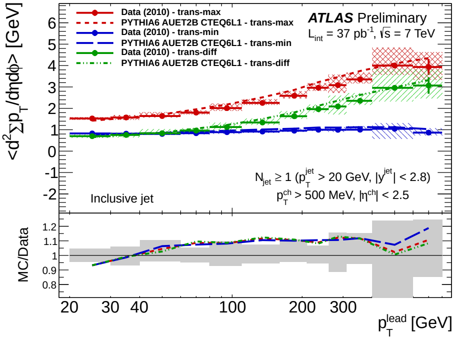
$\sum p_T$ and N_{ch} vs p_T^{lead}, inclusive jet, total transv. region

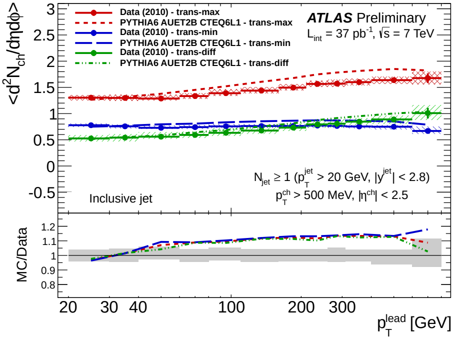




- the total transverse activity increases with p_T^{lead} according to both, the $\sum p_T$ and N_{ch}
- MC models reproduce data well, PYTHIA 6 (most UE tunning attention) surprisingly further than HERWIG++ and HERWIG/JIMMY

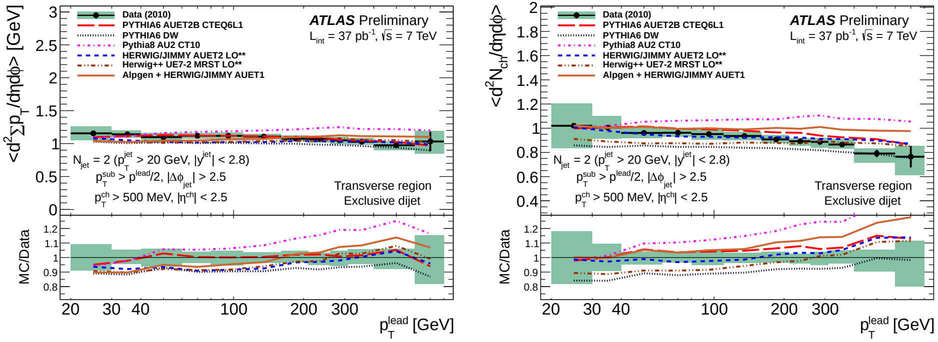
$\sum p_{\mathrm{T}}$ and N_{ch} vs $p_{\mathrm{T}}^{\mathrm{lead}}$, trans-max/min/diff observables





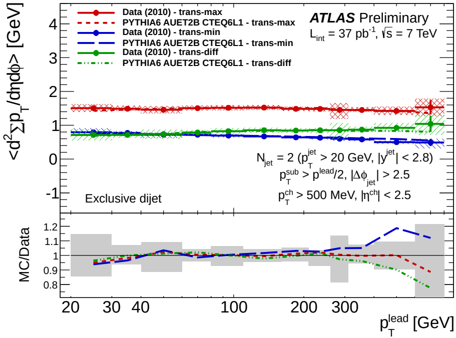
- the trans-max activity grows with $p_{\mathrm{T}}^{\mathrm{lead}}$, while trans-min complement is almost constant according to both, the $\sum p_{\mathrm{T}}$ and N_{ch}
- compatible with interpretation: trans-min region being less affected by the hard part of UE
- trans-diff (most sensitive to additional hard scattering) increases with $p_{\mathrm{T}}^{\mathrm{lead}}$

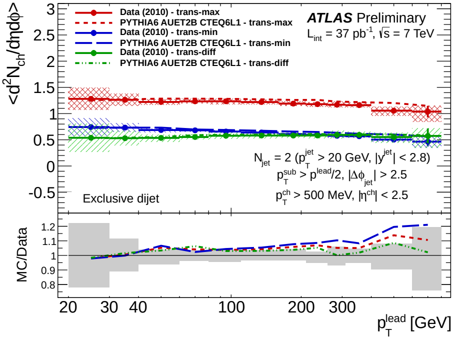
$\sum p_T$ and N_{ch} vs p_T^{lead}, exclusive dijet, total tran. region



- the total transverse activity slightly decrease with p_T^{lead} according to both, the $\sum p_T$ and N_{ch}
- the MC models describe exclusive dijet observables better than inclusive jet ones (PYTHIA 6 models particularly improved)

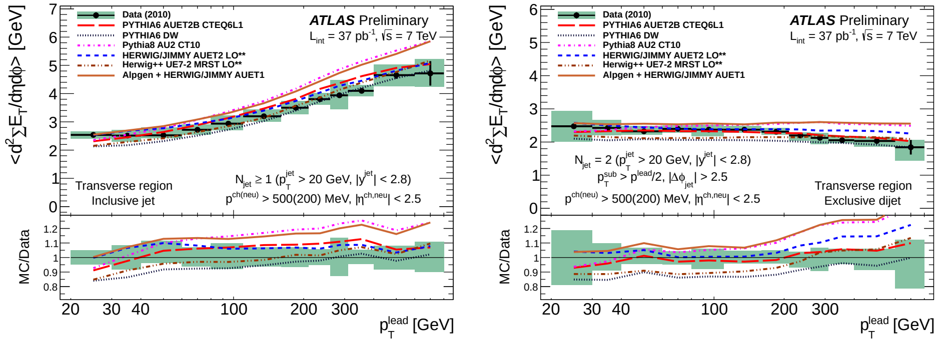
$\sum p_T$ and N_{ch} vs p_T^{lead}, trans-max/min/diff observables





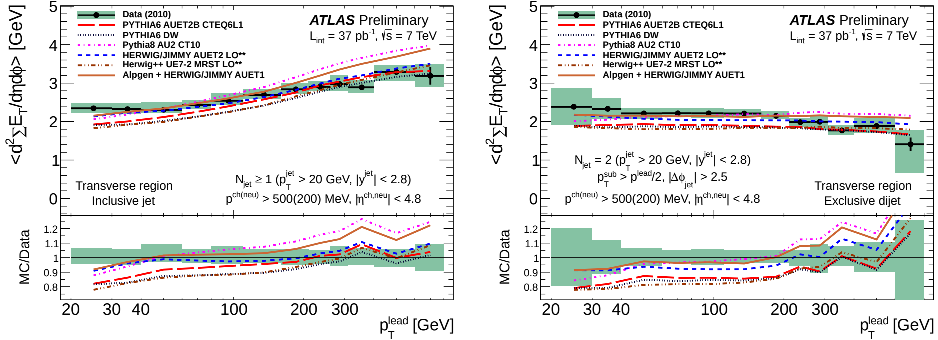
- for N_{ch}, both, trans-max and trans-min are falling with p_T^{lead}
- for $\sum p_T$, trans-max roughly constant, trans-min falls with p_T^{lead}
  $\Rightarrow$ major effect of the exclusive dijet selection is to exclude events where extra jets were produced by MPI activity $\Rightarrow$
  only events with low average transverse activity pass the selection
- trans-diff is essentially flat with p_T^{lead}

$\sum E_T$ vs p_T^{lead} for the central η region



- trends are similar to those for track-based observables
- the comparison between the data and MC models is comparable to that seen for charged particle $\sum p_T$ plots

$\sum E_T$ vs p_T^{lead} for the full η acceptance region



- increased disagreement between the MC models and the data
- the MC models undershoot the observed level of activity at low p_T^{lead} values in both the inclusive and exclusive event selections
  $\rightarrow$ it is notable as all MPI models have been tuned to observables measured for central rapidities
- models predict a faster rise of E_T vs p_T^{lead} than seen in the data

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3. Summary
   - Summary of the Event Shapes Analysis
   - Summary of the Underlying Events Analysis

Summary. Event shapes in inclusive 7 TeV proton-proton interactions

- the event shape observables (transverse thrust, transverse thrust minor, and transverse sphericity) measured in inelastic *pp* collisions at $\sqrt{s} = 7\ \mathrm{TeV}$ requiring at least 6 charged particles per event selected by a minimum-bias trigger
- the distributions of all three event shape variables show an evolution toward less spherical events as $p_{\mathrm{T}}^{\mathrm{lead}}$ increases, the effect is biggest for the transverse sphericity
- similar dependences of the event shape mean values as functions of N_{ch} and $\sum p_{\mathrm{T}}$ are reconstructed
- with increasing multiplicity evolution toward a more spherical event shape seen
- the PYTHIA6 MC generator with the Z1 tune: the most accurate description of the observed distributions

Summary. Underlying event in jet events at 7 TeV

- measurements sensitive to the underlying event in 7 TeV *pp* collisions at the LHC is presented, observables constructed with respect to calorimeter jets with p_T up to 800 GeV
- using inclusive jet and exclusive dijet events
- rising levels of transverse activity as a function of leading jet p_T in the inclusive jets event selection is observed, except for the inclusive trans-min region
- MC models qualitatively describe behaviours well, but with some discrepancies:
  inclusive jet distributions better described by Herwig generators
  exclusive dijet distributions better described by the Pythia 6
- full $|\eta|$-range cluster observables - larger deviations from MC predictions than in the central region

Backup slides

Sphericity

full momentum tensor of the event:

$$M_{\alpha\beta} = \sum_i p_\alpha^i p_\beta^i \qquad \alpha, \beta = x, y, z$$

- sum runs over all charged particles in the event
- eigenvalues $\lambda_1, \lambda_2, \lambda_3$ are normalized $\sum_i \lambda_i = 1$ and ordered that $\lambda_1 > \lambda_2 > \lambda_3$

Sphericity S measures the summed p_T^2 with respect to the event axis (the line passing through the interaction point and oriented along the eigenvector associated with the largest eigenvalue, λ_1)

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

- $S = 0$ - for a balanced dijet event
- $S = 1$ - for an isotropic event

Monte Carlo Models in Event Shapes Analysis

Generator	Version	Tune	PDF	Focus	Data	From
PYTHIA 6	6.425	AMBT2B	CTEQ6L1	MB	LHC	ATLAS
PYTHIA 6	6.421	DW	CTEQ5L	UE	Tevatron	CDF
PYTHIA 6	6.425	Z1	CTEQ5L	UE	LHC	CMS
PYTHIA 8	8.157	A2	MSTW2008LO	MB	LHC	ATLAS
HERWIG ++	2.5.1	UE7-2	MRST LO**	UE	LHC	Authors
PYTHIA 6	6.425	AMBT1	MRST LO**	MB	Early LHC	ATLAS
HERWIG ++	2.5.0	Default	MRST LO**	UE	LHC	Authors

- predictions from 5 different MC models (PYTHIA 6 AMBT2B, PYTHIA 6 DW, PYTHIA 6 Z1, PYTHIA 8 A2, and HERWIG ++ UE7-2) are compared to observed data
- PYTHIA 6 AMBT1 - reference model for the analysis - used to correct the data for detector effects
- HERWIG ++ 2.5.0 - used for systematic studies

Monte Carlo Models of Underlying Event

All leading-order parton shower generators, differ in hadronisation models and parton shower formalisms:

- PYTHIA6 - hadronisation model based on the Lund string and a p_T- or virtuality-ordered parton shower
  - **AMBT1** - first LHC-data tune, diffraction-suppressed observables from the early ATLA MB measurements, MRST LO$*$ parton density functions (PDFs) and the Pythia p_T-ordered parton shower - in this analysis used to correct the data for detector effects
  - AUET2B CTEQ6L1 - latest set ATLAS UE tunes, improvement: inclusion of a LEP-based retuning of final state shower and hadronisation efects, optimising initial state shower parameters by comparison to ATLAS track jet, jet shapes and dijet decorrelations data; CTEQ6L1 PDF variant
  - DW - virtuality-ordered parton shower and a MPI model not interleaved with the ISR, description of CDF Run II UE and Drell-Yan data, leading-order CTEQ5L1 PDF
- PYTHIA8 - also the FSR, together with ISR emission and MPI scatterings
  - AU2 CT10 - variant of latest ATLAS UE tune, next-to-leading order CT10 PDF
- HERWIG/JIMMY and HERWIG^{++} - cluster hadronisation scheme, parton showers ordered in emission angle; Herwig not simulating multiple partonic interactions: added by the Jimmy package

  ALPGEN - leading-order multi-leg matrix element events, more complex hard process topologies, loop diagram contributions omitted
  - HERWIG/JIMMY AUET2 LO^{++}
  - ALPGEN + HERWIG/JIMMY AUET1 - older tune
  - HERWIG++ UE7-2 MRST LO^{++} - includes a colour reconnection model - good description of both UE and MB data at 7 TeV