Measurement of event shapes in pp collisions @ 7 TeV

Atlas Collaboration

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Prologue : Atlas talk in 2011

We are "trying to make sure LHC data at a new energy regime is described by the Monte Carlo models, which reflect our "best guess" understanding

of the soft QCD processes".

Last year : the current workhorse for tuning was PYTHIA 6 /AUET2B, PYTHIA 8 was under study …

Main variables for MB or UE analyses : leading track P_T^{lead},
multiplicity N_{ch},
total transverse momentum ΣP_T

Conclusion of the talk : tuning never stops ! But ….

The goal of this talk is to explore how far one can go with event shapes

Measuring event shapes

- Why ? Event shapes allow to distinguish in a continuous way between events :

  in which particles are flowing along a single axis

  in which the energy is distributed uniformly over the full solid angle

  ⇒ They are sensitive to both perturbative and non perturbative aspects of QCD

- Where ? In 2010, the LHC beam intensity was not as high as now, pileup was not an issue. The 3 recent papers discussed in this talk thus still use this dataset (proton-proton collisions at 7 TeV) but explore further :

  Charged-particle event shape variables *(arXiv:1207.6915, 30 Jul 2012)*

  |η| dependence of the total transverse energy *(arXiv:1208.6256, 30 Aug 2012)*

  Event shapes at large momentum transfer *(arXiv:1206.2135, 11 Jun 2012)*

- How ? Rather standard set of variables (Thrust, Sphericity,…) but :
  - compare to a large set of Monte Carlo models and tunes.
  - Extend the eta range by using the forward calorimeters
  - Select different types and part of the events to be more sensitive to “soft QCD”: minimum bias, underlying event in dijet events, 3^{rd} jet in multijet events.

1 Using charged tracks in minimum bias events

Observables : thrust, thrust minor, transverse sphericity

Event selection and reconstruction :

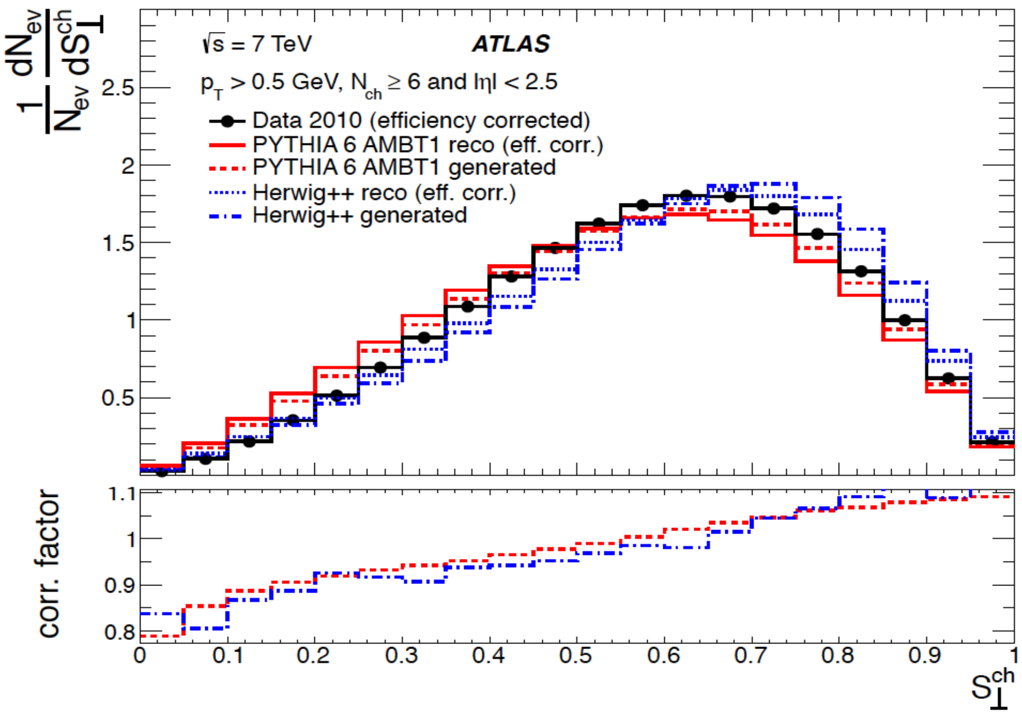
- At least 6 charged tracks in primary vertex (with standard track quality cuts), |η|<2.5
- Suppress the pile-up and/or non collision events by vertex cuts: remaining level is <0.1%
- Correct for trigger and selection efficiencies: ~ no effect on shapes

The full Geant 4 simulation is used to go back to generator level distributions :

- Bin by bin corrections: 0.9 to 1.1
- Systematics : use 2 generators

TABLE I. Summary of systematic uncertainties in %.

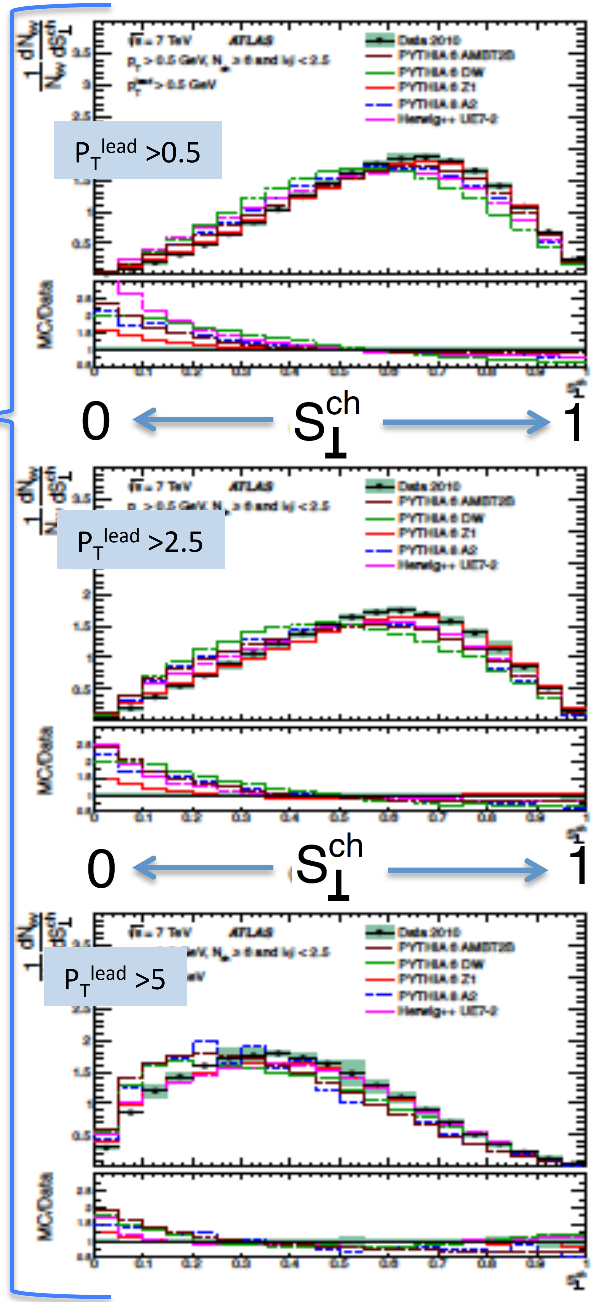
Trigger and vertex efficiency	< 0.1
Track reconstruction	0.1 – 0.5
Correction model difference	1 – 5
PYTHIA correction stat. uncertainty	0.1 – 2
Total systematic uncertainty	1 – 5



Transition between spherical and dijet-like structure ?

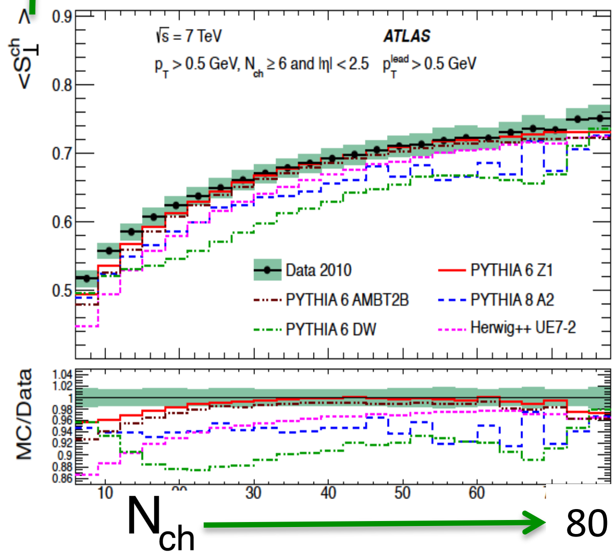
The "usual" 3 variables have been used as probes: P_T^{lead}, N_{ch}, ΣP_T

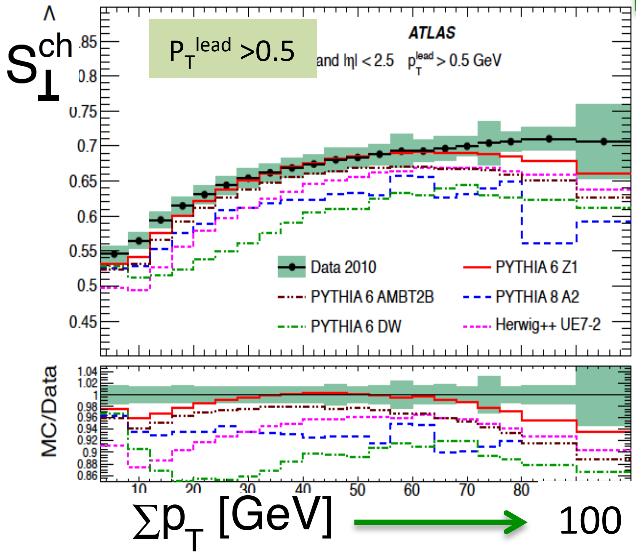
The transverse Sphericity shows a clear transition from spherical to dijet-like events when P_T^{lead} increases.



Other shapes (Thrust and Thrust minor) are less sensitive.

At very high values of the charged track multiplicity (N_{ch}) and total transverse momentum (ΣP_T), the mean values all indicate more spherical events : no evidence for a dijet structure.





Comparison with MC predictions

3 normalized distributions

$\langle S_\perp^{\mathrm{ch}} \rangle$ $\langle \tau_\perp^{\mathrm{ch}} \rangle$, $\langle T_{\mathrm{M}}^{\mathrm{ch}} \rangle$

+ average values as a function of N_{ch} and ΣP_T

Pythia 6 : AMBT2B (improved AMBT1)
DW (Fermilab 2002, not used by Atlas)
Z1 (CMS, 2011)

Herwig++ : UE7-2 (arXiv:1110.2675)

Pythia 8 : A2 **(see talk in this workshop)**

Most accurate description

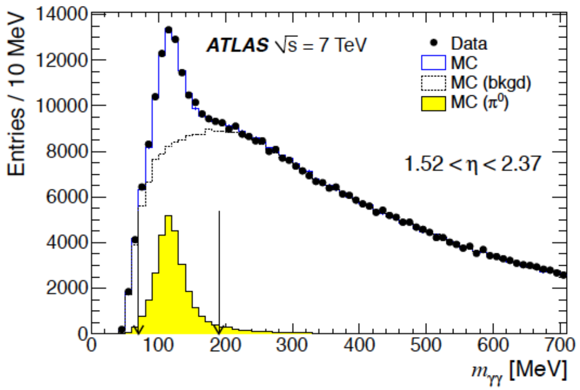
BUT…

All MC generators underestimate the fraction of spherical events
None reproduce the event shape distributions better than within ~10%.

MC tunes based on the properties of the UE show better agreement with data than those based on the inclusive distributions measured in MinBias events.

2 Probing higher pseudo-rapidity with the calorimeters

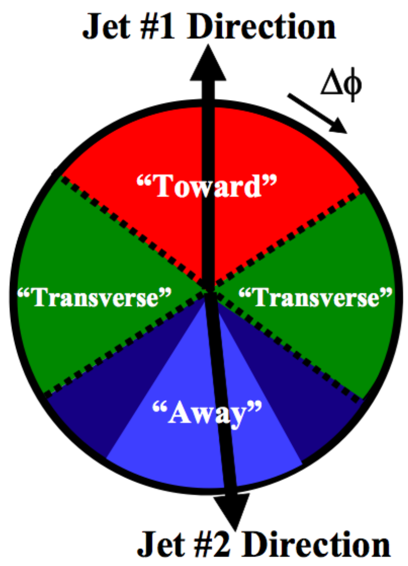
Total transverse energy ΣE_T can be measured in the calorimeters up to $|\eta|=4.8$
(compared to 2.5 with the charged tracks)



- 6 η bins : 0 – 0.8 – 1.6 – 2.4 – 3.2 – 4.0 – 4.8
- Inter-calibration of the barrel and forward calorimeters is checked with the usual "candles" : $\pi^0 \to \gamma\gamma$ invariant mass
- The mean and the distributions of ΣE_T are both measured, giving a complete picture in the full acceptance.

In minimum bias events (as inclusive as possible) :
ΣE_T includes particles at any ϕ

In dijet events (2 well balanced jets with E_T>20GeV, $|\eta|<2.5$) :
one probes the underlying event => ΣE_T includes only particles that are in the "transverse" region ($\pi/3 < \Delta\phi < 2\pi/3$)



Comparison with MC predictions

Definition of ΣE_T for MC :

Charged particles of p>500 MeV & Neutral particles of p>200 MeV

(others below do not deposit enough energy in the calorimeters and are therefore not included)

MC chain used for "corrections" : AMBT1 tune of PYTHIA 6 + Geant 4 + ATLAS reconstruction

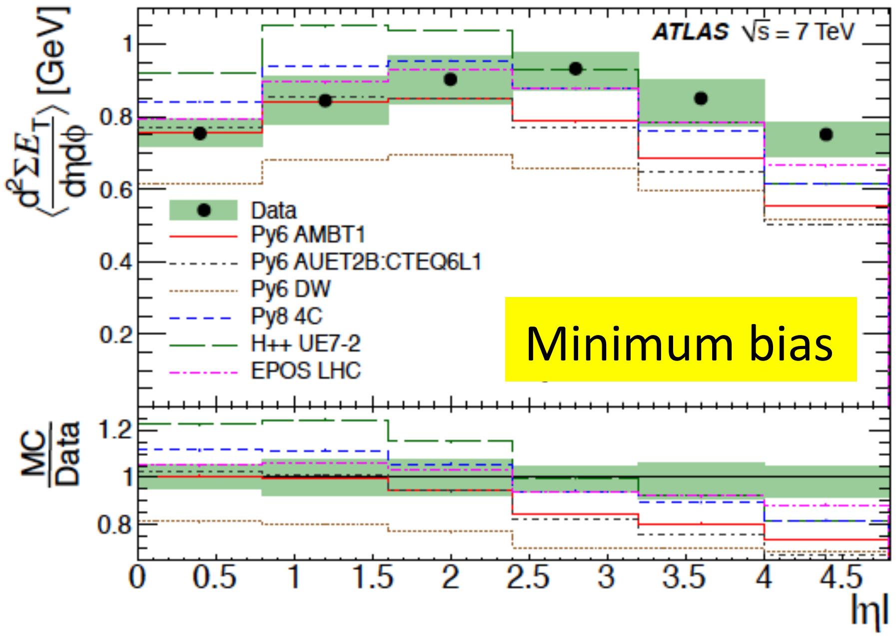
Systematic uncertainties : are larger than statistical one

- Calorimeter energy response: 2-5 % except for "overlap regions" where it goes up to 15 %
- Knowledge of the material upstream of the calorimeter: about 3-5 %
- Physics model dependence is checked with other tunes of PYTHIA 6 (DW, Perugia0), PYTHIA 8 (4C) and Herwig++ (UE7-2) : 2-4 % for minimum bias, < 2 % for di-jets.

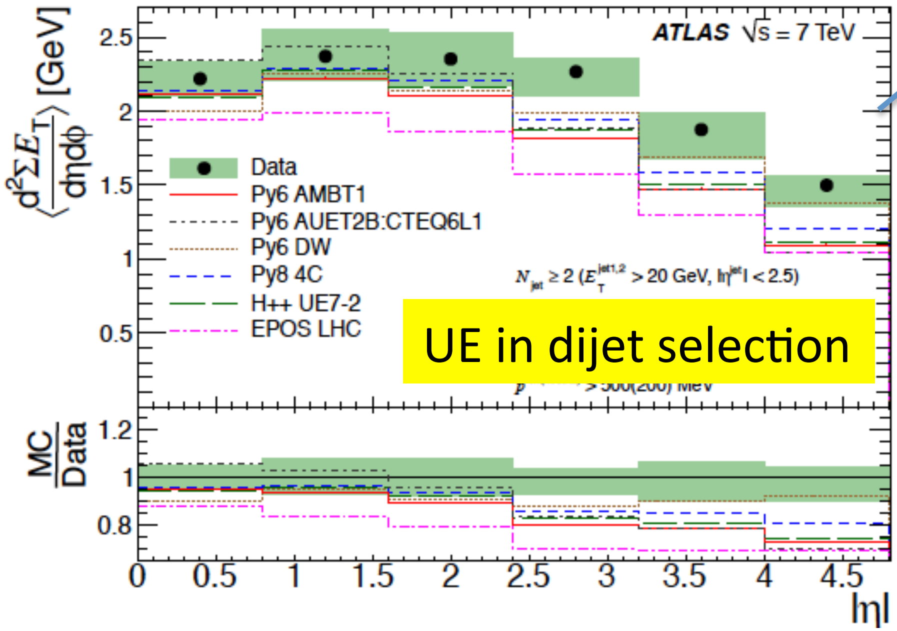
Unfolded data are then compared to more recent tunes and PDF sets

Generator	Version	Tune	PDF
PYTHIA 6	6.425	AUET2B:CTEQ6L1 [32]	CTEQ 6L1
PYTHIA 8	8.153	A2:CTEQ6L1 [33]	CTEQ 6L1
PYTHIA 8	8.153	A2:MSTW2008LO [33]	MSTW2008 LO [34]
EPOS	1.99_v2965	LHC	N/A

Results



(a)

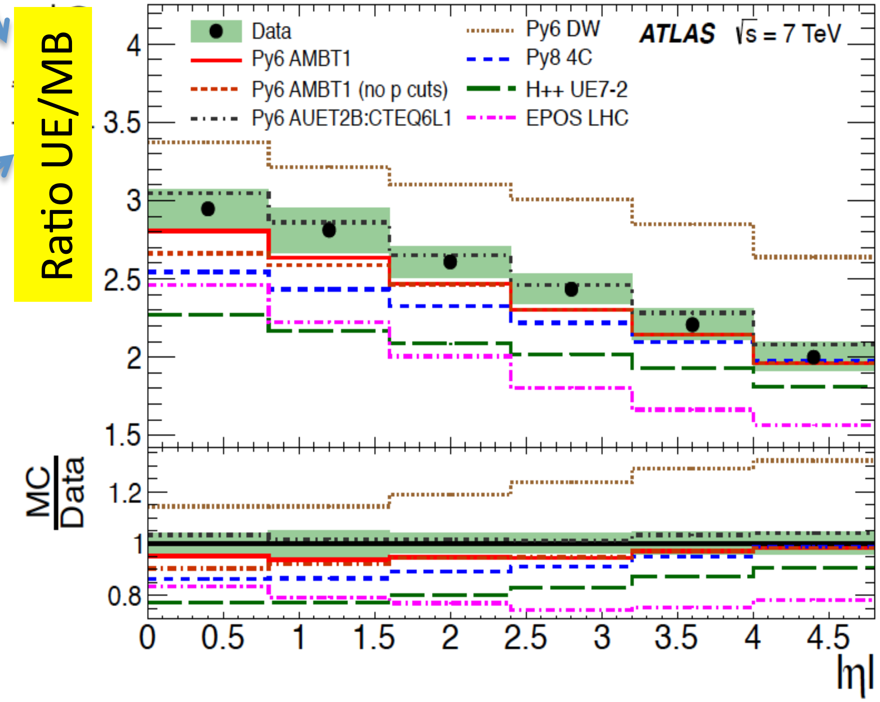


For both samples the unfolded $E_T^{density}$ is too low in the forward region:

up to 20 % for PYTHIA 8

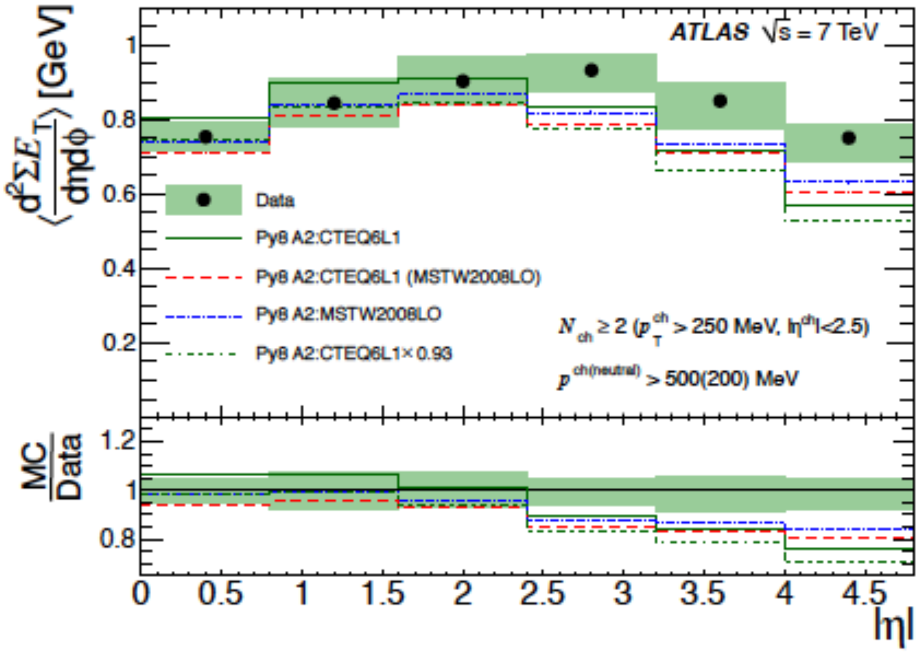
25 to 30% for PYTHIA 6

Ratio UE/MB : the fall-off with η and the widths of the distributions are well reproduced

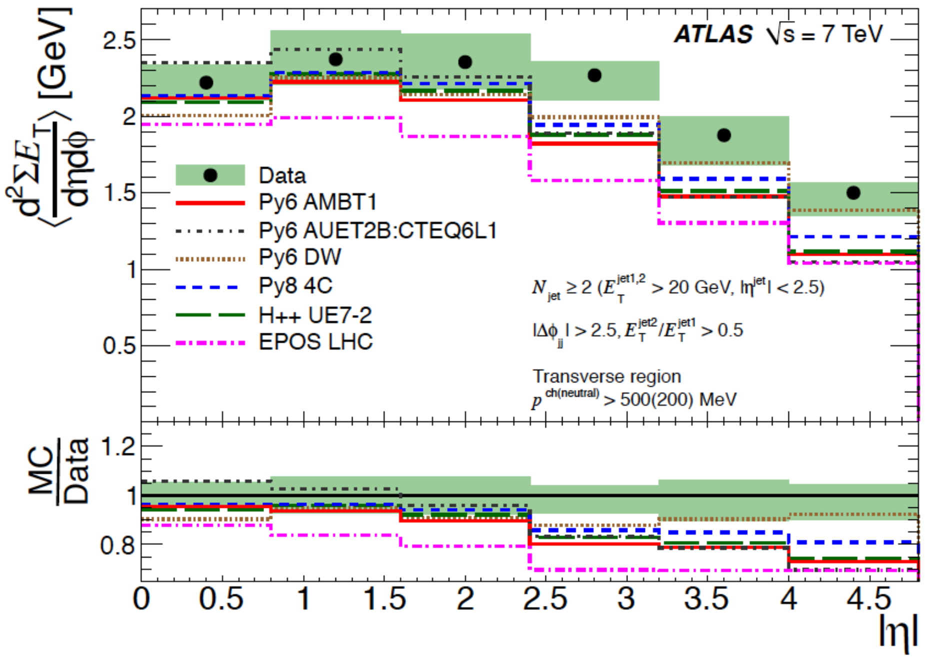


Closer look at Pythia 8 A2 with various PDFs

Minimum bias



UE in Dijets



Conclusion of this analysis :

PDF can reduce the difference (e.g. MSTW2008 LO) but…

It looks like there is a general problem in Pythia 6/8 in the forward region,

while EPOS also can only describe the MinBias part but not the UE part ?

3 Event shapes at large momentum transfer

Multi-jet (≥ 3) events : focus on jets to reduce the effect of the UE

Event selection :

1) Jet reconstruction : anti -Kt algorithm, with a cone of 0.6
2) Require 2 central leading jets (|η|<1) and a 3rd jet with P_T>30 GeV and |η|<1.5

$$y_{23} = \frac{p^2_{T,3}}{H^2_{T,2}},$$

where $H_{T,2} = (p_{T,1} + p_{T,2})$

2 leading jets → require $\frac{1}{2}H_{T,2}$ > 250 GeV

3rd jet → use the ratio y_{23} as a "probe" .

Unfolding procedure to provide "particle-level" quantities :

- Bin-by-bin corrections : < 10 %
- Systematic uncertainty due to the generator dependence: <8% for y23, ~10% for the others

+ "Usual" global shape variables are also studied : Sphericity S and transverse sphericity S_T ,
Aplanarity A
Transverse Thrust and its minor component

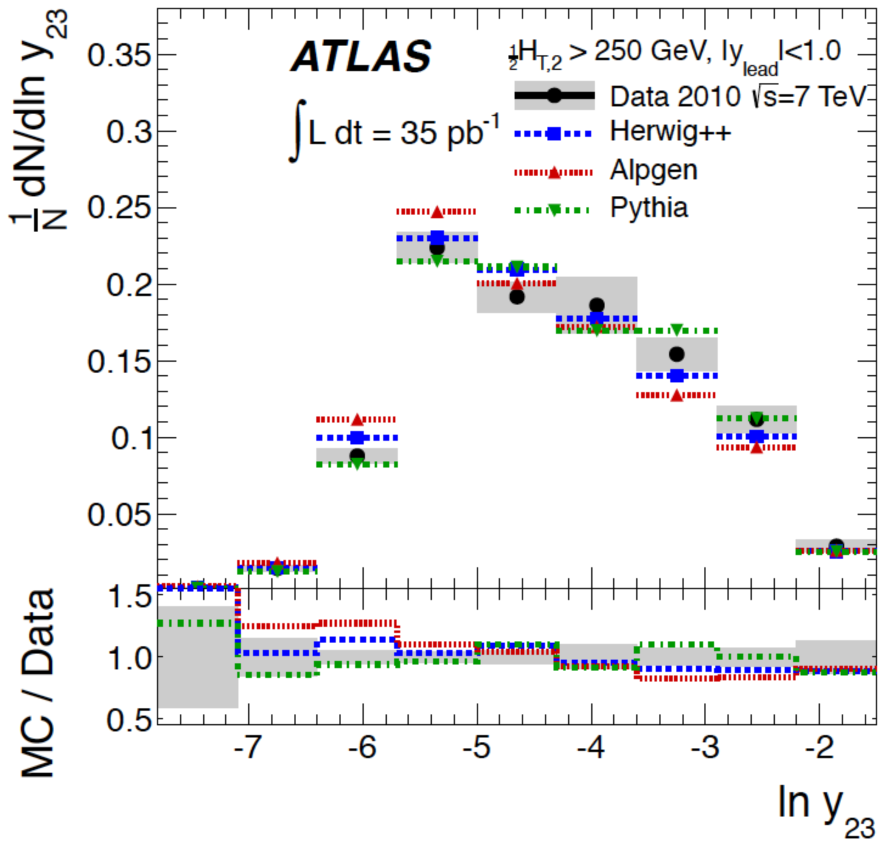
Comparison with MC predictions

Generators were chosen for their ability to describe other ATLAS jet-based measurements

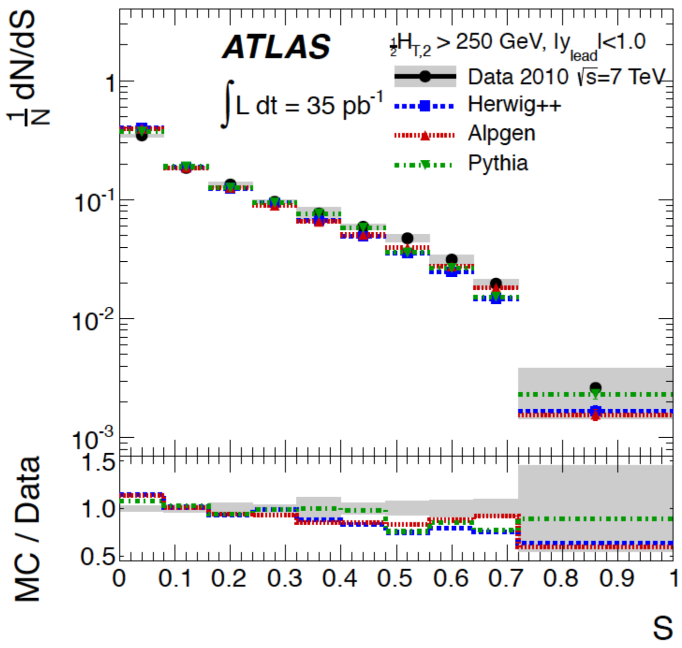
Primary generator : ALPGEN 2.13 (matrix element, up to 6 final-state partons)
with CTEQ6L1 LO PDFs
+ HERWIG 6.510 (PS / hadronization)
+ JIMMY 4.31 (for the UE)

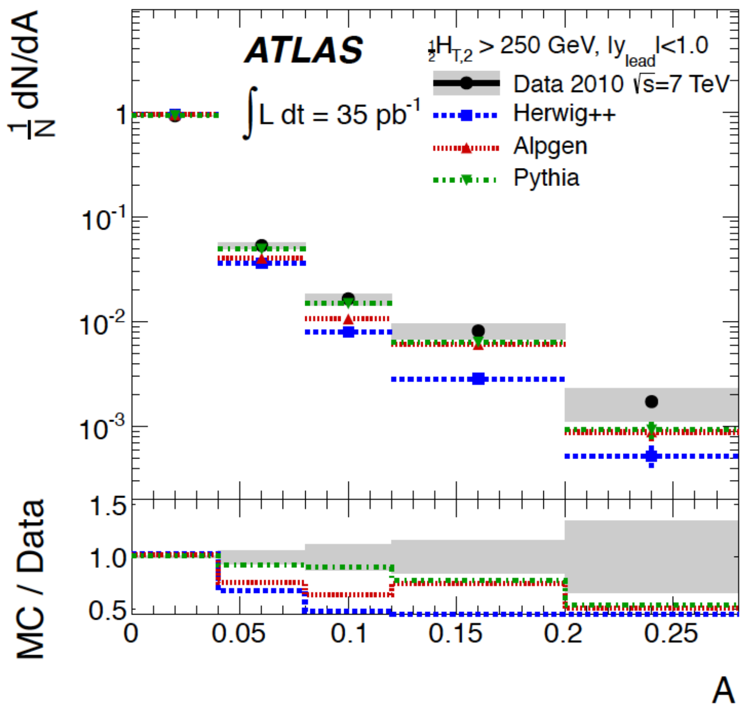
Cross checks by two Parton shower programs :
PYTHIA 6.423 : Perugia 2010 tune; CTEQ6L1 LO
HERWIG++ : MRST2007 LO* PDFs

Reasonable agreement is obtained for all shapes

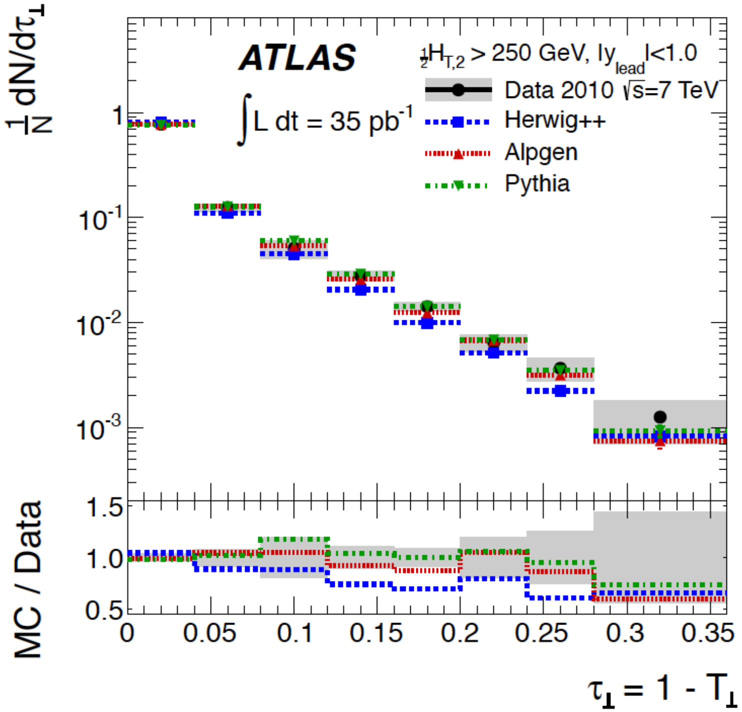


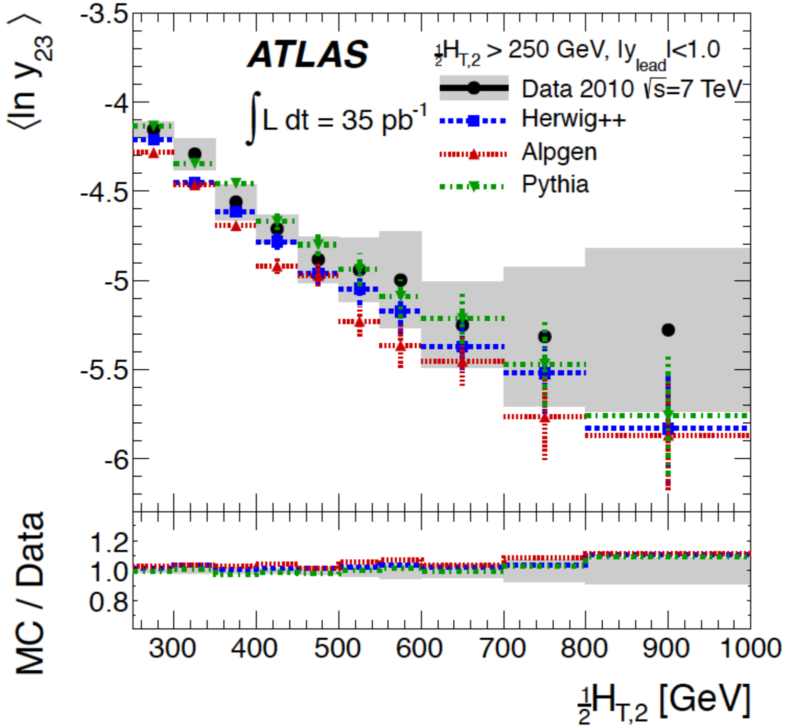
Event shape distributions

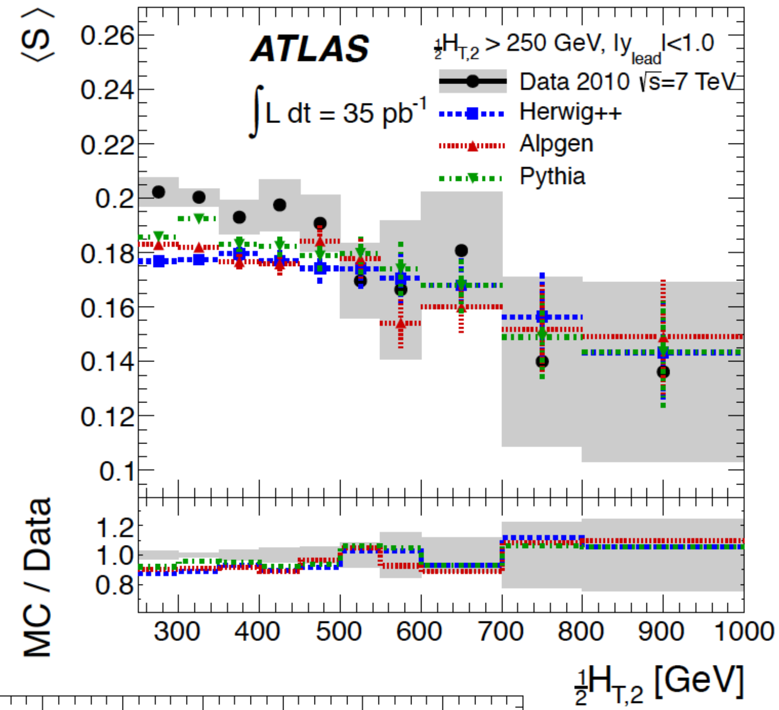




However, the dependence on $H_{T,2}$ is needed to evaluate the explicit dependence on the kinematic properties and determine potential differences in the modeling ….





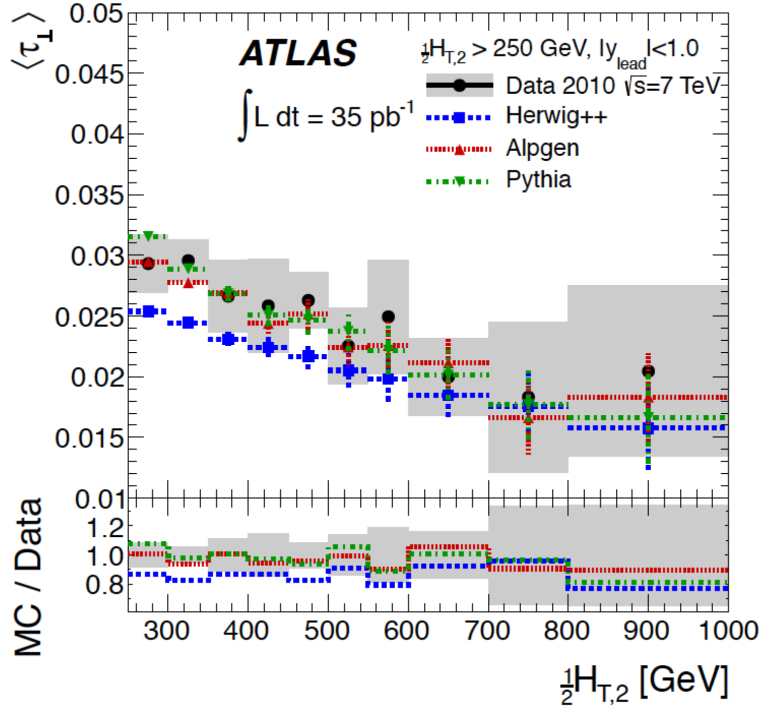


Conclusions :

PYTHIA (Perugia 2010) and ALPGEN seem to be more accurate than HERWIG++

LO MC are able to provide a reasonable description of multi-jet events.

The importance of the tune chosen, hadronization and UE should be kept in mind



Conclusion

$\|\eta\|$	$\langle\frac{d^2\Sigma E_T}{d\eta d\phi}\rangle$ [GeV]	Stat. [%]	E_1^* [%]	E_2 [%]	M_1 [%]	M_2 [%]	M_3^* [%]	P_1 [%]	Total [%]
0.0 – 0.8	0.753	±0.19	$^{+3.2}_{-2.9}$	—	±2.9	—	±0.51	±2.6	$^{+5.1}_{-4.9}$
0.8 – 1.6	0.844	±0.17	$^{+5.4}_{-4.9}$	—	±3.2	±0.49	±1.2	±4.6	$^{+7.9}_{-7.5}$
1.6 – 2.4	0.902	±0.16	$^{+4.0}_{-3.8}$	—	—	±0.89	±5.0	±3.4	$^{+7.4}_{-7.2}$
2.4 – 3.2	0.932	±0.16	$^{+2.4}_{-5.0}$	—	—	—	±3.0	±2.5	$^{+4.6}_{-6.4}$
3.2 – 4.0	0.850	±0.15	$^{+4.3}_{-4.4}$	−6.2	—	—	±2.7	±3.2	$^{+6.0}_{-8.7}$
4.0 – 4.8	0.750	±0.14	$^{+2.7}_{-2.7}$	−6.8	—	—	±0.8	±3.6	$^{+4.6}_{-8.2}$

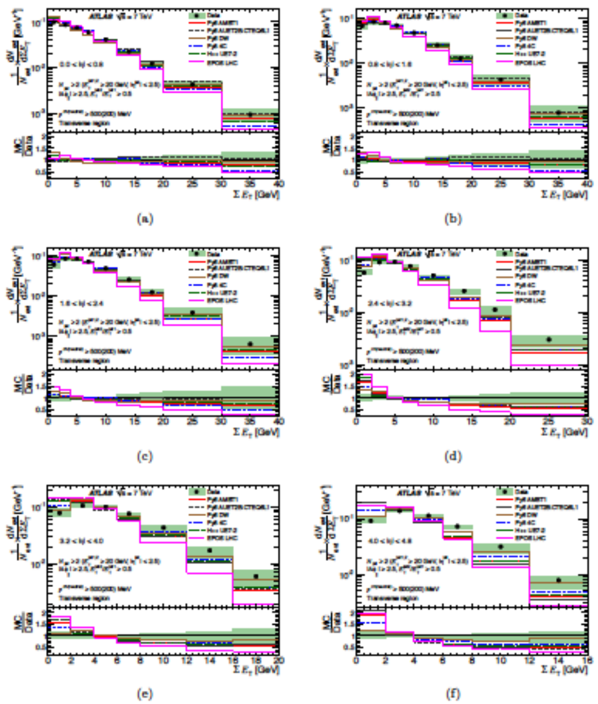
Table 3. Measured $E_T^{density}$ and systematic uncertainty breakdown for the minimum bias data. The systematic uncertainties marked with a $*$ are uncorrelated between $|\eta|$ bins.

The analysis of the data taken by the ATLAS detector @ 7 TeV in 2010 has been refined and allows more and more detailed checks and comparisons of the MC generators available

$\|\eta\|$	$\langle\frac{d^2\Sigma E_T}{d\eta d\phi}\rangle$ [GeV]	Stat. [%]	E_1^* [%]	E_2 [%]	M_1 [%]	M_2 [%]	M_3^* [%]	P_2 [%]	J [%]	Total [%]
0.0 – 0.8	2.22	±0.61	$^{+4.3}_{-4.2}$	—	±1.3	—	±0.23	±2.2	$^{+1.6}_{-1.3}$	$^{+5.3}_{-5.1}$
0.8 – 1.6	2.37	±0.54	$^{+7.2}_{-6.4}$	—	±2.5	±0.38	±0.96	±0.12	$^{+1.3}_{-1.3}$	$^{+7.8}_{-7.1}$
1.6 – 2.4	2.35	±0.52	$^{+5.3}_{-5.0}$	—	—	±0.97	±5.5	±0.41	$^{+0.98}_{-0.92}$	$^{+7.8}_{-7.6}$
2.4 – 3.2	2.27	±0.50	$^{+3.8}_{-7.0}$	—	—	—	±0.64	±0.55	$^{+0.80}_{-0.37}$	$^{+4.0}_{-7.1}$
3.2 – 4.0	1.88	±0.51	$^{+6.1}_{-5.8}$	−8.2	—	—	±1.1	±1.3	$^{+0.46}_{-0.17}$	$^{+6}_{-10}$
4.0 – 4.8	1.50	±0.47	$^{+3.8}_{-3.6}$	−9.0	—	—	±0.6	±1.6	$^{+0.13}_{-0.03}$	$^{+4.2}_{-9.8}$

Table 4. Measured $E_T^{density}$ and systematic uncertainty breakdown for the dijet data. The systematic uncertainties marked with a $*$ are uncorrelated between $|\eta|$ bins.

This talk is based on 3 recent papers where many more distributions and tables are available



M_1 [%]	M_2 [%]	M_3^* [%]	P [%]	J [%]	Total [%]
$^{+1.5}_{-1.6}$	—	$^{+0.27}_{-0.28}$	±3.4	$^{+1.6}_{-1.3}$	$^{+4.3}_{-4.2}$
$^{+0.64}_{-0.69}$	$^{+0.10}_{-0.11}$	$^{+0.25}_{-0.26}$	±4.6	$^{+1.3}_{-1.3}$	$^{+5.1}_{-5.1}$
—	$^{+0.08}_{-0.08}$	$^{+0.43}_{-0.47}$	±3.5	$^{+0.98}_{-0.92}$	$^{+3.9}_{-3.9}$
—	—	$^{+2.3}_{-2.5}$	±2.6	$^{+0.80}_{-0.37}$	$^{+3.8}_{-4.2}$
—	—	$^{+1.5}_{-1.6}$	±3.4	$^{+0.46}_{-0.17}$	$^{+4.1}_{-4.6}$
—	—	$^{+0.19}_{-0.20}$	±3.9	$^{+0.13}_{-0.03}$	$^{+4.1}_{-4.7}$

ata to that for the the minimum bias data, and uncertainties marked with a $*$ are uncorrelated

We do believe that event shapes provide information complementary to inclusive particle distributions and are thus helpful for improving the MC description of the LHC data !

Backup slide : event shape variables

0 for a perfectly balanced, pencil like, dijet topology
Maximal for a spherical or isotropic event

Transverse Thrust : $T_{\perp} = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|}$ => $\tau_{\perp} = 1 - T_{\perp}$ and event plane : $\hat{z}$, $\hat{n}_T$

Transverse Thrust minor : out-of-event-plane-energy-flow $T_M = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_m|}{\sum_i |\vec{p}_{T,i}|}$, $\hat{n}_m = \hat{n}_T \times \hat{z}$

Momentum tensor : $S^{\alpha\beta} = \frac{\sum_i p_i^{\alpha} p_i^{\beta}}{\sum_i |\vec{p}_i|^2}$ or $M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$ has 3 eigenstates λ

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

Transverse Sphericity : $S_{\perp} = \frac{2\lambda_2}{\lambda_1 + \lambda_2},$

Aplanarity : $A = \frac{3}{2}\lambda_3.$