Measurements of event shapes and particle production with the ATLAS detector

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on behalf of the ATLAS Collaboration

MPI @ LHC 2014 – VI International Workshop on Multiple Partonic Interactions at the LHC
Krakow, Poland, 3-7 November 2014

November 7, 2014

Overview

1. Measurement of charged-particle EVENT SHAPE variables in inclusive $\sqrt{s} = 7\ \mathrm{TeV}$ *pp* interactions with the ATLAS detector
   Phys. Rev. D 88, 032004 (2013) [arXiv:1207.6915]

2. The differential production cross section of the $\phi(1020)$ meson in $\sqrt{s} = 7\ \mathrm{TeV}$ pp collisions measured with the ATLAS detector
   Eur. Phys. J. C (2014) 74:2895 [arXiv:1402.6162]

3. Measurement of the transverse polarization of Λ and $\bar{\Lambda}$ hyperons produced in proton-proton collisions at $\sqrt{s} = 7\ \mathrm{TeV}$ using the ATLAS detector
   Preliminary results

Event Shapes

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

- theoretically sound variables
- enable detailed tests of the phenomenological models of QCD in leading order MC programs $\Rightarrow$ input for tuning MC generators
- ratios of final state observables $\Rightarrow$ reduced sensitivity to theoretical and experimental uncertainties
- indirect probe of multi-jet topologies
    - vanish in the limit of a pure $2 \to 2$ process
    - increase to a maximum for uniformly distributed energy within event

transverse sphericity

complement to transverse thrust:

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

transverse thrust minor:

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

$$\hat{\boldsymbol{n}}_m = \hat{\boldsymbol{n}}_\perp \times \hat{\boldsymbol{z}}$$

Event and Track Selection

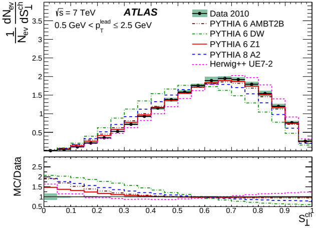
the data collected in April 2010 with a minimal prescale factor for the *minimum-bias trigger* (peak luminosity $\approx$ 1.9 $\times$ $10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)

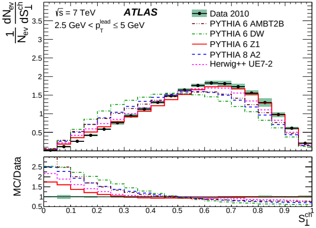
events rejected if they contain any other vertex with $\geq$ 4 tracks apart from the primary interaction vertex of the event

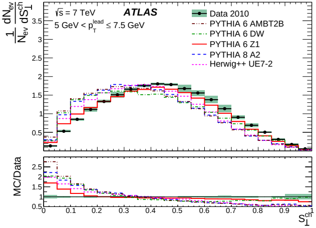
events required to contain at least 6 tracks fulfilling the criteria:

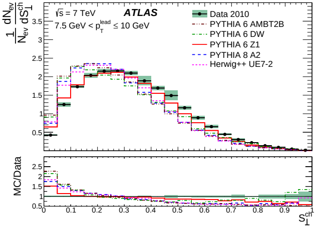
- $p_{\mathrm{T}} > 0.5\ \mathrm{GeV}$; $|\eta| < 2.5$
- a minimum of one pixel and 6 SCT hits;
- a hit in the innermost pixel layer, if the corresponding pixel module was active;
- transverse and longitudinal impact parameters wrt the primary vertex, $|\mathbf{d_0}| < \mathbf{1.5\ mm}$ and $|\mathbf{z_0}|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

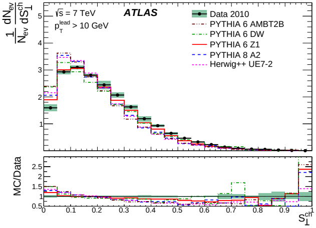
Transverse Sphericity Distributions







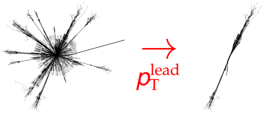




$$S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}$$

$\lambda_1^{xy} > \lambda_2^{xy}$ – eigenvalues of:

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



lower p_T^{lead} ranges: spherical events prevalence

$\tau_\perp$ and T_M are less sensitive to p_T^{lead} increase!

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

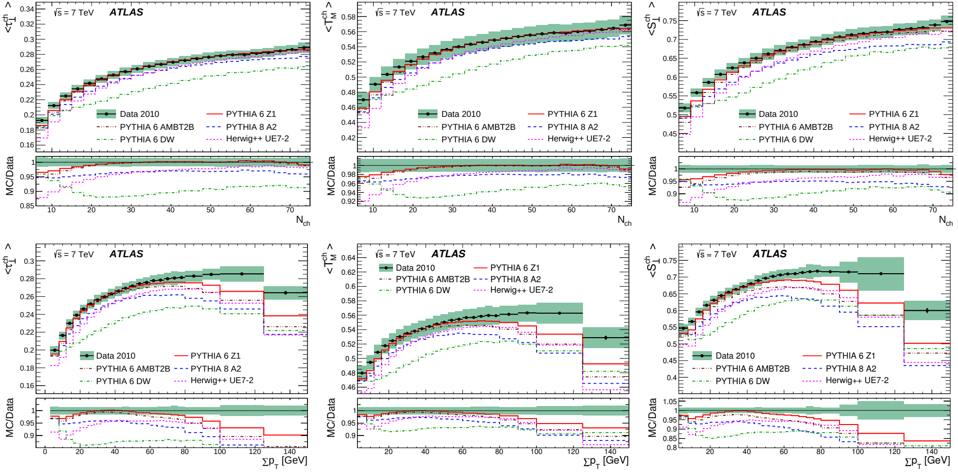
PYTHIA 6 tune Z1 tuned to UE at LHC agrees best

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	$\tau_{\perp}^{\mathrm{ch}}$	$T_{\mathrm{M}}^{\mathrm{ch}}$	$S_{\perp}^{\mathrm{ch}}$
$0.5\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{lead}} \leq 2.5\ \mathrm{GeV}$	0.227 ± 0.002	0.508 ± 0.002	0.618 ± 0.005
$2.5\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{lead}} \leq 5.0\ \mathrm{GeV}$	0.240 ± 0.006	0.514 ± 0.005	0.579 ± 0.013
$5.0\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{lead}} \leq 7.5\ \mathrm{GeV}$	0.227 ± 0.007	0.490 ± 0.006	0.449 ± 0.019
$7.5\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{lead}} \leq 10\ \mathrm{GeV}$	0.210 ± 0.010	0.459 ± 0.007	0.337 ± 0.017
$p_{\mathrm{T}}^{\mathrm{lead}} \geq 10\ \mathrm{GeV}$	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 $2.5\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{lead}} \leq 5.0\ \mathrm{GeV}$, before decreasing
- similar trend observed by the ALICE Collaboration, transverse sphericity distribution, charged particles with $|\eta| < 0.8$ in inelastic 7 TeV *pp* collisions (Eur. Phys. J. C72 (2012) 2124 [arXiv:1205.3963])

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 $\Rightarrow$ 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

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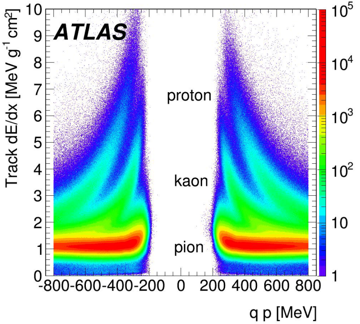
$\phi \to K^+K^-$

data from April 2010, integrated luminosity of 383 μb^{-1}
probe strangeness production at a soft scale $Q \sim 1$ GeV, sensitive to s-quark and low-x gluon densities $\to$ sensitive to proton parton distribution function

trigger selection: one MBTS hit above treshold from either side
event selection: primary vertex, at least two tracks with $p_T > 150$ MeV

track selection: more than one pixel cluster and more than one SCT hit
$p_T > 230$ MeV (tracking efficiency for kaon tracks)
$p < 800$ MeV (particle identification); $|\eta| < 2.0$

only tracks from PV used, fitted with a kaon-mass assumption

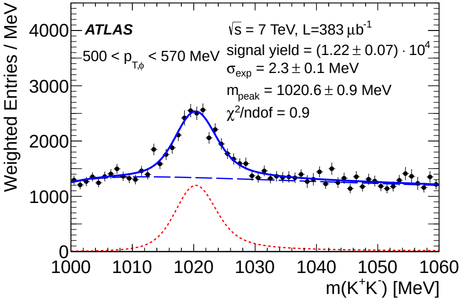


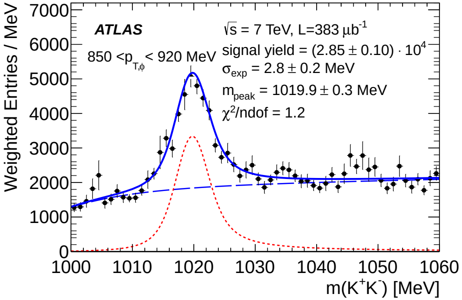
expected energy loss for $p = 500$ MeV:
2.4 (kaon); 1.2 (pion) MeV g^{-1}cm^2
required probability:
$P_{\text{pion}} < 0.1$ & $P_{\text{kaon}} > 0.84$

ϕ(1020) candidates: oppositely charged track pairs, combine to invariant mass:
$1000 < m(K^+K^-) < 1060$ MeV

Signal extraction

weight assigned to each ϕ(1020) candidate to correct for losses : trigger, vertex and track reco. eff., kaon ID eff., tracks out of range



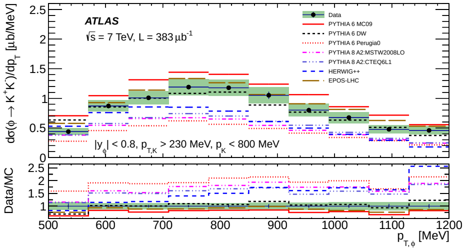


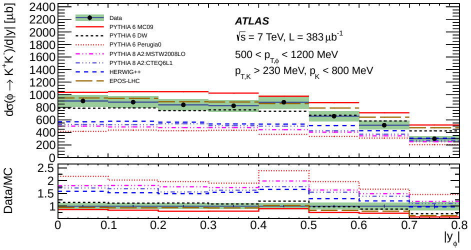
signal shape $\rightarrow$ relativistic Breit-Wigner formula $\rightarrow$ convoluted with a Gaussian resolution function

signal added to an empirical background description $\rightarrow$ parameters initial values $\rightarrow$ fit to a sample with two kaons of the same charge

Results

$$\sigma_\phi \times BR(\phi \to K^+K^-) = 570 \pm 8\ (\text{stat}) \pm 68\ (\text{syst}) \pm 20\ (\text{lumi})\ \mu\text{b}$$
$$(500 < p_{T,\phi} < 1200\ \text{MeV},\ \ |y_\phi| < 0.8)$$





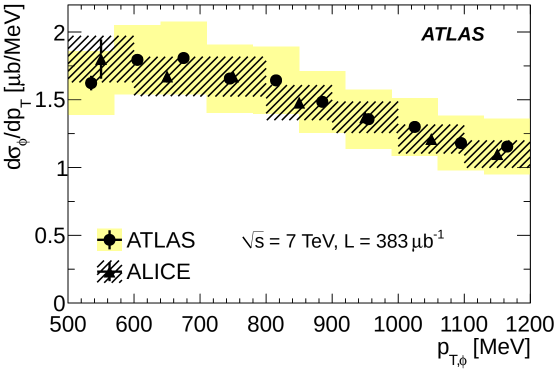
σ_ϕ increases with $p_{T,\phi}$ in 500 – 700 MeV (due to $p_{T,K}$ > 230 MeV)
decreases with $p_{T,\phi}$ for $p_{T,\phi} > 850$ MeV
decreases with $|y_\phi|$ for $|y_\phi| \geq 0.5$ (due to p_K < 800 MeV)
is stable with $|y_\phi|$ for $|y_\phi| \leq 0.5$

best description by PYTHIA 6 DW and EPOS-LHC tune

Comparison to ALICE

σ_ϕ extrapolated to a cross section in the region $500 < p_{T,\phi} < 1200$ MeV and central rapidity region $|y_\phi| < 0.5$ using MC particle level information

PYTHIA 6 used $\rightarrow$ 10% variation between different generators included as additional systematic uncertainty



- in agreement within 10% in the first two bins
- in agreement within 3% in the other bins
- well within the systematic uncertainties

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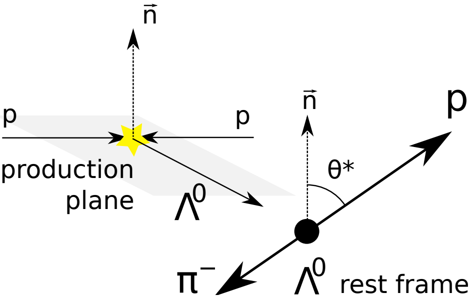
Transverse polarization of Λ and $\bar{\Lambda}$ hyperons



P measured as a function of p_T and Feynman x-variable x_{F}:

$$x_{\mathrm{F}} = p_{\mathrm{z}}/p_{\mathrm{beam}}$$

$p_{\mathrm{z}} \equiv p_{\mathrm{z}}(\Lambda)$
p_{beam}= 3.5 TeV

in this analysis x_{F} up to ~ 0.01
(good statistics only up to 0.002)

polarization measured in direction normal to the production plane:

$$\vec{n} = \hat{p}_{\mathrm{beam}} \times \vec{p}$$

$\hat{p}_{\mathrm{beam}}$ - aligned with proton beam
$\vec{p}$ - momentum of Λ hyperon

decays $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

probability distribution of θ^* angle:

$$g(t; P) = \frac{1}{2}(1 + \alpha P t)$$

$t = \cos\theta^*$
P - polarization in $\vec{n}$ direction
$\alpha = 0.642 \pm 0.013$
(World average value)

Selection and measurement strategy

data from the beginning of 2010, integrated luminosity of 760 μb^{-1}

trigger selection: at least one hit in either of the two MBTS sides

event selected: at least one reconstructed collision vertex

decay vertex required to lie within the inner volume of the last layer of the SCT detector - transverse decay distance restricted to 45 cm

long-lived 2-prong decay candidates, invariant mass calculated using hypotheses $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, $K^0_S \to \pi^+\pi^-$, $\gamma \to e^+e^-$

Polarization measured by analyzing the angular distribution of Λ and $\bar{\Lambda}$ decay products modified by detector efficiency and resolution effects:

$$g_{\rm det}(t'; P) \propto \frac{1}{2}\left[(1+\alpha P t)\,\varepsilon(t)\right] \otimes R(t', t)$$

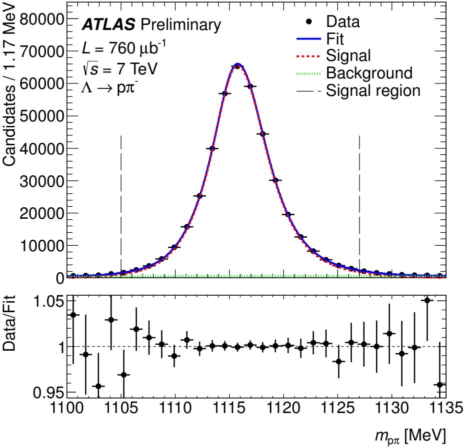
$t' \equiv \cos\theta^*_{\rm det}$ - measured decay angle; $\varepsilon(t)$ - reconstruction efficiency
$R(t', t)$ - resolution function convoled with the decay angle distribution

Measurement strategy

Method of moments: for any P, the first moment expressed as a linear combination of the first moments of distributions with $P = 0$ and $P = 1$

$$E(P) = \int_{-1}^{1} \mathrm{d}t'\ t' g_{\mathrm{det}}(t'; P) = E(0) + [E(1) - E(0)]P$$

$E(0)$ and $E(1)$ estimated using MC (mean for samples with $P = 0(1)$)



correction for background contrib.
→ the first moments calculated separately in the signal and sideband regions

polarization of background independent of $m_{p\pi}$ (cross-checked with MC)
→ the value measured in the sidebands used for the signal region

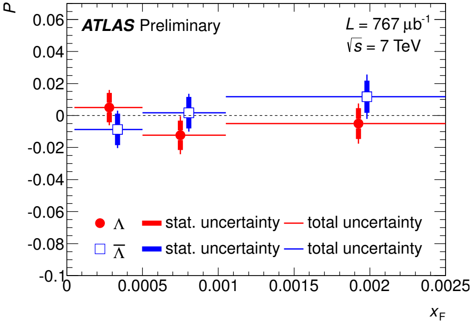
Results

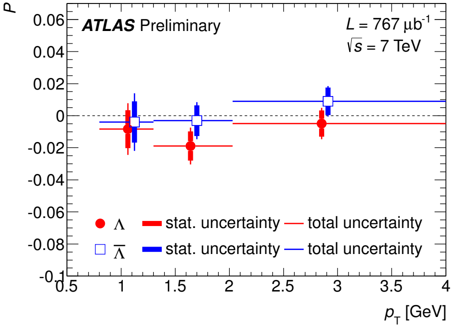
$P_\Lambda = -0.010 \pm 0.005(\text{stat}) \pm 0.004(\text{syst})$

$P_{\bar{\Lambda}} = 0.002 \pm 0.006(\text{stat}) \pm 0.004(\text{syst})$

$0.8 < p_T < 15$ GeV; $|\eta| < 2.5$

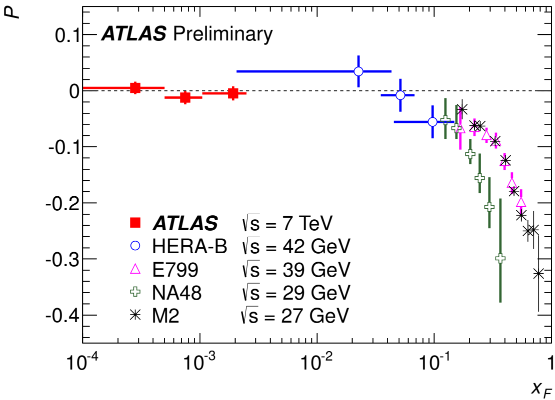
$5 \times 10^{-5} < x_F < 0.01$





- polarizations in p_T and x_F bins: less than 2% (consistent with zero within estimated uncertainty)
- polarization of $\bar{\Lambda}$ was measured consistent with zero by all the previous experiments

Polarization of Λ



comparison is non-trivial, each measurement made at different $\sqrt{s}$ and covers different phase space

- some energy dependence could be introduced → about 50% of Λ in ATLAS are produced in decays – Pythia estimate (40% in NA48)
- assume: polarization of the original baryons diluted in the decay
  → measured polarization expected to be consistent with or smaller than the extrapolation ✓ satisfied in this measurement

Summary

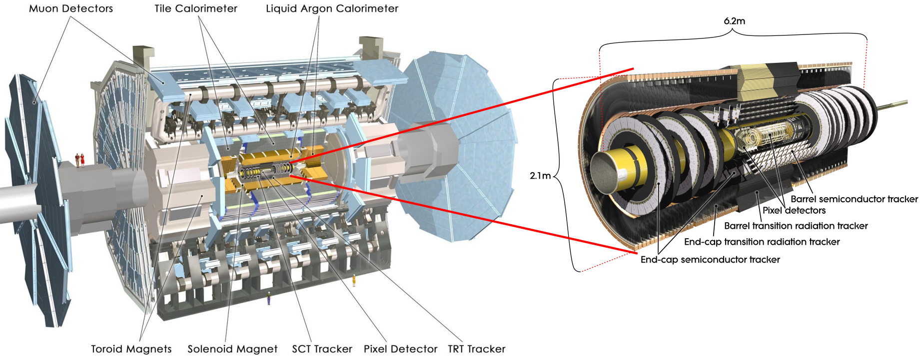
- less spherical with $p_{\mathrm{T}}^{\mathrm{lead}}$ increase, acc. to all three event shape variables
  more spherical with increasing multiplicity
  most accurate description: PYTHIA6 MC generator with the Z1 tune

- $\sigma_{\phi} \times BR(\phi \to K^{+}K^{-}) = 570 \pm 8$ (stat) $\pm$ 68 (syst) $\pm$ 20 (lumi) μb
  best description of $\sigma_{\phi}(p_{\mathrm{T}})$ and $\sigma_{\phi}(|y_{\phi}|)$ by PYTHIA 6 DW and EPOS-LHC

- $P_{\Lambda} = -0.010 \pm 0.005(\mathrm{stat}) \pm 0.004(\mathrm{syst})$
  $P_{\bar{\Lambda}} = 0.002 \pm 0.006(\mathrm{stat}) \pm 0.004(\mathrm{syst})$
  P in p_{T} and x_{F} bins: consistent with zero within estimated uncertainty
  $P_{\Lambda}(x_{\mathrm{F}})$ and $P_{\bar{\Lambda}}(x_{\mathrm{F}})$ match the behavior expected from older experiments

Backup slides

Atlas Detector



the ATLAS detector - almost full solid angle around the collision point coverage
electromagnetic & hadron calorimeter, muon spectrometer

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 $2.82 < |\eta| < 3.84$

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)

Sphericity

full momentum tensor of the event:

$$M_{\alpha\beta} = \sum_i p^i_\alpha p^i_\beta \qquad \alpha, \beta = x, y, z$$

- 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

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: $0 \leq S_\perp < 1$

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

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:

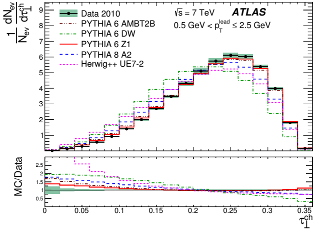
- $0.5\ \mathrm{GeV} < \mathrm{p_T^{lead}} < 2.5\ \mathrm{GeV}$; $2.5\ \mathrm{GeV} < \mathrm{p_T^{lead}} < 5.0\ \mathrm{GeV}$;
- $5.0\ \mathrm{GeV} < \mathrm{p_T^{lead}} < 7.5\ \mathrm{GeV}$; $7.5\ \mathrm{GeV} < \mathrm{p_T^{lead}} < 10.0\ \mathrm{GeV}$;
- $p_{\mathrm{T}}^{\mathrm{lead}} > 10.0\ \mathrm{GeV}$

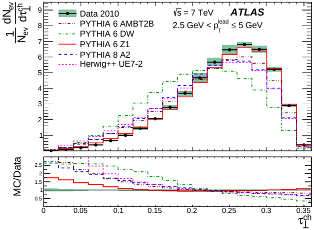
$p_{\mathrm{T}}^{\mathrm{lead}}$ - transverse momentum of the highest p_{T} (leading) charged particle

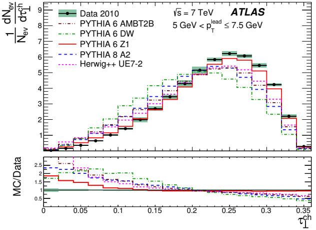
II. Average values: $\langle\tau_{\perp}^{ch}\rangle, \langle T_{\mathrm{M}}^{ch}\rangle, \langle S_{\perp}^{ch}\rangle$ as functions of N_{ch}, $\sum p_{\mathrm{T}}$

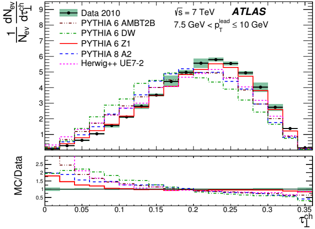
- N_{ev} - number of events with six or more charged particles within the selected kinematic range
- N_{ch} - number of charged particles in an event
- $\sum p_{\mathrm{T}}$ - scalar sum of transverse momenta of charged particles in the event

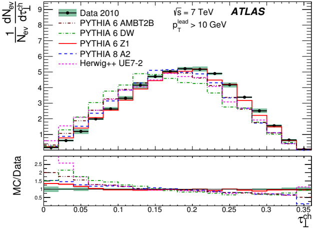
Complement of the Transverse Thrust Distributions











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

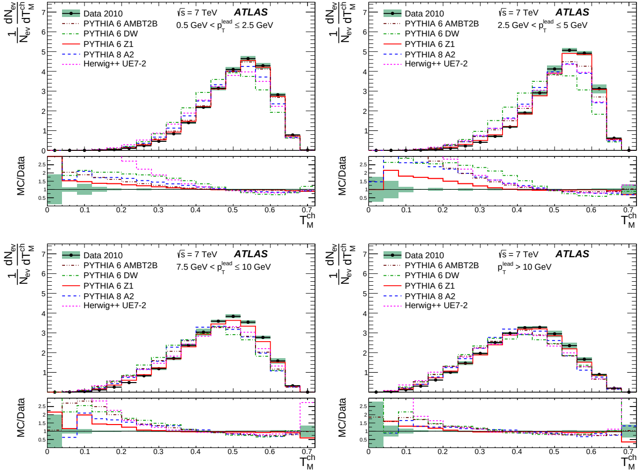
all models tend to better reproduce data selected with higher $p_{\mathrm{T}}^{\mathrm{lead}}$ ranges

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



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