Measurement of Underlying Event Observables with the ATLAS detector

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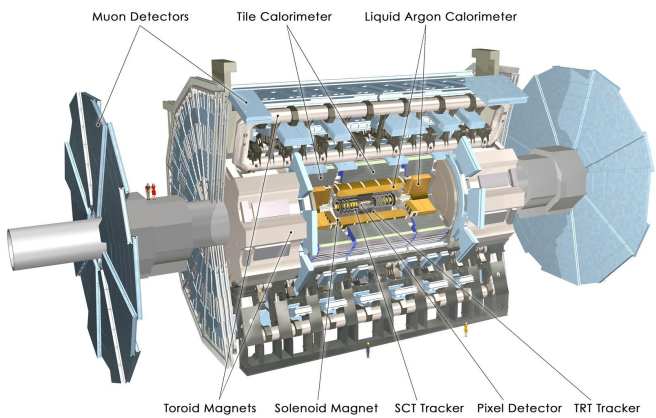
Overview

- Measurement of charged-particle distributions sensitive to underlying event in $\sqrt{s} = 13$ TeV proton-proton collisions with the ATLAS detector at the LHC – Preliminary results

- Measurement of event-shape observables in $Z \to \ell^+\ell^-$ events in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC

  Eur. Phys. J. C. (2016) 76:375, arXiv:1602.08980



Motivation

- **Underlying Event** = soft processes unavoidably accompanying hard parton-parton scatterings in *pp* collisions with a high momentum transfer
  - interactions between proton remnants, MPI, initial and final state QCD radiation

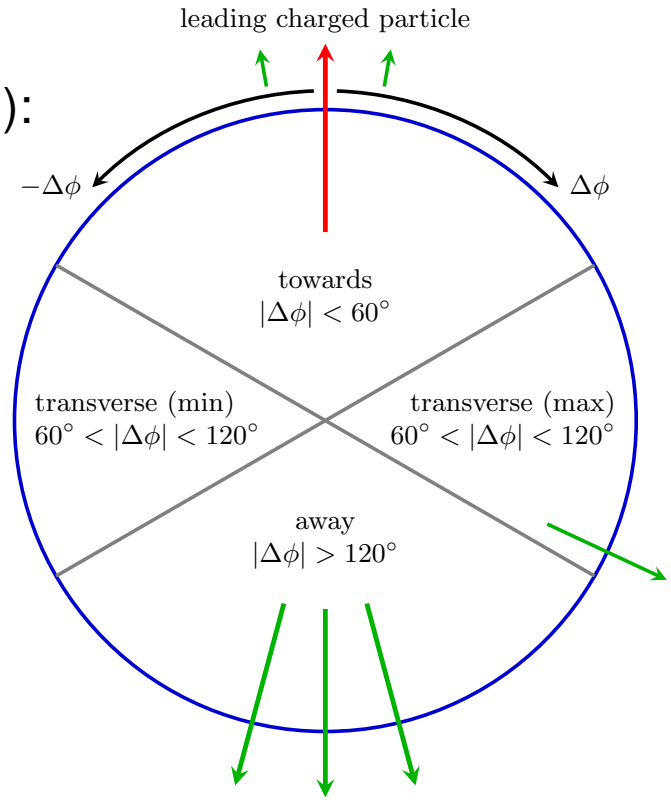
- Soft interactions not reliably calculable by theory – dominated by low-scale QCD interactions, in which the strong coupling strength diverges and pertubative methods of QCD lose predictivity

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

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

Measurement of Underlying Event

- η, φ plane divided into regions around leading (the highest p_{T}) object (track, calo. cluster, jet...):
  - $|\Delta\varphi| < 60^{\circ}$ - **toward**
  - $60^{\circ} < |\Delta\varphi| < 120^{\circ}$ - **transverse**
  - $|\Delta\varphi| > 120^{\circ}$ - **away**
- towards and away regions dominated by particle production from the hard process $\rightarrow$ relatively insensitive to the softer UE
- transverse region more sensitive to UE



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 (higher $\sum p_{\mathrm{T}}$) includes both MPI and hard-process contamination
- **trans-min**: observables in the less-active transverse region (lower $\sum p_{\mathrm{T}}$) most sensitive to MPI effects (pedestal)
- **trans-diff**: difference of trans-max and trans-min clearest measure of hard-process contamination

Measured Observables

Observable	Description
binned variables	
$p_{\mathrm{T}}^{\mathrm{lead}}$	Transverse momentum of the leading charged particle
$\lvert\Delta\phi\rvert$	Absolute difference in particle azimuthal angle from the leading particle
unbinned variables	
$\langle N_{ch}/\delta\eta\delta\phi\rangle$	Mean number of charged particles per unit $\eta-\phi$ (in radians)
$\langle\sum p_{\mathrm{T}}/\delta\eta\delta\phi\rangle$	Mean scalar p_{T} sum of charged particles per unit $\eta-\phi$ (in radians)

$\delta\phi = 2\pi/3$ – for toward, away an transverse regions
$\pi/3$ – for the single-sided trans-min and trans-max regions
$2\pi/n_{\mathrm{bins}}$ – for each of the n_{bins} equally-sized bins in $\lvert\Delta\phi\rvert$ distributions

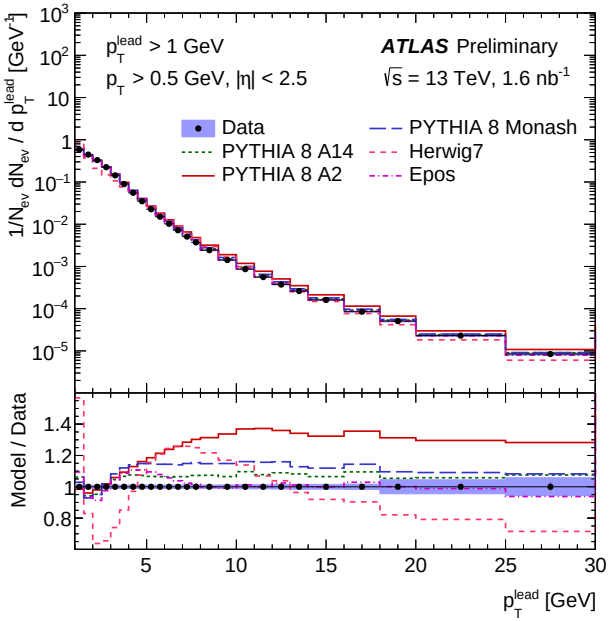
$\delta\eta = 5$ in all cases

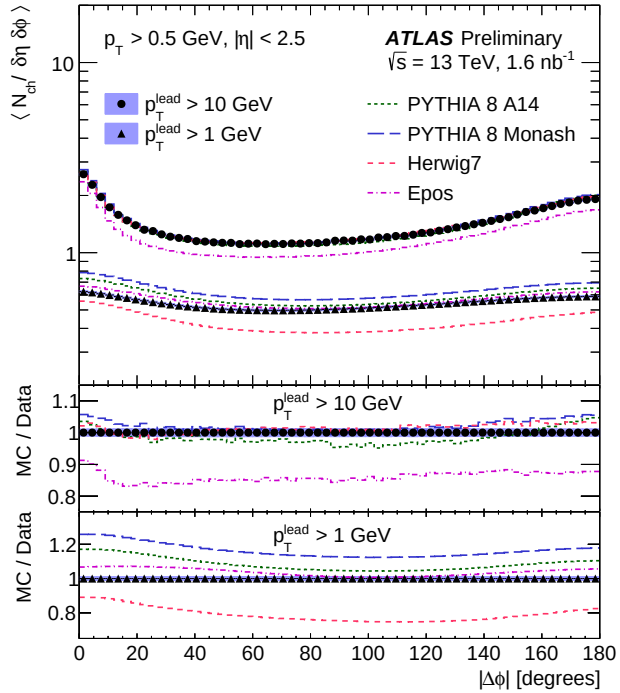
mostly dependences of these quantities on the $p_{\mathrm{T}}^{\mathrm{lead}}$:
low $\rightarrow$ high $p_{\mathrm{T}}^{\mathrm{lead}}$ $\propto$ smooth transition: minimum bias $\rightarrow$ hard scattering regime

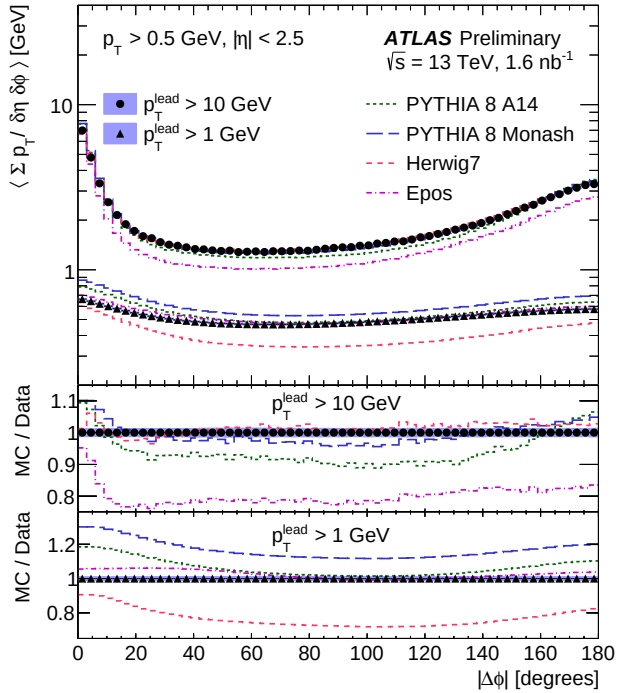
Event and Track Selection

- $\sqrt{s} = 13$ TeV data taken in a special configuration of the LHC: low beam currents, reduced beam focusing, producing a low mean number of interactions per bunch ($0.003 \leq \langle \mu \rangle \leq 0.03$)
- trigger: one or more MBTS counters above treshold on either side of the detector
- integrated luminosity of 1.6 nb^{-1}
- events: required to contain 1 reconstructed vertex from ≥ 2 tracks with $p_{\mathrm{T}} > 100$ MeV
  required to contain at least one track with $p_{\mathrm{T}}^{\mathrm{lead}} > 1$ GeV
  corrected to the particle level, including a correction for leading particle realignment
  66 million data events passed the trigger and vertex selection
- track selection criteria: $p_{\mathrm{T}} > 0.5\ \mathrm{GeV}$; $|\eta| < 2.5$

Leading charged particle p_T and Angular distributions







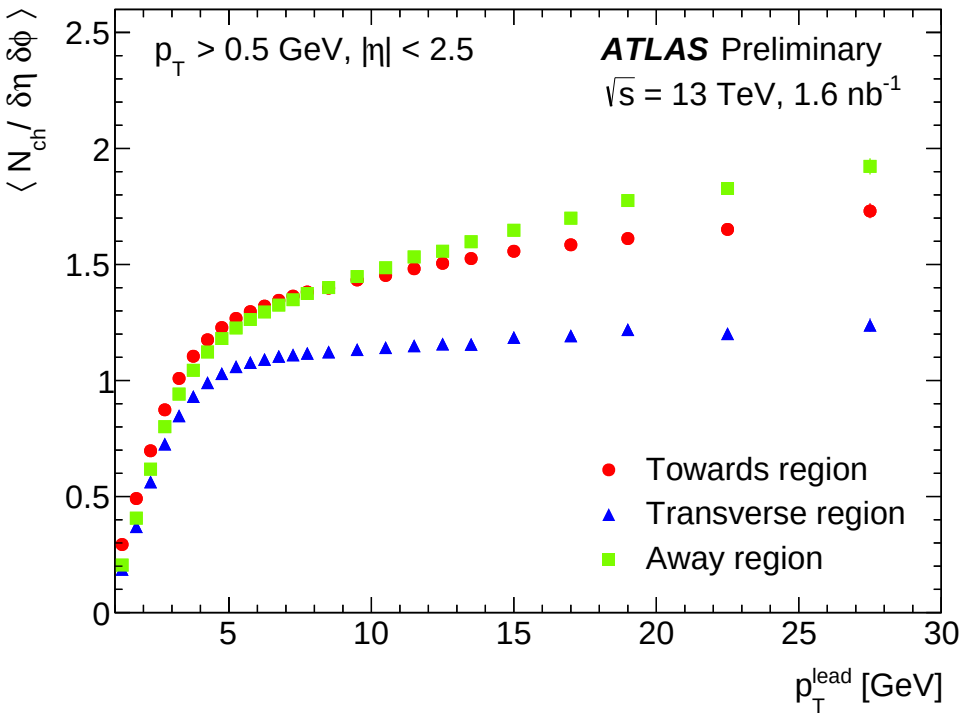
N_{ev} vs p_T^{lead}: steeply falling distribution with a change of slope for $p_T^{lead} \geq 5$ GeV broadly modelled by all generators, best description by EPOS and PYTHIA 8 A14

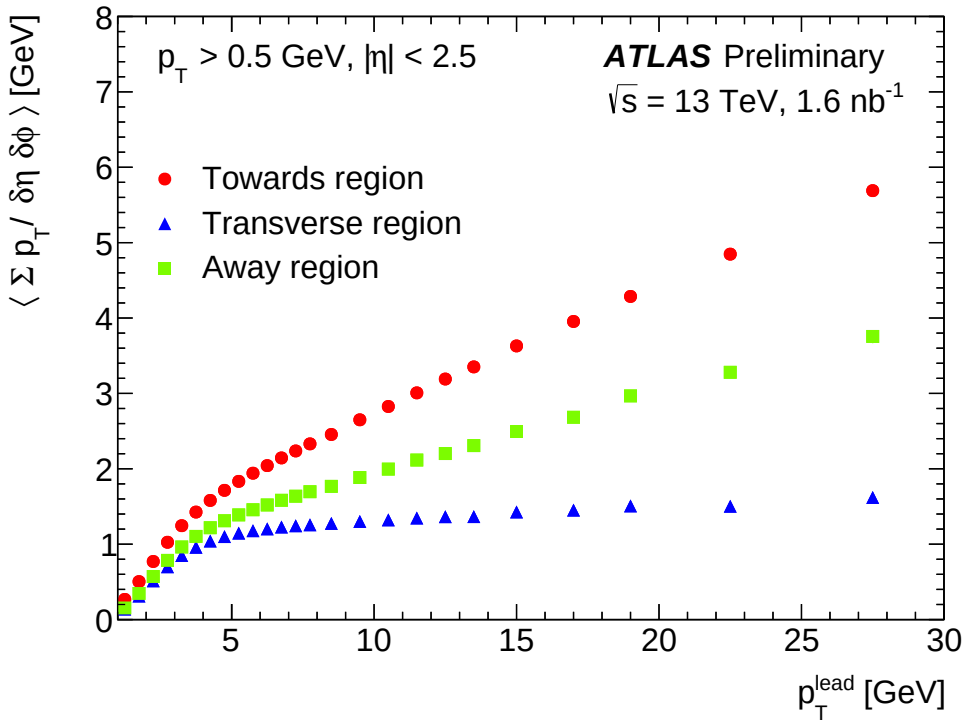
$p_T^{lead} > 1$ GeV $\rightarrow$ $p_T^{lead} > 10$ GeV – transition from relatively isotropic minimum bias scattering to the emergence of hard partonic scattering structure and a dominant axis of energy flow, no clear best MC:

more inclusive selection ($p_T^{lead} > 1$ GeV) – EPOS

hard-scattering selection ($p_T^{lead} > 10$ GeV) – HERWIG7 and Pythia 8 Monash

N_{ch} and $\sum p_T$ densities in azimuthal regions



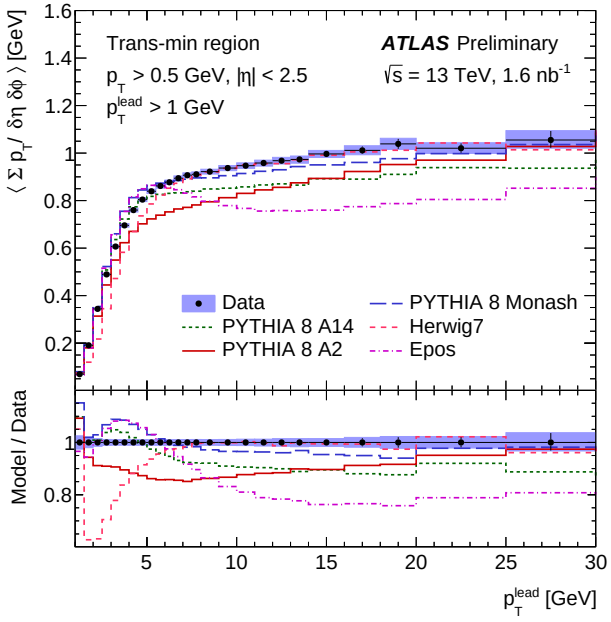


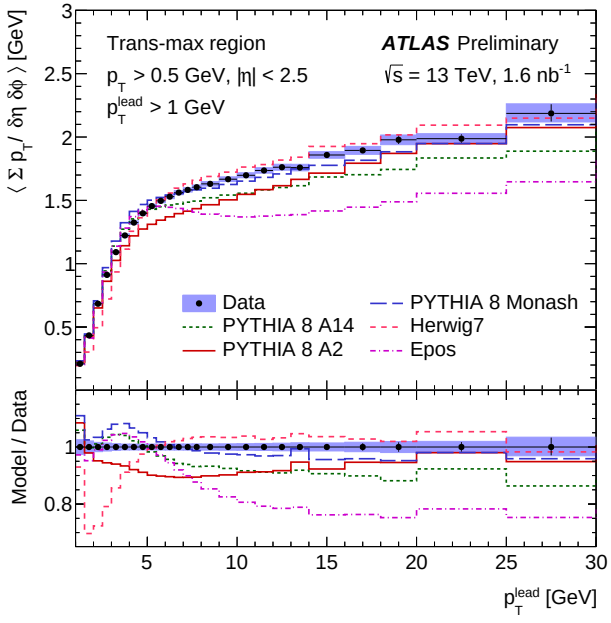
general shape: first very rapid rise in activity – 3 regions not strongly distinguished
abrupt transition at $p_T^{lead} \approx 5$ GeV, above it distinct behavior of 3 regions

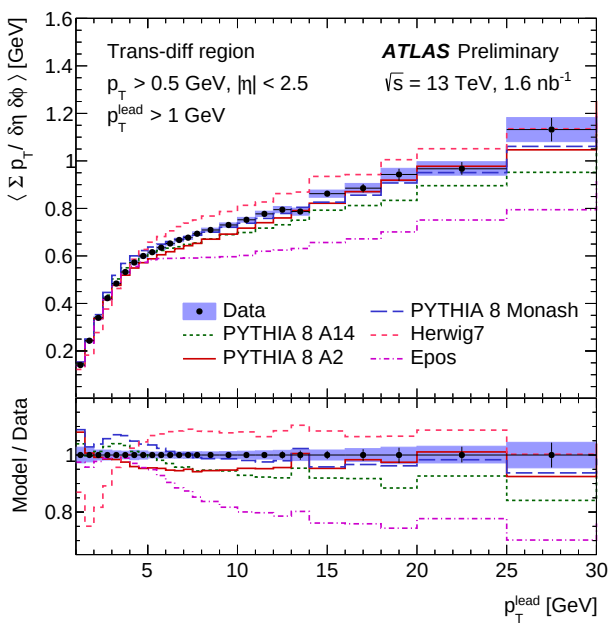
different shape of the *transverse* region: almost completely plateaus after $p_T^{lead} \approx 5$ GeV
$\rightarrow$ hard process dominates the *towards* and *away* regions, which continue to increase in activity as the hard process scale grows, but *transverse* region is relatively unaffected

$p_T^{lead} > 7$ GeV: *away* region with highest multiplicity, despite not containing p_T^{lead} track
the *towards* region is the most active by $\sum p_T$ for all p_T^{lead} values

$\sum p_T$ densities in trans-min/max/diff regions







trans-min: best description by PYTHIA 8 Monash and Herwig7 (in the plateau region)
PYTHIA 8 A2 (mild but broad undershoot extending up to $p_T^{lead} \approx 20$ GeV)
and Herwig7 (severe undershoot for $p_T^{lead} < 5$ GeV) mismodel the transition

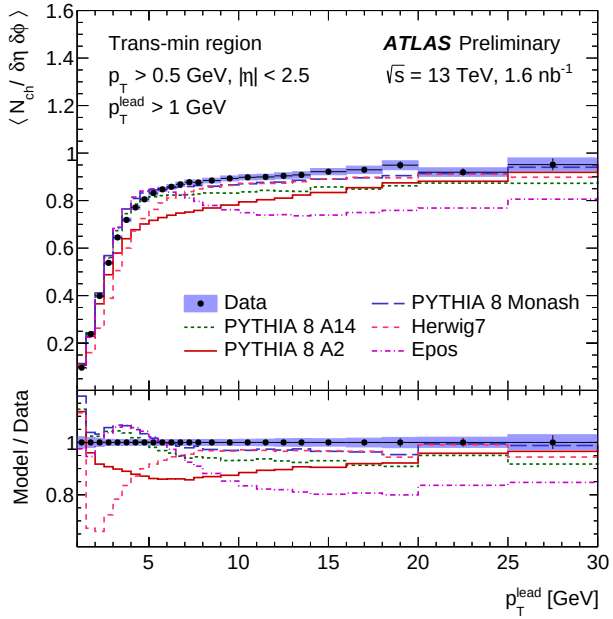
trans-max: similar, undershoot of PYTHIA 8 A2 slightly better

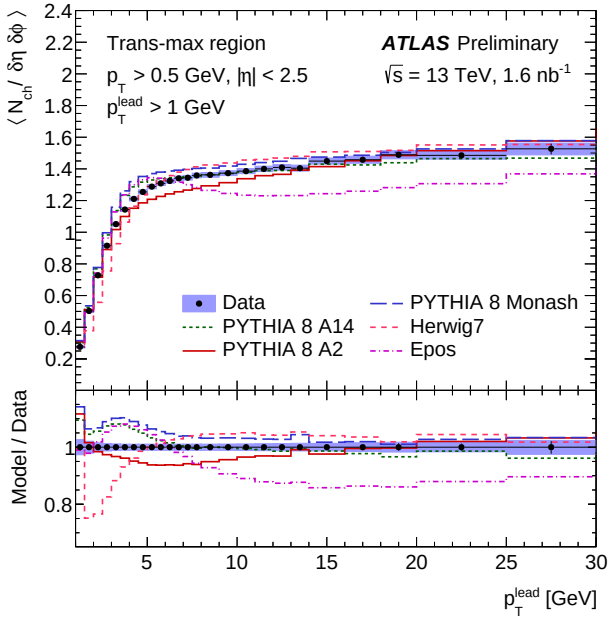
trans-diff: best description by PYTHIA 8 Monash and A2 tunes

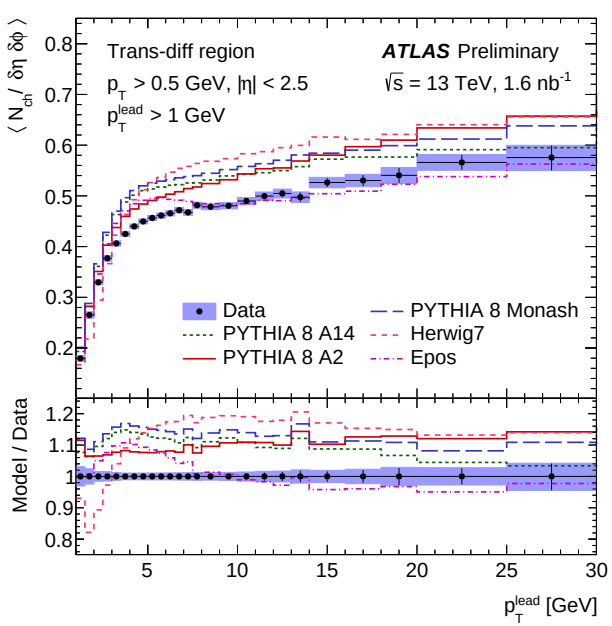
EPOS not able to model the level of underlying event activity for higher p_T^{lead}

PYTHIA 8 A14 used much for the hard process simulation in ATLAS predicts activity $\sim$ 10% below the data $\rightarrow$ some re-tuning for 13 TeV event modelling may yield performance benefits

N_{ch} densities in trans-min/max/diff regions







trans-min: same as in case of $\sum p_T$

trans-max: models cluster together more tightly providing good description for $p_T^{lead} > 10$ GeV except EPOS

trans-diff: mostly flat ∼ 10% overshoots from all models except EPOS

no obvious best model for all observables: PYTHIA 8 Monash agrees well except of trans-diff N_{ch} density & Herwig7 has comparable performance for $p_T^{lead} > 5$ GeV

Event shape observables in $Z \to \ell^+\ell^-$ events at 7 TeV

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

- sensitive to UE properties
- quantities that are experimentally easy to access
- enable detailed tests of phenomenological QCD models
  $\Rightarrow$ input for tuning MC generators
- ratios of final state observables $\Rightarrow$ reduced sensitivity to theoretical and experimental uncertainties

events containing $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$

Z-boson – without colour charge $\to$ does not affect hadronic activity in the collision
observables calculated using charged particles excluding the Z-boson decay products

observables measured in different ranges of the Z-boson transverse momentum
$p_{\mathrm{T}}(\ell^+\ell^-)$: 0 – 6; 6 – 12; 12 – 25; $\geq$ 25 GeV

small $p_{\mathrm{T}}(\ell^+\ell^-)$ values – low jet activity from the hard process $\to$ high sensitivity to UE
high $p_{\mathrm{T}}(\ell^+\ell^-)$ values – at least one high p_{T} jet recoiling against the $\ell^+\ell^-$ system
$\to$ reasonably described by pertubative calculations of the hard process

Event shape observables

Normalized distributions: $(1/N_{ev})dN/d\mathcal{O}$

N_{ev} - number of all selected events

$\mathcal{O}$ are following observables:

- N_{ch} – charged particle multiplicity
- $\sum p_{\mathrm{T}}$ – scalar sum of transverse momenta of selected charged particles in the event
- The Beam thrust $\mathcal{B} = \sum p_{\mathrm{T}} \cdot e^{-|\eta|}$ – sum over all selected charged particles of transverse momentum weighted by rapidity
  $\rightarrow$ contributions from forward and backward particles suppressed
  $\sum p_{\mathrm{T}}$ and $\mathcal{B}$ have different sensitivities to hadronic activity from initial-state radiation

Transverse Thrust $\mathcal{T}$, Spherocity $\mathcal{S}$ and $\mathcal{F}$-parameter

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

$$\mathcal{S} = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \vec{n}|}{\sum_i p_{\mathrm{T},i}} \right)^2$$

$\mathcal{O}$	dijet	isotropic
$\mathcal{T}$	1	$2/\pi$
$\mathcal{S}$	0	1
$\mathcal{F}$	0	1

$$\mathcal{F} = \frac{\lambda_1}{\lambda_2};$$

$\lambda_1 < \lambda_2$ - two eigenvalues of the transverse momentum tensor M^{lin}:

$$M^{\mathrm{lin}} = \sum_i \frac{1}{p_{\mathrm{T},i}} \begin{pmatrix} p_{x,i}^2 & p_{x,i}\, p_{y,i} \\ p_{x,i}\, p_{y,i} & p_{y,i}^2 \end{pmatrix}$$

- the sum over the $\vec{p}_{\mathrm{T},i}$ of all charged particles in the event
- $\hat{\boldsymbol{n}}_\perp$ - the unit vector of the *thrust axis* maximizing the expression found iteratively
- $\vec{n}$ - vector in the transverse plane which minimises the expression coincides with one of the transverse momentum vectors $\vec{p}_{\mathrm{T},i}$

Event and Track Selection

$\sqrt{s} = 7$ TeV data collected in 2011 requiring a Z boson candidate decaying to an e^+e^- or $\mu^+\mu^-$ pair - restricted to a subsample with mean number of pp collisions per bunch crossing ~ 5 and not > 7 to reduce PU (integrated luminosity $\approx 1.1\ \mathrm{fb}^{-1}$)

- events were required to contain a primary vertex – the vertex with the highest $\sum(p_{\mathrm{T}}^{\mathrm{trk}})^2$ to reject events from cosmic-ray muons and other non-collision backgr. vertex must have at least one track with $p_{\mathrm{T}} > 400$ MeV
- selected electrons and muons were required $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$ for electrons $1.37 < |\eta| < 1.52$ also excluded – passive detector material in ECAL
- $Z \to \ell^+\ell^-$ signal events, when $m_{\ell^+\ell^-} \in [66, 116]$ GeV
- 2.6×10^5 events in electron channel and 4.1×10^5 in muon channel passed
- track selection criteria: $p_{\mathrm{T}} > 0.5\ \mathrm{GeV}$; $|\eta| < 2.5$

Corrections

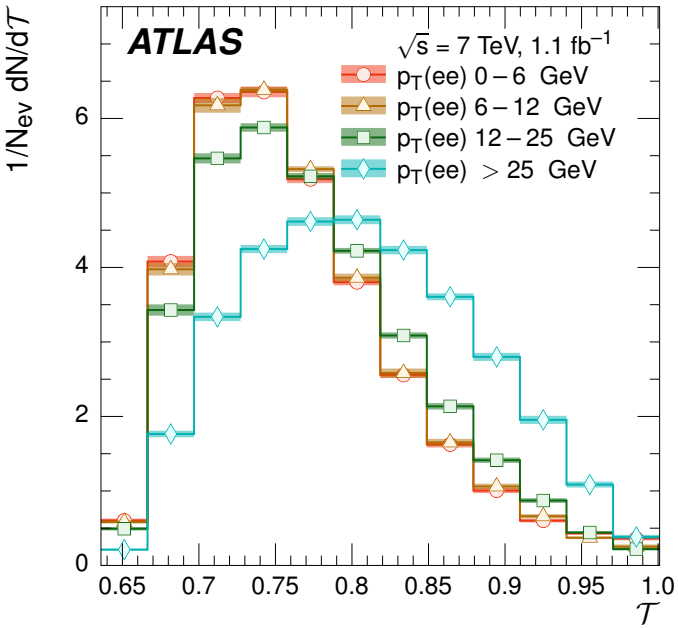
- **Lepton track removal**: $e^{\pm}$ can interact with material in front of the ECAL
  $\rightarrow$ bremsstrahlung & photon conversion $\rightarrow$ multiple tracks
  $\rightarrow$ tracks not used if they fell inside a cone of $\Delta R_{e,\mathrm{trk}} = 0.1$ around any selected $e^{\pm}$
  $\rightarrow$ applied also to the muon channel to treat two channels as similarly as possible

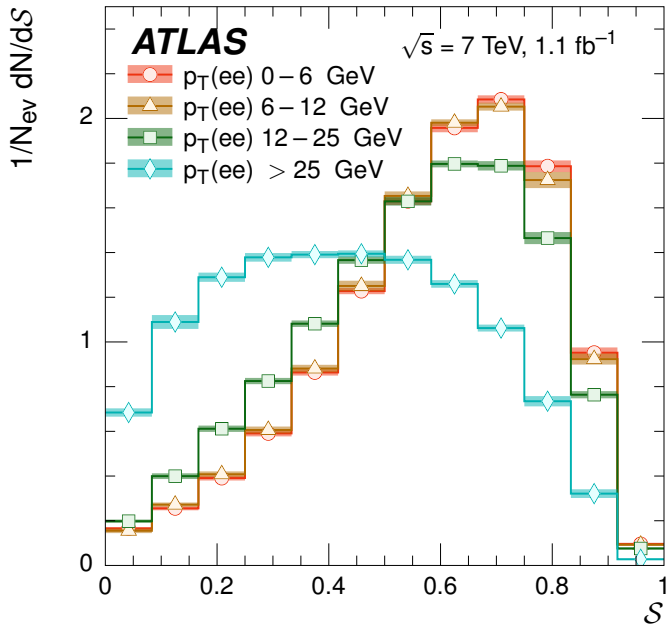
- **Pile-up correction**: Hit Backspace Once More (HBOM) approach: arXiv:1012.5104, New J. Phys. **13**, 053033 (2011)

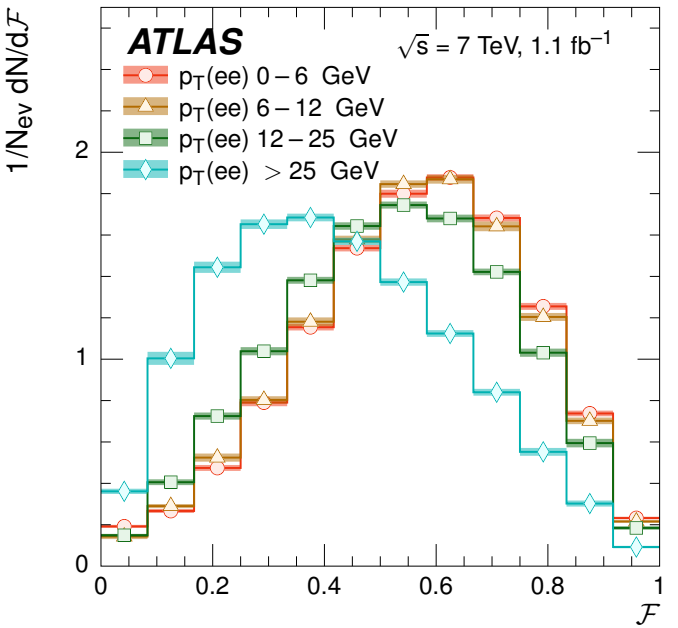
- **Background treatment**: only for multijet events with misidentified lepton candidates $\rightarrow$ estimated from data

- **Unfolding**: $\mathcal{O}$ corrected for contributions from non-primary particles, detector efficiency and resolution effects, Bayesian approach, PYTHIA 8 and SHERPA

Transverse Thrust, Spherocity and $\mathcal{F}$-Parameter



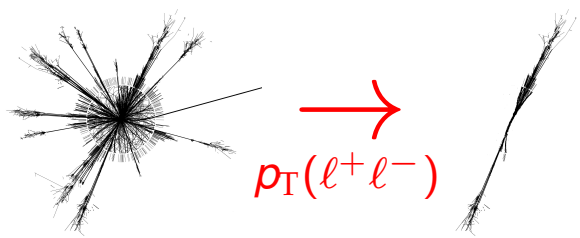




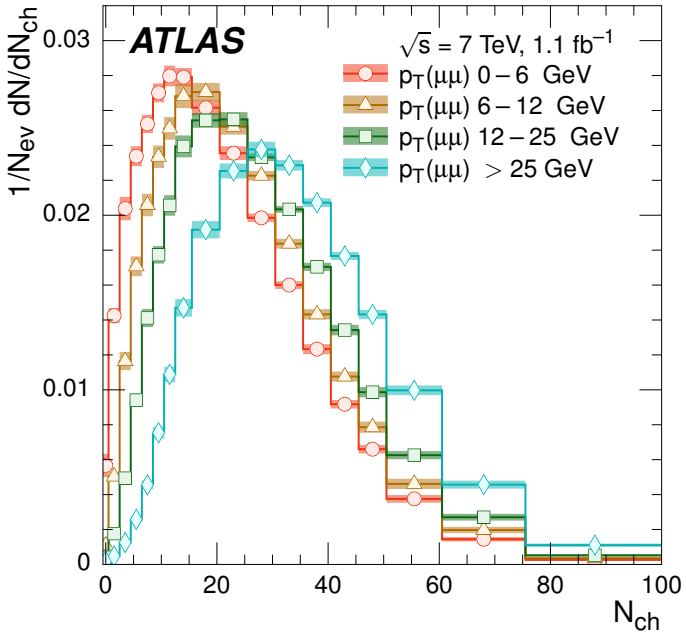
same results in the muon channel

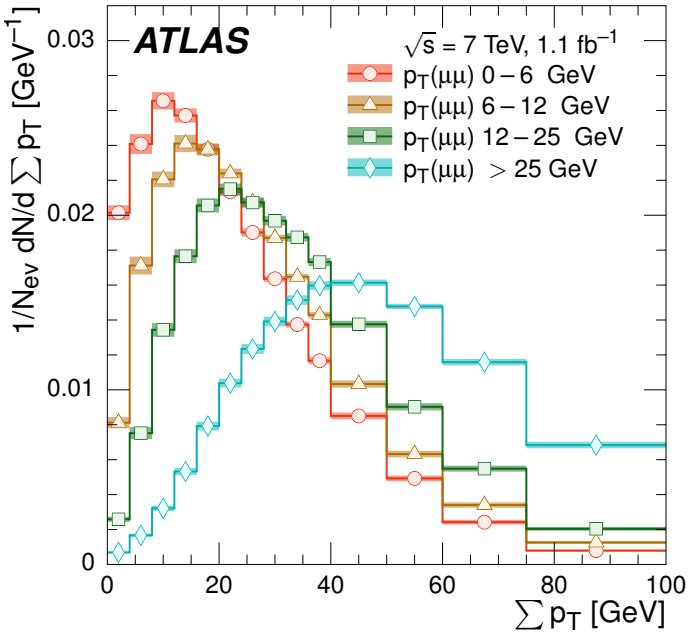
lower $p_{\mathrm{T}}(\ell^+\ell^-)$ ranges: spherical events prevalence

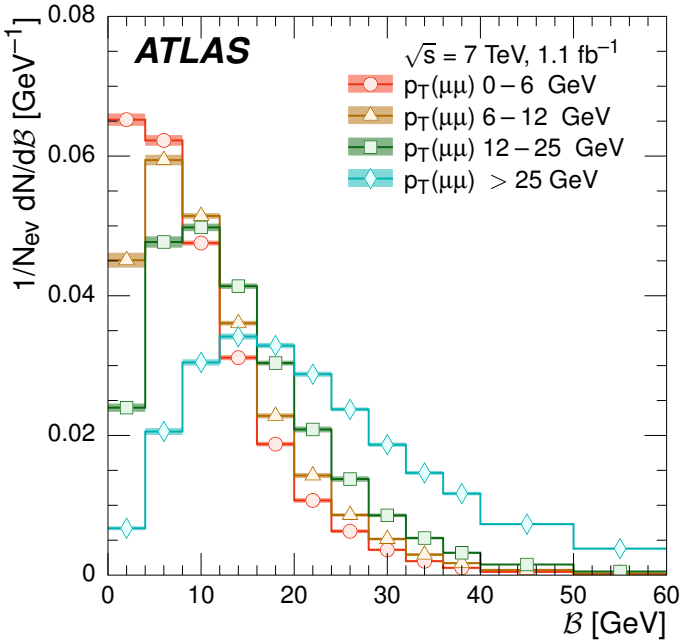
$p_{\mathrm{T}}(\ell^+\ell^-) > 12\,\mathrm{GeV}$: shift to less spherical events



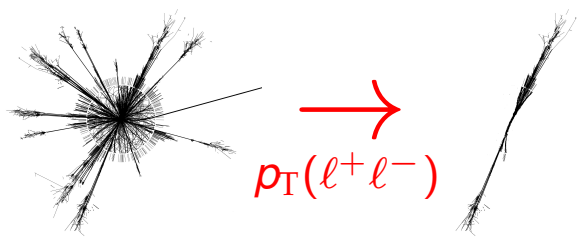
Observables depending explicitly on N_{ch}



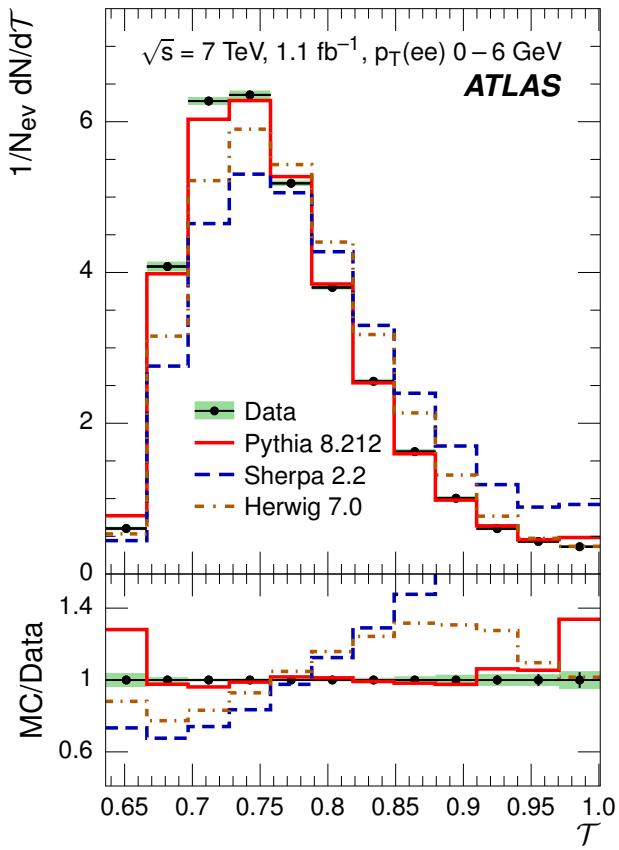


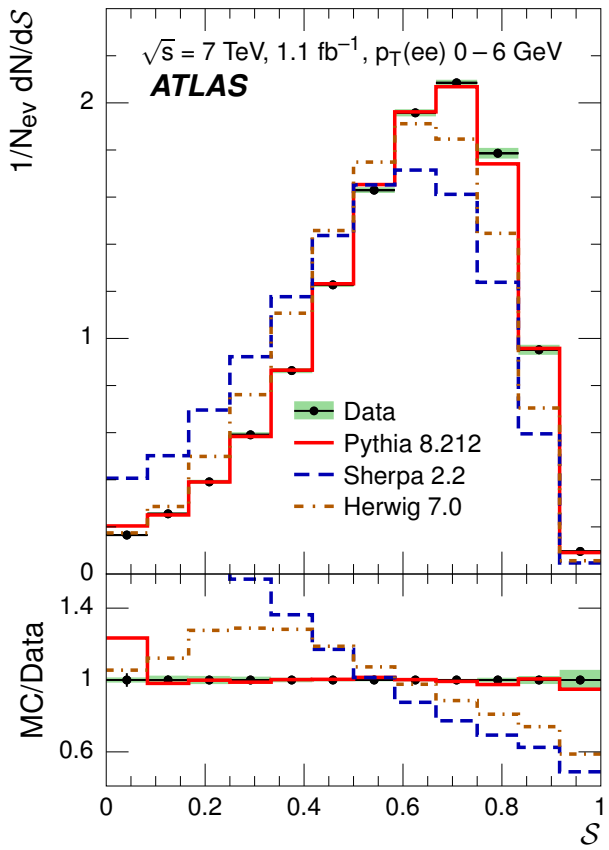


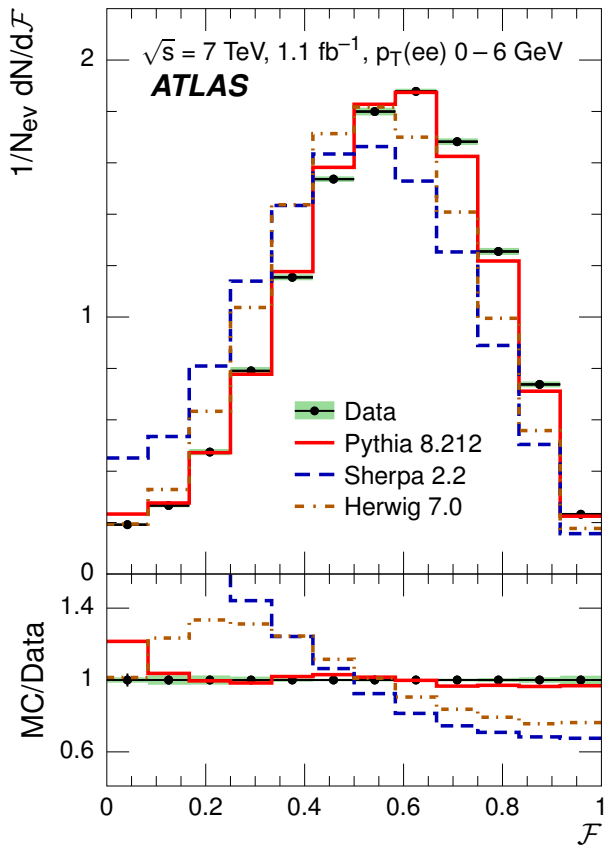
same results in the electron channel
as $p_{\mathrm{T}}(\ell^+\ell^-)$ rises, i.e. as recoiling jets emerge,
N_{ch} increases, as do $\sum p_{\mathrm{T}}$ and beam thrust



Event Shape Observables for $p_{\mathrm{T}}(\ell^+\ell^-) < 6\,\mathrm{GeV}$

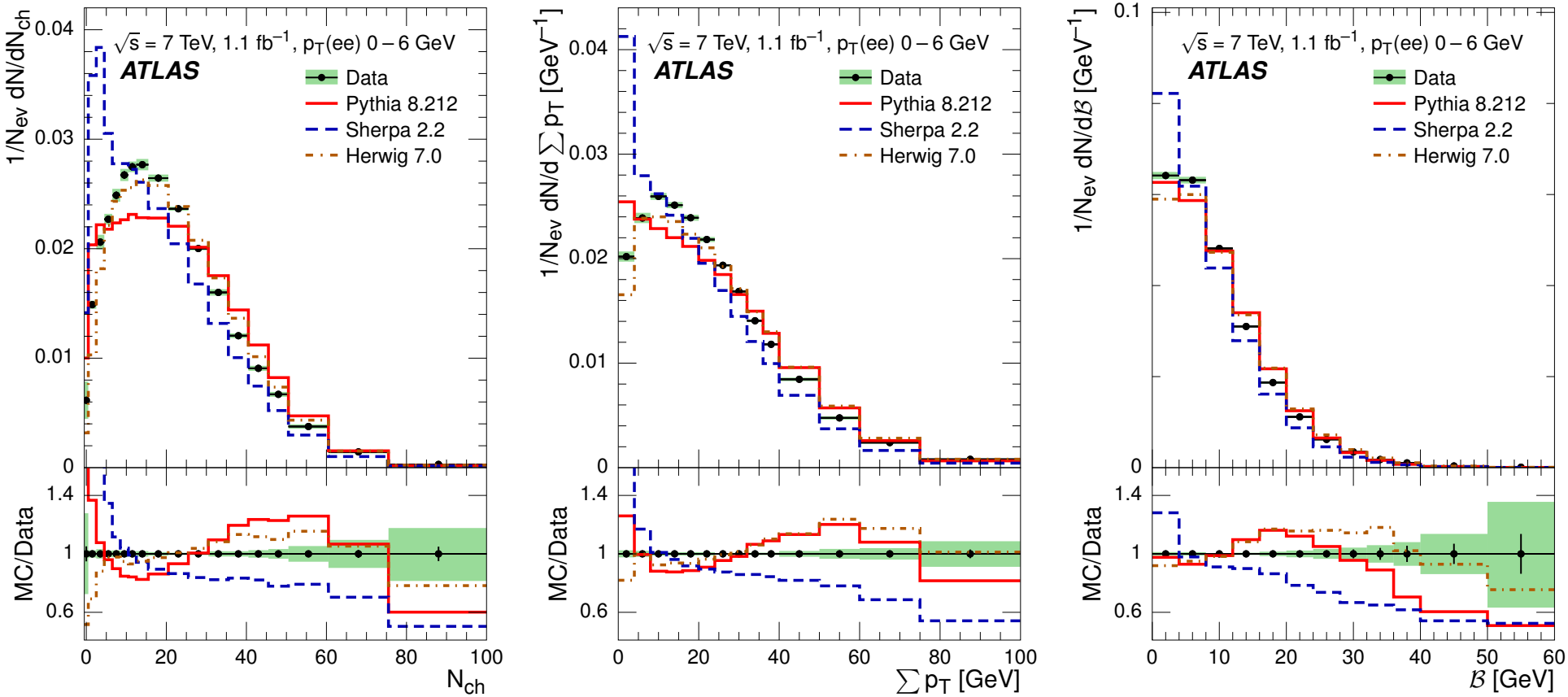






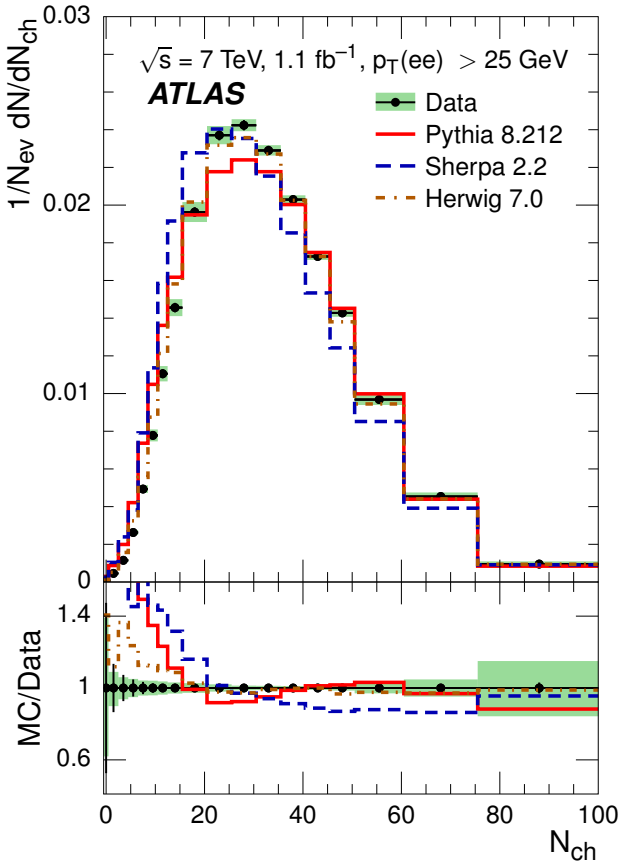
- $p_{\mathrm{T}}(\ell^+\ell^-) < 6\,\mathrm{GeV}$ bin: expected to be characterised by low jet activity
  $\rightarrow$ particularly sensitive to UE characteristics
- PYTHIA 8 shows very good agreement with the data
- very similar results in the muon channel

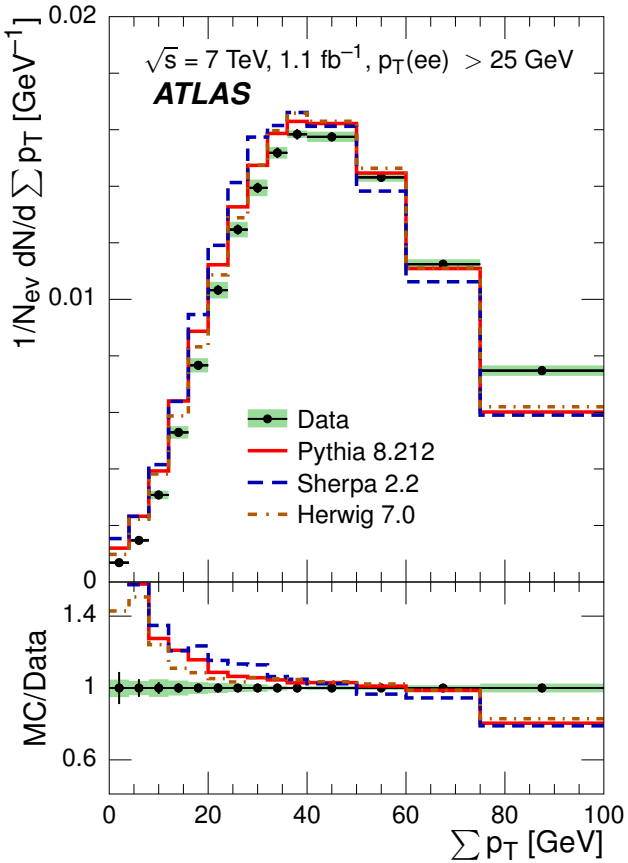
Observables depending on N_{ch} for $p_T(\ell^+\ell^-) < 6\,\text{GeV}$

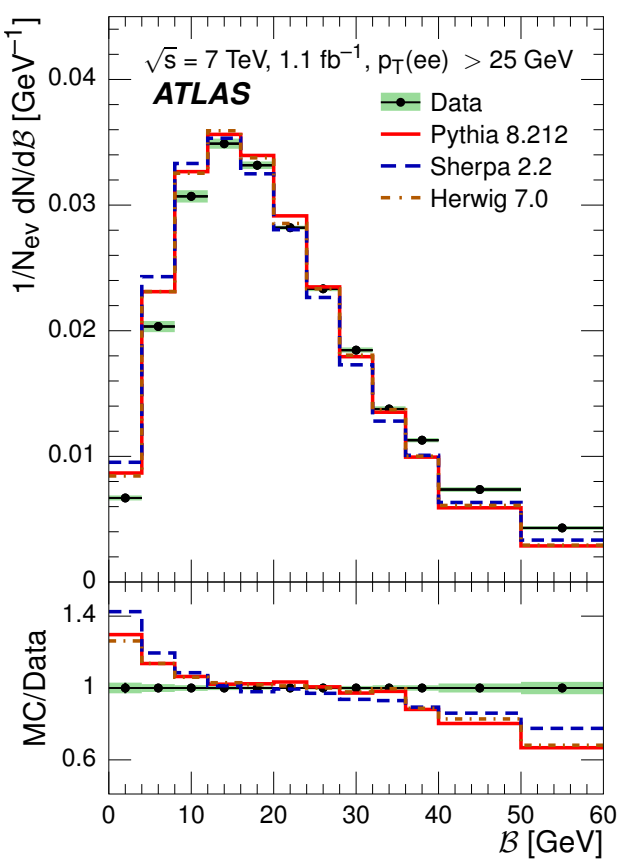


- none of the generators succeeding fully, very similar results in the muon channel
- best agreement for HERWIG7, followed by PYTHIA 8
- low N_{ch} and $\sum p_T$ values: challenging region for all 3 generators
  - $\rightarrow$ sensitive to the way beam-remnant interactions are modelled in the MC
  - $\rightarrow$ better agreement for $\mathcal{B}$ where tracks with larger $|\eta^{trk}|$ are suppressed

Observables depending on N_{ch} for $p_T(\ell^+\ell^-) > 25\text{GeV}$







- $p_T(\ell^+\ell^-) > 25\,\text{GeV}$ bin: expected to contain at least one jet of high transverse momentum recoiling against the Z boson
  $\rightarrow$well described by the hard matrix element
- better agreement than for $p_T(\ell^+\ell^-) < 6\,\text{GeV}$, but still significant deviation
- best agreement for HERWIG7, followed by PYTHIA 8

Summary

Underlying event at $\sqrt{s} = 13$ TeV:

- no obvious best model for all observables: PYTHIA 8 Monash agrees well except of trans-diff N_{ch} density & Herwig7 comparable for $p_{\mathrm{T}}^{\mathrm{lead}} > 5$ GeV
- trans-diff N_{ch} density: mostly flat $\sim 10\%$ overshoots from all models but EPOS
- EPOS particular discrepant features for higher $p_{\mathrm{T}}^{\mathrm{lead}}$
- PYTHIA 8 A14 predicts activity $\sim 5 - 10\%$ below the data except trans-diff N_{ch} density

Event shape observables in $Z \to \ell^+\ell^-$ events at $\sqrt{s} = 7$ TeV:

- better predictions of all 3 MC generators at high $p_{\mathrm{T}}(\ell^+\ell^-)$ and for the observables that are less sensitive to the number of charged particles in the event (transverse thrust, spherocity, and F-parameter) – PYTHIA 8 best
- significant differences from data at low values of N_{ch}, $\sum p_{\mathrm{T}}$ and beam thrust in certain $p_{\mathrm{T}}(\ell^+\ell^-)$ regions