Measurements of particle production and underlying event properties with ATLAS

DIS 2015, Dallas, Texas, April 2015

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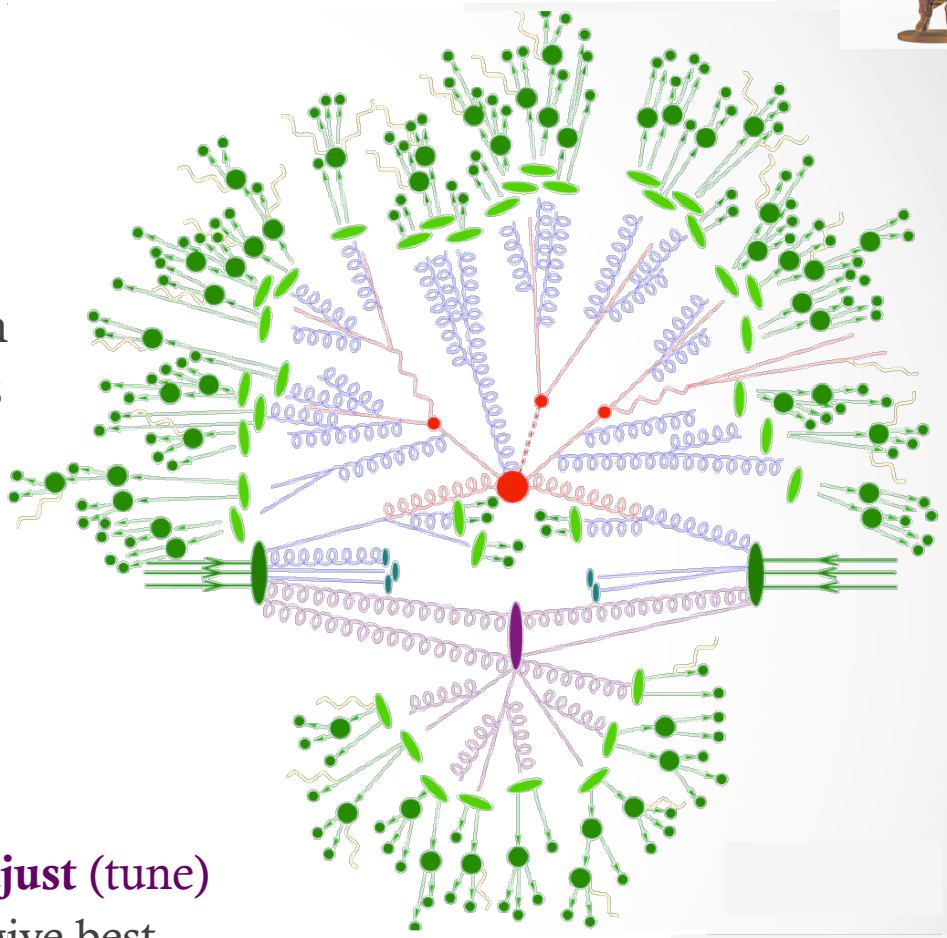
on behalf of the ATLAS Collaboration

motivation



- **soft QCD physics** (low momentum transfer, strong force interactions) **dominates** total pp cross section
- … but not well understood; description involves **non-perturbative QCD**; relies on phenomenological models
- almost every observable influenced by **non-perturbative** QCD effects
- soft QCD distributions can be used to **test phenomenological models** and **adjust** (tune) parameters of existing MC models to give best description of data – necessary for both **precision physics** and **searches**

ATLAS soft QCD results

- **ATLAS** has wealth of measurements in **soft QCD** and diffraction from LHC Run 1
  - charged particle **multiplicities**, **underlying event** characteristics, **elastic** and **inelastic** pp cross sections, **hadron production** cross sections, event level **correlations** between particles, **event shape** variables, **pseudorapidity dependence** of total Et, …

➛ many of these already used to provide important input to phenomenological models

- today, focus only on most recent ATLAS measurements of particle production and underlying event properties:

1. underlying event in jets – EPJC 74 (2014) 2965
2. underlying event in Z boson production – EPJC 74 (2014) 3195
3. Λ and $\bar{\Lambda}$ transverse polarisation – PRD 91 (2015) 032004

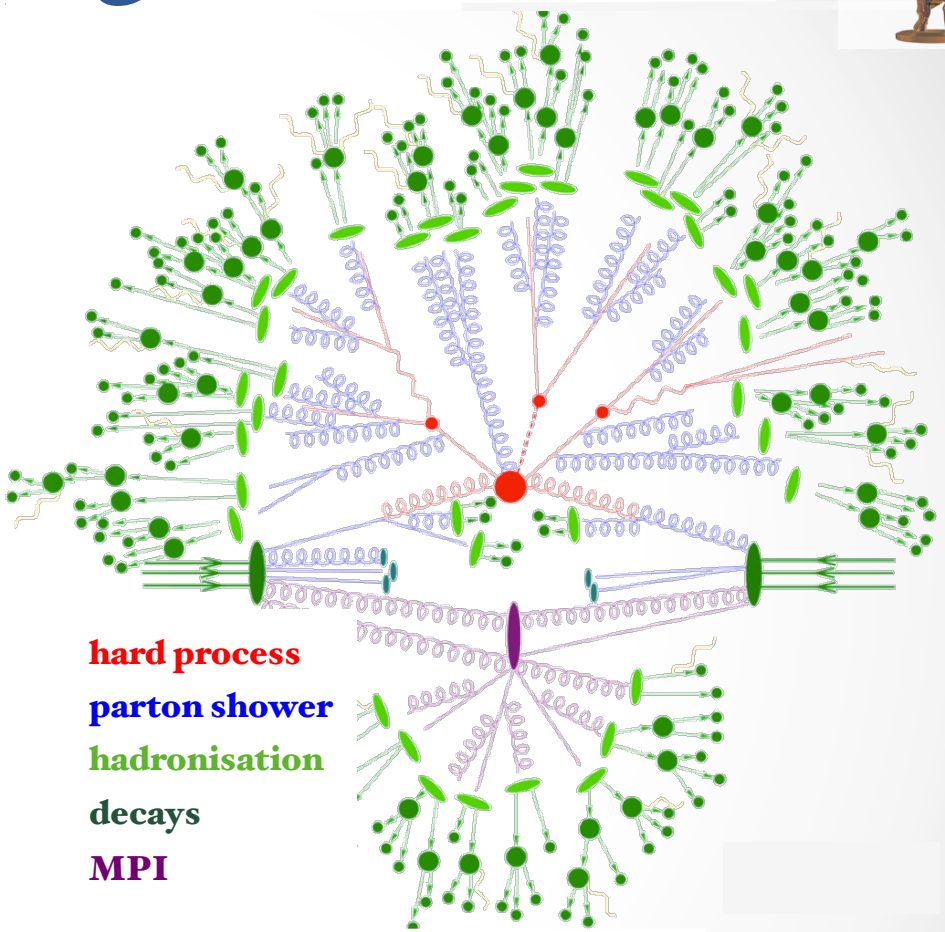
- see also separate ATLAS talks on **total elastic pp cross section** (L. Adamczyk) and **Bose Einstein correlations** (I. Sykora)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Soft_QCD

underlying event

- **underlying event**: all hadronic activity **except** the hard scatter (beam-beam remnants, multiparton interactions (MPI); contributions from ISR, FSR)

- process of interest usually hard scatter
- underlying event is unavoidable background to most collider observables
- not well predicted since non-perturbative effects dominate
- **not possible** to unambiguously assign particles to hard scatter versus underlying event

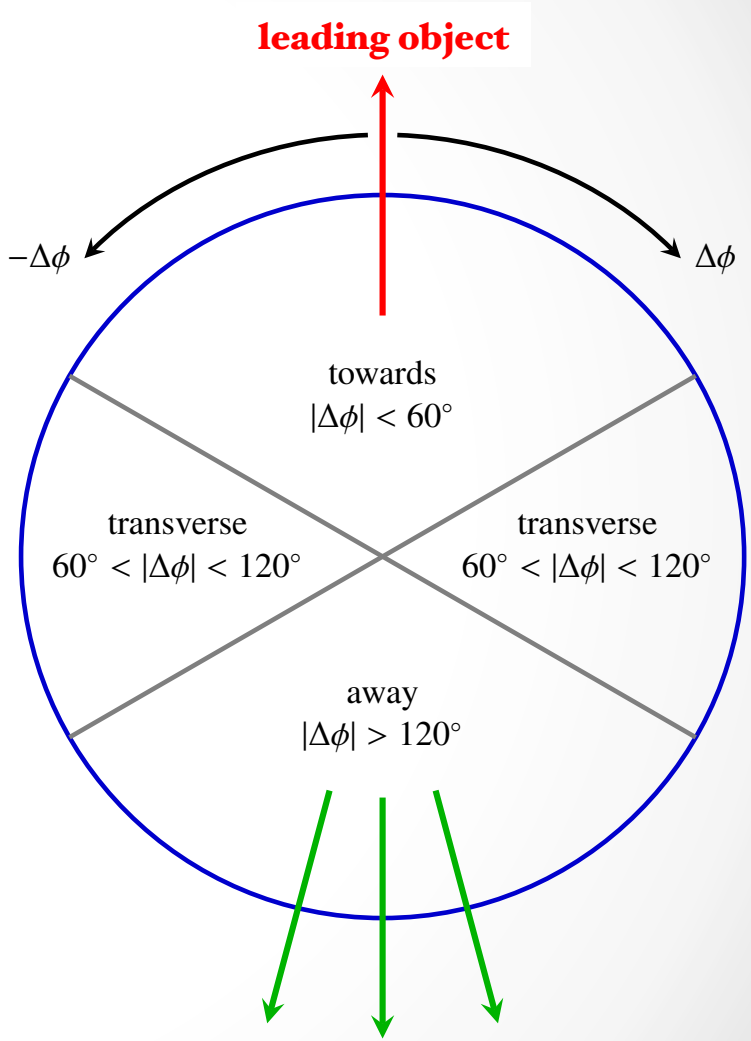


- use **underlying event** and other soft QCD distributions to test phenomenological models and "tune" the MC event generators to give best description of data

underlying event topology

- identify **hard scatter** using **reference object** (e.g. jet, vector boson)
- traditionally, 3 azimuthal regions defined with respect to **leading object**

- **transverse** region sensitive to underlying event
- **away** region has larger contributions from high-Pt recoil, modelled by pQCD
- **transverse** region further subdivided into **trans-max** and **trans-min**, depending on amount of activity
  - max and min calculated separately for each observable
- with Z events, **towards** region can also be probed



MC models and tunes

- comparison to number of Monte Carlo (MC) models/tunes in what follows
- **leading order + parton shower MCs** e.g.
- Pythia8, PYTHIA6: Pt (or virtuality) ordered showers, Lund string hadronisation, MPI model for underlying event

  tunes: P8: (ATLAS) AU2; P6: Perugia2011(C), (pre-LHC) DW
- Herwig++, HERWIG+Jimmy: angular ordered shower, cluster hadronisation, MPI model for underlying event

  tunes: H++: UE7-2, UE-EE-3; HERWIG+JIMMY: (ATLAS) AUET1,2
- **higher order** e.g. Powheg-Box (used in conjunction with above LO+PS MCs)
- **multileg generators** e.g. Alpgen, Sherpa, matched to parton showers (Sherpa has its own hadronisation and underlying event model with author tune)

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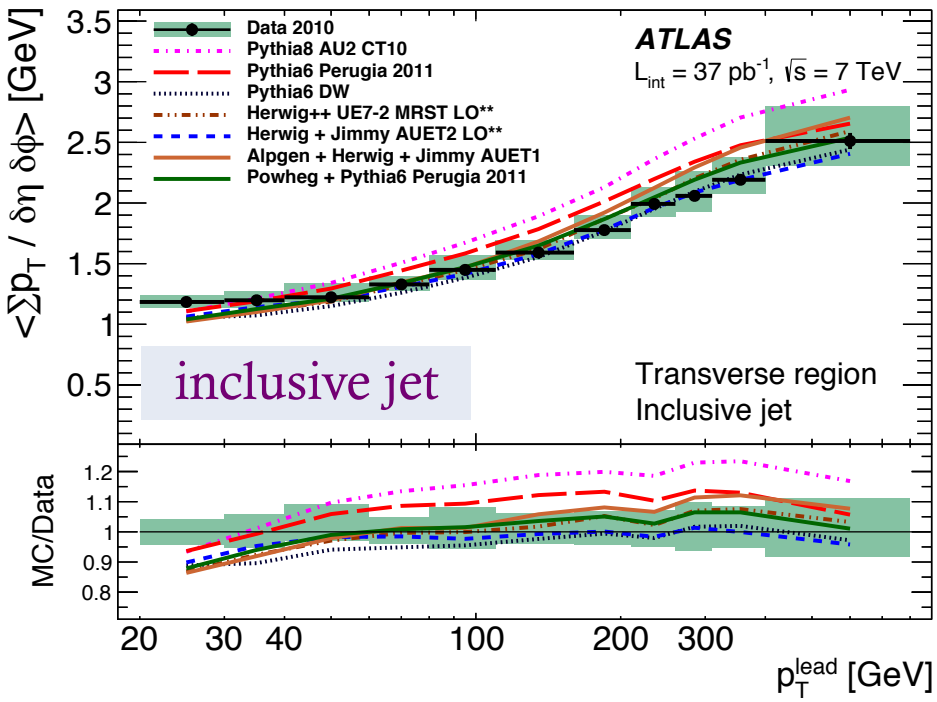
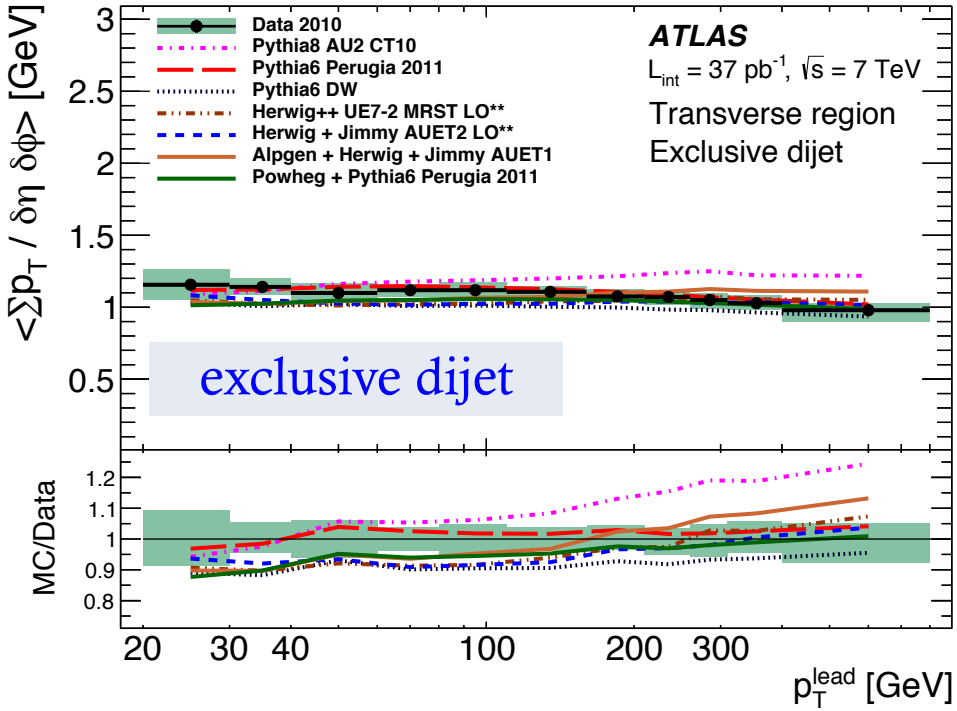
underlying event in jet events

ATLAS has measured in both **inclusive jet** and **exclusive dijet** event topologies





transverse region ΣPt density distributions

- rise for inclusive jet selection – significant contribution from pQCD
- exclusive almost flat – veto on additional activity, less sensitivity to pQCD effects

MC models generally better describe exclusive profile

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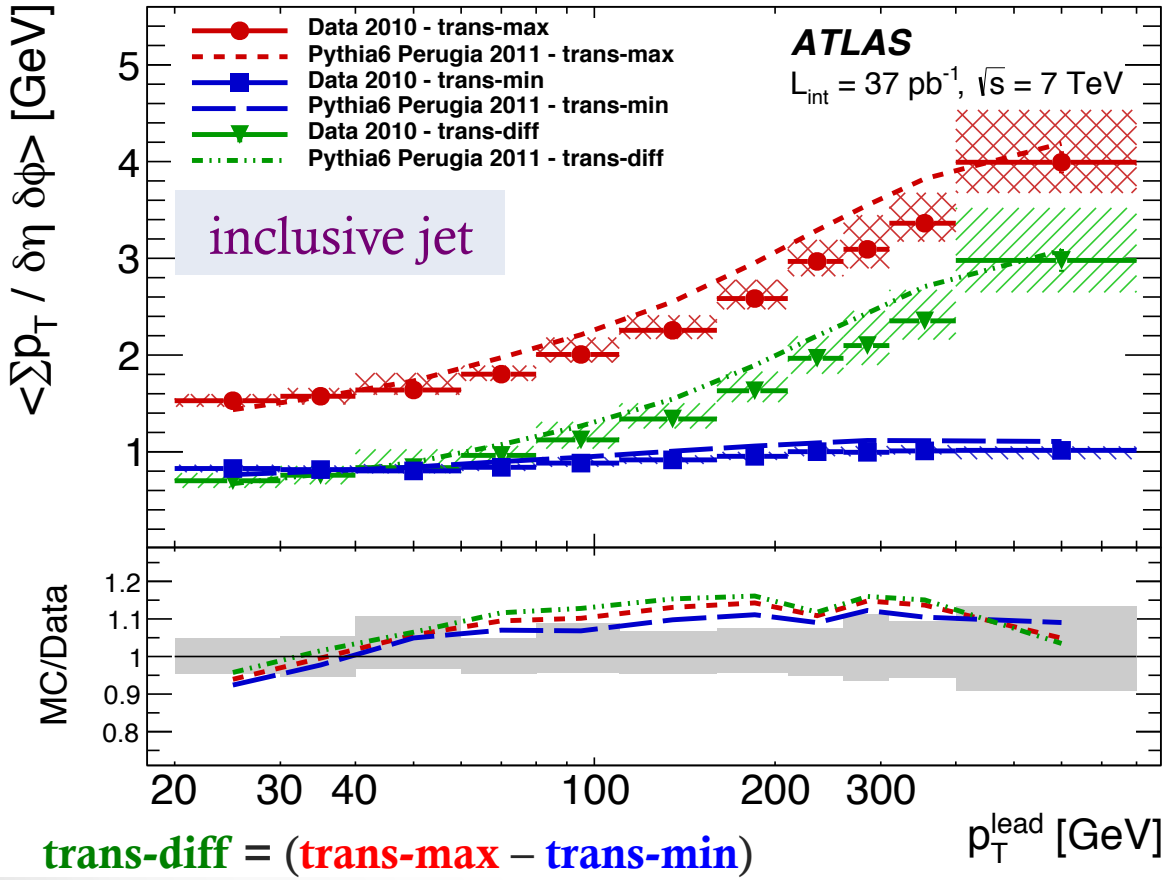
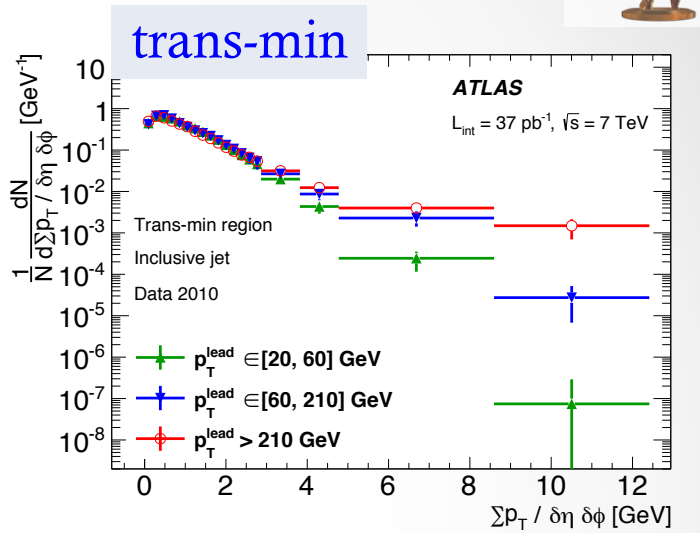
underlying event in jet events

transverse region distributions, inclusive jet



trans-diff = (trans-max – trans-min)



- inclusive, transverse region rise comes from **trans-max**
- **trans-min** flat:
  - underlying event activity independent of hard scale (for hard enough scales)
  - only in high ΣPt density tails, some sensitivity to perturbative component

(exclusive dijet selection flat or even slight downward trend in **all** trans- regions – see backups)

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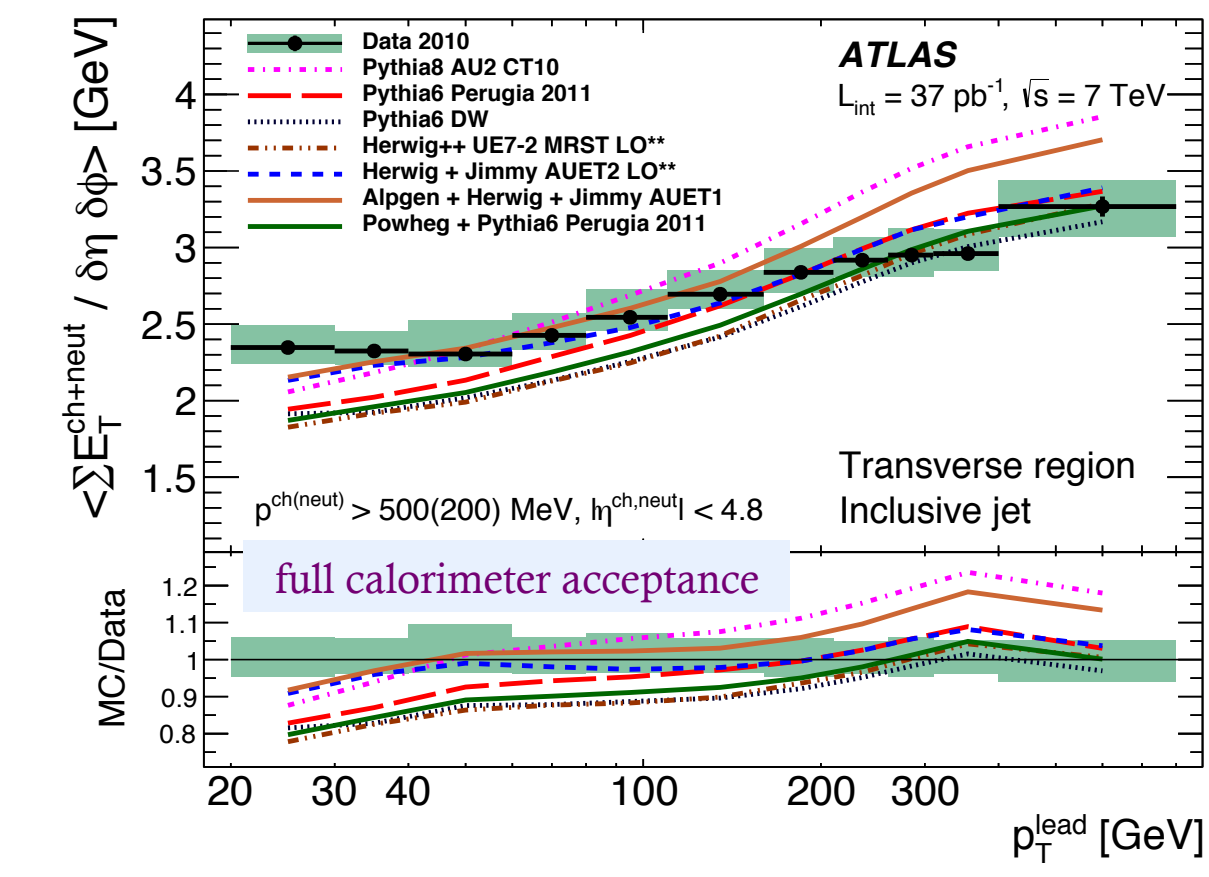
underlying event in jet events

transverse region charged and neutral particle ΣEt densities



- measured from calorimeter clusters; in same acceptance as charged particle ΣPt densities shown previously, and also in full ATLAS calorimeter acceptance
- generally worse description by MC models in full acceptance than for central rapidities

- note, MPI models to date, tuned to observables measured for central rapidities

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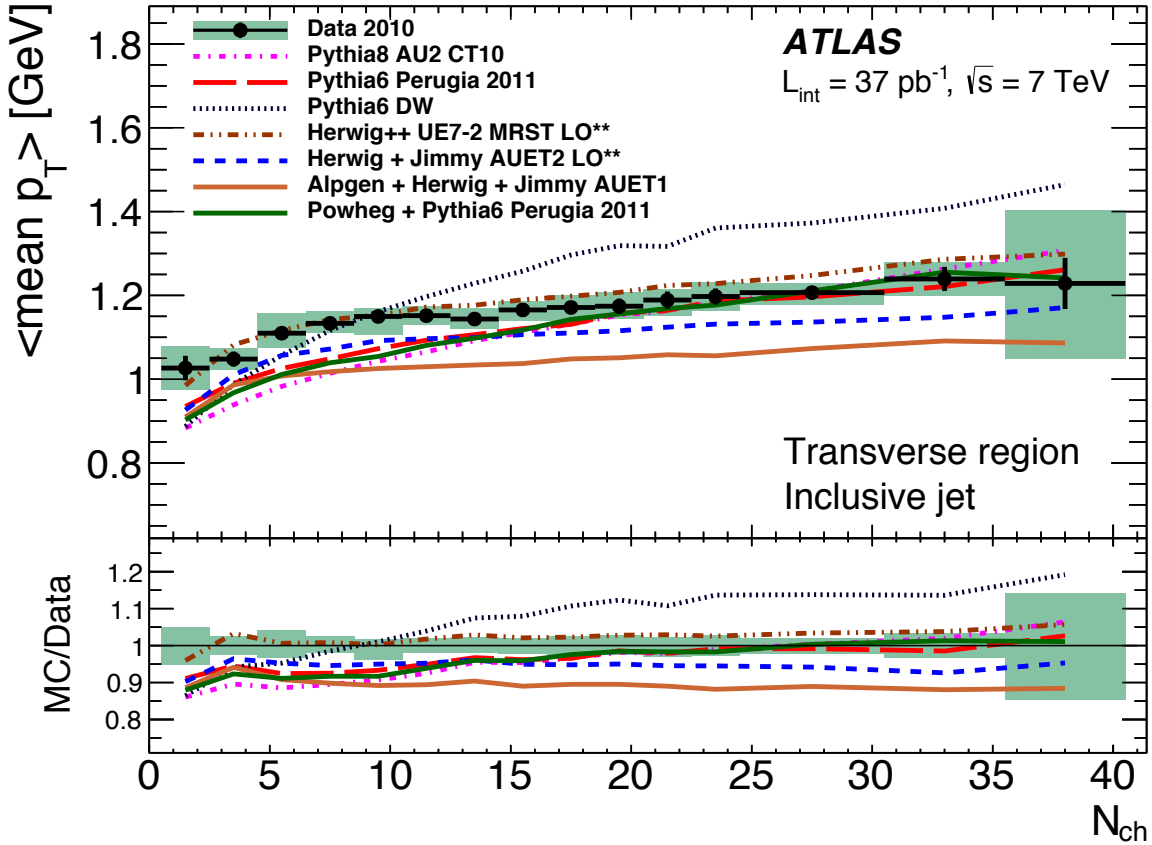
underlying event in jet events

transverse region mean Pt versus Nch



- distribution sensitive to colour reconnection
- **HERWIG+JIMMY** models (also including **ALPGEN**) undershoot not unexpected – no colour reconnection
- **Pythia6 DW** overshoots (old tune, no LHC data)
- inclusive jet shown; similar features seen in exclusive selection

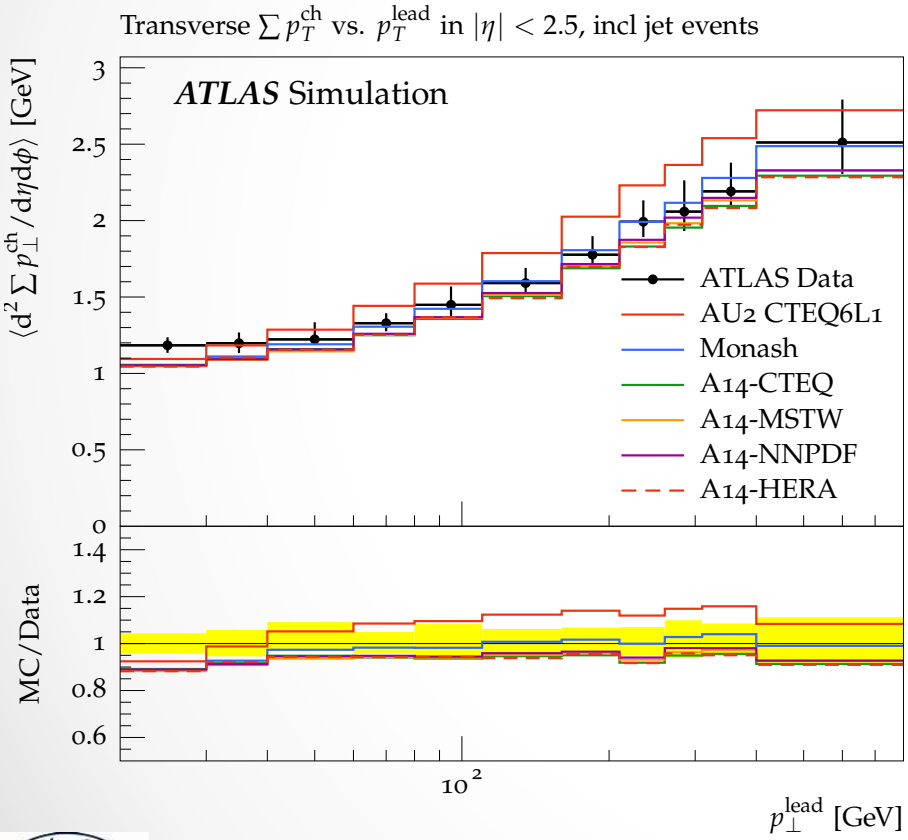
- deficiency at low Nch in modern **Pythia6** and **8** tunes not necessarily expected

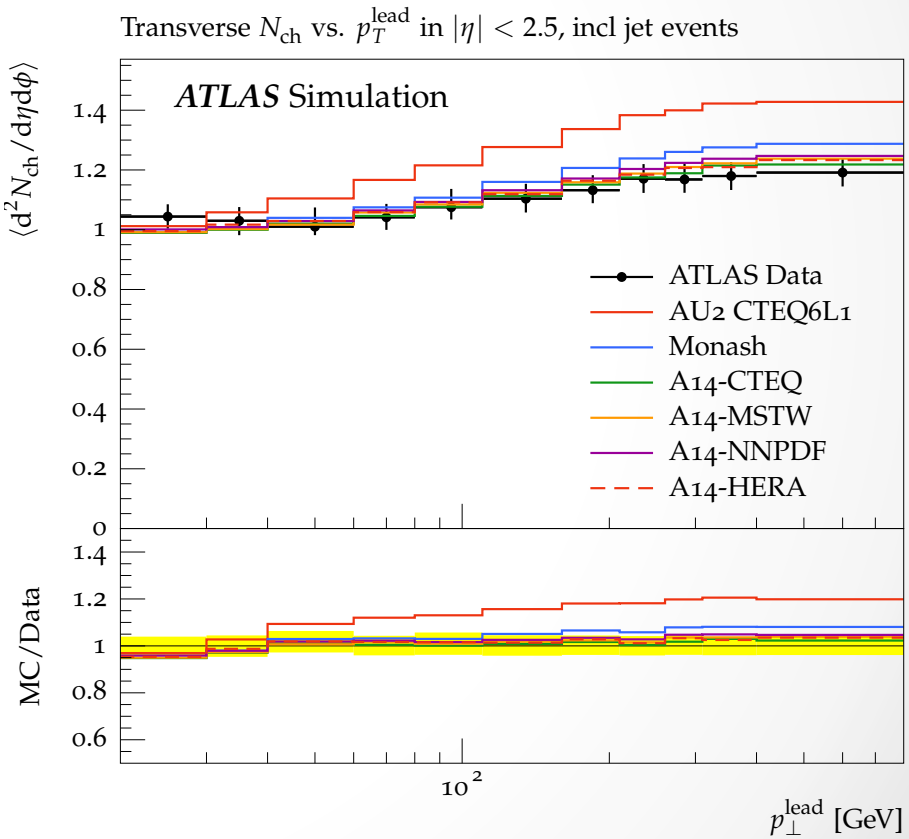
(equivalent observable from ATLAS charged particle underlying event analysis included in those tunes)

alternative MC Pythis8 tunes

- more modern Pythia8 tunes now available (for variety of PDFs)
- improved description of underlying event characteristics

(new ATLAS (A14) tune family includes these data, Monash (Pythia author tune) does not)





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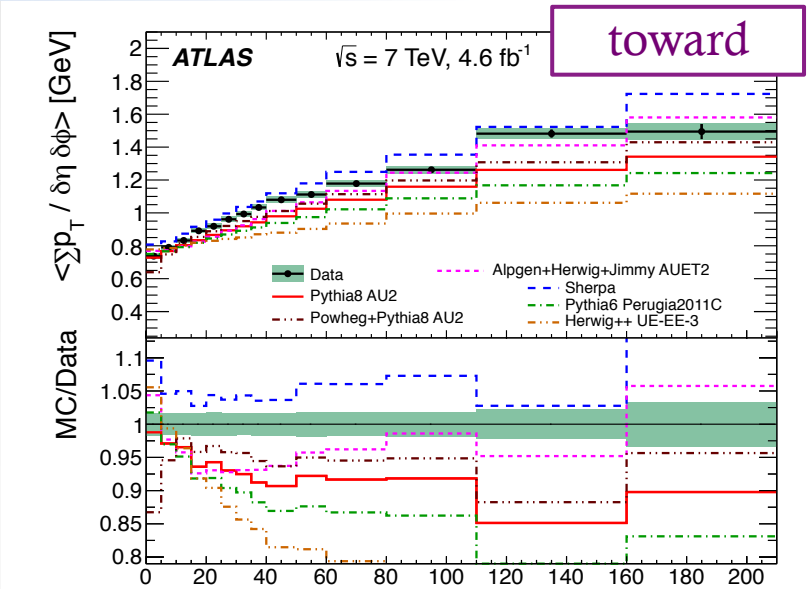
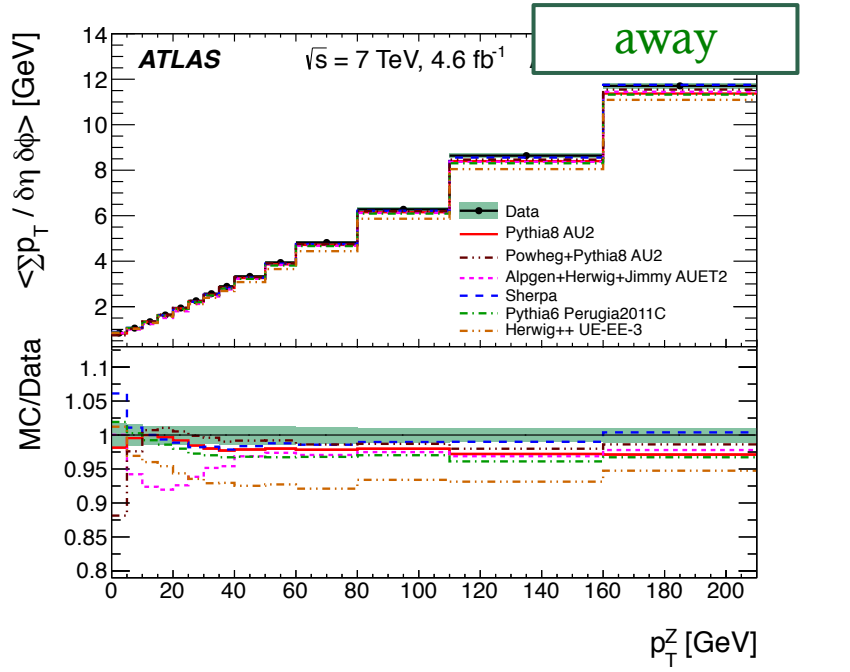
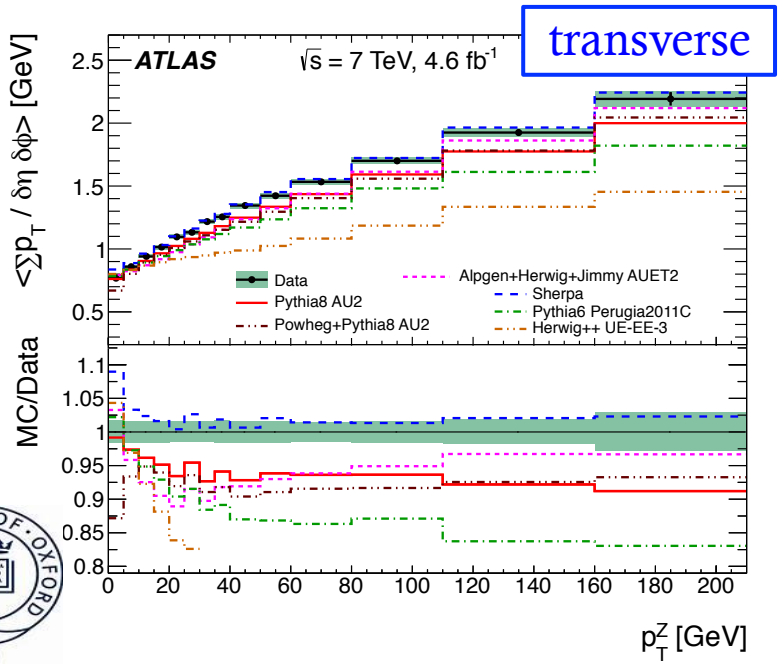
underlying event in Z events







- low-Pt region less sensitive to pQCD – useful for non-perturbative model tuning
- **away** region dominated by jets balancing Z-Pt
- **toward** and **transverse** most sensitive to underlying event – but also influenced by additional jets from hard scatter

note: distributions shown using Born leptons (before QED FSR); also available with dressed leptons

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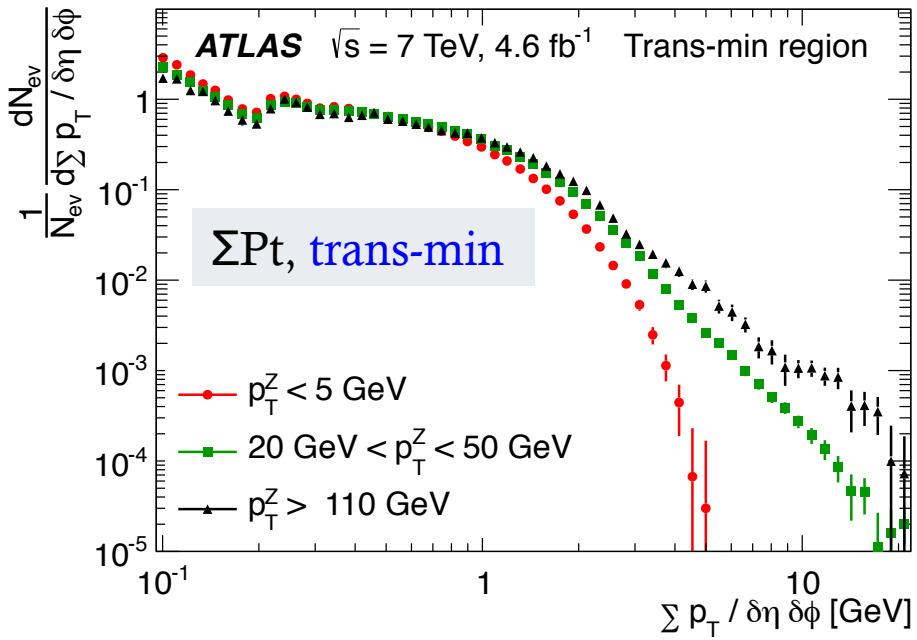
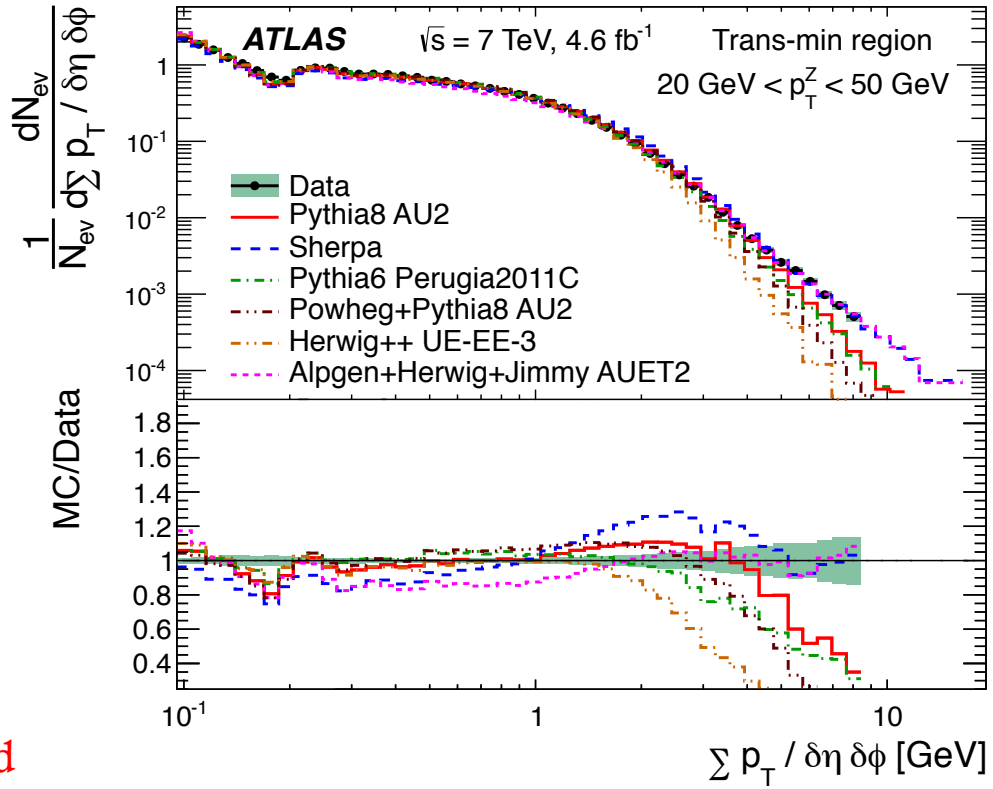
underlying event in Z events

trans-min ΣPt density distributions (in bins of Z-Pt)





- **trans-min** independent of Z-Pt until around 1 GeV – consistent with no hard scattering contribution, and underlying event activity independent of hard scale

… and tails described best by LO multileg MCs

- difference in tails suggests even **trans-min** not free from additional hard jets

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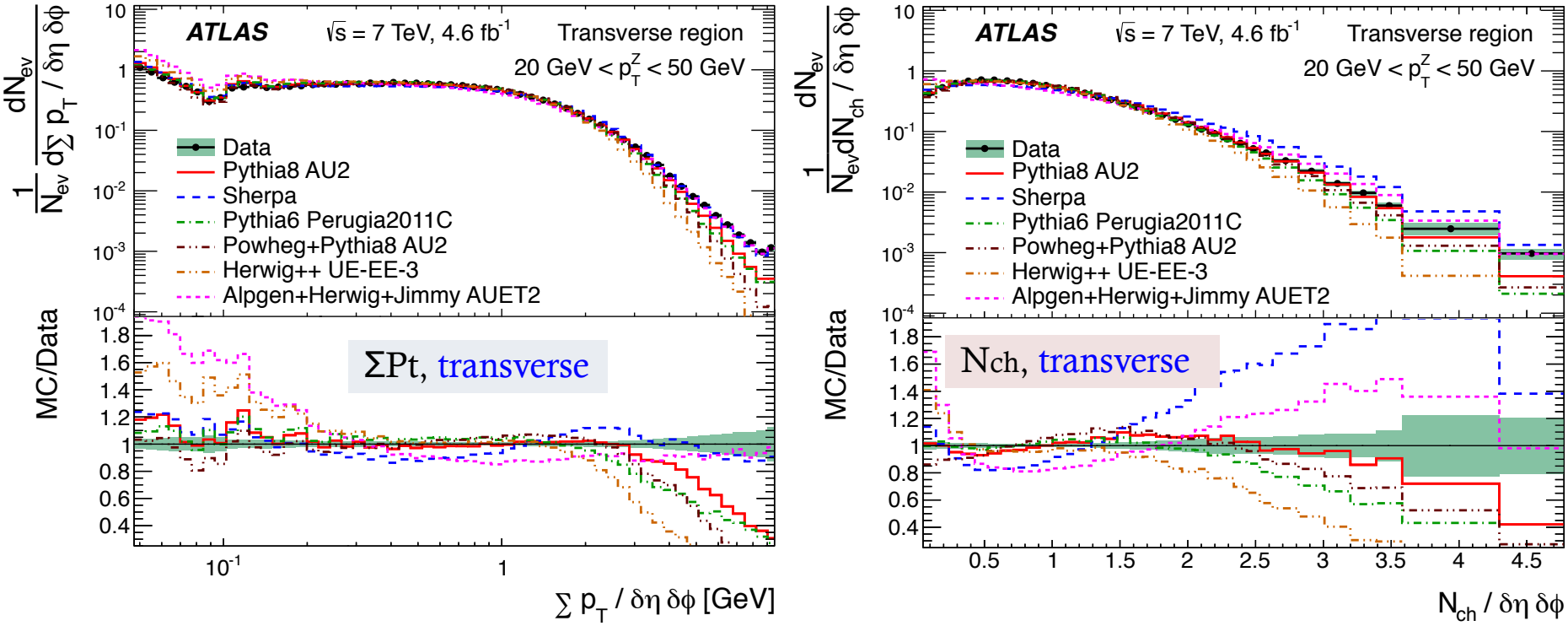
underlying event in Z events

MC model description of ΣPt and Nch density distributions



- very large spread in models, especially at low and high ΣPt and Nch densities
  - LO **multileg** MCs do best at high ΣPt density
  - only **Pythia8** tune gives reasonable description of Nch

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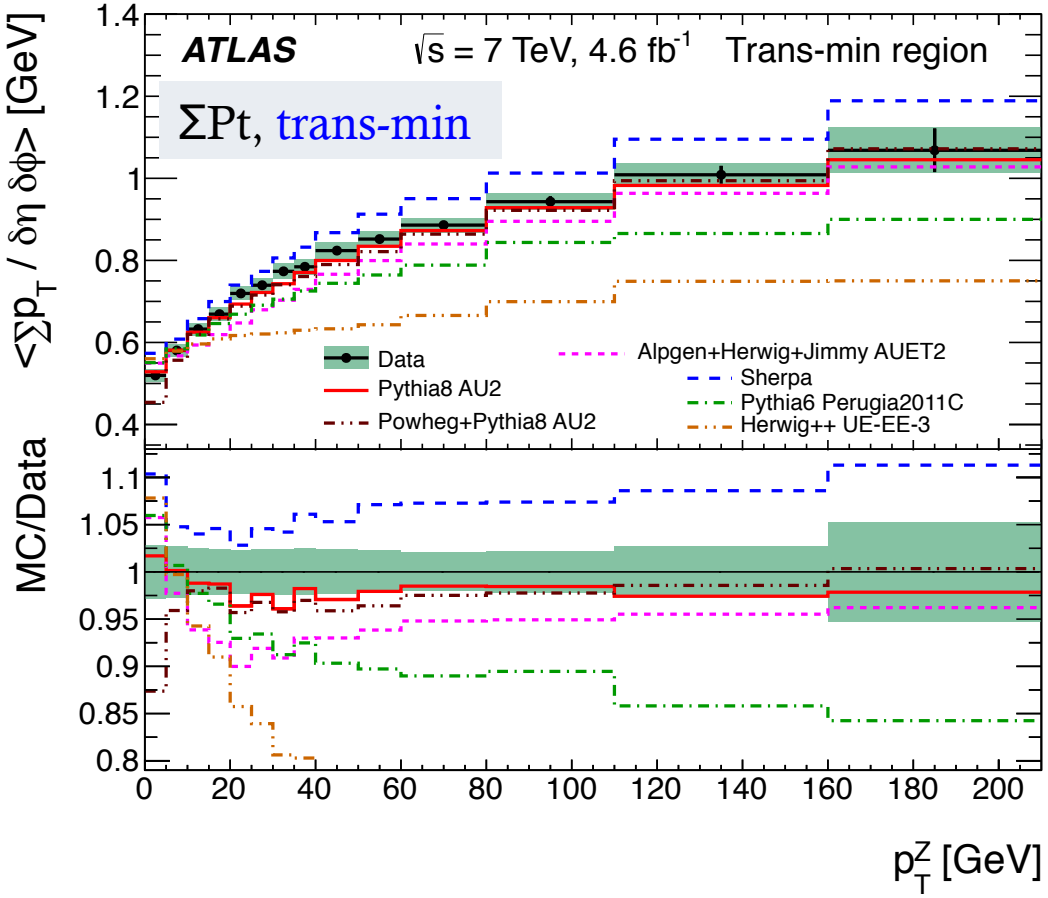
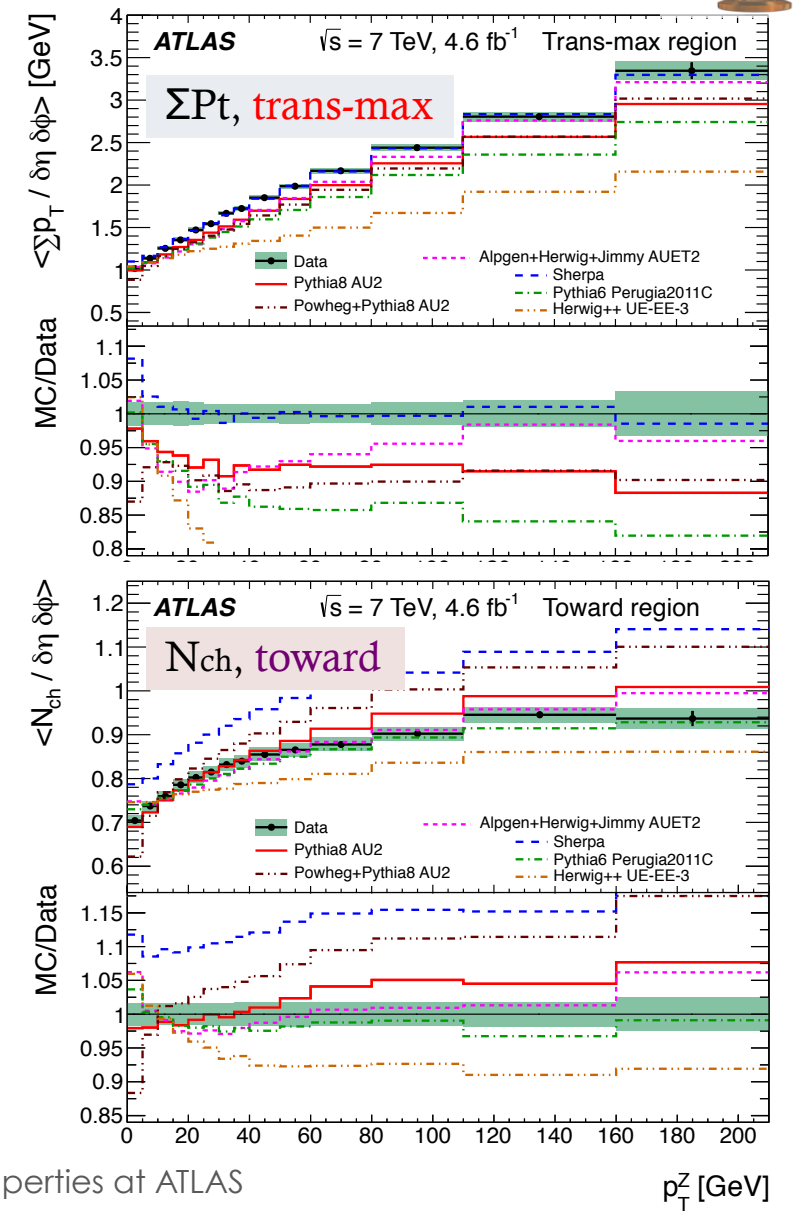
underlying event in Z events





- **ΣPt and Nch profiles** – no clear winner for all observables and regions simultaneously

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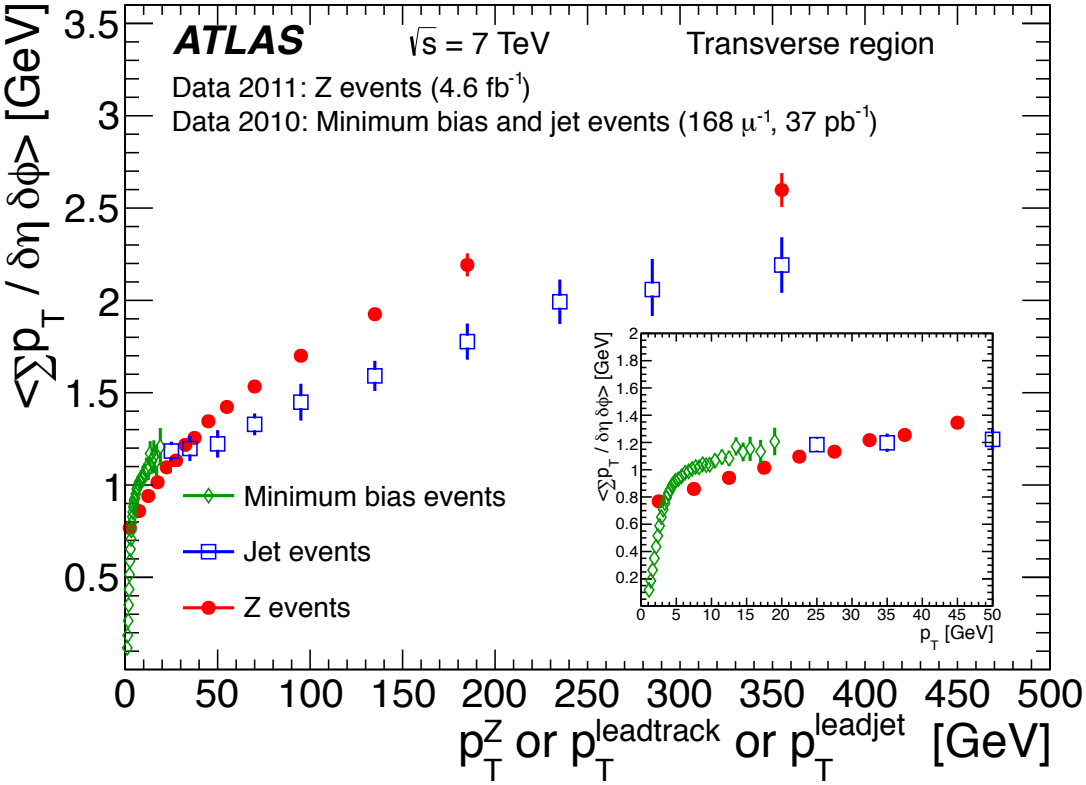
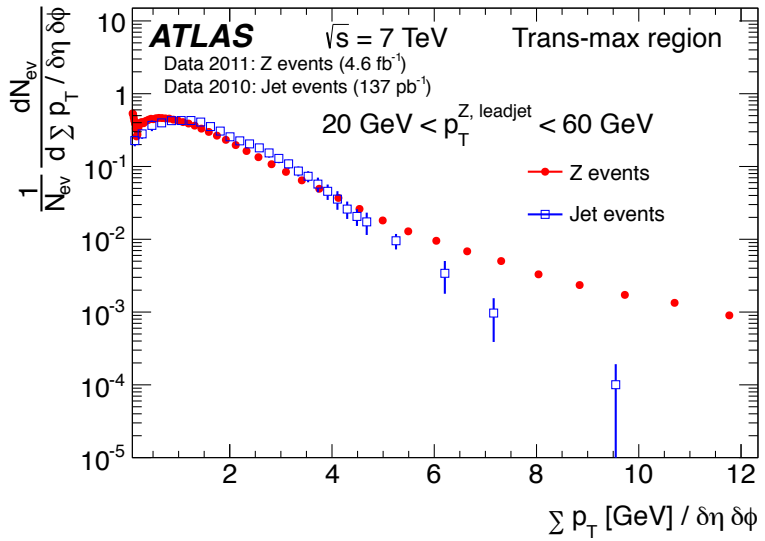
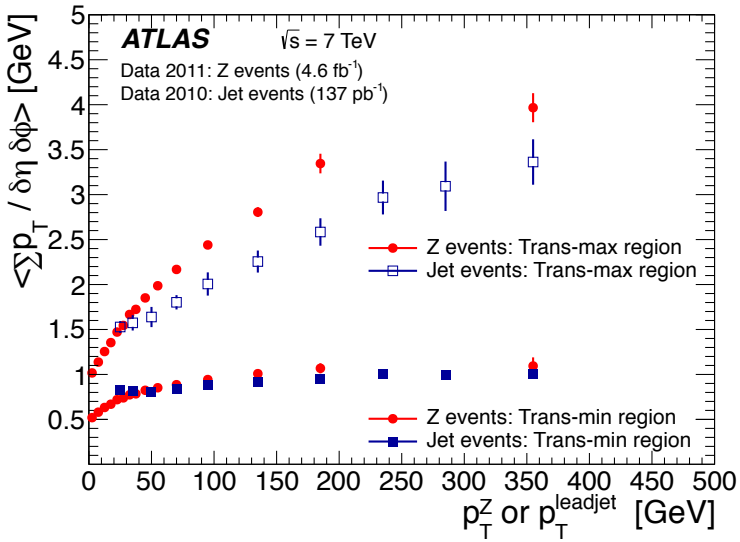
underlying event universality?







- smooth transition between leading charged particle and jet underlying event analyses
- differences in Z and jet analyses due to selection …

… **trans-min** is identical

Λ and $\overline{\Lambda}$ transverse polarisation

- **motivation:**
- contrary to expectation, **previous experiments** have found that Λ's (and other hyperons) produced in unpolarised pp and pA collisions have large (up to 30%) **transverse polarisation**
- at same time, $\overline{\Lambda}$ polarisation found to be consistent with zero at all experiments

- for Λ's, polarisation dependent on kinematic variables:
- **increases with increasing Λ Pt** (up to 1 GeV saturation)
- **decreases as Feynman $|x_F|$ approaches zero**
- no strong dependence on centre-of-mass energy observed

- **no current model adequately describes all observations**

- measurements in **new kinematic regions** could provide additional insight into mechanism responsible

- ATLAS extends kinematic reach of past experiments to higher Λ Pt and lower x_F

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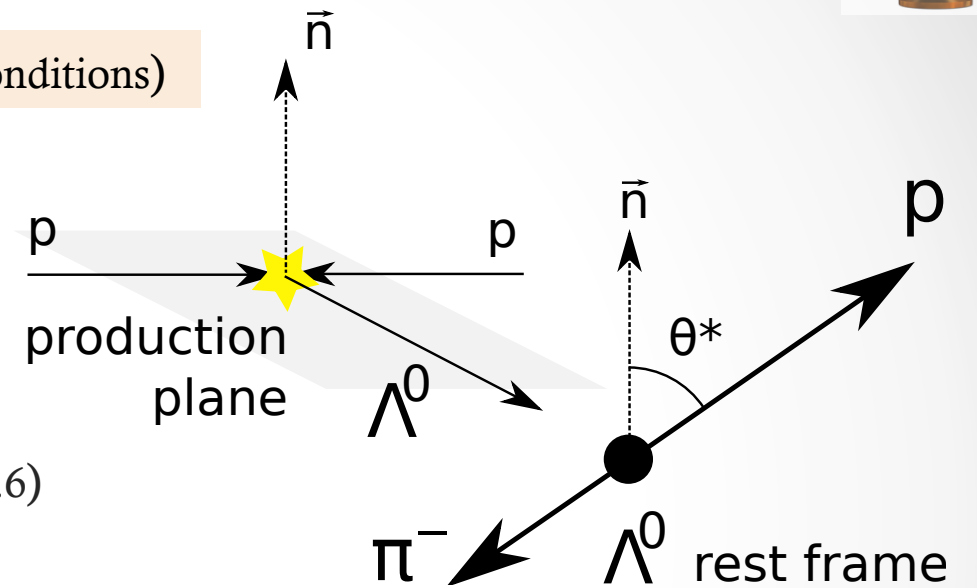
Λ and $\bar{\Lambda}$ transverse polarisation

ATLAS 2010 data, 710 μb-1 (low pileup conditions)



- $\Lambda \rightarrow p\pi-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi+$ decays
- fiducial phase space:
  - $0.8 < pt < 15$ GeV
  - $5\times10^{-5} < x_F < 0.01$ (previous exps: 0.01–0.6)
  - $|\eta| < 2.5$
- angular distribution given by:

$$g(\cos\theta^*) = \tfrac{1}{2}\,(1 + \alpha P \cos\theta^*)$$

where α=0.642±0.013 is world average value of parity violating decay asymmetry for the Λ

- polarisation measured in direction **normal** to production plane

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

- **only transverse component can be non-zero**
- as function of **pt** and **xF** = pz/pbeam

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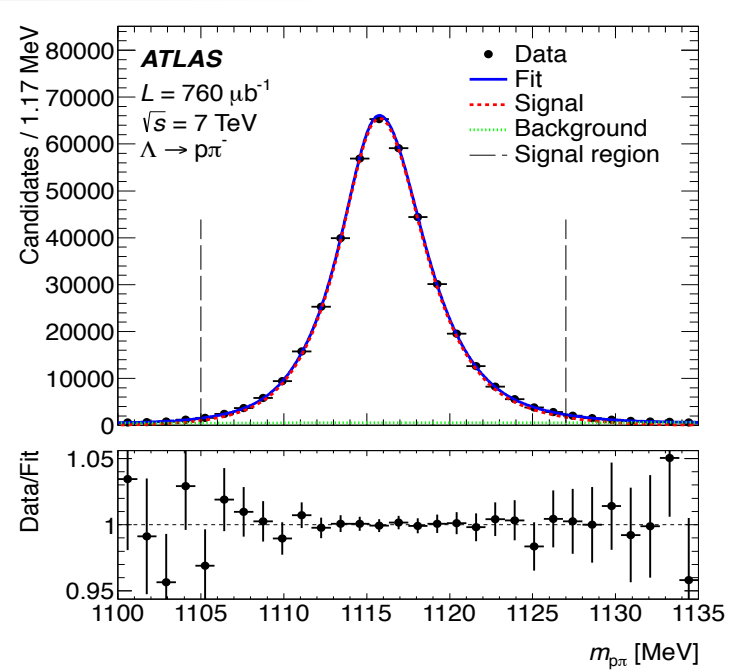
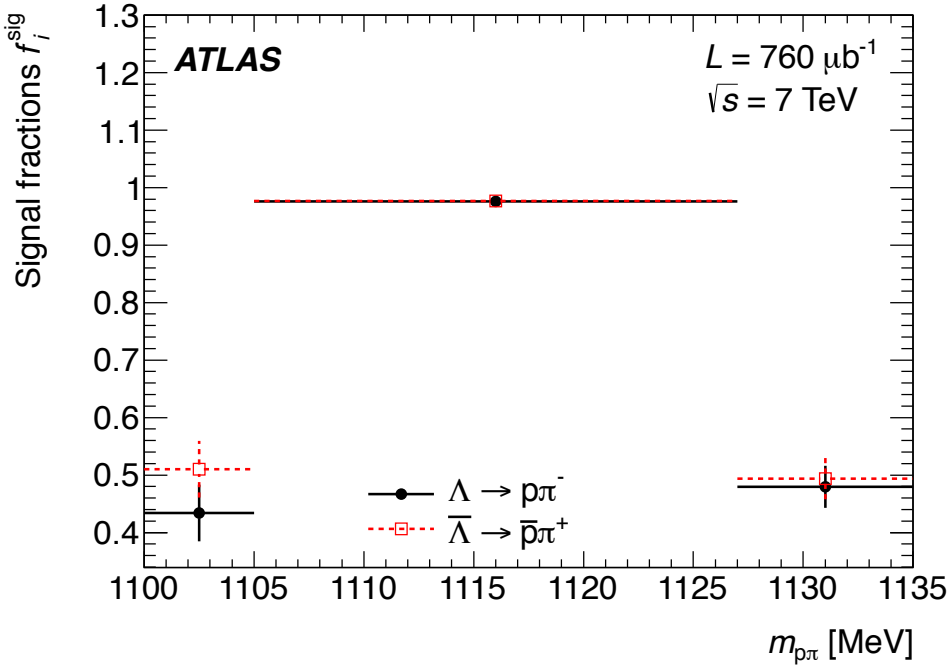
Λ and $\bar{\Lambda}$ transverse polarisation

signal extraction:

- apply selection criteria to reduce combinatorial and physics (Ks→ππ, γ→ee) backgrounds
- search for long-lived, two-prong decays and construct invariant mass distribution





- divide invariant mass range into **signal region** and **sidebands**
- multi-parameter fit to extract the fraction of signal events f_i^{sig}

perform separately in the 3 mass regions i=1,2,3 i.e. signal and two sidebands

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Λ and $\bar{\Lambda}$ transverse polarisation

polarisation extraction:

- reconstructed decay angle distribution: $g_{\rm det}(t';P) \propto \frac{1}{2}\int_{-1}^{1} dt\ [(1+\alpha P t)\ \varepsilon(t)]\ R(t',t)$

  t, t' are the true and reconstructed values of cosθ*

  ε(t) is the reconstruction efficiency

  R(t',t) is the resolution function

- **method of moments:**
- exploit fact that first moment (**expectation value**) of angular distribution can be written as a **linear combination** of first moments of angular distributions with P=0 and P=1

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

E(0), E(1) estimated using MC simulation with P set to 0 and 1

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Λ and $\bar{\Lambda}$ transverse polarisation

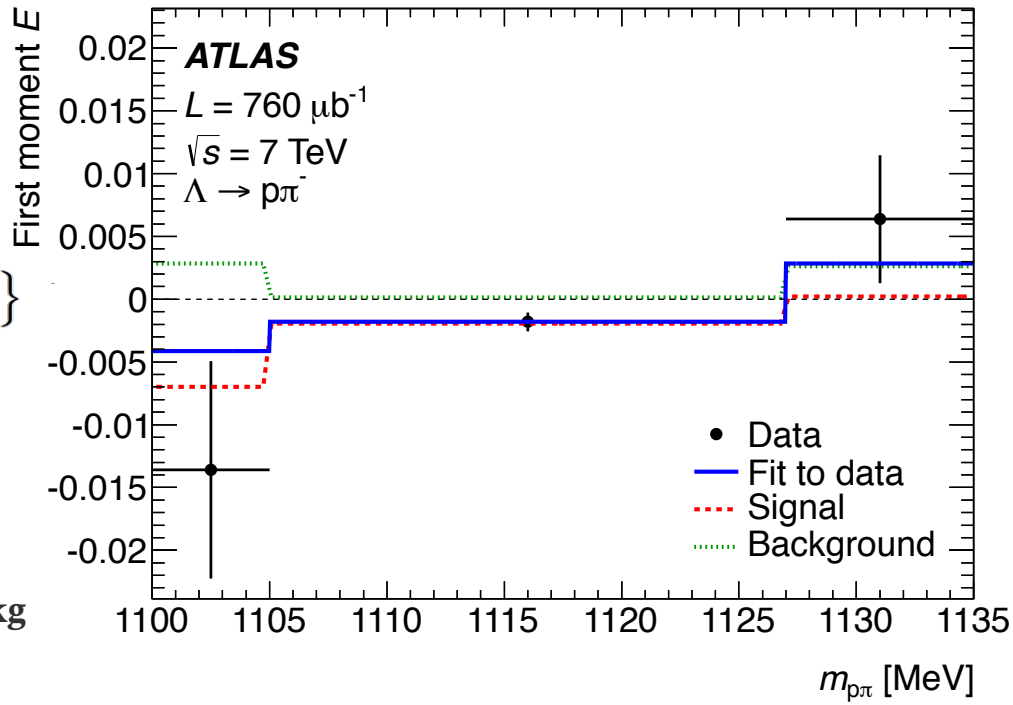
background contribution

- to correct for background, first moment calculated separately in signal and sidebands
- first moment of angular distribution of background, E_{bkg}, assumed independent of $m_{p\pi}$ – verified with MC

expect first moment in each of the three mass regions:

$$E_i^{\rm exp}(P, E_{\rm bkg}) = f_i^{\rm sig}\{E_i^{\rm MC}(0) + [E_i^{\rm MC}(1) - E_i^{\rm MC}(0)]P\} + (1 - f_i^{\rm sig})E_{\rm bkg},$$

- $E_i^{\rm MC}(0)$, $E_i^{\rm MC}(1)$ known from MC
- signal fraction from fit to $m_{p\pi}$



- simultaneous extraction of **P** and **E_{bkg}** in least squares fit:

$$\chi^2(P, E_{\rm bkg}) = \sum_{i=1}^{3} \frac{[E_i - E_i^{\rm exp}(P, E_{\rm bkg})]^2}{\sigma_{E_i}^2}$$

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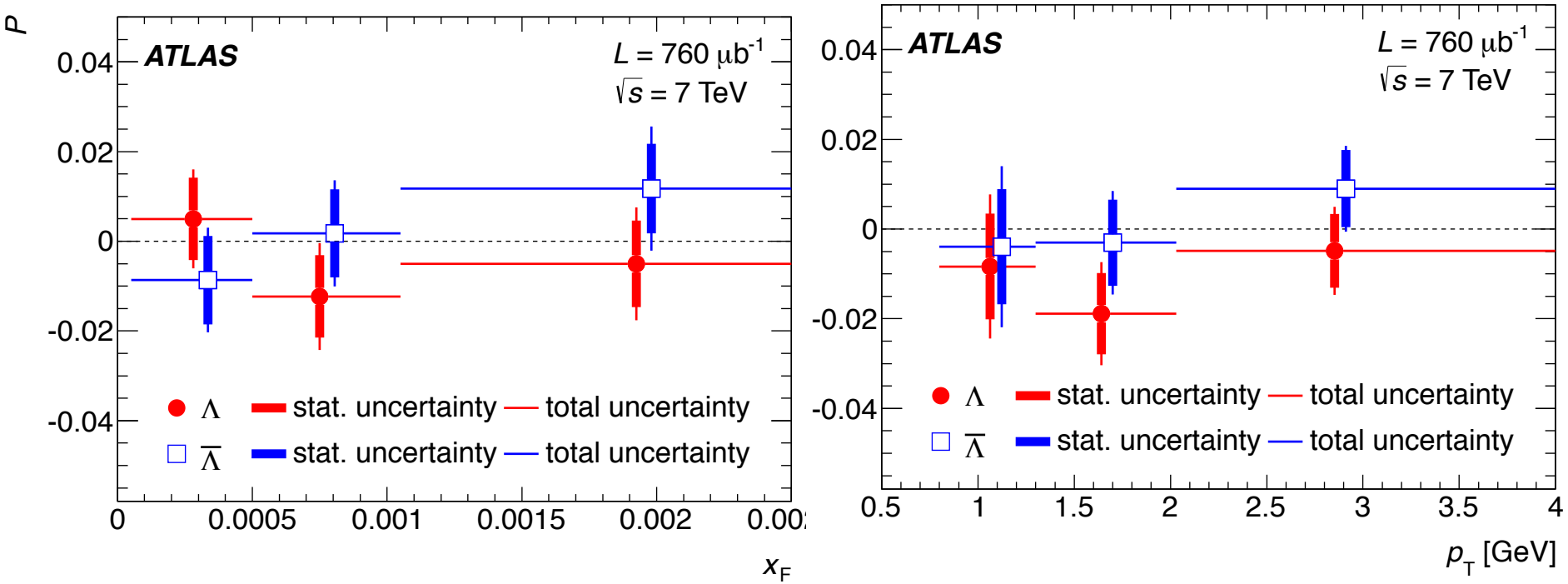
Λ and $\bar{\Lambda}$ transverse polarisation



- polarisation in bins of xF and pt: <2% and consistent with zero in all bins
  – no significant dependence on xF or pt observed
- polarisation in full fuducial phase space consistent with zero:

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

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

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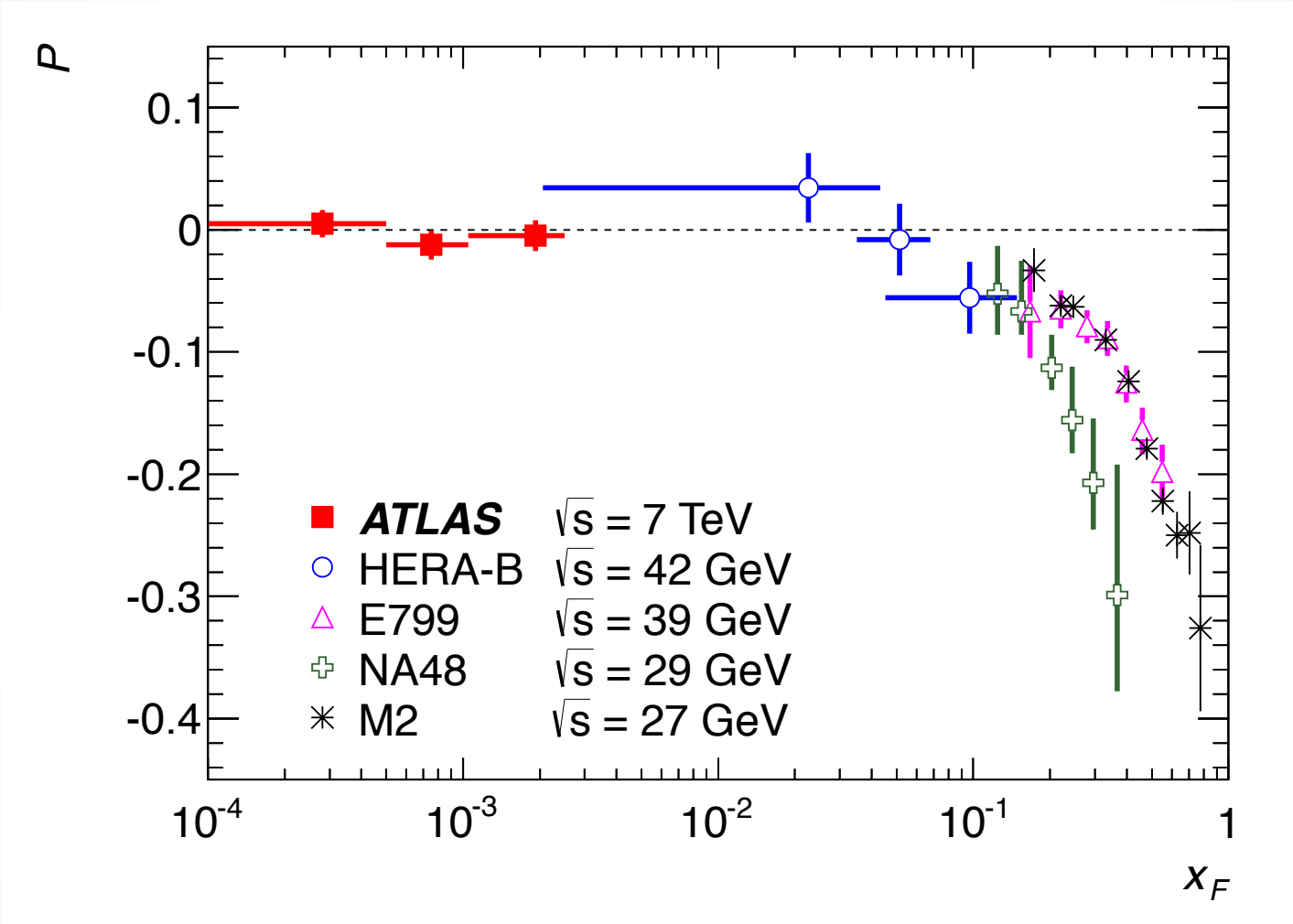
Λ and $\bar{\Lambda}$ transverse polarisation



- ATLAS results **consistent with extrapolation of fit** from previous measurements

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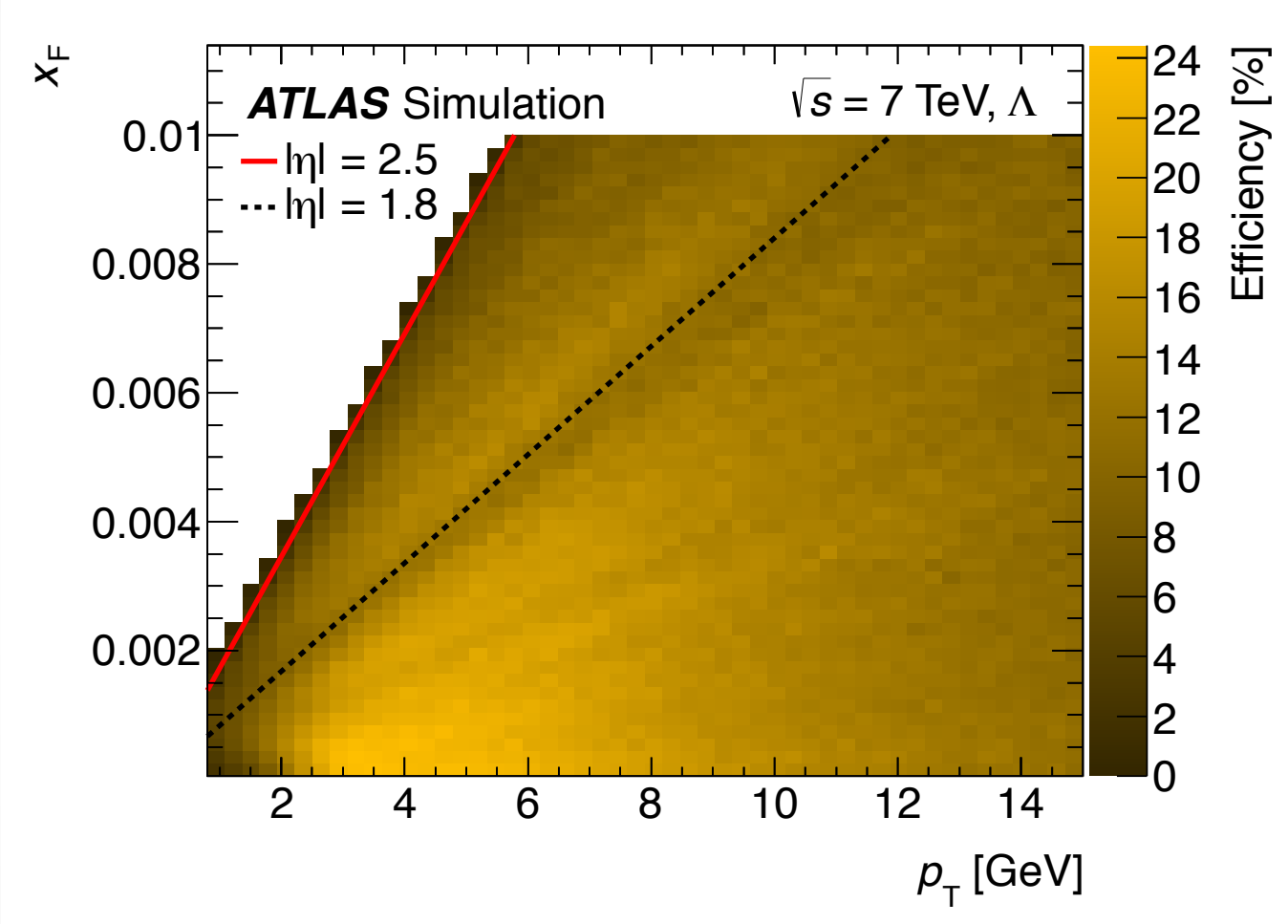
Λ and $\bar{\Lambda}$ transverse polarisation



- reconstruction efficiencies are provided as function of pt and xF in HEPDATA, to allow model builder to weight their Λ baryons for comparison with ATLAS data

summary

- ATLAS continue to publish measurements on observables sensitive to non-perturbative pp modelling effects

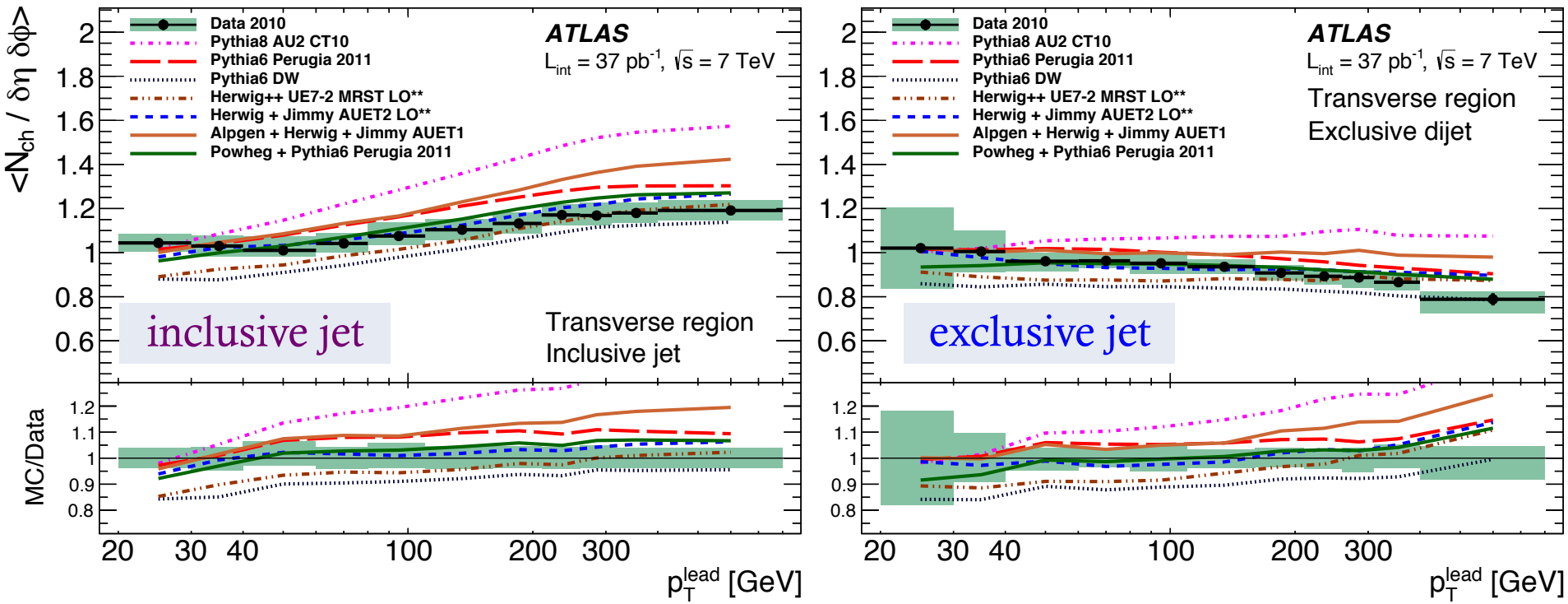
- new measurements of underlying event observables in jet and Z bosons
  - large variety of multiplicity and momentum/energy distributions measured
  - underlying event shown to be sensitive to details of modelling
  - measurement can be used to further improve description
  - ATLAS run II measurements can provide further tests of $\sqrt{s}$ dependence

- new measurements of Λ and $\overline{\Lambda}$ hyperon transverse polarisation
  - ATLAS measurement consistent with Λ polarisation of zero – in agreement with expectation from extrapolated fits to past data
  - $\overline{\Lambda}$ also observed to be zero, consistent with other experiments

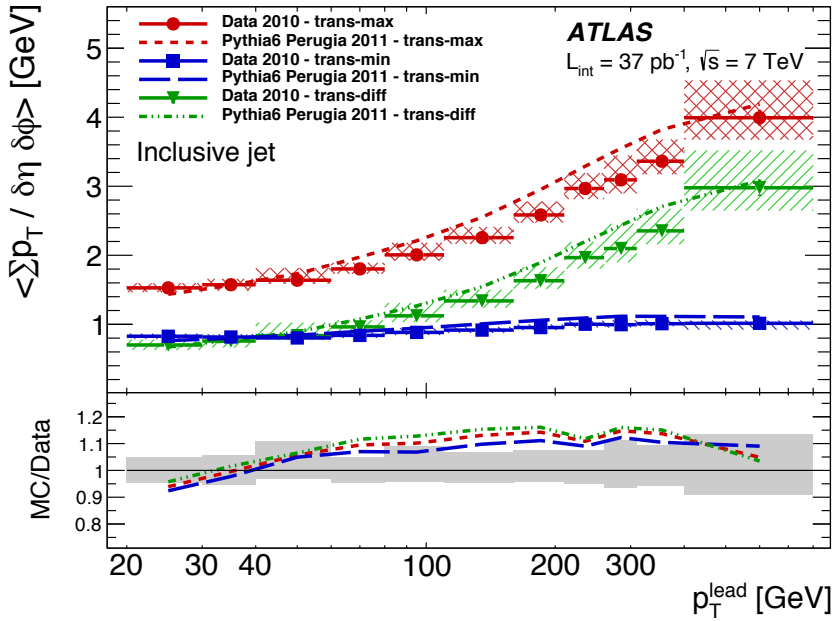
backups

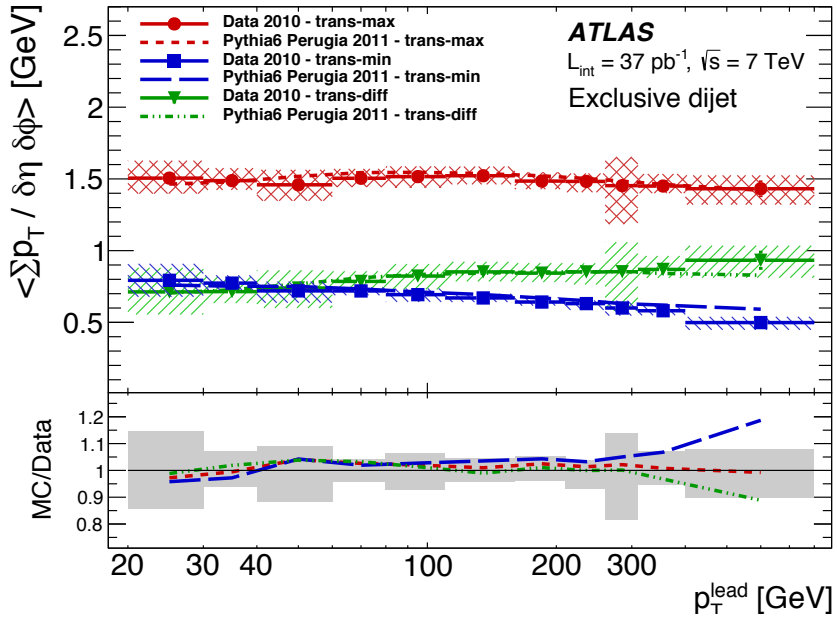
underlying event in jet events

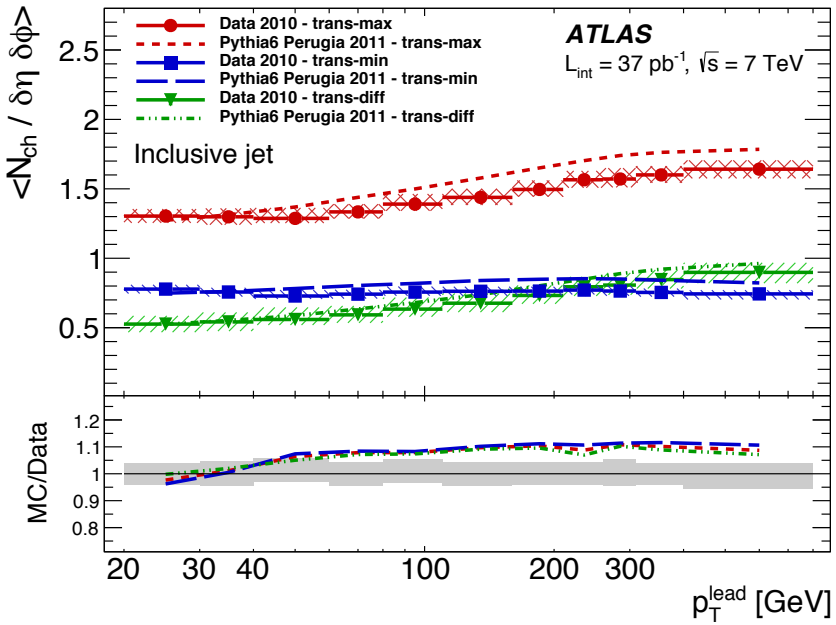
Nch density profiles

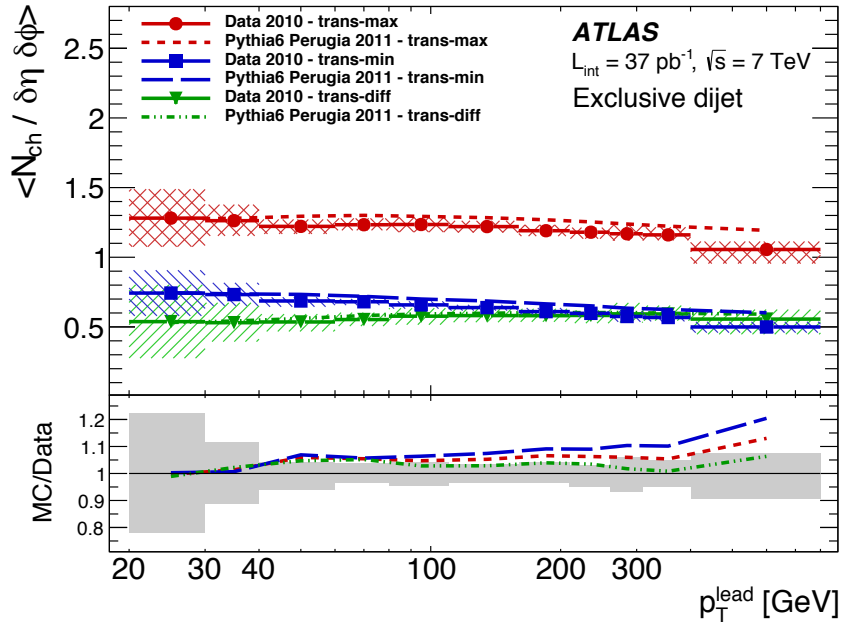


underlying event in jet events

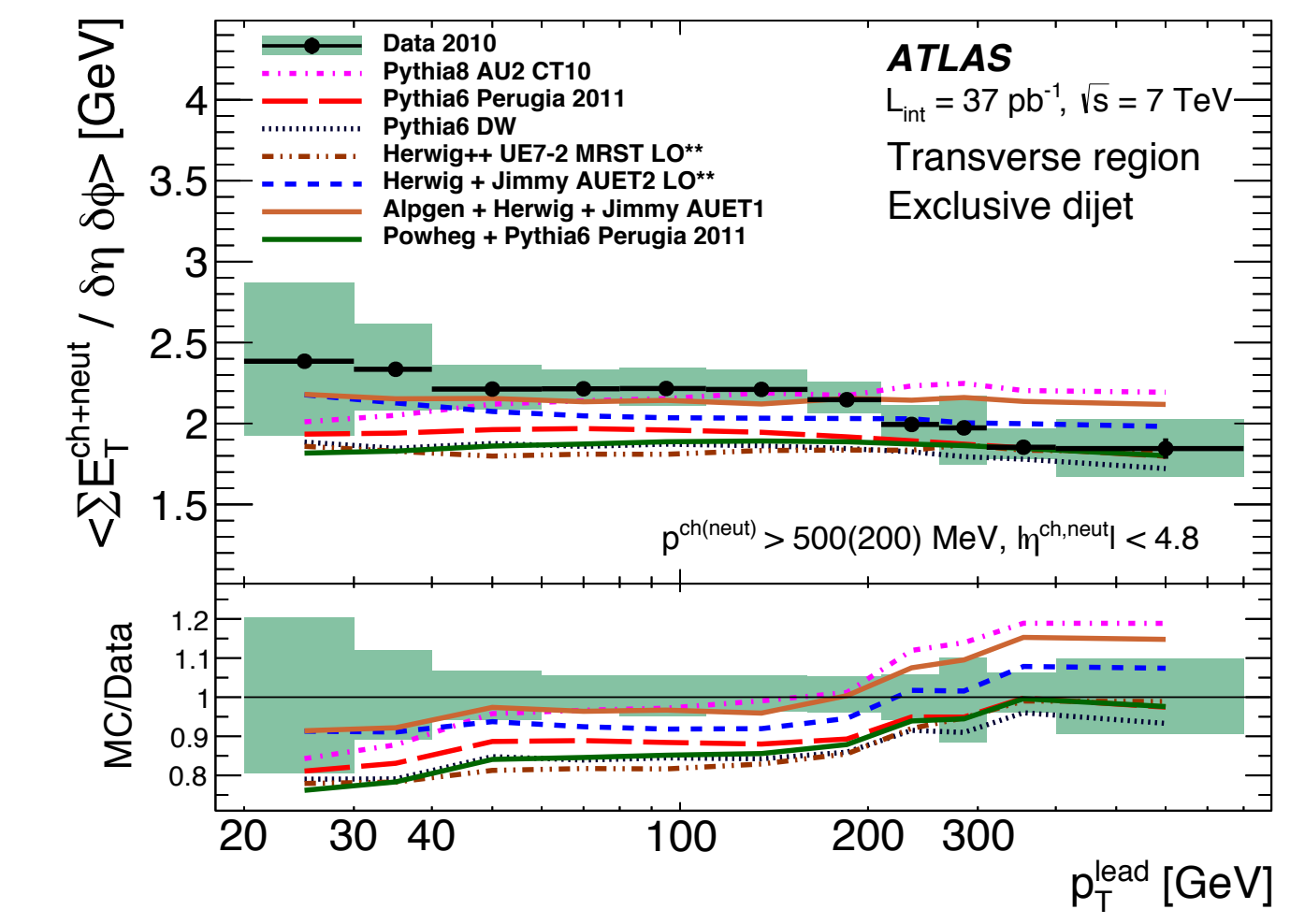




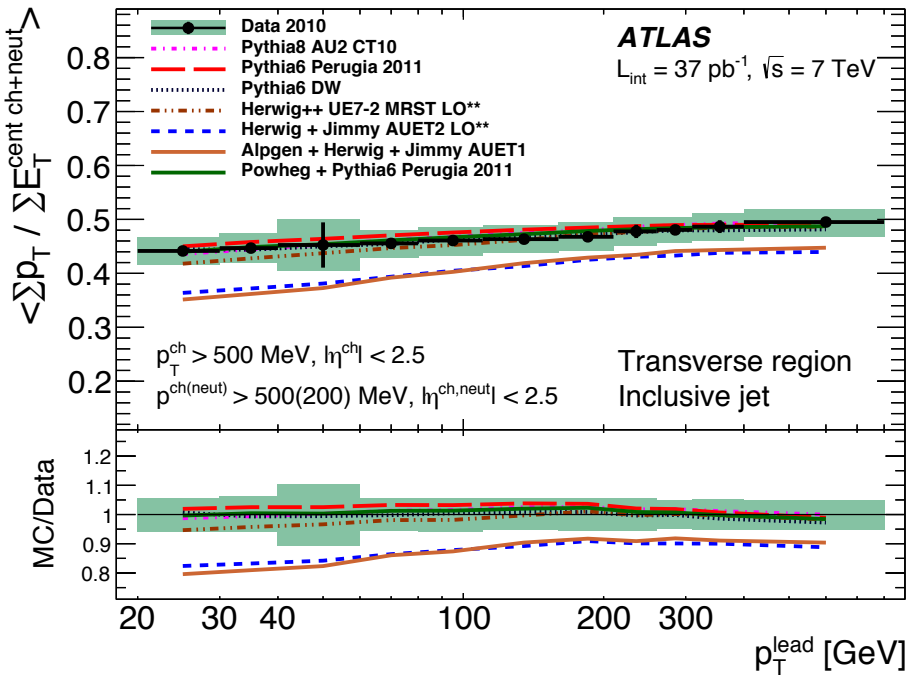


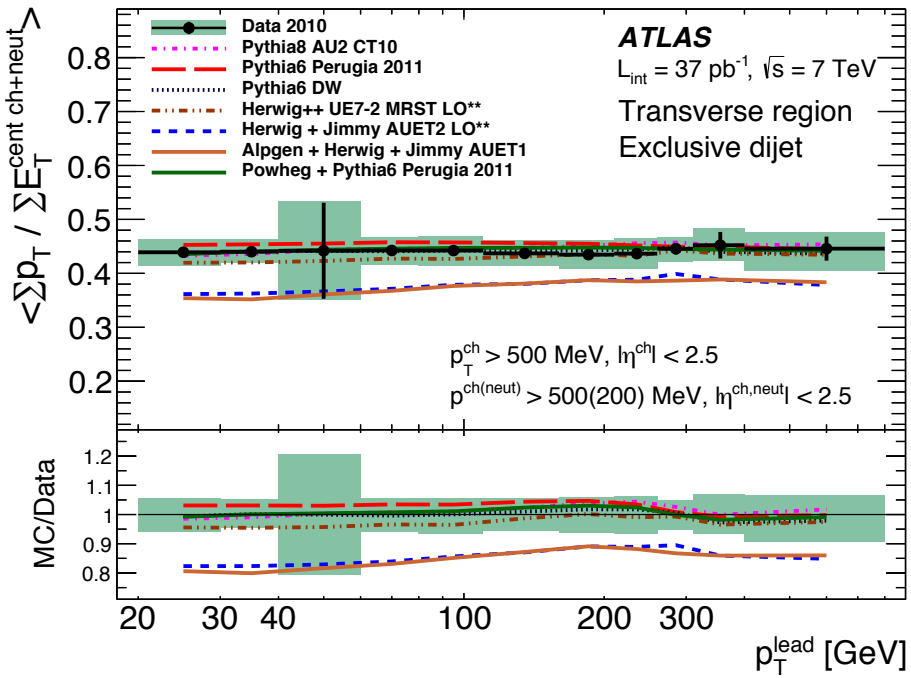


underlying event in jet events

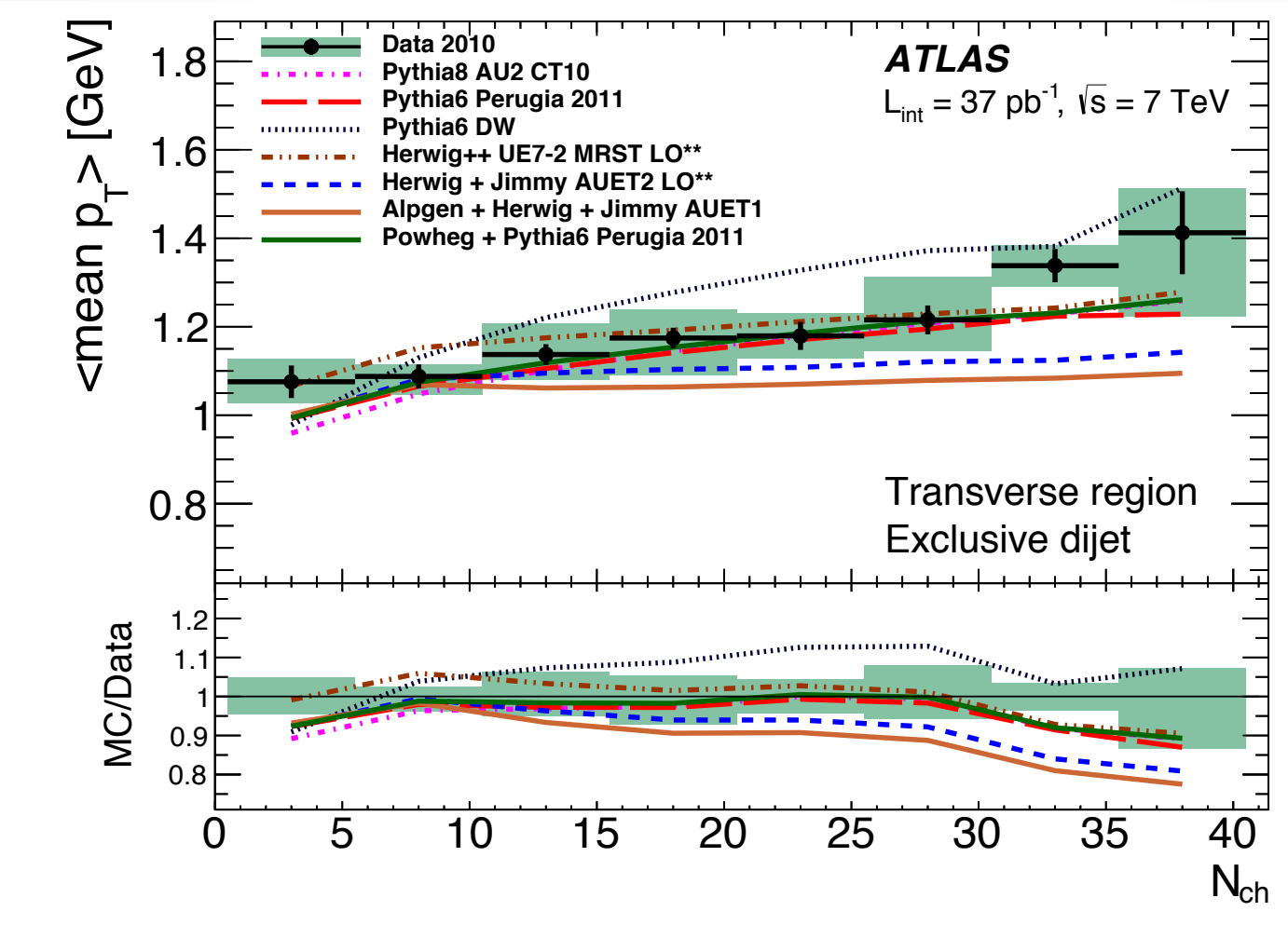


underlying event in jet events

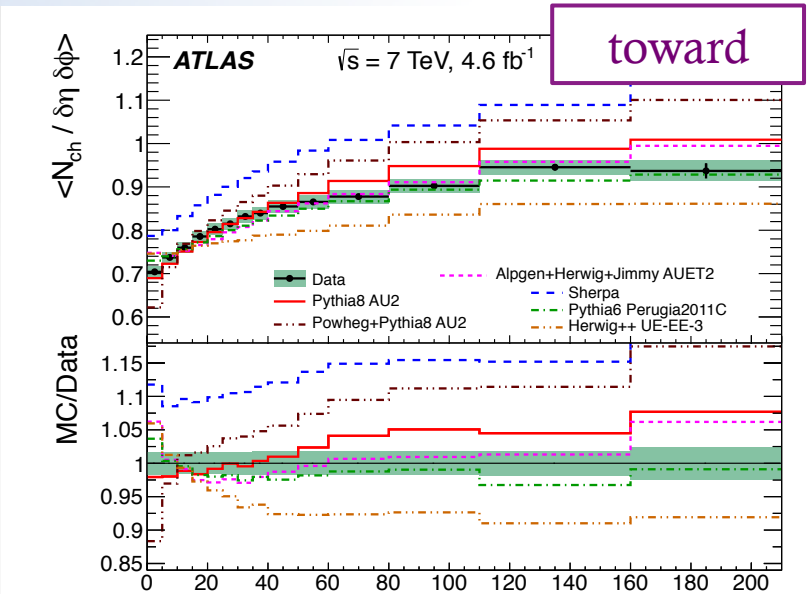


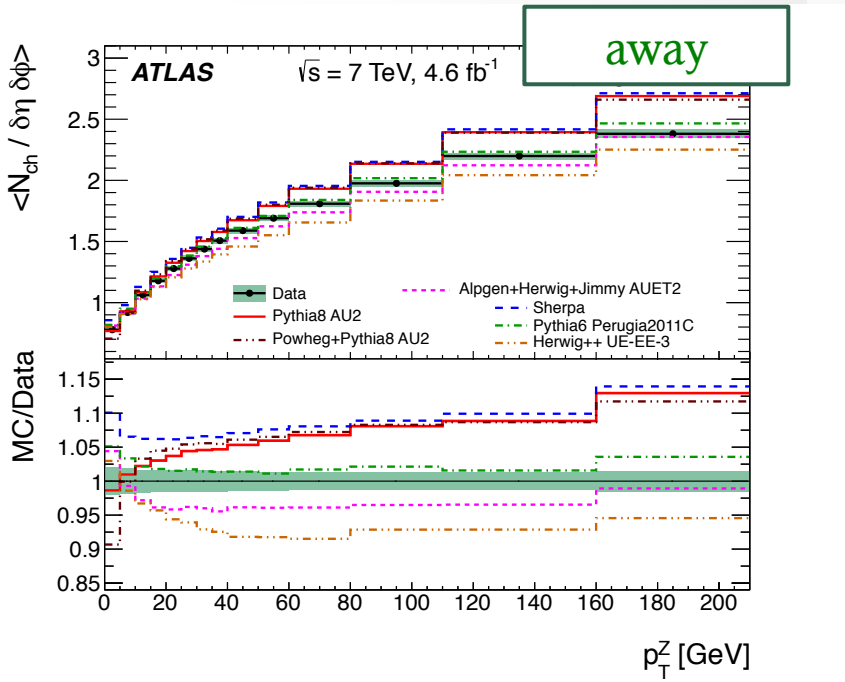


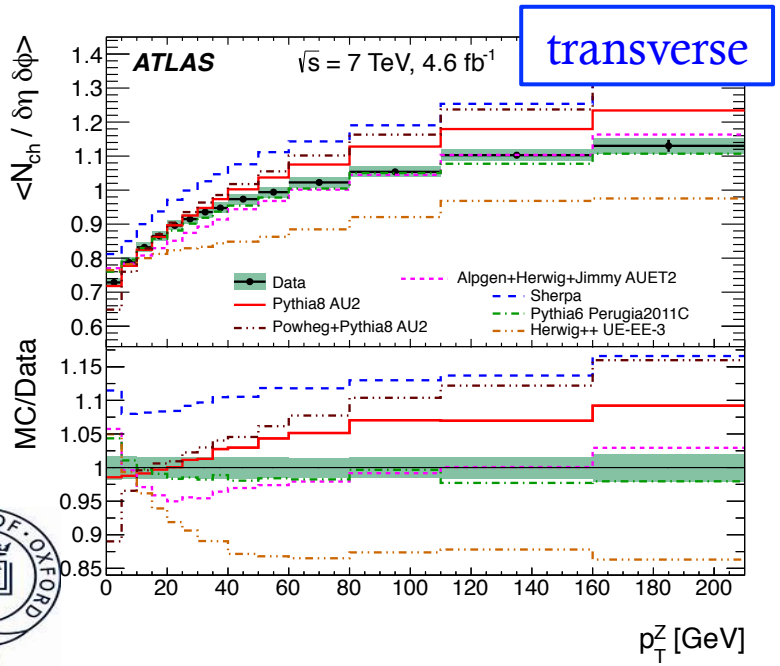
underlying event in jet events



underlying event in Z events







Nch profiles

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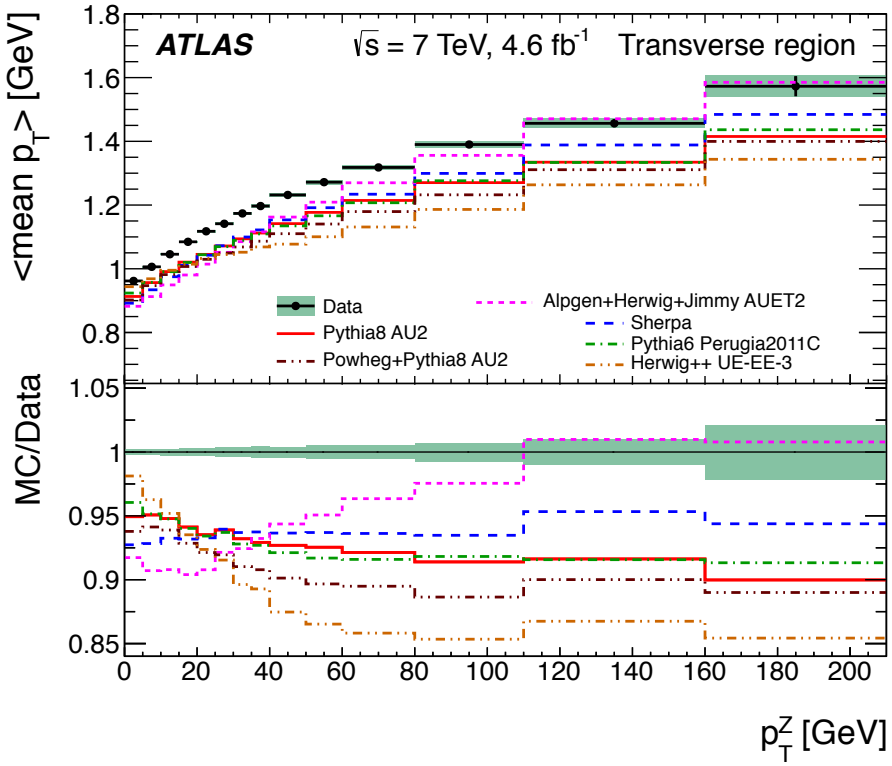
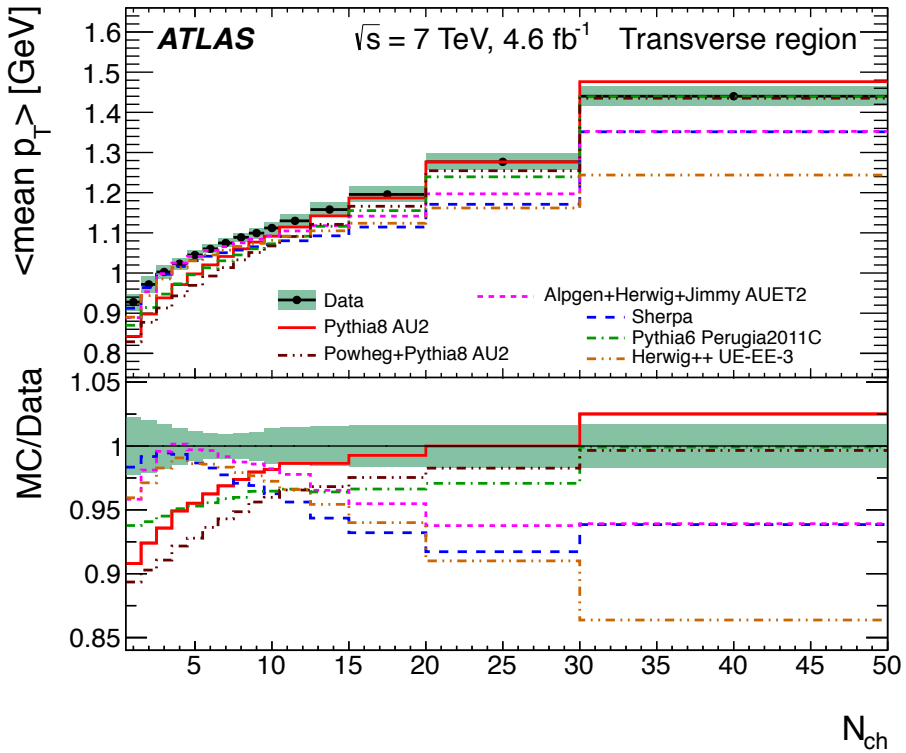
underlying event in Z events





- **mean Pt versus Z-Pt and Nch**

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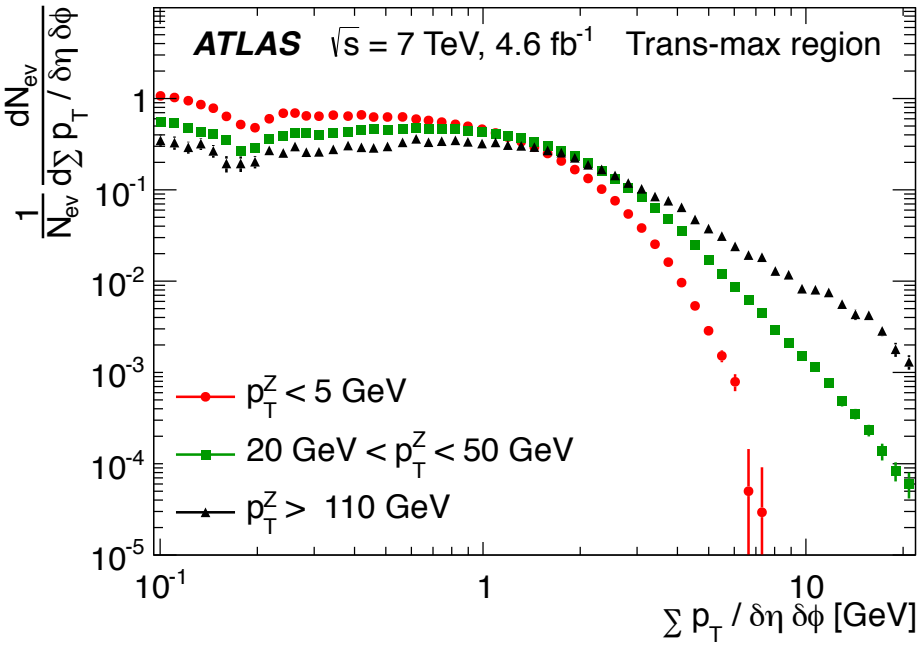
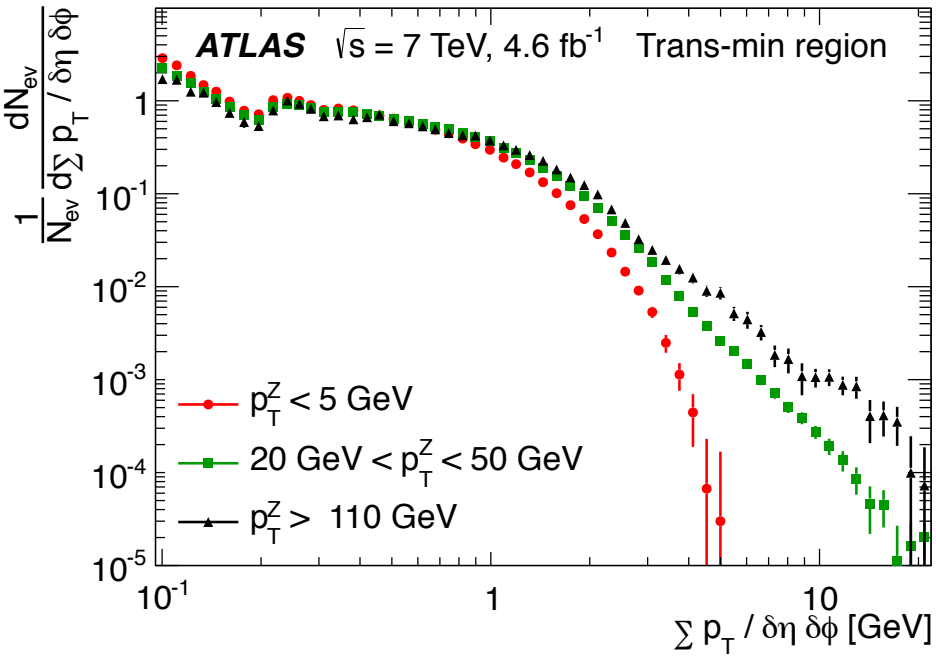
underlying event in Z events





underlying event observables

- study properties of soft **charged** and **neutral** particles

densities and averages

- mean Pt of charged particles: <Pt>
- multiplicity density of charged particles: $N_{ch}/\delta\eta\delta\phi$
- Pt density of charged particles: Σ Pt/$\delta\eta\delta\phi$
- Et density of **all** particles: Σ Et/$\delta\eta\delta\phi$

- distributions unfolded to hadron level
- jet analysis: full 2010 data – lower pileup
- Z analysis: 2011, corrected for pileup

particle spectra

- charged particle Pt spectrum
- charged particle multiplicity spectrum

- use charged tracks and calorimeter deposits to reconstruct particle kinematics