Measurements of the pseudorapidity dependence of the total transverse energy in proton-proton collisions at $\sqrt{s}=7$ TeV with ATLAS

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- on behalf of the ATLAS collaboration -

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Introduction

- Most processes at the Large Hadron Collider (LHC) are *low momentum transfer strong force interactions*
  - perturbative QCD breaks down and we rely on phenomenological models to describe underlying physics
- It is essential that these soft-QCD processes are well described by Monte Carlo event generators to allow an accurate modelling of:
  - multiple *proton-proton* interactions ("pileup")
  - multiple *parton* interactions (soft processes occuring in the same pp interaction as a hard parton-parton scatter)
- Previous measurements probing particle kinematics in this regime have typically relied on tracking detectors
  - limited to central region of detectors
- We have far fewer constraints on the forward region!

Measurement

- What are we measuring?

  (A) The mean ΣE_T per unit η-φ as a function of |η|

  ➡("E_T density" / "Energy Flow") ➡ $$\frac{1}{N_{evt}} \frac{d\Sigma E_T}{d\eta d\phi}$$

  (B) The ΣE_T distribution in each bin of |η| ➡ $$\frac{1}{N_{evt}} \frac{dN_{evt}}{d\Sigma E_T}$$

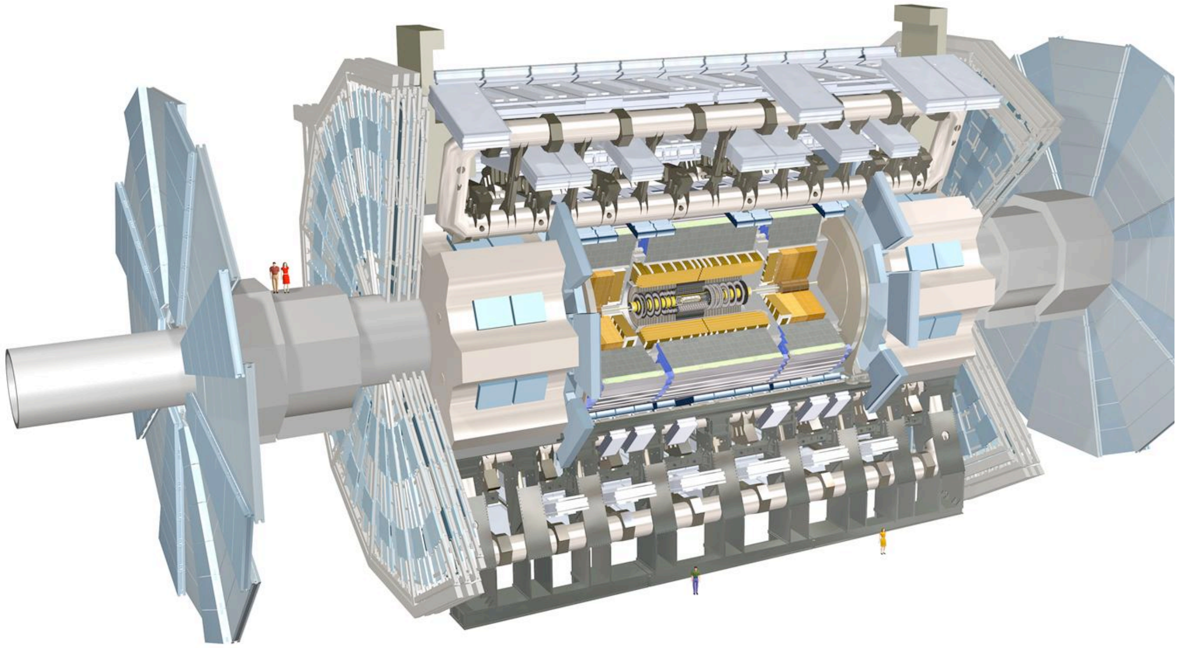
- Measurement is performed in *two* different event classes using early 2010 data:
  (1) **inclusive pp-collisions** ("minimum bias sample")
    - vital to ensure good description of **multiple proton-proton interactions** in high luminosity runs

  (2) **central dijet system** ("dijet sample")
    - probe particle kinematics in the **underlying event**

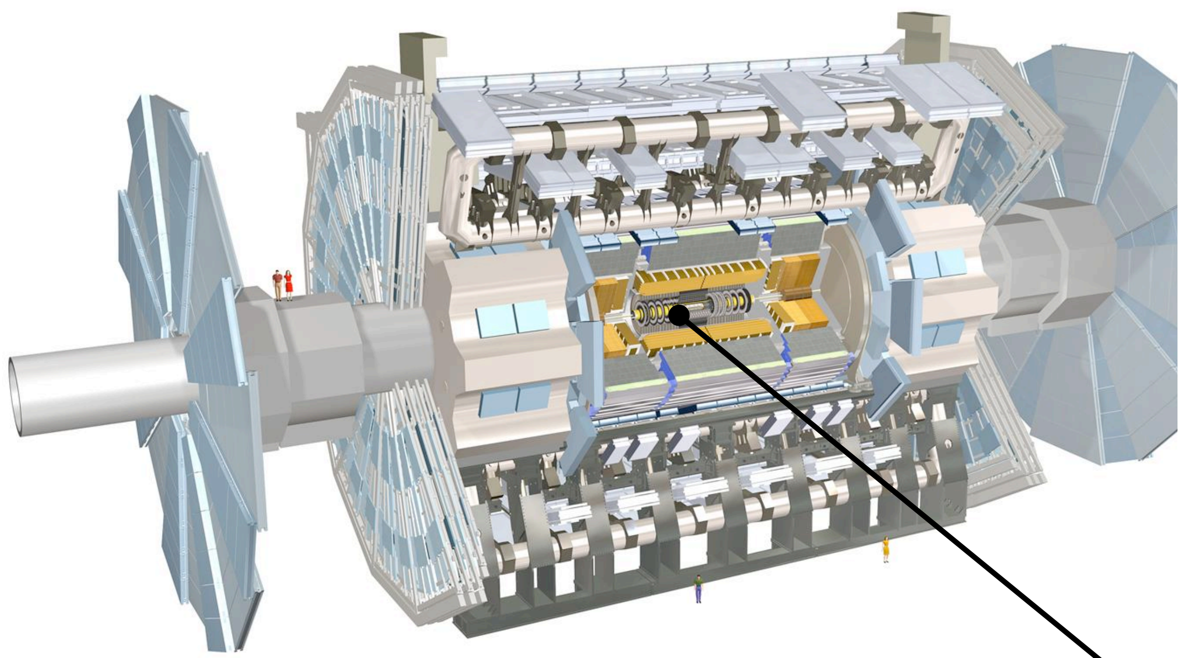
- Measurement is performed using ***calorimeter clusters*** in the region |η| < 4.8

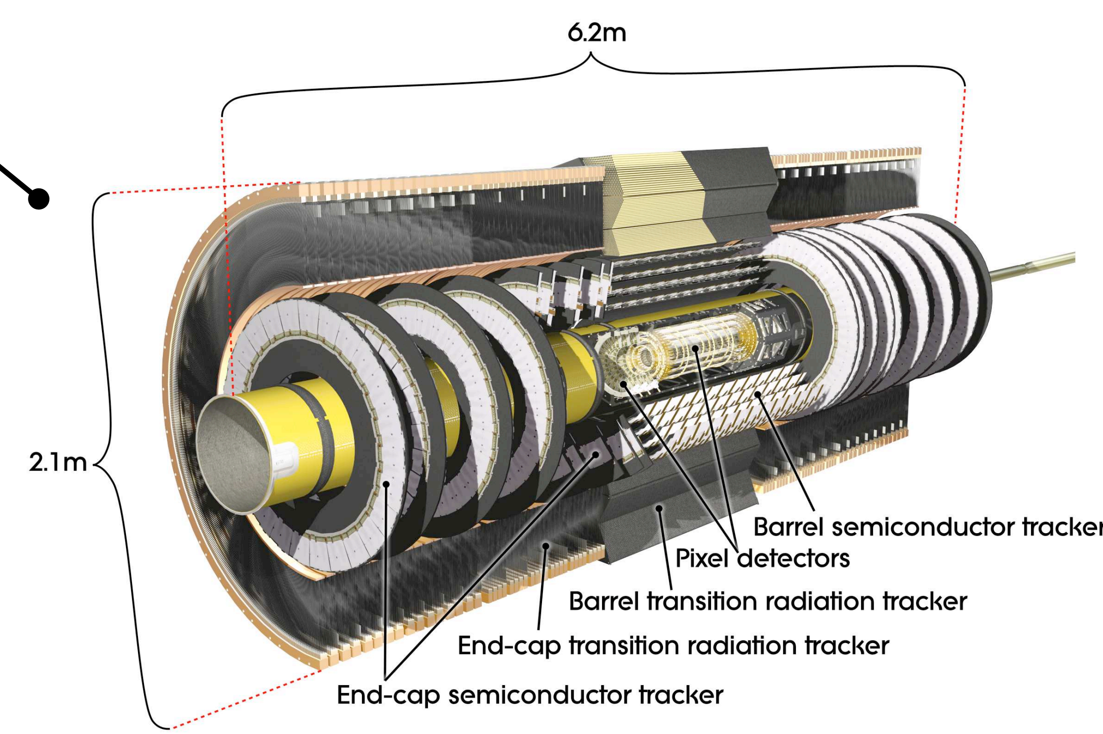
➡ a more complete picture of non-perturbative QCD within the entire acceptance of LHC general purpose detectors

ATLAS detector



ATLAS detector

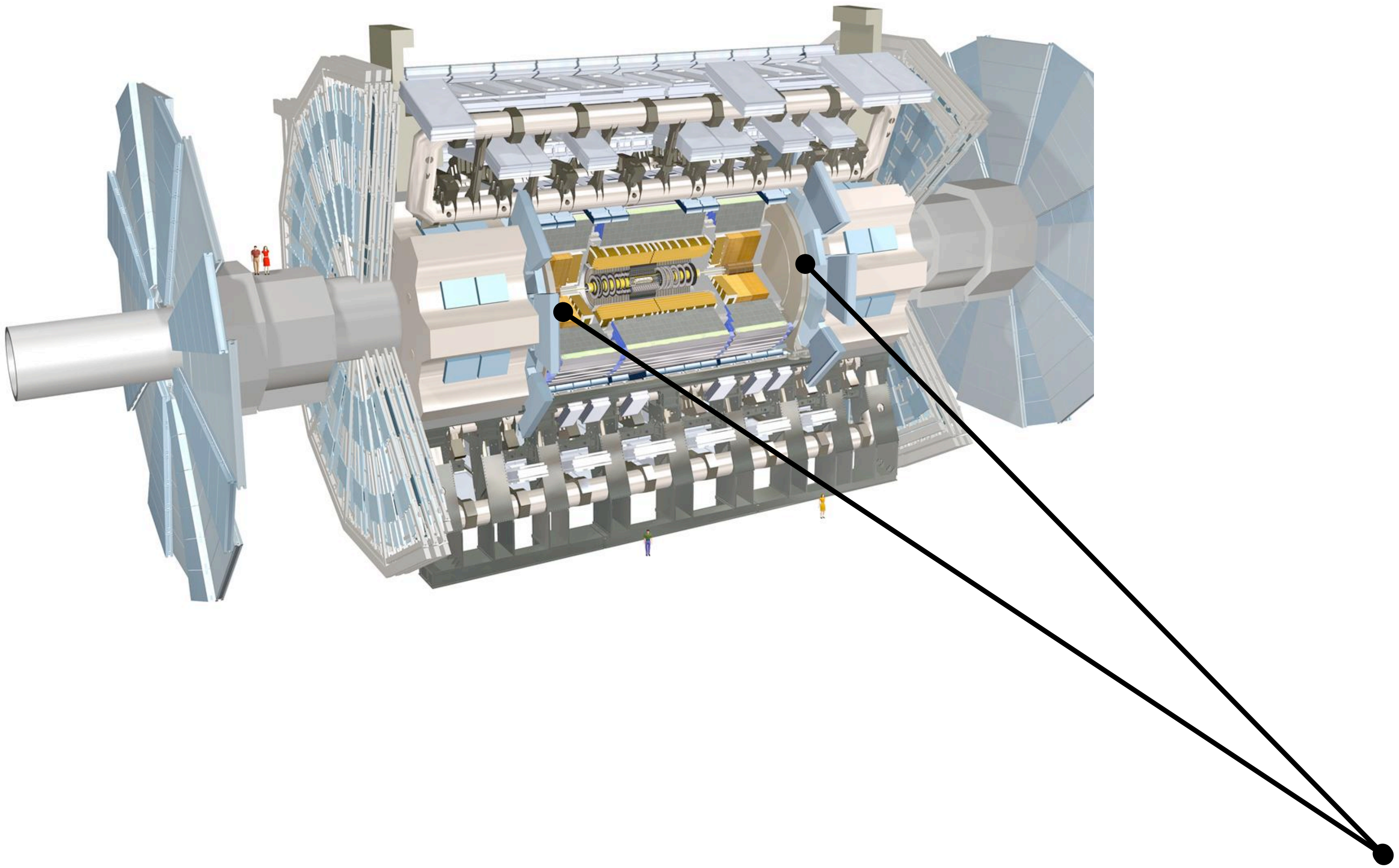


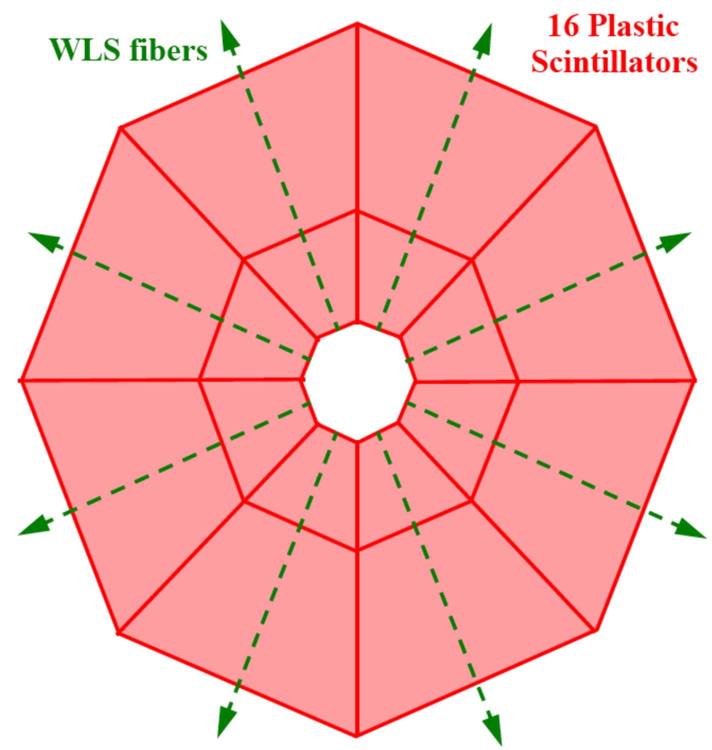


Inner Detector Tracker (|η|<2.5)

- Pixel detectors, semi-conductor tracker, transition radiation tracker
- Immersed in a 2T solenoidal magnetic field

ATLAS detector

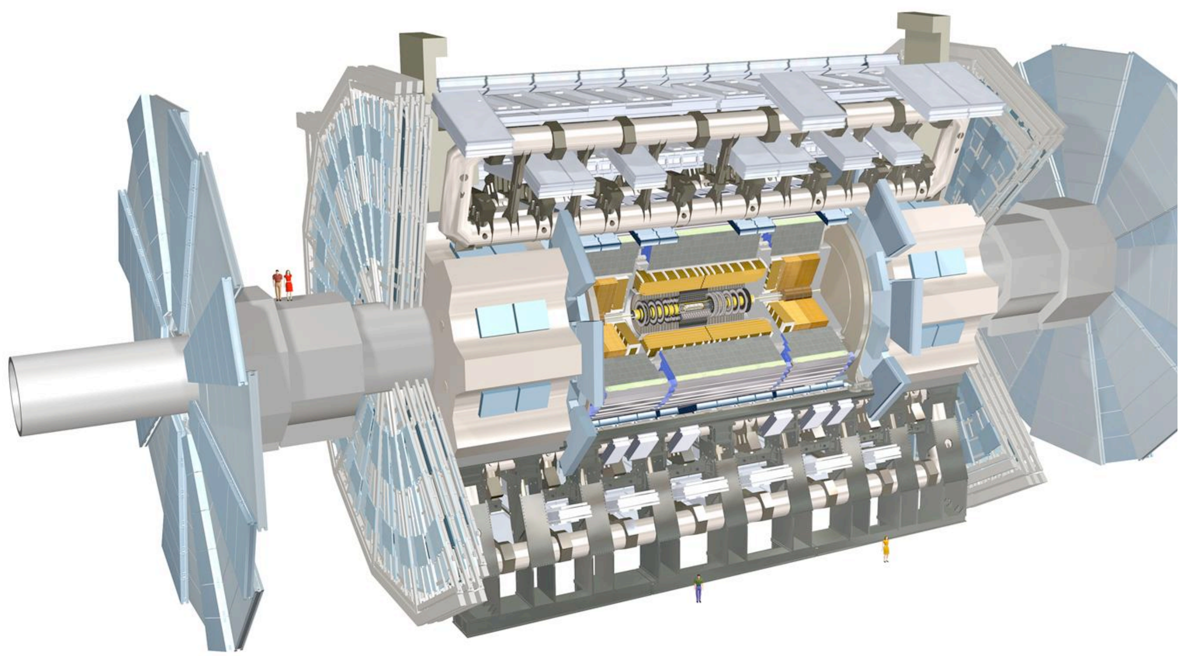




Minimum Bias Trigger Scintillator (MBTS) disks sensitive to charged particles in 2.9 <|η|<3.84

- use to trigger on inelastic pp collision events.
- 16 counters on each side of ATLAS; require hit on at least one side.

ATLAS detector



Electromagnetic calorimeters (|η|<3.2):

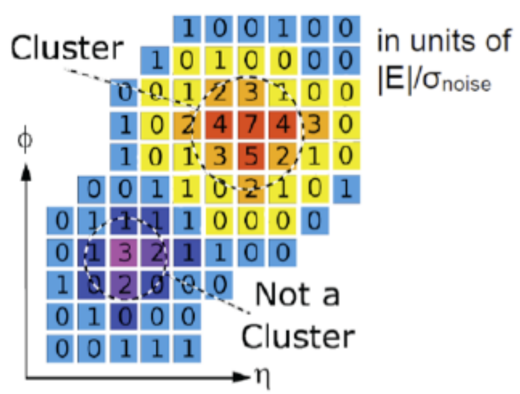
- LAr technology, high granularity
  - $\Delta\eta \times \Delta\varphi$ = {0.003x0.10, 0.025x0.025, 0.01x0.01}

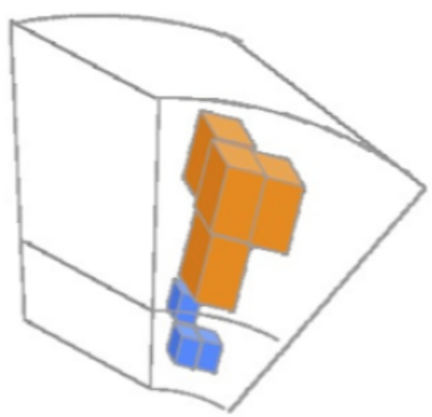
Hadronic calorimeters:

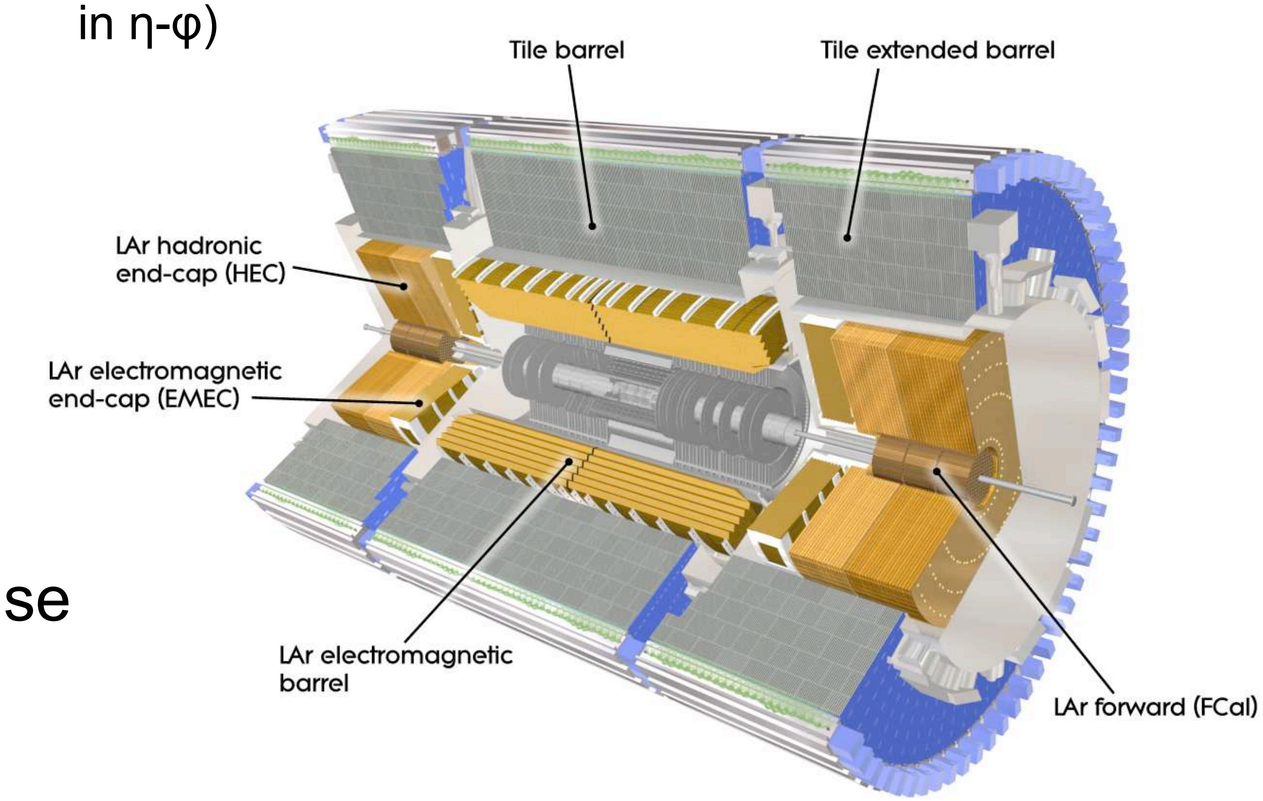
- Central (|η|<1.7), steel absorbers/scintillating tiles
  - $\Delta\eta \times \Delta\varphi$ = {0.1x0.1, 0.2x0.1}
- Endcap (1.5<|η|<3.2), LAr technology
  - $\Delta\eta \times \Delta\varphi$ = 0.1x0.1

Forward calorimeters (3.1<|η|<4.9):

- Electromagnetic and hadronic, LAr technology
  - cells alligned parallell to beam axis, rather than in projective towers (read-out granularity not constant in η-φ)







1. Clustering seeded with |E|>4σ cells
2. Iteratively add neighbours above different noise thresholds (4σ-2σ-0σ)

Event selections

- Use first low instantaneous luminosity runs at √s=7 TeV
  - ensures negligible contribution from multiple proton-proton interactions (“pileup”)

Inclusive pp event selection (7 μb^{-1})

Detector Level

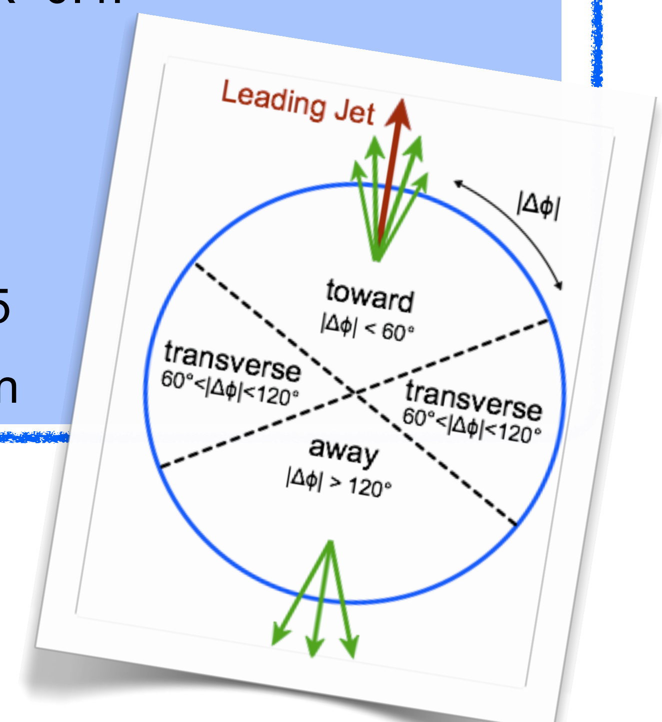
- Pass Minimum Bias Trigger Scintillator trigger
- Single primary vertex 2 p_T>150 MeV tracks
- Veto events with vertices w/ >4 associated tracks

Particle Level

- At least 2 central (|η|<2.5) charged particles w/ p_T > 250 MeV

Central dijet event selection (585 μb^{-1})

- Inclusive pp (detector level/truth level) event selection
- Two leading Anti-Kt jets w/ R=0.4:
  - E_T > 20 GeV
  - |η|<2.5
  - |Δφ| > 2.5 rad
  - E_T(jet2)/E_T(jet1) > 0.5
- Probe the ***transverse*** region



Final object selection

Detector Level

- All EM-scale topological clusters with |η|<4.8 (include E<0 clusters for noise cancellation)

Particle Level

- $|p_{charged}|$ > 500 MeV, $|p_{neutral}|$ > 200 MeV

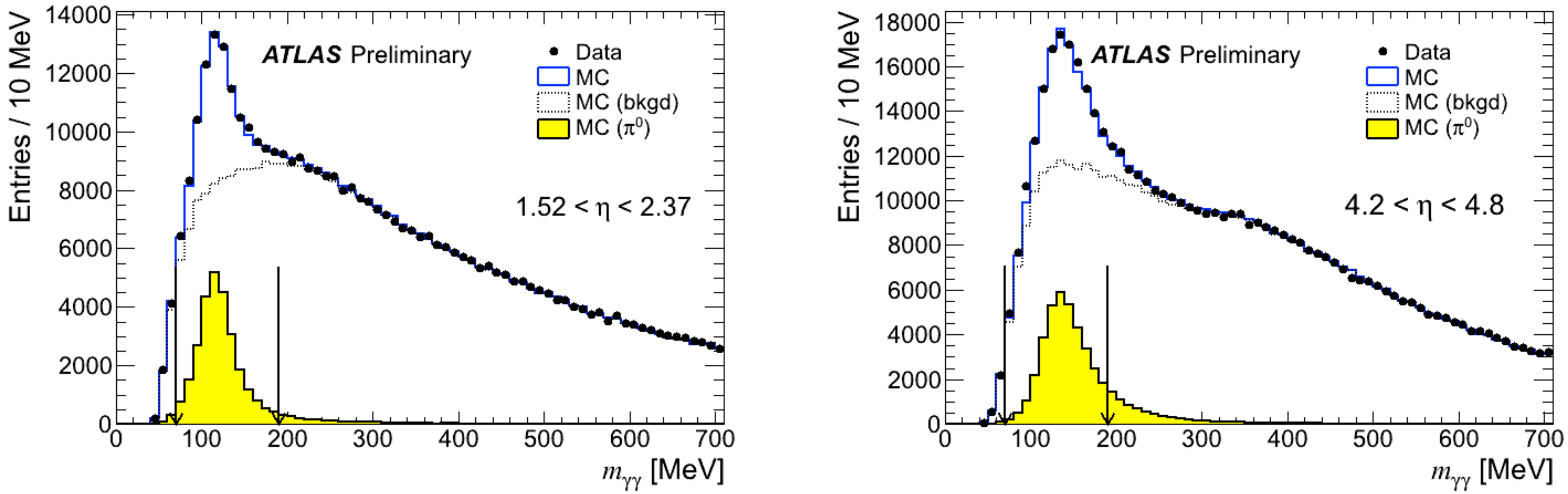
}

ATLAS calorimeters have limited sensitivity to lower momenta particles:
- particles swept out by magnetic field
- particles lose energy in material upstream

- Correct detector level measurement back to particle level using an iterative **Bayesian unfolding** technique

Response to EM particles

- How well does the MC describe the energy response to low energy particles?
  - validate the simulated response with the di-photon mass in $\pi^0 \rightarrow \gamma\gamma$ candidates
- Compare data to MC signal+background templates in |η|-regions corresponding to calorimeter subsystems
  - signal templates: match pairs of clusters to generator photons from π^0 decay
  - background templates: pairs of clusters without a match
- Cluster energy in signal template scaled by energy response factor
  - vary scale factor and minimize χ^2 between data and MC to determine best fit
  - deviations from unity mostly 2-3%, but as large as 10% in some |η|-regions
- Apply scale factor to cluster energy in MC before unfolding data



Systematic errors

UCL

Dominant systematic uncertainties:

- Calorimeter energy response
  - accuracy with which MC simulates calo response to low energy particles
- Monte Carlo physics model dependence
  - model dependence in unfolding
- Detector material description
  - knowledge of material upstream of calorimeters
- Jet energy scale (dijet)
  - accuracy with which MC simulates JES

In final plots these are combined in quadrature together with the statistical uncertainty

Other systematic checks:

- cluster energy resolution
- jet energy resolution (dijet)
- jet spectral shape uncertainty (dijet)
- pileup
- position of the forward calorimeter
- variation between data runs (inclusive pp)
- vertex z-position
- $|\eta|$-binning choices

Negligible

Systematics from energy response

- Determine energy response systematics for *electromagnetic* and *hadronic* particles separately, then obtain average using `Pythia 6 AMBT1` prediction for relative contribution from different particle types.

- Energy response systematic for electromagnetic particles:
  - variations in $m_{\gamma\gamma}$ fit range, background shape, matching criteria in signal template, simulation of energy resolution, etc.
  - generally 2-4%, but as high as 15% in regions where calorimeter subsystems overlap

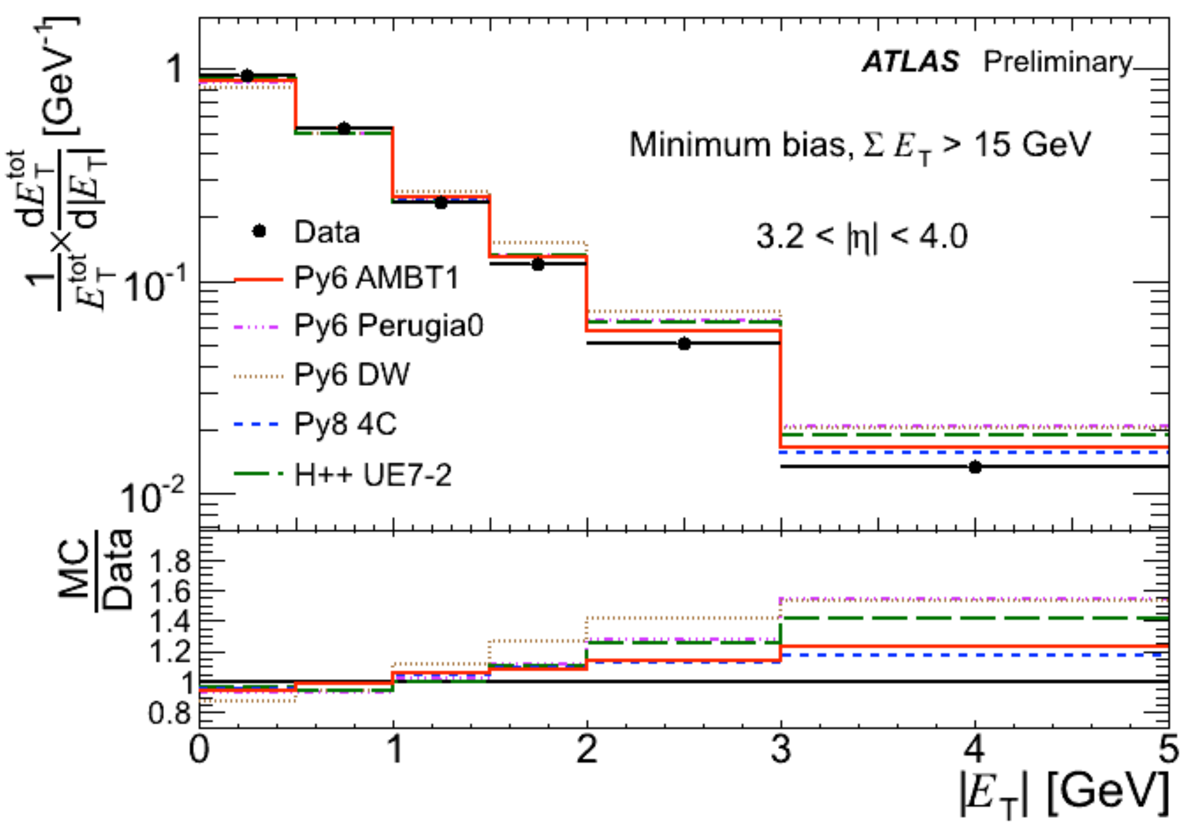
- Energy response systematic for hadronic particles:
  - **region covered by tracking detector**: E/p for charged isolated $\pi^{\pm}$
    - uncertainty derived from difference in data and MC in p and $|\eta|$ bins
  - **forward region**: test-beam studies of charged $\pi^{\pm}$

$\|\eta\| < 0.8$	$0.8 < \|\eta\| < 2.4$	$2.5 < \|\eta\| < 3.2$	$\|\eta\| > 3.2$
±3.5%	±5%	+5%	+9%

Model dependence

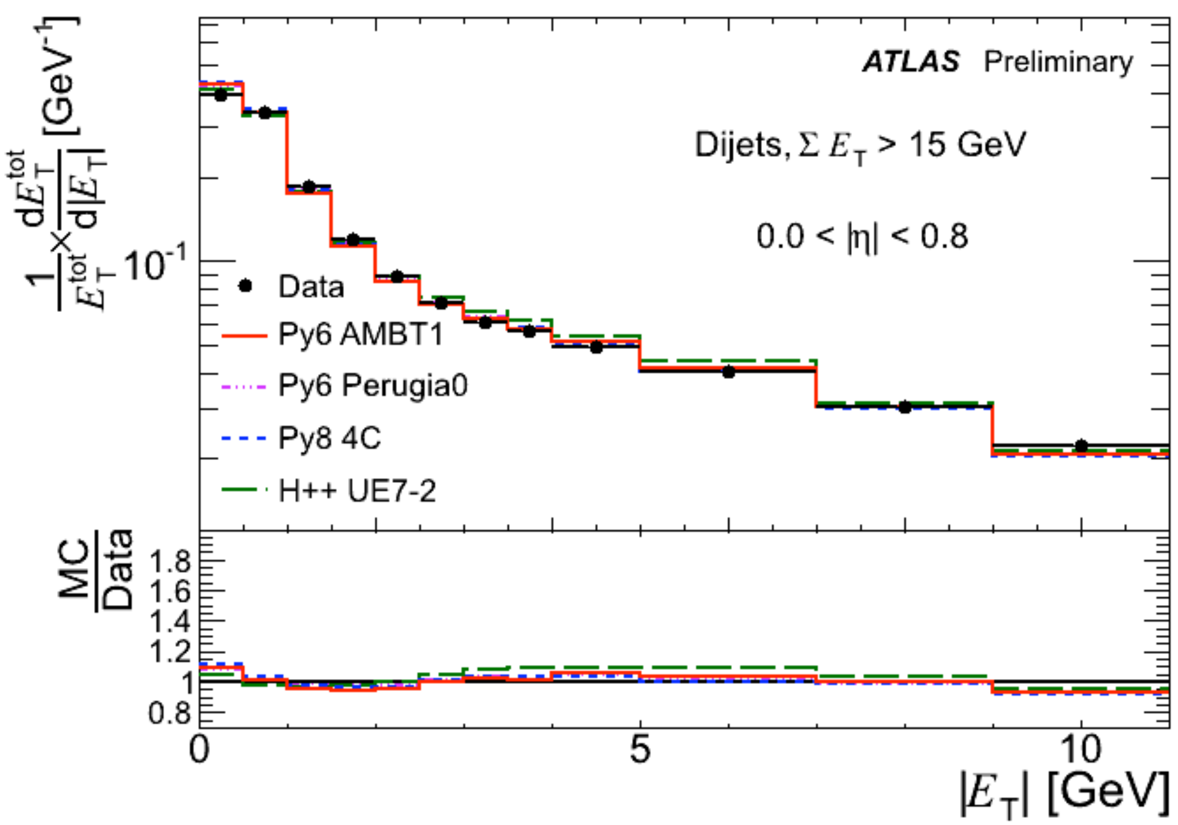
- MC model used to correct the data needs to accurately describe the particle kinematics
- Minimise model dependence on ΣE_T spectrum:
  - reweight ΣE_T in MC to data
  - iterate unfolding (using unfolded data as new prior after each iteration)
- Residual model dependence on the E_T of individual particles
  - *compare relative contribution to* ΣE_T from particles of a given E_T in various models. Select most discrepant model to assess possible biases in the unfolding.

Inclusive pp sample



Pythia 6 DW most discrepant
‣ 2-4% uncertainty

Dijet sample



Herwig++ UE7-2 most discrepant
‣ 2% or less

Other systematic sources

- **Material description**
  - Particles may lose energy in material upstream of the calorimeters
    - MC simulation used for detector corrections must have an accurate description of the true material in the forward region of the detector
  - Recalculate detector corrections with a special MC sample with additional material introduced into the forward region
    - compare to nominal and symmetrise difference to account for both over- and under-estimation of material
    - uncertainty varies between 0.2%-5.5%

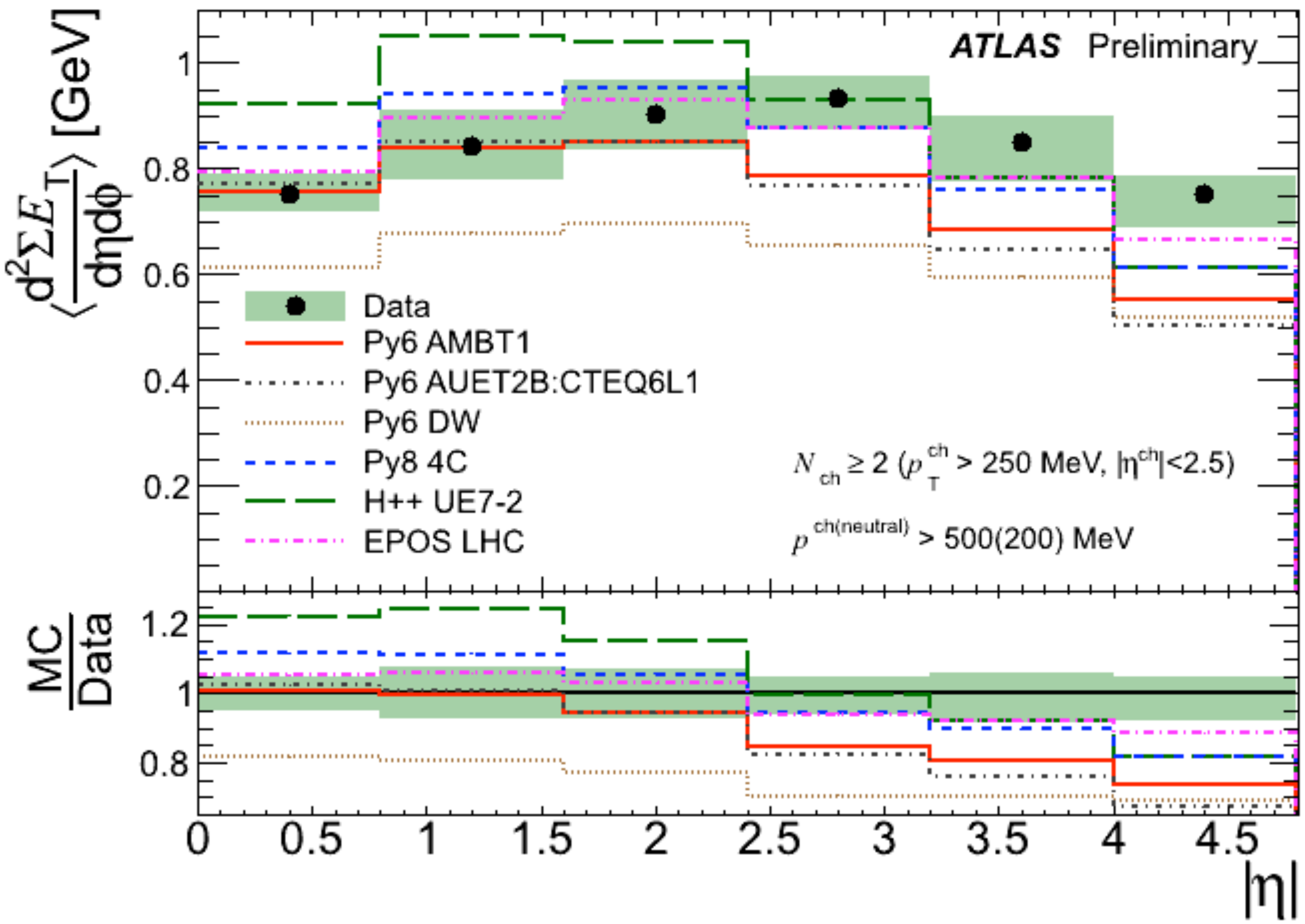
- **Jet energy scale**
  - Differences in the jet energy scale between data and MC can bias the correction of events that pass the detector level event selection, but fail the particle level selection (and vice versa)
    - *uncertainty varies between 1.6% in most central region ($0.0<|\eta|<0.8$) and 0.13% in the most forward region ($4.0 < |\eta| < 4.8$)*

Results: E_T density

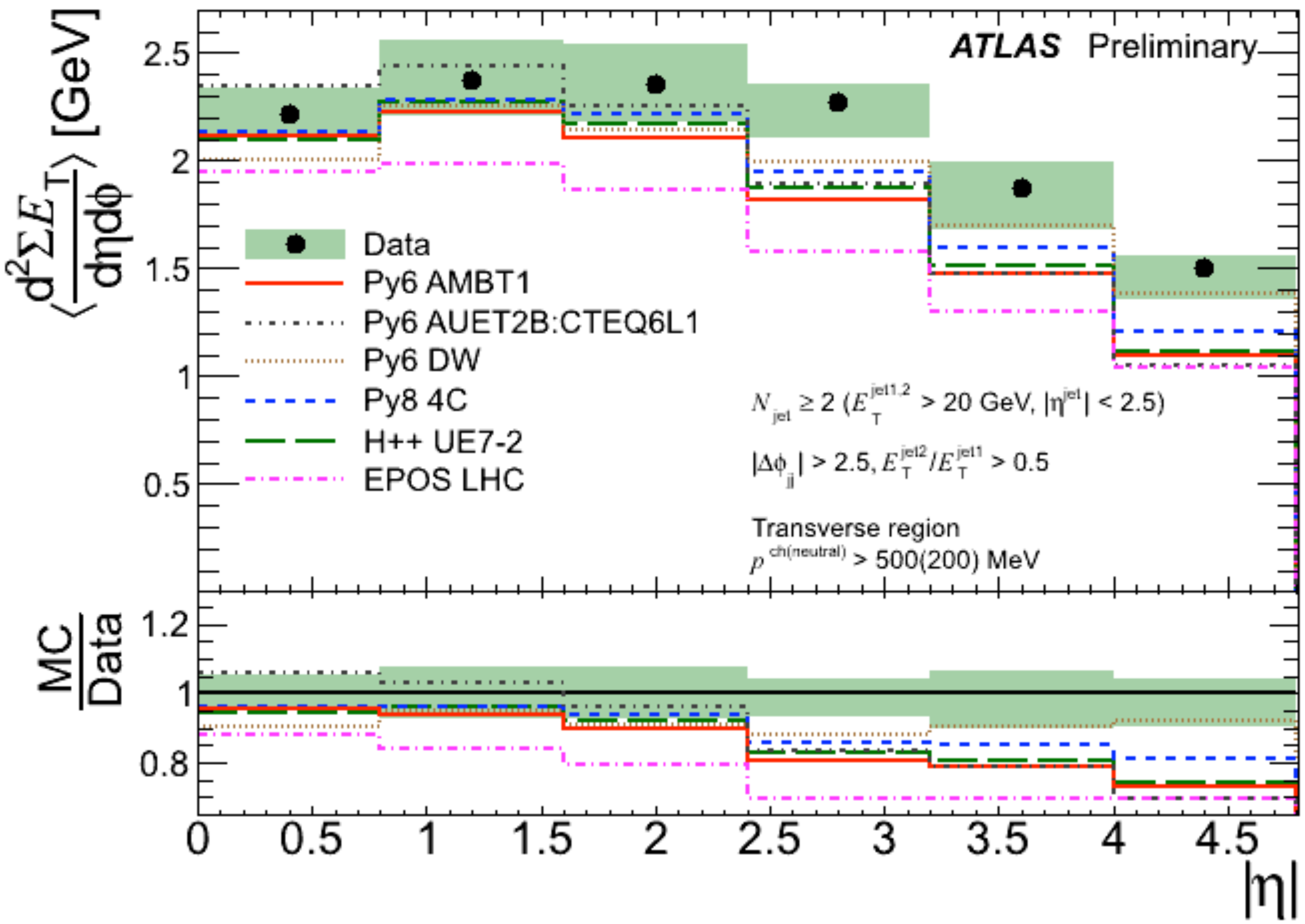
<u>Inclusive pp:</u>

- **`Py6 AMBT1`**: central region well described, but underestimates activity at high |η| (tuned to ATLAS data using information from tracker)
- **`Py6 DW`**: underestimates activity in all |η|-bins, but good description of shape (η-depedence)
- **`Py8 4C / H++ UE7-2`**: overestimates central region, underestimate forward region
- **`EPOS LHC`**: best description across |η|, but falls off slightly too fast

➡ **All models/tunes underestimated forward activity**



Results: E_T density



Dijet (transverse region):

- **Py6 AUET2B:CTEQ6L1**: slightly overestimates energy in central region
- **Py6 DW**: underestimates activity in all |η|-bins, but good description of shape (η-depedence)
- **EPOS LHC**: underestimates in both central and forward regions

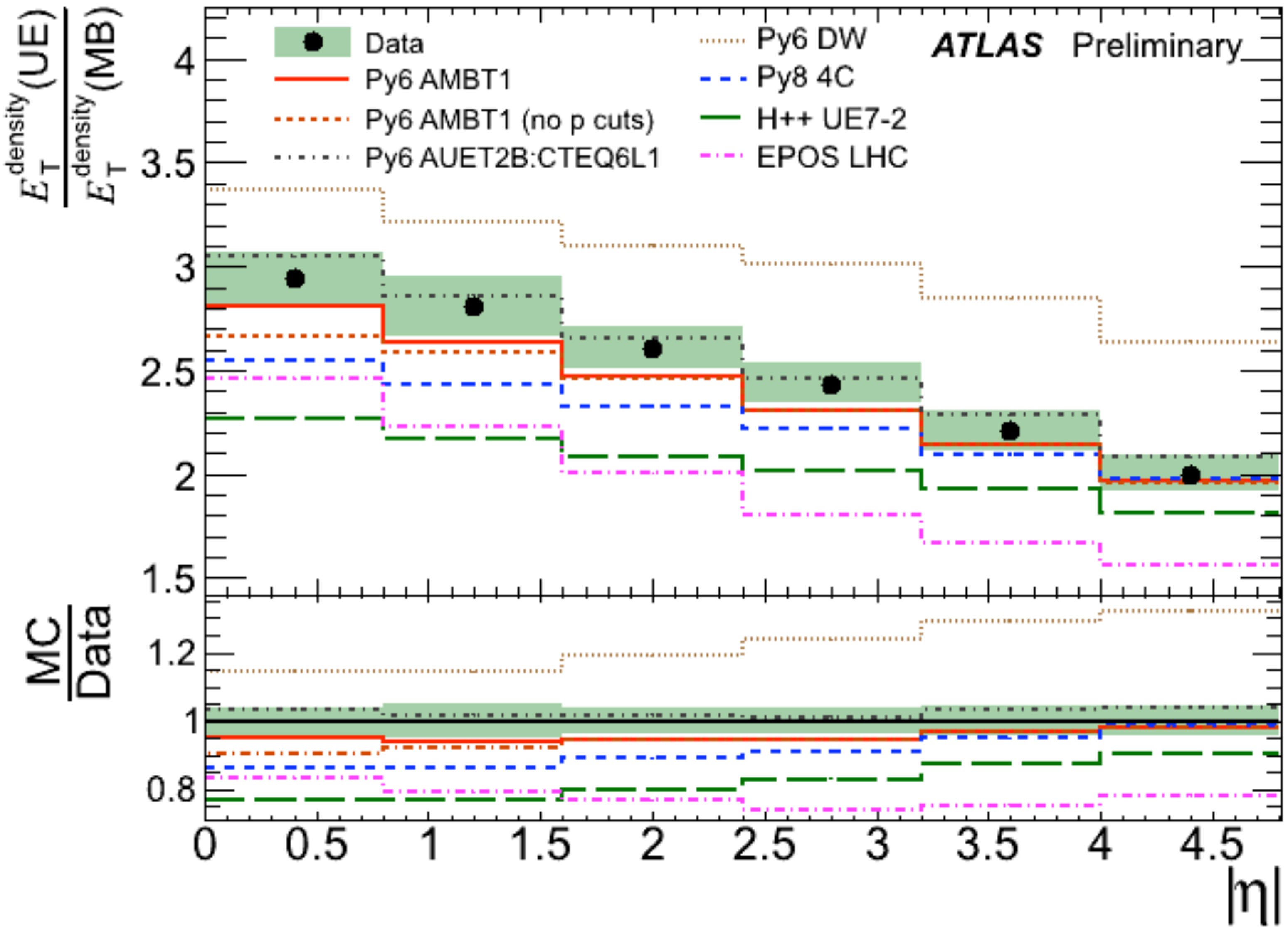
➡ **Central region reasonably well described by most models; forward region underestimated (20%-30%)**

E_T density (UE) / E_T density (MB)

- E_T density in the *transverse* region of events with a central dijet system is larger than in inclusive pp collisions...
  - ...event selection suppresses peripheral collisions and biases the events towards small impact parameter collisions, where multiple parton-parton interactions are more likely to occur

- Fall-off with |η| well reproduced, especially by `Pythia 6 AMBT1` and `Pythia6 AUET2B:CTEQ6L1`

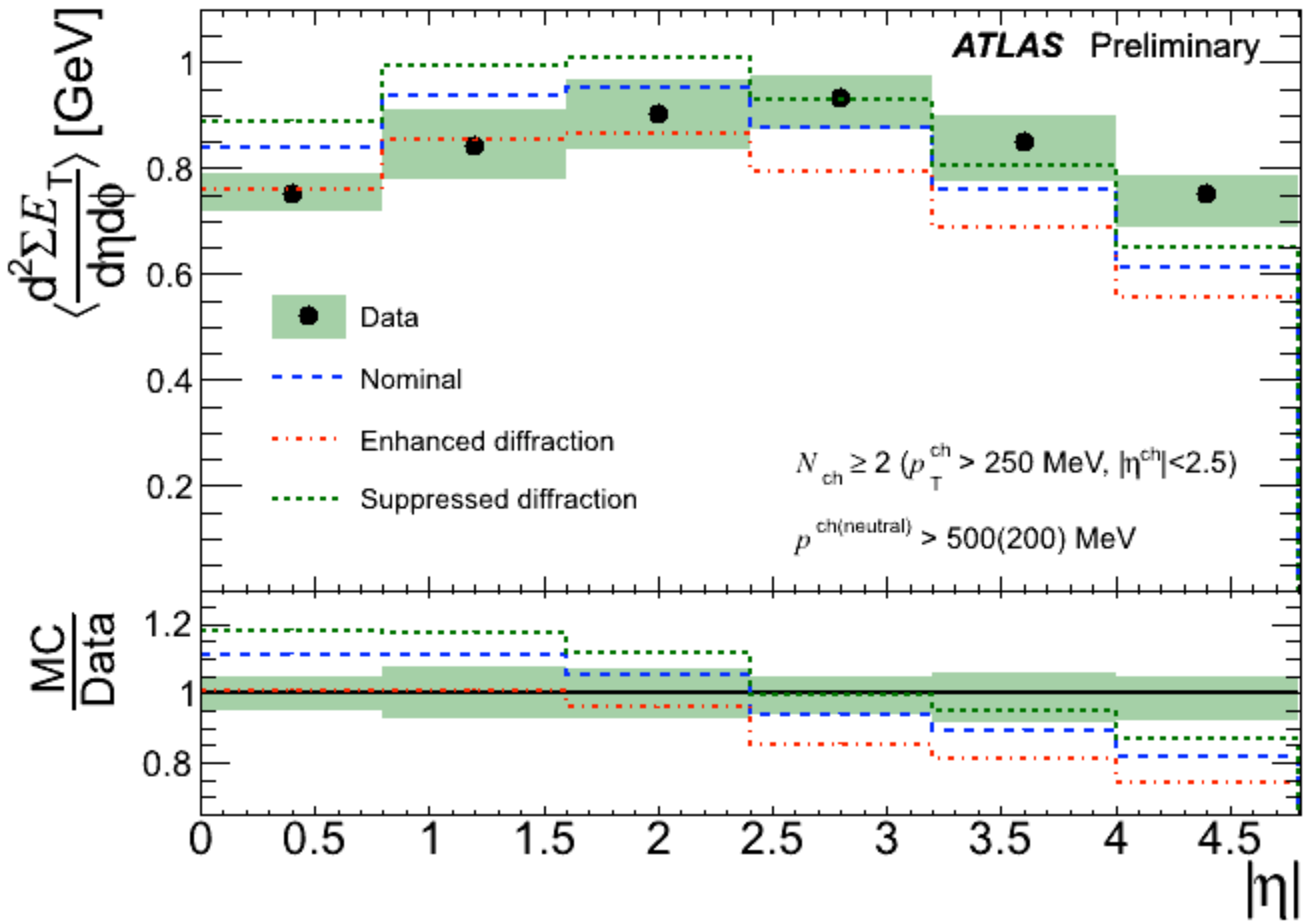
- `Pythia 6 AMBT1 (no p cuts)`:
  - Fall-off party due to momentum cuts applied to particles included in ΣE_T calculation. In the dijet sample particles tend to have *higher momenta*, hence fewer particles are removed.



Variations in diffractive contribution

- Probe sensitivity to relative fraction of diffractive events
  - Diffractive scatters tend to have less activity than non-diffractive scatters (especially in central region)
- Enhance/suppress relative diffractive contribution by 50% in **`Pythia8 4C`**, whilst keeping ND contribution constant
- Enhanced diffraction gives lower average activity, but shape is roughly similar

Inclusive pp sample



Variations in PDFs

- **Parton Distribution Functions** will affect both overall activity and |η| dependence

- Compare data to `Pythia 8 A2` family of tunes:

  (A) **Compare tunes**

  - tuning parameters to `MSTW2008LO` increases overall activity

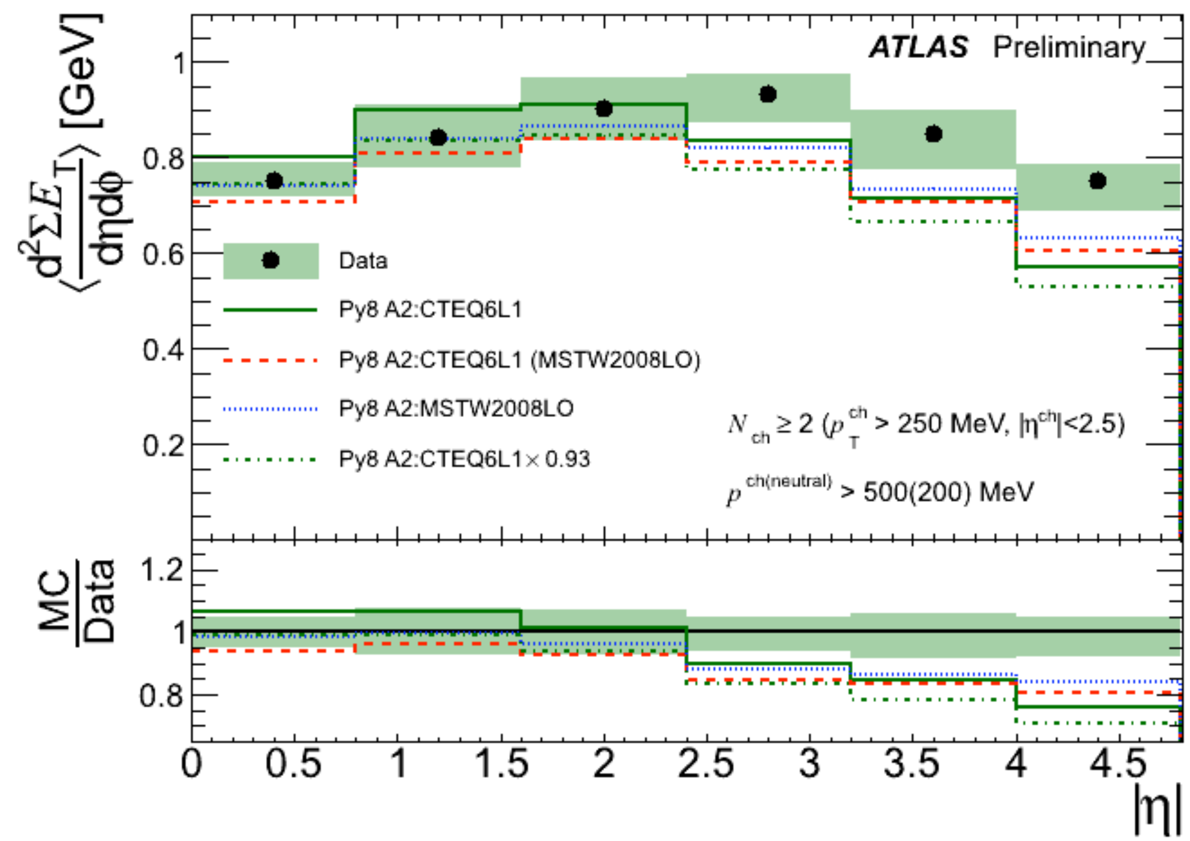
  (B) **Probe PDF dependence** → keep tune parameters constant and replace `CTEQ6L1`→`MSTW2008LO`

  - decreases amount of energy in central region; increases amount in forward region (increase in both high and low-x gluon PDF *wrt*. to mid-x region)

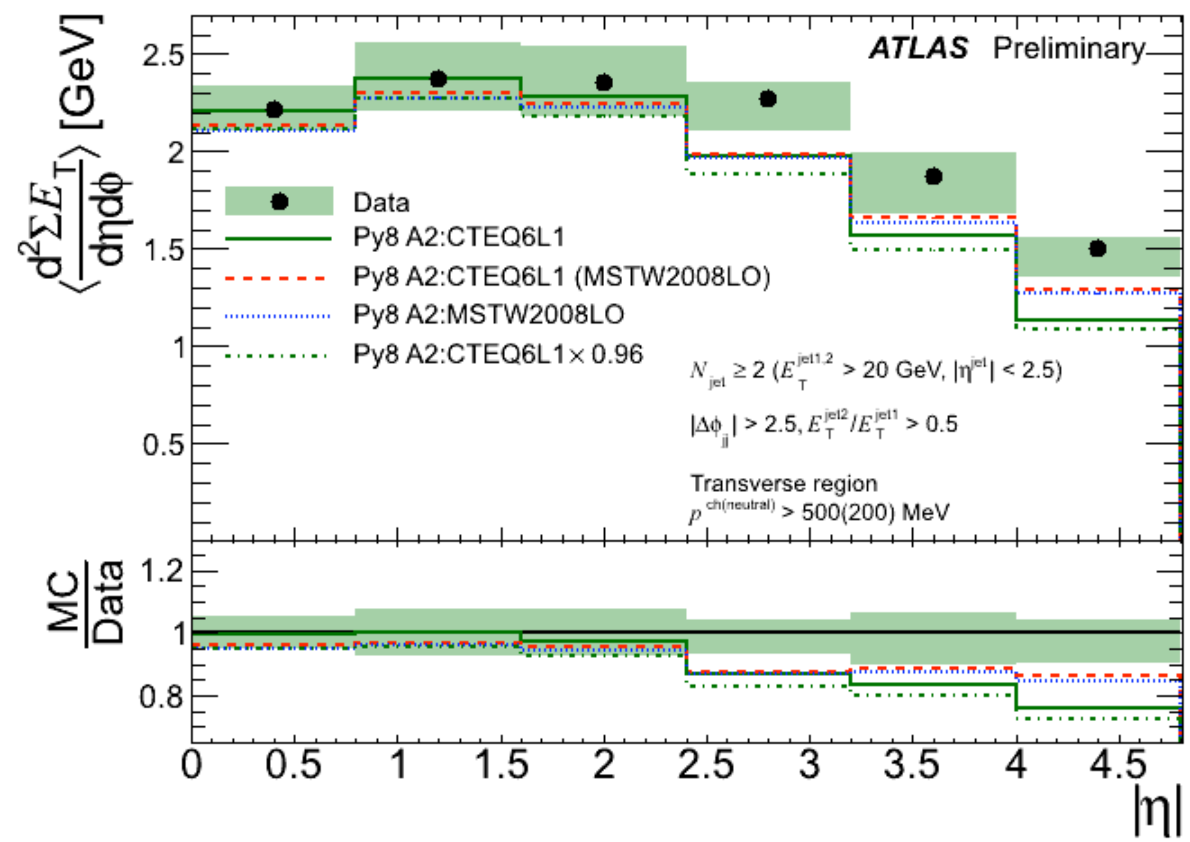
  (C) **Relative forward/central activity** → scale `A2:CTEQ6L1` so that it agrees with `A2:MSTW2008LO` in most central η bin

  - `A2:MSTW2008LO` provides better description in forward region

Inclusive pp sample

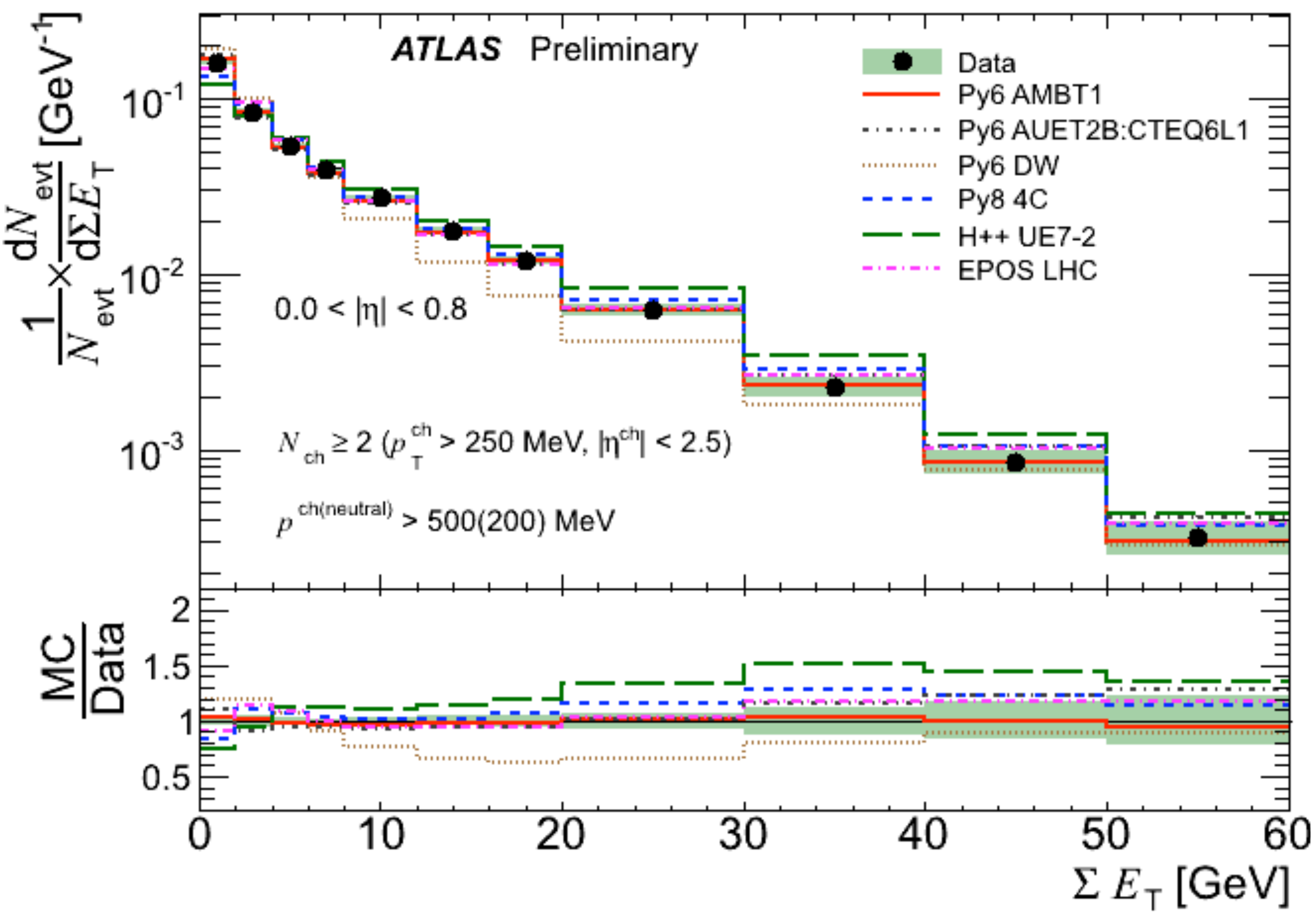


Dijet sample

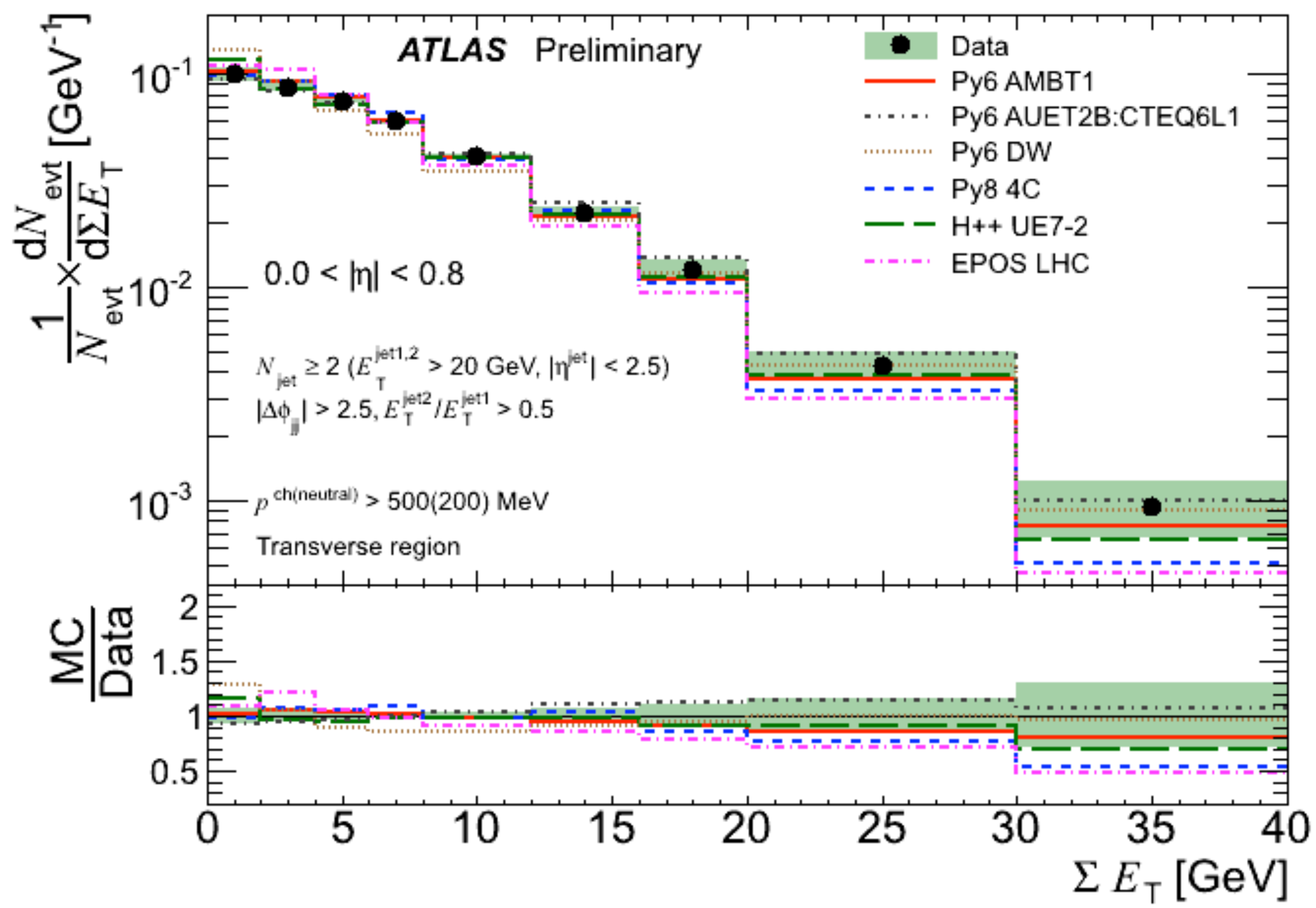


ΣE$_T$ distributions (0.0<|η|<0.8)

- Unfolded ΣE$_T$ spectra
  - distributions are broader in the region |η| < 3.2 with more events populating the tails, *i.e*. more variation in ΣE$_T$ from event to event in central part of detector
  - Features reproduced by MC:
    - Inclusive pp: `Pythia 6 AMBT1` provides best description of ΣE$_T$ shape in the central region
    - Dijet: all tunes do a reasonable job, `Pythia 8 4C` underestimates high ΣE$_T$ tails



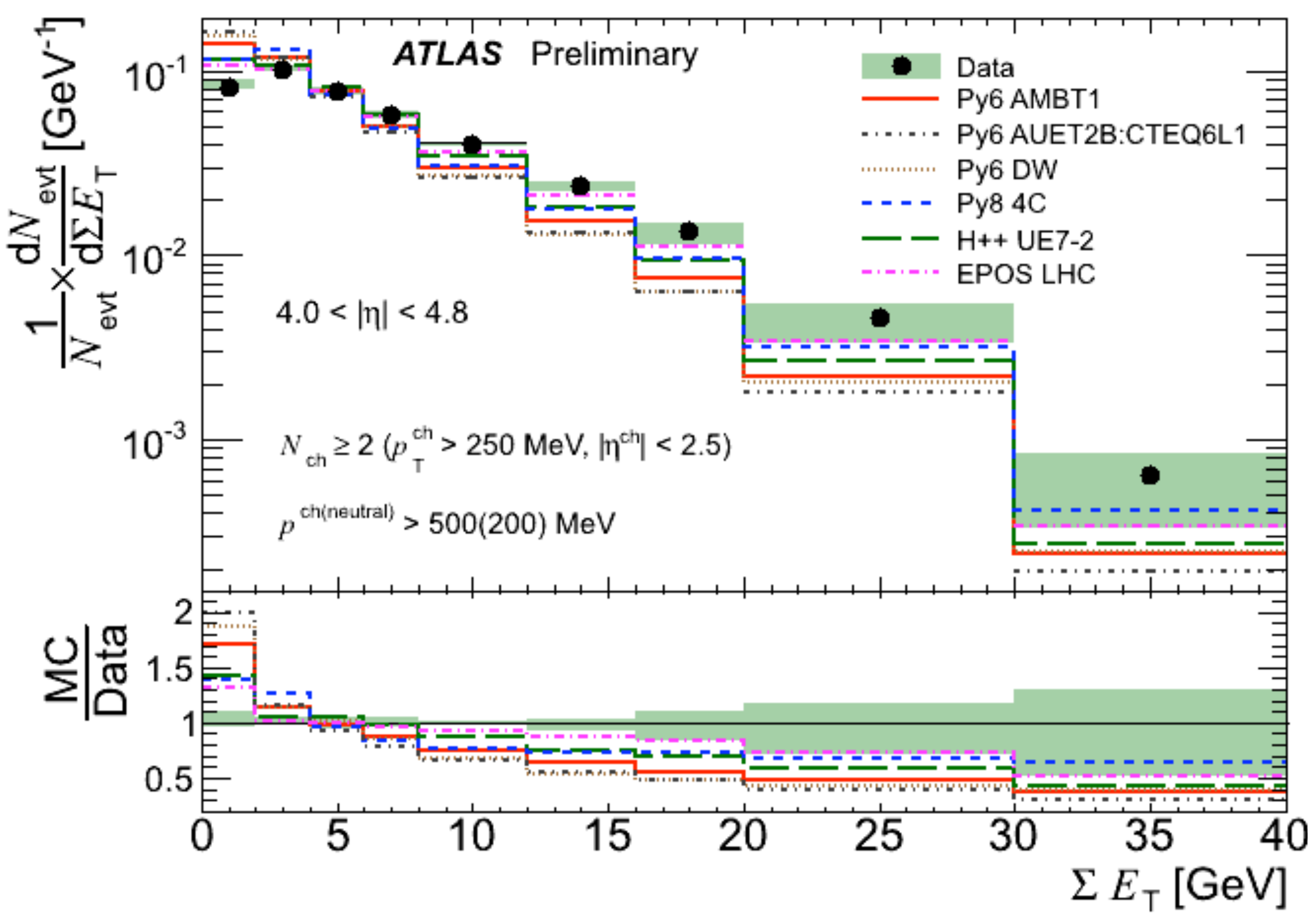
Inclusive pp sample



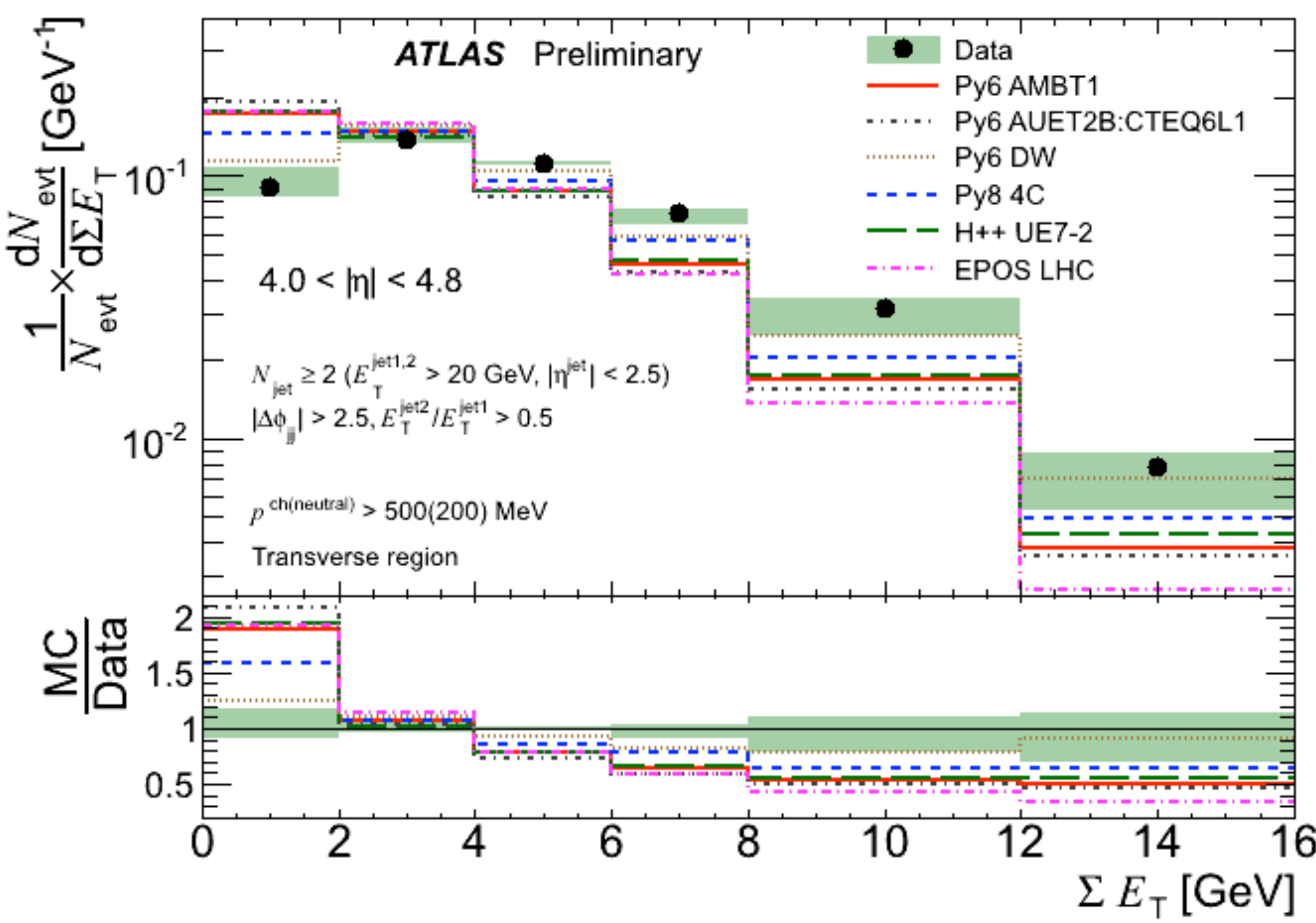
Dijet sample

ΣE_T distributions ($4.0<|\eta|<4.8$)

- Unfolded ΣE_T spectra:
  - distributions peak at higher values in forward region due to momentum cuts applied
  - **ΣE_T in forward region largely underestimated**



Inclusive pp sample



Dijet sample

Summary

- Measurements of the ΣE_T of particles in bins of particle η in **inclusive proton-proton collisions** and events with a **central dijet system** using early 2010 data recorded by ATLAS

- First measurements of its kind to utilise the entire acceptance of the ATLAS calorimeters:
  - probe activity in region $|\eta|<4.8$ to provide a more complete picture of activity from pileup and UE
  - provide information on correlations of systematic uncertainties

- Corrected distributions are compared to various MC models and tunes
  - Almost all flavours of MC models/tunes ***underestimate*** activity in forward region ($|\eta|>2.4$) relative to the central region by 20-30%
  - `Pythia 8 A2:MSTW2008LO` provides a comparatively better description of the activity in the forward region (now used for pileup simulation...)
  - `EPOS LHC` describes the inclusive pp minimum bias data very well (but still underestimates the activity in the forward region)

- Should allow us to prepare tunes that more accurately describe both *pileup* and the *underlying event* ➔ can impact high-p_T physics predictions...

Backup

Systematic uncertainties

- To assess uncertainty on unfolded data from systematic sources:
  - *unfold data with MC shifted by 1σ and compare to nominal unfolded data.*
- Provide information on correlations of systematic uncertainties:
  - *between bins*
  - *between different distributions*
  - *between inelastic pp and dijet datasets (→ assumed to)*
- Split each systematic source into different components and present in tabulated form along with unfolded data:

Uncorrelated E-scale between bins

1) $m_{\gamma\gamma}$ fits
2) E/p-measurements

Correlated E-scale between bins

- FCal testbeam (only affects two most forward bins)

Correlated material sources

1) extra material in front of barrel calorimeter
2) increase in material density in barrel-endcap transition region

Uncorrelated material source:

3) extra material in ID (+its services) and in forward region (+ material density of pump in forward region)

Physics model uncertainty

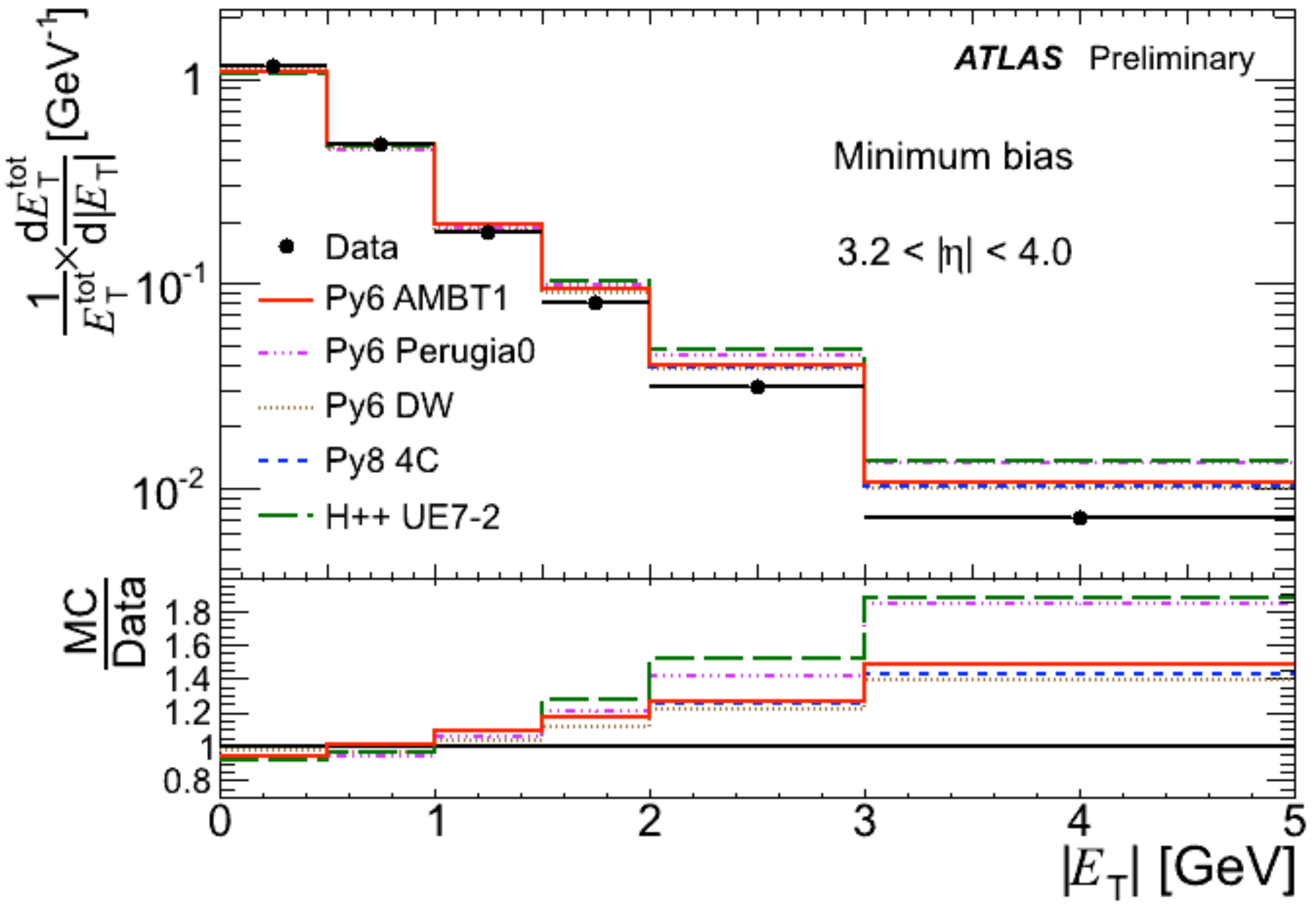
Correlations between bins indicated by **sign** of uncertainty:

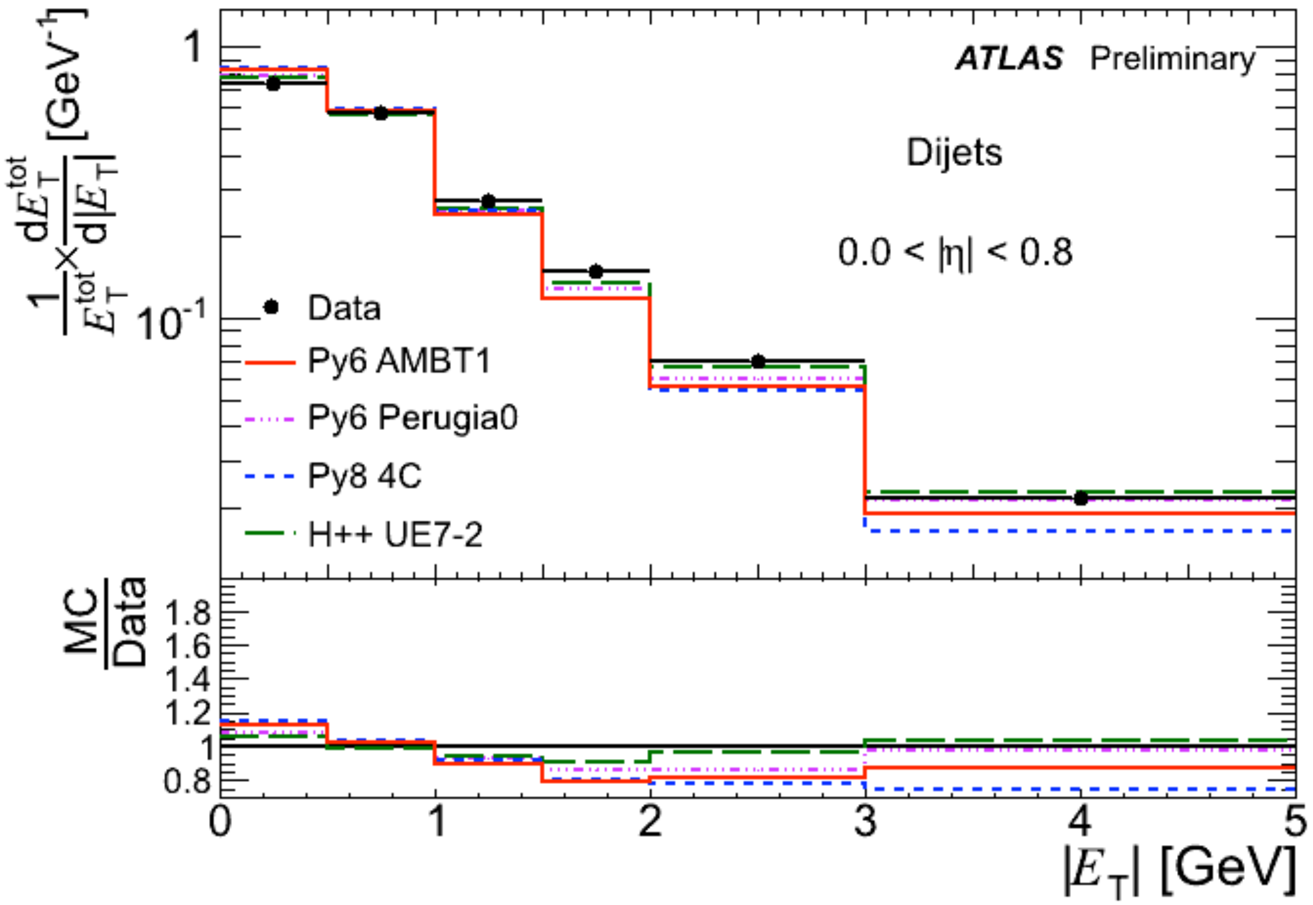
First 4 bins are correlated with each other, and anti-correlated with remaining bins

ΣE_T (GeV)	$\frac{1}{N_{evt}}\frac{dN_{evt}}{d\Sigma E_T}$	Stat. (%)	E_1^a (%)	E_2 (%)	M_1 (%)	M_2 (%)	M_3^a (%)	P_1 (%)	Total (%)
0 – 2	0.161	0.35	$^{+2.0}_{-2.1}$	0	$\mp$ 2.1	0	$\mp$ 0.38	$\pm$0.07	$^{+3.0}_{-3.1}$
2 – 4	0.0835	0.32	$^{+1.3}_{-1.4}$	0	$\mp$ 1.2	0	$\mp$ 0.21	$\mp$4.5	$^{+4.8}_{-4.8}$
4 – 6	0.0533	0.40	$^{+0.24}_{-0.39}$	0	$\mp$ 0.90	0	$\mp$ 0.16	$\mp$3.8	$^{+3.9}_{-3.9}$
6 – 8	0.039	0.46	$^{-0.20}_{+0.00}$	0	$\pm$ 0.23	0	$\pm$ 0.04	$\mp$0.44	$^{+0.68}_{-0.71}$
8 – 12	0.0271	0.49	$^{-0.57}_{+0.56}$	0	$\pm$ 1.4	0	$\pm$ 0.24	$\pm$2.2	$^{+2.7}_{-2.7}$
12 – 16	0.0177	0.57	$^{-1.3}_{+1.5}$	0	$\pm$ 1.8	0	$\pm$ 0.31	$\pm$3.5	$^{+4.3}_{-4.2}$
16 – 20	0.0121	0.67	$^{-2.5}_{+2.5}$	0	$\pm$ 2.4	0	$\pm$ 0.43	$\pm$3.6	$^{+5.1}_{-5.1}$
20 – 30	0.00619	0.75	$^{-4.6}_{+4.8}$	0	$\pm$ 4.1	0	$\pm$ 0.73	$\pm$4.2	$^{+7.7}_{-7.5}$
30 – 40	0.00226	1.2	$^{-7.5}_{+8.4}$	0	$\pm$ 7.9	0	$\pm$ 1.4	$\pm$5.5	$^{+13}_{-12}$
40 – 50	0.000855	1.9	$^{-10}_{+12}$	0	$\pm$ 8.7	0	$\pm$ 1.5	$\pm$8.1	$^{+17}_{-16}$
50 – 60	0.000321	2.5	$^{-13}_{+15}$	0	$\pm$ 13	0	$\pm$ 2.3	$\pm$10	$^{+22}_{-21}$

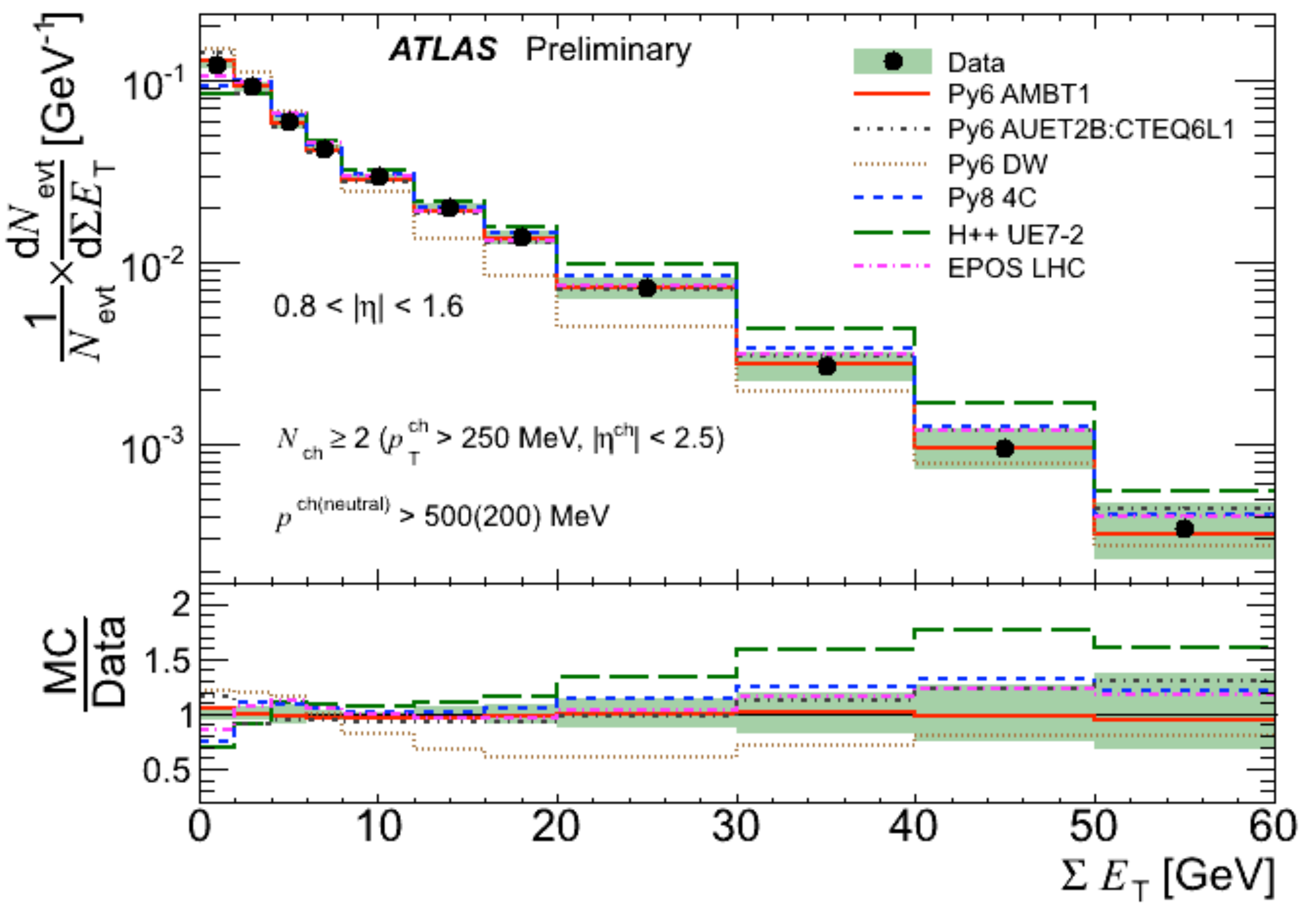
Table 6. *Measured* $\frac{1}{N_{evt}}\frac{dN_{evt}}{d\Sigma E_T}$ *and systematic uncertainty breakdown for the minimum bias data in the region* $0.0 < |\eta| < 0.8$.

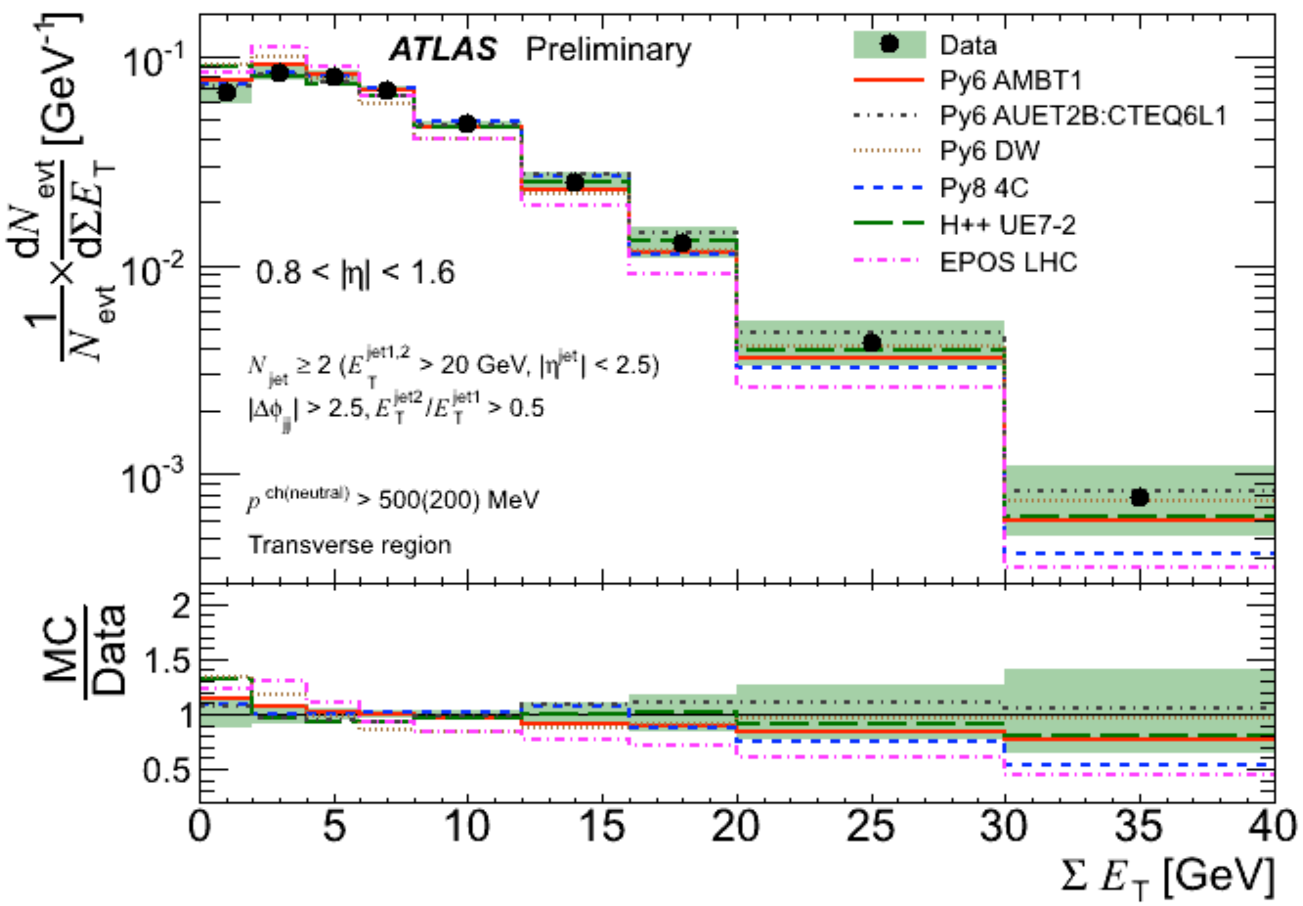
Model dependence



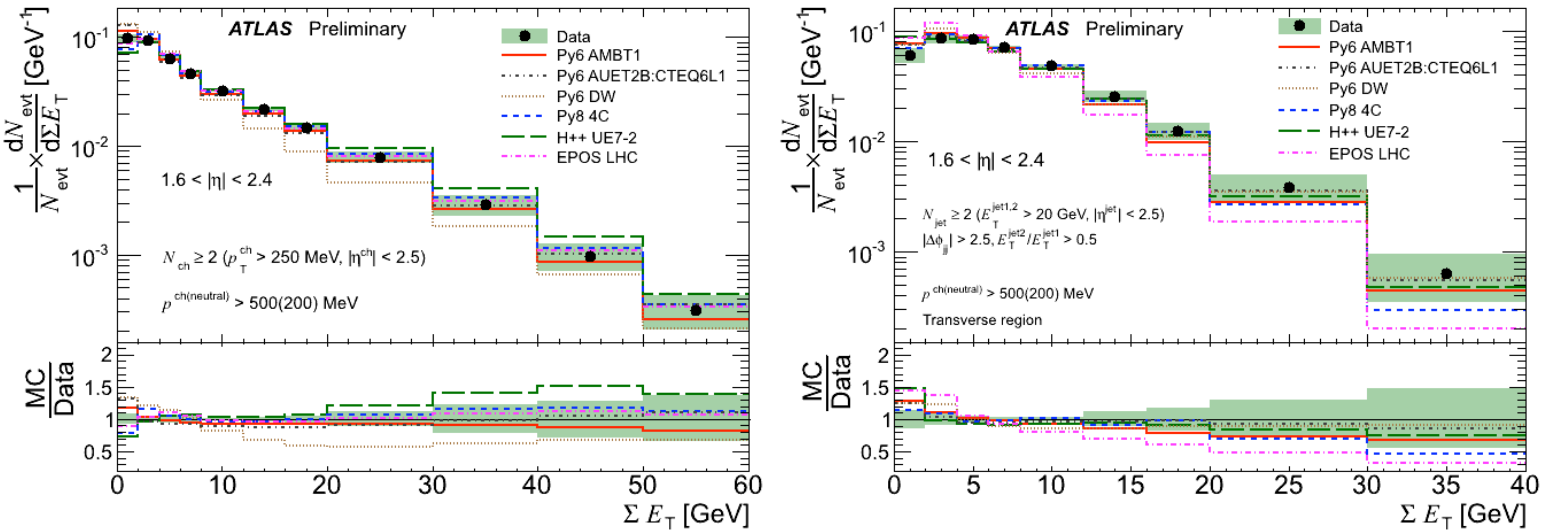


ΣE$_T$ distributions (0.8<|η|<1.6)

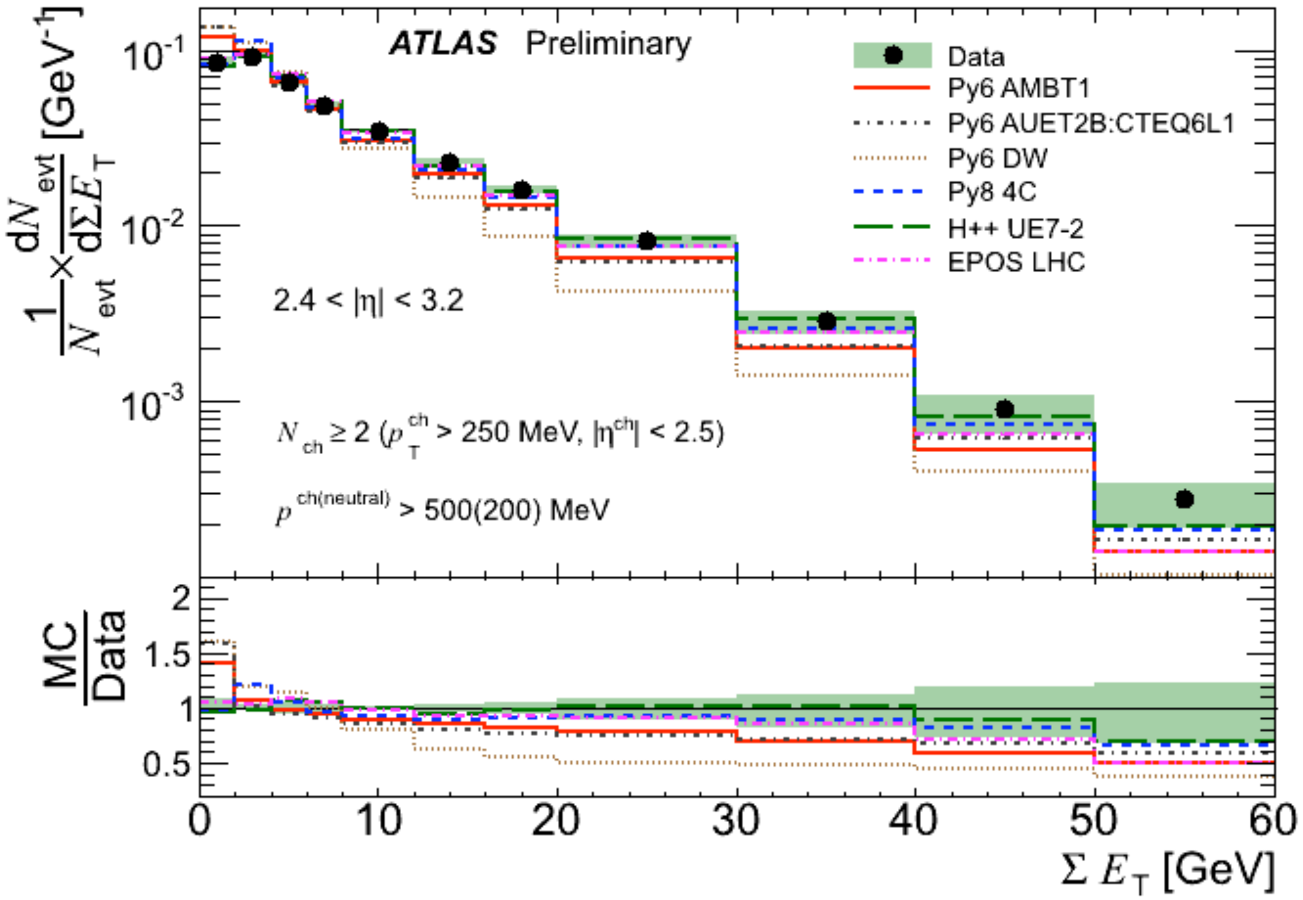


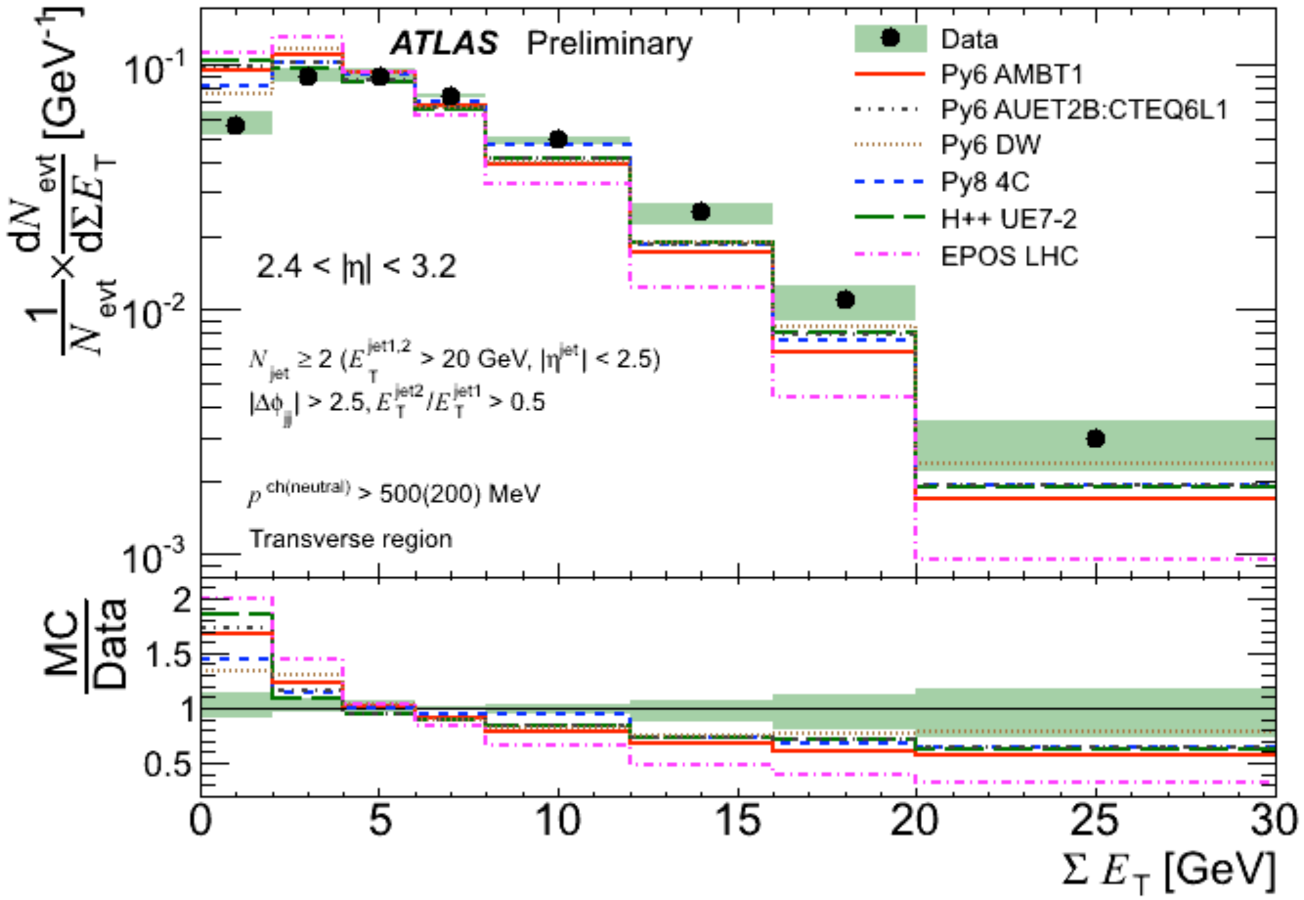


ΣE$_T$ distributions (1.6<|η|<2.4)



ΣE_T distributions ($2.4<|\eta|<3.2$)





ΣE_T distributions ($3.2<|\eta|<4.0$)