ATLAS Measurements of Radiation in Top Events

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On behalf of the ATLAS Collaboration

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Introduction

- Modelling uncertainties are a significant source of uncertainty in top quark measurements:
  - Cross-section, mass, charge asymmetry, ...
- Important to probe the modelling by making precise measurements that can be compared to the theoretical predictions.
- Today will present recent ATLAS measurements sensitive to additional QCD radiation and MC based studies on the impact of radiation in other observables.

Outline

- MC Models
- Measurement of ttbar production with a veto on additional jet activity.
- Measurement of jet multiplicity distribution in ttbar events.
- MC study of jet shapes in ttbar events.
- MC study of pseudo-top quark distributions.
- Summary

MC Models

- Full details in: ATL-PHYS-PUB-2012-006
- MC@NLO + Herwig / Jimmy, AUET2 tune.
- POWHEG + Pythia, P2011C tune.
- POWHEG + Pythia, AUET2 tune.
- POWHEG + Herwig / Jimmy, AUET2 tune.

→ NLO + PS

- Sherpa, Sherpa default tune.
- Madgraph + Pythia, Z2 tune.
- Alpgen + Herwig / Jimmy, AUET2 tune.
- Alpgen + Pythia, P2011 tune.
    - Additional scale varied samples - ME & PS simultaneously; only ME.

→ Multi-leg LO + PS

- AcerMC + Pythia, P2011C tune with varied Pythia parameters.

→ LO + PS

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Measurement of $t\bar{t}$ production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector

Eur.Phys.J. C72 (2012) 2043. arXiv:1203.5015

Jet Veto Measurement

arXiv:1203.5015

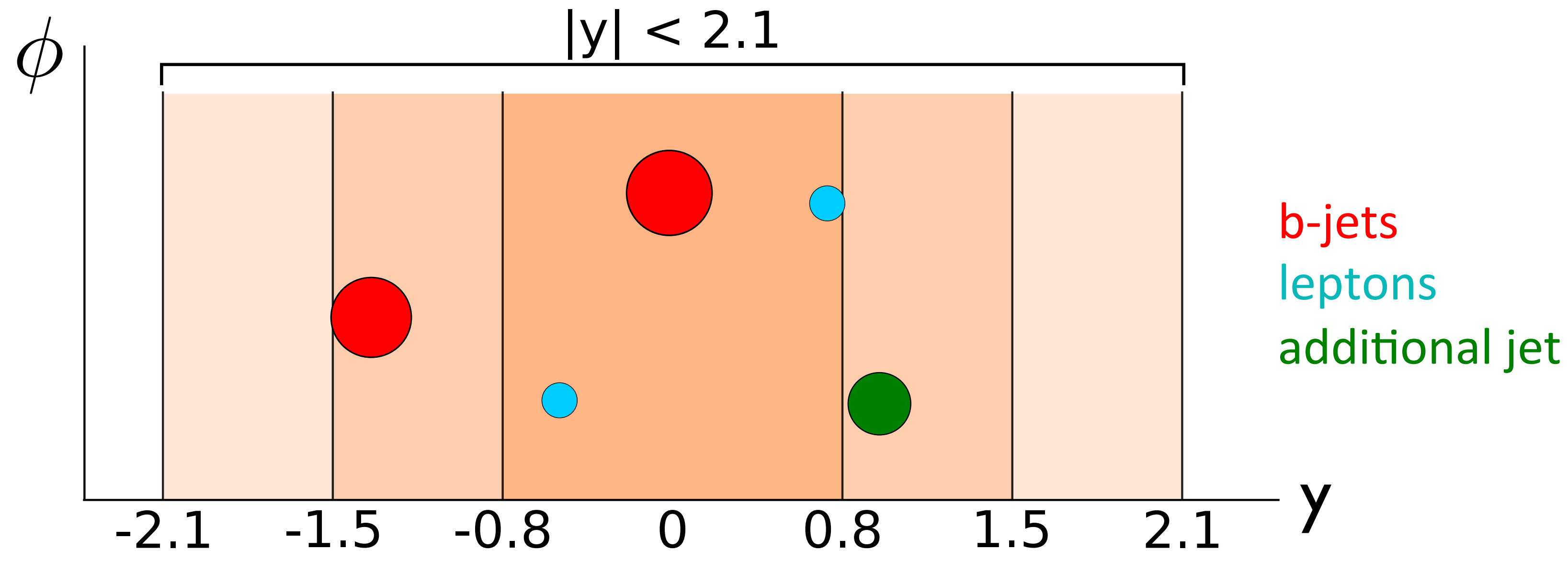
- Study the fraction of ttbar events that do not contain an additional jet, in a central rapidity region, with $p_T > Q_0$:

$$f_{\rm gap}(Q_0) = \frac{n_{\rm gap}(Q_0)}{N_{t\bar{t}}}$$

- Alternatively, we can take the sum of the p_T of the jets falling into each rapidity region and define:

$$f_{\rm gap}(Q_{\rm sum}) = \frac{n_{\rm gap}(Q_{\rm sum})}{N_{t\bar{t}}}$$

- Use dilepton events with two reconstructed b-jets to easily identify the additional jet(s).



- Four rapidity regions: |y| < 0.8   0.8 ≤ |y| < 1.5   1.5 ≤ |y| < 2.1 |y| < 2.1

- Measurement is corrected for detector effects and presented in a well defined fiducial region.

Jet Veto Measurement

- Can express the gap fraction in terms of a ratio of cross-sections:

$$f_{\text{gap}}(Q_0) = \frac{n_{\text{gap}}(Q_0)}{N_{t\bar{t}}} = \frac{\sigma^f_{t\bar{t}+0\text{ jet}}}{\sigma^f_{t\bar{t}}} = 1 - \frac{\sigma^f_{t\bar{t}+\geq 1\text{ jet}}}{\sigma^f_{t\bar{t}}}$$

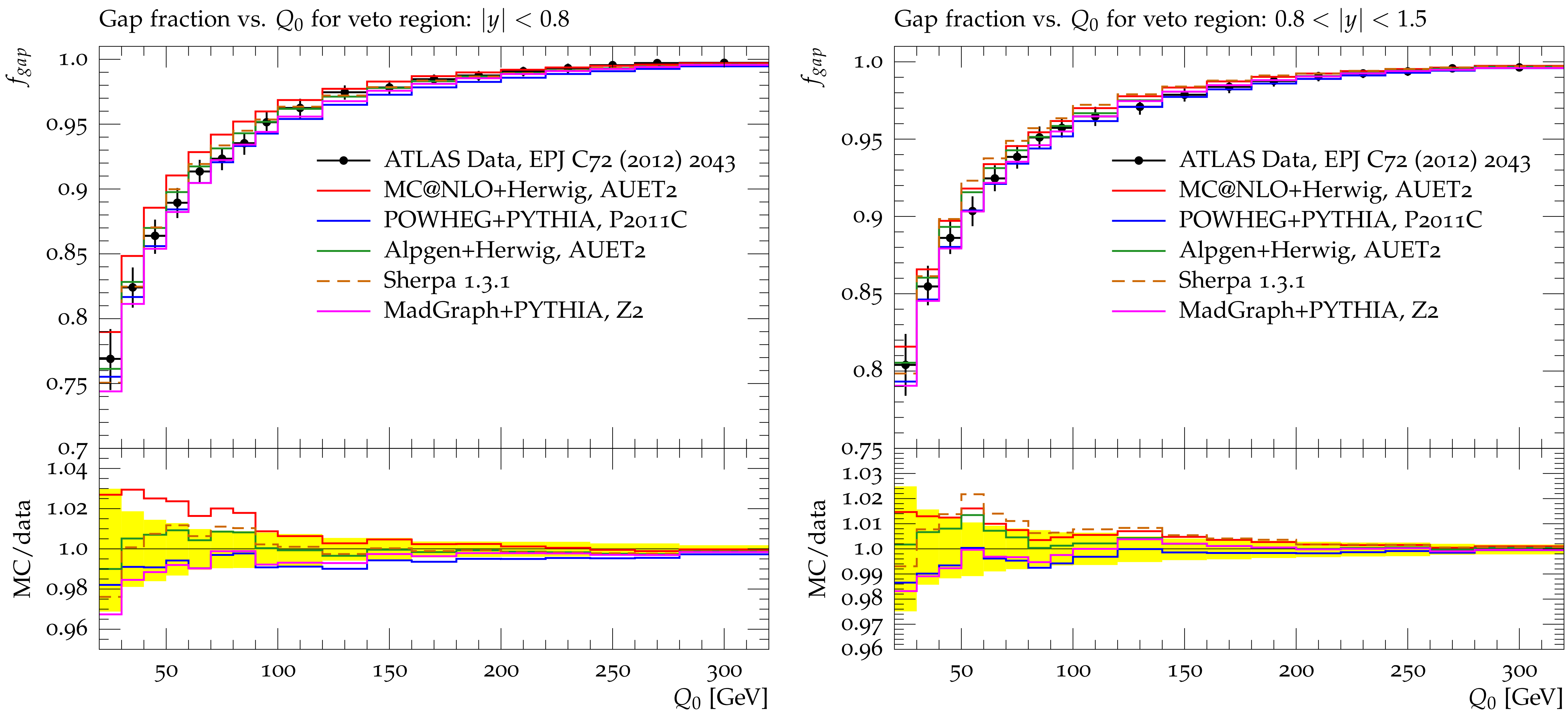
- Where:

$$\sigma^f_{t\bar{t}} = \text{fiducial cross-section for dilepton } t\bar{t} \text{ events.}$$

$$\sigma^f_{t\bar{t}+0\text{ jet}} = \text{fiducial cross-section for dilepton } t\bar{t} \text{ events with no additional jet with } p_T > Q_0 \text{ GeV}$$

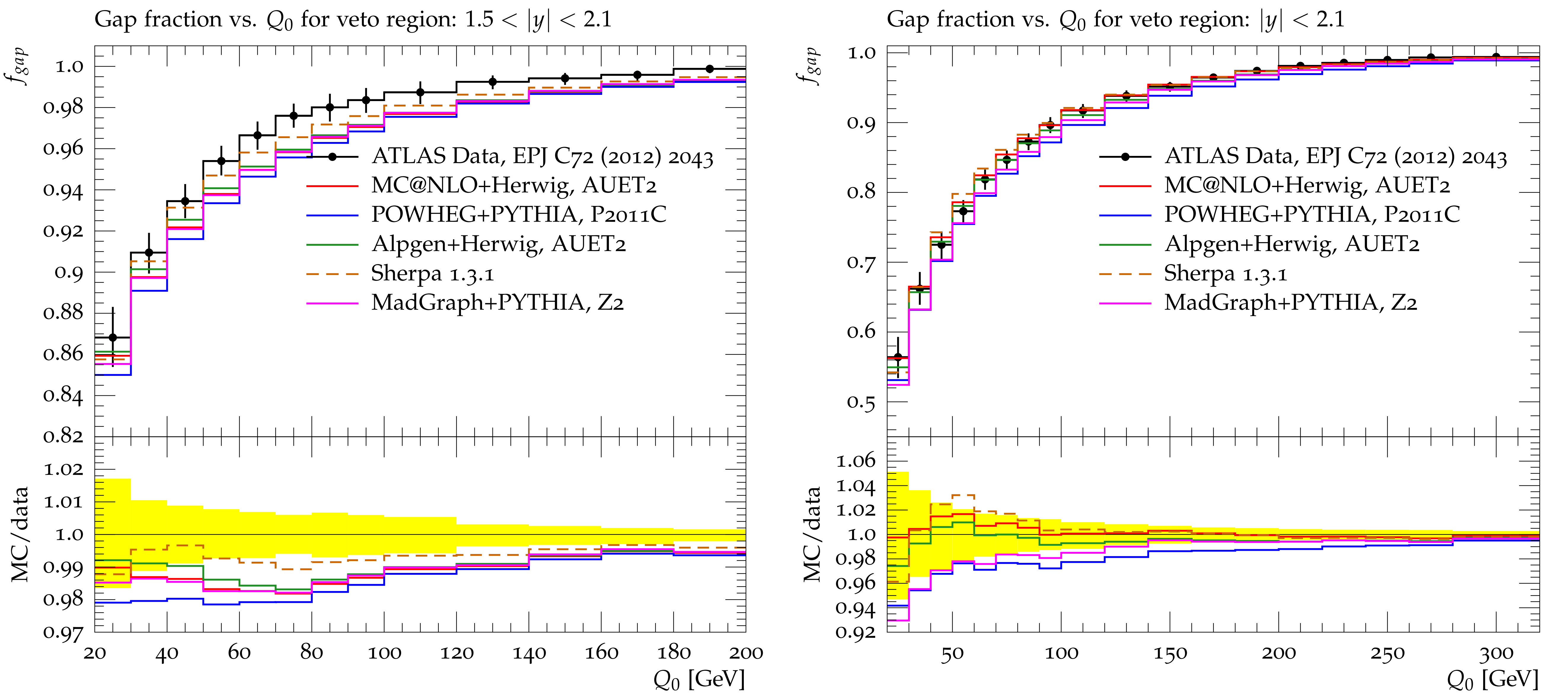
$$\sigma^f_{t\bar{t}+\geq 1\text{ jet}} = \text{fiducial cross-section for dilepton } t\bar{t} \text{ events with at least one additional jet with } p_T > Q_0 \text{ GeV}$$

Jet Veto Measurement



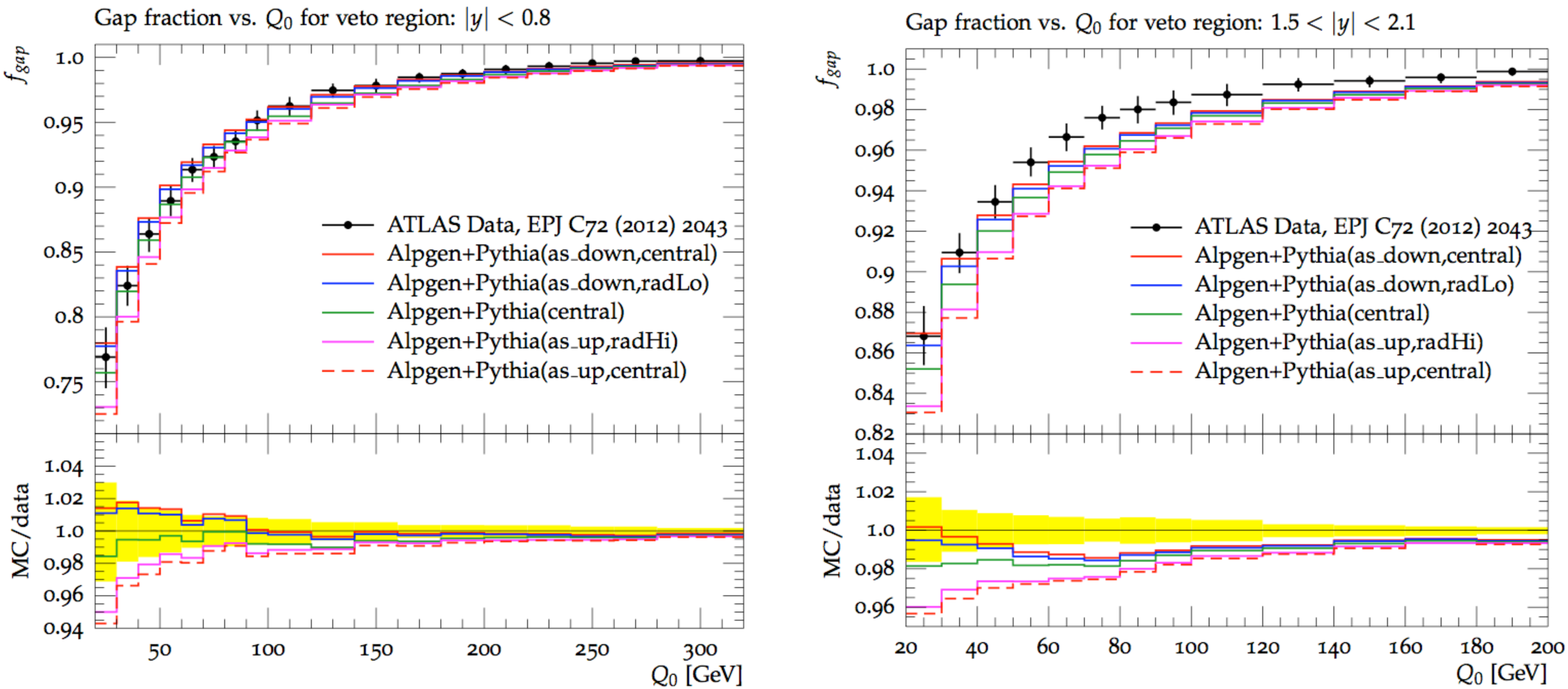
- Generally good description by both NLO & multi-leg generators
- MC@NLO overshoots data in central region (too little radiation).

Jet Veto Measurement



- All generators produce too much radiation in the forward region.
- Best description overall from Sherpa.

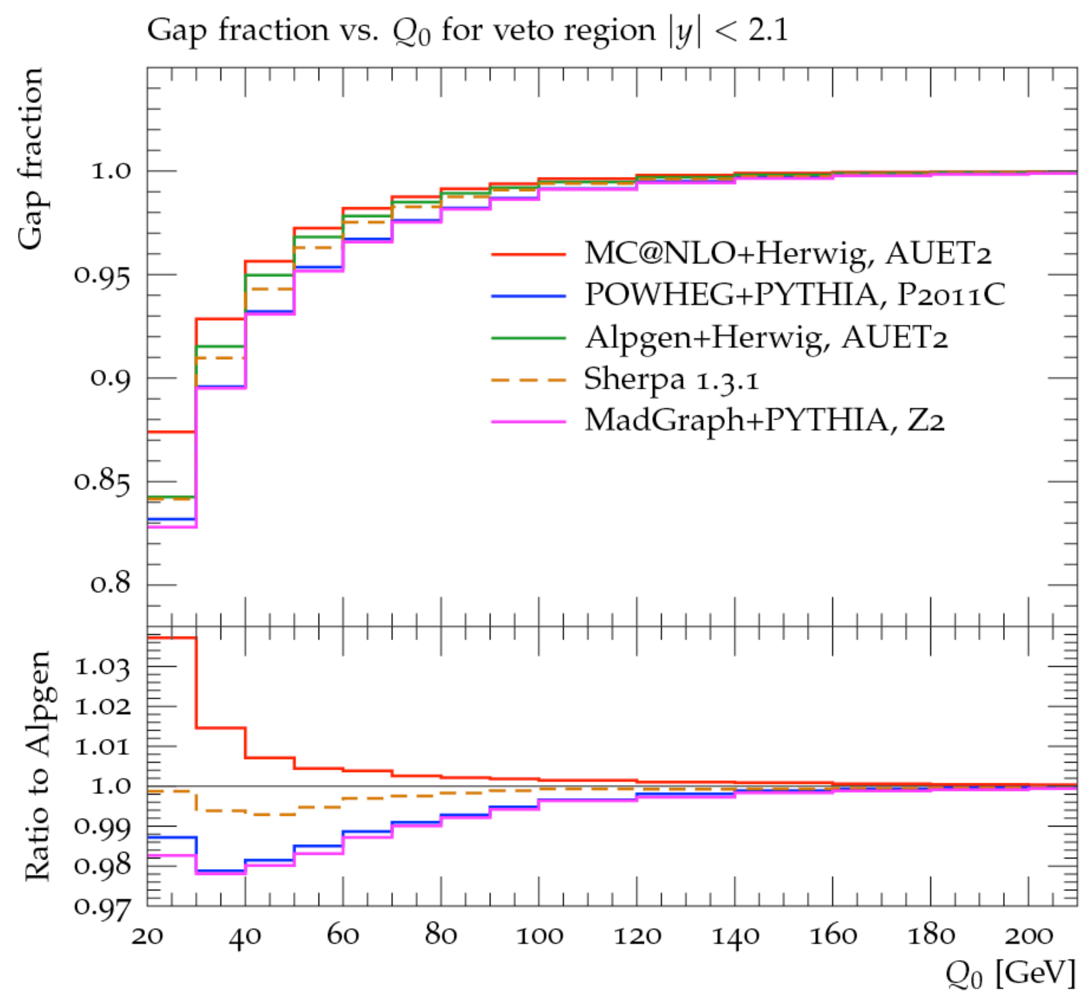
Jet Veto Measurement



- Scale variation is on the renormalization scale of α_s in the matrix element calculation. The radHi/Lo samples also consistently change the scale in the parton shower.
- Scale variations give a reasonable envelope, apart from forward region.
- Samples with increased α_s not consistent with the data.

Jet Veto Measurement

- Can extend definition of gap fraction to measure fraction of events without two jets above the scale Q_0 - More directly probes radiation beyond the first emission.
  - No data measurement, just comparison of MC predictions.



- MC@NLO producing less events with two additional jets than the other generators. Powheg & Madgraph both have slightly more radiation than Sherpa & Alpgen.

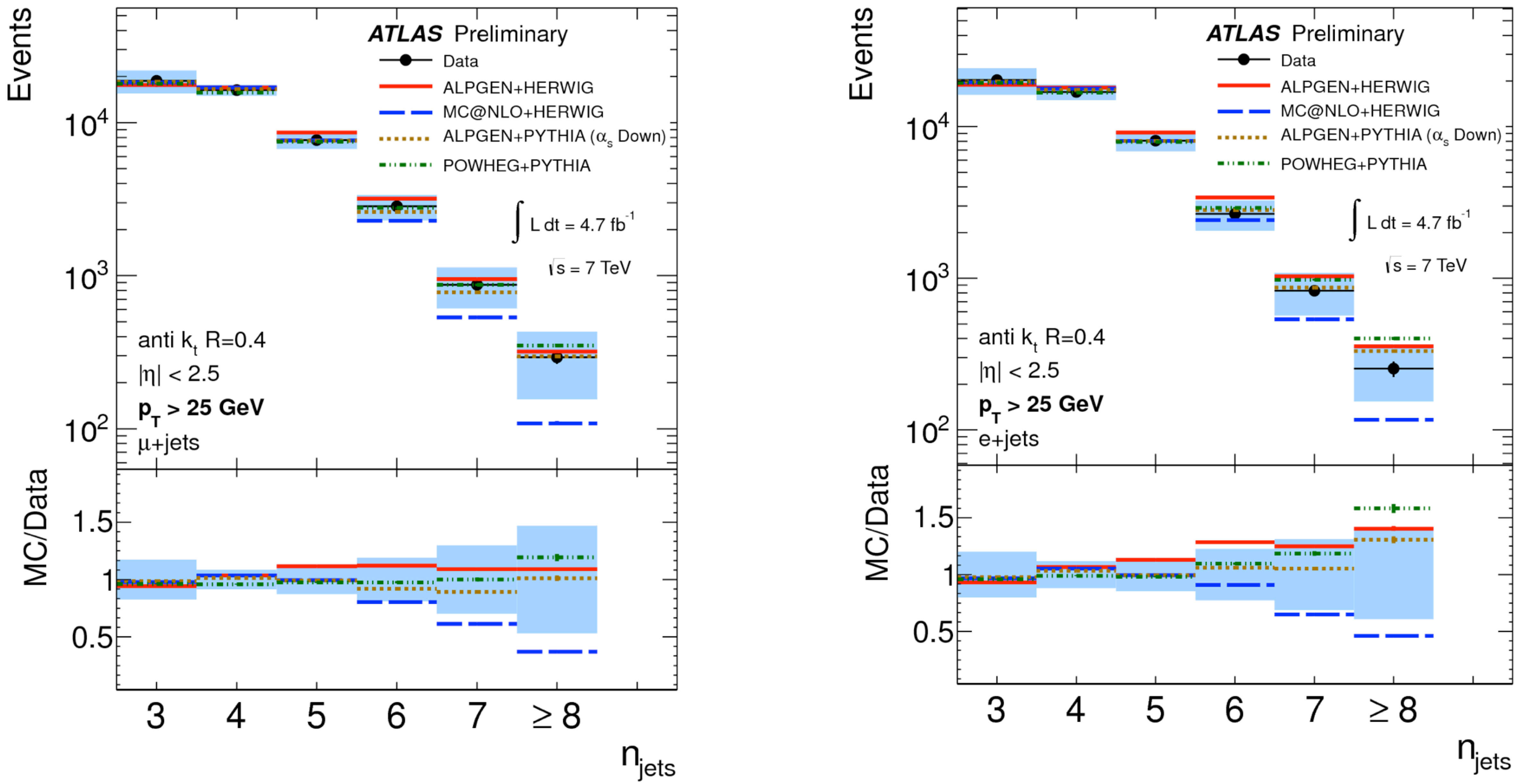
Measurement of the jet multiplicity in top–anti-top final states produced in 7 TeV proton–proton collisions with the ATLAS detector

ATLAS-CONF-2012-155

Jet Multiplicity Measurement

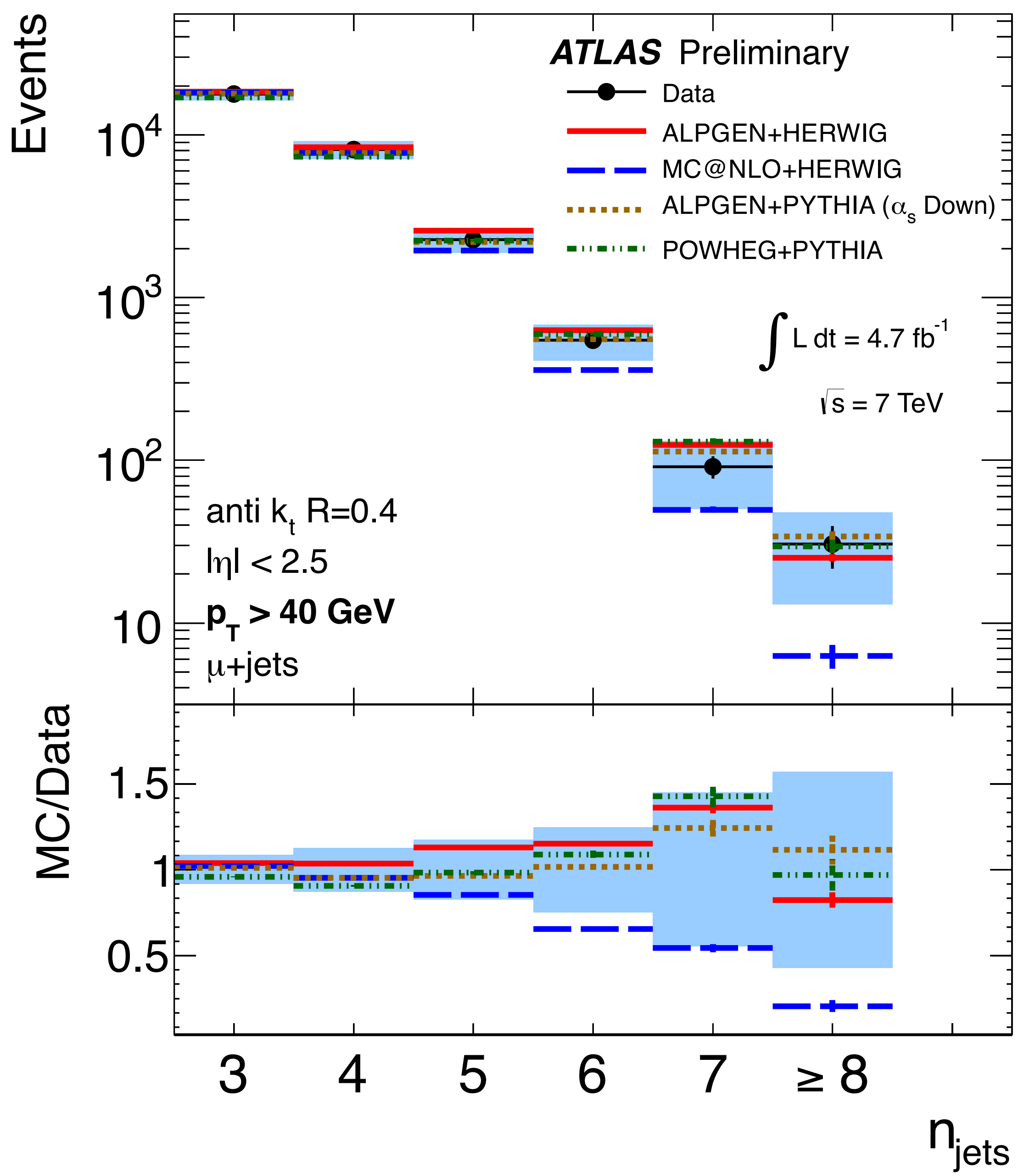
- Using single lepton events, measure the number of events as a function of jet multiplicity, for n(jets) > 2.
- Measurement is made for several different jet p_T thresholds, 25, 40, 60 & 80 GeV.
- Reconstructed distributions are corrected for detector effects & presented in a well measured fiducial region.
- Probes the absolute number of events and higher jet multiplicities compared to the veto analysis.

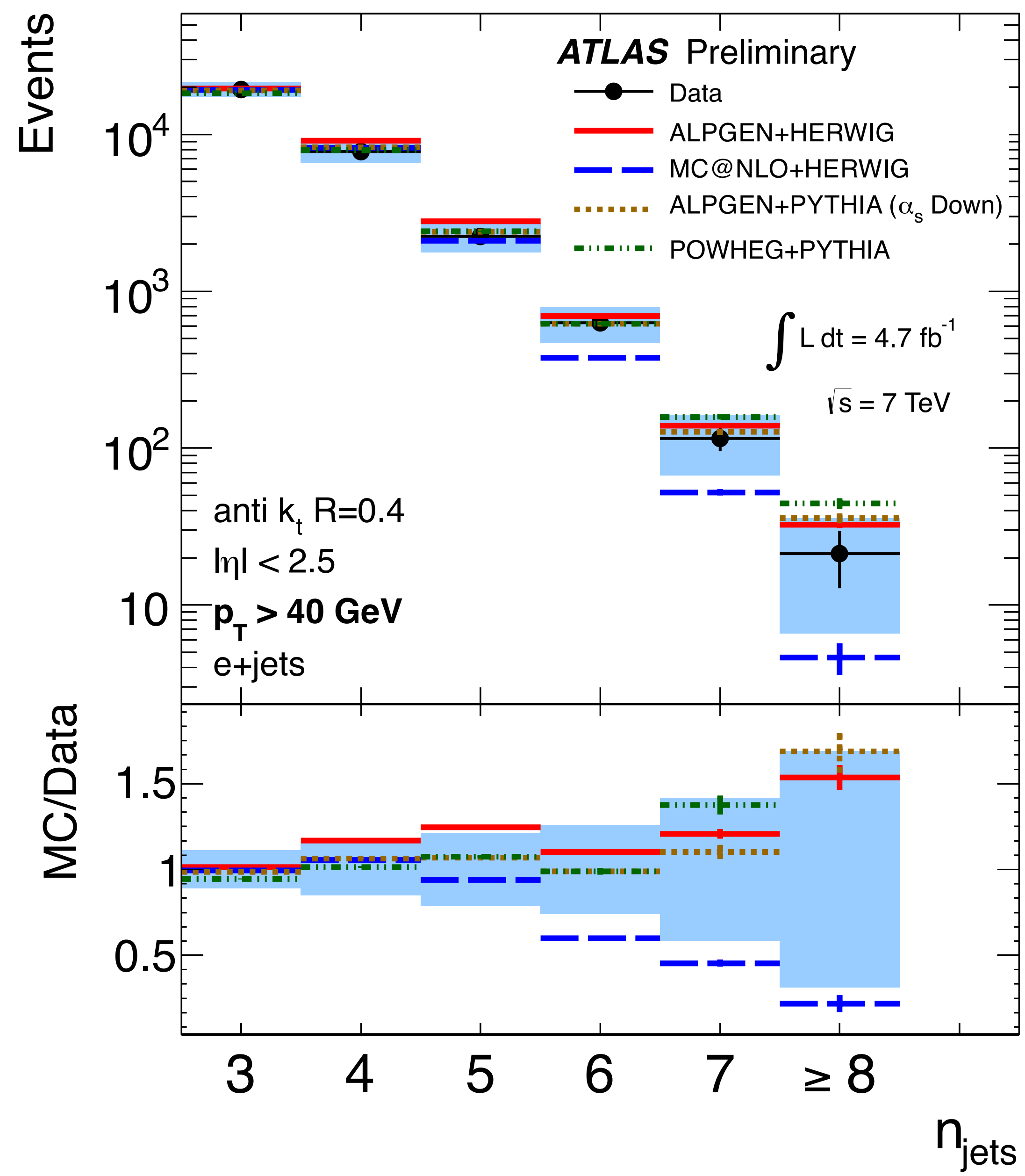
Jet Multiplicity Measurement



- Data well modelled by Powheg and Alpgen - but MC@NLO+Herwig undershoots data at high jet multiplicities.

Jet Multiplicity Measurement





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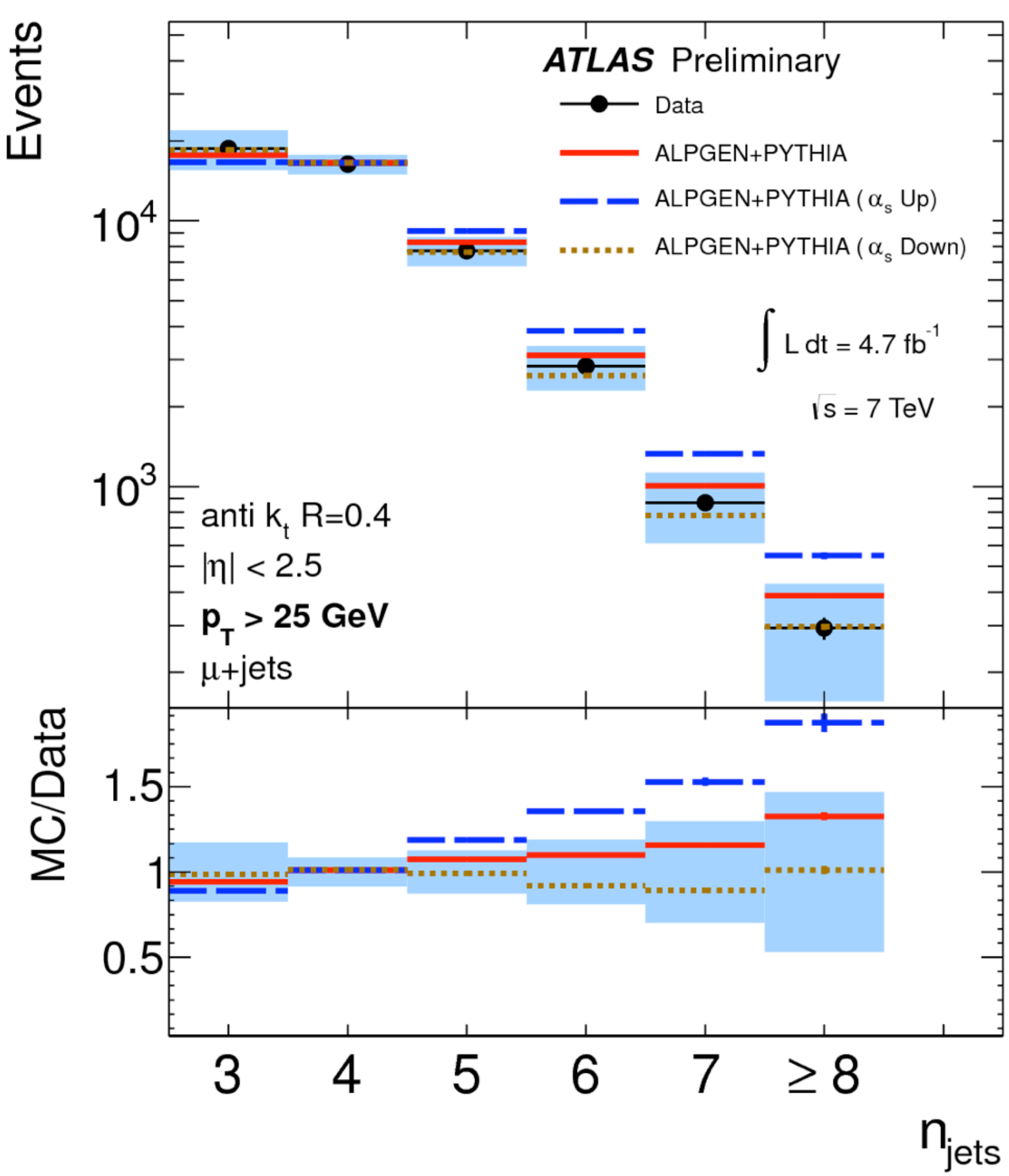

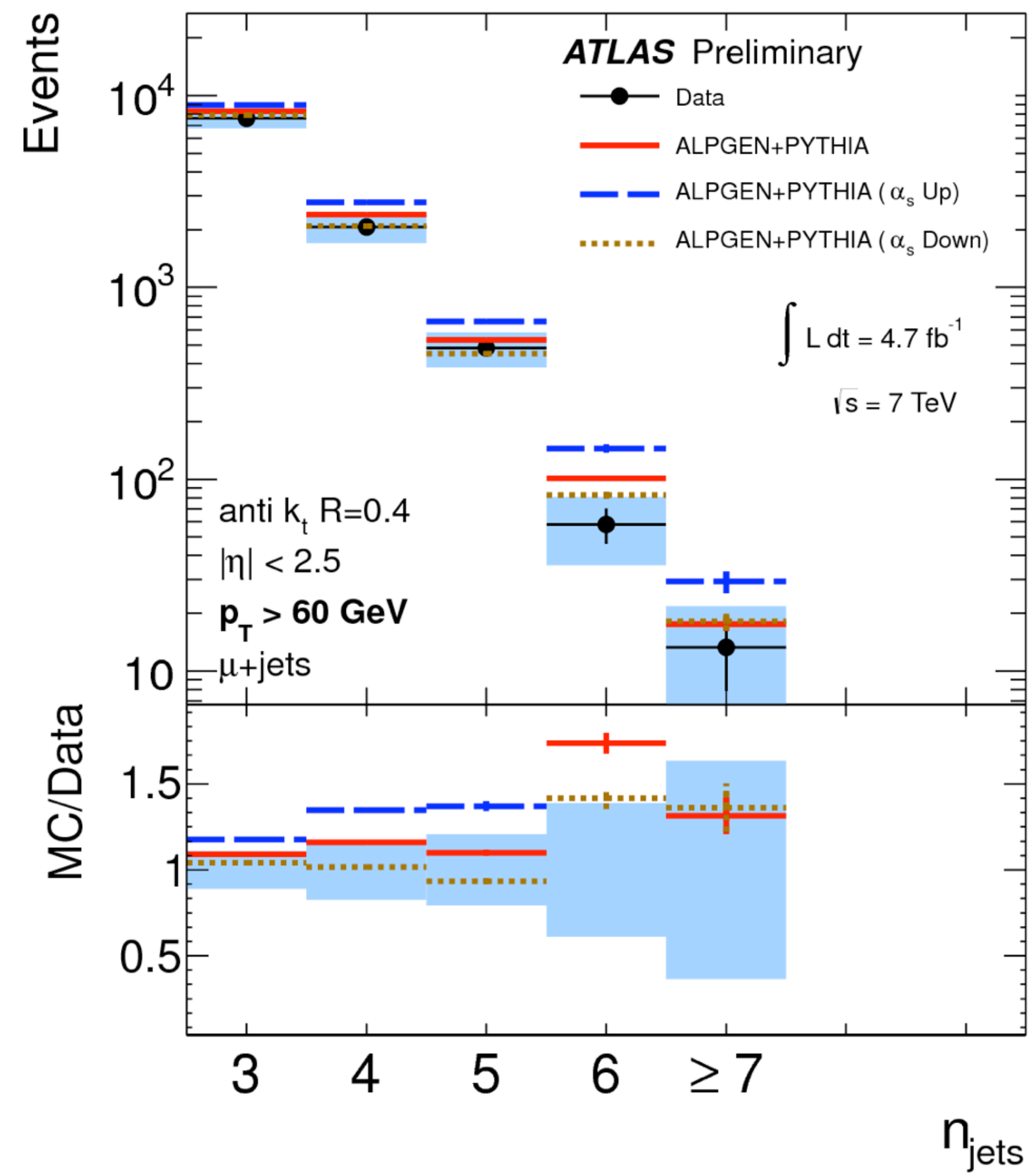

- Alpgen samples with scale variations give a reasonable envelope.
- Samples with increased α_s not consistent with the data - consistent picture with gap fraction analysis.

Jet shapes in top quark events

ATL-PHYS-PUB-2012-006

Jet Shapes

- Gap fraction & jet multiplicity analysis very good for probing high pT jet radiation, but no real sensitivity for softer radiation.
- Measurements of jet shapes are sensitive to the evolution of the hard parton into a jet of stable particles (hadronization also important).
- Top sample provides a clean sample of jets, both light flavour jets (from W decay) and heavy flavour jets ($t \rightarrow Wb$) to test the MC modelling.

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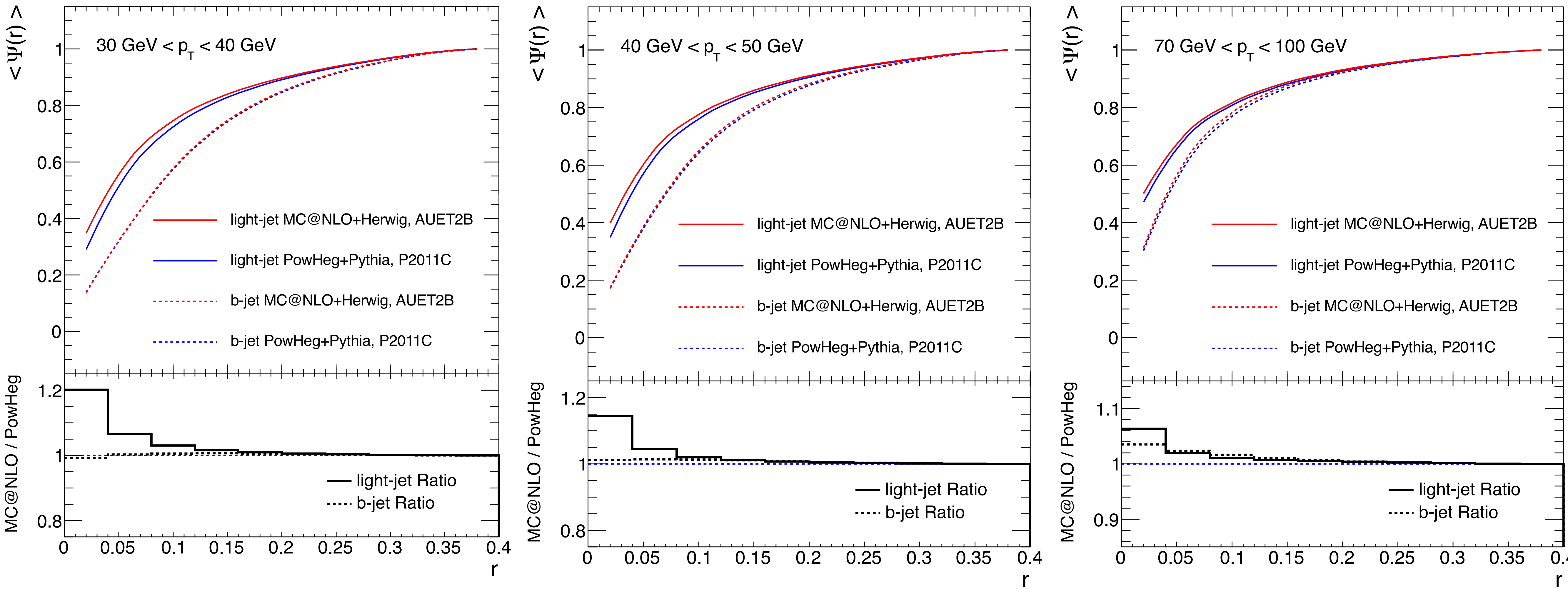
Jet Shapes

- Study conducted at particle level.
- Study:

$$\Psi(r) = \frac{p_T(0,r)}{p_T(0,R)}; \quad r \leq R.$$

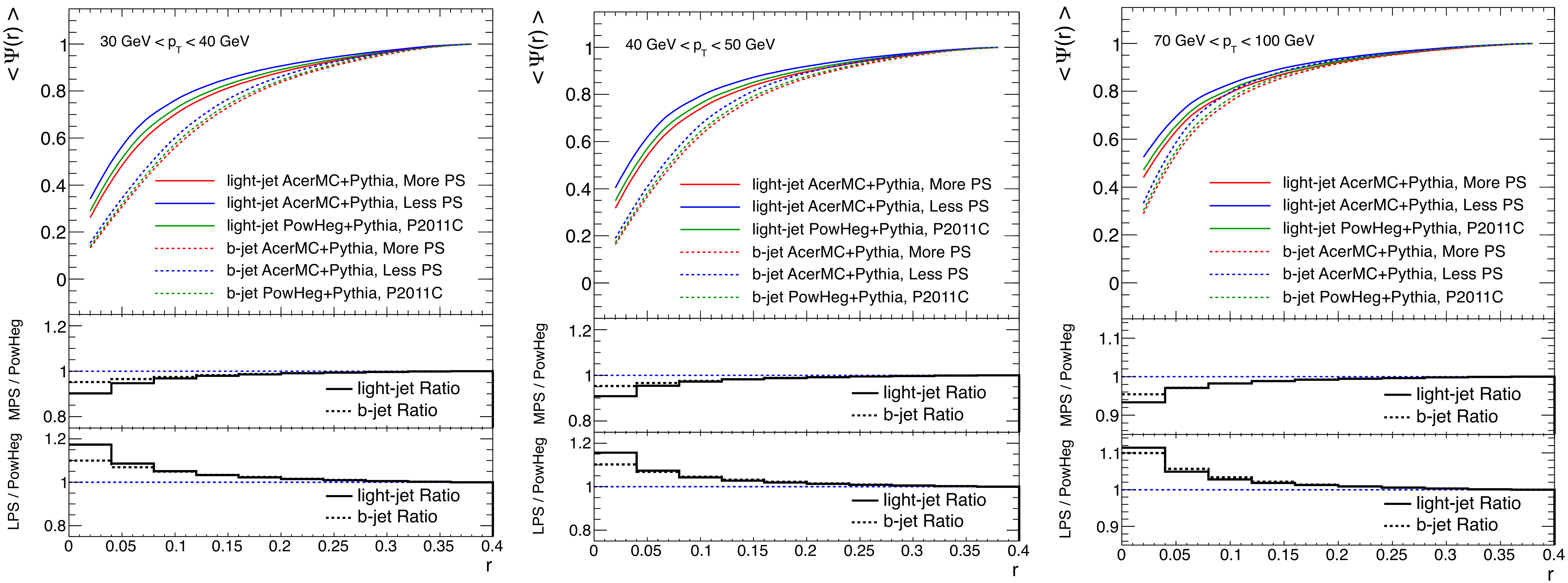
- Jets are separated according to whether they originate from the b-quark ($t \rightarrow Wb$) or the hadronic W boson decay ($W \rightarrow qq'$).
- Jets are required to have $p_T > 30$ GeV and to be well separated from other jets ($\Delta R > 0.8$).
  - Jets required to match to the partons from the top decay and are separated into jets originating from b & light-flavour quarks.

Jet Shapes



- Some spread between MC@NLO+Herwig & Powheg+Pythia for light jet shapes.
- b-jet shapes are more consistent.

Jet Shapes



- Samples with varied pythia parameters produce changes in both light and b-jet shapes.
- Potential to measure these distributions & constrain the models.

Pseudo top quark distributions

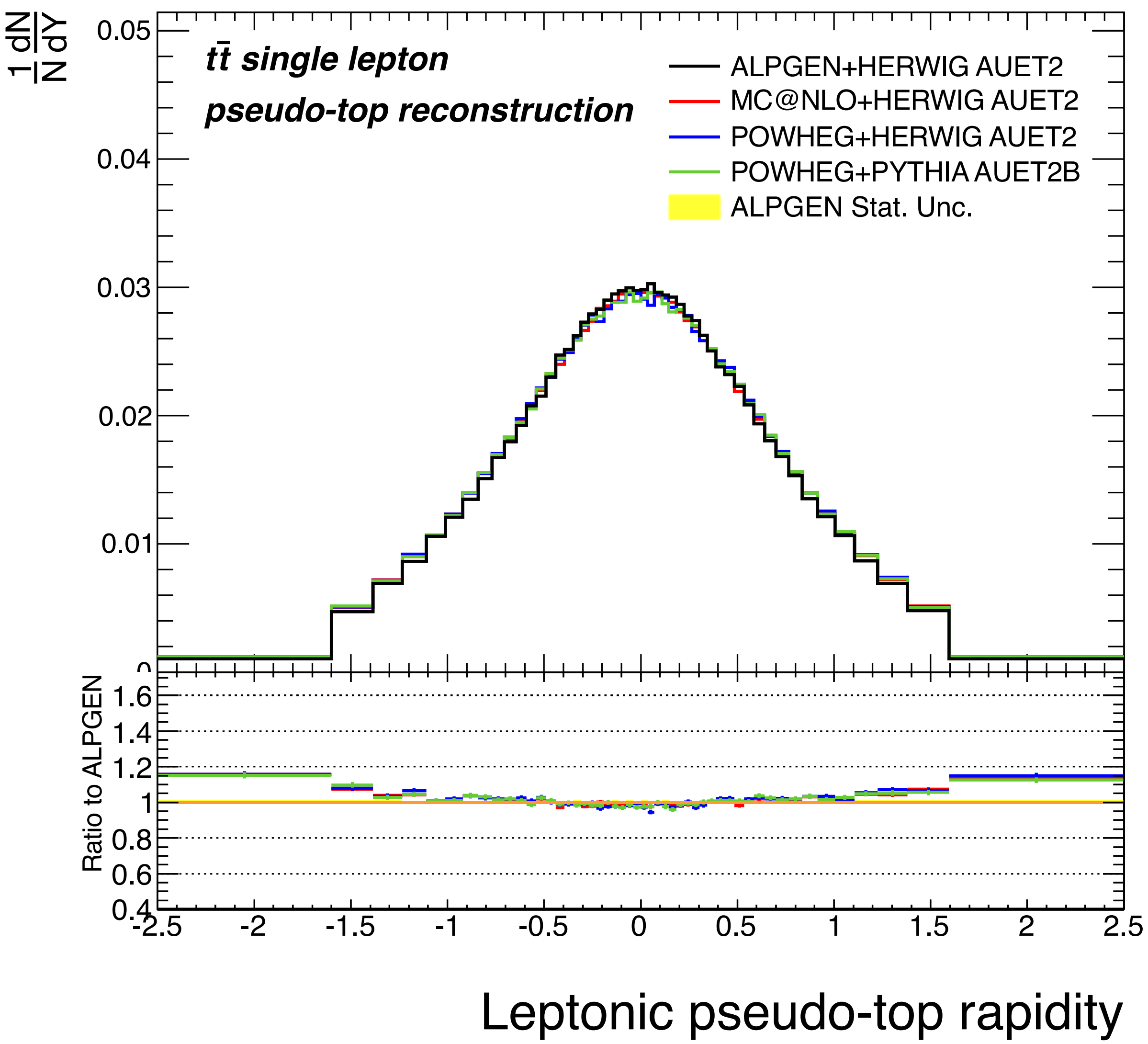
ATL-PHYS-PUB-2012-006

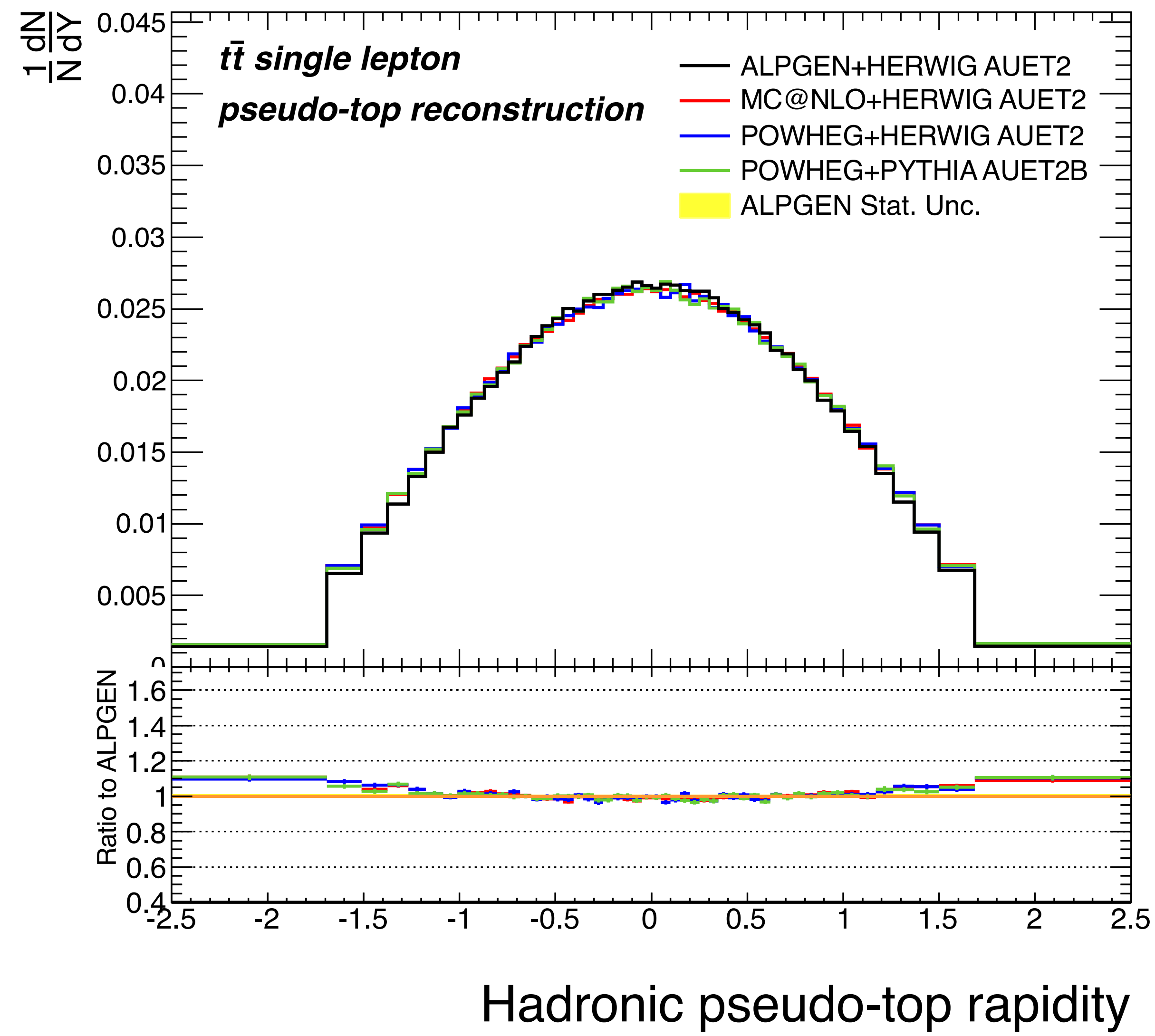
Pseudo Top Quark Reconstruction

- Select events at particle level consistent with the top quark lepton + jets final state:
  - 1 lepton, ≥4 jets (p_T > 25 GeV $|\eta|$ < 2.5), 2 of which must be matched to b-hadrons.
- Then build pseudo-top quark vectors from simple algorithm:
  - Hadronic W boson from two jets closest in ΔR.
  - Leptonic W boson from lepton and sum of neutrinos.
  - Build hadronic top from hadronic W boson and b-jet combination which best matches the top mass.
  - Leptonic top then built from leptonic W boson plus remaining b-jet.
- Major difference to 'traditional' top reconstruction - no attempt to correct back to parton level.
- Definition very close to objects measured in detector - good candidate for unfolded measurements at hadron level.

Pseudo Top Quark Distributions

- Comparison of shape of MC predictions:

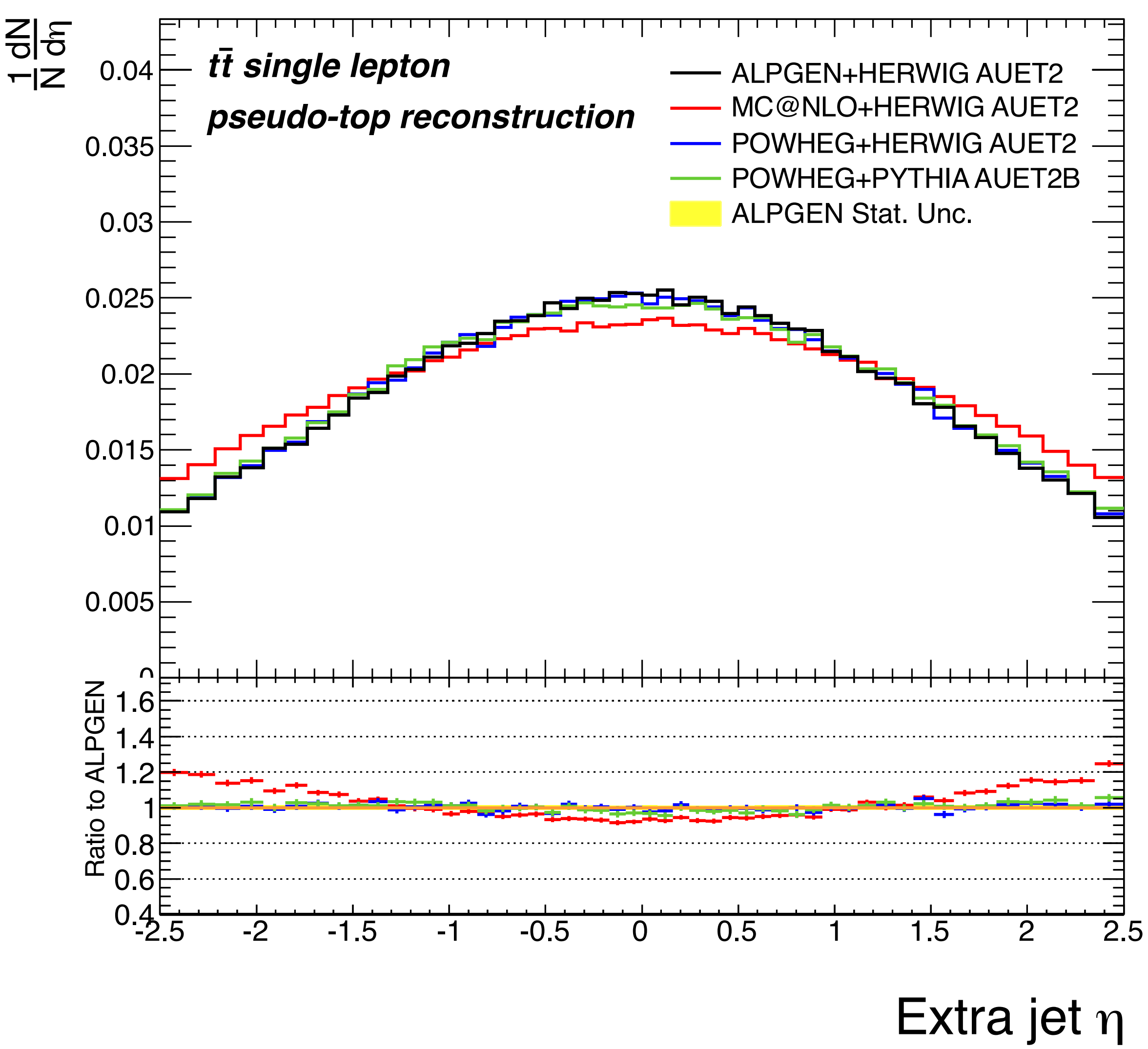


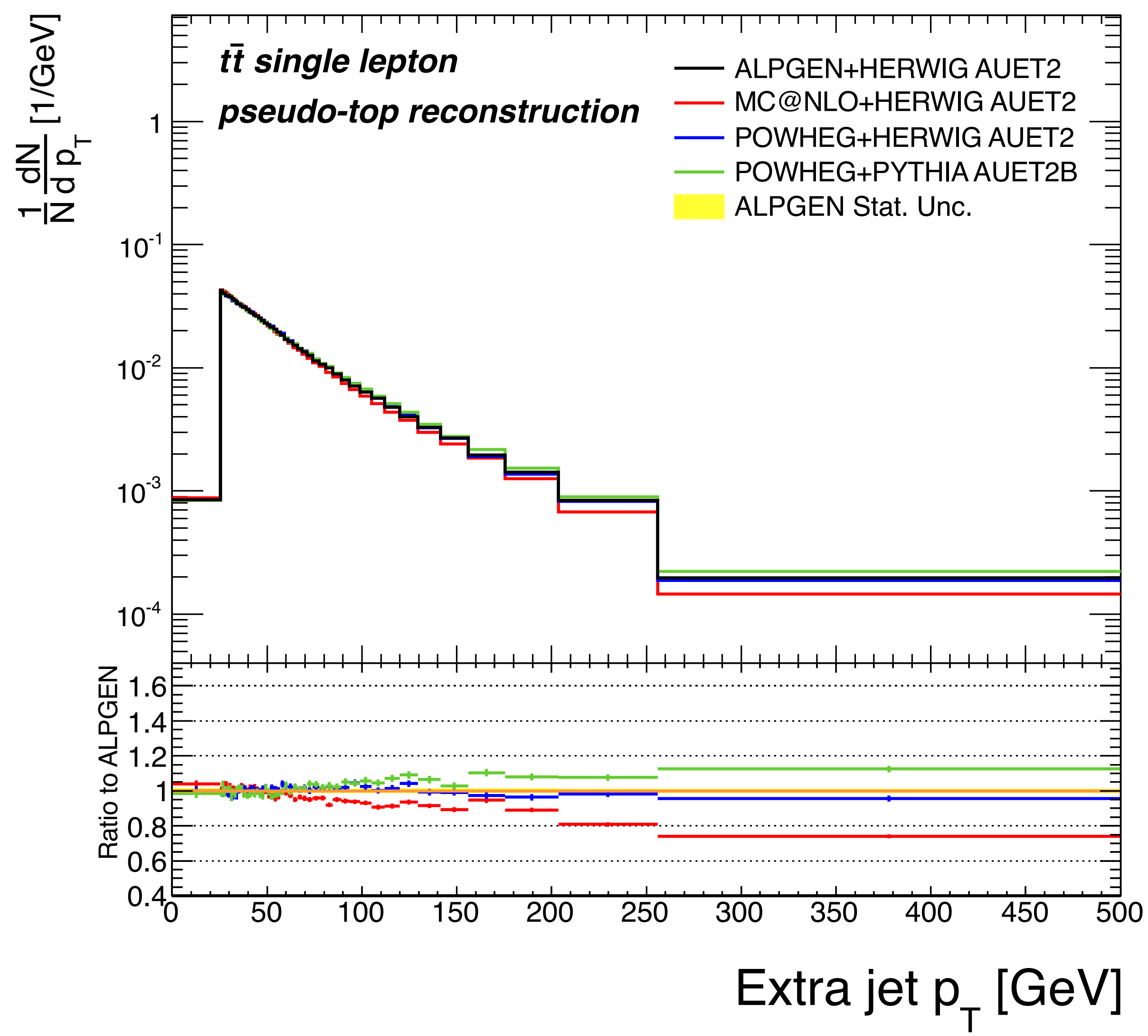


- Alpgen producing more central tops than other generators.

Pseudo Top Quark Distributions

- Comparison of shape of MC predictions for jets not used in the top reconstruction:





- MC@NLO+herwig produces significantly broader η distribution - as seen in JHEP 0701 (2007) 013 - also consistent with deficit of jets in MC@NLO for |y|<0.8 in jet veto analysis.

Summary

- Precise measurements of top quark properties rely on a good understanding of the modelling of top quark events.
- Presented first two ATLAS measurements that give important information on the modelling of hard jet radiation in top events.
    - Indications that MC@NLO+Herwig produces too few high pT jets.
    - Some tension in the forward region for all generators - too many jets produced.
- MC study of jet shape variables provides a window on softer QCD effects.
- This should just be the start of LHC measurements - the high luminosity 8 TeV data will provide a great top sample for further studies.

Links

- Top quark production with a veto on central jet activity:
  - http://arxiv.org/abs/1203.5015
  - Data points in HepData: http://hepdata.cedar.ac.uk/view/ins1094568
  - Rivet routine: https://rivet.hepforge.org/trac/browser/tags/rivet-1.8.1/src/Analyses/ATLAS_2012_I1094568.cc
- Jet multiplicity in top quark events:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-155/
- Public note with updated MC comparisons, jet shapes & pseudo tops:
  - ATL-PHYS-PUB-2012-006, soon at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

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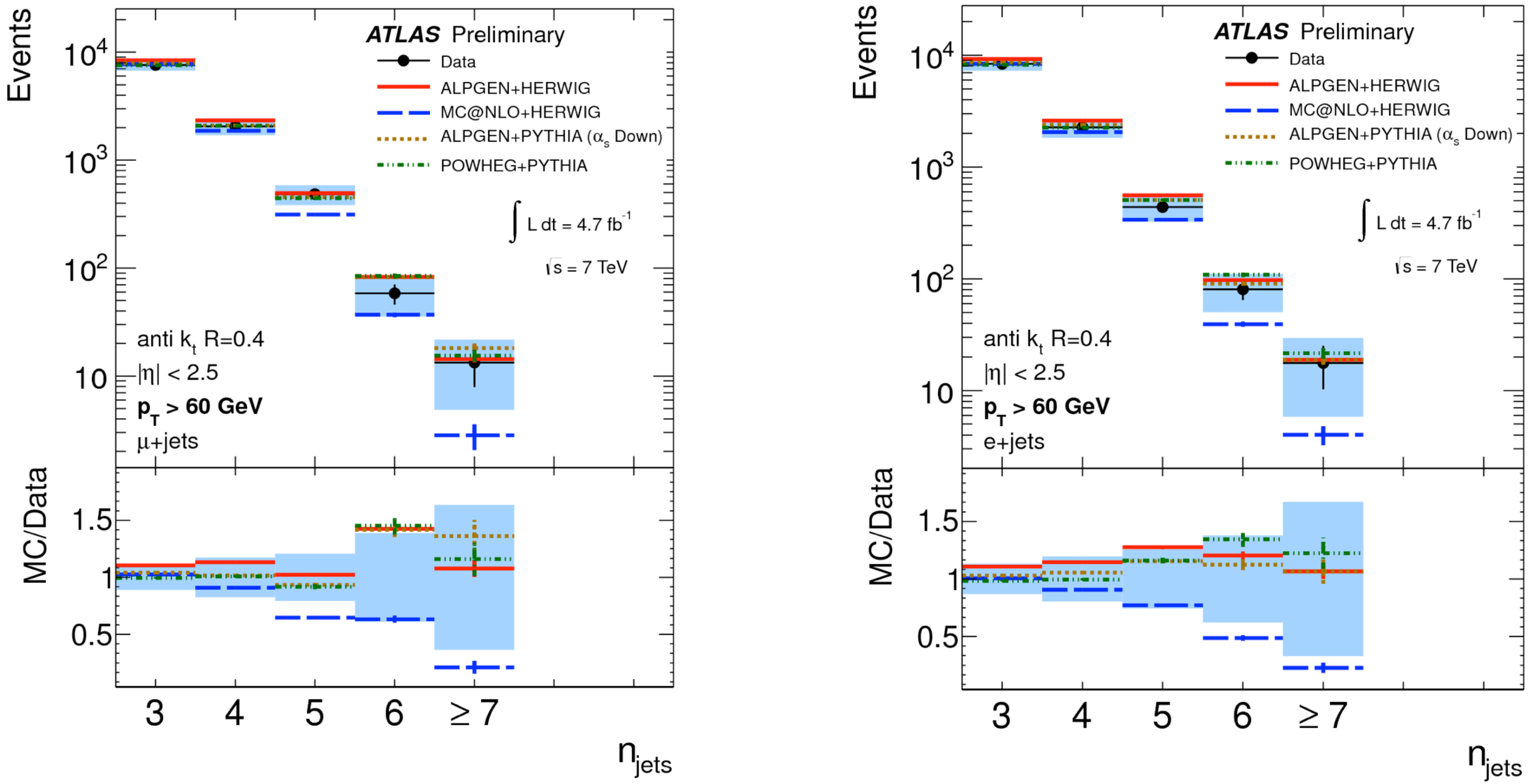
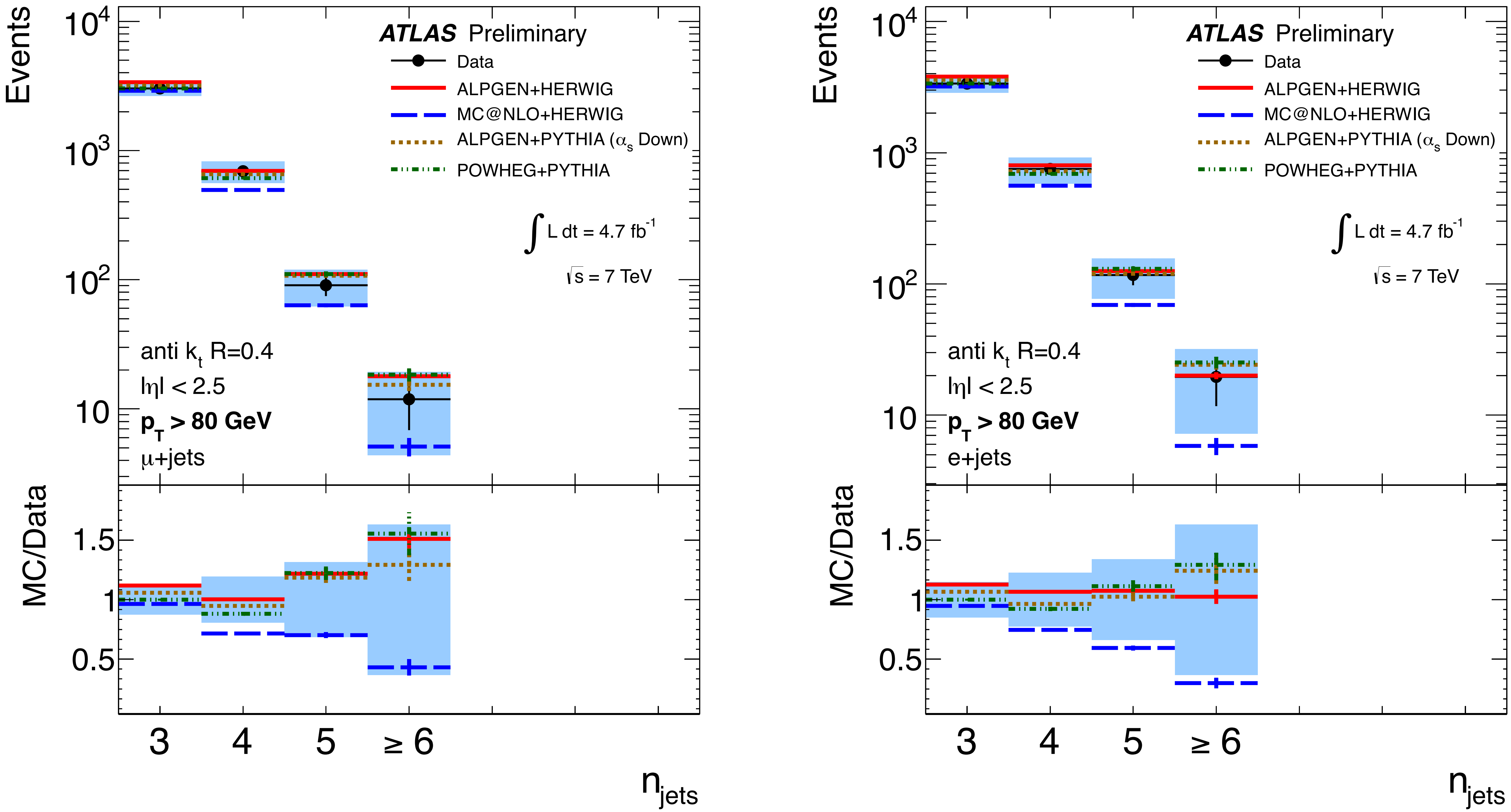
Backup

Jet Multiplicity Measurement



- Data well modelled by Powheg and Alpgen - but MC@NLO+Herwig undershoots data at high jet multiplicities.

Jet Multiplicity Measurement



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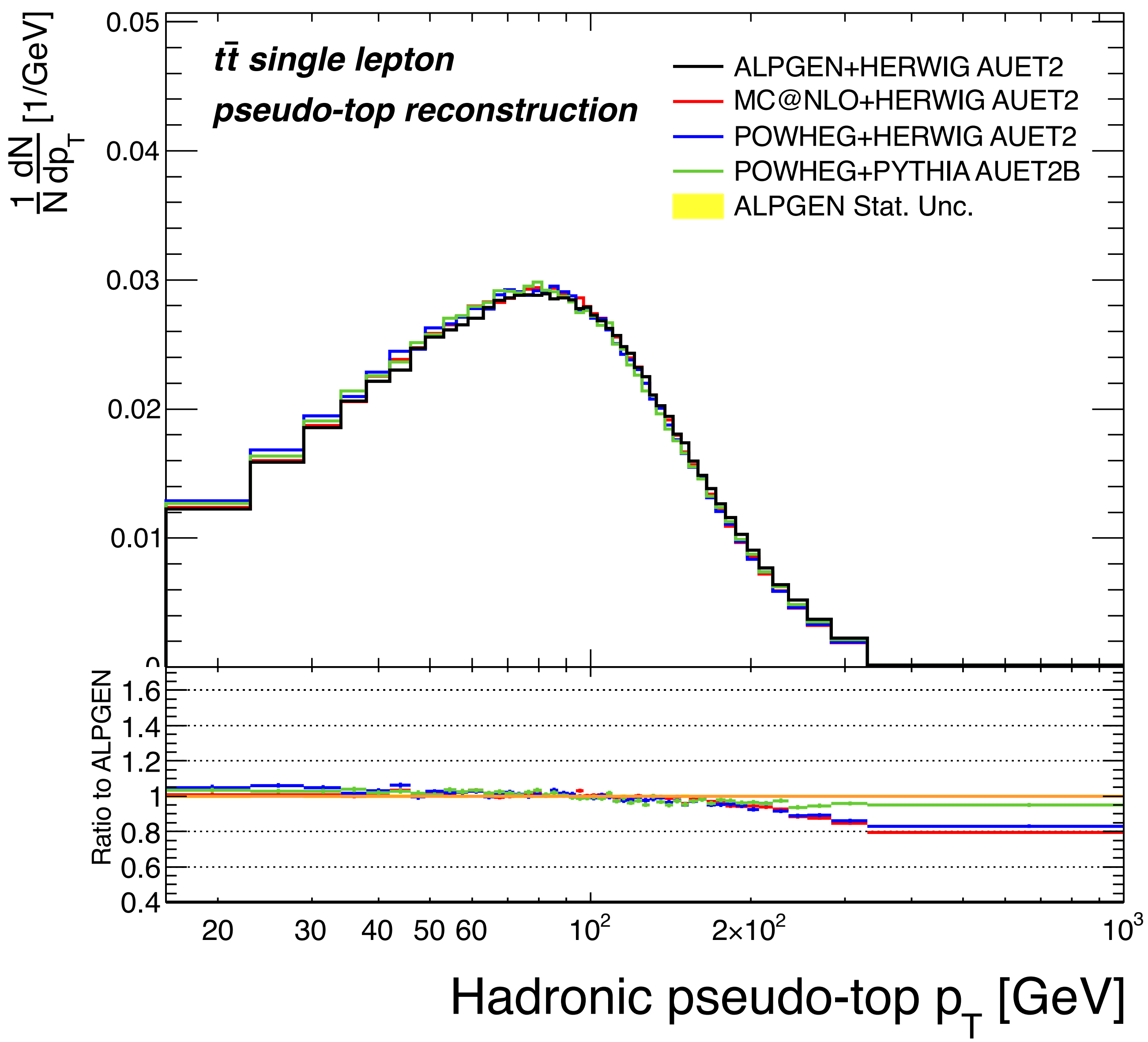

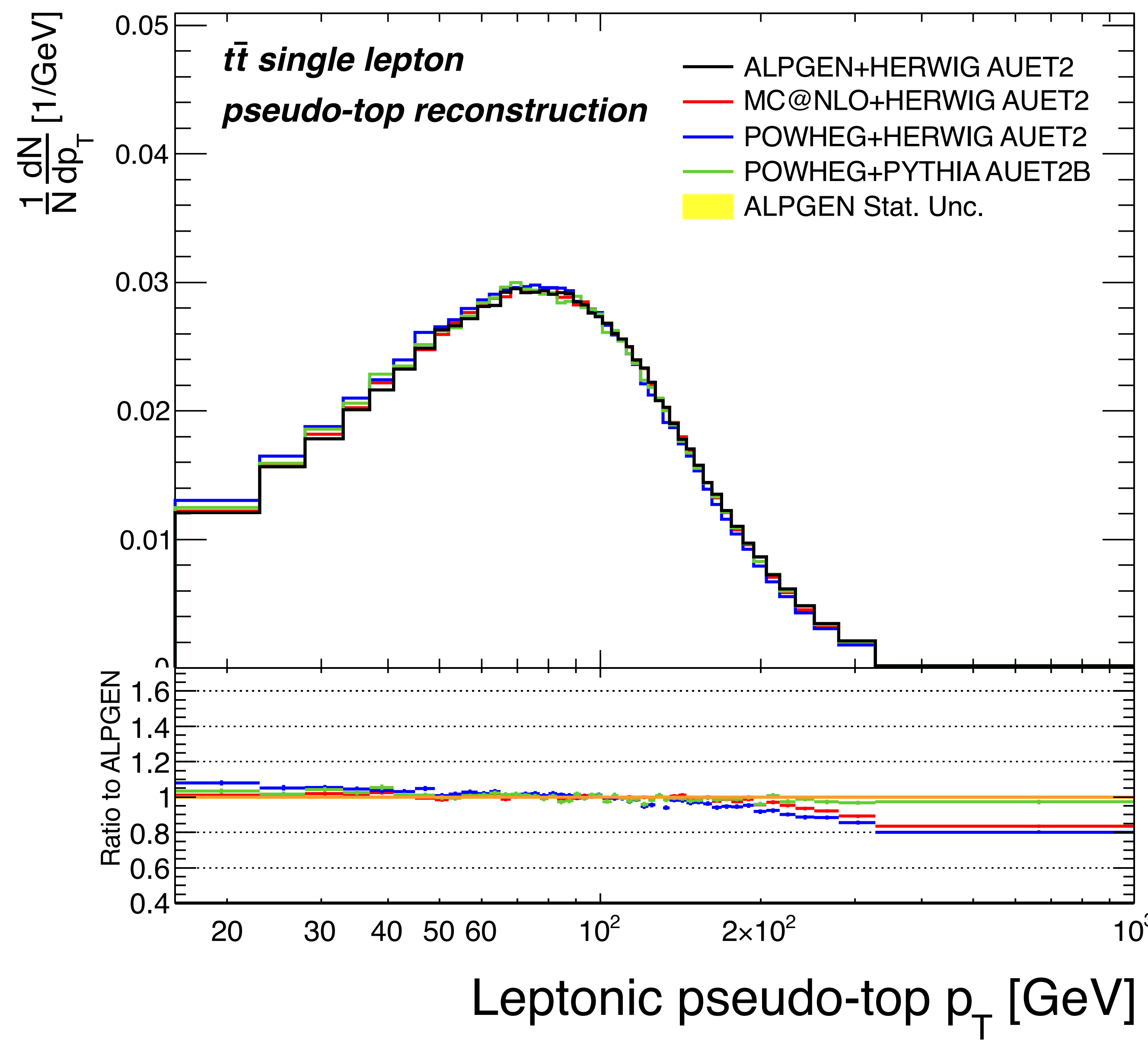

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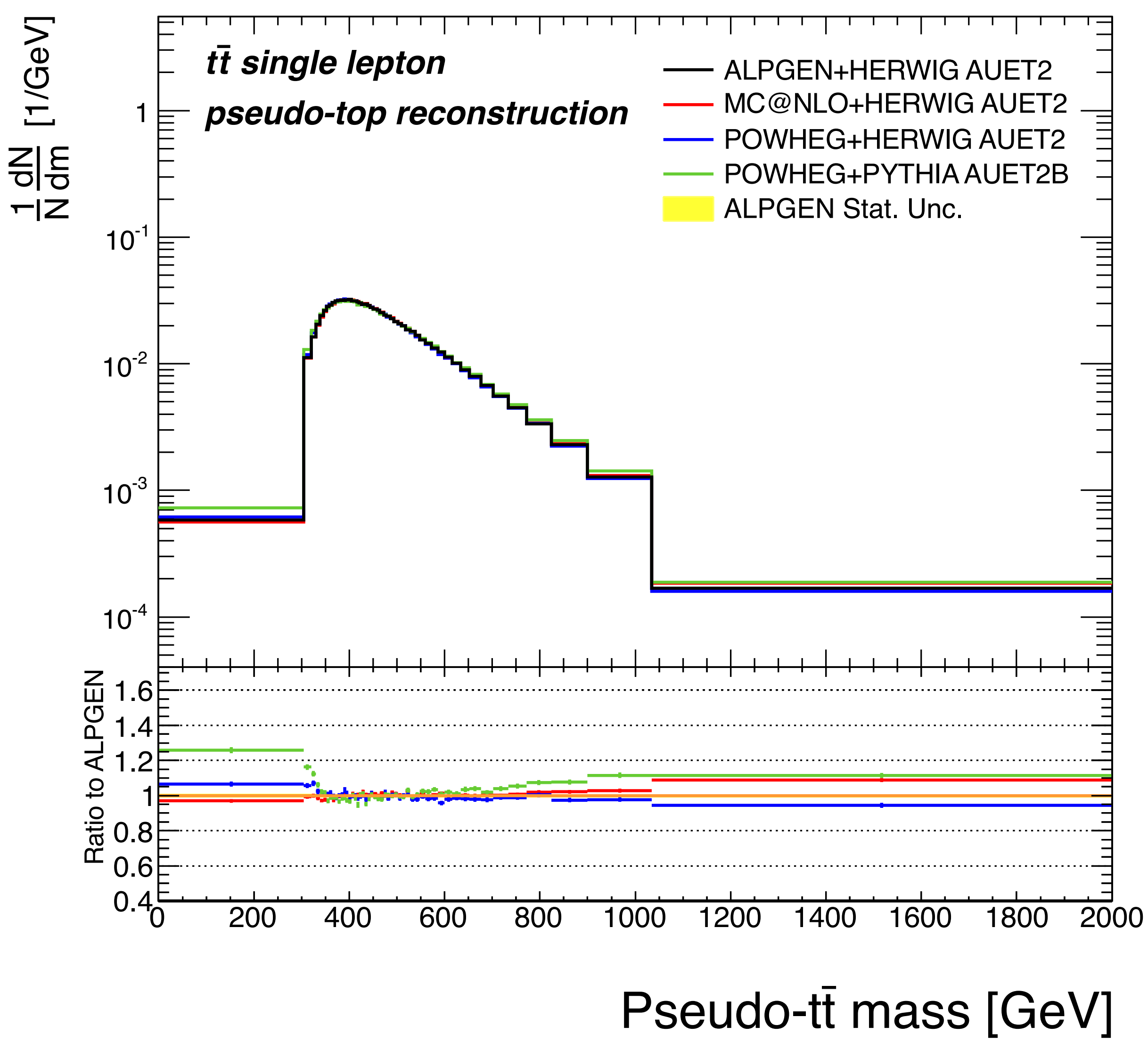

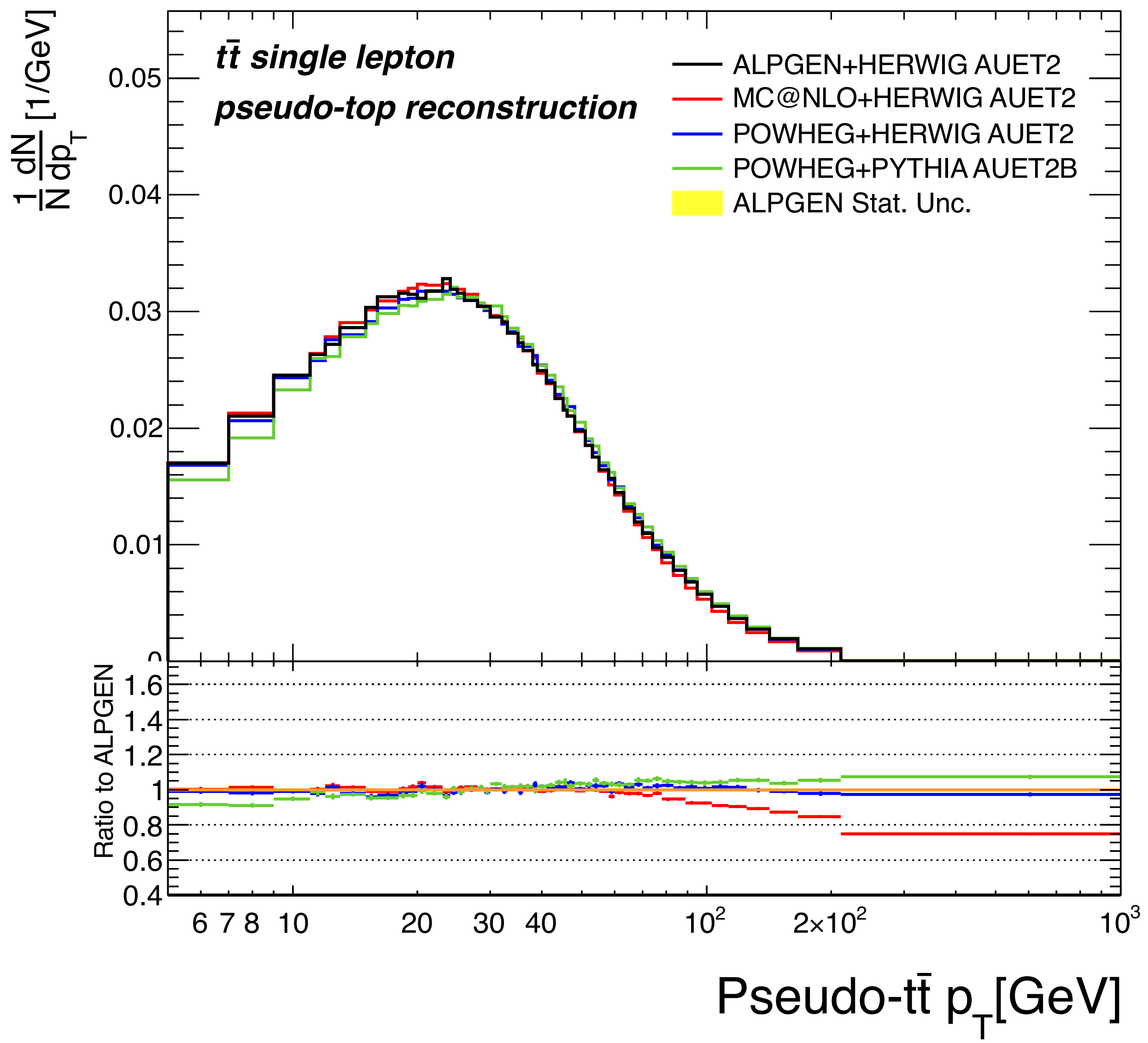

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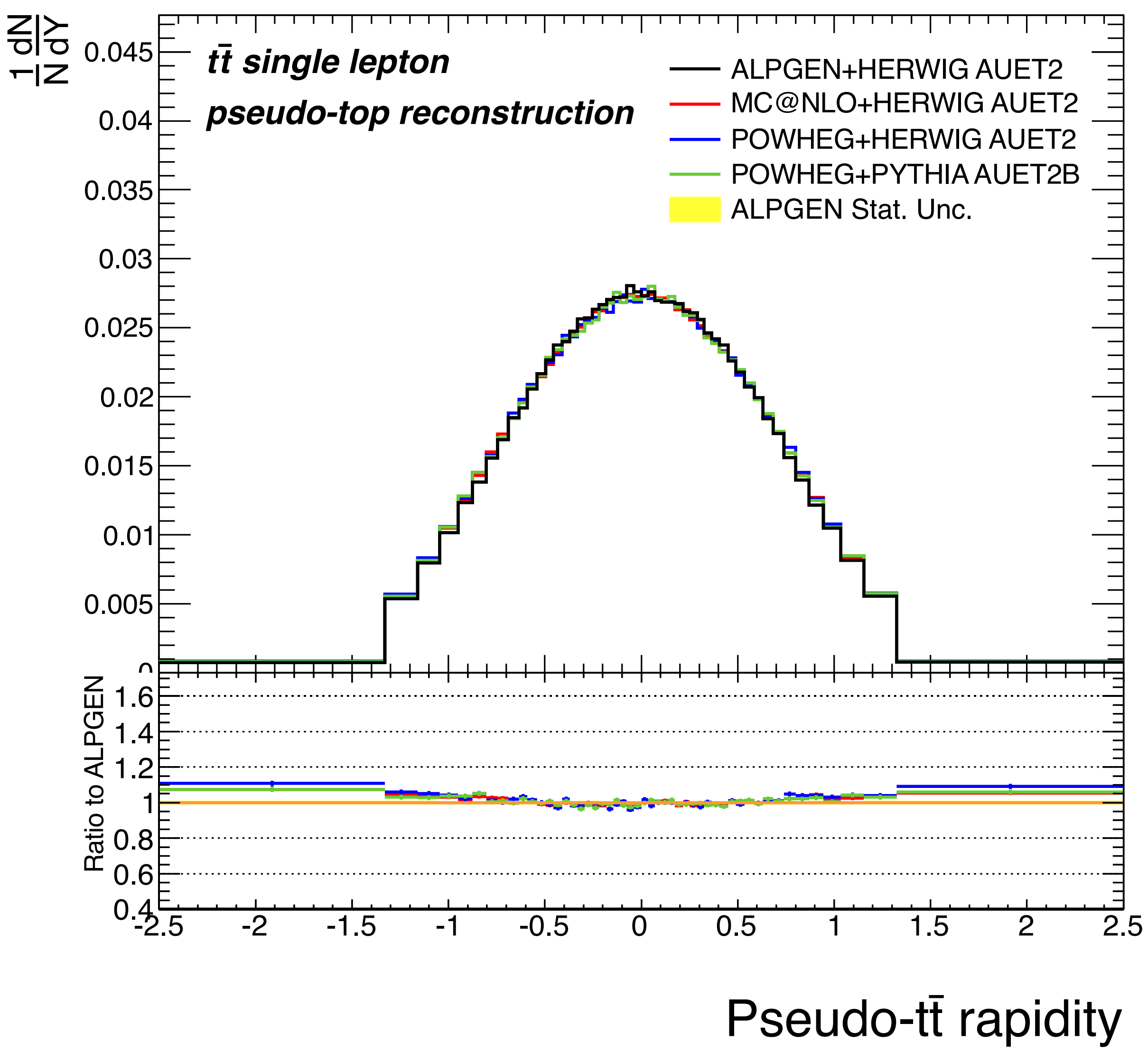

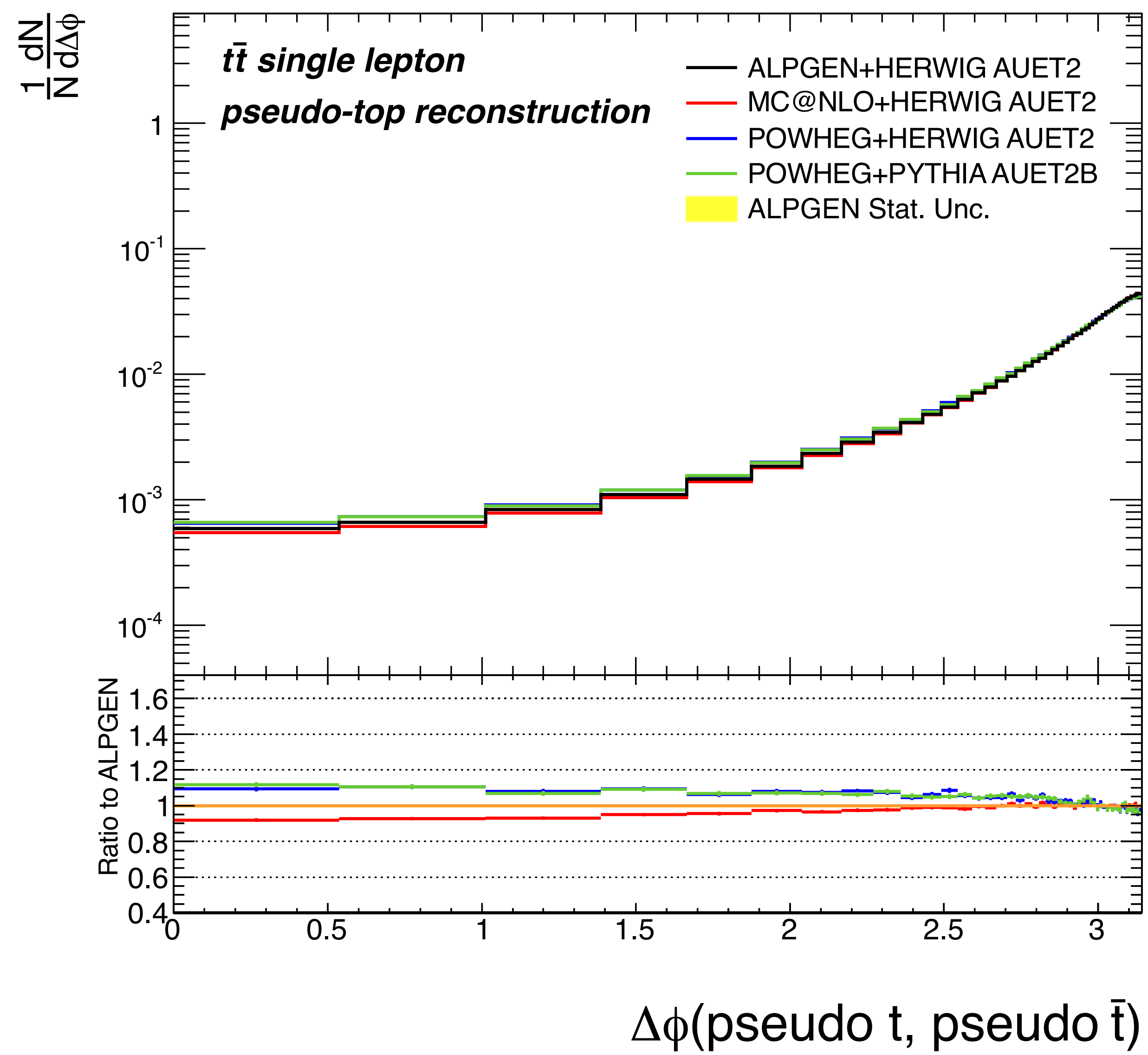

Pseudo Top Quark Distributions

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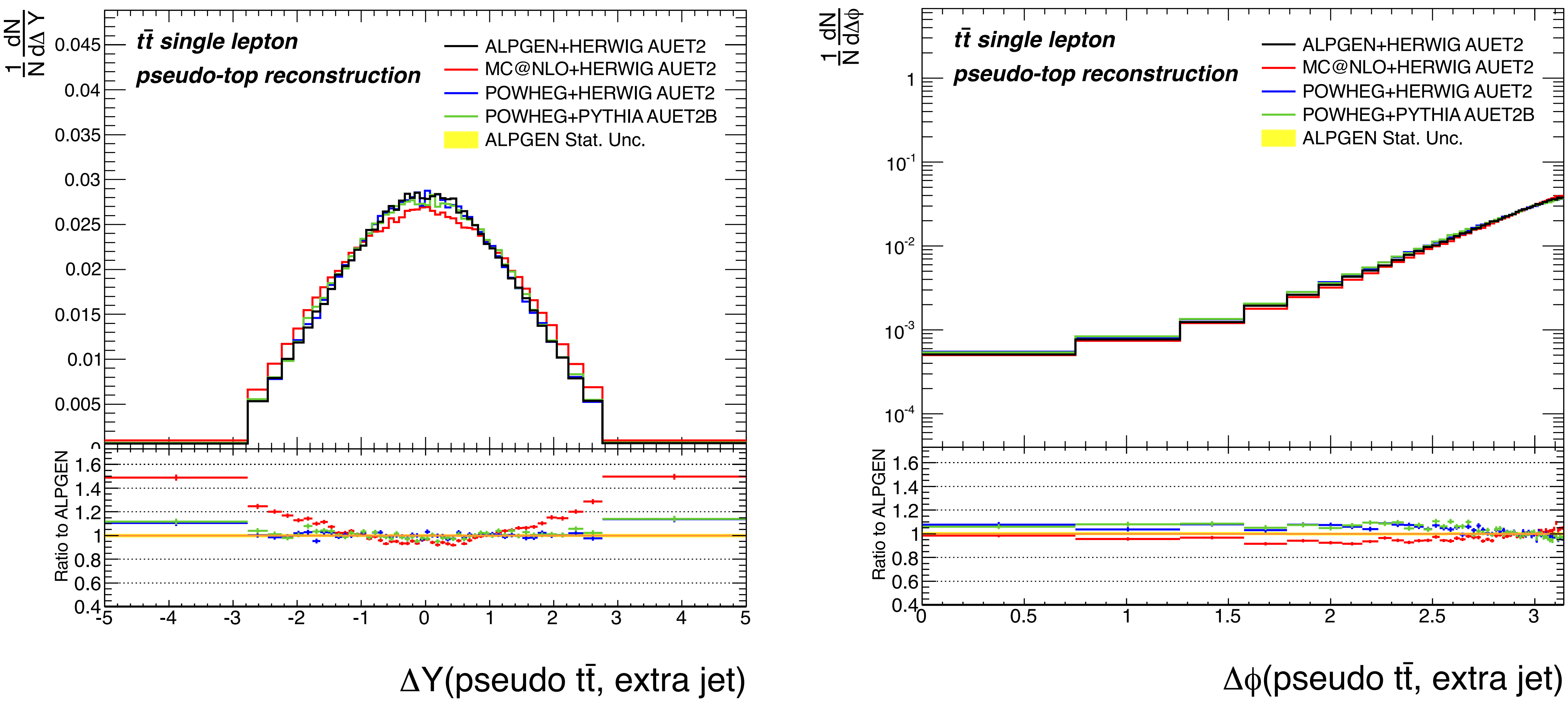
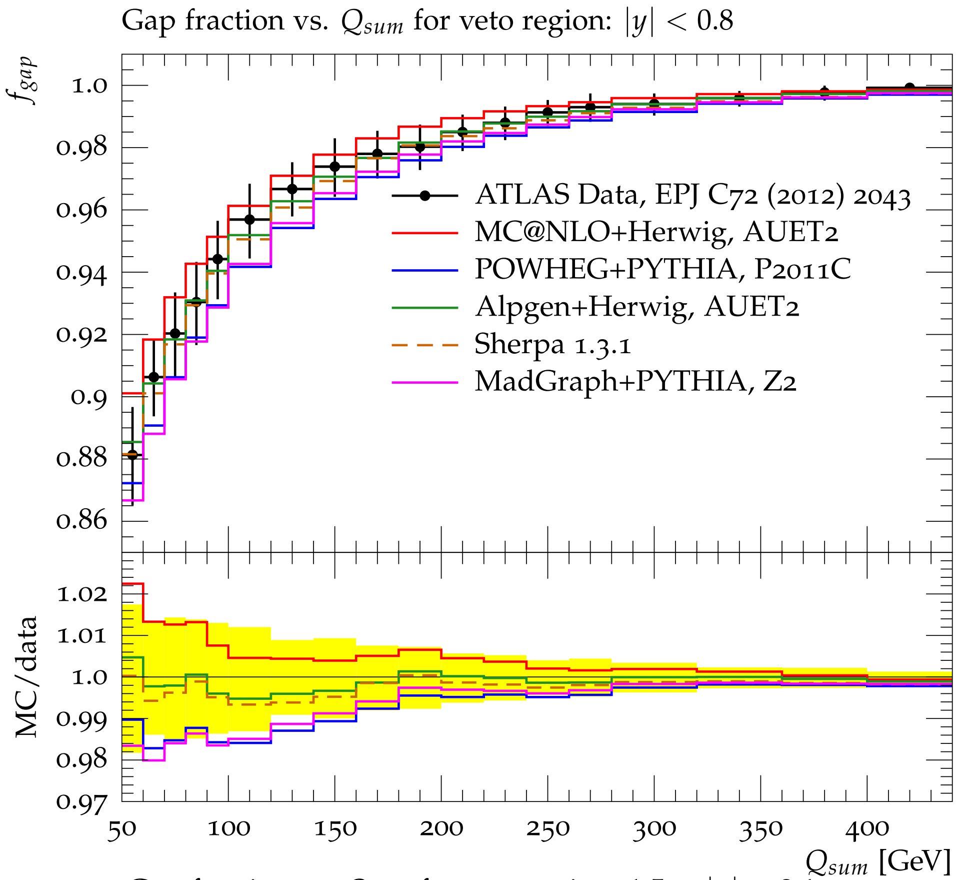
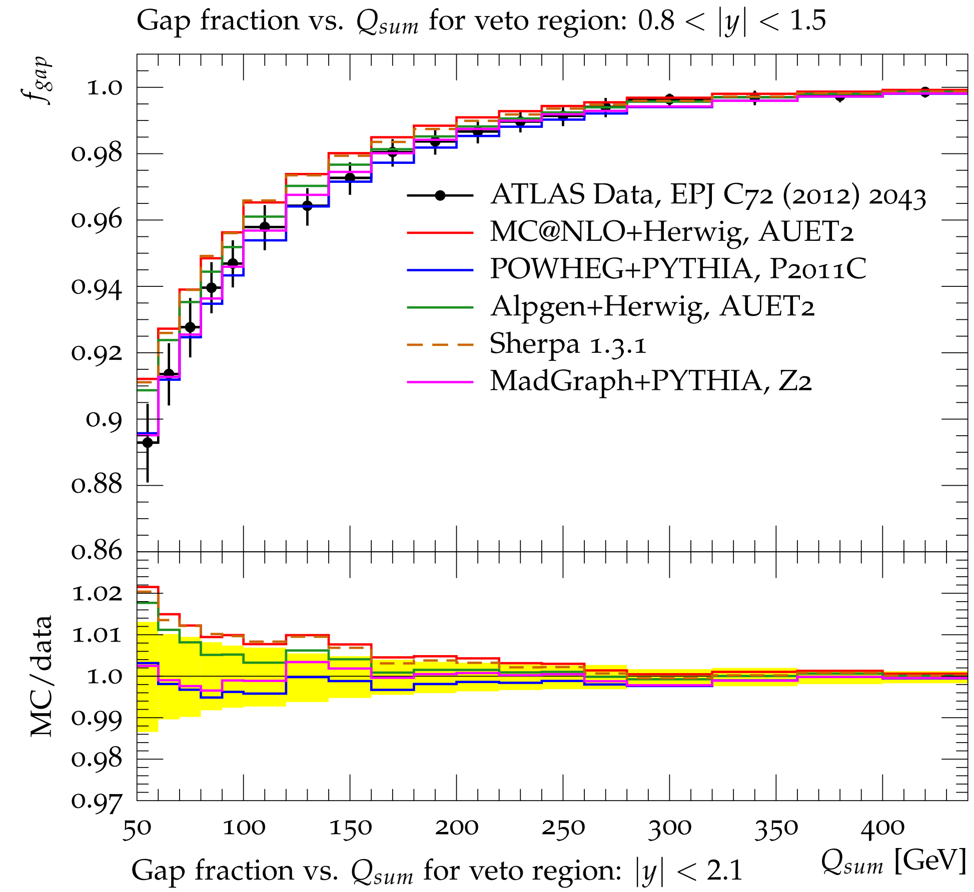
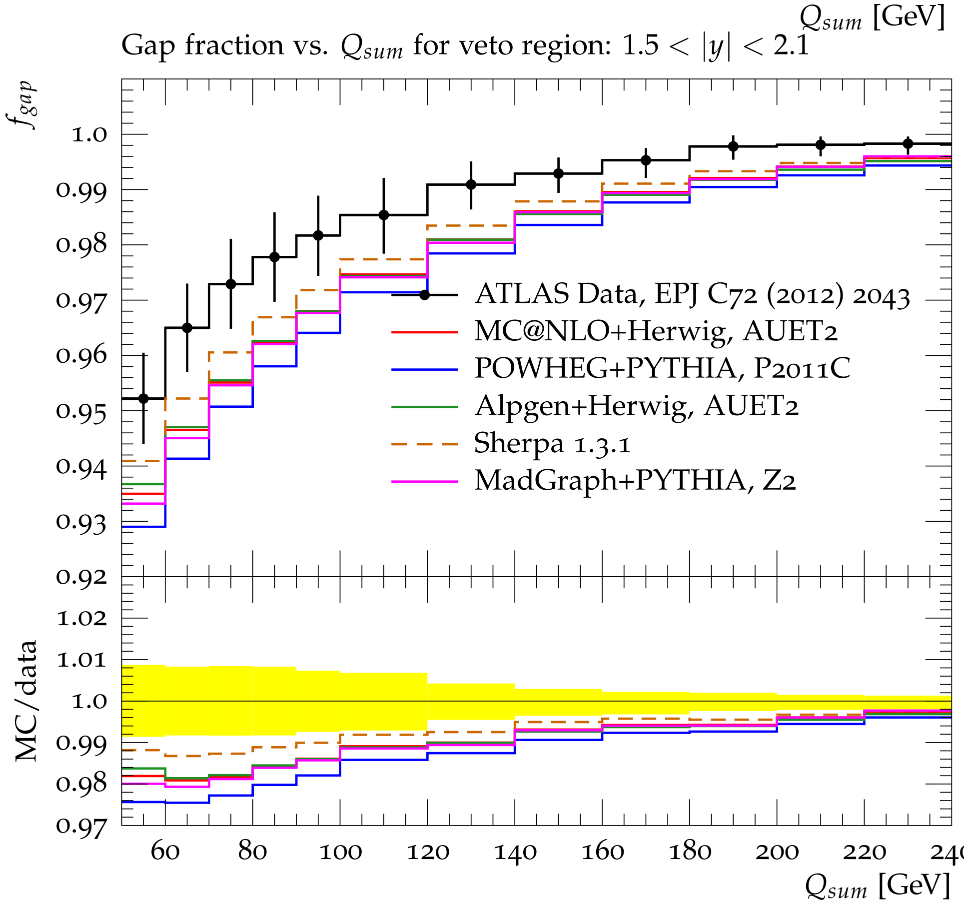
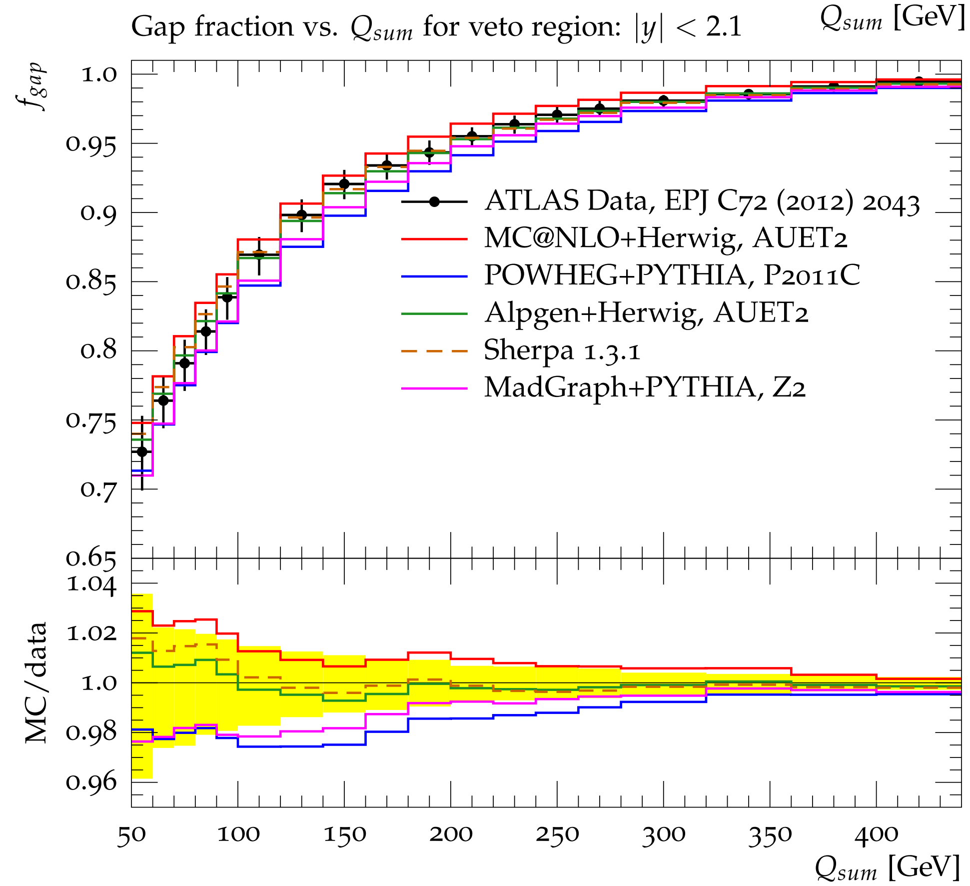


Jet Veto Measurement



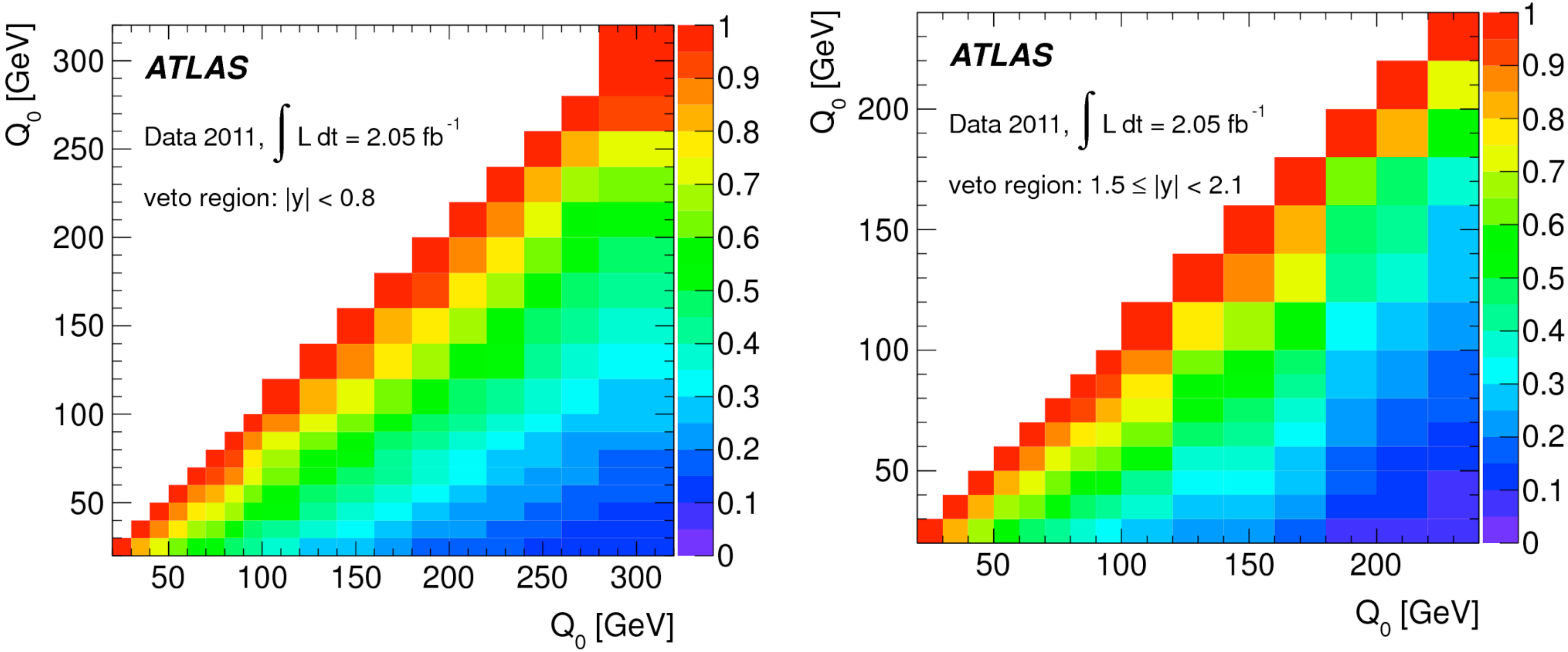






Jet Veto Measurement

- Statistical correlations between measurement points available in HepData.



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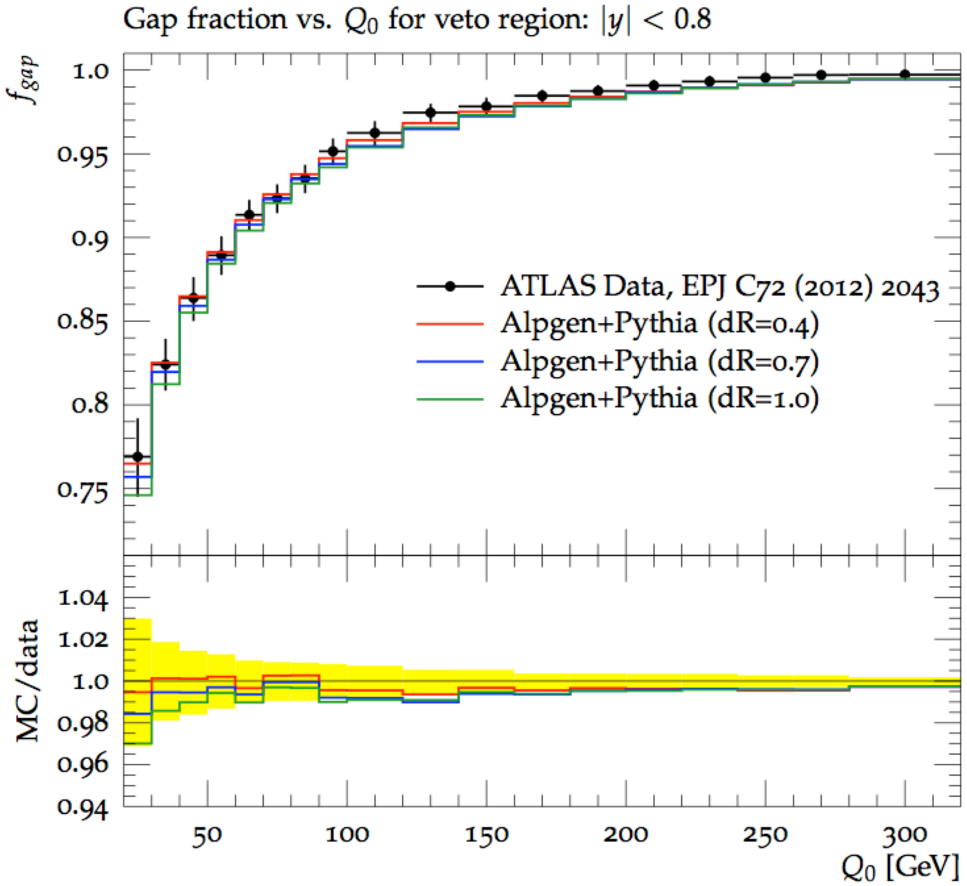

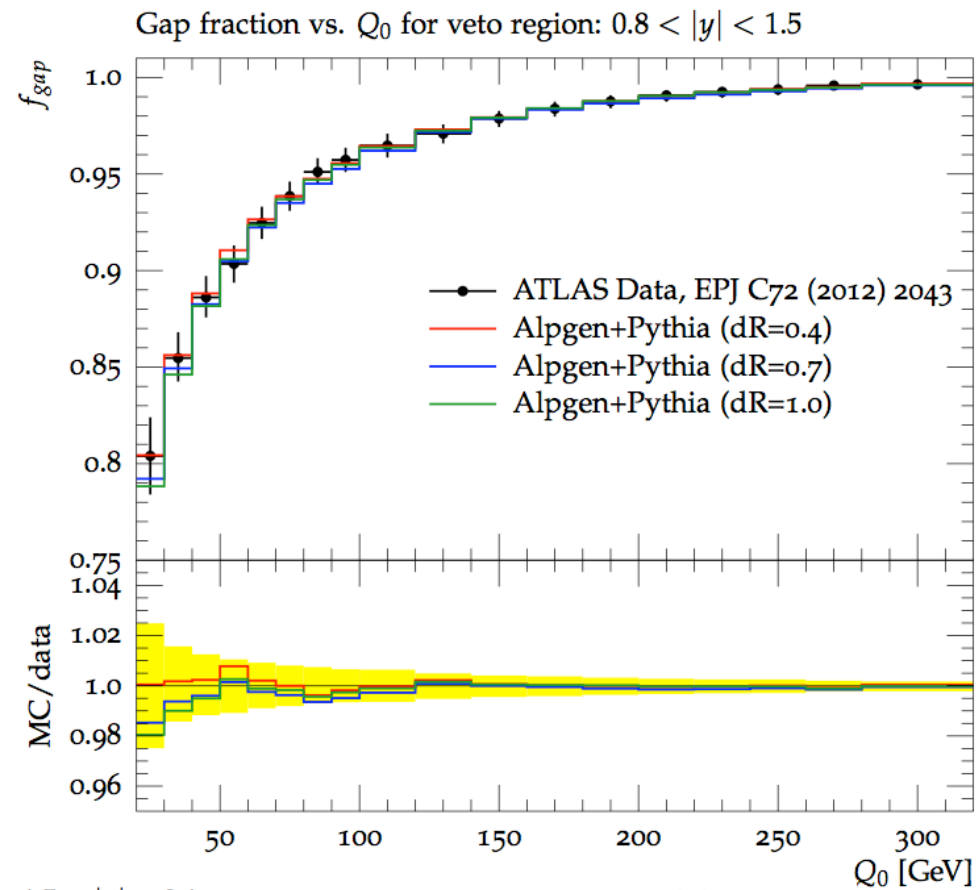

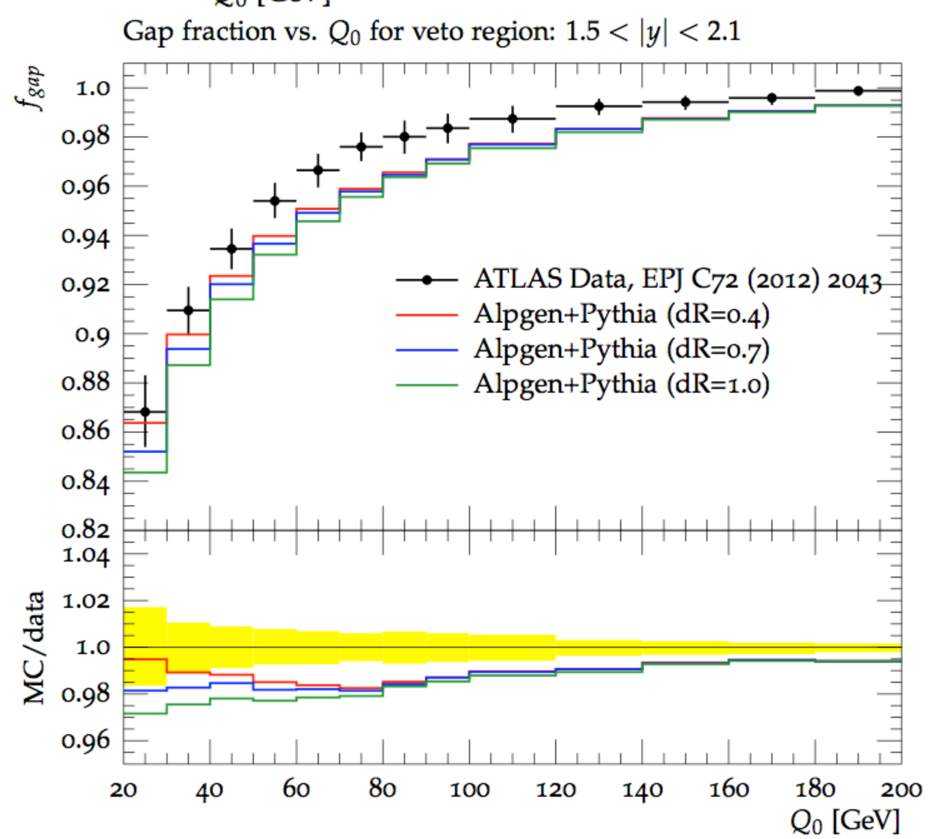

MC Models

- The MC@NLO+Herwig, AUET2 sample is simulated using the MC@NLO [3] event generator (v4.01) with the CT10 [4] parton distribution function (PDF). An NLO matrix element (ME) is used for the $t\bar{t}$ hard scattering process. Parton showers, hadronisation and the underlying event are modelled using the Herwig (v6.520) [5] and Jimmy (v4.31) [6] generators. The Herwig and Jimmy ATLAS AUET2 tune [7] is used. The hard process scale is kept to the MC@NLO generator default which is the average of the top quark (t) and the anti-top quark ($\bar{t}$) transverse masses:

$$Q^2 = \frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2, \quad (1)$$

where $p_{T,t(\bar{t})}$ corresponds to the transverse momentum of the top or anti-top quark and m_t is the top quark mass. The renormalisation and factorisation scales are set to the value of the scale Q.

- The Powheg+Pythia, P2011C sample is generated using Powheg-hvq (patch4) [8], [9] with CT10 PDF. An NLO matrix element is used for the $t\bar{t}$ hard scattering process. The parton shower (PS) and the underlying event are simulated using Pythia (v6.425) with CTEQ6L1 [10] PDF and the corresponding Perugia 2011C tune [11] intended to be used with this PDF. The hard process (renormalisation and factorisation) scales are kept to the generator default value that corresponds to:

$$Q^2 = m_t^2 + p_T^2, \quad (2)$$

where m_t and p_T are the top quark mass and the top quark transverse momentum, evaluated for the underlying Born configuration (i.e. before radiation).

MC Models

- The Powheg+Pythia, AUET2B sample is generated using the same matrix element events as the Powheg+Pythia, P2011C sample. The parton shower and the underlying event are added using Pythia with CTEQ6L1 PDFs and the corresponding ATLAS AUET2B tune [12].

- The Powheg+Herwig, AUET2 sample is generated using the same matrix element events as Powheg+Pythia, P2011C sample. The parton shower and the underlying event were added using the Herwig and Jimmy with the CT10 PDFs and ATLAS AUET2 tune [7].

- The Alpgen+Herwig, AUET2 sample is generated using Alpgen (v2.13) together with Herwig and Jimmy generators. In Alpgen up to five additional final state partons are used in the matrix elements describing the hard scattering process in leading order. For the matrix element calculations and the parton shower evolution the CTEQ6L1 PDF is used. The corresponding AUET2 Herwig and Jimmy tune [7] to the ATLAS data is used. The choice of the hard process scale is kept to the generator default[1]:

$$Q^2 = \sum m_T^2, \text{ with } m_T^2 = m^2 + p_{\mathrm{T}}^2, \tag{3}$$

  where the sum runs over heavy quarks and light jets[2] with mass m and transverse momentum p_{T}. The renormalisation and factorisation scales are set to the value of the scale Q. The parton level phase space cuts used for the matrix element level event generation are set using the following Alpgen parameters: `ptjmin`=15 GeV and `drjmin`=0.7. The parameters used for MLM matching [13] are set using the following Alpgen parameters: ETCLUS=20 GeV and RCLUS=0.7.

MC Models

- The ALPGEN+PYTHIA, P2011 sample is generated using ALPGEN (v2.14) complemented with the parton shower and hadronisation based on PYTHIA used with the Perugia 2011 tune [11]. The CTEQ5L PDF [14] is used for both the hard process and the parton shower. The hard process scale choice and the parton level phase space cuts used for generating the sample are the same as for the ALPGEN+HERWIG, AUET2 sample apart from the ALPGEN parameters settings `xlclu`=0.26 GeV and `lpclu`=1, recommended to be used with the Perugia 2011 tune for matched generators [15]. The MLM matching parameters are set to the same values as in the ALPGEN+HERWIG, AUET2 sample.

  Additional samples are produced to estimate the effect of more or less radiation. The number of additional partons is altered by varying the ALPGEN renormalisation scale associated with the strong coupling α_S in the matrix element calculation. The scale is varied by a factor of two relative to the original scale k_T between two partons (setting the `ktfac` parameter to 0.5 and 2.0). Two different procedures are used. In the first approach, the scale of α_S is changed within the matrix element calculation only while the parton shower tune and scale choice are the same as for the central sample. These samples are referred to as ALPGEN+PYTHIA(as_down,central) and ALPGEN+PYTHIA(as_up,central). In a second approach, the scale of α_S is consistently varied in the ME and the parton shower and referred to as ALPGEN+PYTHIA(as_down,radLo) and ALPGEN+PYTHIA(as_up,radHi) respectively. The Perugia 2011 radLo and radHi tunes [11] are used for the sample generation accordingly.

  In order to assess the modelling uncertainty due to the particular choice of the `drjmin` and RCLUS ALPGEN parameters (called dR in the following) in the matrix element and shower, additional systematic variations (dR=0.4 and dR=1.0) are considered. In the matrix element, dR constrains the minimal difference between the partons, in the MLM matching, the cluster radius as well as the minimum jet-parton separation to meet the definition of a jet for parton-jet matching.

MC Models

- The SHERPA (version 1.3.1) [16] samples are generated with CTEQ6L1 PDF. The hard scattering is simulated using a matrix element with up to three additional partons in the final state. For the hadronisation and the underlying event the generator default tune is used. This provides an independent LO matrix element calculation with a different matching scheme (CKKW [17]) between the matrix element and the parton shower.

- The MADGRAPH+PYTHIA, Z2, sample is generated using MADGRAPH[19] (v5.1.1.0) with the CTEQ6L1 PDF. The PYTHIA(v6.424) generator with the Z2 tune [20] by the CMS collaboration is used for parton showers and hadronisation. The $t\bar{t}$ events with up to three additional partons in the (leading order) ME are generated and the kt-MLM matching scheme is used [13].

- The ACERMC+PYTHIA LessPS and MorePS samples are generated with the ACERMC generator [18] (v3.8) interfaced with PYTHIA (v6.425). For both ME and parton shower the CTEQ6L1 PDF is used and the corresponding CTEQ6L1 tune of Perugia 2011 author tune series (Perugia 2011C) is used for PYTHIA. On top of the central tune, variations of PYTHIA parameters controlling initial and final state radiation (ISR/FSR) are performed without retuning of other parameters in order to obtain a simple estimate of the effect of the ISR/FSR uncertainty. The parameters changed with respect to the Perugia 2011C values are as follows: LessPS sample: PARP(67)=0.60, PARP(64)=3.50, PARP(72)=0.11 GeV, MorePS sample: PARP(67)=1.40, PARP(64)=0.90, PARP(72)=0.37 GeV. The parameter variations are selected such that the variation samples bracket top observables data, including the jet gap fraction measurement data [1].