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Comparison of Monte Carlo generator predictions for gap fraction and jet multiplicity observables in $t\bar{t}$ events

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Abstract

Predictions from several Monte Carlo generators are compared with each other and the data for observables in events with top-antitop quark pair at the LHC. Data taken by ATLAS in 2011 at $\sqrt{s} = 7$ TeV is used. The focus is on observables sensitive to additional parton radiation: jet multiplicities and gap fraction observables. Generators that have been used for ATLAS analyses of the data collected in the first LHC proton physics run as well as new generators that will be used in the upcoming LHC run are included. The goal of the note is to collect information and studies for discussions between the communities of the ATLAS and CMS experiments and theoretical colleagues.

1 Introduction

The Monte Carlo (MC) generator modelling of events in which top-antitop quark ($t\bar{t}$) pairs are produced is of large importance for the LHC physics programme. Modelling is one of the major systematic uncertainties in measurements of the top cross sections, top quark properties and measurements of associated production of the Higgs boson with a $t\bar{t}$ pair ($t\bar{t}H$ production) amongst others. These measurements often require good modelling of several aspects of the $t\bar{t}$ production. The hard process parton level event should provide an accurate description of the top decay products kinematics and correlations. At the same time, observables dealing with final states with a large number of jets, including heavy flavour jets, need to be well described. Several measurements also have notable sensitivity to the modelling of the internal jet structure, color reconnection and other modelling aspects related to the particle decays and hadronization. The event generation furthermore needs to be fast enough to enable the experiments to produce samples of integrated luminosity several times larger than the integrated luminosity of the data.

In this note MC generator predictions are compared with each other and with the experimental data for $t\bar{t}$ observables at the LHC. The focus are observables sensitive to additional light parton radiation: jet multiplicities and gap fraction observables. Other modelling aspects, such as internal jet structure modelling are not discussed. The gap fraction is related to the probability of no additional jets being produced in a certain detector region and has been measured as a function of the transverse momentum (p_{T}) of the highest p_{T} additional jet or the transverse momentum sum of all jets. MC predictions for gap fraction observables are compared with experimental data from Ref. [1] using the corresponding Rivet [2] implementation. The comparison of predictions for the differential cross-section as a function of jet multiplicity is also presented. The jet multiplicity comparisons are done for observables similar to the ones measured in Ref. [3]. Since no Rivet implementation is available for this measurement, the predictions are not compared to experimental data.

The $t\bar{t}$ samples used by ATLAS and CMS analyses with data from first LHC proton physics run (Run I) as well as those from generators the ATLAS collaboration anticipates to use in the future are included. Run I data corresponds to data taken from March 2010 to December 2012. During this period data was taken at centre-of-mass energies of $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV. The goal of the note is to collect information and studies for discussions between the communities of the ATLAS and CMS experiments and theoretical colleagues. Detailed documentation of the generator setup and performance studies of the Run I samples are intended for the comparison of the current radiation modelling systematic uncertainties strategies adopted by ATLAS and CMS. The studies of new generator setups aim to provide material for future recommendations of $t\bar{t}$ baseline and variation samples to be used by ATLAS and CMS analyses.

The note is organized as follows. A description of the MC setups used in the note is available in section 2. The jet multiplicities and gap fraction observables are defined in section 3. Comparisons of these observables in MC samples used for ATLAS Run I radiation systematics are documented in section 4, while in section 5 the comparisons are extended to next-to-leading order (NLO) generator samples, including those with parameter variations and setups not yet frequently used in Run I analyses.

For the studies in this note, the $t\bar{t}$ dilepton decay channel is used. The studied observables are defined using stable truth particles [1]. Generated samples of proton-proton collisions at centre-of-mass energy of 7 TeV are used, to enable the comparisons to the experimental data analyses available in the Rivet framework.

[1] Particles that have a mean lifetime $c\tau > 10$ mm are used.

2 Monte Carlo generator samples

2.1 Sample settings overview

The MC generator samples discussed in this note are as follows. A summary of generator settings used for samples discussed in this note is available in Table 2.1.

- The Powheg + Pythia6, P2011C sample is generated using Powheg-hvq [4, 5, 6] (patch4) with CT10 [7] parton distribution function (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 Pythia6 [8] (v6.425) with CTEQ6L1 [9] PDF and the corresponding Perugia 2011C tune [10] intended to be used with this PDF. The hard process (renormalisation Q_r and factorisation Q_f) scales are fixed at the generator default value Q that is defined by:

$$Q = \sqrt{m_t^2 + p_T^2}, \quad (1)$$

  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).

- The Powheg + Pythia6, P12 [10] sample settings are similar to the ones used for the Powheg + Pythia6, P2011C sample. The differences are as follows. The hard process event is generated with Powheg-BOX (version 1, r2885) [11]. The Pythia6 (v6.427) tune used for the parton shower and underlying event is the author Perugia 2012 tune for CTEQ6L1 PDF. In addition samples with same nominal settings as Powheg + Pythia6, P12 sample and systematic variations of Powheg and Pythia6 parameters are produced. Samples with Powheg parameter variations are labeled as Pow + Py,$\mu_r = X$, $\mu_f = Y$, hdamp $= Z$ in section 5. The following Powheg parameter variations are performed: multiplicative factors μ_r (μ_f) of renormalisation (factorisation) scale are set to value X (Y). Independent scale variations of μ_r and μ_f by a factor of 0.5 and 2 are performed, fulfilling condition $0.5 < \mu_r/\mu_f < 2$. The parameter hdamp controls the separation of the real matrix element in a singular R_s and a finite R_f part by setting the fraction of R_f events to be $\frac{p_{\mathrm{T}}^2}{\mathrm{hdamp}^2 + p_{\mathrm{T}}^2}$. The default Powheg behavior corresponds to hdamp $= \infty$, while setting hdamp to a finite value effectively corresponds to damping of high-p_{T} radiation in Powheg. It has been recommended in Ref. [12] that scale variations in Powheg should be performed in the presence of damping, else variation effects are underestimated in the current Powheg-BOX implementation. In the studies in section 5, hdamp is set to values of top mass m_t, $2m_t$ and $4m_t$. In addition to Powheg parameter variations, samples in which Pythia6 parameters are varied are produced as well. Samples labeled Pow + Py, scale+radLo and scale+radHi in section 5 are using renormalisation and factorisation scale variations in presence of damping as well as the Perugia 2012 radHi and radLo variations of the Perugia 2012 tune. The Perugia 2012 tune and the corresponding variations are available in Pythia6 versions ≥ 6.427. Note that for the same settings of Powheg parameters, predictions of Powheg + Pythia6, P12 for jet multiplicity and gap fraction observables are very similar to predictions of Powheg + Pythia6 with P2011C.

- The Powheg + Herwig, AUET2 sample is generated using the same matrix element events as the Powheg + Pythia6, P2011C sample. The parton shower and the underlying events are added using the Herwig (v6.520) [13] and Jimmy (v4.31) [14] generators. While for the matrix element the CT10 PDFs are used, the CTEQ6L1 PDF and the corresponding ATLAS AUET2 tune [15] is used for the parton shower and hadronization settings. Variations of Powheg parameters as in Powheg + Pythia6, P12 are also studied for Powheg samples showered with Herwig.

sample	ME gen.	PS/UE gen.	ren./fac. scale	ME & PS/UE PDF	tune
	ATLAS analyses samples, 7 TeV				
Powheg + Pythia6, P2011C	Powheg-hvq (patch4)	Pythia6 v6.425	$Q = \sqrt{m_t^2 + p_T^2}$	CT10 & CTEQ6L1	Perugia 2011C
Powheg + Herwig, AUET2	Powheg-hvq (patch4)	Herwig v6.520 Jimmy v4.31	$Q = \sqrt{m_t^2 + p_T^2}$	CT10 & CTEQ6L1	AUET2
MC@NLO + Herwig, AUET2	MC@NLO v4.01	Herwig v6.520 Jimmy v4.31	$Q = \sqrt{\frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2}$	CT10	AUET2
MC@NLO + Herwig, $\mu_r = \mu_f = 0.5(2.0)$	same settings as MC@NLO + Herwig, AUET2, but with ren. and fac. scale varied simultaneously by factor 0.5(2.0)				
Alpgen + Herwig, AUET2	Alpgen v2.13	Herwig v6.520 Jimmy v4.31	$Q = \sqrt{\sum m_T^2}$, with $m_T^2 = m^2 + p_T^2$	CTEQ6L1	AUET2
Alpgen + Pythia6, P2011	Alpgen v2.14	Pythia6 v6.425	$Q = \sqrt{\sum m_T^2}$, with $m_T^2 = m^2 + p_T^2$	CTEQ5L	Perugia 2011
Alpgen as_down,radHi	same settings as Alpgen + Pythia6, P2011 but with ren. scale in ME and PS varied simultaneously by factor 0.5 and UE retune				Perugia 2011 radHi
Alpgen as_down,radLo	same settings as Alpgen + Pythia6, P2011 but with ren. scale in ME and PS varied simultaneously by factor 2.0 and UE retune				Perugia 2011 radLo
AcerMC + Pythia6 Less PS and More PS	AcerMC 3.8 + `PARP(67), PARP(64) and PARP(72)` variations	Pythia6 v6.425	$Q = 2m_t$	CTEQ6L1	Perugia 2011C
	ATLAS analyses samples, 8 TeV				
Alpgen + Pythia6, P2012	Alpgen v2.14	Pythia6 v6.425	$Q = \sqrt{\sum m_T^2}$, with $m_T^2 = m^2 + p_T^2$	CTEQ5L	Perugia 2012
Alpgen as_down,radHi	same settings as Alpgen + Pythia6, P2012 but with ren. scale in ME and PS varied simultaneously by factor 0.5 and UE retune				Perugia 2012 radHi
Alpgen as_down,radLo	same settings as Alpgen + Pythia6, P2012 but with ren. scale in ME and PS varied simultaneously by factor 2.0 and UE retune				Perugia 2012 radLo
AcerMC + Pythia6 AUET2B Less PS and More PS	AcerMC 3.8 + `PARP(67), PARP(64), PARP(72), PARJ(82)` variations	Pythia6 v6.426	$Q = 2mt$	CTEQ6L1	AUET2B
	CMS analyses samples				
MadGraph + Pythia6, Z2 (used in 7 TeV analyses)	MadGraph v5.1.1.0	Pythia6 v6.424	$Q = \sqrt{m_t^2 + \sum p_T^2(jet)}$	CTEQ6L	Z2
MadGraph + Pythia6, Z2* (used in 8 TeV analyses)	MadGraph v5.1.4.8	Pythia6 v6.426	$Q = \sqrt{m_t^2 + \sum p_T^2(jet)}$	CTEQ6L	Z2*
	samples used in this note, but so far not used in published ATLAS or CMS analyses				
Powheg + Pythia6, P12	Powheg-BOX v1, r2885	Pythia6 v6.427	$Q = \sqrt{m_t^2 + p_T^2}$	CT10 & CTEQ6L1	Perugia 2012
Pow + Py (Hw), $\mu_r = X, \mu_f = Y$, `hdamp`=Z	same settings as Powheg + Pythia6, P12 (Powheg + Herwig, AUET2), but with Powheg ren. and fac. scale varied by factor X and Y and Powheg parameter `hdamp` set to value Z				
Pow + Py, scale+radLo(radHi)	same as Powheg + Pythia6, P12, but with simult. ren., fac. scale variations in presence of damping and Pythia6 Perugia 2012 radLo (radHi) tunes				
MC@NLO + Herwig++, UEEE4 LO**	MC@NLO v4.09	Herwig++ 2.6.3	$Q = \sqrt{\frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2}$	CT10 & MRSTMCal LO**	UEEE4 LO**
aMC@NLO + Herwig++, UEEE4 LO**	aMC@NLO v2.1.1	Herwig++ 2.6.3	$Q = \sqrt{\frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2}$	CT10 & MRSTMCal LO**	UEEE4 LO**
aMC@NLO + Herwig++, $\mu_r = \mu_f = 0.5(2.0)$	same settings as aMC@NLO + Herwig++, UEEE4 LO**, but with ren. and fac. scale varied simultaneously by factor 0.5(2.0)				
aMC@NLO + Herwig, AUET2	aMC@NLO v2.1.1	Herwig v6.520 Jimmy v4.31	$Q = \sqrt{\frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2}$	CT10	AUET2

Table 1: Matrix element generator, parton shower/underlying event generator, renormalisation and factorisation scale settings, PDF used for ME and PS/UE generator and tune used for each of Monte Carlo samples discussed in this note.

- The MC@NLO + Herwig, AUET2 sample is generated using the MC@NLO event generator (v4.01) [16, 17] with the CT10 PDF. An NLO matrix element (ME) is used for the $t\bar{t}$ hard scattering process. The parton shower, hadronisation and the underlying event are modelled using the Herwig (v6.520) and Jimmy (v4.31) generators. The CT10 PDF with the corresponding ATLAS AUET2 tune [15] is used for parton shower and hadronization settings. The hard process scale Q is fixed at the MC@NLO generator default which is defined as the average of the top quark (t) and the anti-top quark ($\bar{t}$) transverse masses:

$$Q = \sqrt{\frac{p_{T,t}^2 + p_{T,\bar{t}}^2}{2} + m_t^2}, \tag{2}$$

  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. These settings are also used for the renormalisation and factorisation scale variation samples, in which multiplicative factors μ_r (μ_f) of renormalisation (factorisation) scale are varied (MC@NLO + Herwig, $\mu_r = \mu_f = 2.0$ and MC@NLO + Herwig, $\mu_r = \mu_f = 0.5$ in section 5).

- The MC@NLO + Herwig++, UEEE4 LO** $t\bar{t}$ sample is generated with the MC@NLO event generator (v4.09). The PDF and scale choices are the same as for the MC@NLO + Herwig, AUET2 sample. The parton shower, hadronisation and the underlying event are modelled using the Herwig++ (v2.6.3) [18] generator. The UE-EE-4 (MRST LO**) author Herwig++ tune and the corresponding MRSTMCal LO** [19] PDF are used.

- The aMC@NLO + Herwig++, UEEE4 LO** $t\bar{t}$ sample is generated with the aMC@NLO event generator implemented in MadGraph 5 framework [20] (version 2.1.1). An NLO matrix element (ME) and CT10 PDF is used for the $t\bar{t}$ hard scattering process. The renormalisation and factorisation scales are set to be the same as implemented in MC@NLO defined in Eqn. 2. The top quarks produced in the matrix element are decayed using MadSpin preserving all spin correlations. The parton shower, hadronisation and the underlying event are modelled using the same setup as used for the MC@NLO + Herwig++, UEEE4 LO** sample. These settings are also used for the renormalisation and factorisation scale variation samples, in which multiplicative factors μ_r (μ_f) of renormalisation (factorisation) scale are varied (aMC@NLO + Herwig++, $\mu_r = \mu_f = 2.0$ and aMC@NLO + Herwig++, $\mu_r = \mu_f = 0.5$ in section 5).

- The aMC@NLO + Herwig, AUET2 $t\bar{t}$ sample is generated with the same setup as the aMC@NLO + Herwig++, UEEE4 LO** $t\bar{t}$ sample for the aMC@NLO and the same setup as the MC@NLO + Herwig, AUET2 sample for Herwig.

- The Alpgen + Herwig, AUET2 sample is generated using Alpgen (v2.13) together with the Herwig and Jimmy generators. In Alpgen up to five additional final state partons are used in leading order (LO) hard process matrix elements. For the matrix element calculations and the parton shower evolution the CTEQ6L1 PDF is used. The corresponding AUET2 Herwig and Jimmy tune [15] to the ATLAS data is used. The choice of the hard process scale Q is fixed at the generator default[2] defined by:

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

  where the sum runs over heavy quarks and light jets[3] with mass m and transverse momentum p_{T}. The renormalisation and factorisation scales are set to the value of the scale Q. The parton

[2]That corresponds to the value of Alpgen parameter `iqopt` = 1.
[3]Defined to be light quarks and gluons used for matching to jets during MLM matching.

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 [21] are set using the following ALPGEN parameters: ETCLUS = 20 GeV and RCLUS = 0.7.

- The ALPGEN + PYTHIA6, P2011 sample is generated using ALPGEN (v2.14). The parton shower and hadronisation are added with PYTHIA6 (v6.425), used with the Perugia 2011 tune [10]. The CTEQ5L PDF [22] 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 parameter settings `xlclu` = 0.26 GeV and `lpclu` = 1, recommended to be used with the Perugia 2011 tune for matched generators [23]. The MLM matching parameters are set to the same values used for the ALPGEN + HERWIG, AUET2 sample.

  Additional samples are produced to estimate the effect of more or less radiation (ALPGEN as_down,radLo and as_up,radHi in section 4). In these samples the renormalisation scale in the ALPGEN matrix element and PYTHIA6 parton shower is varied simultaneously by a factor of two relative to the original scale. This is achieved by setting the ALPGEN parameter `ktfac` parameter to 0.5 (2.0) and using the Perugia 2011 radHi(radLo) tunes [10]. The Perugia radHi and radLo tunes include variations of the parton shower infra-red cutoff values and underlying event parameters, such that the tuned observables are well described also after the renormalisation scale variation. The factorisation scale is not varied in these samples. Details on parameter settings are available in subsection 2.2. Variation samples based on Perugia 2011 with CTEQ5L PDF used in figures in section 4 were used for 7 TeV analyses, while for 8 TeV similar variation samples based on Perugia 2011C tune with CTEQ6L1 PDF were used.

- The ACERMC + PYTHIA6 Less PS and More PS $t\bar{t}$ samples are generated with the ACERMC generator [24] (v3.8) interfaced with PYTHIA6 (v6.425). $t\bar{t}$ hard process is generated with leading order (LO) matrix element, including top decays, hence six final state particles. As opposed to multi-leg generators, only lowest multiplicity final state is provided by ACERMC. The hard process scale Q is set to:

$$Q = 2m_t \, . \tag{4}$$

  The CTEQ6L1 PDF is used for both the ME and the parton shower calculations, and the corresponding CTEQ6L1 tune from the Perugia 2011 author tune series (Perugia 2011C) is used for PYTHIA6. On top of the central tune, variations of PYTHIA6 parameters controlling initial and final state radiation (ISR/FSR) are performed without retuning of other parameters. The parameter variations are selected such that the variation samples bracket the observed distributions in the ATLAS $t\bar{t}$ data, including the jet gap fraction measurement data [1]. Details on parameter settings are available in subsection 2.2. Variation samples based on Perugia 2011C used in figures in section 4 were used for 7 TeVanalyses, while for 8 TeVsimilar variation samples based on ATLAS AUET2B tune [25] were used.

The generator tunes used for all samples include early LHC data, but do not include data with top quarks in the final state. All MC generator samples are produced within the ATLAS software framework. In addition, a sample generated within the CMS software framework is used for some of the studies.

- The MADGRAPH + PYTHIA6, Z2, sample is generated using MADGRAPH[20] (v5.1.1.0) with the CTEQ6L1 PDF. The PYTHIA6 (v6.424) generator with the Z2 tune [26] 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 [21]. These samples were used by CMS as a baseline for radiation systematics variation samples for 7 TeVanalyses, while similar MadGraph + Pythia6, Z2* tune samples were used for radiation systematics variation samples for CMS 8 TeVanalyses.

In the following, Powheg, MC@NLO and aMC@NLO will be called NLO MC generators, Alpgen and MadGraph will be called multi-leg MC generators while AcerMC will be called Born-level generator.

2.2 Comparison of ATLAS and CMS radiation systematics samples

When comparing or combining $t\bar{t}$ observables measurements published by ATLAS and CMS, it is often relevant to know how exactly the associated systematic uncertainties were obtained. It is interesting to understand, if one of the collaborations quotes smaller uncertainties because it is using a different strategy or because its measurement is less sensitive to the systematic variation in question. When combining the measurements it is important to estimate the degree of correlation between the uncertainty sources quoted by each of ATLAS and CMS. In this subsection details of ATLAS radiation systematics strategy and a comparison to CMS strategy described in Ref. [27] are provided.

For Run I publications, ATLAS has been using two radiation systematic uncertainties variation sets: AcerMC + Pythia6 samples used by most analyses until summer 2013 and Alpgen + Pythia6 samples used for most analyses afterward. CMS has been using MadGraph + Pythia6 samples to evaluate the radiation systematic uncertainties.

The parameter variations in Alpgen + Pythia6 as_down,radLo and as_up,radHi samples are similar to the samples used by CMS to evaluate the radiation systematic uncertainties. The multi-leg MadGraph + Pythia6 samples are used by CMS for this purpose. ATLAS Alpgen + Pythia6 7 TeV (8 TeV) samples are based on Perugia 2011 (Perugia 2012) tunes [10]. CMS MadGraph + Pythia6 samples are based on Z2 (Z2*) tunes for $\sqrt{s}$ = 7 TeV (8 TeV). Central sample settings of most relevance for radiation systematics variations are comparable between the ATLAS Alpgen + Pythia6 and CMS MadGraph + Pythia6 samples as detailed in Table 2.2. The central values of parameters listed in Table 2.2 are the same in Perugia 2011 and Perugia 2012 tunes. Central values of Z2 and Z2* differ slightly from Perugia tunes values. Both Z2 and Z2* are using same central values. The values and variations in the Table apply to both 7 TeV and 8 TeV samples. In both sets of variation samples, the renormalisation scale used for running strong coupling constant is varied by a factor of one half and two with respect to the nominal value to obtain the variation samples. The variation is done simultaneously in the matrix element and parton shower. On the parton shower side, the parameters controlling the renormalisation scales in initial and final state radiation are varied simultaneously. It should be noted that the parameters can correspond to either a multiplicative or a dividing factor and can be factors of a renormalisation scale to a power of either one or two. In particular the value of parameters `PARP(72)` and `PARP(61)` corresponds to Λ_{QCD} used in running strong coupling in FSR and ISR [8]. Parameter `PARP(64)` corresponds to a multiplicative factor of renormalisation scale in running strong coupling used in ISR. Hence, increasing the value of `PARP(64)` by a factor of four has the same effect as decreasing the value of `PARP(61)` by a factor of two. Thus, the values of parameters do not always correspond to a dimensionless multiplicative factors of half and two, despite this being their effective action on the renormalisation scale.

While the renormalisation scale variations and settings are similar between the ATLAS Alpgen + Pythia6 and CMS MadGraph + Pythia6 samples used for radiation systematic uncertainties, there are also differences between the samples used by ATLAS and CMS. In particular there are differences in the factorisation scale variations and underlying event parameter variations as follows. Factorization scale is varied by a factor of 0.5 (2.0) simultaneously with the renormalisation scale in the radiation systematic uncertainties variation samples by CMS [27]. There is no factorisation scale variations in radiation systematic uncertainties samples used by ATLAS (the factorisation scale systematic uncertainties is covered in a dedicated category instead). In the CMS MadGraph + Pythia6 radiation systematic uncertainties

	CMS	ATLAS	
	MadGraph +Pythia6	Alpgen +Pythia6	AcerMC +Pythia6 **7 TeV (8 TeV)**
nominal sample settings			
FSR: `PARP(72)`	0.25 GeV	0.26 GeV	0.26 (0.527) GeV
ISR: `PARP(64)`	1.0	1.0	1.0 (0.68)
`PARP(61)`	0.25 GeV	0.26 GeV	0.26 (0.192) GeV
ME: `alpsfact/ktfac`	1.0	1.0	-
Less PS (as_down,radLo) sample settings			
FSR: `PARP(72)`	0.125 GeV	0.13 GeV	0.11 (0.150) GeV
ISR: `PARP(64)`	4.0	-	3.50 (4.08)
`PARP(61)`	-	0.13 GeV	same as nominal
ME: `alpsfact/ktfac`	2.0	2.0	-
More PS (as_up,radHi) sample settings			
FSR: `PARP(72)`	0.50 GeV	0.52 GeV	0.37 (0.425) GeV
ISR: `PARP(64)`	0.25	-	0.90 (1.02)
`PARP(61)`	-	0.52 GeV	same as nominal
ME: `alpsfact/ktfac`	0.5	0.5	-

Table 2: Settings of parameters controlling renormalisation scale in ATLAS and CMS samples used in Run I $t\bar{t}$ radiation systematic uncertainties samples. The `PARP(72)` and `PARP(64), PARP(61)` are Pythia6 parameters related to the renormalisation scale used for final and initial state radiation. The `alpsfact` and `ktfac` are MadGraph and Alpgen parameters are related to the renormalisation scale used for the hard process matrix element. For parameters corresponding to Λ_{QCD}, the value is passed for 5 flavours and is used for leading order evolution of the running strong coupling. The table entries containing - correspond to cases when a parameter in the variation samples is left to the nominal sample setting or when a parameter does not apply to the sample.

samples Pythia6 parameters other than the I/FSR renormalisation scale are not varied. In the ATLAS Alpgen + Pythia6 radiation systematic uncertainties samples, other Pythia6 parameters are varied as well, as given by the radLo and radHi tunes of the Perugia family [10]. In particular the infra-red cut-offs of both the initial (`PARP(62)`) and final (`PARJ(82)`) state radiation and parameters controlling the underlying event activity (`PARP(82), PARP(90)`) are varied as well. ATLAS uses comparable, but not identical strategies for Alpgen + Pythia6 radiation systematic uncertainties used in 7 TeV and 8 TeV analyses. The 7 TeV Alpgen + Pythia6 radiation systematic uncertainties sample settings are as given in section 2. The 8 TeV Alpgen + Pythia6 systematic uncertainties samples are produced with Pythia6 version 6.427 and Perugia 2012 radLo and radHi tunes instead.

The parameter variations in AcerMC + Pythia6 More and Less PS samples are based on Perugia 2011C tune for 7 TeVand on AUET2B tune for 8 TeV variation samples. Compared to Alpgen + Pythia6 samples, AcerMC + Pythia6 samples have received tighter constraints from top experimental data. The variations of the renormalisation scales in these samples is therefore somewhat smaller than the range used in the multi-leg variation samples. Apart from the renormalisation scales the following Pythia6 parameters are varied as well:

- in AcerMC + Pythia6 More and Less PS samples used for 7 TeV analyses, the parameter `PARP(67)` controlling colour coherence imposed on the hardest QCD emission is varied,
- in AcerMC + Pythia6 More and Less PS samples used for 8 TeV analyses, the parameter `PARP(67)` as well as parameter `PARJ(82)`, controlling the final state radiation infra-red cutoff is varied.

The exact settings of AcerMC + Pythia6 radiation systematic uncertainties samples used by ATLAS 7 TeV and 8 TeV analyses are available at [28]. The parameters changed in 7 TeV samples with respect to the Perugia 2011C tune are as follows: Less PS sample: `PARP(67)` = 0.60, `PARP(64)` = 3.50, PARP(72) = 0.11 GeV, More PS sample: PARP(67) = 1.40, PARP(64) = 0.90, PARP(72) = 0.37 GeV. The parameters changed in 7 TeV samples with respect to the AUET2B tune are as follows: Less PS sample: PARP(67) = 0.75, PARP(64) = 4.08, PARP(72) = 0.150 GeV, PARJ(82) = 1.66 GeV, More PS sample: PARP(67) = 1.75, PARP(64) = 1.02, PARP(72) = 0.425 GeV, PARJ(82) = 0.5 GeV. Variations of PARP(64) and PARP(72) are summarized in Table 2.2.

While AcerMC + Pythia6 samples are easier to generate and tune to experimental data, multi-leg Alpgen + Pythia6 have a better predictive power for additional hard resolved QCD radiation. While in AcerMC + Pythia6 samples these stem from the parton shower approximation, a multi-leg Alpgen + Pythia6 predictions have leading logarithmic accuracy. During $t\bar{t}$ production at LHC phase-space for additional hard emissions is abundant. Analyses are frequently affected by the presence of extra jets in the final state, in which case multi-leg generator is likely better suited than a Born-level generator predicting only a lowest multiplicity final state. An advantage of Alpgen + Pythia6 variation samples is also that after the change of parton shower parameters, a retune of underlying event parameters is performed in order to keep the agreement with low-p_{T} QCD data [10].

Despite some differences with the CMS MadGraph + Pythia6 samples, the main parameter variations used in ATLAS and CMS samples are comparable. When performing the combination between the ATLAS and CMS analyses, the radiation modeling uncertainties in $t\bar{t}$ can thus likely be treated as correlated between the experiments, when the uncertainty depends predominantly on parameter variations (rather than e.g. analysis-specific data-driven constraints or statistical uncertainty).

3 Gap fraction and jet multiplicity observables

The **gap fraction** and **jet multiplicity** observables in $t\bar{t}$ dilepton channel events are used for comparisons in sections 4 and 5. In this section the observables are defined and the corresponding LHC measurements are discussed.

The **gap fraction** observables in $t\bar{t}$ events were first measured by the ATLAS collaboration at the centre-of-mass energy 7 TeV in Ref. [1]. Measurements of the gap fraction observables have also been performed by CMS in Ref. [3, 29] at 7 and 8 TeV. The $t\bar{t}$ events are selected in the dilepton decay channel with two identified b-jets from the top quark decays. The observables are defined as follows.

- $f(Q_0)$ is defined as

$$f(Q_0) = \frac{n(Q_0)}{N}, \tag{5}$$

  where N is the number of selected $t\bar{t}$ events and $n(Q_0)$ is the subset of these events that do not contain an additional high-p_{T} ($p_{\mathrm{T}} > 25$ GeV) jet with transverse momentum, p_{T}, above a threshold, Q_0, in a rapidity interval ($|y| < 0.8$ and $|y| < 2.1$ are considered in this note).

- $f(Q_{\mathrm{sum}})$ is defined as

$$f(Q_{\mathrm{sum}}) = \frac{n(Q_{\mathrm{sum}})}{N}, \tag{6}$$

  where $n(Q_{\mathrm{sum}})$ is the number of $t\bar{t}$ events in which the scalar transverse momentum sum of the additional high-p_{T} jets in the rapidity interval is less than Q_{sum}.

The gap fraction defined using Q_0 is mainly sensitive to the leading-p_{T} emission accompanying the $t\bar{t}$ system, whereas the gap fraction defined using Q_{sum} is sensitive to all hard emissions accompanying the $t\bar{t}$ system. The gap fraction variables were observed to be sensitive to the modeling of the additional parton radiation in $t\bar{t}$ final states as well the renormalisation and factorisation scale choices. The observables have subsequently been used to establish and constrain the parameter variations in samples used for the initial and final state systematic uncertainties and to select setups that give a good description of the data. In the following various MC generator predictions are compared to the gap fraction observables measured by ATLAS in Ref. [1]. This is the only gap fraction measurement in $t\bar{t}$ events implemented in Rivet framework.

In addition to the gap fraction observables, the generator predictions are also compared for the normalized differential cross-section as a function of jet multiplicity for jets with $p_{\mathrm{T}} > 30$ GeV and $p_{\mathrm{T}} > 60$ GeV. The event and object selection used for the jet multiplicity comparisons is the same as the event selection used for the gap fraction measurement in Ref. [1]. The electrons are required to have transverse energy $E_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.47$ and the muons are required to have transverse momentum $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. Jets are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.4$. The jets are reconstructed using anti-k_t jet algorithm with a radius parameter $R = 0.4$ [30]. All stable particles apart from muons and neutrinos are considered for jet reconstruction in simulated samples. For the jet multiplicity comparisons no b-tagging requirement is made for the jets. The p_{T} requirements are set to the same values as in the CMS collaboration measurement in Ref. [3], in which all jets are required to have $|\eta| < 2.4$ and $p_{\mathrm{T}} > 30$ GeV. The jet multiplicities are measured as a function of a p_{T} cut. In the case of $p_{\mathrm{T}} > 30$ GeV requirement, the 0 and 1 jet bins are included in the total cross-section used for normalization. Such range is intended to ease the comparison with the MC samples used by CMS. Since no Rivet implementation is available for this measurement, the predictions are not compared to experimental data. Comparisons of the radiation systematics samples used by ATLAS and CMS can however use to compare the strategies used by both collaborations to assign radiation systematics. The radiation systematics samples used by CMS are compared with each other and with the experimental data in Ref. [3]. Apart from CMS single and dilepton decay channel measurement at $\sqrt{s} = 7$ TeV in Ref. [3], jet multiplicity measurements have also been performed by ATLAS in single lepton channel at $\sqrt{s} = 7$ TeV [31] and CMS in single and dilepton decay channels at $\sqrt{s} = 8$ TeV [29].

4 ATLAS Run I radiation systematics samples

In this section MC model predictions used by ATLAS for $t\bar{t}$ radiation systematic uncertainties during Run I are compared for the gap fraction and jet multiplicity observables. The observables are defined in section 3.

During the Run I ATLAS has relied on tree-level generators for estimating uncertainties due to the initial and final state radiation modelling. The samples generated with AcerMC + Pythia6 were used for the I/FSR systematic uncertainties in $t\bar{t}$ production in most ATLAS top group results published before the Summer 2013. For the results published after Summer 2013, the samples generated with Alpgen + Pythia6 will be used in most ATLAS publications. The sample settings are given in section 2. The predictions of the AcerMC + Pythia6 More and Less PS samples for the jet multiplicity and gap fraction observables are shown in Fig. 1. The predictions of the Alpgen + Pythia6 as_down,radLo and as_up,radHi samples are shown in Fig. 2.

In the following the effect of the previously described two radiation systematics variations are illustrated on the example of the inclusive $t\bar{t}$ production cross section measured with the ATLAS data sample collected in 2012 at $\sqrt{s} = 8$ TeV [32]. Opposite-sign $e\mu$ pair in the final states are used for the analysis. The numbers of events with exactly one and exactly two b-tagged jets were counted and used to simultaneously determine the cross section and the efficiency to reconstruct and tag a b-jet from a top quark decay. The inclusive cross-section was measured to be:

$$\sigma_{t\bar{t}} = 237.7 \pm 1.7\ \text{(stat.)} \pm 7.4\ \text{(syst.)} \pm 7.4\ \text{(lumi.)} \pm 4.0\ \text{(beam energy) pb}, \tag{7}$$

where the four uncertainties arise from data statistics, experimental and theoretical systematic effects, the integrated luminosity, and the uncertainty on the knowledge of the LHC beam energy. The relative total uncertainty of the measurement is 4.8 %. The relative systematic uncertainty of the measurement

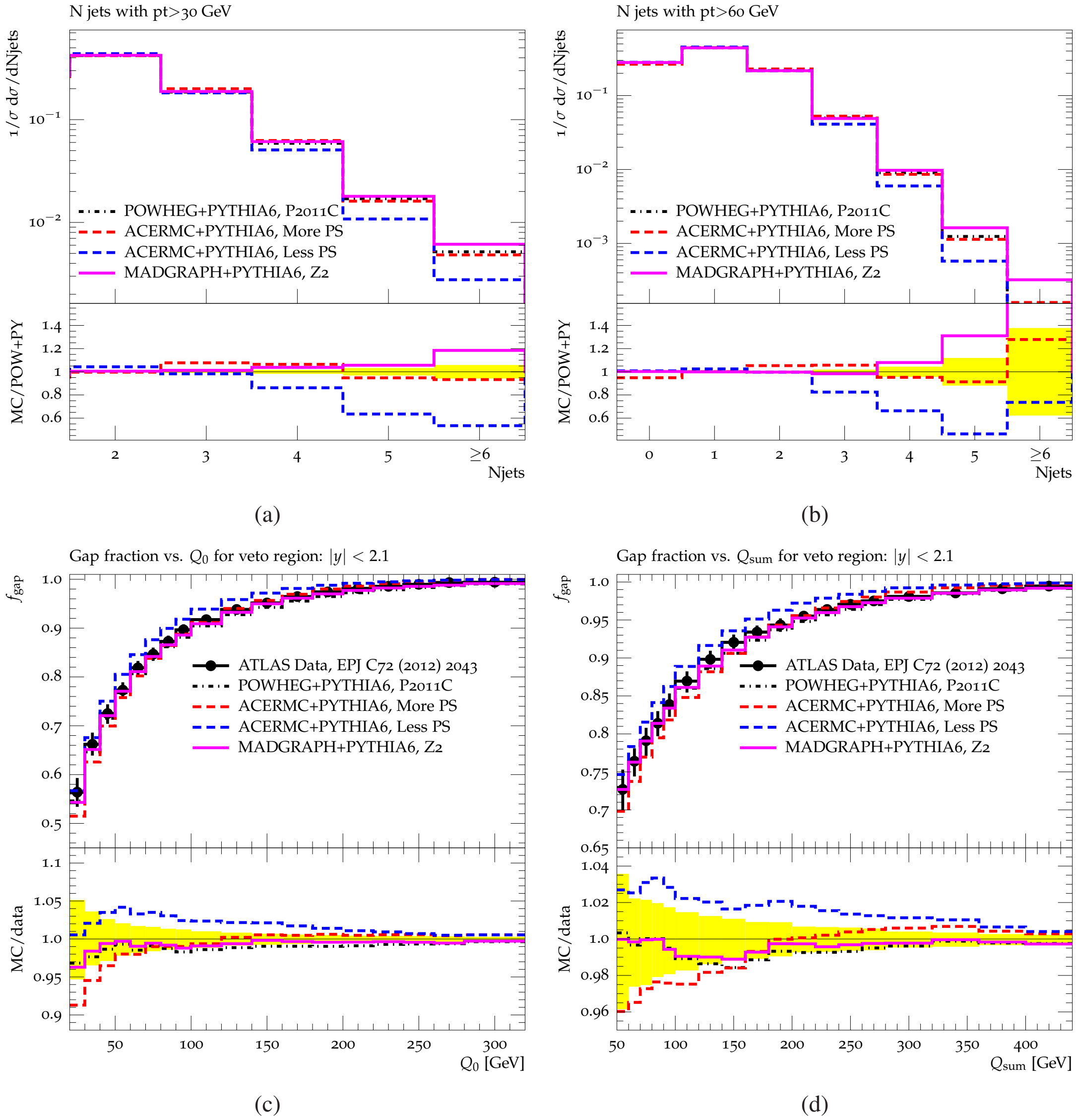


Figure 1: The AcerMC + Pythia6 More PS and Less PS sample predictions are compared for the jet multiplicity and gap fraction observables in $t\bar{t}$ dilepton channel events. The Powheg + Pythia6, P2011 and MadGraph + Pythia6, Z2 predictions are also shown. The normalized differential cross-section as a function of jet multiplicity is shown for the jets with (a) $p_T > 30$ GeV, (b) $p_T > 60$ GeV. In the ratio the Powheg + Pythia6, P2011 prediction is used for reference. The yellow band corresponds to the statistical uncertainty of the reference sample. The comparisons to the gap fraction observables [1] (c) $f(Q_0)$ and (d) $f(Q_{sum})$ are shown. The data is represented as closed (black) circles with statistical uncertainties. The yellow band is the total experimental uncertainty on the data (statistical and systematic). The theoretical predictions are shown as solid and dashed coloured lines. All samples apart from MadGraph + Pythia6, Z2 sample are showered within the ATLAS framework. The MadGraph + Pythia6, Z2 sample is showered within the CMS framework.

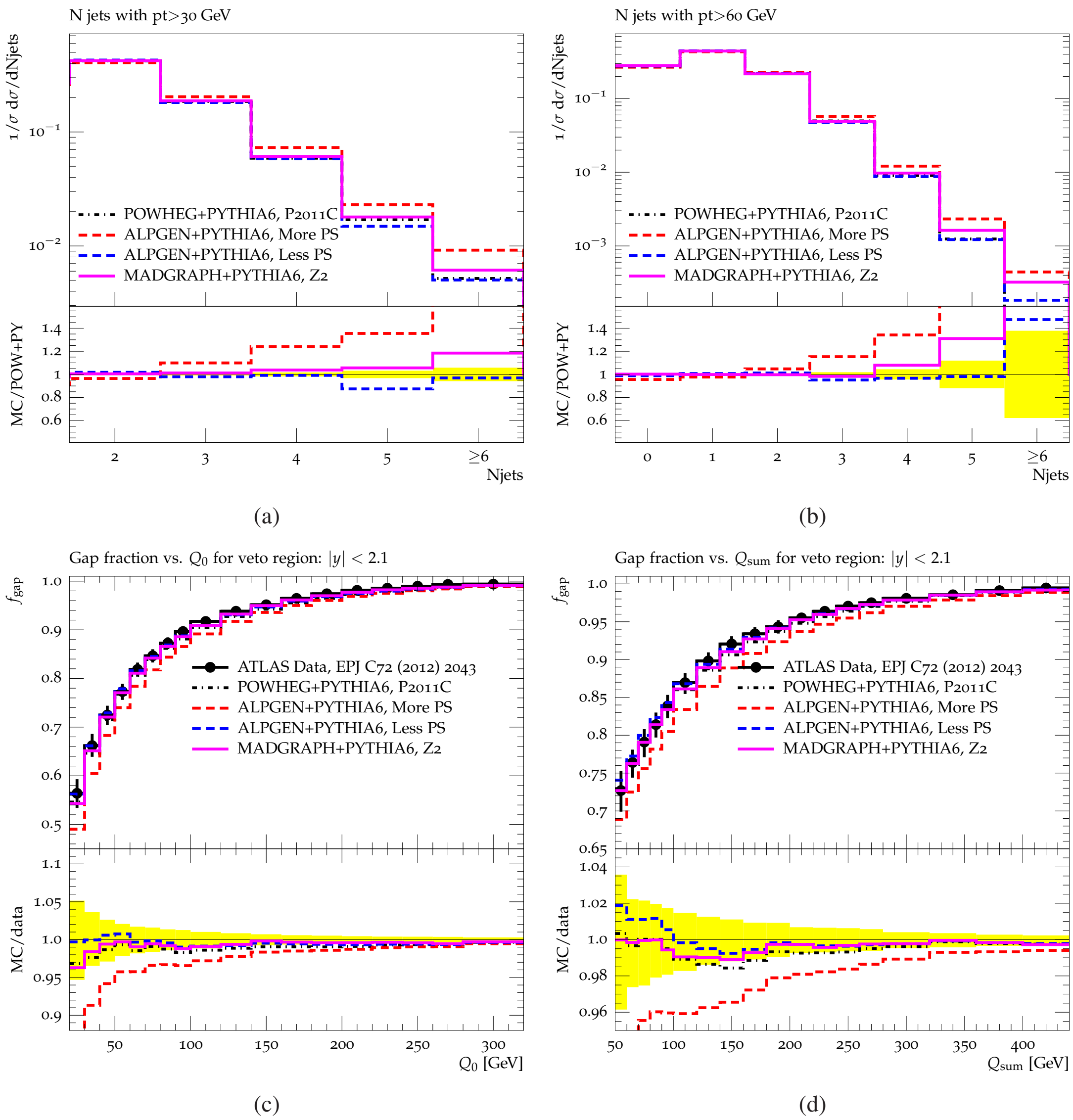


Figure 2: The ALPGEN + PYTHIA6 as_down,radLo and as_up,radHi sample predictions are compared for the jet multiplicity and gap fraction observables in $t\bar{t}$ dilepton channel events. The POWHEG + PYTHIA6, P2011 and MADGRAPH + PYTHIA6, Z2 predictions are also shown. The normalized differential cross-section as a function of jet multiplicity is shown for the jets with (a) $p_T > 30$ GeV, (b) $p_T > 60$ GeV. The comparisons to the gap fraction observables [1] (c) $f(Q_0)$ and (d) $f(Q_{sum})$ are shown. The data and theory predictions are represented in the same way as in Fig. 1.

	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
AcerMC + Pythia6	0.76 ± 0.06	0.26 ± 0.12	1.23 ± 0.18
Alpgen + Pythia6	1.36 ± 0.03	0.21 ± 0.08	1.78 ± 0.11

Table 3: Radiation systematic uncertainties uncertainty of the inclusive $t\bar{t}$ cross-section measurement [32] and its components: preselection efficiency $\epsilon_{e\mu}$ and tagging correlation C_b. In Ref. [32] the uncertainty was evalued using the AcerMC + Pythia6 samples. For comparison, the Alpgen + Pythia6 values were evaluated by replacing the AcerMC Less PS and More PS samples with Alpgen as_down,radLo and as_up,radHi samples accordingly.

is 3.1 %. When evaluated with the AcerMC + Pythia6 samples, the relative systematic uncertainty due to radiation is 1.2 %. When evaluated with the Alpgen + Pythia6 samples, the relative systematic uncertainty due to radiation is 1.8 %. The systematic uncertainty due to radiation receives contributions from the following sources:

- preselection efficiency $\epsilon_{e\mu}$ that requires a presence of an opposite-sign $e\mu$ pair but has no b-tagged jets requirement,
- tagging correlation $C_b = \epsilon_{bb}/\epsilon_b^2$, where ϵ_b is a probability that a b-jet passes the selection and is tagged and ϵ_{bb} is a probability that both b-jets pass the selection and are tagged,
- effect of radiation on the background contribution. (Evaluated by using the Less PS and More PS samples for Wt-channel events, which are the dominant background.)

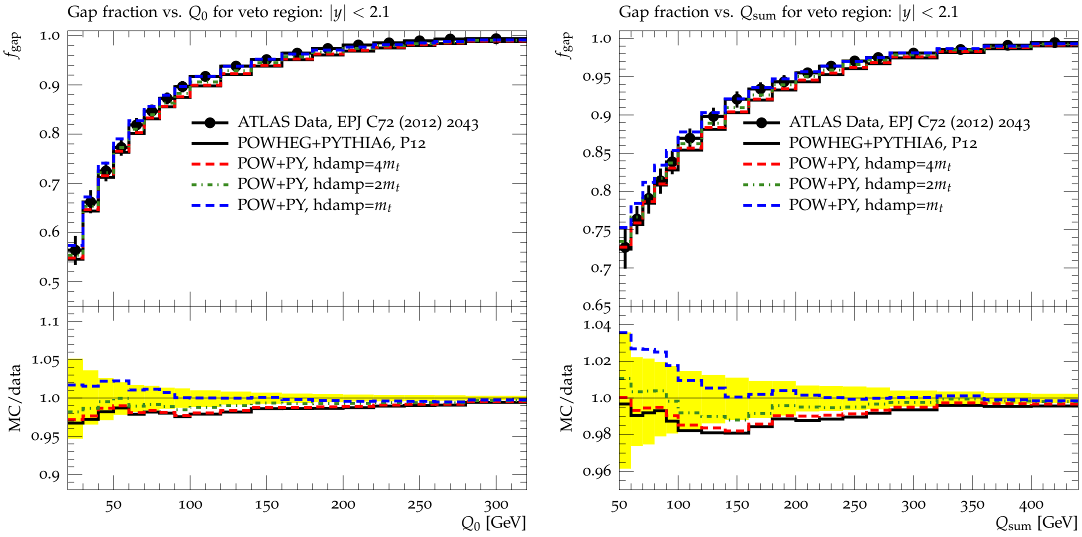
Radiation systematic uncertainty of the inclusive $t\bar{t}$ cross-section measurement [32] and its components: preselection efficiency $\epsilon_{e\mu}$ and tagging correlation C_b are passed in Table 4 for each of AcerMC + Pythia6 and Alpgen + Pythia6 samples.

In the case of AcerMC + Pythia6 Less PS and More PS samples, somewhat smaller radiation uncertainty is obtained than in the case of Alpgen + Pythia6 Less PS and More PS samples. While this is consistent with the smaller parameter variation ranges used in the AcerMC + Pythia6 samples, it is observed to be analysis-dependent, whether AcerMC + Pythia6 or AcerMC + Pythia6 samples yield larger uncertainties.

Overall the difference between AcerMC + Pythia6 More PS and Less PS and the difference between Alpgen + Pythia6 as_down,radLo and as_up,radHi pairs is comparable for the gap fraction and jet multiplicity observables, as can be seen in Figs. 1, 2. Only at high Q_0, $Q_{\rm sum}$ and large jet multiplicity there are larger differences visible between the AcerMC and Alpgen samples.

5 NLO generators and uncertainties

In this section predictions of generators using NLO hard process interfaced to the parton shower generators are compared for gap fraction observables. The exact sample settings are given in section 2 and observables are defined in section 3. The effects of scale and parton shower variations similar to the ones used for LO generators in section 4 are inspected. Furthermore, a few NLO generators are interfaced to multiple parton shower programs. In addition to models used for Run I analyses, a few newer generators are included in the comparisons if their setup has been validated and their performance found to be broadly satisfactory.



(a) (b)

Figure 3: The Powheg + Pythia6, P12 sample and the predictions with different values of damping parameter `hdamp` are compared for the gap fraction observables [1] in $t\bar{t}$ dilepton channel events. (a) $f(Q_0)$ and (b) $f(Q_{\rm sum})$ are shown in rapidity interval $|y|$ <2.1. The data is represented as closed (black) circles with statistical uncertainties. The yellow band is the total experimental uncertainty on the data (statistical and systematic). The theoretical predictions are shown as solid and dashed coloured lines.

5.1 Powheg

First parameter variations for the case of Powheg + Pythia6, P12 sample are studied. In case of Powheg it has been noted in Ref. [12], that the renormalisation and factorisation scale variations result in underestimate of uncertainties, unless a scale variation is performed in the presence of damping, switched on by `hdamp` parameter described in section 2. Variations of Powheg renormalisation and factorisation scale variations and variations of parameter `hdamp` as well variations of Pythia6 parton shower settings are explored for gap fraction observables.

Since the value of parameter `hdamp` is not known from first principles, several values are considered in Fig. 3. Predictions of Powheg + Pythia6, P12 sample for gap fraction observables (a) $f(Q_0)$ and (b) $f(Q_{\rm sum})$ are shown in rapidity interval $|y|$ <2.1 for values of `hdamp` parameter of m_t, $2m_t$ and $4m_t$. As expected, the larger values of `hdamp` are closer to the nominal Powheg + Pythia6, P12 prediction, which corresponds to parameter `hdamp` set to ∞. The sample produced with `hdamp` $= m_t$ yields a notably higher gap fraction than the nominal setup. For scale variation studies in the following figures value of `hdamp` $= 2m_t$, close to value of 400 GeV considered in [12] is used. The prediction of sample with `hdamp` $=$ $2m_t$ is in agreement with gap fraction data and is well suited to be a baseline for renormalisation and factorisation scale variations.

In Fig. 4 predictions of Powheg + Pythia6, P12 for the gap fraction observables are shown for renormalisation and factorisation scale variations without and with damping. Multiplicative factors of renormalisation (μ_r) and factorisation (μ_f) scales are varied using the reweighting features of Powheg-BOX. It has been checked that the conclusions remain the same when estimating the scale variation effects by generating (as opposed to reweighting) the events. (a,c,e) $f(Q_0)$ and (b,d,f) $f(Q_{\rm sum})$ are shown in rapidity interval $|y| < 2.1$. For samples Pow + Py, $\mu_r = X$, $\mu_f = Y$, `hdamp` $= 2m_t$, that correspond to scale variation in presence of damping the following observations can be made: difference between the scale variation samples is significant. The renormalisation (top row) and factorisation (middle) scale variations in the presence of damping are of comparable size and in the same direction, so the simultaneous renormalisation and factorisation scale variations (bottom row) results in a larger variation than the independent variations. For samples Pow + Py, $\mu_r = X$, $\mu_f = Y$, that correspond to scale variations in absence of damping, effects of scale variations are negligible (< 1 %).

In Fig. 5 Powheg + Pythia6, P12 predictions with simultaneous renormalisation and factorisation scale variations in presence of damping are accompanied by Pythia6 tune variations. The tune variations correspond to Perugia2012 radLo and radHi tunes. These variations are used for ATLAS radiation systematics samples based on Alpgen + Pythia6 for analyses done at $\sqrt{s} = 8$ TeV. In the Pythia6 parton shower, the default value of the 5 flavour Λ_{QCD} used for leading order evolution of the running coupling is 0.26 GeV. For the radLo and radHi setups, the value is varied by a factor of 0.5 and 2.0, simultaneously in the initial and final state radiation, as listed in Table 2.2. These variations correspond to the P12 tunes family. The sample variations in radLo and radHi setups include all parameters varied in these tunes. The running coupling evolution and Λ_{QCD} in the matrix element generation are left to the CT10 PDF values. Apart from Powheg + Pythia6, also predictions for Powheg + Herwig and MC@NLO + Herwig are shown. The MC@NLO + Herwig prediction is not covered by the Powheg + Pythia6 uncertainty band obtained by simultaneous scale variations in the ME and PS. The Powheg + Herwig prediction is contained within the uncertainty band.

5.2 MC@NLO and aMC@NLO

In the following, renormalisation and factorisation scale variations for the cases of MC@NLO + Herwig, AUET2 and aMC@NLO + Herwig++, UEEE4 LO** samples are compared to gap fraction observables. While MC@NLO + Herwig, AUET2 is a standard setup used in many ATLAS publications, aMC@NLO + Herwig++, UEEE4 LO** is a new setup under study. The variation samples are compared to Powheg + Pythia6, P12 sample and Powheg + Herwig, AUET2 sample produced with generators frequently used by ATLAS for $t\bar{t}$ samples. A newer sample generated with MC@NLO + Herwig++, UEEE4 LO** is also included.

In Fig. 6 MC@NLO + Herwig, AUET2 sample and the renormalisation and factorisation scale variation predictions are compared for the gap fraction observables. Apart from simultaneous renormalisation and factorisation scale variations, MC@NLO + Herwig, UEEE4 LO** sample predictions are shown as well. (a,c) $f(Q_0)$ and (b,d) $f(Q_{\mathrm{sum}})$ are shown in rapidity intervals of $|y| < 0.8$ (top) and $|y| < 2.1$ (bottom). The spread between the scale variations obtained with MC@NLO + Herwig, AUET2 sample is smaller than the spread between the Powheg + Pythia6, P12 sample predictions with different values of renormalisation and factorisation scale and damping parameter `hdamp` shown in Fig. 4 (bottom). The MC@NLO + Herwig, UEEE4 LO** sample predictions are not covered by MC@NLO + Herwig, AUET2 scale variation band.

In Fig. 7 aMC@NLO + Herwig++, UEEE4 LO** sample the renormalisation and factorisation scale variation predictions are shown. Apart from simultaneous renormalisation and factorisation scale variations, aMC@NLO + Herwig, AUET2 sample predictions are shown as well. (a,c) $f(Q_0)$ and (b,d) $f(Q_{\mathrm{sum}})$ are shown in rapidity intervals of $|y| < 0.8$ (top) and $|y| < 2.1$ (bottom). The spread between the scale variations obtained with aMC@NLO + Herwig++, UEEE4 LO** is comparable to the spread between the Powheg + Pythia6, P12 sample predictions with different values of renormalisation and factorisation scale and damping parameter `hdamp` shown in Fig. 4 (bottom). The aMC@NLO + Herwig, AUET2 sample predictions are not covered by the scale variation band in regions of approximately $Q_0 <$ 50 GeV and $Q_{\mathrm{sum}} < 150$ GeV. Good agreement between the data and MC is observed for aMC@NLO + Herwig++, UEEE4 LO** sample, apart from the lowest bins in $Q_0 < 50$ GeV, for which lower gap fraction values are predicted than observed.

In Fig. 8 aMC@NLO + Herwig++, UEEE4 LO** sample renormalisation and factorisation scale variation band is compared to gap fraction observables data as well as MC@NLO + Herwig, AUET2,

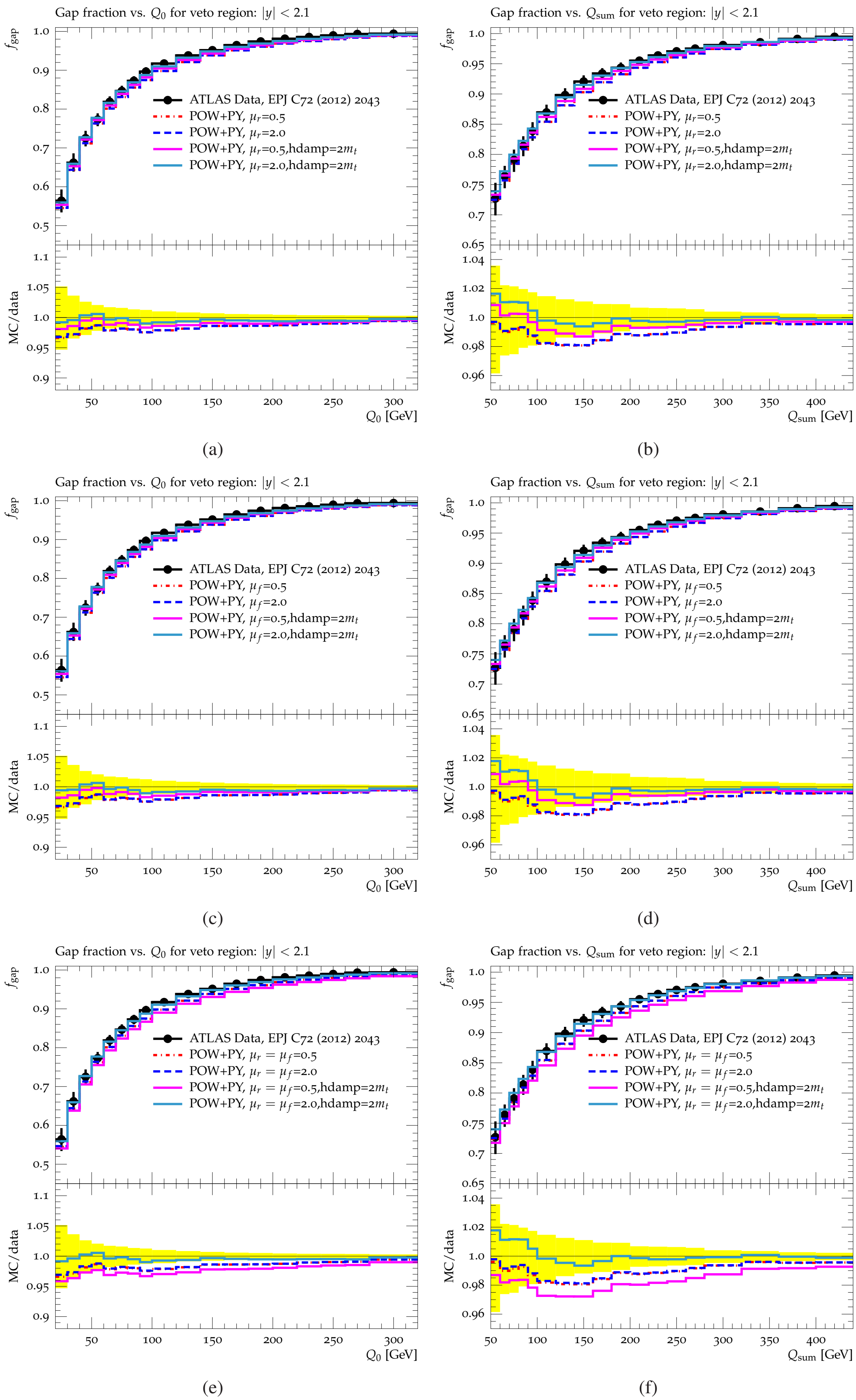


Figure 4: The POWHEG + PYTHIA6, P12 sample and the predictions for for renormalisation and factorisation scale variations without and with damping are compared for the gap fraction observables [1] in $t\bar{t}$ dilepton channel events. $f(Q_0)$ (left) and $f(Q_{sum})$ (right) are shown in rapidity interval $|y|$ <2.1. renormalisation (top row) and factorisation (middle) scale variations as well as simultaneous renormalisation and factorisation scale variations (bottom) are shown. The data and theory predictions are represented in the same way as in Fig. 3.

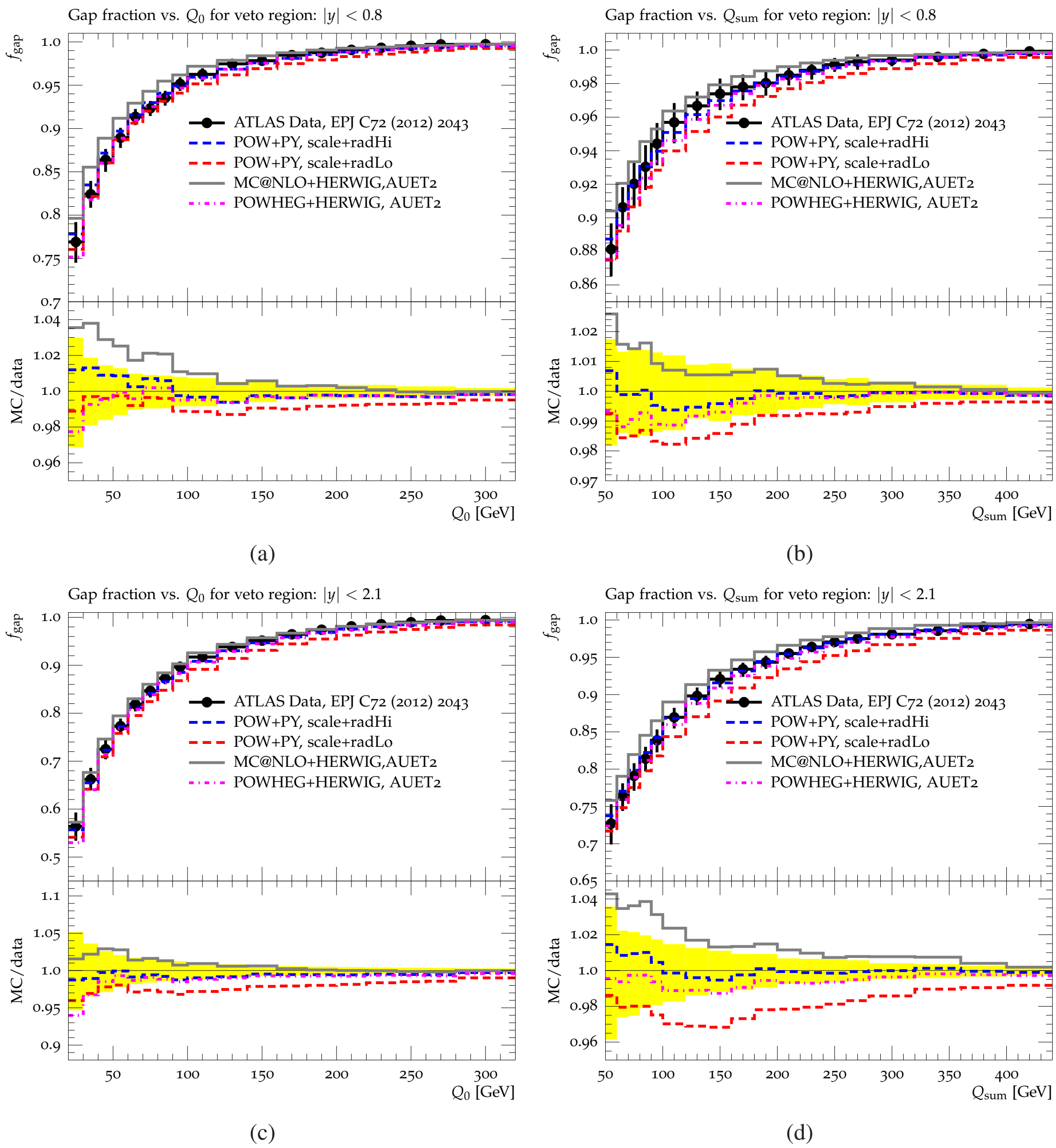


Figure 5: The Powheg + Pythia6, P12 sample predictions with simultaneous renormalisation and factorisation scale variations in presence of damping and Pythia6 tune variations are compared for the gap fraction observables [1] in $t\bar{t}$ dilepton channel events. (a,c) $f(Q_0)$ and (b,d) $f(Q_{\mathrm{sum}})$ are shown in rapidity intervals of $|y|$ <0.8 (top) and $|y|$ <2.1 (bottom). Powheg + Herwig and MC@NLO + Herwig predictions are shown as well. The data and theory predictions are represented in the same way as in Fig. 3.

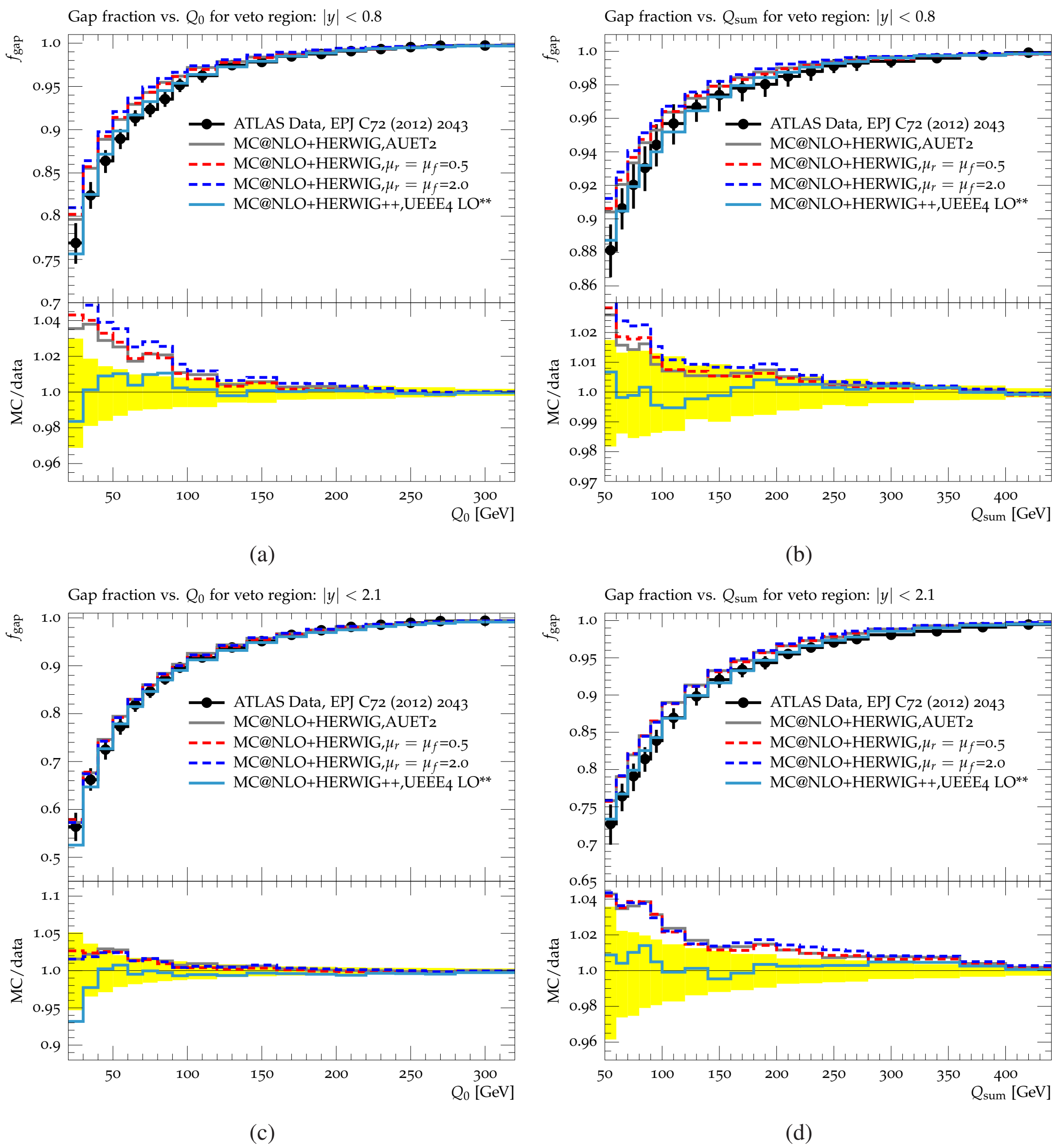


Figure 6: The MC@NLO + Herwig, AUET2 sample and renormalisation and factorisation scale variation predictions are compared for the gap fraction observables [1] in $t\bar{t}$ dilepton channel events. MC@NLO + Herwig++, UEEE4 LO** sample predictions are shown as well. (a,c) $f(Q_0)$ and (b,d) $f(Q_{\text{sum}})$ are shown in rapidity intervals of $|y| < 0.8$ (top) and $|y| < 2.1$ (bottom). MC@NLO + Herwig++, UEEE4 LO** sample predictions are shown as well. The data and theory predictions are represented in the same way as in Fig. 3.

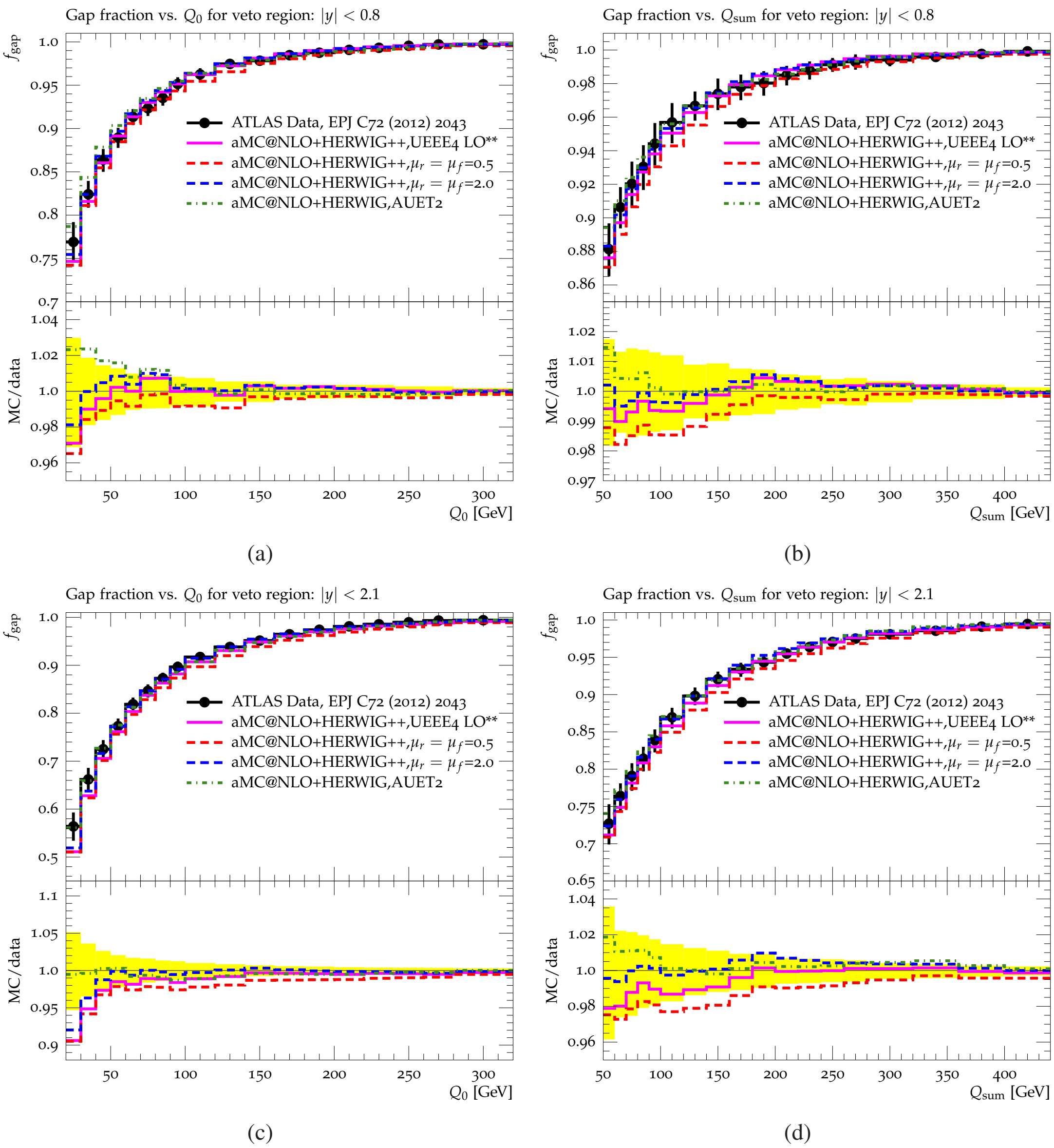


Figure 7: The aMC@NLO + HERWIG++, UEEE4 LO** sample and renormalisation and factorisation scale variation predictions are compared for the gap fraction observables [1] in $t\bar{t}$ dilepton channel events. (a,c) $f(Q_0)$ and (b,d) $f(Q_{\rm sum})$ are shown in rapidity intervals of $|y| < 0.8$ (top) and $|y| < 2.1$ (bottom). aMC@NLO + HERWIG, AUET2 sample predictions are shown as well. The data and theory predictions are represented in the same way as in Fig. 3.

Powheg + Pythia6, P12 and Powheg + Herwig, AUET2 sample predictions. Comparisons are done for (a,c) $f(Q_0)$ and (b,d) $f(Q_{\mathrm{sum}})$ in rapidity intervals of $|y| < 0.8$ (top) and $|y| < 2.1$ (bottom). The MC@NLO + Herwig, AUET2 sample is not contained within the variation band. The Powheg + Pythia6, P12 sample is contained within the variation band apart from lowest bins in Q_0 (which nonetheless contain a sizable fraction of events). The Powheg + Herwig, AUET2 sample prediction is contained within the variation band.

5.3 Conclusions on NLO generators and uncertainties

The effects of the renormalisation and factorisation scale variations and parton shower parameter variations are explored for Powheg + Pythia6, P12, MC@NLO + Herwig, AUET2 and aMC@NLO + Herwig++, UEEE4 LO**. It is observed that:

1. Powheg renormalisation and factorisation scale variations yield small effects in absence of damping, but the effects are significantly larger when variations are performed in presence of damping (using parameter `hdamp`). This is in agreement with observations in [12]. For the gap fraction observables, MC@NLO + Herwig, AUET2 prediction is not contained in the variation band obtained with damping, even if parton shower variations are performed on top of renormalisation and factorisation scale variations as well.

2. renormalisation and factorisation scale variations performed with MC@NLO + Herwig have an effect that is larger than the effect of variations in Powheg + Pythia6 in absence of damping, but smaller than the effect of variations in Powheg + Pythia6 in the presence of damping. MC@NLO + Herwig scale variations do not bracket Powheg + Pythia6 or Powheg + Herwig predictions. It is however interesting to note that renormalisation and factorisation scale variations performed with aMC@NLO + Herwig++, UEEE4 LO**, a new sample under study, bracket Powheg + Pythia6 and Powheg + Herwig in large part of the phase-space.

Thus when estimating NLO generator uncertainty some care should be dedicated to the variation parameters selection, else an uncertainty estimated with a single combination of a NLO generator and parton shower with their parameter variations will likely be an under-estimate of the modelling uncertainty. In case of Powheg setting a parameter `hdamp` to a value of $\sim 2m_t$ is observed to notably affect the central prediction as well as uncertainty band obtained by renormalisation and factorisation scale variations. These observation might be of relevance when choosing the modeling uncertainty strategy or when looking for generator setups that are able to describe the LHC $t\bar{t}$ experimental data.

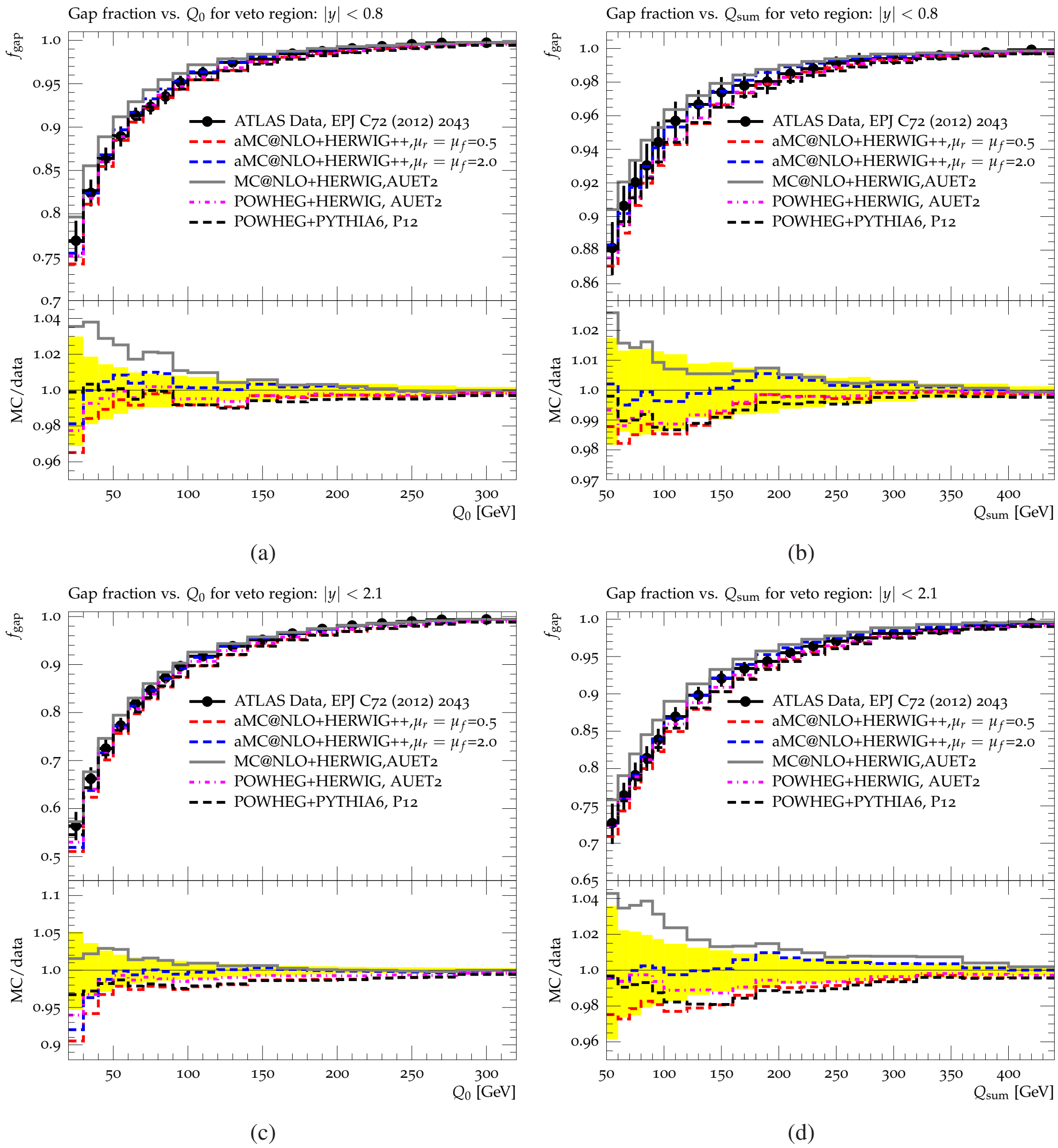


Figure 8: The aMC@NLO + HERWIG++, UEEE4 LO** sample renormalisation and factorisation scale variation predictions are compared to the gap fraction observables [1] in $t\bar{t}$ dilepton channel events and MC@NLO + HERWIG, AUET2, POWHEG + PYTHIA6, P12 and POWHEG + HERWIG, AUET2 predictions. The data and theory predictions are represented in the same way as in Fig. 3.

6 Conclusions

The Monte Carlo generator predictions are compared with each other and with the experimental data for $t\bar{t}$ observables at the LHC. The focus is on observables sensitive to additional parton radiation: jet multiplicities and gap fraction observables. The $t\bar{t}$ samples used by ATLAS Run I analyses as well as some of the generators the collaboration anticipates to use in the future are discussed. Their detailed settings, performance and response to parameter variations is presented.

The tree level Born and multi-leg generator LO samples used by ATLAS to evaluate radiation systematic uncertainties during Run I are discussed in detail. They are compared for the jet multiplicity and gap fraction observables as well as for the uncertainty predictions of the inclusive cross section measurement in dilepton decay channel. The two approaches are observed to be broadly consistent and compatible with the experimental data. The settings of ATLAS and CMS samples used for radiation systematic uncertainties are compared. The renormalisation scale variations, likely driving the radiation uncertainty in most analyses, are treated on comparable footing in the ATLAS and CMS samples. The differences between the ATLAS and CMS approaches are also pointed out. These comparisons might be of value for the ATLAS and CMS combination efforts.

The effects of the renormalisation and factorisation scale and parton shower parameter variations are explored for several NLO generators interfaced with various parton shower generators: Powheg with Pythia6 and Herwig, MC@NLO with Herwig and Herwig++ as well as aMC@NLO with Herwig and Herwig++. For these generators and the considered observables, the following conclusion can be made. When estimating NLO generator uncertainty some care should be dedicated to the variation parameters selection, else an uncertainty estimated with a single combination of a NLO generator and parton shower with their parameter variations will likely be an under-estimate of the modelling uncertainty. In case of Powheg setting a parameter `hdamp` to a value of $\sim 2m_t$ is observed to notably affect the central prediction as well as uncertainty band obtained by renormalisation and factorisation scale variations. These observation might be of relevance when choosing the modeling uncertainty strategy or when looking for generator setups that are able to describe the LHC $t\bar{t}$ experimental data. In all considered variation setups, there are models that are not contained withing the variation bands (in at least some regions of phase-space). Testing different matrix element and parton shower generator combinations therefore seems worthwhile.

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