

12pt

# Monte Carlo Simulation of Top Quark pair production in dilepton channel

Summerstudent Report

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**Abstract:** Monte Carlo simulations with three different event generators (Pythia 8, Cascade 2.3.14 and Powheg interfaced with Pythia) are made for recent CMS measurements of jet multiplicity of Top Quark events, evaluated in the dilepton channel. The Analysis is coded in Rivet and interfaced with each of the event generators.

# 1 Introduction

The Top quark is the heaviest of the quarks and the heaviest elementary particle so far ( $m_t = 173\text{GeV}$ , almost as heavy as a gold atom. It is the only quark which decays before hadronization, so there are no decay products from bound states in the final state.

The Large Hadron Collider (LHC) with its current energy of 8 TeV is a "top factory", it produces a huge statistic of  $t\bar{t}$  pairs, so also decay channels with small branching ratio (BR) could be measured precisely. At these Energies the fraction of  $t\bar{t}$  with additional hard jets is large ( $\approx 50\%$ ) [1].

Also the  $t\bar{t}$  process is here dominated by gluon-gluon fusion, so  $t\bar{t}$  is a kind of benchmark for other standard model processes which share the production mechanism [3]. A better understanding of these processes is needed because in higher order QCD Calculations are also contributions from initial and final state radiation (ISR, FSR), so it is possible to test them. It is needed to get a good description of multijet processes, which are also background for new physics searches.

Region of interest is the dilepton channel, it is the decay channel with the smallest branching ratio ( $\approx 4.5\%$ ). Contributions are from  $ee$ ,  $\mu\mu$ ,  $e\mu$  and from leptonic  $\tau$  decays. It is the cleanest decay channel, since there are no additional hadronic decay products and low background.

There are 2 b-jets from top decay, the additional jets do not come from top decay but from ISR and FSR, and apart from this only leptons and missing transverse energy (mainly from neutrinos) in the final state.

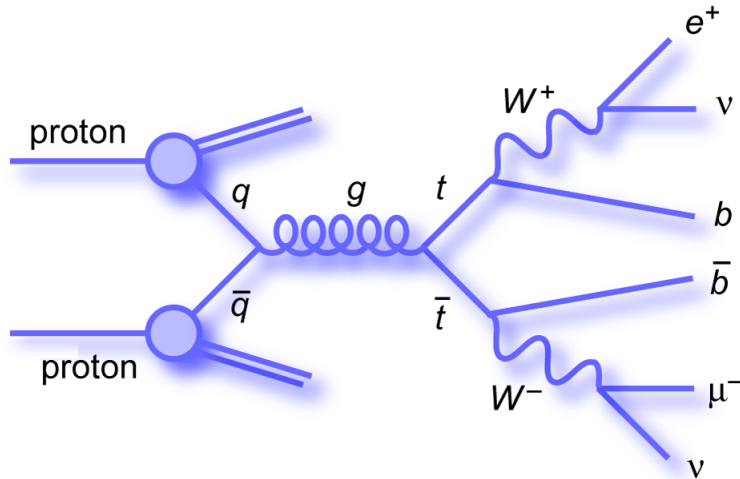


Figure 1: *Dileptonic decay of the  $t\bar{t}$ -pair* [5]

For parts of [1] (cross section, gap fraction) an analysis is written with Rivet (Robust Independent Validation of Experiment and Theory, <http://rivet.hepforge.org/>). Rivet is a framework for event generator testing and tuning and can be linked to various event generators. For comparison with data it is possible to get data from HepData records.

Trying to reproduce the results (also MC results!) from the paper is a cross check, for really being able to compare it is necessary to use one of the MC generators that were also used there. This will be Powheg, but unfortunately there were some problems, so correctly normalized Powheg results are only available for the cross section with "hard cuts".

## Top Pair Branching Fractions

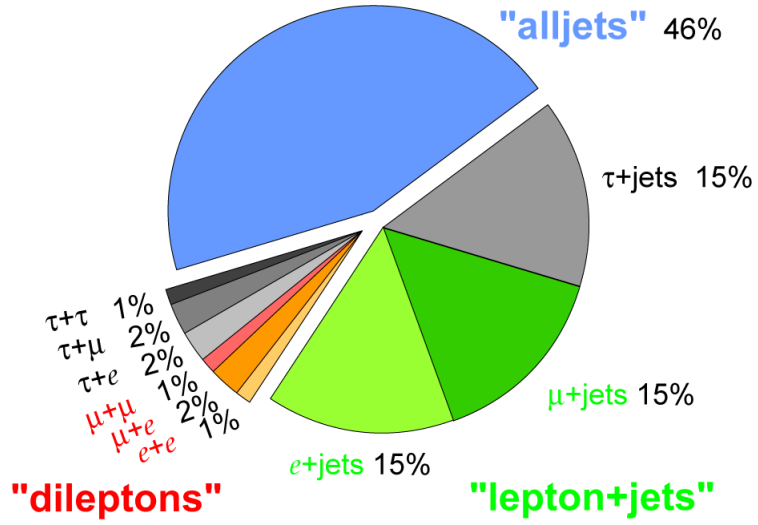


Figure 2: The branching ratio for decay into dilepton channel is about 4.5%. [2]

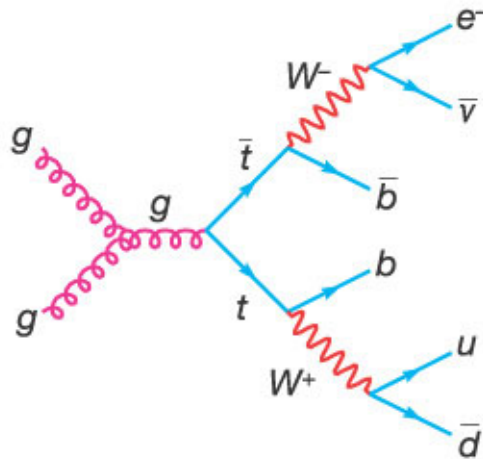


Figure 3: Top quark pair production via gluon-gluon fusion and decay in dilepton channel

## 2 Generators

### 2.1 Pythia 8

Pythia 8 is a MC generator for high energy events, completely written in  $C++$  and a standalone framework. Its initial- and final-state algorithms are based on  $p_{\perp}$ - ordered evolution. Initial-state evolution, multiple interactions and the final-state evolution are interleaved into one common decreasing  $p_{\perp}$  sequence [6].

This generator is leading-logarithm, its parton shower is based on the ordering of the shower outcome by transverse momentum  $p_T$ [7]. Next to leading order calculations are not taken into account.

### 2.2 Cascade

Cascade is a Hadron level MC generator for  $ep$  and  $pp$  scattering. It uses the CCFM evolution equation in a backward evolution approach for angular ordered parton showers, proton remnant and hadronization are done via a standard hadronization program like Pythia [8]. Also it agrees well with standard next to leading order calculations, where applicable [9].

### 2.3 Powheg

Powheg is a MC generator which implements next to leading order calculations in shower MC programs. It can be interfaced with all parton shower programs that support the Les Houches Interface. Here it is used interfaced with Pythia 6 for the parton Shower [10]. According to the POWHEG method, the hardest radiation is generated first, using exact next to leading order matrix elements. This output can be interfaced to any standard MC generator, which is either  $p_T$  ordered or allows implementation of a  $p_T$ -veto. Interfacing to angular ordered programs cannot guarantee the double-log accuracy of the whole result [11].

### 3 Event Selection

Region of interest is the dilepton Channel, where a produced  $t\bar{t}$ -pair decays into  $t \rightarrow b + W^+$  and  $\bar{t} \rightarrow \bar{b} + W^-$ , and the  $W$  bosons decay each into a charged lepton and a neutrino.

The reconstruction and selection of the data is described in more detail in [1]. Used were muons with transverse momentum  $p_T > 20\text{GeV}$  within the pseudorapidity region  $|\eta| < 2.4$ . They are required to have a relative isolation of  $I_{rel} < 0.15$ .

The Definition of  $I_{rel}$  is as follows: the sum of all transverse momenta of all neutral and charged reconstructed particle candidates, except the muon itself, inside an cone in  $\eta - \phi$  space of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ , divided by the muon transverse momentum [1].

Electrons are required to have a transverse energy  $E_T > 20\text{GeV}$ ,  $|\eta| < 2.4$  and  $I_{rel} < 0.15$ . Jets are selected if  $|\eta| < 2.4$  and the transverse momentum is at least  $p_T > 30\text{GeV}$ .

For selecting an event the following properties are required: a combination of at least two isolated leptons of opposite charge, at least two jets, of which at least two have to be b-tagged, so only the additional jets could be b-tagged or not, and a large missing transverse energy  $\cancel{E}_T > 40\text{GeV}$ , usually originating from neutrinos. In the  $ee$  and  $\mu\mu$  channels the invariant mass of the lepton pair has to be outside a Z-boson mass window of  $91 \pm 15\text{GeV}$ .

To avoid miscounting leptons as jets, "good" jets are the ones where no leading lepton is in a cone of 0.4 with respect to the jet. Only good jets are processed further, others rejected. A b-jet is defined to contain the decay products of a b-hadron [1].

For MC Simulation slightly different cuts than these "hard cuts" were used, the relative isolation of the leptons and the missing transverse energy was skipped, also the mass requirements for the lepton pair, only the kinematics in the final state were used to be able to compare with the experimental data and the corresponding MC simulations, since the same cuts were used there.

As accidentally first all the cuts were programmed in, it is possible to compare both simulations with data and with themselves.

	$p_T$	$ \eta $	additional Info
$ee$	$> 20\text{GeV}$	$< 2.4$	ANTIKT algorithm $R = 0.5$ , reject jet if leading leptons within a cone of 0.4 with respect to the jet
$\mu\mu$	$> 20\text{GeV}$	$< 2.4$	
$e\mu$	$> 20\text{GeV}$	$< 2.4$	
b-jet	$> 30\text{GeV}$	$< 2.4$	

Table 1: selection criteria for the  $t\bar{t}$ - dilepton channel  $\rightarrow$ "normal cuts"

	$p_T$	$ \eta $	dilepton mass	additional Info
$ee$	$> 20\text{GeV}$	$< 2.4$	$> 20\text{GeV}$	outside Z-boson mass window( $\pm 15\text{GeV}$ )
$\mu\mu$	$> 20\text{GeV}$	$< 2.4$	$> 20\text{GeV}$	outside Z-boson mass window( $\pm 15\text{GeV}$ )
$e\mu$	$> 20\text{GeV}$	$< 2.4$		
b-jet	$> 30\text{GeV}$	$< 2.4$		ANTIKT algorithm $R = 0.5$ , reject jet if leading leptons within a cone of 0.4 with respect to the jet
$E_{\cancel{T}}$	$> 40\text{GeV}$			

Table 2: harder event selection criteria for the  $t\bar{t}$ - dilepton channel (accidentally first also implemented)→”hard cuts”

# 4 Results

## 4.1 Differential cross section as a function of jet multiplicity

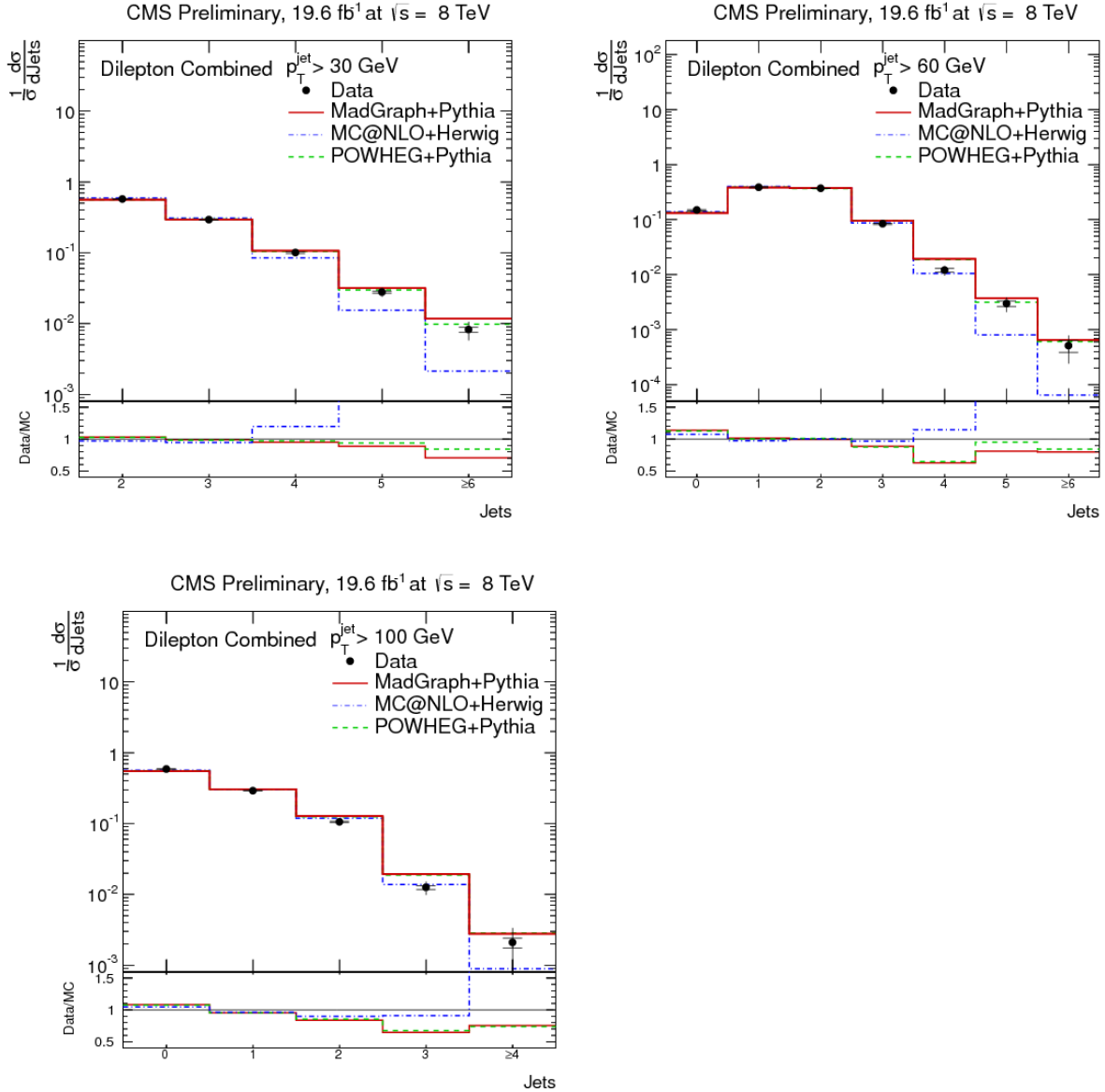
The differential cross section as a function of jet multiplicity is defined as

$$\frac{d\sigma_{tt}}{dN} = \frac{N_{data}^i}{\Delta_x^i \mathcal{L}}$$

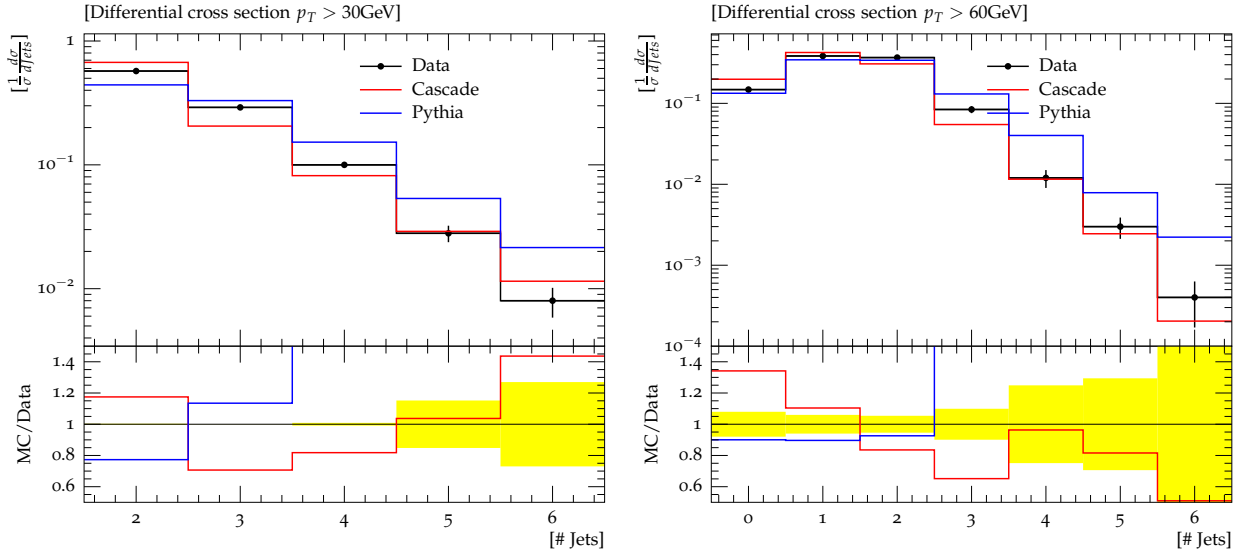
where  $N_{data}^i$  are the number of Events in data in bin  $i$ ,  $\Delta_x^i$  is the bin width and  $\mathcal{L}$  is the integrated luminosity.

Practically to do is counting how many jets (b-jets and additional jets) are there for each of the three  $p_T$  thresholds: 30GeV, 60GeV and 100GeV.

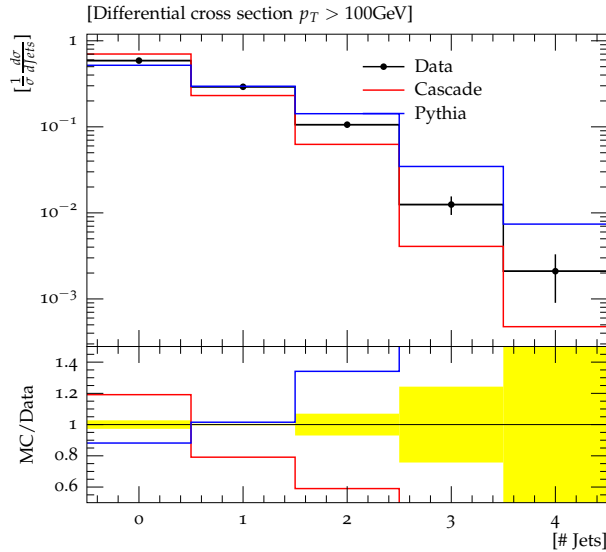
For comparison are here first the plots from the paper [1]:



### 4.1.1 Normal cuts



a) Differential cross section for  $p_T > 30\text{GeV}$     b) Differential cross section for  $p_T > 60\text{GeV}$

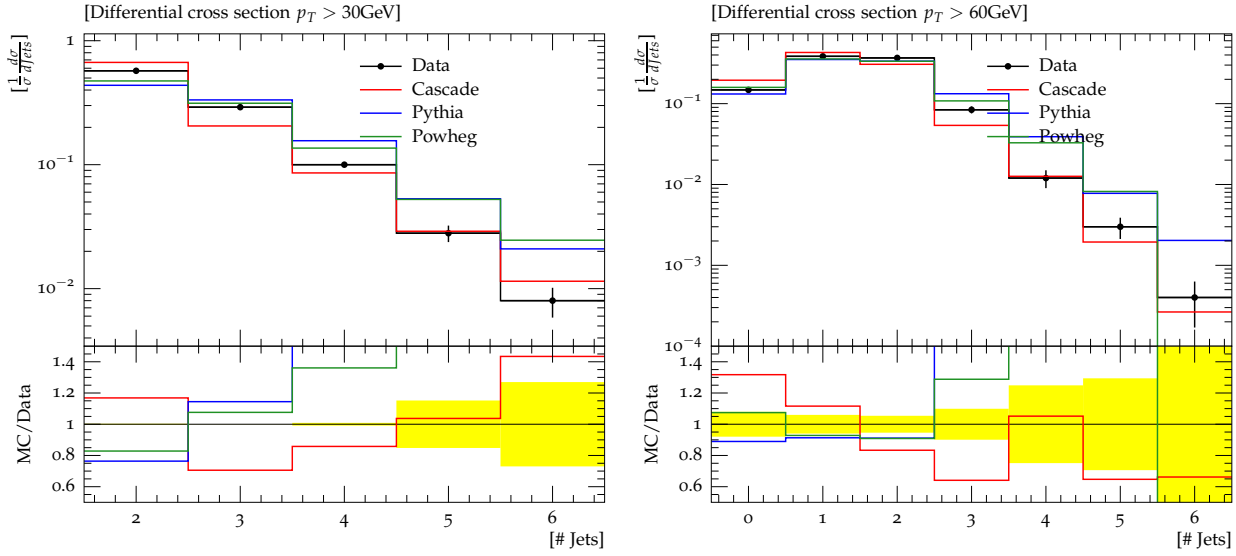


c) Differential cross section for  $p_T > 100\text{GeV}$

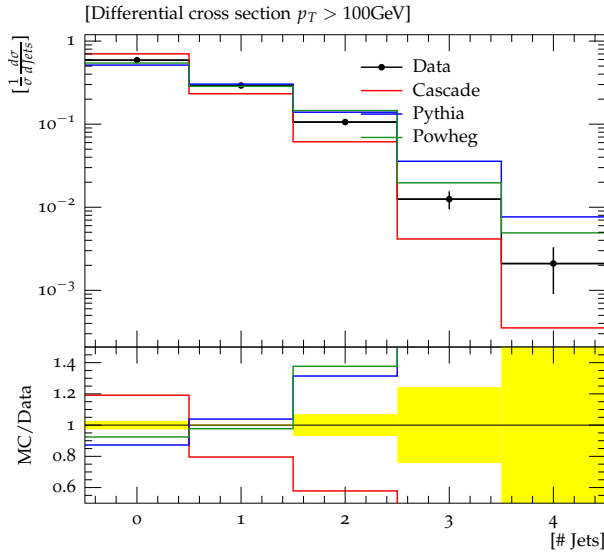
Results for the cross section: Cascade gives a quite reasonable description of the data, Pythia also but tends to overestimate the jet multiplicity. On the x-axis is the number of jets, the y-axis shows the differential cross section. In the last bin are also the higher jet multiplicities  $\geq 6$ ,  $\geq 4$ , but plotting with the AIDA framework is somehow difficult...



## 4.1.2 Hard cuts



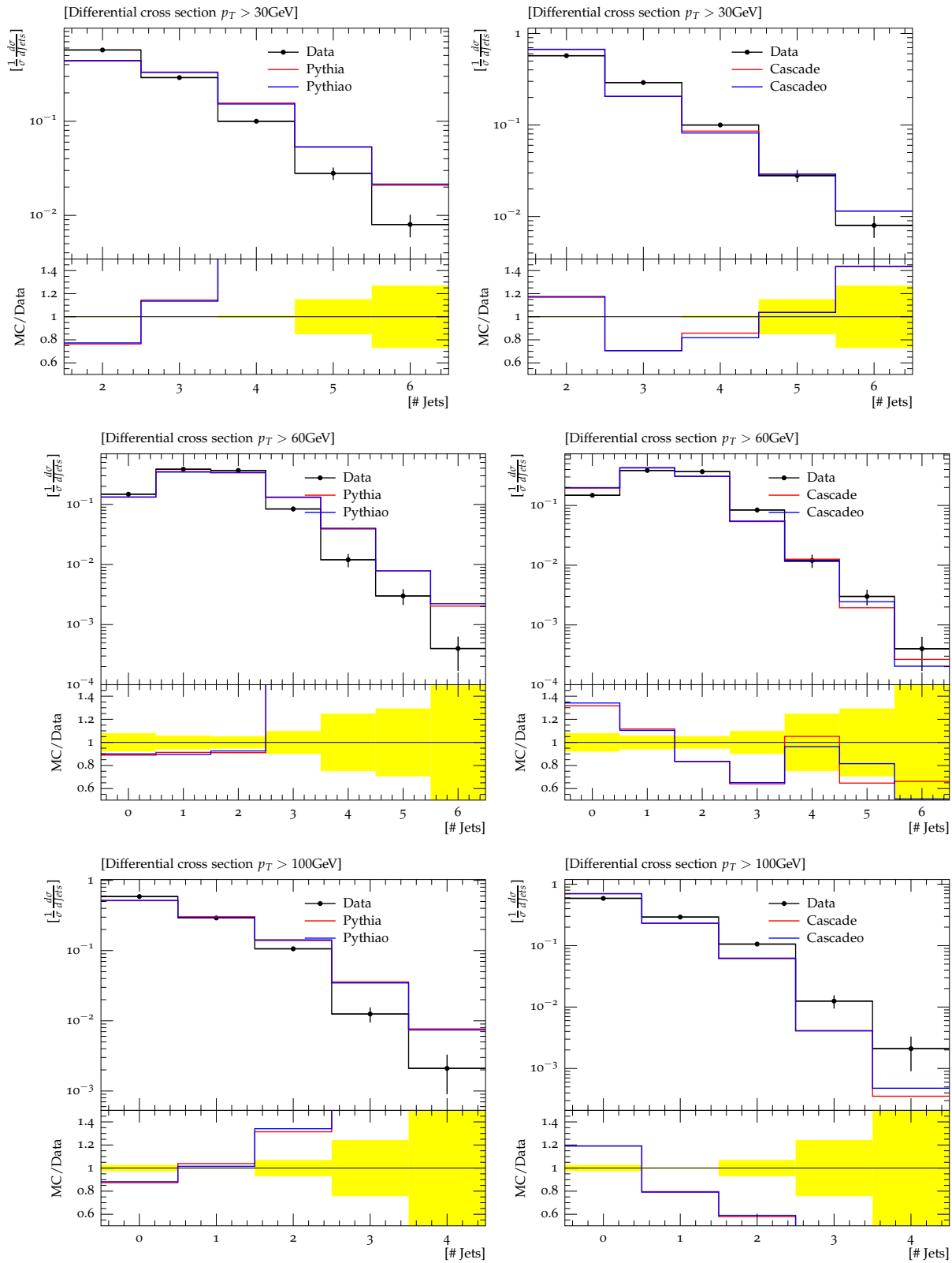
a) Differential cross section for  $p_T > 30 \text{ GeV}$  (hard cuts)      b) Differential cross section for  $p_T > 60 \text{ GeV}$  (hard cuts)



c) Differential cross section for  $p_T > 100 \text{ GeV}$  (hard cuts)

Results for the cross section with the harder set of cuts: nearly the same result, here it was possible to include the Powheg MC, which gives a result very similar to Pythia 8. They share the  $p_T$  order in their mechanism, since Powheg was linked to Pythia 6. The description of the data is reasonably well. In the last bin are also the higher jet multiplicities  $\geq 6$ ,  $\geq 4$ .

### 4.1.3 Comparison between normal and hard cuts

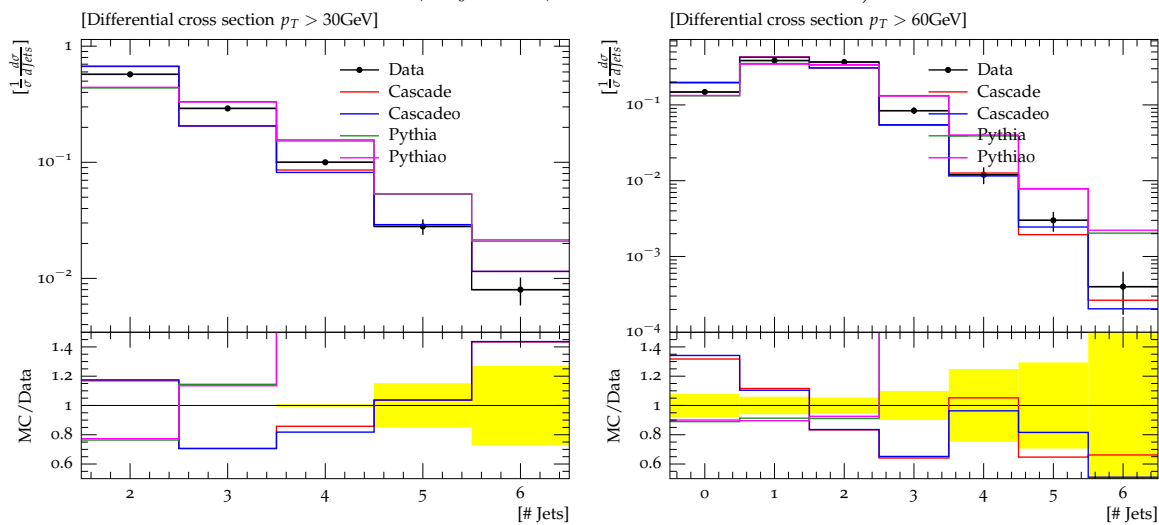


Left column: Comparison between normal and hard cuts for Pythia 8,  $p_T > 30\text{GeV}$ ,  $p_T > 60\text{GeV}$  and  $p_T > 100\text{GeV}$ . Pythia labeled are the hard cuts, Pythia0 labeled the normal cuts. The Differences are very small.

Right column: Comparison between normal and hard cuts for Cascade,  $p_T > 30\text{GeV}$ ,  $p_T > 60\text{GeV}$  and  $p_T > 100\text{GeV}$ . Cascade labeled are the hard cuts, Cascade0 labeled the normal cuts. The Differences are also very small.

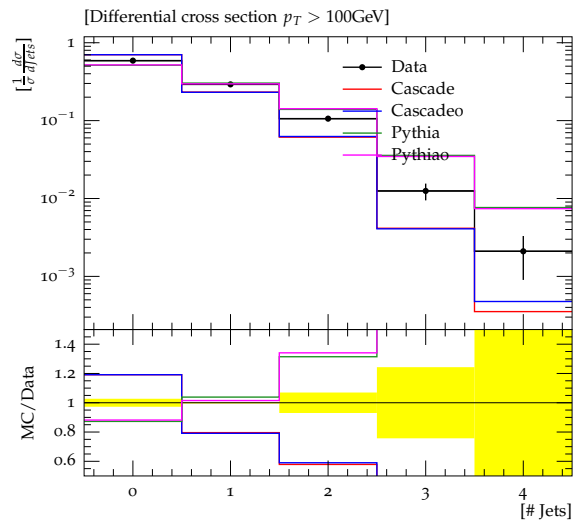
The differences between normal and hard cuts are very small, so there is good agreement between the whole event selection and the selection via kinematic cuts.

At last both Pythia 8 and both Cascade results are shown in comparison with data (Pythia, Cascade labeled are hard cuts, Pythia0, Cascade0 normal cuts):



a) Differential cross section for  $p_T > 30\text{GeV}$ , both cuts

b) Differential cross section for  $p_T > 60\text{GeV}$ , both cuts



c) Differential cross section for  $p_T > 60\text{GeV}$ , both cuts

## 4.2 Gap Fraction

The gap fraction is defined as the fraction of events, which do not contain additional jets above a given threshold in  $p_T$ . So it is considering also initial- and final-state radiation and is therefore sensitive to jet activity arising from quark and gluon radiation. It is formally defined as

$$f(p_T) = \frac{N(p_T)}{N_{total}}$$

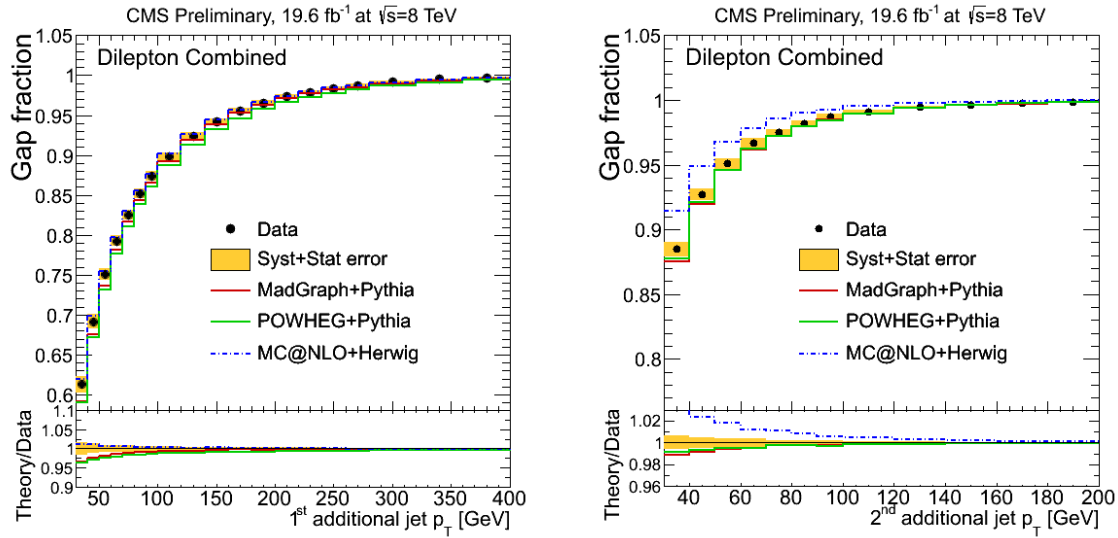
where  $N(p_T)$  : is the number of selected events that do not contain an additional jet above a chosen  $p_t$  value and  $N_{total}$  is the number of selected events.

Considered for gap fraction are the 1st additional jet (additional jet with highest  $p_T$ ), the 2nd additional jet (additional jet with 2nd highest  $p_T$ ) and the  $H_T$ .  $H_T$  is defined as the scalar sum of the transverse momentum of all additional jets in each selected event:

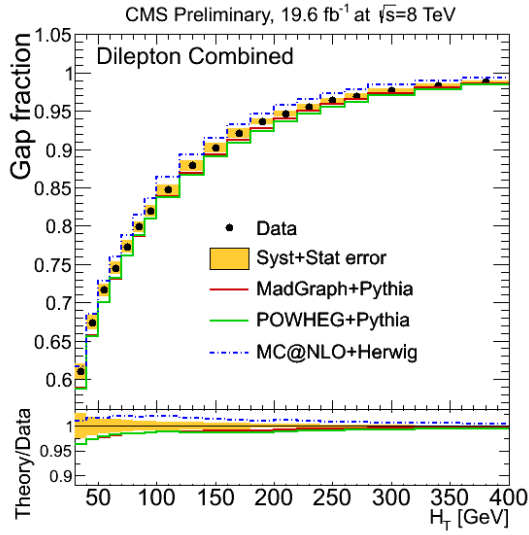
$$f(H_T) = \frac{N(H_T)}{N_{total}}$$

with  $N(H_T)$  the number of events in which the sum of the scalar transverse momentum of the additional jets is less than a certain threshold [1].

For comparison are here first the plots from the paper [1]:

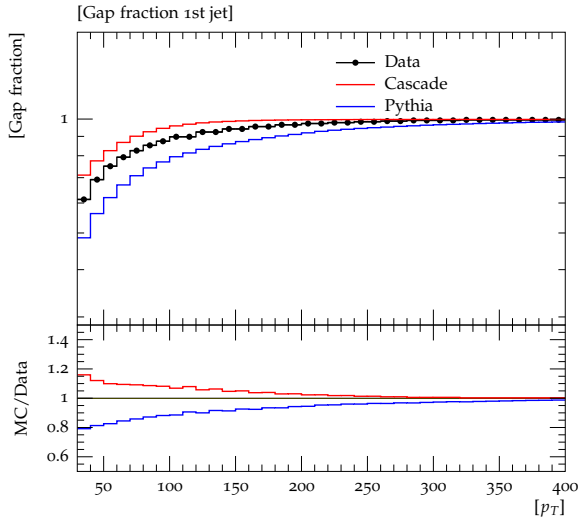


a) Gap fraction of the 1st additional jet [1] b) Gap fraction of the 2nd additional jet [1]

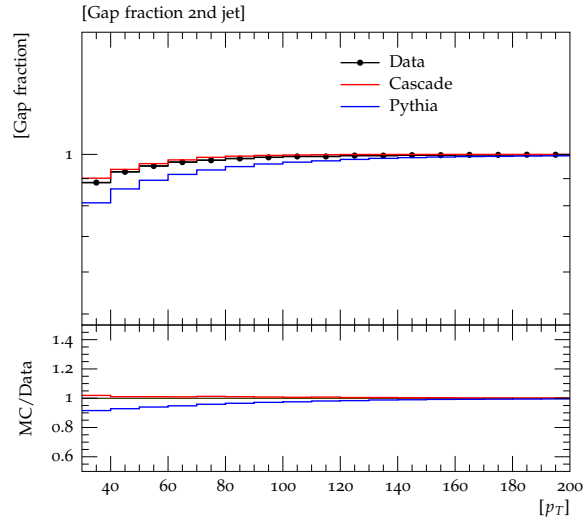


c) Gap fraction HT [1]

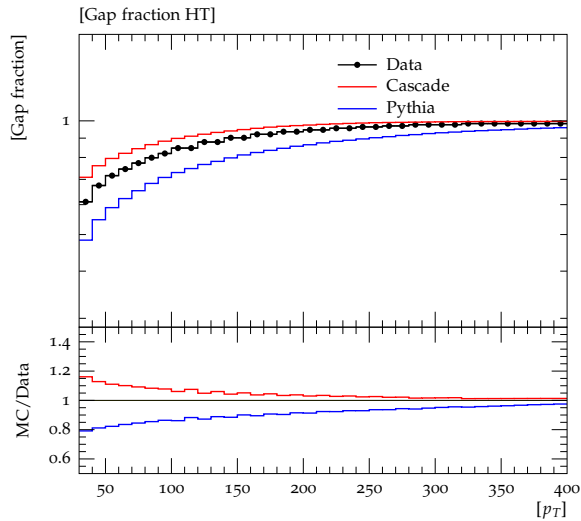
#### 4.2.1 Normal cuts



a) Gap fraction of the 1st additional jet



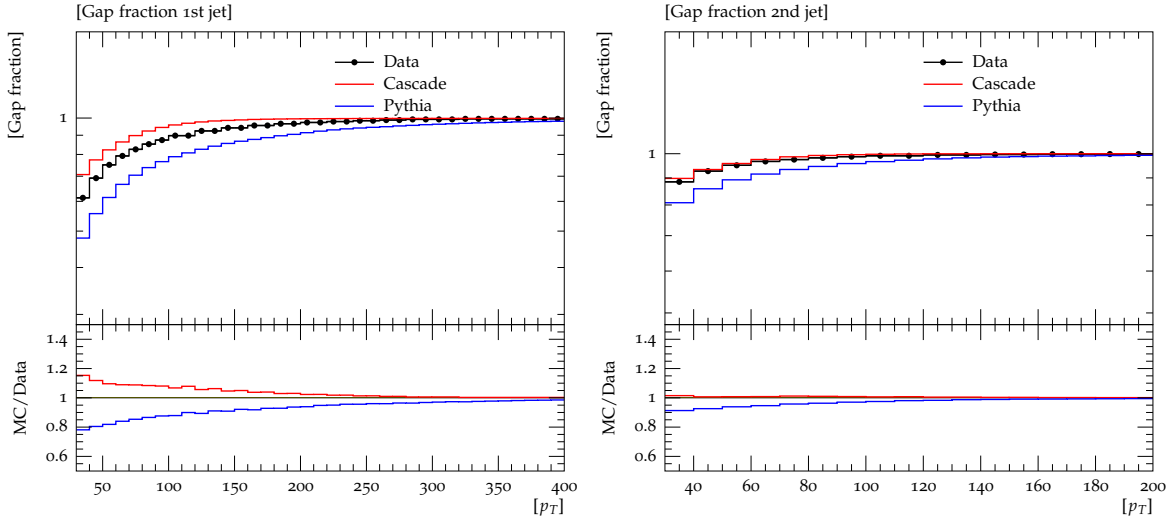
b) Gap fraction of the 2nd additional jet



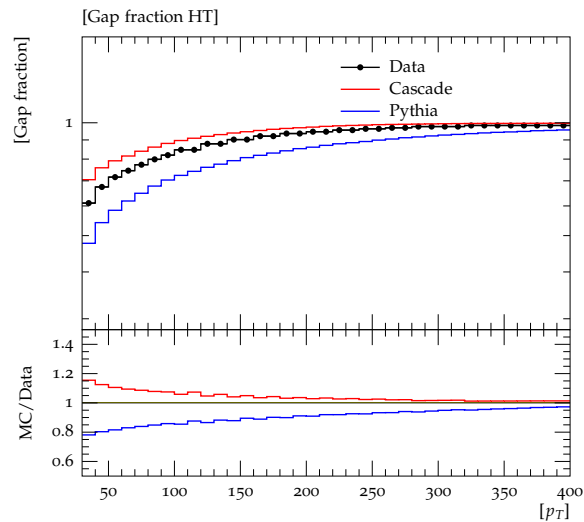
c) Gap fraction HT

Cascade tends to overestimate the gap fraction, Pythia 8 underestimates it. Cascade describes the gap fraction of the 2nd additional jet quite good, the overall description is rather reasonable, "the truth seems to lie in between" the two different generation mechanisms (angular ordering of Cascade and  $p_T$  ordering of Pythia).

4.2.2 Hard cuts



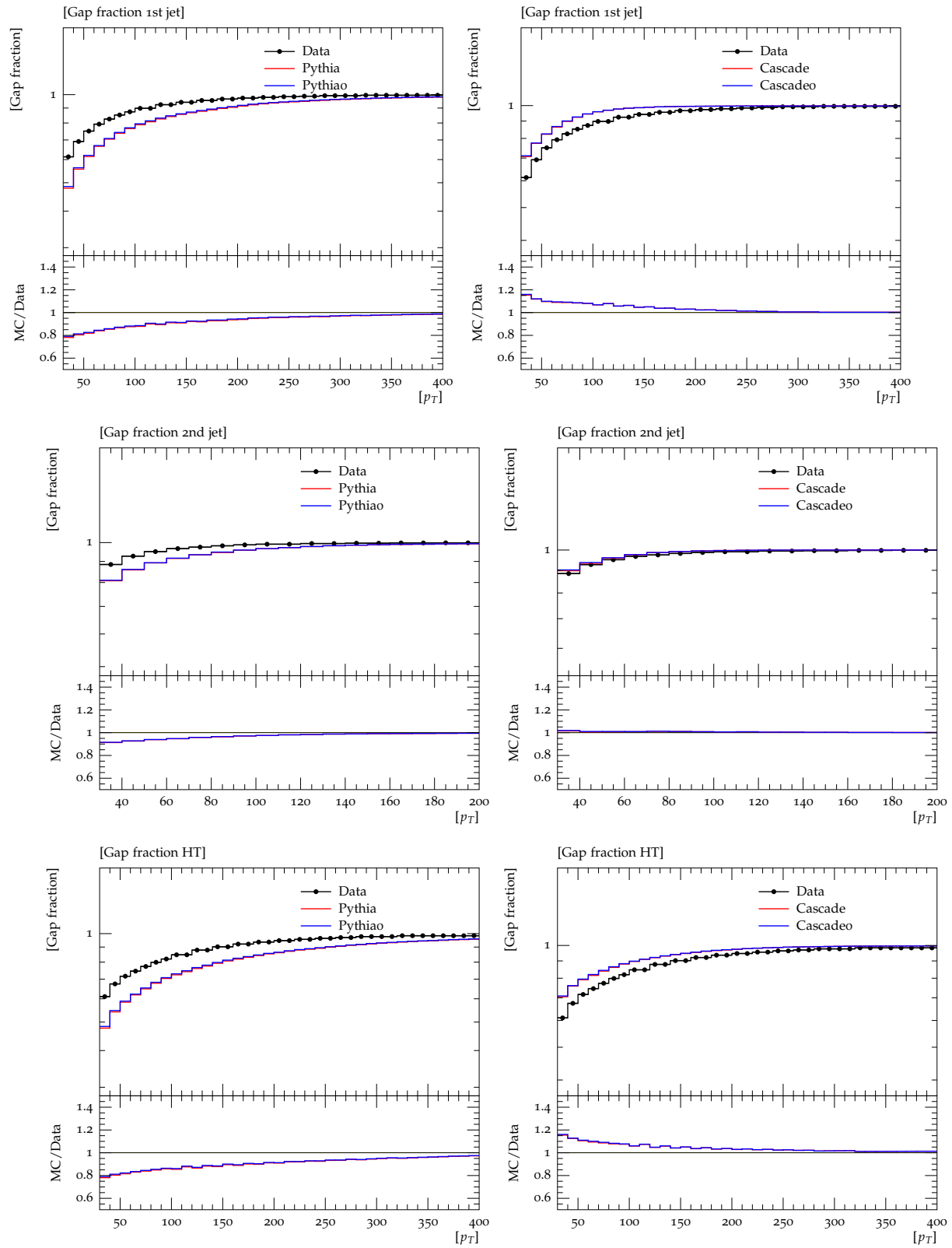
a) Gap fraction of the 1st additional jet (hard cuts)      b) Gap fraction of the 2nd additional jet (hard cuts)



c) Gap fraction HT (hard cuts)

The result is again nearly the same as with the normal cuts.

### 4.2.3 Comparison between normal and hard cuts

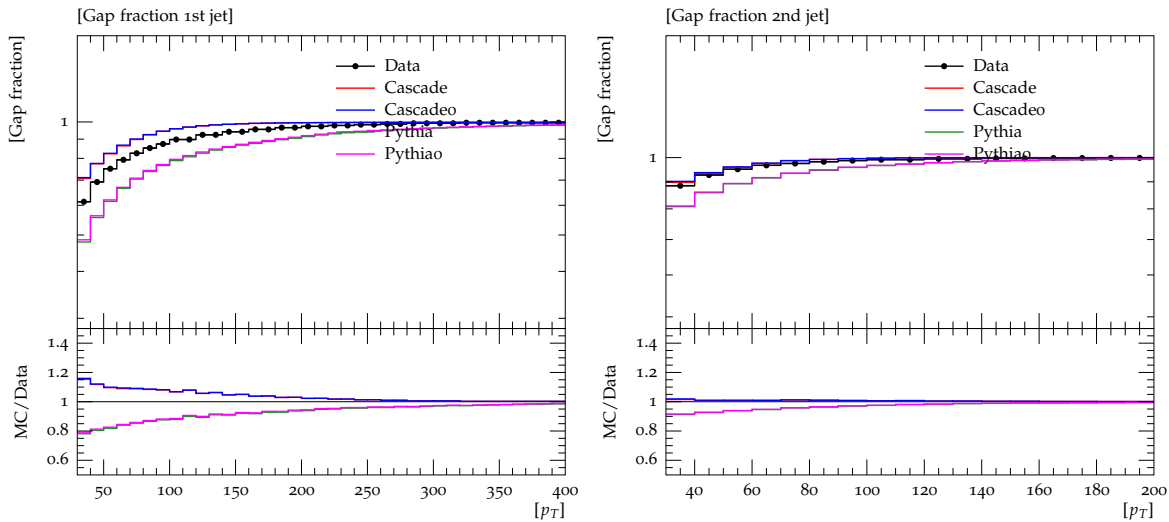


Left column: Comparison between normal and hard cuts for Pythia 8 for the gap fraction of the 1st jet, 2nd jet and HT. Pythia labeled are the hard cuts, Cascade labeled are the hard cuts, Pythia0 labeled the normal cuts. The Differences are very small.

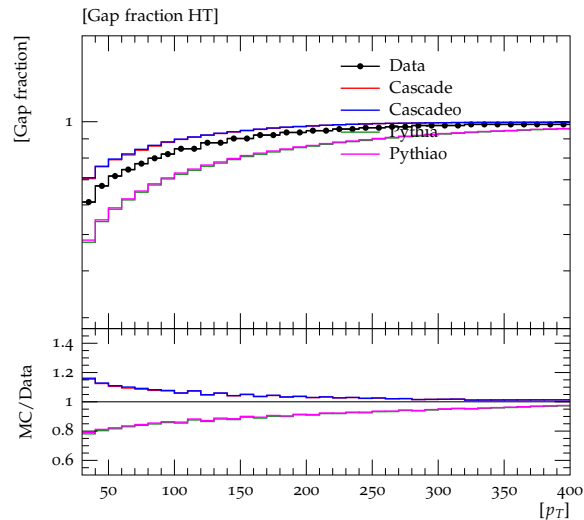
Right column: Comparison between normal and hard cuts for Cascade for the gap fraction of the 1st jet, 2nd jet and HT. Cascade labeled are the hard cuts, Pythia0 labeled the normal cuts. The Differences are very small.

The differences between normal and hard cuts are again very small, so there is good agreement between the whole event selection and the selection via kinematic cuts shown.

At last both Pythia 8 and both Cascade results are shown in comparison with data (Pythia, Cascade labeled are hard cuts, Pythia0, Cascade0 normal cuts):



a) Gap fraction of the 1st additional jet, both cuts      b) Gap fraction of the 2nd additional jet, both cuts



c) Gap fraction of HT, both cuts



### 4.3 Gap Fraction in different $|\eta|$ regions

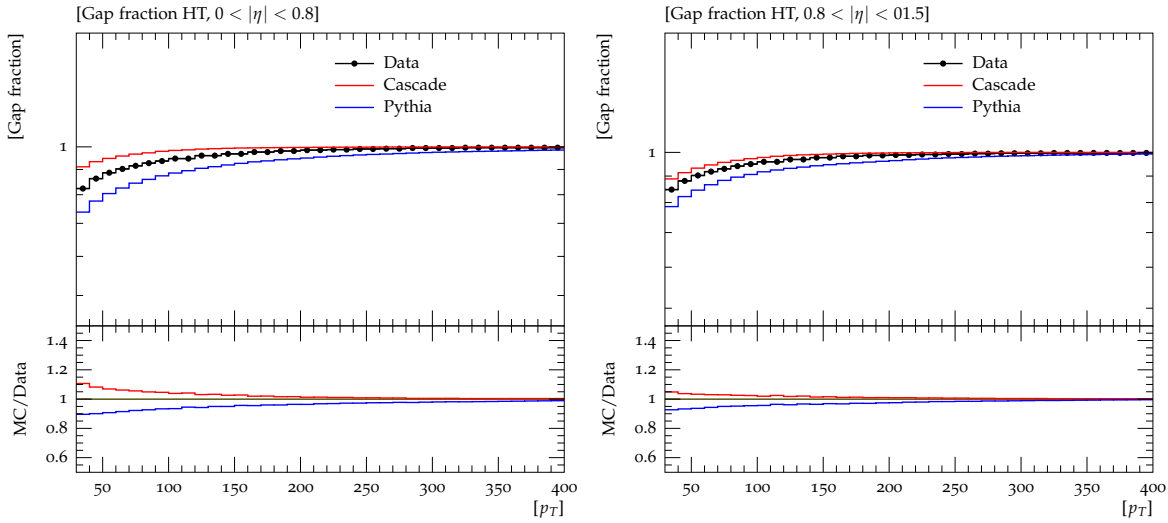
It is also possible to obtain the gap fraction in different pseudorapidity ( $\eta$ ) regions. Therefore only jets falling into the chosen region of  $|\eta|$  are considered:

$$f(p_T) = \frac{\text{\#of events with no jet above the } p_T \text{ threshold in the considered } |\eta| \text{ region}}{\text{\#of selected events}}$$

In case of HT, only jets in the required  $|\eta|$  region contribute to the scalar sum.

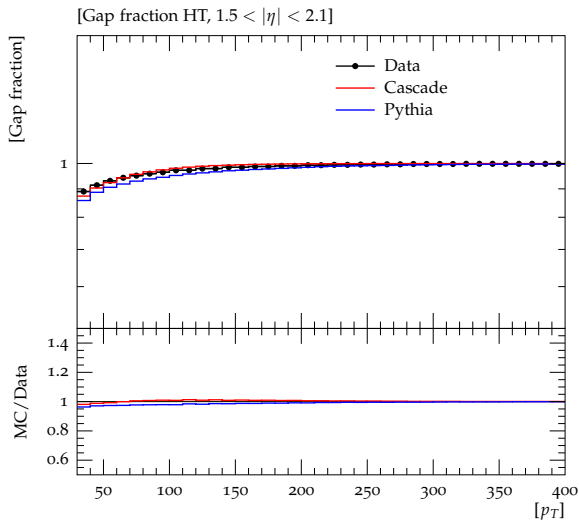
All three cases were simulated for three different  $|\eta|$  regions:  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$ , corresponding to the measured data and simulations in [1].

#### 4.3.1 Normal cuts

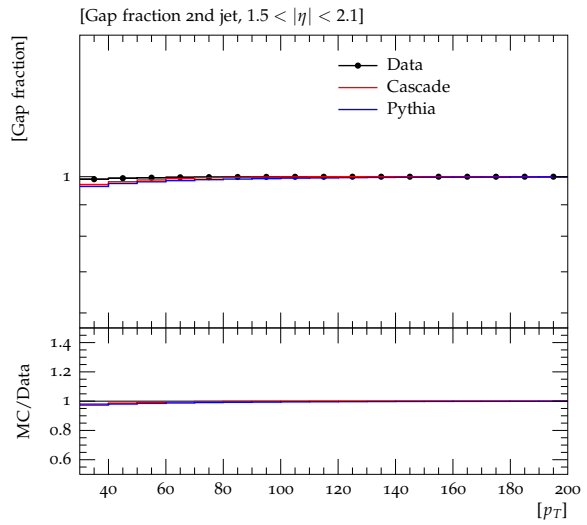
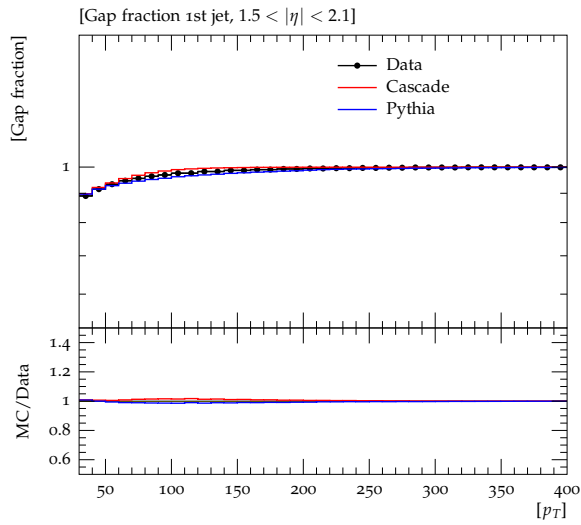
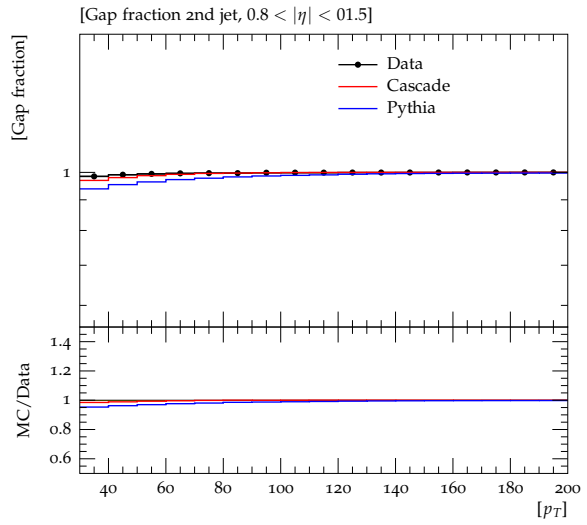
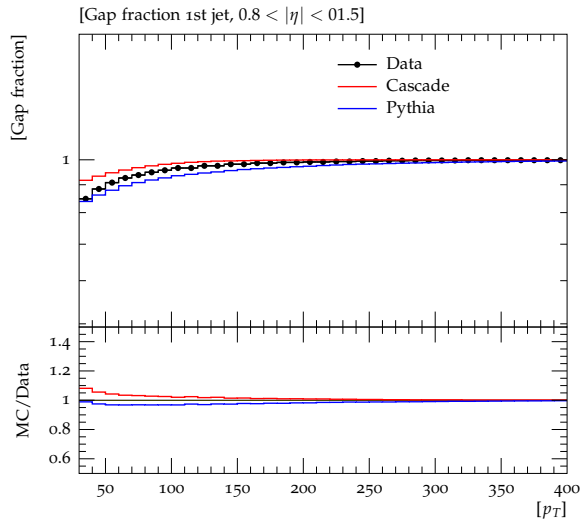
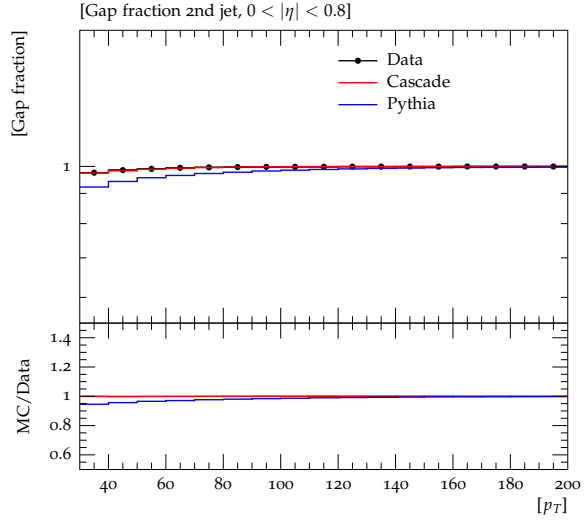
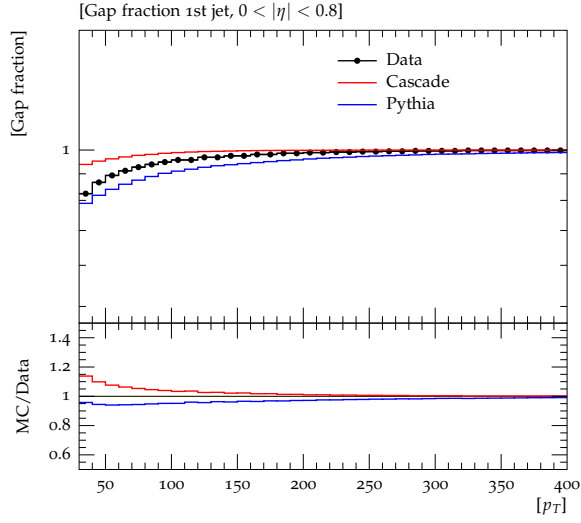


a) Gap fraction HT  $0 < |\eta| < 0.8$

b) Gap fraction HT  $0.8 < |\eta| < 1.5$



c) Gap fraction of HT  $1.5 < |\eta| < 2.1$

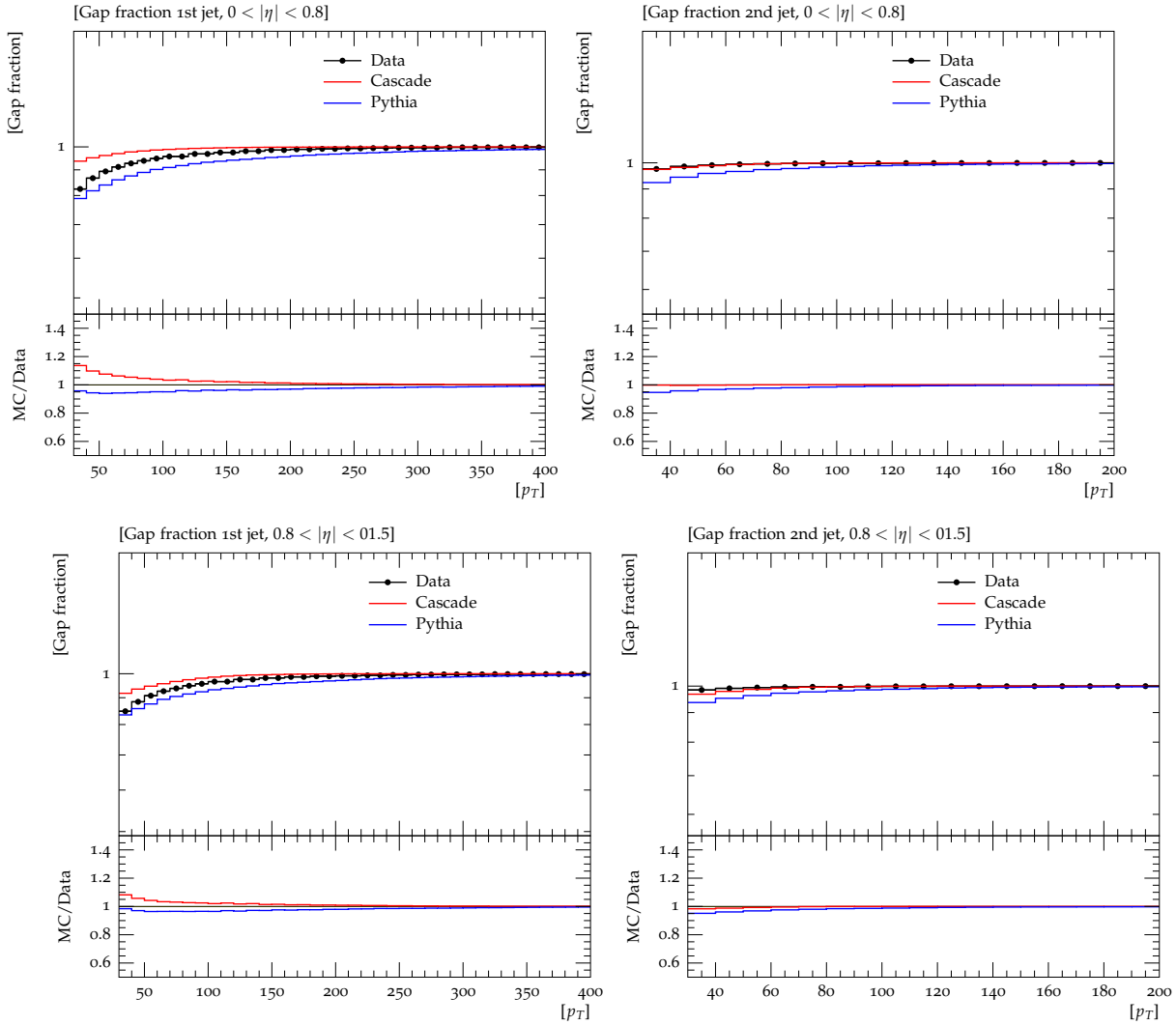


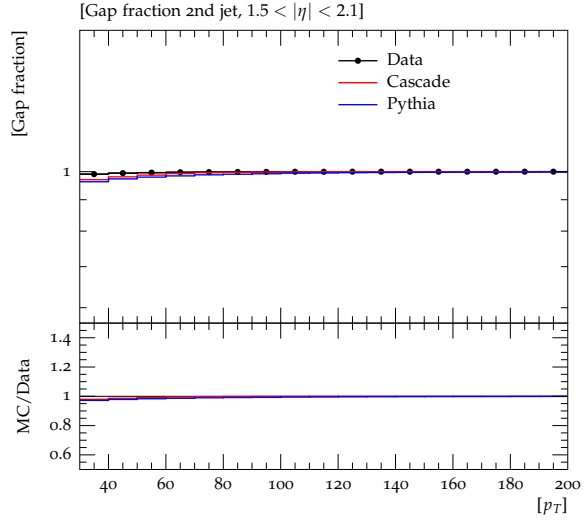
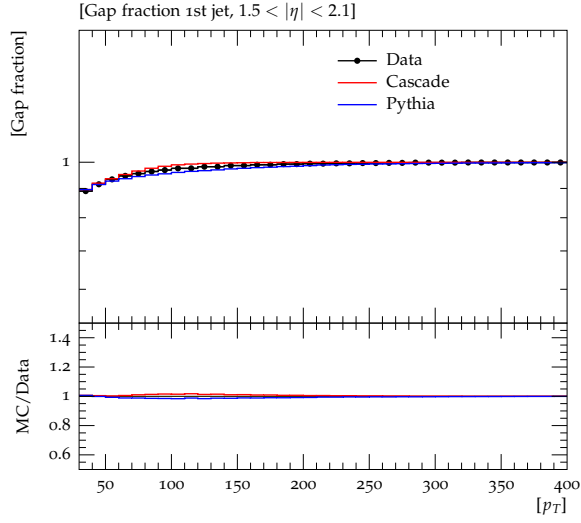
Left column: Gap fraction of the first jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$

Right column: Gap fraction of the 2nd jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$

The description gets better with rising  $|\eta|$ , Cascade does a little better job than Pythia, which might correspond to its angular ordering that let its result get better in non-extreme (not very low or high)  $|\eta|$  regions - the description of the data is worst (and a little worse than Pythia) in the  $|\eta| < 0.8$  region.

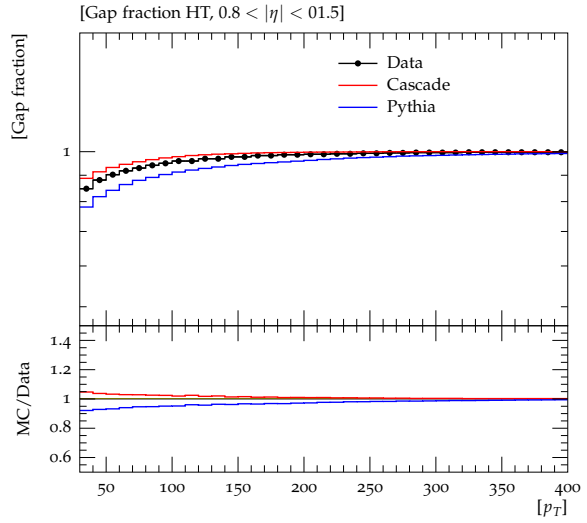
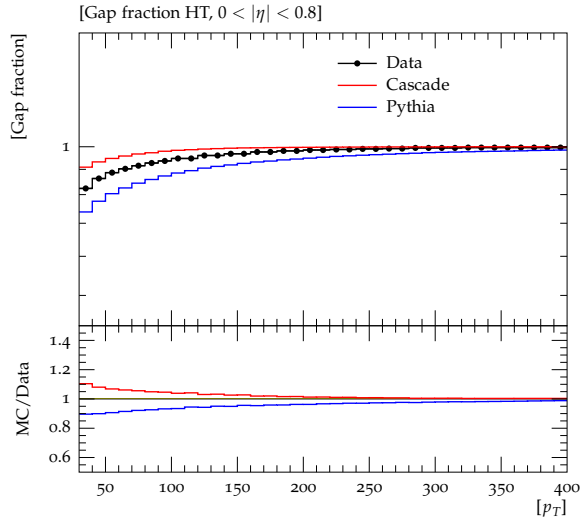
### 4.3.2 Hard cuts





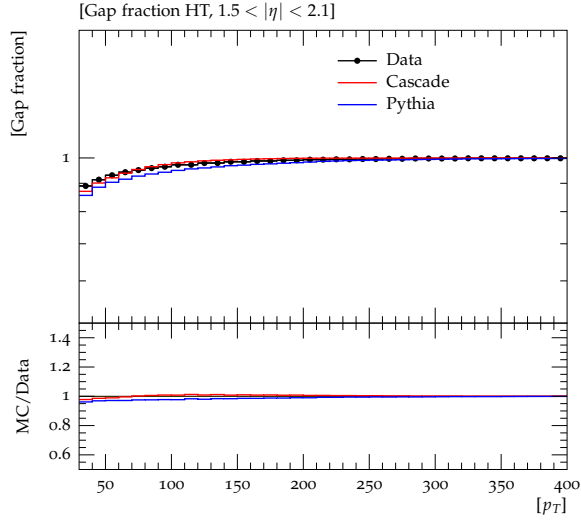
Left column: Gap fraction of the first jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$  (hard cuts)

Right column: Gap fraction of the 2nd jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$  (hard cuts)



a) Gap fraction HT  $0 < |\eta| < 0.8$  (hard cuts)

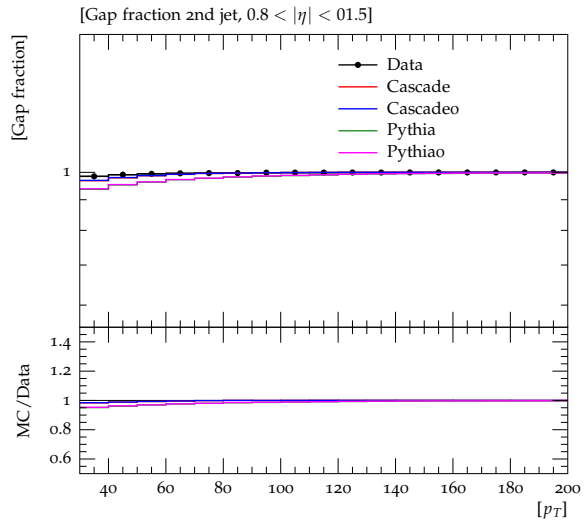
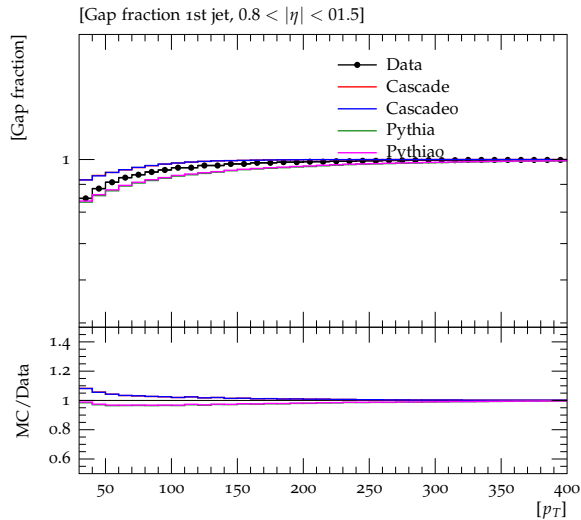
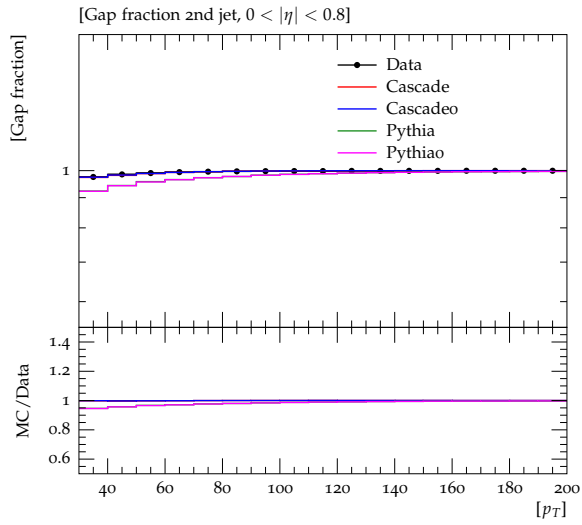
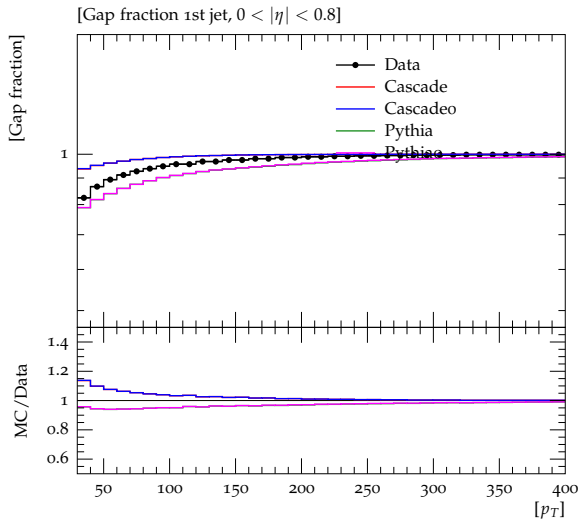
b) Gap fraction HT  $0.8 < |\eta| < 1.5$  (hard cuts)

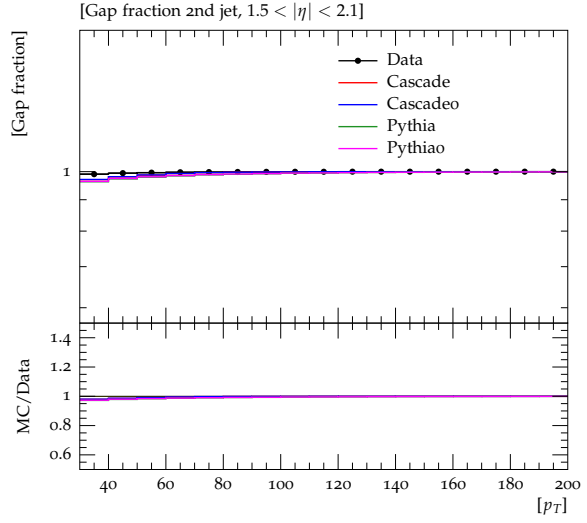
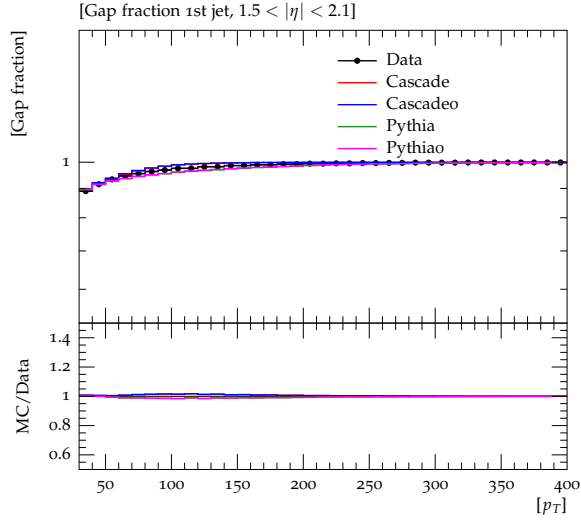


c) Gap fraction of HT  $1.5 < |\eta| < 2.1$   
(hard cuts)

The results for the hard cuts are again nearly the same as for the normal cuts.

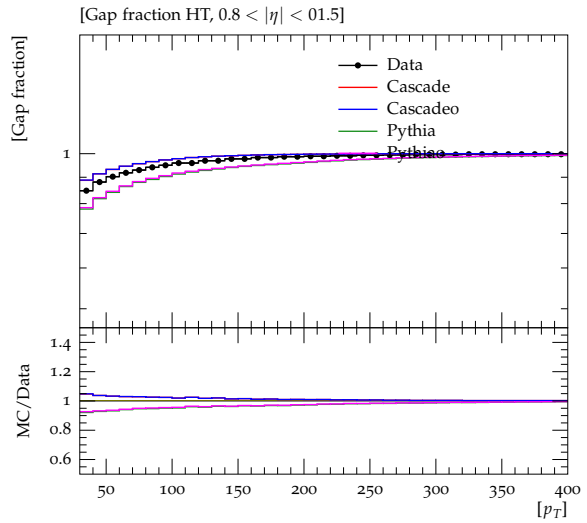
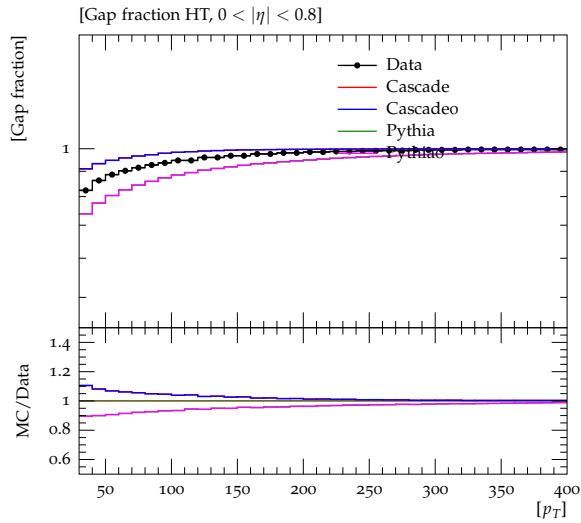
### 4.3.3 Comparison between normal and hard cuts





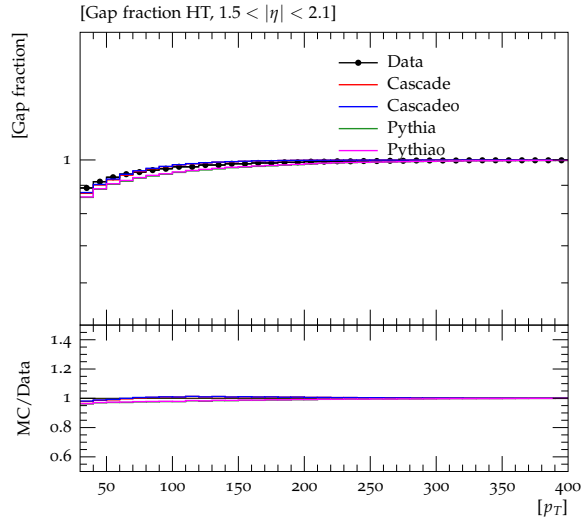
Left column: Gap fraction of the first jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$

Right column: Gap fraction of the 2nd jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  $1.5 < |\eta| < 2.1$



a) Gap fraction HT  $0 < |\eta| < 0.8$

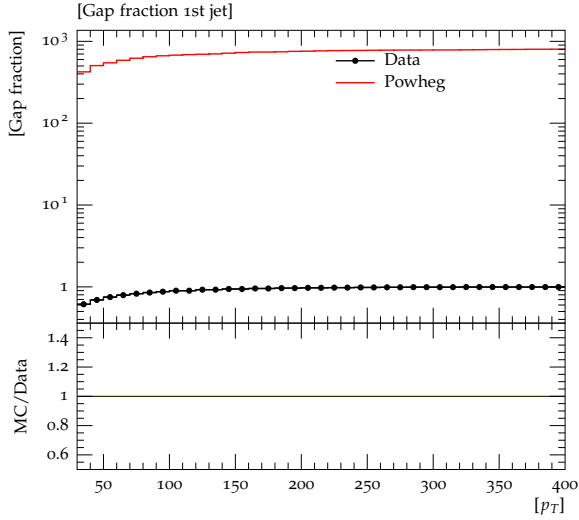
b) Gap fraction HT  $0.8 < |\eta| < 1.5$



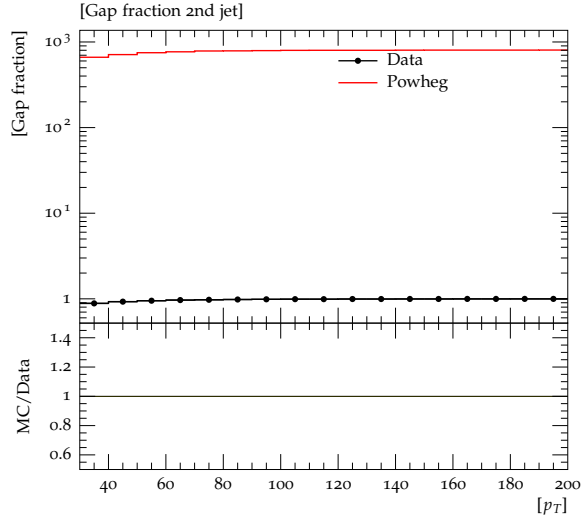
c) Gap fraction of HT  $1.5 < |\eta| < 2.1$  As can be seen in the histograms, there is very low difference between the two sets of cuts (in most bins they overlap).

### 4.3.4 Powheg

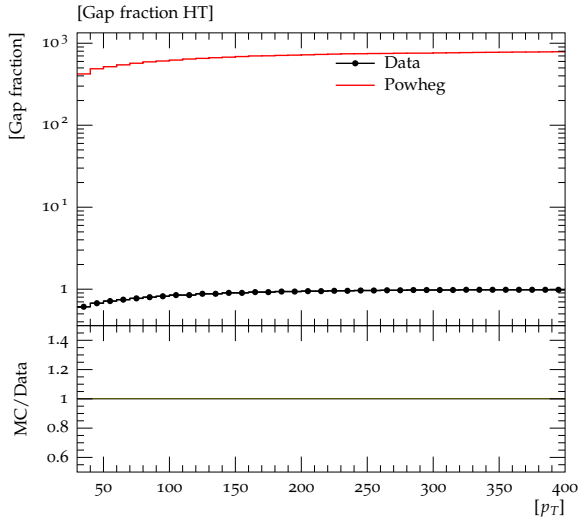
As there were some problems with the Powheg program, only many samples could be simulated and merged, which led to some problems with the correct normalization/scaling. Normalised samples were simply added, so comparison with data and the other MC generators is only possible by eye in the histogram. Also there was not enough time to run the simulation without the harder cuts, so only the hard cuts histograms are available. Although the ones for the gap fraction will be shown here:



a) Gap fraction of the 1st jet, Powheg

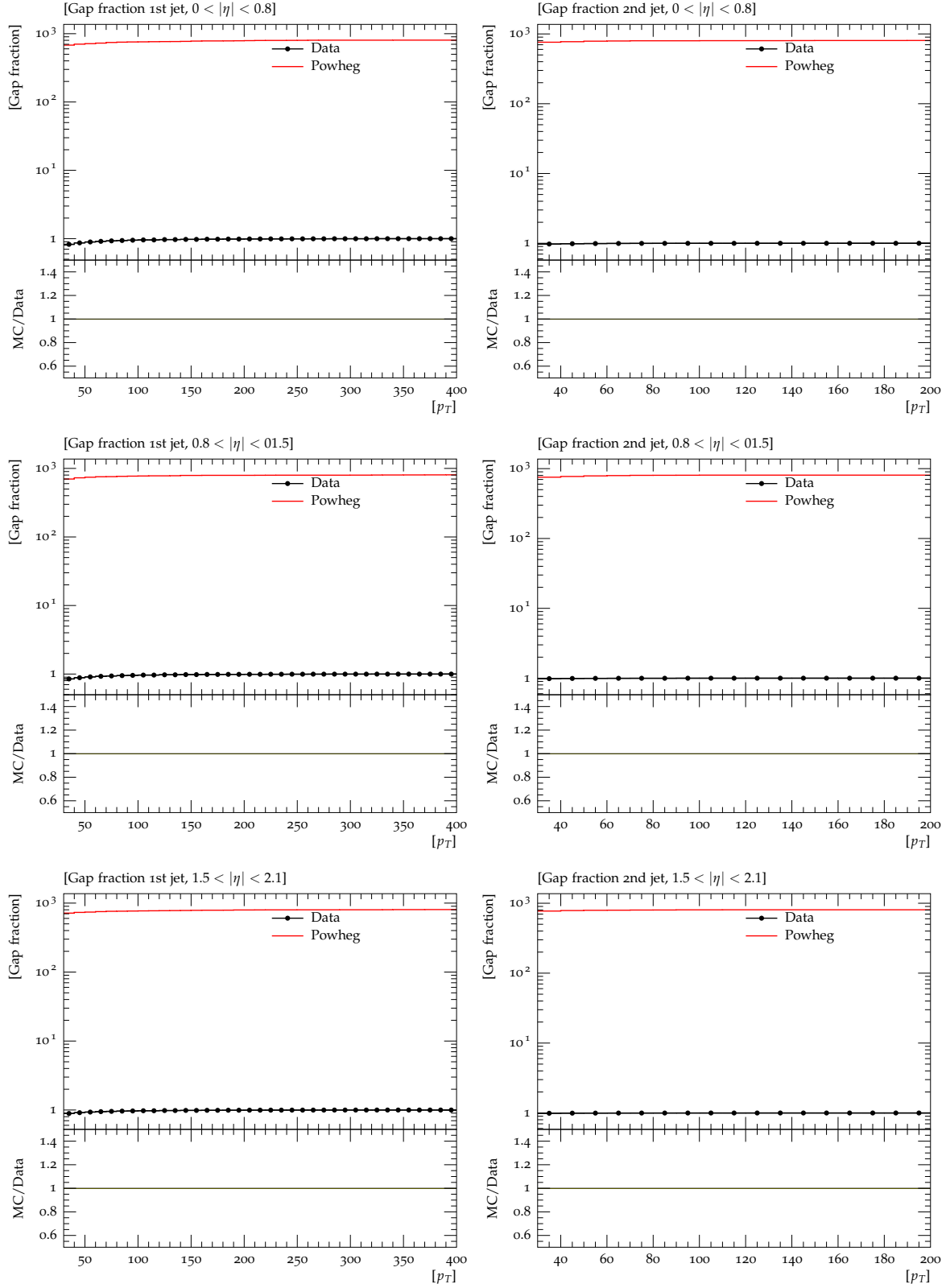


b) Gap fraction of the 2nd jet, Powheg

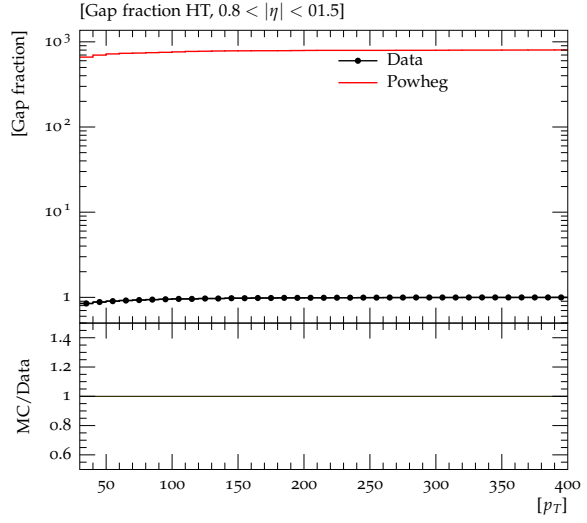
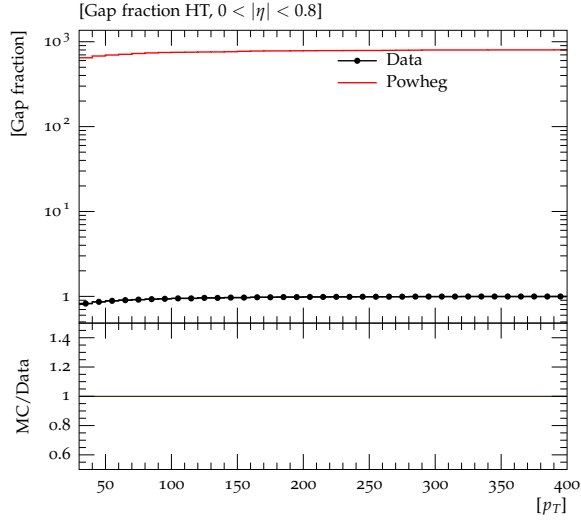


c) Gap fraction of HT, Powheg

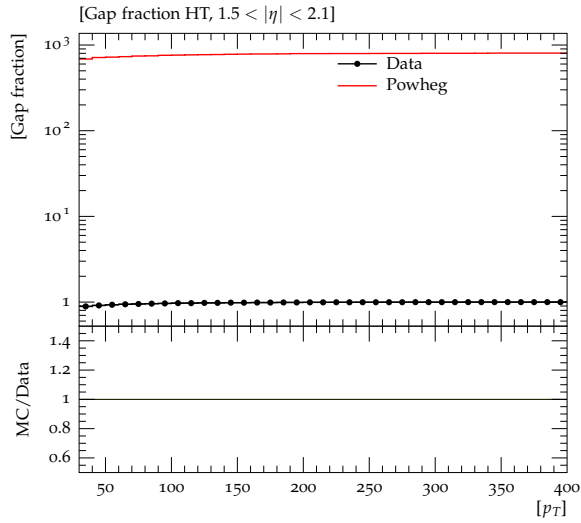




Left column: Gap fraction of the first jet Right column: Gap fraction of the 2nd  
in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and jet in  $0 < |\eta| < 0.8$ ,  $0.8 < |\eta| < 1.5$  and  
 $1.5 < |\eta| < 2.1$  (Powheg)  $1.5 < |\eta| < 2.1$  (Powheg)



a) Gap fraction HT  $0 < |\eta| < 0.8$  (Powheg)    b) Gap fraction HT  $0.8 < |\eta| < 1.5$  (Powheg)



c) Gap fraction of HT  $1.5 < |\eta| < 2.1$  (Powheg)

The shape *seems* to fit quite good to the data, but it is not possible to say even if it is over- or underestimating the gap fraction or other statements on the quality of the simulation. First thing for further research will be getting Powheg to run and compare this simulation to the ones from the paper in detail, since Powheg was used there also.

## 4.4 $t\bar{t}$ System transverse momentum

According to a recent paper [12] it seems to be interesting to take a closer look at the  $p_T$  of the  $t\bar{t}$  system. Simulated was using Pythia 8 and Cascade, and two slightly different Rivet analyses were written: One (toppt.cc) directly accesses the transverse momentum of the  $t\bar{t}$  system via questioning whether there are the decay products of a top quark pair in the event and then directly gets  $p_x$  and  $p_y$  and calculates  $p_T = \sqrt{p_x^2 + p_y^2}$ , the other analysis (top2.cc) performs first the event selection for the dilepton channel which was used for the cross section and gap fraction and then asks again directly for the  $p_T$ . This is only possible in simulations, as in experiment decayed particles have to be reconstructed and are not all known.

Also two slightly different approaches were used to get the  $p_T$  of the  $t\bar{t}$  system: First the direct approach - if there is a top and an antitop in the event get its  $p_x$  and  $p_y$  and calculate the  $p_T$ . Second was questioned whether all decay products of the  $t\bar{t}$  pair ( $b, \bar{b}, W^+, W^-$ ) and itself were in the event and then again the momenta of the t-quarks were directly accessed and filled into the histogram.

Both ways were plotted in a histogram with binning of 10GeV and a fine binning of 1GeV width, to be able to take a closer look at the very low transverse momentum region of the  $t\bar{t}$  system.

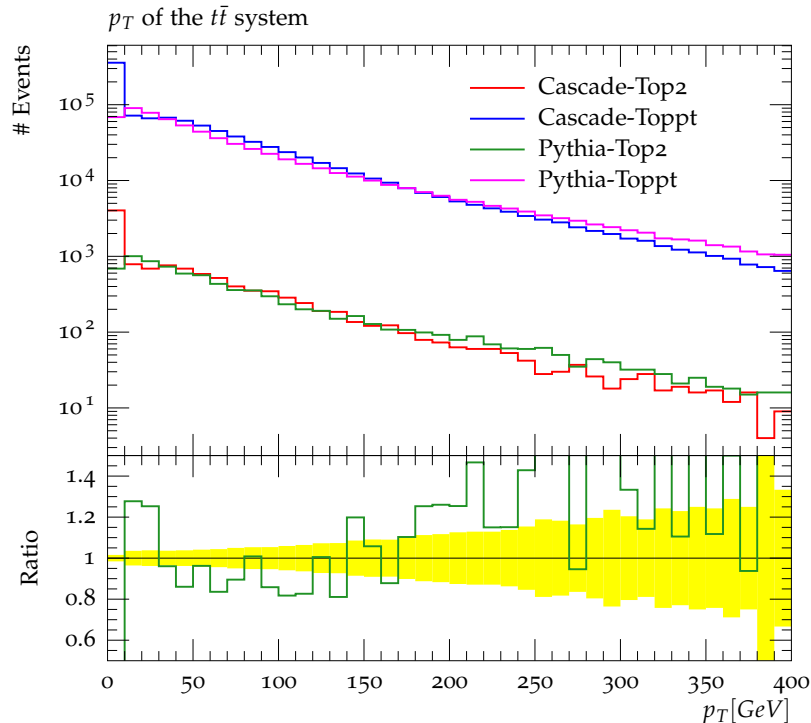


Figure 4: *Direct approach to the  $p_T$  of the  $t\bar{t}$  system*

The toppt.cc analysis, which first performs the dilepton event selection has far less events in it, roughly 100 times, but the shape is roughly the same. The reason is, that about one percent of all generated top events match the dilepton channel criteria, this was also the case for the cross section and gap fraction analysis. Most  $t\bar{t}$  pairs are produced at low  $p_T$ . Possibly one could normalize everything by the number of events and so be able to compare both analyses

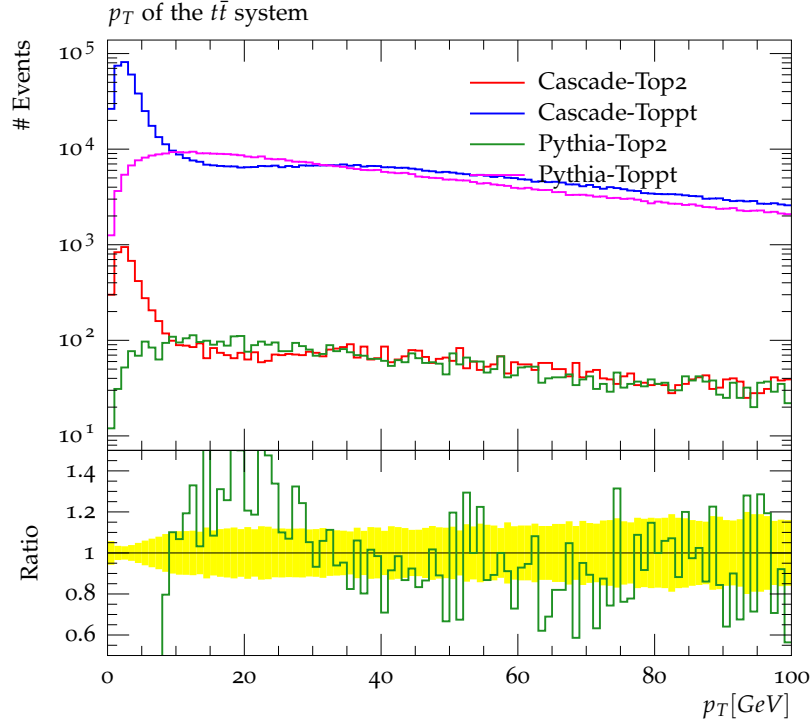


Figure 5: *Direct approach to the  $p_T$  of the  $t\bar{t}$  system, fine binning*

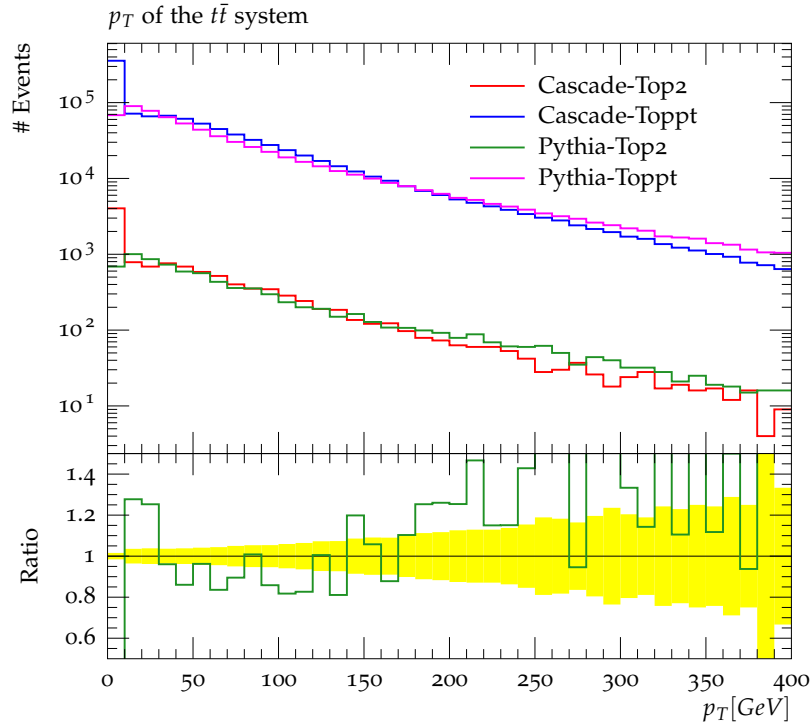


Figure 6: *Look whether there are also  $b, \bar{b}, W^+, W^-$  in the event, then get the  $p_T$  of the  $t\bar{t}$  system*

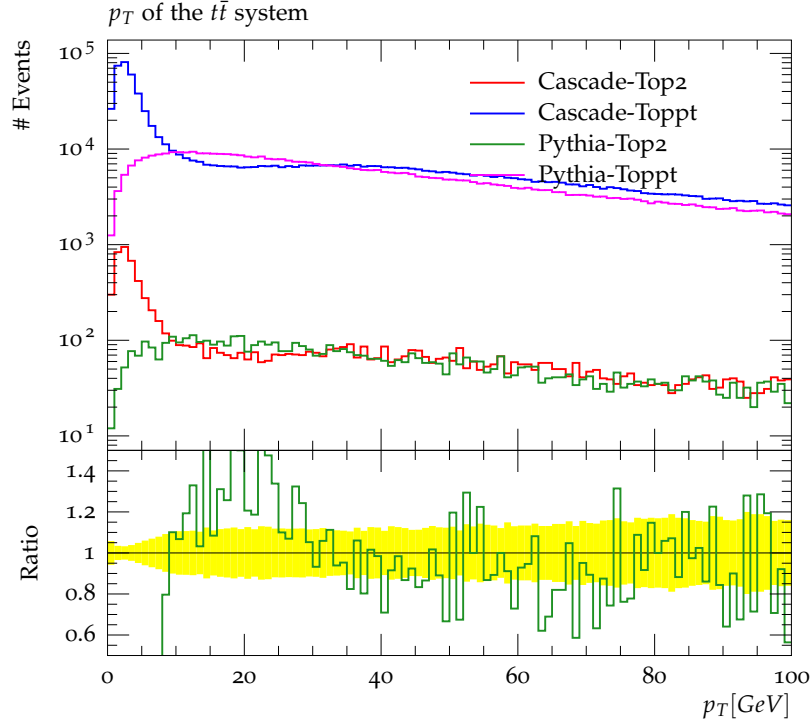


Figure 7: *Look whether there are also  $b, \bar{b}, W^+, W^-$  in the event, then get the  $p_T$  of the  $t\bar{t}$  system, fine binning*

better. Surprising is the difference between Cascade and Pythia in the histograms with fine binning. Cascade shows again a peak at low  $p_T$ , Pythia shows far less events in the first  $\tilde{10}GeV$ . The source of this behaviour might lie in the different mechanisms of the MC generators, with some data provided for the  $p_T$  of the  $t\bar{t}$  system it can be decided which generator describes the data better and can be considered for further studies.

## 5 Acknowledgments

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