Boson Production at the LHC: Monte-Carlo Comparisons of Transverse Momentum and Jet Production

Adam Bailey

September 14, 2011

DESY Summer Student Programme 2011

Abstract

This paper investigates the transverse momentum and jet differential cross-section of single Z and W boson events with simulations using the Pythia 6.4 generator. This includes the effects of varying different parameters within the simulation, and the effect that ATLAS tuning to QCD data has on these events. The variation of α_s and the intrinsic momentum were found to change the p_T distribution by up to 20% and 40% respectively. The ISR momentum cut-off and intrinsic momentum cut-off were found to have little effect. The tuned simulations were found to give varying results for different PDFs with differences of up to 30%. The LO PDFs gave lower cross-sections than the MC adapted ones. The MC adapted PDFs were found to give a large amount of extra jets at low transverse momentum.

1 Introduction

In high energy pp collisions intermediate vector bosons are formed by the interaction of partons within the proton. The produced boson subsequently decays to produce other particles. Due to the nature of the parton distribution function (PDF) and QCD effects such as initial state radiation (ISR) the boson is produced with a transverse momentum component along the beam line (p_T). This transverse momentum allows these QCD effects to be studied from experimental data, and using Monte-Carlo simulations.

There are two sources of the boson transverse momentum. First of all the partons have a momentum within the proton rest frame, so even if the two protons have exactly opposite momenta there can be an excess transverse momentum of the boson. It is when the sum of the colliding parton's momenta has a component along the beam line that the produced boson has transverse momentum. This contribution is known as the intrinsic momentum. The other effect comes from the ISR. If an incoming quark first radiates a gluon before the main collision, the gluon carries away some of the momentum causing the quark to recoil. This momentum can be in any direction, so it contributes to the transverse momentum. Due to confinement the gluons must undergo hadronisation, and therefore will create jets.

This paper investigates the transverse momentum and jet production from single Z and W boson decaying to leptons events generated in Pythia 6.4. First the effects of changing parameters related to the ISR and the intrinsic momentum of the partons within the simulation are investigated. The other section is on how recent ATLAS tunes to pure QCD data affect the transverse momentum and jets in single vector boson events.

The next sections discuss previous experimental data and how events are simulated using Monte Carlo generators. The Event Generation section describes specific details of the parameters relating to this paper. Following this are the results and discussion of both the parameter variation and generator tuning.

1.1 Measurements

The Z boson transverse momentum was previously measured in $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions at Tevatron by the CDF and D0 experiments. These used samples of $Z \rightarrow e^+e^-$ events to reconstruct the momentum of the Z boson. The features of the electrons produced by a Z boson decay are distinctive, as they usually have large transverse momenta, large angular separation from each other and from other products from the interaction. This allows them to be distinguished from electrons produced by other processes by performing cuts on the data. Background events that pass these cuts are estimated using Monte-Carlo simulation so that only the electrons from Z boson decays remain. Both experiments found the data agreed with the QCD predictions [1] [2].

Since these measurements a similar study has been done at the LHC using pp collisions at $\sqrt{s} = 7$ TeV where a larger p_T range could be measured. This used a similar method to find the Z boson events. Here both e^+e^- pairs and $\mu^+\mu^-$ pairs were used. A good agreement with various event generators was found [3].

1.2 Monte Carlo Simulations

Monte-Carlo simulations are based on both perturbative calculations and phenomenological models. Event generators work using a method called factorisation. They do not simulate the entire event in one step, but split it into separate parts. These parts are considered sequentially, with some using output from previous parts of the event. This allows the parts to be handled in different ways. For pp collisions processes such as the hard collision, where the momentum transfer is high can be caclulated up to a certain order in perturbation theory. However, in addition to the hard process there is the parton shower where gluons or quarks are radiated that cannot be calculated perturbatively. So factorisation theory means that the hard process can be separated from the showers. The non-perturbative parton shower is described using phenomenological models that are tested by how well they agree with data [4].

1.3 PDFs

An important input to the simulation is the PDF. The PDF determines the density distribution of the partons within the proton. There are a range of PDFs available, which are mostly extracted from lepton proton collisions at HERA. These PDFs are used at the LHC. The parton shower, multiple parton interactions (MPI) and the nature of the intrinsic momentum are all sensitive to the form of the PDF.

For a particular PDF the parameters within the simulation can be tuned to give a better agreement with the data. This paper uses the A*T2 tunes from the ATLAS group that are based on data from the Tevatron and $\sqrt{s} = 7$ TeV LHC results. These used data that was available at both experiments, which was the di-jet angular decorrelation, the jet shapes and track jet fragmentation [5]. Further details of the PDFs used in this study and on the tune parameters are discussed in the next section.

1.3.1 Leading Order PDFs

Leading order PDFs are made based on theoretical calculations and experimental data. It is known that for high momentum fractions there are higher order effects that become significant that are not included in LO PDFs. As the data will of course include effects from all order the PDFs must be modified so that they agree with both theory and experiment. This is done by a method called global fitting which first of all writes the parton distribution function in terms of a trial set of parameters. The PDF is then generated for other scales of parameters and compared to data to find which one is the best. This type of PDF is a standard one to use within LP generators [6].

1.3.2 Monte Carlo Adapted PDFS

The modified leading order PDFs are designed specifically for use within LO Monte-Carlo generators. They attempt to mimic the behavior of NLO generator by using some NLO calculations such as for the QCD coupling constant to improve the agreement with data. Some parts however can only be calculated to LO within the generator. They are designed to behave like a LO PDF for low momentum fractions, but more like a NLO PDF at high momentum fractions where the LO calculations do not fit the data. To improve the LO PDF behavior it was found that more gluons were required at a higher momentum fraction. To do this these PDFs allow a relaxation of the momentum-sum rule so that momentum is not always conserved. The MRST PDF modifications are based entirely on actual experimental data, whereas for CT09MC2 simulated LHC data from another PDF is also used. The difference between the MRSTLO* and MRSTLO** PDFs is that the MRSTLO** does not use the standard QCD scale [7] [8].

2 Event Simulation

The event simulation in this paper is based on $\sqrt{s} = 14$ TeV pp collisions at the LHC. The events are modelled in Pythia 6.4 for all parts of the simulation. The events analysed are single Z or W boson production with decays into leptons only. Cuts are applied on the psuedorapidity ($|\eta| < 2.4$), lepton transverse momentum ($p_T >$ 20 GeV) and boson mass ($66 < m_Z < 116$ GeV) which are the same cuts used in reference [3].

The event generator used for all of this paper is Pythia 6.4 [9], a leading order generator. Pythia allows the user to change a wide variety of parameters within the simulation which makes it ideal for this study. Events are recorded and analysed within the HEPMC analysis tool.

A total of five different PDFs are used in this study; the AMBT1, CTEQ6L1, CT09MC2, MRSTLO** and MSTW2008LO. AMBT1 is a tuned version of MRSTLO*, so parameters listed for MRSTLO* also apply to AMBT1. CTEQ6L1 and MSTW2008LO are standard leading order PDFs, whereas AMBT1, CT09MC2 and MRSTLO** are modified leading order PDFs.

2.1 Parameter Variations

Using the tuned CTEQ6L1 PDF (see next section), parameters were changed to see how they affected the transverse momentum distribution and jet production. These parameters are used in the tuning so it is important to see their effects. The parameters which are changed are summarised in table 1. Sets of 300 000 events were used for this section.

Table 1: Settings used for parameter variations.

Parameter	Pythia 6 Setting	Range Used
Scaling of $1/\alpha_s$	PARP(64)	0.5 to 2.0
p_T minimum cut-off	PARP(62)	0.5 to 2.5 GeV
Intrinsic Momentum	PARP(91)	0.5 to 4 GeV
Intrinsic Momentum maximum cut-off	PARP(93)	5.0 to 20 GeV

2.2 ATLAS Tunes for Various PDFs

For a particular PDF the parameters within the simulation can be tuned to give a better agreement with the data. This paper uses the A*T2 tunes from the ATLAS group that are based on data from the Tevatron and $\sqrt{s} = 7$ TeV LHC results. These used pure QCD data that was available at both experiments, which was the di-jet angular decorrelation, the jet shapes and track jet fragmentation [5]. Further details of the PDFs used in this study and on the tune parameters are discussed in the next section.

To compare the effects of the transverse momentum tuned versions of the PDFs are used. For these sets of 500 000 events were generated. The tunes used are from reference [5]. Here the main settings are summarised.

Table 2: ATLAS tuning parameters.

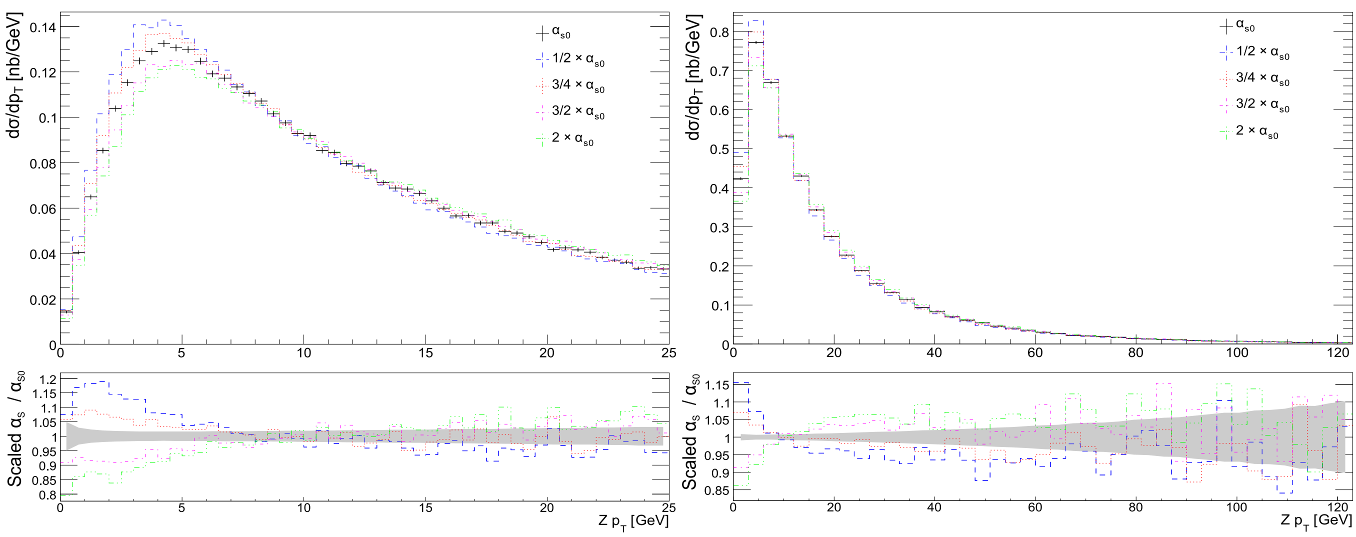
PDF	PARP(62)	PARP(64)	PARP(72)
CTEQ6L1	1.13	0.68	0.53
MSTW2008LO	1.26	1.11	0.49
MRSTLO*	2.29	0.57	0.42
MRSTLO**	2.17	0.60	0.43
CT09MC2	2.20	0.73	0.36

The parameters changed are PARP(62) which is the ISR p_T cut-off, PARP(64) the ISR scale factor on α_s and PARP(72) is the Λ_{QCD} for final state radiation showering from ISR partons. For more details please see reference [5].

3 Results and Discussion

3.1 Parameter Variations

3.1.1 Strong Coupling Constant α_s



(a) (b)

Figure 1: Z p_T differential cross-section for the scaling of α_s, (a) is for < 25 GeV and (b) is the whole distribution.

The value of the strong coupling constant α_s was scaled by different values. The transverse momentum shows that changing α_s does have an effect. The ones with an increased α_s give larger momentum at the high end and a lower momentum at low transverse momentum. This is due to the effect that α_s has on the initial state radiation. Having a larger strong coupling means that the probability of emitting a gluon before the main collision is higher, so there is an excess for the high end of the momentum. The reason that the low momentum end that the differential cross-section is reduced is that all of the data sets have the same number of events. So having more at one part must mean that it is compensated for elsewhere.

Changing α_S therefore affects the whole distribution. The effect of the compensation means that it is useful for chaning increasing one side while reducing the other. The overall effect gives a range of $\pm 5\%$ at the high end and up to $\pm 20\%$ at the low end, so it has the largest effect on the low part of the distribution even though the transverse momentum from ISR is across the whole momentum range.

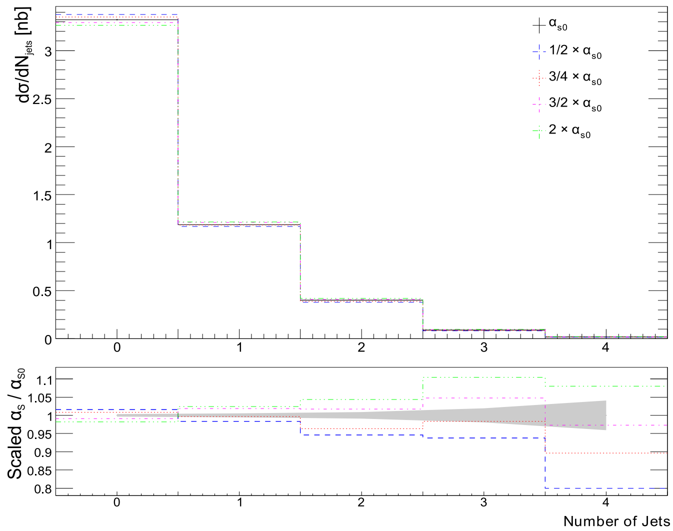


Figure 2: Jet differential cross-section for scaling of α_s.

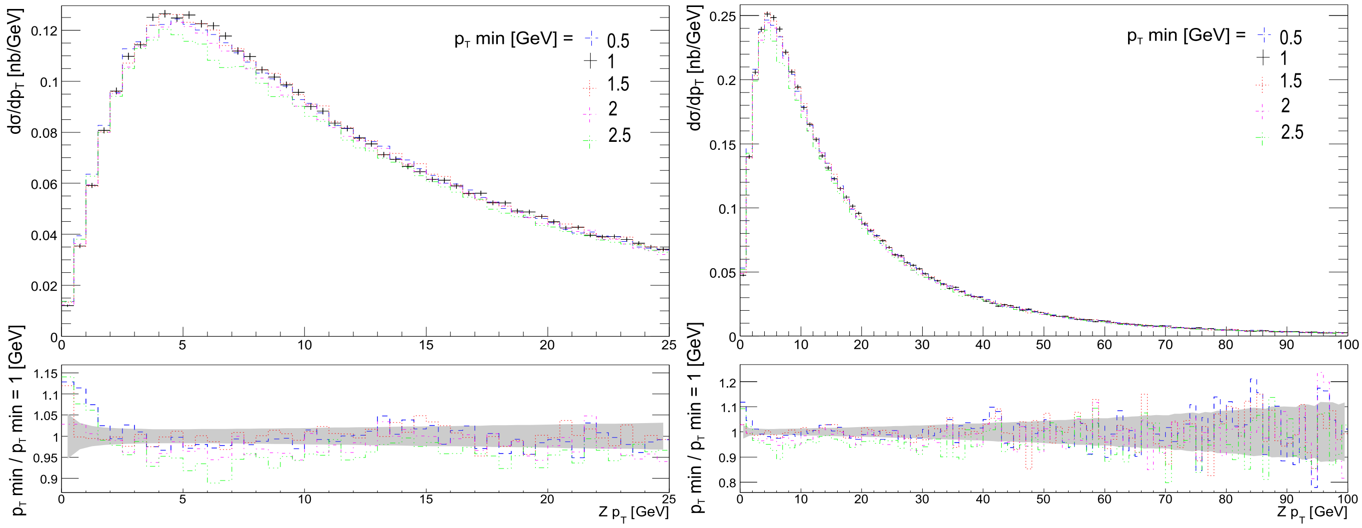
α_s also has a small effect on the number of jets produced. An increase gives a slight increase in the amount of jet prodcution for both one jet and multi jet events, and vice verse for a decreased α_s. This effect is only 5-10% for up to three jets, and the larger difference for four jets is due to low statistics. This means that it is not a good parameter for changing the jet production. However this is quite useful as it means that the transverse momentum distribution can be changed using α_s without affecting the jet production too much.

3.1.2 ISR p_T Cut-off

Table 3: Full cross-section of CTEQ6L1 for ISR p_T cut-offs.

PARP(62)	σ (nb)
0.5	5.041
1.0	5.026
1.5	5.031
2.0	4.950
2.5	4.872

Changing the ISR momentum cut-off was found to have an influence on the cross-section when the cut-off was increased. For a cut-off of 2.0 and above the cross-section starts to decrease slightly, whereas below this value it remains constant. This indicates that the high cut-off starts to reduce the number of events.



(a) (b)

Figure 3: Z p_T differential cross-section for the variation of the ISR p_T cut-off, (a) is for < 25 GeV and (b) is the whole distribution.

The effects of the minimun p_T cut-off on the ISR does not have a significant effect on the transverse momentum distribution, even though it does affect the cross-section slightly. It is possible that the two highest cuts are slightly reduced overall, due to the cross-section, however this is not clear even with the higher statistics used here.

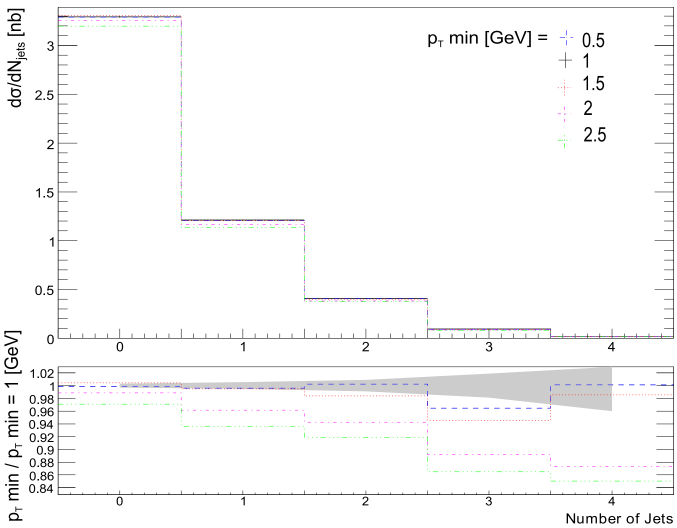
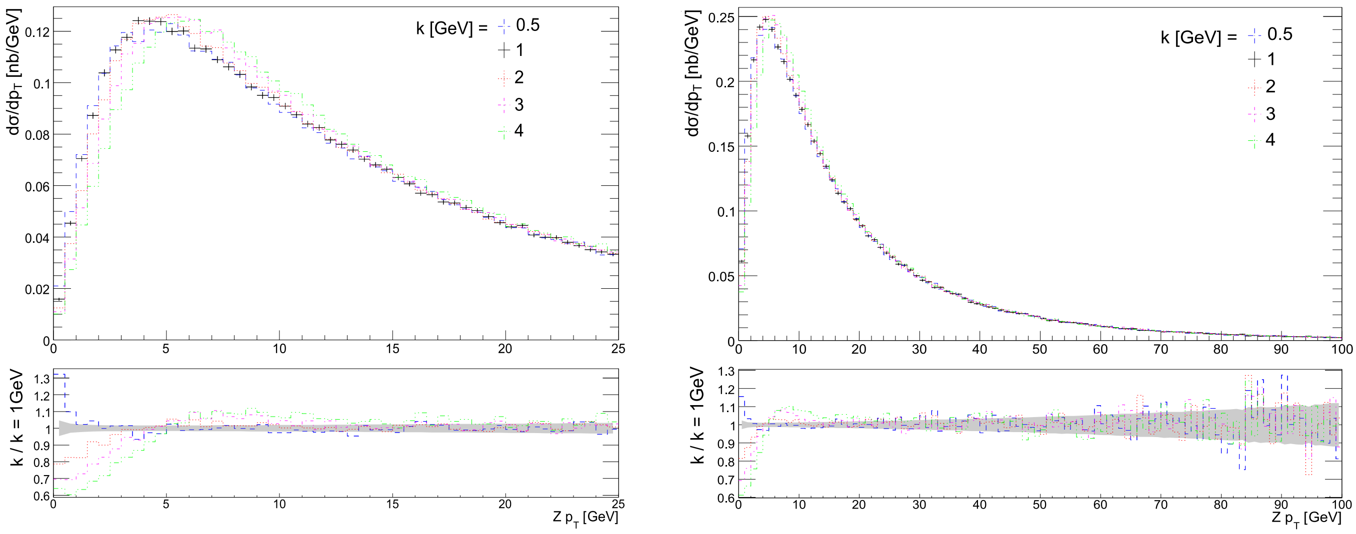


Figure 4: Jet differential cross-section for p_T cut-off variation.

There is also no large effect seen on the shape of the jet distribution, which is expected if the momentum is the same. However here it is possible to see a slight effect from the cross-section, as the increased p_T plots are lower than the others by a small amount. The lack of effect that this has on the distributions is surprising as it was one of the parameters used in the tuning.

3.1.3 Intrinsic Momentum



(a) (b)

Figure 5: Z p_T differential cross-section for the variation of the intrinsic momentum, (a) is for < 25 GeV and (b) is the whole distribution.

Varying the intrinsic momentum has a large effect on the lowest end of the transverse momentum. The difference is as large as 40% for increasing and 30% for decreasing the intrinsic momentum. However when looking at the distribution above approximately 15 GeV there is no difference at all. This is expected as the intrinsic momentum does not affect the ISR which is what gives the transverse momentum at this energy. For the ones where the intrinsic momentum is increased, the reduction below 5 GeV is compensated by an increase between 5-10 GeV. This is moving the peak of the momentum distribution to a higher value.

Therefore this parameter gives a good way of changing only the low part of the transverse momentum distribution while keeping the high momentum part the same. The slope on the left hand side of the peak is affected the most over only a few bins and to the right of the peak the effect is spread over a wider range.

The intrinsic momentum was found to have no effect on the production of jets as would be expected, so is not shown.

3.1.4 Intrinsic Momentum Cut-off

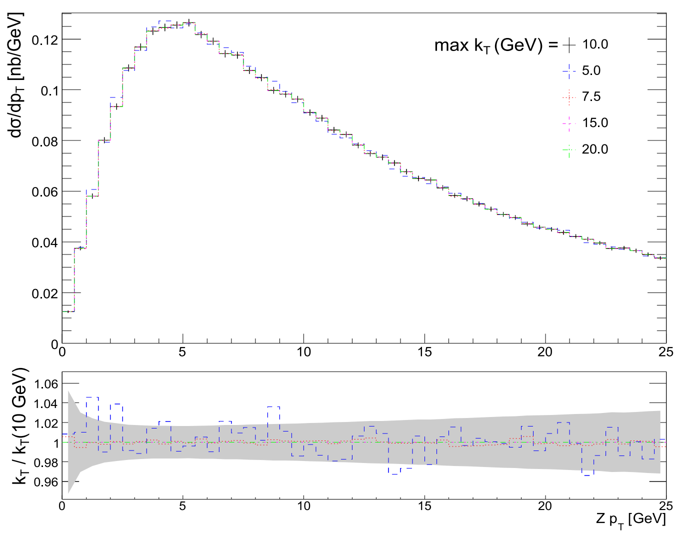


Figure 6: Z p_T differential cross-section < 25 GeV for variation of the intrinsic momentum cut-off.

The ISR maximum momentum was found to have no effect. For a reduced maximum there was statistical differences, however for the increased ones they were exactly the same as the 10 GeV default value. This indicates that there is possibly a problem within the simulation causing this to not be set correctly.

3.2 PDF Tunes

The tuned PDFs from reference [3] are compared for both single Z and single W boson production. The results are compared to the AMBT1 tune, which is a tuned version of MRSTLO* that describes the data well.

3.2.1 Cross-sections

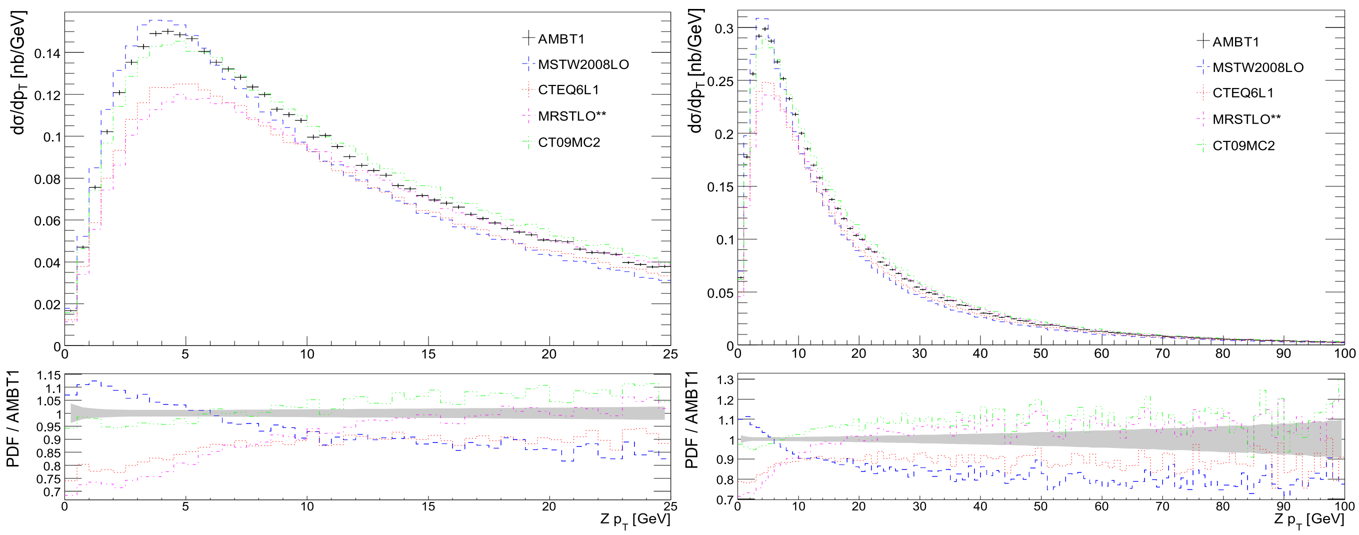
Table 4: Cross-section of tuned PDFs.

PDF	Z σ (nb)	W σ (nb)
AMBT1	5.725	19.40
CTEQ6L1	5.022	18.21
MSTW2008LO	5.261	17.26
MRSTLO**	5.353	18.02
CT09MC2	5.946	20.23

It was found that the cross-section of the Z and W production differed significantly between the different PDFs. Variation is expected as the PDF affects the initial state of the colliding hadrons however a difference of up to 15% is larger than expected. It can be seen that the two LO PDFs have the lowest cross-sections and that the three modified LO PDFs are higher for the Z. However for W boson production the MRSTLO** cross-section is lower than the LO PDF CTEQ6L1. It is expected that the MC adapted PDFs give a higher cross-section, so it is unusual that the MRSTLO** is nearer to the standard LO PDFs.

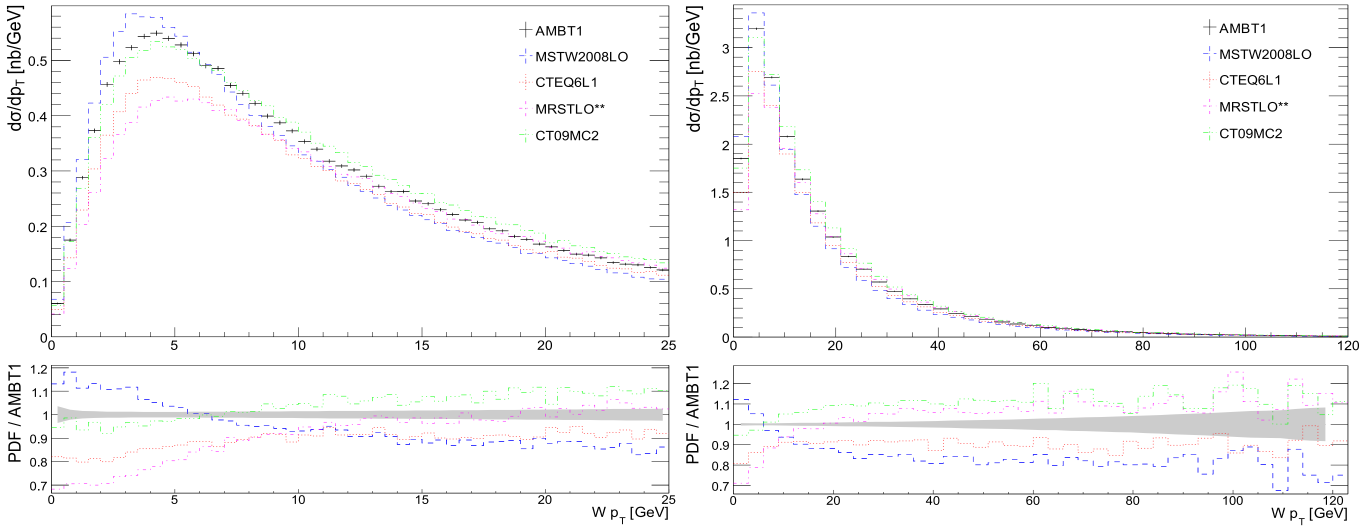
This is expected as they are designed to take into account the higher order effects, which would increase the cross-section.

3.2.2 Transverse Momentum Distribution



(a) (b)

Figure 7: Z p_T differential cross-section for tuned PDFs, (a) is for < 25 GeV and (b) is the whole distribution.



(a) (b)

Figure 8: W p_T differential cross-section for tuned PDFs, (a) is for < 25 GeV and (b) is the whole distribution.

The choice of PDF can be seen to have a significant effect on the transverse momentum ditribution, which is due to the PDF affecting the ISR and the intrinsic momentum of the partons. The effects are very similar for both Z and W bosons, with only slight differences of the particular values but the same shape and behaviour of both.

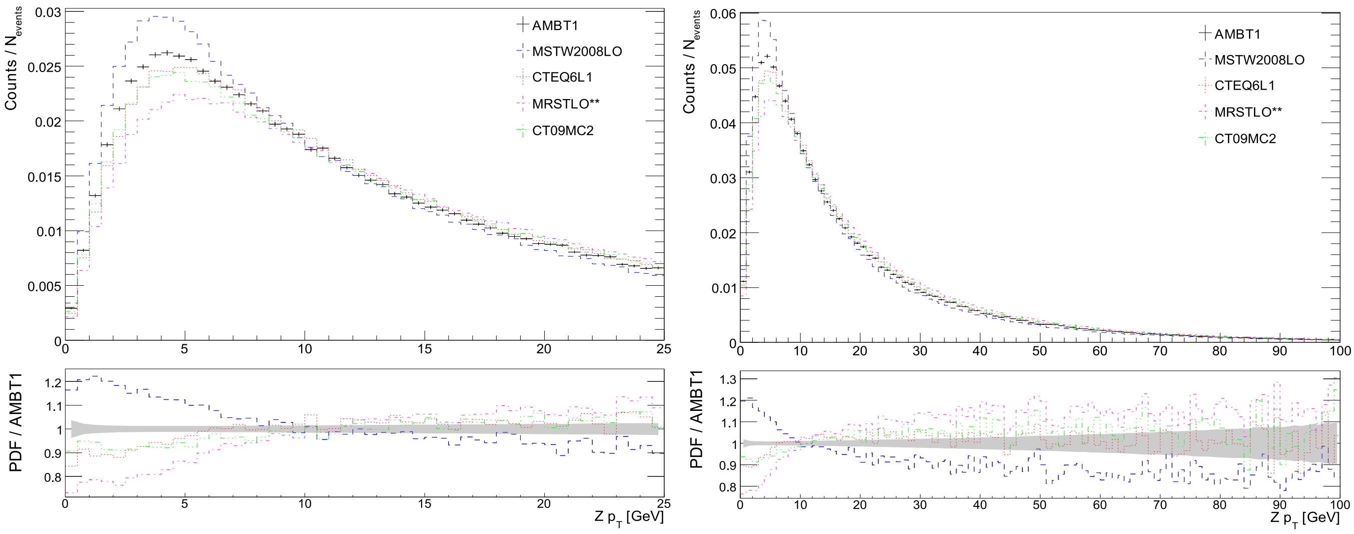
The largest variation between the tunes is at the lowest end of the transverse momentum distribution. Here the MRSTLO** PDF gives similar behaviour to the CTEQ6L1 PDF, but they are 30% and 20% below the AMBT1 tune respectively. By the 15-20 GeV point both of these have flattened out, but the MRSTLO** goes to 5-10% above the AMBT1 values whereas CTEQ6L1 stays 10% below. For MRSTLO** this implies that it is good at including the higher order effects but does not behave like a normal LO PDF at low momenta.

The MSTW2008LO PDF shows different behavior to the others; it starts out above AMBT1 then decreases to a value that is 20% below at the high end. This is most likely due to the different α_s scaling that is used, as MSTW2008LO is the only one which decreases α_s. This leads to less ISR giving the lower value at high transverse momentum. The excess at the low end is then due to the normalisation effect, as the under estimate at the high end must be compensated for.

CT09MC2 is the flattest of the compared PDFs, and only differs from AMBT1 by 5-10% over the whole distribution. This is the closest fit to AMBT1. The slight over-estimate above 6 GeV could be compensated for by changing the α_s scaling.

Overall the modified LO PDFs give a better fit to the AMBT1. This is expected as AMBT1 is also a modified LO PDF. This does imply that they are a better fit to the data than the regular LO PDFs, as AMBT1 is a good fit to data. This is partly due to their cross-sections being closer to that of AMBT1 than the LO PDFs. If the cross-sections of the CTEQ6L1 anbd MSTW2008LO were higher (while keeping the same shape) then especially at the high end they would be a better fit.

To determine how much of an effect the cross-section had on the distribution, the Z plots were normalised again to the number of events, so that the area of the histogram is one.



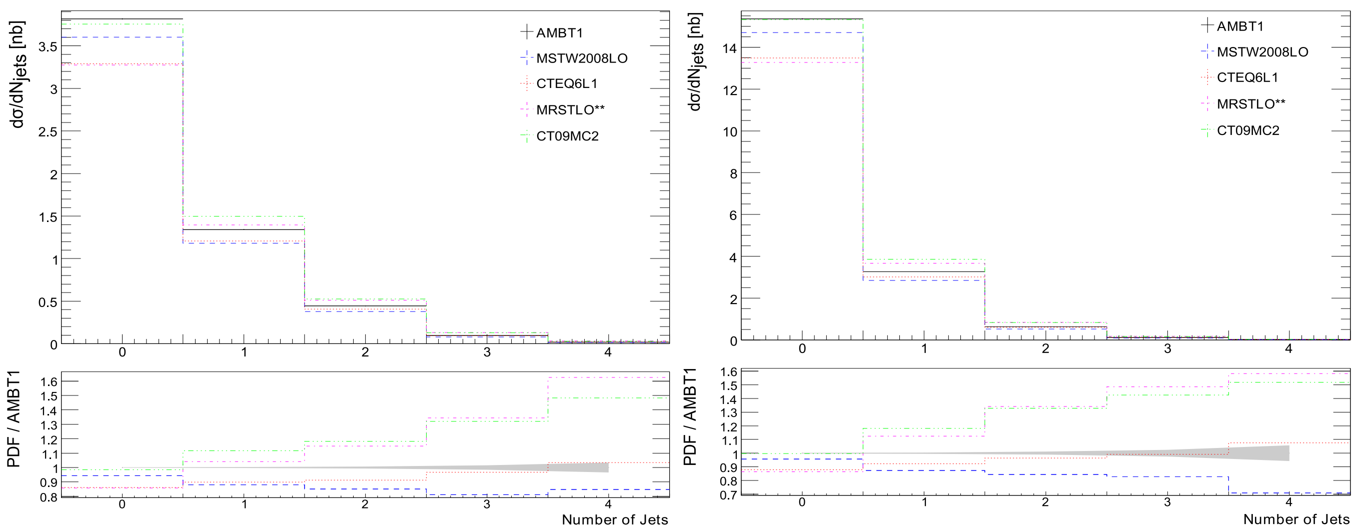
(a) (b)

Figure 9: Z transverse momentum distribution for tuned PDFs normalised to one, (a) is for < 25 GeV and (b) is the whole distribution.

The largest difference from before is seen in the standard LO PDFs as expected. The CTEQ6L1 PDF is now 10% closer than before which means that it is a very close fit to AMBT1 at the high end. The difference at the low end is now only 10% below. As MSTW2008LO was partly above and partly below AMBT1 the new normalisation improves the part that was below AMBT1, but makes the part that was above worse. This suggests that CTEQ6L1 gives a good shape for the distribution, but just under-estimates the cross-section. MSTW2008LO still has the effect of the α_s scale from before.

The modified LO PDFs were not affected by this as much, because they already had more similar cross-sections to AMBT1. CT09MC2 is slightly further away below 10 GeV but is closer above. This is again a good indication that it is the correct shape. MRSTLO** is similar to MSTW2008LO, as it was partly above and partly below AMBT1. In this case however the low end is brought closer and the high end is moved futher away. The steep slope on the ratio plot for this PDF means that it is not giving the correct shape for the distribution.

3.2.3 Jet Production

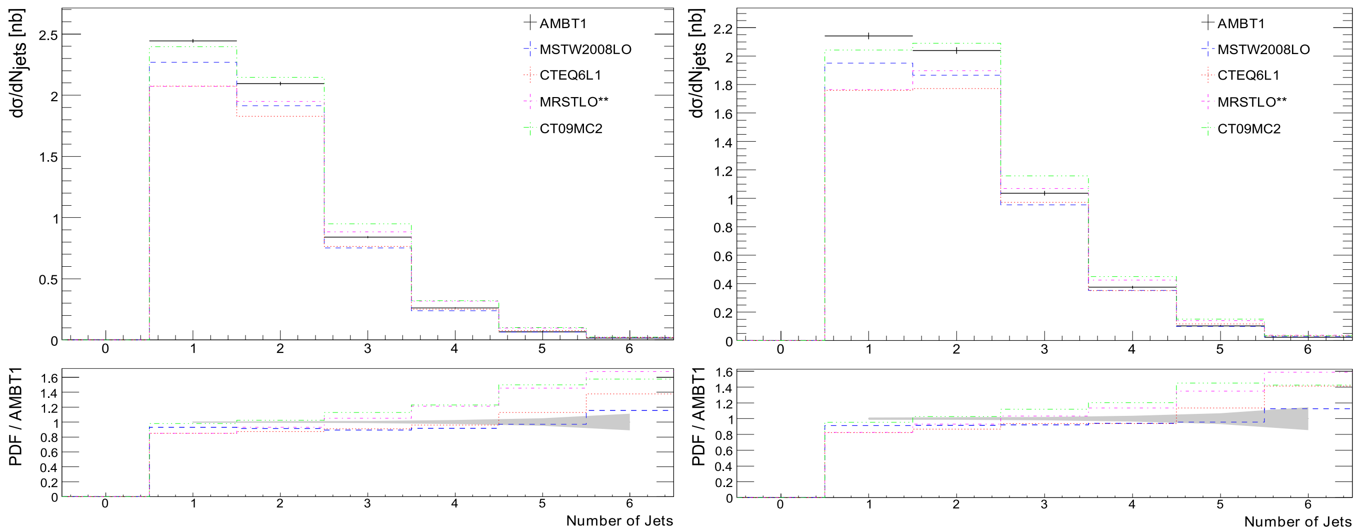


(a) (b)

Figure 10: Jet differential cross-section for Z (a) and W (b).

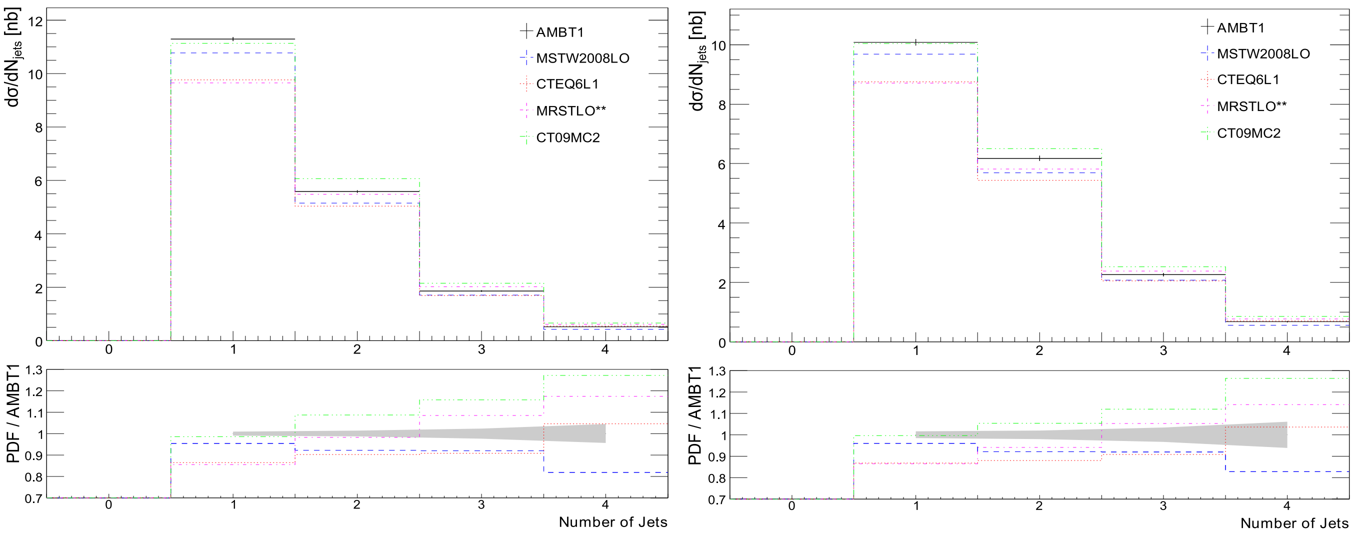
The number of jets shows a clear difference in the behavior of the LO PDFs and the modified LO PDFs for both W and Z boson events. MRST2008LO and CTEQ6L1 produce a similar number of jets to AMBT1, however the MC adapted PDFs show large differences. The adapted PDFs give a larger difference from AMBT1 the higher the number of jets. For zero jet production the MRSTLO** and CT09MC2 PDFs are actually quite close, however at four jet production the differences are just over 60% and just below 50% respectively. CTEQ6L1 starts about a 10% below then moves to the same value as AMBT1 for three and four jet production. MSTW2008LO shows the opposite behavior, getting further away from AMBT1 for higher bins. This could again be due to the different α_s scaling of MSTW2008LO. Even though the LO PDFs have different cross-sections to AMBT1, they are quite close.

To see which jets were causing the excess, cuts on the minimum jet momentum were done.



(a) (b)

Figure 11: Z jet differential cross-section for tuned PDFs, (a) is for > 40 and (b) > 60 GeV.



(a) (b)

Figure 12: W jet differential cross-section for tuned PDFs, (a) is for $p_T > 40$ and (b) > 60 GeV.

The cut for jets > 40 GeV gives a significant improvement from the standard plot for both. For the CT09MC2 and MRSTLO** PDFs the four jet production is now just over 20% different from AMBT1. There is a further improvement for the 60 GeV cut but only of a few percent. The CTEQ6L1 and MSTW2008LO do not show any large differences from before.

Therefore it is the low transverse momentum jets which cause most of the difference in the modified LO PDFs. The modified LO PDFs are designed to give more partons at a higher momentum fraction, which are more likely to give off ISR and produce extra jets. The high momentum jets usually come from particles relating to the main event, so the cuts include less of the jets produced by the ISR which are therefore the ones giving the extra jets.

4 Conclusion

The parameter variations showed that the α_s and intrinsic momentum scaling had significant effects on the boson transverse momentum. The α_s affected the whole distribution whereas the intrinsic momentum only affected it below 15 GeV. The α_s variation only has a minimal effect on the jet production and the intrinsic momentum has no effect. Therefore these parameters are useful for tuning to the transverse momentum. The p_T cut did not significantly change the transverse momentum or jets, although it did start to reduce the cross-section for the higher cuts. Decreasing the intrinsic momentum cut-off did not affect the distributions apart from statistical changes, and increasing it did not have any effect at all suggesting a problem with this setting inside the simulation.

The transverse momentum and jet distribution was investigated for the ATLAS tunes that were tuned to other data. The five PDFs tested gave significant differences in the transverse momentum and jet differential cross-sections for both single Z and W boson events. For the transverse momentum it was up to 30% and up to 60% for the jets. The MC adapted PDFs behaved differently to the LO PDFs, with CT09MC2 being very close to the AMBT1 tune used as a standard. The cross-sections of the CT09MC2 and AMBT1 PDFs were the highest, which is closer to agreement with a NLO calculation. However CT09MC2 and MRSTLO** gave a large amount of extra jet production. By looking only at higher momentum jets it was found that these extra jets were mostly at low transverse momentum. The LO PDFs and AMBT1 did not show this behaviour.

By including the transverse momentum and jet differential cross-sections in future tuning the models used in the simulation can be constrained further so that they agree with more sets of data.

References

[1] CDF Collaboration, *Transverse Momentum and Total Cross Section of e^+e^- pairs in the Z-Boson Region from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. Lett. 84 (2000) No. 5.

[2] D0 Collaboration *Differential Production Cross-Section of Z Bosons as a Function of Transverse Momentum at $\sqrt{s} = 1.8$ TeV*. Phys. Rev. Lett. 84 (2000) No. 13.

[3] ATLAS Collaboration, *Measurement of the transverse momentum distribution of $Z/\gamma*$ bosons in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, arXiv:1107.2381 [hep-ph].

[4] T. Sjöstrand, *Monte Carlo Tools*, arXiv:0911.5286 [hep-ph].

[5] ATLAS Collaboration, *ATLAS tunes of Pythia 6 and Pythia 8 for MC11*, ATL-PHYS-PUB-2011-009.

[6] D.E. Soper *Parton Distribution Functions*, Nucl. Phys. B 53 (1997).

[7] Hung-Liang Lai et al., *Parton distributions for event generators*, arXiv:0910.4183 [hep-ph].

[8] A. Sherstnev and R. S. Thorne, *Different PDF approximations useful for LO Monte Carlo generators*, arXiv 0807.2132.

[9] T. Sjostrand, S. Mrenna, P.Z. Skands, *Pythia 6.4 Physics and Manual*, JHEP 05 (2006) 026.