Analysing pp $\rightarrow$ W$\rightarrow \tau\nu_\tau$ events using HepMCAnalysis Tool for different PDFs, Tunes and Generators

Marc Sangel, University of Bielefeld, Germany

September 7, 2011

DESY Summer Student Program 2011

Supervisor: Sebastian Johnert

ATLAS group

Abstract

In this project we consider the decay pp $\rightarrow$W $\rightarrow \tau\nu_\tau$ generated by proton-proton collisions in Monte Carlo event generators. The HepMC Analysis Tool is used to analyze this process by generating histograms for several physical observables. This process is used to compare different parton distribution functions and tunes for Pythia 6 and to compare different generators.

Contents

1 Introduction **3**

2 Analysis Structure **4**
2.1 HepMC Output 4
2.2 HepMCAnalysis Tool 4
2.3 Generators 5
2.4 Parton Distribution Functions 5
2.5 Tunes 6
2.6 Efficiencies 6

3 Results **6**
3.1 Generators 6
3.2 Parton Distribution Functions 9
3.3 Efficiency 10
3.4 Tunes 13

4 Summary and Outlook **14**

1 Introduction

The Standard Model (SM) of particle physics is one of the best experimental confirmed theories in modern physics. The unification of Quantumelectrodynamics and weak interaction to a theory of electroweak interaction requires a new bosonic particle called Higgs which is necessary to understand the fact that the electroweak gauge bosons are not massless. In order to unify the electroweak and the strong interaction to a so called Grand Unified Theory (GUT) it has been shown that supersymmetry (SUSY) is included in most of the known approaches. SUSY predicts a lot of new particles which have to be heavier than all known particles of the Standard Model. Furthermore the Higgs mass is predicted to be heavier than 114.4 GeV. [1] Therefore it is mandatory to reach high center of mass energies to produce these kind of particles in proton-proton collisions. The Large Hadron Collider (LHC) has a designed center-of-mass energy of $\sqrt{s}$ =14 TeV [2] and is therefore capable for a search for particles beyond the Standard Model.
In order to find new physics one has to understand the signal and background processes. The τ lepton plays an important role in the final state of Higgs and SUSY searches. Therefore the SM decays W$\rightarrow$ $\tau\nu_\tau$ and Z$\rightarrow$ $\tau\tau$ are important background processes. The process W$\rightarrow$ $\tau\nu_\tau$ is considered in this report because the cross section $\sigma(W \rightarrow \tau\nu_\tau)$ is ten times higher than $\sigma(Z \rightarrow \tau\tau)$.
Due to the fact that hadrons are not pointlike, collisions of protons cause a hard process as well as a huge amount of complicated subprocesses like initial state radiation (ISR), final state radiation (FSR) and multiple parton interactions (MI).
The usage of Monte Carlo (MC) event generators like Herwig and Pythia is auxiliary to understand the signal and background processes in such collisions. The analysis of these MC events is done with the HepMCAnalysis Tool.
The comparison of simulated and measured behaviour of physical observables then can lead to the discovery of new particles.
In order to describe the structure of hadrons one uses parton distribution functions (PDF). The adjustment of generators to measured data can be done with tunes. In this report is basically shown the comparison of different generators and PDFs but also a short part about different tunes.

2 Analysis Structure

In this section the analysis structure is described. Therefore a short introduction to the HepMC format, the HepMC Anaylsis Tool and the generator input is given.

2.1 HepMC Output

MC generators generate events which are saved in several formats. In fig. 1 left side such a physical event is given with its content like PDFs, the hard process, parton cascade, hadronization and the subsequent decay products as shown in fig. 1 left side. The HepMC format (fig. 1 right side) converts this structure in a simple graph structure consisting of particles and vertices. A particle stores information like its four momentum, flow, a particle ID and status information. Each vertex maintains a listing of its incoming and outgoing particles, while each particle points back to its production vertex and decay vertex. [3]

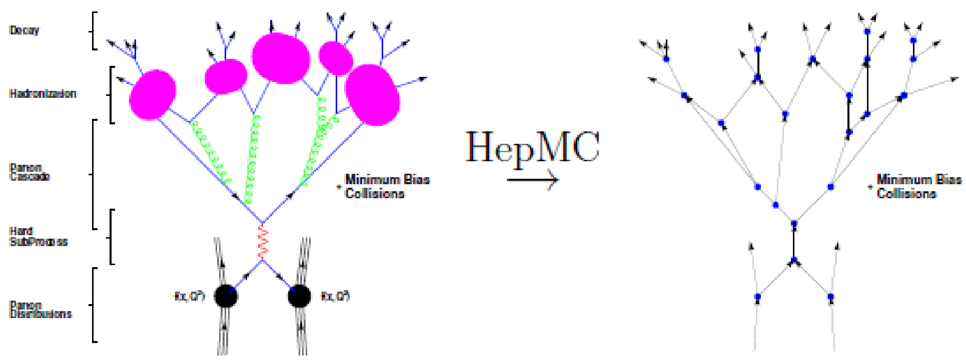

Figure 1: The complex structure of an event (left) simplified by the HepMC format in a vertex and particle structure (right) [3]

2.2 HepMCAnalysis Tool

The HepMC Analyis Tool is a stable and extendable framework for MC generator validation and comparison written in C++ which allows an easy access to generator studies. [4]

The framework provides a software environment to run and analyze different MC generators. Steering files used to modify the generator settings (see fig. 2). A generated event is saved in the HepMC format which can be analyzed by the HepMC Anaysis Tool. The analysis of every single event is done by a class library with several physics processes like pp $\rightarrow$W $\rightarrow \tau\nu_\tau$. The results of the analysis are filled in histograms which are saved in a ROOT file at the end.

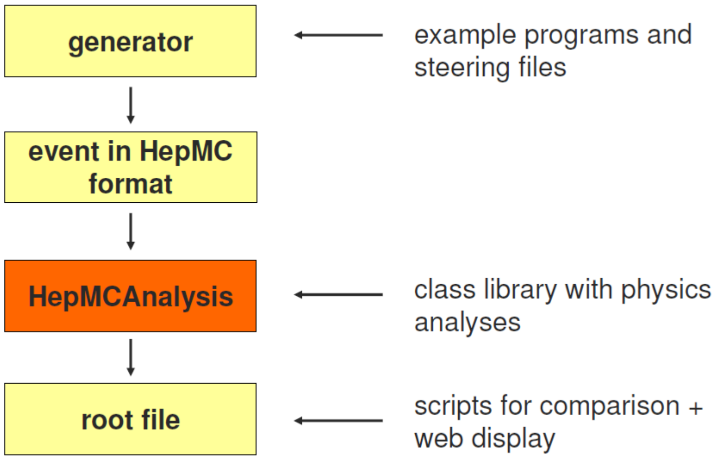

Figure 2: The workflow of the HepMCAnalyis Tool

2.3 Generators

The MC Generators Pythia and Herwig are considered in this report. In both generators the hard process is calculated until leading order of the parton distribution function. According to the Lund-String model there is a connection in Pythia called string between partons to ensure that there are no free quarks. These strings have a certain energy which increases with greater parton distances. Therefore the formation of a $q\bar{q}$ pair is favourable. [5]
It is assumed in Herwig that all gluons decay in quark-antiquark pairs. The hadronisation is described by building groups where all quarks are composed to color neutral objects (clusters). Dependend on the mass these clusters can either decay in two stable hadrons or two stable hadrons and additional unstable hadrons. [6]
The generators Herwig++ 2.4.2 [7], Pythia6 425.2 [8] and Pythia8 142 [9] are compared in this report.

2.4 Parton Distribution Functions

A comparison of PDFs in different orders of pertubative QCD is given in this report. In QCD hadrons consist of so called partons, for example valence quarks, sea quarks and gluons. A parton distribution function is a probability density for finding a parton with a certain longitudinal momentum fraction x at momentum transfer Q^2. [10]
It has been known, that there are big differences between leading order (LO) and next to leading order (NLO) pdfs for certain regions of x . In order to improve LO pdfs one invented modified leading order (LOmod or LO*) pdfs to approximate a NLO behaviour of LO pdfs. This is done by using the NLO definition of the strong coupling α_s for LO PDFs and by relaxing the momentum sum rule in input. [11]
In this report the PDFs CTEQ66 (NLO) [12], MRST2007lomod [13], MSTW2008lo90cl

(LO) [14] and HERAPDF15NNLO [15] are compared.

2.5 Tunes

In order to describe LHC experiments mostly non pertubative QCD is needed which is by necessity deeply phenomenological. This leads to a number of relativly free parameters in MC generators. Therefore tunes (collection of parameters) are needed to give the generator a better agreement with the measured data. In this report the tunes AUET2B [16], AMBT1 [16], Perugia2010 [17] and DW [18] are compared in combination with the MRST2007lomod PDFs.

2.6 Efficiencies

Due to technical constraints of the ATLAS detector it is necessary to consider several cuts for filling histograms, which lead to a more realistic look. Therefore the Wtaunu analysis class of the HepMC Analysis Tool has been extended to generate additional histograms, which are only filled if the p_T^τ, η^τ, the transverse part of the sum of the neutrino momenta $(\sum p^\nu)_T$ and the angle $\Delta\phi(p^\tau, \sum p^\nu)$ are in visible intervals. Following cuts were established:

- 20 GeV $\leq p_T(\tau) \leq$ 60 GeV
- $|\eta(\tau)| \leq$ 2.5 and not in 1.3$\leq |\eta(\tau)| \leq$1.7
- $(\sum p^\nu)_T \geq$ 30 GeV
- $\Delta\phi(p^\tau, \sum p^\nu) \geq 0.5$

The efficiency is calculated by dividing the number of events after all cuts by the total number of events. In this study the total number of events is always 100000.

3 Results

In this section the most important results of the pp $\rightarrow$W$\rightarrow$ $\tau\nu_\tau$ analysis are presented. The comparison of the p_T of the W boson and τ lepton, the rapidities y and pseudorapidities η and the angle ϕ play an important role for this analysis. Furthermore there is a comparison of diagrams for charged particles because the most concise differences for PDFs and generators occur in these histograms.

3.1 Generators

In fig. 3 one can see the transverse momentum and the rapidity of the W boson for different generators. There is a peculiar deviation of the Herwig++ diagram from the Pythia diagrams in the rapidity plot for rapidity values between 2 and 4 and between -4 and -2.

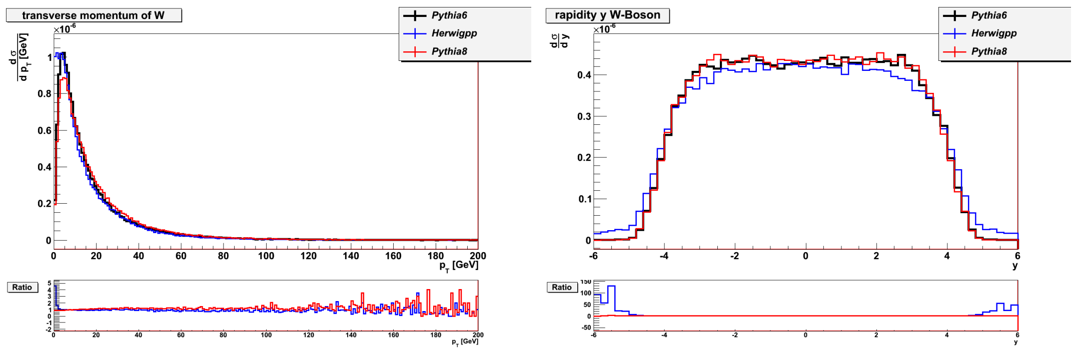

Figure 3: Transverse momentum (left) and rapidity y (right) of W

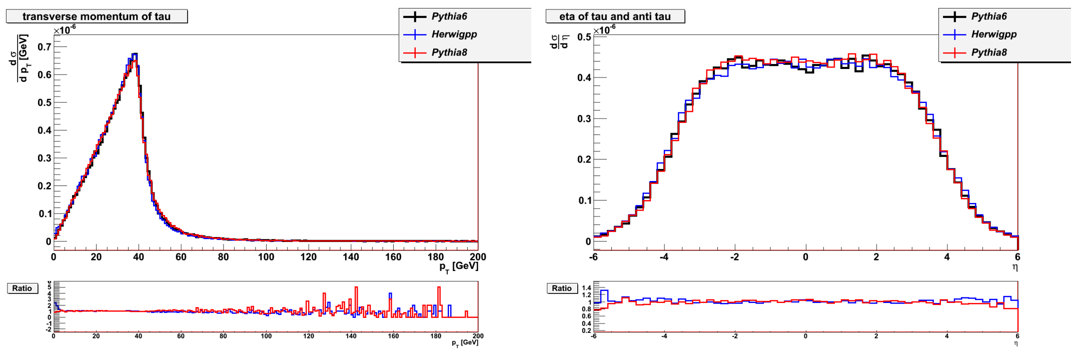

Figure 4: Transverse momentum (left) and η (right) of τ

In fig. 4 the transverse momentum and the pseudorapidity η is shown for the τ lepton. The results show a good agreement between the different generators. But there is a big difference between Pythia6 and Pythia8 in the charged particle diagrams, whereas the deviation of Pythia6 and Herwig++ is not that big as shown in fig. 5 and 6. The Pythia8 histogram for η of charged particles (fig.5) is much lower than the ones of the other two generators because all histograms are normalized to the cross section. But there is also a difference in the shape which can not be described by the cross section differences. Apparently this deviation is caused by another standard tune of Pythia8 based on the so called Tune 1 with further physics features. [19]
In order to have a better approximation of nature it is more interesting to consider histograms with cuts. In fig. 7 the transverse momentum and rapidity of the W boson is shown with a $\Delta\phi$ cut (sec. 2.6, item four). In contrast to fig. 3 now there are noticeable differences between all generators. Especially Herwig++ shows a different behaviour compared with the Pythia histograms. On the other hand one has to attend to the fact that histograms after cuts contain less entries so that statistical fluctuations become more significant.

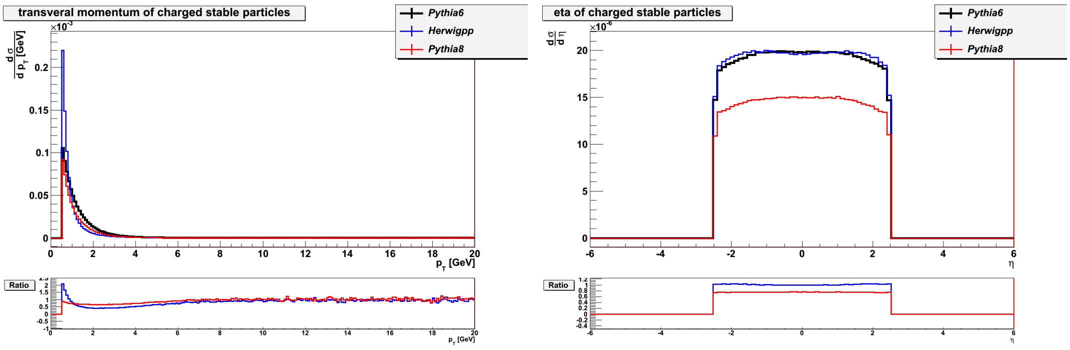

Figure 5: Transverse momentum (left) and η (right) of charged particles

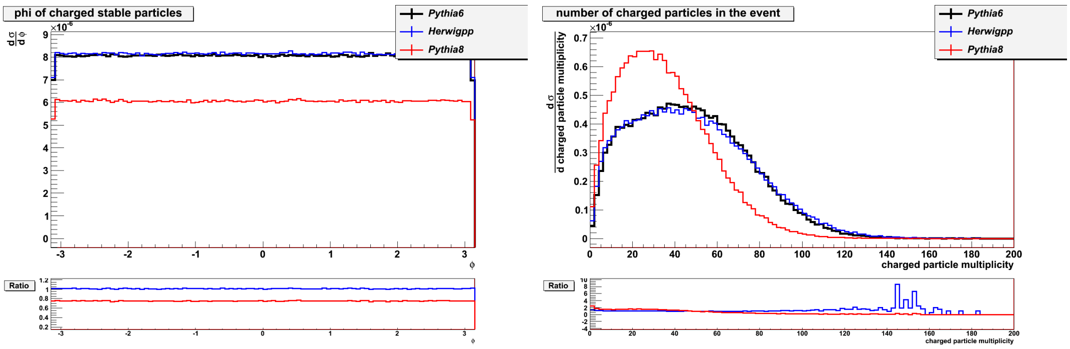

Figure 6: ϕ (left) and multiplicity (right) of charged particles

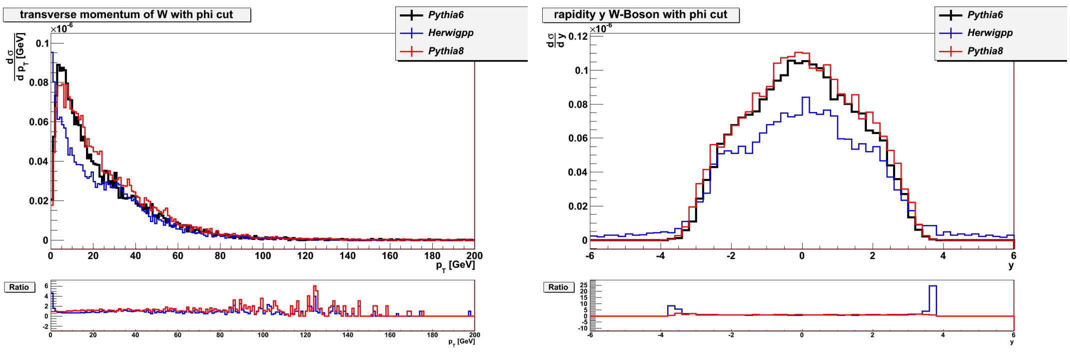

Figure 7: Transverse momentum (left) and rapidity y (right) of W with $\Delta\phi$ cut

3.2 Parton Distribution Functions

In this section the results for different parton distribution functions are shown in several histograms. As shown in [11] there should be a significant deviation of LO pdfs from NLO pdfs. Especially in the rapidity diagram the LO histogram should be lower than any other. The results in fig. 8 are in good agreement with this observation.
On the other hand the LOmod pdf should give a good approximation of NLO pdfs. This is the case for histograms in fig. 8. These results are also in good agreement with [11].

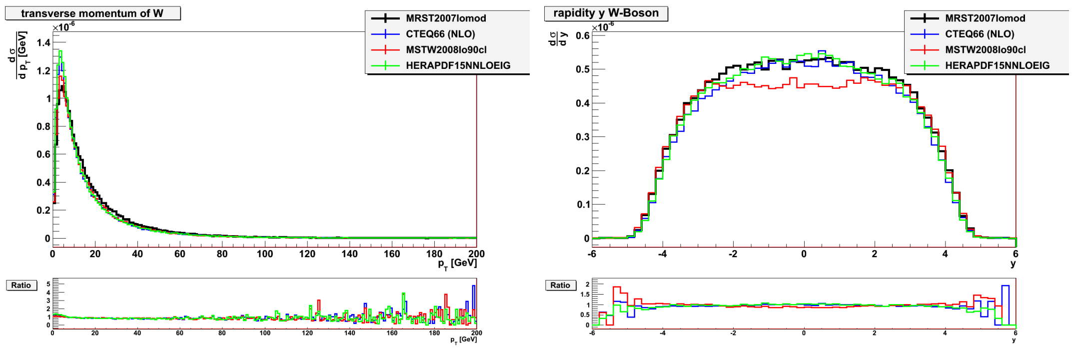

Figure 8: Transverse momentum (left) and rapidity y (right) of W

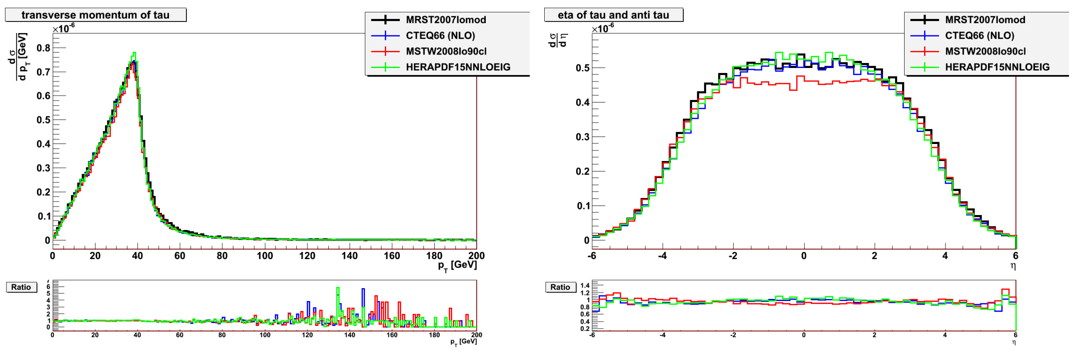

Figure 9: Transverse momentum (left) and η (right) of τ

However the differences between the PDFs are actually very small for the W and τ diagrams in comparison with diagrams of charged particles. In fig. 10 the transverse momentum of charged particles is shown. The LO and especially the LOmod PDF show a big deviation, whereas the difference between NLO and NNLO is not very significant. The LOmod has a much bigger deviation from the NLO PDF than the LO. This can be seen in the η histogram in a much better way due to the normalisation to the cross section. However in this case the best approximation of NLO is not given by LOmod.

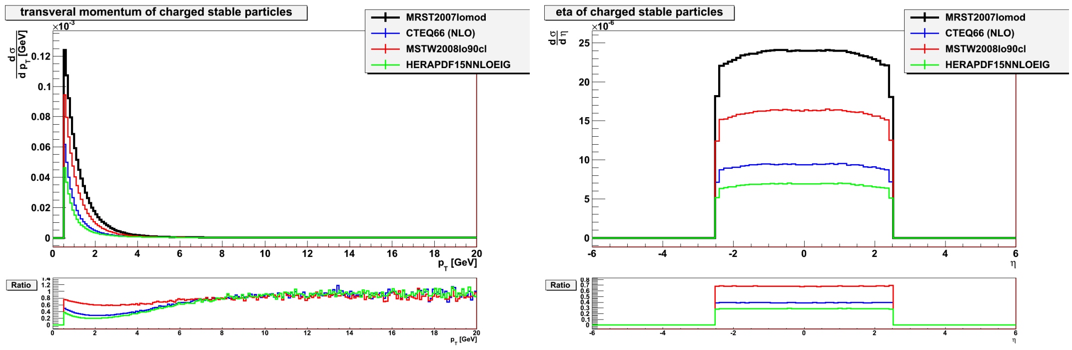

Figure 10: Transverse momentum (left) and η (right) of charged particles

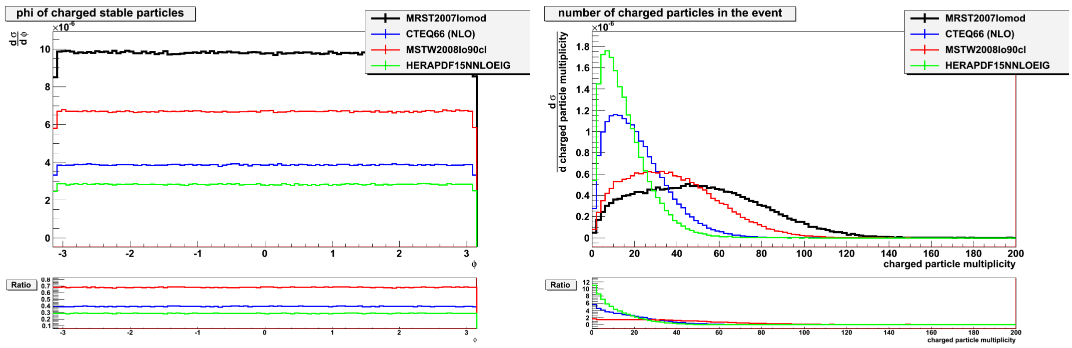

Figure 11: ϕ (left) and multiplicity (right) of charged particles

3.3 Efficiency

In table 1 one can see the cut flow (see sec. 2.6) for different PDFs. These results are made for leptonically and hadronically decaying τ leptons. Due to the fact that leptonic τ decays can not easily distinguished from W$\rightarrow$ $e\nu_e$ and W$\rightarrow$ $\mu\nu_\mu$ decays, the ATLAS results in [20] deal only with hadronically decaying τ leptons. As a first approximation the number of events after the cuts are multiplied with the decay ratio $\frac{``hadronically\ decaying\ taus''}{``all\ decaying\ taus''} = 0.6427$. [1]
In table 2 one can see the efficiencies for hadronically and leptonically decaying τ leptons and in table 3 the efficiencies for only hadronically decaying τs.

Table 1: Number of events after each cut for hadronically and leptonically decaying τs

cut	number of events	error
MRST2007lomod		
without cut	100000	316.228
$p_T(\tau)$	77770	278.873
$\|\eta(\tau)\|$	42835	206.966
$(\sum p^\nu)_T$	14030	118.448
$\Delta\phi(p^\tau, \sum p^\nu)$	13617	116.692
CTEQ66 (NLO)		
without cut	100000	316.228
$p_T(\tau)$	78182	279.61
$\|\eta(\tau)\|$	44171	210.169
$(\sum p^\nu)_T$	13804	117.49
$\Delta\phi(p^\tau, \sum p^\nu)$	13482	116.112
MSTW2008lo90cl		
without cut	100000	316.228
$p_T(\tau)$	78215	279.669
$\|\eta(\tau)\|$	41773	204.384
$(\sum p^\nu)_T$	13116	114.525
$\Delta\phi(p^\tau, \sum p^\nu)$	12762	112.969
HERAPDF15NNLOEIG		
without cut	10000	316.228
$p_T(\tau)$	78277	279.78
$\|\eta(\tau)\|$	44714	211.457
$(\sum p^\nu)_T$	13752	117.269
$\Delta\phi(p^\tau, \sum p^\nu)$	13427	115.875

Table 2: Efficiency for hadronically and leptonically decaying τs

PDF	efficiency	error
CTEQ66	0.13482	0.00123692
MSTW2008lo80cl	0.12762	0.00119961
MRST2007lomod	0.13617	0.00124383
HERAPDF15NNLOEIG	0.13427	0.00123409

Table 3: Efficiency for hadronically decaying τs only

PDF	efficiency	error
CTEQ66	0.08988	0.000825
MSTW2008lo80cl	0.08508	0.0008
MRST2007lomod	0.09078	0.000829
HERAPDF15NNLOEIG	0.089513	0.000823

The efficiency published by ATLAS [20] is 0.0975 with an error of 0.0019. This result differs a bit to the result in table 3 which is caused by another tune. The ATLAS result is based on the AMBT1 LO* [21] tune and the results in table 3 are rely on the Pythia6 standard tune [18] which is based on Tevatron experience and the Field's tune A. For this reason the result for the LOmod pdf MRST2007lomod is most similar to the ATLAS result.

3.4 Tunes

There are a lot of possible combinations of tunes and parton distribution functions. In fig. 12 one can see some deviations of the Perugia2010 tune from the other tunes as well as a lower first bin for the AUET2B tune. The distributions of W rapidity show all in all no significant differences.

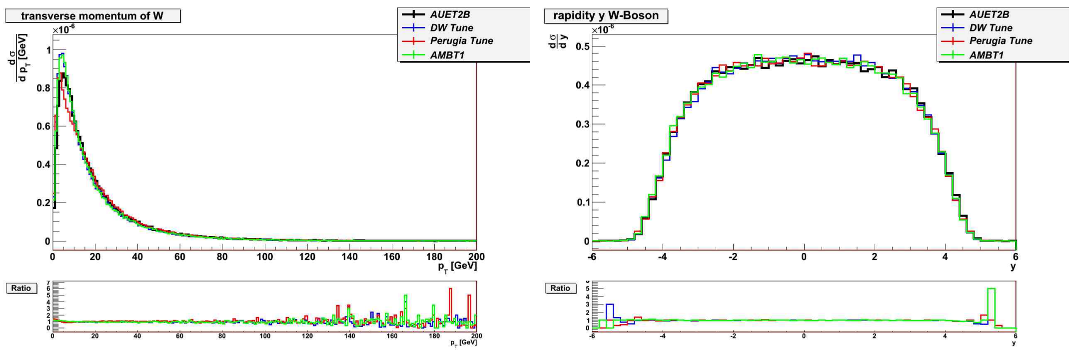

Figure 12: Transverse momentum and rapidity y of W

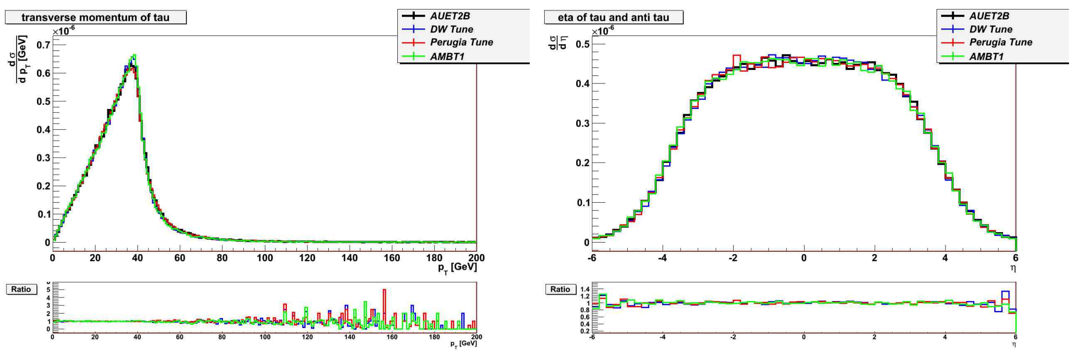

Figure 13: Transverse momentum and η of τ

The τ distributions show a very similar behaviour like the W distributions. The head of Perugia2010 and AUET2B p_T distribution is a little bit lower than the other two and the pseudorapidities η are all in all very close.
The differences between tunes are less than the differences between the parton distributions.

4 Summary and Outlook

The comparsion of different generators has shown a good agreement of kinematic quantities for W and τ observables. Furthermore the behaviour of parton distribution functions for W and τ histograms is like expected. The LOmod pdf gives a good approximation of the NLO pdf as already shown in [11]. The result of the efficiency is also very similar to the ATLAS result taking into account that different tunes were used. The comparison of tunes has only shown little differences.

References

[1] Physics Letters B **667**, Issues 1-5, (2008).

[2] LHC DesignReport, https://ab-div.web.cern.ch/ab-div/publications/LHC-DesignReport.html, (7.9.2011)

[3] M. Dobbs and J. B. Hansen, Comput. Phys. Commun. **134** (2001) 41.

[4] C. Ay, S. Johnert, J. Katzy, Z. -H. Qin, J. Phys. Conf. Ser. **219** (2010) 032029.

[5] Torbjorn Sjostrand et al. High-energy-physics event generation with PYTHIA 6.1. Comput. Phys. Commun., **135**: 238 - 259, (2001)

[6] G. Corcella et al. HERWIG 6.5 release note. (2002), [arXiv:0210213, [hep-ph]]

[7] M. Bahr *et al.*, Eur. Phys. J. C **58** (2008) 639 [arXiv:0803.0883 [hep-ph]].

[8] T. Sjoestrand, S. Mrenna, P. Skands, PYTHIA 6.4 Physics and Manual, [arXiv:0603175 [hep-ph]]

[9] T. Sjoestrand, S. Mrenna, P. Skands, A Brief Introduction to PYTHIA 8.1, [arXiv:0710.3820 [hep-ph]]

[10] A.V. Belitsky, A.V. Radyushkin, Unraveling hadron structure with generalized parton distributions, [arXiv:0504030v3 [hepo-ph]]

[11] A. Sherstnev and R. S. Thorne, Eur. Phys. J. C **55** (2008) 553 [arXiv:0711.2473 [hep-ph]].

[12] P.M.Nadolsky, H.-L.Lai, Q.-H.Cao, J. Huston, J.Pumplin, D.Stump, W.-K.Tung and C.-P.Yuan. [arXiv:0802.0007 [hep-ph]]

[13] A. Sherstnev and R. Thorne, Parton Distributions for LO Generators [arXiv:0711.2473v2 [hep-ph]]

[14] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, Parton distributions for the LHC [arXiv:0901.0002 [hep-ph]]

[15] J.M. Campbell, J.W. Huston, W.J. Stirling, Hard Interactions of Quarks and Gluons: a Primer for LHC Physics [arXiv:0611148v1 [hep-ph]]

[16] The ATLAS Collaboration, ATLAS tunes of Pythia6 and Pythia8 for MC11, (2011)

[17] P.Z. Skands, Tuning Monte Carlo Generators: The Perugia Tunes (2011) [arXiv:1005.3457v4 [hep-ph]]

[18] R.Field, Min-bias and underlying event in Run 2 at CDF, Acta Pys. Olon. B **36** (2005) 167

[19] http://home.thep.lu.se/ torbjorn/php8153/Welcome.php (7.9.2011)

[20] ATLAS Collaboration, Measurement of the W to tau nu Cross Section in pp Collisions at sqrt(s) = 7 TeV with the ATLAS experiment [arXiv:1108.4101v1 [hep-ex]] (2011)

[21] The Atlas Collaboration, ATLAS-CONF-2010-031