Implementation of a $W \to \tau\nu_\tau$ analysis class for the HepMCAnalysis Tool

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Abstract

In this project an analysis class for the HepMCAnalysis Tool will be developed and implemented. The HepMCAnalysis Tool was developed for Monte Carlo generator validation and comparison. It is already used in different applications like GENSER (Generator Service LCG project) and in Atlas. It was also used in the Monte Carlo schools at DESY. The class will evaluate the physics process $p + p \to W \to \tau + \nu_\tau$ on generator level by histogramming the distributions of significant observables. This process plays an important role in the background of Higgs and supersymmetric particle decays into τ-leptons.

Contents

1 Introduction

The LHC started operating in November 2009 and became the world's largest particle accelerator with a current center-of-mass energy of $\sqrt{s} = 7$ TeV. Due to the large center-of-mass energy the LHC is able to explore new energy regions which includes searches for particles with higher mass. This includes searches for physics beyond the Standard Model, e.g. supersymmetric partners of the SM particles, extra dimensions etc. Furthermore the physicists hope to find the predicted Higgs particle.

The discovery of a new particle demands a proper understanding of the signal and background processes. Therefore Monte Carlo generators are used to predict the behaviour of experimental observables which are then compared to the data.

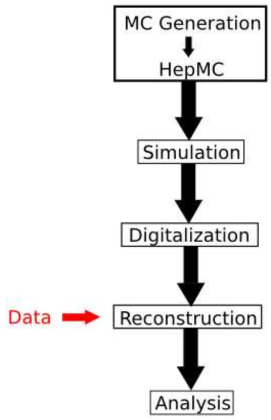


Figure 1: Analysis Chain.

In order to compare the simulated events with the taken data, the events have to be generated first via Monte Carlo generators like Pythia [1, 2] and Herwig [3, 4]. The Monte Carlo generators (MC generators) contain e.g. the type of colliding particles and the center-of-mass energy. Events are generated by taking several aspects into account like multiple parton interactions, initial and final state radiation and hadronization. Afterwards the performance of the detector has to be simulated. After the digitalization of the simulated data, the recorded data and the simulated data have to be reconstructed.

The discovery of new particles depends on the precision and accuracy of the used MC generator. Therefore the generators have to be tested and validated. In this project the validation of the MC generators is done with the HepMCAnalysis Tool (see chapter 2.2) using the HepMC format (see chapter 2.1). The ambition of the project is the implementation of the process $p + p \rightarrow W \rightarrow \tau + \nu_\tau$ in the HepMCAnalysis Tool and the evaluation for several MC generators.

2 Framework

In this chapter the HepMC format is introduced, which is used in the HepMCAnalysis Tool. Afterwards the tool and its machinery is presented.

2.1 HepMC output

The generated events of a Monte Carlo generator are stored next to other formats also in the HepMC format. The graph structure of a physics event is shown in the left plot of figure 2. The event includes the parton distribution functions, the hard subprocess, parton cascades, hadronisation and the decay. The similar representation of a physics event in HepMC format is illustrated in the right plot of figure 2. The HepMC format differentiates

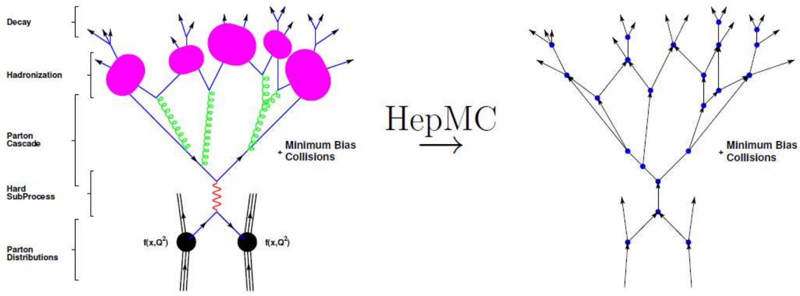


Figure 2: Graphical visualisation of a collision event (left) and the concerning structure as a HepMC event (right) [5].

between particles and vertices. Each particle carries information about its four-momenta, flow, particle identification (ID) and status information. Moreover each particle points back to its production and decay vertex. The vertices connect the different particles with each other. Therefore each particle belongs at least to one vertex. The vertex comprises the position, ID and weight information. Each vertex contains the information of the incoming and outgoing particles [5].

2.2 HepMCAnalysis Tool

The HepMCAnalysis Tool is a framework for comparison and validation of MC generators [6]. It provides an easy access to generator level studies. It covers various aspects of event generation such as hard processes, parton shower, multiple parton interaction, underlying event and hadronisation. Furthermore the tool comprises a class library containing several physics processes to analyse HepMC outputs of the Monte Carlo generators and to histogram the results.

The technical workflow of the HepMCAnalysis Tool is shown in figure 3. The tool provides example programs for some MC generators: Pythia6, Pythia8, Herwig, Herwig++ and Cascade. Further generators are planned. The tool uses centrally installed generator libraries of Genser (Generator Service Project) [7] to produce the HepMC output format.

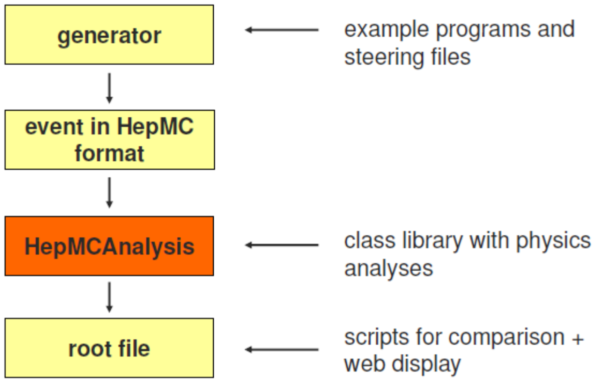


Figure 3: Working steps of the HepMCAnalysis Tool from the event generation to the output.

Then the HepMC output is processed in the analysis classes such as top quark or Z-boson analysis and also an easy extendable class framework for user analysis. These analysis classes include the baseAnalysis which provides several basic functions like Init() [1], Process (HepMC::GenEvent* hepmcevt) [2] and Finalize() [3]. Furthermore more common algorithms for the reconstruction of physical analysis objects like JetFinder and missing transverse energy calculations are contained. The structure of the class library is illustrated in figure 4. The different analysis classes inherit the functions and algorithms of the baseAnalysis and

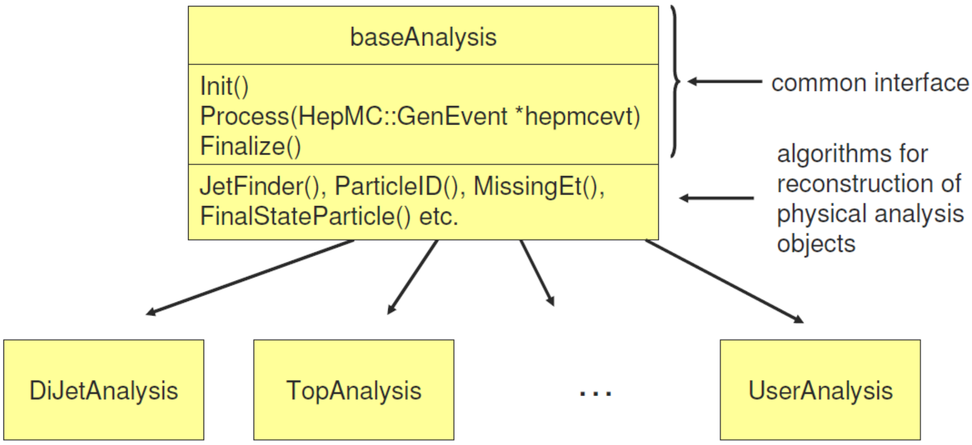


Figure 4: Graphical illustration of class library structure.

improve them according to their necessity. In them, the event is analysed and the results are filled in histograms. The tool comprises in addition a script to compare and display the histograms. The comparisons of histograms are done via a Kolmogorov-Smirnov and a χ^2-test.

[1]The function Init() initializes the histograms for the different distributions.
[2]The function Process() analyses the event.
[3]The function Finalize() does some final calculations and stores the histograms into ROOT [8] files.

3 Analysis

In this chapter the process which will be implemented in the HepMCAnalysisTool is introduced as well as the analysis procedure. The histograms for the W-boson and for the decay products are presented and discussed. Furthermore characteristics of different Monte Carlo generator versions are demonstrated and explained.

3.1 Analysis class

The chosen physics process is the decay of the W-boson into a τ-lepton and its corresponding neutrino ν_τ:

$$p + p \rightarrow W \rightarrow \tau + \nu_\tau$$

One of the main goals of the LHC is the discovery of new particles like the Higgs boson and/or supersymmetric particles (SUSY). For this reason, the τ-lepton is an important final state particle in the decay of the Higgs or supersymmetric particles, see fig. 5.

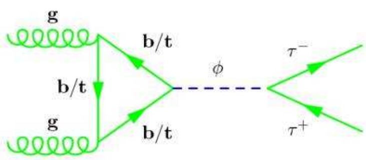


Figure 5: Feynman diagramm of the decaying Higgs-boson into two τ-leptons [9].

So $W \rightarrow \tau\nu_\tau$ and $Z \rightarrow \tau\tau$ are fundamental background processes. The decision to implement a class for $W \rightarrow \tau\nu_\tau$ is due to the higher NNLO cross-section [10]:

$$\begin{aligned} \sigma(W \rightarrow \tau\nu_\tau) &= 20.5 \text{ pb} \\ \sigma(Z \rightarrow \tau\tau) &= 2.02 \text{ pb.} \end{aligned}$$

3.2 Analysis Steps

At first the available UserAnalysis class was amplified for the process by including relevant histrograms such as the transverse momenta of the W-boson and its decay products, angular variables like ϕ, η and the pseudorapidity, mass distributions of the particles as well as the number of charged particles in the event. Furthermore the configuration files for the Monte Carlo generators have been included.
Afterwards the analysis has been applied to 100,000 events for four different MC generators: Pythia6, Pythia8, Herwig, Herwig++. In order to validate and compare the different MC generators, different versions of each generator have been tested and compared via a Kolmogorov-Smirnov- and a χ^2-test.

The following versions have been applied:

- Pythia6: 6.4.21.2, 6.4.23.2
- Pythia8: 135, 140
- Herwig: 6.510.2, 6.510.3
- Herwig++: 2.4.1, 2.4.2

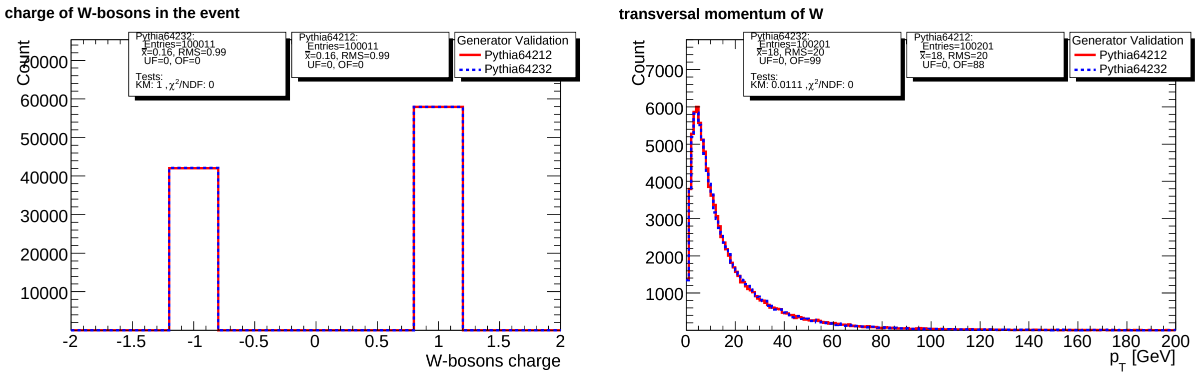
The results are discussed in the next section.

3.3 Results

The results of the analysis are discussed for the MC generator Pythia6. The versions 6.4.21.2 and 6.4.23.2 are compared to each other. The histograms have also been produced for the three other MC generators but are not shown in this report. The plots are available on the webpage `http://hepmcanalysistool.desy.de/summerstudent2010/index.html` .

3.3.1 W-boson

First of all the results of the W-boson are discussed. The charge of the generated particles is depicted in fig. 6a. It can be extracted from the plot that more W-bosons with a positive charge are produced.



(a) (b)

Figure 6: Charge of generated W-bosons (a) and transverse momentum of W-boson (b), generated with Pythia6.

This behaviour is due to the fact, that the W^+-boson can be produced from an up-type quark and an anti down-type quark, e.g. $u + \bar{d} \to W^+$ whereas the W^--boson can be produced from a down-type quark and an anti up-type quark, e.g. $d + \bar{u} \to W^-$. The considered process is the collision of two protons, which contain each two up and one down valence quarks. Therefore the possibility that an up quark interacts is two times higher than the interaction of a down quark. Furthermore the parton distribution function of the anti-down quark is slightly higher than the one of the anti-u-quark, see fig. 7.

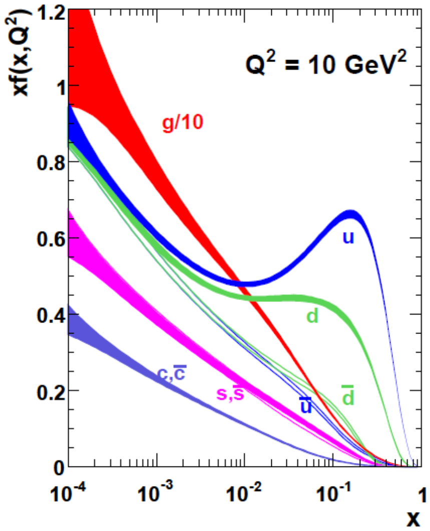
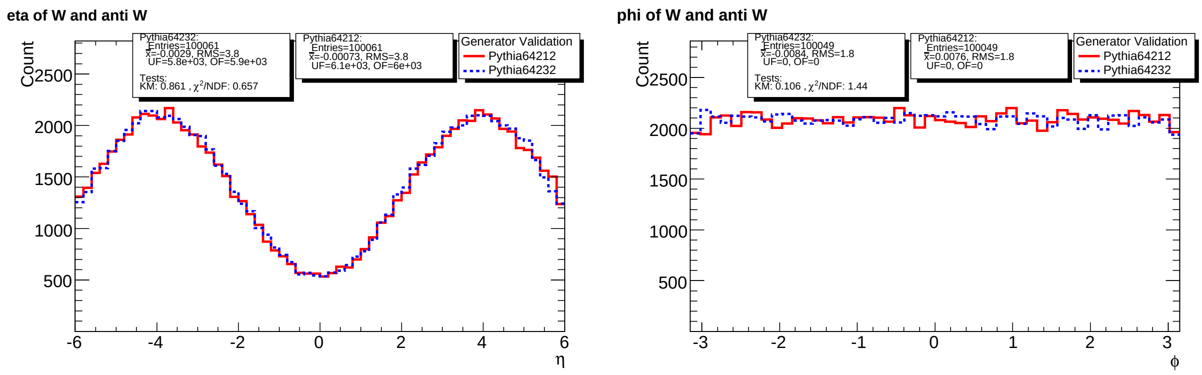


Figure 7: MSTW 2008 NLO parton distribution functions at $Q^2 = 10\ \text{GeV}^2$ [11].

The transverse momentum of the W-boson is illustrated in figure 6b.



(a)

(b)

Figure 8: Pseudorapidity of generated W-bosons (a) and angular distribution ϕ of W-boson (b), generated with Pythia6.

As it can be seen, the W-boson carries only a small transverse momentum due to its high mass. The W-boson is produced almost at rest and decays after a short time. The direction of the W-boson can also be determined of the pseudorapidity, which is defined as

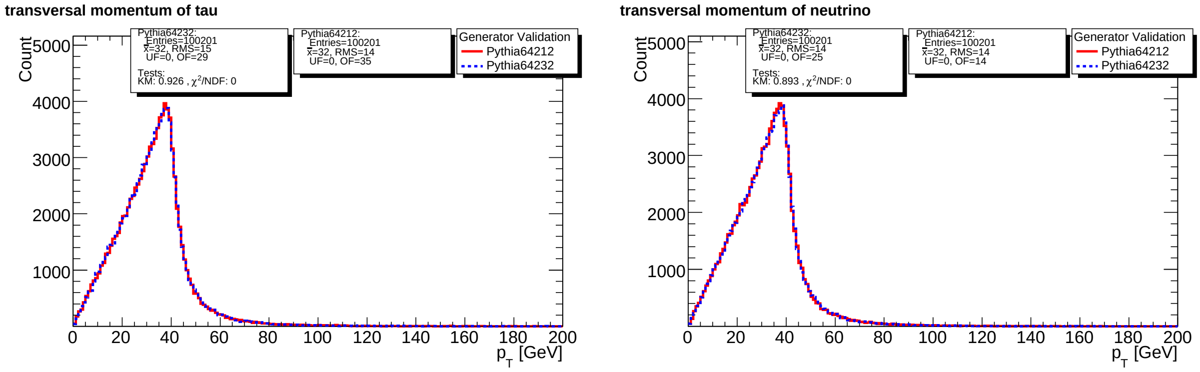
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] .$$

If the W-boson is produced perpendicular to the beam axis, $\theta = 90°$, the pseudorapidity becomes $\eta = 0$. A large pseudorapidity implies a vanishing angle θ. According to fig. 8a the pseudorapidity is symmetric with respect to the beam-axis.

The angular variable ϕ is uniformely distributed, see fig. 8b. This means, that the particles uniformely produced in the plane perpendicular to the beam axis.

3.3.2 Decay products

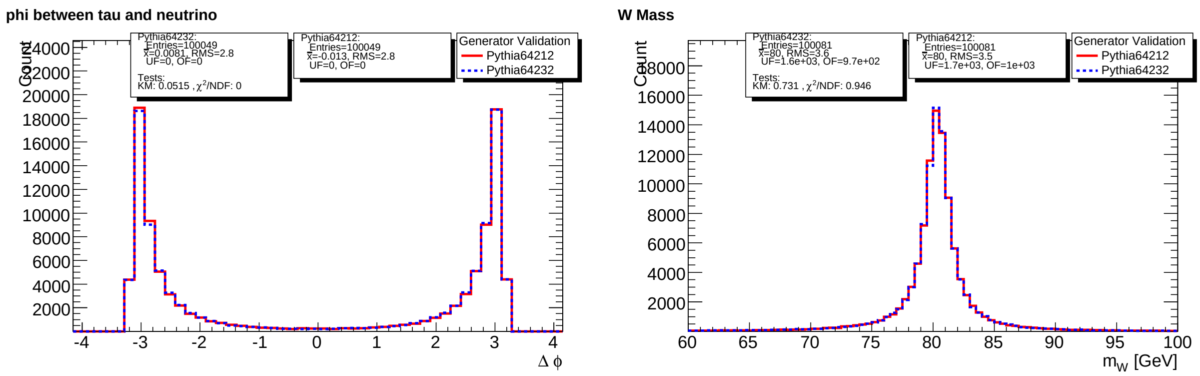
The transverse momenta of the decay products τ and ν_τ is shown in fig. 9.



(a) (b)

Figure 9: Transverse momentum of the τ-lepton (a) and its corresponding neutrino ν_τ (b), generated with Pythia6.

Both particles have almost the same momentum distributions with a maximum around $p_T \approx 40$ GeV/c, which coincide with the half mass of the W-boson, see fig. 10b. Compared to the mother particle, the τ-lepton (m = 1776.82 ± 0.16 MeV/c^2) as well as the neutrino are massless. This involves that both decaying particles get half of the energy of the W-boson which defines the momentum. In order to conservate transverse momenta, the particles must be emitted back-to-back. This can be also seen by plotting the angle ϕ between the τ-lepton and the neutrino, see fig. 10a. The angle between the decay products is $\pm\pi$.



(a) (b)

Figure 10: $\Delta\phi$ between τ and ν_τ (a) and the mass of the W-boson (b), generated with Pythia6.

The number of charged tracks in the decay of the τ-lepton is depicted in figure 11. The τ-lepton can either decay leptonically into electrons and muons and its corresponding neutrinos or either hadronically into π's or K-mesons. The plot indicates that the τ decays more often into one charged particle, e.g. $\tau \rightarrow \mu + \nu_\mu + \nu_\tau$ or $\tau \rightarrow \pi + \nu_\tau$. The particle data group (PDG) [12] quote that the τ-lepton decays to 85.36 ± 0.08 % into one charged particle and with 15.56 ± 0.08 % into three charged particles. The ratio of the number of events with one track respectively three tracks compared to the total number of events in the histograms are in good agreement with the branching ratios of the PDG.

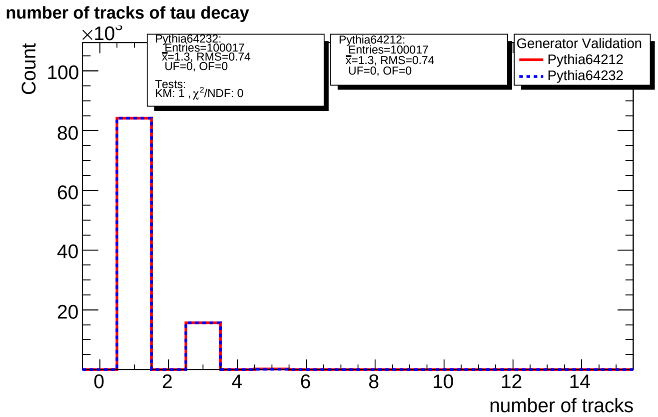
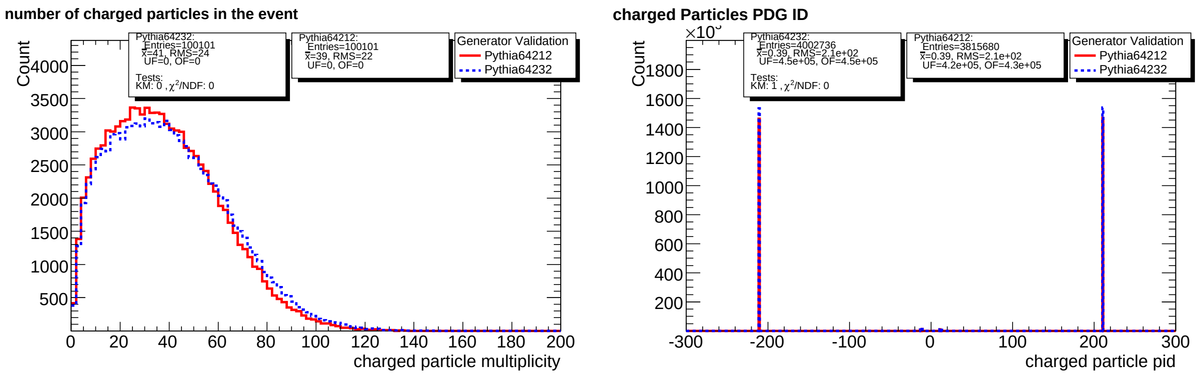


Figure 11: Number of charged tracks in the decay of the τ-lepton.

Furthermore the class contains an analysis of the charged stable particle in the event. The number of charged particles is shown in figure 12 and varies between zero and approximately 140. The large number of charged particles can be explained by initial and final state radiation and the multiple parton interaction. Moreover the particle identification is illustrated in figure 12. Most of the particles are pions which are produced in the decay of the τ-leptons as well as muons and electrons.



(a)

(b)

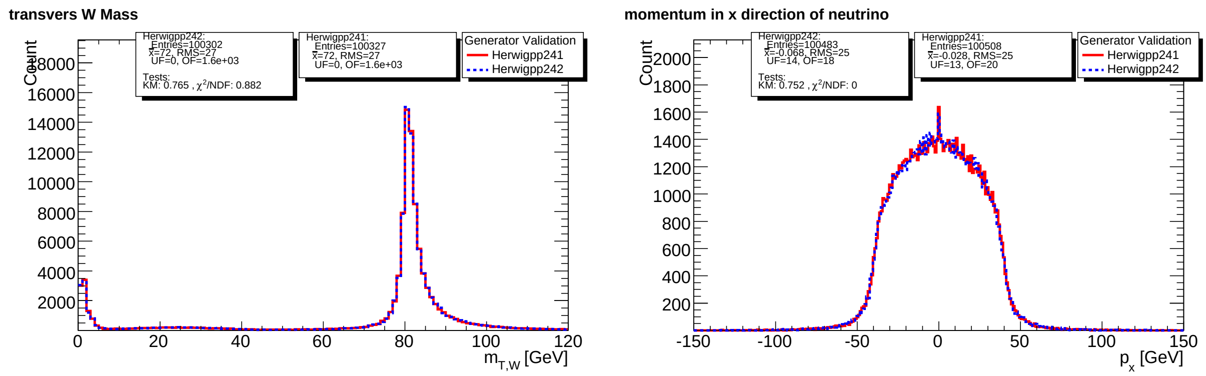
Figure 12: Number of charged particles in the event (left) and their pdg identification number (right), generated with Pythia6.

3.4 Characteristics

In this section characteristics of several MC generators are shown and solutions are presented.

3.4.1 Herwig++

The transverse mass of the generated W-bosons is illustrated in figure 13a. As expected the distribution peaks at a value around the W-boson mass peak. Nevertheless there are W-bosons which are not on their mass shell and peak around zero. This behaviour occurs for all tested versions.
The W-bosons are unphysical and are produced in electroweak interactions with a τ-lepton. These W-bosons cause a further needle of the neutrino momentum at $p_T \approx 0$ GeV/c, see fig. 13b. In order to avoid the massless W-bosons, a mass cut has to be applied.



(a) (b)

Figure 13: Transverse mass of the W-boson and the momentum in x-direction of the tau-neutrino generated with Herwig++.

A bug in the Herwig++ version 2.4.1 occured. The transverse momentum of the τ-leptons was shifted to higher momenta, see fig. 14. This bug was caused by a misspelling of the pdg identification number for some particles which should be parents/ancestors of the τ-leptons. In version 2.4.2 the bug was removed.

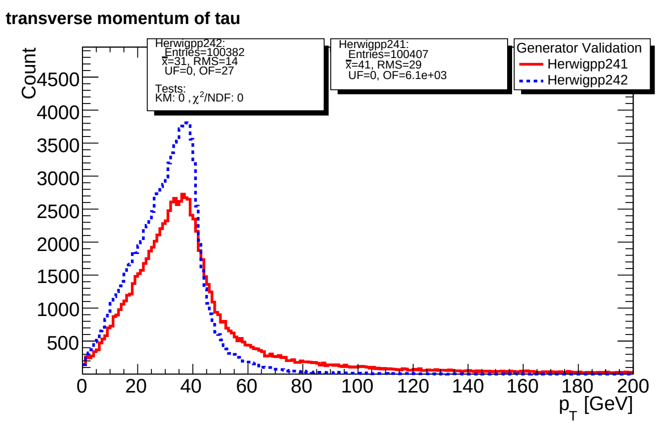
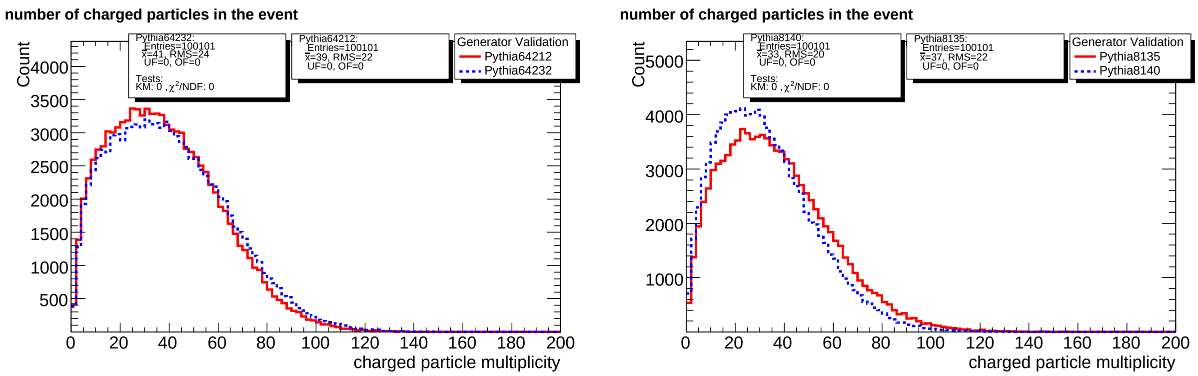


Figure 14: Bug of the Herwig++ generator in the transverse momenta distribution of the τ-lepton.

3.4.2 Pythia6 and Pythia8

The number of charged particles in the event is shown in fig. 15a for the Pythia6 generator. The number of particles per event has been shifted to higher numbers from version 6.4.21.2 to version 6.4.23.2. This error occured due to a bug in PYSIGH concerning the multiple-interaction framework [13]. This bug causes an increase of $< 10\%$ in the average charged multiplicity. On the contrary the number of charged particle has been shifted due to smaller numbers for the generator Pythia8, see fig. 15b.



(a) (b)

Figure 15: Number of charged particles for the two MC generators Pythia6 (a) and Pythia8 (b).

3.4.3 Herwig

The histograms have also been produced with the Monte Carlo generator Herwig and are also available on the webpage. The results showed no special characteristics.

4 Summary and Outlook

The analysis class for the physics process $p + p \rightarrow W \rightarrow \tau + \nu_\tau$ has been developed and important distributions for validation and comparison of MC generators have been included. The analysis class has been applied to different MC generators and different versions. Different versions of one MC generator have been compared by Kolmogorov-Smirnov- and χ^2-tests. The various physical variables for the generated W-bosons as well as for the decay products are distributed as expected. Furthermore a webpage `http://hepmcanalysistool.desy.de/summerstudent2010/index.html` with the plot results has been created.

The analysis class Wtaunu will be implemented in the next version of the HepMCAnalysis Tool.

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