Influence of Multiple-Parton Interactions on the Production of a light Standard Model Higgs Boson associated with a W Vector Boson at the LHC

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September 16, 2008

Abstract

The following article desribes the work I did within the scope of this year's DESY Summer Student Programme. The basic outcome is that within a range of about 20% the application of the event generator PYTHIA yields the same cross sections for the examined Higgs discovery channel and its backgrounds as the calculation of low-order Feynman diagrams if the fragmentation process is not considered. Within these simplified settings, I was also able to increase the signal to background ratio for the Higgs production associated with the creation of a W boson by more than a factor of 2 by introducing additional cuts on the final state particles.

Introduction

The Higgs boson as the last fundamental component of the Standard Model of Elementary Particle Physics to be discovered, has drawn the attention of many scientists to examine ways to do so at the LHC [1]. One of the possible discovery channels is the production of a Higgs boson associated with a vector boson. However, for the special case of this vector boson being a leptonically decaying W and the Higgs being in the intermediate mass range so that it decays into $b\overline{b}$, A. Del Fabbro and D. Treleani showed in 1999 that double-parton interactions provide a sizeable background to this process [2]. They used mathematical computer packages to calculate the contribution of leading order Feynman diagrams and a K-factor of 1.8 to account for higher order corrections.

The purpose of the following investigation is mainly to examine the reproducibility of those results with the Monte Carlo event generator Pythia 6.4 [7] and the effect of the slightly different up-to-date cuts proposed for the study of this process [12]. Furthermore, I aim to devise different kinematical observables and additional cuts which result in a more favourable signal to noise ratio for the detection of the Higgs boson in this particular channel.

A Higgs boson with a mass below the W^+W^- threshold decays most frequently into a $b\overline{b}$ pair [1]. Because of that and the possibility of identifying jets coming from b quarks efficiently, this decay channel is one of the possible ways to observe Higgs boson production at the LHC. Unfortunately, it suffers from a lot of background from $b\overline{b}$ production in the numerous hadronic collisions. To reduce this background, additionally the detection of a single lepton from the decay of a W boson is required resulting in the overall process $pp \rightarrow WH \rightarrow l\ \nu\ b\overline{b} + X$.

In contrast to analytical and numerical calculations of cross sections for high-energy collisions based on low-order Feynman diagrams, Monte Carlo event generators provide a means to take the more complicated, unpredictable nature of these events into account [8]. In PYTHIA hard interactions above a minimal transverse momentum scale are chosen according to the analytically or numerically determined pQCD matrix elements. In addition parton showers (PS) are employed to account for bremsstrahlung which occurs because colour (and often electromagnetic) charges are accelerated in a collision. We distinguish so-called initial state radiation (ISR) from the incoming partons and final state radiation (FSR) from the outgoing ones. Furthermore, there are different fragmentation models implemented to incorporate hadronization processes.

More than 20 years ago T. Sjöstrand, one of the main authors of PYTHIA, already indicated the potential importance of multiple-parton interactions in hadronic collisions [9]. Since then there have been different attempts to include the possibility of having several parton-parton interactions at once in the event generating process. Due to the long computing times, I was only able to study the effect of the so-called "Old Model" which only includes parton showers for the hardest process involved [7].

Methods and Results

Preparation

The first PYTHIA runs were mainly concerned with the process gg → H in which I kept the Higgs boson stable and plotted its transverse momentum dsitribution. I checked different bin widths, different numbers of events and the differences between multi-parton scattering switched on and off which were basically only statistical fluctuations (see fig.(1)). For all studies of multiple interactions I used the old PYTHIA model with R.D. Field's Tune A [11].

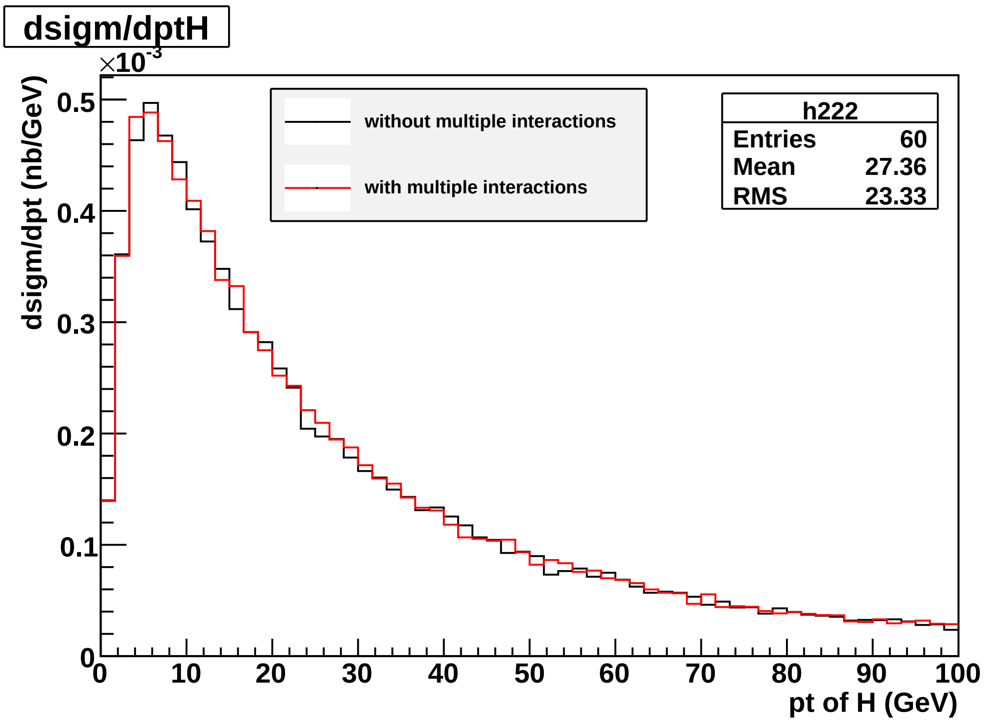

Figure 1: gg → H, comparison between MPI on (MSTP(81)=1) and off (MSTP(81)=0) with Itune=100 and 50,000 events (large increase in computing time) ⇒ no big differences, $M_{Higgs} = 125\,\text{GeV}$

In contrast to those tests, using different parton density functions (PDFs) really had an observable impact. Figure (2) shows a 20% variance in peak height of the differential cross sections between the events generated with a leading order and next to leading order PDFs, respectively.

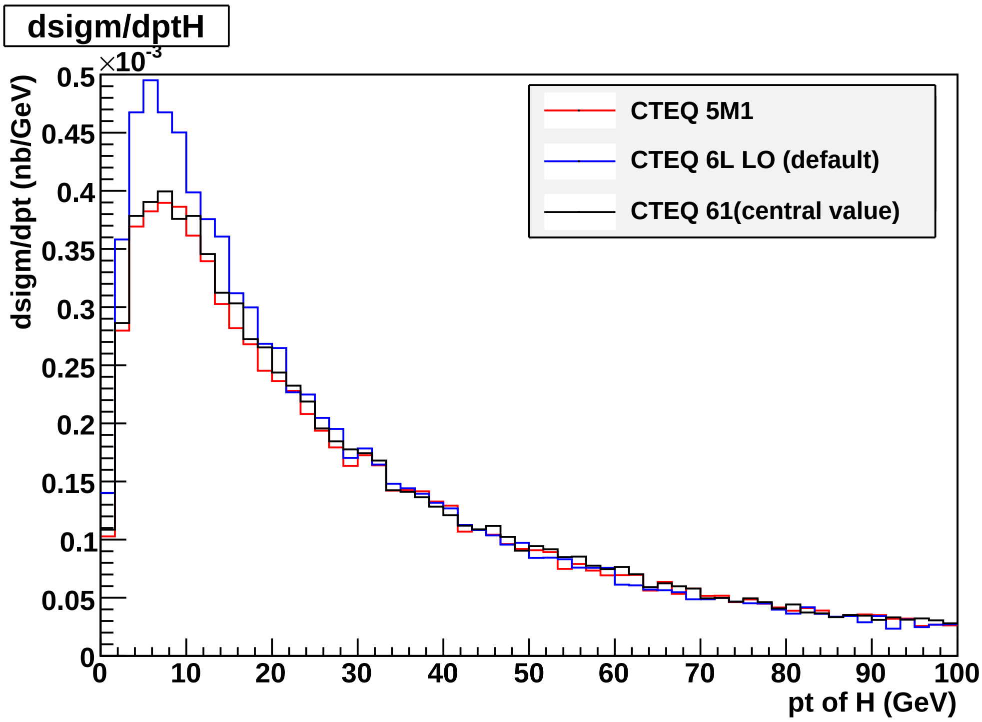

Figure 2: gg $\rightarrow$ H, comparison between different PDFs $\Rightarrow$ clear difference between LO and NLO PDFs, Itune= 0, MSTP(81)=0, $M_{Higgs} = 125\,\mathrm{GeV}$

Afterwards, I allowed for the Higgs boson to decay and examined the effect of final state radiation on the invariant mass distribution of the b and $\overline{\mathrm{b}}$ quarks (see fig. (3) and fig. (4)). It is easily seen that the quarks lose energy by radiating gluons. Hence, even if we were able to detect quarks rather than hadrons it is important to have a good reconstruction of the energy they had immediately after being produced. Otherwise one could not determine the Higgs mass exactly even without any background present.

Since the results obtained so far looked qualitatively reasonable, I tried to reproduce some quantative results from different papers considering the process pp $\rightarrow$ b$\overline{\mathrm{b}}$. At first I used the values of the PYTHIA parameters given in the appendix of [4] and in the caption of the following figures to arrive at almost the same transverse momentum distribution for the b quarks (fig. (5)) as N. Carrer *et al* whereas the obtained $\Delta\phi(\mathrm{b}\overline{\mathrm{b}})$ distribution (fig. (6)) shows a higher and narrower peak towards π. The reasons for that behaviour could not be clarified completely but we expect them to be changes between different PYTHIA versions (6.150 in contrast to 6.4).

After that I introduced the cuts on the rapidity y employed in "Benchmark cross sections for heavy-flavour production" by O. Behnke *et al* from [3], namely $|y| < 2.5$. Although PYTHIA offers the possibility to cut on the hard matrix element these cuts were performed on the final state particles as this is closer to what is done in experiment. The resulting p_t distribution of b quarks is very similar to that obtained with CASCADE, another event generator, and NLO calculations (see fig. (7)).

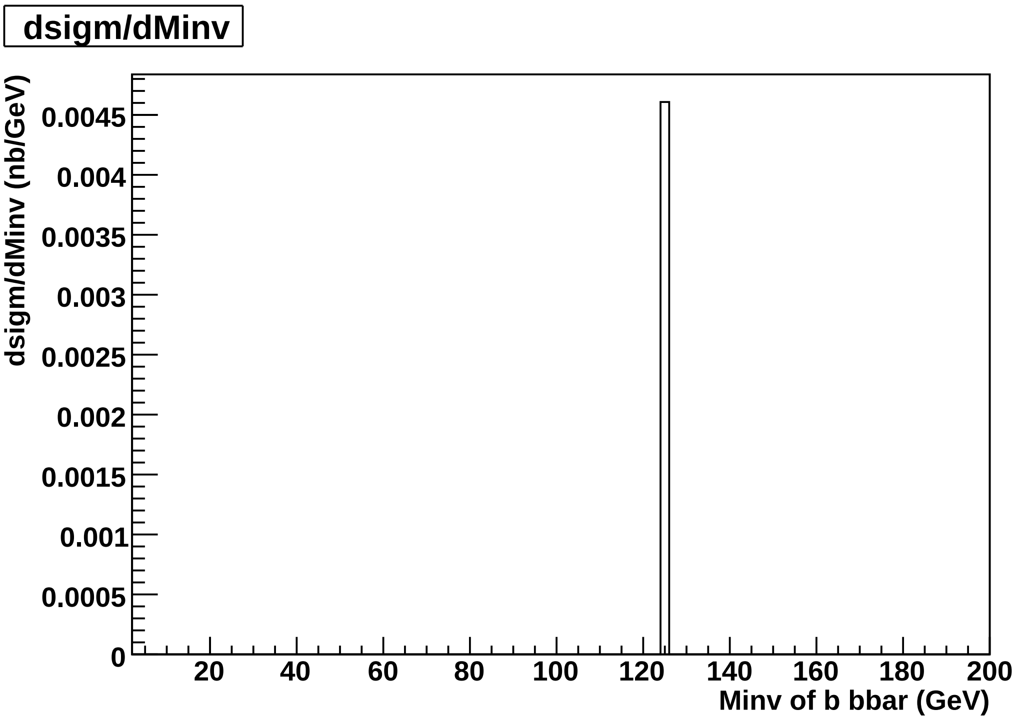

Figure 3: gg $\rightarrow$ H $\rightarrow$ b$\overline{\rm b}$, invariant mass distribution of b$\overline{\rm b}$ pair before radiating gluons, Itune=100, no MPI, $M_{Higgs} = 125\,\mathrm{GeV}$

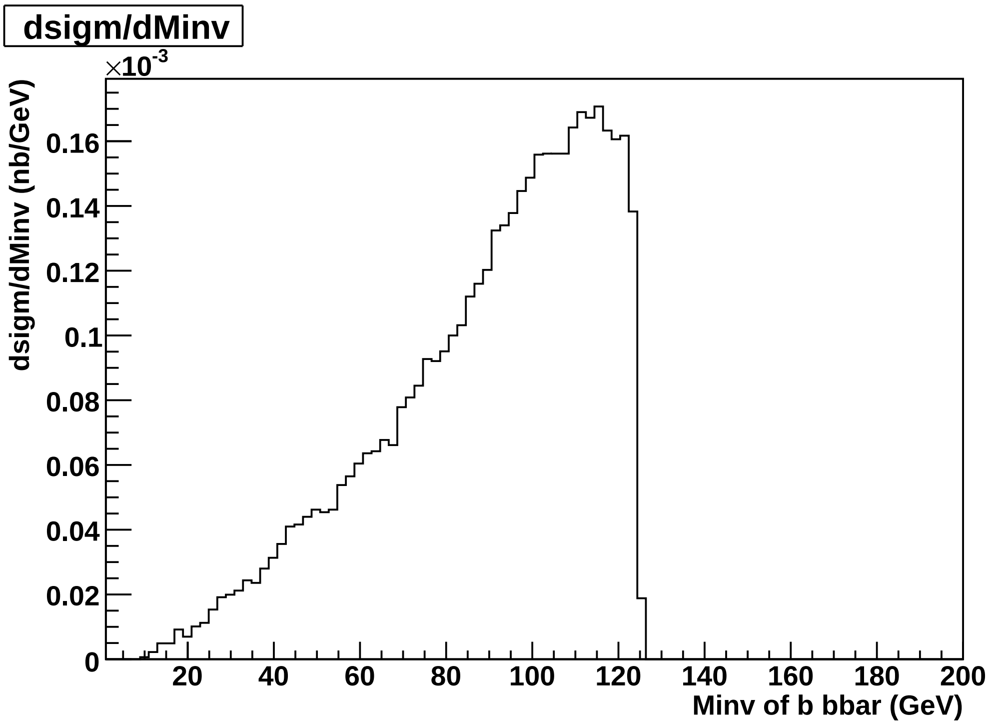

Figure 4: gg $\rightarrow$ H $\rightarrow$ b$\overline{\rm b}$, invariant mass distribution of b$\overline{\rm b}$ pair after radiating gluons, Itune=100, no MPI, $M_{Higgs} = 125\,\mathrm{GeV}$

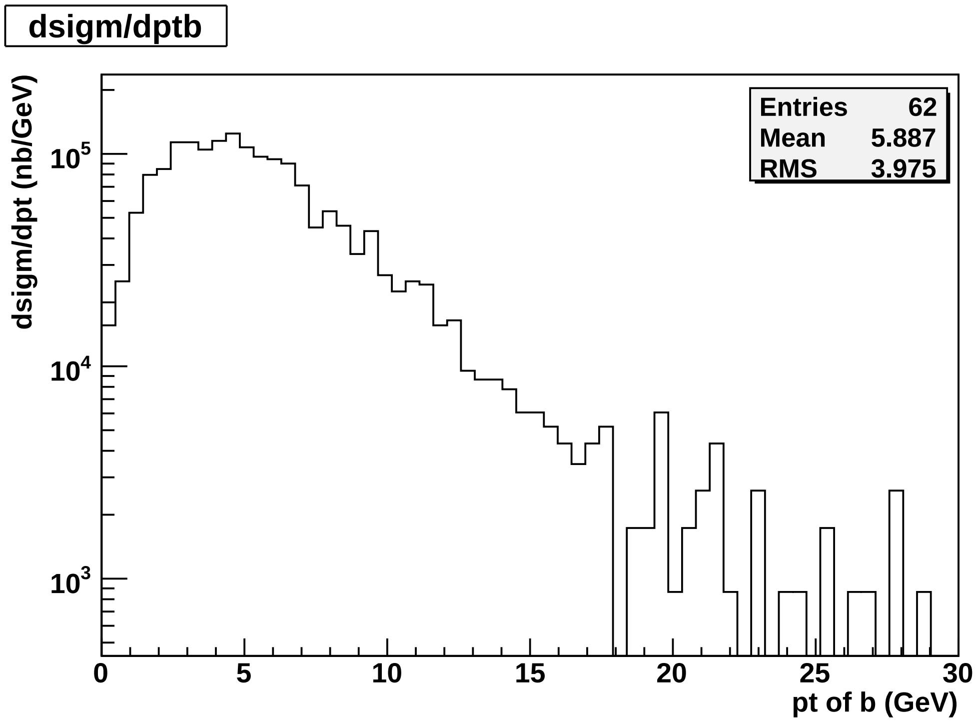

Figure 5: pp $\to$ b$\overline{\rm b}$, reproduction of results from [4] , CKIN(3)= 2.75, CTEQ 4L, MSTP(81) =0, MSTP(61)=1, MSTP(71)=1, MSTP(2)=2, MSTP(32)=2, PARP(34)=1, PARP(67)=1, PARP(71)=1, MSTP(91)=1, PARP(91)=1, PARP(93)=5, $M_{Higgs} = 125\,\mathrm{GeV}$, $M_b = 4.75\,\mathrm{GeV}$, $M_c = 1.2\,\mathrm{GeV}$

The signal process

Being confident of the performance of PYTHIA and my ability to handle it, I started analysing the signal process pp $\to$ WH $\to$ l ν b$\overline{\rm b}$ + X with the parton distribution function MRST98 used by A. Del Fabbro *et al* in order to reproduce their results. The outcome is summarised in table (1). I have also added the values for the CTEQ 5L PDF, since this is the one used for multiple-parton interactions later. The given uncertainties are only the errors implied by statistics. From that we can already conclude that within a tolerance of 20% the events generated by PYTHIA result in the same values for the cross sections of the signal process as those calculated by completely different methods.

The cuts studied here are, of course, those employed by A. Del Fabbro *et al.* In table (2) I present them together with the Atlas cuts from [12] applied later.

Table 1: comparison of obtained results with those from [2]

conditions	σ_{tot} (fb)	Del Fabbro and Treleani
$m_H = 120\,\mathrm{GeV}$, with PS, without cuts, MRST98	199.2 ± 0.5	228 fb
$m_H = 120\,\mathrm{GeV}$, without PS, without cuts, MRST98	200.4 ± 0.5	
$m_H = 120\,\mathrm{GeV}$, with PS, without cuts, CTEQ 5L	181.2 ± 0.2	
$m_H = 120\,\mathrm{GeV}$, with PS, with cuts, MRST98	102.2 ± 0.4	82.4 fb
$m_H = 120\,\mathrm{GeV}$, without PS, with cuts, MRST98	100.7 ± 0.4	
$m_H = 120\,\mathrm{GeV}$, with PS, with cuts, CTEQ 5L	88.8 ± 0.2	
$m_H = 100\,\mathrm{GeV}$, with PS, without cuts, MRST98	417 ± 1	510 fb
$m_H = 100\,\mathrm{GeV}$, with PS, with cuts, MRST98	200.0 ± 0.7	167 fb

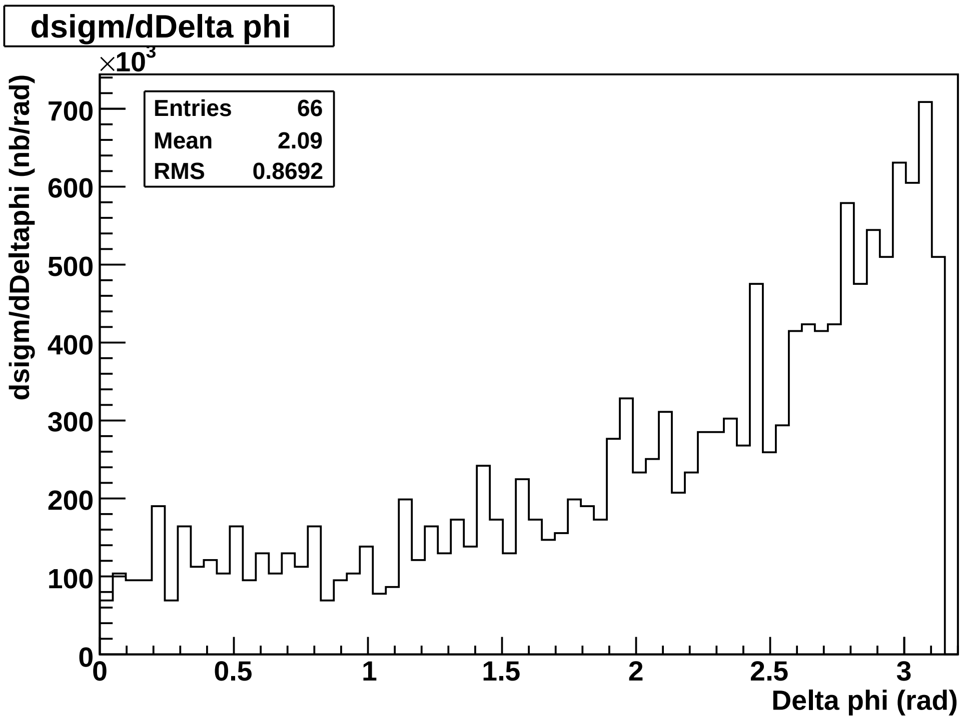

Figure 6: pp $\to$ b$\overline{\text{b}}$, reproduction of results from [4], CKIN(3)= 2.75, CTEQ 4L, MSTP(81) =0, MSTP(61)=1, MSTP(71)=1, MSTP(2)=2, MSTP(32)=2, PARP(34)=1, PARP(67)=1, PARP(71)=1, MSTP(91)=1, PARP(91)=1, PARP(93)=5, $M_{Higgs} = 125\,\text{GeV}$, $M_b = 4.75\,\text{GeV}$, $M_c = 1.2\,\text{GeV}$

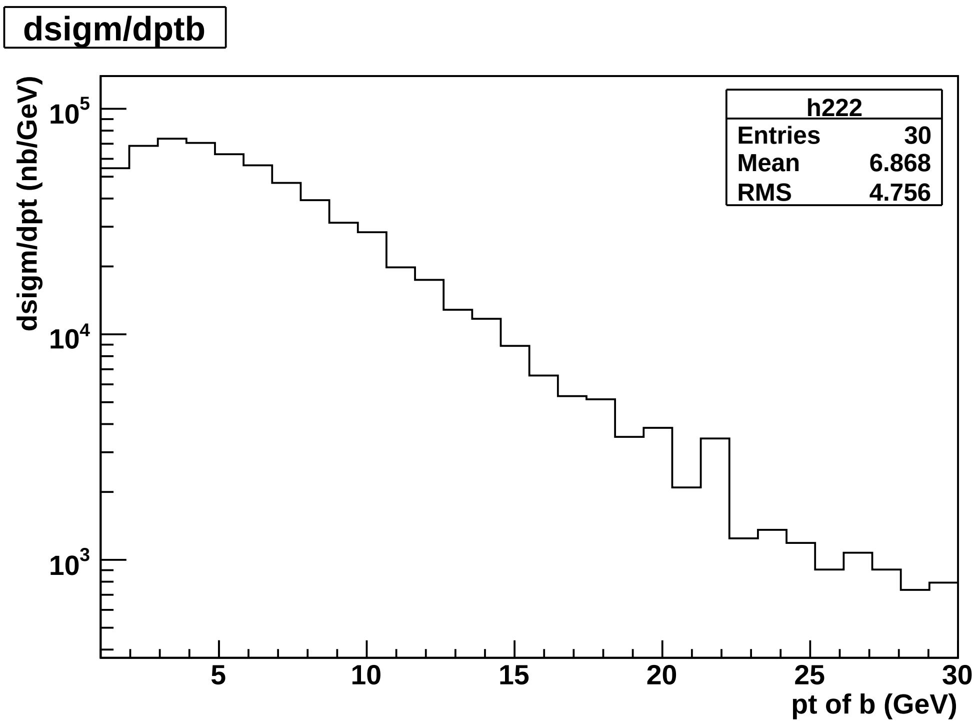

Figure 7: pp $\to$ b$\overline{\text{b}}$, transverse momentum distribution of b with CTEQ 5L and 1,000,000 events, $|y| \leq 2.5$ (cut on hard process matrix element), Itune=0, MSTP(81) =0, $M_{Higgs} = 125\,\text{GeV}$

Table 2: comparison of suggested cuts from [2] and [12]

variable	Atlas	Del Fabbro and Treleani
p_t of detected lepton	$\geq 20\,\mathrm{GeV}$	$\geq 20\,\mathrm{GeV}$
η of detected lepton	≤ 2.5	≤ 2.5
p_t of b	$\geq 25\,\mathrm{GeV}$	$\geq 15\,\mathrm{GeV}$
η of b	≤ 2.5	≤ 2
p_t of $\overline{\mathrm{b}}$	$\geq 25\,\mathrm{GeV}$	/
η of $\overline{\mathrm{b}}$	≤ 2.5	/
$\Delta R_{b,\bar{b}}$	/	≥ 0.7
$\Delta R_{l,b}$	/	≥ 0.7

Background processes

The first background process I studied was pp $\rightarrow$ ZW $\rightarrow$ l ν b$\overline{\mathrm{b}}$ resulting in the well-known Z-resonance peak shown in fig. (8).

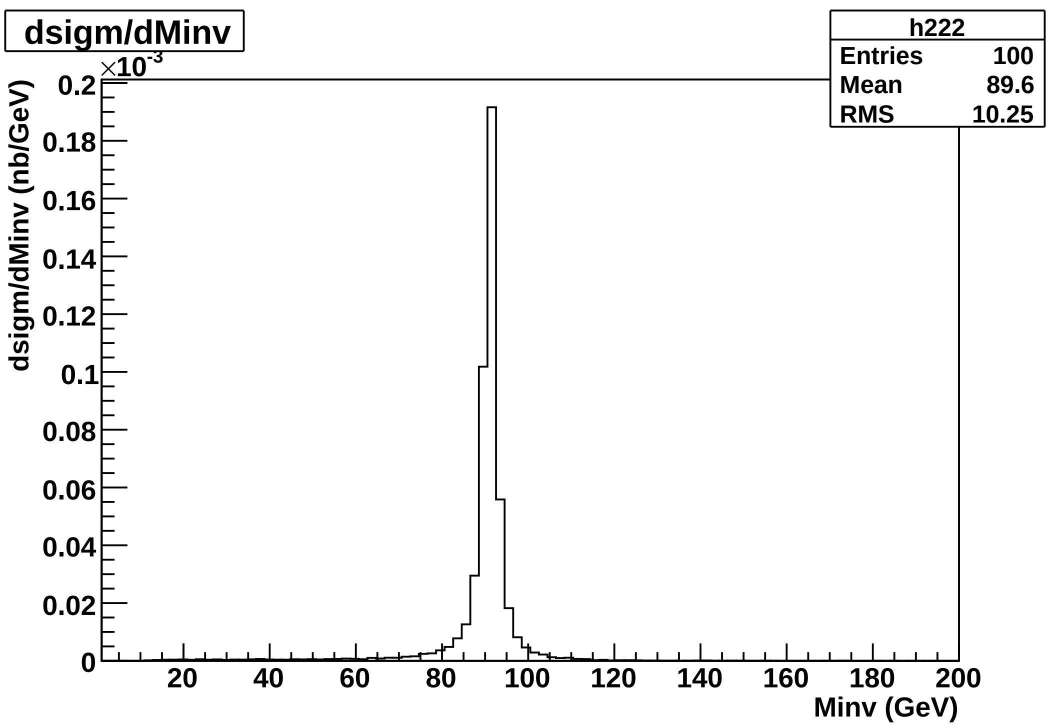

Figure 8: pp $\rightarrow$ b$\overline{\mathrm{b}}$ + l ν from q$\overline{\mathrm{q}'}$ $\rightarrow$ ZW, invariant mass distribution of b$\overline{\mathrm{b}}$ pair before radiating gluons, Itune=0, MRST98 (central gluon/alphas), MSTP(81) =0, M_{Higgs} = 120GeV, 1,000,000 events, no cuts

Since it is difficult to read off the values of the cross section at the invariant masses of interest, I included the otherwise similar plot of the Z peak with applied Treleani cuts with a logarithmic scale for the differential cross section. From that we see that at $M_{inv} = 120\,\mathrm{GeV}$ the differential cross section is of the order of $0.1\frac{\mathrm{fb}}{\mathrm{GeV}}$ (fig.(9)).

Afterwards I considered the single top background pp $\rightarrow$ W $\rightarrow$ t $\overline{\mathrm{b}}$ where the top quark decays into b and a W which in turn decays leptonically. To do so I increased the invariant mass of the PYTHIA single W production process to 173.8 GeV, the old value for the top mass used by A. Del Fabbro *et al.* The outcome without cuts is shown in figure (10). From that one can estimate the total cross section in a mass range for the Higgs boson of 30 GeV which is in

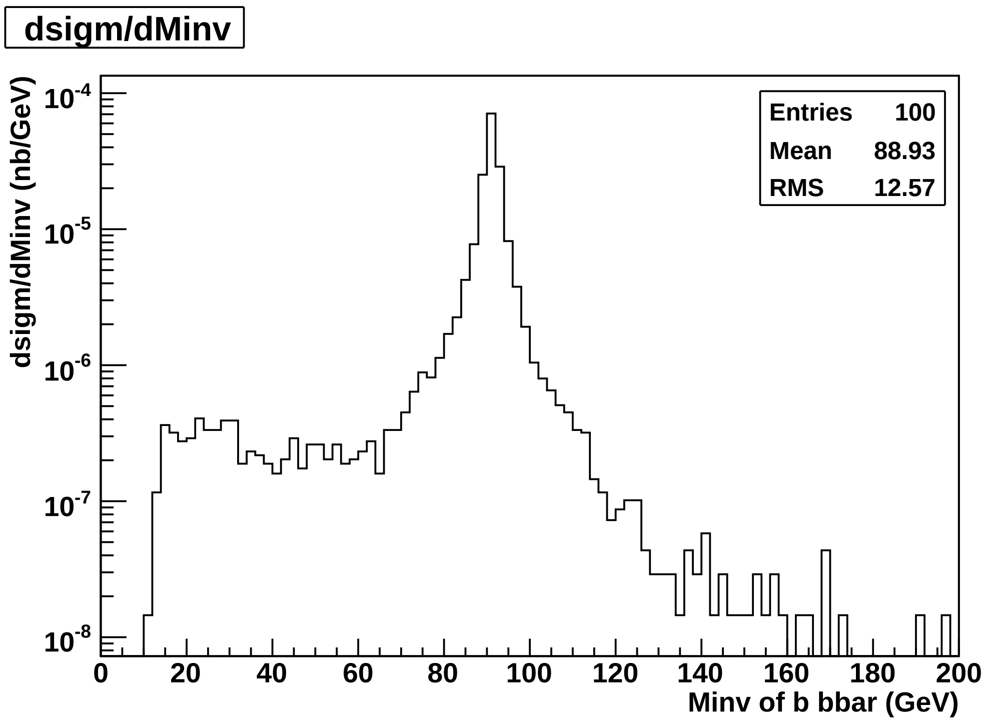

Figure 9: pp $\rightarrow$ b$\overline{\text{b}}$ + l ν from q$\overline{\text{q}'}$ $\rightarrow$ ZW, invariant mass distribution of b$\overline{\text{b}}$ pair before radiating gluons, Itune=0, MRST98 (central gluon/alphas), MSTP(81) =0, M_{Higgs} = 120GeV, 1,000,000 events, with cuts

accordance with that obtained in [12].

Since all background processes where a W boson is involved can be generated by the single W production process in PYTHIA and this provides the largest contribution to the background by one order of magnitude, I subsequently only consider this process without any limits on the invariant mass of the hard process. The next figure shows the still over-estimated background to the Higgs production with cuts. We discovered a bug in the program yesterday and fixed it but the corrected program did not run fast enough to make it into this report. Fortunately, to get the background purely coming from multiple scattering, one only has to substract the values for the cross sections with multiple-parton interactions switched on from those without multiple scattering because there is no way to distinguish the two in the output of a PYTHIA run generating multiple interactions.

As you will see in figure (11), even with several days of computing time and the usage of the old multiple-interaction model in contrast to the more elaborate new one the statistics for the background caused by multiple-parton interactions were not good enough to arrive at any firm conclusions.

Despite the bad statistics the results indicate to be within the same 20% range of the Treleani results as the signal process. One reason for the bad statistics of the multiple-parton events is that they become more and more unlikely the heavier the Higgs boson as is already shown in the plots in [2]. Thus they do not seem to be very important any more in the mass range above that already excluded for the Higgs boson. The physical reason for that is obviously the larger required energy to produce a b$\overline{\text{b}}$ pair in the Higgs mass range studied additional to a W boson in those cases.

As stated earlier, I also studied the influence of the more modern Atlas cuts [12]. The resulting signal and the single-scattering background are shown in figure (12). The mulitple-

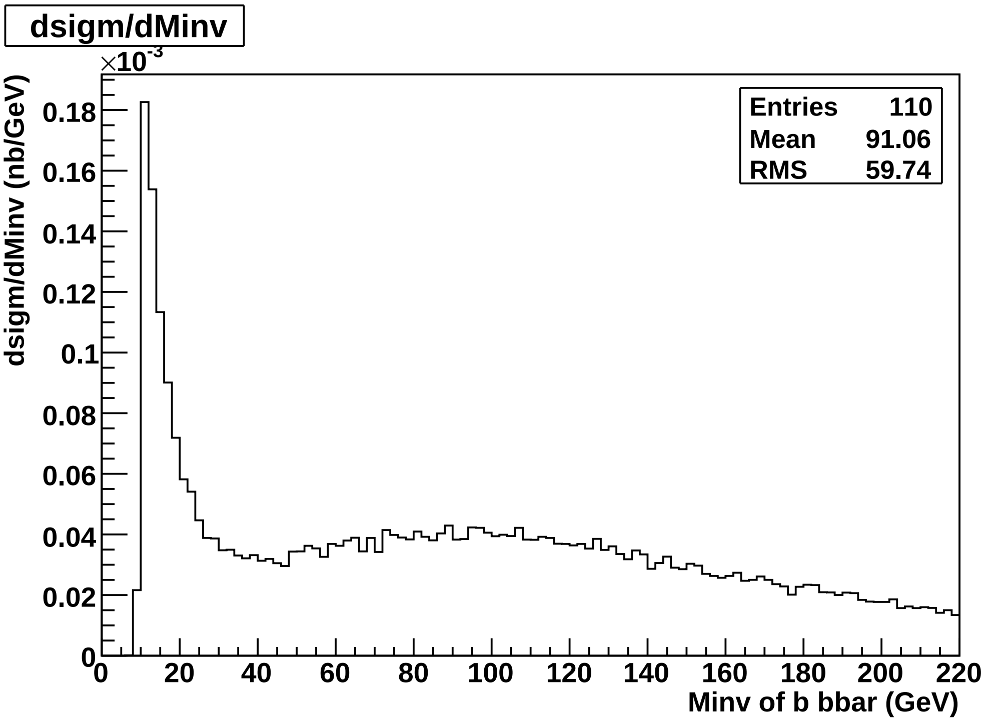

Figure 10: pp $\rightarrow$ b$\overline{\text{b}}$ + l ν from q$\overline{\text{q}'}$ $\rightarrow$ W (CKIN(1) =173.8), invariant mass distribution of b$\overline{\text{b}}$ pair before radiating gluons, Itune=0, MRST98 (central gluon/alphas), MSTP(81) =0, M_{Higgs} = 120GeV, 1,000,000 events, without cuts

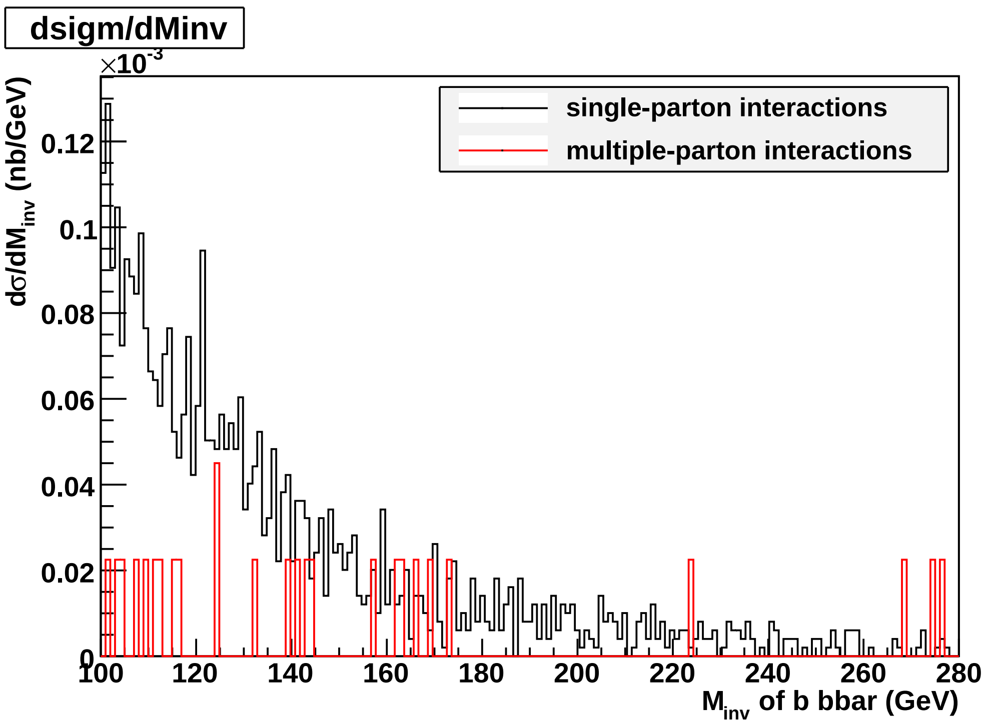

Figure 11: pp $\rightarrow$ b$\overline{\text{b}}$ + l ν from pp$\rightarrow$WH and from pp $\rightarrow$ W, invariant mass distribution of b$\overline{\text{b}}$ pair before radiating gluons, MRST98 (central gluon/alphas) for single-scattering, Itune=100 for MPI, M_{Higgs} = 120GeV, 5,000,000 events for the signal, 30,000,000 events for single-scattering background, 15,000,000 events with multiple-parton interactions switched on, with Treleani cuts

scattering distribution looks similar to that shown before with the same statistics problem.

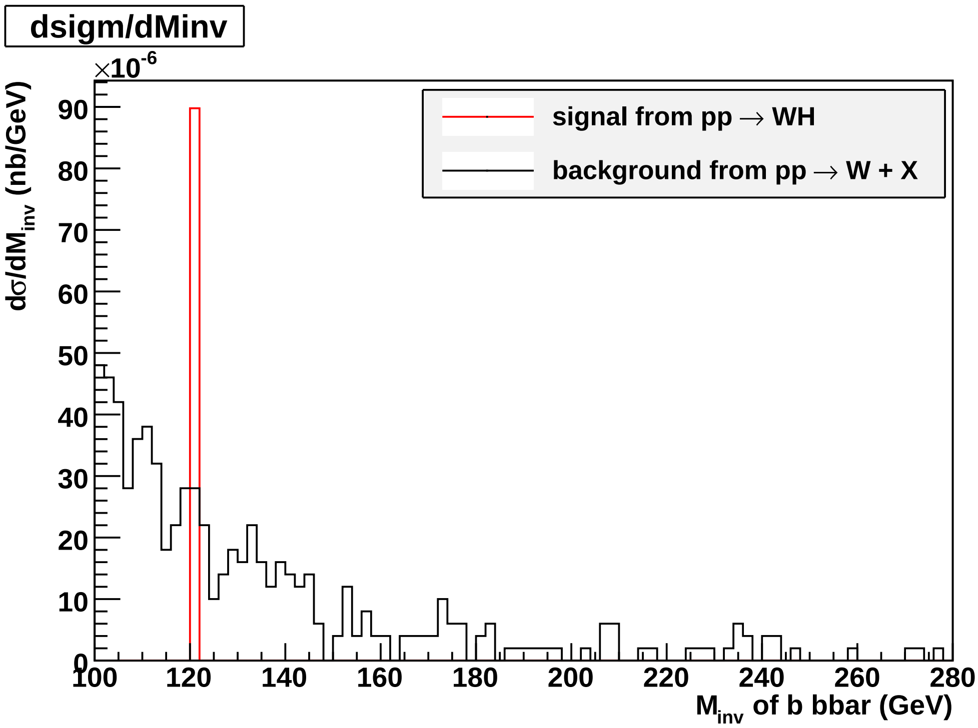

Figure 12: pp $\to$ b$\bar{\text{b}}$ + l ν from pp$\to$WH and from pp $\to$ W, invariant mass distribution of b$\bar{\text{b}}$ pair before radiating gluons, CTEQ 5L, Itune=100 for MPI, M_{Higgs} = 120GeV, 5,000,000 events for the signal, 30,000,000 events for single-scattering background, 15,000,000 events with multiple-parton interactions switched on, with Atlas cuts

As I would have liked to show you, the cuts applied by A. Del Fabbro and D. Treleani affect the background a little more than the Atlas cuts but do not seem to be as feasible as the latter. In both cases we have a signal to background ratio of about 3 in the rather simplified setting employed. While waiting for the results from the high statistics multiple-interaction runs which still have not been completed, I considered the combined transverse momentum distribution of the b quarks and the W

$$p_t = \sqrt{(p_x^b + p_x^{\bar{b}} + p_x^W)^2 + (p_y^b + p_y^{\bar{b}} + p_y^W)^2}$$

and the angle between the added transverse momenta of the b quarks $\mathbf{p}^{b\bar{b}} = (p_x^b + p_x^{\bar{b}}, p_y^b + p_y^{\bar{b}})$ and that of the W boson in a range between 0 and π

$$\gamma = |\,\arctan(\frac{\mathbf{p}_x^{b\bar{b}}}{\mathbf{p}_x^{b\bar{b}}}) - \arctan(\frac{\mathbf{p}_x^W}{\mathbf{p}_x^W})|$$

In figures (13) to (16) I present the different distributions for the signal and the single-scattering background.

Looking at those graphs, I wondered what impact additional cuts on the p_t defined above and γ might have. So I tried $p_t \leq 40\,\text{GeV}$ and $\gamma \geq 2.5$ and got a signal to background ratio which is enhanced by a factor slightly greater than 2 with respect to applying the suggested Atlas cuts alone. According to what I have learned about detectors during that program it should be possible to apply these cuts in practise. My results are depicted in figure (17).

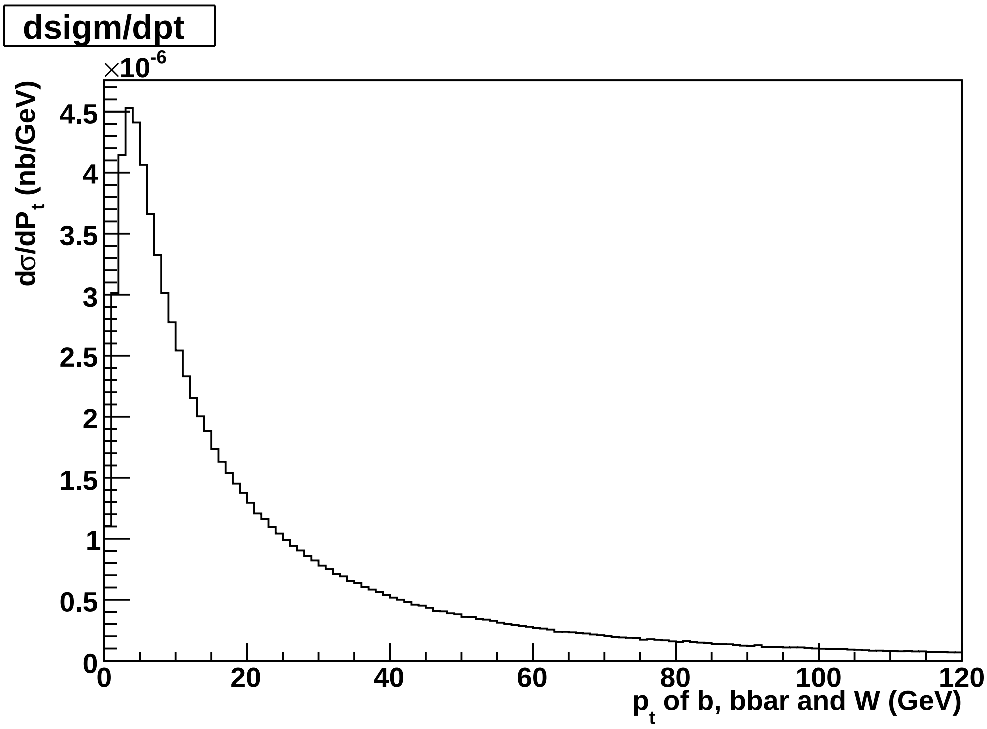

Figure 13: pp $\rightarrow$ b$\overline{\rm b}$ + l ν from pp$\rightarrow$WH, combined transverse momentum distribution of b$\overline{\rm b}$ and W, CTEQ5L, Itune=100 for MPI, M_{Higgs} = 120GeV, 5,000,000 events, with Atlas cuts

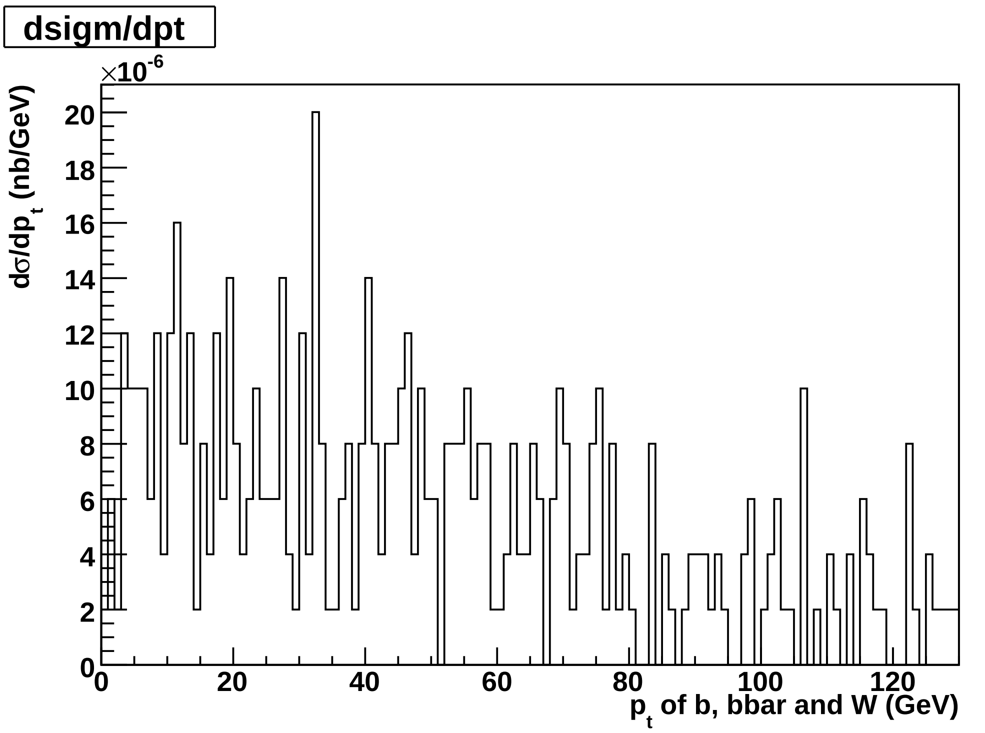

Figure 14: pp $\rightarrow$ b$\overline{\rm b}$ + l ν from pp$\rightarrow$W + X, combined transverse momentum distribution of b$\overline{\rm b}$ and W, CTEQ5L, Itune=0, M_{Higgs} = 120GeV, 30,000,000 events, with Atlas cuts

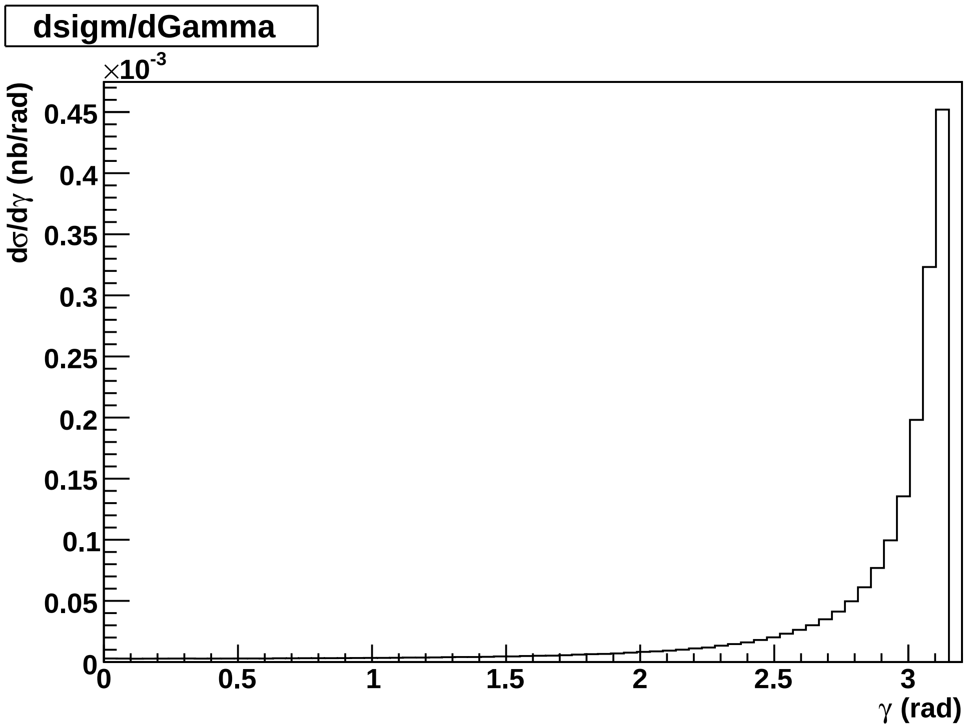

Figure 15: pp $\rightarrow$ b$\overline{\rm b}$ + l ν from pp$\rightarrow$WH, distribution of the angle between the added transverse momenta of b and $\overline{\rm b}$ and that of W, CTEQ5L, Itune=100 for MPI, M_{Higgs} = 120GeV, 5,000,000 events, with Atlas cuts

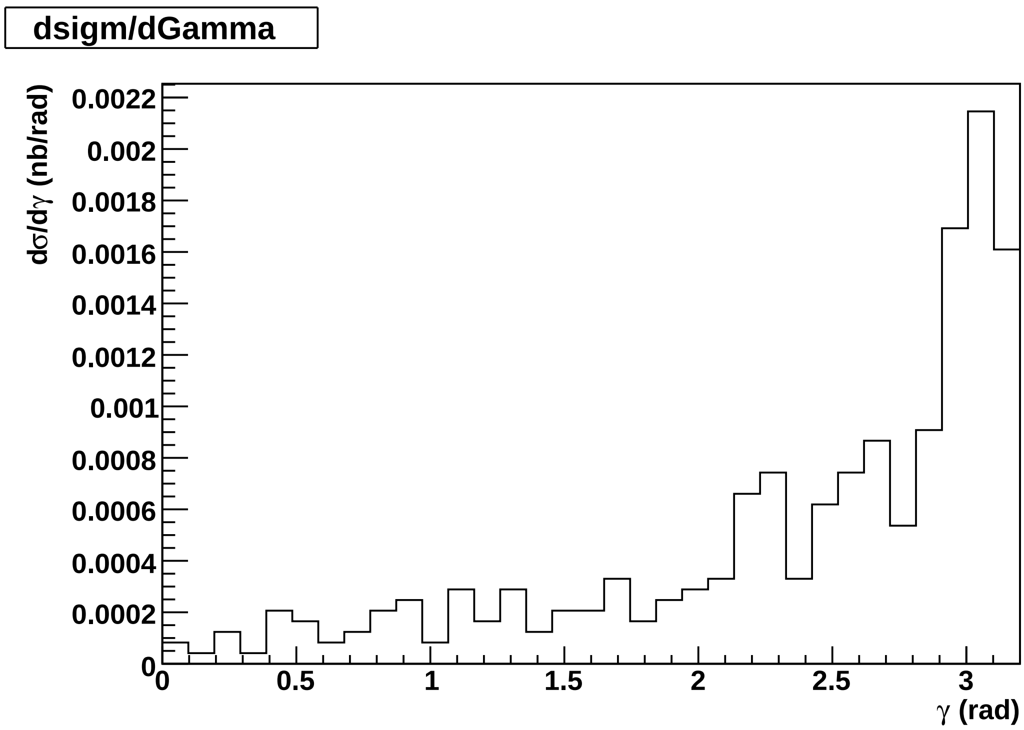

Figure 16: pp $\rightarrow$ b$\overline{\rm b}$ + l ν from pp$\rightarrow$W + X, distribution of the angle between the added transverse momenta of b and $\overline{\rm b}$ and that of W, CTEQ5L, Itune=0, M_{Higgs} = 120GeV, 30,000,000 events, with Atlas cuts

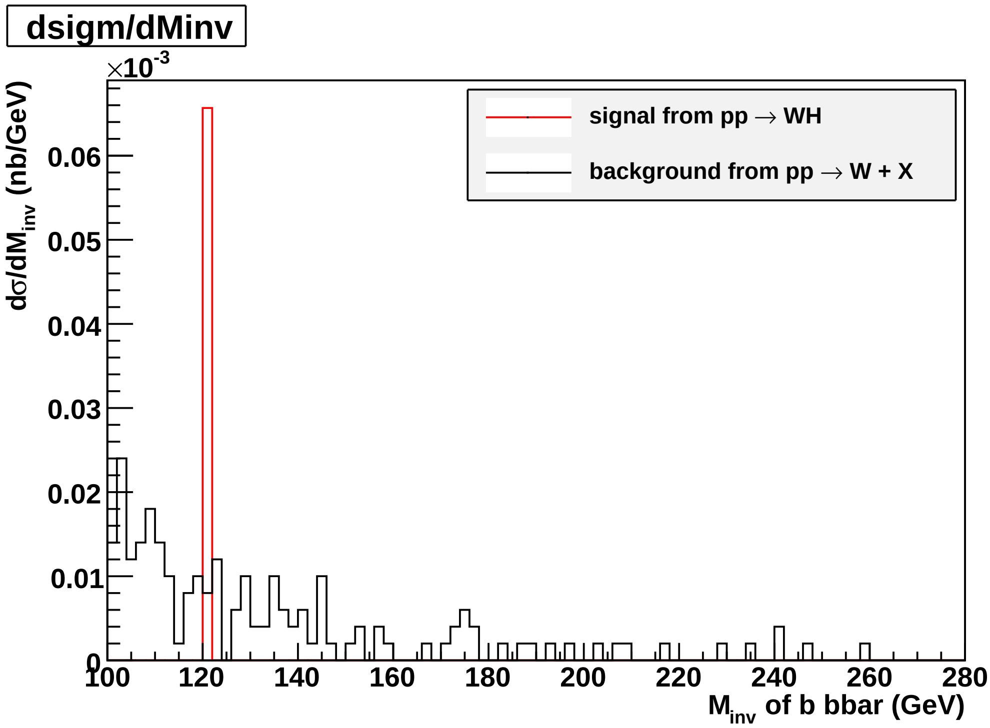

Figure 17: pp $\rightarrow$ $b\overline{b}$ + l ν from pp$\rightarrow$WH and from pp $\rightarrow$ W, invariant mass distribution of $b\overline{b}$ pair before radiating gluons, CTEQ 5L, Itune=100 for MPI, M_{Higgs} = 120GeV, 5,000,000 events for the signal, 30,000,000 events for single-scattering background, 15,000,000 events with multiple-parton interactions switched on, with Atlas and my cuts

Conclusion and Outlook

We have seen that A. Del Fabbro and D. Treleani were probably right that multiple-parton interactions constitute a sizeable background to the Higgs discovery channel in which an associated W boson is produced but only at smaller Higgs masses than currently discussed. Concentrating mainly on a Higgs mass of 120 GeV and ignoring the fragmentation process, within a range of approximately 20% the PYTHIA runs resulted in the same cross sections for the studied processes as did their numerical calculations.

To extend the investigation undertaken so far one should first of all study a greater range of possible masses for the Higgs boson. Then the next step would be to include fragmentation and jet algorithms. Furthermore, the multiple-parton interactions should be studied with more statistics and preferably the new model implemented for them in PYTHIA.

Apart from comparing PYTHIA results with already existing ones obtained in different ways, I tried additional cuts on the examined processes that strongly affected the background while leaving enough signal to enhance signal to background ratio by a factor of 2. Maybe the proposed kinematical variables are useful additions to the standard ones. At least, it seems like performing cuts on them results in a better chance to actually find the Higgs. Here it is, of course, necessary to try different values for the cuts than my spontaneous guess.

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