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**USING RAPIDITY GAPS TO DISTINGUISH BETWEEN
HIGGS PRODUCTION BY W AND GLUON FUSION**

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Using Rapidity Gaps to Distinguish Between Higgs Production by W and Gluon Fusion

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Abstract

The possibility of distinguishing between two higgs production mechanisms, W fusion and gluon fusion, due to rapidity gap existence is investigated using the Monte Carlo event generator PYTHIA. It is shown that, considering the designed CM energy and luminosity for the LHC, it is not possible to distinguish between the two higgs production processes as, for a given integrated luminosity, they lead to the same number of events containing a rapidity gap.
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1 Introduction

A rapidity gap is a region in rapidity space with no hadrons. It has been studied for a long time in diffractive scattering physics.

In 1986 Dokshitzer, Khoze and Troyan [1] suggested that due to its peculiar color flux, a W fusion process producing a Higgs boson could also lead to a rapidity gap. As each hadron is a color singlet, when they emit a W boson, which is a color singlet too, they remain in singlet states, although separated in systems of quark and diquark. Therefore, the initial hadrons do not need to exchange color. The quark which emitted the W may exchange color with the diquark belonging to the same hadron, in order to fragment. According to the LUND string model [2], a string will be stretched between the quark and the diquark of each hadron (see fig.1). When both strings fragment, almost all the hadrons formed are expected to be comprised, roughly speaking, between the incident beam direction and that given by the jet containing the quark that emitted the massive vector boson. Fig. 2 shows a typical plot in $\eta \times \Phi$ (rapidity \times azimuthal angle) space, for an event of this kind [3]. The jets shown in the figure come from the hadronization of the quark which emitted the vector boson (it is possible to use them as tagging jets). Each jet is supposed to occupy about a 0.7 radius circle [3] (in $\eta \times \Phi$ space). The idea is to look for a gap in the region between the tangents to those jets. Imposing the higgs to decay into a Z pair, which in turn is forced to decay into muon pairs, no hadron production occurs besides that from the hadronization of the beam remnants. On the other hand, in gluon fusion each hadron emits a color octet (the gluon), and therefore turns into a colored object. Hence the initial hadrons remnants must exchange color with each other in order to become color neutral again (see fig. 1). Moreover, unlikely vector bosons, gluons themselves emit quarks and other gluons, which will hadronize later, thus filling the central rapidity region.

The purpose of this work is to discuss the possibility of using the existence of the rapidity gap for distinguishing Higgs boson production by W fusion from that by gluon fusion. It is organized in the following way: in section 2, some problems which appear in a gap analysis are discussed, and the approaches already existing on this subject are presented; in section 3 the event generation for this work is described; in section 4, the generated events are analyzed, the gap survival probability and the number of events having gaps occurring for a fixed integrated luminosity are obtained for various higgs mass, and many situations, where different cuts had been imposed;

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it is shown that although for some cases there is a big gap survival probability, for higgs produced by W fusion the number of events having a gap which occur in an accelerator like the LHC is very small for low higgs masses and null for the bigger ones; when the number of events having gaps is bigger for W fusion, it is of the same order for gluon fusion, thus being impossible to distinguish the two higgs production processes, independently of some earlier conjectured problems, like pile up events. Finally, in section 5, some ideas and conclusions are presented.

2 Gap Survival Probability

In order to use a rapidity gap for identifying the higgs production mechanism, some problems have to be overcome. For example, although in a W fusion the hadrons are expected to be close to the initial beams directions, it might occur that some of them appear in the central region (in fact, it will be shown that this is the case in many events). Furthermore, each incident proton is composed of several partons, and it is possible that more than one scattering occurs, therefore filling up the region between the tagging jets (these are called *multiple interactions* in this paper). Moreover, problems arise from the high luminosity designed for the accelerator (as is the case for the LHC). More than one proton-proton scattering may occur in the same bunch crossing, producing the so-called *pile up* events. That will produce even more hadrons, probably filling completely the central region. It will be shown, however, that at least for LHC pile up events are not the worst problem. It is hard to distinguish between the two higgs production mechanisms, even when no pile up events are considered. Besides those problems, there are others that will not be discussed here such as gaps produced by statistical fluctuations in the background events, gaps produced by other color singlet scattering (such as $WW \rightarrow Z \rightarrow ZZ$) and the most common ones, diffractive scatterings. These problems have already been studied by many authors [4, 5, 6, 7] and do not address the problem investigated in this paper, which is the use of rapidity gaps to distinguish between higgs production by gluon and W fusion.

Due to the difficulties mentioned above, added to the smallness of the involved cross sections it is necessary to quantify the probability that a gap be observed, and furthermore, the possibility of using its existence in experimental analysis. Bjorken [3] proposed a variable, the *gap survival probability*, determined in the following way: if $P(s, b)$ is the probability

that two protons pass through each other with impact parameter b with no interaction occurring, except the hard one, the gap survival probability is given by:

$$S = \frac{\int F(b)P(s, b)d^2b}{\int F(b)d^2b} \quad (1)$$

where $F(b)$ is a factor associated with the hard collision, being essentially a measure of the overlap of the parton densities in the colliding hadrons. Eq. 1 is evaluated under some conditions (eikonal approximation, gaussian form for $F(b)$ and for the eikonal itself); $S \sim 5\%$ is obtained.

In Ref. [8] the same calculation is performed, but using several different models for hadron collisions. They obtain, for LHC energies, a gap survival probability lying between 5.3 % and 22.1 % (five models are analyzed, and just for one of them, the Reggeon Model, one gets a probability as high as 22.1 %; for the other four, it is below 8.2 %).

An important observation must be made at this point. The gap survival probability, as proposed by Bjorken, and used in Ref. [8], gives the probability that, in a proton-proton collision, only one parton-parton scattering occurs. It does not imply, necessarily, that a rapidity gap exists, because an eventual gap can be filled by the hadronization of the beam remnants, as already mentioned. This aspect has not been taken into account in the above references.

Previous papers [9, 10] had used Monte Carlo simulation to analyze some aspects of the problem. The main conclusions are: a) for W fusion a rapidity distribution shows two peaks; the dip between these peaks increases for increasing higgs masses and the distance between the peaks increases with CM energy [9]; when multiple interactions are included, a $p_t = 2$ GeV cut on charged particles recovers the dip [9]; b) $S \sim 3\%$ is obtained for W fusion, $S > \sim 0.01\%$ for the background ($q\bar{q} \rightarrow WW$ and $t\bar{t} \rightarrow WW$) and a null gap survival probability for $gg \rightarrow h$. The present work broadens the scope of the former papers, taking into account a larger range of higgs masses, and mainly, using the processes cross-sections and the LHC luminosity in order to obtain the number of events per year presenting a surviving rapidity gap instead of the probability of having such a gap.

3 Event Generation

The events for this work have been generated with PYTHIA [11], using as distribution functions CTEQ set L2 [12]. The top quark is supposed to have mass 174 GeV. A simple calorimeter is simulated with LUCCELL, a jet algorithm included in PYTHIA. That calorimeter covers the rapidity region from $\eta = -5$ to $\eta = 5$, with segmentation: $\eta \times \Phi = \frac{10}{50} \times \frac{2\pi}{30} \simeq 0.2 \times 0.2$. PYTHIA includes some models for simulating multiple interactions, and we had chosen the default, that is the simplest one. This model is described both in the program manual and in Ref. [13].

We have considered higgs produced both by gluon fusion and by W fusion, with mass varying from $m_h = 300 \text{ GeV}$ to $m_h = 700 \text{ GeV}$, supposing a pp collision with 14 TeV of CM energy. In both processes the higgs decay into a Z bosons pair, each of which then decay into a muon pair. That choice helps preventing the production of hadrons that could fill an eventual gap¹. For both processes, three groups of events from now on called Group I, Group II and Group III have been produced. There is a set of common cuts, cuts A, applied to the three groups, described below. The three groups have been submitted to different cuts (besides cuts A) in order to determine the fraction of events containing gaps using different selection criteria for events and gap definitions. All these cuts have been largely discussed in literature, and therefore they will be presented here without further justification. For each group the number of generated events is such that, after imposing the respective group cuts (without including cuts A), 10,000 events remain. The groups are defined in the following way: a) **Group I** A tag is applied to two jets, and the gap is looked for between these jets. It is known that although this double tagging eliminates considerably the background, it reduces the signal too. Nevertheless we adopted such a cut because it could enhance the rapidity gap signature. Here we demand that the event has at least two jets with $E_{\perp} > 40 \text{ GeV}$ and $|\eta| > 2$. These choices are imposed because the quarks that emit the W boson acquires transversal momentum of order $m_W/2$ and follows approximately the initial beam direction. If more than two jets satisfy the above conditions, the two with the largest transversal moments are picked up. The rapidity gap width is looked for in a region defined as being the distance in rapidity space between the tagging jets, $\Delta\eta = \eta_1 - \eta_2 - 1.4$, as seen in Fig. 2, where η_1 and η_2 are the jets rapidities.

¹Gluon fusion, $gg \rightarrow h \rightarrow ZZ \rightarrow \mu\mu\mu\mu$, has been produced with Pythia's process number 102, while W fusion, $gg \rightarrow h \rightarrow ZZ \rightarrow \mu\mu\mu\mu$, has been generated with Pythia's process number 124. [13]

The value 1.4 is subtracted due to jet width in rapidity space. Cuts A are applied too. b) **Group II** Here only one jet is tagged and the applied cuts are similar to those used in Ref. [15]. The event is accepted if there is at least a jet with energy $E > 1 \text{ TeV}$ and $2.0 < |\eta| < 5.0$. In this case a gap is looked for inside a fixed interval, symmetric around $\eta = 0$, and with width $\Delta\eta = 4$ ($-2.0 < \eta < 2.0$). Cuts A are applied too. c) **Group III** No cut beyond that from cuts A have been applied to this Group. GEM [14] adopted this kind of analysis. The gap widths here is defined in the same way as for Group II.

Cuts A are applied to all events. They consist of [14, 15]: a) $|\eta^i| < 2.5$ and $p_{\perp}^i > 10 \text{ GeV}$. Most of the papers on this matter demand four leptons obeying these conditions. But, as this is very restrictive, we have relaxed it, demanding four leptons with $p_{\perp}^i > 10 \text{ GeV}$ but just three of them had to have $|\eta^i| < 2.5$; b) For the signal, leptons are produced isolated. They were accepted if inside a region of radius $R = \sqrt{\Phi^2 + \eta^2} = 0.3$ around each of them no more than 5 GeV of transversal energy had been deposited; c) It must be possible to produce, using all four accepted leptons, two pairs with invariant mass next to the Z mass: $|M_{ll} - M_Z| < 10 \text{ GeV}$; d) Muon identification and track matching; e) At least one Z for which $p_Z > \sqrt{M_{ZZ}^2 - 4M_Z^2}$, where M_{ZZ} is the Z pair invariant mass.

4 Analysis

4.1 Gap Survival Probability

The figures presented in this sections have been obtained in the following way: a) 10,000 W fusion and 10,000 gluon fusion for each of the five higgs masses considered have been subjected separately to cuts A; the fraction of events surviving the cuts in each case $F_{cc}(m_h, process)$ were then obtained. This procedure does not affect the sample, because the cuts applied concern the part of the event that will not be used in the final analysis, i.e., the leptons and Z's. It is not relevant which of the events are thrown away in this case. F_{cc} is about 60 % for gluon fusion and about 70 % ($m_h = 300 \text{ GeV}$) to 80 % ($m_h = 700 \text{ GeV}$) for W fusion events; b) For each group events, I, II and III, a number of events is generated such that, after being applied the specific cuts, 10,000 events remain. c) N_{gap} is the number of events, for each Group, for each process and for each higgs mass, which survive, that is, which maintain the region where the gap is searched for with no

hadrons. N_{gap} is obtained for three different cases: i) All charged particles are included, except for the muons selected by cuts A; ii) Charged particles with $p_{\perp} > 1$ GeV, except for the muons selected by cuts A; iii) Charged particles with $p_{\perp} > 2$ GeV, except for the muons selected by cuts A. c) N_{gap} is divided by the total number of generated events (before any kind of cut is done), producing S_{bef} for the three situations analyzed above, (i), (ii) and (iii). d) For each case, S_{bef} is multiplied by the corresponding fraction of events surviving to cuts A and by 100, producing S .

Next figures represent S . A) Fig. 3 shows the gap survival probability for events from Group I. In the upper part, multiple interactions have not been added yet. If no p_{\perp} cut is applied (Fig. 3.a), S is very small for any higgs mass, unlike what could be expected from theoretical approaches. It occurs probably because hadrons produced by the fragmentation of the beam remnants reach the detector central region in many events. This fact shows that even if the main interaction could occur separated from the secondary ones, few events would be completely clean. When p_{\perp} cuts are considered, however, the gap survival probability increases, as may be seen in Fig 3 (b) and (c), and if just $p_{\perp} > 2$ GeV particles are accepted, S lies between 5 and 9% for higgs masses between 300 and 700 GeV. S grows with higgs mass as later observed [1]. Things change completely when multiple interactions are included. Good results are obtained just when particles with $p_{\perp} < 2$ GeV are left behind (Fig. 3). If no p_{\perp} cut is imposed, no gap is found for any higgs mass and any process. B) In Fig. 4 the same analysis is performed for Group II events. In such case, even without p_{\perp} cuts, S lies between 4 and 8%. Using p_{\perp} cuts, results are even better for W fusions, but some of the gluon fusions will have rapidity gaps too. It should be noted that unlike for W fusions, for gluon fusion, S decreases with the higgs mass. Taking into account multiple interactions, it is again clear that p_{\perp} cuts have to be imposed; if only particles with $p_{\perp} > 1$ GeV are accepted, S lies between 3 and 5% for W fusion. Nevertheless, some gluon fusion events will produce gaps too, mainly for lower higgs masses. If $p_{\perp} > 2$ GeV is imposed, a more expressive S value is found for W fusion, between 22% and 33%. But once more, the same cut leads gluon fusion to produce events with gaps. C) Fig. 5 shows the same analysis for Group III events. Once more the gap survival probability increases when p_{\perp} cuts are applied, both for W and gluon fusion. The results here are slightly smaller than for Group II. Group III events (Fig. 5) show results quite similar to that from Group II. If no p_{\perp} cuts are applied, $S \sim 0$, and for increasing p_{\perp} cuts, S grows up both for W and gluon fusion. Nevertheless, S behaves oppositely with increasing

higgs mass in W fusion and in gluon fusion.

Based upon what had been seen until now, one could conclude that in some circumstances the gap presence is very clear. For example, for a heavy higgs $m_h \sim 700$ GeV, $S \sim 26$ % for Group III events and $S \sim 32$ % for Group II events, in both cases taking into account final charged hadrons with $p_{\perp} > 2$ GeV, $\Delta\eta = 4$ and with multiple interactions included. In both cases, for gluon fusion $S < 5$ %. For a lighter higgs, the results are not so good. For $m_h = 300$ GeV, $S \sim 15$ % for Group III events and $S \sim 23$ % for Group II events, but the respective S values for gluon fusion are 6% and 8%. As all those events passed by the same cuts, one could have events with a rapidity gap that could had been produced either by gluon or W fusion.

4.2 Number of Events/Year

But there is one very important point that should be included in the analysis. It is the cross section for each of the processes, gluon and W fusion producing higgs. To get the next figures, S has been multiplied by the respective process cross section, and by the luminosity LHC is supposed to have ($\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1} \sim 100$ events/fb-year). When these factors are taken into account, Fig. 6, 7 and 8 show the number of events which will keep a gap in an year for m_h in the range 300-700 GeV. They are obtained, respectively from Group I, Group II with $\Delta\eta = 4$ and Group III with $\Delta\eta = 4$ events. Each figure presents in the upper part, the results obtained without including multiple interactions and in the lower part, results including multiple interactions. As before, for both situations, three cases have been considered: a) all charged hadrons have been taken into account; b) charged hadrons with $p_{\perp} > 1$ GeV taken into account; c) charged hadrons with $p_{\perp} > 2$ GeV taken into account.

It is not difficult to see that the results are not very good, either including or not multiple interactions. For Group I (Fig. 6), less than two events with a higgs produced by W fusion will produce a gap in each year, when final charged hadrons with $p_{\perp} > 2$ GeV are counted. With a softer cut, not even one event will be observed in one year. For Group II, although the number of events with rapidity gap produced by W fusion processes is larger than that for Group I, it is still small and, what is worse, has the same magnitude that gluon fusion process has. For Group III, the only situation in which event with rapidity gap could be expected is that showed in Fig. 8(a), which is not a realistic one, since no multiple interaction has been included.

5 Conclusion

Some conclusions may be drawn from our investigation: a) for W fusion, $S >$ increases with m_h , and for gluon fusion this behavior is opposite; b) on the other hand, $N_{ev/year}$ decreases with m_h , both for gluon and W fusion; c) no gap could be observed without p_t cuts; d) after p_t cuts, both W and gluon fusion have gaps, therefore being impossible to use the gap existence in distinguishing them; e) the above results do not depend on pile up, which have not been included; f) as the integrated luminosity is the same for W and gluon fusion, and for any higgs mass, the cross section is responsible for the $N_{ev/year}$ behavior with higgs mass.

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Figure 1: Color exchange for (a) a W fusion and for (b) a gluon fusion, according to LUND string model

Figure 2: Expected logplot for an event from process $pp \rightarrow WWX \rightarrow hX \rightarrow ZZX \rightarrow \mu^+\mu^-\mu^+\mu^-$. It shows the way $\Delta\eta$ is defined for Group I events

Figure 3: S for GROUP I events.

Figure 4: S for GROUP II events.

Figure 5: S for GROUP III events.

Figure 6: Number of events having a gap for GROUP I events.

Figure 7: Number of events having a gap for GROUP II events.

Figure 8: Number of events having a gap for GROUP III events.

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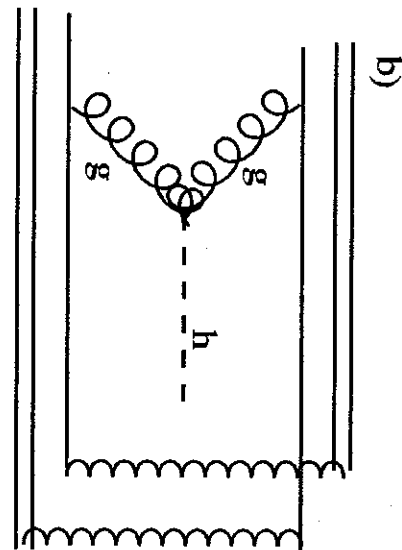
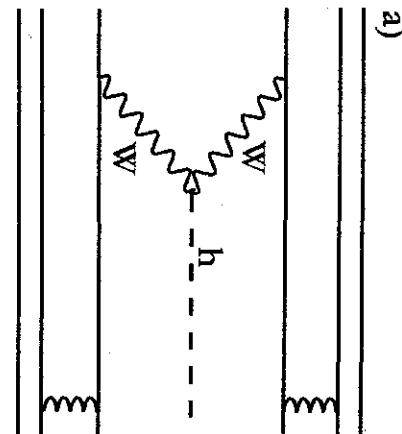
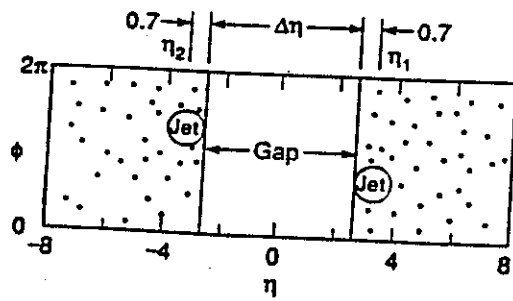


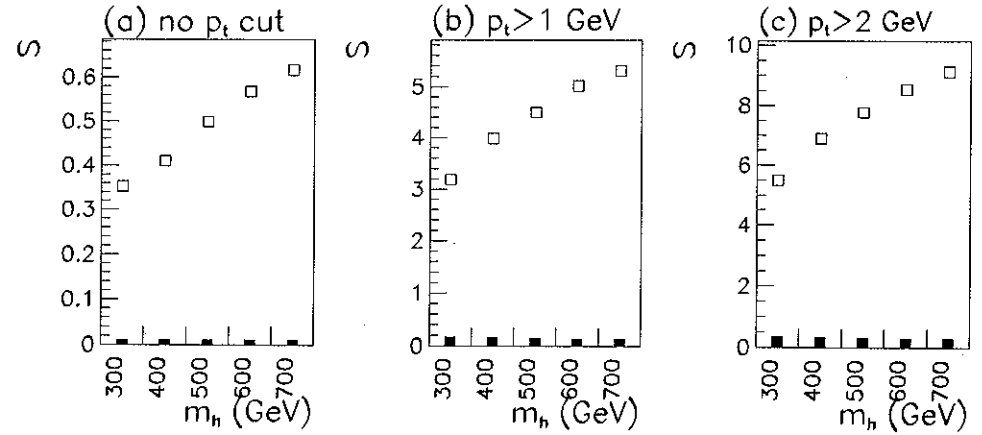
fig 2



GROUP I

multiple interactions not included

■ gg
□ WW



multiple interactions included

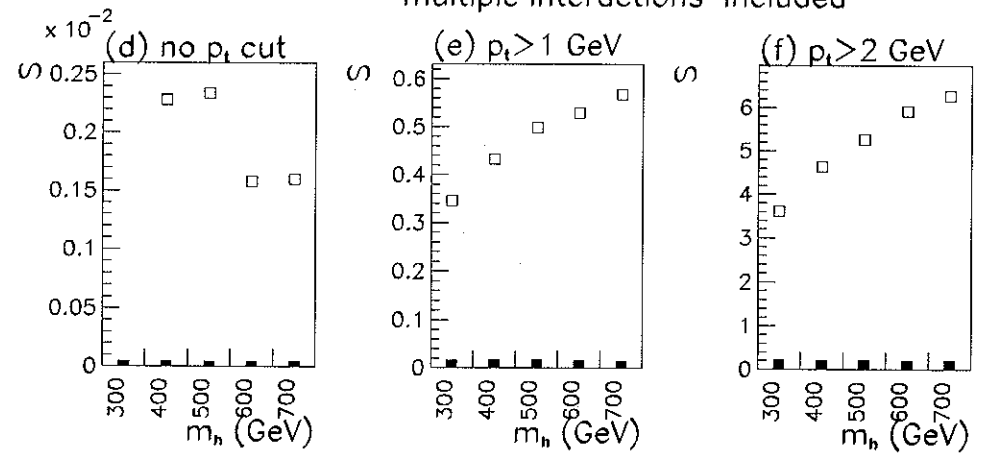
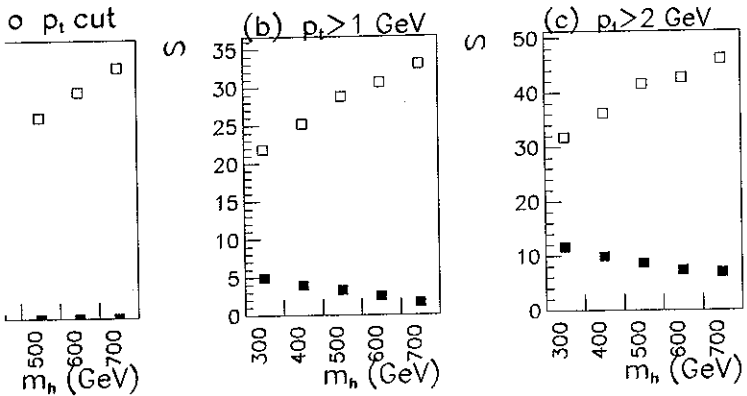


Fig.3

GROUP II

multiple interactions not included

□ WW
■ gg



multiple interactions included

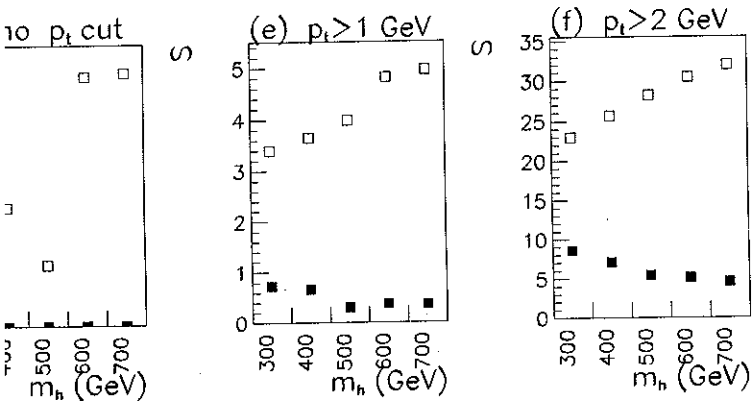
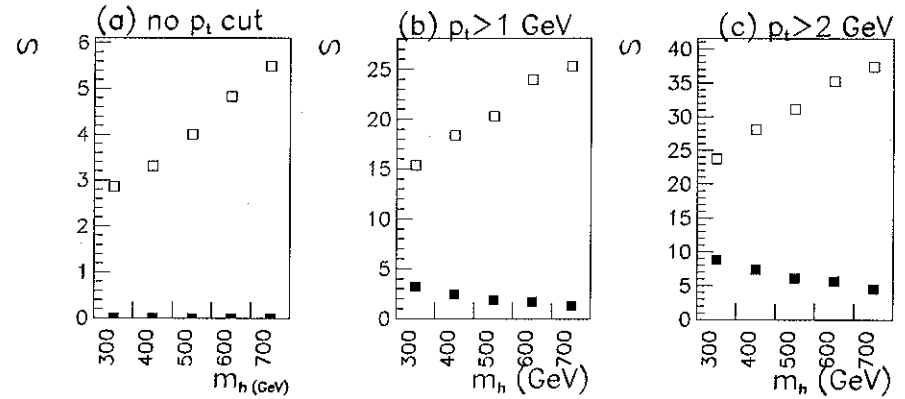


Fig. 4

GROUP III

multiple interactions not included



multiple interactions included

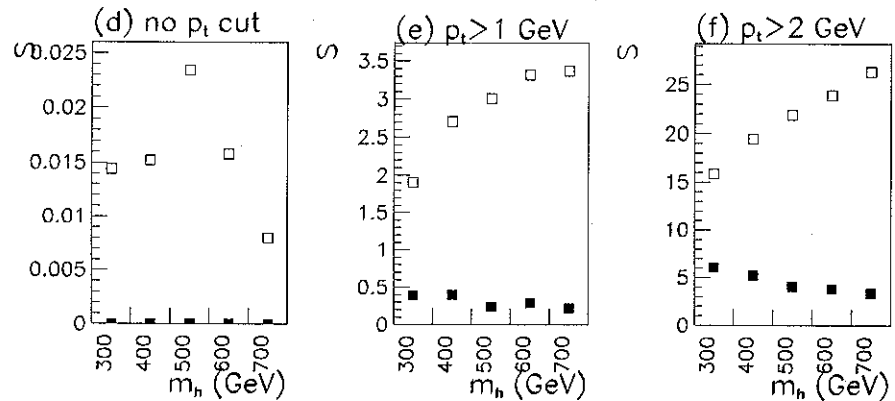
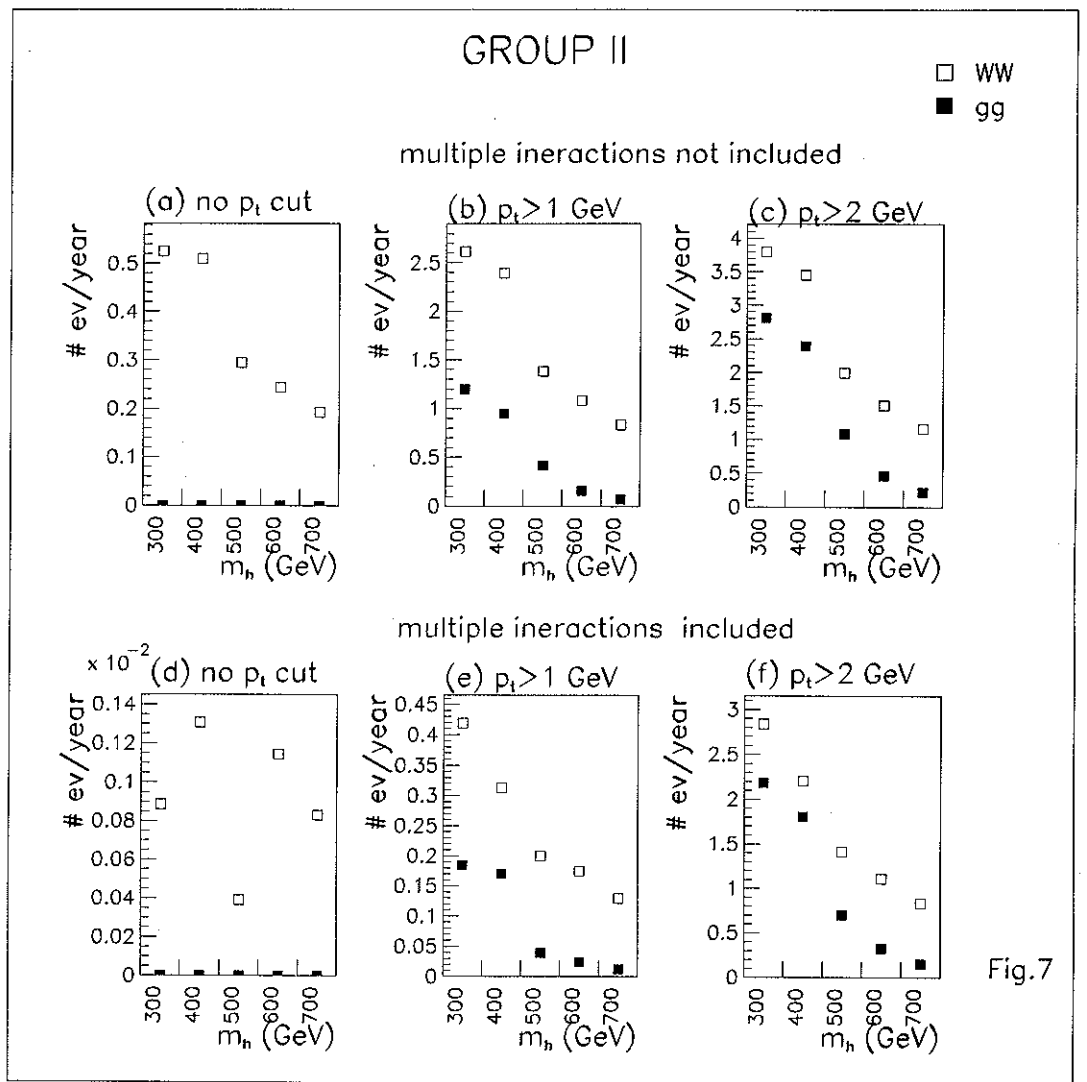
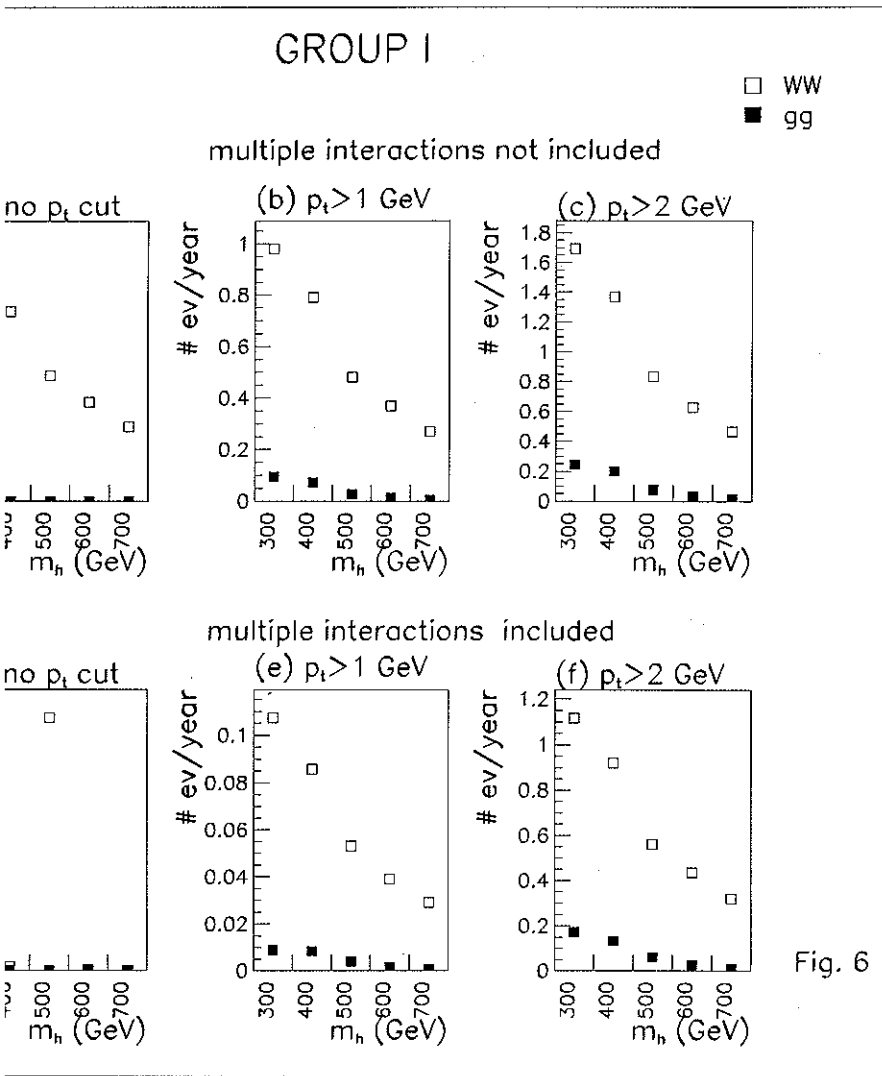


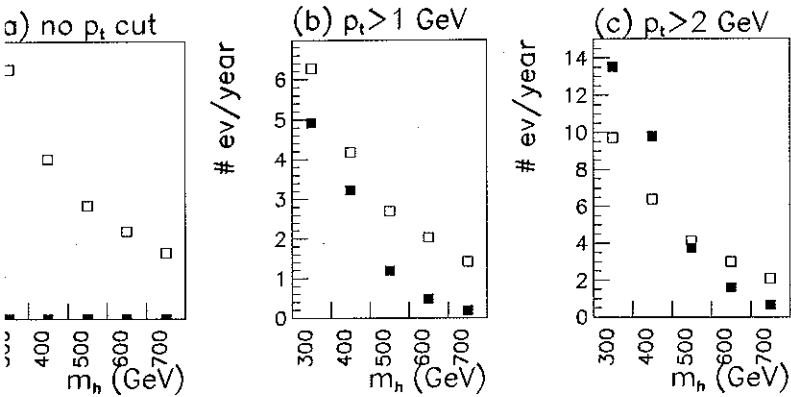
Fig. 5



GROUP III

□ WW
■ gg

multiple interactions not included



multiple interactions included

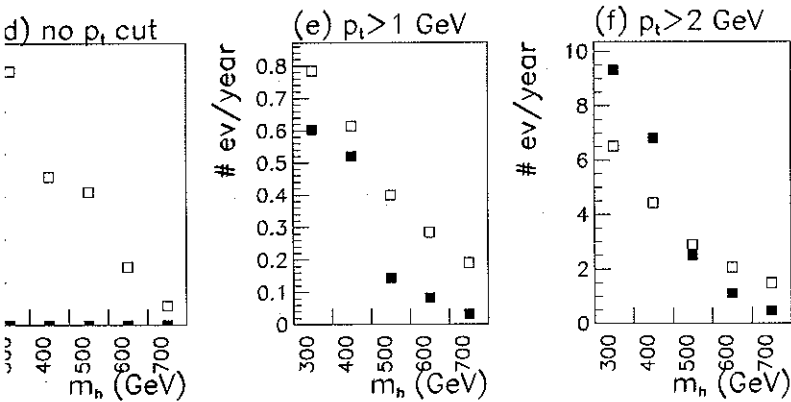


Fig.8