«ETTORE MAJORANA» CENTRE FOR SCIENTIFIC CULTURE

ERICE PREPRINT SERIES

EMCSC/93-05
CERN/LAA/MSL/93-33
29 November 1993

HEAVY HIGGS SEARCH WITH HADRON SUPERCOLLIDERS UP TO $\sqrt{s} = 200$ TeV

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Abstract

In addition to a light Higgs ($M_H \approx 0.1$ TeV) a heavy one is expected ($M_H \approx 1$ TeV). The knowledge of the two Higgs masses allows to predict the masses of as many as thirty sparticles expected in the simplest Supergravity theory. The production of a heavy Higgs ($M_H \gg 2M_Z$) is studied via Monte Carlo at three hadron supercollider energies: $\sqrt{s} = 16$ TeV (LHC), $\sqrt{s} = 40$ TeV (SSC) and $\sqrt{s} = 200$ TeV (ELN/Eloisatron), for three masses: $M_H = 500, 750, 1000$ GeV. The 4-muon decay mode is investigated, in the presence of the "irreducible" background. The collider energy becomes a crucial parameter for the Higgs discovery as the Higgs mass increases. For a Higgs as heavy as 1 TeV the winning parameter is energy, not luminosity.

To be submitted to Il Nuovo Cimento

1. INTRODUCTION

Purpose of this paper is to clarify a basic point: i.e. if a Higgs particle exists with a heavy mass ($M_H \approx 1 \text{ TeV}$), what is the best way to search for it. In this paper we address exactly this problem and conclude that for the discovery of a TeV-mass Higgs the best collider is ELN/Eloisatron.

In the Standard Model (SM) particles get their mass by means of the Higgs mechanism [1]. One of today's hottest problems in particle physics is, thus, finding the Higgs particle. There is no way to theoretically predict the mass of this so much needed particle. The most likely expectation is for a light Higgs ($M_h \approx M_Z$). The present mass limit from LEP [2] is $M_h \gtrsim 60 \text{ GeV}$, where M_h refers not only to the minimal Standard Model Higgs [3] but also to the Higgs expected by Supergravity Models [4,5]. The discovery of a light Higgs would not diminish the interest for the existence of a heavier Higgs; on the contrary.

The simplest electroweak symmetry breaking scenario with a single Higgs boson is only mildly constrained experimentally, with the above quoted lower bound and no firm indirect experimental upper bound. On the other hand this simple scenario cannot be the answer to the many problems affecting the Standard Model.

There is no question about the need of Supersymmetry in order to overcome the hierarchy problem; and this requires two Higgs doublets. Unfortunately the introduction of Supersymmetry increases significantly the number of unknown parameters in the theory, mainly because this symmetry must be softly broken at low energies.

A generic low-energy Supersymmetry Model, the so-called Minimal Supersymmetric extension of the Standard Model (MSSM), needs at least twenty one parameters; thus the need for "local" Supersymmetry, i.e. Supergravity. Here the number of parameters can be drastically reduced [5] to two, $\tan\beta$ and $m_{1/2}$, plus the top-quark mass (m_t), hopefully to be determined soon at Fermilab. In Supergravity the number of sparticles expected is as large as thirty. The light and the heavy Higgs are needed to describe the whole scenario. So the discovery of a light Higgs ($M_h \approx 100 \text{ GeV}$) in no case can close the issue of understanding the "scalar" sector of the theory. On the other hand, once the light Higgs is discovered, finding where the heavy one is ($M_H \approx 1 \text{ TeV}$), is going to represent the key question of high energy physics.

For the sake of a quantitative comparison let us consider the simplest, string-derivable, Supergravity Model $SU(5) \times U(1)$ [6]. In the "strict no-scale" case of this model there is a striking result: as $\tan\beta$ is a function of m_t and $m_{1/2}$, it is possible to search for solutions where $B(M_U) = 0$ (this is in fact the condition dictated by the "strict no-scale" case). It is found that there are only two possible solutions for $\mu > 0$ and $\mu < 0$. For $\mu < 0$, solutions exist only for $m_t \gtrsim 140 \text{ GeV}$. This means that the value of m_t determines the sign of μ . If the top quark is discovered at Fermilab with $m_t > 140 \text{ GeV}$,

then the lower Higgs mass must be $M_h \gtrsim 100$ GeV and the heavier Higgs mass is going to be in the multi-hundred GeV range. On the other hand if μ is positive, then the predicted top-quark mass is $m_t \lesssim 135$ GeV. In this case the light Higgs mass is expected to be $M_h \lesssim 100$ GeV and the heavy Higgs mass $M_H \equiv 530$ GeV.

The conclusion of this discussion is that, the most constrained Supergravity Model, i.e. "strict no-scale" $SU(5) \times U(1)$, tells us how crucial is studying the scalar sector of the theory in the multi-hundred GeV range.

We have taken 500-1000 GeV as the reference mass range to answer, with a detailed Monte Carlo simulation, the question: what would be the best collider to discover the Higgs, if its mass is in the TeV range. Let us emphasize again that the light Higgs is expected to be in the 0.1 TeV range but, in order to disentangle the problem of finding what is the physics beyond the Standard Model, it is necessary to think quantitatively on how to find out the existence of a Higgs as heavy as 1 TeV. In fact, the knowledge of the two Higgs masses (M_h and M_H) would allow to work out the complete spectrum of thirty sparticles.

So far extensive phenomenological and Monte Carlo studies have been carried out, by us [7,8] and many other authors [9,10], in order to define the strategy to discover a Higgs particle in superhigh energy hadron-hadron interactions. Of course, this strategy critically depends on the Higgs mass. In the present work, for the heavy — sometimes called "obese" — Higgs case, i.e. when $M_H \gg 2M_Z$, three particular mass values are studied: $M_H = 500, 750$ and 1000 GeV. In these conditions, the cleanest channel to detect the Higgs would be [7-10]: $H^0 \rightarrow Z^0 Z^0 \rightarrow \ell^+ \ell^- \ell^+ \ell^-$, i.e. via its four charged lepton decay chain.

Our study is based on Monte Carlo simulations performed at the energies of the three existing projects for future pp colliders: $\sqrt{s} = 16$ TeV (LHC), $\sqrt{s} = 40$ TeV (SSC)*) and $\sqrt{s} = 200$ TeV (ELN). We use the Lund Model event generator PYTHIA [11], even at the energy of 200 TeV. At this energy, as discussed in [12], predictions and extrapolations strongly depend on the structure function parametrization used. The purpose of this paper is to focus on the $\sqrt{s}$ -parameter and show how relevant this becomes as the Higgs mass increases.

2. THE HIGGS SIGNAL

In the present effective theory for heavy Higgs production in pp interactions there are many different processes contributing; however only the processes with greatest

*) By the time this paper was published, the SSC Project was cancelled by the US Government. We still use the value $\sqrt{s} = 40$ TeV as an intermediate step in between LHC and ELN energies. In fact ELN is supposed to cover the energy range (10-200) TeV.

cross-sections (namely, gg fusion and WW fusion) are retained for this study [7-10,13]. The Higgs cross-section via gg fusion strongly depends on the top quark mass; here its value has been fixed at 130 GeV^{**}). In the heavy Higgs mass range considered, the $H^0 \rightarrow Z^0 Z^0$ branching ratio is assumed to be almost independent of the mass and approximately equal to 0.3 [14]. The branching ratio for $Z^0 \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu, \tau$) is 0.03 for each leptonic channel [15]. Therefore the branching ratio for the whole process is about 3×10^{-4} . Since it is so small, statistics plus background are the most limiting factors for the observation of this channel. Here we restrict ourselves to the case where both Z's decay into muons. Of course the situation would improve by a factor of four if electrons were also taken into account.

In the following we assume a luminosity of $4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at all energies, which means an integrated luminosity of $4 \times 10^5 \text{ pb}^{-1}$ in one year of data taking (with an estimated running time of 10^7 s/year). At a first approximation, we do not consider the experimental limitations due to the detector efficiency and to the energy, momentum and angular resolutions. For event simulation and cross-section calculations, we use the PYTHIA (version 5.6)/JETSET (version 7.3) Monte Carlo package [11], with the default (i.e. EHLQ1) set of parton structure functions.

Tables 1-3 show the Higgs production cross-sections for four different processes ($q\bar{q}$ annihilation, gg fusion, ZZ and WW fusion) times the overall branching ratio of the 4-muon decay chain, for the energies and masses considered. It is obvious that gg fusion and WW fusion are the dominant production processes.

3. THE IRREDUCIBLE BACKGROUND

A Higgs signal in the particular channel under study would be a peak in the 4-muon invariant-mass spectrum, sitting on the background continuum.

The non-resonant background, e.g. $t\bar{t}$, $b\bar{b}$, $c\bar{c}$, $Z^0 t\bar{t}$, $Z^0 b\bar{b}$, $Z^0 c\bar{c}$, with at least one $\mu^+ \mu^-$ pair other than from Z^0 decay, has not been considered since this can be (in principle) easily reduced by selecting $\mu^+ \mu^-$ pairs with invariant masses in a convenient interval around the Z^0 mass. We are therefore left with the so-called *irreducible* background due to the QCD continuum production of Z^0 pairs ($q\bar{q} \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $gg \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$) or to the *pile-up* of two single Z^0 events (mainly $q\bar{q} \rightarrow Z^0 \rightarrow \mu^+ \mu^-$) within the detector time resolution.

The Higgs width plays an important role in the Higgs search, since it increases with the mass according to the relation: $\Gamma_H = 0.5 M_H^3$ (with Γ_H and M_H in TeV) [16]. In other

^{**}) For large Higgs masses ($\approx 1 \text{ TeV}$), one would rather expect $m_t \approx 170 \text{ GeV}$ [3]. We still use $m_t = 130 \text{ GeV}$ as in the past [7,8], even though we know that this is a conservative choice as far as the Higgs cross-section via gg fusion is concerned.

words, for a very high mass (750-1000 GeV), the Higgs resonant structure becomes very broad and could only be identified as a hump rather than a peak above the background. This justifies our assumption to neglect the experimental resolution for muon detection, which is of no relevance in this case. Nevertheless, as we will see in sect. 4, a 200 TeV pp collider would still see a clean Higgs signal even at $M_H = 1$ TeV.

In the PYTHIA event generator used in our Monte Carlo, the process $gg \rightarrow Z^0 Z^0$ is not implemented. This contribution to the background — which considerably increases as $\sqrt{s}$ increases and cannot be neglected at 200 TeV — has been accounted for by multiplying the $q\bar{q}$ cross-section by an appropriate $\sqrt{s}$ -dependent factor [7,8,13]. The *irreducible* background cross-sections (times branching ratio) are shown in table 4 for the three $\sqrt{s}$ -values considered.

4. SIGNAL VERSUS BACKGROUND

In order to disentangle the Higgs signal from the *irreducible* background, their basic features have been systematically studied, as functions of M_H and $\sqrt{s}$, namely: the distributions of $\cos\theta_\mu^*$ (the cosine of the angle of each decay muon in the Z^0 rest frame with respect to the Z^0 flight direction), the μ and Z^0 transverse momenta ($p_{T\mu}$ and p_{TZ}) and the μ rapidity (y_μ). Figures 1-3 show some of these distributions for $M_H = 500$ GeV and $\sqrt{s} = 16$ TeV, for $M_H = 750$ GeV and $\sqrt{s} = 40$ TeV, and for $M_H = 1000$ GeV and $\sqrt{s} = 200$ TeV. The mean values of the $p_{T\mu}$ and p_{TZ} distributions, for all the M_H and $\sqrt{s}$ values considered, are shown in tables 5 and 6, respectively. Figure 4 shows the same distributions as in figs. 1-3 for the background due to *pile-up* at $\sqrt{s} = 16$ GeV: a very large fraction of the muons are produced with $p_{T\mu}$ smaller than 10 GeV, as compared with the *irreducible* background case (see figs. 1b and 4b).

From figs. 1c-3c it is evident that the muons coming from the Higgs decay are more likely to be produced in the central region (i.e. at small $|y_\mu|$) than those coming from the background. This is true at any energy and any Higgs mass. The higher is M_H , the narrower is the y_μ distribution; its width increases of course with the energy, more for the signal than for the background, as one can see from the $|y_\mu|_{\max}$ values of the distributions given in table 7.

For the signal, the mean value of the $p_{T\mu}$ distribution is shifted upwards with respect to the background (see for instance fig. 1b). This shift is almost $\sqrt{s}$ -independent but depends on M_H , corresponding to about a factor of 2, 3 and 4 for $M_H = 500, 750$ and 1000 GeV, respectively (see table 5). For the p_{TZ} distribution, the shift is more pronounced (see for instance fig. 1d). The signal distribution is expected to have a peak at $p_{TZ} = 0.5M_H (1 - 4 M_Z^2/M_H^2)^{1/2}$ [13]. This obviously means that the shift with respect to the background distribution should be more and more evident with increasing Higgs

mass, as it appears in table 6: in this case the shift roughly corresponds to the factors 3.5, 5 and 6 for the three M_H values considered. Again it is almost $\sqrt{s}$ -independent.

Also significant is the difference in the $\cos\theta_\mu^*$ distributions of the muons, whose behaviours for signal and background are expected to be, respectively: $d\sigma/d\cos\theta_\mu^* \approx \sin^2\theta_\mu^*$ and $d\sigma/d\cos\theta_\mu^* \approx 1 + \cos^2\theta_\mu^*$, owing to the difference in polarization of the produced Z 's (longitudinally polarized when originating from Higgs decay, mainly transversely polarized when coming from $q\bar{q}$ continuum [7-10,13]) .

Following the above considerations, we have imposed cuts on the transverse momentum variables of signal and background events: $p_{T\mu}$ -cut, i.e. $p_{T\mu} > 30, 40, 50, 60$ GeV (for each μ), and p_{TZ} -cut, i.e. $p_{TZ} > 100, 150, 200, 250$ GeV (for each Z^0). A cut on the muon rapidity has also been imposed in order to account for the limited possibility of a detector to cover the forward region: y_μ -cut, i.e. $|y_\mu| < 3$ (for each μ). Of course this cut becomes more restrictive as $\sqrt{s}$ increases (see table 7). A cut on the $\cos\theta_\mu^*$ variable would have a smaller impact [7], compared with $p_{T\mu}$ -cut and p_{TZ} -cut. Therefore we do not include it in our present analysis.

As far as the background due to *pile-up* is concerned, this is estimated to produce about 2×10^3 events/year at $\sqrt{s} = 16$ TeV and about 3×10^3 at $\sqrt{s} = 40$ TeV, for a bunch-crossing period of 15 ns. With the above defined cuts, this background would be almost entirely eliminated.

5. ANALYSIS AND RESULTS

In the following analysis, for a given value of the Higgs mass (500, 750, 1000 GeV), a comparison between the results at the three $\sqrt{s}$ -energies has been carried out. The parameters used to measure the quality of the cuts are: the signal/background ratio S/B , the purity $S/(S+B)$ and the efficiency S/S_{tot} , where S_{tot} is the total number of Higgs events analyzed (before cuts) and S and B are the numbers of Higgs and of *irreducible* background events surviving (after cuts).

In figs. 5, 6 and 7 the S/B ratio is presented as a function of $p_{T\mu}$ -cut and of p_{TZ} -cut, with and without y_μ -cut (see sect. 4), for $M_H = 500, 750$ and 1000 GeV, respectively, at LHC, SSC and ELN energies. Clearly, for any Higgs mass, this ratio increases as $p_{T\mu}$ -cut increases (in the range $30 \div 60$ GeV) at fixed $\sqrt{s}$. For a fixed $p_{T\mu}$ -cut, it increases with increasing $\sqrt{s}$. In addition, the S/B ratio improves when the condition $|y_\mu| < 3$ (y_μ -cut) is imposed. The best S/B values are obtained at $\sqrt{s} = 200$ TeV (ELN) where, in particular, at $p_{T\mu} > 60$ GeV, the S/B ratio remains greater or equal to one even for $M_H = 1$ TeV.

As far as p_{TZ} -cut is concerned, relatively lower S/B values are obtained when compared with the $p_{T\mu}$ -cut case, although the behaviour of S/B vs. p_{TZ} -cut is similar. At

$M_H = 500$ GeV, due to the kinematics (see distribution of fig. 1d), above 150 GeV the S/B ratio decreases as p_{TZ} -cut increases.

Let us now focus on $p_{T\mu}$ -cut, which will be the most straightforward cut to apply in an experiment. In fig. 8 the purity vs. efficiency plots corresponding to $M_H = 500, 750$ and 1000 GeV, respectively, illustrate the correlation between these two quantities as a function of $p_{T\mu}$ -cut: namely for increasing $p_{T\mu}$ -cut values, the purity increases whereas the efficiency decreases. The ELN energy appears to be more favourable than that of SSC or LHC, in particular for the very heavy Higgs (1 TeV) case. For $p_{T\mu} > 60$ GeV, the points corresponding to the additional y_μ -cut are also shown in fig. 8: these give the best purity in all cases. However, it should be noticed that the rapidity cut implies a sizable reduction of the efficiency at the maximum energy (200 TeV) since, as already mentioned in sect. 4, the higher is $\sqrt{s}$, the wider is the muon rapidity plateau.

In order to better visualize the results of our analysis, the 4-muon invariant mass spectra corresponding to $M_H = 500, 750$ and 1000 GeV are presented in figs. 9, 10 and 11, respectively, at the three supercollider energies considered so far. The spectra are first shown without cuts, then with the conditions: $p_{T\mu} > 60$ GeV and $|y_\mu| < 3$ (for each muon). It is interesting to remark that at ELN a signal from a Higgs with mass up to 1 TeV might be clearly visible even without drastic cuts.

6. CONCLUSION

We have studied via Monte Carlo simulation the possibility to detect a heavy Higgs ($M_H \gg 2M_Z$) at three possible $\sqrt{s}$ -values, corresponding to the three currently ongoing projects for hadron supercolliders: LHC (16 TeV), SSC (40 TeV) and ELN/Eloisatron (200 TeV). We have assumed a luminosity of $4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and considered the "golden" decay of the Higgs into four muons in the presence of the *irreducible* background from Z^0 -pairs. The message is clear: the higher is $\sqrt{s}$, the better a heavy Higgs would be observable in one year (or less) of running. In particular, a Higgs as heavy as 1 TeV can only be discovered at ELN, the winning parameter being energy, not luminosity.

Table 1

PYTHIA cross-sections (in pb) vs. M_H for $H^0 \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ at $\sqrt{s} = 16$ TeV.

Process	$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
$q\bar{q}$	6.56×10^{-5}	2.55×10^{-5}	9.79×10^{-6}
gg	8.71×10^{-4}	1.25×10^{-4}	3.23×10^{-5}
$Z^0 Z^0$	8.53×10^{-5}	3.06×10^{-5}	1.20×10^{-5}
$W^+ W^-$	1.80×10^{-4}	6.58×10^{-5}	2.65×10^{-5}

Table 2

PYTHIA cross-sections (in pb) vs. M_H for $H^0 \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ at $\sqrt{s} = 40$ TeV.

Process	$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
$q\bar{q}$	5.19×10^{-4}	2.64×10^{-4}	1.17×10^{-4}
gg	4.97×10^{-3}	8.89×10^{-4}	2.42×10^{-4}
$Z^0 Z^0$	4.65×10^{-4}	2.16×10^{-4}	1.09×10^{-4}
$W^+ W^-$	1.03×10^{-3}	4.78×10^{-4}	2.22×10^{-4}

Table 3

PYTHIA cross-sections (in pb) vs. M_H for $H^0 \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ at $\sqrt{s} = 200$ TeV.

Process	$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
$q\bar{q}$	7.18×10^{-3}	4.52×10^{-3}	1.98×10^{-3}
gg	5.62×10^{-2}	1.21×10^{-2}	3.75×10^{-3}
$Z^0 Z^0$	5.06×10^{-3}	2.72×10^{-3}	1.51×10^{-3}
$W^+ W^-$	1.04×10^{-2}	5.62×10^{-3}	1.13×10^{-3}

Table 4

Cross-sections (in pb) vs. $\sqrt{s}$ for $q\bar{q} \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $gg \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^-$ as given by PYTHIA and ref. [7], respectively.

Process	$\sqrt{s} = 16$ TeV	$\sqrt{s} = 40$ TeV	$\sqrt{s} = 200$ TeV
$q\bar{q}$	1.49×10^{-2}	3.86×10^{-2}	1.36×10^{-1}
gg	$0.27 \times \sigma_{q\bar{q}}$	$0.45 \times \sigma_{q\bar{q}}$	$\sigma_{q\bar{q}}$

Table 5

Mean values (in GeV) of the $p_{T\mu}$ distributions for all the M_H and $\sqrt{s}$ values considered.

$\sqrt{s}$ (TeV)	Background $\langle p_{T\mu} \rangle$	Signal $\langle p_{T\mu} \rangle$		
		$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
16	44.2	106.4	133.2	181.4
40	47.0	109.3	157.1	192.0
200	53.6	116.5	167.8	203.8

Table 6

Mean values (in GeV) of the p_{TZ} distributions for all the M_H and $\sqrt{s}$ values considered.

$\sqrt{s}$ (TeV)	Background $\langle p_{TZ} \rangle$	Signal $\langle p_{TZ} \rangle$		
		$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
16	54.5	198.7	255.1	348.3
40	59.4	204.2	300.4	365.2
200	72.2	217.3	315.8	379.4

Table 7

Maximum values of the y_μ distributions for all the M_H and $\sqrt{s}$ values considered.

$\sqrt{s}$ (TeV)	Background $ y_\mu _{\max}$	Signal $ y_\mu _{\max}$		
		$M_H = 500$ GeV	$M_H = 750$ GeV	$M_H = 1000$ GeV
16	~ 7.5	~ 4.5	~ 3.5	~ 3
40	~ 8	~ 5	~ 4	~ 3.5
200	~ 10	~ 8	~ 7	~ 6.5

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FIGURE CAPTIONS

- Fig. 1. For $M_H = 500$ GeV and $\sqrt{s} = 16$ TeV: a) distribution of $\cos\theta_\mu^*$, where θ_μ^* is the angle of each decay muon in the Z^0 rest frame with respect to the Z^0 flight direction; b) distribution of the muon transverse momentum $p_{T\mu}$; c) distribution of the Z^0 transverse momentum p_{TZ} ; d) distribution of the muon rapidity y_μ . The distributions for the signal ($H^0 \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$) and *irreducible* background (double $Z^0 \rightarrow \mu^+ \mu^-$), superimposed, as indicated, correspond to an integrated luminosity of $4 \times 10^{-5} \text{ pb}^{-1}$.
- Fig. 2. The same as in fig. 1 for $M_H = 750$ GeV and $\sqrt{s} = 40$ TeV.
- Fig. 3. The same as in fig. 1 for $M_H = 1000$ GeV and $\sqrt{s} = 200$ TeV.
- Fig. 4. The same as in fig. 1 only for background due to *pile-up* (single $Z^0 \rightarrow \mu^+ \mu^-$) at $\sqrt{s} = 16$ TeV.
- Fig. 5. For $M_H = 500$ GeV at LHC, SSC and ELN energies (as indicated): a) signal to background ratio (S/B) as a function of $p_{T\mu}$ -cut; b) the same plus the condition $|y_\mu| < 3$; c) signal to background ratio as a function of p_{TZ} -cut; d) the same plus the condition $|y_\mu| < 3$.
- Fig. 6. The same as in fig. 5 for $M_H = 750$ GeV.
- Fig. 7. The same as in fig. 5 for $M_H = 1000$ GeV.
- Fig. 8. Purity ($S/(S+B)$) versus efficiency (S/S_{tot}), see text, at LHC, SSC and ELN energies (as indicated) for: a) $M_H = 500$ GeV; b) $M_H = 750$ GeV; c) $M_H = 1000$ GeV.
- Fig. 9. Four-muon invariant mass for $M_H = 500$ GeV:
a) $\sqrt{s} = 16$ TeV, no cuts; b) $\sqrt{s} = 16$ TeV, $p_{T\mu} > 60$ GeV, $|y_\mu| < 3$;
c) $\sqrt{s} = 40$ TeV, no cuts; d) $\sqrt{s} = 40$ TeV, $p_{T\mu} > 60$ GeV, $|y_\mu| < 3$;
e) $\sqrt{s} = 200$ TeV, no cuts; f) $\sqrt{s} = 200$ TeV, $p_{T\mu} > 60$ GeV, $|y_\mu| < 3$.
The signal+background and background spectra (superimposed, as indicated) correspond to an integrated luminosity of $4 \times 10^{-5} \text{ pb}^{-1}$.
- Fig. 10. Four-muon invariant mass for $M_H = 750$ GeV: a)-f) as in fig. 9.
- Fig. 11. Four-muon invariant mass for $M_H = 1000$ GeV: a)-f) as in fig. 9.

$\sqrt{s} = 16 \text{ TeV}$ $M_H = 500 \text{ GeV}$

Figure 1

$\sqrt{s} = 40 \text{ TeV}$ $M_H = 750 \text{ GeV}$

Figure 2

$\sqrt{s} = 200 \text{ TeV}$ $M_H = 1 \text{ TeV}$

Figure 3

$\sqrt{s} = 16 \text{ TeV}$

Figure 4

Figure 5

Figure 6

$M_H = 1000 \text{ GeV}$

Figure 7

Figure 8

Figure 9a

Figure 9b

Figure 9c

Figure 9d

Figure 9e

Figure 9f

Figure 10a

Figure 10b

Figure 10c

Figure 10d

Figure 10e

Figure 10f

Figure 11a

Figure 11b

Figure 11c

Figure 11d

Figure 11e

Figure 11f