Abstract

We examine a method of studying the $Z$ polarization in $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ in proton-proton collisions at the Large Hadron Collider (LHC). Included are the dominant contributions: gluon fusion production of the Higgs boson, continuum production of $Z$ pairs, and the $Z+$missing jet QCD background. The polarization signal is distinguishable from the background for Higgs masses less than or equal to $\sim 700$ GeV, for an integrated luminosity of $10^5$ pb$^{-1}$.

I. INTRODUCTION

Polarization information from the decays of weak gauge bosons provide an important clue to their production mechanism. In particular, if a weak boson pair is produced from the decay of a heavy Higgs boson, the bosons are largely longitudinally polarized. On the other hand, continuum production of weak bosons yields primarily transversely polarized bosons. Extracting the polarization signal from weak boson decays will be important to characterize a Higgs boson signal. Alternative models with a strongly interacting electroweak symmetry breaking sector also have enhanced longitudinal boson pair production rates. The polarization of the weak bosons may be one way to differentiate between signal and background.

Polarization effects in Higgs boson decay into the ‘gold-plated mode’ $H \to ZZ \to \ell^+\ell^-\ell_1^+\ell_2^-$ have been investigated in detail in the literature. At the proposed Large Hadron Collider (LHC) with proton-proton collisions at $\sqrt{S} = 14$ TeV and an annual integrated luminosity of $10^5$ pb$^{-1}$, polarization information for high mass Higgs bosons will be difficult to extract with the limited statistics. To aid in a Higgs boson search at the LHC, and as a complementary analysis, we have proposed using the process $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$. This decay mode has a factor of six enhancement over the gold-plated mode when $\ell = e, \mu$. Our analysis involves the average value of a quantity obtained from the charged lepton angular decay distribution, which differs for leptons coming from longitudinally polarized $Z$‘s, ($Z_L$) and transversely polarized $Z$‘s ($Z_T$). The precise quantity is described in Section II.

By considering the average value rather than the decay distribution itself, there are two advantages. First, the statistics in an experiment at the LHC will be inadequate to examine angular decay distributions as a function of transverse mass or missing transverse momentum of the event for heavy Higgs boson decays. The average of the lepton angular decay distribution nevertheless distinguishes between background and signal plus background.
Second, the average value of this quantity is fairly insensitive to theoretical uncertainties in the differential cross sections related to scale choices and higher order corrections.

Our goal in this paper is to establish the feasibility of this polarization measurement at the LHC using the process $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$. Consequently, we consider only the dominant contributions to the event rate with a charged lepton pair and large missing transverse momentum. We examine the polarization signal in heavy Higgs production and decay to charged leptons pairs and missing energy for $10^5$ pb$^{-1}$ of integrated luminosity. Our results suggest that with sufficient enhancement of longitudinal boson scattering in some non-resonant strongly interacting vector boson models, the polarization signals may be observable at high energies.

In the next section, we describe the heavy Higgs boson signal of interest, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, and the polarization variable. In Section III, we discuss the various Higgs boson production mechanisms and background processes. In Section IV, we show that with the dominant contributions to the signal, irreducible and reducible backgrounds, a Higgs boson signal in the mass range considered here, from 400-800 GeV, can be extracted except at the highest Higgs masses. A factor of four increase in integrated luminosity makes polarization signals at $m_H = 800$ GeV feasible. We also show the effects of experimental cuts and uncertainties associated with theory and statistics. In Section V, we summarize our conclusions.

II. HIGGS SIGNAL IN Z POLARIZATION

We begin with a discussion of $H \rightarrow ZZ$. The Higgs boson mass range considered here is 400-800 GeV. This range was chosen because for masses lower than $\sim 400$ GeV, the QCD background rates for $Z$+missing jet are very high. In the mass range below 400 GeV, the gold-plated mode has an event rate large enough for unambiguous Higgs identification. The upper bound was chosen based on unitarity estimates of the maximum allowed Higgs mass, first done by Lee, Quigg and Thacker. Over this range of Higgs masses, the branching fraction into $Z$ pairs is approximately 33%, with the remaining width primarily due to $W$ pair production.

Essential to our analysis is the fact that the Higgs boson decays preferentially into longitudinally polarized weak bosons. A straightforward calculation of the ratio of the polarized widths gives

$$
\frac{\Gamma(H \rightarrow Z_LZ_L)}{\Gamma(H \rightarrow Z_TZ_T)} = \frac{m_H^4 (1 - 2m_Z^2/m_H^2)^2}{8 m_Z^4} = 38 - 708
$$

(2.1)

for masses $m_H = 400 - 800$ GeV. Already at $m_H = 500$ GeV, the ratio is 100. The angular decay distribution of the charged leptons from the $Z$ decay characterize the polarization of the $Z$. Defining the angle $\theta$ by the $Z$ momentum axis and the charged lepton three momentum in the $Z$ rest frame, the angular decay distributions, with $z \equiv \cos \theta$, are

$$
\phi_L(z) = \frac{3}{4}(1 - z^2)
$$

(2.2)

$$
\phi_T(z) = \frac{3}{8}(1 + z^2)
$$

(2.3)
for longitudinally and transversely polarized $Z$'s respectively. With these distributions, one sees that $\langle |z| \rangle = 3/8$ for purely longitudinal $Z$'s and $\langle |z| \rangle = 9/16$ for purely transverse $Z$'s. This is the effect that we exploit.

The large enhancement factor in the ratio of longitudinal to transverse polarized $Z$'s is very promising, but unfortunately, the longitudinal polarization four-vector is not boost invariant in general. The ratio in Eq. (2.1) is valid for Higgs decay only in its rest frame. The ratio decreases as one boosts the Higgs to larger momenta. For gold-plated modes, one can boost back to the Higgs rest frame and use the $Z$ momenta in that frame to define the polarization axes. This has been studied in Refs. [11]. With one $Z$ decaying to neutrinos, it is not possible to unambiguously determine the Higgs rest frame. The heavy Higgs masses considered here are large enough that the typical boosts from the Higgs rest frame to the collider frame are small, so one still sees a significant enhancement in the production of $Z$’s with longitudinal polarization in the hadron center of mass (collider) frame. We use the momentum axis of the reconstructed $Z$ in the collider frame to define the angle $\theta$ for the $\ell^-$ angular distribution.

In our numerical results presented below, we evaluate the average value of $z^* \equiv |z| = |\cos \theta|$. By constructing the longitudinal polarization four-vector $\epsilon_L$ in the collider frame from the reconstructed $Z$ momentum $p_Z = p_\ell + p_\ell$, namely,

$$
\epsilon_L = \frac{1}{M_Z}(|\vec{p}_Z|, E_z \vec{p}_Z) ,
$$

one finds for $p_\ell$, the charged lepton momentum in the collider frame, that

$$
z^* = \frac{2}{M_Z} |\epsilon_L \cdot p_\ell| .
$$

We evaluate the average value of $z^*$ as a function of transverse mass $M_T$ where

$$
M_T^2 = [(\vec{p}_T^2 + m_Z^2)^{1/2} + (\vec{\rho}_T \cdot \vec{m}_Z^2)^{1/2}]^2 - (\vec{p}_T + \vec{\rho}_T)^2
$$

Here, $\vec{\rho}_T$ refers to the momentum carried by the neutrino pair transverse to the beam axis. For muons, the experimental evaluation of $\langle z^* \rangle$ should be very precise. The experimental errors associated with missing transverse momentum enter into the determination of the transverse mass, not the evaluation of $z^*$.

Operationally, our procedure here is to evaluate the dominant contributions to the total cross section for $pp \rightarrow \ell^+ \ell^- + \vec{\rho}_T$ and to determine their average $z^*$ values as a function of transverse mass, then take the cross section weighted average:

$$
\langle z^* \rangle = \frac{\sum \langle z^* \rangle \sigma_i}{\sum \sigma_i} .
$$

We make the following cuts on the transverse momentum and rapidity of the charged leptons, as well as a cut requiring that the charged lepton pair reconstruct to a $Z$:

$$
p_T^\ell > 20 \text{ GeV} \quad (2.8)
$$

$$
|y_\ell^\ell| < y_\ell^e \quad (2.9)
$$

$$
M_Z - \Gamma_Z < M_\ell^+\ell^- < M_Z + \Gamma_Z \quad (2.10)
$$
We consider two choices for $y^\ell_c$: $y^\ell_c = 2.5$ and $y^\ell_c = 3$. Increasing the transverse momentum cut for the charged leptons has the effect of reducing the separation between the purely longitudinal and purely transverse values for $\langle z^* \rangle$. As a practical matter, the invariant mass cut has no effect on our calculations presented below because the dominant background contributions include $Z \to \ell^+ \ell^-$ in the final state. In our calculations, we use the narrow width approximation for the $Z$ decay to leptons. The invariant mass cut does reduce backgrounds from, e.g., $t\bar{t} \to bbW^+W^- \to \ell^+\ell^-\nu\bar{\nu}X$.

In the next section we describe the various contributions to the total signal plus background cross section. In our numerical results, we include only $\ell = \mu$, however, we do not factor in efficiencies in our evaluation of event rates. We use the leading order CTEQ3 parton distribution functions and five-flavor $\Lambda = 132$ MeV in our evaluation of the cross sections. In terms of the incoming parton momenta $p_1$ and $p_2$, the factorization and renormalization scales are set to $\mu^2 = (p_1 + p_2)^2$.

III. CROSS SECTIONS

The dominant Higgs signal production mechanism for $\sigma(pp \to H \to ZZ)$ depends on the top quark mass. The reports of the discovery of the top quark with a mass of $m_t \simeq 175$ GeV [10] mean that the largest contribution to $\sigma(pp \to H)$ at LHC energies for $m_H = 400 - 800$ GeV comes from gluon fusion $gg \to H \to ZZ$, where the gluons couple to the Higgs through a triangle diagram with a top quark internal loop. In principle, one should include non-resonant $gg \to Z_LZ_L$ contributions, however, at $\sqrt{S} = 14$ TeV, these contributions are small. Contributions to Higgs production with top quarks in the initial or final state are suppressed so as to give no appreciable contribution to the cross section. In what follows, we set $m_t = 175$ GeV.

A second important production mechanism for $Z$-pairs is through vector boson fusion. Initially, calculations were done using the effective $W$ approximation, giving $WW \to H$ and $ZZ \to H$, using the $W$ and $Z$ distributions in the proton. More recently, full calculations of $qq \to VVqq \to Hqq$ and related processes are done instead. Using the Higgs resonance portion of $qq \to ZZqq$ and related processes with quarks and antiquarks in the initial state, we find that the cross section from vector boson fusion is $1/10$ to $1/3$ of the gluon fusion cross section for the mass range from 400-800 GeV. In line with our aim to evaluate the feasibility of the polarization measurement, we only include the dominant gluon fusion part of the Higgs cross section and comment below on the effect of changing the normalization of the signal part of the contribution to $\ell^+\ell^- + \hat{p}_T$.

The production of $Z$ pairs from quark fusion is the dominant contribution to the irreducible background to the $H \to ZZ$ signal in the Higgs resonance region. We include here the leading order contribution: $q\bar{q} \to ZZ$, as in Ref. The transverse and longitudinal $Z$ boson contributions to the total $q\bar{q} \to ZZ$ differential cross section, as a function of the $Z$-pair invariant mass, are shown in Fig. 1. Also indicated is the $gg \to H \to ZZ$ result for $m_H = 600$ GeV. Longitudinal $Z$-pair production is indicated by the dashed lines. As advertised, the $q\bar{q} \to ZZ$ contribution significantly dominates the irreducible background. The next to leading order to $q\bar{q} \to ZZ$, with crossed diagrams, gives an enhancement of a factor of $\sim 1.2 - 1.3$ in the cross section. Our Monte Carlo calculation of $pp \to ZZ$ relies
on the leading order matrix element for the irreducible background, but we discuss below
the consequences of increasing the normalization of this background.

The QCD process with production of a single $Z$ plus missing jet is the largest reducible
background. At leading order in $\alpha_s$, this comes from $q\bar{q} \to Zg \to \ell^+\ell^-g$ and crossed
diagrams. A fraction of the events will have the final state parton which is missed in the
detector, so it contributes to events with $\ell^+\ell^- + \not{p}_T$. We model this background by imposing
the selection cuts outlined in Sec. II, together with a requirement that the rapidity of the
parton $y^p$ satisfy

$$|y^p| > y^p_c.$$  \hfill (3.1)

The idea here is that for high rapidity partons, the parton “jet” is outside of the detector
coverage, and thus is “missing.” We consider two values of $y^p_c$: $y^p_c = 3$ and $y^p_c = 4$. The
combination of $y^p_c = 4$ with $y^\ell_c = 2.5$ is particularly difficult to satisfy for this background
process. The rate for single $Z$ production at large $p_T$ is very high compared to the rate for
$Z$-pairs at the same transverse momentum, so the rapidity cuts are essential.

The $Z$+missing jet background is the largest reducible background. Other processes, not
included in this analysis, have some of the ingredients of the $\ell^+\ell^-\nu\bar{\nu}$ signal, but typically have
additional activity in the event. For example, the cross section for $gb \to Zb \to \ell^+_1\ell^-_1 c\ell^-_2\bar{\nu}_2$ is
large. When the $b$ decays outside of the central region, it is included in the $Z+$ missing jet
background. When it decays in the central region, at high transverse momentum of $\ell^+_1 + \ell^-_1$,
the electron and quark jet will largely align with the missing momentum. Cuts that veto
these events are required. The requirement of no central jets, together with the invariant
mass cut in Eq. (2.10), also eliminates the background from $gg \to t\bar{t} \to \ell^+\nu\ell^-\bar{\nu}\bar{b}\bar{b}$.

To illustrate the dominant signal, irreducible and reducible backgrounds, we show
d$\sigma$/d$M_T$ in Figs. 2 and 3. The solid lines show the gluon fusion contribution to Higgs
production. The dashed line shows $q\bar{q} \to ZZ$, and the dotted line indicates the QCD
$Z$+missing jet contribution. The fully correlated decays of one $Z$ to one family of charged
leptons, and the other $Z$ to neutrino pairs, is included in the $ZZ$ cross sections. The cuts
applied are those in eqs. (2.8-2.10,3.1). In Fig. 2, we have set $y^p_c = y^\ell_c = 3$. The reducible
background is quite large for $M_T < 700$ GeV, making these cuts less than ideal except for
very high mass Higgs bosons. A better choice is shown in the next figure. Fig. 3 shows the
same quantities with $y^p_c = 4$ and $y^\ell_c = 2.5$.

The transverse mass peaks stand out well for $m_H = 400$ GeV and 600 GeV in Fig.
3. The event rates are such that the discovery mode will be the four-charged-lepton final
states. Using the cuts in Fig. 3 for the $\mu^+\mu^- + \not{p}_T$ final states, we find 770 signal events for
$m_H = 400$ GeV in the range of $M_T = 350 - 450$ GeV and 240 background events in the same
range, assuming an integrated luminosity of $10^5$ pb$^{-1}$. For $m_H = 600$ GeV, the same cuts
yield 160 events for the Higgs signal and 77 events for the background for $M_T = 500 - 700$
GeV. An 800 GeV Higgs boson yields 24 signal events and 19 background events in a range
of $M_T = 700 - 900$ GeV. Using the cuts in Fig. 2, the signal event rates are slightly higher,
but the background event rates are significantly higher except for the highest mass range.
For $M_T = 700 - 900$ GeV and $m_H = 800$ GeV, the signal remains at 24 events and the
background is 25 events for the Fig. 2 cuts.
IV. RESULTS FOR $\langle Z^* \rangle$

We present our results in a series of figures where we show the value of $\langle z^* \rangle$ as a function of transverse mass. Here, $\langle z^* \rangle$ is evaluated via Eq. (2.7). Combining the reducible and irreducible backgrounds, we write Eq. (2.7) as

$$\langle z^* \rangle = \frac{\langle z^* \rangle_S \sigma_S + \langle z^* \rangle_B \kappa \sigma_B}{\sigma_S + \kappa \sigma_B},$$

(4.1)

for the signal (S) and background (B) differential cross sections indicated in Figs. 2 and 3 with $\kappa = 1$.

The values of $\langle z^* \rangle$ are subject to uncertainties which include the relative normalization of the signal to background, as well as measurement uncertainties. A K-factor $\kappa$ in Eq. (4.1) is included to estimate the error associated with QCD corrections by changing the relative normalization of the signal to background cross sections. A value of $\kappa = 1.5$ is a rough estimate of the theoretical uncertainty in the background calculation.

We begin with $y^k_c = y^p_c = 3$, and plot $\langle z^* \rangle$ versus $M_T$ for 400, 600 and 800 GeV Higgs bosons in Figs. 4a, 4b and 4c. The result of Eq. (4.1) with $\kappa = 1$ is shown by the solid line and $\kappa = 1.5$ is given by the dotted line. The values of $\langle z^* \rangle_S$ are indicated by the dot-dashed line, and $\langle z^* \rangle_B$ are indicated by the dashed line. The 400 and 600 GeV Higgs boson transverse mass peaks in Fig. 2 translate to dips in the value of $\langle z^* \rangle$ as the cross section moves from background dominated to signal dominated. The broader dip for the case of $m_H = 800$ GeV is still evident. The reducible $Z+$missing jet background nearly obscures the dip for $m_H = 400$ GeV when $y^k_c = y^p_c = 3$.

We now turn to the rapidity cuts that reduce the $Z+$missing jet background. In Figs. 5a, 5b and 5c, we show $\langle z^* \rangle$ versus $M_T$ for $y^k_c = 2.5$ and $y^p_c = 4$. These plots have error bars with our estimate of the uncertainty in the measurements of $\langle z^* \rangle$ due to statistics. The error bars were estimated by using events generated by a Monte Carlo generator with the three dominant signal, reducible and irreducible background contributions. The Monte Carlo events passing the cuts are grouped by transverse mass bin. Values of $\langle z^* \rangle$ are determined for many collections of $N$ events for a particular bin, where $N$ is the theoretically predicted number of events in the bin based on an integrated luminosity of $10^5$ pb$^{-1}$. The error bar for the bin is the standard deviation of these values of $\langle z^* \rangle$. In Fig. 5c, we have slightly offset the central values of the transverse mass bins to better exhibit the overlapping error bars.

For $m_H = 400 − 600$ GeV, the polarization signal plus background is distinguishable from the polarization with no Higgs boson contribution. For $m_H = 800$ GeV, the distinction between $\langle z^* \rangle$ with and without the Higgs boson is difficult to make with an integrated luminosity of $10^5$ pb$^{-1}$ because of limitations due to the statistical error. If the event rate can be increased by a factor of four, then this method looks more promising. For $m_H = 700$ GeV, the cross section is large enough to reduce the statistical errors and make a distinction between background and signal plus background values of $\langle z^* \rangle$ feasible. Since our event rates are determined using leading order matrix elements and only dominant contributions, the error bars presented here may be conservative. However, the error bars are indicative of how difficult the full angular distribution measurements will be for heavy Higgs masses.
V. CONCLUSIONS

Resonant peak searches in the four charged lepton decay modes of heavy Higgs decay, \( H \rightarrow ZZ \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \), remain the preferred path to Higgs boson discovery, except at the highest Higgs masses considered here. Before the integrated luminosity achieves \( 10^5 \text{ pb}^{-1} \), measurements of \( \langle z^* \rangle \) for \( m_H = 400 \text{–} 600 \text{ GeV} \) are a reasonable alternative to the full angular distributions described in Ref. [8]. In a scenario with \( m_H = 800 \text{ GeV} \) at the LHC with \( 10^5 \text{ pb}^{-1} \), event rates are low and the peak is not pronounced. A measurement of \( \langle z^* \rangle \) supplements a measurement of an enhanced cross section for \( pp \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \), and characterizes the production mechanism of the \( Z \) pair, however an integrated luminosity of more than \( 10^5 \text{ pb}^{-1} \) is required for a measurable difference between signal plus background and background alone in the \( \langle z^* \rangle \) distribution according to our dominant production analysis. For masses smaller than 800 GeV, this method can characterize the production mechanism for \( Z \)-pairs. Our results suggest that this technique may also be applied to study models [1] with enhanced, non-resonant or broad-resonant, longitudinal vector boson scattering.

ACKNOWLEDGMENTS

Work supported in part by National Science Foundation Grants No. PHY-9307213 and PHY-9507688. MHR thanks F. Paige, Chung Kao and H. Baer for useful conversations.
REFERENCES

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[1] For several models, see, e.g., J. Bagger, et al., Phys. Rev. D52 (1995) 3878.
[2] R. N. Cahn, et al., in Experiments, Detectors and Experimental Areas for the SSC, proceedings of the Workshop, Berkeley, CA, 1987, eds. R. Donaldson and M. Gilchriese (World Scientific, Singapore, 1988).
[3] M. J. Duncan and M. H. Reno, in Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders, Argonne National Laboratory, 1993, eds. J. L. Hewett, A. R. White and D. Zeppenfeld, 413.
[4] M. J. Duncan and M. H. Reno, in Proceedings of the Eighth Meeting of the Division of Particles and Fields of the American Physical Society, University of New Mexico, Albuquerque, 1994, ed. Sally Seidel, (World Scientific, Singapore, 1995) 473.
[5] R. N. Cahn and M. S. Chanowitz, Phys. Rev. Lett. 56 (1986) 1327.
[6] B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. Lett. 38 (1977) 883; Phys. Rev. D16 (1977) 1519.
[7] M. J. Duncan, Phys. Lett. B179 (1986) 393.
[8] T. Matsuura and J. J. van der Bij, Z. Phys. C51 (1991) 259.
[9] H. L. Lai, et al., Phys. Rev. D51 (1995) 4763.
[10] F. Abe, et al. (CDF Collaboration), Phys. Rev. Lett. 74 (1995) 2626; Phys. Rev. D50 (1994) 2966; S. Abachi et al. (D0 Collaboration), Phys. Rev. Lett. 74 (1995) 2632. April 1994.
[11] D. A. Dicus, C. Kao and W. W. Repko, Phys. Rev. D36 (1987) 1570; E. W. N. Glover and J. J. van der Bij, Nucl. Phys. B321 (1989) 561; Phys. Lett. B219 (1989) 488.
[12] J. F. Gunion, H. E. Haber, F. E. Paige, Wu-Ki Tung and S. S. D. Willenbrock, Nucl. Phys. B294 (1987) 621.
[13] S. Dawson, Nucl. Phys. B249 (1985) 42.
[14] U. Baur and E. W. N. Glover, Nucl. Phys. B347 (1990) 12.
[15] J. Ohnemus and J. F. Owens, Phys. Rev. D43 (1991) 3626; B. Mele, P. Nason and G. Ridolfi, Nucl. Phys. B357 (1991) 409.
FIGURES

FIG. 1. Separate contributions to the $M_{ZZ}$ differential cross section for $pp \to ZZ + X$: $q\bar{q} \to ZZ$ (solid line), which is the sum of $q\bar{q} \to Z_TZ_T$, $Z_LZ_T$ (dot-dashed lines) and $Z_LZ_L$ (dashed lines) and the resonant $gg \to H \to ZZ$ contribution (solid line) and $gg \to H \to Z_LZ_L$ (dashed lines) for $m_H = 600$ GeV. No cuts were applied to these distributions.

FIG. 2. Differential cross section for $pp \to ZZ + X$ as a function of transverse mass $M_T$, with contributions from: $q\bar{q} \to ZZ$ (dashed line) the QCD $Z$+missing jet background (dotted line) and resonant gluon fusion (solid line) for $m_H = 400, 600$ and $800$ GeV. The sum of the three contributions is indicated with the heavy solid line. The rapidity cuts are $y_p^c = y_{\ell}^c = 3$.

FIG. 3. Differential cross section for $pp \to ZZ + X$ as a function of transverse mass $M_T$, with contributions from: $q\bar{q} \to ZZ$ (dashed line) the QCD $Z$+missing jet background (dotted line) and resonant gluon fusion (solid line) for $m_H = 400, 600$ and $800$ GeV. The sum of the three contributions is indicated with the heavy solid line. The rapidity cuts are $y_p^c = 4$ and $y_{\ell}^c = 2.5$.

FIG. 4. The values of $\langle z^* \rangle$ versus $M_T$ for a) $m_H = 400$ GeV, b) $m_H = 600$ GeV and c) $m_H = 800$ GeV, with $y_p^c = y_{\ell}^c = 3$. The solid line comes from the evaluation of Eq. (4.1) with $\kappa = 1$, the dotted line, with $\kappa = 1.5$. The Higgs values alone are shown with the dot-dashed line, and the background alone, with the dashed line.

FIG. 5. The values of $\langle z^* \rangle$ versus $M_T$, as in Fig. 4, for a) $m_H = 400$ GeV, b) $m_H = 600$ GeV and c) $m_H = 800$ GeV, with $y_p^c = 2.5$ and $y_{\ell}^c = 4$. The error bars represent a statistical error calculated assuming an integrated luminosity of $10^5 \text{ pb}^{-1}$. 
$pp \rightarrow \ell \bar{\ell} \not{p_T} X$

$\sqrt{s} = 14$ TeV

$p_T^{\ell} > 20$ GeV

$y_c^\ell = 3$, $y_c^p = 3$
$m_H = 400 \text{ GeV}$

$y_c^\ell = y_c^p = 3$
$m_H = 400$ GeV

$y_c^\ell = 2.5, \; y_c^p = 4$
$m_H = 600 \text{ GeV}$

$y_c^\ell = 2.5$, $y_c^p = 4$
