arXiv:hep-ph/0009336 v1 28 Sep 2000

Searching for the Higgs Boson at Hadron Colliders using the Missing Mass Method

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Abstract

If the Higgs is produced with a large enough cross section in the *exclusive* reaction $p+\bar{p} \rightarrow p+H+\bar{p}$ it will give rise to a peak at M_H in the *missing mass* (MM) spectrum, calculated from the 4-momenta of the beam particles and the outgoing p and $\bar{p}$. The resolution in MM can be approximately 250 MeV, independent of M_H from 100 GeV to 200 GeV. This high resolution makes a search feasible over nearly this full mass range at the Tevatron with 15 fb^{-1} as hoped for in Run II.

PACS numbers: 13.85.Qk, 12.38.Qk

Typeset using REVTEX

The predominant mode for Higgs production at hadron colliders is gg-fusion [1,2] through a virtual top quark loop. The dominant decay mode up to 135 GeV is to $b\bar{b}$, above which the WW^* mode becomes increasingly important until $M_H > 2M_W$ (160 GeV) when both W are real. By 200 GeV the ZZ mode has grown to 26%. The $\tau^+\tau^-$ mode decreases from 7.6% at 110 GeV to about 2% at 150 GeV. The intrinsic width of a Higgs over this mass region rises, from 5 MeV at $M_H = 130$ GeV, to 16 MeV at $M_H = 150$ GeV, to 650 MeV at $M_H = 180$ GeV [1], so mass resolution is crucial in increasing the signal:background $S : B$ ratio.

One has until now considered the observation of the Higgs in the intermediate mass region 110 GeV to 130 GeV in inclusive reactions to be impossible because of the small $S : B$. The mass resolution in reconstructing a $b\bar{b}$ di-jet is about 10 GeV - 15 GeV, and the QCD background is indeed overwhelming when the signal is so spread out. A high price has to be paid to improve the $S : B$ ratio by selecting relatively rare cases where it is produced in association with a massive particle (W, Z, t) or where it decays to $\gamma\gamma$ (branching fraction $\approx 2 \times 10^{-3}$), where much better mass resolution can be obtained than for the $b\bar{b}$ di-jets.

In the exclusive process $p + \bar{p} \to p + H + \bar{p}$, with no other particles in the final state (we talk in this note in Tevatron terms although all the arguments clearly refer also to the LHC), we use the known 4-momenta of the incoming and outgoing p and $\bar{p}$ to calculate the missing mass from $MM^2 = (p_{b1} + p_{b2} - p_3 - p_4)^2$. The visibility of a signal will depend on the spread in these quantities; any overall scale factor such as would come e.g. from uncertainty in the magnetic fields in the Tevatron only affects the central value, i.e. M_H if a signal is seen. The momentum spread of the incoming beams [3] is 1.0 $\times 10^{-4}$ at the beginning of a store and rises to about 1.6 $\times 10^{-4}$ after 20 hours of collisions. The position of the interaction point $x_\circ, y_\circ, z_\circ$ can be reconstructed with $\sigma \approx 4\mu$m, 4μm and 10μm respectively for central $b\bar{b}$ jets, and about a factor two worse [1] for l^+l^- final states. The outgoing p and $\bar{p}$ tracks can be

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[1] We assume both leptons are tracked in the silicon vertex detectors.

measured after 18.8m of 4.34 Tesla dipoles using several layers of crossed and tilted silicon pixel detectors giving $\sigma_x = \sigma_y \approx 2.5\mu$m over ≈ 1.0m, thus $\sigma_{x'} = \sigma_{y'} = 2.5 \times 10^{-6}$. If $\sqrt{s}$ is the center of mass energy, 2 TeV at the Tevatron in Run II, and the outgoing scattered beam particles have lost fractions ξ_1, ξ_2 of their incident momenta ($\xi = 1 - x_F$ where x_F is Feynman-x), we have approximately $MM^2 = \xi_1 \xi_2 s$. The spread in the reconstructed missing mass, δ_{MM} is a combination of the relative spread $\frac{\delta p_b}{p_b}$ in the beam particles' momenta p_b and the resolution of the "dipole spectrometers" which use the primary interaction point and the outgoing track. With the above parameters this is ≈ 250 MeV, independent of MM.

We note that this method is not limited to Higgs searches but would be sensitive to any relatively narrow massive objects with vacuum quantum numbers.

The visibility of the Higgs by this technique clearly depends on the size of the cross section for the process where the Higgs is produced (in the central region) completely exclusively, i.e. the p and $\bar{p}$ go down the beam pipes each having lost about $\frac{M_H}{2}$ in longitudinal momentum and no other particles are produced. The mechanism is as usual $gg \rightarrow H$ through intermediate loops of heavy particles (predominantly a top loop); this normally leaves the p and $\bar{p}$ in color-octet states and gives rise to color strings filling rapidity with hadrons. However some fraction of the time one or more other gluons can be exchanged which neutralize (in a color sense) the p and $\bar{p}$ and can even leave them in their ground state. In Regge theory this is the double pomeron exchange (DPE) process. Several attempts have been made to calculate this cross section. In 1990 Schäfer, Nachtmann and Schöpf [4] considered diffractive Higgs production at the LHC and SSC, concluding that the cross sections for the exclusive process could not be reliably predicted. Müller and Schramm [5] made a calculation, also for nucleus-nucleus collisions, and concluded that the exclusive process is immeasurably small. In 1991 Bialas and Landshoff [6] calculated from Regge theory that about 1% of all Higgs events may have the p and $\bar{p}$ in the DPE region of $x_F \approx 0.95$, but they did not estimate the *fully exclusive* cross section. In 1994 Lu and Milana [7] obtained an estimate "well below what is likely to be experimentally feasible". In 1995 Cudell and Hernandez [8] made a lowest order QCD calculation with the non-perturbative form factors of the proton tuned to reproduce elastic and soft diffractive cross section measurements. They presented the exclusive production cross section as a function of M_H up to 150 GeV at $\sqrt{s} = 1.8$ TeV. They found a cross section decreasing slowly with M_H from 45 fb at 110 GeV, 13.5 fb at 150 GeV and, by extrapolation, 6.0 fb at 170 GeV (all within a factor two). The total Higgs production cross section by the dominant gg-fusion mechanism is [2] 900 fb, 364 fb and 247 fb respectively so the exclusive fraction decreases from 5% to about 2.4% over this mass range, even higher than the Bialas and Landshoff estimate. There are two very recent calculations. Khoze, Martin and Ryskin [10] find $\sigma(p + p \rightarrow p + H + p) = 0.06$ fb for $M_H = 120$ GeV at $\sqrt{s} = 2$ TeV if the probability S^2_{spect} not to have extra rescattering in the interaction is $S^2_{spect} = 0.1$. Kharzeev and Levin [11] find much more optimistically 19 - 140 fb for $M_H = 100$ GeV at the Tevatron, but do not present the M_H-dependence. Although there are serious differences in the theoretical predictions, we shall show that the more optimistic predictions allow a Higgs discovery at the Tevatron in Run II over the full mass range from 110 GeV to 180 GeV. We take the Cudell and Hernandez (CH) prediction as our benchmark, ignoring any gain from the $\sqrt{s}$ increase from 1.8 TeV to 2.0 TeV and noting that the CH estimate has a factor ≈ 2 uncertainty. It will be seen that even if the true exclusive cross section is lower by an order of magnitude a discovery is still possible over most of this mass range.

We now consider signals and backgrounds, first for $b\bar{b}$, then for $\tau^+\tau^-$ and lastly for $WW^{(*)}$. Table 1 shows a compilation of results.

TABLES

M_H (GeV)	$\sigma(CH)$ (fb)	Mode	BR	σ.BR.BR (fb)	Events 15fb^{-1}	Background /250 MeV
110	45	$b\bar{b}$	0.770	34.6	260	3.75
		$\tau^+\tau^-$	0.076	3.4	26	< 0.1
130	25	$b\bar{b}$	0.525	13.1	96	0.75
		$\tau^+\tau^-$	0.054	1.35	10.0	< 0.1
		WW^*	0.289	0.72	5.4	$\ll 1$
150	13.5	WW^*	0.685	0.93	7.0	$\ll 1$
170	6.0	W^+W^-	0.996	0.58	4.3	$\ll 1$
180	3.5	W^+W^-	0.935	0.34	2.5	$\ll 1$

TABLE I. For various Higgs masses, the exclusive production cross section according to Cudell and Hernandez at 1.8 TeV. Column 5 shows the cross section × branching fractions either to two b-jets or to two charged leptons. A factor 0.5 has been applied to events and background for acceptance/efficiency.

For the $b\bar{b}$ dijet background we take CDF's published cross section [12] $\frac{d\sigma}{dM_{JJ}}$ for two b-tagged jets, which starts at 150 GeV, and extrapolate the fit to the data (which is a factor 2-3 higher than the PYTHIA prediction) down to 110(130) GeV finding 200(40) pb/GeV (in $|\eta| < 2.0, |cos(\theta^*)| < 2/3$). From our other DPE studies, of lower mass dijets [13], we expect that about 10^{-5} of these are DPE ($p+\bar{p} \to p+G+b+\bar{b}+G+\bar{p}$), where G represents a rapidity gap exceeding about 3 units, assuming this fraction is not E_T-dependent. If the fraction is smaller, so much the better. That gives 0.5(0.1) fb per 250 MeV bin, to be compared with a signal of around 45(25) fb [8]. With 15 fb^{-1} and assuming 50% acceptance for both signal and background we have 260(96) events (see Table 1) on a background of 3.75(0.75). Even if the CH predictions are optimistic by an order of magnitude these signals exceed 10σ. We have not put in a factor for b-tagging efficiency (which affects the signal and the background the same way apart from differences in the angular distributions); in CDF it was about 35% per jet in Run I at $M_{JJ} = 200$ GeV. It will be higher in Run II with more silicon coverage and at smaller masses; also we only have to tag one jet, so this is probably a very modest reduction in both signal and background. We have put in an acceptance of 50% for the forward p and $\bar{p}$ for the signal and background, assuming the $|t|$-distribution is as expected for high mass DPE. The $S : B$ ratio rises with M_H in this mass region 110-130 GeV.

The Higgs branching fraction to $\tau^+\tau^-$ drops from 7.6% at 110 GeV to 5.4% at 130 GeV, as the WW^* mode grows in competition. Backgrounds to the proposed search could come from normal Drell-Yan $(DY)/Z$ production together with 0,1, or 2 associated high-x_F tracks; in the first two cases leading (anti-)protons come from different events (pile-up); we discuss ways of minimizing this later. In the third case the events look like continuum DPE production of DY pairs, together with associated particles. CDF found [14] single diffractive (SD) production of W at the level of (1.15 ± 0.55)% of non-diffractive (ND) production. A recent CDF study [13] of jet production at low E_T has found a breakdown of factorization for jet production in the sense that $\frac{\sigma_{DPE}}{\sigma_{SD}} \approx 5 \times \frac{\sigma_{SD}}{\sigma_{ND}}$. Let us assume this fraction is the same for high-mass DY, and then assume (conservatively) factorization break-down by the same factor 5 for high mass DY. Then DPE production of high mass DY is at the relative level of 5.10^{-4}. From a CDF study [15] of high mass e^+e^- and $\mu^+\mu^-$ we infer that $\frac{d\sigma}{dM}$ for the region 110-130 GeV is 100 ± 40 fb GeV^{-1}. Therefore the cross section for $p\bar{p} \to pG\mu^+\mu^- XG\bar{p}$, where X represents additional associated hadrons, n_{ass} of which are charged tracks, is expected to be about 100 fb GeV^{-1} $\times$ 5.10^{-4} $=$ 0.05 fb.GeV^{-1} or 0.2 events in 15 fb^{-1} in a 250 MeV bin. Note however that for the exclusive Higgs production process $n_{ass} = 0$, while for generic DY/Z production $< n_{ass} > \approx 16$ [16] for $p_T \geq 0.2$ GeV, $|\eta| \leq 1$. We claim that the observation of lepton pairs with no associated tracks, $n_{ass} = 0$, would already be good evidence for exclusive Higgs production The CH cross section $\sigma(p+\bar{p} \to p+H+\bar{p}) \times$ branching fraction $H \to \tau^+\tau^-$ of 3.4 (1.3) fb at 110 (130) GeV gives 26 (10) events on a background of less than 1 event if we include a 50% acceptance/efficiency factor. High p_T τ are easily recognized: one-prong decays are 85% and three-prong are 15%. A high p_T 3-prong τ decay is quite distinct from a QCD hadronic jet because it is tightly collimated, with $M_{eff} < M_\tau = 1.78$ GeV.

The Higgs branching fraction to $WW^{(*)}$ rises from 29% at 130 GeV to 69% (97%) at 150 (170) GeV (see Table 1). Beyond 180 GeV it falls because of competition from the $ZZ^{(*)}$ mode. We will only consider the leptonic decay modes of the W because of the spectacular cleanliness of the event vertices: either $ee, e\mu, \mu\mu, e\tau, \mu\tau$ or $\tau\tau$ and no other charged particle tracks ($n_{ass} = 0$), together with large $\not{E}_T$ and the forward p and $\bar{p}$.

Precision timing ($\approx$ 30 ps) on the p and $\bar{p}$ will not only check that they came from the same interaction but can pin down the vertex z_{vtx} to about 1 cm. To estimate the signal we extrapolate the Cudell and Hernandez (1.8 TeV) exclusive cross sections from 150 GeV (11 - 16 fb) to 180 GeV (2.5 - 5 fb). Putting in $BR(H \to WW^{(*)})$, a 10% probability that both W decay leptonically, and assuming that, by using lower than usual trigger thresholds on the central leptons and $\not{E}_T$, we can keep the efficiency at 50%, we find in 15 fb^{-1} 7 events for $M_H = 150$ GeV falling to 2.5 events at $M_H = 180$ GeV. To estimate the background we refer to the observation of five W^+W^- events by CDF [17] [2] which gave $\sigma(p+\bar{p} \rightarrow W^+W^-X)$ $= 10.2 \pm 6.5$ pb which we assume to be roughly uniform over $160 < M_{WW} < 180$ GeV so $d\sigma/dM \approx 0.5$ pb GeV^{-1}. Below 160 GeV the cross section for WW^* will be smaller. The observed W^+W^- cross sections are consistent with Standard Model NLO expectations, ignoring the Higgs, of $\sigma(p+\bar{p} \rightarrow W^+W^-X) = 10$ pb at 1.8 TeV. We multiply by the 10% probability that *both* W decay leptonicaly and apply a 50% "efficiency" for detecting the $p, \bar{p}$ and both leptons and recognizing the event as $l^+l^-\not{E}_T$. This is high compared with the efficiency in ref [19], which was 5.4% - 8.9%, because due to the lack of background we can surely lower the selection cuts on $\not{E}_T, p_T(e), p_T(\mu)$ and $p_T(\tau)$ significantly. We assume as before that about 5×10^{-4} of these are from DPE, giving $\approx 3 \times 10^{-3}$ fb/250 MeV. For any non-diffractive background we can asssume that the associated charged multiplicity on the WW vertex is Poisson-distributed with a mean of about 16, which is what CDF observes [16] for Z events. This non-diffractive background then has a completely negligible tail at $n_{ass} = 0$. Thus the backgrounds in all the dilepton channels with $n_{ass} = 0$ are negligible, and even 3 or 4 events at the same MM would constitute a discovery.

In order not to be limited by the number of interactions in a bunch crossing one should not use a method requiring rapidity gaps (as normally measured in counters or calorimeters). This is where the strength of using only leptonic decays of the W^+W^- enters. Tracking back the l^+ and l^- to their common vertex (which can be done using the SVX detectors in CDF to a precision $\sigma_x = \sigma_y \approx 10\mu$m and $\sigma_z < 20\mu$m) there will, for the exclusive process, be *no other particles* coming from the same vertex, $n_{ass} = 0$. All "normal" production of W-pairs will on the contrary have a highly active vertex with many associated hadrons. (Even in the absence of dipole spectrometers one can plot n_{ass} and look for a peak at $n_{ass} = 0$. This would be "evidence" for exclusive Higgs production. Enough events of this kind would enable one to make fits of kinematic quantities as a function of M_H.) One can then plot the missing

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[2] DØ earlier found one e^+e^- event [18] in 14 pb^{-1}.

mass MM for these superclean events with two and only two oppositely charged leptons on a vertex, with and without $\not{E}_T$. A Higgs signal will be a cluster of events at the same MM within the resolution ($\approx$ 250 MeV).

If the exclusive cross section is indeed big enough to provide a few events in the data, but continuum background were to be an issue, one has further recourse to angular distributions [20]. The H is a scalar and decays isotropically, while generic W^+W^- production is not isotropic with respect to the beam axis; also the W's (like the τ's) will have opposite polarizations. This is not generally true for the backgrounds, so one can plot quantities sensitive to these kinematic features as a function of MM to look for localised structure.

With multiple interactions in a bunch crossing a background could come from two single diffractive collisions, one producing the p and the other the $\bar{p}$. One way of reducing this is to require longitudinal momentum balance. However "pile-up" can be reduced by one to two orders of magnitude by backing up the silicon detectors in the pots by counters with excellent timing resolution. A conventional fast detector would be a quartz (for radiation hardness) block producing Cerenkov light viewed by a fast photomultiplier. One can achieve 30 ps timing resolution on the p and $\bar{p}$, much better than the ($\approx$ 1 ns) spread between random concidences. There are ideas [22] for Fast Timing Cerenkov Detectors ($FTCD$) using microchannel plates which might achieve a resolution of a few ps. The sum of the p and $\bar{p}$ times is a constant for genuine coincidences, and their difference Δt is a measure of z_{vtx} at the level of 1 cm (for Δt = 30 ps).

In Run IIA both CDF and DØ will have one dipole spectrometer arm. There are various studies that can be done already in Run IIA, before the second arm spectrometer is installed, to learn more about the feasibility of this proposed Higgs search.

1) Measure the $b\bar{b}$ dijet mass spectrum, $M_{b\bar{b}}$, over the mass range up to 150 GeV to complement the earlier CDF measurement [12].

2) Measure the l^+l^- mass spectrum in the region of $M_{l^+l^-}$ 80-180 GeV, carefully studying the associated charged multiplicity n_{ass} on the primary l^+l^- vertex for different mass ranges.

3) Measure the production of exclusive χ_c° and χ_b° states. Note that some of these states

have the same quantum numbers [3], $I^G J^{PC} = 0^+0^{++}$, as the vacuum and the Higgs.

In summary, using the missing mass method that we propose, the resolution in Higgs mass can be improved to 250 MeV, increasing the $S:B$ by a factor $\approx$ 40 - 60. The method works not only for $b\bar{b}$ Higgs decay but also for $\tau^+\tau^-$, W^+W^- and ZZ decays, and the number of neutrinos in the final state is irrelevant for the mass resolution.

This work was supported by the U.S. Department of Energy and the Institute for Theoretical and Experimental Physics (ITEP),Russia. We thank P.Bagley and C. Moore for information on the Tevatron, and V.Kim, D.Kharzeev and E.Levin for discussions on exclusive Higgs production.

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[3] Allowed quantum numbers for exclusive states in DPE are $I^C = 0^+$ but any J^P [23].

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