Diffractive Higgs Boson Production at the Fermilab Tevatron and the CERN Large Hadron Collider

R. Enberg,[1] G. Ingelman,[1,2] A. Kissavos,[1] and N. Tîmneanu[1]
[1]*High Energy Physics, Uppsala University, Box 535, S-75121 Uppsala, Sweden*
[2]*Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22603 Hamburg, Germany*
(Received 2 April 2002; published 31 July 2002)

Improved possibilities to find the Higgs boson in diffractive events, having less hadronic activity, depend on whether the cross section is large enough. Based on the soft color interaction models that successfully describe diffractive hard scattering at DESY HERA and the Fermilab Tevatron, we find that only a few diffractive Higgs events may be produced at the Tevatron, but we predict a substantial rate at the CERN Large Hadron Collider.

DOI: 10.1103/PhysRevLett.89.081801 PACS numbers: 14.80.Bn, 12.38.Lg, 13.85.Rm

The Higgs boson is predicted as the physical manifestation of the mechanism giving masses to the fundamental particles in the standard model. The discovery of this missing link is of top priority in particle physics. Based on the discovery [1,2] of diffractive hard scattering processes [3], it has been considered whether the Higgs can be more easily observed in diffractive events at high energy hadron colliders. The lower hadronic activity in such events with large rapidity gaps should improve the possibilities to reconstruct the Higgs from its decay products.

In single diffraction a beam hadron emerges quasielastically scattered with a large fraction of the original momentum and separated by a gap in polar angle (pseudorapidity $\eta = -\ln \tan\theta/2$) from a produced hadronic system X. Particularly clean events are produced in so-called double Pomeron exchange (DPE), where both beam hadrons emerge intact separated by rapidity gaps from a centrally produced X system. An extreme possibility is exclusive Higgs production, $p\bar{p} \to p\bar{p}H$, where the central system is just a Higgs boson that may be reconstructed using a missing mass method [4]. The crucial question for the usefulness of these diffractive Higgs production processes is whether their cross sections are large enough.

Predicted cross sections vary by orders of magnitude between calculations based on different models [5]. Some predictions for the Fermilab Tevatron are large enough to be of experimental interest, whereas others are not. The more limited energy, compared to the CERN Large Hadron Collider (LHC), implies a stronger kinematical suppression to produce the heavy Higgs boson in such an X system, having only a fraction of the overall invariant mass of the collision. In this Letter we improve on this theoretical uncertainty by presenting results on diffractive Higgs production based on the recently developed soft color interaction models. In contrast to other models used for estimating the diffractive Higgs cross section, our models have proven very successful in reproducing experimental data on diffractive hard scattering processes both from the DESY ep collider HERA and from $p\bar{p}$ collisions at the Tevatron [6]. This puts us in a good position to give predictions on diffractive Higgs production.

The soft color interaction (SCI) model [7] and the generalized area law (GAL) model [8] were developed in an attempt to better understand nonperturbative QCD dynamics and provide a unified description of all final states. The basic assumption is that soft color exchanges give variations in the topology of the confining color string fields which then hadronize into different final states, e.g., with and without rapidity gaps or leading protons. Also other kinds of experimental results are described in a very economical way with only one new parameter. Particularly noteworthy is the turning of a $c\bar{c}$ pair in a color octet state into a singlet state producing charmonium [9] in good agreement with observed rates.

The SCI model [7] is implemented in the Lund Monte Carlo programs LEPTO [10] for deep inelastic scattering and PYTHIA [11] for hadron-hadron collisions. The hard parton level interactions are given by standard perturbative matrix elements and parton showers, which are not altered by the softer nonperturbative effects. The SCI model then applies an explicit mechanism where color-anticolor (corresponding to nonperturbative gluons) can be exchanged between the emerging partons and hadron remnants. The probability for such an exchange cannot be calculated and is therefore taken to be a constant given by a phenomenological parameter P. These color exchanges modify the color connections between the partons and thereby the color string-field topology, resulting in different final states after the standard Lund model [12] has been applied for hadronization (Fig. 1).

The GAL model [8] is similar in spirit, but is formulated in terms of interactions between the strings and not the partons. Soft color exchanges between strings also change the color topology, resulting in another string configuration (Fig. 1). A generalization of the area law suppression e^{-bA} in the Lund model gives the probability for two strings to interact as $P = P_0[1 - \exp(-b\Delta A)]$ depending on the resulting change ΔA of the areas swept out by the strings in momentum space. The exponential factor favors

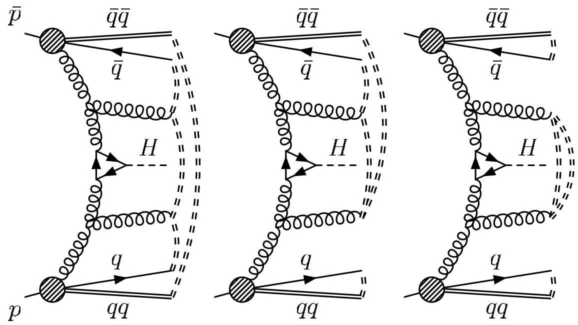

FIG. 1. Higgs production in $p\bar{p}$ collisions with string topologies (double-dashed lines) before and after soft color interactions in the SCI or GAL model, resulting in events with one or two rapidity gaps (leading particles).

making "shorter" strings, e.g., events with gaps, whereas making "longer" strings is suppressed. The fixed probability for soft color exchange in SCI is thus in GAL replaced by a dynamically varying one.

The Monte Carlo implementations of SCI and GAL generate complete events with final state particles. This allows an experimental approach to classify events depending on the final state: e.g., gaps or no gaps, leading (anti)-protons, charmonium, etc. Thus, one obtains predictive models where a single parameter (P and P_0), regulating the amount of soft color exchanges, has a universal value determined from HERA rapidity gap data.

The SCI and GAL models give various diffractive hard scattering processes by simply choosing different hard scattering subprocesses in PYTHIA. Rapidity gap events containing a W, a dijet system, or bottom quarks are found to be in agreement with Tevatron data [6]. The CDF data [13] on dijets in DPE events are also reproduced [6,14], both in cross section and in more exclusive quantities such as the dijet mass fraction. Thus, our models successfully pass these tests given by processes with similar dynamics as diffractive Higgs production.

The properties of the Higgs boson in the standard model are fixed, except for its mass. The present lower limit is 114.1 GeV and χ^2 fits to electroweak data favors $m_H <$ 212 GeV [15]. The latest LEP data give an indication ($\sim 2.1\,\sigma$) of a Higgs with a mass of 115.6 GeV [16]. We therefore use $m_H = 115$ GeV as our main alternative, but also consider m_H up to 200 GeV.

Higgs production at the Tevatron and the LHC can proceed through many subprocesses, which are included in PYTHIA version 6 [11]. The dominant one is $gg \to H$, which accounts for 50% and 70% of the cross section (for $115 < m_H < 200$ GeV) at the Tevatron and LHC, respectively. In this process (see Fig. 1), the gluons couple to a quark loop with the dominant contribution from the top due to its large coupling to the Higgs. Other production channels are $q_i\bar{q}_i \to H$, $q_i\bar{q}_i \to ZH$, $q_i\bar{q}_j \to WH$, $q_iq_j \to q_kq_lH$, and $gg \to q_k\bar{q}_kH$. Their relative contributions depend on both the Higgs mass and the center of mass energy.

The overall cross sections are obtained by folding the subprocess cross sections with the parton density distributions (we use CTEQ5L [17]). This basic factorization is proven for inclusive hard scattering processes. It is assumed to hold in our model also since the soft hadronization processes should not influence the cross section for the hard subprocess, but affect only the distribution of hadrons in the final state.

After the standard parton showers in PYTHIA, SCI or GAL is applied using the parameter values $P = 0.5$ and $P_0 = 0.1$, respectively. This gives a total sample of Higgs events, with varying hadronic final states. Single diffractive Higgs events are selected using one of two criteria: (1) a leading (anti)proton with $x_F > 0.9$ or (2) a rapidity gap in $2.4 < |\eta| < 5.9$ as used by the CDF Collaboration. Applying the conditions in both hemispheres results in a sample of DPE Higgs events. The resulting cross sections and relative rates are shown in Fig. 2 as a function of the Higgs mass and for $m_H = 115$ GeV in Table I. The results have an uncertainty of about a factor of 2 related to details of the hadron remnant treatment and choice of parton density parametrization.

The cross sections at the Tevatron are quite low in view of the luminosity to be achieved in Run II. Higgs in DPE events are far below an observable rate. For $m_H =$ 115 GeV, only tens of single diffractive Higgs events are predicted. Only the most abundant decay channel, $H \to b\bar{b}$, can then be of use, and a very efficient b-quark tagging and Higgs reconstruction is required. The conclusion for the Tevatron is that the advantage of a simplified

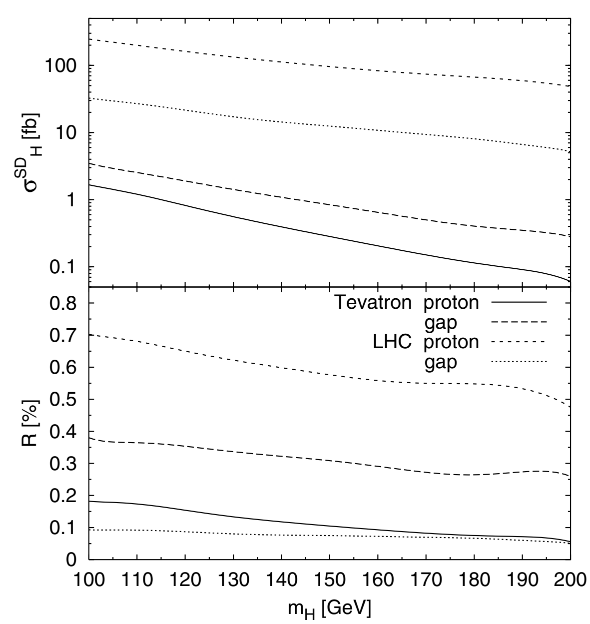

FIG. 2. Predictions from the SCI model for Higgs production in single diffractive events defined by a leading proton or rapidity gap criterion at the Tevatron and LHC. Absolute cross sections and relative ratio (single diffractive to all Higgs) versus the Higgs mass.

TABLE I. Cross sections at the Tevatron and LHC for Higgs in single diffractive (SD) and DPE events, using leading proton or rapidity gap definitions, as well as relative rates (SD/all and DPE/SD) and number (#) of events, obtained from the soft color exchange models SCI and GAL.

	Tevatron		LHC	
$m_H = 115$ GeV	$\sqrt{s} = 1.96$ TeV		$\sqrt{s} = 14$ TeV	
	$\mathcal{L} = 20$ fb^{-1}		$\mathcal{L} = 30$ fb^{-1}	
σ [fb] Higgs total	600		27 000	
	SCI	GAL	SCI	GAL
Higgs in SD:				
σ [fb] leading-p	1.2	1.2	190	160
σ [fb] gap	2.4	3.6	27	27
R [%] leading-p	0.2	0.2	0.7	0.6
R [%] gap	0.4	0.6	0.1	0.1
$\#H$ + leading-p	24	24	5700	4800
$\hookrightarrow \#H \to \gamma\gamma$	0.024	0.024	6	5
Higgs in DPE:				
σ [ab] leading-p's	0.12	0.24	190	160
σ [ab] gaps	2.4	7.2	0.27	5.4
R [%] leading-p's	0.01	0.02	0.1	0.1
R [%] gaps	0.1	0.2	0.001	0.02
$\#H$ + leading-p's	0.0024	0.0048	6	5

reconstruction of the Higgs in the cleaner diffractive events is not really usable in practice due to a too small number of diffractive Higgs events being produced.

In contrast, the high energy and luminosity available at the LHC facilitate a study of single diffractive Higgs production, where the striking $H \to \gamma\gamma$ decay should also be observed. Also a few DPE Higgs events may be observed. The quality of a diffractive event changes, however, at LHC energies. Besides the production of a hard subsystem and one or two leading protons, the energy is still enough for populating forward detector rapidity regions with particles. As seen in Fig. 3, the multiplicity of particles is considerably higher at the LHC, compared to the Tevatron. The requirement of a "clean" diffractive Higgs event with a large rapidity gap in an observable region cannot be achieved without paying the price of a lower cross section. Requiring gaps instead of leading protons gives a substantial reduction in the cross section, as seen in Table I. Note that the high luminosity mode of LHC cannot be used, since the resulting pileup of events would destroy the rapidity gaps.

The Monte Carlo model does not include any specific mechanism for the exclusive reaction $pp \to ppH$, and our simulations did not produce any such events.

For comparison we have also investigated single diffractive Higgs production in the Pomeron model. This is based on the Regge framework with the exchange of a Pomeron with vacuum quantum numbers [18], given by an effective Pomeron flux [1]. In case of a hard scattering process, which resolves an underlying parton level process, a parton structure of the Pomeron may be considered [1], and the data on diffractive deep inelastic scattering from HERA can be well described by fitting parton density functions in the Pomeron [19]. Applying exactly the same model for $p\bar{p}$ gives, however, diffractive hard scattering cross sections that are up to 2 orders of magnitude larger than what is observed at the Tevatron. Although this can be cured by appropriately modified Pomeron flux functions, it may indicate a deeper nonuniversality problem of the Pomeron model [6].

To get numerical estimates we use the Pomeron model implemented in the POMPYT Monte Carlo [20]. The parton densities in the Pomeron are from a fit (parametrization I in [21]) to the diffractive structure function measured at HERA. The Pomeron flux [22] has been renormalized [23] so as to reproduce the observed relative rates of diffractive hard scattering processes both at HERA and the Tevatron.

The Pomeron model is constructed to give a leading proton with a spectrum essentially as $1/(1 - x_F)$. It is developed for situations where $x_F \to 1$ dominates and is usually taken to be trustworthy only for $x_F > 0.9$. As shown in Fig. 4, however, this distribution is strongly distorted in this case due to the kinematical condition imposed by the Higgs mass. At the Tevatron energy, the cross section is dominated by smaller x_F. This makes the results of the model sensitive to a phase space region where the Pomeron model cannot be safely applied. In particular, the diffractive Higgs cross section will depend on whether the usual requirement $x_F > 0.9$ is applied or not. The resulting cross section also depends strongly on what conditions for diffraction are applied. The requirement at the Tevatron experiments of no particles in the rapidity region $2.4 < |\eta| < 5.9$ imposes a very strong reduction. If the gap can be in a more forward rapidity region, based on extended detector coverage, a much larger rate of diffractive

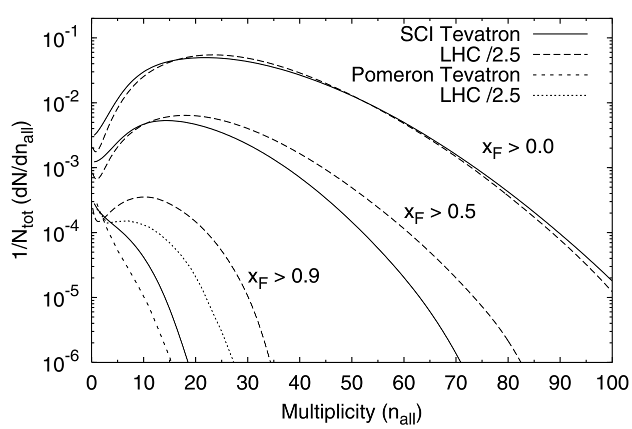

FIG. 3. Multiplicity (for LHC divided by 2.5) in the region $2.4 < |\eta| < 5.9$ in the hemisphere of a leading proton with the indicated minimum x_F, for Higgs events from the SCI and the Pomeron models.

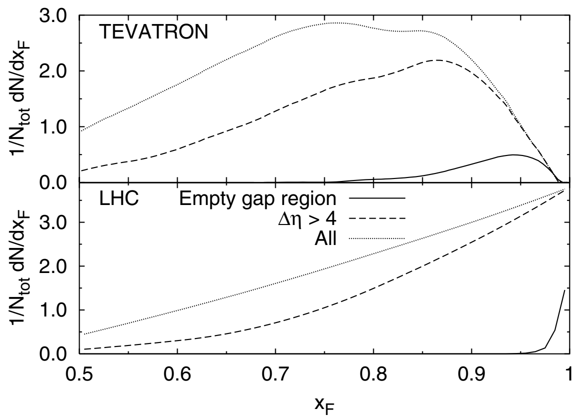

FIG. 4. Distribution in $x_F = p_{\|}/p_{\max}$ of leading protons in single diffractive Higgs production in the Pomeron model (POMPYT Monte Carlo) applied to Tevatron and LHC energies. Curves are for all such events (dotted line), events with no particles in $2.4 < |\eta| < 5.9$ (solid line), and with a gap of size at least four units in rapidity (dashed line).

Higgs is obtained as illustrated in Fig. 4. Similar, but not as strong, effects are also present at LHC energies.

In view of this, predictions for the diffractive Higgs cross section will be somewhat uncertain in the Pomeron model. To give some numbers, nevertheless, we use criterion (1) with a leading proton with $x_F > 0.9$, but no specific gap requirement. This gives a cross section of 2.8 fb for single diffractive Higgs production at the Tevatron and 410 fb at the LHC. This includes reduction factors of 5.2 and 9.2, respectively, from the Pomeron flux renormalization [23], making HERA and Tevatron data compatible but leaving an extrapolation uncertainty for the LHC energy.

In contrast to the Pomeron model, the SCI and GAL models are constructed to describe different final states through a general mechanism for soft color exchanges giving a smooth transition between diffractive and non-diffractive events. This implies a better stability with respect to variations of the conditions used to define diffractive events. Moreover, the energy dependence of SCI and GAL has proven successful. Data on various diffractive hard scattering processes at HERA and Tevatron are well reproduced. The soft color exchange models should, therefore, give more reliable predictions.

In conclusion, we have investigated the prospects for discovering the Higgs boson in diffractive events having a lower hadronic background activity that should simplify the reconstruction of the Higgs from its decay products. We find that the rate of diffractive Higgs events at the Tevatron will be too low to be useful. Therefore, the Higgs must here be searched for in normal events with their larger hadronic activity. At LHC diffractive events are not as clean as expected, since the large available energy produces an increased hadronic activity. Still, LHC should facilitate studies of Higgs in single diffraction and the observation of some DPE events with a Higgs boson.

[1] G. Ingelman and P. E. Schlein, Phys. Lett. **152B**, 256 (1985).
[2] UA8 Collaboration, R. Bonino *et al.*, Phys. Lett. B **211**, 239 (1988); A. Brandt *et al.*, Phys. Lett. B **297**, 417 (1992); **421**, 395 (1998).
[3] G. Ingelman, hep-ph/9912534.
[4] M. G. Albrow and A. Rostovtsev, hep-ph/0009336.
[5] A. Bialas and P. V. Landshoff, Phys. Lett. B **256**, 540 (1991); H. J. Lu and J. Milana, Phys. Rev. D **51**, 6107 (1995); D. Graudenz and G. Veneziano, Phys. Lett. B **365**, 302 (1996); J. R. Cudell and O. F. Hernandez, Nucl. Phys. **B471**, 471 (1996); M. Heyssler, Z. Kunszt, and W. J. Stirling, Phys. Lett. B **406**, 95 (1997); V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. C **14**, 525 (2000); M. Boonekamp, R. Peschanski, and C. Royon, Phys. Rev. Lett. **87**, 251806 (2001); B. Cox, J. Forshaw, and B. Heinemann, Phys. Lett. B **540**, 263 (2002).
[6] R. Enberg *et al.*, Phys. Rev. D **64**, 114015 (2001).
[7] A. Edin *et al.*, Phys. Lett. B **366**, 371 (1996); Z. Phys. C **75**, 57 (1997).
[8] J. Rathsman, Phys. Lett. B **452**, 364 (1999).
[9] A. Edin *et al.*, Phys. Rev. D **56**, 7317 (1997); C. Brenner Mariotto *et al.*, Eur. Phys. J. C **23**, 527 (2002).
[10] G. Ingelman *et al.*, Comput. Phys. Commun. **101**, 108 (1997).
[11] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
[12] B. Andersson *et al.*, Phys. Rep. **97**, 31 (1983).
[13] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **85**, 4215 (2000).
[14] N. Timneanu *et al.*, hep-ph/0206147, proc. DIS 2002.
[15] D. Abbaneo *et al.*, Report No. CERN-EP-2000-016.
[16] LEP Higgs Working Group, hep-ex/0107029.
[17] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).
[18] K. Goulianos, Phys. Rep. **101**, 169 (1983).
[19] H1 Collaboration, T. Ahmed *et al.*, Phys. Lett. B **348**, 681 (1995); C. Adloff *et al.*, Z. Phys. C **76**, 613 (1997); ZEUS Collaboration, M. Derrick *et al.*, Z. Phys. C **68**, 569 (1995).
[20] P. Bruni *et al.*, http://www3.tsl.uu.se/thep/pompyt/.
[21] T. Gehrmann and W. J. Stirling, Z. Phys. C **70**, 89 (1996).
[22] A. Donnachie and P. V. Landshoff, Phys. Lett. B **191**, 309 (1987); **198**, 590(E) (1987).
[23] K. Goulianos, Phys. Lett. B **358**, 379 (1995); K. Goulianos and J. Montanha, Phys. Rev. D **59**, 114017 (1999).