

Higgs Hadroproduction at Large Feynman x

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Abstract

We propose a novel mechanism for the production of the Higgs boson in hadronic collisions, which utilizes the presence of heavy quarks in the proton wave function. In these inclusive reactions the Higgs boson carries 80% or more of the projectile's momentum. We predict that the cross section $d\sigma/dx_F(p\bar{p} \rightarrow HX)$ for the inclusive production of the Standard Model Higgs coming from nonperturbative intrinsic bottom Fock states is of order 50 fb at LHC energies, peaking in the region of $x_F \sim 0.9$. Our estimates indicate that the corresponding cross section coming from gluon-gluon fusion at $x_F = 0.9$ is negligible, of order of 0.07 fb, and therefore this peak should be clearly visible. The predicted cross section for the production of the Standard Model Higgs coming from nonperturbative intrinsic bottom Fock states in the proton is sufficiently large that detection at the Tevatron may be possible.

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1 Introduction

Theoretical predictions for the production of the Higgs at the Tevatron and the LHC, and the relevant QCD backgrounds, have been extensively developed [1, 2]. The main hadroproduction mechanisms for $pp(\bar{p}) \rightarrow HX$ are gluon fusion $gg \rightarrow H$ through the top quark triangle loop, weak-boson fusion subprocesses such as $q\bar{q} \rightarrow q\bar{q}WW \rightarrow q\bar{q}H$, Higgs-strahlung processes $q\bar{q} \rightarrow W(Z)H$, and associated top pair production $gg \rightarrow t\bar{t}H$, which again utilizes the large coupling of the Higgs to the heavy top quark. A common characteristic of these reactions is the strong dominance of the production cross section $d\sigma/dx_F^H$ at central rapidities, i.e. $x_F^H = 2p_L^H/\sqrt{s} \simeq 0$, particularly for the reactions initiated by the gluon distribution in the colliding proton or antiproton. In each case the cross section falls as a power of $(1 - x_F^H)^n$ at large x_F^H , $n \simeq 3 \rightarrow 5$, as one approaches the fragmentation regions.

In this paper we will discuss a novel QCD mechanism for Higgs hadroproduction in which the Higgs is produced at large $x_F^H \geq 0.8$, a regime where we expect that backgrounds from other QCD and Standard Model processes should be small.

One can demonstrate from the operator product expansion [3] that the proton has finite probability for its wavefunction to contain intrinsic heavy flavors $s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t}$ through its quantum fluctuations. The dominant $|uudQ\bar{Q}\rangle$ bound-state configuration occurs when the wavefunction is minimally off its energy-shell; i.e., the most likely configuration occurs when all of the constituents have the same rapidity [4, 5]. In terms of the light-front fractions $x_i = k_i^+/P^+$, the light-front wavefunction of a hadron is maximal when the constituents have light-front momentum fractions $x_i \propto \sqrt{k_{\perp i}^2 + m_i^2}$ with $\sum_i x_i = 1$. Thus the heavy Q and \bar{Q} quarks in the $|uudQ\bar{Q}\rangle$ Fock state will carry most of the proton's momentum. A typical configuration is $x_Q \sim x_{\bar{Q}} \sim 0.4$ and $x_q \sim 0.07$.

The most direct test of intrinsic charm is the measurement of the charm quark distribution $c(x, Q^2)$ in deep inelastic lepton-proton scattering $\ell p \rightarrow \ell' cX$. The data from the European Muon Collaboration (EMC) experiment [6], show an excess of events in the charm quark distribution at $x_{bj} \approx 0.3$, at a rate at least an order of magnitude beyond predictions based on gluon splitting and DGLAP evolution. Next-

to-leading order (NLO) analyses [7] show that an intrinsic charm component, with probability of order 1%, is needed to fit the EMC data in the large x_{bj} region. This value is consistent with an estimate based on the operator product expansion [3]. The importance of further direct measurements of the charm and bottom distributions at high x_{bj} in deep inelastic scattering has been stressed by Pumplin, Lai, and Tung [8, 9]. These authors also give a survey of intrinsic charm models derived from perturbation theory and non-perturbative theory (based on meson-nucleon fluctuations), as well as the current experimental constraints from deep inelastic lepton scattering.

Intrinsic charm leads also to the production of charmed hadrons at high x_F and to charmonium production at high x_F in hadronic collisions. A review is presented in ref. [10]. Measurements of $pp \rightarrow \Lambda_c X$ at high x_F and small p_T have been reported by the SELEX experiment at Fermilab [11, 12], in agreement with intrinsic charm predictions [13]. The observation of doubly charmed baryon $\Xi_{cc}^+(3520)$ with mean $\langle x_F \rangle \simeq 0.33$ has also been reported by the SELEX collaboration [14], which points to the presence of double-IC Fock state fluctuations $|uudc\bar{c}\bar{c}\bar{c}\bar{c}\bar{c}\bar{c}\rangle$ in the proton. Such fluctuations also lead to the production of two J/ψ 's [15] at large x_F and small p_T . Double- J/ψ events at a high combined $x_F \geq 0.5$ were in fact observed by NA3 [16].

As noted in ref. [10], the presence of high- x intrinsic heavy quark components in the proton's structure function will also lead to Higgs production at high x_F through subprocesses such as $gb \rightarrow Hb$; such reactions could be particularly important in MSSM models in which the Higgs has enhanced couplings to the b quark [17].

In this paper we shall show how one can utilize the combined high x momenta of the Q and \bar{Q} pair to produce the Higgs inclusively in the reaction $pp \rightarrow HX$ with 80% or more of the beam momentum. The underlying subprocess which we shall utilize is $(Q\bar{Q})g \rightarrow H$.

The probability for intrinsic heavy quark Fock states is suppressed as $\frac{\Lambda^2}{m_Q^2}$, corresponding to the power-fall off the matrix element of the effective non-Abelian twist-six $gg \rightarrow gg$ operator $\langle p|G_{\mu\nu}^3|p \rangle$ in the proton self-energy [3]. This behavior also has been obtained in explicit perturbative calculations [18]. However, the $\frac{1}{m_Q^2}$ suppression in the intrinsic heavy quark probability is effectively compensated by the Higgs coupling to the heavy quark, which is of order $G_F m_Q^2$ in the rate. In fact, as we shall

show, production from the heavy intrinsic $|uudb\bar{b}\rangle$ Fock state is also enhanced due to the increased probability of its overlap with the small-size Higgs wavefunction in comparison with $|uudc\bar{c}\rangle$. Since $x_F^H = x_1(Q\bar{Q}) - x_g$, the Higgs is produced with approximately the sum of the Q and \bar{Q} momenta, and therefore the Higgs hadroproduction cross section $\frac{d\sigma}{dx_F}(pp \rightarrow HX)$ benefits from intrinsic charm, bottom, and even intrinsic top fluctuations in the projectile hadron.

It is also important to note that the dominant $|uudQ\bar{Q}\rangle$ Fock state of the projectile proton, arising from the cut of the G^3 non-Abelian operator in the proton self energy, requires the $Q\bar{Q}$ pair to be in a color-octet configuration. Thus the $Q\bar{Q}$ pair in the proton $|(uud)_{8C}(Q\bar{Q})_{8C}\rangle$ Fock state can be converted, by a single gluon exchange with the target in the hadronic collision, to a color-singlet Higgs through the matrix element $\langle (Q\bar{Q})_{8C} | G^{\mu\nu} | H \rangle$. A second gluon exchange with the target nucleon allows one to produce the Higgs diffractively or semi-inclusively: $pp \rightarrow H + p + X$, where the final state proton from the target is produced isolated in rapidity [10].

Intrinsic heavy quark Fock states can thus be remarkably efficient in converting collision energy to Higgs production energy. We thus advocate searching for the Higgs at values of x_F as large as 0.8. The characteristic shape of the IQ Higgs signal will be a peak at large x_F , sitting on the rapidly falling power-law suppressed contributions from central rapidity Higgs hadroproduction processes such as $gg \rightarrow H$. QCD backgrounds to the $H \rightarrow b\bar{b}$ decay from subprocesses such as $gg \rightarrow b\bar{b}$ will also be power law suppressed at high x_F .

It is interesting that in principle it is possible to use the 7 TeV LHC beam and the $gQ\bar{Q} \rightarrow H$ subprocess in a fixed target mode $pA \rightarrow HX$, which together with nuclear Fermi momentum, can lead to light Higgs production at threshold.

In a previous paper [10] we considered doubly diffractive Higgs production $pp \rightarrow p + H + p$, arising from the heavy quark Fock state component, where the Higgs is produced in the fragmentation region of one of the colliding protons. The presence of a large rapidity gap and the possibility to perform a missing mass measurement which only needs detection of the two final-state protons substantially increases the chances to detect the high x_F Higgs particle, since its decay to a specific channel is not required. In this case the magnitude of the cross section of Higgs production

reaches a level which can be measured at LHC with a proper trigger system.

In this paper we will estimate the cross section for inclusive Higgs production, both at the LHC and the Tevatron, arising from the proton heavy quark Fock state. Although we do not have the advantage of the missing mass experiment as in the exclusive doubly-diffractive case, the cross section itself is considerably larger. Since the Higgs can acquire most of the momentum of the intrinsic heavy quark pair, it will be produced at quite large x_F values, where the background from multi-particle production is small.

2 Inclusive Hadroproduction of the Higgs from Intrinsic Heavy Flavors

We start our analysis with the totally inclusive case, described by the diagram of Fig. 1. Since the remnants of both protons are color octets, no rapidity gap is ex-

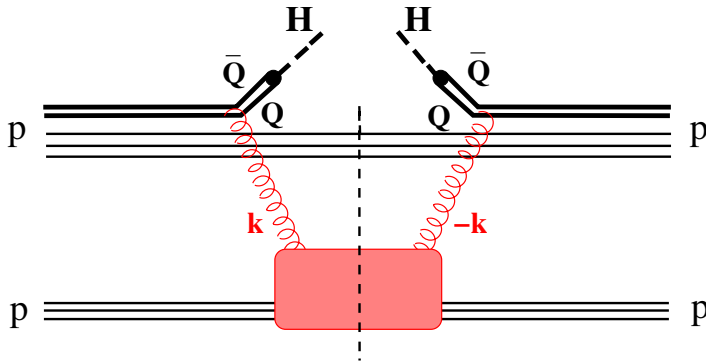


Figure 1: Representation of the cross section for inclusive Higgs production. The dashed line shows the unitarity cut.

pected.

Assuming that the intrinsic $\bar{Q}Q$ pair is in a color-octet P -wave state, the corre-

sponding cross section can be readily obtained. It is given by

$$\begin{aligned} \frac{d\sigma}{dk^2 dz} &= P_{IQ}(z) \frac{2\pi\alpha_s(k^2)}{3} \frac{\mathcal{F}(x, k^2)}{k^4} \left| \int d^2r H^\dagger(\vec{r}) e^{-i\vec{k}\cdot\vec{r}/2} \left(1 - e^{i\vec{k}\cdot\vec{r}}\right) \Psi_{\bar{Q}Q}(\vec{r}) \right|^2 \\ &= P_{IQ}(z) G_F \frac{\alpha_s(k^2)\mathcal{F}(x, k^2)}{k^2 \delta^2} \times \begin{cases} \ln(\delta) & \text{if } Q = c, b \\ \frac{1}{8} \left[1 + \frac{1-\delta}{\delta} \ln(1-\delta)\right] & \text{if } Q = t \end{cases} \quad (1) \end{aligned}$$

Here \vec{k} and $z = x_F$ are the transverse momentum and longitudinal momentum fraction of the Higgs particle, and $\delta = M_H^2/4m_Q^2$. We assume that $M_H < 2m_t$. In this expression $P_{IQ}(z)$ is the heavy quark pair distribution function which will be specified later, $H(\vec{r})$ is the relevant light-front wave function of the Higgs in the impact parameter representation, G_F is the Fermi constant, $\Psi_{\bar{Q}Q}$ is the $\bar{Q}Q$ wave function of the $Q\bar{Q}$ pair in the proton, and $\mathcal{F}(x, k^2) = \partial G(x, k^2)/\partial(\ln k^2)$ is the unintegrated gluon density, where $G(x, Q^2) = x g(x, Q^2)$, and $x = M_H^2/zs$. The specific form of these functions will be discussed below.

3 Elements of the Calculation

3.1 The Unintegrated Gluon Density

The unintegrated gluon density, $\mathcal{F}(x, k^2) = \partial G(x, k^2)/\partial(\ln k^2)$, is the transverse momentum differential of $G(x, Q^2) = x g(x, Q^2)$. It preserves the infrared stability of the cross section, since \mathcal{F} vanishes at $k^2 \rightarrow 0$. The phenomenological gluon density fitted to data includes by default all higher order corrections and supplies the cross section with an energy dependence important for the extrapolation to very high energies. One can relate the unintegrated gluon distribution to the phenomenological dipole cross section fitted to data for $F_2(x, Q^2)$ from HERA, as was done in Ref. [19],

$$\mathcal{F}(x, k^2) = \frac{3\sigma_0}{16\pi^2\alpha_s(k^2)} k^4 R_0^2(x) \exp\left[-\frac{1}{4} R_0^2(x) k^2\right]. \quad (2)$$

Here $R_0(x) = 0.4(x/x_0)^{0.144}$ fm (with $x_0 = 3 \times 10^{-4}$), and $\sigma_0 = 23.03$ mb [19].

3.2 The Higgs Wavefunction

The P -wave LF wave function of the Higgs in impact parameter representation is given by the Fourier transform of its Breit-Wigner propagator:

$$H(\vec{r}) = i \frac{\sqrt{3} G_F}{2\pi} m_Q \bar{\chi} \vec{\sigma} \chi \frac{\vec{r}}{r} \left[\epsilon Y_1(\epsilon r) - \frac{ir}{2} \Gamma_H M_H Y_0(\epsilon r) \right] . \quad (3)$$

This is the effective LF form factor representing the effective $L = 1$ coupling of the scalar Higgs to $c\bar{c}$ or $b\bar{b}$. Here G_F is the Fermi constant, χ and $\bar{\chi}$ are the spinors for c and \bar{c} respectively and

$$\epsilon^2 = \alpha(1 - \alpha)M_H^2 - m_Q^2 , \quad (4)$$

where α is the fraction of the LF momentum of the Higgs carried by the c -quark. The functions $Y_{0,1}(x)$ in Eq. (3) are the second-order Bessel functions and Γ_H is the total width of the Higgs. If we assume $\Gamma_H \ll M_H$, we can neglect the second term in Eq. (3).

The LF wavefunction Eq. (3) assumes that the Higgs mass is much larger than the quark masses, which is true for the charm and bottom quarks. However, since it is expected that $2m_t > M_H$, the Higgs wave function in this case has the form

$$H_{tt}(\vec{r}) = \frac{\sqrt{3} G_F}{2\pi} m_t \bar{\chi} \vec{\sigma} \chi \frac{\vec{r}}{r} \epsilon_t K_1(\epsilon_t r) , \quad (5)$$

where $K_1(x)$ is the modified Bessel function and

$$\epsilon_t^2 = m_t^2 - \alpha(1 - \alpha)M_H^2 . \quad (6)$$

The probabilities computed from the wave functions Eqs. (3) and (6) require regularization in the ultraviolet limit [20, 21], as is the case of the $\bar{q}q$ wave function of a transverse photon. Such wave functions are not solutions of the Schrödinger equation, but are distribution functions for perturbative fluctuations. They are overwhelmed by very heavy fluctuations with large intrinsic transverse momenta or vanishing transverse separations. Such point-like fluctuations lead to a divergent normalization, but they do not interact with external color fields, i.e., they are not observable. All of the expressions for measurable quantities, including the cross section, are finite.

3.3 Modeling the Heavy-Quark Intrinsic Distribution

As discussed above, we shall assume the presence in the proton of an intrinsic heavy quark (IQ) component, a $\bar{Q}Q$ pair, which is predominantly in a color-octet state. We will consider two models, corresponding to the nonperturbative or perturbative origin of the intrinsic heavy quark Fock state $|uudQ\bar{Q}\rangle$. In the nonperturbative model, the heavy component $Q\bar{Q}$ will interact strongly with the remnant $3q$ valence quarks. Such nonperturbative reinteractions of the intrinsic sea quarks in the proton wavefunction can lead to a $Q(x) \neq \bar{Q}(x)$ asymmetry as in the ΛK model for the $s\bar{s}$ asymmetry [22, 23]. As is the case for charmonium, the mean $\bar{Q}Q$ separation is expected to be considerably larger than the transverse size $1/m_Q$ of perturbative $\bar{Q}Q$ fluctuations. We thus will assume that the nonperturbative wave function for the $Q\bar{Q}$ is an S-wave solution of the Schrödinger equation. Assuming an oscillator potential we have

$$\Psi_{\bar{Q}Q}^{npt}(\vec{r}) = \sqrt{\frac{m_Q\omega}{2\pi}} \exp(-r^2 m_Q \omega/4) , \quad (7)$$

where ω is the oscillation frequency. The mean heavy inter-quark distance is

$$\langle r_{\bar{Q}Q}^2 \rangle = \frac{2}{\omega m_Q} . \quad (8)$$

We will give further details on the nonperturbative model in the next subsection.

Alternatively, the IQ component can be considered to derive strictly perturbatively from the minimal gluonic couplings of the heavy-quark pair to two valence quarks of the proton; this is likely the dominant mechanism at the largest values of x_Q [24]. In this case the transverse separation of the $\bar{Q}Q$ is controlled by the energy denominator, $\langle r_{\bar{Q}Q}^2 \rangle = 1/m_Q^2$ which is much smaller size than the estimate given by Eq. (8) for the nonperturbative model.

Since the Higgs is produced from an S -wave $\bar{Q}Q$, the perturbative distribution amplitude is ultraviolet stable. We can normalize P_{IQ} to the probability to have such a heavy quark pair in the proton and take the perturbative wavefunction as

$$\Psi_{\bar{Q}Q}^{pt}(\vec{r}) = \frac{m_Q}{\sqrt{\pi}} K_0(m_Q r) . \quad (9)$$

Here the modified Bessel function $K_0(m_Q r)$ is the Fourier transform of the energy denominator associated with the $\bar{Q}Q$ fluctuation. We assume the Q and \bar{Q} quarks

carry equal fractional momenta. For fixed α_s , the energy denominator governs the probability of the fluctuation in momentum space, since the charm quarks are treated as free particles in the perturbative analysis.

3.3.1 Nonperturbative Intrinsic Heavy Quarks—Further Details

In principle, one can construct the complete Fock state representation of hadronic LF wave function by diagonalizing the LF Hamiltonian. Here we will model the intrinsic heavy quark component by using the method of Ref. [25] in which one uses a Lorentz boost of a wave function assumed to be known in the hadron rest frame. The Lorentz boost will also generate higher particle number quantum fluctuations which are missed by this procedure; however, this method is known to work well in some cases [26, 27], and even provides a nice cancelation of large terms violating the Landau-Yang theorem [28].

We shall assume that the rest frame intrinsic heavy quark wave function has the Gaussian form (in momentum space),

$$\tilde{\Psi}_{IQ}(\vec{Q}, z) = \left(\frac{1}{\pi\omega\mu} \right)^{3/4} \exp \left(-\frac{\vec{Q}^2}{2\omega\mu} \right). \quad (10)$$

Here $\omega \simeq 300$ MeV stands for the oscillator frequency and $\mu = M_{\bar{Q}Q}M_{3q}/(M_{\bar{Q}Q} + M_{3q})$ is the reduced mass of the $\bar{Q}Q$ and $3q$ clusters. For further estimates we use $M_{\bar{Q}Q} = 3$ GeV and $M_{3q} = 1$ GeV, although the latter could be heavier, since it is the P -wave.

We can relate the 3-vector \vec{Q} to the effective mass of the system, $M_{eff} = \sqrt{\vec{Q}^2 + M_{\bar{Q}Q}^2} + \sqrt{\vec{Q}^2 + M_{3q}^2}$, by using LF variables, \vec{Q} and z ,

$$M_{eff}^2 = \frac{Q_T^2}{z(1-z)} + \frac{M_{\bar{Q}Q}^2}{z} + \frac{M_{3q}^2}{1-z}, \quad (11)$$

where Q_T is Qs transverse component. Then the longitudinal component Q_L in the exponent in (10) reads,

$$Q_L^2 = \frac{M_{eff}^2}{4} + \frac{(M_{\bar{Q}Q}^2 - M_{3q}^2)^2}{4M_{eff}^2} - \frac{M_{\bar{Q}Q}^2 + M_{3q}^2}{2} - Q_T^2, \quad (12)$$

and the LF wave function acquires the form,

$$\Psi_{IQ}(Q, z) = K \exp \left\{ -\frac{1}{8\omega\mu} \left[M_{eff}^2 + \frac{(M_{\bar{Q}Q}^2 - M_{3q}^2)^2}{M_{eff}^2} \right] \right\}, \quad (13)$$

where

$$\begin{aligned}
K^2 &= \frac{1}{8Q_L} \left(\frac{1}{\pi\omega\mu} \right)^{3/2} \exp\left(\frac{M_{\bar{Q}Q}^2 + M_{3q}^2}{2\omega\mu} \right) \left[1 - \frac{(M_{\bar{Q}Q}^2 - M_{3q}^2)^2}{M_{eff}^4} \right] \\
&\times \left[\frac{Q_T^2(2z-1)}{z^2(1-z)^2} - \frac{M_{\bar{Q}Q}^2}{z^2} + \frac{M_{3q}^2}{(1-z)^2} \right]. \tag{14}
\end{aligned}$$

We can now calculate the z -dependence of the function $P_{IQ}(z)$ introduced in Eq. (1),

$$\frac{P_{IQ}(z)}{P_{IQ}} = \int d^2Q |\Psi_{IQ}(Q, z)|^2. \tag{15}$$

We shall assume $P_{IQ} = 0.01$ for intrinsic charm, and a suppression factor proportional to $1/m_Q^2$ for heavier flavors.

3.3.2 Perturbative Intrinsic Heavy Quarks—Further Details

The light-front wave function of a perturbative fluctuation $p \rightarrow |3q\bar{Q}Q\rangle$ in momentum representation is controlled by the energy denominator,

$$\Psi_{IQ}(Q, z, \kappa) \propto \frac{z(1-z)}{Q^2 + z^2m_p^2 + M_{\bar{Q}Q}^2(1-z)}. \tag{16}$$

Here \vec{Q} is the relative transverse momentum of the $3q$ and $\bar{Q}Q$ clusters of the projectile. The effective mass of the $\bar{Q}Q$ pair depends on its transverse momentum ($\vec{\kappa}$) $M_{\bar{Q}Q}^2 = 4(\kappa^2 + m_Q^2)$. The Higgs production amplitude is controlled by the convolution of the IC $\bar{Q}Q$ wave function with the P -wave $\bar{Q}Q$ wave function of the Higgs together with the one-gluon exchange amplitude. The result has the form

$$\begin{aligned}
&\int_0^\infty d\kappa^2 \Psi_{IQ}(Q, z, \kappa) \left[H_{\bar{Q}Q}(\vec{\kappa} + \vec{k}/2) - H_{\bar{Q}Q}(\vec{\kappa} - \vec{k}/2) \right] \\
&\propto z(1-z) \frac{\ln \left[\frac{|M_H^2 - 4m_Q^2|(1-z)}{Q^2 + 4m_Q^2(1-z) + m_p^2 z^2} \right]}{M_H^2(1-z) + Q^2 + m_p^2 z^2}. \tag{17}
\end{aligned}$$

This expression peaks at $1-z \sim m_p/M_H$; therefore the logarithmic factor hardly varies as function of Q^2 . (In the semi-inclusive case, the momentum transfer to the

target proton is restricted by its form factor.) Making use of this we perform the integration in Eq. (15) and arrive at the following z -distribution,

$$\frac{P_{IQ}(z)}{P_{IQ}} = Nz(1-z) \frac{\left\{ \ln \left[\frac{|M_H^2 - 4m_Q^2|(1-z)}{4m_Q^2(1-z) + m_p^2 z^2} \right] \right\}^2}{M_H^2(1-z) + m_p^2 z^2}, \quad (18)$$

where N is a constant normalizing the integral over z to unity.

4 Results

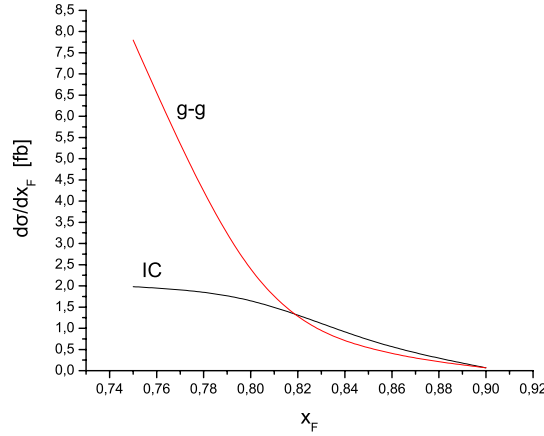


Figure 2: The cross section of inclusive Higgs production in fb , coming from the non-perturbative intrinsic charm distribution, at LHC ($\sqrt{s} = 14$ TeV) energies. For comparison we show also an estimate of the cross section for gluon-gluon fusion.

We present in Fig. 2 the prediction for the inclusive Higgs production cross section $d\sigma/dX_F(p\bar{p} \rightarrow HX)$ coming from the intrinsic non-perturbative charm distributions at LHC ($\sqrt{s} = 14$ TeV) energies. We have included for comparison an estimate of the gluon-gluon cross section, which is usually considered the dominant process for Higgs production. Since the gluon distribution is not well known in the high- x_F range, we have used as an ansatz the representative form $x_F d\sigma/dx_F = 6(1-x_F)^5$ (in pb) for $M_H = 120$ GeV at the LHC. This form is consistent with the height of the rapidity

plateau $d\sigma/dy \simeq 3.5 \rightarrow 5.5$ pb at $y = 0$, computed for gluon fusion at NNLO in ref. [29], and it gives the integrated rate $\sigma(pp \rightarrow HX) = 44$ pb, which is consistent with the NNLO result of ref. [30]. We also assume a Higgs mass of 120 GeV for our estimates of the intrinsic heavy quark contributions.

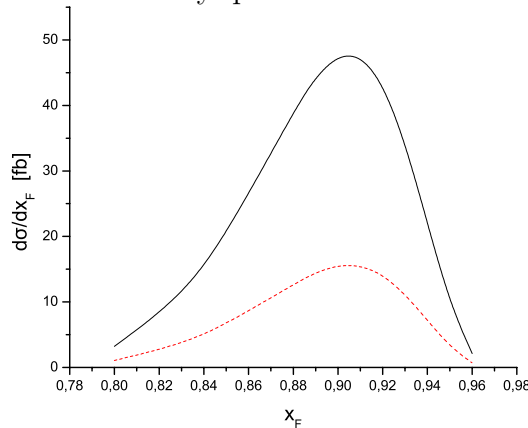


Figure 3: The cross section of inclusive Higgs production in fb , coming from the nonperturbative intrinsic bottom distribution, at both LHC ($\sqrt{s} = 14$ TeV, solid curve) and Tevatron ($\sqrt{s} = 2$ TeV, dashed curve) energies.

The same analysis can be repeated for inclusive Higgs production from intrinsic bottom (IB), assuming that the probability for Fock states in the light hadron to have an extra heavy quark pair of mass M_Q scales as $1/M_Q^2$, which is a result that can be obtained using the operator product expansion. The result is shown in Fig.3. Notice that the cross section for inclusive Higgs production from intrinsic bottom is much higher than the one coming from intrinsic charm. Although it is true that the Higgs-quark coupling, proportional to m_Q , cancels in the cross section with $P_{IQ} \propto 1/m_Q^2$, the matrix element between IQ and Higgs wave functions has an additional m_Q factor. This is because the Higgs wave function is very narrow and the overlap of the two wave functions results in $\Psi_{\bar{Q}Q}(0) \propto m_Q$. Thus, the cross section rises as m_Q^2 , as we see in the results.

We can compare our predictions for inclusive Higgs production coming from

IB with our previous ansatz for the Higgs production gluon-gluon fusion process $x d\sigma/dx = 6(1-x)^5$ (in pb). At the maximum ($x_F = 0.9$) of the IB curve we get a value of roughly 50 fb, while there gluon-gluon gives 0.067 fb. Thus this high- x_F region is the ideal place to look for Higgs production coming from intrinsic heavy quarks.

We obtain essentially the same curves for Tevatron energies ($\sqrt{s} = 2 \text{ TeV}$), although the rates are reduced by a factor of approximately 3.

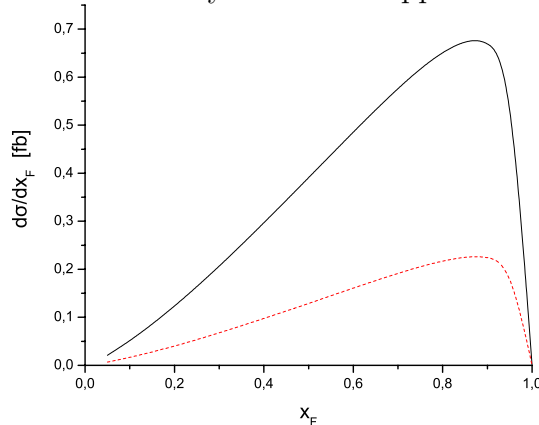


Figure 4: The cross section of inclusive Higgs production in fb coming from the perturbative intrinsic charm distribution, at both LHC ($\sqrt{s} = 14 \text{ TeV}$, solid curve) and Tevatron ($\sqrt{s} = 2 \text{ TeV}$, dashed curve) energies.

We also show in Fig.4 the results for Higgs production coming from the perturbative charm distribution. The magnitude of the production cross section is considerably reduced with respect to the non-perturbative case.

The contributions of intrinsic bottom and top of perturbative origin to inclusive Higgs hadroproduction substantially exceed the IC contribution. Although the probability to find intrinsic heavy quarks in the proton is very small (the OPE predicts $1/m_Q^2$ scaling for perturbative IB and IT [3],) the stronger Higgs coupling to heavy quarks and the larger projection of the intrinsic heavy quark Fock state to the Higgs $\bar{Q}Q$ wave function overcompensate this smallness. As a result, the IB contribution is about one order of magnitude larger than IC according to Eq. (1), and the IT con-

tribution turns out to be close in magnitude to that of IB, but peaked at higher x_F . See also the discussion of ref.[10] for the case of doubly diffractive Higgs production.

5 Summary and Outlook

The existence of heavy intrinsic Fock states in hadron wavefunctions is a consequence of the quantum fluctuations inherent to QCD. In contrast to Abelian theory, the probability for heavy quark Fock states such as $|uudQ\bar{Q}\rangle$ in the proton is only suppressed by Λ^2/M_Q^2 because of the contribution of the non-Abelian operator $G_{\mu\nu}^3$ to the hadronic self-energy. As we have shown in this paper, the coupling of high- x intrinsic charm and bottom quark-antiquark pairs in the proton to the Higgs particle leads to a remarkably large cross section for the hadroproduction of the Higgs at longitudinal momentum fractions as large as $x_F \simeq 0.8$. The intrinsic heavy quark mechanism is thus extraordinarily efficient in converting projectile momentum and energy to Higgs momentum. The coupling of intrinsic bottom to the Higgs is favored over intrinsic charm because of its enhanced wavefunction overlap. In the intrinsic heavy quark mechanism the momentum of both the intrinsic heavy quark and antiquark in the $|uudQ\bar{Q}\rangle$ Fock state of the projectile combine to produce the Higgs at large x_F . This feature of the model can be explicitly tested and normalized by measuring the production of P-wave heavy quark Fock states at high x_F , such as $p\bar{p} \rightarrow \chi_C X$.

We predict that the cross section $d\sigma/dx_F(p\bar{p} \rightarrow HX)$ for the inclusive production of the Standard Model Higgs coming from nonperturbative intrinsic bottom Fock states is of order 50 fb at LHC energies, peaking in the region of $x_F \sim 0.9$. Our estimates indicate that the corresponding cross section coming from gluon-gluon fusion in this same region is negligible, of order of 0.07 fb, and therefore this peak should be clearly visible. We have not included possible extra contributions from intrinsic $t\bar{t}$ pairs. The rate for doubly diffractive Higgs production $p\bar{p} \rightarrow p + H + \bar{p}$ at high x_F has been computed in ref. [10].

The results of our paper suggest new strategies for the detection of the Higgs. The Higgs is produced from intrinsic heavy quarks at high longitudinal momentum, but its transverse momentum p_{\perp}^H is of the order of the heavy quark mass which is relatively

small, and the sum of the transverse momenta of its decay products will tend to vanish. Thus if the Higgs decays to two jets such as $b\bar{b}$, each jet will be produced with a transverse momentum $\leq M_H/2$ and longitudinal momentum $\simeq P_H/2$. The typical production angle is then $\theta_{cm} \simeq 2M_H/x_F\sqrt{s}$. For example, $\theta_{cm} \simeq 8^\circ$ for $M_H = 110$ GeV, $x_F = 0.8$, and $\sqrt{s} = 2$ TeV. The detection of the Higgs at $x_F^H \sim 0.8$ at Tevatron or the LHC will thus require forward detection capabilities. One can also increase the production angle of each jet by lowering the CM energy of the collider or by arranging collisions with asymmetric beams. Conceivably, the Higgs could even be produced in pp collisions at RHIC energies.

We also expect a background to Higgs production at large x_F in the $H \rightarrow b\bar{b}$ channel which arises from the production of intrinsic $b - \bar{b}$ pairs in QCD. Since the mean transverse momenta of quarks inside the intrinsic bottom wavefunction of the proton is small, the $b - \bar{b}$ background events which have large invariant mass come from unequal sharing of quark longitudinal momentum. In contrast, the $b - \bar{b}$ pairs from the Higgs signal have a spherically symmetric phase space. One can thus enhance the signal to background ratio by selecting $b - \bar{b}$ jets carrying the same longitudinal momenta. The net signal-to-background ratio in the $b - \bar{b}$ channel is expected to be similar for the gg fusion and IQ mechanisms.

There are other interesting tests of intrinsic heavy quark Fock states, which could be performed at the Tevatron. For example, consider $p\bar{p} \rightarrow W^+DX$ in which the weak boson W^+ is produced at large $x_F^W \sim 0.4$ in the proton fragmentation region. The W^+ can be created from the pair annihilation subprocesses $c\bar{d} \rightarrow W^+$ (which is Cabibbo suppressed), or $c\bar{s} \rightarrow W^+$. The annihilating c can come from the IC state of the projectile proton and the \bar{s} can arise from the strange sea of the antiproton. The unique signal for this IC process is the associated production of a forward leading $D^+(\bar{c}u)$ or $D^0(\bar{c}d)$, which is also produced at high x_F^D in the proton fragmentation region. It is created from the coalescence of the high- x spectator intrinsic \bar{c} with a valence quark. One can similarly test for intrinsic bottom in the reaction $p\bar{p} \rightarrow W^-BX$, in which the W^- is produced at large $x_F^W \sim 0.4$ in the proton fragmentation region from the annihilation subprocess $b\bar{u} \rightarrow W^-$ (which is CKM-suppressed) or $b\bar{c} \rightarrow W^-$. The annihilating b can come from the IB state of the projectile proton,

and the \bar{c} can be an anti-charm quark produced at low- x by gluon splitting. The signal for this IB process is the associated production of a leading $B^+(\bar{b}u)$ or $B^0(\bar{b}d)$, which is also produced at high x_B in the proton fragmentation region. It is created from the coalescence of the spectator intrinsic \bar{b} with a valence quark. Other tests include the reactions $gc \rightarrow Z^0/\gamma+c$ where the Z^0 plus the tagged final-state charm jet have large x_F [8]. It has also been found that intrinsic bottom could even contribute significantly to exotic processes such as neutrino-less $\mu^- - e^-$ conversion in nuclei [31]. All of the above mentioned tests require detailed calculations which consider other possible production mechanisms and backgrounds.

If the Higgs boson is detected at large Feynman x , it would not only confirm the structure of the intrinsic heavy-quark Fock states as predicted by QCD, but also the fundamental coupling strengths of the Higgs bosons to heavy quarks.

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