Spin-Spin Asymmetries in Large Transverse Momentum Higgs Boson Production

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Abstract

We examine the spin-dependence of standard model Higgs boson production at large transverse momentum via the processes $gg \rightarrow gH^0$, $qg \rightarrow qH^0$, and $q\bar{q} \rightarrow gH^0$. The partonic level spin-spin asymmetries ($a_{LL}$) for these processes are large at SSC/LHC energies.
The prospects for probing the spin-dependence of the standard model of particle physics at collider and supercollider energies have recently received renewed attention [1], partly because of the successful experimental tests of the Siberian snake concept [2]. Polarization options at collider energies [3, 4] and supercollider energies [5, 6] and the physics programs possible at such facilities have been discussed extensively.

Predictions for the longitudinal spin structure of hard scattering events at such energies require two ingredients: a knowledge of the helicity structure of the contributing matrix elements and parameterizations of the spin-dependent parton distributions of the proton. Lowest order predictions for the spin structure of many standard collider processes now exist, often quoted as partonic level asymmetries,

\[ \hat{a}_{LL} \equiv \frac{\hat{\sigma}(++) - \hat{\sigma}(+-)}{\hat{\sigma}(++) + \hat{\sigma}(+-)}, \]

(where \( \pm \) refers to the helicity of the incident partons parallel or antiparallel to the polarized incident nucleon.) Polarized lepton-nucleon production experiments have provided some knowledge of the spin structure of the valence quark distribution in the nucleon (at relatively large \( x \)) but the spin dependence of the sea quark and gluon distributions is yet to be measured directly, and, in fact, a large part of a program of polarized \( pp \) collisions at RHIC would be a comprehensive mapping out of these distributions [7].

As mentioned above, many calculations of the partonic level asymmetries for standard model processes exist (see, e.g., [8], [9]–[11] and references therein). While likely not relevant for a first generation program of polarized \( pp \) collisions at collider energies, the production of the standard model Higgs boson (\( H^0 \)) at a polarized supercollider (such as SSC or LHC) has also been discussed to some extent [12]. The calculations
of Ref. [6] have focused on low transverse momentum $H^0$ production via gluon fusion ($gg \to H^0$) and weak gauge boson fusion ($qqqq \to W^+W^- \to H^0$) and the partonic level asymmetries in these cases are known to be quite large, e.g. $\hat{a}_{LL}(gg \to H^0) = +1$.

Higgs boson production at large transverse momentum, via the processes $gg \to gH^0$, $qg \to qH^0$, and $qq \to gH^0$ has also been considered in the unpolarized case by Ellis et al. [12] and Baur and Glover [13]. The matrix elements for these processes, depending as they do on heavy quark loops, are, in general, quite complicated functions of the kinematic variables $\hat{s}$, $\hat{t}$, $\hat{u}$, $M_t$, and $M_H$ but simplify dramatically in the limit of $M_t >> M_H, \hat{s}, \hat{u}, \hat{t}$. It was noted in Ref. [11], that in this limit the partonic level asymmetries for these processes reduce to those for the production of a $^1S_0$ quarkonium state, which are known to be reasonably large [9]. In this note, we extend this preliminary observation concerning the spin dependence of large transverse momentum Higgs boson production in three obvious ways. We first explore the effects of a finite heavy quark mass on the partonic level asymmetries ($\hat{a}_{LL}$) and then calculate the average spin-spin asymmetry $<\hat{a}_{LL}>$ in high $p_T$ $H^0$ production at SSC and LHC energies to determine a rough measure of the ‘analyzing power’ of such processes. Finally, we estimate the range in observable longitudinal spin-spin asymmetries $A_{LL}$ by using several parameterizations of the polarized gluon distributions indicating a range in the current uncertainty about the contribution of gluons to the proton spin.

The cross-section for $qq \to H^0g$ (and the crossed process $gg \to qH^0$) depend only on a single heavy quark triangle graph and the resulting $ggH^0$ form factor appears as a simple multiplicative factor in the amplitude. While this factor changes the total cross-section, it as no effect on the helicity structure of the matrix elements so the
partonic level spin-spin asymmetries for these two processes are independent of $M_t$ and are given by

$$\hat{a}_{LL}(qg \to qH^0) = \frac{s^2 - \bar{u}^2}{s^2 + \bar{u}^2}$$

(1)

and

$$\hat{a}_{LL}(q\bar{q} \to gH^0) = -1.$$  

(2)

These asymmetries were plotted for several values of $\sqrt{s}/M_H$ in Ref. [11] for illustration. The amplitude for the dominant $gg \to gH^0$ process depends on both triangle and box diagrams and can be expanded in terms of two invariant functions (see, e.g., Ref. [12], Eqn.(A.6)) so that the helicity structure of the interaction does, in fact, depend on the mass of the quark in the internal loops. In the notation of Ref. [12], one has

$$\frac{d\hat{\sigma}}{dt} = \frac{1}{16\pi s^2} \frac{1}{4 \cdot 64} \sum_{\text{spins,colors}} |\mathcal{M}|^2$$

(3)

where the spin and color summed invariant matrix elements are given by

$$\sum |\mathcal{M}|^2 = \alpha_w^2 \frac{96}{s^2 \bar{u}^2} M_H^8 (|A_2(\hat{\bar{s}}, \hat{\bar{u}}, \hat{\bar{t}})|^2 + |A_2(\hat{\bar{u}}, \hat{\bar{s}}, \hat{\bar{t}})|^2 \\ + |A_2(\hat{\bar{t}}, \hat{\bar{u}}, \hat{\bar{s}})|^2 + |A_4(\hat{\bar{s}}, \hat{\bar{t}}, \hat{\bar{u}})|^2).$$

(4)

The dimensionless functions $A_2$ and $A_4$ are given in terms of standard loop integrals and thus depend on the quark loop mass and are actually proportional to the gluon helicity amplitudes which we require for the partonic level spin-spin asymmetry. In fact, we find

$$\hat{a}_{LL}(gg \to gH^0) = \frac{|A_4(\hat{s}, \hat{t}, \hat{u})|^2 + |A_2(\hat{s}, \hat{t}, \hat{u})|^2 - |A_2(\hat{u}, \hat{s}, \hat{t})|^2 - |A_2(\hat{t}, \hat{u}, \hat{s})|^2}{|A_4(\hat{s}, \hat{t}, \hat{u})|^2 + |A_2(\hat{s}, \hat{t}, \hat{u})|^2 + |A_2(\hat{u}, \hat{s}, \hat{t})|^2 + |A_2(\hat{t}, \hat{u}, \hat{s})|^2}.$$  

(5)

In the $M_t \to \infty$ limit, one has

$$A_4(\hat{s}, \hat{t}, \hat{u}) \to -\frac{1}{3}, \quad A_2(\hat{s}, \hat{t}, \hat{u}) \to -\frac{s^2}{3M_H^2}.$$  

(6)
so that the partonic level asymmetry is simply

\[ \hat{a}_{LL}(gg \to gH^0) = \frac{M_H^8 + \hat{s}^4 - \hat{t}^4 - \hat{u}^4}{M_H^8 + \hat{s}^4 + \hat{t}^4 + \hat{u}^4} \]  

which is the same result as for \( gg \to g^1S_0 \) quarkonium production as found in Ref. [11].

As the only change is in the purely gluon induced processes, we illustrate results for that sector only. In Fig. 1 we plot the partonic level asymmetries versus the center-of-mass angle (\( \cos(\theta^*) \)) for several values of \( \hat{s}/M_H^2 \) in the large \( M_t \) limit. (We note that when \( \hat{s} \to M_H^2 \) the asymmetry approaches the limit +1, corresponding to \( gg \to H^0 \), independent of angle.) In Fig. 2, we then plot the ratio of the ‘exact’ expressions for the partonic level \( \hat{a}_{LL} \) (Eqn. 5) to the infinite quark mass limit (Eqn. 7) versus \( \cos(\theta^*) \) for the same values of \( \hat{s}/M_H^2 \) and two values of \( M_t/M_H \). In general, the asymmetries are somewhat reduced for finite values of \( M_t \) but not dramatically so.

We next plot in Fig. 3 the differential cross-sections for large transverse momentum \( H^0 \) production, \( d\sigma/dp_T \) versus \( p_T \) for two choices of \( M_H \) and for SSC and LHC energies to acquire some feel for the event rates possible using these mechanisms. As a test of our calculation, we are able to reproduce the corresponding figures from Refs. [12, 13]. Then to ensure that the spin-dependence of the matrix elements is large in the kinematic regions for high \( p_T \) Higgs boson production, in Fig. 4 we plot the average partonic level asymmetry, defined via

\[ <\hat{a}_{LL}> = \frac{\sum_{ij} \int dx_a \int dx_b f_i(x_a, Q^2) f_j(x_b, Q^2) d\hat{\sigma}_{ij} \cdot \hat{a}_{ij}^{LL}}{\sum_{ij} \int dx_a \int dx_b f_i(x_a, Q^2) f_j(x_b, Q^2) d\hat{\sigma}_{ij}} \]

where \( f_i(x, Q^2) \) are the appropriate parton distributions. We use EHLQ2 distributions [14] for consistency with Ref. [12] as well as the choice of momentum scale \( Q^2 = \)
and include all three relevant subprocesses. We see that the average partonic level asymmetries are quite reasonable in all of the kinematic regimes relevant for high $p_T$ Higgs production. Finally, we can include the effects of the polarized parton distributions by calculating values of the observable spin-spin asymmetry,

$$A_{\text{LL}} \equiv \frac{\sum_{ij} \int dx_a \int dx_b \Delta f_i(x, Q^2) \Delta f_j(x, Q^2) d\sigma_{ij} \cdot \hat{a}_{ij}^L}{\sum_{ij} \int dx_a \int dx_b f_i(x, Q^2) f_j(x, Q^2) d\sigma_{ij}}$$

(9)

where now the $\Delta f_i(x, Q^2) \equiv f_i^{(+)}(x, Q^2) - f_i^{(-)}(x, Q^2)$ are defined in terms of the spin dependent parton distributions. Using the parameterizations of the polarized parton distributions given by Soffer et al. [6] and Bourrely et al. [15], we then find the asymmetries plotted in Fig. 5. These two choices are representative of a standardly small gluon polarization in the nucleon (Ref. [6]) and EMC-motivated ‘large’ gluon contribution to the proton spin (Ref. [15]) and therefore give some idea of the possible range in observable spin dependence in this reaction. In neither case is the observable asymmetry larger than 1%; since the average partonic level asymmetry, $<\hat{a}_{\text{LL}}>\,$, was seen to be large (Fig. 4), the small observable asymmetry is due to the smallness of the polarized gluon distribution in the kinematic region probed.

In conclusion, we have found that the partonic level longitudinal spin-spin asymmetries in the kinematic regions relevant for large $p_T$ Higgs boson production are quite large but that the observable spin dependence depends critically on the, as yet unmeasured, polarized gluon distribution in the proton. Hopefully, measurements of various standard model processes (such as jet and direct photon production) with a polarized proton-proton colliding beam facility such as at RHIC will provide the first direct information on the size of the gluon contribution to the proton spin.

We are very grateful for conversations with U. Baur and R. Stuart, who also kindly provided us with various computer programs. This work was supported in part by the
National Science Foundation under grant PHY–9001744 (R.R.), by the Texas National Research Laboratory Commission under an SSC Junior Faculty Fellowship (R.R.), by the University of Wisconsin Alumni Research Foundation (M.D.), by the U. S. Department of Energy under contract DE-AC02-76ER00881 (M.D.), and by the Texas National Research Laboratory Commission under grant No. RGFY9173 (M.D.).
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Figure Captions

Fig. 1. Partonic level asymmetries $\hat{a}_{LL}$ for $gg \to gH^0$ versus $\cos(\theta^*)$ (where $\theta^*$ is the center-of-mass scattering angle) in the $M_t \to \infty$ limit. $\hat{s}/M_H^2 = 2 (20, 200)$ is shown in the solid (dashed, dotdashed) curve.

Fig. 2. Ratio of ‘exact’ partonic level asymmetry $\hat{a}_{LL}$ to that in the $M_t \to \infty$ limit ($\hat{a}_{LL}(\infty)$) versus $\cos(\theta^*)$ for two values of $M_t/M_H$ ($M_t/M_H = 0.2$ (0.8) on the left (right) respectively). Three values of $\hat{s}/M_H^2$ are shown as in Fig. 1. We use the fact that the angular distribution is symmetric around $y = \cos(\theta^*) = 0$.

Fig. 3. Differential cross-section, $d\sigma/dp_T$ (nb/GeV) versus $p_T$ (GeV) for Higgs boson production for $M_H = 100 \text{GeV}$, (200 GeV) for $\sqrt{s} = 40 \text{TeV}$ dashed (dotdashed) curve, and for $\sqrt{s} = 17 \text{TeV}$ solid (dotted) curve. The parton distributions of Ref. [14] are used (EHLQ2) with the scale choice $Q^2 = M_H^2 + p_T^2$.

Fig. 4. The average partonic level asymmetry $\langle \hat{a}_{LL} \rangle$ (as defined in Eqn. 8) in the quantity $d\sigma/dp_T$ versus $p_T$ (GeV). Curves are labelled as in Fig. 3.

Fig. 5. The observable spin-spin asymmetry, $A_{LL}$ (defined in Eqn. 9) in the quantity $d\sigma/dp_T$ versus $p_T$ (GeV). Asymmetries for $\sqrt{s} = 40 \text{ TeV}$, $M_H = 200 \text{ GeV}$ and $M_t = 130 (\infty) \text{ GeV}$ for the polarized parton distribution functions of Ref. [6] solid (dotted) curve, and Ref. [15] dashed (dotdashed) curve.