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Possibility of determining gluon polarization via polarized top pairs in gamma-proton scattering

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ABSTRACT

We study the possibility for directly measuring the polarized gluon distribution in the process $\gamma p \to \bar{t}t$. It is shown that polarization asymmetry of the final top quarks is proportional to the gluon polarization. With available energy and luminosity, the collision of a polarized proton beam and a Compton backscattered photon beam can create polarized top quarks which carry the spin information of the process. Energy dependence and angular distributions of the polarization asymmetry of the top pairs has been discussed including statistical uncertainty.

1. Introduction

After the discovery of quarks and gluons as constituent partons inside the nucleons, one of the major question was how the spin of the nucleon is composed by its partons. It is now clear that the spin of the nucleon cannot be shared by valence quarks only. Early information about this feature came from Deep Inelastic Scattering (DIS) of polarized leptons and polarized nuclear targets [1]. Important results were obtained from the data on the spin dependent structure function of the nucleon $g_1(x, Q^2)$ by European Muon Collaboration (EMC) [2]. Following years, several experiments had been performed at SLAC [3], CERN [4] and DESY [5] to understand the spin structure of the proton in the framework of quantum chromodynamics (QCD). Precise measurements on the $g_1^{p,d}(x, Q^2)$ were done by the Spin Muon Collaboration (SMC) [4] for several Bjorken-x and Q^2 values. These results have reached the precise determination of the quark contribution to the proton spin. Therefore, DIS experiments showed that the quarks carry 1/4 of the proton spin and the remaining parts belongs to the gluon and orbital angular momenta of the quarks and gluons. The spin of the proton can be written in terms of its polarized parton distributions integrated over x-region. Then, based on QCD, the spin sum rule of the proton can be written in terms of parton contributions

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \tag{1}$$

where the right-hand side consists of the contributions of quarks, gluons and their orbital angular momenta. DIS is a fixed target experiment with limited x-region, so it has not enough precision in determining gluon polarization. In addition to the DIS experiments in CERN, DESY and SLAC, Relativistic Heavy Ion Collider (RHIC) has started to operate since 2001 with high energy polarized proton beams. One of the major goals of RHIC covers measuring gluon polarization in the proton [6,7]. DIS and RHIC data have led to the fact that gluon contribution to the proton spin is very small than expected. The fraction of individual contributions of each term in the above sum rule is still an open question. Thus, the determination of the spin carried by gluons has been a challenging task for experimentalists and theorists.

Although several asymmetry definitions are sensitive to gluon polarization, both DIS and RHIC experiments have theoretical uncertainties in determining gluon polarization extracted from physical processes involved in scattering. In *ep* scattering polarized gluon distribution always comes together with quasi-real photon distribution function and quark fragmentation function to hadrons. In *pp* scattering with hadronic final states, the product of gluon–gluon or quark–gluon distributions and quark fragmentation functions are included by the cross sections. In order to reduce these theoretical uncertainties one needs a direct way to measure ΔG alone. In theoretical point of view, this is possible only through real gamma-proton scattering. At earlier works, the scattering of a polarized real gamma beam on a polarized fixed nuclear target was studied to investigate polarized gluon distribution with J/Ψ, K and π meson production at final states [8]. RHIC experiments with polarized proton beams at 100 GeV energy (or $\sqrt{s} = 200$ GeV collider energy) has been done for a few years. RHIC at Brookhaven National Laboratory has the capability of polarized proton beams

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Table 1
Center of mass energy estimations of parent ep and its γp option for a collision of linear electron beam and RHIC polarized proton beams.

E_e (GeV)	E_p (GeV)	E_{ep} (GeV)	$E_{\gamma p}^{max}$ (GeV)
500	100	447	407
500	150	548	499
500	200	632	576
500	250	707	644
750	100	548	499
750	150	671	611
750	200	775	706
750	250	866	789
1000	100	632	576
1000	150	775	706
1000	200	894	815
1000	250	1000	911
1250	100	707	644
1250	150	866	789
1250	200	1000	911
1250	250	1118	1019
1500	100	775	706
1500	150	949	864
1500	200	1095	998
1500	250	1225	1116

up to 250 GeV. Therefore, it is reasonable to consider a scattering of a polarized proton beam with a real photon beam where high energy photon beam can be achieved through Compton backscattering of parent linear electron beam [9]. Center of mass energy estimations in parent ep collisions and its γp mode are given in Table 1 at linear electron beam and RHIC proton beam energy regions.

In this work, the possibility of probing gluon polarization with polarized top–antitop quark pair production will be discussed in $\gamma p \to \bar{t}t$ process. This process occurs via $\gamma g \to \bar{t}t$ subprocess with t and u channels. As will be seen in the next section, polarization of the top–antitop pairs or one of the top quarks is correlated to the gluon polarization in the cross section. Observation of polarized tops in the final state or top-polarization asymmetry is sensitive to gluon polarization. When the gluon polarization is absent final top polarization vanishes. In the next section, we give the details of the top polarization, the scattering of polarized gluon with unpolarized real photons, asymmetry definitions and numerical results at possible energy and luminosity values. Section 3 is devoted to conclusion and discussion.

2. Polarized top quark pair production and asymmetry in $\gamma p \to \bar{t}t$

Let us first discuss the features of top quarks and its polarization. The top quark is the most massive fundamental fermion which plays a special role to test QCD and to probe new physics. Because of its large mass, top quark decays immediately through weak interaction after being produced, without hadronization. Therefore, decay products give information directly on top quark properties. In particular, top pair production is quite suitable to draw the spin information of the process which can be determined from the angular distributions of their electroweak decay products [10]. In the Standard Model (SM), the dominant electroweak decay chain of the top quark is

$$t \to W^+ b \to b\ell^+\nu / b\bar{d}u. \tag{2}$$

The correlation among the top spin and its decay product can be shown simply in the top quark rest frame. In this frame, the decay angular distribution is given by

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\alpha_i} = \frac{1}{2}(1 + \beta_i \cos\alpha_i), \tag{3}$$

where α_i is the angle between the top quark ith decay product and top quark spin quantization axis. β_i is called the correlation degree between the decay products and top spin where $\beta_i = 1$ for $i = \ell^+, \bar{d}, \bar{s}$ and $\beta_i = -0.4$ for $i = b$. More details about the above expression and its implication can be found in Ref. [11]. Thus, the top polarization asymmetry can provide additional observables when initial particle polarizations are taken into account.

As a first step to achieve cross section, the t and u channel amplitudes for the subprocess $\gamma g \to \bar{t}t$ is written below

$$iM_1 = \left(-ig_s\frac{\lambda^a}{2}\right)(-ig_e Q_t)\left[\bar{u}_1\gamma^\mu \frac{i}{\not{q}_1 - m_t}\gamma^\nu v_2\right] e^\nu(k_1)e^\mu(k_2), \tag{4}$$

$$iM_2 = \left(-ig_s\frac{\lambda^a}{2}\right)(-ig_e Q_t)\left[\bar{u}_1\gamma^\nu \frac{i}{\not{q}_2 - m_t}\gamma^\mu v_2\right] e^\nu(k_1)e^\mu(k_2), \tag{5}$$

with

$$q_1 = k_1 - p_2, \qquad q_2 = k_2 - p_2,$$
$$u_1 = u(p_1, s_1), \qquad v_2 = v(p_2, s_2), \tag{6}$$

where k_1, k_2, p_1 and p_2 are momenta of the photon, gluon, top quark and antitop quark. $e(k_1)$ and $e(k_2)$ are the polarization vectors of the photon and the gluon. g_s, g_e and Q_t are strong coupling, electromagnetic coupling and electric charge number of the top quark. λ^a are Gell-Mann matrices. If we assume $\vec{k}_1$ and $\vec{k}_2$ are in the $\hat{z}$ and -$\hat{z}$ direction, the gluon polarization vector in the helicity basis can be given by

$$e^\mu(k_2) = \frac{1}{\sqrt{2}}(0, \lambda_g, -i, 0), \quad \lambda_g = \mp 1. \tag{7}$$

As will be explained below, we do not need polarization of the photon then we sum over photon spins in the squared amplitude. In order to obtain the cross section which depends on the spins of the final top quarks we use the following projection operator

$$\sum_{s_1} u(p_1, s_1)\bar{u}(p_1, s_1) = \frac{1}{2}\left(1 + \gamma^5 \not{s}_1\right)(\not{p}_1 + m_t) \tag{8}$$

where the spin of the top quark s_1 in the helicity basis is

$$s_1^\mu = \lambda_t\left(\frac{|\vec{p}_1|}{m_t}, \frac{E_1}{m_t}\frac{\vec{p}_1}{|\vec{p}_1|}\right), \quad \lambda_t = \pm 1. \tag{9}$$

Depending on the helicities $\lambda_g, \lambda_t, \lambda_{\bar{t}}$ of the gluon, top and antitop quarks, we have calculated the differential cross section for the subprocess $\gamma g \to \bar{t}t$ by squaring Feynman amplitudes and using trace method

$$\begin{aligned}\frac{d\hat{\sigma}}{dz}&(\lambda_g, \lambda_t, \lambda_{\bar{t}}) \\ &= \frac{\beta N_c \pi \alpha \alpha_s Q_t^2}{4\hat{s}(1-\beta^2 z^2)^2}\Big[-4\beta\lambda_g\big\{\big(\beta^2 - 1\big)(\lambda_t - \lambda_{\bar{t}}) + \beta(\lambda_t + \lambda_{\bar{t}})\big(1 - z^2\big)z\big\} \\ &\quad + 2\beta^4(\lambda_t\lambda_{\bar{t}} - 1)\big(1 + \big(1 - z^2\big)^2\big) + 4\beta^2\big(1 + \lambda_t\lambda_{\bar{t}}z^2\big)\big(1 - z^2\big) \\ &\quad - 2(\lambda_t\lambda_{\bar{t}} - 1)\Big]\end{aligned} \tag{10}$$

where $\hat{s} = (k_1 + k_2)^2$ is the square of the center of mass energy of the photon–gluon or $t\bar{t}$ pair. It is easy to get the cross section which depends on λ_g and λ_t by summing over $\lambda_{\bar{t}}$ when the polarization of only one of the top quarks is considered

$$\begin{aligned}\frac{d\hat{\sigma}}{dz}(\lambda_g, \lambda_t) &= \frac{\beta N_c \pi \alpha \alpha_s Q_t^2}{4\hat{s}(1-\beta^2 z^2)^2}\Big[-8\beta\lambda_g\lambda_t\big\{\big(\beta^2 - 1\big) + \beta z\big(1 - z^2\big)\big\} \\ &\quad + 4\big\{-\beta^4\big(1 + \big(1 - z^2\big)^2\big) + 2\beta^2\big(1 - z^2\big) + 1\big\}\Big],\end{aligned} \tag{11}$$

where