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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

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

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

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

where

$$z = \cos\theta, \qquad \beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}. \tag{12}$$

$N_c = 1/2$ and $\alpha_s = g_s^2/(4\pi)$ are the color factor and the strong coupling constant. For completeness, let us integrate over scattering angle to obtain total cross section for the subprocess

$$\begin{aligned}
&\hat{\sigma}(\lambda_g, \lambda_t, \lambda_{\bar{t}}) \\
&\quad = \frac{\beta N_c \pi \alpha \alpha_s Q_t^2}{4\hat{s}} \Bigg[4\lambda_g(\lambda_t - \lambda_{\bar{t}}) \left\{ \frac{1}{2}\left(1-\beta^2\right) \log\frac{1+\beta}{1-\beta} + \beta \right\} \\
&\qquad + \frac{4}{\beta^3} \Bigg\{ (1 - \lambda_t\lambda_{\bar{t}})\beta^5 - (2 - \lambda_t\lambda_{\bar{t}})\beta^3 - 3\lambda_t\lambda_{\bar{t}}\beta \\
&\qquad + \frac{1}{2}\log\frac{1+\beta}{1-\beta}\big[-(1 - \lambda_t\lambda_{\bar{t}})\beta^6 + \lambda_t\lambda_{\bar{t}}\beta^4 \\
&\qquad + 3(1 - \lambda_t\lambda_{\bar{t}})\beta^2 + 3\lambda_t\lambda_{\bar{t}}\big] \Bigg\} \Bigg],
\end{aligned} \tag{13}$$

$$\begin{aligned}
\hat{\sigma}(\lambda_g, \lambda_t) = \frac{2\beta N_c \pi \alpha \alpha_s Q_t^2}{\hat{s}} \Bigg[\lambda_g \lambda_t \left\{ \frac{1}{2}\left(1-\beta^2\right) \log\frac{1+\beta}{1-\beta} + \beta \right\} \\
+ \left\{ \left(\frac{3}{\beta} - \beta^3 \right) \frac{1}{2} \log\frac{1+\beta}{1-\beta} + \beta^2 - 2 \right\} \Bigg].
\end{aligned} \tag{14}$$

In both cross sections the gluon helicity appears as a product by the top quark helicity. This feature creates a nonzero asymmetry which vanishes when the gluon or top quark is unpolarized. Another way to get an asymmetry is to have a polarized photon beam if the final quarks are taken unpolarized. But the polarizations of the Compton backscattered photons have the distribution with respect to their energy. This is an additional uncertainty coming from the determination of the photon polarization. This is one of the reason that we consider unpolarized photon beam. As can be seen from both cross sections it is possible to define two different asymmetries

$$A_1 = \frac{\sigma_+(\lambda_t = 1) - \sigma_+(\lambda_t = -1)}{\sigma_+(\lambda_t = 1) + \sigma_+(\lambda_t = -1)} = \frac{\Delta\sigma}{\sigma}, \tag{15}$$

$$A_2 = \frac{\sigma_+(\lambda_t = 1, \lambda_{\bar{t}} = -1) - \sigma_+(\lambda_t = -1, \lambda_{\bar{t}} = 1)}{\sigma_+(\lambda_t = 1, \lambda_{\bar{t}} = -1) + \sigma_+(\lambda_t = -1, \lambda_{\bar{t}} = 1)} = \frac{\Delta\sigma_2}{\sigma_2}, \tag{16}$$

where σ_+ denotes the spin dependent cross section with the positive helicity of the proton. Integrated cross section $\Delta\sigma$ and σ over momentum fractions can be written by

$$\Delta\sigma = \int_{x_1^{\min}}^{x_1^{\max}} dx_1 \int_{x_2^{\min}}^{1} dx_2\, f_\gamma(x_1) \Delta g\left(x_2, Q^2\right) \Delta\hat{\sigma}(\hat{s}), \tag{17}$$

$$\sigma = \int_{x_1^{\min}}^{x_1^{\max}} dx_1 \int_{x_2^{\min}}^{1} dx_2\, f_\gamma(x_1) g\left(x_2, Q^2\right) \hat{\sigma}(\hat{s}), \tag{18}$$

where Δg, g are the polarized and unpolarized gluon distribution function and f_γ is the energy spectrum of the Compton backscattered photons [9]. The gluon-spin dependent part of the cross section $\Delta\hat{\sigma}$ and the unpolarized part $\hat{\sigma}$ for the subprocess is given by

$$\Delta\hat{\sigma} = \frac{2\beta N_c \pi \alpha \alpha_s Q_t^2}{\hat{s}} \left[\left(1-\beta^2\right) \log\frac{1+\beta}{1-\beta} + 2\beta \right], \tag{19}$$

$$\hat{\sigma} = \frac{2 N_c \pi \alpha \alpha_s Q_t^2}{\hat{s}} \left[\left(3-\beta^4\right) \log\frac{1+\beta}{1-\beta} + 2\beta\left(\beta^2 - 2\right) \right]. \tag{20}$$

Similar expressions for $\Delta\sigma_2$ and σ_2 can be extracted from related cross sections.

Now let us consider the case where polarization of one of the top quarks will be observed. In order to detect top spin polarization through weak decay products the decay channel $b\bar{b}(\nu\ell)(jj)$ (golden channel) with their branching ratio 30% is the most favorable. The important thing is to know the reasonable number of events in the final state which makes a sizable detection. In Fig. 1 the number of events are shown as a function of energy for luminosity $L = 20\ \text{fb}^{-1}$. Polarized and unpolarized cross sections and comparison with pp scattering for the unpolarized case are taken into account. $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ cross sections are provided in Appendix B. We have used LSS2006 parton distribution functions (PDF) for polarized gluon distribution. LSS2006 consists of positive polarized gluon density $\text{SET} = 1$, negative polarized gluon density $\text{SET} = 2$ and the one that changes sign as a function of x $\text{SET} = 3$ [12]. For unpolarized gluon distribution, MRST2006 PDF [13] have been used. Energy spectrum of Compton backscattered photons f_γ is given in Appendix A. The number of events has been defined as $N = L\sigma Br$ where L and Br are luminosity and semi-leptonic branching ratio. As can be seen from Fig. 1, number of events for unpolarized $\gamma p \to \bar{t}t$ process is higher than polarized one because of final state polarization sum. From comparison, at lower energies number of events from $\gamma p \to \bar{t}t$ is substantially larger than the number of events from $pp \to \bar{t}t$ process. For example, at $\sqrt{s} = 700$ GeV the factor of increase is about 80, at $\sqrt{s} = 1000$ GeV it is about 20. This is due to the energy carried by parton which is higher in γp scattering.

To investigate gluon polarization, top quark spin asymmetry A_1 can be regarded as the best observable. The plot of this asymmetry as a function of energy is shown in Fig. 2 for LSS2006 polarized gluon distribution function with $\text{SET} = 1, 2, 3$.

From Fig. 2 we see that the asymmetry becomes maximum about at $\sqrt{s} = 800$ GeV. This highly sizable asymmetry value comes from the high mass of the top quark.

Angular distribution of top quark asymmetry is shown in Fig. 3 for $\sqrt{s} = 800$ GeV with the same polarized gluon distributions as in Fig. 2. Higher asymmetry appears in the forward and backward region. As seen from the figures, the asymmetries for $\text{SET} = 1$ and $\text{SET} = 3$ show almost the same behavior.

We have calculated statistical uncertainty δA_1 of the asymmetry A_1 by the following formula

$$\delta A_1 = \frac{1}{P}\sqrt{\frac{1 - A_1^2 P^2}{N}}, \tag{21}$$

where N is the number of events for the unpolarized final state and P is the proton beam polarization. An estimation has been made for the differential asymmetry as a function of scattering angle of the top quark with $P = 0.7$, $L = 20\ \text{fb}^{-1}$ and 30% semi-leptonic branching ratio at $\sqrt{s} = 1000$ GeV. Table 2 shows this estimation for LSS2006, $\text{SET} = 1$. Higher energy and luminosity will make the statistical uncertainty better.

As discussed in the beginning of the section, the asymmetry A_2 does the same job. In this case, one should measure polarizations of both of the top quarks. Then the leptonic channels of top pairs give clearer signals with a branching ratio 5%. This branching ratio creates 6 times lower number of events than semi-leptonic channel at the same energy and luminosity. This feature can be compensated with higher center of mass energy and higher luminosity.

3. Conclusion

Contribution of the polarized gluon distribution to the polarized proton can be directly probed by Compton backscattered pho-

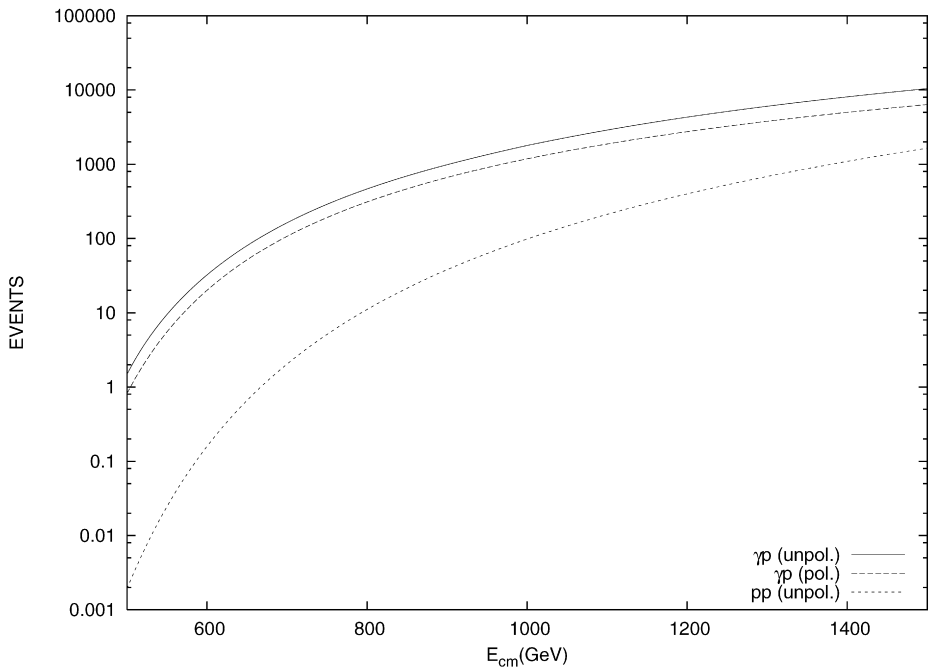

Fig. 1. Number of events as a function of energy for polarized, unpolarized $\gamma p \to \bar{t}t$ cross sections and for unpolarized $pp \to \bar{t}t$ cross section with luminosity 20 fb^{-1}. For polarized gluon density LSS2006 with SET = 1 is used.

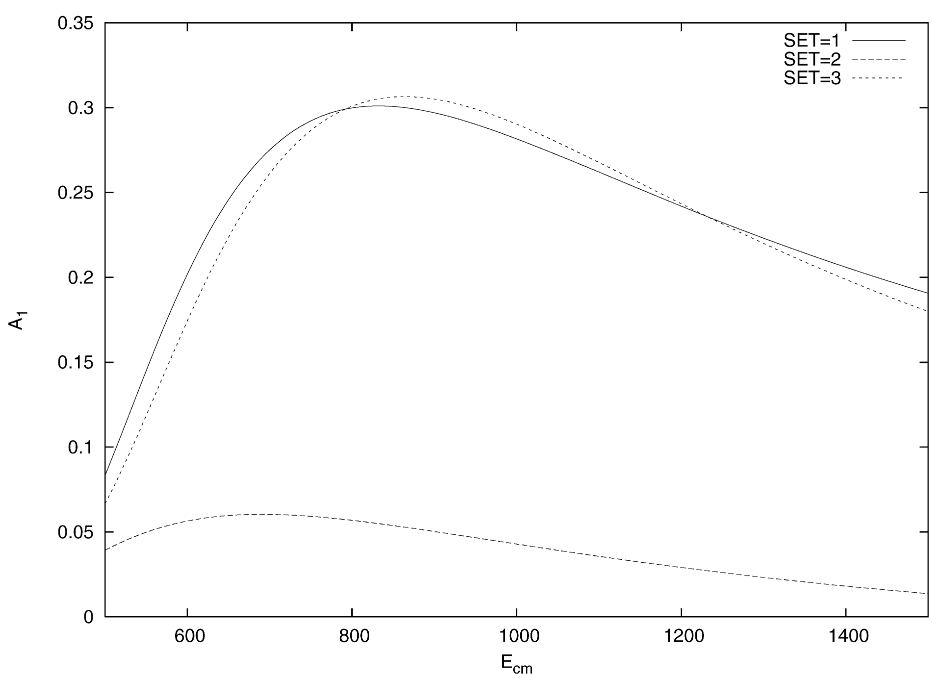

Fig. 2. Top quark spin asymmetry as a function of center of mass energy $\sqrt{s}$ for LSS2006 polarized gluon distribution function with SET = 1, 2, 3.

ton beam in the process $\gamma p \to \bar{t}t$. Measuring the polarization of the top quarks in the final state provides the spin information of the process based on the fact that the top quark decays without hadronization. When enough energy and luminosity are available in γ-proton collision to produce top quarks, polarization asymmetry of the final top quarks is the promising observable for determining gluon polarization. However, there are several points to study for designing and establishing such an experiment including detector. Since our work is devoted to the discussion of the theoretical steps only, experimental arguments are out of our scope.

Appendix A. Compton backscattered photons

After the development on the research for linear electron-positron colliders, future γe, $\gamma\gamma$ and γp modes with real photons have been discussed as complementary to basic colliders. In this section we give the spectrum of the real gamma beam obtained by the Compton backscattering of laser photons off linear electron beam

$$f_{\gamma/e} = \frac{1}{g(\zeta)}\left[1 - y + \frac{1}{1-y} - \frac{4y}{\zeta(1-y)} + \frac{4y^2}{\zeta^2(1-y)^2}\right], \qquad \text{(A.1)}$$

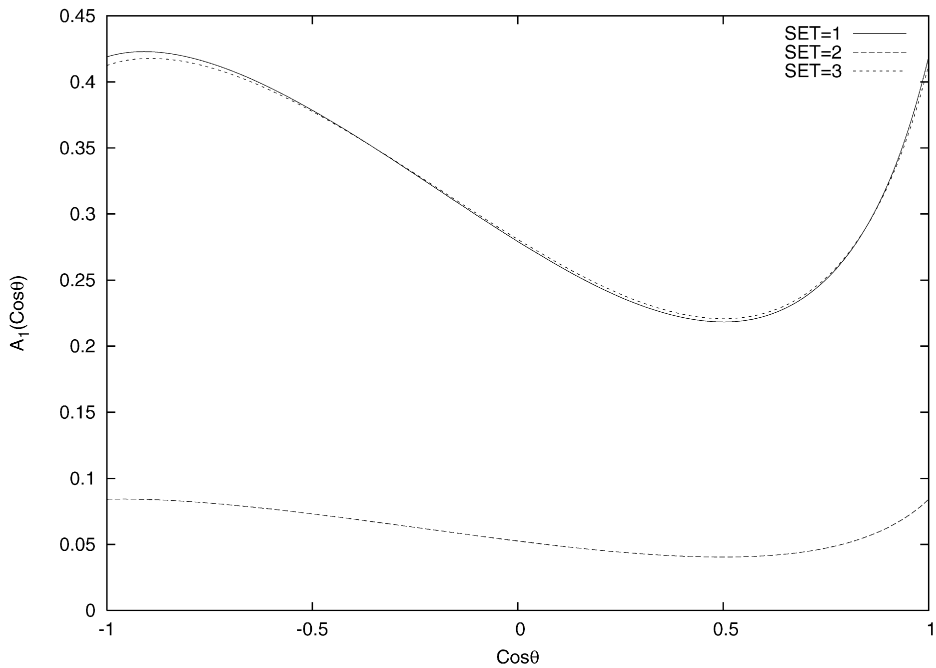

Fig. 3. Differential top quark spin asymmetry $A_1(\cos\theta)$ as a function of scattering angle $\cos\theta$ for $\sqrt{s} = 800$ GeV. LSS2006 polarized gluon distribution function with SET = 1, 2, 3 has been used.

Table 2
An estimation of Statistical uncertainty for the differential asymmetry at $\sqrt{s} = 1000$ GeV with $L = 20\ \text{fb}^{-1}$ and $P = 0.7$. Here $z = \cos\theta$.

z	$A_1(z)$	$\delta A_1(z)$
−1	0.43	0.04
−0.8	0.42	0.04
−0.6	0.39	0.05
−0.4	0.34	0.05
−0.2	0.30	0.05
0	0.25	0.05
0.2	0.21	0.05
0.4	0.18	0.05
0.6	0.18	0.05
0.8	0.23	0.04
1	0.43	0.04

where

$$g(\zeta) = \left(1 - \frac{4}{\zeta} - \frac{8}{\zeta^2}\right)\log(\zeta+1) + \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(\zeta+1)^2}, \tag{A.2}$$

with

$$y = \frac{E_\gamma}{E_e}, \qquad \zeta = \frac{4E_0E_e}{M_e^2}, \qquad y_{\max} = \frac{\zeta}{1+\zeta}. \tag{A.3}$$

Here, E_0 and E_e are energy of the incoming laser photon and initial energy of the electron beam before Compton backscattering. E_γ is the energy of the backscattered photon. The maximum value of y reaches 0.83 when $\zeta = 4.8$.

Appendix B. Cross sections for $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$

In proton–proton scattering the differential cross sections contributing to $t\bar{t}$ final states are given below [14]

$$\frac{d\hat{\sigma}}{dt}(q\bar{q} \to t\bar{t}) = \frac{4\pi\alpha_s^2}{9s^4}\left[\left(m^2-t\right)^2 + \left(m^2-u\right)^2 + 2m^2s\right], \tag{B.1}$$

$$\begin{aligned}\frac{d\hat{\sigma}}{dt}(gg \to t\bar{t}) = \frac{\pi\alpha_s^2}{8s^2}\Bigg[&\frac{6(m^2-t)(m^2-u)}{s^2} - \frac{m^2(s-4m^2)}{3(m^2-t)(m^2-u)} \\ &+ \frac{4(m^2-t)(m^2-u) - 8m^2(m^2+t)}{3(m^2-t)^2} \\ &+ \frac{4(m^2-t)(m^2-u) - 8m^2(m^2+u)}{3(m^2-u)^2} \\ &- \frac{3(m^2-t)(m^2-u) + 3m^2(u-t)}{s(m^2-t)} \\ &- \frac{3(m^2-t)(m^2-u) - 3m^2(u-t)}{s(m^2-u)}\Bigg],\end{aligned} \tag{B.2}$$

where m is the top quark mass and s, t and u are the Mandelstam invariants for the subprocess.

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