PROCEEDINGS OF SCIENCE

Determining spin dependent gluon distributions from top quark pair production at the LHC

Gary R. Goldstein[a,*]

[a] *Tufts University, Department of Physics and Astronomy, Medford, MA, 02155, U.S.A.*

E-mail: gary.goldstein@tufts.edu

Inclusive top quark pair production at the LHC proceeds primarily via gluon fusion. Decays of the polarized top pairs through various particle and jet channels have strong angular dependences reflecting the top and anti-top polarizations that produce a variety of correlations among the decay products - particles and jets. Those correlations are determined by the spin dependent gluon distributions from the unpolarized colliding protons. Combinations of the gluon distributions, either polarized or unpolarized, can be accessed experimentally through angular dependences of top decay products, as will be shown, along with preliminary predictions from a model of gluon distributions.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

PoS(DIS2024)240

The structure of the hadrons, as determined by QCD, has been studied for many years, especially focused on the nucleon. Theoretical efforts to model that structure via interacting quarks and gluons are constrained by non-perturbative physics at nucleon size.

There are several kinds of gluon and quark distributions within the nucleon and other hadrons. The most general structures are the Generalized Transverse Momentum Distribution Functions (GTMD's), that depend on the virtual photon+nucleon scattering variables $(x, \xi, \Delta, k_t^2, Q^2)$. Integrations over k_t^2 or Δ reduce these to Generalized Parton Distributions (GPDs) or Transverse Momentum Distributions (TMDs), respectively. Unintegrated models for either of these distributions default back to GTMDs, and through Fourier transforms, to Wigner distributions [**?**]. The model that will be in the background here, providing a direction for coupling the top pairs to the gluon distributions,is a particular extension of a model for GPD's - the Reggeized spectator model referred to as the "flexible parameterization" scheme [**?**], which has a natural generalization to the gluon and sea quark GPDs [**?**]. The model for gluon GPDs, with parameterization fixed by various constraints, is directly related to the gluon transversity pdf, $h_1^g(x, Q^2)$ and for non-exclusive or semi-inclusive processes (SIDIS), is the TMD $h_1^g(x, \vec{k}_T^2)$. We carry over a spectator picture for quark color triplet and spectator diquark color anti-triplet to the gluon plus spectator picture. This makes the struck nucleon to have a color octet gluon plus a color octet with baryon number 1. The struck gluon interacts with a probing virtual photon by charged pair of produced quarks in a color octet symmetric state [**?**]. These details will be described in work in progress.

The gluon TMDs are the distributions that can be measured in the process being advocated here, the production of single top-antitop pairs in proton+proton interactions at the LHC. To adumbrate the spin correlations for the gluons and the top pairs, I will use the GPDs that can be formally connected to the amplitudes for the process. Thereafter, the substitution of TMDs for the GPDs is straightforward.

The emphasis in this paper, will be on the top-antitop spin correlations, since these are seldom discussed. Relevant features of the gluon distributions have been discussed in Ref. [**?**] and details will be presented in a forthcoming paper. Of course, other heavy flavor quark pairs can carry similar information, but the distinctive decays of top into b-jets and on-shell W's (that subsequently decay into lepton + neutrino) makes top flavor favorable. Bottom quark pairs have many fragmentation and decays channels, some of which can be quite recognizable, although rare.

1. Top-Antitop Spin Correlations

Before the discovery of the top quark at the Fermilab Tevatron, one proposed method to disentangle the signal for top quark production from the daunting background of multiple hadron events was to concentrate on the spin correlations of the top and antitop decay products. The "golden events" were expected to be the dilepton events in which two very energetic opposite sign leptons would signal the weak decays of each top into b-quarks and W's, the latter decaying leptonically. The actual observations of top quarks by the D0 [**?**] and CDF [**?**] groups did not use the spin correlations. Nevertheless, these correlations provide a test of the QCD mechanism [**?**]. The LHC now produces many more top quarks. The higher energy makes quark-antiquark annihilation less important than gluon fusion. Gluon fusion, involving the merging of two vector particles, gives rise

PoS(DIS2024)240

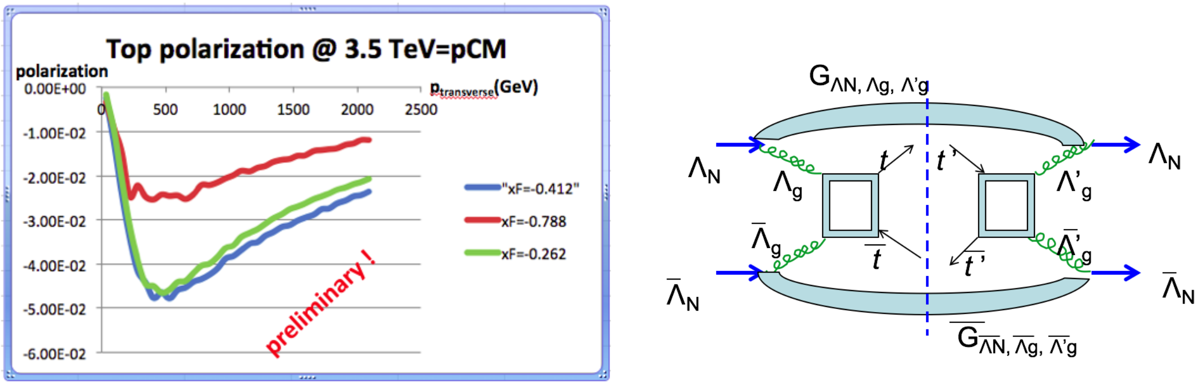

Figure 1: Predicted top polarization from p+p collisions at 3.5 TeV vs. p_T at 3 values of x_F, based on perturbative QCD model of Dharmaratna and Goldstein Ref. [**?**]. (left) Illustration of cross section for definite helicities in p+p $\longrightarrow$ t+$\bar{t}$ +X. (right)

to quite distinct spin correlations among the top decay products. I will present the corresponding spin density matrices and angular correlations.

What is known about single polarization of the top only or antitop only in the pair production? Recent determination at the LHC of top single spin asymmetry (SSA) are small - from ATLAS $A_p = -0.035 \pm 0.040$ and from CMS $A_p = 0.005 \pm 0.01$ [**?**]. An explanation based on one loop QCD calculations with an ansatz for "recombination" [**?**], predicts peaks close to -0.05 vs. p_T, over a range of x_F as shown in Fig. **??**. This prediction is within the small values and their uncertainties determined by both CMS and ATLAS. The measurement of such single spin asymmetries will test an important mechanism whereby QCD can perturbatively generate appropriate interferences to polarize heavy quarks [**?**] or non-perturbatively through sets of light quark pair production [**?**] work in progress.

The top quark decays through the weak interaction, primarily into a W and b-jet. This happens rapidly, since the top mass is so large, making the weak coupling sufficient to produce the decay probability competitive with the strong interaction. Because of this rapid quark decay, there is not enough time for top quarks to form top hadronic states. There are no top mesons or baryons.The W in the decay, in turn, can decay into a charged quark pair or lepton + neutrino pair. The semi-leptonic decays of the top quark afford the best opportunity for polarization analysis [**?**]. The opposite-sign leptons usually have very high transverse momenta and are accompanied by b-quark jets. So the double correlation of top spins is manifested in the joint decay distributions into leptons and b-jets. Other decay channels involved are presented elsewhere [**?**].

As shown in Ref. [**?**], the amplitude for a polarized top quark at rest to decay into a measured b-quark and antilepton (or u-quark) along with an unobserved neutrino (or ignoring the $\bar{d}$ jet) is completely determined in the Standard Model. Since the neutrino is not observed, its 3-momentum is fixed to lie on an ellipse in a lepton-b-quark coordinate system. Using an associated ellipse construction for the unmeasured neutrino momentum allows for the specification of the top-antitop center of mass and the related polarization. This process is described in detail in ref.[**?**]. An alternative approach to extracting missing momenta and polarizations uses cubic equations from momentum conservation.

The quark or gluon spin correlations are transmitted to the decay products. The correlations between the lepton directions and the parent top spin (in the top rest frame) produce correlations between the lepton directions, which has been expressed as a weighting factor [**?**] in the light quark-antiquark annihilation mechanism.

The gluon fusion mechanism for the weighting factor for unpolarized gluons, is summed over gluon helicities. This gives rise to a fourth order angular distribution:

$$
\begin{aligned}
W(\theta, p, p_{\bar{l}}, p_l) \;=\; & \frac{1}{4} - \frac{1}{4}\Big\{\big[(1-\beta^2)^2 + \sin^4\theta)\big]\,(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} + \\
& +[-(1-\beta^2)^2 - (1-2\beta^2)\sin^4\theta](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} + \\
& +[(1-\beta^4) - 2\beta^2\sin^2\theta + \sin^4\theta](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} + \\
& +2(\beta/\gamma)\sin^3\theta\cos\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\Big\} \\
& /4\left[(1-\beta^4) + 2\beta^2\sin^2\theta + (1-2\beta^2)\sin^4\theta\right]. \qquad (1)
\end{aligned}
$$

where m is the top quark mass, θ is the top quark production angle in the quark-antiquark or $\bar{t}\,t$ CM frame, p is the light quark or gluon CM momentum, β is the magnitude of the relativistic velocity of the top or antitop quark in the CM, $\hat{p}_{\bar{l}}$ is the l^+ momentum direction in the top rest frame and $\hat{p}_l$ is the corresponding l^- direction in the antitop rest frame.

We can now separate the dilepton angular distributions into different components for the four different combinations of gluon distributions. For the (LP, LP) case, which measures the linearly polarized gluon pair.

$$
\begin{aligned}
W^{(LP,LP)}(\theta, p, p_{\bar{l}}, p_l) \;=\; & -\frac{1}{4} + \frac{1}{4}\Big\{[(1-\beta^4) + \beta^2\sin^2\theta(-2 + (2-\beta^2)\sin^2\theta)](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} + \\
& +[(1-\beta^4) + \beta^2\sin^2\theta(2-\beta^2\sin^2\theta)](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} + \\
& +[-(1-\beta^2)^2 + \beta^2(2-\beta^2)\sin^4\theta](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} + \\
& -4(\beta^2/\gamma)\sin^3\theta\cos\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\Big\} \\
& /\left[(1-\beta^2)^2 + \beta^4\sin^4\theta\right]. \qquad (2)
\end{aligned}
$$

In Figure **??** we show the directional correlation distributions for an unpolarized gluon distribution and a linear-transverse polarized gluon distribution. We have not included any particular values of gluon distribution functions. For that, we would convolute our spectator model distributions with the weights. The distributions are rich in dependences on the energies and angles for the t + t̄ pair and the dilepton momenta. The $W_{i\,j}$ is the θ and β dependent factor multiplying the Cartesian components of $\hat{p}(\mu^+)_i\ \hat{p}(\mu^-)_j$, plotted for varying β, the magnitude of relativistic velocity of the top in the t + t̄ Center-of-Mass frame. The lepton momenta are determined in their top or antitop rest frames. Coordinates in the t + t̄ CM are determined as follows. The t + t̄ pair have momentum $\vec{p}_{t+\bar{t}}$ in the p+p collider CM. In the t + t̄ CM the pair of gluons (or quark-antiquark) has zero 3-momentum, so the orientation of one gluon relative to the top in the t + t̄ CM is the angle θ boosted from the p+p CM.

For illustration we chose the polar angle of the t + t̄ CM to be $\theta = \pi/8$ and varied β. The resulting weighting factors are remarkable for the clear distinction between unpolarized and polarized gluons.

References

[1] Ashman, et al. Phys. Lett. B **206** (1988) 364.

[2] C. Lorce and B. Pasquini, Phys.Rev. D**84** (2011) 014015.

[3] G. R. Goldstein, J. O. Hernandez and S. Liuti, Phys. Rev. D **84** (2011) 034007; *ibid* Phys. Rev. D **91** (2015) 114013; *ibid*, J. Phys. G: Nucl. Part. Phys. **39** (2012) 115001.

[4] G.R. Goldstein, S. Liuti, J.O. Gonzalez Hernandez, J. Poage *work in progress*; G.R. Goldstein and S. Liuti, “QCD Evolution 2014", IJMP: Conf. 37(2015) 1560038.

[5] S. Abachi, *et al.*, Phys. Rev. Lett. **74** (1995) 2422.

[6] F. Abe, *et al.*, Phys. Rev. Lett. **74** (1995) 2626.

[7] Gary R. Goldstein,“*Spin Correlations in Top Quark Production and the Top Quark Mass* ”*in* Proceedings of the 12th International Symposium on High Energy Spin Physics, Amsterdam, edited by C.W. deJager *et al.*, World Scientific, Singapore, 1997, p. 328.

[8] (ATLAS) Phys. Rev. D**93** (2016) 012002; *ibid*, Phys. Rev. Lett. **114** (2015) 142001; (CMS) S. Chatrchyan, *et al.* Phys. Rev. Lett. **107** (2011) 021802; *ibid*, Phys. Rev. Lett. **112** (2014) 182001.

[9] W.G.D. Dharmaratna and G.R. Goldstein, Phys. Rev.**D41** (1990) 1731; *ibid*, Phys.Rev. **D53** (1996) 1073; G.R. Goldstein, Polarization of inclusively produced Λ_c in a QCD based hybrid model, in *Proceedings* Λ_c *Workshop*, (Fermilab (1999)) and arXiv:hep-ph/9907573.

[10] G. Goldstein, S. Liuti, D. Sivers, in Gluons and the quark sea at high energies: Distributions, polarization, tomography, D. Boer, et al. (Aug, 2011) e-Print: 1108.1713 [nucl-th]

[11] D. Boer, *et al.*, Phys. Rev. Lett. **106** (2011) 132001; C. Pisano, *et al.*, *JHEP***10** (2013) 024.

[12] W. Bernreuther, et al., Phys. Rev. Lett. **87** (2001) 242002.

[13] G. Mahlon and S. Parke, Phys. Rev.**D81** (2010) 074024, and references therein.

[14] R. H. Dalitz and G. R. Goldstein, Phys. Lett. B287 (1992) 225; *ibid* Phys. Rev. D45 (1992) 1531.

[15] D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Rev. D 68 (2003) 094013.

[16] G.R. Goldstein and M. J. Moravcsik, *Ann. Phys.* (N.Y.) **98** (1976) 128; **195** (1989) 213.
....

PoS(DIS2024)240