Double Transverse Spin Asymmetries at 
Next-To-Leading Order in QCD

A. Mukherjee, M. Stratmann and Werner Vogelsang

Presented at 16th International Spin Physics Symposium, Spin 2004
Trieste, Italy
October 10 to 16, 2004

Physics Department
Nuclear Theory Group
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

Managed by Brookhaven Science Associates, LLC
for the United States Department of Energy under
Contract No. DE-AC02-98CH10886
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DOUBLE TRANSVERSE-SPIN ASYMMETRIES AT NEXT-TO-LEADING ORDER IN QCD

A. MUKHERJEE
Lorentz Institute, University of Leiden, 2300 RA Leiden, The Netherlands

M. STRATMANN
Institute für Theoretische Physik, Universität Regensburg
D 93040 Regensburg, Germany

W. VOGELSANG
(1) Physics Department, Brookhaven National Laboratory
Upton, New York 11973, USA
(2) RIKEN-BNL Research Center, Bldg. 510a, Brookhaven National Laboratory,
Upton, New York 11973 - 5000, USA

We present a technique to calculate the cross sections and spin asymmetries for transversely polarized \( pp \) collisions at NLO in QCD and report on the use of this technique for the processes \( p^+p^+ \rightarrow \gamma X, p^+p^+ \rightarrow \pi X \) and \( p^+p^+ \rightarrow t^+t^-X \).

1. Introduction

Combined experimental and theoretical efforts in the past few years have led to an improved understanding of the unpolarized parton distributions \( f(x,Q^2) \) and the helicity distributions \( \Delta f(x,Q^2) \) of the nucleon. It is known that the complete understanding of the partonic structure of a spin \( \frac{1}{2} \) object like a nucleon is given in terms of \( f(x,Q^2), \Delta f(x,Q^2) \) and by the transversity distributions \( \delta f(x,Q^2) \), which give the number densities of partons having the same polarization as the nucleon, when the nucleon is transversely polarized, minus the number with opposite polarization: \( \delta f(x,Q^2) \) remain quantities about which we have the least knowledge and are at present the focus of much experimental activity.

Transversity will be probed in the double transverse spin asymmetries in transversely polarized \( pp \) collisions at the BNL Relativistic Heavy Ion Collider (RHIC). The potential of RHIC in accessing transversity through...
double transverse spin-asymmetries $A_{TT}$ in the Drell-Yan process was estimated in $^1$. Other relevant processes include high $p_T$ prompt photon and jet production $^2$. Apart from DY, the other calculations were done at leading order (LO). It is known that the next-to-leading order (NLO) QCD calculations are necessary in order to have a firm theoretical prediction.

2. Projection Technique

Apart from the motivations given above, interesting new technical questions arise beyond LO in the calculations of cross sections involving transverse polarization. Unlike the longitudinally polarized case, where the spin vectors are aligned with the momentum, the transverse spin vectors specify extra spatial directions and as a result, the cross section has non-trivial dependence on the azimuthal angle of the observed particle. For $A_{TT}$ this dependence is always of the form $^3$

$$\frac{d^3\sigma}{dp_Td\eta d\Phi} \equiv \cos(2\Phi)\left(\frac{d^2\sigma}{dp_Td\eta}\right),$$

for a parity conserving theory with vector coupling, here the $z$ axis is defined by the direction of the initial partons in their center-of-mass frame and the spin vectors are taken to point in the $\pm x$ direction. Therefore the integration over the azimuthal angle is not appropriate. This makes it difficult to use the standard techniques developed for NLO calculations of unpolarized and longitudinally polarized processes here because all these techniques usually rely on the integration over the full azimuthal phase space and also on particular reference frames which are related in a complicated way to the center-of-mass frame of the initial protons. In $^4$ a new general technique was introduced which facilitates NLO calculations with transverse polarizations by conveniently projecting on the azimuthal dependence of the cross section in a covariant way. The projector

$$F(p, s_a, s_b) = \frac{s}{\pi t u} \left[ 2 (p \cdot s_a) (p \cdot s_b) + \frac{t u}{s} (s_a \cdot s_b) \right],$$

reduces to $\frac{\cos(2\Phi)}{\pi}$ in the center-of-mass frame of the initial protons. Here $p$ is the momentum of the observed particle in the final state. The cross section is multiplied with the projector and integrated over the full azimuthal phase space. Integrations of the terms involving the product of the transverse spin vectors $s_a, s_b$ with the momenta can be performed using a tensor decomposition. After this step, there are no scalar products involving $s_i$ left in the matrix element. For the integration over the phase space, one
can now use the standard techniques from the unpolarized and longitudinally polarized cases. This method is particularly convenient at NLO, where one uses dimensional regularization and the phase space integrations are performed in $n$ dimensions.

### 3. Applications

As an example, we discuss the use of this technique for high $p_T$ prompt photon production. The LO process is $q\bar{q} \rightarrow \gamma g$. We multiply $\delta |M|^2$ by the projector $F(p, s_a, s_b)$ and integrate over the full $\Delta \phi$ in a covariant way. At NLO, there are two subprocesses contributing: $qq \rightarrow \gamma X$, where $X = q\bar{q}$, and $q\bar{q} \rightarrow \gamma X$, where $X = q\bar{q} + gg + q'\bar{q}'$. For $2 \rightarrow 3$ processes, one integrates over the phase spaces of the unobserved particles, after multiplying with the projector and eliminating the scalar products with the spin vectors using tensor decomposition. Owing to the presence of the ultraviolet, infrared and collinear singularities, one has to introduce a regulator. We choose dimensional regularization: UV poles in the virtual diagrams are removed by renormalization of the strong coupling constant. Infrared singularities cancel between the real emission and virtual diagrams. After this, only collinear singularities remain, which result from collinear splitting of an initial-state parton into a pair of partons. These correspond to long-distance contribution to the partonic cross section. From the factorization theorem it follows that such contributions need to be factored into the parton distributions. We have imposed an isolation cut to remove the background contribution. All final-state collinear singularities then cancel. The isolation constraint was imposed analytically by assuming a narrow isolation cone.

For our numerical predictions, we model the transversity distribution by saturating Soffer's inequality $\delta f(x, \mu) \approx 0.6 \text{ GeV}^{-2}$ and for higher scales, $\delta f(x, \mu)$ are obtained by solving the QCD evolution equations. Figure 1 shows the results for the prompt photon production in transversely polarized $pp$ collisions. Our numerics apply to the PHENIX detector at RHIC. The scale dependence becomes much weaker at NLO. The corresponding asymmetries are given in $\ref{sec:asymmetries}$.

For the Drell-Yan lepton pair production in transversely polarized $pp$ collisions the LO subprocess is $q\bar{q} \rightarrow l^+l^-$. The real emission $2 \rightarrow 3$ subprocess is $q\bar{q} \rightarrow l^+l^-g$. We multiply the squared matrix element by the projector and integrate over the phase space. We obtain the known result for the DY process.
Figure 1. Predictions for the transversely polarized prompt photon production cross sections at LO and NLO, for $\sqrt{s} = 200$ and 500 GeV. The LO results have been scaled by a factor of 0.01. The shaded bands represent the theoretical uncertainty if $\mu_F = \mu_R$ is varied in the range $p_T/2 \leq \mu_F \leq 2p_T$. The lower panel shows the ratios of the NLO and LO results for both c.m.s. energies.

For inclusive pion production in transversely polarized process the LO channels are $qq \rightarrow qX, q\bar{q} \rightarrow qX, q\bar{q} \rightarrow q'X, q\bar{q} \rightarrow gX$. At NLO there are $O(\alpha_s)$ corrections to the above processes and the additional channel $qq \rightarrow gX$. We have used the projection technique to calculate the cross section at NLO and the numerical results are in progress.

Acknowledgments

AM thanks the organizers of the 16th International Spin Physics Symposium for a wonderful conference and hospitality and FOM for support. WV is grateful to RIKEN, Brookhaven National Laboratory and the U.S. Department of Energy (contract number DE-AC02-98CH10886) for providing the facilities essential for the completion of his work.

References