PROCEEDINGS OF SCIENCE

A_N in Single-Inclusive Particle Production from Proton-Proton Collisions

Daniel PITONYAK*
RIKEN BNL Research Center
E-mail: dpitonyak@quark.phy.bnl.gov

Koichi KANAZAWA
Temple University
E-mail: koichi.kanazawa@temple.edu

Yuji KOIKE
Niigata University
E-mail: koike@nt.sc.niigata-u.ac.jp

Andreas METZ
Temple University
E-mail: metza@temple.edu

We analyze the cause of transverse single-spin asymmetries (TSSAs) in pion and direct photon production from proton-proton (pp) collisions. Two main approaches are used to describe these observables: collinear twist-3 (CT3) factorization and the Generalized Parton Model (GPM). We argue that within the CT3 framework, the fragmentation term can describe very well TSSAs in high transverse momentum charged and neutral pion production in pp collisions at the Relativistic Heavy Ion Collider (RHIC). In addition, TSSAs in direct photon production can be a rich source of information; namely, one can cleanly access the Qiu-Sterman function, test the process dependence of the Sivers function, and distinguish between the CT3 and GPM formalisms.

QCD Evolution 2015 -QCDEV2015-
26-30 MAY 2015
Jefferson Lab (JLAB), Newport News Virginia, USA

*Speaker.

PoS(QCDEV2015)011

1. Introduction

Transverse single-spin asymmetries (TSSAs) (typically denoted A_N) have been around for close to 40 years [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13], with measurements performed at Argonne National Lab, FermiLab, AGS, and RHIC. Large effects were found in these experiments that initially contradicted the predictions of perturbative QCD (pQCD) in the 1970s, which stated within the naïve collinear parton model that TSSAs should be extremely small [14]. However, it was determined in the 1980s that this model was not sufficient to generate large effects; rather, one must include collinear twist-3 (CT3) quark-gluon-quark correlations in the nucleon [15]. In the 1990s this CT3 approach was worked out in more detail for proton-proton collisions [16, 17, 18, 19]. Over the last decade, several other analyses furthered the development of this formalism — see [20, 21, 22, 23, 24, 25, 26, 27, 28, 29] and references therein. Nevertheless, also in the 1990s it was put forth that these TSSAs had another origin due to the transverse momentum dependence of partons — see [30, 31, 32, 33, 34] and references therein. This approach, called the Generalized Parton Model (GPM), involves the Sivers [35], Collins [36], and Boer-Mulders [37] TMD functions. (We mention that, since most likely a rigorous factorization formula involving TMD functions does not hold for single-inclusive processes (which have only one scale), the GPM can only be considered a phenomenological model.) In Sec. 2 we focus on the results from the CT3 framework and briefly mention those of the GPM. In particular, we show how the CT3 fragmentation mechanism can give a very good description of all high transverse momentum RHIC data on A_N in $p^\uparrow p \to \pi X$ both as a function of x_F and of P_T. In addition, we analyze all quark-gluon-quark pieces of A_N in $p^\uparrow p \to \gamma X$ and conclude that the Qiu-Sterman function dominates the asymmetry. We also demonstrate how this observable allows one to test the process dependence of the Sivers function and distinguish between the CT3 and GPM approaches. Finally, we summarize and give an outlook in Sec. 3.

2. Phenomenological Results for A_N^π and A_N^γ

One of the main issues with TSSAs in $p^\uparrow p \to \pi X$ (denoted A_N^π), or any single-inclusive process, is that one cannot disentangle distribution effects (i.e., those due to the incoming protons) from fragmentation effects (i.e., those due to the outgoing pion). For many years within the CT3 framework it was assumed that the Qiu-Sterman (QS) function T_F, which is a certain quark-gluon-quark correlator associated with the transversely polarized proton that has a model independent relation to the the TMD Sivers function $f_{1T}^\perp$, was the dominant source of A_N^π [19, 21]. However, a fit of the QS function to A_N^π data led to a result that was inconsistent with an extraction of $f_{1T}^\perp$ from semi-inclusive deep-inelastic scattering (SIDIS) data. This became known as the "sign mismatch" crisis [38]. It was found that more flexible parameterizations of the Sivers function could not resolve the issue [39], which caused speculation that T_F might not be the main cause of A_N^π. In fact, by looking at A_N data on the target TSSA in inclusive DIS [40, 41], the authors of Ref. [42] argued that the QS function could not be the dominant source of A_N^π. Rather, fragmentation effects from the outgoing pion, first completely calculated by two of the authors (A.M. and D.P.) [27], have the potential to lead to large A_N^π, as we first showed in Ref. [43]. We refer the reader to those two papers for details on the theoretical and phenomenological analyses. The results of the latter are shown in Fig. 1 (for A_N^π vs. x_F) and Fig. 2 (for A_N^π vs. P_T). One sees that we are able to describe all RHIC

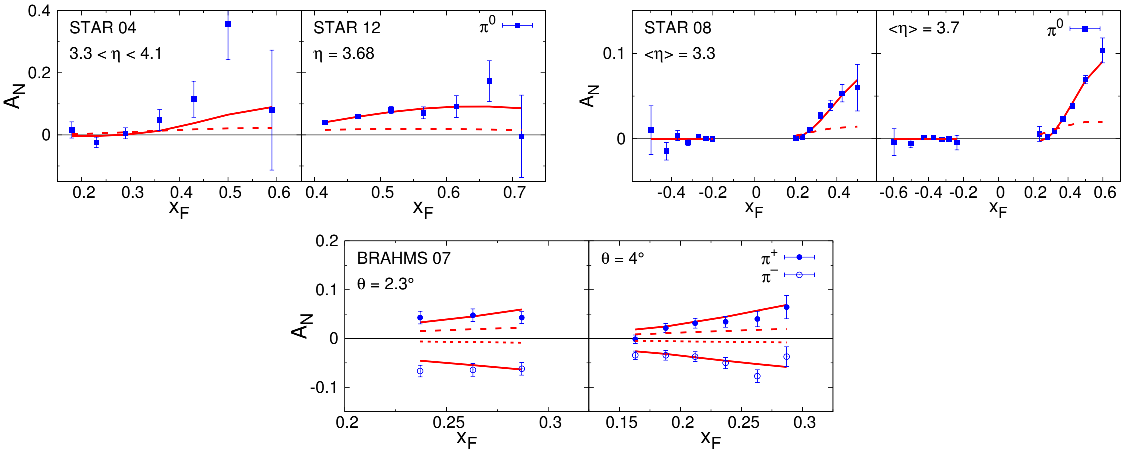

Figure 1: Fit results for $A_N^{\pi^0}$ (data from [6]) and $A_N^{\pi^\pm}$ (data from [8]). The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

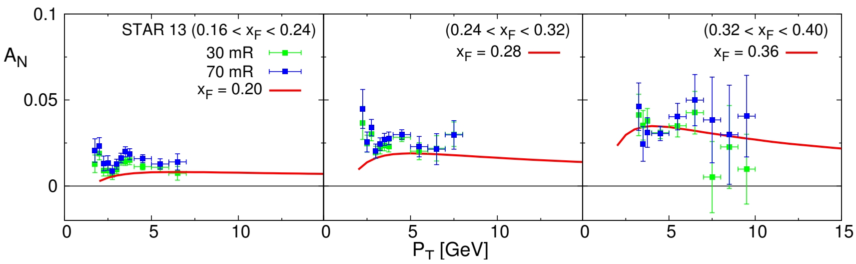

Figure 2: $A_N^{\pi^0}$ as function of P_T at $\sqrt{S} = 500\,\mathrm{GeV}$ (data from [44]).

high transverse momentum A_N^{π} data very well both as a function of x_F and of P_T. In particular, the dashed curves in Fig. 1 highlight the importance of the quark-gluon-quark fragmentation correlator $\hat{H}_{FU}^{\Im}$, i.e., one does not find agreement with A_N^{π} if $\hat{H}_{FU}^{\Im} = 0$.

In the GPM, the part of A_N^{π} coming from the transversely polarized proton enters through the Sivers function, while the piece of the asymmetry coming from the outgoing pion enters through the Collins function. Both of these effects have been analyzed recently [33, 34] by using the TMD functions extracted from SIDIS and e^+e^-. While neither of these sources alone seem to match all of the RHIC data, one may argue that their sum could give the entire effect. However, this only occurs because in the GPM the Sivers effect has the same sign as the data.[1] This leads to a distinct difference between the GPM and CT3 formalisms in their predictions for the TSSA in $p^{\uparrow}p \to \gamma X$ (see below).

The direct photon TSSA (denoted A_N^{γ}) has been investigated in Refs. [17, 21, 23, 45, 46, 47, 48, 49, 50, 51]. There are a few pieces of A_N^{γ} that enter from the side of the incoming protons[2]: (1) the (soft-gluon pole (SGP) chiral-even) QS function, (2) soft-fermion pole (SFP) chiral-even quark-gluon-quark functions, (3) SGP and SFP quark-gluon-quark chiral-odd functions, and (4) SGP

[1] In the CT3 framework the Sivers-type (QS) piece, due to the sign mismatch, gives a contribution that is opposite to the data (and in fact small in magnitude) if one uses the Sivers function from SIDIS.

[2] We will ignore the effects coming from fragmentation photons, which can be largely suppressed in experiments using isolation cuts.

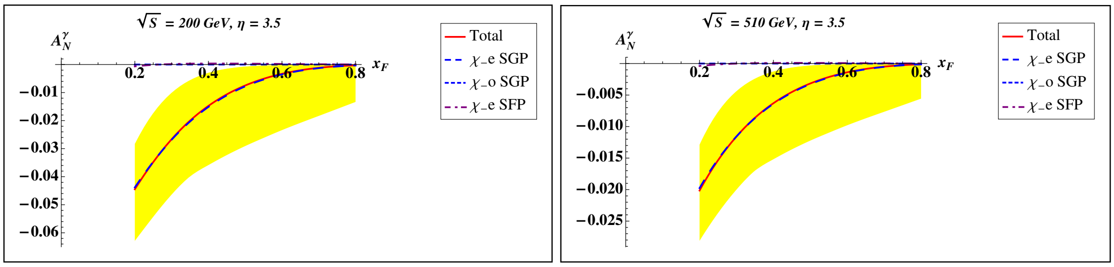

Figure 3: A_N^γ vs. x_F at $\sqrt{S} = 200\,\text{GeV}$ (left) and $\sqrt{S} = 510\,\text{GeV}$ (right) for fixed $\eta = 3.5$. The thick band is our estimate for the error in the asymmetry based on the uncertainty in the Sivers function.

tri-gluon functions. The work in [47] already showed that (4) is negligible. The natural assumption has been that (1) is dominant, but there is no reason *a priori* that (2), (3) cannot give a large asymmetry. Therefore, in [51] we analyzed numerically (1), (2), (3) in order to determine what is the main source of A_N^γ, and we refer the reader to that paper for details on the phenomenology. The results of this study are shown in Fig. 3 for typical RHIC kinematics. One sees that for this observable the total asymmetry (solid line) is solely due to the (SGP chiral-even) QS function (dashed line), where we have taken the Sivers function from SIDIS as our input.

PHENIX and STAR are currently measuring A_N^γ [52, 53, 54], and a clear signal of a nonzero asymmetry from their experiments would provide a rich source of information. First, because the QS function dominates A_N^γ, one should be able to cleanly extract this correlator in order to see if it is consistent with the Sivers effect in SIDIS. Second, because we take the Sivers function from SIDIS as our input for the QS function, one can learn about the process dependence of the Sivers function [55], which is an important prediction from our current understanding of TMDs. That is, a clear negative signal would be a strong indication of process dependence, while a clear positive A_N^γ would be equivalent to *not* seeing a change in sign in the Sivers effect when going from SIDIS to Drell-Yan (i.e., the Sivers function is universal in a strict sense). Finally, the GPM has also been used to investigate A_N^γ, in particular the piece that comes from the Sivers function, and found that the asymmetry is *positive* and on the order of 5-7% [34]. Thus, a clear signal from PHENIX and/or STAR would allow one to distinguish between CT3 and GPM.

3. Summary and Outlook

Transverse single-spin asymmetries in single-particle production have been around for close to 40 years, yet their origin still remains unclear. Within perturbative QCD, two frameworks have been at the forefront to analyze A_N: collinear twist-3 factorization and the Generalized Parton Model. The former had been plagued in the past by the so-called “sign mismatch” crisis. However, we have recently demonstrated that the CT3 fragmentation mechanism could be the main source of A_N^π, which also resolves this issue. Moreover, our analysis maintains consistency between the spin/azimuthal asymmetries in pp collisions and those in SIDIS and e^+e^-. Within the GPM, A_N^π cannot be accounted for by either the Sivers effect or Collins effect alone, but rather needs the sum of the two sources. However, the sign of the former agrees with the data, which is opposite to what one finds in the CT3 formalism. This leads immediately to the two approaches giving opposite predictions for A_N^γ. This observable, which PHENIX and STAR are currently measuring, can yield quite useful information. Not only could one distinguish between the CT3 and GPM but also test the process dependence of the Sivers function and cleanly extract the QS function. The spin community must continue to work towards an explanation of TSSAs both on the experimental and theoretical/phenomenological sides. For example, one can look at A_N^π in lepton-nucleon collisions at HERMES, JLab, COMPASS, and a future Electron-Ion Collider [56, 57, 58, 59] or in high luminosity proton-proton collisions at the proposed AFTER@LHC experiment [60, 61].

Acknowledgments

This work has been supported by the Grant-in-Aid for Scientific Research from the Japanese Society of Promotion of Science under Contract No. 26287040 (Y.K.), the National Science Foundation under Contract No. PHY-1516088 (K.K. and A.M.), and the RIKEN BNL Research Center (D.P.).

References

[1] R. D. Klem, J. E. Bowers, H. W. Courant, H. Kagan, M. L. Marshak, E. A. Peterson, K. Ruddick and W. H. Dragoset *et al.*, Phys. Rev. Lett. **36**, 929 (1976).

[2] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976).

[3] D. L. Adams *et al.* [E581 and E704 Collaborations], Phys. Lett. B **261**, 201 (1991); D. L. Adams *et al.* [E704 Collaboration], Phys. Lett. B **264**, 462 (1991).

[4] K. Krueger *et al.*, Phys. Lett. B **459**, 412 (1999).

[5] C. E. Allgower, K. W. Krueger, T. E. Kasprzyk, H. M. Spinka, D. G. Underwood, A. Yokosawa, G. Bunce and H. Huang *et al.*, Phys. Rev. D **65**, 092008 (2002).

[6] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **92**, 171801 (2004) [hep-ex/0310058]; B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **101**, 222001 (2008) [arXiv:0801.2990 [hep-ex]].

[7] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **95**, 202001 (2005) [hep-ex/0507073].

[8] J. H. Lee *et al.* [BRAHMS Collaboration], AIP Conf. Proc. **915**, 533 (2007).

[9] I. Arsene *et al.* [BRAHMS Collaboration], Phys. Rev. Lett. **101**, 042001 (2008) [arXiv:0801.1078 [nucl-ex]].

[10] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. D **86**, 032006 (2012) [arXiv:1205.2735 [nucl-ex]].

[11] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. D **86**, 051101 (2012) [arXiv:1205.6826 [nucl-ex]].

[12] L. C. Bland *et al.* [AnDY Collaboration], arXiv:1304.1454 [hep-ex].

[13] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. D **90**, 012006 (2014) [arXiv:1312.1995 [hep-ex]]; Phys. Rev. D **90**, 072008 (2014) [arXiv:1406.3541 [hep-ex]].

[14] G. L. Kane, J. Pumplin and W. Repko, Phys. Rev. Lett. **41**, 1689 (1978).

[15] A. V. Efremov and O. V. Teryaev, Sov. J. Nucl. Phys. **36**, 140 (1982) [Yad. Fiz. **36**, 242 (1982)]; Phys. Lett. B **150**, 383 (1985).

[16] J.-w. Qiu and G. F. Sterman, Phys. Rev. Lett. **67**, 2264 (1991).

[17] J.-w. Qiu and G. F. Sterman, Nucl. Phys. B **378**, 52 (1992).

[18] V. M. Korotkiian and O. V. Teryaev, Phys. Rev. D **52**, R4775 (1995).

[19] J.-w. Qiu and G. F. Sterman, Phys. Rev. D **59**, 014004 (1999) [hep-ph/9806356].

[20] H. Eguchi, Y. Koike and K. Tanaka, Nucl. Phys. B **752**, (2006) [arXiv:hep-ph/0604003].

[21] C. Kouvaris, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **74**, 114013 (2006) [arXiv:hep-ph/0609238].

[22] H. Eguchi, Y. Koike and K. Tanaka, Nucl. Phys. B **763**, 198 (2007) [arXiv:hep-ph/0610314].

[23] Y. Koike and K. Tanaka, Phys. Lett. B **646**, 232 (2007) [Erratum-ibid. B **668**, 458 (2008)] [hep-ph/0612117].

[24] Y. Koike and K. Tanaka, Phys. Rev. D **76**, 011502 (2007) [hep-ph/0703169].

[25] Y. Koike and T. Tomita, Phys. Lett. B **675**, 181 (2009) [arXiv:0903.1923 [hep-ph]].

[26] K. Kanazawa and Y. Koike, Phys. Rev. D **82**, 034009 (2010) [arXiv:1005.1468 [hep-ph]]; Phys. Rev. D **83**, 114024 (2011) [arXiv:1104.0117 [hep-ph]].

[27] A. Metz and D. Pitonyak, Phys. Lett. B **723**, 365 (2013) [arXiv:1212.5037 [hep-ph]].

[28] K. Kanazawa and Y. Koike, Phys. Rev. D **88**, 074022 (2013) [arXiv:1309.1215 [hep-ph]].

[29] H. Beppu, K. Kanazawa, Y. Koike and S. Yoshida, Phys. Rev. D **89**, 034029 (2014) [arXiv:1312.6862 [hep-ph]].

[30] M. Anselmino, M. Boglione and F. Murgia, Phys. Lett. B **362**, 164 (1995) [hep-ph/9503290].

[31] M. Anselmino and F. Murgia, Phys. Lett. B **442**, 470 (1998) [hep-ph/9808426].

[32] M. Anselmino, M. Boglione, U. D'Alesio, E. Leader, S. Melis and F. Murgia, Phys. Rev. D **73**, 014020 (2006) [hep-ph/0509035].

[33] M. Anselmino, M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia and A. Prokudin, Phys. Rev. D **86**, 074032 (2012) [arXiv:1207.6529 [hep-ph]].

[34] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin, Phys. Rev. D **88**, 054023 (2013) [arXiv:1304.7691 [hep-ph]].

[35] D. W. Sivers, Phys. Rev. D **41**, 83 (1990); Phys. Rev. D **43**, 261 (1991).

[36] J. C. Collins, Nucl. Phys. B **396**, 161 (1993) [hep-ph/9208213].

[37] D. Boer and P. J. Mulders, Phys. Rev. D **57**, 5780 (1998) [hep-ph/9711485]; D. Boer, Phys. Rev. D **60**, 014012 (1999) [hep-ph/9902255].

[38] Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **83**, 094001 (2011) [arXiv:1103.1591 [hep-ph]].

[39] Z.-B. Kang and A. Prokudin, Phys. Rev. D **85**, 074008 (2012) [arXiv:1201.5427 [hep-ph]].

[40] A. Airapetian *et al.* [HERMES Collaboration], Phys. Lett. B **682**, 351 (2010) [arXiv:0907.5369 [hep-ex]].

[41] J. Katich *et al.* Phys. Rev. Lett. **113**, 022502 (2014) [arXiv:1311.0197 [nucl-ex]].

[42] A. Metz, D. Pitonyak, A. Schäfer, M. Schlegel, W. Vogelsang and J. Zhou, Phys. Rev. D **86**, 094039 (2012) [arXiv:1209.3138 [hep-ph]].

[43] K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, Phys. Rev. D **89**, 111501(R) (2014) [arXiv:1404.1033 [hep-ph]].

[44] S. Heppelmann [STAR Collaboration], PoS DIS **2013**, 240 (2013).

[45] X. Ji, J. w. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **73**, 094017 (2006) [hep-ph/0604023].

[46] K. Kanazawa and Y. Koike, Phys. Lett. B **701**, 576 (2011) [arXiv:1105.1036 [hep-ph]].

[47] Y. Koike and S. Yoshida, Phys. Rev. D **85**, 034030 (2012) [arXiv:1112.1161 [hep-ph]].

[48] L. Gamberg and Z. B. Kang, Phys. Lett. B **718**, 181 (2012) [arXiv:1208.1962 [hep-ph]].

[49] K. Kanazawa and Y. Koike, Phys. Lett. B **720**, 161 (2013) [arXiv:1212.3071].

[50] L. Gamberg, Z. B. Kang and A. Prokudin, Phys. Rev. Lett. **110**, 232301 (2013) [arXiv:1302.3218 [hep-ph]].

[51] K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, Phys. Rev. D **91**, 014013 (2015) [arXiv:1410.3448 [hep-ph]].

[52] PHENIX Beam Use Proposal: Run-15 and Run-16, May 2014.

[53] RHIC Beam Use Request for Runs 15 and 16: The STAR Collaboration, June 2014.

[54] E. C. Aschenauer, A. Bazilevsky, M. Diehl, J. Drachenberg, K. O. Eyser, R. Fatemi, C. Gagliardi and Z. Kang *et al.*, arXiv:1501.01220 [nucl-ex].

[55] J. C. Collins, Phys. Lett. B **536**, 43 (2002) [hep-ph/0204004].

[56] A. Airapetian *et al.* [HERMES Collaboration], Phys. Lett. B **728**, 183 (2014) [arXiv:1310.5070 [hep-ex]].

[57] K. Allada *et al.* [Jefferson Lab Hall A Collaboration], Phys. Rev. C **89**, 042201 (2014) [arXiv:1311.1866 [nucl-ex]].

[58] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin, Phys. Rev. D **89**, 114026 (2014) [arXiv:1404.6465 [hep-ph]].

[59] L. Gamberg, Z. B. Kang, A. Metz, D. Pitonyak and A. Prokudin, Phys. Rev. D **90**, 074012 (2014) [arXiv:1407.5078 [hep-ph]].

[60] K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, Adv. High Energy Phys. **2015**, 257934 (2015) [arXiv:1502.04021 [hep-ph]].

[61] M. Anselmino, U. D'Alesio and S. Melis, Adv. High Energy Phys. **2015**, 475040 (2015) [arXiv:1504.03791 [hep-ph]].