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Research Article

Transverse Single-Spin Asymmetries in Proton-Proton Collisions at the AFTER@LHC Experiment

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We present results for transverse single-spin asymmetries in proton-proton collisions at kinematics relevant for AFTER, a proposed fixed-target experiment at the Large Hadron Collider. These include predictions for pion, jet, and direct photon production from analytical formulas already available in the literature. We also discuss specific measurements that will benefit from the higher luminosity of AFTER, which could help resolve an almost 40-year puzzle of what causes transverse single-spin asymmetries in proton-proton collisions.

1. Introduction

Transverse single-spin asymmetries (TSSAs), denoted by A_N, have been a fundamental observable since the mid-1970s to test perturbative quantum chromodynamics (pQCD). Such measurements were first conducted at FermiLab, where large effects were found in $pBe \rightarrow \Lambda^{\uparrow} X$ [1]. These results contradicted the naïve collinear parton model, which said that A_N should be extremely small [2], and doubts were raised as to whether pQCD can actually describe these reactions [2]. However, in the 1980s it was shown that if one went beyond the parton model and included collinear twist-3 (CT3) quark-gluon-quark correlations in the nucleon, substantial TSSAs could be generated [3, 4]. In the 1990s this CT3 approach was worked out in more detail for proton-proton collisions, first for direct photon production [5–7] and then for pion production [8]. Over the last decade, several other analyses furthered the development of this formalism; see [9–19] and references therein. During the same time, another mechanism was also put forth to explain TSSAs in proton-proton collisions. This approach involves the Sivers [20, 21], Collins [22], and Boer-Mulders [23, 24] transverse momentum dependent (TMD) functions and became known as the Generalized Parton Model (GPM); see [25–29] and references therein. (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 addition to all of this theoretical work, many experimental measurements of A_N have been performed at proton-(anti)proton accelerators [30–42]. Most of the experimental data in the more negative x_F region has come in the form of light-hadron asymmetries A_N^h, for example, $h = \pi, K, \eta$, with the exception of the jet asymmetry $A_N^{\rm jet}$ measured a few years ago at the Relativistic Heavy Ion Collider (RHIC) by the $\rm A_N$DY Collaboration [40]. (Throughout the paper we will use the convention $x_F = 2l_z/\sqrt{S}$, where l is the momentum of the outgoing particle, and the transversely polarized proton moves along the $-z$-axis. That is, $x_F \rightarrow -1$ means large momentum fractions $x^{\uparrow}$ of the parton probed inside the transversely polarized proton. This setup causes x_F to be opposite in sign to the one used in collider experiments (like those at RHIC).) Plans are also in place to measure the direct photon asymmetry A_N^{γ} at RHIC by both the PHENIX Collaboration and the STAR Collaboration [43–45].

Although much progress has been made in understanding TSSAs, there is not a definitive answer on what their origin might be. In the CT3 approach it was assumed for many years that a soft-gluon pole (SGP) chiral-even quark-gluon-quark (qgq) matrix element called the Qiu-Sterman (QS) function $T_F(x, x)$ was the main cause of A_N^π [8, 11]. However, this led to a so-called "sign-mismatch" between the QS function and the TMD Sivers function $f_{1T}^\perp$ extracted from semi-inclusive deep-inelastic scattering (SIDIS) [46]. This issue could not be resolved through more flexible parameterizations of the Sivers function [47]. Moreover, the authors of [48] argued, by looking at A_N data on the target TSSA in inclusive DIS [49, 50], that $T_F(x, x)$ cannot be the main source of A_N^π. This observation led us last year in [51] to analyze A_N^π by including not only the QS function but also the fragmentation mechanism, whose analytical formula was first fully derived in [18] (the so-called "derivative term" was first computed in [52]) (see also [17, 53, 54] for fragmentation terms in other processes). We found in this situation for the first time in pQCD that one can fit all RHIC high transverse momentum pion data very well without any sign-mismatch issue. Furthermore, we showed that a simultaneous description of TSSAs in $p^\uparrow p \rightarrow \pi X$, SIDIS, and $e^+e^- \rightarrow h_1 h_2 X$ is possible. Nevertheless, more work must be done to confirm/refute this explanation and its predictions. We mention that, in the GPM, one cannot draw a definitive conclusion as to whether the Sivers or Collins mechanism is the main cause of A_N^π [28, 29]. (In principle the Boer-Mulders function and gluon Sivers function can also contribute to the GPM formalism, but these pieces have not been analyzed in the literature.) This is due to the theoretical error bands being too large, since the associated TMD functions are mostly unconstrained in the large-$x^\uparrow$ regime covered by the data [28, 29]. For a detailed discussion of the GPM formalism and its predictions for the AFTER experiment, see [55].

In addition, in order to have a complete knowledge of TSSAs, it is important to have a "clean" extraction of the QS function from observables like A_N^{jet} and A_N^γ that do not have any fragmentation contributions. (We will ignore photons coming from fragmentation [56], which can be largely suppressed by using isolation cuts.) (For recent analyses of A_N^γ in $p^\uparrow A$ collisions, see [57, 58].) This is necessary in order to help resolve the sign-mismatch issue and better understand the role of rescattering effects in the nucleon. The jet asymmetry has been studied in [11, 46, 59, 60] and the direct photon asymmetry has been investigated in [6, 11, 12, 56, 59–64]. It is important to point out that other contributions to A_N^{jet} and A_N^γ exist besides the one from the (SGP qgq chiral-even) QS function. These other pieces include (i) soft-fermion pole (SFP) chiral-even qgq functions, (ii) SGP and SFP qgq chiral-odd functions, and (iii) SGP trigluon functions. For A_N^γ the numerical analyses in [59, 64] show that (i) is negligible for $x_F < 0$ while the study in [64] draws a similar conclusion for (ii) as does the work in [62] for (iii). That is, for A_N^γ, the QS function dominates the asymmetry. We mention that, at present in the GPM, A_N^γ is predicted to have the *opposite sign* to that from the CT3 approach [29]. Therefore, as was emphasized in [64], this observable could allow us for the first time to clearly distinguish between the two frameworks as well as learn about the process dependence of the Sivers function [65], which is a feature of this nonperturbative object that is crucial to our current understanding of TMD functions.

For A_N^{jet} the conclusions as to which piece dominates are not as clear. The study in [66, 67] provides evidence that (ii) should be small in the whole x_F-region. The work in [59] shows that the same is most likely true for (i) but that analysis suffers from the sign-mismatch issue. Also, in [19] there is an indication that (iii) could be significant. Therefore, it will be necessary to reassess the impact of (i) and (iii) on A_N^{jet}. Nevertheless, one can gain insight into these other terms by looking at the contribution from the QS function and comparing it with data.

Given the open issues that still remain, it is an opportune time for the Large Hadron Collider (LHC) to produce data on TSSAs in proton-proton collisions via the AFTER experiment. These measurements will not only add to the data from FermiLab, AGS, and RHIC but also, through the high luminosity of the experiment [68, 69], probe certain features that remain ambiguous. For example, the behavior of A_N^π at large pion transverse momentum l_T appears to fall off very slowly (or is even flat), a feature which the theory says should persist to high l_T [29, 51, 55, 59] (see also [70] in the context of $\Lambda^\uparrow$ production). However, the data from RHIC [71] has too large error bars (or not enough statistics) in this high-l_T region to ascertain whether or not this is true. Also, A_N^{jet} measured by A_NDY [40] has large error bars as x_F becomes more negative, which makes it difficult to determine whether or not the QS function alone can describe that data. Moreover, as previously mentioned, A_N^γ has never been measured before, yet it could be a tremendous opportunity to learn about the process dependence of the Sivers function and distinguish between the CT3 and GPM frameworks. Already, PHENIX and STAR plan to carry out such experiments [43–45].

Therefore, in this paper we give predictions within the CT3 formalism for A_N^π, A_N^{jet}, and A_N^γ at AFTER@LHC kinematics. (For related work on charmonium and bottomonium production we refer to [72, 73].) Since the relevant analytical formulas already exist within the literature, in Section 2 we focus on the phenomenology and refer the reader to the appropriate papers on the underlying theory. These numerical results are summarized in Section 3, and there we highlight again how AFTER can offer unique insight into TSSAs in proton-proton collisions, which is a truly fundamental observable to test pQCD at higher twist.

2. Pion, Photon, and Jet TSSAs at AFTER

We start first with A_N^π, where we follow our numerical work in [51]. (We also refer the reader to [11, 13, 18] for more formal discussions of the relevant analytical formulas.) There we took into account the contribution from the QS function and the fragmentation term. The former has a model-independent relation to the Sivers function [74], while the latter involves three nonperturbative CT3 fragmentation functions (FFs): $\widehat{H}$, $\widehat{H}_{FU}^{\Im}$, and H. Of these, $\widehat{H}$ has a model-independent connection to the Collins function [18, 52]

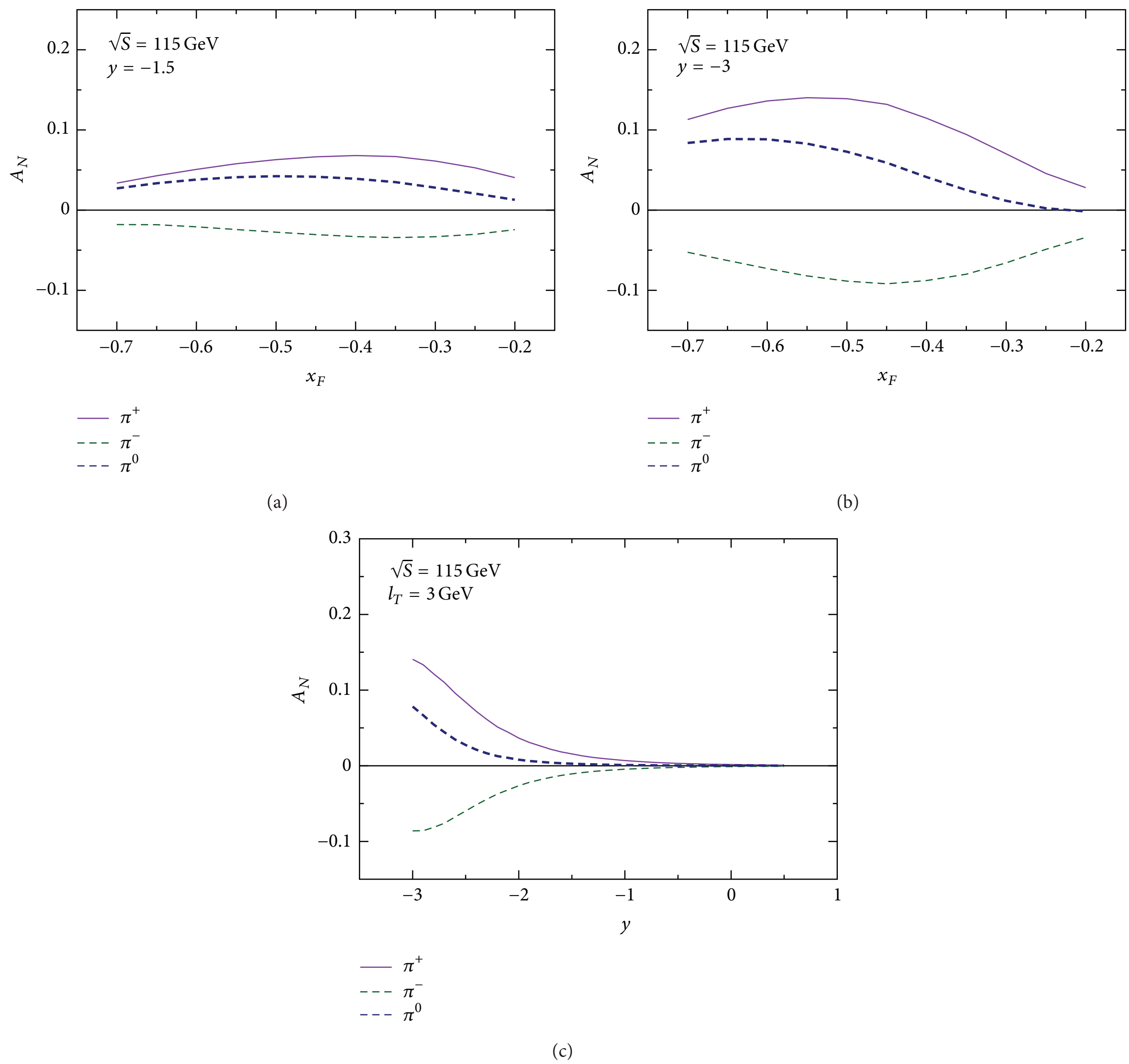

Figure 1: A_N^π versus x_F at fixed $y = -1.5$ (a) and $y = -3$ (b) and A_N^π versus y at fixed $l_T = 3$ GeV (c). All plots are at $\sqrt{S} = 115$ GeV for pion production at AFTER.

and H can be written in terms of the other two through a QCD equation-of-motion relation [18]. In Figures 1 and 2 we provide predictions for neutral and charged pion production at AFTER based on our fit in [51]. One sees in Figure 1 from A_N^π versus x_F that the magnitude of the asymmetry can be anywhere from ~5–10% and from A_N^π versus y that it increases with more negative (center-of-mass) rapidity y. (Recall the relation between x_F, y, and l_T: $x_F = 2\, l_T \sinh(y)/\sqrt{S}$, so A_N versus x_F (A_N versus y) at fixed y (l_T) implies a running in l_T (x_F).) One also notices that A_N^π turns over at more negative x_F values, which was also observed in some of the STAR data [33, 34, 39]. In Figure 2, where we show A_N^π versus l_T, one sees that the asymmetry is flat or falls off very slowly as l_T increases, a feature that had also been measured by STAR [71]. It will be important to establish with more precision if this flatness persists at higher-l_T values, say 12–15 GeV, and AFTER, with its much higher luminosity, will be in a position to make such a measurement.

We next look at A_N^{jet} and A_N^γ, which do not receive contributions from FFs. As we discussed in Section 1, the former may receive nonnegligible contributions from terms other than the QS function, while for the latter we recently showed in [64] that the QS function is the dominant piece to that asymmetry. (All of the analytical expressions for A_N^γ can be found in [64] while those for A_N^{jet} are determined simply by setting $D_1(z)$ (the unpolarized FF) to $\delta(1-z)$ in the equations for A_N^π given in [11, 14, 19, 66, 67].) (We note the A_N^γ analytical formulas for the piece involving chiral-odd functions are new from [64], while those involving chiral-even functions were derived before in the literature, and the relevant references are

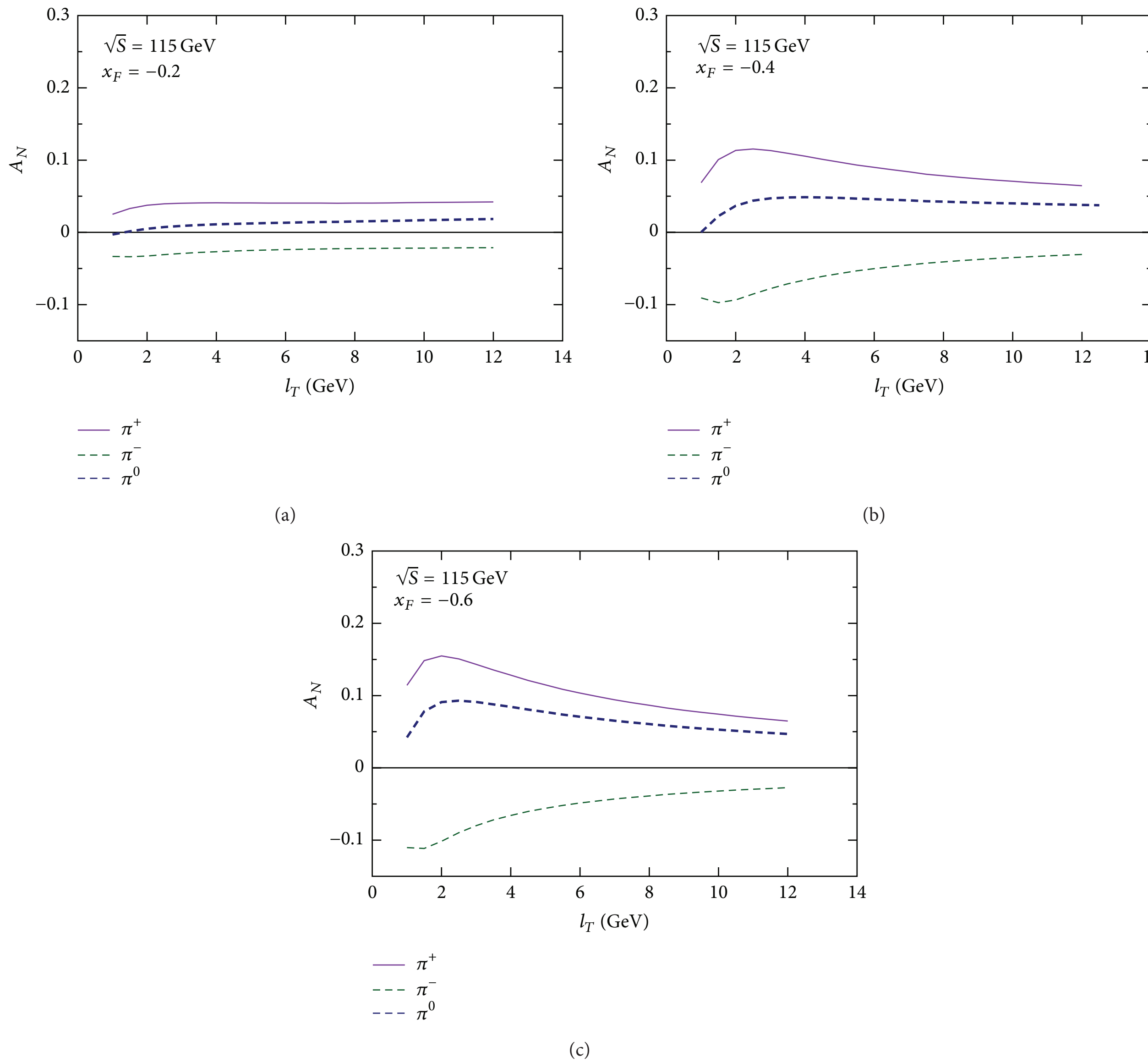

Figure 2: A_N^{π} versus l_T at fixed $x_F = -0.2$ (a), $x_F = -0.4$ (b), and $x_F = -0.6$ (c) at $\sqrt{S} = 115$ GeV for pion production at AFTER.

cited therein.) However, given that the other pieces for A_N^{jet} are not reliably known, for that asymmetry we will only look at the contribution from the QS function using its relation to the Sivers function, while for A_N^{γ} we adopt our work in [64]. In Figures 3 and 4 we show results for jet and photon production at AFTER. We see that A_N^{jet} is very small, although we caution the reader that the Sivers function (which we use as input for the QS function) is mostly unconstrained in the large-$x^{\uparrow}$ region, and when this uncertainty is taken into account, one could obtain a measurable asymmetry [60]. Also, as we mentioned, there is the potential for (chiral-even) SFP and/or trigluon functions to make an impact. Therefore, in order to determine if the Sivers function alone can describe A_N^{jet}, along with the current data from A_NDY, we need more precise data in the far backward region, which should be possible at AFTER. (We note that STAR has preliminary data on electromagnetic "jets" that could also be helpful [75].)

Unlike the jet asymmetry, A_N^{γ} could be on the order of ~−5% at less negative x_F and more negative y (see Figures 3(a) and 3(b)) or smaller l_T and less negative x_F (see Figure 4). Both of these observations are consistent with the behavior of A_N^{γ} as a function of rapidity (see Figure 3(c)), where the asymmetry peaks at $y \sim -2$ (with $l_T = 3$ GeV), which corresponds to $x_F \sim -0.2$. Since the QS function is the dominant source of the asymmetry, we can have "clean" access to it. We state again that the GPM framework at present predicts A_N^{γ} to be *positive* [29]. Therefore, a clear nonzero signal for this observable would help to distinguish between the CT3 and GPM formalisms. However, we emphasize that should data contradict the predictions of the GPM, this does not invalidate the results obtained for TMD observables that

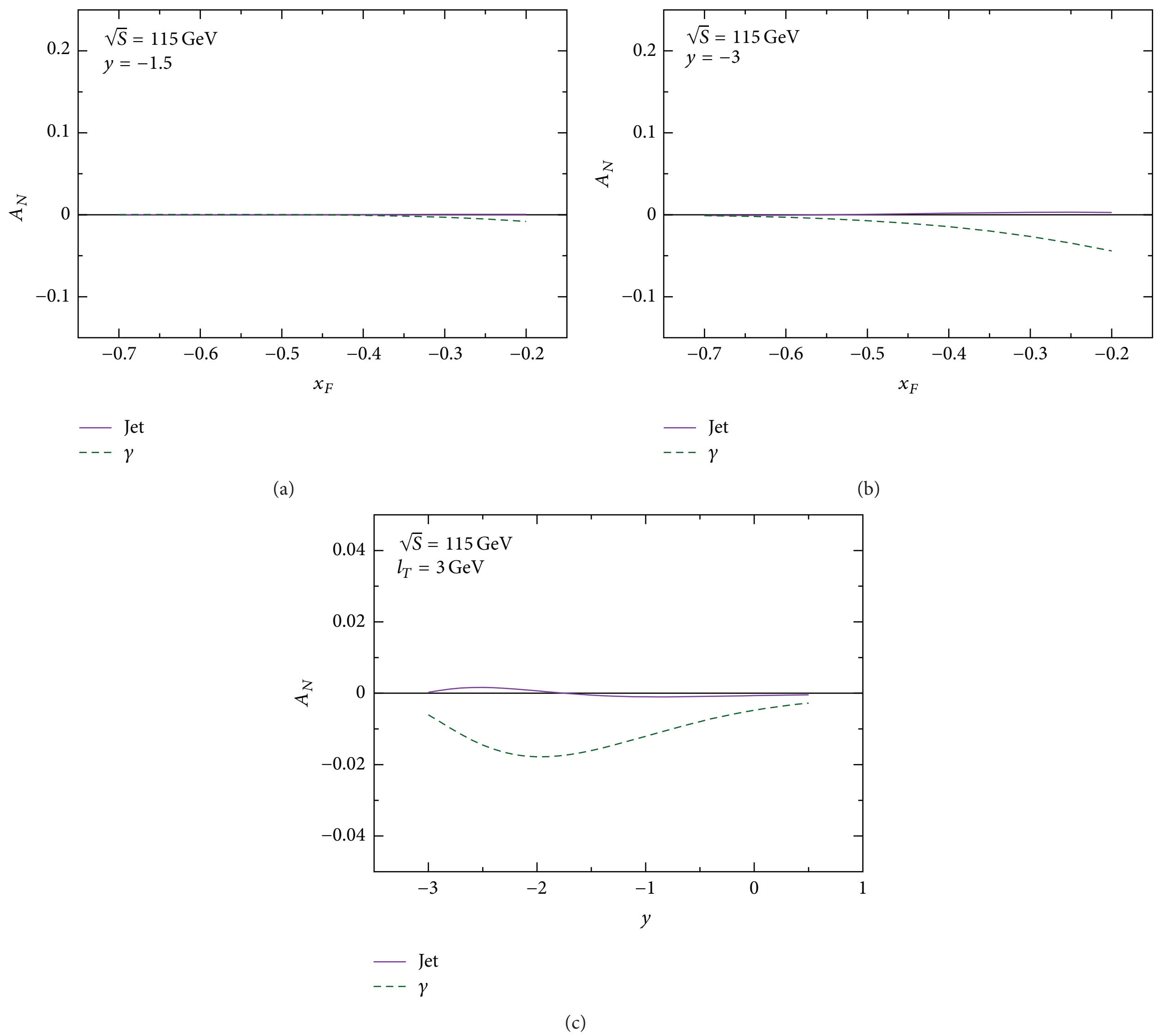

Figure 3: A_N versus x_F at fixed $y = -1.5$ (a) and $y = -3$ (b) and A_N versus y at fixed $l_T = 3\,\text{GeV}$ (c). All plots are at $\sqrt{S} = 115\,\text{GeV}$ for jet/photon production at AFTER.

are based on rigorous TMD factorization proofs. Also, since we use the Sivers function from SIDIS as our input for the QS function, we can learn about the predicted process dependence of the Sivers function.

3. Summary and Outlook

In this paper we have discussed TSSAs in single-inclusive pion, jet, and photon production from proton-proton collisions, that is, $p^{\uparrow}p \rightarrow \{\pi, \text{jet}, \gamma\}\ X$, at kinematics relevant for the proposed AFTER@LHC experiment. These asymmetries have been fundamental observables to test pQCD at higher twist for close to 40 years, and much work has been performed on both the theoretical and experimental sides. Nevertheless, issues still remain as to the origin of these TSSAs, which makes a measurement of A_N at the LHC via the AFTER experiment timely. For A_N^{π} we have found that AFTER should expect (absolute) asymmetries on the order of 5–10% as a function of x_F and increasing as the rapidity becomes more negative. Also, the l_T dependence of A_N^{π} still falls off slowly and flattens out at high l_T. For A_N^{jet} we predict a very small asymmetry, but we must remember that uncertainties in the Sivers function could allow for a measurable observable [60] and also that other contributions (like chiral-even SFP and trigluon) could make an impact. Lastly, for A_N^{γ} we expect asymmetries on the order of ~ −5% and decreasing with more negative x_F and increasing l_T. These are opposite in sign to the ones predicted from the GPM [29].

Even though these observables have been (or are planned to be) measured at RHIC, AFTER has the ability, through its much higher luminosity, to not only supplement the RHIC data but also provide important information on still unknown issues. For example, it will be key to determine

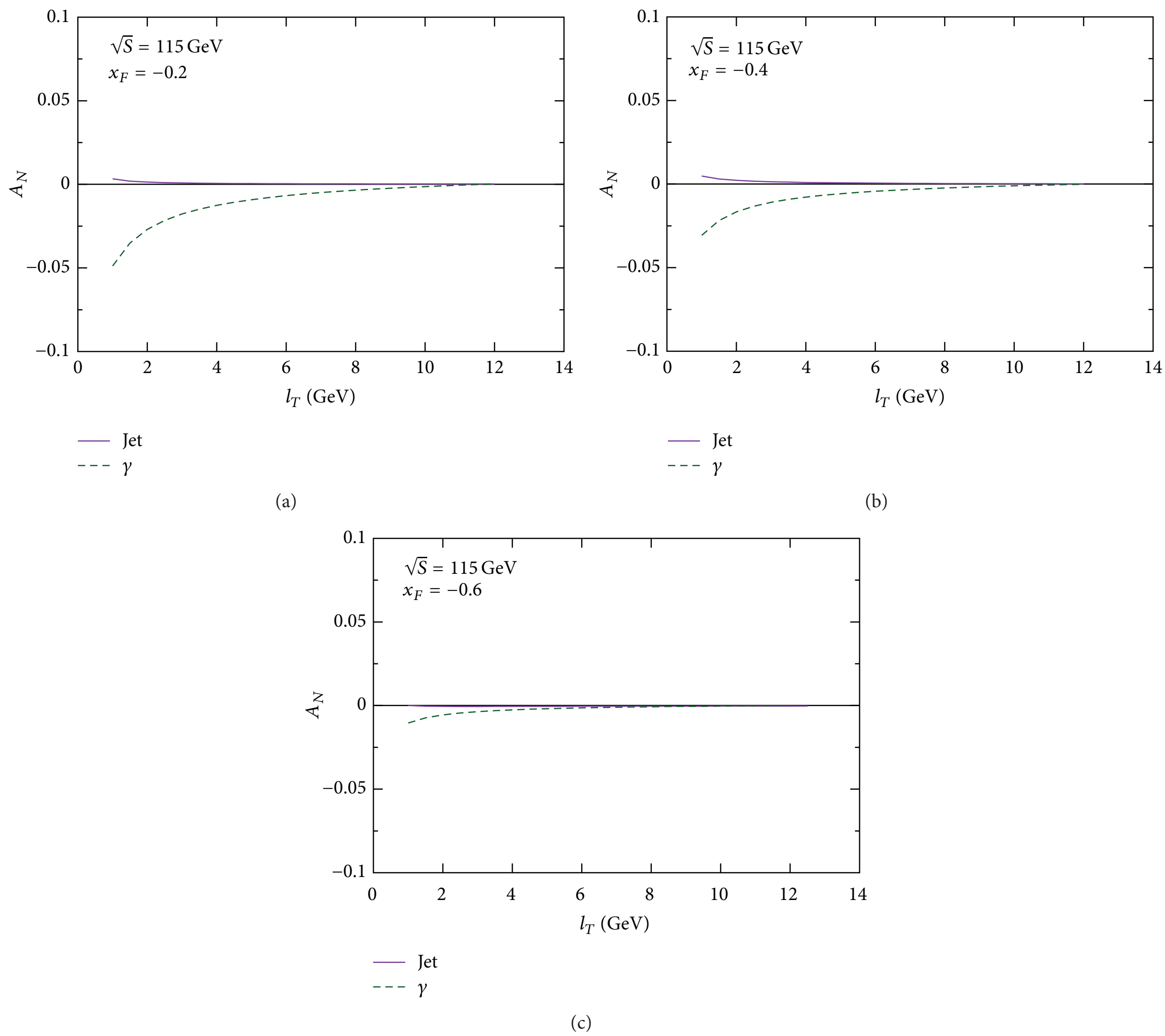

FIGURE 4: A_N versus l_T at fixed $x_F = -0.2$ (a), $x_F = -0.4$ (b), and $x_F = -0.6$ (c) at $\sqrt{S} = 115$ GeV for jet/photon production at AFTER.

if A_N^{π} stays flat at higher-l_T, say to 12–15 GeV, like theory predicts [29, 51, 55, 59, 70] and STAR has evidence for [71]. Also, higher statistics should allow for more precise measurements of A_N^{jet} at more negative x_F, which will be necessary to determine if the QS function is the sole source of that asymmetry. Moreover, A_N^{γ} has never been measured before and provides the opportunity to clearly distinguish between the CT3 and GPM frameworks and learn about the process dependence of the Sivers function. Given the questions that remain as to the origin of TSSAs, which has been unresolved for almost 40 years, AFTER could provide valuable data on these observables.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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