sPHENIX Spin and Forward Physics

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Abstract. The PHENIX experiment is designing a forward upgrade, fsPHENIX, to accompany the central sPHENIX upgrade. fsPHENIX will include the addition of a spectrometer in the forward direction capable of measuring electrons, photons, and hadrons. The motivation for the forward spectrometer includes the measurement and separation of the Sivers and Collins effects via single transverse spin asymmetries in the Drell-Yan process and jet observables with the use of polarized proton collisions, the study of cold nuclear matter effects in proton-nucleus collisions including the calibration of quarkonium, and A+A measurements aimed at giving a 3D “image” of the medium via flow measurements and an understanding of the system expansion via photon measurements.

1. Introduction

The PHENIX experiment is proposing to replace the current PHENIX spectrometer at mid-rapidity with sPHENIX [1], which also frees up space to allow for the addition of a spectrometer, fsPHENIX, in the forward direction capable of measuring electrons, photons, and hadrons. Such a forward detector (1<|η|<4) is being designed for: 1) the study of forward transverse asymmetries in polarized p+p collisions with the aim of separating the Sivers and Collins effects and to understand factorization and universality of transverse momentum dependent parton distribution functions (TMDs), 2) cold nuclear matter measurements in p+A collisions to provide a calibration of quarkonium (J/ψ and Ψ families) and information about the initial state of heavy ion collisions, and 3) A+A collisions to provide a 3D “image” of the medium and to understand the system expansion via photons.

2. Forward Transverse Asymmetries (polarized p+p collisions)

Over the past 10 years, PHENIX and RHIC spin have extracted the gluon helicity distribution, Δg(x), in the proton through the measurement of longitudinal double spin asymmetries in polarized proton collisions. While these measurements have been a great success, they have also revealed that taking only the longitudinal snapshot of the proton does not allow us to fully account for the proton’s spin. In particular, the transverse spin structure is needed to access the orbital angular momentum. In the end, the transverse structure of the nucleus will be needed to complete our understanding of the proton.

Transverse single spin asymmetries emerge as left-right asymmetries in scattering processes with one of the colliding particles momentum perpendicular to the polarization vector: $A_N = (dσ_T - dσ_L) / (dσ_T + dσ_L)$. They were originally expected to be very small at RHIC energies, as in collinear QCD $A_N \sim m_q a_s / p_T$. However they were observed in pion production in various experiments ranging in center-of-mass energies from $\sqrt{s} \approx 4.9$ GeV and 19.6 GeV and have...
persisted all the way to $\sqrt{s}=500$ GeV in forward meson production. These observations have led to extensions of the pQCD description which introduce chiral-odd objects into the process, thereby allowing the necessary spin flip to create a transverse asymmetry. A consistent theoretical framework has been developed to describe transverse momentum dependent observables in hard scattering processes. At large transverse momenta the Qiu-Sterman mechanism describes Transverse Momentum Dependent (TMD) observables as higher-twist effects (twist-3 quark-gluon and gluon-gluon correlators) [2]. So far, the predicted fall-off with $p_T$ has not been observed. At smaller transverse momentum, corresponding to the intrinsic transverse momentum of partons in hadrons, the Sivers [3] and Collins [4] effects can generate transverse spin asymmetries. The Sivers mechanism is an initial-state effect due to the correlation between the proton spin and the intrinsic transverse quark momentum. It requires orbital angular momentum of the quarks and provides access to non-collinear PDFs. The Collins effect is a final-state effect due to the correlation between the proton and quark spin (quark transverse spin distribution or transversity) and a spin dependent fragmentation function (the Collins fragmentation function). These mechanisms lead to a consistent picture for single transverse asymmetries in hard processing as the calculations agree in the region of overlap [5]. Phenomenological analyses of both effects exclusively have been shown to reproduce the data in the observed kinematic range. Comparison between experiments (polarized p+p and semi-inclusive DIS measurements) relies on assumed functional forms of the transverse momentum dependent distribution functions. This is one of the topics of active debate in combination with universality of these functions and the formalism of factorization of initial and final state interactions with the hard scattering pQCD process. Collinear factorization for hadron-hadron scattering is well established and universality of the parton distributions is justified. There is less experimental data for polarized case, but the data is supportive and most theoretical foundations are common. This is the foundation for $\Delta G$ and $\Delta \bar{q}$ programs. Going beyond the twist-2 collinearly factorized picture is essential to explore QCD dynamics and fully understand the spin structure of the nucleon. Exploring the validity of factorization and universality of transverse momentum dependent (TMD) parton distributions factorization is key.

An attempt has been made to extract the Sivers function through a global fit of the $A_N$ data [6]. The results are shown in Figure 1, and it is clear it is effectively unconstrained for $x_F>0.4$, i.e. the region accessible by PHENIX. In order make progress, it is essential to map out Sivers function over a wide kinematic range. Drell-Yan is a particularly attractive channel as it involves no parton fragmentation.

![Figure 1. Sivers Drell-Yan asymmetry as extracted by [6] in a “Global” analysis. The world data poorly constrain the function for $x_F>0.4$. One of them main motivations for forward sPHENIX is to map out the function in this region.](image-url)
and is a direct correlation of intrinsic transverse quark properties and proton spin. Coupled with a solid theoretical understanding of factorization, it provides a fundamental test of our understanding of QCD. In \( \sqrt{s}=500 \text{ GeV} \), we expect the largest asymmetry of about 8% at rapidities around 3 to 4, see Figure 2 [7]. Figure 3 shows the results for the background reduction for different acceptances of the forward spectrometer in the relevant invariant mass range. Our studies so far include only very basic assumptions of detector performances. These initial feasibility studies show the QCD background decreases with increasing rapidity and the measurement becomes possible. Measurement of jet asymmetries in the forward direction is also sensitive to the quark-gluon correlation function, providing an independent measurement of the Sivers function (Figure 4) [8]. The Collins effect manifests itself through an azimuthal anisotropy in the distribution of hadrons in final state jets with respect to the proton spin component normal to the scattering plane. Large asymmetries are expected in the forward direction (Figure 5) [9]. A measurement of the left-right asymmetry of identified particles inside a jet would then be directly sensitive to the Collins fragmentation function.

![Figure 2.](image1.png)  
**Figure 2.** The expected A_N for Drell-Yan dilepton production at RHIC for \( \sqrt{s}=200 \text{ GeV} \) and \( \sqrt{s}=500 \text{ GeV} \) [7]. The uncertainties shown as yellow bands are a result of the uncertainties from the Sivers function extracted from SIDIS data.

![Figure 3.](image2.png)  
**Figure 3.** Event generator studies of Drell-Yan versus hard QCD jet background for different detector acceptances in the forward direction as a function of invariant mass. The dip below 3 GeV/c² is a result of the settings of the PYTHIA event generator.

Precision measurements of single transverse spin asymmetries for single identified charged pions (Collins effect) and for identified hadron pairs (Interference Fragmentation Function, IFF) will lead to the first measurement of quark transversity distributions at large \( x > 0.35 \). A comparison of quark transversity extracted from TMD Collins observables and from collinear IFF asymmetries will provide a powerful test of the TMD framework and evolution.

In order to disentangle these effects and determine their respective contributions, new measurements are needed over a wide kinematic range, preferentially at higher transverse momenta \( p_T \) extending to large \( x_F \). Also, it is of high importance to make use of different probes, i.e., measure asymmetries of different particles or correlations of particles. The Drell-Yan measurements require charge sign determination and e/π separation, while the jet measurements require good jet reconstruction (electromagnetic and hadronic calorimetry), particle ID as the Collins effect different for different hadrons (RICH), and a magnetic field and tracker to determine the charge sign of the hadrons.

The forward sPHENIX upgrade, then, is designed to measure jet correlations/structure and Drell-Yan. The measurements will allow the separation of Sivers & Collins and test TMD parton
distribution factorization and universality. The ultimate goal is that the measurements lead to a complete understanding of the theoretical framework so that the theory can make progress in providing a quantitative link between the Sivers function and orbital angular momentum.

Figure 4. The expected Sivers $A_N$ for jets [8].

Figure 5. Expected Collins $A_N$ effect in jets [9].

3. Cold Nuclear Matter (p +A Collisions)

It is a central goal of the sPHENIX forward upgrade to systematically survey the cold nuclear matter effects in high energy nuclear collisions. The physics motivations include the calibration of quarkonium ($J/\psi$ and $\Upsilon$ families) and precise knowledge of the initial state of heavy-ion collisions. RHIC can make unique contributions with its $\sqrt{s}$ dependence, the possibility of using different species, and access to low $Q^2$. The design is driven by the need for large data samples, access to $1>\eta>4$, and detectors sensitive to electrons, photons, charged hadrons, and jets.

Quarkonimum measurements in heavy-ion collisions are directly related to the temperature of the system. However, currently we are limited by our understanding of quarkonium. In order to fully calibrate quarkonium, there are a number of topics that must be quantitatively understood including parton initial energy loss, quark PDFs, gluon PDFs, and the absorption or breakup cross-sections.

Measurements of Drell Yan vs $\sqrt{s}$, $\gamma$-jet, open heavy flavor, and quarkonium in p+A collisions is sensitive to the various effects in different ways (Figure 6). Using a redundant set of measurements will allow the isolation of the necessary components. The sPHENIX forward upgrade will significantly extend the kinematic reach and channels of measurement.

A critical part of gaining a quantitative insight into the properties of the sQGP is developing a complete understanding of the initial state - the distribution of partons, primarily gluons, in the colliding Au nuclei. Compelling theoretical arguments have been made that the distribution of gluons in a heavy nucleus “saturates” at small $x$, the so-called “Color Glass Condensate” (CGC), suppressing very low-$x$ gluons and pushing them to higher-$x$. This is a calculable regime of gluons at high density but weak coupling. The effect is enhanced by large nuclei which provide an $A^{1/3}$ amplification (relative to p+p) since there are simply more partons available. For the same reason the effect is also sensitive to the centrality of the collision. Figure 7 shows a schematic illustration of the region of $x$ and $Q$ where this saturation should take place. The exact location of the line in Figure 7 between pQCD dominated physics and CGC physics is not well known. It is known, however, that within the framework of the CGC, this line will move depending on the centrality of the collision as indicated by the arrow. The saturation assumed by these authors is present in the initial state before the nuclei collide. Hence, the study of proton-nucleus collisions will be important in distinguishing these effects from final state
effects such as the formation of a quark-gluon plasma. Moving forward in rapidity, to regions covered by forward sPHENIX, therefore, may provide measurements within the CGC region. The CGC predicts a suppression of the away side jet at low-x for forward $\eta$, and the effect should become larger as the collisions become more central.

![Figure 6](image1.png)

**Figure 6.** Sensitivity of channels to make quarkonium calibration.

![Figure 7](image2.png)

**Figure 7.** A schematic diagram of regions in the nucleus, showing the CGC region bordered by a line representing $Q_0$.

There may be an intriguing connection between the CGC and TMDs. TMD factorization is violated for dijet production in hadron hadron collisions. However, it is possible to get back effective TMD factorization in the case of small x partons at high density (i.e, the “CGC regime”), which is probed by quarks or photons. While TMD parton distributions are not universal, they can be constructed from building blocks which are. In particular, they can be constructed by the unintegrated Gluon PDFs $G^{(1)}(x,q^\perp)$ and $G^{(2)}(x,q^\perp)$. Interestingly, the quantities derived via the CGC and TMD approaches are identical. There is, therefore, an equivalence between the TMD and CGC approaches in the CGC regime [10]. In order to explore this connection, we need to measure photon-jet and dijets at low-x in p or p+A collisions.

4. Heavy-ions (A+A Collisions)

The forward spectrometer give the opportunity to take a 3D “image” of the medium. At mid-rapidity we only see the evolution/final state of the “slice” of the fluid which is initially at rest longitudinally. Flow measurements in the forward direction can help complete the picture (Figure 8) [11].

Measurement of photons in the forward direction also provides information on the system expansion/early evolution and gives access to the high baryon density region (Figure 9) [12].
5. Detector Considerations

Precision Drell-Yan measurements require excellent dilepton identification and the ability to reduce backgrounds from correlated charm and beauty decays. The forward sPHENIX Drell-Yan measurements will be via dielectrons, and will require an electromagnetic calorimeter and charged particle tracking as well as heavy flavor tagging for background rejection.

The forward sPHENIX detector will greatly extend our ability to measure the Collins and Sivers asymmetries at forward rapidities by performing full jet reconstruction. Experimentally, the measurement of transverse spin effects within jets will require electromagnetic and hadronic calorimetry for jet reconstruction, particle tracking to determine the fractional momentum of hadrons or hadron pairs in the jet and particle ID to avoid cancelling of transverse spin effects in the fragmentation of different hadrons. Precise studies of the Sivers and Collins effects in different channels with the sPHENIX forward upgrade will make it possible to decompose the large transverse
single spin asymmetries that historically have been observed in polarized proton-proton collisions and to identify and quantify the contributions from different spin effects.

The fsPHENIX upgrade is currently in a conceptual phase. A straw-man conceptual design is shown in Figure 10. The exact detector performance design requirements for these physics channels are being determined. The currently envisioned sPHENIX forward detector will have an acceptance from a pseudorapidity of 1.2 < η < 4. Particle identification is based on a Ring Imaging Cherenkov Detector. It believed that a hadronic calorimeter with a modest energy resolution will energy smearing for Collins measurements in jets within acceptable limits. The forward electromagnetic calorimeter may consist of a re-stack of the current PHENIX electromagnetic calorimeters (EMCal) and the MPC-EX towers. Early simulation results indicate that the performance of the EMCal will be sufficient.

6. ePHENIX

A subsequent upgrade adding an electron detector in the opposite direction would further evolve sPHENIX into a detector for inclusive, semi-inclusive and exclusive processes in deep inelastic electron-proton and electron-nucleus scattering, referred to as ePHENIX, utilizing a future high intensity electron beam at RHIC.

7. Outlook

sPHENIX Forward will significantly extend physics capabilities. The additional of the new forward detector will enable us to understand large SSA, separating contributions from the Sivers effect and Collins function. The forward detector will also provide calibration for quarkonium measurements and probe CNM effects in d+A (connections with CGC and TMDs?). Potential also exists to explore 3D image of medium in Au+Au collisions.

A staged implementation approach is planned. The first stage will include only the EMCal, charged particle ID, and charge sign. This is sufficient for the Drell-Yan and Quarkonia measurements. Then add jet followed by identified hadron capabilities. The sPHENIX forward spectrometer would also be well matched with ePHENIX.

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