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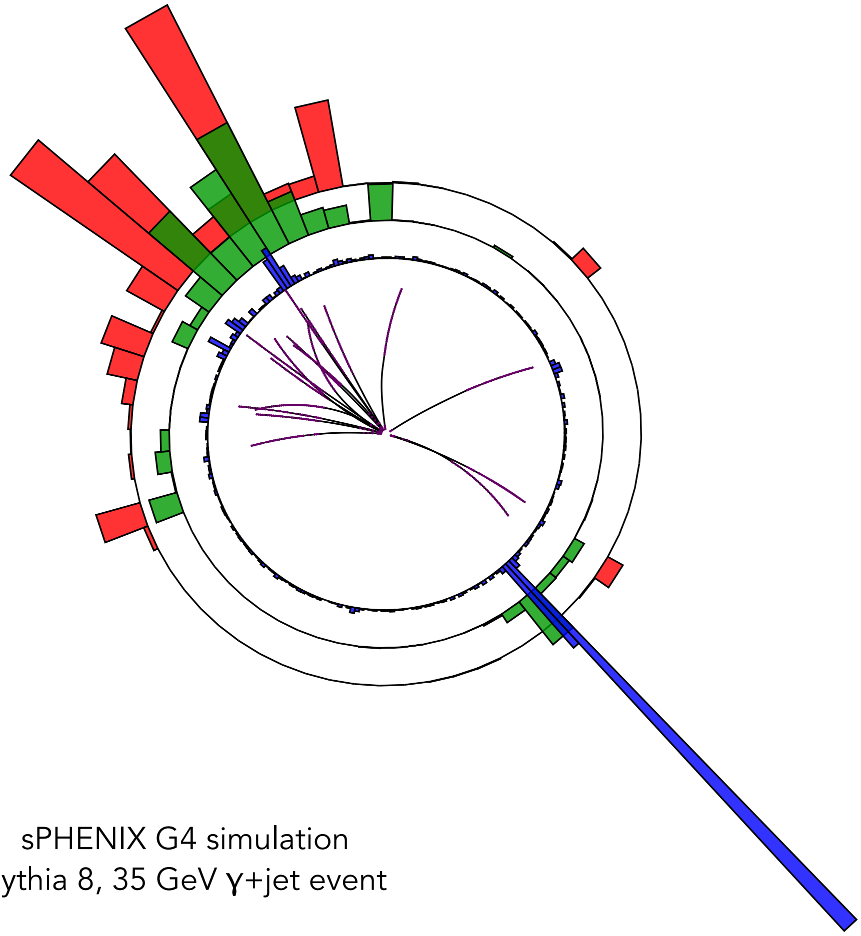
Medium-Energy Nuclear Physics Measurements with the sPHENIX Barrel



sPHENIX G4 simulation
Pythia 8, 35 GeV γ+jet event

The sPHENIX Collaboration
October 10, 2017

Executive Summary

sPHENIX is a planned upgrade to the PHENIX experiment at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). The concept for sPHENIX originated with a charge from the BNL Associate Laboratory Director to the PHENIX and STAR collaborations to document their research plans for the coming years. The resulting PHENIX decadal plan [1] described the critical hot and cold QCD measurements enabled by a mid-rapidity barrel incorporating hadronic calorimetry and a suitably instrumented forward arm. The Medium-Energy Nuclear Physics community has highlighted the physics accessible via forward measurements and this is reflected in the PHENIX decadal plan. At the same time, the PHENIX plan also described the substantial improvement in current medium-energy nuclear physics measurements possible at mid-rapidity with the capabilities of the sPHENIX barrel coupled with the high luminosity and polarization of the RHIC accelerator.

The PHENIX decadal plan subsequently gave rise to the sPHENIX science proposal which focused tightly on the QGP studies enabled by its excellent capability mid-rapidity measurements of jets and heavy quarkonia at RHIC. Even with that focus, the required mid-rapidity detector retains the capability for important medium-energy nuclear physics measurements, and several key measurements are described in this document. The sPHENIX collaboration continues to benefit greatly from the contributions made by collaborators whose interest is medium-energy nuclear physics research. In Sections 1–5 we detail the physics and show projections for how sPHENIX will improve current medium-energy nuclear physics results, and in Section 6 we show how the cost-effective reuse of existing forward detectors could extend those results. Finally, in Section 7 we show how these measurements could be addressed in a possible run plan.

Contents

Introduction

The science proposal for sPHENIX focused on a jet and bottomonium physics program addressing fundamental questions about the properties of the strongly coupled quark-gluon plasma discovered at RHIC [2]. However, the midrapidity sPHENIX detector as currently designed, combined with the versatile machine capabilities of RHIC, will also provide key opportunities for cold QCD measurements that should be exploited by the Medium-Energy Nuclear Physics community. These opportunities include improving constraints on the gluon spin contribution to the spin of the proton at large x values, extending measurements related to the nucleon tensor charge, and increasing knowledge of nuclear parton distribution functions (PDFs). Further measurements will probe quarkonium production mechanisms, which remain poorly understood, search for novel non-Abelian color effects, study J/Ψ photoproduction, and examine hadronization in a variety of QCD environments. A number of these measurements will be directly complementary in several different ways to future measurements at the proposed Electron-Ion Collider (EIC), for example by providing constraints for distributions in different kinematic regions, by searching for color effects that differ in hadron-hadron versus lepton-hadron collisions, by performing initial measurements that allow the magnitude of an effect to be gauged before the EIC and thus aid planning and design, and by providing the community with experience in certain relevant experimental techniques before the EIC.

1 Physics with Longitudinally Polarized Beams: Constraining ΔG

Understanding what builds up the spin of the proton, a complex system of quark and quark-antiquark pairs bound together by gluons, has been one of the central topics of high energy spin physics for the last four decades. Gluons known to carry about half of the proton momentum have been considered as a main candidate to contribute also to the spin of the proton. The recent discovery at RHIC of sizable gluon polarization ΔG in the proton at intermediate momentum fraction shed new light on our understanding of nucleon spin structure. sPHENIX will improve the precision of double helicity asymmetry (A_{LL}) measurements in jet production, being the main drivers of ΔG measurements at RHIC, by a factor of > 4, which will considerably improve the precision of ΔG constraints in the momentum fraction region $0.05 < x < 0.4$. For the first time the A_{LL} measurements in the "golden" direct photon channel, with improved statistical precision by a factor of > 10, will provide a crucial systematic check of ΔG constraints in the nucleon from other observables. With the future EIC high precision data providing ΔG constraints at lower x, sPHENIX data at intermediate and high x will be essential for a high precision determination of the full gluon spin contribution to the proton spin.

Measuring the gluon polarization ΔG has been one of the main goals of the RHIC spin program. With the past years' advances in machine luminosity, experimental efficiencies, and triggering, the RHIC experiments have obtained breakthrough results from inclusive jet (STAR) and π^0 (PHENIX) double helicity asymmetry measurements. Including these results in the global next-to-leading-order (NLO) perturbative QCD (pQCD) fit of the helicity parton distribution functions (PDFs) showed significant positive polarization of gluons in polarized protons for gluon momentum fractions of $x > 0.05$ [3]. The PHENIX collaboration has already published all their collected midrapidity data for π^0 A_{LL} at both

$\sqrt{s}$ =200 GeV and 510 GeV. The ongoing analysis of forward π^0 data is expected to extend the ΔG constraint to lower x. STAR results on inclusive jet and dijet measurements from the data collected up to 2013 are either published or have preliminary status. The biggest $\sqrt{s}$ =200 GeV data set from 2015 is still being analyzed. When finalized, the results from these data are expected to further improve the ΔG constraint at $x > 0.05$ and extend it down to $x \sim 10^{-3}$. The inclusive jet and dijet data collected by STAR in 2015 at $\sqrt{s}$ =200 GeV are expected to be the dominant contributor to the ΔG constraint at $x > 0.05$. With the planned RHIC running in the sPHENIX era, measurements in the sPHENIX barrel region will significantly improve RHIC measurements related to ΔG at $x > 0.05$. In addition, these measurements will provide crucial systematic cross checks for ΔG utilizing direct photon A_{LL} and charged hadron (h^+ and h^-) A_{LL}, which have not yet been explored well in PHENIX and STAR due to limited integrated luminosity and detector capabilities. The limited precision results for direct photons (PHENIX) and charged pions/hadrons (PHENIX and STAR) have been released from earlier RHIC runs' data, the analyses of higher luminosity data from the most recent runs are ongoing.

Direct photon production has been considered a "golden" channel for ΔG constraint because the main contributing process in RHIC kinematics is gluon Compton scattering ($qg \to q\gamma$). For π^0 and jet production, on the other hand, basically all hard scattering processes (gg, qg, and qq) contribute. The main challenge for direct photon reconstruction in the sPHENIX barrel EMCal is the separation between a single photon and two merged photons from a π^0 decay. With the EMCal granularity $\Delta\phi \times \Delta\eta = 0.024 \times 0.024$, the two-photon merging probability is 50% for π^0 p_T ~8 GeV/c. Thanks to the projective geometry of the EMCal, a transverse shower profile analysis can be done with high precision, which can further extend the range for identification of single photon clusters from merged clusters to about 12-15 GeV/c. This conclusion is based on our experience with PHENIX EMCal data, and the corresponding simulation studies for the sPHENIX barrel EMCal are ongoing. In addition, the wide and uniform sPHENIX EMCal and HCal acceptance will allow the effective use of isolation cuts to separate direct photons from π^0 signals at higher p_T.

Figure 1-left shows the projected statistical uncertainties for direct photon A_{LL} in the sPHENIX barrel acceptance in comparison to the results of the DSSV14 global fit [3], which reflects the positive gluon polarization in the proton at $x > 0.05$ constrained by the RHIC π^0 and jet data. The main background contribution for direct photon measurements comes from π^0s, either from merged clusters which pass the shower profile cut for a single photon or from the cases when one of the decay photons is out of the acceptance or below energy threshold and the other passes the isolation cut requirement. In the range of $p_T < 15$ GeV/c, the π^0 A_{LL} will be measured (with separated clusters below 10 GeV/c, and from identified merged clusters above 10 GeV/c) and then used to correct the direct photon A_{LL} measurement. Above 15 GeV/c, the cluster A_{LL} measurements will have contributions from both direct photons and π^0s (with the direct-photon-to-π^0 yield ratio varying from 1 to 3 in the range from 15 GeV/c to 30 GeV/c, after the isolation cut) and can be compared to theory calculations with known photon and π^0 fractional contributions.

The sPHENIX direct photon measurements will not only serve as a crucial test for the existing ΔG constraint, but will also make a significant contribution to the ΔG fit at $x > 0.05$. Reconstruction of direct photon-jet events provides access to leading-order partonic kinematics, and therefore will contribute to finer mapping of ΔG as a function of x.

Another powerful systematic check for a ΔG constraint is the comparison of the A_{LL} asymmetries for π^-, π^0, π^+. These asymmetries are expected to be ordered in value due to the significant contribution of qg scattering to pion production in our kinematic range, plus the fact that up and down quarks, which contribute preferentially to π^+ and π^-, respectively, are known to be oppositely polarized. (For qg scattering the observed A_{LL} is proportional to the product of quark and gluon polarization, at LO.) Due to the barrel hadronic calorimeter and its triggering capabilities, sPHENIX will be able to effectively trigger and collect charged hadron data, which are dominated by charged pions. Figure 1-right shows the projected statistical uncertainties for charged hadron and π^0 A_{LL} and a comparison to the DSSV14 prediction for π^-, π^0, π^+ asymmetries. Such high precision data will significantly constrain the helicity PDF global fit results.

Being optimized for jet measurements (including triggering directly on jet energy) with high DAQ rate capabilities, sPHENIX will be an ideal place for high precision spin-dependent measurements involving jets. sPHENIX will collect about a factor of 10 more high-p_T inclusive jet and dijet data at $\sqrt{s}$ =200 GeV beyond the data already collected at RHIC (mainly by STAR), which, coupled with sPHENIX's excellent trigger efficiency and high rate capability, will shrink the A_{LL} uncertainties by a factor of more than 4. Figure 2 shows the projected statistical uncertainties for inclusive jet A_{LL} measurements from sPHENIX. RHIC inclusive jet data have made the most prominent contribution to the ΔG constraint at $x > 0.05$. Therefore, sPHENIX jet data are expected to provide a significantly improved constraint for ΔG within this x range. Dijet measurements will allow for better control of partonic kinematics and hence better constraint of the $\Delta G(x)$ shape. Figure 3 shows the x_1-x_2 coverage for dijets in 200 GeV p+p collisions at sPHENIX.

From RHIC projected collision rates (up to $\sim$10 MHz in $p + p$ at $\sqrt{s}$ =200 GeV) and sPHENIX trigger and DAQ rate capabilities (up to 15 kHz), we expect to collect the whole sampled luminosity for hadrons at $p_T > 8$ GeV/c, π^0 and photons at $p_T > 6$ GeV/c, and inclusive jets at $p_T > 10$ GeV/c. The lower p_T data will be collected with lower threshold triggers, scaled down to fit the reserved fraction of the DAQ bandwidth. The statistical precision for A_{LL} in the lower p_T bins is expected to be on the level of $(1-3) \times 10^{-4}$. The relative luminosity determination between bunches with different spin configurations has been a key element for precise A_{LL} measurements at RHIC. As was demonstrated by PHENIX, it can be measured on the level of 10^{-4} or better. All in all, the measurements discussed in this section require about 1/3 of the available sPHENIX DAQ bandwidth.

In conclusion, sPHENIX and the high projected RHIC luminosities will bring us to the era of precision ΔG measurements, where high-statistics datasets will provide several channels with different theoretical and experimental systematic uncertainties. These measurements will have a strong impact on the ΔG constraint in the range $0.05 < x < 0.4$, the region already proven to contribute significant gluon polarization. These data will be truly complementary to the future Electron-Ion Collider (EIC) data, which will provide a high precision constraint for ΔG at lower x, approximately in the range $0.0001 < x < 0.05$ [4]. In addition, in any overlapping x range the data will serve as a universality test for helicity PDFs. With the future EIC high precision data, the uncertainty for the ΔG integral will be limited by the measurements at higher x provided exclusively by RHIC available data to date [4]. Therefore, improving ΔG measurements at RHIC is of crucial importance.

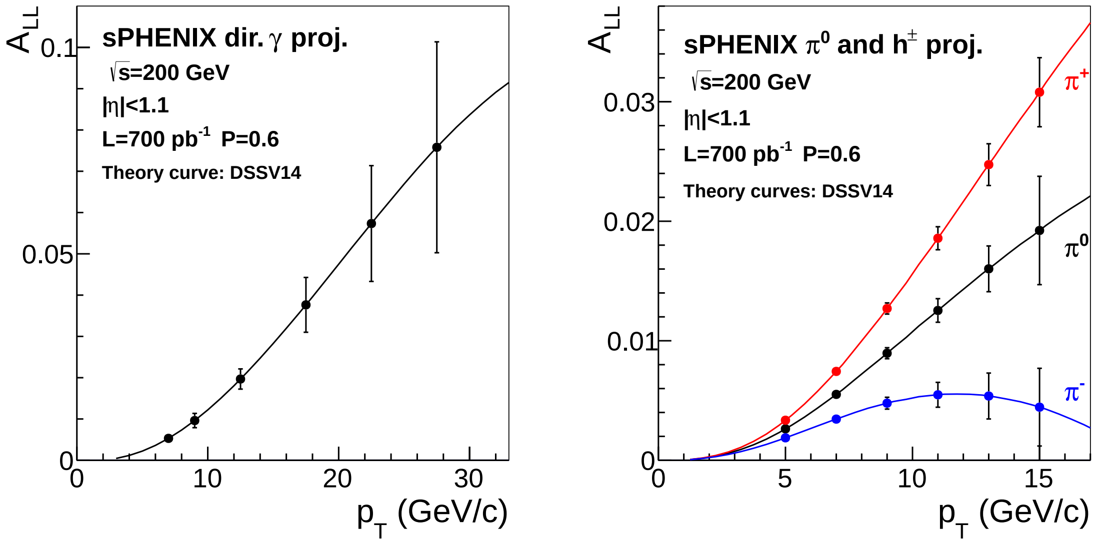


Figure 1: (Left) Projected statistical uncertainties for direct photon A_{LL} in the sPHENIX barrel acceptance (points), and a prediction for direct photon A_{LL} from DSSV14 (curve); projected uncertainties include a conservative 60% combined efficiency to account for photon identification efficiency and fiducial and isolation cuts. (Right) Projected statistical uncertainties in the sPHENIX barrel acceptance for A_{LL} for π^0s (black points), positive hadrons (red points) and negative hadrons (blue points), and DSSV14 prediction for π^0, π^+, π^- asymmetries (curves). Projected uncertainties include a conservative 70% combined efficiency to account for fiducial cuts and tracking efficiency for charged hadrons, and a p_T-dependent efficiency for π^0s to account for fiducial cuts and π^0 identification efficiency (either from two-photon mass reconstruction or merged cluster identification), with combined π^0 efficiency dropping from 80% to 30% from the lowest to the highest p_T bins shown.

2 Physics with Transversely Polarized Beams

The unique high-energy transversely polarized proton beams available at RHIC offer opportunities to study a variety of spin-spin and spin-momentum correlations in the proton. The quark transversity distribution is a spin-spin correlation that is related to the nucleon tensor charge, believed to be reliably calculated via lattice QCD but not yet well constrained experimentally due to the limited kinematic coverage of existing data. The tensor charge has furthermore recently been found to be of interest to access physics beyond the standard model; see e.g. [5]. The existing data come so far from fixed-target semi-inclusive DIS and are limited both in scale and x. Midrapidity sPHENIX measurements of hadron-in-jet and dihadron asymmetries can substantially extend the reach of transversity measurements in both x and Q^2 before the EIC. In addition several other transverse spin effects can be probed at central rapidities by sPHENIX such as D meson, jet, and direct photon asymmetries.

2.1 Transversity-Related Measurements

The transversity parton distribution of the nucleon describes the difference in densities of a parton's spin aligned versus anti-aligned with the transverse spin of the nucleon and relative

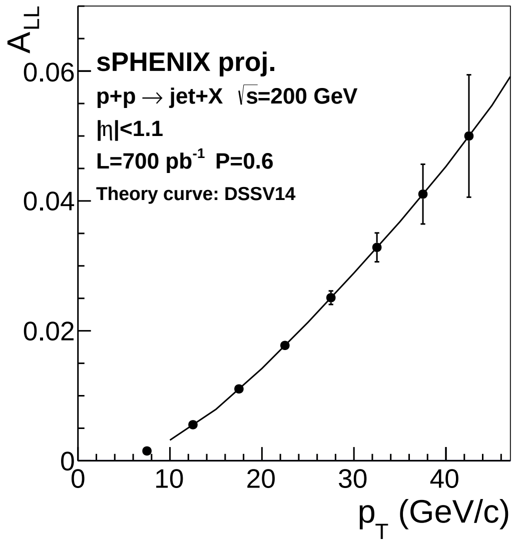


Figure 2: Projected statistical uncertainties for inclusive jet A_{LL} in the sPHENIX barrel acceptance (points), and the calculation from DSSV14 (curve). The estimates are done for jets reconstructed with an anti-k_T algorithm with R=0.3. Also included are jet reconstruction efficiencies from a GEANT4 simulation of the sPHENIX detector (90% at 10 GeV/c and increasing at higher p_T), full luminosity collected at $p_T > 10$ GeV/c and scaled down sample at lower p_T (with lower trigger energy threshold).

to its large momentum direction. It is the third and least known leading-twist collinear parton distribution function and its integrals relate to the tensor charge, which is expected to be a quantity reliably extracted from lattice simulations. As transversity is a chiral-odd quantity, it cannot be measured in inclusive deep-inelastic lepton-nucleon scattering (DIS) and requires another chiral-odd quantity to access it. With the exception of the so-far inaccessible double transverse-spin asymmetries in Drell-Yan production, all methods of accessing transversity apply chiral-odd fragmentation functions such as the transverse-momentum-dependent (TMD) Collins fragmentation function [6] and the collinear dihadron interference fragmentation function (IFF) [7]. Both have been extracted in electron-positron annihilation [8, 9, 10, 11, 12] and have been used in the corresponding semi-inclusive deep-inelastic scattering (SIDIS) measurements by HERMES [13, 14, 15] and COMPASS [16, 17, 18] to obtain information on the transversity distribution functions for up and down quarks. However, the available data are rather limited, are being taken at predominantly low scales and do not extend above an x of 0.3. Furthermore, the SIDIS measurements are predominantly sensitive to the up quark transversity and other flavors are only poorly constrained. The recent STAR measurements have shown that both channels, Collins fragmentation and interference fragmentation, are also accessible at RHIC at midrapidity [19, 20] and show nonzero signals. As the scales in these measurements are given by either the jet transverse momentum (Collins) or the transverse momentum of the hadron pair (IFF), the scales are mostly higher than what is currently possible in fixed-target SIDIS. Moreover, these measurements are particularly valuable to constrain the down quark transversity

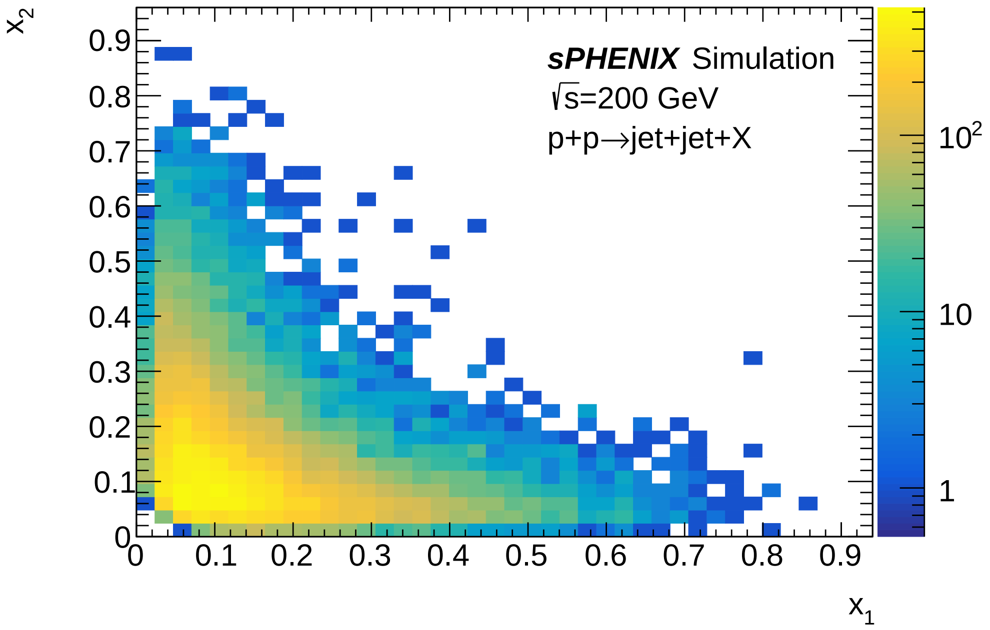


Figure 3: x_1-x_2 coverage for dijets in 200 GeV $p + p$ collisions at sPHENIX.

distribution because the hard interaction is via the strong interaction and, therefore, down quarks are not suppressed by their electromagnetic charge. Recent theoretical advances related to measurements of hadrons in jets [21, 22] allow a direct interpretation of the proton-proton Collins measurements in terms of the chiral-odd distribution and fragmentation functions of interest. This is shown in Ref. [23], where transversity for all available SIDIS, e^+e^- and RHIC data is successfully extracted in a single global fit. The corresponding IFF measurements are in a collinear factorization picture and therefore the RHIC measurements can in principle be used directly in global fits with the SIDIS and e^+e^- data, as has been successfully shown in Ref. [24]. The high-rate capability of the sPHENIX detector paired with its excellent tracking precision will allow for a substantial expansion of the STAR measurements in terms of statistical precision and should open some access to higher x for the highest available jet or dihadron transverse momenta. The current STAR Collins measurements at a center-of-mass energy of 200 GeV are obtained for transversely polarized beams with average polarization of around 60% and an integrated luminosity of about 22 pb^{-1}. Assuming the 200 GeV polarized proton runs proposed for sPHENIX with a third of the total luminosity being accumulated with transverse proton polarization, integrated luminosities of about 90 pb^{-1} and 261 pb^{-1}, respectively, can be accumulated. These datasets will improve the precision of the current STAR results by a factor of three or more where they overlap and will reach higher jet energies and therefore higher x_1 due to the greater luminosities. In comparison to the statistics at 500 GeV to be taken before sPHENIX, the same jet-transverse momentum relates to a lower x_1, and therefore 200 GeV measurements are preferable to reach higher x_1. However, the expected comparable precision for similar x_1 is also a good test of the QCD evolution of these Collins asymmetries which are not very well known so far. Figure 4 shows that the average x_1 for central jets of transverse momenta surpassing 12 GeV can reach values as high as 0.35. They therefore increase the reach above the previously accessible region and at high scales. In contrast, the planned fixed-target SIDIS measurements with electron beam energies of 11 GeV can only reach scales of about 3 GeV - a range where higher-twist effects will undoubtedly complicate the interpretation of the data [25].

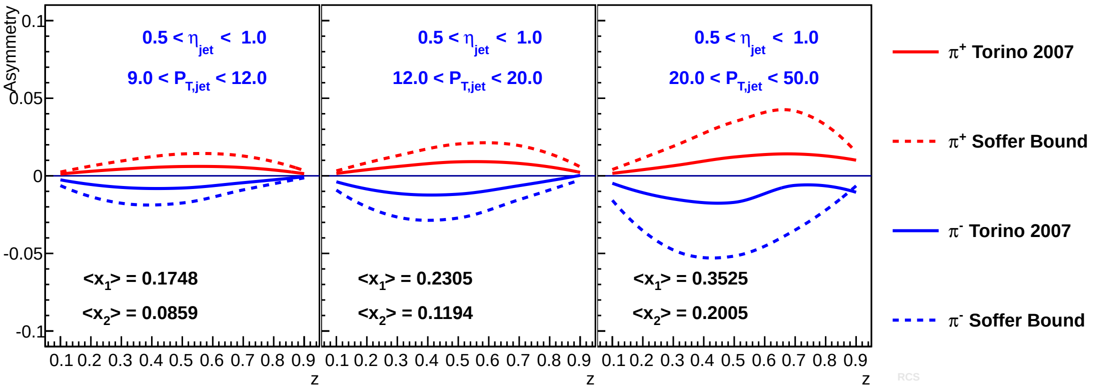


Figure 4: Range of expected Collins asymmetries in sPHENIX kinematics, given between the 2007 Torino transversity fit (solid lines) of SIDIS and e^+e^- data [26] and the Soffer bound (dashed lines) based on the unpolarized and helicity PDFs only. The different panels display various jet transverse momentum ranges for jets in the rapidity $0.5 < \eta < 1.0$ region.

For the interference fragmentation related measurements, the higher statistics expected with sPHENIX will enable a finer binning in both transverse momentum of the hadron pair and its invariant mass. Again, the transverse momentum will allow the average x of the polarized proton to be varied and thus improve our knowledge related to the corresponding quark transversity towards higher x. Furthermore, the sPHENIX EMCal should enable also charged–neutral pion pair IFF measurements, which could improve the flavor-separated extraction of transversity, although the corresponding fragmentation function information is so far not available from e^+e^- annihilation.

2.2 Other Transverse-Spin-Related Measurements

While most inclusive single-spin asymmetries have been observed at forward rapidities, there are a few measurements which are also of interest at central rapidities. Several heavy-flavor-related single-spin asymmetries, which are sensitive to tri-gluon correlators and the higher-twist component related to the integral of the gluon Sivers function [27], are expected to show nonzero asymmetries at small to moderate Feynman-x (x_F) according to model calculations [28]. Presently, some asymmetry measurements of muons from heavy flavor decays at slightly forward rapidities exist from PHENIX [29]. These measurements are consistent with the predictions, but lack the precision to clearly identify a nonzero asymmetry. With the increased precision of sPHENIX and the potential capability to fully reconstruct D mesons via their hadronic decays (rather than detecting them via their leptonic decays), such measurements become feasible at pseudorapidities smaller than

1. According to model calculations [30], the inclusive direct photon and jet single spin asymmetries at small to moderate x_F could be of interest as well. So far, no measurements at central rapidities exist for either of these channels.

TMD-factorization breaking has been predicted in hadronic collisions where at least one final-state hadron is measured [31]. The effect, also known as color entanglement, leads to partons being quantum mechanically correlated across colliding protons. Since this is specifically a non-Abelian effect it must be measured in hadronic collisions. A first measurement of nearly back-to-back dihadron and direct photon-hadron correlations studied the effect covering an x range of only 0.02-0.06 at $\sqrt{s} = 510$ GeV [32]. With the increased pseudorapidity coverage of the sPHENIX barrel, measurements can be made over a significantly larger range of x to determine if there are any correlations between x and k_T which led to the intriguing conclusions of Ref. [32]. Since sPHENIX is also a dedicated jet detector, the measurement of jets rather than hadrons will allow for the partonic momentum fractions to be determined at leading order, which will provide more robust conclusions. Additional tests can be made to understand the role, if any, of fragmentation in TMD-factorization breaking processes by comparing direct photon-hadron with direct photon-jet correlations, for example. Additionally, spin asymmetries have been predicted to arise due to entanglement effects in p+p collisions in the photon-jet channel [33], but have not yet been measured. Measurements of transverse single spin asymmetries of direct photons and direct photon-jet have also been proposed in p+A collisions as a probe for effects from color entanglement [34, 35].

3 Nuclear Parton Distribution Functions

The sPHENIX barrel will improve our knowledge of nuclear PDFs via measurements of inclusive hadrons, jets, γ-jet correlations, dijets and Drell-Yan in p+A compared to $p + p$ collisions. These data taken together will cover an x range from several times 10^{-2} up to ~ 0.4 and a Q^2 range where nuclear PDF effects are expected to be substantial.

Compared to our knowledge of parton distributions in a free proton, our understanding of parton distributions in nuclei, even the one-dimensional collinear PDFs in nuclei, is still quite limited. It has been known since the 1980s that PDFs in nuclei are not simply superpositions of the PDFs in the free proton and neutron, with the cross section ratios for DIS on heavier nuclei compared to deuterium revealing patterns of suppression and enhancement as a function of x. At x above ~ 0.8, measurements show enhancement due to Fermi motion in heavier nuclei. For $0.3 \lesssim x \lesssim 0.8$, suppression is observed, known as the EMC effect (after the European Muon Collaboration [36]). The EMC effect remained poorly understood for many years, but exciting recent evidence suggests that it may be due to local nuclear density and short-range nucleon-nucleon correlations [37]. At $0.1 \lesssim x \lesssim 0.3$, nuclear DIS data show an enhancement, known as antishadowing, which remains poorly understood, and below $x \sim 0.1$ a suppression referred to as shadowing is observed.

Figure 5 shows the recent EPPS16 global fit of nuclear PDFs [38] based on data from fixed-target DIS, fixed-target neutrino scattering, fixed-target Drell-Yan, PHENIX pion production in d+Au, and LHC Z and W production, as well as dijet production in p+Pb. Uncertainties are generally quite large for all parton flavors. The down valence distribution uncertainties are also notably larger than those for the up valence distribution.

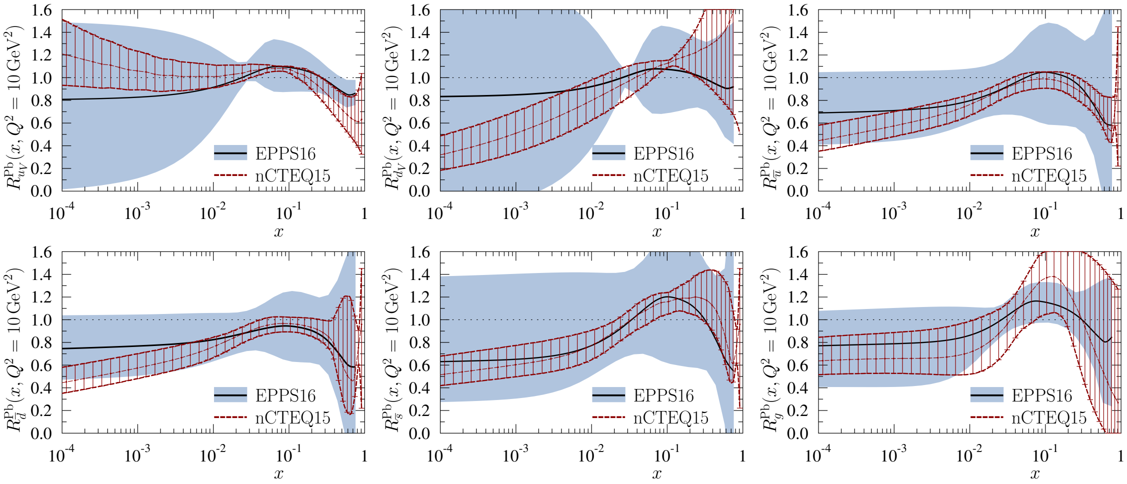


Figure 5: Results from the EPPS16 global fit of nuclear PDFs for the different parton flavors [38] compared to the nCTEQ15 nuclear PDF fit [39].

Proton-nucleus collisions at RHIC will allow us to improve our knowledge of how parton behavior is modified in nuclei, using a wide range of probes - inclusive hadrons, jets, γ-jet correlations, dijets, and Drell-Yan - to exploit this unique opportunity. Different observables offer complementary strengths, from the very large statistics available in single hadron production to the full reconstruction of parton kinematics at leading order in dijets and Drell-Yan. Compared to inclusive hadron or jet/dijet production, Drell-Yan offers the advantages of no nuclear interactions in the final state and explicit tagging of antiquarks. Explicit tagging of antiquarks is not possible with inclusive DIS, due to the fact that the virtual photon is sensitive only to electromagnetic charge. Detailed simulation studies to determine the possible background rejection for Drell-Yan measurements at midrapidity are underway.

Measurements of inclusive hadrons, jets, γ-jet correlations, dijets and Drell-Yan with the sPHENIX barrel will cover an x range from several times 10^{-2} for inclusive hadron measurements up to the values shown in Fig. 3 for dijets. Because of the lower $\sqrt{s}$ at RHIC these measurements will be at a significantly lower Q^2 than at the LHC, and nuclear PDF effects are expected to be substantial. The planned p+p and p+A running for sPHENIX will provide a comprehensive set of observables that can be used to further constrain nuclear PDF extractions. The fact that different observables will have different systematics and cover slightly different ranges in x should make this a powerful dataset for improving our knowledge of nuclear PDFs.

4 Quarkonium Measurements

With heavy quarkonium measurements already a major component of the heavy-ion-motivated sPHENIX physics program, several quarkonium measurements of interest to the Medium-Energy Nuclear Physics community will be possible. Upsilon and J/Ψ polarization measurements will shed further light on heavy quarkonium production mechanisms, the p_T-

dependent cross sections will provide additional information on the production mechanisms as well as constrain unpolarized transverse-momentum-dependent gluon PDFs, and J/Ψ photoproduction measurements may enable access to Generalized Parton Distributions.

Upsilon measurements are a key component of the existing sPHENIX program to study the quark-gluon plasma. The sPHENIX barrel will be an excellent detector to study upsilon polarization via the angular distribution of its decay electrons, with greatly improved acceptance compared to the PHENIX detector, which has already been used to perform a similar measurement of J/ψ polarization [40]. STAR has also measured J/ψ polarization [41]. Heavy quarkonium polarization is sensitive to the production mechanism, which remains an unresolved question for both the J/ψ and the upsilon. As an example of very recent theoretical work, numerical values for longitudinal polarization have been predicted within the Color Evaporation Model for midrapidity upsilon as well as J/ψ production in 200 GeV $p + p$ collisions [42]. sPHENIX has been optimized for measurements of upsilons rather than J/ψ; however, studies indicate that it should be possible to trigger on inclusive J/ψ mesons above 2.5–3.0 GeV p_T in $p + p$, permitting polarization measurements for the J/ψ as well.

In addition to measuring heavy quarkonium polarization, the p_T-dependent cross sections can be measured for both the upsilon and the J/ψ. These will provide complementary information regarding the production mechanism(s) and may furthermore offer sensitivity to gluon transverse-momentum-dependent (TMD) PDFs and/or TMD-factorization breaking; see Section 2.

Photoproduction of J/ψ in ultraperipheral Au+Au and p+Au collisions may also be possible to measure; however, the ability to trigger on these events needs to be studied in detail. PHENIX has published a measurement of J/ψ from ultraperipheral Au+Au collisions, with the trigger based on a Beam-Beam Counter veto, energy in the central EMCal, and at least 30 GeV deposited in one or both of the Zero Degree Calorimeters [43]. Photoproduction provides a means of accessing Generalized Parton Distributions and is particularly sensitive to the gluonic structure of the nucleus [44, 45].

5 Further Measurements

A variety of other Medium-Energy Nuclear Physics measurements will be possible with the sPHENIX barrel detector:

- Λ and $\bar{\Lambda}$ cross sections, polarization, and spin transfer in (polarized) $p + p$ collisions to learn about baryon hadronization and strange hyperon production in particular, and polarizing fragmentation functions. Spontaneous hyperon polarization in unpolarized hadronic collisions was discovered in 1976 [46] and remains poorly understood. There has been renewed interest in hyperon polarization recently due to the first-ever observation of Λ and $\bar{\Lambda}$ polarization in e^+e^- annihilation at BELLE in 2016 [47].
- Hadron-in-jet, γ-jet, and dijet measurements multidifferential in momentum fraction z of the jet carried by the produced hadron and in j_T, the transverse momentum of the hadron with respect to the jet axis in $p + p$. These jet profile studies will provide information on hadronization within a jet, and γ-jet and dijet measurements will provide different mixes of quark and gluon hadronization.
- Hadron-in-jet, γ-jet, and dijet measurements in p+A compared to $p + p$ to study

nuclear modification of hadronization.

- If the MAPS vertex detector (MVTX) is built, hadronization of charm and bottom quarks can be studied via measurement of heavy flavor jets and the profile of particles within them.

The measurements listed above are already known to be feasible, and the detailed analysis methods should be developed based on simulated data in the near future, accelerating the physics results once real data become available.

6 Additional Opportunities with the PHENIX MPC and MPC-EX

The MPC forward electromagnetic calorimeter and MPC-EX preshower detector were crucial additions to the PHENIX detector setup, allowing measurements of forward photons and neutral hadrons and corresponding correlations with particle production at central rapidity. These measurements have had a high impact on both polarized physics and low-x physics in nuclei, including the Color Glass Condensate search. The MPC(-EX) installation in sPHENIX will require minimal resources and no interference with the rest of the sPHENIX detector, and will considerably expand the scope of physics measurements in sPHENIX.

7 Possible sPHENIX Run Plan

The current strawman sPHENIX run plan envisions two runs (11.5 and 23.5 physics weeks long) with proton-proton collisions (p+p) and one run (11.5 physics weeks long) with proton-gold collisions (p+Au) (see Table 1). These runs are expected to yield 1050 pb^{-1} (200 pb^{-1}) integrated luminosity for p+p and 1.46 pb^{-1} (0.33 pb^{-1}) integrated luminosity for p+Au without vertex cut (within a vertex range of ±10 cm). The estimates are based on RHIC collider projections from May 12, 2017 [48]. In addition, the calculations of the integrated luminosity assume a ramp-up curve followed by steady-state physics running at the mean of minimum and maximum projected luminosity and sPHENIX uptime (60% in the first two years and 80% afterwards, including DAQ dead time). The physics projections for photon, hadron, and jet measurements discussed in this document (which do not require vertex detectors) are based on the integrated luminosities without vertex cut, with a splitting of 2:1 between longitudinal and transverse spin polarization for the p+p runs.

Table 1: Possible five-year run plan for sPHENIX. The recorded luminosity (Rec. L) and first sampled luminosity (Samp. L) values are for collisions with z-vertex $|z| < 10$ cm. The final column shows the sampled luminosity for all z-vertex values, relevant for calorimeter only measurements.

Year	Species	Energy [GeV]	Wks	Rec. L	Samp. L	Samp. L (all-z)
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

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