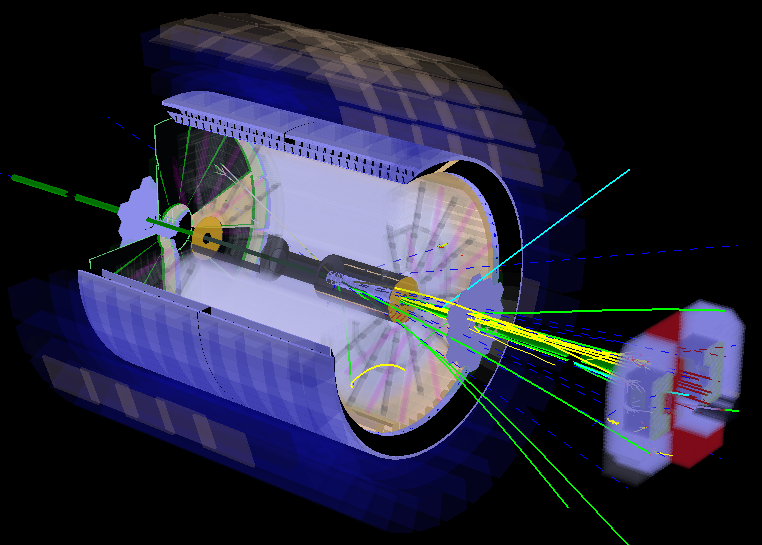
**A polarized p+p and p+A program for the next years**

**The STAR Collaboration**



**Version 3**

**May 2014**

1 The science of polarized p+p and p+A 3

1.1 Polarised p+p 4

1.1.1 Kinematics of inclusive forward jets in p+p with the proposed forward upgrade 4

1.1.2 CONFINED MOTION OF PARTONS IN NUCLEONS: 7

1.1.3 The Helicity Structure of the proton 18

1.2 The search for exotics in p+p 18

1.3 THE NUCLEUS AS A LABORATORY FOR QCD 23

1.3.1 PHYSICS OF HIGH GLUON DENSITIES AND LOW-X IN NUCLEI 23

2 STAR Upgrades 32

2.1 Forward Calorimeter System 32

2.2 FORWARD TRACKING SYSTEM 33

# The science of polarized p+p and p+A

Quantum Chromodynamics (QCD), the theory of strong interactions, is a cornerstone of the Standard Model of modern physics. It explains all strongly interacting matter in terms of point-like quarks interacting by the exchange of gauge bosons, known as gluons. This strongly interacting matter is responsible for 99% of the visible mass in the universe. Over the past several decades, a rich picture has come to light, with several overarching questions remaining that have been and continue to be addressed by the RHIC p+p and pA program:

* What is the nature of the spin of the proton?
* How do quarks and gluons hadronize into final-state particles?
* How can we describe the multidimensional landscape of nucleons and nuclei?
* What is the nature of the initial state in nuclear collisions?

Much of our present knowledge of nucleon structure comes from deep-inelastic leptonnucleon scattering (DIS) experiments, with a great wealth of data on the unpolarized structure of the proton available from HERA [[[1]](#endnote-1)]. From HERA we have learned that quarks carry 50% of the momentum of the proton, with the other half carried by gluons, which dominate for x <0.1.

Despite all that has been learned through DIS measurements, studying nucleon structure in a wide variety of reactions is essential in order to piece together a complete picture. Hadron-hadron interactions offer several advantages. Direct access to gluons is possible through parton-parton scattering, making measurement of the spin contribution of the gluon to the spin of the proton a key component of the RHIC program. W-Boson production and the Drell-Yan process are both golden probes to cleanly access antiquark distributions in hadron-hadron collisions. Drell-Yan will become an increasingly important part of the future RHIC p+p and p+A program. Comparing observations from DIS and hadronic interactions also allows us to test the assumptions of universality across processes in describing hadron structure and hadronization within the framework of perturbative QCD (pQCD). In the high-energy limit of pQCD, calculations in which the quarks and gluons are treated as nearly free particles moving collinearly with their parent hadron, and in which hadronic interactions are assumed to factorize into a) parton distribution functions (PDFs) within the initial-state hadron, b) partonic hard-scattering cross sections, and c) fragmentation functions (FFs) describing the hadronization of the scattered parton, have had tremendous success in describing hadronic cross sections at high energies over the past several decades. The collider energies available at RHIC, put high-*pT* reactions comfortably within a regime described by factorized pQCD. It is worth noting that the relevant perturbative scale in DIS is Q2, while in hadron-hadron interactions it is the square of the transverse momentum (*pT2*) of the produced jet or particle, and while both *Q2* and *x* are known in DIS, in hadron-hadron measurements the *pT* of the produced particle is correlated with *x*, but a given *pT* bin typically samples from a range of *x* values. At high energy, there remain two fundamental aspects of the nucleon partonic structure, which are rather poorly determined by experiment. One is the nature of the nucleon spin; the other is go beyond our current simple one-dimensional picture of nucleons by correlating the information on the individual parton contribution to the spin of the nucleon with its transverse momentum and spatial distribution inside the nucleon.

The questions have also manifested themselves in the nuclear physics performance milestones from DOE. Table 1‑1 list the current nuclear physics performance milestones related to the RHIC p+p physics program. There is currently only on NP performance milestone related to the RHIC p+A program, it asks to “Determine the gluon densities at low x in cold nuclei via p+Au or d+Au collisions (DM8, 2012).

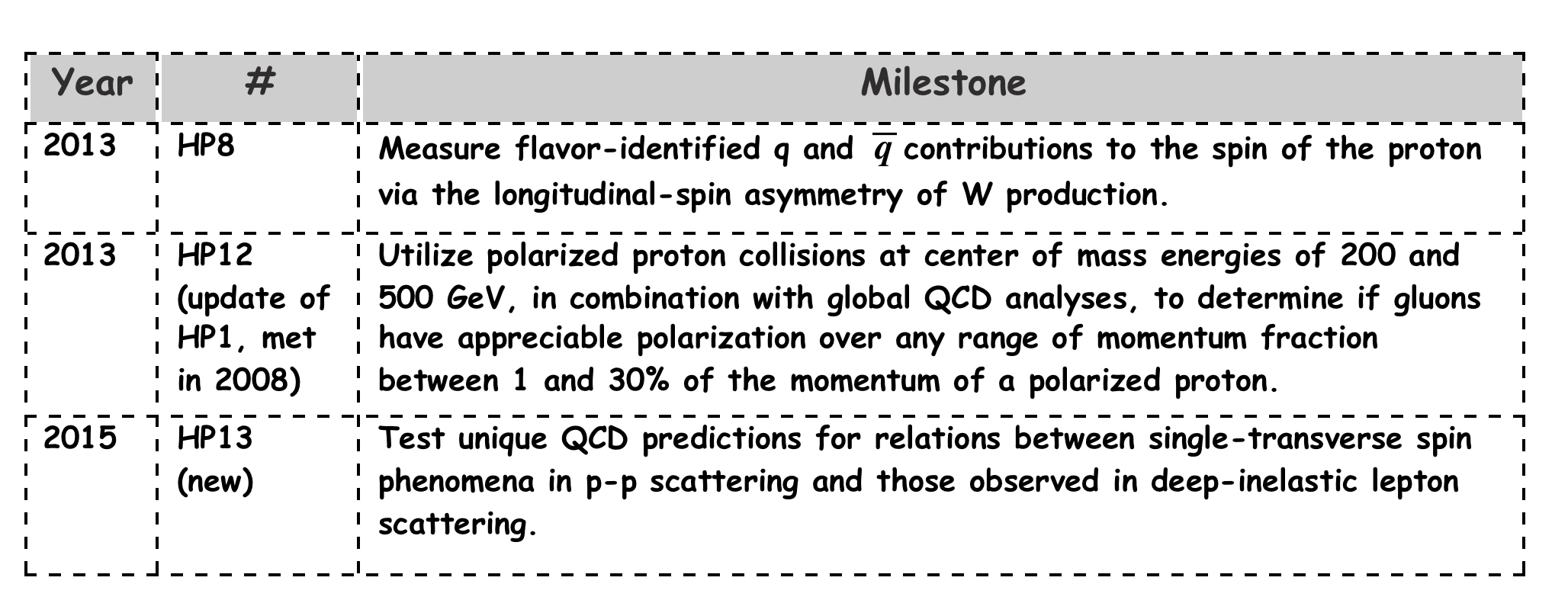


Table ‑: Current nuclear physics performance milestones related to the RHIC p+p physics program.

In the following sections we will describe how STAR is planning to address these questions in the next years.

## Polarised p+p

Describe in detail the physics why it is important to unravel the helicity structure of the proton and what going beyond one-dimensional pdfs brings for our understanding of QCD. This needs a comprehensive description of Sivers, Collins, vs. Twist-3 and SIDIS vs. DY and pp. What does the sign change really teach us.

### Kinematics of inclusive forward jets in p+p with the proposed forward upgrade

Both the measurement of the helicity structure and the transverse spin structure of the nucleon use reconstructed jets and di-jets to narrow the phase space of partonic kinematics. Since jets serve as proxies for the scattered partons, reconstructed jets allow the selection of events with a specific weighting of the fractional momenta of the parent protons carried by the scattering partons, assuming a 2-2 process. Here we call the fractional momentum carried by the parton coming from the beam along the *z*-axis (towards the proposed forward upgrade instrumentation) *x*1, and the fractional momentum carried by the other parton *x*2.

For measurements of *ALL* it is important to select events where one *x* is determined with good accuracy within the kinematic region in which one wants to measure g(x) and the other *x* is in a region, where the helicity distribution is well known, i.e. in the region of medium to high values *of x*. The transverse spin structure of the nucleon on the other hand is usually accessed using transverse single spin asymmetries and semi-inclusive measurements. This means one measures azimuthal asymmetries of the final state, where the distribution function of interest couples to a spin dependent fragmentation function that serves as a polarimeter. Consequently we studied how in single- and di-jet events, the jet pseudorapidity ** and *pT* are related to the underlying partonic variables *x1* and *x2*. We also studied the matching between reconstructed jets and scattered partons and the resolutions with which the parton axis can be reconstructed from the reconstructed detector jets. The latter is important to evaluate how well azimuthal asymmetries around the outgoing parton axis will be reconstructed by looking at asymmetries of reconstructed particles around the reconstructed jet axis.

For this study we used 500k events simulated with Pythia Tune A at √s=500 GeV and a minimum partonic *pT* (CKIN3) of 3 GeV. We then used a fast simulation of the detector resolutions of the STAR barrel and the forward upgrade. For the purpose of this study we assumed a tracking detector with three planes at distances from the interaction point of 70 cm, 105 cm and 140 cm. Each plane is comprised of 1.2% radiation lengths of material with resolutions in the azimuthal direction between 0.11 and 0.85 mm/. Furthermore, we simulated a detector subsystem combining hadronic and electromagnetic calorimeters (FCS) with hadronic resolution and an electromagnetic resolution of . In this setup, except for those tracks with very low energy, the track momentum is reconstructed in the FCS and the tracking is used mainly for charge discrimination. Jets were reconstructed with an anti-*kT* algorithm with a radius of 0.7. An association between reconstructed jets and scattered partons is defined to be a distance in - space of less than 0.5.

In the following, we refer to reconstructed jets as “detector jets” and jets found using stable, final state particles “particle jets.” The outgoing partons in the event are determined by using the corresponding entries in the Pythia record, so there is no partonic jet finding.

|  |  |
| --- | --- |
| x1VsX2_Pythia.png | Figure 1‑1: Distribution of the partonic variables *x*1 and *x*2 for events with a jet with GeV/*c* and . *x*1 values of around 0.6 can be reached whereas *x*2 goes as low as . |

Figure 1‑1 shows the regions of *x* that can be accessed by jets in the forward region. A minimum jet *pT*of 3 GeV/*c* was chosen to ensure that the momentum transfer is sufficiently high for pQCD calculations to be valid. At high *x*, values of *x*~0.6 should be reachable. This compares well with the current limit of SIDIS measurements, *x~0.3*, and encompasses the region in *x* that dominates the tensor charge. To investigate the possibility of selecting specific *x* regions, in particular high *x*, the dependence of *x* on the jet *pT*and pseudorapidity was studied. Figure 1‑2 shows *x1* as a function of jet *pT* and Figure 1‑3 and Figure 1‑4 show the** dependence for two *pT* bins. For both the *η* and *pT* dependences one can observe two bands: One that exhibits an ** or *pT* dependence and one that remains at low *x*. Based on the profile plots in Figure 1‑3 and Figure 1‑4, high *x* can be reached with small dilution for high ** and *pT*.

|  |  |
| --- | --- |
| x1_Vs_Pt_Pythia.png | Figure 1‑2: *x1* versus jet *pT*. As expected, there is a correlation between the *x* accessed and the *pT* of the jet. However, there is an underlying band of low *x*1 values. This can be improved by further restricting the ** range of the jet. Here . |
| x1_Vs_Eta_Pythia.png | Macintosh HD:Users:avossen:Documents:pythiaVsTppmc:x1_vs_eta_jetCut5_pythia.png |
| Macintosh HD:Users:avossen:Documents:pythiaVsTppmc:x1_eta_profile_pythia_jetCut3.png | Macintosh HD:Users:avossen:Documents:pythiaVsTppmc:x1ProfileX_pythia_JetCut5.png |
| Figure 1‑3: *x*1 vs jet **. The upper figure shows a 2D histogram and the lower figure the profile plot. Here a minimum jet *pT* of 3 GeV/*c* was required. One can see that the events are split into two bands. One exhibits a strong correlation with **, whereas the other is flat at low *x*1. In the region of the forward upgrade *x1* values between 0.15 and 0.3 are accessible. | Figure 1‑4: Same as in Figure 1‑3 but with a minimum jet *pT* of 5 GeV/c. This shows that additional *pT* cuts allow one to push the accessible mean *x* to higher values. In this case, *x*1 values between 0.2 and 0.4 are achievable. |

For measurements of azimuthal asymmetries of jets or hadrons within a jet to probe the transverse spin structure of the nucleon it is important to reconstruct reliably the outgoing parton direction. Therefore, the matching of reconstructed jets to scattered partons was studied (Figure 1‑5). Figure 1‑6 and Figure 1‑7 show the mean distance of partons to associated detector jets and detector jets to associated particle jets. In general, matching and parton axis smearing improves with *pT*, which may be connected to the jet multiplicity that rises with transverse momentum. Figure 1‑8 and Figure 1‑9 give the *pT* and resulting *z* smearing for the reconstructed jets. Here, *z* is defined as the fractional energy carried by the fragmenting hadron. The reconstruction of the transverse momentum is poor, but z exhibits a more favorable correlation. Possible explanations are compensation between jet and hadron momentum smearing and the domination of the *z* correlation by high multiplicity jets where the jet *pT* reconstruction is more reliable.

|  |  |
| --- | --- |
| matching_pythia.png | Figure 1‑5: Matching Fraction between detector jets and partons. The matching fraction at low *pT* is only around 50%, but grows to over 90% for high *pT*. Unfortunately, the statitcs at high *pT*in the forward region is small. |
| partonDetRes_pythia.png | particlePartonRes_Pythia.png |
| Figure 1‑6: Mean distance between matching parton and detector jets. For most jets the mean distance in ** space is around 0.2, but depends strongly on the jet *pT*. | Figure 1‑7: Mean distance between detector and particle jets. Detector and particle jets are closer to each other than the detector jets to the parton. The regions of large distance are caused by the lack of coverage between barrel and forward instrumentation and the lower minimum *pT* cut for the particle jets. |

|  |  |
| --- | --- |
| pTSmearing_Pythia_Eta4.png | zSmearingPythia_Eta4.png |
| pTSmearing_Pythia_Eta5.png  Figure 1‑8: Transverse momentum smearing for reconstructed jets compared to that of the associated parton. The upper rows show the smearing for jets with and the lower row for those with . | zSmearingPythia_Eta5.png  Figure 1‑9: Smearing of *z*, the fractional momentum of the outgoing parton/jet the carried by the outgoing hadron. The upper rows show the smearing for jets with and the lower row for those with . |

### CONFINED MOTION OF PARTONS IN NUCLEONS:

A natural next step in the investigation of nucleon structure is an expansion of our current picture of the nucleon by imaging the proton in both momentum and impact parameter space. At the same time we need to further our understanding of color interactions and how they manifest themself in different processes. In the new theoretical framework of transverse momentum dependent (TMD) parton distributions we can obtain an image in transverse as well as in longitudinal momentum space (2+1 dimensions). This has attracted renewed interest, both experimentally and theoretically, in transverse single spin asymmetries (SSA) in hadronic processes at high energies, which have a more than 30 years history. Measurements at RHIC have extended the observations from the fixed-target energy range to the collider regime, up to and including the highest center-of-mass energies to date in polarized p+p collisions. Figure 1‑10 summarizes the measured asymmetries from different experiments as functions of Feynman-*x* (*xF ~ x1-x2*).

The surprisingly large asymmetries seen are nearly independent of  over a very wide range. To understand the observed SSAs one has to go beyond the conventional collinear parton picture in the hard processes. Two theoretical formalisms have been proposed to generate sizable SSAs in the QCD framework: transverse momentum dependent parton distributions and fragmentation functions, which provide the full transverse momentum information, and the collinear quark-gluon-quark correlations, which provide information about the average transverse momentum. At RHIC the *pT*-scale is sufficiently large to make the collinear quark-gluon-quark correlation formalism the appropriate approach to calculate the spin asymmetries. Here, various underlying mechanisms can contribute and need to be disentangled to understand the experimental observations in detail, in particular the *pT*-dependence. These mechanisms are associated with the spin of the initial state nucleon (Sivers/Qiu-Sterman effects) and outgoing hadrons (Collins effects).

|  |
| --- |
|  |
| Figure ‑: Transverse single spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as function of Feynman-*x.* |

The Sivers function, , describes the correlation of the parton transverse momentum with the transverse spin of the nucleon. A non-vanishing means that the parton distribution will be azimuthally asymmetric in the **transverse momentum space** relative to the nucleon spin direction. The Collins function, ,describes a correlation of the transverse spin of a scattered quark and the transverse momenta of the fragmentation products and as such can lead to an asymmetry of the distribution of hadrons in jets. Contrary to the Sivers effect, the Collins fragmentation function is universal among different processes: SIDIS, e+e- annihilation, and *p*+*p* collisions. This is of special importance to the *p*+*p* case where it is always coupled to the chirally odd quark transversity distribution, which describes the transverse spin preference of quarks in a transversely polarized proton.



STAR pioneered in the last years the research in p+p collisions to identify observables, which will help to separate the contributions from initial and final states, and will give insight to the transverse spin structure of hadrons. In the following it will be discussed how the current and future STAR data will help to answer the following burning questions.

* Do the large transverse single spin asymmetries survive at high center-of-mass energies?
* Can the subprocess responsible for AN uniquely be identified?
* Is the observed pT-dependence of AN consistent with theory expectations in pQCD
* Can the TMD evolution, which is different from the well-known DGLAP evolution, be seen in the RHIC data?

Our current understanding is based on the already taken or soon to be taken data sets listed in Table 1‑2.

|  |  |  |  |
| --- | --- | --- | --- |
| **Year** | **√s (GeV)** | **Recorded Luminosity for transversely polarized p+p** | **<P>** |
| 2006 | 200 | 8.5 pb-1 | 57 |
| 2008 | 200 | 7.8 pb-1 | 45 |
| 2011 | 500 | 25 pb-1 | 48 |
| 2012 | 200 | 22 pb-1 | 61/58 |
| 2015 | 200 | 50 pb-1 | 60 |
| 2016 | 500 | 400 pb-1 (7w) / 900 pb-1 (14w) | 50 |

Table ‑: Luminosity recorded by STAR in the past transverse polarized p+p runs from 2006 onward.

The luminosities listed for 2015 and 2016 are projected.

STAR primary contributions to the transverse spin physics have been through the study of forward neutral pion production in p+p collisions (see, for example, ref. [[[2]](#endnote-2),[[3]](#endnote-3)]). This effort has been extended to include the first measurements at *√s* = 200 GeV of the transverse spin asymmetry *AN* for the *η* meson [[[4]](#endnote-4)]. The Run-11 data taken with transverse polarization at *√s* = 500 GeV have revealed several surprising results. Figure 1‑11 shows the transverse single spin asymmetry *AN* for electromagnetic jets detected in the forward meson spectrometer (FMS) at 2.5 <  < 4.0 as function of the jet *pT* for different photon multiplicities and jet energy ranges. It can be clearly seen that with increasing number of photons in the electromagnetic jet (increasing jettiness of the event) the asymmetry becomes smaller. Jets with an isolated *0*have the largest asymmetry consistent with the asymmetry in inclusive *0*events, as seen from the right-most panel in Figure 1‑10. For all jet energies and photon multiplicities in the jet, the asymmetries are basically flat as function of jet *pT*, a feature also already seen for inclusive *0*asymmetries. Recently, it has been proposed that in the collinear, twist-3 factorization approach a significant portion of the sizable inclusive pion asymmetries seen at forward pseudorapidity is due to twist-3 fragmentation functions coupled to transversity [[[5]](#endnote-5)]. This calculation is the first one, which showed similar to the experiment [[[6]](#endnote-6)] a flat *pt* dependence for *AN.* The ability for this approach to describe adequately the effects seen at SIDIS and at RHIC is a potentially significant breakthrough in the longstanding mystery surrounding the nonzero inclusive asymmetries at forward pseudorapidity (e.g. Ref. [[[7]](#endnote-7)]). For these reasons, the most desirable kinematic region for future study at RHIC is in the region of .

To further study these effects the transverse single spin asymmetry *AN* of these electromagnetic jets was also measured if in addition a correlated away side jet in the rapidity range -1 <  < 2 was required. Figure 1‑12 shows clearly that for requiring an additional correlated away-side jet the asymmetry for isolated forward 0s becomes smaller. For further details see reference [[[8]](#endnote-8)]. Both these observations raise serious questions how much of the large forward *0*asymmetries are caused by 2🡪2 parton scattering processes.

|  |
| --- |
|  |
| Figure ‑: The transverse single spin asymmetry *AN* for electromagnetic jets detected in the forward meson spectrometer (2.5 < ** < 4.0) as function of the jet *pT* and the photon multiplicity in the jet in bins of the jet energy. |

|  |
| --- |
|  |
| Figure ‑: The transverse single spin asymmetry AN for electromagnetic jets detected in the forward meson spectrometer (2.5 < ** < 4.0) as function of the jet pT and the photon multiplicity in the jet in bins of the jet energy (red points). The blue points represent the transverse single spin asymmetry AN if further a correlated away side jet in the rapidity range -1 <  < 2 was required. The blue and red bands represent the systematic uncertainties. |

To disentangle the different subprocesses even further it is important to identify more exclusive measurements (which are particularly sensitive to certain processes). Table 1‑3 identifies observables, which will help to separate the contributions from initial and final states, and will give insight to the transverse spin structure of hadrons. Most observables in p+p collisions can only be related to the transverse spin structure of hadrons through the twist-3 formalism, where only one hard scale is required. For the TMD framework, a second scale is required, as can be provided in di-jets, W, Z, or Drell-Yan production.

|  |  |
| --- | --- |
| **Sivers** | **Transversity *h(x)* x Collins FF** |
| *AN* as function of rapidity, *ET, pT* and *xF* for inclusive jets, direct photons and charmed mesons  *AN* as function of rapidity, *pT* for W*±*, Z0 and DY | *AN* as function *pT* and the invariant mass of the hadron pair (IFF)  Hadron correlations within a jet  *AUT* as function of the azimuthal dependence of the correlated hadron pair on the spin of the parent quark |

Table ‑: Observables to separate the contributions from initial and final states to the transverse single spin asymmetries. 2-scale processes are indicated in blue and 1-scale ones in black.

An important aspect of the Sivers effect, which has emerged from theory, is its process dependence and the color gauge invariance. In SIDIS, the quark Sivers function is manifested in association with a final state effect from the exchange of (any number of) gluons between the struck quark and the remnants of the target nucleon. On the other hand, for the virtual photon production in the Drell-Yan process, the Sivers asymmetry appears as an initial state interaction effect. As a consequence, the quark Sivers functions are of opposite sign in these two processes and this non-universality is a fundamental prediction from the gauge invariance of QCD. The experimental test of this sign change is one of the open questions in hadronic physics (NSAC performance measure HP13) and will provide a direct verification of QCD factorization. The COMPASS experiment at CERN is pursuing this sign change through DY using a pion beam and new initiatives have been proposed e.g. at FNAL.

While the required luminosities and background suppressions for a meaningful measurement of asymmetries in Drell-Yan production are challenging, other channels can be exploited in *p*+*p* collisions, which are similarly sensitive to the predicted sign change. These include prompt photons, W*±* and Z bosons, and inclusive jets. These are either already accessible with the existing STAR detector or need only modest upgrades and require continued polarized beam operations.

Figure 1‑13 shows the most up-to-date theoretical predictions for the transverse single spin asymmetries for W*±*, Z0 Bosons from reference [6] including TMD-evolution.

|  |  |  |
| --- | --- | --- |
| z0.eps | w_plus.eps | w_minus.eps |
| Figure ‑: Theoretical predictions from reference [6] for the transverse single spin asymmetries for W*±*, Z0 Bosons for 0 GeV <pt < 3 GeV. The yellow bands represent the uncertainties for the asymmetry. At negative rapidity this is mainly caused by the till today unconstrained sea quark Sivers functions. | | |

The transversely polarized data set in Run-11 at *√s* = 500 GeV allowed to reconstruct the transverse single spin asymmetries for *AN*for W*±* and Z0 Bosons. Especially the measurement of the *AN*for W*±* Bosons is challenging where, contrary to the longitudinally polarized case, it is required to completely reconstruct the W-Bosons as the kinematic dependences of *AN*can not easily be resolved through the high *pT* decay lepton, for details see [[[9]](#endnote-9),[[10]](#endnote-10)]. Due to the large STAR acceptance it was possible to reconstruct the W-Boson kinematics from the recoil jet, a technique used at D0, CDF and the LHC experiments to reconstruct the W-Boson kinematics. Figure 1‑14 shows the transverse single spin asymmetries for *AN*for W*±* as function of the W-Boson rapidity *y*. The asymmetries have also been reconstructed as function of the *pT* of the W-boson. For the *Z0*-Boson the asymmetry could only be reconstructed in one bin in *y* with the current limited statistics (25 pb-1). Details for this analysis can be found in [[[11]](#endnote-11)]. The analysis represents an important proof of principal similar to the first Run-9 W*± AL* measurement.

|  |  |
| --- | --- |
| hd_Wp_AsymAmpSqrtVsRap.eps | hd_Wm_AsymAmpSqrtVsRap.eps |
| Figure ‑: The transverse single spin asymmetries for *AN*for W*±* as function of the W-Boson rapidity y. | |

W*±* bosons production due to is maximum parity violating nature provides an ideal tool to study the spin-flavor structure of sea quarks inside the proton. Such a measurement of the transverse single spin asymmetry will provide the world wide first constraint on the sea quark Sivers function in a *x*-range, where the measured asymmetry in the  and  unpolarized sea quark distribution functions, as measured by E866 [[[12]](#endnote-12)], can only be explained by strong non-pQCD contributions. At the same time, this measurement is also able to access the sign change of the Sivers function. Figure 1‑15 shows the projected uncertainties for transverse single spin asymmetries of W*±*, Z0 Bosons as function of rapidity and *pT* for a delivered integrated luminosity of 400 (900) pb-1 and an average beam polarization of 50%. The 400 (900) pb-1 correspond to 7 (14) weeks running with a dynamic \* squeeze through the duration of a RHIC fill. The dynamic \* squeeze provides a factor 2 increase of the luminosity in a fill, compared to Run-13, as the luminosity profile through the fill is kept flat.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure ‑: The projected uncertainties for transverse single spin asymmetries of W*±*, Z0 Bosons as function of rapidity and pT for a delivered integrated luminosity of 900 pb-1 and an average beam polarization of 50%. | | |

Transverse single spin asymmetries in direct photon production provide a different path access to this sign change through the Twist-3 formalism. Figure 1‑16 right shows the statistical and systematic uncertainties for the direct photon AN. The asymmetry can be measured up to xF ~ 0.7 where the 0 asymmetries are largest. Figure 1‑16 left shows the level of achieved background suppression for charged particles as well as photons from decays, i.e. 0, using the forward meson spectrometer (FMS) and its preshower without any significant loss in the direct photon yield. Ideally, neutral pion asymmetries are measured simultaneously in the same xF-range. Merged clusters in the FMS from pion decay become problematic at pZ≈60 GeV or more; here the preshower/converter will help to increase the signal/background fraction and extend the reach in xF.

|  |
| --- |
|  |
| Figure ‑: (left) The number of events at √s=500 GeV for a delivered luminosity of 400 pb-1 for direct photons, charged hadrons and photons from decays, i.e. 0 before (solid) and after (dashed) detector responses have been applied. (right) Statistical and systematic uncertainties for the direct photon AN after background subtraction. |

As described above for a complete picture of nucleon spin structure at leading twist, one must consider not only unpolarized and helicity distributions but also those involving transverse polarization, such as the transversity distribution, [[[13]](#endnote-13), [[14]](#endnote-14), [[15]](#endnote-15)]. The transversity distribution can be interpreted as the net transverse polarization of quarks within a transversely polarized proton [11]. Transversity is difficult to access due to its chiral-odd nature, requiring the coupling of the distribution to another chiral-odd distribution. Recently, semi-inclusive deep inelastic scattering (SIDIS) experiments have successfully probed transversity through two channels: asymmetric distributions of single pions, coupling transversity to the transverse-momentum-dependent (TMD) Collins fragmentation function [[[16]](#endnote-16)], and asymmetric distributions of di-hadrons, coupling transversity to the so-called “interference fragmentation function” (IFF) [[[17]](#endnote-17)] in the framework of collinear factorization. Taking advantage of universality and robust proofs of TMD factorization for SIDIS, the recent results [[[18]](#endnote-18), [[19]](#endnote-19), [[20]](#endnote-20), [[21]](#endnote-21)] have been combined with *e*+*e*- measurements [[[22]](#endnote-22), [[23]](#endnote-23)] isolating convolutions of Collins and IFFs for the first global analyses to extract simultaneously the transversity distribution and polarized fragmentation functions [[[24]](#endnote-24), [[25]](#endnote-25)]. In spite of this wealth of data, the kinematic reach of existing SIDIS experiments, where the range of Bjorken-*x* values don't reach beyond , limits the current extractions of transversity.

|  |
| --- |
|  |
| Figure ‑: Preliminary Collins asymmetries for leading charged pions within jets produced with and GeV/*c* [26]. Asymmetries are shown as a function of pion *z* and *jT*. Statistical uncertainties indicated by error bars, while systematic uncertainties are shown as shaded error bands. |

|  |  |
| --- | --- |
|  | Figure 1‑18: Preliminary di-hadron asymmetries for charged pions produced within . Asymmetries are shown as a function of di-hadron pseudorapidity. Error bars indicate statistical uncertainties. |

As shown in Figure 1‑17 and Figure 1‑18, the STAR detector at RHIC has seen evidence of non-zero Collins [[[26]](#endnote-26)] and di-hadron asymmetries [[[27]](#endnote-27)] in preliminary data from and at and GeV. These results are from 2.2 pb-1 of transversely polarized data with 58% polarization taken in 2006, and demonstrate for the first time that transversity is accessible from polarized proton collisions at RHIC. By accessing the Collins asymmetry through the distribution of pions within a jet, one may also extract the *kT* dependence of transversity, giving insight into the multidimensional dependence of the distribution. While TMD factorization is broken in for *p+p* scattering, di-hadron asymmetries utilize collinear factorization. Thus, not only can more precise measurements of these effects in *p+p* improve our knowledge of transversity, such measurements may prove invaluable to understanding longstanding theoretical questions, such as, the depth of any existing TMD factorization breaking. Extractions at RHIC kinematics also allow the possibility for understanding the TMD evolution of the Collins fragmentation function (e.g. Ref. [[[28]](#endnote-28)]) by comparing to those extractions from SIDIS and *e+e-* data. Probing transversity in *p+p* collisions also provides broader access to the various quark flavors than is available in SIDIS.

|  |
| --- |
|  |
| Figure 1‑19: Expected Collins asymmetries assuming the Torino parameterization [21] within a leading-order PYTHIA Monte Carlo for charged pions within jets produced with and GeV/*c*. The expectations assume 1 fb-1 of integrated luminosity, and statistical uncertainties are smaller than the size of the points. Jets are reconstructed utilizing an anti-*kT* algorithm, and the asymmetries are calculated relative to the axis of the hard scattered parton. |

Both the Collins and di-hadron asymmetries depend directly on the partonic spin transfer parameter which approaches unity as one moves toward forward scattering in the partonic center of mass, where . Furthermore, transversity remains quite poorly constrained for . To extend the measurements of transversity to the high x region has many important insights:

* one can access the tensor charge  [[[29]](#endnote-29)] a quantity essential to understand the nucleon structure at leading twist and calculable in lattice calculations.
* The difference between the helicity distributions and the transversity distributions for quarks and antiquarks provides a direct, x-dependent, measure of nonzero orbital angular momentum components in the wave function of the proton.
* current transversity extractions seem to indicate that the Soffer bound  is violated, if proven by high statistics data at high-*x* it would have consequences on fundamental assumptions of strong interactions [[[30]](#endnote-30)].

The planned STAR upgrades for the second half of this decade include expansion of the TPC tracking capability by about one half of a unit of pseudorapidity as well as charged-particle tracking capability and hadronic calorimetry to the forward subsystems, spanning the range [[[31]](#endnote-31)]. Tracking upgrades are critically necessary for Collins and di-hadron measurements that require robust charge-sign discrimination. A more thorough discussion of these upgrades and their capabilities is given in Chapter 2.

In Figure 1‑19 we show the expected Collins asymmetries for at and GeV. Jets are required to have a minimum *pT* of 3 GeV/c. The 2008 transversity and Collins fragmentation function parameterization by the Torino group [21] has been inserted into a leading-order PYTHIA simulation using CDF Tune A. Jets are reconstructed utilizing an anti-*kT* algorithm, and the asymmetries are calculated relative to the associated hard-scattered parton. The projections assumed 1 fb-1 of luminosity with 60% beam polarization. Particle kinematics are reconstructed assuming a fast simulation for detector smearing based on a silicon forward tracking system and electromagnetic and hadronic caolorimetry. Asymmetries of nearly 2% are expected for both flavors of pions. In Figure 1‑20 we show a comparison of di-hadron asymmetries at the “detector” level, with the fast simulation detector smearing, to those at the “particle” level, before simulated detector smearing. Based on the simulation, the effects of kinematic smearing to the asymmetries are expected to be quite small. This suggests that within the same subsystem, one can simultaneously measure in a robust fashion the Collins asymmetry within the TMD framework and the di-hadron asymmetry within the collinear framework. These measurements are critical for extending current understanding of transversity and questions concerning TMD evolution, factorization breaking, and universality, as well as longstanding questions about the nature of large inclusive asymmetries seen in *p+p* collisions.

|  |
| --- |
|  |
| Figure 1‑20: Comparison of IFF asymmetries at the “detector” level and at the “particle” level for charged pions produced within . Asymmetries are shown as a function of di-hadron invariant mass, and assuming a parameterization derived from fragmentation function measurements at Belle [20]. The projections assume 1 fb-1 of integrated luminosity, and statistical uncertainties are smaller than the size of the points. |

In Figure 1‑21 we show the expected Sivers asymmetries [[[32]](#endnote-32)] for at 2.8 and GeV. Jets are reconstructed in the same manner as discussed above for the Collins asymmetries, and the Torino parameterization is assumed for the Sivers function [21]. Since the inclusive jet asymmetry provides only a single hard scale, namely, jet *pT*, the twist-3 framework is most naturally suited for theoretical expectation. However, the current estimates give a sense for the size of such effects. One can see that for 1 fb-1 statistics may be sufficient to observe a nonzero asymmetry. However, the effects are expected to be quite small, at an order less than 1%. The magnitude of this projection is qualitatively similar to existing inclusive jet asymmetries at forward pseudorapidity [[[33]](#endnote-33)].

Recent theoretical work [[[34]](#endnote-34)] has found that by taking into account initial-state and final-state interactions between the hard scattered parton and the polarized remnant, extractions of the Sivers function from SIDIS data [15,16] are consistent with existing inclusive jet data from *p+p* scattering [33]. The extracted Sivers functions were used to derive the twist-3 function [[[35]](#endnote-35)] that was then used to compute the corresponding inclusive jet asymmetry for *p+p* scattering. The prediction compares favorable to the measured asymmetry, indicating a process-dependence to the Sivers effect. Due to the small size of the apparent inclusive jet asymmetries more precise measurements are needed.

|  |
| --- |
|  |
| Figure 1‑21: Expected Sivers asymmetries based on the Torino parameterization [21] within a leading-order PYTHIA Monte Carlo for jets produced with and GeV/*c*. The expectations assume 1 fb-1 of integrated luminosity, and statistical uncertainties are smaller than the size of the points. Jets are reconstructed utilizing an anti-*kT* algorithm, and the asymmetries are calculated relative to the axis of the hard scattered parton. |

In addition to the inclusive jet measurements outlined above, di-jet measurement allow further probes of the transverse momentum dependent structure of the nucleon. Here the relative transverse momentum between the jets, *kT*, gives the additional soft scale needed for the TMD framework. In addition, accessing functions like Sivers [32] and Boer-Mulders [[[36]](#endnote-36)] in *p+p* collisions allows one to explore additional asymmetries that may result from the “color-entanglement” in *p+p*, which also leads to the breakdown of factorization theorems [[[37]](#endnote-37)].

### The Helicity Structure of the proton

## The search for exotics in p+p

#### Glueballs at RHIC:

QCD predicts the existence of bound states of gluons with no constituent quarks, glueballs [[[38]](#endnote-38)]. An existence proof and characterization of these compound objects offer unique insight into the strong interaction since the gluon self-interaction is exclusively responsible for the mass of glueballs. The search for these exotic states and their possible role within the family of mesons is a long-standing quest in hadron spectroscopy [[[39]](#endnote-39)]. Glueballs are preferentially produced in gluon-rich processes such as  annihilation [[[40]](#endnote-40), [[41]](#endnote-41). [[42]](#endnote-42)], the radiative decay of *J*/*Ψ-*meson [[[43]](#endnote-43), [[44]](#endnote-44)], and central exclusive production (CEP) [[[45]](#endnote-45), [[46]](#endnote-46), [[47]](#endnote-47), [[48]](#endnote-48), [[49]](#endnote-49), [[50]](#endnote-50)] in . The CEP at high-energies is a process in which glueballs are supposed to be copiously produced. In CEP, two protons are scattered diffractively into the forward direction without exchanging valence quarks through double Pomeron exchange (DPE). The absence of valence quarks in the production process makes CEP a favorable place to look for hadronic production of glueballs. RHIC can be exploited to study the potential for producing such exotic meson states through the glue-rich production mechanisms.

DPE processes create two rapidity gaps between the beam rapidities and the central region. The process is defined as and all of the energy lost by the initial protons during the interaction is used in the production of the central system *MX*. Theoretical predictions of the evolution of the different exchange mechanisms with center of mass energy √s suggest that Reggeon-Reggeon and Reggeon-Pomeron exchange mechanisms are expected to decrease with energy as *s*-1and *s*-0.5while in double Pomeron exchange mechanism, Pomeron-Pomeron remains a constant [[[51]](#endnote-51)]. That implies that to relatively suppress Reggeon contributions in double diffractive processes, the center of collision energy needs to be sufficiently high, where also larger rapidity gaps are expected. At √s = 500 GeV, where the beam rapidity is 6**.**3, ~5 units of symmetric rapidity gaps leave ~2 units of central rapidity region, which is expected to give a good kinematic coverage to reach *MX*~ 3 GeV/*c*2 assuming the central rapidity spans 2log(*MX*/*Mp*). Since the Pomeron is assumed to carry vacuum quantum numbers, Pomeron-Pomeron can only yield states with *IGJPC*= 0+0++ and 0+2++ for the lowest-lying states. Identifying that the leading exchange process is dominated by double Pomerons requires observing suppression of vector and pseudo-vector mesons such as ρ meson in the process, since they cannot be formed from two states with *I*= 0. The energy dependent decrease of ρ production in central productions has been observed by WA92 (√s = 12.6 GeV) and WA102 (√s = 23.8 GeV) [[[52]](#endnote-52)], which experimentally supports that suppression of non-DPE mechanism as center of energy increases in the diffractive processes. But abundant production of the *a1*(1260) measured by WA102 (√s=29.1 GeV) [[[53]](#endnote-53)] calls the hypothesis that the leading contribution in central production at this energy regime is Pomeron-Pomeron in question. Also the angular distribution of some produced mesons at this energy behaves as in photon-photon fusion, which leads to their interpretation as the vectorial interaction of Pomerons, but it also can be attributed to have a significant contribution from Reggeons. At √s = 500 GeV, it is expected that the dominance of the Pomeron-Pomeron process in the central region is more likely to occur. Even though the spin structure of the Pomeron coupling is yet to be fully explored, non-trivial spin effects are expected to be insignificant in the Pomeron dominated inelastic diffractive process at high-energy. Since RHIC is delivering protons with transverse and longitudinal polarization, studying spin dependence in DPE processes will potentially provide an extra constraint in filtering Pomeron induced double diffractive processes.

#### Tagging forward protons with Roman Pots at STAR (Phase II\*):

Although identification of a rapidity gap can be utilized for studying diffractive processes, it is imperative to tag and reconstruct the forward proton to eliminate possible ambiguities of a rapidity gap tag, which can be contaminated by background due to low multiplicity non-diffractive processes. The rapidity gap tag also does not provide information on whether the initial proton remains intact after the collision or is excited into a low-mass state with small energy loss, which could still yield a rapidity gap. Tagging forward protons, i.e., detecting scattered protons in a diffractive process requires reaching inside of the beam pipe since the scattering angles are very small of the order of a few *m*rad and smaller. By detecting the scattered proton in Roman Pots (RPs), one can reconstruct its momentum from the measured positional and directional information of the protons in the given beam optics.

For the initial phase of the new program (Phase I), which probes small-*t* region, the Roman Pots used for the pp2pp experiment have been integrated with STAR detector. They are positioned at 55**.**5 m, 58**.**5 m from the nominal interaction point (IP). The schematic layout of RPs is shown in Figure 1‑22. Each RP contains four planes of silicon strip detectors (SSD) (two vertical and two horizontal) to provide redundancy for the track reconstruction. During RHIC Run-9, 70M of events, including **30M** of elastic events, were successfully taken with the Phase I set-up [[[54]](#endnote-54)].

For Phase II\*, the RP system will be moved to be installed between RHIC DX-D0 magnets, at 15.8 m and 17.6 m from the IP as shown in Figure 1‑22 and Figure 1‑23, extending the acceptance and the reach in *t* for a more optimized setting for diffractive events with larger **|***t***|**. Figure 1‑24 shows the expected *t*-distributions for the scattered protons measured in the RPs in the Phase II\* setups at = 200 GeV. The acceptance in high-*t* region for the phase II\* setup is limited by the aperture of the DX magnet. Since no special accelerator optics is required in the configuration for the Phase II\* set-up, running in parallel with other physics program in STAR is possible, and we will be able to utilize high luminosity in search for rare physics processes.

|  |
| --- |
| :rp.png |
| Figure ‑: The layout of the RPs with the STAR detector (not to scale). The Phase I RPs setup to detect scattered protons with low-*t* are located after two dipole magnets (DX, D0) and three quadruples at 55.5 m and 58.5 m from the interaction point (IP), respectively. For measuring protons with higher-*t* (Phase II\*), sets of RPs will be positioned between DX and D0 magnets, at 15.8 m and 17.6 m from IP. |

In Figure 1‑25, a preliminary measurement of the invariant mass spectrum of the +- pairs produced in the central exclusive process is shown. The data were obtained with the STAR detector at √s = 200 GeV in 4 days running during Run-9. The Roman Pots (Phase I set-up) were used to tag forward protons and the invariant mass of the pion pair was obtained using tracks reconstructed in the TPC. To select CEP events the balance of momenta of the outgoing protons and central +- pair was required.

|  |  |
| --- | --- |
|  | Figure ‑: Design of the new DX-D0 chamber showing the two vertical Roman Pot stations. The installation will be done in 2014. |

|  |  |
| --- | --- |
| ::::::::Downloads:acc.png | Figure ‑: Acceptance in t for Phase II\* setup. The acceptance of protons for both RPs at 15.8 m and 17.6 m are shown in red and the acceptance for the front RP at 15.8m only are shown in blue. The acceptance for Phase I is also shown for comparison. The inset plot shows the distribution of accepted protons in the front RP. The *t*-acceptance reach scales with  so at √s =500 GeV, the maximum reach of |*t*| is 6.25 times larger. |

|  |  |
| --- | --- |
|  |  |
| Figure ‑: Invariant mass distributions for two opposite charged pions in the exclusive central diffraction in at = 200 GeV. The distribution in red is non-exclusive background estimated from events with like-sign charge pion pairs. Errors are statistical only. | Figure ‑: Estimated accepted phase-space distributions of invariant mass *MX* decaying into  +-,+-+-(hatched)and +- (cross-hatched) from 25M DPE events simulated in at √s = 500 GeV with Phase II\* set-up. |

**Central Exclusive Production (CEP) in proton – proton collisions:**

Lattice QCD calculations [[[55]](#endnote-55)] have predicted the lowest-lying scalar glueball state in the mass range of 1500-1700 MeV/*c*2, and tensor and pseudo-scalar glueballs in 2000-2500 MeV/*c*2. Experimentally measured glueball candidates for the scalar glueball states are the *f0****(****1500****)*** and the *f0***(**1710**)** in central production as well as other gluon-rich reactions. The glueballs are expected to be intrinsically unstable and decay in diverse ways, yielding typically two or more mesons. The *f0***(**1710**)** stateis expected todecay into *K*and the *f0***(**1500**)** into  and 4. For the tensor meson sector *IGJPC* **=** 0**+**2**++**, the established (*f2***(**1950**)**) and not-well established states such as *f2***(**1910**)**, *f2***(**2150**)**, have been less explored. The challenge is partly due to a small production cross-section and also not being able to clearly separate Reggeon contribution complicated by nearby mixing and interpretation.

One of the challenges in identifying a glueball state unambiguously lies in difficulties of isolating a glueball state from the conventional meson state that shares the same quantum numbers. To first identify that the diffraction process is dominated by gluon-rich DPE, the leading quantum number of centrally produced system is required to be made of two vacuum quantum numbers. From the DPE process, to filter potential gluon binding processes, kinematic variables can be utilized.

Correlations of transverse momentum of scattered protons in CEP have been suggested as means to discriminate different intrinsic structures of the centrally produced object (“glueball-filter”) [[[56]](#endnote-56)]. A possible dynamics behind the filtering mechanism is that small momentum transfer processes are expected to enhance *gg*kinematic configurations since the gluons can flow directly into the final state in the process.

It is not theoretically well known, how the mixing between glueballs and nearby states will play a role in the dynamics of glueball candidates. The energy regime, where glueball candidates from central production have been identified so far are estimated to be significantly from non-DPE processes. It is imperative that wide kinematic and acceptance coverage to extract information of the production of glueball candidates at an energy regime where double Pomeron exchange is expected to be a dominant process in double diffractive process.

**Data Collection;**

The expected reconstructed kinematic phase-space distributions of centrally produced system decaying into pions and kaons at √s = 500 GeV are shown in Figure 1‑26. The invariant mass range 1-2.5 GeV/c2 is kinematically well accessible in pion and kaon decay channels. At √s = 200 GeV, the coverage for the accepted phase-space will not be significantly suffered since dominant limitation factor for high-*t* coverage is experimental acceptance and particle identification.

With the Phase-II\* in Run-15 we expect to collect a data sample in a wider-*t* range, allowing for much larger statistics as compared to that in Figure 1‑25**.** Thus allowing a detailed study of the structure seen there. It is estimated that with 5 weeks of pp running in Run-15 with integrated luminosity of 40 pb-1 recorded, we can collect > 1.5×10**5** exclusive **+****-** data sample (> 15K in 1< *M****X*** < 2 GeV/*c*2)for analysis. The estimate was done with assumptions *dN/dt* ∝ σ(ππ) and the exclusive data sample collected during Run-9. With the luminosity of L > 10 30 cm-2s-1, the data taking rate for the CEP events is expected to be limited by DAQ, and the assumed rate for the CEP data collection is 200 Hz. Given the larger-*t* range covered by the Phase II\* RPs compared to Run-9 (Phase I), the purity of the CEP trigger will be expected to be much improved due to decrease of elastic backgound. With the improvements we will likely collect O(100K) exclusive CEP samples in the mass region of 1-2 GeV/*c*2 which warrants a sample enables differential spin-parity analysis of the exclusively produced states.

## THE NUCLEUS AS A LABORATORY FOR QCD

Our quest to understand QCD processes in Cold Nuclear Matter (CNM) centers on the following fundamental questions:

* What are the dynamics of partons at very small and very large momentum fraction (x) in nuclei, and at high gluon-density. What are the nonlinear evolution effects (i.e. saturation)?
* What are the pQCD mechanisms that cause energy loss of partons in CNM, and is this intimately related to transverse momentum broadening?
* What are the detailed hadronization mechanisms and time scales and how are they modified in the nuclear environment?

Various aspects of these questions are being attacked by numerous experiments and facilities around the world. Deep inelastic scattering on nuclei addresses many of these questions with results from HERMES at DESY [[[57]](#endnote-57)], CLAS at JLab [[[58]](#endnote-58)], and in the future at the JLab 12 GeV upgrade and eventually an Electron-Ion Collider [[[59]](#endnote-59)]. This program is complemented with hadron-nucleus reactions in fixed target p+A experiments at Fermilab (E772, E886, and soon E906) [[[60]](#endnote-60)] at the CERN-SPS. The combination of RHIC p+Au and LHC p-Pb data provides an unprecedented lever-arm in center-of-mass energy and makes a beam-energy scan at RHIC, modulo surprising discoveries, not the highest priority for upcoming pA runs. One unique property of RHIC to run different beam species on the other hand will be one of the priorities of p+A run in the end of the century.

### PHYSICS OF HIGH GLUON DENSITIES AND LOW-X IN NUCLEI

The main emphasis of the 2015 and later p+A runs is to determine the initial conditions of the heavy ion nucleus before collision. Our current understanding of nuclear parton distribution functions (nPDFs) is still very limited. Figure 1‑27 shows a summary of some of the most recent nPDFs. The central values and their uncertainties for up-valence quarks, up-sea quarks and gluons are shown. The yellow bands indicate regions in *x* where the fits are not constrained by data [[[61]](#endnote-61)]. This plot shows clearly that high precision data over a wide *x-Q2* range are needed. Such data are needed for different nuclei as the A-dependence of nPDFs cannot be predicted from first principles in pQCD.

|  |
| --- |
|  |
| Figure ‑: A summary of some of the most recent nPDFs. The central values and their uncertainties for up valence, sea and gluons are shown. The yellow bands indicate regions in *x* where the fits are not constrained by data. |

Current measurements at RHIC strongly suggest that the suppression of single hadrons [[[62]](#endnote-62),[[63]](#endnote-63)] and back-to-back di-hadron correlations [[[64]](#endnote-64)] in d+Au collisions seen at forward rapidities at RHIC [[[65]](#endnote-65)] can be interpreted as strong hints for the onset of saturation effects. This would go beyond the modification of nPDFs predicted by pQCD fits to the current world data. At this point, though, the interpretation that the onset of saturation effects has be seen, is not unique, for two main reasons.

|  |  |
| --- | --- |
|  | Figure ‑: Kinematic coverage in the *x-Q2* plane for p+A collisions at RHIC, along with previous e+A measurements, the kinematic reach of an electron-ion collider (EIC), and estimates for the saturation scale *Qs* in Au nuclei and protons. Lines are illustrative of the range in *x* and *Q2* covered with hadrons at various rapidities. |

First, as shown in Figure 1‑28, for the kinematic reach of RHIC energies the saturation scale is moderate, on the order of a few GeV2, so measurements sensitive to the saturation scale are by necessity limited to semi-hard processes, and effects due to kinematic limits must be fully addressed.

Second, and more importantly, in measurements to date in d(p)+A collisions both the entrance and exit channels have components that interact strongly, leading to severe complications in the theoretical treatment. In d(p)+A collisions, these complications can be ameliorated by removing the strong interaction from the final state, using photons W+/-, Z0 and Drell-Yan electrons. Beyond this, the possibility of using polarized protons at RHIC to probe saturation phenomena is just beginning to be explored [[[66]](#endnote-66),[[67]](#endnote-67)], utilizing the large transverse single-spin asymmetries seen in p+p collisions at forward rapidity (which do not require a polarized ion beam) to explore the onset of saturation.

The polarized p+Au run in 2015 will be the first step to obtain data addressing the questions listed at the beginning of chapter 1.3. Due to its higher luminosity it will enable STAR to study more luminosity hungry processes. In the following a list of the key measurements for Run-15 are listed, no scan in beam species is proposed to be done in 2015. But our understanding of the initial partonic structure of nuclei would greatly benefit for a scan in beam species in later years.

1. RpA for direct photons in the rapidity range 3<<4:

Direct photons are one of the key channels to separate strong interaction in the entrance and exit channels in d(p)+A collisions, because the have no strong interaction in the final state.

|  |
| --- |
| Plot underway. |
| Figure ‑: RpA for direct photons measured with the FMS and its preshower in the rapidity range 3<<4. The assumed detector performance and cuts applied are the same as for Figure 1‑16. The statistical uncertainties are based on recorded luminosities of 100 pb-1 for p+p and 300 nb-1 for p+Au. |

1. J/Ψ production in ultra-peripheral collisions (UPC) provides like direct photon measurements the unique opportunity if the J/Ψ is detected through its leptonic channel to study only the effects of strong interactions in the initial state. This measurement provides access to the spatial gluon distribution by measuring the distribution of dσ/dt. As follows from the optical analogy, the Fourier-transform of the square root of this distribution is the source distribution of the object probed. In Figure 1‑30 the differential cross-section dσ/dt for - production in UPC is shown, to study the gluon distribution in the gold nucleus, events need to be tagged were the photon is emitted from the proton. The events were generated with the Sartre event generator [[[68]](#endnote-68),[[69]](#endnote-69)], an p+A (e+A) event generator specialized for diffractive exclusive vector meson production based on the bSat dipole model [[[70]](#endnote-70)] and its linearization, the bNonSat model [[[71]](#endnote-71)]. The coherent distribution in Figure 1‑30 can be further used to obtain information about the gluon distribution in impact parameter space through a Fourier transform [[[72]](#endnote-72)].

|  |
| --- |
|  |
| Figure ‑: The cross section as function of –t for J/Ψ production in UPC in p+A collisions. The uncertainties represent the statistics for a recorded luminosity of 300 nb-1 in p+A collisions. The variable -t represents the vector sum of the transverse momenta of the J/Ψ and the outgoing proton, This variable is well suited to suppress events where the “UPC-photon” is emitted by the Au-nucleus. The outgoing proton information is measured in the STAR Roman Pot system for 0.1< tp< 0.2. |

1. Di-hadron correlations are still the golden channel at RHIC to observe saturation. The away-side peak in the di-hadron correlations representsthe back-to-back contribution to the coincidence signal as function of the azimuthal angle difference between the two pions in a p+A collision. It should disappear going from *p*+*p* to d+Au if saturation sets in. A record luminosity of 300 nb-1 in Run-15 would give the unique opportunity to vary the trigger and associated particle *pt*from low to high values and such crossing the saturation boundary as shown in as shown in Figure 1‑28 and reinstate the correlations for central p+A collisions for forward-forward 0’s.
2. Single Transverse Spin Asymmetry in Polarized Proton-Nucleus Collisions: As a result of exciting recent theoretical developments, the scattering of a polarized proton on an unpolarized nuclear target appears to have the potential to extend and deepen our understanding of QCD. In the frame where the nucleus is relativistic, its wave function consists of densely packed quarks and gluons, which constantly split and merge with each other. At high enough energies the density of the gluons is so high that the saturation regime is reached, characterized by strong gluon fields and scattering cross sections close to the unitarity bound. The saturated wave function is often referred to as the Color Glass Condensate (CGC) and is reviewed in detail in [[[73]](#endnote-73)]. The nuclear effects on *AN* may shed important light on the strong interaction dynamics in nuclear collisions. While the theoretical approaches based on CGC physics predict that hadronic *AN* should decrease with increasing size of the nuclear target [[[74]](#endnote-74),[[75]](#endnote-75),[[76]](#endnote-76)], some approaches based on perturbative QCD factorization predict that *AN* would stay approximately the same for all nuclear targets [[[77]](#endnote-77)]. Figure 1‑30 clearly shows that the requested statistics in Run-15 for p+p and p+Au, respectively, will be sufficient to measure transverse spin observables in pA.

|  |
| --- |
|  |
| Figure ‑: The projected statistical and systematic uncertainties for the ratio of ANpA/ANpp measured for 0’s in the STAR FMS for the requested transverse p+p and p+A running. The colored curves follow Eq. 17 in Ref. [51] assuming Qsp = 1 GeV (solid) and Qsp = 0.5 GeV (dotted) with QsA = A1/3 Qsp. |

As shown above hard probes in *p*+A(*d*+A) collisions at RHIC can provide us with very important constraints on the nPDFs, especially at scales where the DGLAP evolution is expected still to be applicable, i.e., at *Q > Qs*. Given the kinematic constraints at RHIC, very forward hadron production measurements (low-*x*) are not well suited to study leading-twist shadowing since the Q2 values are substantially too low. Typically nPDFs are calculated at most down to Q2 ~1.69 GeV2. Of special importance at RHIC will be measurements of correlated charm in *p*+A collisions at mid- or slightly forward rapidities or gamma-jet correlation measurements at forward rapidities (see section 1.3.3), which will help to pin down the nuclear gluon distributions, while Drell-Yan pairs are expected to set further constraints on the nuclear effects for the sea quark distributions. The Drell-Yan process, , plays a special role among interactions with hadron beams. In contrast to hadronic final states, in Drell-Yan scattering the values of *x1, x2*, and *Q2(=M2)* can be reconstructed on an event-by-event basis. In addition, factorization has been proven, rather than just assumed, for Drell-Yan di-lepton production. As such, for many years Drell-Yan cross sections have played a key role to constrain sea quark distributions in nucleon and nuclear PDF fits. (For example, see the discussions in [[[78]](#endnote-78),[[79]](#endnote-79)].)

When measured in the forward direction, Drell-Yan di-lepton production in *p*+A collisions at RHIC can provide access to sea quark distributions in the nucleus at *x <* 0*.*001 (for details see Figure 1‑32). This is nearly an order of magnitude lower *x* than the current nuclear DIS data, and over an order of magnitude lower *x* than the Drell-Yan data that form the primary inputs for EPS09. Furthermore, measurements of the Drell-Yan nuclear dependence at RHIC can also provide significant constraints on the nuclear gluon distribution at very low *x* via evolution [78]. As such, Drell-Yan measurements at RHIC will provide essentially model-independent information about the nuclear modifications of the gluon distribution well into the *x* regime where the *0-0* correlation measurements indicate gluon saturation may be important. It is noted that forward *J/Ψ* production will be measured concurrently with Drell-Yan scattering. *J/Ψ* production in these kinematics is dominated by *gg* fusion, so this will provide complementary information about the gluon density at very low *x*.

|  |  |
| --- | --- |
|  |  |
|  | |

Figure ‑: The *x1-x2* distribution for DY production for 2 bins of the lepton pair mass at √s =200 GeV with the leptons being in the rapidity range 2.5 < *η* < 4.0.

#### Study the capabilities of DY measurement with forward tracking and calorimeter systems

The biggest challenge of DY measurement is to suppress the overwhelming hadronic background. The total DY cross-section is on the order of 10-5­ ~ 10-6 of the hadronic scattering cross-sections, therefore the probability of mis-identifying a hadron track as e+/e- has to be suppressed down to 0.1% with reasonable electron efficiencies. To that end we have studied the combined electron/hadron discriminating power of the proposed forward tracking and calorimeter systems. We found that by applying multivariate analysis techniques to the features of EM/hadronic shower development and momentum measurements we can achieve 200 to 2000 hadron rejection power from 15 GeV to 50 GeV with 80% electron detection efficiency. The hadron rejection power was subsequently parameterized in terms of hadron energy and pseudorapidity and used in the fast simulation to estimate DY signal-to-background ratios. In the following paragraphs we will describe the procedures of our simulation and discuss some of the results.

We have implemented the exact geometry of the forward calorimeter system into STAR simulation framework, the details of the geometry can be found in chapter 2.1. Due to the segmentation of the system into EM and hadronic sections as well as high-granularity EMcal we will be able to measure the shower development in both longitudinal and transverse directions. In practice we have simulated the response of the calorimeter system to single electrons and . To discriminate EM shower against hadronic shower by the calorimeter we used three observables:

1. **Eratio:**

the ratio of a 5x5 EMcal cluster energy to the sum of the energies of the same 5x5 EMcal cluster and the projected 5x5 Hcal cluster.

1. **Swidth:**

the effective EMcal shower width defined as where is the distance of the *i*th tower to the centroid of a 5x5 EMcal cluster, is the energy of that tower. The summation is over the 25 towers in the 5x5 EMcal cluster around the highest tower.

1. **NTratio:**

the number of EM towers with energies above 100MeV divided by the total number of EMcal and Hcal towers above the same threshold. All the towers come from a pre-defined 5x5 EMcal cluster around the highest tower and the corresponding 5x5 Hcal cluster.

Figure 1‑27 shows the distribution of these three variables for 30 GeV electrons and respectively.

|  |  |  |
| --- | --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\Eratio_30GeV.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\Swidth_30GeV.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\NTatio_30GeV.gif |
| Figure ‑: Eratio, Swidth & NTratio distribution for 30 GeV electrons (Signal) and (Background). See text for explanation. | | |

The forward tracker helps rejecting hadrons by measuring total track momentum. The ratio of energy deposit in EMcal to track momentum (E/P ratio) could serve as an additional information in separating e+/- from charged hadrons. The momentum resolution was obtained from a standalone simulation of the forward tracking system and parameterized as a function of energy and pseudorapidity. Figure 1‑28 shows momentum resolution at *η* = 2.5 and 4.0.

|  |  |
| --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\pres_eta2.5.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\pres_eta4.0.gif |
| Figure 1‑34: track momentum resolution of the forward tracking system. | |

Figure 1‑29 shows the E/P ratio for 30 GeV electrons and .

|  |  |
| --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\Epatio_30GeV.gif | Figure ‑: E/P ratio of 30 GeV electrons (blue)  and (red) |

The above four observables were used as inputs to a boosted decision trees (BDT) algorithm. The BDT contains 1000 binary decision trees each has a depth of 4 and corresponds to a particular partition of the 4-dimensional feature space into signal(electron) and background(hadron) regions. They’re trained sequentially using half of the electron/ samples generated. Mis-identified tracks from the previous decision trees were given a higher weight in training the subsequent trees. In the end each decision tree was given an index representing its performance during the training. In the validation stage the decision of track id was made based on the collective response of all of the decision trees, with each of their responses weighted by the performance index. The boosting algorithm takes advantage of using not only the discriminating power of each single feature observables but also the correlations between them. Figure 1‑30 shows the electron/hadron discriminating power vs track energy with 80% electron efficiency.

|  |  |
| --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\eh80eff_fcstrk.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\discrVsEeta.gif |
| Figure ‑: e/h discriminating power from combined forward tracking and calorimeter systems | |

To obtain an estimate of DY signal to background ratio the above discriminating power was further parameterized in terms of pseudorapidity and energy as shown on the right panel of Figure 1‑30. We have generated 4 billion PYTHIA pp events at 200 GeV with *CKIN(3)* = 3 GeV and a forward filter requiring a total > 3 GeV in any of the four jet-patch-like regions in 2.5 < *η* < 4.0. All basic QCD 2->2 scatterings as well as heavy flavor channels were enabled. As a reference we note that 2.5 *pb-1* pAu luminosity is equivalent to 500 *pb-1* pp luminosity, which translates to 240.5 billion pp events with the above setting. At the same time, DY production through *q* annihilations and qg scattering were separately generated and scaled to 500 *pb-1*.

Left panel of Figure 1‑31 shows the yield of track pairs from QCD background sample with the proposed cuts applied accumulatively to illustrate the background reduction process. The final background counts from the 4 billion sample after gamma/neutron removal + track energy cuts + charge sign requirement and e/h discrimination is shown by the green points. The right panel shows the background reduction power after each stage of the cuts.

|  |  |
| --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\4bbkgred.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\4bbkgredpower.gif |
| Figure ‑: QCD background reduction with kinematics cuts and e/h rejections | |

The final background yield was then fit by an exponential and rescaled to 500 *pb-1*. The left panel of Figure 1‑32 shows the normalized background yield together with DY productions. The green band represents the statistical uncertainties of the background yield and its shape. The right panel shows the DY signal to background ratio as a function of pair mass.

|  |  |
| --- | --- |
| C:\Users\admin\Downloads\plots_for_pppA_Loi\bkgrederr_half_4bnopt.gif | C:\Users\admin\Downloads\plots_for_pppA_Loi\rsigbkg_4bnopt.gif |
| Figure ‑: DY signal and background yield from 500 *pb-1* pp200 GeV collisions | |

Finally we note that the current projection of DY signal/background ratio was obtained without any photon conversion background. The lack of information on the exact amount of materials upstream of the calorimeter makes it difficult to estimate the level of conversion background.

#### Direct Photon plus Jet

The analysis of the angular dependence of two-particle correlations in hadronic collisions has proven to be an essential tool for testing the underlying QCD dynamics [[[80]](#endnote-80)]. In forward-forward correlations facing the *p*(*d*) one selects a large-*x* parton in the *p*(*d*) interacting with a low-*x* parton in the nucleus. For *x <* 0*.*01 the low-*x* parton will be back-scattered in the direction of the large-*x* parton. Due to the abundance of gluons at small *x*, the backwards-scattered partons are dominantly gluons, while the large-*x* partons from the *p*(*d*) are dominantly quarks.

Direct photon plus jet (direct γ+jet) events, dominantly produced through the gluon compton scattering process, g+q→γ+q, are sensitive to the gluon densities of the nucleon and nuclei in p+p and p+A collisions. Through measurements of longitudinal double spin asymmetry in polarized p+p collisions and azimuthal correlations in p+A collisions for direct γ+jet production, one can study the gluon helicity density and gluon saturation phenomena at small-x. Unlike di-jet production that is governed by both the Weizsäcker-Williams and dipole gluon densities, direct γ+jet production only accesses the dipole gluon density, which is better understood theoretically [[[81]](#endnote-81)]. On the other hand, direct γ+jet production is experimentally more challenging due to small cross section and large background contribution from di-jet events in which photons from fragmentation or hadron decay could be misidentified as direct photons. We have studied the feasibility to perform direct γ+jet measurements with the upgraded STAR detector in polarized p+p collisions at √s=500 GeV and unpolarized p+p and p+Au collisions at *√sNN*=200 GeV. PYTHIA-8.189 [[[82]](#endnote-82)] is used to produce direct γ+jet and di-jet events. In order to suppress di-jet background, the leading photon and jet are required to be balanced in transverse momentum, and . Both the photon and jet have to be in the forward acceptance with GeV/c in 500 (200) GeV p+p collisions. The photon needs to be isolated from other particle activities by requiring the fraction of electromagnetic energy deposition in the cone of *ΔR*=0.1 around the photon is more than 95% of that in the cone of *ΔR*=0.5. Jets are reconstructed by an anti-*kT* algorithm with *ΔR*=0.5. After applying these selection cuts, the signal-to-background ratio is around 3:1 [[[83]](#endnote-83)]. The expected number of selected direct γ+jet events is around 1.2 million with 500 pb-1 delivered luminosity in polarized p+p collisions at √s=500 GeV. Such a measurement would constrain the gluon helicity density in 0.0003<*x*<0.003 (see Figure 1‑38). The expected number of selected direct γ+jet events is around 100k with 500 pb-1 (2.5pb-1) delivered luminosity in p+p (p+Au) collisions at *√sNN*=200 GeV. This would allow a direct photon-hadron correlation study to examine whether the gluon density in 0.001<*x*<0.005 in the Au nucleus is saturated (see Figure 1‑38).

|  |  |
| --- | --- |
|  |  |
| Figure ‑: Gluon x distributions for direct γ+jet events after selection cuts (see text for details) in p+p collisions at *√s*=500 (left) and 200 (right) GeV, respectively. | |

# STAR Upgrades

## Forward Calorimeter System

The STAR forward upgrade is mainly driven to explore QCD physics in the very high or low region of the Bjorken x. Previous STAR efforts using the FPD and FMS detectors, in particular, the refurbished FMS with pre-shower detector upgrade in Runs 2015-2016, have demonstrated that there are outstanding QCD physics opportunities in the forward region as we have outlined in the previous sections. In order to go much beyond what STAR would achieve with the improved FMS detector, STAR proposes a forward detector upgrade with superior detection capability for neutral pions, photons, electrons, jets and leading hadrons covering a pseudo-rapidity region of 2.5-4.5.

At the core of the forward detector upgrade is the Forward Calorimeter System (FCS). The design of the FCS is driven mainly by detector performance, the integration into the STAR system and the cost optimization. Whenever possible we also minimize the number of mechanical components and the construction and operation resources needed from the collaboration in order to carry out the forward upgrade project under the expected constraints for budget and other resources.

The FCS consists of a Spaghetti ElectroMagnetic Calorimeter (SPACal) followed by a Lead and Scintillating Plate sampling Hadronic Calorimeter (HCal). The SPACal is made of Tungsten powder and scintillating fibers as such it has achieved one of the highest densities and among the most compact calorimeters. The Moliere radius of the SPACal is about 2.3 cm and we have chosen the size of each module to be 2.5x2.5x17 cm3 corresponding to 23X0 in length. The HCal is made of Lead and Scintillator tiles with a tower size of 10x10x81 cm3 corresponding to 4 interaction length. Our goal is to have a fully compensated calorimeter system. The proposed FCS has 120x80 SPACal towers and 30x20 HCal towers covering an area of 3x2 m2. We are currently investigating the possibility to locate the FCS closer to the interaction vertex reducing the number of towers necessary for the same pseudo-rapidity coverage.

|  |  |
| --- | --- |
|  |  |
| Figure ‑: Location of the FCS at the West side of the STAR Detector system and a GEANT model of  the FCS in the STAR simulation software | |

Figure 2‑1 shows the location of the proposed FCS at the West side of the STAR detector system and a schematic description of the FCS in the STAR Monte Carlo simulation software. The read-out for the SPACal will be placed in the front so that there will be no significant dead gaps between the SPACal and the HCal. Wave-length shift slats are used to collect lights from HCAL scintillating plates to be detected by photon sensors at the end of the HCal. Multiple Silicon PMTs will be used to read out each SPACal and HCal module, 4 for SPACal and 8 for HCal, respectively.

The SPACal construction technique using Tungsten powders and scintillating fibers and the compact read-out scheme using SiPMTs have been the subject of a detector R&D project by a team of STAR groups from UCLA, TAMU, PSU, IU and BNL under the support of the BNL/JLab EIC generic detector R&D program. In 2012 we constructed several prototype SPACal modules and carried out a beam test at FNAL to prove the validity of the basic concept for Tungsten powder and scintillating fiber construction technique. In 2013-2014 with additional support from STAR for the calorimeter R&D, we refined the SPACal construction technology and built wedge-shaped SPACal modules for EIC barrel applications and normal SPACal modules for STAR FCS applictions. We also developed a novel construction technique for HCal by stacking Lead and Scintillator plate in-situ. An array of 4x4 prototype HCal modules were constructed at the FNAL testing beam site by students and post-docs just before the test run. We envision that a full HCal detector can be assembled at the STAR experimental hall within a few months during the summer shutdown period.

|  |  |
| --- | --- |
|  | EResolution_nobeamspread.png |
| Figure ‑: Prototype of HCAL calorimeter being assembled at FNAL for the test run. Energy resolution of the FCS for electrons and hadrons measured at test run at FNAL in 2014 | |

Figure 2‑2 shows a newly constructed array of 4x4 HCal modules at the FNAL testing beam facility. The right panel shows the energy resolutions for the FCS SPACal and HCal detectors as a function of the beam energy. SiPMTs were used for the read-out of both calorimeter detectors. The measured energy resolution as a function of beam energy is consistent with our Monte Carlo simulations for the detector performance. The measured values have been used in our physics simulations for the proposed forward detector upgrade. We have established a viable detector construction technology and proved the feasibility of SiPMT read-out scheme for the proposed STAR FCS. The performance of the prototype FCS testing at FNAL in March 2014 demonstrated that the proposed FCS detector will meet the STAR physics requirement.

## FORWARD TRACKING SYSTEM

In addition to the FCS, a Forward Tracking System (FTS) is also under consideration for the STAR forward upgrade project. Such a FTS has to cope with the STAR 0.5 Tesla Solenoid magnet field to discriminate charge sign for transverse asymmetry studies and those of electrons and positrons for Drell-Yan measurements. It needs to find primary vertices for tracks and point them towards the calorimeters in order to suppress pile-up events in the anticipated high luminosity collisions, or to select particles from Lambda decays. It should also help with electron and photon identifications by providing momentum and track veto information. In order to keep multiple scatterings and photon conversion background under control, the material budget of the FTS has to be small. These requirements present a major challenge for detector design in terms of position resolution, fast readout, high efficiency and low material budget.

STAR has considered two possible detector technology choices: the Silicon detector technology and Gas Electron Multiplier (GEM) technology. STAR has gained considerable experience in both technologies from the FGT (Forward GEM Tracker) construction and the Intermediate Silicon Tracker (IST) construction in recent years. Several groups are pursuing GEM-based detector R&D under the auspices of generic EIC R&D program. Further evaluation of the GEM tracker option based on the STAR FGT experience will be needed if STAR will pursue such a technology.

Silicon detectors have been widely used in high-energy experiments for tracking in the forward direction. For example, Silicon strip detectors have been successfully used at many experiments: the Dzero experiment at the Tevatron, CMS and LHCb at the LHC, and PHENIX at the RHIC. More recent designs incorporate hybrid Silicon pixel detectors, which resulted in the improvement of position resolutions and removal of ghost hits, but unfortunately they also significantly increased the cost and material budget. According to preliminary Monte Carlo simulations, charge sign discrimination power and momentum resolution for the FTS in the STAR Solenoid magnet depends mostly on phi resolution, and is insensitive to the r-position resolution. Therefore a Silicon mini-strip detector design would be more appropriate than a pixel design. We are evaluating a design that consists of three to four disks at z locations at about 70 to 140 cm. Each disk has wedges covering the full 2π range in ϕ and 2.5-4 in η. The wedge will use Silicon mini-strip sensors read out from the larger radius of the sensors. Compared to the configuration of reading out from the edges along the radial direction, the material budget in the detector acceptance will be smaller since the frontend readout chips, power and signal buses and cooling lines can be placed outside of the detector acceptance.

STAR will continue to evaluate these technology options for the FTS design. More R&D efforts are needed to demonstrate the technical feasibility of these options through Monte Carlo simulations and detector prototyping. We hope to narrow the choice when we develop the technical proposal for the STAR forward upgrade in the coming a few years.

1. [] H1 Collaboration, F. Aaron et al. Combined measurement and QCD analysis of the inclusive ep scattering cross

   sections at HERA. JHEP, 01:109, 2010. arXiv:0911.0884. [↑](#endnote-ref-1)
2. [] L. Adamczyk et al., Neutral pion cross section and spin asymmetries at intermediate pseudorapidity in polarized

   proton collisions at √s = 200 GeV, Phys. Rev. D **89** (2014) 012001; arXiv:1309.1800 [↑](#endnote-ref-2)
3. [] B. I. Abelev *et al.*, Phys. Rev. Lett. **101**, 222001 (2008), arXiv: 0801.2990 [↑](#endnote-ref-3)
4. [] L. Adamczyk et al.,Transverse Single-Spin Asymmetry and Cross-Section for 0 and  Mesons at Large Feynman-x

   in Polarized p+p Collisions at √s=200 GeV, Phys. Rev. D **86** (2012) 051101; arXiv:1205.6826 [↑](#endnote-ref-4)
5. [] K. Kanazawa, Y. Koike, A. Metz, D. Pitonyak, arXiv:1404.1033. [↑](#endnote-ref-5)
6. [] St. Heppelmann, CIPANP-2012,

   https://indico.triumf.ca/getFile.py/access?contribId=349&sessionId=44&resId=0&materialId=slides&confId=1383 [↑](#endnote-ref-6)
7. [] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. Lett. 101, 222001 (2008). [↑](#endnote-ref-7)
8. [] M. M. Mondal, talk at DIS-2014:

   <http://indico.cern.ch/event/258017/session/6/contribution/216/material/slides/1.pptx> [↑](#endnote-ref-8)
9. [] Z.-B. Kang and J.-W. Qiu, Testing the Time-Reversal Modified Universality of the Sivers Function, Phys. Rev.

   Lett. **103** (2009) 172001, arXiv:0903.3629 [↑](#endnote-ref-9)
10. [] A.Metz and J. Zhou, Transverse spin asymmetries for W-production in proton-proton collisions, Phys. Lett. B **700**

    (2011) 11, arXiv:1006.3097

    M.G. Echevarria, A. Idilbi, Z.-B. Kang and I. Vitev, QCD Evolution of the Sivers Asymmetry, Phys. Rev. D **89**

    (2014) 074013, arXiv:1401.5078 [↑](#endnote-ref-10)
11. [] S. Fazio, talk at DIS-2014, http://indico.cern.ch/event/258017/session/11/contribution/219/material/slides/0.pptx [↑](#endnote-ref-11)
12. [] E.A. Hawker et al., "Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea", Phys. Rev. Lett. 80, 3715 (1998) [↑](#endnote-ref-12)
13. [] J. Ralston and D.Soper, Nucl. Phys. B152, 109 (1979). [↑](#endnote-ref-13)
14. [] R. Jaffe and X. Ji, Nucl. Phys. B375, 527 (1992). [↑](#endnote-ref-14)
15. [] P. Mulders and R. Tangerman, Nucl. Phys. B461, 197 (1996). [↑](#endnote-ref-15)
16. [] J. C. Collins, Nucl. Phys. B396, 161 (1993). [↑](#endnote-ref-16)
17. [] J. C. Collins, S. F. Heppelmann, and G. A. Ladinsky, Nucl. Phys. B420, 565 (1994). [↑](#endnote-ref-17)
18. []A. Airapetian et al. (HERMES Collaboration), Phys. Rev. Lett. 94, 012002 (2005); 103, 152002 (2009); Phys. Lett. B693, 11 (2010). [↑](#endnote-ref-18)
19. [] V. Y. Alexakhin et al. (COMPASS Collaboration), Phys. Rev. Lett. 94, 202002 (2005); E. S. Ageev et al. (COMPASS Collaboration), Nucl. Phys. B765, 31 (2007); M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. B673, 127 (2009); M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. B692, 240 (2010); C. Adolphetal. (COMPASS Collaboration), Phys. Lett. B717, 376 (2012); N. Makke (COMPASS Collaboration), arXiv:1403.4218. [↑](#endnote-ref-19)
20. [] A. Airapetian et al. (HERMES Collaboration), JHEP 0806, 017 (2008). [↑](#endnote-ref-20)
21. [] C. Adolph et al. (COMPASS Collaboration), Phys. Lett. B713, 10 (2012). [↑](#endnote-ref-21)
22. [] R. Seidl et al. (Belle Collaboration), Phys. Rev. Lett 96, 232002 (2006); Phys. Rev. D 86, 039905(E) (2012). [↑](#endnote-ref-22)
23. [] A. Vossen et al. (Belle Collaboration), Phys. Rev. Lett. 107, 072004 (2011). [↑](#endnote-ref-23)
24. [] M. Anselmino et al., Phys. Rev. D 75, 054032 (2007); Nucl. Phys. B, Proc. Suppl. 191, 98 (2009); Phys. Rev. D 87, 094019 (2013). [↑](#endnote-ref-24)
25. [] A. Bacchetta, A. Courtoy, and M. Radici, Phys. Rev. Lett. 107, 012001 (2011). [↑](#endnote-ref-25)
26. [] R. Fatemi, AIP Conf. Proc. 1441, 233 (2012). [↑](#endnote-ref-26)
27. [] A. Vossen, *Il Nuovo Cimento* C35, 59 (2012). [↑](#endnote-ref-27)
28. [] Z.-B. Kang, Phys. Rev. D 83, 036006 (2011). [↑](#endnote-ref-28)
29. [] R. L. Jaffe and X. Ji, Phys. Rev. Lett. 67, 552 (1991); Nucl. Phys. B375, 527 (1992). [↑](#endnote-ref-29)
30. [] J.P. Ralston arXiv:0810.0871 [↑](#endnote-ref-30)
31. [] E. Aschenauer et al. (RHIC Spin Collaboration), arXiv:1304.0079. [↑](#endnote-ref-31)
32. [] D. Sivers, Phys. Rev. D 41, 83 (1990); 43, 261 (1991). [↑](#endnote-ref-32)
33. [] L. C. Bland et al. (ANDY Collaboration), arXiv:1304.1454. [↑](#endnote-ref-33)
34. [] L. Gamberg, Z.-B. Kang, A. Prokudin, Phys. Rev. Lett. 110, 232301 (2013). [↑](#endnote-ref-34)
35. [] A. V. Efremov and O. V. Teryaev, Sov. J. Nucl. Phys. 36, 140 (1982); Phys. Lett. 150B, 383 (1985); J.-W. Qiu and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991); Phys. Rev. D 59, 014004 (1998). [↑](#endnote-ref-35)
36. [] D. Boer and P. J. Mulders, Phys. Rev. D 57, 5780 (1998). [↑](#endnote-ref-36)
37. [] T. Rogers, Phys. Rev. D88, 1, 014002 (2013) [↑](#endnote-ref-37)
38. [] E. Klempt and A. Zaitsev, Phys. Rept. **454 1** (2007) [↑](#endnote-ref-38)
39. [] W. Ochs, J. Phys. **G 40** 043001 (2013) [↑](#endnote-ref-39)
40. [] [Crystal Barrel Collaboration], Phys. Lett. **B 291**, 347 (1992) [↑](#endnote-ref-40)
41. [] [OBELIX Collaboration], Phys. Lett. **B 322**, 431 (1994) [↑](#endnote-ref-41)
42. [] U. Wiedner, [PANDA Collaboration], Prog. Part. Nucl. Phys. **66**, 477 (2011) [↑](#endnote-ref-42)
43. [] [MARK-III Collaboration], Phys. Rev. **D 33**, 1222 (1986), [↑](#endnote-ref-43)
44. [] [BES Collaboration], Phys. Lett. **B 453**, 319 (2004) [↑](#endnote-ref-44)
45. [] M. Albrow, arXiv:1010.0625 (2010) [↑](#endnote-ref-45)
46. [] [AFS Collaboration], Nucl. Phys. B 264, 154 (1986) [↑](#endnote-ref-46)
47. [] [WA91 Collaboration], Phys. Lett. B 353, 589 (1995) [↑](#endnote-ref-47)
48. [] [WA102 Collaboration] Phys. Lett. 453, 316 (1999) [↑](#endnote-ref-48)
49. [] A. Austregesilo [COMPASS Collaboration], arXiv:1402.2170 (2014) [↑](#endnote-ref-49)
50. [] M. Albrow, A. Swiech, M. Zurek [CDF Collaboration] arXiv:1310.3839 (2013) [↑](#endnote-ref-50)
51. [] S.N. Ganguli and D.P. Roy, Phys. Rep. **67**, 201 (1980) [↑](#endnote-ref-51)
52. [] T.A. Armstrong et al., Z. Phys. **C51**, 351 (1991) [↑](#endnote-ref-52)
53. [] A. Kirk, Phys. Lett. **B 489**, 29 (2000) [↑](#endnote-ref-53)
54. [] L. Adamczyk et al., Phys. Lett. **B 719,** 62 (2013) [↑](#endnote-ref-54)
55. [] UKQCD Collaboration, Phy. Rev. **D 82**, 034501 (2010) [↑](#endnote-ref-55)
56. [] F. Close, A. Kirk, Phys. Lett. **B 397**, 333 (1997) [↑](#endnote-ref-56)
57. [] HERMES Collaboration, A. Airapetian et al., Phys. Lett., B577:37–46, 2003. arXiv:hep-ex/0307023

    HERMES Collaboration, A. Airapetian et al., Phys. Lett. B684:114–118, 2010. arXiv:0906.2478 [↑](#endnote-ref-57)
58. [] W. Brooks and H. Hakobyan, Nucl. Phys, A830:361c–368c, 2009. arXiv:0907.4606 [↑](#endnote-ref-58)
59. [] W. Brooks, Physics with nuclei at an Electron Ion Collider. 2010. arXiv:1008.0131. [↑](#endnote-ref-59)
60. [] E866 Collaboration, M. Vasilev et al., Phys. Rev. Lett., 83:2304–2307, 1999. arXiv:hep-ex/9906010 [↑](#endnote-ref-60)
61. [] H. Paukkunen, DIS-2014, http://indico.cern.ch/event/258017/session/1/contribution/222/material/slides/0.pdf [↑](#endnote-ref-61)
62. [] BRAHMS Collaboration, I. Arsene et al., Phys.Rev.Lett. 93, 242303 (2004), nucl-ex/0403005. [↑](#endnote-ref-62)
63. [] STAR Collaboration, J. Adams et al., Phys.Rev.Lett. 97, 152302 (2006), nucl-ex/0602011. [↑](#endnote-ref-63)
64. [] PHENIX Collaboration, A. Adare et al., Phys.Rev.Lett. 107, 172301 (2011), 1105.5112. [↑](#endnote-ref-64)
65. [] J. L. Albacete and C. Marquet, Phys.Rev.Lett. 105, 162301 (2010), 1005.4065. [↑](#endnote-ref-65)
66. [] Z.-B. Kang and F. Yuan, Phys.Rev. D84, 034019 (2011), 1106.1375. [↑](#endnote-ref-66)
67. [] Y.V. Kovchegov and M.D. Sievert, Phys. Rev. D **86**, 034028 (2012), Erratum-ibid. D **86**, 079906 (2012)

    arXiv:1201.5890 [↑](#endnote-ref-67)
68. [] T. Toll and T. Ullrich, arXiv:1307.8059 [hep-ph] (2013). [↑](#endnote-ref-68)
69. [] T. Toll and T. Ullrich, Phys. Rev. C 87, 024913 (2013). [↑](#endnote-ref-69)
70. [] H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016 (2006). [↑](#endnote-ref-70)
71. [] H. Kowalski and D. Teaney, Phys. Rev. D 68, 114005 (2003). [↑](#endnote-ref-71)
72. [] S. Munier, A. M. Stasto and A. H. Mueller, Nucl. Phys. B 603, 427 (2001). [↑](#endnote-ref-72)
73. [] H. Weigert, Prog. Part. Nucl. Phys. **55** (2005) 461.

    E. Iancu and R. Venugopalan, hep-ph/0303204.

    F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60 (2010) 463.

    Y. V. Kovchegov and E. Levin, Quantum Chromodynamics at High Energy. Cambridge University Press, 2012.

    J. Jalilian-Marian and Y. V. Kovchegov, Prog. Part. Nucl. Phys. 56 (2006) 104. [↑](#endnote-ref-73)
74. [] D. Boer, A. Dumitru, and A. Hayashigaki, Phys. Rev. D **74** (2006) 074018.

    D. Boer and A. Dumitru, Phys. Lett. **B556** (2003) 33.

    D. Boer, A. Utermann, and E. Wessels, Phys. Lett. **B671** (2009) 91. [↑](#endnote-ref-74)
75. [] Z.-B. Kang and F. Yuan, Phys. Rev. D **84** (2011) 034019. [↑](#endnote-ref-75)
76. [] Y. V. Kovchegov and M. D. Sievert, Phys. Rev. D **86** (2012) 034028. [↑](#endnote-ref-76)
77. [] J.-W. Qiu, talk at the workshop on “Forward Physics at RHIC”, RIKEN BNL Research Center, BNL, 2012. [↑](#endnote-ref-77)
78. [] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904**, 065 (2009). [↑](#endnote-ref-78)
79. [] H.L. Lai et al., Eur. Phys. J. **C12**, 375 (2000).

    A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. **C4**, 463 (1998). [↑](#endnote-ref-79)
80. [] J. Jalilian-Marian, Prog.Theor.Phys.Suppl. 187 (2011) 123, arXiv:1011.1601 [↑](#endnote-ref-80)
81. [] J. Jalilian-Marian and A. Rezaeian, Phys. Rev. D86, 034016 (2012); A. Rezaeian, Phys. Rev. D86, 094016 (2012). [↑](#endnote-ref-81)
82. [] T. Sjöstrand, S. Mrenna and P. Skands, Comput. Phys. Comm. 178, 852 (2008). [↑](#endnote-ref-82)
83. [] Di-jet production from PYTHIA-8.189 is scaled down due to its overestimation of inclusive π0 yields than those reported by BRAHMS in Phys. Rev. Lett. 98, 252001 (2007) and STAR in Phys. Rev. Lett. 97, 152302 (2006). [↑](#endnote-ref-83)