

**RHIC Beam Use Request**

**For Runs 15 and 16**

**The STAR Collaboration**

**Version 5**

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# Executive Summary

# Highlights from STAR Science Programs:

## Polarized Proton+Proton Data:

### The Proton Helicity Structure:

The STAR spin physics program seeks to advance our understanding of the spin and flavor structure of the proton in terms of its constituent quarks and gluons, exploiting the unique capability of RHIC to provide access to high-energy polarized p+p collisions.  Using longitudinally polarized beams, one can probe the helicity preferences of the gluons and (flavor-separated) quarks and antiquarks, to gain insight in the contribution of each to the total spin of the proton.  With spins transverse to the proton momentum direction, p+p collisions exhibit kinematic and dynamical effects that are directly sensitive to quark transversity and partonic motion within the proton.  This program is complemented by studies of polarized p+p elastic scattering and central exclusive production, in which a far-forward proton is detected intact.

RHIC has completed very successful polarized p+p runs both at *√s* = 200 GeV, √s = 500 GeV, and *√s* = 510 GeV. The STAR recorded luminosity and the average beam polarization as measured by the H-jet polarimeter are summarized in Table 2‑1 for runs since 2009.

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| **Year** | **√s (GeV)** | **Recorded Luminosity for Transverse p+p** | **Recorded Luminosity for Longitudinal p+p** | **<P>** |
| 2009 | 200  500 |  | 25 pb-1  10 pb-1 | 55  39 |
| 2011 | 500 | 25 pb-1 | 12 pb-1 | 53/54 |
| 2012 | 200  510 | 22 pb-1 | 82 pb-1 | 61/58  50/53 |
| 2013 | 510 |  | 300 pb-1 | 50/53 |

Table ‑: The STAR recorded luminosity and the average beam polarization as measured by the H-jet polarimeter.

These data sets formed the basis for papers and new preliminary results, which are highlighted in the following. Since the last PAC the STAR spin-working group published one paper in PRD [[[1]](#endnote-1)] and submitted two to PRL [[[2]](#endnote-2),[[3]](#endnote-3)]. The later two present milestones in our understanding of the proton helicity structure and address how the spin of the proton is distributed among it constituents.

The inaugural run at √s = 500 GeV in 2009 yielded the first but still statistics challenged measurement of the longitudinal single-spin asymmetries *AL* in W+ and W- production and their subsequent calculable leptonic decay [[[4]](#endnote-4)]. The rapid analysis of the 2011 (√s = 500 GeV ) and the high statistics 2012 (√s = 510 GeV) longitudinal polarized p+p data sets yielded the first results for W*±* providing impact on the light sea (anti-)quark polarizations. Figure 2‑1 shows the final result of the longitudinal single-spin asymmetry, *AL*, for W*±* production as a function of lepton pseudorapidity *e*, in comparison to theory predictions. The STAR preliminary *AL* results based on the 2012 data set alone, have been included pQCD-fit by the DSSV group [[[5]](#endnote-5)]. A clear improvement on the determination of the polarization of the light sea quarks was observed. For a shift away from the current best mean value was observed, reflecting that the new STAR data lie above the central curve based on DSSV fits to semi-inclusive and inclusive data. Already, with only the preliminary 2012 STAR data, the new global analysis showed a preference for in the range x > 0.05. New pQCD fits based on the published STAR data are already underway by the DSSV and NNPDF groups.



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| Figure ‑: Longitudinal single-spin asymmetry, *AL*, for *W±* production as a function of lepton pseudorapidity *e*, in comparison to theory predictions. | Figure ‑: Midrapidity (|**| < 0.5, upper panel) and forward rapidity (0.5 < |**| < 1, lower panel) inclusive jet *ALL* vs. parton jet *pT*, compared to predictions from several NLO global analyses. The error bars are statistical. The gray boxes show the size of the systematic uncertainties. |

In 2009, with improved luminosity and polarization, as well as upgraded triggering and data acquisition systems at STAR, the uncertainties on the published inclusive jet *ALL*measurements at √*s* = 200 GeV could be considerably improved. Figure 2‑2 shows the final inclusive jet *ALL* vs. parton jet *pT* at midrapidity (|**| < 0.5, upper panel) and forward rapidity (0.5 < |**| < 1, lower panel), compared to predictions from several NLO global analyses from 2009 data. The error bars are statistical. The gray boxes show the size of the systematic uncertainties. The impact of the new inclusive jet data on the polarized gluon distribution and its integral was studied using the reweighting method developed by the NNPDF group [[[6]](#endnote-6)], which allows to include new experimental data into an existing PDF set without the need to repeat the entire fitting process. The obtained results are shown in Figure 2‑3. The integral of *g(x,Q2=10* GeV2*)* over the range 0.05 < *x* < 0.5 is 0.06 ± 0.18 for the original NNPDF fit and 0.21 ± 0.10 when the fit is reweighted using the STAR jet data. The DSSV group has performed a new global analysis [[[7]](#endnote-7)] including the STAR jet *ALL* results. They find that the integral of *g(x,Q2=10* GeV2*)* over the range *x* > 0.05 is at 90% C.L., consistent with the value STAR finds by reweighting the NNPDF fit. The jet data thus imply a polarization of gluons in the proton at intermediate momentum scales.



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|  | Figure ‑: Gluon polarizations from NNPDF (blue dot-dashed curve, hatched uncertainty band), and from a modified version of NNPDF that we obtain when including the 2006 and 2009 STAR inclusive jet *ALL* results through reweighting (red solid curve and uncertainty band). |

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### The 2+1 Dimensional Structure of the Proton

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 in different processes. In the new theoretical framework of transverse momentum dependent parton distributions (TMDs) we can obtain an image in the transverse as well as 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. First measurements at RHIC have extended the observations from the fixed-target energy range to the collider regime up to the highest center-of-mass energies to date at RHIC. Figure 2‑4 summarizes the measured asymmetries from different experiments as functions of Feynman-*x* (*xF ~ x1-x2*).

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

The surprisingly large asymmetries seen are nearly independent of √*s* over a very broad range. To understand the observed significant 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 correlation, which provides information about the average transverse momentum. STAR has made several important contributions to this program, primarily through study of forward neutral pion production in p+p collisions (see, for example, ref. [1,[[8]](#endnote-8)]). This effort has been extended to include the first measurements at *√s* = 200 GeV of the transverse spin asymmetry *AN* for the *η* meson [[[9]](#endnote-9)]. The Run-11 data taken with transverse polarization at *√s* = 500 GeV have revealed several surprising results. Figure 2‑5 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* and the photon multiplicity in the jet in bins of the jet energy. It can be clearly seen that with increasing number of photons in the electromagnetic jet (increasing jettiness of the event) the asymmetry becomes smaller and smaller. Jets with isolated *0*have the largest asymmetry consistent with the asymmetry in inclusive *0*events, as seen from the right-most panel in Figure 2‑4. 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.

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| 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. |

To further study these effects the transverse single spin asymmetry *AN* of these electromagnetic jets was measured if in addition a correlated away side jet in the rapidity range -1 < ** < 2 was required. Figure 2‑6 shows clearly that for requiring an additional correlated away-side jet the asymmetry for isolated forward 0s becomes smaller. For further details see reference [[[10]](#endnote-10)].

All these observations raise serious questions how much of the large forward *0*asymmetries is caused by 2🡪2 parton scattering processes.

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| 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. |

The Sivers function is one of the transverse momentum dependent parton distribution functions of special interest. It describes the correlation of 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. There is evidence of a quark Sivers effect in semi-inclusive DIS (SIDIS) measurements of the HERMES, COMPASS, and JLab Hall-A experiments [[[11]](#endnote-11)]. An important aspect of the Sivers effect, which has emerged from theory lately, 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 key open questions in hadronic physics (NSAC performance measure HP13) and will provide a direct verification of QCD factorization.



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.

The transverse polarized data taking 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 as, contrary to the longitudinal 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 [[[12]](#endnote-12),[[13]](#endnote-13)]. 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 2‑7 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* due to the limited statistics (25 pb-1) of the Run-11 transverse polarized data set. Details for this analysis can be found in [[[14]](#endnote-14)]. The Run-11 transverse analysis represents an important proof of principle, as the Run-9 W*± AL* measurement was in the longitudinal case. The proposed high statistics run for Run-16 will allow to access the sign change and to constrain the presently unknown sea quark Sivers functions.

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| 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*. | |

### Cold Nuclear Matter

Prompted by the discovery of a long-range correlation in pseudo-rapidity (“ridge”) in high-multiplicity p+p and p+A collisions at the LHC, STAR and PHENIX have been investigating the possibility of such a correlation in d+Au collisions at RHIC. PHENIX has reported an excess correlation when subtracting the per-trigger correlated yields in peripheral d+Au collisions from those measured in central d+Au collisions. Under the assumption that jet-correlated yields have no dependence on the event centrality, such an excess could be interpreted as a “ridge”. The STAR detector has a large pseudo-rapidity coverage ideal for in-depth studies of the features of the correlations in d+Au collisions. In particular, STAR has studied the following aspects: 1) possible biases in the selection of centrality through multiplicity cuts resulting in larger jet-correlated yields in central vs. peripheral collisions; 2) the relative pseudo-rapidity (*Δη*) dependence of any excess correlated yields over a large range of *Δη*; 3) how the correlation depends on the trigger and associated particles being like-sign vs. unlike-sign pairs, and 4) the dependence of an excess in the correlated yields on the charge of the associated particle. We find thatthere is indeed a significant dependence on the associated-particle charge. As seen in the figure, the near-side (*ΔΦ*~0) excess in the correlation at large *Δη* is only prominent when the associated particle is positive, hinting toward a possible effect from the beam nuclei in d+Au collisions.

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|  | Figure ‑: Per-trigger correlated yields of particles for 0-20% central d+Au events, for -4.5<Δη<-2, for positive associated particles (red) and negative associated particles (blue). The trigger particle is from the TPC and the associated particle is from the FTPC in the Au-beam direction. The centrality is determined by the Zero-Degree Calorimeter to minimize any bias from the jets in the events |

# Run-14 Performance Report

# Run-15 BUR request on p+p and p+A collisions

We request 12 weeks of polarized p+p operation at *√s* = 200 GeV in Run-15. The data would be split between longitudinally and transversely polarized data taking at STAR. As the polarization directions at IR-6 and IR-8 are completely independent from each other there is no interference between PHENIX and STAR choosing different polarization directions. Based on the latest guidance from CAD we assume a delivered integrated luminosity of 45 pb-1 for the first 5 weeks and 15 pb-1/week for the later weeks, for a total delivered integrated luminosity of ~150 pb-1 with an average polarization of 60%. With an average data taking efficiency of 0.7 this would result in an integrated recorded luminosity of ~100 pb-1. The running time would be split equally between transverse and longitudinal running. Such a data set would significantly advance the STAR spin physics effort; in particular, our analyses would focus on:

* Increased precision in measurements of the double-spin asymmetry *ALL* in inclusive jet and coincident di-jet production; the impact of such measurements is discussed in section 4.1
* Increased statistics in transversely polarized data together with the qualitatively new measurement capability afforded by equipment installed for Run-15 in the form of the Roman Pot Phase-II\* and the FMS preshower. This will allow us to address the underlying physics causing the large transverse single spin asymmetries *AN* at forward rapidities by measuring less inclusive observables, including IFF, jets and direct photons as discussed in section 4.2

STAR assumes for 2015 a run with 22 cryo-weeks and proposes 5 weeks of transversely polarized p+A collisions, 6 weeks of longitudinally polarized p+p collisions, and 6 weeks of transversely polarized p+p collisions. The following smaller detector upgrades need to be completed for the proposed program:

1. the Roman pot system of pp2pp is moved to a new location in the DX-D0 region (for details see section 6.1)
2. a pre-shower detector is installed in front of the STAR FMS (for details see section 6.2)

## Physics with 200 GeV longitudinally polarized p+p collisions

The final results, obtained in Run-9, on the double-spin asymmetry *ALL* in inclusive jet production at √s = 200 GeV from 20 pb-1 sampled with 58% average beam polarization are shown in Figure 2‑2. The latest *g(x,Q2)* extractions from DSSV and from STAR through the NNPDF reweighting technique make it abundantly clear that the uncertainties on the polarized gluon distribution need to be further decreased in the *x*-range currently already covered by measurements and that measurements are needed to extend to thus far unexplored *x*-range, in particular at low *x*.

Run-15 is an integral part of a three-step plan to further advance our knowledge about the polarized gluon distribution and its integral. The plan follows these steps:  (1) reduce the statistical and systematic uncertainties of the workhorse of the STAR *Δg* program, inclusive jet *ALL*. (2) Make use of correlation measurements such as di-jets and di-hadrons, which give access to the partonic kinematics and thus the functional form of *Δg(x)* (Note: and, where η1,2 represent the pseudorapidities of the two outgoing partons). The functional form of *g(x)* also provides insight in the dynamical origin of gluons inside the proton. First results from di-jets from STAR have been released. (3) Access lower *x* by performing measurements at √*s* = 500 GeV and at large forward rapidity. A first step in this direction has been made in Ref. [1] by measuring *ALL* with the STAR Endcap EM Cal (0.8<**<2.0) for √*s* = 200 GeV (see Fig. 7 in [1]).

A new data set of 50 pb-1 with 60% longitudinal polarization as anticipated for Run-15 will improve the uncertainties by a factor of nearly 2 at high *pT* > 15 GeV/*c* while a smaller improvement by about √2 is still achievable at smaller *pT*, where the measurements will become systematics limited. Doing so will provide significant further constraints on the polarized gluon distribution, especially for large momentum fractions *x*. The anticipated improvement in statistics on *ALL* and the complementarity in kinematics with √s = 510 GeV data is shown in Figure 4‑1. To quantify the impact of these inclusive jet *ALL* data sets on *g(x,Q2)* a pQCD fit in the DSSV framework based on pseudo data of the different data sets has been performed. Figure 4‑2 shows the improvement of the *χ2* profile for the integrated gluon contribution in the *x* region currently probed at RHIC. The current uncertainties for will be reduced by a factor of 2. The √s=510 GeV data sample will extend the *x*-range constrained by data down to *x* ~ 0.02.



Figure 4‑3, Figure 4‑4 and Figure 4‑6 show the existing and projected statistical uncertainties for the di-jet *ALL* as function of di-jet mass for different di-jet combinations. It is clearly visible that the new Run-15 data set will lead to a significant improvement over the preliminary STAR measurements of the di-jet *ALL* at √s = 200 GeV from Run-9 [15].

Figure 4‑5 illustrates nicely how the probed *x1-x2* correlation changes from high to low *x* as function of the rapidity combination of the two jets.

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| Inclusive jets A_LL Runs 12+14 proj |  |
| Figure 4‑1: The expected precision for *ALL* vs. *pT* for inclusive jets at *√s* = 200 GeV p+p collisions after the proposed Run-15 data are combined with the existing Run-9 measurements (brown diamonds).  Also shown are the current Run-9 results (red diamonds) and the expected precision at √*s* = 510 GeV from Run-12 (blue squares), together with model predictions for both energies from GRSV-Std and DSSV 2008. | Figure 4‑2: The improvement of the χ2 profile for the integrated gluon contribution in the *x* region currently probed at RHIC for √*s* = 200 GeV. The different curves represent including different data sets, red including the √*s* = 510 GeV data from Run-12 and Run-13 (red), blue including the expected data from Run-15 (blue) and black represent a fit to all data at once. |

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| Figure ‑: *ALL* di-jet as function of di-jets mass for different di-jet combinations from the Run-9 √*s* = 200 GeV data taking [[[15]](#endnote-15)]. | |

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|  | Figure ‑: Projected statistical uncertainties for *ALL*of di-jets at mid-forward rapidity and into the STAR Endcap (0.8<**<2.0) at √*s* = 510 GeV as function of the di-jet mass for two different di-jet combinations. The delivered luminosity of 500 pb-1 corresponds to the sum of Run-11 to Run-13. |

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| Figure ‑: The probed *x*1-*x*2 correlation for di-jets as function of the rapidity combination of the two jets. |

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| Figure ‑: Projected statistical uncertainties for the di-jett *ALL* as function of di-jets mass for different di-jet rapidity combinations for the upcoming Run-15 √*s* = 200 GeV data taking. The assumed delivered luminosity is 75 pb-1 and an average polarization of 60%. |

Combining the √*s* = 200 GeV di-jet *ALL* results from Run-9 and Run-15 with the results already taken and currently analyzed √*s* = 510 GeV di-jet *ALL* from Run-12 and Run-13 will provide stringent constrains on the functional shape of the gluon distribution as well as on the overall value.

STAR can extend the physics reach of its gluon polarization measurement even further by tapping the low-*x* region accessible with both inclusive *π*0 and di-hadrons (*π*0s) and direct photon *ALL* in the FMS. (Details about direct photon capabilities in the FMS are discussed in sections 4.2, 5.1 and 6.2). Figure 4‑7 shows the projected statistical uncertainties for inclusive *0* in the FMS. The main systematic uncertainties will be the relative luminosity, the ongoing analysis of the Run-12 data reaches in the order of 10-3 or better. This measurement will provide an important first test for the future to measure double spin asymmetries at forward rapidity. Further systematic uncertainties are a scale uncertainty in the order of 6% due to the beam polarization measurements and some point-to-point systematics due to background in the order of a 2-3%.

All these different measurements will have a direct impact on any polarized NLO pQCD global analysis such as DSSV by supplying data in a previously unexplored kinematic region.

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|  | Figure ‑: Projected statistical uncertainties for the *0* double spin asymmetry for an integrated recorded luminosity of 50 pb-1.  The measurement is based on loose *0* cuts (necessary for large *pt*).  This result uses a 35 mR cone for two photon selection.  The trigger from run 12 was FMS Jet Patch 2. It is this that defines the lower *pT* response and can be set to anything we choose. In Run 12 we used a Jet Patch 1 with prescaling to sample the distribution to lower *pt* (~ 1 GeV lower).  The pseudo-rapidy range is the full range of the FMS 2.7<**<4. |

## Physics with 200 GeV transversely polarized p+p collisions

Determining the underlying physics process responsible for the large transverse single spin asymmetries at forward rapidities (see Figure 2‑4) is the new spin puzzle for the 21st century. As discussed earlier the processes deemed to be responsible go beyond the conventional collinear parton picture in the hard processes. The two theoretical formalisms, which can generate sizable SSAs in the QCD framework are: transverse momentum dependent parton distributions and fragmentation functions, which provide the full transverse momentum information and the collinear quark-gluon-quark correlation, which provides the average transverse information. The most prominent mechanisms in these frameworks possibly responsible for the large *AN* are transversity in combination with the Collins fragmentation function or the Sivers distribution function together with transverse momentum dependent fragmentation functions. To disentangle the different subprocesses it is important to make less inclusive measurements. Table 4‑1 identifies observables, which will help to separate the contributions from initial and final states, and will give insight to the transverse spin structure of the proton. Depending the observable is a one-scale process, like most of the processes in p+p collisions; we will probe the transverse spin structure of hadrons through the twist-3 formalism. Only 2-scale processes, like di-jets, W*±*, Z0 and DY, probe directly TMDs.

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| **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.

In the following, the STAR capabilities to measure these different observables in Run-15 will be discussed. With its broad acceptance for charged particles in the TPC, STAR is well positioned to carry out the study of di-hadron correlations within a jet, *i.e.*, at relatively small opening angle, where one works with the transverse momentum *pT* and the invariant mass of the pair, rather than with individual particle *pT*. These correlations can be described in terms of the product of the transversity *h(x)* and the so-called Interference Fragmentation Function, IFF, which is a chiral-odd quantity. Extracting the IFF in polarized *p+p* collisions at high energy is of particular interest as it will constrain *h(x)* at higher values of *x* than competing measurements in semi-inclusive DIS. Recent first results are shown in Figure 4‑7.

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|  | Figure ‑: (top)Preliminary measurements of the transverse single-spin asymmetry *AUT*, as defined in the text, as a function of the invariant mass of the unlike-sign di-pion. The choice of cone cut radius is strongly correlated with the average transverse momentum of the pair, as can be seen in the kinematic plot (bottom). |

The second observable is leading charged pions inside a reconstructed jet. In this case one is looking for correlations between the azimuthal distribution of the pion inside the jet and the spin orientation of the parent proton. Similarly to the IFF case, these correlations are sensitive to the product of transversity *h(x)* and the Collins Fragmentation Function *D(z),* also a chiral odd quantity. Measurements in semi-inclusive deep inelastic and electron-positron scattering have shown *D(z*) to be sizable and increasing with increasing pion momentum fraction *z*. Figure 4‑8 shows a recent measurement of this Collins asymmetry *AN* made using mid-rapidity jets reconstructed at STAR. It was calculated by forming the ratio of the of sum of the *sin(ϕh-ϕS)* weighted events and the sum of the polarization *P* weighted events. Systematic errors were conservatively estimated to be +/-0.023 for the *π*+ and *π* - results independently.

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| RESULTS.gif | Figure ‑: Preliminary results of the Collins moment for leading *π*+ (red) and *π*- (blue) particles within mid-rapidity jets reconstructed by the STAR detector. Statistical errors are shown on data points and the grey shaded band indicates the systematic error bar for *π*+ and *π*- separately. |

Both the IFF and Collins analysis were exploratory measurements made using Run-6 transverse data. Indications of non-zero asymmetries motivated the extended 200 GeV running during Run-12 and are part of the motivation for continued transverse running in Run-15. Accelerator performance and high sampling rates at STAR during the 2012 run resulted in a sampled FOM of ~ 7.74 pb-1 in 5 weeks, compared to the ~2.2 pb-1 of transverse data taken in 2006 used in the STAR analysis, which indicate non-zero asymmetries. Data collected in Run-12 will allow these asymmetries to be measured with higher precision and increased kinematic coverage, see for quantitative projections. These data will also be used to tighten the constraints on the mid-rapidity inclusive jet *AN*, which will dominantly sensitive to the gluon Sivers contribution.

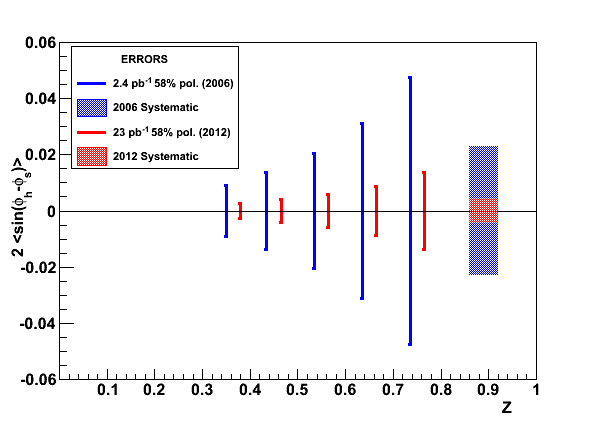
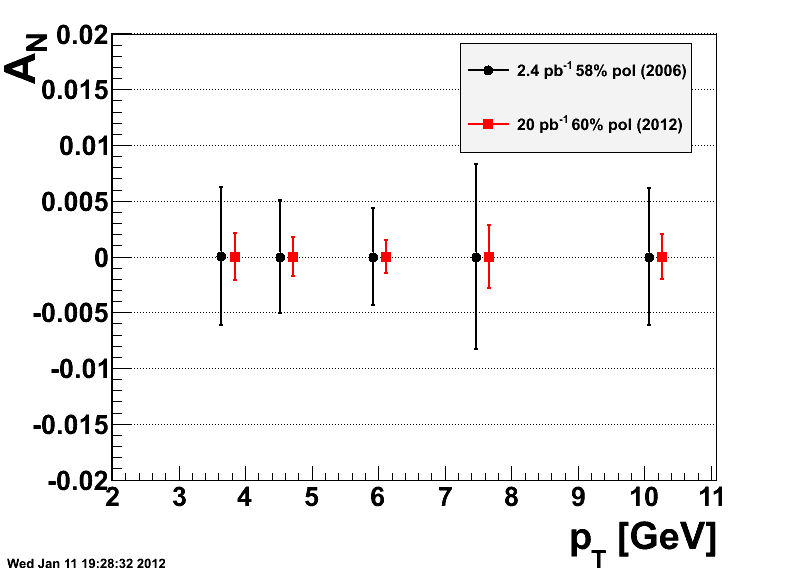
 

Figure ‑: Run-6 errors compared to Run-12 (√s= 200 GeV) projections for the ‘’Collins-jet asymmetry’’ (left) and for the mid-rapidity Interference Fragmentation Function (right).

Following the motivation for transverse polarized physics described in section 2.1.2, a transverse polarized p+p run with an integrated sampled luminosity of 50 pb-1 in Run-15 will allow us to answer several open questions. Does the *pT*-dependence for the different asymmetries shown in Figure 2‑5 and Figure 2‑6 turn over from flat and follow the pQCD expected 1/*pT* behavior? Can the underlying sub-process(es) responsible for the large forward *AN* be identified and delineated?

Figure 4‑10 shows the projected uncertainties for Run-12+Run-15 for IFF for different pion combinations. The uncertainties for the Collins asymmetry as shown in Figure 4‑7 will be reduced by a factor of 1.4 for Run-15 compared to Run-12. These two Run-15 results together with the Run-12 data will provide a powerful data set for global fits to extract transversity and to further constrain the Collins and interference fragmentation functions. The STAR data will be extremely crucial to constrain transversity at high *x* where currently absolutely no data exist. Both data sets are very stringent tests to models trying to explain the transverse physics phenomena in p+p and especially the cause of the large forward pion *AN*.

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|  | Figure ‑: Run-12 + Run-14 projections for the mid-rapidity Interference Fragmentation Function compared to the results based on Run-6. |

Having a first measurement of the direct photons *AN* with the FMS will be extremely crucial to understand the contribution of the Sivers-mechanism to the forward *AN*. For the measurement of the direct photons it will be important to have the pre-shower described in section 6.2 installed in front of the FMS. Direct photons are a rare process. Therefore it is important to suppress background from leptons, hadrons and **0 as much as possible. Figure 4‑11 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 4‑11 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.

The background from charged tracks is removed by matching FMS clusters with hits in the preshower. The position resolution in the FMS is much better than the single tower size, so the preshower granularity is defining the limit on the matching cut. The matching distribution for charged particles exhibits a distinct peak at about half of the width of the preshower channels and it falls off steeply towards larger values, making the veto condition very effective to remove this kind of background from the direct photon signal. Photons from meson decays have to be separated from the direct photon sample by their event topology. For this, a two-fold selection is applied to the clusters in the FMS. Any event that contains two or more clusters above a certain threshold (1.0 GeV) is discarded. The remaining clusters are required to have an energy of 10.0 GeV or more. This initial cut is reducing the photon background more effectively with increasing *pT* (dashed line). Further refinement of this cut will be done with the real data to be able to study the *xF*-dependence of the transverse single-spin asymmetries with good accuracy. For the background asymmetry, an upper limit of measured neutral pion asymmetries was used to estimate the systematic uncertainties (0.0<AN(xF)<0.18). An additional pT-cut of 2.0 GeV is used for the xF-distribution.

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*.

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| Figure ‑: (Left) The number of events at √*s*=200 GeV for a recorded luminosity of 40 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 compared to theoretical predictions based on different assumptions for the Sivers function [[[16]](#endnote-16)]. |

The observation, see section 2.1.2, that the transverse single spin asymmetries drop with increased jettiness of the event, could indicate that the underlying subprocess causing the large transverse single spin asymmetries in the forward direction is of diffractive nature. The roman pot phase II\* upgrade (see section 6.1) will allow to make a measurement of *AN* **0 for single and double diffractive events by tagging one or both protons in the Roman Pots. A discovery of large transverse single spin asymmetries in diffractive processes would open a new avenue to study the nature of pomerons in p+p collisions.

## Physics with Tagged Forward Protons at STAR

There are two main reactions that can be studied with tagged forward protons: polarized proton-proton elastic scattering and Central Exclusive Production (CEP) in double Pomeron exchange (DPE). Since the proton beams at RHIC are polarized we will study the spin dependence of diffraction.

A process of unique interest at RHIC is the central production process through the DPE mechanism *pp**→ pMXp*. The two protons stay intact after the interaction, but they lose momentum to the Pomeron and the Pomeron-Pomeron interaction produces a system *M****X*** at mid-rapidity of the colliding protons.

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

Tagging and measuring the forward protons is important since it removes the ambiguity of a (complementary) rapidity gap tag, which has a background due to the low multiplicity of diffractive events. The momentum balance between the scattered protons and the centrally produced system, exclusivity condition, allows obtaining a relatively background free data sample, like the one obtained in Run-9 at √s = 200 GeV, for which the statistics of the data sample was limited because of the luminosity and the *t*-range for that run.

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| **::::::::Downloads:acc.png** | Figure ‑ : Acceptance in |*t|* for Phase-II\* setup. The acceptance 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. |

In Figure 4‑13 a preliminary measurement of the invariant mass spectrum of the ********pairs produced in the exclusive process *p+p -> p+MX+p* is shown. The data were obtained with the STAR detector at RHIC at √*s* = 200 GeV in 4 days running during Run-9. The Roman Pots were used to tag forward protons and the invariant mass of the pion pair was obtained using tracks reconstructed in the STAR Time Projection Chamber (TPC). To select CEP events the balance of momenta of the outgoing protons and central ******** pair was required.

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|  | Figure ‑: Invariant mass distributions for two opposite charged pions in the exclusive central diffraction in p+p -> p+ MX(-)+ p at *√s* = 200 GeV. The distribution in red is non-exclusive background estimated from events with like-sign charge pion pairs. Errors are statistical only. |

One of the interesting physics topics that can be explored at RHIC is a glueball search [[[17]](#endnote-17)] in the Double Pomeron Exchange (DPE) process. Because of the constraints provided by the double Pomeron interaction, the glueballs, and other states coupling preferentially to gluons, are expected to be produced with much reduced backgrounds compared to standard hadronic production processes.

Two of the gluons in the DPE process, could merge into a mesonic bound state without a constituent quark, a glueball in the central production *p+p* → *p+M****X+****p*. The lattice QCD calculations predict the lowest-lying scalar glueball state will have a mass in the range 1500-2000 MeV/*c***2**, with tensor and pseudoscalar glueballs in the range 2000-2500 MeV/*c***2** [[[18]](#endnote-18)]. Experimentally measured candidates for the scalar glueball states are the *f****0***(1500) and the *f****0***(1710) in central production as well as other gluon-rich reactions such as *p‾p* annihilation, and radiative *J* decay. The glueballs are expected to be intrinsically unstable and decay in diverse ways, yielding typically two or more mesons.

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 4‑13. Thus allowing a detailed study of the structure seen there.

­Simulations indicate that during 5 weeks of pp running in Run-15 (40 pb-1) one can collect 1.5×10**5** exclusive ****+******-** data sample (15K in 1< *M****X*** < 2 GeV/*c*2)for analysis, estimated from the exclusive data sample collected during Run-9. The expected rate assumes 200 Hz DAQ rate for the physics.

#### Elastic scattering at medium |t|

Elastic *pp* (and *p*‾*p*) scattering is a paradigm in the study of the diffraction process at the highest available energies. The special role of the elastic channel, contributing about 20% of the total cross section, can be interpreted in terms of the optical theorem, as the shadow of many inelastic channels, open at high energies: in this respect the elastic amplitude is considered to be mainly imaginary and helicity-conserving. This is reflected in the phenomenological features of a simple Pomeron Regge-exchange, with vanishing spin-flip, which implies a decrease of polar­ization asymmetries as energy increases.

Almost the entire energy range of this proposal has been inaccessible to proton-proton scattering in the past. A measurement of the total cross section, *****tot*** and spin dependence of the elastic scattering in the *t*-range [0.02, 0.12] will be studied.

## Physics with transversely polarized p+A collisions

### Unpolarized observables:

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 addressed by numerous experiments and facilities around the world. Deep inelastic scattering on nuclei addresses many of these questions with results from HERMES at DESY [[[19]](#endnote-19)], CLAS at JLab [[[20]](#endnote-20)], and in the future at the JLab 12 GeV upgrade and eventually an Electron-Ion Collider [[[21]](#endnote-21)]. This program is complemented with hadron-nucleus reactions in fixed target p+A experiments at Fermilab (E772, E886, and soon E906) [[[22]](#endnote-22)] at the CERN-SPS.

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|  | 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. |

Current measurements at RHIC of the suppression of single hadrons [[[23]](#endnote-23),[[24]](#endnote-24)] and back-to-back di-hadron correlations [[[25]](#endnote-25)] in d+Au collisions have been interpreted as strong hints that the saturation scale, and the onset of saturation effects are accessible at forward rapidities at RHIC [[[26]](#endnote-26)]. At this point, though, these interpretations are not unique, for two main reasons.

First, as shown in Figure 4‑14 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. To some level this can be addressed at the LHC, where the larger energies allow for measurements deeper into the saturation regime, especially at forward rapidities. First measurements have been made at mid-rapidity by ALICE [[[27]](#endnote-27)], which correspond approximately to *y*=3-4 at RHIC. This measurement shows no suppression of single hadrons for *pT* > 2 GeV/c, as predicted by saturation models [[[28]](#endnote-28),[[29]](#endnote-29)], however, alternative models also predict this feature of the data [[[30]](#endnote-30)]. Key tests at the LHC will come at more forward rapidities, where saturation effects are expected to be stronger and distinct from other descriptions [27,28].

Second, and more importantly, in measurements to date in p+A collisions both the entrance and exit channels have components that interact strongly, leading to severe complications in the theoretical treatment. In p+A collisions, these complications can be ameliorated by removing the strong interaction from the final state, using photons and Drell-Yan electrons. Beyond this, the possibility of using polarized protons at RHIC to probe saturation phenomena is just beginning to be explored [[[31]](#endnote-31)], 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.

Observables sensitive to parton saturation: Till today the golden channel at RHIC to observe strong hints of saturation are di-hadron correlations. The STAR di-hadron correlation results from Run-8 are shown in Figure 4‑15, it shows the (efficiency uncorrected) probability to find an associated 0 given a trigger 0, both in the forward region covered by STAR’s Forward Meson Spectrometer (FMS). Shown is the coincidence signal versus azimuthal angle difference between the two pions in p+pcollisions (left) compared to peripheral (center) and central d+Au collisions (right) [[[32]](#endnote-32)]. Thetrigger and associated *pT* ranges are indicated in the figure. All the distributions present two signalcomponents, surmounting a constant background representing the underlying event contribution(larger in *d*+Au). The near-side peak represents the contribution from pairs of pions belonging tothe same jet. It is not expected to be affected by saturation effects, therefore it is a useful tool tocheck the effective amount of broadening in the away-side peak. This away-side peak representsthe back-to-back contribution to the coincidence probability, which should disappear in going from *p*+*p* to d+Au if saturation sets in. The data show that the width of the near-side peak remains nearly unchanged from p+pto d+Au, and particularly from peripheral to central *d*+Au collisions. Central d+Au collisions show a substantially reduced away side peak that is significantly broadened. Shown in the right plot of Figure 4‑15 is a comparison with theoretical expectations using the CGC framework. The calculation uses a fixed saturation scale *Qs* and considers valence quarks in the deuteron scattering off low-*x* gluons in the nucleus with impact parameter *b* = 0 [[[33]](#endnote-33),[[34]](#endnote-34)].

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| Figure ‑: Uncorrected coincidence signal versus azimuthal angle difference between two forward neutral pions in p+pcollisions (left) compared to peripheral (center) and central *d*+Au collisions (right) [31]. Data are shown with statistical errors and fit with a constant plus two Gaussian functions (in red). CGC expectations [31,32] have been superimposed (in blue) on the data for central *d*+Au collisions. |

These data have been obtained from a sampled luminosity of 44 nb-1. For an upcoming p+Au Run at RHIC the projection is 175 nb-1/week after startup of the machine assuming a data taking efficiency of 70% and a run length of 5 weeks STAR could record 300 nb-1. This 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 Figure 4‑14 and reinstate the correlations for central p+A collisions for forward-forward 0’s (see Figure 4‑15 right plot). At forward rapidities  cross section falls with *1/pT6*so that to obtain the same statistical accuracy for *pTtrig>3* GeV a factor 11 in recorded luminosity would be needed. The requested 300 nb-1 would give a factor of 6 increase in sampled luminosity, which together with the improved performance of the FMS and the STAR triggering, should make it possible to study the di-hadron correlations also at higher *pT* and such crossing the the saturation boundary. To conclude the investigation the suppression of di-hadrons at forward rapidities at RHIC are a clear sign of saturation, a high-statistics *A*-scan will be needed in the future.

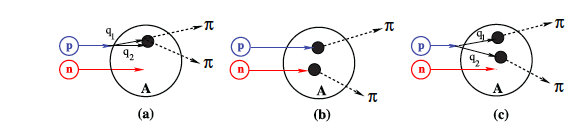


Figure ‑: Contributions to two-pion production in d+A collisions through the double-interaction mechanism [[[35]](#endnote-35)].

Studying di-hadron correlations in p+A collisions instead of d+A collisions has also the advantage that certain alternative interpretations can be ruled out. In reference [33], the authors point out that the contributions from double-parton interactions to the cross sections for d+A ➝ **0**0X are not negligible. This mechanism is illustrated in Figure 4‑16. They find that such contributions become important at large forward rapidities, and especially in the case for d+A scattering. Whether or not this mechanism provides an alternative explanation of the suppression of the away-side peak in **0-**0is not settled. However, this new insight provides a strong argument for performing the proposed correlation studies in p+A, and not in d+A collisions. In addition, p+A collisions will facilitate cleaner centrality selections than possible in d+A, thus improving studies of the impact parameter dependence of nuclear and saturation effects.

The higher luminosity in the upcoming 2015 p+A run will also enable to study more luminosity hungry processes, i.e. direct photon, photon – jet, photon - hadron correlations.

#### The gluon parton distribution function in the nuclear medium:

The main emphasis of the 2015 and later p+A runs is to determine the initial conditions of the heavy ion nucleus before collision. Figure 4‑17 [[[36]](#endnote-36)] illustrates that our current understanding of nuclear parton distribution functions (nPDFs) is still very limited. The need to improve our knowledge on nPDFs is manifested in the NSAC performance Milestone DM18 “Determine gluon densities at low x in cold nuclei via p+Au or d+Au collisions”

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| 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. |

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.

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. Figure 4‑18 shows the RpA for direct photons in the rapidity range 3<**<4 using the FMS and its pre-shower following an analysis as discussed in section 4.2.

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|  | 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 4‑11. The statistical uncertainties are based on recorded luminosities of  100 pb-1 for p+p and 300 nb-1 for p+Au.  The systematic uncertainties are due to the remaining backgrounds (see Figure 4‑11 (left)). |

*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. To study the gluon distribution in the gold nucleus, events need to be tagged were the photon is emitted from the proton. To study STARs capabilities for such a measurement events were generated with the Sartre event generator [[[37]](#endnote-37),[[38]](#endnote-38)], an p+A (e+A) event generator specialized for diffractive exclusive vector meson production based on the bSat dipole model [[[39]](#endnote-39)] and its linearization, the bNonSat model [[[40]](#endnote-40)]. In Figure 4‑19 the differential cross-section *d/dt* for *J/Ψ*-production in UPC is shown before and after kinematic cuts on the J/Ψ and outgoing proton kinematics. To ensure coherent scattering the Au-breakup is vetoed using the ZDCs. To select events where the “UPC-photon is generated from the proton (blue points) instead of the Au-nucleus (red points), the *J/Ψ*-rapidity is required to be 0< ** < 3.5 and that the *pt* of the J/Ψ and the *pT* of the proton as measured in the STAR roman pot system balance themselves. The coherent distribution in Figure 4‑19 can be further used to obtain information about the gluon distribution in impact parameter space through a Fourier transform [[[41]](#endnote-41)].

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| Figure ‑: (left) 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. No cuts on the J/Ψ kinematics or the outgoing proton kinematics have been applied. The red points are for the case that the UPC-photon is generated by the Au and for blue by the proton.  (right) 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< |*t*p|< 0.2. | |

#### Cold nuclear effect on open heavy flavor and heavy quarkonia production:

The 200GeV p+p beam request is to set the baseline reference for heavy ion measurements, particularly driven by the precision for the D0 *RAA* measurements. We will make use of both untriggered data (minimum bias triggers) for precision D0 spectrum measurement at low pT and triggered data to extend the pT reach up to ~ 10GeV/c. Therefore we request 500M p+p minimum bias events with |Vz|<5 cm to allow a first RAA assessment with reasonable precision. The fraction of events with real vertices within |Vz|<5 cm using an online 5 cm cut is about 40% due to the VPD Vz resolution in p+p collisions with the software slewing correction. Therefore to record this data set needs about a 12-week beam time with 400Hz DAQ rate and 72 DAQ hours with HFT per week.

The precision of high pT heavy flavor hadron spectra can be improved by utilizing the EMCal higher tower (HT) triggered data set to trigger on one hadron leg and to sample the full luminosity. HT triggered data has been successfully used to measure the high *pT KS* and ** yield in p+p collisions to improve the baseline precision for RAA calculations [[[42]](#endnote-42)]. Figure 4‑20 left plot shows the trigger efficiency for charged pions with two different HT thresholds from 200GeV p+p in Run-6. This has been vetted using large minimum bias sample data. We will apply the same technique to measure the D-meson production with triggering on one charged daughter leg. At high pT, the combinatorial background in the D-meson reconstruction in p+p collisions is small. To maximize the sampled luminosity, we will not be constrained by the HFT acceptance for this measurement. In a 12-week p+p 200GeV run in Run-15, the total sampled luminosity within |Vz|<30cm with affordable bandwidth rate (BHT0\*VPDMB with no prescale) and also considering the VPD minimum bias triggering efficiency and the vertex selection fraction is about 8 pb-1. Figure 4‑20 right plot shows relative errors of D0 raw yields reconstructed in 100M 0-10% central Au+Au events, 500M p+p MB events and 8 pb-1 sampled luminosity events in p+p with HT0 triggers. The triggered sample from p+p collisions will allow a comparable precision as central Au+Au collisions up to 10 GeV/*c*. In order to reach comparable precision at low *pT* region as in Au+Au collisions requested above, we need about 2B minimum bias p+p events, which will require multiple years of 200GeV p+p collisions.

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| Figure ‑: (Left) Barrel EMC trigger efficiency for charged pions with two different HT thresholds obtained from 2006 analysis [11]. (Right) Projected relative statistical uncertainties for 100M 0-10% central Au+Au events, 500M p+p minimum bias events, and 8 pb-1 sampled luminosity in p+p 200 GeV events with the HT0 (ET > 2.6GeV) trigger. | |

#### p+Au run request:

To understand the cold nuclear matter (CNM) effect on the charmed meson production, we request to take 5 weeks of p+Au collisions at 200 GeV to collect 300M good minimum bias events and sample 40 nb-1 luminosity within |*Vz*|<5 cm. The request datasets are determined to have comparable statistics for the nuclear modification factor measurement as that from the Au+Au 200 GeV dataset collected in Run-14 and the p+p 200 GeV dataset requested above for Run-15. The p+Au request in Run-15 will be a starting point to provide a good precision measurement of the inclusive charmed hadron spectrum.

Figure 4‑20 right plot also includes the statistical error projection from 300M minimum bias p+Au collisions at 200 GeV. It provides comparable precision with 500M p+p reference data to allow the first assessment on the CNM effects on the charmed meson production.

The cold nuclear matter effects on heavy quarkonia production are critical in understanding the hot and dense medium effect of heavy quarkonia production in Au+Au collisions. It has long been a hot topic for discussion [[[43]](#endnote-43)]. With the newly installed MTD, STAR will be able to sample the full luminosity with the di-muon trigger leading to high precision measurements of J/ψ🡪µ+µ- at low pT. For *pT* = 0 – 4 GeV/c, the statistical uncertainty of the J/ψ🡪µ+µ- RAA measurements will be about 10% with 300 nb-1 p+Au collisions and 90 pb-1 p+p collisions sampled by di-muon trigger. For *pT* = 4 – 8 GeV/c, the statistical uncertainty of the J/ψ🡪e+e-. RAA measurements will be about 5% with 50 nb-1 p+Au collisions and 10 pb-1 p+p collision sampled by HT1 (*ET* > 3.5 GeV) trigger in |*Vz*| < 30cm. For *pT* = 8 – 10 GeV/c, the statistical uncertainty of the J/ψ🡪e+e- RAA measurements will be about 15% with 300 nb-1 p+Au collisions and 90 pb-1 p+p collision sampled by HT2 (*ET* > 5.4 GeV) trigger.

#### The ridge in p+A and d+A collisions at RHIC:

In p+Pb collisions at the LHC, an unambiguous two-particle correlation is observed at large pseudorapidity ** and small azimuthal difference **. This is conventionally called the ridge. There are two leading theoretical explanations. One is the color glass condensate where small-x gluons are saturated below the saturation scale of *Qs* in transverse momentum. At transverse momentum ~*Qs*, two-gluon production is enhanced at small ** over a large range in **. The other is hydrodynamic expansion in response to initial interaction geometry fluctuations. The anisotropy in final-state azimuthal distribution can be as large as 10% to explain the LHC ridge observation.

The two physics mechanisms likely give difference predictions to the collision energy dependence of the ridge. It is therefore important to measure the ridge or the lack thereof at RHIC energies. STAR has analyzed the Run-3 d+Au data of approximately 10 million minimum bias events. Long-range near-side correlations (ridge) are observed in the TPC (**~1.5) and FTPC (**~3). The observed correlations have strong dependence on the particle charges. This suggests physics mechanisms other than anisotropic flow. In order to unravel the underlying physics mechanisms, detailed studies of the long-range correlations with much greater statistics are needed.

The long-range correlations in FTPC acceptance are dominated by positive associated particles, but no like- and unlike-sign difference is observed, while a difference between like- and unlike-sign correlations is observed at large ** in the TPC acceptance. We estimate the required integrated luminosity to observe a like- and unlike-sign difference in the FTPC assuming the difference is 20%. Our current measured magnitude of the long-range correlation in the FTPC is *d2N/dd* ~ 0.001 with an error of 50%. In order to measure a 20% difference with an accuracy of 5%, we need a factor of 100 increase in statistics. The current data are for top 20% centrality. We would like to do the measurement for the top 5% d+Au, i.e. x4 increase in luminosity. In addition, the current data use 1<*pT*<3 GeV/c for both the trigger and associated particles. One would like to make the measurements for higher *pT*, say *pT*>2 GeV/c for both the trigger and associated particles. This would require a 100 increase in statistics. This would require a total 400 billion min-bias events. Taking p+Au total cross-section of 2 barn, this would correspond to an integrated luminosity of 200 nb-1.

#### Cronin effect and strangeness enhancement in small-size systems:

The reason for requesting *p*+Au collisions is to study the particle type dependence of the Cronin effect, and strangeness enhancement in small-size systems. From experiences in Run-8 *d*+Au collisions, the study of particle type dependence of the Cronin effect at intermediate pT requires more statistics compared to that to study the strangeness enhancement. Therefore we estimate the required statistics based on the measured RdAu from Run-8 *d*+Au 200 GeV collisions. The collected statistics in Run-8 is about 70M minimum bias events. After the event selection 30M events remain.

In the light flavor physics working group, one key study is to see whether there is a particle species dependence or baryon-meson dependence of the Cronin effect by comparing the RdAu of φ meson with other hadrons. The measured RdAu for KS0, φ mesons and Λ hyperons in 0-20% central collisions from Run-8 is shown in Figure 4‑21.

One can see a clear separation between KS0 and Λ hyperons at intermediate pT. But for φ mesons the result is not as clear. The large uncertainties for the φ meson RdAu are mainly due to a poor p+p reference sample (only 6.5M p+p non-single diffractive events from the year 2002 have been used). The uncertainties for the p+p reference could be controlled within ~5% at intermediate pT (2-4 GeV/c) with about 0.5B events from Run-9 and Run-12. If we assume φ mesons RdAu is close to Λ hyperons at around 3 GeV/c, RdAu (φ) /RdAu (KS0) should be about 1.6. Considering that the ratio RdAu (φ) /RdAu (KS0) should decrease with the number of participant nucleons, the RdAu (φ) /RdAu (KS0) ratio should be about 1.3 in *p*+Au collisions at the same centrality. To have a 3-sigma significance, we need to control the relative uncertainty on RdAu (φ) /RdAu (KS0) within 10% at pT around 3 GeV/c. In Run-8 *d*+Au 0-20% centrality, the relative uncertainty on φ meson raw yields at 3-3.5 GeV/c is about 8.3%. We need to control the error bar within 6% to make the uncertainty of RdAu (φ) /RdAu (KS0) within 10%. Therefore, a factor of 2 more statistics is needed compared to Run-8 *d*+Au collisions. Considering that φ meson yields in *p*+Au collisions are about a half of those in *d*+Au collisions, we need about 7022 = 280M minimum bias *p*+Au events to make a good measurement.

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| figrdauallrun8 | Figure ‑: RdAu for KS0, φ mesons and Λ hyperons in 0-20% *d*+Au central collisions from Run-8. |

### Polarised observables

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 [[[44]](#endnote-44)].

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|  | Figure ‑: Quark SSA from Eq. (81) in [[[45]](#endnote-45)] plotted as a function of *kT* for different values of the target radius: R = 1 fm (blue curve), R = 1.4 fm (red curve), and R = 2 fm (gold curve) for  = 0.7. |

Scattering a polarized probe on this saturated nuclear wave function may provide a unique way of probing the gluon and quark transverse momentum distributions (TMDs). In particular, the single transverse spin asymmetry *AN* may provide access to the elusive nuclear Weizsaecker-Williams (WW) gluon distribution function [[[46]](#endnote-46)], which is a solid prediction of the CGC formalism [[[47]](#endnote-47)] but is very difficult to measure experimentally. 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 [[[48]](#endnote-48),[[49]](#endnote-49),[[50]](#endnote-50)] (see Figure 4‑22), some approaches based on perturbative QCD factorization predict that *AN* would stay approximately the same for all nuclear targets [[[51]](#endnote-51)]. The asymmetry *AN* for prompt photons is also important to measure. The contribution to the photon *AN* from the Sivers effect [[[52]](#endnote-52)] is expected to be non-zero, while the contributions of the Collins effect [[[53]](#endnote-53)] and of the CGC-specific odderon-mediated contributions [[[54]](#endnote-54)] to the photon *AN* are expected to be suppressed [40,[[55]](#endnote-55)]. Clearly experimental data on polarized proton-nucleus collisions is desperately needed in order to distinguish different mechanisms for generating the single spin asymmetry *AN* in nuclear and hadronic collisions.

Figure 4‑23 clearly shows that the requested statistics of 40 pb-1 and 300 nb-1 for p+p and p+Au, respectively, are sufficient to measure transverse spin observables in p+A collisions. The curves represent the theoretical prediction [41] for the suppression of SSA in the nuclear medium. This measurement will not only allow to get a handle on the saturation scale, but will also help to understand the underlying sub-process leading the large forward SSA in transverse polarized p+p. To distinguish further between the different theoretical models predicting a suppression of *AN* in p+A, it will be also essential to measure *AN* fordirect photons. More details about the pre-shower in front of the FMS and its performance as well as the capabilities to measure *AN* for direct photons can be found in section 2.1.2.

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|  | 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. [41] assuming *Qsp* = 1 GeV (solid) and *Qsp* = 0.5 GeV (dotted) with *QsA* = *A1/3 Qsp*. |

Access to the generalized parton distribution Eg: “How are the quarks and gluons, and their spins distributed in space and momentum inside the nucleon? What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?” These are key questions, which need to be answered to understand overall nucleon properties like the spin structure of the proton. The formalism of generalized parton distributions (GPDs) provide till today the only theoretical framework, which allows some answers to the above questions [[[56]](#endnote-56)]. The experimentally best way to constrain GPDs is through exclusive reactions in DIS, i.e., deeply virtual Compton scattering. RHIC with its possibility to collide transversely polarized protons with heavy nuclei has world-wide the unique opportunity to measure AN for exclusive J/ψ in ultra-peripheral p↑+Au collisions (UPC) [58[[57]](#endnote-57)]. A non-zero asymmetry would be the first signature of a non-zero GPD E for gluons, which is sensitive to spin-orbit correlations and is intimately connected with the orbital angular momentum carried by partons in the nucleon and thus with the proton spin puzzle. To measure AN for exclusive J/ψ in ultra-peripheral p↑+Au collisions provides an advantage in rate as the emission of the virtual photon from the gold nucleus is enhanced by *Z2* compared to ultra-peripheral p↑+p collisions. Detecting the scattered polarized proton in “Roman Pots” and vetoing the break-up of the gold nucleus can ensure exclusivity of the process. The event generator SATRE [[[58]](#endnote-58)], which also describes well the STAR results for r0 results for UPC in AuAu collisions, has been used to simulate exclusive J/ψ -production in p↑+Au UPC (see Figure 4‑24 for the two contributing processes).

To select the J/ψ with the photon generated from the Au-beam cuts in the RP as installed for PHASE-II\* need to be applied, at 200 GeV the RP PHASE-II\* system has a *t*-acceptance from -0.016 GeV2 to -0.2 GeV2.

Figure 4‑25 shows the generated *t*-spectra for the beam generating the photon (left) and the target beam (right). Requiring no hit in the RP phasing the Au-beam (-*t* > -0.016 GeV2) or in the ZDC and a hit in the RP phasing the proton beam (-0.016 > -*t* > -0.2 GeV2) together with the J/ψ decay electrons in the BEMC results in 250 exclusive J/ψ’s for a recorded luminosity of 300 nb-1, which is enough to have a look to the *AN*in one bin for *t*. This statistics can be increased by also using the muons of the J/ψ decay detected in the MTD. Current studies using rapidity gap triggers to tag diffraction and/or exclusive J/ψ production will show the statistics can be further increased.

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| p  p’  Au  Au’  magenta | Au  Au’  p  p’  black | Figure 4‑25: Possible processes to generate exclusive *J/ψ in p*↑+Au UPC in one case the photon is generated by the proton beam (left) in the other by the gold beam (right). |
|  |  | Figure ‑: Generated *t*-spectra for the beam generating the photon (left) and the target beam (right) using the SATRE MC generator. |

# Run-16 Request

## Transverse polarized p+p running at √s=500 GeV

In addition to the physics motivations already discussed in section 2.1.2 and 4.2 there are two very basic questions in transverse spin physics, for which finding answers will be of fundamental interest for QCD. One is the question about the evolution of transverse dependent parton distribution functions and fragmentation functions, which is different to the well-known evolution following DGLAP [[[59]](#endnote-59)]. The other important aspect is the process dependence and the color gauge invariance of the Sivers function. 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, and the W*±*, Z0 Boson production, 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 and will provide a direct verification of QCD factorization. The transverse single spin asymmetries for direct photon production provide also access to this sign change through the Twist-3 formalism. The importance of measuring this sign change is also reflected in the fact that it was made an NSAC performance measure for hadronic physics, HP13. The COMPASS experiment at CERN is pursuing this sign change using a pion beam and new initiatives have been proposed e.g. at FNAL.

As already discussed in section 2.1.2 STAR was able in a pilot run with transverse polarized p+p collisions at √*s*=500 GeV to measure the transverse single spin asymmetries *AN* for fully reconstructed W*±*, Z0 Bosons based on a recorded integrated luminosity of 25 pb-1. Figure 5‑1 shows the most up-to-date theoretical predictions for the transverse single spin asymmetries for W*±*, Z0 Bosons from reference [12] including TMD-evolution.

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| z0.eps | w_plus.eps | w_minus.eps |
| Figure ‑: Theoretical predictions from reference [12] 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 due to the unknown sea quark Sivers function.  The production of W*±* bosons at √*s*=500 GeV provides an ideal tool to study the spin-flavor structure of sea quarks inside the proton. The left-handed W boson only couples to (anti)quarks of a certain helicity, giving rise to large parity-violating single spin asymmetries in polarized p+p collisions at RHIC. In addition, the coupling of the W’s to the weak charge correlates directly to quark flavor. Ignoring quark mixing, W*±* bosons are produced through interactions. 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 [[[60]](#endnote-60)], can only be explained by strong non-pQCD contributions. Of course the same measurement is also able to access the sign change of the Sivers function. Figure 5‑2 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 55%. The 400 (900) pb-1 correspond to 7 (14) weeks running and a dynamic \* squeeze through the fill. The dynamic \* squeeze provides a factor 2 increase of the luminosity in a fill as the luminosity profile through the fill is kept flat. | | |

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| 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 400 (900) pb-1 and an average beam polarization of 55%. | | |

A high statistics run at √*s* = 510 GeV in combination with the existing Run-12 data sample at √*s* = 200 GeV and the proposed √*s* = 200 GeV measurements in Run-15 gives the possibility to study the TMD evolution through the following processes:

* Interference fragmentation
* AN for direct photons
* AN for jet observables sensitive to the Sivers fct or transversity times Collins FF

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| Figure ‑: Transverse single spin asymmetries for hadron–jets (left) sensitive to the Collins mechanism and inclusive jets (right) sensitive to the sivers mechanism at √s=500 GeV from Run-11 (25 pb-1). | |

Figure 5‑3 shows the transverse single spin asymmetries for hadron–jets (left) sensitive to the Collins mechanism and inclusive jets (right) sensitive to the Sivers mechanism for gluons at √*s*=500 GeV from Run-11 (25 pb-1). A high luminosity run will provide the possibility to have enough statistics to test if the trends seen in the Collins-like jets at high *z* persist with higher luminosity as well as to make a high precision measurement of the gluon Sivers function in the Twist-3 formalism through *AN* for inclusive jets. The uncertainties shown in Figure 5‑3 will shrink by a factor 4 with the proposed Run-16. This measurement will be completely complementary to the results by the ANDY collaboration done at √*s*=500 GeV for **>3 [[[61]](#endnote-61)].

The ultimate test for the TMD evolution would be to measure *AN* for W*±*, Z0 Boson and DY production. To obtain a significant measurement of *AN*for DY production, the DY leptons need to be detected at rapidities 2 to 4 for a lepton pair mass of 4 GeV2 and bigger. This is a highly non-trivial measurement, as backgrounds mainly due to QCD2🡪2 processes need to be suppressed by a factor up to 106. Current preliminary studies indicate that initial measurements could be achieved by adding a new postshower behind the existing FMS. The design of such a postshower could be copied right from the FMS preshower (see section 6.2), but dropping the 3rd layer. More detailed simulations are ongoing over the next months.

Transverse single spin asymmetries in direct photon production provide a different path access to this sign change through the Twist-3 formalism. Figure 5‑4 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 5‑4 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 following the analysis technique described in section 4.2.

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| 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. |

STAR’s capability to measure *AN* for direct photons, for W*±* and Z0 bosons, and possibly for DY will provide the world-wide unique opportunity to simultaneously test TMD evolution, access the Sivers function for sea quarks, and test the predicted sign-change for the Sivers function with three different processes for two different theoretical approaches. It offers a viable path to address performance measure HP13 at RHIC.

# Detector and Upgrades relevant to BUR

## The Phase-II\* Upgrade of the Roman Pots around STAR

In their 2011 report the PAC recommended that a solution is found to run the physics program with tagged forward protons under normal conditions or concurrently with the rest of the RHIC program. Thus to enable measurements like diffraction in p+p and p+A, the Roman Pots are required to be relocated to the DX-D0 region. To stage the cost of the full implementation of these upgrade an intermediate phase-II\* in Run 15-16 will be realized as described below:

Roman Pot in STAR Phase-I, Phase-II\* and Phase-II:

* Current configuration (Phase-I): two horizontal (at 55.5m) and two vertical (at 58.5m) Roman Pots (RPs) each in outgoing Yellow and Blue beam (Detector: 75x45mm2) [data taking in Run-9]
* **Phase-II\*:** reconfiguration of Phase-I detectors. Two vertical RP each at ~15.8 m and at ~17.6 m (Detector: Phase-I detector) [installation in 2014, data taking ready for Run-15]
* Phase-II: two vertical + one horizontal and two vertical and one horizontal RPs each (new Si-Detector: 100x70mm2)

A schematic layout of Phase-II\* is shown in Figure 6‑1 and Figure 6‑2.

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| 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. |

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|  | Figure ‑: Layout of the design of the new DX-D0 chamber showing the Roman Pot stations. They will be installed in 2014. |

Phase-II\* has comparable *t*-acceptance till 0.8 GeV2 as Phase-II, for physics studies at high *t* the full Phase-II needs to be realized. The design and location of Phase-II\* identified in collaboration with the CAD experts, allows the full implementation of Phase-II at a latter time. To have Phase-II\* realized for Run-15 the design of the vacuum pipe needs to be finalized this summer, such that parts can be order and fabricated in time that the installation of the new vacuum chamber and the Roman Pots can be realized in the shutdown summer 2014.

The Roman Pot detectors used for the pp2pp experiment [[[62]](#endnote-62)] and STAR Run-9 [[[63]](#endnote-63)] installed in the location of Phase-II\*, will be used to tag very forward protons, thus selecting processes, in which the proton stays intact.

## A Preshower for the FMS

STAR is building a preshower detector in front of the FMS, which will help distinguish photons, electrons/positrons and charged hadrons. This detector will be comprised of two layers of perpendicularly arranged scintillator slats (PS1 and PS2), followed by a lead converter and a subsequent third layer of scintillator slats (PS3). PS1 and PS2 will be used to identify neutral particles (photons) from charged particles (hadrons and electrons), while PS3 after the converter will help separating electromagnetic showers (photons and electrons) from charged hadrons.

The preshower detector will be located in front of the FMS at a little less than 7 m downstream of the nominal interaction point in STAR and will cover a transverse area of about 2x2 m2 with a 40x40 cm2 cutout in the center for the beam pipe. The preshower layers will be divided into quadrants. The detector will be segmented to ~80 scintillator slats per layer, and the granularity of the array is going to match that of the FMS loosely as indicated in Figure 6‑3.

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| Figure ‑: Geometry of the layers of a preshower detector in front of the FMS electromagnetic calorimeter in STAR. Left: Layered setup of scintillators (grey) with a Pb converter (blue) and SiPM and FEE board (green). Right: Matching of granularity of preshower (layer 3, red) with the tower size of the FMS (black and blue). | |

Due to up to 400 gauss of magnetic field from the STAR solenoid magnet, SiPMs (MPPC) were chosen for the readout instead of conventional PMT. The scintillation light from a scintillator slat will be read out by two 3x3mm Hamamatsu S12572-050P (PS1 & PS2) and S12572-025P (PS3) MPPC (SiPM), which will be mounted on a FEE board and attached to light guides at the end of the scintillator slat as shown in Figure 6‑4. The initial tests of the SiPM and scintillator slats have been finished. The construction of the detector will take place summer 2014, followed by testing and installation to STAR before the 2015 RHIC run.

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| Figure ‑: To keep the taper angle small while making it compact, there will be one light guide with a “two mountain structure” glued at each end of a scintillator slat. A small board with two SiPM will be attached to the end of the light guides. The FEE board will be mounted along the light guide for compactness as well as to give mechanical stability. | |

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