Research Plan for Spin Physics at RHIC

Abstract

1 Executive Summary

Briefly describe the physics case/highlights of the RHIC Spin program, the detector and accelerator capabilities and their development, and the plans over the next few years.

In this report we present our research plan for the RHIC spin program. The Department of Energy's Office of Nuclear Physics Science and Technology Review Committee, in their report of September 2004, recommended preparation of a plan that covers 1) the science of RHIC spin, also in the context of work world-wide; 2) the requirements for the accelerator; 3) resources that are required including timelines; and 4) the impact of a constant effort budget to the program. The RHIC Spin Plan Group was charged by Thomas Kirk, BNL Associate Director for High Energy and Nuclear Physics, to create this plan.

The RHIC spin physics program contributes to a developing understanding of the known matter in our universe. This matter is predominantly nucleons, protons and neutrons of atomic nuclei. Deep inelastic scattering of high energy electrons from protons established in the 1960s that the nucleons are built from quarks.Quantum chromodynamics (QCD) is now believed to be the theory of the nuclear force, with protons built from quarks and the QCD force carrier, the gluons.Unpolarized studies have verified many predictions of QCD, probing deeply inside the proton using unpolarized colliders at very high energy. These experiments have determined with great precision the unpolarized structure of the nucleons, the distributions of quarks, gluons, and anti-quarks.

There has also been considerable progress, and a major surprise, studying the spin structure of the nucleons. *Polarized* deep inelastic experiments (DIS) from the 1980s to now, done at the SLAC, CERN, and DESY accelerator laboratories, have shown that the quarks and anti-quarks in the proton and neutron carry very little of the spin of the nucleon, on average. Roughly 75% of the nucleon spin must be carried by its gluons and by orbital angular momentum. This was seen as quite surprising in 1989 when it was first discovered. Although the QCD theory does not yet provide predictions for this structure, it was expected that the quarks would carry the nucleon spin. This polarized DIS result indicated that the proton and neutron have surprising spin structure, and probing this structure has become a major focus in our field.

The DIS experiments probe the nucleon using the electromagnetic interaction. The electromagnetic interaction scatters through electric charge, directly observing the effect of the charged quarks and anti-quarks in the nucleon, but not the electrically-neutral gluons.

The RHIC spin program, colliding polarized protons at $\sqrt{s}$=200 GeV and above, uses the strongly interacting quarks and gluons from one colliding proton to probe the spin structure of the other proton. The RHIC program is particularly sensitive to the gluon polarization in the proton, which will be independently measured with several processes. In addition, parity-violating production of W bosons at RHIC will offer an elegant method to directly measure the quark and anti-quark contributions to the proton spin, sorted by type of quark. These measurements explore the structure of longitudinally polarized protons. The transverse spin structure of the proton can be different from longitudinal, and this is also a major topic at RHIC, and large spin asymmetries have already been observed.

The RHIC spin program is underway. Highly polarized protons, P=45%, have been successfully accelerated to 100 GeV, using unique sets of magnets called Siberian Snakes in the RHIC accelerator. The first polarized collisions at $\sqrt{s}$=200 GeV took place in 2001, and polarization and luminosity have been increased substantially since then. The RHIC spin accelerator complex includes a new polarized source providing very high intensity polarized (P=80%) H^- ions, new "partial" Siberian Snake magnets in the AGS accelerator, four "full" Siberian Snakes in RHIC, and eight sets of Spin Rotator magnets in RHIC. Polarization is measured with new devices in the LINAC accelerator, the AGS, and in RHIC. Absolute polarization was determined at 100 GeV using a polarized atomic hydrogen gas "jet" target in RHIC in 2004. Progress in polarization and luminosity has been made by combining machine work with periods of sustained collisions for physics.

The two large RHIC detectors, PHENIX and STAR, have photon, electron, charged hadron, and muon detectors, all important for the spin program. Measurements of the unpolarized cross sections for π^0 and direct γ production, reported by the RHIC experiments, are described well by QCD predictions. These predictions are based on a perturbative expansion of QCD and calculations have been carried out to two orders for all important RHIC spin processes. Theoretical understanding of these important probes for spin physics at RHIC is robust. First spin measurements from RHIC have been published, showing a large spin asymmetry for π^0 produced in the collision of transversely polarized beams, and a helicity asymmetry for π^0 production, sensitive to gluon polarization, consistent with zero.

We now summarize our findings on the four areas in the charge.

Science. Gluon polarization will be measured at RHIC using several independent methods: π^0, jet, direct γ and γ+ jet, and heavy quark production. Results from the different methods will both overlap to allow us to test our understanding of the processes involved, and expand the range of momentum fraction for the measurements. We want to learn both the average contribution to the proton spin of the gluons, as well as a detailed map. We use first the higher cross section processes, π^0 and jet production, and, as we reach higher luminosity and polarization, the clean but rarer process of direct γ production. We plan to emphasize these measurements for $\sqrt{s}$=200 GeV collisions from 2005-2008. At that time, we expect to have reached a precision that can clearly distinguish between zero gluon polarization and a minimal ("standard") gluon polarization. A large gluon polarization, consistent with the gluon carrying most of the spin of the proton, would be precisely measured. In this period we will also pursue the question of the transverse spin structure. Gluons, massless spin 1 particles, cannot contribute to the transverse spin. Large transverse spin asymmetries have been seen for DIS and now for RHIC, so this topic is also a potential window into a new understanding of the structure of the nucleons.

Production of W bosons, the carrier of the weak interaction, has an inherent handedness. At RHIC we plan to use this "parity violation" signal to directly measure the polarization of the quark and anti-quark that form the W boson. To do this we will run at the top RHIC energy, $\sqrt{s}$=500 GeV. This will provide the first direct measurements of anti-quark polarization in the proton, with excellent sensitivity. We plan to begin these measurements in 2009. The W measurements will require completed detector improvements for both PHENIX and STAR.

The RHIC spin results will provide precise measurements of gluon and anti-quark polarization. With these results we will also understand the role of the remaining contributor to the proton spin, orbital angular momentum. We will have also explored our understanding of the interconnected results from the different RHIC spin probes, and from the DIS measurements. The sensitivity at RHIC for gluon polarization is shown in Figure 1, where we also include the sensitivity for the ongoing DIS experiment at CERN, which measures gluon polarization by the production of hadrons. From the figure, we see that RHIC will provide precise results over a large range in momentum fraction, characterizing the gluon contribution to the proton spin.

Figure 1: Delta G/G(x) vs. log x with a model, showing the x range for various RHIC processes and with expected uncertainties. Also indicate 200 and 500 GeV data. Include COMPASS expected uncertainties for $Q^2 > 1$.

The sensitivity of RHIC for anti-quark polarization is shown in Figure 2. We will measure the ubar and dbar anti-quark polarization to about ± 0.01, as well as u and d quark polarization. The measurement is direct and very clean, using parity violating production of W bosons. DIS measurements also study anti-quark polarization. The method has the disadvantage of theoretical uncertainties on modeling the fragmentation and the advantage that the method is accessible today. The RHIC and DIS methods probe the proton at very different distances, or Q^2, where RHIC corresponds to X Fermi and DIS to Y Fermi, compared to the proton radius 1 Fermi. The theory of QCD prescribes how to connect the results from different probing distances–the description of unpolarized DIS results over a very large distance range is one of the major successes of QCD. Both the anti-quark and the gluon results from RHIC and DIS test the QCD assumption of universality: the physics for both proton and lepton processes can be described with the same underlying quark, anti-quark, and gluon distributions.

Figure 2: Delta Q/Q(x) vs. log x with a model, for u, d, ubar and dbar. Show RHIC expected uncertainties, DIS (or show A_1^p with DIS measurements and RHIC sensitivities?).

We emphasize that the planned RHIC program will make major contributions to our understanding of matter. Our results will complement the DIS measurements, completed and planned. We include in our report expectations from a next stage of DIS–colliding polarized electrons with polarized protons and neutrons which probes still further into the structure of matter. As we develop theoretical tools to apply QCD to understand this structure, these spin results will provide a deep test of our understanding of the fundamental building blocks of matter.

Performance Requirements. The program requires RHIC beams with high polarization, and high integrated luminosity. For our sensitivities above we have used P=0.7 and luminosity 300 pb^{-1} at $\sqrt{s}$=200 GeV and 800 pb^{-1} at $\sqrt{s}$=500 GeV. (Note that this would be "delivered" luminosity, while the figures would use recorded luminosity. We would make this point in the body of the report.)

The polarization level is presently P=0.45, and is expected to reach 70% polarization by 2006. This improvement is anticipated from new Siberian Snakes installed in the AGS in 2004 and 2005.

The average luminosity at store must be increased by a factor 15 to reach the integrated luminosity goals in three years of running, 10 physics weeks per year. To achieve this will require completion of the planned vacuum improvements in RHIC, expected for 2007. The luminosity increase then comes from reaching a bunch intensity of 2×10^{11}. A limit will be caused by beam-beam interactions that change and broaden the betatron tune of the machine, moving part of the beam into a beam resonance region where beam is then lost. Work in 2004 discovered a new betatron tune for RHIC that greatly improves loss from the beam-beam interaction. RHIC at our luminosity goal will be above previously reached tune spread limits, and will be close to vacuum limits from the development of electron clouds.

Reaching these goals requires learning by doing. We plan to study limits and develop approaches to improve the polarization and luminosity during physics runs by including beam studies for one shift per day. It is also important that a sustained period of running and development be followed, if possible each year. It is this approach that has led to the major improvements for heavy ion luminosity and to our improvements to this date in polarization and proton luminosity.

Experiment Resources. The PHENIX and STAR detectors are complete, for the gluon polarization program. Improvements to both detectors are required to carry out the W physics program. Both experiments also plan upgrades that benefit both the heavy ion and spin programs, significantly extending the range of physics probes for spin.

PHENIX. The present online event selection for muons, the channel used for W physics, will need to be improved for the W luminosity. New resistive plate chambers (RPC) are being proposed to provide the tighter event selection, along with electronics changes to the muon tracking readout. The RPC proposal was submitted to NSF in January 2005, with a cost estimate of \$1.8M. The tracking readout proposal has been submitted to the Japan Society for the Physical Sciences, with a cost of \$1.0M. The planned timeline for both is to complete for the 2008 run.

STAR. New tracking for forward electrons from W decay is necessary for the W program. It is planned to propose this upgrade in 2006 to DOE, with an estimated cost of \$5M, although research and development on the technology (GEM detectors) is proceeding and the cost estimate is rough at this time. The forward tracking detector is to be completed for the 2010 run, with part of the detector in place earlier.

Heavy Ion/Spin Upgrades–PHENIX. PHENIX plans a barrel micro vertex detector which gives access to heavy quark states and to jet physics based on tracking. The heavy quark data will add a new probe for gluon polarization at lower momentum fraction (shown on Fig. 1). The jet information will be used in correlated (γ+jet) measurements, which better determine the subprocess kinematics for gluon polarization measurement. A second upgrade being planned is to change the brass "nose cones", used as a filter for the muon arms, to active calorimeters that will measure photons, π^0 and jet energy. The nose cone calorimeters would provide a larger momentum fraction range for the gluon polarization measurements. Both are important upgrades for the heavy ion physics program. The vertex detector is planned for the 2008 run, and the nose cone calorimeter proposal is being developed now.

Heavy Ion/Spin Upgrades–STAR. Expanded forward calorimeters are being proposed for STAR to NSF in January 2005. The calorimeters will measure the gluon density for proton-gold collisions, and will also provide very significant spin measurements. With the calorimeters, forward π^0, γ, and jet events can be observed, giving sensitivity to gluon polarization at lower momentum fraction, as shown on Fig. 1. A second upgrade driven by the heavy ion program, a barrel inner tracker, will give access to heavy quark measurements for spin. The forward calorimeters are to be in place for the 2007 run. The barrel inner tracker is to be completed for the 20?? run.

To summarize, the muon trigger improvements for PHENIX and the forward tracking upgrade for STAR are necessary for the W physics program shown in Fig. 2. PHENIX expects to be ready for a full 500 GeV program by 2009, and STAR expects to have part of its detector ready for 2009, and the full tracker for 2010. Heavy ion/spin upgrades are being planned that significantly expand the range and sensitivity for spin measurements.

Impact of 10 and 5 Physics Weeks per Year We have been requested in the charge to consider two scenarios: 10 and 5 spin physics weeks per year. We would like to emphasize that we expect the actual running plan to be developed from the experiment beam use proposals. Our consideration of these scenarios should not suggest that we advocate a change to this successful approach.

We show in Fig. 3 the impact of 10 and 5 spin physics weeks per year. The ”target” represents the luminosity used for the sensitivities shown in the figures above. With 10 weeks per year, we achieve the $\sqrt{s}$=200 GeV target in 3 years, where we assume that we successfully climb the learning curve to reach the target store luminosity. The 500 GeV running target is also expected to be achieved in 3 years (there is a natural luminosity improvement for 500 GeV of a factor of 2.5 over 200 GeV from the smaller cross section beams).

With 10 spin physics weeks per year, our proposed target sensitivities can be reached running at $\sqrt{s}$=200 GeV from 2005-2008, and at $\sqrt{s}$=500 GeV from 2009-2012, where we have assumed that 2009 will be an ”engineering” year, learning to handle the high luminosity and to commission the new detectors. This is our proposal.

As can be seen in Fig. 3, running 5 spin physics weeks per year (we have interpreted this as running 10 spin physics weeks every two years to improve end effects), each program, 200 GeV and 500 GeV, takes more than 6 years. Under this scenario RHIC would run roughly 25% of the year, and both the heavy ion and spin programs would be stretched a factor of greater than two in calendar time.

Fig. 3: pp luminosity projections for 10 and 5 physics weeks per year (5=10/2).

2 The case for RHIC Spin

2.1 Introduction: what we know so far, what else we would like to learn, and why

• initial information on spin structure of the nucleon, spin “crisis” & spin sum rule
• motivation for studies of gluon polarization Δg and for further studies of quark polarization
• parton angular momenta
• transverse-spin asymmetries, transversity, parton correlations, parton transverse momentum & spin, and what they tell us about the nucleon
• physics of elastic scattering
• wider context of nucleon spin structure
• why polarized pp scattering to answer these questions ? What can it probe ? Complementarity to DIS
(leads into next section)

2.2 Unpolarized pp scattering (Werner, Stefan)

• Introduction: lay out ideas, how do we describe inelastic pp scattering?
• pQCD, collinear factorization (and beyond), lowest and higher orders etc.
• (perhaps:) uncertainties
• π^0, γ measurements from RHIC
robust understanding of probes used for spin structure
• fractions of subprocesses (midrapidity & forward)
• from that, identify the probes that are most sensitive to gluons etc.

2.3 Probing longitudinal spin structure of the nucleon

• pQCD with spin, subprocess analyzing power (**Marco**)
• gluon: π, jet, γ, γ+jet, $Q\bar{Q}\ldots$ (**Steve,Yuji, Hal,Les**)
• what are the key predictions for Δg processes? (**Werner, Marco+…**)
show spin asymmetries A_{LL} for π^0, jet, γ and their dependence on Δg. Use for example currently estimated uncertainty on Δg from DIS and give estimates of how precise measurements need to be "at least" in order to obtain a significant improvement. This will provide the "minimum requirements". Discuss relevance of "correlation observables" such as jet+photon, pion+pion, etc. Discuss development with time.
• (anti)quarks, W (**Naohito,Bernd**)
• this should include in particular a discussion of importance of 500 GeV running.

2.4 Transverse spin structure

• why it is different from longitudinal (**Jianwei**)

• history, previous A_N measurements (**Les,Matthias,Akio**)
- Description of E704[1] and why it was a surprise[2]
- Theory developments since then: Sivers[7], Collins[8] and Boer[9] with k_T factorization. Also describe collinear twist-3 approach[10, 11]
- Predictions for $\sqrt{s} = 200$ GeV[12, 13, 10, 11] and more recent developments[14]
- More recent pp experiments[3] and SDIS experiments[4, 5]
- RHIC results[6], A_N at large x_F stays at an order larger $\sqrt{s}$
- Need cross section at $\sqrt{s} = 200$ GeV arguments? Note that there is separate section for it
- Fig1 shows A_N from 3 RHIC experiments

• mapping A_N in x_F and p_T plane (**Les,Matthias,Akio**)
- Mapping A_N in x_F and pT plane
- pQCD prediction of $1/p_T$ dependence and importance of measurement, need for more data
- Interests in very large x_F[15] and soffer bounds[16]
- Negative x_F and sensitivity to gluon Siver's functions[14][6]
- Global fits with pp data and SDIS(?)

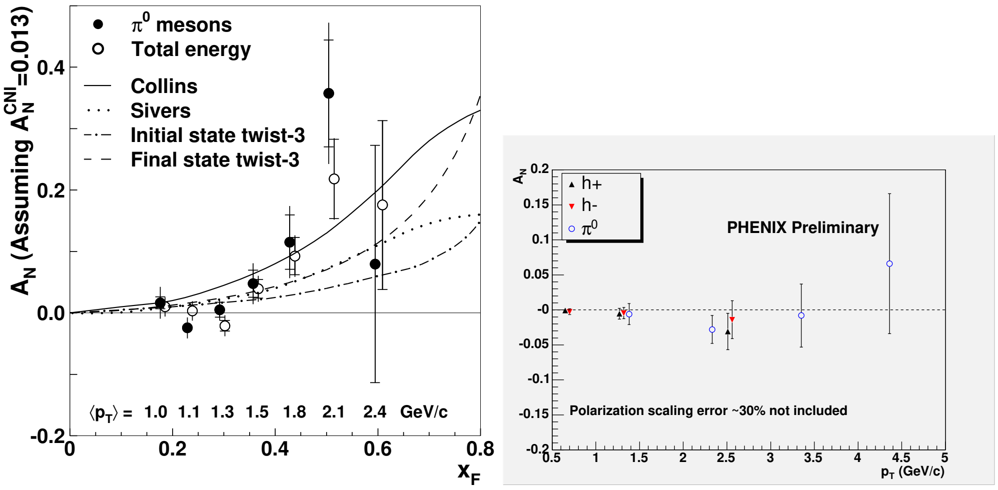

Figure 1: Single Spin asymmetry A_N for π^0 production at STAR (Left), π^- production at BRAHMS (Middle) as function of x_F at forward rapidity. A_N for $\pi^{\pm}$ production from PHENIX (Right) as function of p_T at mid-rapidity.

- L and P requirements
- Fig2 shows projection for A_N as function of p_T for STAR

• Away side di-jet/hadron for Sivers (**Les,Matthias,Akio**)
- Need to go beyond inclusive measurement to disentangle different effects (except A_N for "inclusive" jet at forward)
- Di-jet measurement for gluon sivers measurement for non-power supressed/direct k_T sensitivity[17]
- Di-hadron measurements at forward $\longrightarrow$ to access large x quark sivers?
- Connection to parton motion/orbital angular momentum/GPD, "modified" universality, etc? (maybe in theory section?)
- L and P requirements
- Fig3 shows theory prediction for di-jet A_N (no exp error estimate yet)

• Near side di-hadron for Collins (**Les,Matthias,Akio**)
- Transversity, last unmeasured leading twist quark PDF, no gluon transversity, Lattice results(maybe in theory section?)
- Collins and Interference FF[8], and describe models[18]
- How to measure - azimuthal correlation between hadrons within a jet
- Getting FF from e+e- to turn into Transversity measurement[19][20]
- Measuring over large p_T and rapidity range to see x_{BJ} dependence of transversity
- L and P requirements
- Fig(yet coming): transversity measurement at PHENIX with 30/pb and P=0.5 by Matthias

• A_{TT}(jet, photon, DY) and beyond (**Les,Matthias,Akio**)
- This measures $\delta q \times \delta qbar$ [21], no need for FF, but small
- DY need more luminosity[22]
- Transversity from J/psi[23]
- Sivers from D mesons[24]

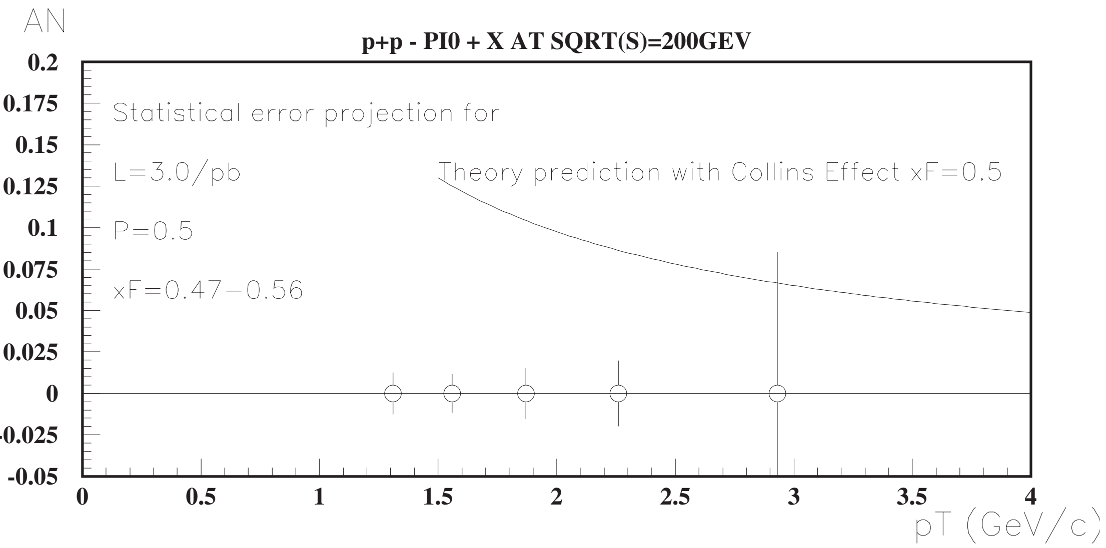

Figure 2: Statistical error projection for A_N as function of p_T for π^0 production at STAR. A theory prediction for Collins effect (need citation!) for $x_F = 0.5$ is also shown.

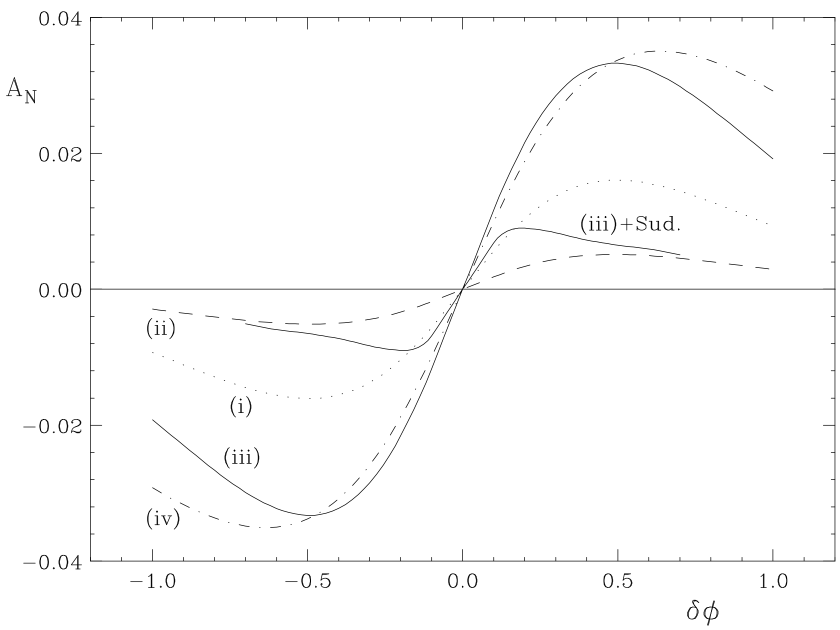

Figure 3: Predictions for the spin asymmetry AN for back-to-back dijet production at $sqrts = 200$ GeV, for various different models for the gluon Sivers function. The solid line marked as "(iii)+Sud" shows the impact of leading logarithmic Sudakov effects on the asymmetry for model (iii)[17].

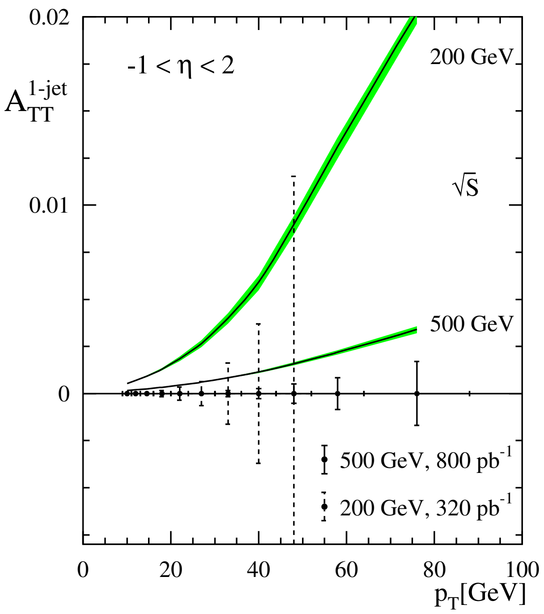

Figure 4: Maximally possible A_{TT} for single-inclusive jet production at $sqrts = 200$ and 500 GeV as a function of pT. Jet rapidities are integrated over $-1 < \eta < 2$. The shaded bands represent thetheoretical uncertainty in A_{TT} estimated by varing scale by factor 2. Also indicated as error bars is the expected statistical accuracy with design luminosity of the RHIC [21].

- L and P requirements
- Fig4 shows maximum A_{TT}^{jet} and projection for STAR acceptance

• assess what requirements would be for key measurements here, and how they would compare to longitudinal running(**Les,Matthias,Akio**)

- 3/pb, p=0.5 : Inclusve
- 10/pb, p=0.5 : Sivers from di-jet/hadron
- 30/pb, P=0.5 : Transversity measurement from di-hadron correlations within a jet
- 100/pb, P=0.7 : A_{TT} of jet/hadron
- 1000/pb, P=1.2 : DY
- 1/3 to 1/4 of beam time, and we'll have intermediat physics as LP develops.
- STAR and PHENIX are independent for choice of long and trans
- Most of measurements prefers $\sqrt{s} = 200$ GeV

2.5 "What else is going on in the world"

• briefly discuss current efforts in DIS and their expected results & timelines (**Ernst, Akio**)

2.6 Elastic scattering (Larry, Elliot, George, Sandro)

2.7 Future plans/ideas at RHIC

• $W + c$ (**Yuji ?**)
• physics beyond the Standard Model? (**Vladimir**)
• other opportunities possibly offered by high-luminosity running (and/or a new detector)
• opportunities with polarized beams in p+heavy-ion physics (**Les**)

2.8 Connection to eRHIC (Abhay)

3 Accelerator–present & future (Wolfram, Mei)

- successes so far
- expected development in polarization and luminosity over next few years
- polarimetry **(Gerry, Sandro)**
- expectations with 10, 5 physics week scenarios
- long-term perspective (RHIC II, new ideas for luminosity etc.)

4 Experiments

4.1 Phenix (Matthias)

- present status & issues to solve
- priorities
- planned upgrades and developments
- required resources

4.2 Star (Steve)

- present status & issues to solve
- priorities
- planned upgrades and developments
- required resources

4.3 Other experiments

- Brahms (**Flemming**)
- New detector
- eRHIC detector
- pp2pp (**Wlodek**)
- jet (**Sandro**)

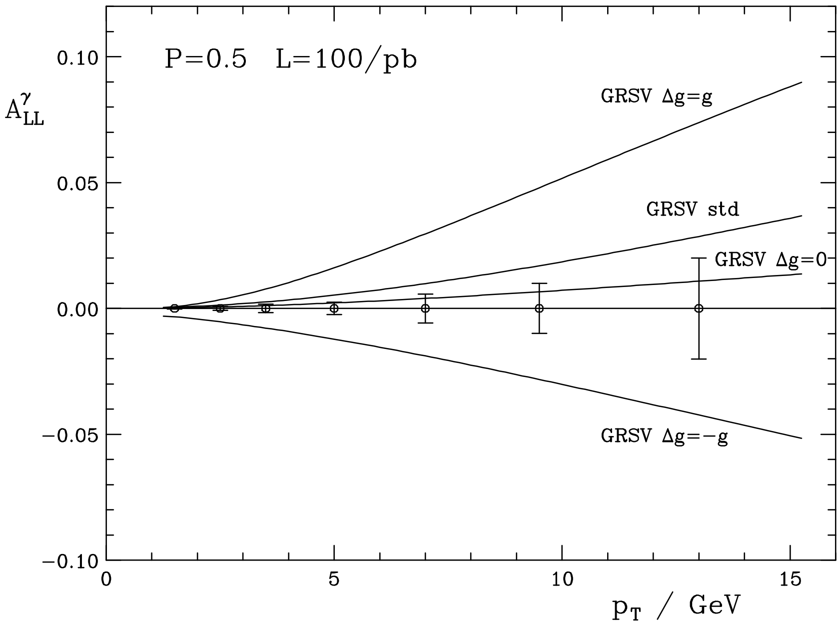

Figure 5: Spin asymmetry A_{LL} for prompt photon production for various gluon polarizations. Expected error bars are for $P = 50\%$ and $\mathcal{L} = 100$/pb. Phenix acceptance.

5 Spin plan schedule (Gerry)

5.1 5 physics weeks

5.2 10 physics weeks

6 Summary (Gerry)

Acknowledgments

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