1 Experiments (Brahms, PHENIX, and STAR)

This section describes the three experiments capable of making spin measurements.

1.1 PHENIX

RHIC has made great strides towards providing high luminosity beams of highly polarized protons. To make statistically sensitive asymmetry measurements with low systematics requires well understood detectors; clean, highly selective triggers, reliable measurements of beam luminosity and polarization, and the ability to take and analyze data at high rates. In this section we discuss the current and proposed capabilities of the PHENIX detector in the context of meeting the challenges of the spin program.

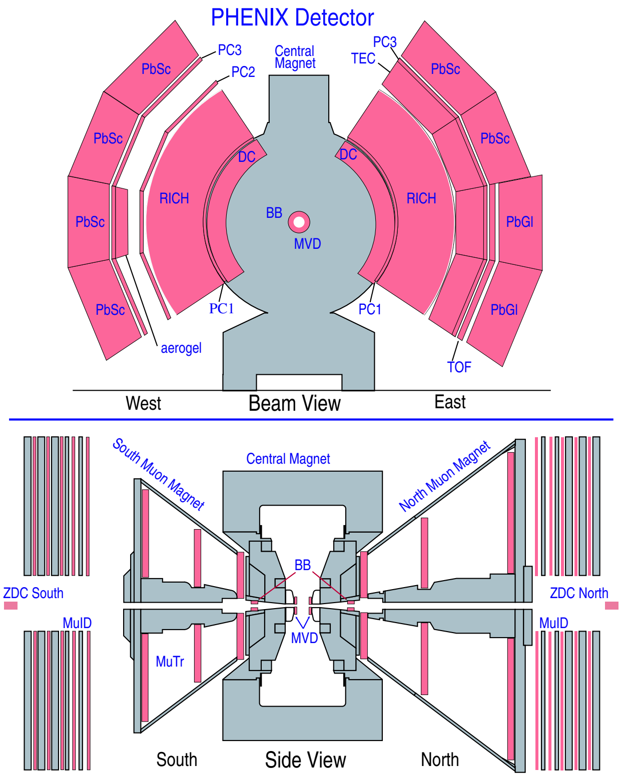

Figure 1: Plan view and side views of the PHENIX detector.

As shown in Fig. 1, the PHENIX detector comprises four instrumented spectrometers (arms) and two global detectors. The east and west central arms are located at central rapidity and instrumented to detect electrons, photons, and charged hadrons. The north and south forward arms have full azimuthal coverage to detect muons. In addition, the zero degree calorimeters (ZDCs) and beam-beam counters (BBCs) measure the time and position of the collision vertex.

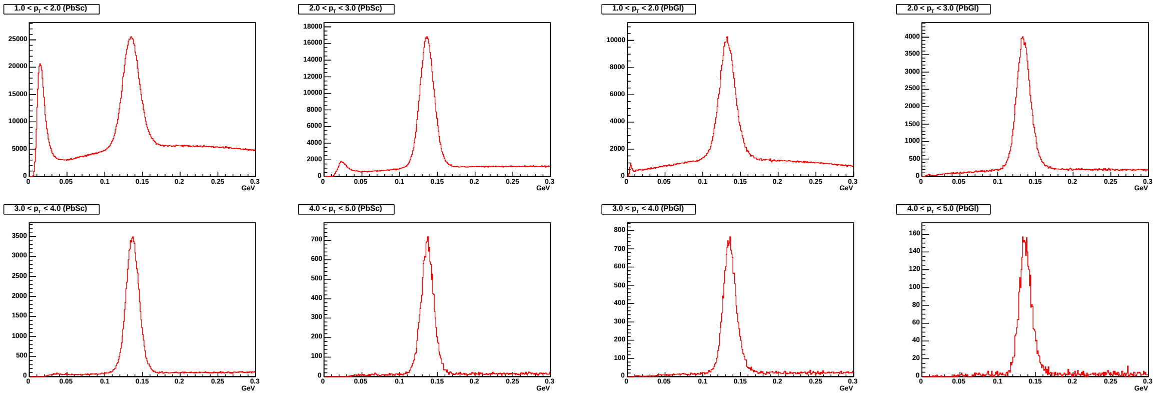

Figure 2: The π^0 mass spectrum in 1 GeV p_T bins 1-2 GeV/c, 2-3 GeV/c, 3-4 GeV/c and 4-5 GeV/c. The left four panels are for lead scintillator (PbSc), and the right four panels are for lead glass (PbGl) calorimeter sectors. Events are collected using the high p_T photon trigger of the EMCal. The combinatorial background is $\sim$30% for a p_T range from 1 to 2 GeV/c, and $\sim$5% for $p_T > 5$ GeV/c. The two-photon invariant mass resolution is 8.5% in the first p_T bin and 6.4% in the last p_T bin.

1.1.1 PHENIX Central Arms

The PHENIX central arms consist of tracking systems for charged particles and electromagnetic calorimetry. We require a calorimeter with the ability to distinguish isolated photons from those from π^0 decays over a large p_T range. A thorough understanding of the calorimeter and associated triggers is vital for these measurements.

The calorimeter (EMCal) is the outermost subsystem of the central arms, located at a radial distance of $\sim$5 m from the beam line. Each arm covers a pseudorapidity range of $|\eta|<0.35$ and an azimuthal angle interval of $\Delta\phi\approx 90°$, and is divided into sectors containing a lead scintillator (PbSc) calorimeter or lead glass (PbGl) calorimeter. Each calorimeter tower subtends a solid angle $\Delta\phi\times\Delta\eta \sim 0.01\times 0.01$, ensuring the two photons from π° decay are resolved up to a p_T of 12 GeV/c. Shower profile analysis can extend this p_T range beyond 20 GeV/c. The energy calibration used the position of the two photon invariant mass peak from π° decay, the energy deposit from minimum ionizing charged particles traversing the EMCal (PbSc), and the momentum determined by the tracking detectors of electrons and positrons identified by the ring-imaging Čerenkov detector. It has been shown that the energy resolution was better than 1.5%. The effective energy resolution was deduced by comparing the measured energy and momentum for identified electrons and positrons and from the widths of the π° invariant mass peaks as shown in Fig.2.

The number of recorded high-p_T π°'s is enhanced by a high-p_T trigger which uses threshold discrimination applied to sums of the analog signals from 4×4 groupings (tiles) of adjacent EMCal towers. A plot of the trigger efficiency as a function of deposited energy is shown in Fig. **??**. The efficiency reached a plateau of 0.9 at $\sim$4 GeV, which is consistent with the geometrical acceptance of the active trigger tiles, and was reproduced by Monte Carlo calculations. Charged particle contamination in the photon sample was minimized by using information from the PHENIX ring-imaging Čerenkov and tracking detectors [**?**].

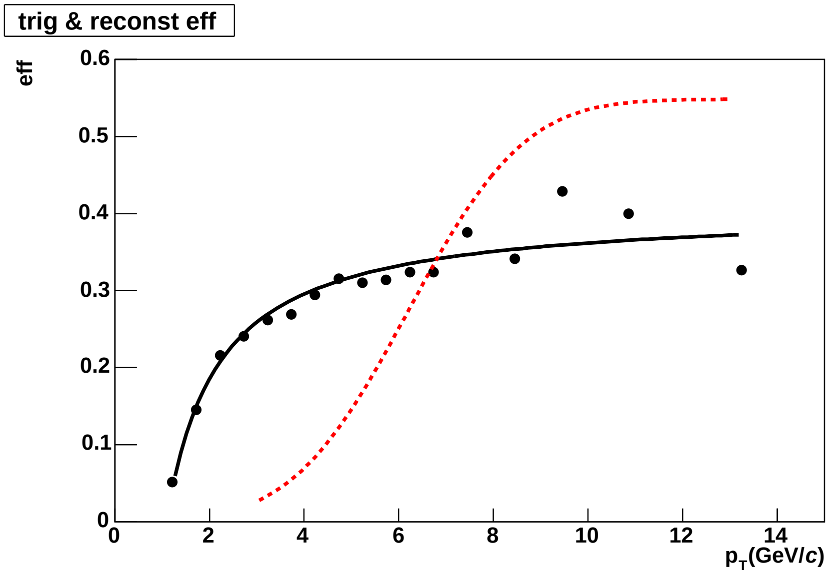

Figure 3: Experimental efficiency for π^0 detection at PHENIX. It includes BBC and EMCal trigger efficiencies, offline data selection, and reconstruction efficiencies. Black points are efficiencies calculated from run2-pp data and the black line is a smoothed curve for eye guidance. It saturates around 35-40%. The dotted red line shows expected efficiency in the future. We can achieve this by removing the BBC coincidence from the trigger and setting the EMCal trigger threshold energy higher.

The calorimeter and trigger performance have enabled PHENIX to make many significant measurements within the first few years of running. Measurements have been made of the cross-section and double-helicity asymmetry for π^0 production (see Figures. **??**, **??**). The prompt photon production cross-section in pp collisions has also been measured ([10], [11]) and the NLO pQCD calculation is in good agreement with the data **??**. In Ref. [11], a photon isolation cut was applied as a first step towards a spin asymmetry measurement. The cut reduces the level of background photons diluting the analyzing power. With increased luminosity we expect improved precision on these measurements, and the first measurements of the double spin asymmetry $A_{LL}^{pp\to\gamma X}$.

The EMCal will also be used for measurements of inclusive electron asymmetries from semi-leptonic decays of charm and beauty produced mainly by gluon-gluon fusion in pp scattering. Electrons in the central arms are identified by the RICH detector (Čerenkov threshold for $\pi^{\pm} \approx$ 4.9 GeV/c) and the EMCal. The yield of electrons can be categorized into nonphotonic electrons mainly from semi-leptonic decays of charm and beauty (see Fig.**??**), and photonic electrons mainly from gamma conversion and Dalitz decays of neutral mesons such as π^0 and η [4].

1.1.2 Muon Arms

The systematic study of J/ψ production at Relativistic Heavy Ion Collider (RHIC) energies with wide p_T and rapidity coverage should provide crucial tests of J/ψ production models. In addition, the RHIC proton-proton results provide a baseline for studying cold and hot nuclear matter

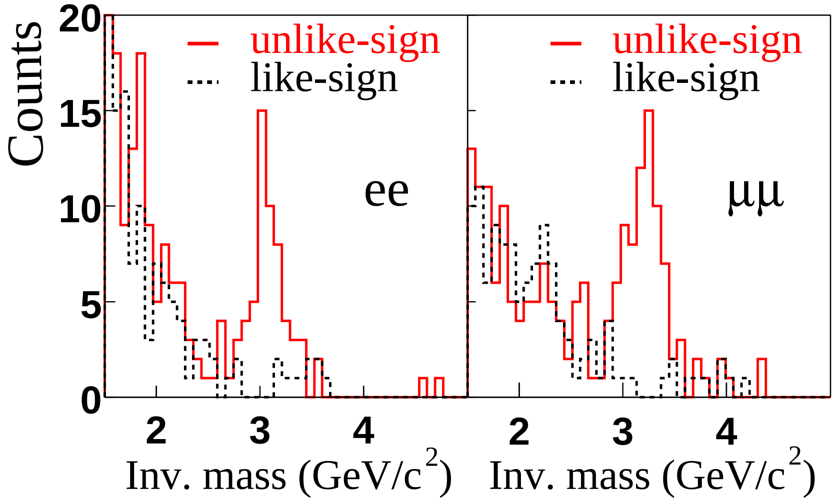

Figure 4:

in proton-nucleus and nucleus-nucleus collisions using J/ψ yields as a probe. PHENIX has two forward spectrometers devoted to the characterization of single and di-muon events in the forward rapidity regions. The central magnet poles act as a hadron absorber in front of a radial field magnet with acceptance from 1.2 $< \eta <$ 2.2 (2.4) in the South (North) spectrometer. Inside the magnetic field, there are three high resolution cathode strip tracking chambers capable of determining space point position to $<$ 100 microns. Downstream of each spectrometer magnet is a Muon Identifier (MuId) which covers the same rapidity region. They consist of five layers of steel absorber sandwiching both horizontal and vertical proportional tubes, with the total thickness of the absorber material of 60cm. The minimum muon momentum able to penetrate all 5 gaps is 2.7 GeV/c, and the pion rejection factor at 3 GeV/c is 400. The MuId is also used as trigger counter as well as identifying the muon. It uses full hit information of the detector, 9 cm in horizontal and vertical direction for each gap, and determines whether a muon candidate road exists for each beam crossing. Triggers on single and double tracks with sufficient depth in the MuId are passed to the global level-1 trigger of PHENIX. J/ψ yields in the muon arm were obtained by reconstructing $\mu^+ - \mu^-$ pairs. Muon tracks were reconstructed by finding a track seed in the MuID and matching it to clusters of hits in each of the three MuTr stations. The momentum was determined by fitting, with a correction for energy loss, the MuID and MuTr hit positions and the vertex position. J/ψ mass resolution of 160 MeV/c^2 in $p - p$ collisions has been achieved as shown in Fig.4. Together with the di-electron measurement in the central arm, PHENIX has published the p_T, rapidity and total cross-sections for J/ψ at $\sqrt{s}$ = 200 GeV/c.

1.1.3 PHENIX Local Polarimetry and Relative Luminosity Detectors

Local polarimeters, sensitive to transverse polarization at collision, were used to set up the spin rotators and monitor the beam polarization direction at the PHENIX interaction point. The local polarimeters utilized a transverse single spin asymmetry in neutron production in pp collisions at $\sqrt{s} = 200$ GeV [5]. For vertically polarized beam a left-right asymmetry is observed for neutrons produced at very forward angles, with no asymmetry for production at very backward angles. A

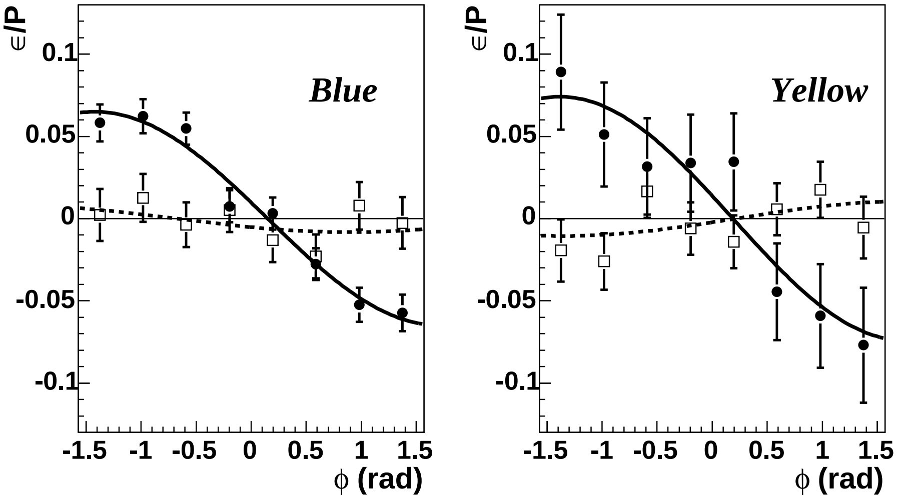

Figure 5: The raw asymmetry normalized by the beam polarization, ϵ/P, as a function of azimuthal angle ϕ, for forward neutron production. The solid points and curve correspond to the spin rotators off (transverse polarization) and the open points and dashed curve correspond to the spin rotators on (longitudinal polarization). Curves are sine function fits to the data, representing possible transverse polarization. The data are for special runs used to set up the spin rotators, where the blue (yellow) polarization was 0.24 and 0.33 (0.08 and 0.28), for spin rotators off and on, correspondingly.

fully longitudinally polarized beam produces no asymmetry.

Neutrons with $E_n > 20$ GeV and production angle $0.3 < \theta_n < 2.5$ mrad were observed by two hadronic calorimeters, the Zero Degree Calorimeters (ZDC) [6], located ± 18 meters from the interaction point. Scintillator hodoscopes at 1.7 interaction length provided the neutron position at the ZDC, and thus the neutron production angle and azimuthal angle $\phi = \arctan(x/y)$ with $\hat{y}$ vertically upward. The $\hat{x}$ axis forms a right handed coordinate system with the $\hat{z}$ axis defined by the beam direction for forward production. Figure 5 shows the observed asymmetry for the spin rotators off and on, for the blue and yellow beams. With the spin rotators off, a left-right asymmetry is observed from the vertically polarized beam. With the spin rotators on, the transverse asymmetry is greatly reduced, indicating a high degree of longitudinal polarization (0.99 and 0.98 for the blue and yellow beams, respectively). A separate run with the spin rotators set to give radial polarization confirmed the direction of the polarization for each beam.

In addition to the polarization of the beams, we require information on the intensities and possibly the profiles of the colliding bunches. This knowledge is necessary because the spin structure information we seek appears in correlations between the rate or angular distribution of specific final states and the spin direction(s) of the colliding protons. However, spin correlated differences in the production rate of particular final states may appear even in the absence of a physics asymmetry simply because the luminosities of the colliding bunches are different. This necessitates measurements of the relative luminosities of the colliding bunches which are insensitive to the beam polarization and of greater precision than the smallest physics asymmetry to be measured. PHENIX is currently equipped with two forward detectors, the BBCs and ZDCs [6, 7], which are primarily sensitive to the pp inelastic and double-diffractive cross-section respectively. They have demonstrated an insensitivity to the colliding bunch polarization at the level of 1.4 $\times$ 10^{-4} and have a high rejection of backgrounds. Scalars attached to these detectors counting a single event per crossing form the successful foundation of the relative luminosity measurements suitable for the current pp luminosity. As RHIC approaches its design luminosity, 2 $\times$ 10^{32} cm^{-2}s^{-1}, there will be multiple pp interactions per bunch crossing, and ambiguities in determining whether the event vertices lay within the PHENIX acceptance. We believe these complications will be overcome by incorporating additional information from the detectors which is linear in the rate such as phototube charge and multiplicity. Bunch profile information from existing RHIC instrumentation, new analysis techniques and trigger logic will be used to minimize the effects of vertex ambiguities on the determination of relative luminosity. Also, a dedicated low cost, small acceptance detector is being considered to address these issues. Finally, we note that the uncertainty on the relative luminosity may be reduced through use of the spin flippers at RHIC, which will allow frequent reversals of the beam helicities.

1.1.4 PHENIX DAQ and Computing

The PHENIX DAQ has been designed from inception as a parallel pipelined buffered system capable of very high rates of nearly deadtime-less data-taking. In this kind of design, data is sent from each detector element in multiple parallel streams, buffered at each stage in the chain to smooth out fluctuations in rate, and then uses simultaneous read and write for the highest possible throughput with existing technology. At present, PHENIX has achieved data rates of over 4 kHz, and with improvements in noise reduction PHENIX should be able to approach the peak design interaction trigger rate of 12.5 kHz. Such high DAQ rates are crucial for providing the capability and flexibility to record the many different kinds of interesting rare events at RHIC.

In addition to the RHIC Computing Facility (RCF) at BNL, PHENIX has regional computing centers around the world. The biggest one is the RIKEN CC-J, Computing Center in Japan. The CC-J has comparable computing resources to the PHENIX part of the RCF, CPU power and data storage capability with the High Performance Storage System (HPSS). The main missions of the CC-J for the PHENIX experiment are the primary simulation center, an Asian regional computing center, and a computing center for the spin physics. In run5, it will be used for the reconstructed data production of all the polarized proton collision data. Raw data are sent from PHENIX to the CC-J as much as possible using a WAN connection in parallel to the RCF HPSS. A sustained transfer rate of the WAN connection between BNL and RIKEN of 10 MB/s has been routine and occassionally 60 MB/s has been sustained. The PHENIX DAQ rate is expected to be 60 - 100 MB/s in near future. The data which are not transferred in real time will be sent later through the WAN, and with tape transfer by air-shipments as a backup plan. A bottleneck of the WAN was upgraded very recently, so the transfer rate may reach 100 MB/s.

1.1.5 PHENIX Detector upgrades

Muon Trigger Upgrade

The flavor separation of quark and anti-quark polarizations for up and down quarks, requires separate high statistics measurements of inclusive lepton counting rate asymmetries: $A_L^{W+\to\mu^+}(p_T)$

Figure 6: This is the muon trigger upgrade layout figure: Matthias et al. can you provide one? -thanks, Abhay

and $A_L^{W^- \to \mu^-}(p_T)$. These measurements translate into the following experimental requirements for the PHENIX muon arms: (a) superior event selection capability in order to reduce the 10MHz collision rate to the data archiving bandwidth available in PHENIX (b) the ability to assign the correct proton polarization (that is bunch crossing number) to a given W-event candidate, (c) tracking resolution to correctly determine the lepton charge sign and (d) good signal to background ratios in the off-line analysis.

Extensive Monte Carlo simulations including a full GEANT simulation of the muon arms show that the existing muon spectrometers are capable of defining a clean sample of W events for the off-line analysis: a requirement of $p_T > 25$ GeV on the transverse momentum of the final state decay muon will remove most of the collision and beam related backgrounds; we expect a signal to background ratio of about 2:1.

A new first level muon trigger is required to improve the online performance of the present first level muon trigger. Rejection factors achieved in the present PHENIX muon trigger, based on information from the existing muon identifier system are about R=250. Measurements at the luminosities needed for the W-physics program will require rejection factors of R$>$5000.

The new first level muon trigger in PHENIX will be based on three fast trigger stations which will be added to each of the PHENIX muon spectrometers. The triggers stations will use Resistive Plate Chamber (RPC) technology developed for the muon trigger in the CMS experiment at LHC. In addition new front end electronics for the existing muon tracker chambers will make is possible to introduce muon arm tracking information in the future muon trigger. Information from the three RPC stations and the muon tracker will be processed in standard PHENIX first level trigger processor boards. The boards carry large Xilinx Fast Programmable Gate Arrays (FPGAs) and can carry out a fast online momentum measurement based on the tracking information from the RPCs and the muon trackers. In addition a timing cut will be applied in the RPC front-end electronics to remove beam backgrounds.

Detailed beam background measurements and beam-loss Monte Carlo simulations were carried out to confirm that the substantial steel absorbers in PHENIX introduce a large asymmetry in the incoming and outgoing beam backgrounds which can be exploited for triggering purposes. Overall the expected rejection power of the new muon trigger is expected to be well above the required level of R>10000.

Matthias et al Funding plans to be included, about 3-4 lines.-Thanks Abhay

PHENIX Silicon Vertex Tracker

PHENIX Collaboration proposes to construct a Silicon Vertex Tracker (VTX) in the next few years. The VTX will substantially enhance the physics capabilities of the PHENIX central arm spectrometer. Our prime motivation is to provide precision measurements of heavy-quark production (charm and beauty) in A+A and p(d)+A collisions, and polarized p+p collisions. In addition, addition of a large acceptance central detector capable of monitoring multiplicities of hadronic final states along with their directions, will enhance PHENIX's capability to study Jets in hadron-hadron collisions. These are key measurements for future RHIC program, both for heavy ion physics which intends to study the properties of dense nuclear medium created in their collisions, and for the exploration of the nucleon spin-structure through polarized pp collisions. While the detailed list of physics measurements possible with the VTX detector are discussed elsewhere [8], the principal measurements associated with polarized pp program are: (1) $\Delta G/G$ from charm and beauty production in polarized pp scattering and (2) x dependence of $\Delta G/G$ from γ-jet correlations The heavy quark production has been measured by PHENIX presently through the observation of inclusive (decay) electrons. These measurements are limited in accuracy by the systematic uncertainties resulting from possible large electron backgrounds originating from Dalitz decays and photon conversions. The measurements are statistical in nature, and one uses different models to distinguish between charm and beauty contributions. The VTX detector will provide tracking with a resolution of $< 50\mu$m over a large coverage both in rapidity $|\eta| < 1.2$ and in azimuthal angle ($\Delta\phi \sim 2\pi$). A significantly improved measurement of heavy quarks in pp collisions is deemed possible over a wide kinematic range with the VTX.

The proposed VTX detector will have four tracking layers. For the inner two layers we propose to use silicon pixel devices with 50x425 μm channels that were developed for the ALICE experiment at CERN/LHC. Our preferred technology for outer two detector layers is a silicon strip detector developed by the BNL Instrumentation Division which consists of 80μm x 3 cm strips layered to achieve an effective pixel size of 80 x 1000 μm. We plan to use SVX4 readout chip developed at FNAL for the strip readout. The main aim in using existing technology has been to reduce the cost and time for R&D that for such a project could ordinarily be rather high and long, respectively.

PHENIX proposes that the project will be mainly funded by two agencies: the DOE Office of Nuclear Physics and RIKEN Institute of Japan. While RIKEN funding of $3M has been available since 2002, it is proposed that the $4.3M for the Strip Layers will be available from DOE starting FY06. If the VTX is funded accordingly, it will built and commissioned in the RHIC - Run 8 which presently is expected to be a long Au+Au run.

PHENIX Nose Cone Calorimeter

A forward spectrometer upgrade is being proposed with the objective of greatly enhancing present capabilities for PHENIX in the forward direction. When completed, the detector will sit near the PHENIX magnet poletips, and will result in a nearly ten-fold increase in rapidity coverage for photons and to some extent for hadrons and jet detection, as well as better triggering capabilities. Newly acquired access to forward production of inclusive jets, direct photons or

Drell-Yan pairs at large xF in nucleon-ion collisions at RHIC will provide a new window for the observation of saturation phenomena expected at high parton number densities which is of importance in the evolution of the partonic distribution functions. In combination with the central arms, the possibility arises of of detecting $\gamma + jet$ in polarized pp with a large rapidity gap, extending the x range over which PHENIX is sensitive to Δg.

The PHENIX Forward Upgrade is constrained by the existing muon spectrometer configuration including its wire chambers, hadron absorber walls and magnet yokes. The core element of the proposed upgrade are compact tungsten calorimeters with silicon pixel readout and fine transverse and longitudinal segmentation built to identify and measure forward electromagnetic activity and provide jet identification and coarse jet energy measurements. The principal performance aspect of the NCC is its ability to run in the unassisted mode (without upstream tracking).

The NCC is an extremely dense sampling calorimeter using tungsten absorber interleaved with silicon readout layers. Geometrical constraints of the PHENIX detector call for a very nontraditional and challenging design. Tungsten has a very short radiation length and a large absorption/radiation length ratio. The electromagnetic shower develops in the very first few cm of the calorimeter depth thus allowing the implementation of both electromagnetic and shallow hadronic compartments within the available 20 cm of space. To further suppress the hadronic contribution to the energy seen in the electromagnetic compartment the electromagnetic calorimeter will be only $\sim$10 radiation lengths deep. The tungsten in the first 16 layers has a thickness of 2.5 mm ($\sim$0.7 X0), and 1.6 cm in the remaining 6 layers serving as hadron rejecter - shower tail catcher (Fig. **??**). The limited depth of the electromagnetic compartment improves the em/hadron shower discrimination but reduces the energy resolution for high energy showers. This is mitigated by fine lateral granularity in both electromagnetic and hadronic compartments (1.5 × 1.5 cm^2 pixels). Measurements in both compartments can be combined to recover the lost resolution.

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