1. Introduction

The Muon Piston Calorimeter Extension (MPC-EX) is a new detector that will be located in front of PHENIX’s existing Muon Piston Calorimeter (MPC), a lead-tungstate electromagnetic calorimeter. One of the primary goals of the MPC-EX upgrade is to measure forward prompt photons in transversely polarized p+p and p+A collisions. These measurements will provide information on the gluon distributions within nuclei and disclose how transverse momentum and spin within a valence parton relates to the spin of the proton or nucleus.

In these proceedings, potential measurements of forward prompt photons with the MPC-EX detector are presented. First, details of the detector design and functionality will be discussed. Then, the prompt photon measurements in p+Au collisions are described as they provide a mechanism to directly study the gluon parton distribution function inside the nucleus. Next, projections for prompt photon single spin asymmetry measurements, $A_N$, in transversely polarized p+p collisions are reported. These measurements will determine the sign of the Sivers effect. Finally, new opportunities to study the prompt photon $A_N$ in polarized p+A collisions are detailed. This will quantify the changing levels of gluon saturation and the proportion of Sivers and Collins spin effects in various nuclei.

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2. MPC-EX detector

The MPC-EX detector serves as both an electromagnetic preshower and charged particle tracker at forward rapidities, 3.1 < |η| < 3.8. The duplicate functionality of the MPC-EX is possible because a dual gain SVX4 readout is used. The SVX4 readout provides the MPC-EX with the sensitivity to measure minimum ionizing peaks at 70 MeV and access full energy electromagnetic showers. The MPC-EX detector design is composed of eight layers of 2 mm tungsten absorber and 6.2 \times 6.2cm^2 silicon mini-pad sensors with a total depth of around 50 mm. Each mini-pad sensor consists of a 4 \times 32 array of mini-pads and each mini-pad has dimensions of 1.8 \times 15mm^2. The mini-pad layers alternate in x- and y-orientation providing increased position resolution. The combined MPC and MPC-EX system will be able to provide charge track identification and reconstruct neutral pions out to the luminosity limit of energies greater than 80 GeV [1].

Existing forward neutral pion measurements in PHENIX are limited to energies below 20 GeV. Above this energy the pion’s two decay photons merge into a single MPC cluster. With the MPC-EX, the pion reconstruction energy range will be extended by a factor of four to above 80 GeV. This is possible because of the improved position resolution of the early shower energy distribution as a result of the MPC-EX’s mini-pad design. Given the detailed early shower information, the two centers of gravity for each photon shower in a π^0 decay can be identified and the mass is calculated for a single-track mass.

The increased pion reconstruction range provides the ability to separate high momentum neutral pions and prompt photons, making a forward prompt photon measurement possible at PHENIX. Forward prompt photons consist of three types of photons: direct photons produced primarily from quark-gluon Compton scattering, fragmentation photons emitted off a final state quark and QED radiation off of an initial state quark. Pythia simulations [2] are used to simulate these photon sources for the purpose of characterizing our detector response. In the case of direct and fragmentation photons, Pythia produces photons at a comparable level to next-to-leading order parton quantum chromo-dynamics (pQCD) calculations [3]. However, Pythia overestimates the production of QED radiation, which is included in the direct photon contribution in the next-to-leading order pQCD calculations. In the 3.1 < |η| < 3.8 rapidity range, direct photons access high-x quarks in the polarized proton projectile with a range of −0.4 < \log_{10}(x_1) < 0 and low-x gluons in the target proton or nucleus with a range of −3.4 < \log_{10}(x_2) < −1.

3. Prompt photons in p+Au collisions

The gluon distribution in heavy nuclei, such as Au, show a strong suppression at low-x relative to the distributions in the proton called gluon shadowing. Gluon shadowing is thought to explain the suppressed production of forward mesons in d+Au collisions relative to p+p collisions [4]. Theoretical models calculate the gluon nuclear modification factor, \( R_{C}^{A} \), to quantify this relative behavior according to Equation 1,

\[
R_{C}^{A} (x, Q^2) = \frac{1}{A} \frac{x G_{A} (x, Q^2)}{x G_{p} (x, Q^2)}
\]

where \( G_{A} (x, Q^2) \) and \( G_{p} (x, Q^2) \) are the gluon distribution function in the nucleus and the proton respectively and \( A \) is the number of partons in the nucleus.

Two competing pictures simultaneously describe these cold nuclear matter effects in p+Au collisions. These are non-perturbative extensions of pQCD and the color glass condensate (CGC) pictures. Non-perturbative extensions to pQCD use transverse momentum dependent parton distribution functions at low-x, a higher twist shadowing effect, initial state energy loss, absorption, modified structure functions and coherent effects to characterize the cold nuclear matter data [5]. The CGC picture uses a classical treatment of high gluon density characterized
by a saturation scale, $Q_{Sat}$, with the assumption that $\alpha_s$ as a function of $Q_{sat}$ is small. The CGC model predicts suppression at low-x, forward rapidity and central collision due to the resulting increased gluon density [6] [7]. Recent theoretical work has found an equivalence between the transverse momentum dependent parton distribution functions at low-x and the CGC model [8]. This provides hope that a similar equivalence may exist between CGC and higher twist shadowing effects. Reconciling these two pictures is important because they provide fundamental understanding of the partonic processes in nuclei and provide the initial conditions to heavy ion collisions at RHIC and the LHC.

We use EPS09 [9] as a baseline for comparison and to highlight the influence a MPC-EX measurement will contribute to our understanding of the gluon distribution at low-x. EPS09 is a next-to-leading order global analysis of nuclear parton distribution functions using cold nuclear matter data from SLAC, NMC, EMC, DIS, Drell Yan and PHENIX midrapidity $\pi^0$. Currently there are large uncertainties in the gluon nuclear parton distribution at low-x. This is due to a lack of data to characterize the gluon distribution at low-x. MPC-EX measurements at forward rapidities will clarify this low-x region in the EPS09 model and any other model of the behavior of low-x gluons.

By measuring prompt photons at forward rapidities in p+Au and p+p collisions, the nuclear modification factor, $R_{pA}$, can measure the level of gluon shadowing or saturation in nuclei. The prompt photon $R_{pA}$, Equation 2, is defined as the ratio of the prompt yield in p+Au collisions, $\gamma_{pA}^{Prompt}$, over the yield in p+p collisions, $\gamma_{pp}^{Prompt}$, scaled by the average number of binary collisions, $N_{Coll}$.

$$R_{pA} = \frac{1}{N_{Coll}} \frac{\gamma_{pA}^{Prompt}}{\gamma_{pp}^{Prompt}}$$

In particular, prompt photons provide a clear measurement of the gluon distribution as their production is dominated by quark-gluon processes as opposed to hadronic signals that are generated by a variety of processes. However, the prompt photon measurement in p+p and p+Au collisions must contend with large backgrounds from hadrons, neutral pions and other decay photons, primarily $\eta$ decays. This analysis first removes as much of the hadron, $\pi^0$ and decay backgrounds as possible using the shower characteristics in the MPC and MPC-EX. Remaining backgrounds are removed through a double ratio calculation, Equation 3,

$$\gamma_{Prompt} = \gamma_{Incl} \times (1 - 1/R_{\gamma})$$

where $\gamma_{Incl}$ and $\pi^0$ are the inclusive photon and $\pi^0$ yields respectively. $R_{\gamma}$ is the ratio of the measured inclusive photon-to-pion ratio over the known and simulated contributions from hadronic decays relative to the $\pi^0$, Equation 4. This method of background subtraction has previously been used in other analyses within the PHENIX collaboration [10].

$$R_{\gamma} = \frac{(\gamma_{Incl}/\pi^0)_{Meas}}{(\gamma_{Incl}/\pi^0)_{Sim}}$$

To simulate the MPC-EX and MPC system’s ability to measure prompt photons, 868 million minimum bias p+p Pythia events are used with a 16.5 GeV MPC trigger and a 50 cm vertex cut. By limiting our prompt photon candidate sample to the highest energy cluster in the event and high transverse momentum clusters, $p_T > 3$ GeV/c, we reduce much of the neutral pion and hadronic backgrounds. Hadronic backgrounds are further removed by cutting on the energy deposited in the MPC-EX to reject minimum ionizing peaks at around 70 MeV. Clusters that have a single-track mass, described in Section 2, close to that of the pion are clearly single-track $\pi^0$ candidates and are rejected. Hadronic and single track $\pi^0$ showers in the MPC and MPC-EX tend to have wider shower shapes than prompt photon showers, by cutting on these distributions
we can further discard these backgrounds. Additionally, isolation cuts are used to reduce the contribution of fragmentation photons in our prompt photon signal. A multivariate analysis was performed to optimize the MPC and MPC-EX shower shape and isolation cuts.

The resulting prompt photon candidates are shown in Figure 1. Prompt photons have a 30% efficiency, while $\pi^0$ have a 3% efficiency resulting in a 49% signal-to-$\pi^0$ ratio and an $R_\gamma$ value of 1.34. Direct photons from quark gluon Compton scattering make up 57% of the prompt photon signal. Remaining fragmentation photons are produced by quark gluon processes 93% of the time and quark anti-quark processes 7% of the time. The direct photon concentration can be increased by tightening isolation and width cuts; this is discussed in further detail in Section 4.

![Figure 1](image_url)

Figure 1. The $p_T$ distribution of prompt photon candidates. The sum of all remaining candidates is shown in black. The remaining $\pi^0$ and $\eta$ contributions are shown in bright green and olive green respectively. Remaining decay photons, primarily from $\omega$ and $\eta'$ decays, are shown in light blue and hadrons are shown in pink. The prompt photons are shown separately for direct and fragmentation photons in red and blue respectively. The prompt photon measurement considers the projected yields at $p_T$ above 3 GeV; this is noted on the plot with a blue dashed line.

3.1. Systematic errors

Our ability to measure gluon saturation or shadowing effects in forward prompt photon yields in $p+Au$ and $p+p$ collisions is limited not by statistics but by systematic errors. The double ratio method allows for the cancelation of many of these systematic errors. The systematic error in $R_\gamma$ is calculated according to Equation 5,

$$\frac{\delta R_\gamma}{R_\gamma} = \frac{\delta \gamma_{Incl}}{\gamma_{Incl}} + \frac{\delta \pi^0}{\pi^0} + \frac{\delta MC_{Sim}}{MC_{Sim}}$$

where $MC_{Sim}$ is the simulated inclusive photon-to-pion ratio, $R_\gamma$ is defined in Equation 4, and $\gamma_{Incl}$ and $\pi^0$ are the inclusive photon and neutral pion yields.

Given our experience with the MPC [11] and the MPC-EX’s capabilities, the $\pi^0$ contribution can be measured to within an estimated systematic error of 6%, including an absolute energy scale uncertainty of 1 to 2%. A 4% relative systematic error in the Monte Carlo simulation of the inclusive photon-to-pion ratio is consistent with the systematic errors determined in PHENIX’s direct photon measurement [10]. The error in $\gamma_{Incl}$ is dominated by the subtraction of the remaining hadronic background. Because this subtraction is model dependent, a 20% error in the component is assumed, resulting in a 0.65% relative systematic error in $\gamma_{Incl}$. These errors combine to produce a relative error in $R_\gamma$ of 7.22%. This is a correlated error between $p+p$ and $p+Au$ measurements. There are additional uncorrelated systematic errors in $R_\gamma$ and $\gamma_{Incl}$ of 1% and 2% respectively due to shifts in the energy scale in $p+p$ and $p+Au$ collisions. These systematic errors are summarized in Table 1.

These systematic errors characterize the MPC-EX’s ability to constrain the allowable band of gluon modification from EPS09 [9]. Photon events are weighted by their $x_F$ and $Q^2$ according to EPS09 and $R_{pAu}$ values are generated for each of the theoretical curves. The EPS09 central
Table 1. Correlated and uncorrelated systematic errors for the prompt photon measurement in p+p and p+Au collisions with the MPC-EX.

| Quantity | Corr. errors | Uncorr. errors |
|----------|--------------|----------------|
| $R_\gamma$ | 7.22% | 1% |
| $\gamma_{Inc}$ | 0.65% | 2% |
| $N_{Coll}$ | – | 3% |

value of gluon suppression is assumed. The $R_\gamma$ and $\gamma_{Inc}$ in p+p and p+Au collisions are varied within their three sigma systematic errors in each direction. For each EPS09 curve the $\chi^2$ is calculated with the simulated data. These $\chi^2$ values are used to determine which curves are within one sigma and within the 90% confidence level of the simulated data. Figure 2 shows these one-sigma and 90% confidence level regions in for the current EPS09 results (hatched) and with the simulated MPC-EX measurement (dark and light blue). When the minimum or maximum EPS09 values are assumed smaller bands are found.

Figure 2. EPS09 exclusion plots in $R_G$ vs $\log_{10}(x_{gluon})$ using the central EPS09 value. The outer hatched bands are the 90% confidence level region of curves. The light blue area represents the 90% confidence level region with the simulated MPC-EX measurement. The dark blue band is the one-sigma region with the simulated MPC-EX measurement.

4. Prompt photon $A_N$ in transversely polarized p+p collisions

Large transverse single spin asymmetries have been measured at FermiLab [12] and RHIC [13] [14]. A particle’s single spin asymmetry quantifies the left-right bias in particle production as defined in Equation 6,

$$A_N = \frac{1}{P} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

(6)

where $\sigma_L$ and $\sigma_R$ are the left and right particle cross-sections and P is the polarization. The mechanisms that generate these asymmetries are related to the initial state effects such as the Sivers Effect or final state effects such as the Collins Effect. The Sivers Effect is a left-right asymmetry associated with the correlation between the parton’s transverse momentum and the nucleon’s spin [15]. The Collins Effect is again a left-right asymmetry where the bias is
generated by the quark’s transverse spin-dependent fragmentation [16]. Semi-inclusive deep-inelastic scattering (SIDIS) results [17] [18] have constrained these two effects using transverse momentum dependent parton distribution extractions [19] [20]. An alternate extraction of these effects is determined using twist-3 transverse-spin-dependent correlations between quarks and gluons. An unanswered question in the field is the sign of the Sivers Effect. The transverse momentum dependent SIDIS extraction of the Sivers Effect produces negative values while with the twist-3 extraction positive values are produced [21] [22].

Preliminary PHENIX results using the MPC have measured large positive transverse single spin asymmetries in forward neutral clusters [23] and identified $\eta$ mesons [24]. However, these measurements cannot isolate the sources of these single spin asymmetries because they sample multiple partonic processes. With the inclusion of the MPC-EX, the measurement of the prompt photon single spin asymmetry in 200 GeV transversely polarized p+p collisions is possible. The prompt photon single spin asymmetry is dominated by the scattering of a valence quark in the polarized projectile off of a gluon in the proton with only a small contribution for transversity and polarized fragmentation functions [22]. The prompt photon $A_N$ measurement will provide a targeted measurement of the Sivers contribution to the single spin asymmetry. It will determine the sign of the Sivers Effect.

The prompt photon single spin asymmetry, $A_N^{\gamma_{\text{prompt}}}$, must be extracted from the inclusive photon asymmetry, $A_N^{\gamma_{\text{incl}}}$, by removing the non-zero asymmetry contributions from $\pi^0$, $\eta$ and other decay photons. This is done according to Equation 7,

$$A_N^{\gamma_{\text{prompt}}} = (1 + 1/r) A_N^{\gamma_{\text{incl}}} - 1/r A_N^{BG}$$

where $A_N^{BG}$ is the background asymmetry and $r$ is the prompt photon-to-photonic background ratio. Equation 8 can determine our sensitivity to measure $A_N^{\gamma_{\text{prompt}}}$ with the MPC-EX by considering the statistical errors in the inclusive photon and background single spin asymmetries.

$$\left(\delta A_N^{\gamma_{\text{prompt}}}\right)^2 = (1 + 1/r)^2 \left(\delta A_N^{\gamma_{\text{incl}}}\right)^2 + \left(1/r \times \delta A_N^{BG}\right)^2$$

For this calculation we use the projected statistical errors of the inclusive photon analysis detailed in Section 3 assuming 50 $pb^{-1}$ of transversely polarized p+p collisions. The high $p_T$ prompt photon measurement is divided into four $p_T$ bins. Additionally, we assume that the MPC-EX can measure the background asymmetries with a minimum of twice the inclusive photon asymmetry precision in each bin, and we suppose a 60% polarization. The sensitivity of the MPC-EX high-x prompt photon $A_N$ measurement as a function of $x_F$ is shown in Figure 3 compared with the twist-3 extraction of the $A_N$ and two semi-inclusive deep inelastic scattering extractions using alternate functional forms. With the MPC-EX’s projected sensitivity, the sign of the Sivers Effect will be determined.

As the prompt photon $A_N$ is measured, instead of the cleaner direct photon asymmetry, the contributions of fragmentation photons must be considered. By tightening isolation and shower width cuts in the simulated prompt photon analysis, we can increase the direct photon concentration in the prompt photon distribution from 57.4% to 78.6% while maintaining a relatively stable ratio of the prompt photon signal to hadronic decay photon background of between 0.34 and 0.31.

By looking at the prompt photon single spin asymmetry at low-x in 200 GeV transversely polarized p+p collisions, we can learn about the low-x gluon distribution in the proton. There are various models of the tri-gluon correlation functions, $O(x)$ and $N(x)$, that describe the gluon distribution’s spin contribution [25]. These models will be primarily constrained by the open heavy flavor production at RHIC. However, the prompt photon $A_N$ at low-x will serve as a complementary measurement that can further constrain these models.
5. Measurements in polarized $p+A$ collisions
RHIC provides a unique opportunity to study transversely polarized $p+A$ collisions \cite{26}, generating a new class of measurements that will provide information on the saturation scale, $Q_{Sat}$, and potential variations in the Collins and Sivers contributions in nuclei. The prompt photon $A_N$ in polarized $p+A$ collisions may have access to changes in the proportion of Sivers and Collins contributions to the single spin asymmetry. The single spin asymmetry of neutral pions in polarized $p+A$ collisions, $A^{pA}_N$, relative to the $p+p$ single spin asymmetry, $A^{pp}_N$, is expected to probe the saturation scales in $p+A$ and $p+p$ collisions in a color-glass framework. By varying the nuclei collided and the centrality of the collisions, the $p_T$ and $Q_{Sat}^p/Q_{Sat}^{A}$ dependence of the $A^{pA}_N/A^{pp}_N$ ratio can be determined \cite{27}. By measuring these single spin asymmetries at forward rapidities, the MPC-EX will access the kinematic region where $p_T$ is close to $Q_{Sat}$.

6. Conclusion
The addition of the MPC-EX to the PHENIX experiment will provide a variety of new measurements in transversely polarized $p+p$ and $p+A$ collisions at RHIC. The prompt photon measurement in $p+Au$ collisions will clarify the nuclear gluon parton distributions function at low-$x$. This will further our understanding of gluon saturation and shadowing in the nucleus and set the initial conditions for heavy ion collisions at RHIC and the LHC. In transversely polarized $p+p$ collisions, the prompt photon single spin asymmetry will determine the sign of the Sivers Effect. This measurement not only will resolve a conflict in the extractions of the Sivers functions using two different functional forms \cite{21}\cite{22}. The error bars contain the statistical errors and the uncertainties due to subtracting the decay photon background asymmetries.

Figure 3. The sensitivity of high-$x$ prompt photon $A_N$ in $\sqrt{s_{NN}} = 200$ GeV transversely polarized $p+p$ collisions as a function of $x_F$ compared to the twist-3 (red solid line) and semi-inclusive deep inelastic scattering (blue dashed and black dotted lines) extractions of the Sivers functions using two different functional forms \cite{21}\cite{22}. The error bars contain the statistical errors and the uncertainties due to subtracting the decay photon background asymmetries.
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