

Forward Calorimeter Upgrades in PHENIX: Past and Future

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Abstract. Over the past few years, the PHENIX detector has undergone several upgrades in the forward region ($1 < |\eta| < 4$). Initially covered only by the muon arms, the addition of the MPC and the future FOCAL expands on the physics capabilities of the PHENIX detector. The focus of these upgrades is toward a better understanding of the Color-Glass Condensate (CGC) and the interplay between the different components of the proton's spin valence/sea quark and gluon contributions. These proceedings highlight the latest results from the MPC related to the CGC as well the newly proposed forward calorimeter detector, FOCAL. Both detectors aim to constrain the current view of gluon saturation at small x in the Color-Glass condensate framework, through correlations using π^0 's (MPC and FOCAL) and isolated direct photons (FOCAL) at high- p_T over a broad range of pseudorapidity.

1. Introduction

Over the course of the next decade, the Relativistic Heavy Ion Collider (RHIC) will study in detail several physics signals in order to understand the role of gluons within the nucleus. At the forefront of these tasks are the measurements of the gluon density at low- x in cold nuclear matter, the proton spin contribution from gluon polarization, to measure γ -jet correlations in Au+Au collisions, and test predictions for the relation between single-transverse spin in pp and those in DIS. The forward calorimeter upgrades will contribute towards these measurements through π^0 and direct- γ identification, at forward angles, with excellent angular and energy resolution. In these proceedings, the first of these challenges is discussed in detail, although all may be possible measurements with the forward detectors.

2. The PHENIX Detector

Currently, the PHENIX detector is comprised of two broadly defined regions: the central arms and the muon arms. The central arm measurements focus on charged hadrons and electromagnetic showers but have limited angular coverage in both ϕ and η , see Fig. 1. The focus of the forward region is μ (prominently toward J/ψ measurements and other similarly muon-decaying channels). For this, the coverage is symmetric in ϕ and extensive in η (Fig. 1). A series of recently implemented detectors (MPC), the in-progress forward silicon vertex detector, and planned FOCAL detector are paving the way *forward* to perform the measurements we desire to make over the next decade.

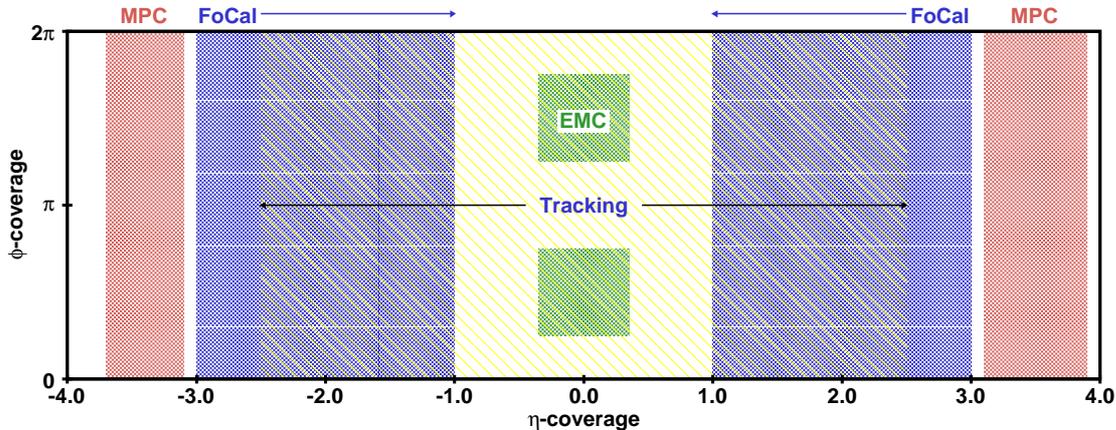


Figure 1. Future coverage of the PHENIX detector after upgrades. The actual coverage of the MPC (red) and EMC (green) are augmented by the proposed FOCAL (blue) and the vertex trackers (yellow hash).

3. The physics challenge

From the $d+Au$ collision program at RHIC, several intriguing results have led theorists to new physics models. In the central region, a region well covered by PHENIX, an enhancement of intermediate- p_T particles (in central collisions relative to peripheral — or relative to pp collisions) is observed, associated to multiple-scattering of soft partons, prior to a hard interaction, giving rise to the *Cronin effect* [1]. In the more forward region a suppression is observed, associated to the *color-glass condensate* (CGC) [2]. The CGC is theorized to arise due to low- x partons, within the gold nucleus, where the nuclear wavefunctions overlap giving rise to saturation and the resultant suppression. This picture is consistent with observations made in electron-proton collisions at HERA [3]. The gold nucleus in $d+Au$ collisions acts as an amplifier to this effect, owing to its thickness. This allows an observation at a larger x than the former $e+p$ collisions, but still of the order of $x \sim 10^{-2} - 10^{-3}$. However, the observation still has to be made at “low- x ”, meaning that at RHIC this measurement will only be accessible at forward angles.

4. MPC contribution to physics goals

For the first collisions of $d+Au$, the PHENIX contribution to the CGC was limited in that the (then) detector measured charged hadrons and photons in the central region [4], later followed by punch-through hadrons [5] and J/ψ [6] measurements at forward angles. In 2006, a new detector, the Muon-Piston Calorimeter was installed. This calorimeter measures energy clusters which may be identified as π^0 's through the direct reconstruction of the invariant mass.

The MPC is a Lead-Tungstate ($PbWO_4$) crystal calorimeter, approximately 18 cm ($20X_0$) long. In the transverse direction, the ~ 200 crystals are segmented into 2.2×2.2 cm blocks. The detector reconstructs π^0 in the low- p_T region (up to $1.7 \text{ GeV}/c$). In reality, owing to the longitudinal boost, this is up to a total energy of about 17 GeV. Above this, as the photons from the π^0 decay merge into a single (inseparable) cluster, only single clusters are measured.

Once the clusters are calibrated and identified, each π^0 is correlated against a trigger π^0 (or charged hadron) from the central arms. Forming the correlation restricts the x range for the hard process to the range $0.006 < x < 0.1$. The *conditional* yields in the MPC are then compared to those from a similar analysis in pp interactions. Figure 2 illustrates the final ratio. For peripheral collisions, at a low number of binary (nucleon-nucleon) collisions, the forward yields are found to be similar to that in pp data (i.e. a ratio close to unity is observed). As expected

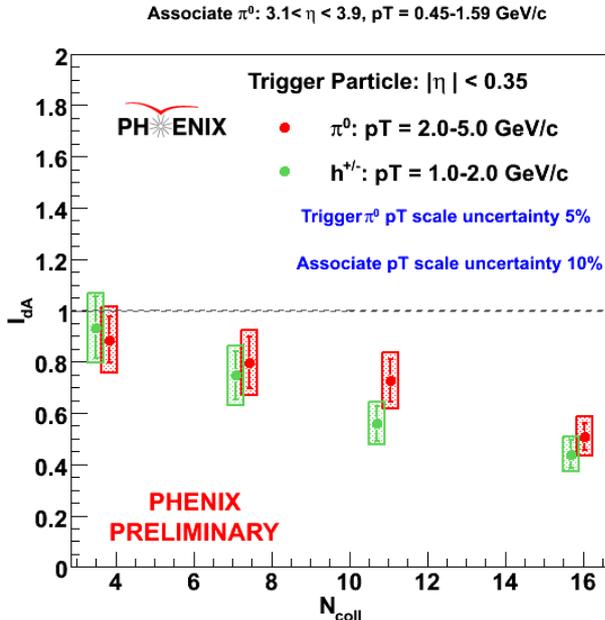


Figure 2. Ratio of conditional yields measured in $d+Au$ collisions divided by that of pp collisions and scaled by the expected number of collisions from the $d+Au$ data.

from the CGC, traversing a thicker nucleus – or thicker part of the nucleus – leads to a larger suppression. More central data (more binary collisions) is suppressed by a factor of two more than the peripheral. This suppression pattern is also observed by other experiments, whereby the central data (those in which the d undergoes the most collisions) are suppressed the most. More details can be found in Ref. [7].

5. A new FOWard CALorimeter: FOCAL

To further our understanding of particle production at forward angles, indeed to access a more direct measure of the color-glass condensate, a new detector (FOCAL) has been proposed. It will measure direct photons at forward angles, and distinguish them from π^0 's. Such a forward measurement, with identified γ , would be unique to the RHIC experiments.

5.1. The FOCAL Detector

FOCAL is a Tungsten-Silicon sampling calorimeter, approximately 16 cm in depth ($\sim 21X_0$) and located ≈ 40 cm from the nominal interaction point. The transverse direction is broken into small (6.2×6.2 cm) *supertowers* which are in turn subdivided into 4×4 pads on the read-out silicon wafers. Longitudinally, the supertowers are split into three segments of seven tungsten-silicon sandwiches (which are summed and read-out as a single signal). In the first segment, eight additional silicon strip wafers are included to facilitate the identification of the direct- γ . These are pairs of x - or y -oriented strips with 128×1 read-outs per wafer (compared to 4×4 in the pads). These strips are located at in the first segment of FOCAL – after $2X_0$, $3X_0$, $4X_0$, and $5X_0$ – in the region where the e.m. showers are in their infancy. Starting the read-out of the strips after two – rather than one – radiation lengths was chosen to optimize the conversion probabilities. The possibility of adding further strip read-out pairs (for example after $6X_0$ or $7X_0$) would not aid in the discrimination of high- p_T π^0 from γ , as the two γ showers from the π^0 begin to spread and merge into each other.

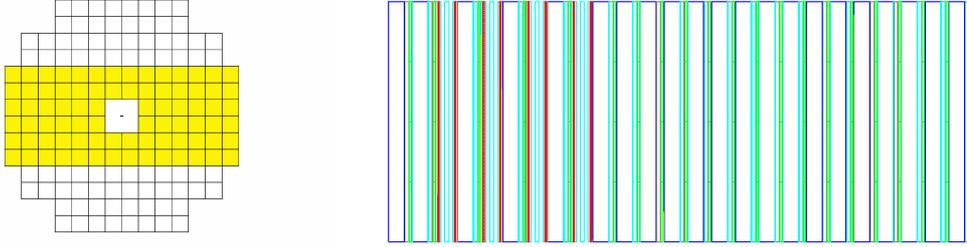


Figure 3. Geometrical layout of FOCAL. The left figure shows the beam-view of the detector, showing the brick structure. Each small square is read-out as a subdivided 4×4 pad. The right figure shows the longitudinal segmentation. The blue represents the tungsten, green shows the position of the pads silicon, and the red shows the strips.

5.2. FOCAL Acceptance

FOCAL will be positioned in the region $1 < \eta < 3$, with the possibility of full azimuthal acceptance. At present, it is proposed to only partially instrument the detector with silicon read-out, shown as yellow in Fig. 3. For reference, from this configuration, for $1.9 < \eta < 3.0$ ($1.5 < \eta < 1.9$) the full azimuth (0.8π) is covered.

The coverage of FOCAL in terms of the fraction of momentum carried by the interacting partons (x) is shown in Fig. 4. The leftmost panel shows the p_T dependence, which is weak, implying that differential measurements in p_T may not further restrict the measured x . The center panel of Fig. 4 shows the η dependence of x . A clear correlation of the gluon-momentum x (labeled x_2) with pseudorapidity is observed. By using FOCAL to probe different photon pseudorapidities, a narrow region of x can be probed. This is further shown in the rightmost panel, where the corresponding x_2 values from narrow slices of η are made. With this detector it is possible to probe x values as low as 10^{-3} . With the MPC (not shown) a slightly lower x

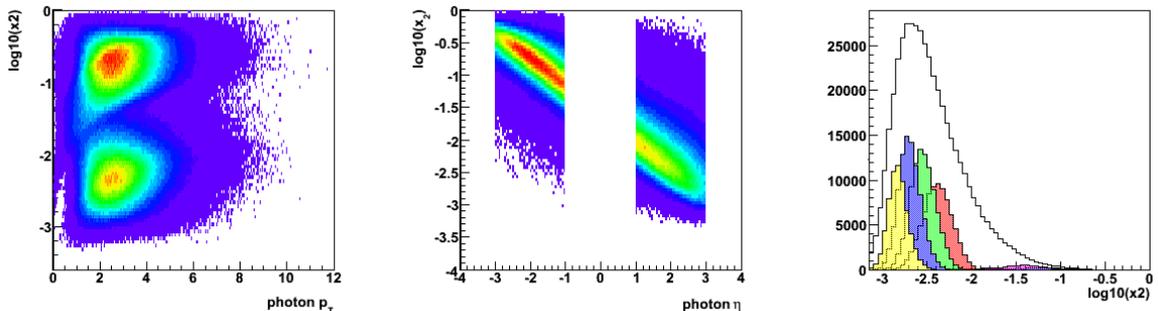


Figure 4. The x coverage of FOCAL. The leftmost panel shows x_2 versus p_T for forward (lower) and backward (upper concentration) photons. The center panel shows the η dependence and the rightmost panel shows x_2 for slices of η in FOCAL.

may be reached owing to its proximity at higher pseudorapidity.

5.3. FOCAL Reconstruction Methods

Reconstruction of showers in FOCAL is divided into two parts: (1) a global reconstruction of the energy, direction, and electromagnetic (e.m.)/hadronic shower discrimination followed by (2) an algorithm to identify π^0 and direct- γ signals. Although FOCAL does not have a mechanically projective geometry, the transversely segmented readout design allows for the tracking of particle showers through the detector in a projective manner: FOCAL is a tracking device. The first part of the reconstruction exploits this fact and utilizes all information available from the whole calorimeter. Clusters in pads and strip layers are used to determine a regression line through seven points in space, corresponding to each pad segment (three) and strip layer (four). A comparison of the candidate track to the features of single and multiple hits in that area completes this part of the reconstruction. However, *this* portion of the reconstruction cannot discriminate two close proximity γ 's (for example from a high energy π^0) and single γ showers.

Isolated showers are expected to reach an energy resolution of $\Delta E/E \sim 23\%/\sqrt{E}$ and an angular resolution of better than $50 \mu\text{rad}$. Discrimination between the e.m. and hadronic showers is made via a χ^2/NDF analysis of the energy deposition and widths in each of the segments, as well as the width in the strips. The expected mean and width is calibrated on a sample of “signal” (see below) simulations which are projected through a full GEANT description of the PHENIX detector and FOCAL. Once established, the same calibrations are applied to all tracks, whether e.m. or hadronic. A larger χ^2/NDF is found for hadronic showers, which either leave a MIP signal (low energy in a given layer) or have a wider shower profile (than e.m.) if a hadronic shower develops.

The second part of the reconstruction concentrates solely on the identification of direct- γ through the rejection of π^0 's. A simplified Hough tracking algorithm is used to track straight line paths through the strip layers of the FOCAL. The x - (or y -) position of all strips in the

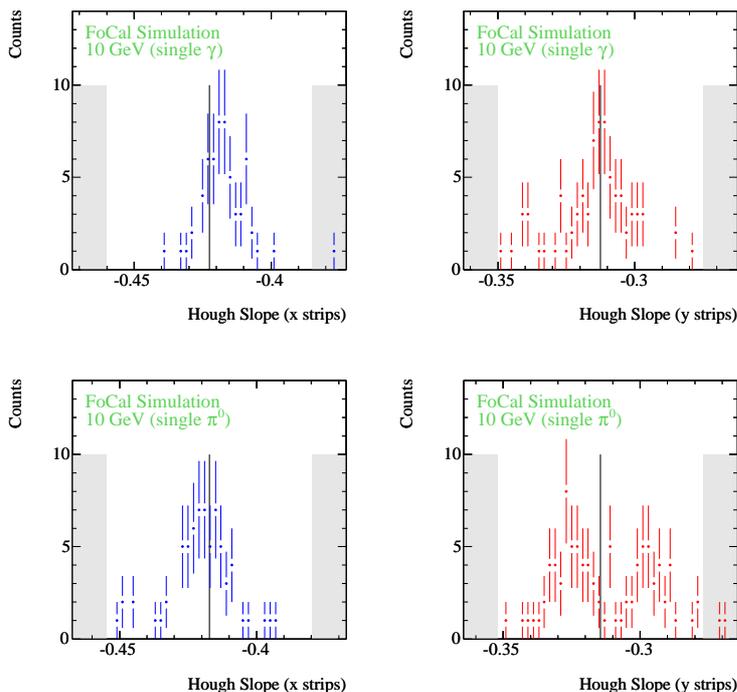


Figure 5. Strip reconstruction of single γ 's (top) and single π^0 's (bottom) for the x/y -direction (left/right). The line in the center represent the reconstructed center of gravity from the pads, the shaded region is the region excluded in the analysis of the strips.

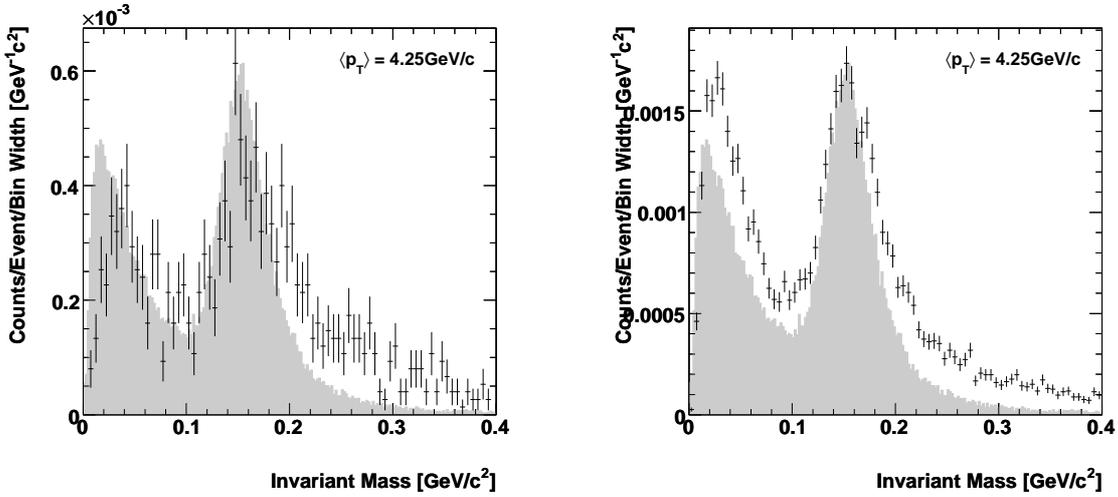


Figure 6. Invariant mass reconstruction of background events (black histogram) in $d+Au$ (left) and pp (right) collisions both at $\sqrt{s_{NN}} = 200$ GeV. For comparison, the grey histogram represents single- γ and π^0 simulations at the same energy. In each sample, the reconstructed transverse momentum is $4.0 < p_T < 4.5$ GeV/c. This corresponds to a total energy of ~ 6.5 (at $\eta=1$) and ~ 26 (at $\eta=2.5$).

vicinity of a reconstructed cluster (in the pads as described above) are divided by their z -position to form a Hough parameter (in this case the slope). Note that only one Hough parameter is calculated, as the collision vertex position is explicitly used in the determination of the first parameter. All Hough parameters (slopes) are histogrammed ready to analyze. Figure. 5 shows the final strip-histograms used in the discrimination of γ and π^0 . The top panels are single-input γ , the bottom are π^0 . The left (right) panels show the x (y) strip layers, all x (y) layers are summed together. The line at the center represents the center-of-gravity reconstructed with the pads (first part described above) and the grey bands represent the edge of the excluded region in the strips analysis, which helps to reduce fake peaks in the full multi-particle HIJING/PYTHIA analysis. Clearly, a two-peak structure is visible in the π^0 (y strips) and is absent in the γ (x and y strips). In such cases, in conjunction with the reconstructed energy, an invariant mass is calculated. Invariant masses reconstructed close to (or above) the π^0 mass are rejected in the analysis. A secondary analysis uses the reconstructed masses close to the expected π^0 mass to directly reconstruct π^0 's.

In the analysis of γ -jet, it is our aim to reject as much of the (predominantly) π^0 background as possible. To fully evaluate this rejection power of the FOCAL for direct- γ analysis, a sample of minimum bias HIJING was used as a background sample, and a second sample of minimum bias HIJING plus an embedded PYTHIA signal (γ +jet) was used to form a “signal” sample in $\sqrt{s_{NN}}=200$ GeV $d+Au$ collisions. Particle distributions resultant from both samples were propagated through full GEANT description of the PHENIX detector, including FOCAL. To evaluate the signal to background in $d+Au$ collisions, the number of signal events were scaled to the level of that expected in data by a factor of $N_{coll} \frac{\sigma_{\gamma-jet}}{\sigma_{inel.pp}} \approx 5 \times 10^{-4}$. At such high E_T in HIJING, the background sample is mostly formed from fragmented jets, embedded γ +jets into the HIJING event are easily visible over the background at modest energies – from about $E=10$ GeV ($E_T \sim 2.7$ GeV at $\eta=2$) – and above this are always selected as the highest energy track (which is used in the analysis).

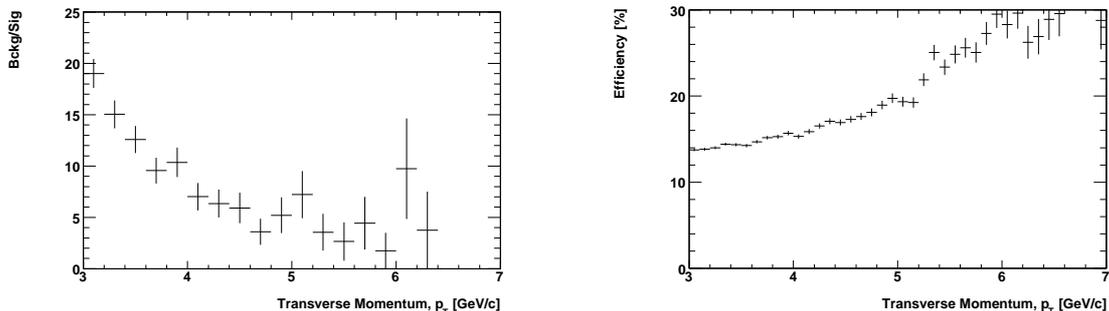


Figure 7. The left panel shows the ratio of background (all particles) to signal (direct- γ) reconstructed tracks, corrected for cross-section in d +Au collisions, on the deuteron-going side. The expected ratio is 5:1 for $p_T > 5$ GeV/ c . For the same p_T , the efficiency (shown on the right panel) is expected to be $\sim 20\%$.

Figure 6 shows a comparison between the reconstructed background (from d +Au and pp collisions) and single-input π^0 . The reconstructed invariant mass, even in the higher multiplicity d +Au background are only slightly altered, with a clear π^0 peak visible. The level at which the algorithm fails to reconstruct the π^0 mass is similar in both cases. In the final analysis, the candidate γ track will be correlated against tracks (as a proxy for jets) in the central arm and in FOCAL. This final candidate sample will contain a significant fraction ($\sim 80\%$) π^0 background, see Figure 7. Note that the correlation in this analysis is explicitly needed to calculate the momentum fraction x associated with the gluon. To evaluate this background, identified π^0 's (for example those seen in Fig. 6) from FOCAL are also correlated to tracks in the central arm or FOCAL, in the same way as for the γ candidates. Analysis is underway to fully evaluate the expected systematic error on the π^0 measurement.

In summary, over the past few years PHENIX has made great strides toward forward measurements to study the properties of the collisions produced at RHIC. With the MPC, we observe a suppression of high- p_T particles (jets) as a function of nuclear thickness traversed in d +Au collisions. With FOCAL, we expect to expand on this by identifying direct- γ to further explore the color-glass condensate. This FOCAL measurement of direct γ 's in d +Au collisions has been shown to reduce the background-to-signal of γ +jet events to a manageable level (5:1).

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