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UNIVERSITY OF CALIFORNIA
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Nuclear Modification of Neutral Pion Production at Low x in $\sqrt{s}=200$ GeV d+Au
and p+p Collisions

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Kenneth Blair Sedgwick

March 2017

Dissertation Committee:

Dr. Richard Seto, Chairperson
Dr. Kenneth Barish
Dr. John Ellison

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The Dissertation of Kenneth Blair Sedgwick is approved:

Committee Chairperson

University of California, Riverside

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In my (protracted) experience as a student I have been fortunate, having accrued a long list of individuals to whom I owe an immense debt of gratitude. First and foremost is my stalwart advisor, Dr. Seto, whose patience and perseverance are remarkable to behold. His commitment to his students is (empirically) boundless; without his encouragement I would have given up long ago. Additionally, I would be remiss were I not to include Dr. Barish, whose support has been invaluable and whose invariably friendly demeanor has helped me to retain my sanity. Over the years I have been privileged to have known and worked with a number of the postdoctoral scholars and graduate students involved with the UCR Heavy Ion/Spin Group: Matt Mendoza, David Kleinjan, Mike Beaumier, Sky Rolnick, Tim Hester, Astrid Morreale, Ondrej Chvala, Richard Hollis, and Aneta Iordanova. Each one is a character in his or her own way—perhaps not an unusual trait for physicists—and I could not have hoped for a more fascinating collection of individuals to spend time with. For their advice, instruction, and friendship I am eternally grateful. The PHENIX collaboration, and in particular those individuals involved with the MPC, must also be included for their tireless assistance, most especially: Matthias Grosse Perdekamp, Mickey Chiu, Beau Meredith, and John Koster.

It would be impossible to convey, in the space of just a few sentences, the sheer magnitude of the support my parents have given me in pursuit of my academic goals. *Preternatural* may be a word not often used in physics dissertations but I can think of no more appropriate adjective to describe their selfless enthusiasm at helping me to succeed. I have never once had to wonder whether they would be available or willing to offer assistance, which might entail, for example: driving for hours on end to transport me to the defense of

my dissertation, dropping me off at or picking me up from the airport at all hours and on short notice, thanklessly helping me with mundane tasks so that I might have more time to study, or even just leaving me to work on my own despite their having an unquenchable desire to *do* something to help. Whatever I have achieved is a testament to their undying love and perpetual advocacy.

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ABSTRACT OF THE DISSERTATION

Nuclear Modification of Neutral Pion Production at Low x in $\sqrt{s}=200$ GeV d+Au and p+p Collisions

by

Kenneth Blair Sedgwick

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, March 2017
Dr. Richard Seto, Chairperson

Nuclear modification factors quantify suppression in particle production due to nuclear effects. They are defined as a ratio of invariant yields, with a numerator derived from a given species of nuclear collision and a denominator derived from a hypothetically equivalent ensemble of independent proton-proton collisions. At large momentum transfer Q^2 and low momentum fraction x , the neutral pion nuclear modification factor $R_{\text{d+Au}}$ for d+Au collisions is useful for investigating initial state gluon saturation. The large initial state gluon multiplicity of the Au nucleus causes saturation effects to occur at lower energies in d+Au collisions, as compared to p+p collisions, resulting in a relative suppression. Measuring the relative suppression $R_{\text{d+Au}}$ can therefore test the validity of competing models describing saturation, including the framework of a color glass condensate (CGC).

Measurements at low x are of particular interest because in this region linear pQCD evolution equations begin to break down. The Froissart theorem places a robust theoretical upper limit on the behavior of hadronic cross sections: a cross section can increase at most like $\ln^2 E$. Equivalently, an hadronic structure function can increase at most like $\ln^2(1/x)$.

Adherence to this theorem is necessary to preserve S -matrix unitarity; no physical system should exhibit behavior to the contrary. However linear evolution equations, which dictate structure function behavior, predict an unchecked growth of low- x gluons, in violation of the theorem. For this reason, it is expected that gluon saturation, via non-linear evolution, will take place at low x to steer the gluon distribution function back within the limitations of the Froissart bound.

Greater suppression is expected at lower Q^2 ; however, at low x , regions of high Q^2 are more difficult to access experimentally. Pushing out to higher Q^2 is important for discriminating between competing theoretical models.

In practice, regions of low x and high Q^2 translate to measurements at, respectively, high rapidity η and high transverse momentum $p_\perp$. The high rapidity $3.1 < \eta < 3.9$ Muon Piston Calorimeter (MPC) detector at PHENIX is ideally suited for measurements of neutral pion R_{d+Au} probing regions of low x . At $\sqrt{s} = 200$ GeV, a combinatoric analysis of neutral pion decay products in the MPC can obtain measurements of R_{d+Au} up to a transverse momentum of $p_\perp = 2$ GeV/ c . However, at $p_\perp$ greater than 2 GeV/ c , photons from neutral pion decay have insufficient spatial separation to be independently resolved in the detector. In this analysis the transverse momentum range of the detector, measuring R_{d+Au} at $\sqrt{s} = 200$ GeV, is extended to $p_\perp = 3.5$ GeV/ c by studying photon pairs from neutral pions that resolve in the MPC as a single cluster. Increased suppression is reproduced at low $p_\perp$, in agreement with previous data. For $p_\perp > 2$ GeV/ c Cronin enhancement is not observed, as anticipated by the CGC framework. However, the data can not rule out the possibility that the observed suppression is the result of extreme nuclear shadowing. Also

presented are invariant neutral pion yields for p+p and d+Au collisions and the invariant neutral pion cross section for p+p collisions at $\sqrt{s} = 200$ GeV.

Contents

List of Figures	xi
List of Tables	xiv
1 Introduction	1
1.1 Saturation at Low x	1
1.2 The Color Glass Condensate	5
1.3 The Cronin Effect	9
1.4 Motivation	10
2 Experimental Apparatus	13
2.1 The Relativistic Heavy ion Collider	13
2.1.1 Overview	13
2.1.2 Stochastic Cooling	14
2.1.3 Rigidity and Asymmetric Hadrons	15
2.1.4 The Acceleration Chain	17
2.2 PHENIX	17
2.2.1 Muon Spectrometer Arms	20
2.2.2 Central Arm Spectrometers	22
2.2.3 Global Event Detectors	22
2.2.4 Centrality and N_{coll} Determination	23
2.3 The Muon Piston Calorimeter	26
2.3.1 Calibration	31
2.3.2 Clustering and Reconstruction	34
3 Measurements	39
3.1 Particle Identification	40
3.2 Data Quality	42
3.2.1 Warn Map	42
3.2.2 Neutral Pion Yield	43
3.2.3 Neutral Pion Mean Invariant Mass	44
3.2.4 Pair Acceptance Function	47
3.3 Merged Cluster Analysis Details	48

3.3.1	ADC Overflow Cut	50
3.3.2	Efficiency	55
3.3.3	Bin Smearing Correction	56
3.3.4	Bias Correction Factor	59
3.3.5	Bin Shift Correction	60
3.4	Systematic Error	61
4	Results	65
4.1	Invariant Yields	65
4.2	Invariant p+p Cross Section	67
4.3	Nuclear Modification Factors	68
5	Conclusion	71
	Bibliography	77

List of Figures

1.1	Feynman diagram depicting deep inelastic scattering. The lepton momenta before and after the collision are k and k' , respectively, and the proton momentum is p . The momentum transfer of the virtual photon is $Q^2 \equiv -q^2$.	3
1.2	Parton distribution functions of the proton for $Q^2 = 10$ GeV, from HERA deep inelastic scattering. The gluon and sea quark distributions are reduced by a factor of 20.	4
2.1	Schematic diagram of the RHIC accelerator complex.	18
2.2	Schematic diagram of the PHENIX experiment as it appeared in 2008. Detector volumes are highlighted in green while magnet volumes are shown in gray.	20
2.3	The BBC charge sum distribution for Run 8 d+Au collisions. Open circles represent PHENIX data while the filled histogram is from the Glauber model simulation. Each color in the filled histogram denotes a different centrality class. From right to left, the centrality classes are 0% to 20% (red), 20% to 40% (green), 40% to 60% (blue), and 60% to 88% (yellow).	27
2.4	N_{coll} distributions for each centrality class. Although centrality is defined in terms of the BBC charge sum, the physical relevance of centrality is expressed in these distributions.	28
2.5	Diagram of an MPC tower showing 1) the APD and preamp, 2) the aluminum APD holder, and 3) the PbWO ₄ crystal.	31
2.6	The south and north MPC detectors rendered isometrically.	32
2.7	MPC position resolution for single photons as a function of simulated photon energy, obtained via PISA simulations.	38
2.8	Position resolution in the MPC varies with reconstructed position. Shown here is the RMS deviation in reconstructed position $(\Delta r)_{\text{RMS}}$ for PISA-simulated single photons with energies between 10 and 20 GeV. The hexagonal pattern mimics the shape of the BBC frame.	38

3.1	Composition of MPC clusters as a function of cluster $p_{\perp}$ for p+p collisions at $\sqrt{s} = 200$ GeV. This data was obtained from simulation and checked against experimentally determined cross sections. The clusters included here are subject to a cut, $x_F > 0.4$, on the Feynman scaling variable $x_F = 2p_z/\sqrt{s}$. The resulting composition is representative of the neutral pion merged cluster contribution in general at high $p_{\perp}$	41
3.2	Warn maps for a.) the north MPC and b.) the south MPC. Towers represented by red squares are excluded from the analysis.	43
3.3	Per-event neutral pion yield vs. run number for a.) minimum bias p+p and b.) minimum bias d+Au data. The red lines delineate the range of acceptable yields.	45
3.4	Neutral pion mean invariant mass values for a.) minimum bias p+p and b.) minimum bias d+Au data in the 60% to 88% centrality range. The red lines delineate the range of acceptable values. The width of each invariant mass peak is indicated by the gray data points, which are plotted one standard deviation below the mean.	46
3.5	Pair acceptance functions versus run number for neutral pions paired with high energy clusters in the MPC. The data sets are a.) p+p and b.) d+Au. Acceptance is plotted on the color axis. Each acceptance function has been normalized to have an average value of 1.	49
3.6	Acceptance χ^2/NDF versus run number for a.) p+p and b.) d+Au data. The red lines indicate the maximum acceptable χ^2/NDF for each data set.	50
3.7	Uncorrected distributions of neutral pion merged clusters per event for d+Au collisions in the a) north MPC and b) south MPC.	51
3.8	Uncorrected distributions of neutral pion merged clusters per event for p+p collisions in the a) north MPC and b) south MPC.	52
3.9	ADC distribution for a single tower. The ADC overflow peak is filled red. The red line, which is not a component of the histogram, denotes the ADC overflow value for this tower.	54
3.10	ADC overflow values versus tower channel ID. The broken line separates south MPC towers, to the left, from north MPC towers, to the right.	54
3.11	For each run, the lowest ADC cutoff energy for any tower is plotted in blue, for the north MPC, and red, for the south MPC.	55
3.12	Embedding efficiencies for the north MPC for a.) p+p events, b.) d+Au events. Efficiencies for d+Au data are separated by centrality class.	56
3.13	Embedding efficiencies for the south MPC for a.) p+p events, b.) d+Au events. Efficiencies for d+Au data are separated by centrality class.	57
4.1	Neutral pion invariant yields for d+Au and p+p collisions in the a.) north and b.) south MPC. Measurements in d+Au collisions are separated by centrality class. The statistical error bars in these figures are small enough to be invisible on most data points.	66
4.2	Neutral pion invariant cross section for p+p collisions in the a.) north and b.) south MPC.	67

4.3	Neutral pion nuclear modification factors as measured in the a.) north and b.) south MPC. Measurements in d+Au collisions are separated by centrality class. Merged cluster results are plotted as closed circles. Also shown, as open squares, are nuclear modification factors obtained via invariant mass reconstruction, as a point of comparison. Statistical error is represented by error bars; systematic error is plotted as shaded bands.	69
4.4	Minimum bias neutral pion nuclear modification factors as measured in the a.) north and b.) south MPC. Statistical error is represented by error bars; systematic error is plotted as a shaded band.	70
5.1	Model predictions of R_{d+Au} for $\sqrt{s} = 200$ GeV d+Au collisions at $\eta = 3.2$. In Figure a.) [21] the red line, exhibiting Cronin enhancement, represents a prediction of neutral pion R_{d+Au} based on pQCD calculations in a multiple scattering framework that incorporates nuclear shadowing. The dotted line omits multiscattering effects. Figure b.) [43] plots R_{d+Au} predictions for charged hadrons in the context of a CGC; a common feature is the absence of a Cronin maximum. The dotted line is $(h^+ + h^-)/2$ while the other lines are h^- with varied model parameters. Figure c.) [67] plots R_{d+Au} predictions in a multiple scattering framework parameterized for extreme shadowing; these exhibit suppression comparable to the CGC calculations. The dashed line is for charged pions, the dot-dashed line for kaons, the dotted line for protons and antiprotons, and the solid line for all charged hadrons. In every figure the data points are BRAHMS minimum bias h^- measurements.	73
5.2	Superposition of model predictions, from Figure 5.1, and the minimum bias measurement of R_{d+Au} in the north MPC. The red line corresponds to Figure 5.1-a: neutral pions in a multiple scattering framework with nuclear shadowing. The blue line corresponds to Figure 5.1-b: $(h^+ + h^-)/2$ in the CGC framework. The black line corresponds to Figure 5.1-c: charged pions in a multiple scattering framework parameterized for extreme shadowing.	74
5.3	STAR neutral pion R_{d+Au} for minimum bias collisions at $\sqrt{s} = 200$ GeV and $\langle\eta\rangle = 4.00$, shown as open circles, superimposed onto the minimum bias R_{d+Au} measurement for the north MPC. Error bars on the STAR data represent statistical error; shaded boxes represent systematic error.	75

List of Tables

2.1	Selected properties of MPC PbWO ₄ crystals.	30
3.1	Conditions on MPC clusters for inclusion in the analysis.	42
3.2	Bias correction factors normalized to N_{coll}	60
3.3	Relative global systematic error for invariant yield and $R_{\text{d+Au}}$. The included values for $C_{\text{bias}}/N_{\text{coll}}$ and $\sigma_{[C_{\text{bias}}/N_{\text{coll}}]}$ are used to calculate the $R_{\text{d+Au}}$ error.	64
3.4	Relative systematic error from all sources for the invariant neutral pion yield.	64
3.5	Relative systematic error from all sources for $R_{\text{d+Au}}$	64

Chapter 1

Introduction

Nuclear modification factors quantify suppression in particle production due to nuclear effects. They are defined as a ratio of invariant yields, with a numerator derived from a given species of nuclear collision and a denominator derived from a hypothetically equivalent ensemble of independent proton-proton collisions. At large momentum transfer Q^2 and low momentum fraction x , the neutral pion nuclear modification factor $R_{\text{d+Au}}$ for d+Au collisions is useful for investigating initial state gluon saturation. The large initial state gluon multiplicity of the Au nucleus causes saturation effects to occur at lower energies in d+Au collisions, as compared to p+p collisions, resulting in a relative suppression. Measuring the relative suppression $R_{\text{d+Au}}$ can therefore test the validity of competing models describing saturation, including the framework of a color glass condensate (CGC).

1.1 Saturation at Low x

The Bjorken variable x was developed in the context of deep inelastic scattering, where it was found that proton structure functions depended not on the resolution scale

Q^2 but, instead, on certain dimensionless variables, of which x is one. This phenomenon is known as Bjorken scaling. Independence from the resolution scale suggested that the proton substructure was truly point-like. This discovery, along with the concept of partons, introduced by Feynman around the same time, would ultimately lead to the development of quantum chromodynamics (QCD). The definition of x is

$$x \equiv \frac{Q^2}{2p \cdot q}, \quad (1.1)$$

where p is the target four-momentum and q is the momentum transfer of the virtual photon, as shown in Figure 1.1. In the infinite momentum frame, the rest frame of the electron in deep inelastic scattering, x is equivalent to the fraction of the proton momentum that participates in the interaction. Hence, in the context of high energy scattering, x is typically referred to as the momentum fraction.

Given that x represents a momentum fraction, parton distribution functions $q(x, Q^2)$ can be viewed as the probability, at fixed Q^2 , of finding a parton of a particular flavor carrying a fraction of the hadron momentum between x and $x + dx$. Therefore, they are intrinsic properties of the hadron itself. For example, parton distribution functions for the proton are shown in Figure 1.2 for $Q^2 = 10 \text{ GeV}$. These functions have been extracted, using the pQCD evolution equation DGLAP, from deep inelastic scattering data from the HERA electron-proton collider and other sources [61]. In the quark-parton model, hadronic cross sections are expressed in terms of structure functions which are, in turn, expressed in terms of the parton distribution functions.

Measurements of $R_{\text{d+Au}}$ at low x are of particular interest because in this region linear pQCD evolution equations begin to break down. The Froissart theorem places a

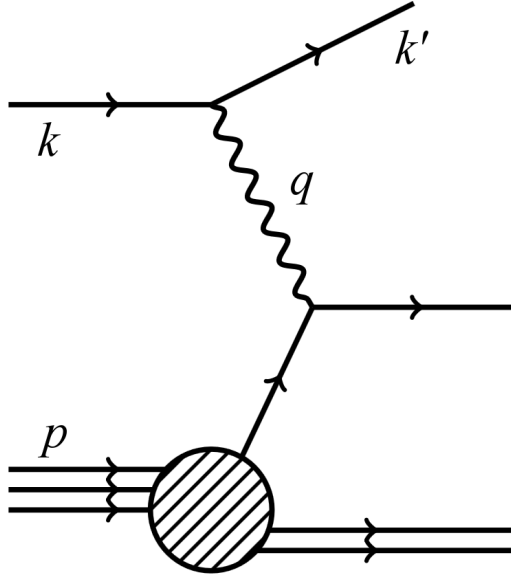


Figure 1.1: Feynman diagram depicting deep inelastic scattering. The lepton momenta before and after the collision are k and k' , respectively, and the proton momentum is p . The momentum transfer of the virtual photon is $Q^2 \equiv -q^2$.

robust theoretical upper limit on the behavior of hadronic cross sections: a cross section can increase at most like $\ln^2 E$. Equivalently, an hadronic structure function can increase at most like $\ln^2(1/x)$. Adherence to this theorem is necessary to preserve S -matrix unitarity; no physical system should exhibit behavior to the contrary. However, linear evolution equations, which dictate structure function behavior, predict an unchecked growth of low- x gluons, in violation of the theorem. For this reason, it is expected that gluon saturation, via non-linear evolution, will take place at low x to steer the gluon distribution function back within the limitations of the Froissart bound. Greater suppression is expected at lower Q^2 ; however, at low x , regions of high Q^2 are more difficult to access experimentally. Pushing out to higher Q^2 is important for discriminating between competing theoretical models.

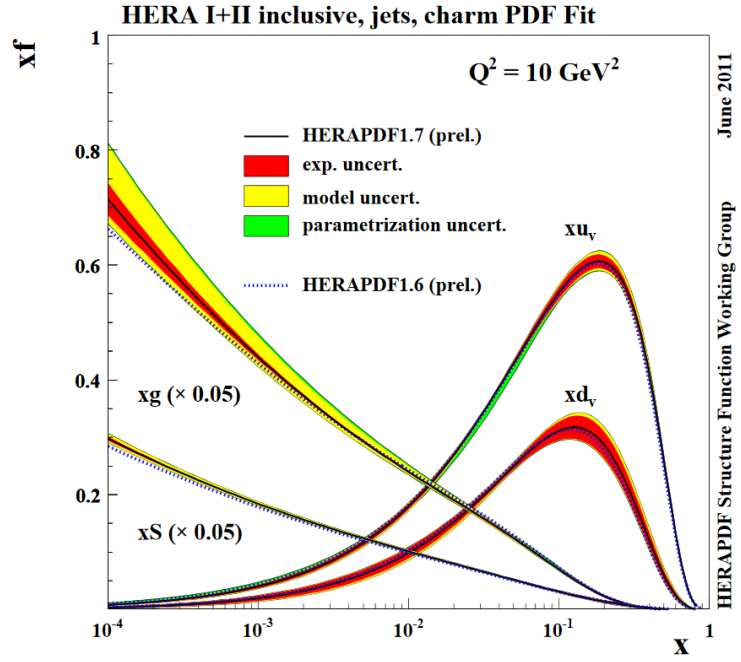


Figure 1.2: Parton distribution functions of the proton for $Q^2 = 10 \text{ GeV}$, from HERA deep inelastic scattering. The gluon and sea quark distributions are reduced by a factor of 20.

1.2 The Color Glass Condensate

Parton distribution functions are obtained from data at a transverse scale Q_0^2 and evolved to a general transverse scale Q^2 via pQCD evolution equations such as DGLAP [35][13][31] and BFKL [63]. DGLAP operates by selecting and summing contributions that appear as terms of $(\alpha_s \ln Q^2)^n$. These terms are the most significant because a large Q^2 compensates for the smallness of α_s . DGLAP is applicable where $1/x$ and Q^2/Q_0^2 are large, as is the case for deep inelastic scattering, where Q_0^2 corresponds to the proton mass. In the case of high energy scattering, however, $Q^2 \simeq Q_0^2$ and terms enhanced by $\ln Q^2$ no longer dominate. Instead, it becomes necessary to sum terms $(\alpha_s \ln 1/x)^n$ enhanced by the smallness of x , and this is what is done in BFKL. Both DGLAP and BFKL are linear, meaning they contain only terms that are independent of parton density. As a result, they break down in regions of high parton density where saturation is expected to occur.

There are a number technical approaches that incorporate saturation, each of which may be viewed as a differing interpretation of the same phenomenon. An example is gluon recombination. Gluon recombination can be attained via the introduction of non-linear terms into pQCD evolution equations. The resulting non-linear equations, e.g. JIMWLK [41] and Balitsky-Kovchegov (BK) [48][19], incorporate destructive interference interactions that arise at high gluon density and naturally limit gluon multiplicity. Essentially, the linear terms generate gluon emission and the non-linear terms introduce corrections representing the potential for gluon recombination. A saturation scale Q_s naturally arises where the recombination and emission terms are of the same order. Additionally, this approach suggests an intuitive geometric interpretation of saturation as the overlapping of gluon wavefunctions in the transverse plane. Phenomenologically, however, non-linear

evolution equations have limitations in that they are derived in limits of x and Q^2 that are difficult to access experimentally [11].

Another approach, the MV model [51][52], developed by McLerran and Venugopalan, exploits the large gluon density within a relativistic nucleus to calculate parton distribution functions in a classical way. In such an environment high occupation numbers allow partons at low x to be treated as a classical charge distribution $\rho(x)$. Degrees of freedom are sorted into two categories: Lorentz contracted and time dilated static valence color charges, described by $\rho(x)$, and soft dynamical gluon fields $\mathcal{A}$. This is necessary because in the saturation regime interactions are governed by weakly-coupled dynamics but in the presence of large gluon fields $\mathcal{A} \sim 1/g$, where $g = \sqrt{4\pi\alpha_s}$, that are inherently non-perturbative. The gluon field $\mathcal{A}$ is analogous to the electromagnetic four-potential; large gluon fields imply high gluon densities, and vice versa [11]. The contribution of the valence charges to the system is weighted by a Gaussian density of states:

$$W_{MV}[\rho] = \exp\left(-\frac{1}{2\mu^2} \int d^2x_{\perp} \rho^2(x)\right), \quad (1.2)$$

where μ^2 is the average charge density per unit area [51]. Observables can be calculated by averaging over all charge configurations ρ while ignoring quantum interference between the configurations. Parton distributions found in this way exhibit saturation; however, the non-perturbative nature of the MV model can limit its predictive power. Often, it is used to obtain initial conditions and calculations are then handed off to perturbative QCD evolution equations to obtain hadron wavefunctions at lower x [11].

Lastly, at high energies multiple scattering may be assumed to have a negligible effect on the transverse position of a parton. This makes it possible to approximate parton trajectories as straight lines, in what is known as an eikonal approximation. The effect is

to greatly simplify the calculation of cross sections for hadrons incident on a nuclear target, as the parton trajectory can be treated as a special direction. In this approximation, Wilson lines, path-ordered exponentials of gluon fields, are used to represent partons as they propagate through a gluon-dense target. Classical techniques, in particular the MV model, can be used to describe the charge distribution of the nuclear target, allowing for the construction of a scattering matrix. A general result of such calculations is that color dipoles with a transverse size much larger than an inverse saturation scale $1/Q_s$ are nearly all absorbed in inelastic interactions within the target; conversely dipoles much smaller than $1/Q_s$ are nearly all allowed to pass through the target unaltered [11].

The color glass condensate (CGC) [40][68][34] is an effective theory engineered to facilitate the investigation of saturation effects that incorporates all of these approaches into a single framework. Just as in the MV model, degrees of freedom are sorted into static valence charges and soft fields occupying low x . The boundary between the two categories is an arbitrary transverse momentum Λ^+ ; however, the theory neutralizes the arbitrariness by employing a Wilsonian renormalization group procedure with the ability to shift Λ^+ to other values systematically. To accomplish this, dynamical modes in a range of momentum adjacent to the boundary are integrated out and the valence charge distribution $W_{\Lambda^+}[\rho]$ is modified, using B-JIMWLK, to incorporate their contribution to observable quantities. In this way, the quantum fluctuations are effectively moved from the QCD side of the theory to the classical side. Evolution in the CGC is handled by JIMWLK or the equivalent Balitsky hierarchy. The BK equation can be used as a convenient approximation to these equations, providing a powerful analytical tool for phenomenological analyses [11]. Because of its ability to fold quantum corrections into a classical calculation, the CGC effective theory

has enjoyed great phenomenological success describing, in terms of non-linear dynamics, small- x data in the heretofore intractable, non-perturbative saturation regime. It provides a unified quantitative framework with good results in a wide range of collision systems, from electron-proton to nucleus-nucleus. For these reasons it is considered to be a leading contender among theories that attempt to describe the saturation regime [11]. Higher order calculations using the CGC are still difficult, but significant progress has been made in deriving next-to-leading order (NLO) corrections. For example, NLO evolution equations have been found [20] [49] and have resulted in greater agreement between theory and data [11].

Alternatives to the CGC formalism incorporate essentially the same ingredients but with differing approaches. Coherence effects manifesting due to high gluon density at low- x are ubiquitous, suggesting that recombination and gluon saturation indisputably play a role in any successful theoretical description of the current data [11]. String fusion, nuclear shadowing, and multiple scattering are examples of proposed alternatives to non-linear recombination for generating coherence either at the nucleon or sub-nucleon level [11]. As one example of a competing framework, the nuclear parton distribution (nPDF) [32][37] approach is a minor modification to the leading twist formalism that uses nuclear PDFs obtained by applying scaling factors to nucleon PDFs. DGLAP handles evolution in Q^2 , while x -dependence is extracted through the fitting of data. Higher twist corrections are possible but can be computationally intensive. This framework generates suppression at low- x of the gluon PDF but its reliance on scarce low- x nuclear data to extract x -dependence limits its precision. Among competing theories, CGC has the largest body of

phenomenological support; however there is much debate regarding which theory is best suited to the description of the initial state of relativistic nuclei.

1.3 The Cronin Effect

Experiments have demonstrated that relativistic heavy ion collisions are very different from scaled nucleon-nucleon collisions. This suggests that non-linear corrections should play a major role in describing data at current collision energies. With respect to single particle production, nuclear effects are typically expressed in terms of nuclear modification factors R_{B+A} which are ratios of the particle yields, for instance R_{d+Au} :

$$R_{d+Au} = \frac{1}{N_{\text{coll}}} \cdot \frac{d^2 N_{d+Au}/dp_{\perp} dy}{d^2 N_{p+p}/dp_{\perp} dy}, \quad (1.3)$$

where N_{coll} is the number of binary, i.e. nucleon-nucleon, collisions in the d+Au collision. A nuclear modification factor equal to unity would indicate that a heavy ion collision behaves identically, in terms of single particle production, to a simple collection of nucleon-nucleon collisions.

A feature known as the Cronin effect can be observed as a hardening of the hadronic $p_{\perp}$ spectrum in nuclear collisions as compared to binary scaled proton-proton collisions. Specifically, nuclear modification factors $R_{BA}(p_{\perp})$ frequently exhibit an enhancement in the range of $1 \text{ GeV}/c \lesssim p_{\perp} \lesssim 2 \text{ GeV}/c$ and a suppression at lower $p_{\perp}$. The prevailing explanation for this phenomenon is that multiple scattering within the nucleus may impart additional transverse momentum to incoming partons, thereby shifting a portion of the hadronic spectra to higher $p_{\perp}$.

Technically, the Cronin effect is defined as a divergence in the total invariant cross sections for hadrons in $p + A$ reactions as compared to binary scaled $p + p$ reactions. However, it is possible to generalize the formulation to $d + Au$ collisions [66]. The effect is parameterized by a Cronin power $\alpha(p_\perp)$ such that $R_{pA}(p_\perp) = A^{\alpha(p_\perp)-1}$. The same relation can be used in the case of $d + Au$ without modification, under the assumption that extra scattering on the deuteron does not make a significant contribution [66]. Empirically, there is a systematic reduction in the Cronin effect with increasing $\sqrt{s}$. Also, the Cronin effect exhibits flavor dependence; it is, for instance, more pronounced for kaons and protons [66].

1.4 Motivation

In practice, regions of low x and high Q^2 translate to measurements at, respectively, high rapidity η and high transverse momentum $p_\perp$. The high rapidity $3.1 < \eta < 3.9$ Muon Piston Calorimeter (MPC) detector at PHENIX is ideally suited for measurements of neutral pion R_{d+Au} probing regions of low x . At $\sqrt{s} = 200$ GeV, a combinatoric analysis of neutral pion decay products in the MPC can obtain measurements of R_{d+Au} up to a transverse momentum of $p_\perp = 2$ GeV/ c . However, at $p_\perp$ greater than 2 GeV/ c , photons from neutral pion decay have insufficient spatial separation to be independently resolved in the detector. In this analysis the transverse momentum range of the detector, measuring R_{d+Au} at $\sqrt{s} = 200$ GeV, is extended to $p_\perp = 3.5$ GeV/ c by studying photon pairs from neutral pions that resolve in the MPC as a single cluster. Increased suppression is reproduced at low $p_\perp$, in agreement with previous data. For $p_\perp > 2$ GeV/ c Cronin enhancement is not observed, as anticipated by the CGC framework. However, the data can not rule out the possibility that the observed suppression is the result of extreme nuclear shadowing. Also

presented are invariant neutral pion yields for p+p and d+Au collisions and the invariant neutral pion cross section for p+p collisions at $\sqrt{s} = 200$ GeV.

As experimental analyses become more refined, the need for an accurate theoretical understanding of the nuclear initial state grows ever more critical. In particular, an understanding of the low- x gluon distribution functions of colliding nuclei is crucial to an accurate description of the thermal medium generated by a heavy ion collision. Extracting transport coefficients—e.g. the ratio of shear viscosity to entropy density—requires the measurement of bulk observables which cannot be accomplished with reasonable precision unless initial conditions are accurately quantified. This, in turn, requires a reliable theoretical formalism to evolve distributions in the saturation regime [11]. As another example, unexpected structure in recent event-by-event analyses of angular correlations still requires adequate explanation. The suspected culprit is the presence of fluctuations in the energy density of colliding nuclei, which may be able to influence final state distributions by means of collective flow; theoretical sources of initial state fluctuations have yet to be given a proper description [11]. Lastly, observables such as nuclear modification factors R_{AA} can be used to probe the matter produced in heavy ion collisions. However, they are susceptible to large influences from initial state effects. Therefore, an accurate characterization of the post-collision medium once again requires a reliable theory of the initial state, in this case to separate initial from final state effects.

Collisions in d+A are better suited than A+A for investigating gluon structure functions and saturation effects since the d+A collisions are assumed to be free from the influence of strong final state QGP effects¹. However, to date available measurements of nu-

¹Recently, this has been called into question [4].

clear modification factors are unable to clearly differentiate between competing theoretical models of nuclear initial conditions [11]. Expanding measurements of nuclear modification factors into still unexplored kinematic regions provides an additional lever arm to constrain these competing frameworks. In conjunction with measurements of single and double inclusive hadron production such investigations may eventually allow for the discrimination of an accurate effective theory.

Chapter 2

Experimental Apparatus

2.1 The Relativistic Heavy ion Collider

2.1.1 Overview

The Relativistic Heavy Ion Collider (RHIC) was constructed with the primary physics objective of observing a deconfined phase of nuclear matter theorized to exist in the presence of extreme temperatures and densities: the quark-gluon plasma (QGP) [36]. Experiments at RHIC achieved this goal, at least in part, with data collected in 2004 that established the existence of a new state of matter in the aftermath of Au+Au collisions: an extended medium of color charges, characterized by ideal fluid flow, that defies description in terms of hadronic degrees of freedom [7][3][16][18]. Nevertheless, questions remain regarding the true nature of the medium, prompting continued research into its properties and the into the initial conditions that precede it. Additionally, as the only heavy ion collider ever built with the ability to collide spin-polarized protons, the importance of RHIC to spin physics is tremendous. Therefore, a large portion of the research undertaken at RHIC focuses on

unraveling the spin structure of the proton. In the near future a major upgrade, eRHIC, will enable polarized electron-ion collisions. Hailed as "the next QCD frontier," this capability will allow experiments at RHIC to explore gluon saturated regimes with unprecedented resolution by using the electromagnetic interaction as a probe [1].

Physically RHIC is an hexagonal intersecting storage ring accelerator with a circumference of 3.8 kilometers that can sustain two counter-rotating beams of either polarized protons or heavy-ions. A schematic of the facility is depicted in Figure 2.1. It features six interaction points, each capable of hosting an individual experiment. To date, four experiments have been installed. The BRAHMS and PHOBOS experiments operated until 2006 and 2005 respectively while the PHENIX and STAR experiments are ongoing. Each of RHIC's two rings is equipped with a pair of Siberian snakes to counteract the inevitable spin precession of polarized beams, which otherwise could result in depolarizing resonances. Spin rotators at each interaction point allow a given experiment to independently select one of three possible spin orientations.

2.1.2 Stochastic Cooling

Over the course of several years RHIC has been incrementally upgraded to feature full three-dimensional stochastic cooling. Cooling in the longitudinal direction (parallel to the beam) became operational for gold ions starting in 2007 [26]; cooling in the vertical direction was operational starting in 2010 (for both beams but not simultaneously) [24]; and simultaneous three-dimensional stochastic cooling for both of RHIC's beams was achieved in 2012 [25].

Beam emittance, the phase-space distribution of ions in a beam, tends to increase over time due to Coulomb scattering between individual ions, a phenomenon known as intrabeam scattering (IBS). Cooling in general counteracts this tendency by increasing the phase space density, the practical consequence being improved luminosity. In the case of stochastic cooling a feedback loop applies a corrective angular deflection, exploiting the curvature of the accelerator to allow the corrective signal to be transmitted ahead of the beam. Ideally, the corrections could be applied to individual particles but, owing to the finite bandwidth of a real cooling system, small groups of particles are affected simultaneously. Over multiple iterations, however, individual particle deviations *are* damped as the random influences of surrounding particles average to zero, to first order, in the feedback gain [57]. Hence the name stochastic cooling is derived. Storage ring accelerators in the limit of high energy beams are subject to a IBS induced growth at a rate which scales with charge number Z and atomic mass number A as $\sim Z^4/A^2$ [60], so artificial cooling is particularly desirable for beams comprising heavy ions. For the data relevant to this analysis, collected in 2008, the stochastic cooling of the gold ions in only the longitudinal direction resulted in a 15% increase in luminosity over the same beams without cooling [26]. As a point of interest, in 2012 full three-dimensional stochastic cooling of both beams, for Uranium-Uranium collisions, resulted in a five-fold increase in luminosity compared to the same beams with no cooling [25].

2.1.3 Rigidity and Asymmetric Hadrons

For a charged particle with a Larmor radius ρ in a field B , magnetic rigidity $B\rho$ characterizes the resistance of the particle to deflection. In terms of Lorentz variables β

and γ this can be expressed as

$$B\rho[\text{Tm}] = 3.3356 \frac{AM_0[\text{GeV}/c^2]}{Z} \beta\gamma, \quad (2.1)$$

given a particle with mass number A , charge number Z , and average rest mass per nucleon M_0 . Rigidity is of particular relevance when colliding hadrons that are asymmetric in terms of mass and charge, as is the case, for example, in d+Au collisions.

When colliding asymmetric hadrons at RHIC—a unique capability at the time of its construction—maintaining roughly equivalent magnetic rigidities in both beams is an important practical consideration. Near the boundaries of each interaction region (IR), both beams must pass through a shared dipole, called the DX magnet. The DX magnets are responsible for deflecting the beams into a single pipe, to facilitate collisions. However, beams with different rigidities will be subject to asymmetric deflections. If the asymmetry is large enough the DX magnets require laborious manual repositioning to accommodate the resulting geometry of the beam paths [36].

At RHIC both beams are circulated at identical speeds to ensure synchronous collisions; therefore, ions with similar mass-to-charge ratios result in beams with similar rigidities. In particular, d+Au collisions are carried out instead of p+Au since

$$(B\rho)_{\text{Au}}/\beta\gamma = 7.7450 \text{ Tm}, \quad (2.2)$$

$$(B\rho)_{\text{d}}/\beta\gamma = 6.2563 \text{ Tm}, \quad (2.3)$$

$$(B\rho)_{\text{p}}/\beta\gamma = 3.1297 \text{ Tm}. \quad (2.4)$$

The difference in rigidities results in a 3.8 mrad beam angle at each interaction point for p+Au collisions and requires repositioning the DX magnets [36]. The angle is reduced to 1 mrad for d+Au collisions [64], sufficient to obviate repositioning.

2.1.4 The Acceleration Chain

RHIC is supported by a sophisticated injector chain capable of generating, accelerating, and processing beams of ions or polarized protons in preparation for injection into the collider. Ions other than protons are supplied by the Electron Beam Ion Source (EBIS) which comprises an ion source, a radiofrequency quadrupole (RFQ) linac, and an interdigital-H (IH) linac. EBIS succeeded the Tandem Van de Graff accelerator in 2012. Polarized protons are supplied by the Optically Pumped Polarized Ion Source (OPPIS) in concert with a 200 MeV RFQ linac known as the Proton Linac. Ions or polarized protons are next sent to the Booster Synchrotron, a fast cycling synchrotron, and then to the Alternating Gradient Synchrotron (AGS), for bunching and further acceleration. Lastly, the beams are sent to RHIC for injection via the AGS-to-RHIC transfer line (AtR). A schematic diagram of the injector chain is shown in Figure 2.1.

2.2 PHENIX

In keeping with the overall mission of RHIC, the Pioneering High Energy Ion Experiment (PHENIX) was designed with the twin physics goals of investigating the QGP and measuring spin structure within the nucleon. Consequently, the experiment is capable of making a wide variety of measurements relevant to the study of both heavy ion and polarized

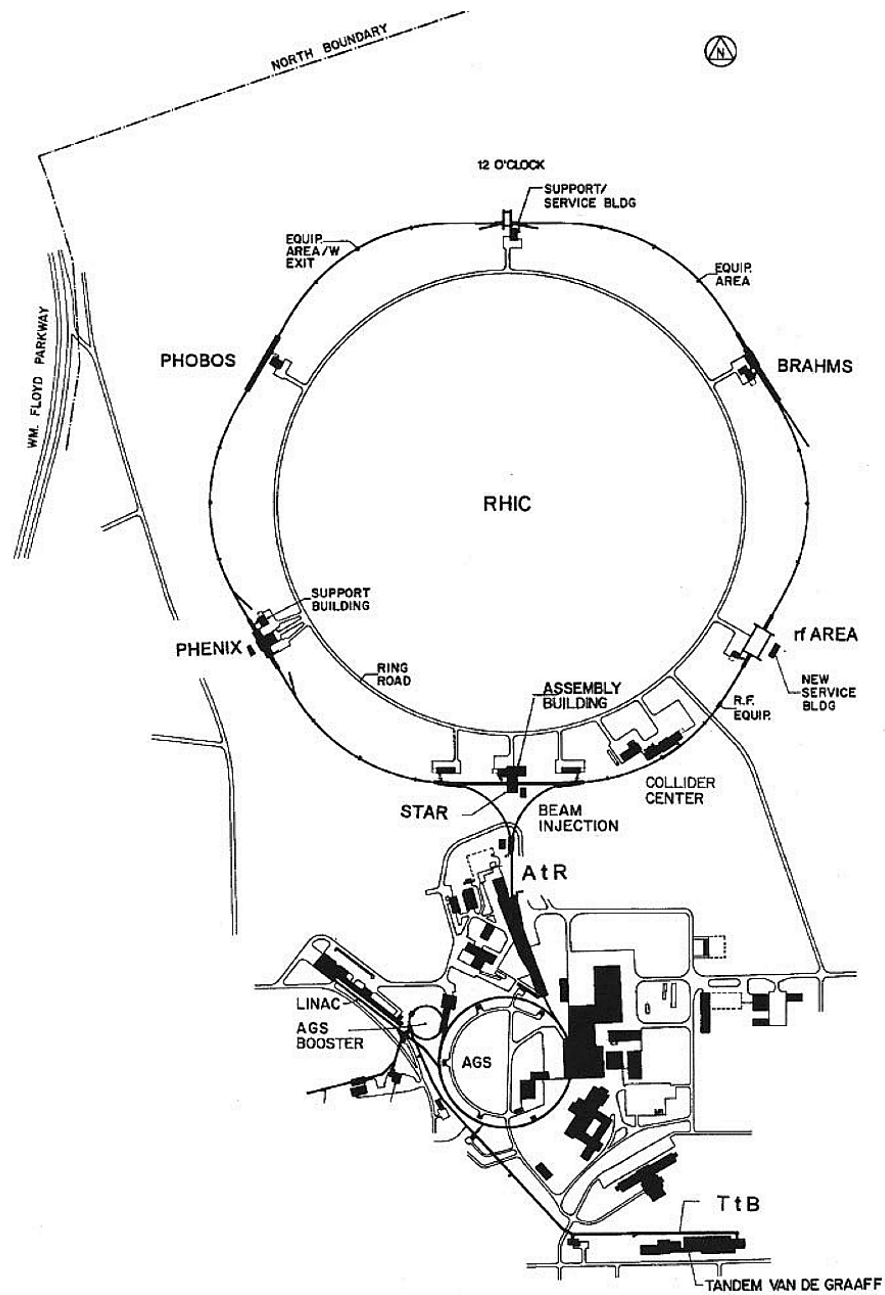


Figure 2.1: Schematic diagram of the RHIC accelerator complex.

proton collisions. PHENIX specializes in lepton and photon measurements over large $p_{\perp}$ and rapidity ranges and features a precision time-of-flight (ToF) detector for identifying charged hadrons. Measurement of hadron production is also possible over a large range of $p_{\perp}$ and rapidity via the observation of photonic and leptonic decay products. Direct photon and lepton pair measurements allow PHENIX to probe the deconfined medium at every stage of its evolution, while circumventing final state interactions. Hadronic measurements enable investigations into both the earliest and most advanced stages of a collision event; namely, the initial conditions preceding a collision and the eventual hadronization of the deconfined medium. Moreover, The large acceptance of PHENIX provides access to experimental regimes that test the limits of current theories, providing critical measurements to the advancement of heavy ion and spin physics.

At the heart of PHENIX are its myriad detectors, organized into four spectrometer arms and a collection of global event detectors. Two mid-rapidity central arm spectrometers, labeled east and west, are responsible for measurements of photons, hadrons, and electrons; two forward-rapidity muon arm spectrometers, labeled north and south, are responsible for measurements of muons. Global event detectors are responsible for generating data that describe the collisions themselves, such as centrality, vertex position, and event time. They also provide data for event triggers¹ [6]. Over the course of its operational life, numerous detectors and upgrades have been added to PHENIX in an effort to continually expand the capabilities of the experiment. Unless otherwise noted, descriptions of detectors given here

¹An event trigger is a set of criteria, involving data from a given event, used to rapidly decide whether the event warrants additional attention. For example, a trigger might decide whether an event is recorded or simply thrown out.

refer to the configuration of PHENIX as of Run 8. A schematic diagram of the experiment is shown in Figure 2.2.

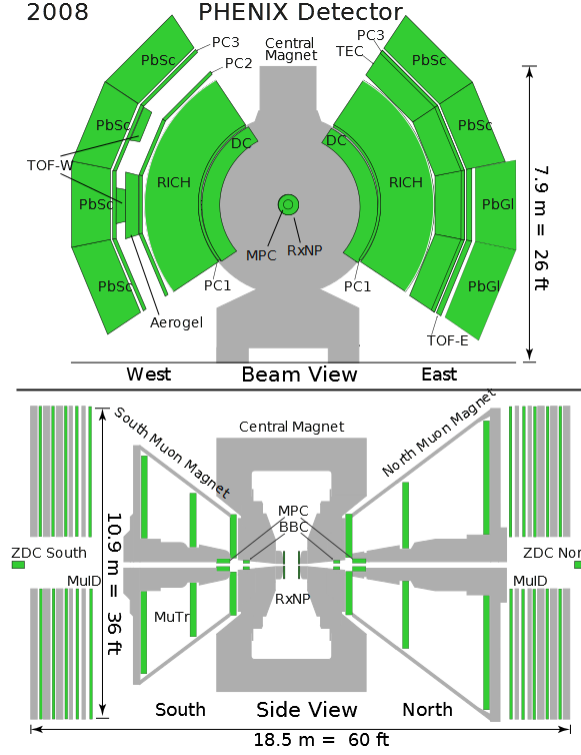


Figure 2.2: Schematic diagram of the PHENIX experiment as it appeared in 2008. Detector volumes are highlighted in green while magnet volumes are shown in gray.

2.2.1 Muon Spectrometer Arms

The muon spectrometer arms at PHENIX track and identify muons with high precision at forward rapidities. They were designed to facilitate the study of a wide variety of observables in support of the overall mission of PHENIX, including Drell-Yan processes, vector meson production, heavy quark production, and W and Z particle production. The arms have a large acceptance of about one steradian each, a rapidity range of approximately $1.2 < |y| < 2.4$ and full azimuthal coverage. Additionally, they feature excellent background

rejection of pions and kaons, with a rejection rate of on the order of 10^{-3} , and the ability to reconstruct muon momenta for both heavy ion and polarized proton collisions [10]. Two detector volumes reside within the muon arms: a magnetic spectrometer muon tracker (MuTr), for precision tracking, and a muon identifier (MuID), for low resolution tracking and background rejection.

The MuTr consists of six planar detector stations, three in each arm, widely spaced in a radial magnetic field. Each station contains multiple layers of cathode strip chambers with varied strip orientations. Together, they give the MuTr a mass resolution of $\sigma(M)/M = 6\%/M$, M in GeV, and a spatial resolution on the order of $100\text{ }\mu\text{m}$ [10]. The radial magnetic field for the MuTr is supplied by the two PHENIX Muon Magnets [15], each of which consists of solenoid coils surrounding a uniquely shaped iron and steel yoke, as shown in Figure 2.2. Notably, the central portions of the yokes, hollow iron cylinders referred to as pistons, house the Muon Piston Calorimeter (MPC), detailed in a later section.

The MuID, positioned after the MuTr, consists of five layers of alternating steel absorber plates and Iarocci tubes, with the first absorber plate also forming part of the yoke for the Muon Magnets. Each Iarocci tube is essentially a long and thin drift chamber, 8.4 cm in width, consisting of eight $100\text{ }\mu\text{m}$ gold-coated beryllium copper wire anodes housed in a graphite-coated plastic cathode tube. A total absorber thickness of 90 cm in the north arm and 80 cm in the south arm reduces the penetrative probability to around 3% for charged pions up to 4 GeV [10], increasing the accuracy of muon identification.

2.2.2 Central Arm Spectrometers

PHENIX includes two central arm spectrometers, or central arms, for mid-rapidity $|\eta| < 0.35$ measurements of photons, electrons, and charged hadrons. The numerous detectors contained within the central arms fall into three basic categories: those responsible primarily for particle tracking, those responsible primarily for particle identification, and a large electromagnetic calorimeter. The Drift Chamber (DC), Pad Chamber (PC), and Time Expansion Chamber (TEC) comprise central arm tracking [5]. The Ring Imaging Cherenkov (RICH) detector, Time of Flight (ToF) counter, and Aerogel Cherenkov Counter (ACC) comprise central arm identification [9]. For polarized proton collisions, the ToF counter relies on an additional Time Zero (T0) counter for improved timing. The electromagnetic calorimeter (EMCal) is responsible for position and energy measurements of photons and electrons [14]. Additional responsibilities of the EMCal include assisting with particle identification and acting as a trigger for high $p_{\perp}$ photons and electrons. Of the eight subdivisions, or sectors, of the EMCal, six are Pb-scintillator (PbSc) sampling calorimeters and two are Pb-glass (PbGl) Cherenkov calorimeters.

Also incorporated into the central arms is the PHENIX Central Magnet which generates a field parallel to the beam line in the volume surrounding the interaction vertex, facilitating mid-rapidity momentum analysis of charged particles [15]. The relative positions of the magnet and detectors are depicted in Figure 2.2.

2.2.3 Global Event Detectors

Event characterization detectors at RHIC include the Reaction Plane Detector (RXNP), the Zero Degree Calorimeters (ZDC), and the Beam-Beam Counters (BBC). Each

of these detectors is depicted in Figure 2.2. The RXNP was designed specifically to estimate the reaction plane Ψ_R , defined as the azimuthal angle of the impact parameter, in heavy ion collisions [62]. Reaction plane measurements are critical to studies of elliptic flow, among other things; however, the RXNP is not used in this analysis. The ZDC, shielded from charged particles by virtue of their location behind the DX dipole magnets, are designed exclusively to detect spectator neutrons in heavy ion collisions [8]. However, measurements in the ZDC are not applicable to d+Au collisions. Therefore, they are also unused; this analysis relies solely on the BBC for event characterization.

The BBC are a pair of identical counters that envelop the beam pipe at a distance of 144 cm from the interaction point, on either side. Acceptance is $3.0 < |\eta| < 3.9$ with complete azimuthal coverage. Each counter contains 64 individual elements consisting of a photomultiplier tube (PMT) coupled to a 3 cm hexagonal quartz Cherenkov radiator; each element has a timing resolution of 52 ± 4 ps [12]. The primary functions of the BBC are to measure event time, to measure vertex position along the beam axis (ZVTX), and to contribute information to the PHENIX Level-1 (LVL1) online trigger. Additionally, charge sum measurements from the BBC can be used to determine centrality. This analysis makes use of the BBC as a minimum bias trigger and to obtain ZVTX and centrality information.

2.2.4 Centrality and N_{coll} Determination

Individual heavy ion collisions can be characterized by two quantities: the number of participants N_{part} , which refers to the number of nucleons that experience an inelastic interaction, and the number of binary collisions N_{coll} , which refers to the total number of inelastic nucleon-nucleon interactions. Determining these quantities is essential to making

meaningful comparisons between different collision species or between results from different experiments. In particular, N_{coll} appears explicitly in Equation 1.3, the definition of $R_{\text{d+Au}}$.

A theoretical framework called the Glauber model, after Roy Jay Glauber, is used to extract these values from experimental data [56]. The model requires two types of data as input: nuclear charge densities obtained from low-energy electron scattering and the energy dependence of the nucleon-nucleon cross section. From this, the model can approximate N_{part} and N_{coll} in terms of the impact parameter b of a collision. This can be done symbolically in an eikonal approximation, valid at high energies, or via a Glauber Monte Carlo (GMC). The latter method is valued for its simplicity and amenability to certain cuts. Both methods produce virtually identical results, diverging only at very high values of b [56]. However, since it is impossible to observe, directly, the impact parameter of a collision, the Glauber model on its own is insufficient. Ultimately, the objective is to obtain N_{part} and N_{coll} from an experimentally observable quantity. To this end, it becomes necessary to introduce the concept of centrality.

Centrality characterizes an event in terms of an empirically more tractable quantity: particle production. Specifically, the centrality c of a given event is defined as

$$c \equiv 100 - p \tag{2.5}$$

where p is the percentile rank, among collisions of the same species, of the number of particles produced [27]. Smaller centrality implies a smaller impact parameter and a greater number of particles. In fact, centrality can be defined in terms of any observable that is expected to be monotonically decreasing with N_{coll} since the percentile rank will remain unchanged. Therefore, in practice, at PHENIX centrality is defined in terms of the percentile

rank of the BBC charge sum Q . Corrections need only be made to compensate for detector response and trigger bias [30][58].

As may be worth noting, it can be shown that for heavy ion collisions centrality and impact parameter satisfy the relation

$$c \simeq \frac{\pi b^2}{\sigma_{\text{inel}}} \quad (2.6)$$

to high precision for all but the most peripheral collisions, where σ_{inel} is the inelastic nucleus-nucleus cross section [27]. For reference, at $\sqrt{s} = 200$ GeV the total inelastic cross section is $\sigma_{\text{inel}} = 2.19$ b for d+Au collisions [58]. Inaccuracy in Equation 2.6 is on the order of $(\Delta n(b)/\hat{n}(b))^2$ where $\hat{n}(b)$ is the mean product multiplicity at a given impact parameter and $\Delta n(b)$ is the width of the multiplicity distribution. Using the Glauber model, comparisons between each side of Equation 2.6 can be made, independent of collision species. Corrections remain on the order of 10^{-3} for impact parameters $b < 13$ fm [27].

The first step in determining N_{coll} for d+Au collisions is to replicate the BBC charge distribution precisely in simulation. Events are generated with a random impact parameter in a distribution $d\sigma/db = 2\pi b$. The GMC determines the number of participants and the number of binary collisions for each event. For every binary collision it is assumed some charge will be generated in the BBC, the amount governed by a negative binomial distribution (NBD) with parameters μ and k [58]. Appropriate values for μ and k are found by conducting a grid search in parameter space and selecting those values that minimize χ^2 in a comparison between the real and simulated charge distributions. The simulated distribution is then normalized to the data in a region $20 \text{ pC} < Q < 120 \text{ pC}$ where the trigger efficiency is expected to approach 100%.

At this point the simulated distribution is compared to the real distribution. The ratio of their integrals reveals the trigger efficiency, found to be 88.4% [58]. The trigger turn-on curve is determined by making a functional fit of the ratio of the distributions themselves. When the turn-on curve is incorporated into the simulated distribution, the result is in an accurate model of the real BBC charge—but with the advantage that, in simulation, the values of N_{part} and N_{coll} are known for each event.

Based on the trigger efficiency, the distribution is taken to represent centralities in a range of 0% to 88%. It is partitioned via quantiles into 88 subsets of equal fractional area. The quantiles thus define centrality, for any event, in terms of the BBC charge sum. The distribution is further subdivided into centrality classes, or ranges of centrality: 0% to 20%, 20% to 40%, 40% to 60%, and 60% to 88%. Figure 2.3 depicts the BBC charge distribution and its centrality classes. For each centrality class N_{part} and N_{coll} distributions are extracted and the mean values are taken as the N_{part} and N_{coll} for that centrality class; the N_{coll} distributions are shown in Figure 2.4. Hence, when analyzing real data, the BBC charge sum is readily mapped to a centrality and a centrality class with an associated N_{part} and N_{coll} . In this way, the easily measured but somewhat idiosyncratic metric of centrality is translated into a more universal characterization, relevant for comparison to other collision species.

2.3 The Muon Piston Calorimeter

Installation of the Muon Piston Calorimeter (MPC) extended the acceptance of neutral pion and jet measurements at PHENIX into highly forward $3.1 < \eta < 3.9$ and

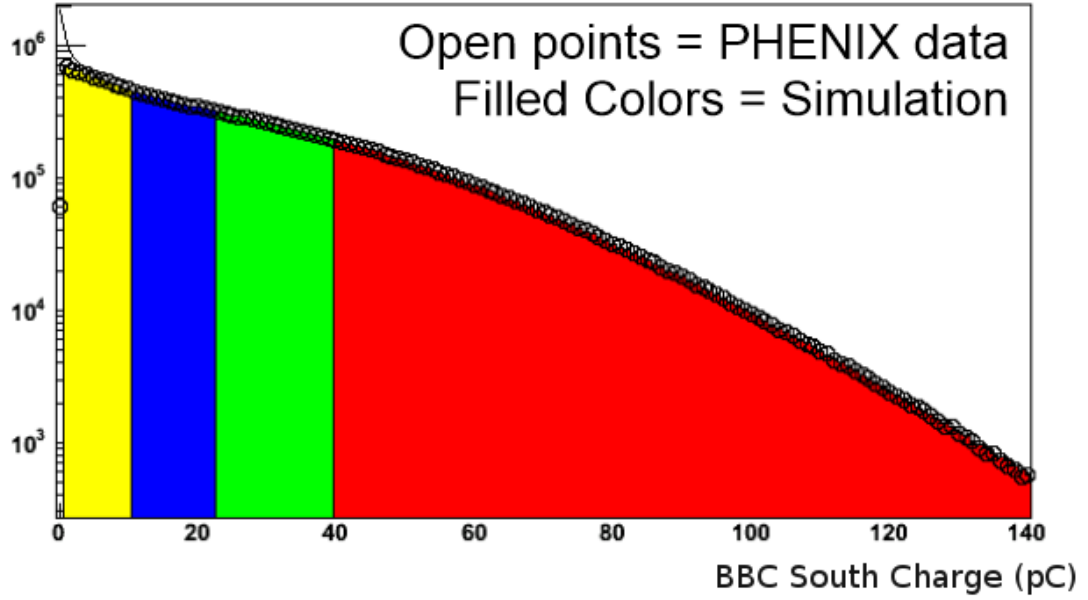


Figure 2.3: The BBC charge sum distribution for Run 8 d+Au collisions. Open circles represent PHENIX data while the filled histogram is from the Glauber model simulation. Each color in the filled histogram denotes a different centrality class. From right to left, the centrality classes are 0% to 20% (red), 20% to 40% (green), 40% to 60% (blue), and 60% to 88% (yellow).

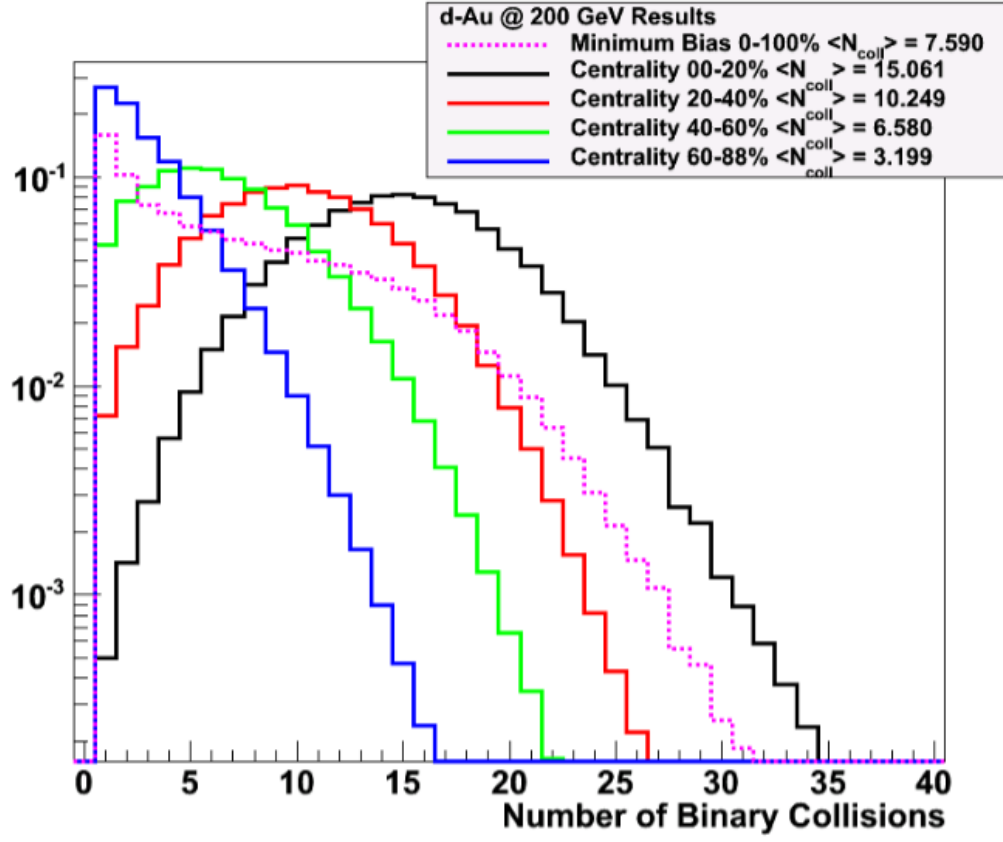


Figure 2.4: N_{coll} distributions for each centrality class. Although centrality is defined in terms of the BBC charge sum, the physical relevance of centrality is expressed in these distributions.

backward $-3.7 < \eta < -3.1$ regions, enabling investigations into spin asymmetry and saturation effects at high rapidity and low momentum fraction x . Previously unused cylindrical cavities, 45 cm in diameter and 43 cm in length, in the north and south muon magnet armatures were exploited to house the MPC detector volumes, as shown in Figure 2.2, without the need to displace any existing detectors or electronics. The limited dimensions of these cavities heavily influenced the design of the MPC.

Numerous lead tungstate PbWO_4 crystals compose the scintillating volume of the MPC. Known for its small Moliere radius $R_M = 2.0$ cm and short radiation length $X_0 = 0.89$ cm, PbWO_4 is ideal for use in an homogenous calorimeter of restricted size. Additionally, the optical properties of PbWO_4 are resistant to radiation damage [69][65][59][28]; this is of particular importance given the proximity of the MPC and the interaction point. The crystals used in the MPC were originally produced as spares for the PHOS calorimeter in ALICE. Therefore, they benefited from the rigorous performance and quality testing undertaken during the construction of that detector [69][39][38]. Selected properties [29][46] of the MPC crystals are summarized in Table 2.1. In total, the scintillating volume of the north MPC, in the forward direction, comprises 216 individual crystals; the south, in the backward direction, comprises 192.

To maximize light yield, each crystal is wrapped in Tyvek, a highly reflective, paper-like material composed of polyethylene fibers and manufactured by DuPont. External to the Tyvek are two additional layers of wrapping material for light-tightness: aluminized Mylar followed by Monokote, an opaque plastic.

Affixed to each crystal, a Hamamatsu S8664-55 PIN avalanche photodiode (APD) converts scintillation photons into charge signals. These signals are subsequently routed

Size	$2.2 \times 2.2 \times 18 \text{ cm}^3$
Density	8.28 g/cm^3
Weight	721.3 g
Moliere Radius	2.0 cm
Radiation Length	0.89 cm
Interaction Length	22.4 cm
Refractive Index	2.16
Main Emission Lines	420, 480-520 nm
Temperature Coefficient	-2%/

Table 2.1: Selected properties of MPC PbWO_4 crystals.

through a preamplifier, one attached to each APD. Together, a crystal, APD, and amplifier constitute an MPC tower, depicted in Figure 2.5. Driver boards, mounted in the muon piston cavities, supply power to and accept signals from up to 24 towers simultaneously. In total, there are 10 driver boards for each of the north and south MPC detectors. Signals from the driver boards are relayed to front end electronics, digitized, and ultimately stored in a PHENIX Raw Data Format (PRDF) file. Prior to being stored for offline analysis, PRDF files are further prepared as data summary tables (DST), which typically condense a detector’s raw signals into derived quantities describing particle candidates—position, energy, etc. However, because the MPC is made up of a relatively small number of towers, it is feasible to store individual tower signals in the MPC DST, thus allowing clustering algorithms and calibration procedures to be modified and refined well after data production has concluded. Figure 2.6 depicts the MPC towers, frame, and driver boards as they appear fully-assembled.

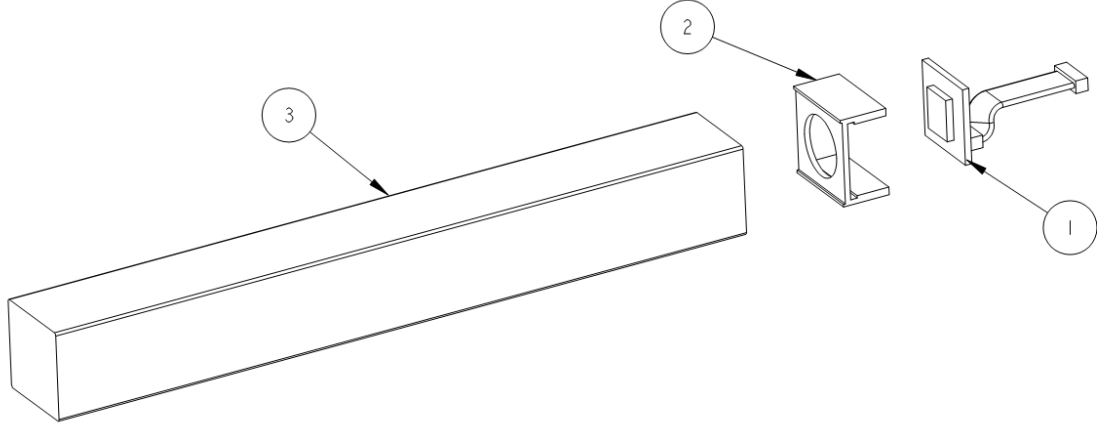


Figure 2.5: Diagram of an MPC tower showing 1) the APD and preamp, 2) the aluminum APD holder, and 3) the PbWO_4 crystal.

2.3.1 Calibration

ADC pedestal values—the ADC output values in the absence of signal—are measured to establish a baseline for energy calibration. The absolute energy scale is then set by observing minimum ionizing particle (MIP) peaks, which have an expected energy of 234 MeV [33]. Fluctuations in crystal response due to temperature variation and radiation damage are partially corrected on a run-by-run basis using an LED monitoring system. Lastly, in offline analysis, the calibrations are verified by comparing a number of measurable quantities with expected values.

To obtain the ADC pedestals, ADC charge is measured when there is no beam in the storage ring, with the MPC configured to take data, and using a noise trigger. Note that when taking data, the MPC records two ADC values for each event. One value ADC_{post} coincides with the event trigger while the other ADC_{pre} is measured exactly four

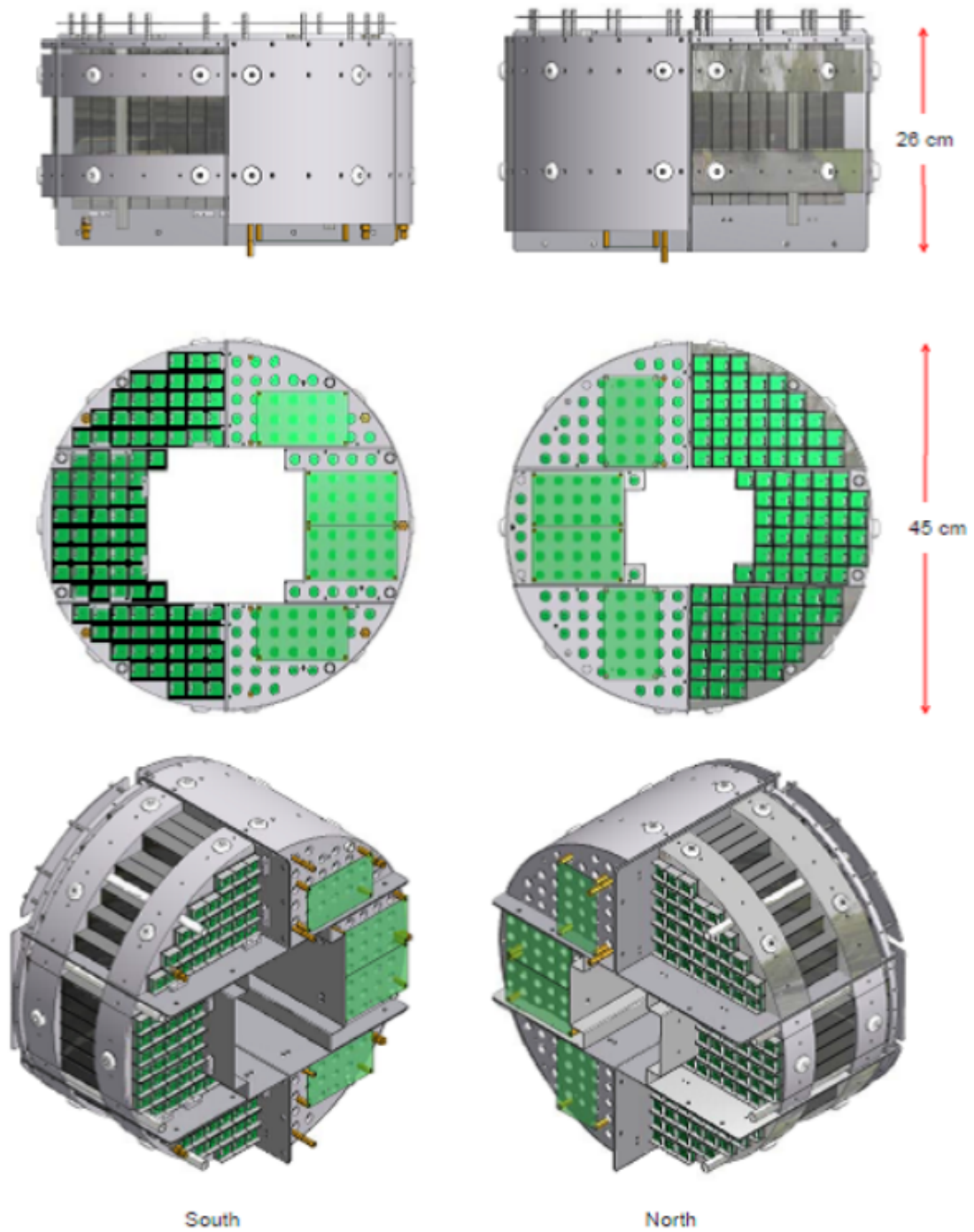


Figure 2.6: The south and north MPC detectors rendered isometrically.

RHIC clock cycles ($4\text{ }\mu\text{s}$) in advance. The difference $ADC_{\text{post}} - ADC_{\text{pre}}$ is taken as the uncalibrated tower energy. This is to subtract out any residual charge that may persist from a previous event. The same procedure is used when obtaining the pedestals, resulting in two pedestal values for each tower: $ADC_{\text{post, pedestal}}$ and $ADC_{\text{pre, pedestal}}$. Pedestal values were found to be stable over the duration of Run 8 [46].

MIP peaks determine the absolute gain for each tower on a fill-by-fill basis². They are obtained by plotting the ADC output spectra, with cuts applied to discriminate against electromagnetic showers and thereby enhance the MIP signal. EM showers tend to generate scintillation in a greater number of surrounding towers as compared to minimum ionizing particles. Additionally, EM showers generated by collision products may activate a BBC detector element along the track connecting the MPC tower and the interaction point. Therefore, cuts are made on the number of adjacent towers generating ADC output and on the vertical distance between the tower track and the nearest activated BBC element. Appropriate values for the cuts are found by conducting a grid search in parameter space and selecting those values that generate the best fit to the MIP peak, when fitting with a power law function summed with a Gaussian.

For a small number of towers no adequate MIP fit can be found for any fill over the entire course of Run 8. Nevertheless, in such a case, the absolute energy scale of a tower can be estimated by comparing its uncalibrated energy spectrum with the spectra of towers whose MIP peaks were successfully found. The spectrum of every tower is first parameterized as $S(Q) = aQ^{-b}$, with parameters a and b and uncalibrated energy Q . For towers with known MIP peaks, the parameter b is correlated with peak position [46]. For

²A fill refers to a single injection of opposing beams into the RHIC storage rings. Each fill lasts for several hours and generates data over multiple runs.

the remaining towers, a functional fit of the the correlation can be used to map the value of b to a value for MIP peak position, allowing an absolute energy scale to be attributed to the tower.

Fluctuations in temperature affect PbWO_4 light yield and APD gain. Additionally, over the course of Run 8 radiation damage resulted in an expected gradual deterioration in PbWO_4 light yield. These effects are partially corrected with the MPC LED monitoring system [47]. For each run, LED light is sent to the MPC towers via optical fiber, at the rate of a few Hz, and the mean ADC response is recorded. This information is then translated, using a smoothing algorithm, into a relative gain for each run. The stability of the LED source itself is monitored with a PIN diode. However, the system is not without limitations. Changes in scintillation response cannot be monitored with LED light. Also, light from the LED monitoring system must travel the entire length of a PbWO_4 crystal, whereas scintillation photons elicited by a shower may originate at any point within the crystal. Nevertheless, in Run 8, time dependent fluctuations of π^0 and η peak positions were successfully eradicated by applying the LED corrections [46].

2.3.2 Clustering and Reconstruction

EM showers spread radially as they propagate through the length of the MPC, generally depositing energy across multiple towers; showers in close proximity may overlap into the same towers. To reconstruct relevant information about incident particles therefore requires a substantial analysis of MPC tower energies.

For a given event, the calibrated energy E of an MPC tower, in terms of its uncalibrated energy Q , is given by

$$E = G \cdot R(t) \cdot Q, \quad (2.7)$$

where G is the absolute gain from MIP analysis, $R(t)$ is the relative gain from the LED monitoring system, and Q is defined in terms of the ADC charge values, as described earlier,

$$Q \equiv ADC_{\text{post}} - ADC_{\text{pre}} - (ADC_{\text{post, pedestal}} - ADC_{\text{pre, pedestal}}). \quad (2.8)$$

The first step towards reconstruction is to group contiguous towers with $E > 10$ MeV into objects called superclusters. A supercluster may contain energy from multiple incident particles. Therefore, a clustering algorithm is employed with the aim of separating out the effects of individual showers. The clustering algorithm operates on a supercluster; for every presumed shower, it generates a single cluster, defined as the sum of information measured by the MPC and pertaining to a given shower. Specifically, the information contained in a cluster includes: the channel identifications of those towers into which the shower deposited a significant amount of energy; the cluster energy, defined as the total energy that can be attributed to the shower, and its distribution amongst individual towers; the cluster position, defined as the centroid of the cluster energy; the cluster dispersion D , defined as the second moment of the cluster energy, in the x and y -directions; and the cluster χ^2/NDF , which characterizes the degree to which the measured radial distribution of shower energy, otherwise known as the shower shape, deviates from that which is expected. Cluster dispersion and χ^2/NDF are used to reject hadronic showers and select EM showers.

The clustering algorithm employs an iterative procedure to quantify individual clusters. Every local maximum within a supercluster is assumed to correspond to exactly one EM shower; a local maximum is defined as a tower with $E > 100$ MeV whose energy exceeds any of its nearest neighbors. The energy and position of a cluster is initially estimated by examining the tower energies of the 3×3 grid of towers centered on a local maximum. Shower shape profiles, obtained via beam tests, are then used to determine the amount of energy the cluster ought to contribute to each tower of the supercluster. If ϵ_n is the energy the n^{th} cluster is expected to contribute to a given tower, then the total predicted tower energy is $\epsilon = \sum_n \epsilon_n$. The fraction $r_n = \epsilon_n/\epsilon$ is taken as the fraction of the measured tower energy E that can be attributed to the n^{th} cluster. In this manner, the total measured energy in every tower of a supercluster is distributed amongst overlapping clusters, providing a refined estimate for each cluster energy. A refined estimate of cluster position $\vec{x}$ is then obtained by calculating the log-weighted³ center of gravity of the new cluster energy: if E'_i is the energy in the i^{th} tower attributed to a given cluster, and if $\vec{x}_i$ is the position of that tower, then the cluster position is given by

$$\vec{x} = \frac{\sum_i w_i \vec{x}_i}{\sum_i w_i}, \quad (2.9)$$

with the weights w_i defined as

$$w_i \equiv \max \left[0, w_0 + \ln \left(\frac{E'_i}{\sum_j E'_j} \right) \right]. \quad (2.10)$$

The constant w_0 is arbitrary but is chosen so as to optimize position resolution. The refined estimates are then fed back into the clustering algorithm. The procedure is iterated a total of six times, sufficient for the energy and position values to stabilize.

³Compared to a linear-weighted center of gravity, a log-weighted center of gravity results in a more accurate estimate of the actual position of an incident particle because the radial distribution of the energy of an EM shower decreases exponentially in its tail [54].

Before they are finalized, further adjustments are made to the cluster position, to correct for the angle of incidence, and to the cluster energy, to correct for leakage. In both cases, the corrections are obtained through simulation. At most, they amount to around 0.6 cm, for position, and around 5%, for energy [54].

The position resolution of the MPC for single photons is dependent on energy but is less than 2 mm at high energies, as shown in Figure 2.7. Due to interference from the BBC and MPC frames, position resolution also exhibits a position dependence, shown in Figure 2.8. Uncertainty in cluster energy can be expressed parametrically:

$$\frac{\sigma_E}{E} = \frac{a}{E} + \frac{b}{\sqrt{E}} + c. \quad (2.11)$$

The first term arises primarily from shot noise in the MPC electronics, the second term from stochastic variation in EM showers, and the last term primarily from calibration error. The values for Run 8 are: $40 \text{ MeV} < a < 70 \text{ MeV}$, $b \approx 0.026\sqrt{\text{GeV}}$, and $c \approx 0.04$ [54]. Clusters in this analysis occupy a range of $15 \text{ GeV} < E \lesssim 70 \text{ GeV}$.

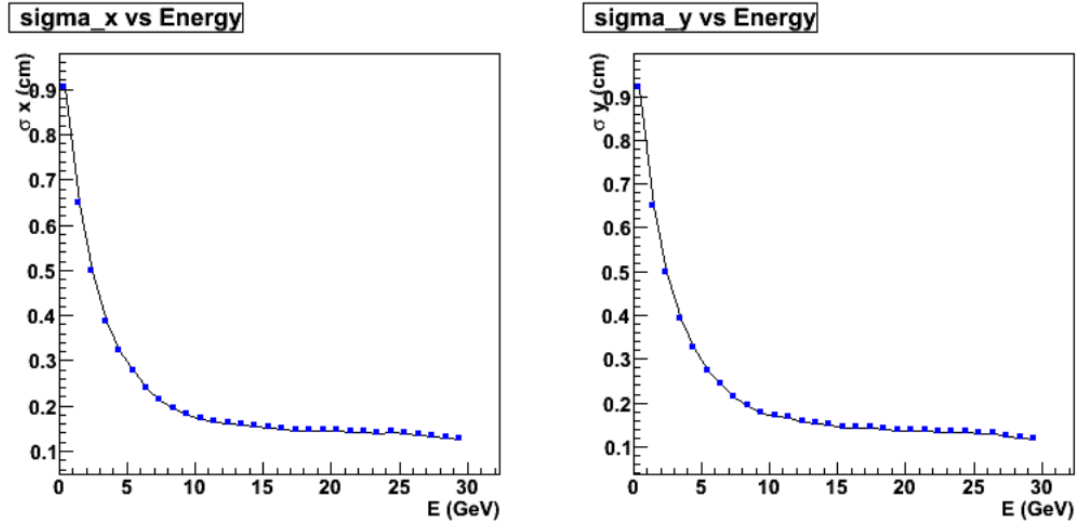


Figure 2.7: MPC position resolution for single photons as a function of simulated photon energy, obtained via PISA simulations.

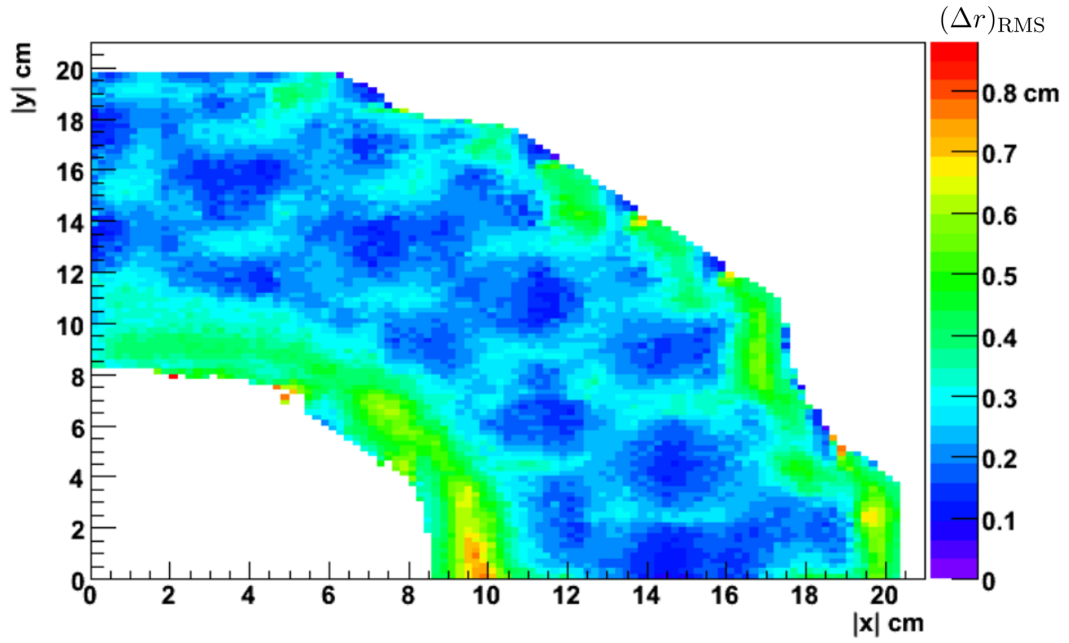


Figure 2.8: Position resolution in the MPC varies with reconstructed position. Shown here is the RMS deviation in reconstructed position $(\Delta r)_{\text{RMS}}$ for PISA-simulated single photons with energies between 10 and 20 GeV. The hexagonal pattern mimics the shape of the BBC frame.

Chapter 3

Measurements

Neutral pions decay into photon pairs with a 98.8% branching ratio. The mean lifetime is extremely small, on the order of 10^{-16} s; therefore, neutral pions produced in a collision will decay, for kinematic purposes, essentially at the collision vertex. For pions with a low enough transverse momentum, $p_T < 2 \text{ GeV}/c$, the photons will have sufficient separation that they can be resolved into separate clusters by the MPC. In this case, a combinatoric analysis of MPC clusters can be used to obtain results such as neutral pion yield and nuclear modification factors. However, for pions with $p_T > 2 \text{ GeV}/c$ the MPC is unable to resolve the photons individually. Instead, overlapping EM showers generated by the photons are interpreted by the clustering algorithm as a single cluster, called a merged cluster. In this case, a combinatoric analysis is no longer possible. Nevertheless, the information contained in merged clusters can still be leveraged to obtain nuclear modification factors for neutral pions at high $p_\perp$.

3.1 Particle Identification

For the purposes of this analysis, a merged cluster refers exclusively to a cluster derived from, and only derived from, the pair of photons produced by a neutral pion decay. For convenience, other clusters, even if they may be caused by two or more overlapping showers, are simply called background clusters.

Pions with energy $E > 12$ GeV are capable of generating merged clusters in the MPC [55]. Below this energy, the separation between the decay photons is always too great. At only slightly higher energies merged clusters become more probable than background clusters. Based on studies of PISA simulations [54], for clusters with $E > 15$ GeV and $p_T > 1$ GeV/ c , neutral pion merged clusters account for more than 75% of the total cluster count. A plot of the composition of MPC clusters, derived from simulations, is shown in Figure 3.1 [46]. This dominance of merged clusters in the MPC at high energies allows meaningful results to be extracted with respect to neutral pions despite the inability, in these regimes, to perform a more typical combinatoric procedure. Moreover, when calculating the ratio R_{d+Au} systematic error from background clusters will largely cancel out since the ratio is only sensitive to relative changes in the cluster composition.

As might be expected, the overlapping showers of a merged cluster present a shower shape profile that differs significantly from a standard cluster. For this reason, a χ^2/NDF cut, useful at lower energies to discriminate against hadronic showers, is not applied in an analysis of merged clusters. However, dispersion is not significantly affected [54] and a dispersion cut is still applied. When examining high-energy MPC clusters, a nuclear-counter effect becomes prevalent. That is, low-energy particles deposit energy directly into

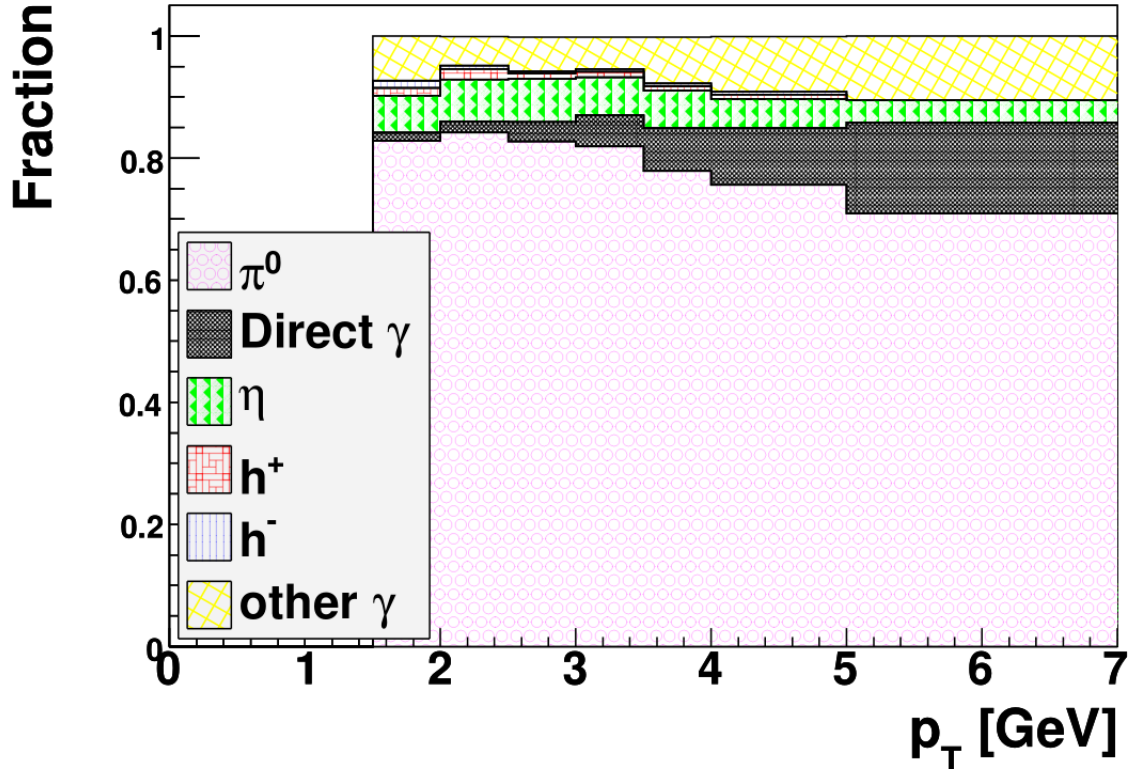


Figure 3.1: Composition of MPC clusters as a function of cluster $p_\perp$ for p+p collisions at $\sqrt{s} = 200$ GeV. This data was obtained from simulation and checked against experimentally determined cross sections. The clusters included here are subject to a cut, $x_F > 0.4$, on the Feynman scaling variable $x_F = 2p_z/\sqrt{s}$. The resulting composition is representative of the neutral pion merged cluster contribution in general at high $p_\perp$.

a tower's APD, generating a false high-energy signal. False high energy clusters of this type are easily recognized by their very low dispersion. All of the energy appears concentrated in a single tower. To exclude these clusters, two cuts are applied. The first is a minimum lateral dispersion requirement. The second is a lower limit on the ratio E_8/E_{cent} , where E_{cent} is the energy of the central tower of a cluster and E_8 is the sum of the energies of the eight surrounding towers. Table 3.1 enumerates the cuts applied to clusters.

Minimum energy:	$E > 15 \text{ GeV}$
Maximum dispersion:	$\max(D_x, D_y) < 4 \text{ cm}^2$
Minimum dispersion:	$\sqrt{D_x^2 + D_y^2} > 0.5 \text{ cm}^2$
Single tower cut:	$E_8/E_{\text{cent}} > 0.14$

Table 3.1: Conditions on MPC clusters for inclusion in the analysis.

3.2 Data Quality

3.2.1 Warn Map

MPC towers that are poorly calibrated or, for other reasons, exhibit abnormal behavior are excluded from the analysis. The list that identifies these towers is called a warn map. For Run 8, the warn map was generated [55] by studying the number of clusters N_{clus} in each MPC tower, using minimum bias p+p and d+Au data. The logarithm $\log(N_{\text{clus}})$ correlates with tower radial position. A plot of the correlation was fit with a line using a least trimmed squares¹ (LTS) regression; outliers, towers whose N_{clus} differed from the fit

¹An LTS regression is similar to an ordinary least squares regression. Both methods attempt to minimize an objective function $S(\beta)$ to fit set of n data points (x_i, y_i) , where β are the parameters of the fit $f(x_i, \beta)$.

by more than 3.5 times the mean squared error σ , were flagged for inclusion in the warn map. A diagram of the warn map is shown in Figure 3.2. During Run 8, it was necessary to exclude two large groups of towers in the north MPC due to conditions that impaired the towers' performance. One group, near the bottom of the diagram in Figure 3.2-a, was blocked by a brace supporting the beam pipe. The other group, on the right of the diagram, was compromised by a faulty driver board.

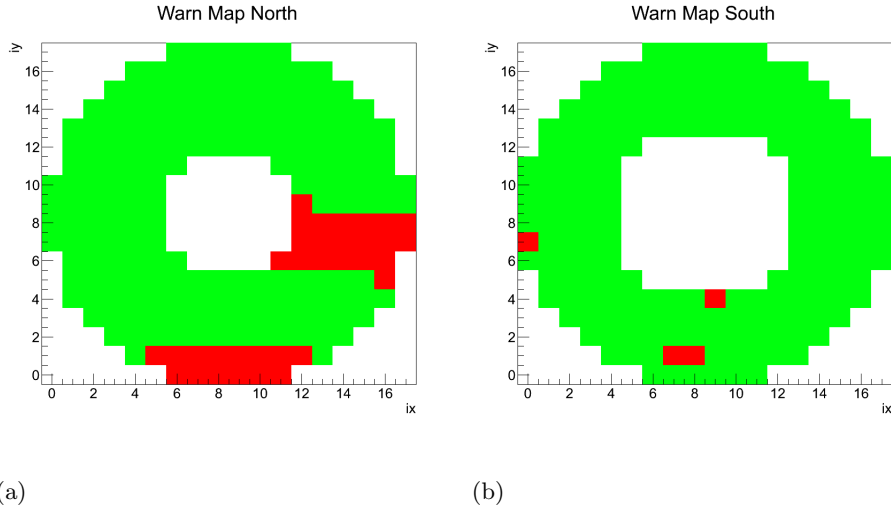


Figure 3.2: Warn maps for **a.)** the north MPC and **b.)** the south MPC. Towers represented by red squares are excluded from the analysis.

3.2.2 Neutral Pion Yield

The quality of individual runs during Run 8 can be assessed in a few ways, one of which is to study the per-event neutral pion yield of each run. The aim is to exclude runs that present suspiciously abnormal results. To this end, the neutral pion yield is obtained, at

The difference is that an LTS regression excludes outlying data points while a least squares regression does not.

low $p_{\perp}$, through a combinatoric analysis² of minimum bias data. In short, random clusters in the MPC, from a single event, are paired together combinatorically. Their energies and positions are fed into the following kinematic equation, valid for $\pi^0 \rightarrow \gamma\gamma$ decays, to reconstruct an invariant mass m :

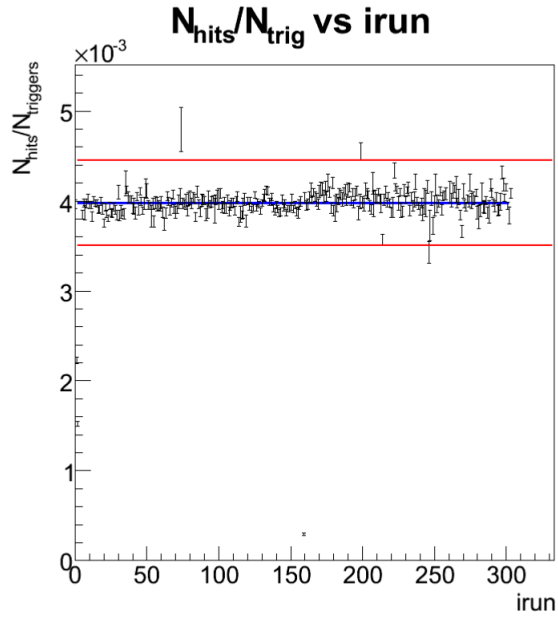
$$m^2 = 2E_1E_2(1 - \cos \alpha), \quad (3.1)$$

where E_1 and E_2 are the energies of the clusters in a pair and α is the angle obtained by tracing their positions to the event vertex. Most pairs reconstruct a random value; however, pairs that happen to have derived from a neutral pion decay will reconstruct a neutral pion mass. The resulting distribution appears as a peak, at the neutral pion mass, couched in a roughly flat, random background. The background can be subtracted and the yield is integrated out of the signal. The results [55] of this process are shown in Figure 3.3. The yield values are fit with an LTS regression. Runs with a yield outside of 3σ are excluded from the analysis.

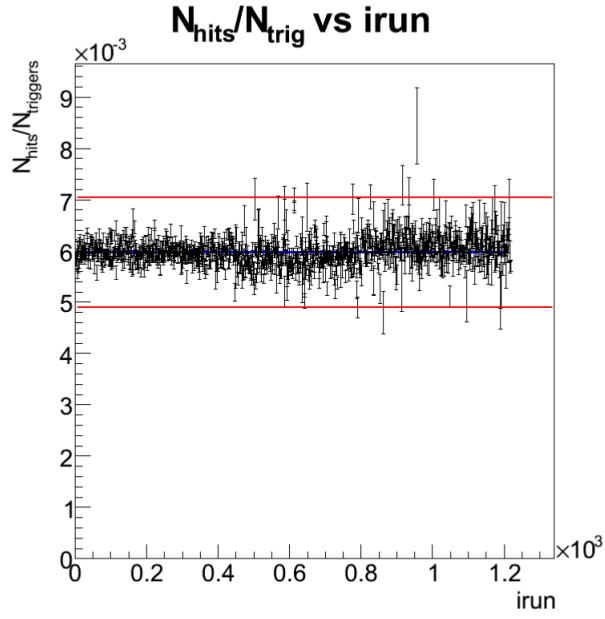
3.2.3 Neutral Pion Mean Invariant Mass

In addition to neutral pion yields, the combinatoric analysis described earlier generates mean values for the invariant neutral pion mass. This information is leveraged as another measure of data quality. The mean invariant mass for each run is compared to the average over all runs. Runs that deviate by more than 1.5% are excluded from the analysis. The values [55] for each run are shown in Figure 3.4.

²Using a combinatoric analysis limits yield extraction to regions of low $p_{\perp}$, such that the photons from a neutral pion decay resolve as separate clusters in the MPC. Although my analysis focuses on high $p_{\perp}$ merged cluster neutral pions, low $p_{\perp}$ neutral pion yields provide a reasonable assessment of the quality of a given

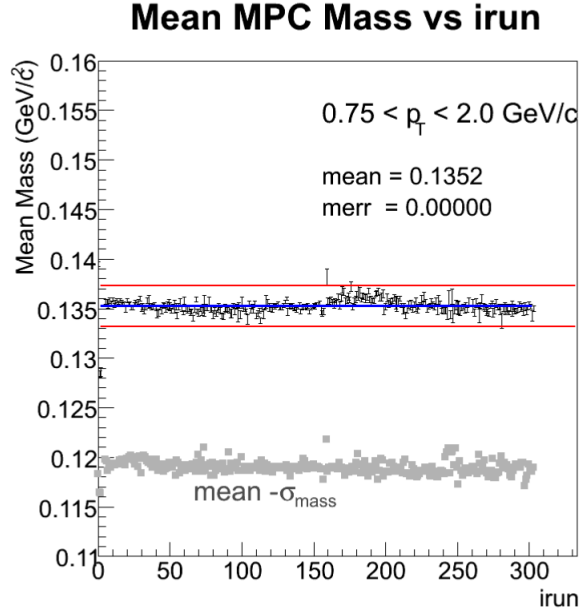


(a)

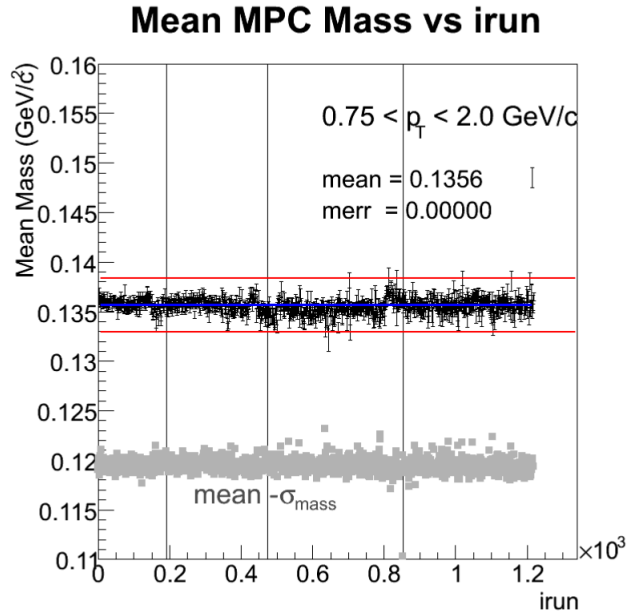


(b)

Figure 3.3: Per-event neutral pion yield vs. run number for **a.)** minimum bias p+p and **b.)** minimum bias d+Au data. The red lines delineate the range of acceptable yields.



(a)



(b)

Figure 3.4: Neutral pion mean invariant mass values for **a.)** minimum bias p+p and **b.)** minimum bias d+Au data in the 60% to 88% centrality range. The red lines delineate the range of acceptable values. The width of each invariant mass peak is indicated by the gray data points, which are plotted one standard deviation below the mean.

3.2.4 Pair Acceptance Function

Pair acceptance functions describe the probability of detecting two particles as a function of their separation, typically as measured in pseudorapidity $\Delta\eta$ or azimuthal angle $\Delta\phi$. They may be found analytically by convoluting two single particle acceptance functions. They may also be measured empirically by plotting the correlation of random particles paired from mixed events. Event mixing precludes the possibility of any actual correlation so that only the pair acceptance is measured. Pair acceptance functions found in this way can provide another useful measure of data quality, on the premise that the acceptance should be stable from one run to another.

Run quality, for this analysis, was assessed [55] by measuring the $\Delta\phi$ pair acceptance of the MPC for neutral pions paired with high energy clusters. Neutral pions were identified as cluster pairs that, using Equation 3.1, reconstruct an invariant mass in the range $0.08 \text{ GeV}/c^2 < m < 0.18 \text{ GeV}/c^2$. High energy clusters were identified using the cuts described in Section 3.1. One advantage to this pairing is that the results are sensitive to issues both in the high energy merged cluster regime, directly applicable to this analysis, and in the regime of lower $p_\perp$ neutral pions situated more comfortably within the MPC acceptance. The pair acceptance function measured for each run was condensed into a scalar χ^2/NDF value, defined as

$$\chi^2/NDF \equiv \sum_{i=1}^N \frac{(y_i - \bar{y})^2}{N\sigma_i^2}, \quad (3.2)$$

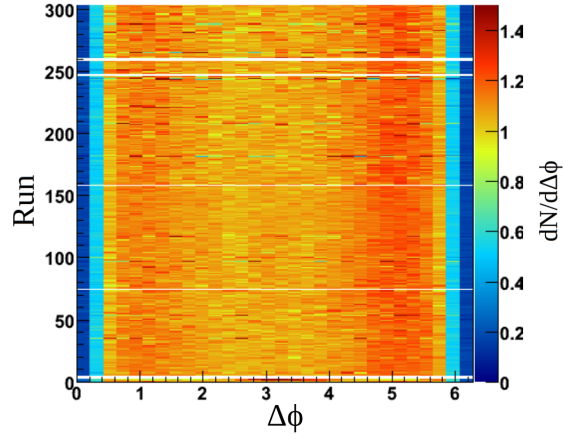
where the sum is over all bins of $\Delta\phi$, y is the acceptance, σ the error in y , and $\bar{y}$ the mean acceptance of a set of five reference runs. Runs are excluded if $\chi^2/NDF \geq 2$, for p+p data,

run while benefiting from an established and detailed understanding, tailored specifically to the MPC, of the combinatoric background [54].

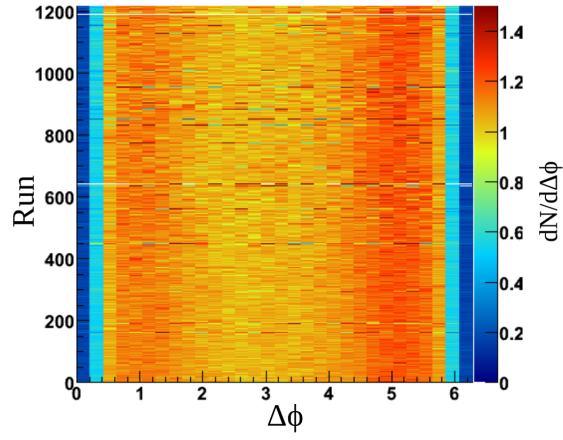
or $\chi^2/NDF \geq 1.5$, for d+Au data. Figure 3.5 shows the measured pair acceptance for each run. Figure 3.6 shows the acceptance χ^2/NDF for each run.

3.3 Merged Cluster Analysis Details

In overview, the steps undertaken to obtain merged cluster neutral pion yields are as follows. Particle identification cuts, detailed in section 3.1, and an ADC overflow cut, detailed in the following section 3.3.1, are applied to the data to obtain a preliminary distribution of neutral pion merged clusters, for p+p collisions and for d+Au collisions of each aforementioned centrality class. Each distribution is normalized to its respective number of events. These preliminary distributions are shown in Figures 3.7 and 3.8. Next, each distribution is adjusted to account for detector acceptance and efficiency. The efficiency corrections are obtained using an embedding procedure, discussed in section 3.3.2, and are adjusted for bin smearing using a process described in section 3.3.3. The distributions are further corrected for trigger bias and normalized to an appropriate value of N_{coll} . These adjustments are discussed in section 3.3.4. Finally, a correction for bin shift is applied, as described in section 3.3.5. This results in merged cluster neutral pion distributions $dN/dp_{\perp}$ that can be easily processed to obtain invariant neutral pion yields, an invariant neutral pion cross section for p+p collisions, and nuclear modification factors $R_{\text{d+Au}}$.



(a)



(b)

Figure 3.5: Pair acceptance functions versus run number for neutral pions paired with high energy clusters in the MPC. The data sets are **a.)** p+p and **b.)** d+Au. Acceptance is plotted on the color axis. Each acceptance function has been normalized to have an average value of 1.

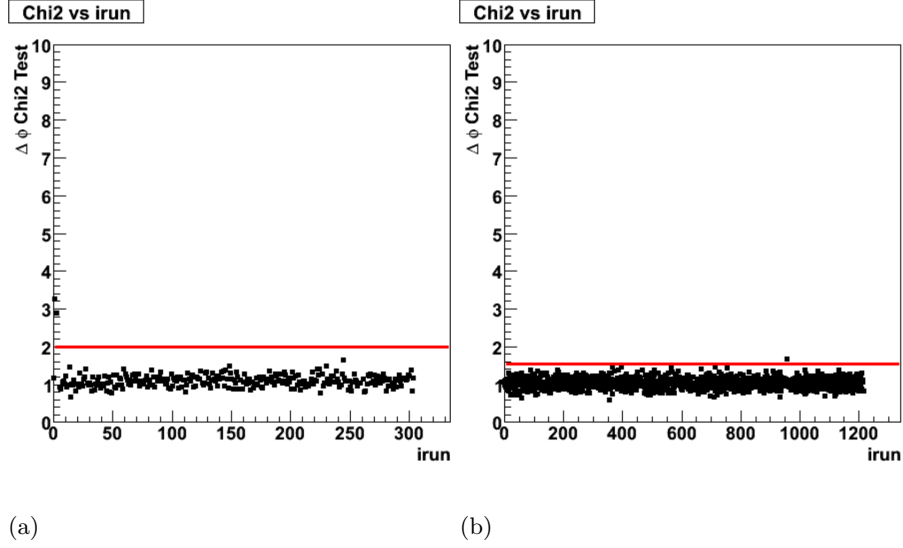


Figure 3.6: Acceptance χ^2/NDF versus run number for **a.)** p+p and **b.)** d+Au data. The red lines indicate the maximum acceptable χ^2/NDF for each data set.

3.3.1 ADC Overflow Cut

The MPC front end electronics (FEE) comprise four front end modules (FEM), each containing six application specific integrated circuits (ASIC). Each ASIC can service up to 24 MPC towers, providing analog-to-digital conversion (ADC) of timing and pulse height for individual tower voltages. However, the ADC for each tower has a limited dynamic range, which can be taxed when studying high energy clusters. For example, the merged clusters in this analysis have a minimum cluster energy of 15 GeV and may exceed 70 GeV. Meanwhile, the saturation energy, due to ADC limitations, for an individual tower in the north MPC near the beginning of Run 8 may vary from 23 GeV to as low as 14.3 GeV. Since the energy from a single cluster is typically spread across multiple towers, high energy measurements are still feasible. However, care must be taken to exclude clusters that may contain saturated towers.

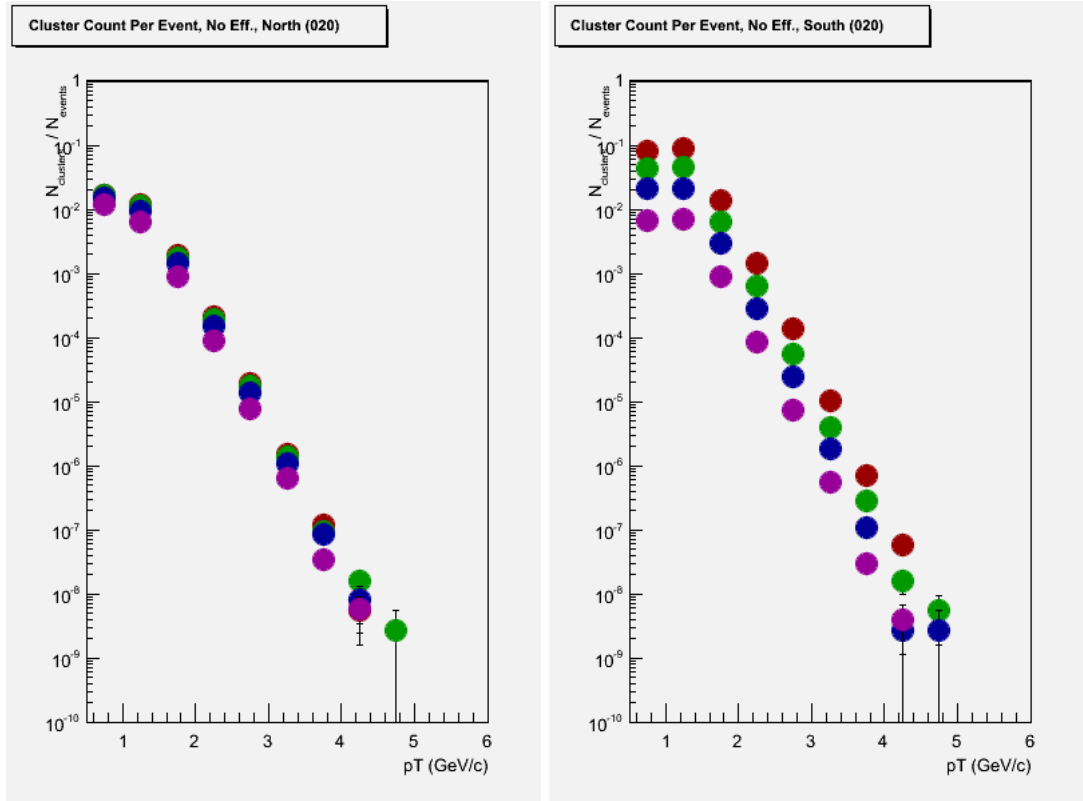
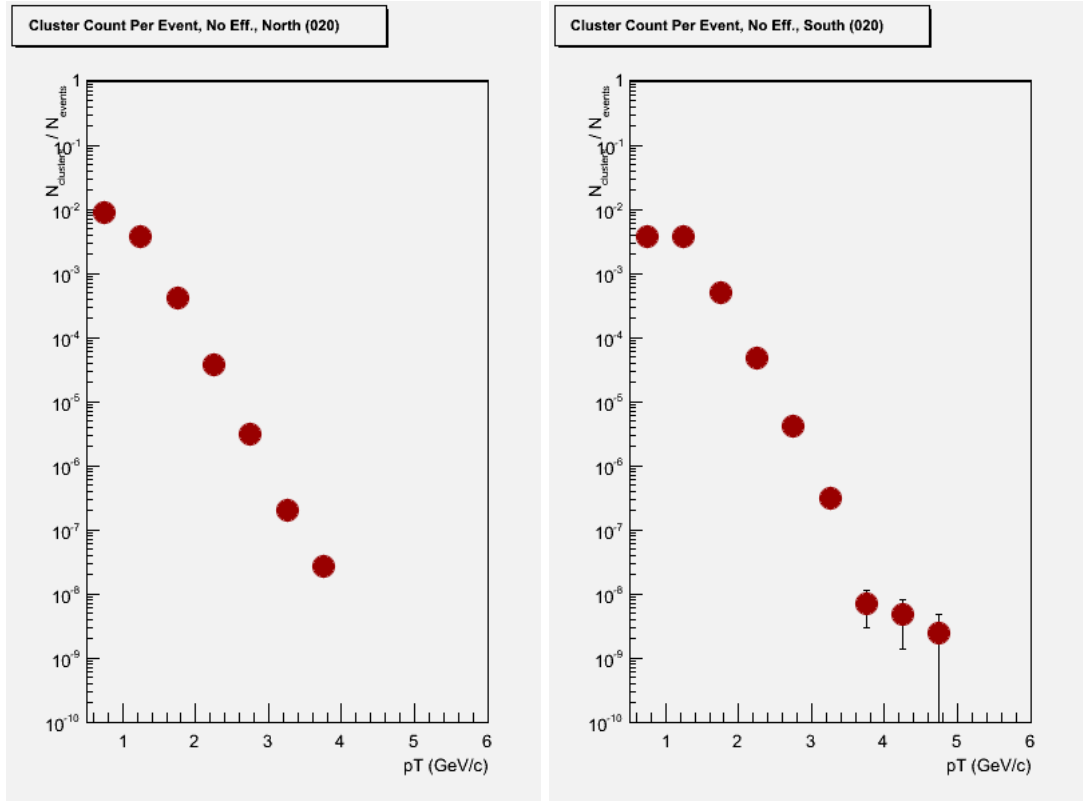


Figure 3.7: Uncorrected distributions of neutral pion merged clusters per event for d+Au collisions in the a) north MPC and b) south MPC.



(a)

(b)

Figure 3.8: Uncorrected distributions of neutral pion merged clusters per event for p+p collisions in the a) north MPC and b) south MPC.

The first step is to determine the ADC overflow value for each MPC tower. This is the value returned once the ADC is saturated, marking the upper edge of the ADC range for a given tower. It is found by measuring the ADC_{post} distribution for each tower over the course of Run 8. The overflow values are identified by a peak in the distribution at the high end of the ADC range. An example of this is shown in Figure 3.9. In some towers no ADC peak is observed, meaning that they did not experience significantly many instances of saturation throughout the course of Run 8. Figure 3.10 shows the measured overflow values for each MPC tower, plotted by channel number.

Once the overflow values are known, they can be converted into energies using the tower gains. Since the gains vary with each run, due primarily to temperature fluctuations and radiation damage to the PbWO_4 crystals, the cutoff energies will also vary. The gains trend upward with time as radiation damage accumulates, so the lowest cutoff energies are near the beginning of Run 8, as can be seen in Figure 3.11. The lowest cutoff energy among all towers in the north MPC, for any run, is found to be 14.3 GeV. Therefore, to exclude clusters with saturated towers in the north MPC, a cut is made on the central tower energy E_{cent} such that clusters with $E_{\text{cent}} > 14.3$ GeV are removed. The same cut is made in the south MPC, at the same energy. Because this energy is higher than the lowest cutoff energy in the south MPC, the systematic errors for measurements made with the south MPC are slightly increased. However, as is apparent in Figure 3.11, for most runs the lowest cutoff energy in the south MPC is in excess of 14.3 GeV. Hence, the severity of the increase in systematic error due to this issue is limited.

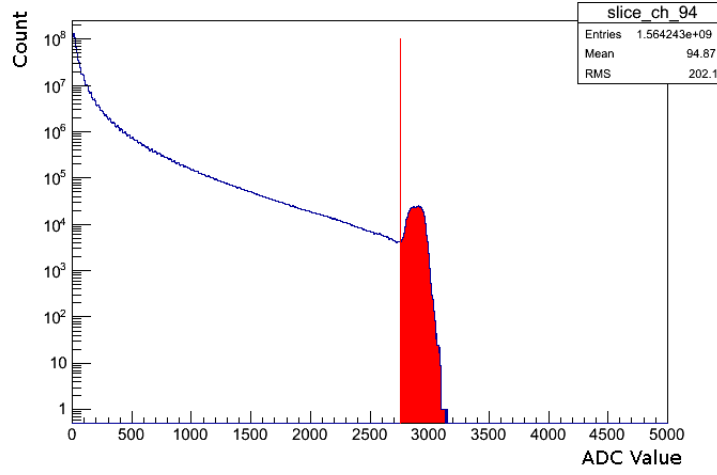


Figure 3.9: ADC distribution for a single tower. The ADC overflow peak is filled red. The red line, which is not a component of the histogram, denotes the ADC overflow value for this tower.

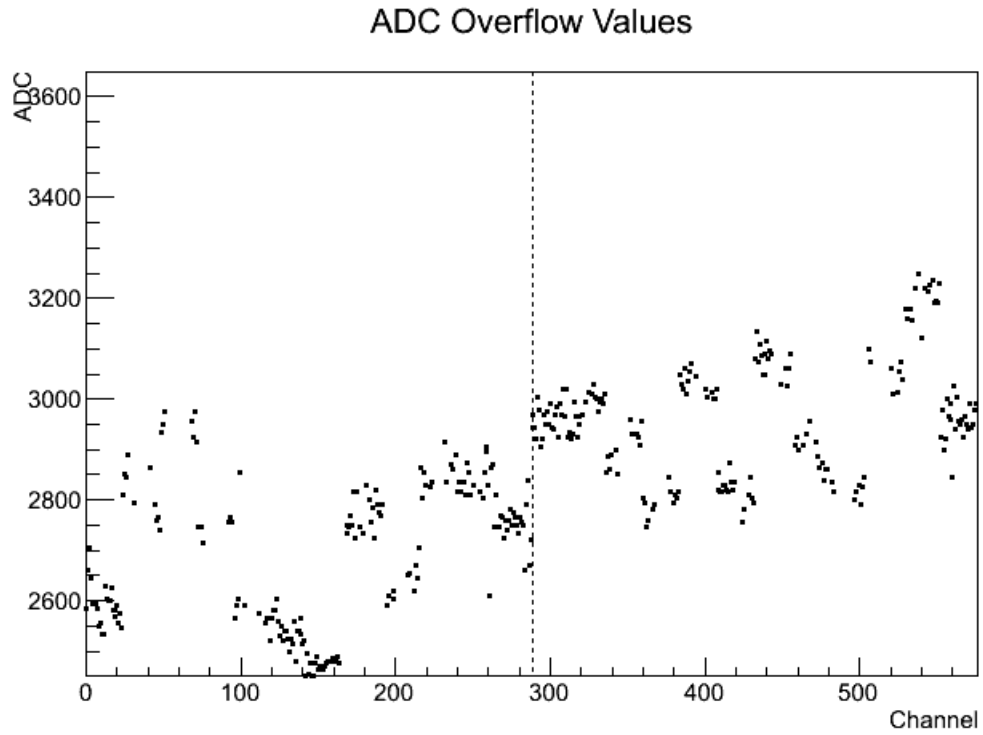


Figure 3.10: ADC overflow values versus tower channel ID. The broken line separates south MPC towers, to the left, from north MPC towers, to the right.

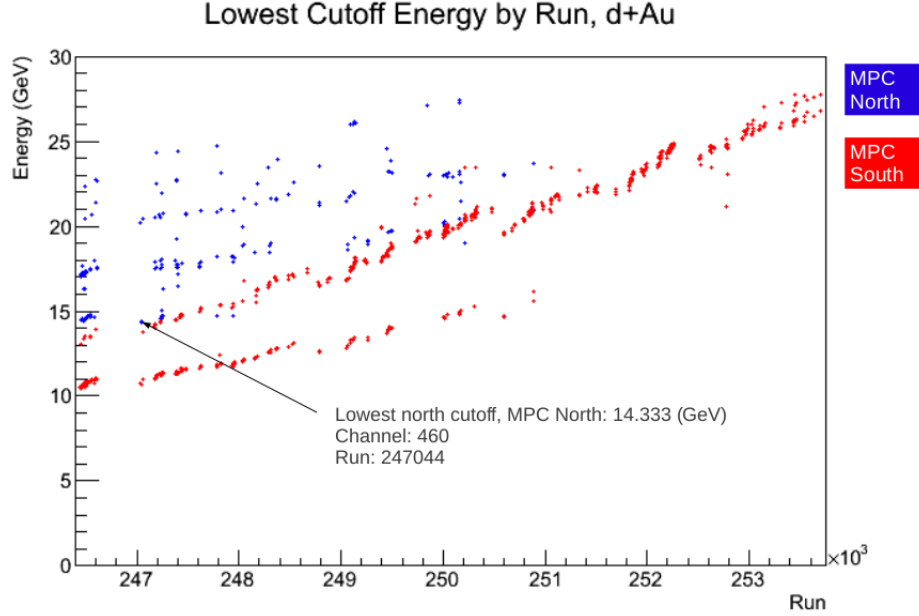


Figure 3.11: For each run, the lowest ADC cutoff energy for any tower is plotted in blue, for the north MPC, and red, for the south MPC.

3.3.2 Efficiency

To obtain neutral pion merged cluster efficiencies in the MPC, an embedding procedure is employed, wherein the simulated detector response to single particles is merged with actual data. This has the advantage, over single particle simulations alone, of accurately incorporating multiplicity effects into the calculation; that is, a loss of efficiency due to the obfuscating presence of multiple clusters.

To begin, single neutral pions are generated in PYTHIA³ such that their point of origin coincides with the collision vertex of a real event. The detector response is then simulated in PISA⁴ and merged with the real event data by additively combining individual

³PYTHIA is a Monte Carlo simulation program capable of generating high energy p+p collisions, and other types of collision involving protons, antiprotons, electrons, and positrons.

⁴PISA is a simulation package for replicating the physical response of detectors and other volumes of PHENIX to incident high energy particles.

tower energies. Tracing the simulated pion through each step of the simulation reveals exactly where in the MPC its energy is deposited and where its cluster should be located. If a corresponding cluster is found in the data from the merged event, then the detection is considered successful. The statistical likelihood of successfully detecting simulated pions is taken as the detector efficiency. Before the efficiencies are finalized, a bin smearing correction, described in the following section, is also applied. The merged cluster efficiencies used in this analysis are shown in Figures 3.12 and 3.13.

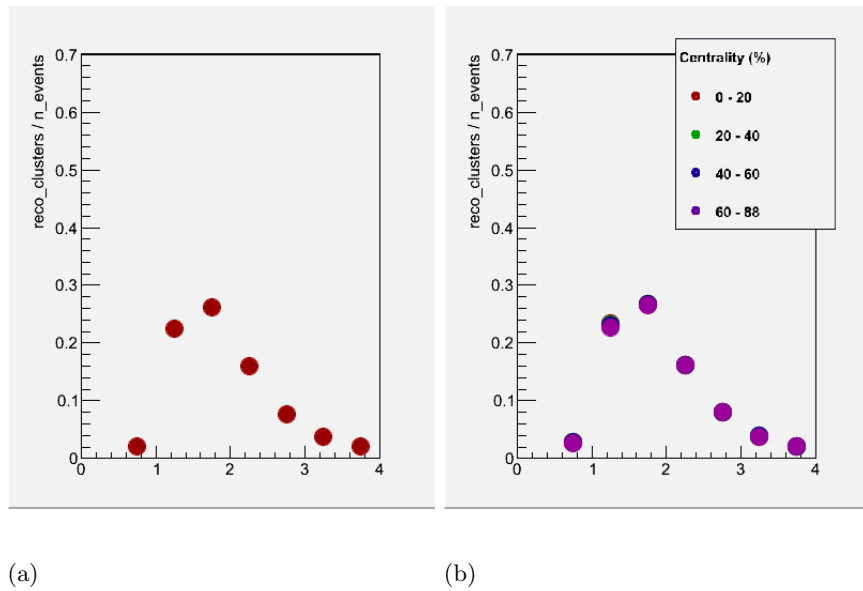


Figure 3.12: Embedding efficiencies for the north MPC for a.) p+p events, b.) d+Au events. Efficiencies for d+Au data are separated by centrality class.

3.3.3 Bin Smearing Correction

Efficiencies are obtained in bins of $p_{\perp}$. However, when determining efficiencies, it is possible that a simulated pion will be detected but its $p_{\perp}$ inaccurately measured, causing it to be placed in the wrong $p_{\perp}$ bin. As a result of this smearing, the efficiencies will vary

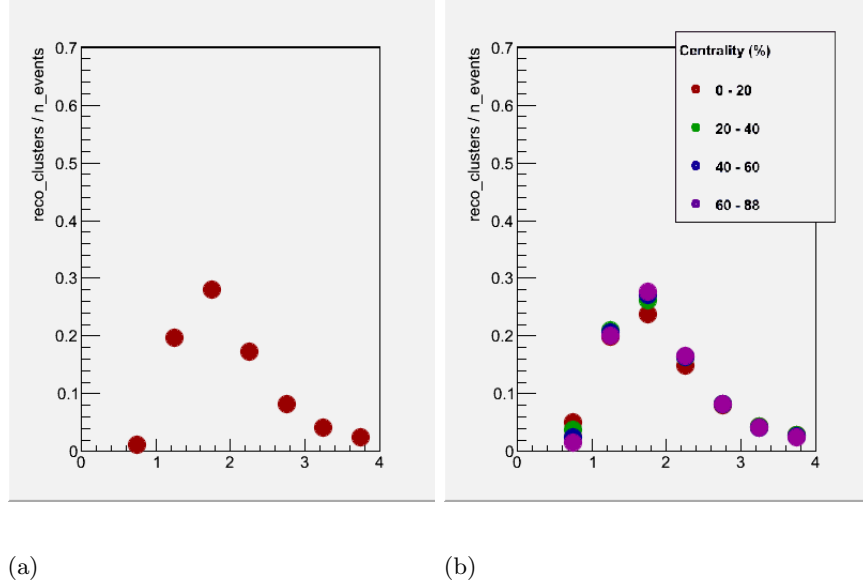


Figure 3.13: Embedding efficiencies for the south MPC for a.) p+p events, b.) d+Au events. Efficiencies for d+Au data are separated by centrality class.

depending on the simulated neutral pion $p_{\perp}$ spectrum. To understand why, consider the i^{th} $p_{\perp}$ bin. The measured pion spectrum y_i is related to the simulated spectrum s_i by the equation

$$y_i = \epsilon_i s_i, \quad (3.3)$$

which defines the efficiencies ϵ_i . However, if bin smearing is a possibility, then there is a finite probability ξ_{ij} that a pion will be found and placed in the i^{th} bin despite having a $p_{\perp}$ that should place it in the j^{th} bin. Note that, in analogy to the efficiencies ϵ_i , the probabilities ξ_{ij} allow for the possibility that the pion will not be found. The relation between the simulated and measured spectra becomes

$$y_i = \sum_j \xi_{ij} s_j, \quad (3.4)$$

where the sum is over all $p_{\perp}$ bins. The equation defining the efficiencies can be rewritten as

$$\epsilon_i = \frac{y_i}{s_i} = \frac{\sum_j \xi_{ij} s_j}{s_i}. \quad (3.5)$$

The numerator depends on every bin of the simulated spectrum, implying that the procedure for determining efficiencies, measuring y_i , will produce useful results only if the simulated spectrum is equivalent to the spectrum generated by real events. This presents a conundrum since the spectrum from real events is not known a priori: the spectrum can not be measured without efficiencies, and the efficiencies can not be determined without the spectrum. The problem is compounded by the expectation that the $p_{\perp}$ spectrum should be rapidly falling, meaning that the smearing is likely to have a significant effect, since the ratio s_j/s_i will be large for $j < i$. One solution would be to determine ξ_{ij} through simulation, instead of ϵ_i . The measured spectrum could then be corrected to the true spectrum by inverting the matrix $\xi = [\xi_{ij}]$. Another solution, which is the PHENIX convention because it is simpler to execute in practice [54], is to measure ϵ_i and use an iterative procedure to incrementally converge on the correct spectrum.

The iterative procedure contains very few steps. It incorporates the basic procedure for obtaining efficiencies through embedding, described in Section 3.3.2. An initial estimate as to the nature of the neutral pion spectrum is required to begin. This is obtained from simulated collisions. The estimate is used to weight simulated single pions which are then processed by the embedding procedure, generating efficiencies. Next, high energy cluster yields are obtained from real data and corrected, using the efficiencies, to become a refined estimate of the neutral pion spectrum. This estimate, once parameterized, is used to weight simulated single pions and a new iteration can begin. The procedure

continues until the pion spectrum converges to a stable state, at which point the efficiencies have been properly corrected.

3.3.4 Bias Correction Factor

The PHENIX minimum bias trigger BBCLL1 has an efficiency of approximately $\epsilon_{\text{MB}} \approx 54\%$ [23][22] for inelastic p+p collisions, which is to say that the triggered cross section for p+p events is only 54% of the actual inelastic p+p cross section. However, it has been found [30] that the trigger itself is biased towards inelastic interactions that generate high $p_{\perp}$ neutral pions. This is because those interactions tend to produce a higher multiplicity of charged particles, making them more likely to satisfy the BBCLL1 requirements. As such, the BBCLL1 efficiency for neutral pions ϵ_{π^0} is actually higher than the minimum bias trigger efficiency, at approximately $\epsilon_{\pi^0} \approx 79\%$ [22]. That is, the triggered cross section for events generating neutral pions is 79% of the actual neutral pion event cross section. Essentially, for a given number of minimum bias p+p events N_{MB} measuring a certain number of neutral pions N_{π^0} , the corrected number of events will be $N_{\text{MB}}^{\text{corrected}} = N_{\text{MB}}/\epsilon_{\text{MB}}$ and the corrected neutral pion yield will be $N_{\pi^0}^{\text{corrected}} = N_{\pi^0}/\epsilon_{\pi^0}$. The corrected per-event yield therefore depends on both efficiencies:

$$\left. \frac{N_{\pi^0}}{N_{\text{MB}}} \right|_{\text{corrected}} = \frac{\epsilon_{\text{MB}} N_{\pi^0}}{\epsilon_{\pi^0} N_{\text{MB}}} = C_{\text{bias}} \frac{N_{\pi^0}}{N_{\text{MB}}}, \quad (3.6)$$

where $C_{\text{bias}} \equiv \epsilon_{\text{MB}}/\epsilon_{\pi^0} \approx 69\%$ is the bias correction factor.

An analogous correction must be made for d+Au events but the calculation [58] is more elaborate because centrality is also affected by trigger bias. The higher multiplicity of charged particles associated with the presence of a neutral pion biases the BBC charge distribution, which defines the centrality bins. As a result, the process for determining

the bias correction is similar to the determination of N_{coll} , detailed in Section 2.2.4. As with the determination of N_{coll} , GMC-NBD simulations are employed to replicate the BBC charge distribution. However, in this case, trigger bias is approximated by scaling the NBD parameters μ and k by a factor $\lambda = 1.55$ for a single binary collision out of the total number N_{coll} . This mimics the increased BBC charge that results from a higher particle multiplicity. The value $\lambda = 1.55$ was chosen because it was found to replicate previous, data-driven results [30]. In this way, a biased simulated BBC charge distribution is constructed that can be compared to a similar, unbiased simulated distribution. Under the assumption that the production of neutral pions scales with N_{coll} , invariant yields are found for each centrality bin for both the biased and unbiased distributions. The ratios of the yields are taken as the bias correction factors.

Correction factors used in this analysis are detailed in Table 3.2.

Species	N_{coll}	$\sigma_{N_{\text{coll}}}$	C_{bias}	$\sigma_{C_{\text{bias}}}$	$C_{\text{bias}}/N_{\text{coll}}$	$\sigma_{[C_{\text{bias}}/N_{\text{coll}}]}$
d+Au 0-20%	15.06	1.013	0.941	0.010	0.062	0.003
d+Au 20-40%	10.25	0.704	1.000	0.006	0.098	0.004
d+Au 40-60%	6.58	0.444	1.034	0.017	0.157	0.008
d+Au 60-88%	3.20	0.193	1.031	0.055	0.332	0.025
p+p	1	0	0.69	0.067	0.69	0.067

Table 3.2: Bias correction factors normalized to N_{coll} .

3.3.5 Bin Shift Correction

Another consequence of a rapidly falling spectrum $dN/dp_{\perp}$ is that the measured pion yield in a given $p_{\perp}$ bin may not accurately reflect the value of $dN/dp_{\perp}$ at the bin center. This is because the yield in a particular bin samples the average value of $dN/dp_{\perp}$ over the

range of the bin, which in general is not the same as the functional value of $dN/dp_\perp$ at the bin center. For a rapidly falling spectrum, the difference can introduce significant error [17]. To correct for the effect it is necessary to either plot the measured yields at an adjusted value of $p_\perp$, or adjust the value of the yields so they are accurate at the bin center $p_\perp$. The latter method is used here.

A fit f to the $p_\perp$ spectrum is used to estimate the functional value $f(p_\perp^{\text{cent}})$ of $dN/dp_\perp$ at the bin center $p_\perp^{\text{cent}}$. Let Δ be the bin width; a correction factor r is calculated as the ratio of the average and functional values:

$$r = \frac{1}{f(p_\perp^{\text{cent}})} \left[\frac{1}{\Delta} \int_{p_\perp^{\text{cent}} - \Delta/2}^{p_\perp^{\text{cent}} + \Delta/2} f(p_\perp) dp_\perp \right]. \quad (3.7)$$

The corrected yield y' in terms of the measured yield y is then, simply

$$y' = \frac{y}{r}. \quad (3.8)$$

3.4 Systematic Error

The energy scale error in the MPC is $\delta E/E \approx 2\%$ [54]. The effect of this error on the measurement of invariant yields depends on the the $p_\perp$ spectrum $dN/dp_\perp$ but has been found to be between 8% and 12% for $p_\perp \geq 2$ GeV [54] [45]. However, this error is canceled for the most part when calculating the ratio $R_{\text{d+Au}}$, since calibrations are not varied between p+p and d+Au datasets. For the purposes of estimating systematic error, the functional form of $R_{\text{d+Au}}$ can be said to be roughly linear, resulting in an energy scale error in $R_{\text{d+Au}}$ of 2%. An additional error of approximately 2% [54] arises from instability in the individual tower gains. Therefore, the total energy scale systematic uncertainty on $R_{\text{d+Au}}$ is cautiously estimated to be 4%.

Background clusters, discussed in section 3.1, are another source of systematic error. They are estimated [54] to compose at most 25% of all clusters over the relevant $p_{\perp}$ range. However, the error will largely cancel in the calculation of R_{d+Au} , as only relative changes in the cluster composition will affect the ratio. The impact of background clusters on the merged cluster calculation of R_{d+Au} can be estimated by a comparison with R_{d+Au} obtained through a combinatoric analysis [54], in a region of $p_{\perp}$ where the two calculations overlap. Combinatoric measurements of neutral pion yield allow for a precise subtraction of background clusters in a way that is impossible in a merged cluster analysis. Excluding data points on the extremes of the $p_{\perp}$ ranges of each analysis, the two methods agree to within 10%.

Systematic error also arises from the simulations used to calculate efficiencies. Photon interactions with the RHIC beam pipe may cause pre-showering prior to any interaction with the MPC. It has been found that the z-vertex dependence of this effect is not adequately replicated in GEANT simulations [54]. The difference leads to a 6% systematic uncertainty. Additionally, the accuracy of embedding simulations has been tested [54] by comparing measured simulated spectra to true simulated spectra. The error was found to be approximately 2%. Adding these errors in quadrature gives a total systematic error arising from simulations of 7%. Some of this error will cancel when calculating the ratio R_{d+Au} . The remaining bias can be cautiously estimated at 4%.

The bin smearing correction may also give rise to systematic error due to inaccuracies in the input spectrum used to weight the embedding simulations. In general, the size of the error will vary with $p_{\perp}$ but variations in the input spectrum have been found [54] to affect the correction by at most 10%.

Lastly, the global systematic errors present in this analysis are those that arise from applying the trigger bias correction factors C_{bias} , detailed in Table 3.2. For d+Au collisions, C_{bias} , N_{coll} , and associated uncertainties are calculated in PHENIX Analysis Note 900 [58]. For p+p collisions, uncertainty in the trigger bias correction factor is taken to be 9.7%, the error in the absolute cross section for minimum bias p+p events [22]. The relative global error for the invariant yield is $\sigma_{C_{\text{bias}}}/C_{\text{bias}}$. The relative global error for $R_{\text{d+Au}}$ can be computed by taking the ratio

$$\frac{[C_{\text{bias}}/N_{\text{coll}}]_{\text{d+Au}}}{[C_{\text{bias}}]_{\text{p+p}}} \quad (3.9)$$

and propagating the errors through to the result. These errors are summarized in Table 3.3 alongside the values of $C_{\text{bias}}/N_{\text{coll}}$ and $\sigma_{[C_{\text{bias}}/N_{\text{coll}}]}$ that determine the global error for $R_{\text{d+Au}}$.

Summaries of all relative systematic errors are presented in Table 3.4, for the invariant yields, and Table 3.5, for $R_{\text{d+Au}}$. Relative systematic errors for the invariant neutral pion p+p cross section are equivalent to those for the p+p invariant yield. In each of these tables, the following terminology is used:

$\sigma_{N_{\text{inv}}}$	Total relative systematic error for the invariant yield,
$\sigma_{R_{\text{d+Au}}}$	Total relative systematic error for $R_{\text{d+Au}}$,
σ_{bg}	Relative systematic error from background clusters,
σ_{binsmear}	Relative systematic error from the bin smearing correction,
σ_{escale}	Relative systematic error from energy scale uncertainty,
σ_{sim}	Relative systematic error from efficiency simulations,
σ_{sum}	The sum of all relative systematic error excluding global systematic error,
σ_{global}	Relative global systematic error.

Species	$[\sigma_{\text{global}}]N_{\text{inv}}$	$[\sigma_{\text{global}}]R_{\text{d+Au}}$	$C_{\text{bias}}/N_{\text{coll}}$	$\sigma_{[C_{\text{bias}}/N_{\text{coll}}]}$
d+Au 0-20%	0.011	0.108	0.062	0.003
d+Au 20-40%	0.006	0.105	0.098	0.004
d+Au 40-60%	0.016	0.110	0.157	0.008
d+Au 60-88%	0.053	0.123	0.332	0.025
p+p	0.097	-	0.69	0.067

Table 3.3: Relative global systematic error for invariant yield and $R_{\text{d+Au}}$. The included values for $C_{\text{bias}}/N_{\text{coll}}$ and $\sigma_{[C_{\text{bias}}/N_{\text{coll}}]}$ are used to calculate the $R_{\text{d+Au}}$ error.

Species	$\sigma_{N_{\text{inv}}}$	σ_{bg}	σ_{binsmear}	σ_{escale}	σ_{sim}	σ_{sum}	σ_{global}
d+Au 0-20%	0.30	0.25	0.10	0.12	0.07	0.30	0.011
d+Au 20-40%	0.30	0.25	0.10	0.12	0.07	0.30	0.006
d+Au 40-60%	0.30	0.25	0.10	0.12	0.07	0.30	0.016
d+Au 60-88%	0.31	0.25	0.10	0.12	0.07	0.30	0.053
p+p	0.32	0.25	0.10	0.12	0.07	0.30	0.097

Table 3.4: Relative systematic error from all sources for the invariant neutral pion yield.

Centrality	$\sigma_{R_{\text{d+Au}}}$	σ_{bg}	σ_{binsmear}	σ_{escale}	σ_{sim}	σ_{sum}	σ_{global}
0-20%	0.17	0.07	0.10	0.04	0.04	0.14	0.108
20-40%	0.16	0.05	0.10	0.04	0.04	0.12	0.105
40-60%	0.19	0.10	0.10	0.04	0.04	0.15	0.110
60-88%	0.17	0.03	0.10	0.04	0.04	0.12	0.123
Min. Bias	0.16	0.05	0.10	0.04	0.04	0.13	0.103

Table 3.5: Relative systematic error from all sources for $R_{\text{d+Au}}$.

Chapter 4

Results

4.1 Invariant Yields

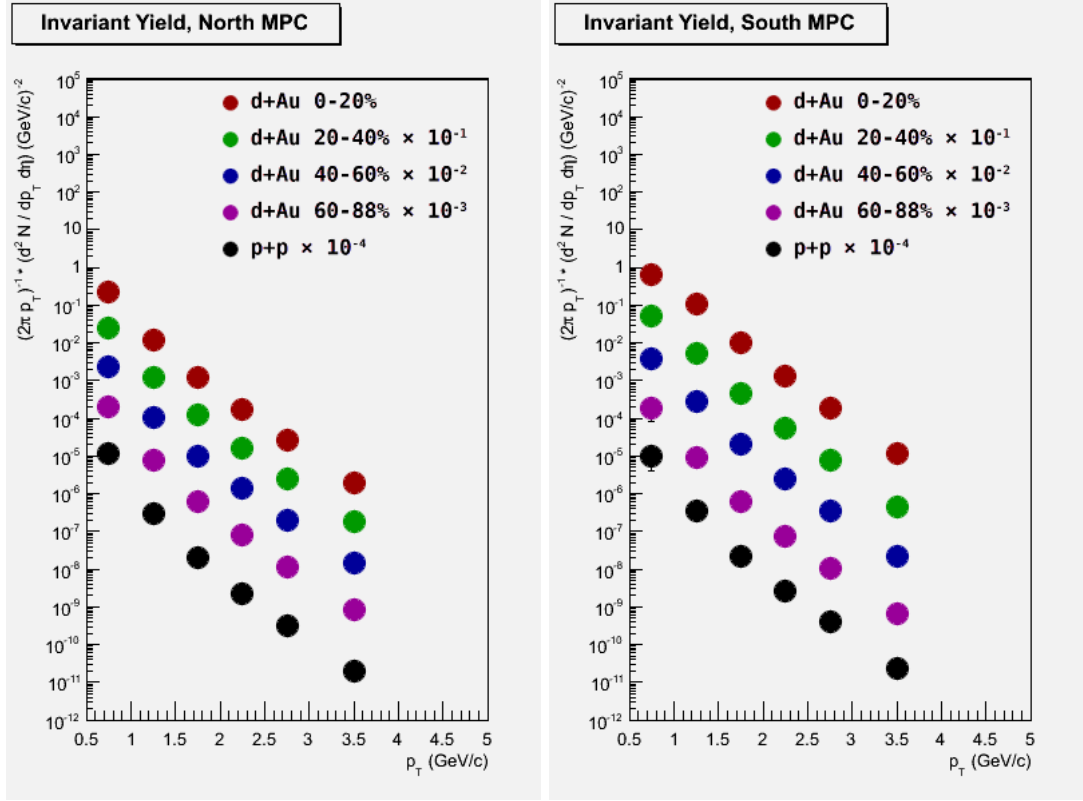
Invariant yield N_{inv} is given by

$$N_{\text{inv}} = E \frac{d^3 N}{dp^3}, \quad (4.1)$$

in terms of the yield N and momentum $\mathbf{p}$. For azimuthally isotropic systems N_{inv} can be written in terms of transverse momentum $p_{\perp}$ and pseudorapidity η :

$$N_{\text{inv}} = \frac{1}{2\pi p_{\perp}} \frac{d^2 N}{dp_{\perp} d\eta}. \quad (4.2)$$

The measured invariant yields for merged cluster neutral pions in the MPC are shown in Figure 4.1.



(a)

(b)

Figure 4.1: Neutral pion invariant yields for d+Au and p+p collisions in the **a.)** north and **b.)** south MPC. Measurements in d+Au collisions are separated by centrality class. The statistical error bars in these figures are small enough to be invisible on most data points.

4.2 Invariant p+p Cross Section

The invariant neutral pion cross section σ_{inv} in p+p collisions is given by

$$\sigma_{\text{inv}} = E \frac{d^3N}{dp^3} \cdot \sigma_{\text{p+p}}, \quad (4.3)$$

where $\sigma_{\text{p+p}} = 42.2$ mb is the total inelastic p+p cross section at $\sqrt{s} = 200$ GeV [23]. Figure

4.2 shows the measured invariant cross sections.

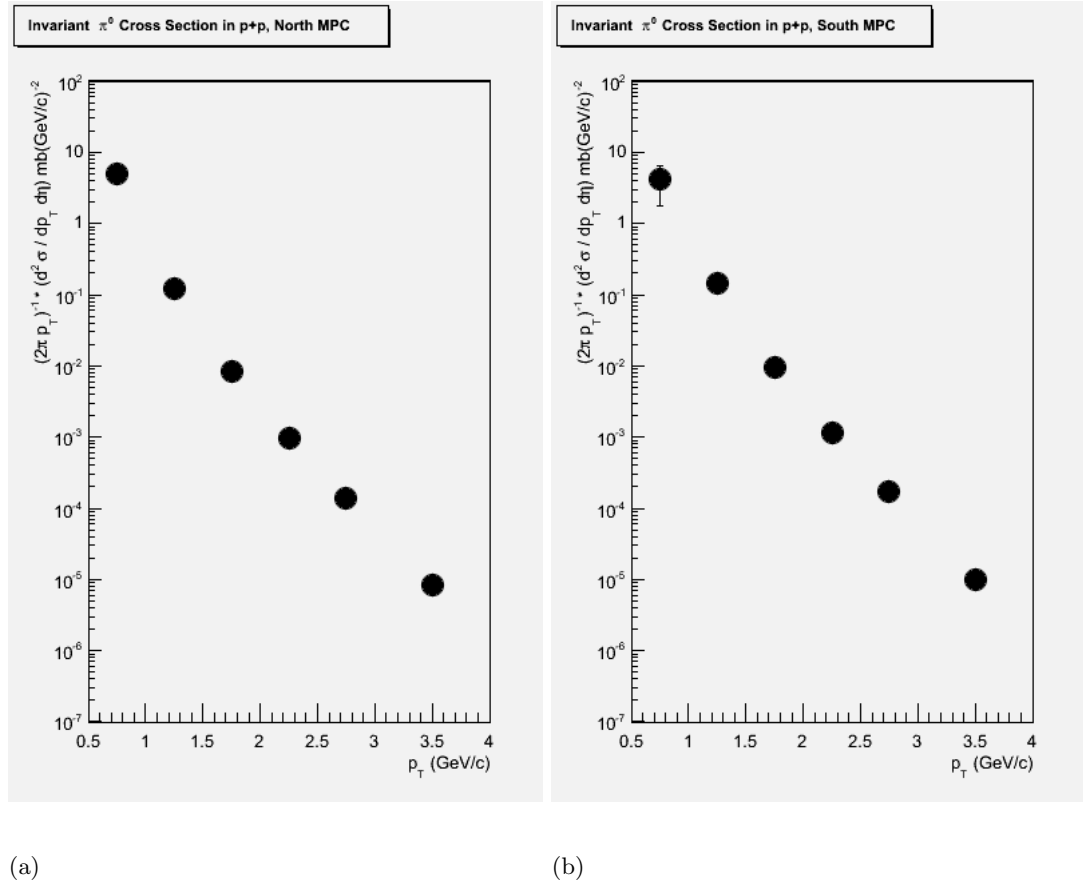


Figure 4.2: Neutral pion invariant cross section for p+p collisions in the **a.)** north and **b.)** south MPC.

4.3 Nuclear Modification Factors

The nuclear modification factor $R_{\text{d+Au}}$ is defined in terms of the invariant yields for d+Au and p+p collisions, normalized to the number of binary collisions N_{coll} :

$$R_{\text{d+Au}} = \frac{[N_{\text{inv}}]_{\text{d+Au}}}{N_{\text{coll}}[N_{\text{inv}}]_{\text{p+p}}} = \frac{1}{N_{\text{coll}}} \cdot \frac{d^2 N_{\text{d+Au}}/dp_{\perp} d\eta}{d^2 N_{\text{p+p}}/dp_{\perp} d\eta} \quad (4.4)$$

Measured nuclear modification factors separated by centrality class are shown in Figure 4.3. Also shown in this figure are nuclear modification factors at lower $p_{\perp}$ obtained via invariant mass reconstruction [54], as a point of comparison. Measured nuclear modification factors for minimum bias collisions are shown in Figure 4.4.

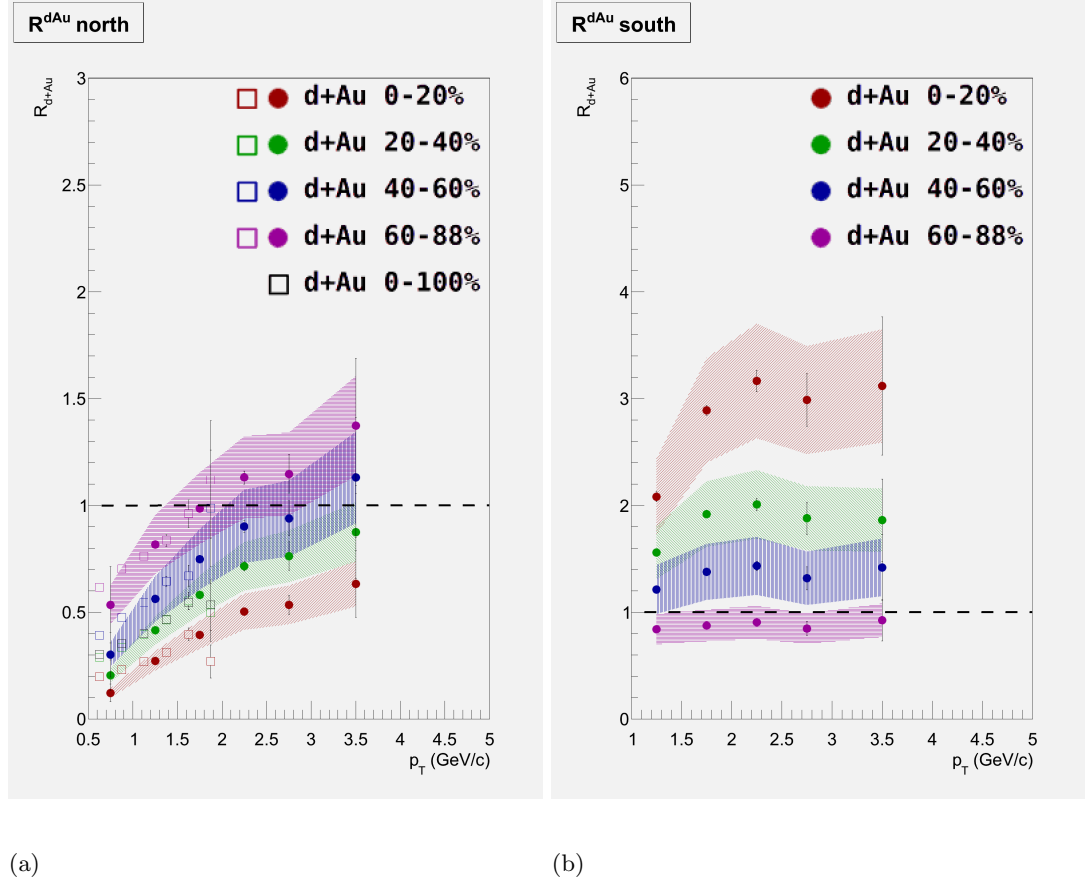
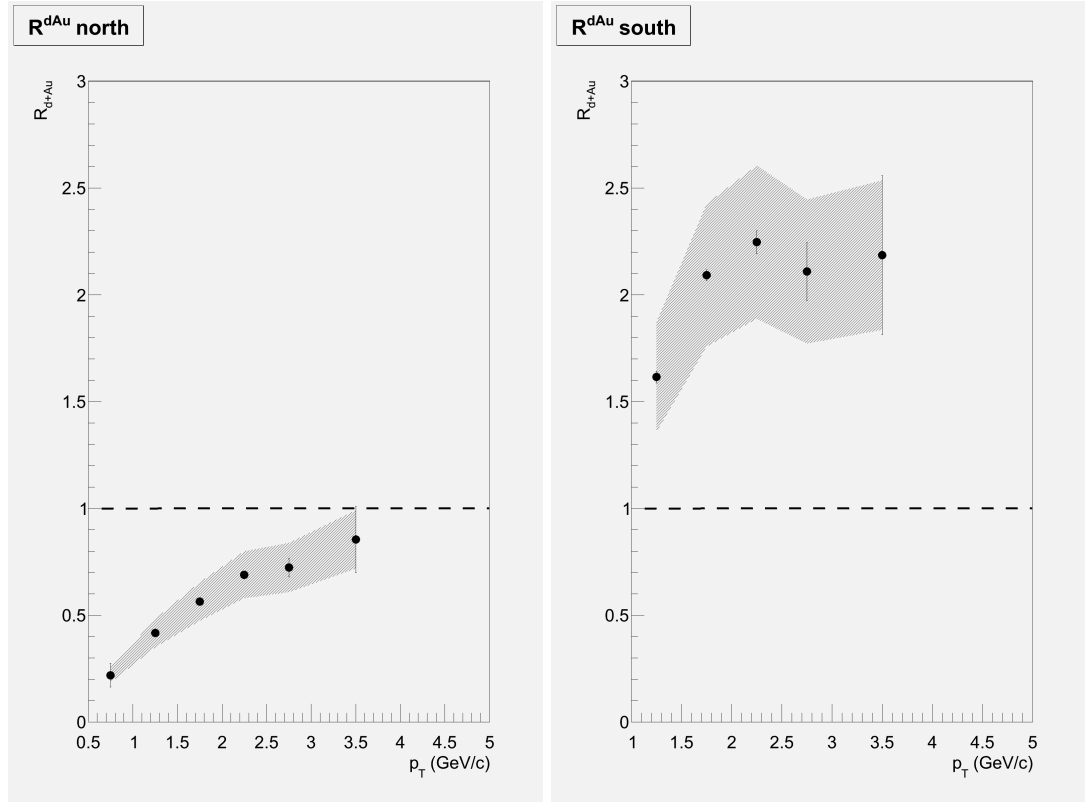


Figure 4.3: Neutral pion nuclear modification factors as measured in the **a.)** north and **b.)** south MPC. Measurements in d+Au collisions are separated by centrality class. Merged cluster results are plotted as closed circles. Also shown, as open squares, are nuclear modification factors obtained via invariant mass reconstruction, as a point of comparison. Statistical error is represented by error bars; systematic error is plotted as shaded bands.



(a)

(b)

Figure 4.4: Minimum bias neutral pion nuclear modification factors as measured in the **a.)** north and **b.)** south MPC. Statistical error is represented by error bars; systematic error is plotted as a shaded band.

Chapter 5

Conclusion

At highly forward rapidity, MPC measurements of minimum bias merged cluster $R_{\text{d+Au}}$ exhibit suppression at high $p_{\perp}$. This result can be compared to model predictions, shown in Figure 5.1, of $R_{\text{d+Au}}$ for minimum bias collisions at $\sqrt{s} = 200$ GeV and $\eta = 3.2$. Figure 5.2 superimposes the most comparable predictions from Figure 5.1 onto the minimum bias nuclear modification factor measurement for the north MPC. In comparison with the prediction for neutral pions from a multiple scattering model, the red line in Figure 5.2, which exhibits a Cronin enhancement, the MPC measurements appear to be more heavily suppressed, with a difference of more than 2σ over the range of the prediction for all but the highest $p_T = 3.5$ GeV/ c . In comparison with the prediction for charged hadrons based on a CGC framework, the blue line in Figure 5.2, the MPC measurements are within 1σ at high $p_{\perp}$. Notably, however, the CGC prediction diverges from measurements at lower $p_{\perp}$. This might partially be explained as a consequence of comparing a prediction for charged hadrons to a measurement for neutral pions. Lastly, in comparison with the prediction for charged pions in a multiple scattering model with leading order twist corrections param-

terized to incorporate extreme nuclear shadowing, the black line in Figure 5.2, the MPC measurements again differ by more than 2σ , excepting the highest $p_\perp$ measurement. While the observed suppression appears to support the CGC prediction at high $p_\perp$, due to the presence of significant systematic error the data does not expressly contradict any of the model predictions.

A comparison can also be made in the forward direction with a result [2] from the STAR collaboration measuring neutral pion R_{d+Au} for minimum bias collisions at $\sqrt{s} = 200$ GeV and $\langle\eta\rangle = 4.00$. The measurement was made using the Forward π^0 Detector (FPD). The STAR measurement is significantly more suppressed than the minimum bias MPC measurement. However, this is likely due to the difference in $\langle\eta\rangle$ between the two measurements, with the MPC at $\langle\eta\rangle \sim 3.5$. Increased η is associated with lower x and, therefore, increased suppression. Figure 5.3 shows the STAR result superimposed onto the minimum bias nuclear modification factor measurement for the north MPC.

In the backwards direction, south MPC R_{d+Au} measurements exhibit an enhancement in hadron production for central collisions but not peripheral collisions. This is consistent with measurements [50] of hadron production at large $-2.2 < \eta < -1.2$ backwards rapidities for d+Au collisions at $\sqrt{s} = 200$ GeV made using the PHENIX muon spectrometers. The physics behind the enhancement is poorly understood but antishadowing at large x within the Au nucleus is one possible explanation [50].

The efficiencies in this analysis were severely reduced by application of the ADC overflow cut, particularly at high $p_\perp$, to the point that statistical error in the efficiencies remained significant even after generating a large number of simulated events. Additionally,

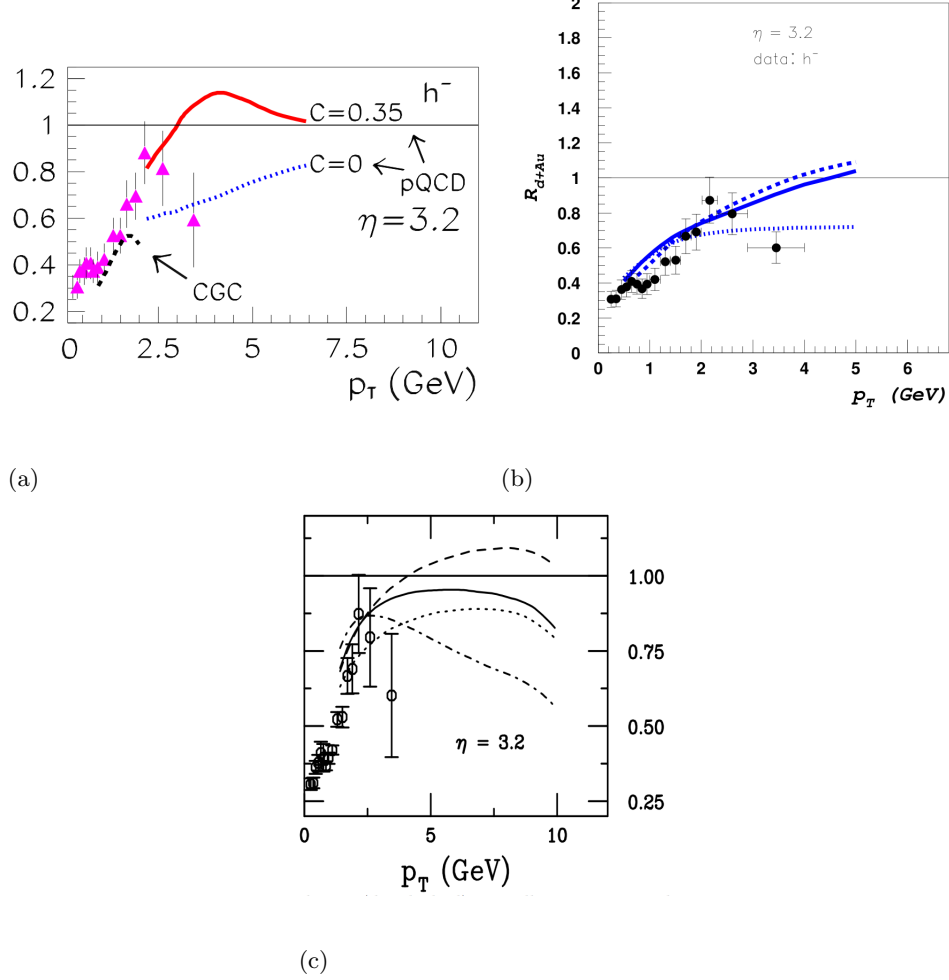


Figure 5.1: Model predictions of R_{d+Au} for $\sqrt{s} = 200$ GeV d+Au collisions at $\eta = 3.2$. In Figure **a.)** [21] the red line, exhibiting Cronin enhancement, represents a prediction of neutral pion R_{d+Au} based on pQCD calculations in a multiple scattering framework that incorporates nuclear shadowing. The dotted line omits multiscattering effects. Figure **b.)** [43] plots R_{d+Au} predictions for charged hadrons in the context of a CGC; a common feature is the absence of a Cronin maximum. The dotted line is $(h^+ + h^-)/2$ while the other lines are h^- with varied model parameters. Figure **c.)** [67] plots R_{d+Au} predictions in a multiple scattering framework parameterized for extreme shadowing; these exhibit suppression comparable to the CGC calculations. The dashed line is for charged pions, the dot-dashed line for kaons, the dotted line for protons and antiprotons, and the solid line for all charged hadrons. In every figure the data points are BRAHMS minimum bias h^- measurements.

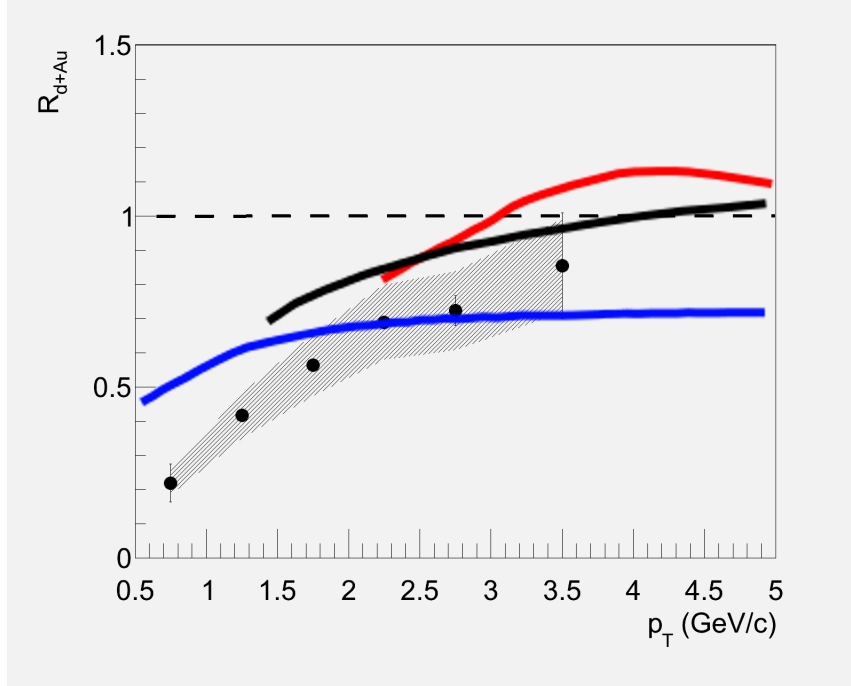


Figure 5.2: Superposition of model predictions, from Figure 5.1, and the minimum bias measurement of R_{d+Au} in the north MPC. The red line corresponds to Figure 5.1-a: neutral pions in a multiple scattering framework with nuclear shadowing. The blue line corresponds to Figure 5.1-b: $(h^+ + h^-)/2$ in the CGC framework. The black line corresponds to Figure 5.1-c: charged pions in a multiple scattering framework parameterized for extreme shadowing.

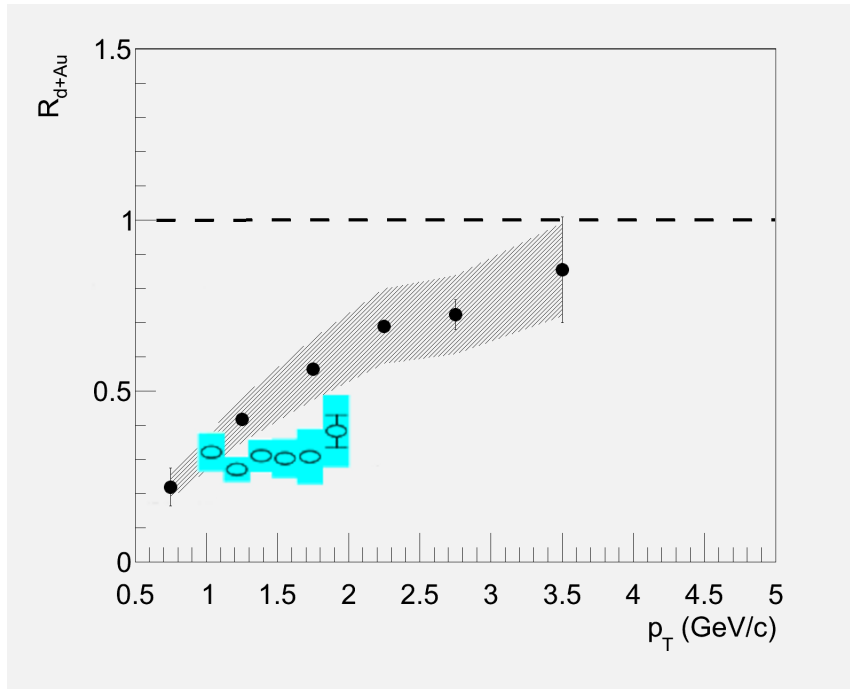


Figure 5.3: STAR neutral pion R_{d+Au} for minimum bias collisions at $\sqrt{s} = 200$ GeV and $\langle\eta\rangle = 4.00$, shown as open circles, superimposed onto the minimum bias R_{d+Au} measurement for the north MPC. Error bars on the STAR data represent statistical error; shaded boxes represent systematic error.

the same cut introduced a large systematic uncertainty for lack of a detailed systematic study, although the bias should largely cancel in measurements of $R_{\text{d+Au}}$. The analysis would benefit from a more careful application of the ADC cut. One possibility would be to vary the cutoff energy for each tower, rather than relying on a global cutoff energy, thereby preserving statistics. If coupled with a substantial study of systematic effects, such an approach could be successful in reducing uncertainty in the $R_{\text{d+Au}}$ measurement, especially in the highest transverse momentum bin.

While predictions based on the CGC are in agreement with the measured $R_{\text{d+Au}}$ at high $p_{\perp}$, the multiple scattering and extreme nuclear shadowing models cannot be definitively ruled out. This result only underscores the need for enhanced measurements of nuclear modification factors at low x and high Q^2 . The MPC-EX detector, which is already taking data, may soon achieve precisely that goal. Its improved resolution allows it to resolve individual photons from high $p_{\perp}$ neutral pions that would appear as a single merged cluster in the MPC. A combinatoric analysis of neutral pion yield in the MPC-EX will, therefore, be able to improve the precision and extend the $p_{\perp}$ range of $R_{\text{d+Au}}$ measurements at low x , well beyond the limitations of a merged cluster analysis in the MPC.

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