Nuclear Effects in d-Au Collisions with PHENIX at RHIC

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Electromagnetic Interactions with Nucleons and Nuclei

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Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Outline

- Nuclear effects in nucleon structure: can we determine the initial state in heavy ion collisions at RHIC?
- Cross sections at forward rapidity:
  - Experimental observables and results.
- Di-hadron correlations (separated in rapidity):
  - Idea + forward detector upgrades
  - First results
- Outlook: Analysis plan for the 2008 d-Au data sample.
Elliptic Flow $v_2$ for Charm: Indicates Quark Level Thermalization & Strong Coupling

Connection between experimental observable and theory through hydrodynamic models:

Initial state often from Color Glass Condensate or event generators!

Major upgrades planned for heavy flavor channels:
10 x RHIC Lumi. + vertex detectors

Improve hydro calculations + knowledge of initial state!

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Motivation:
Characterize initial state in heavy ion collisions.
Probe gluon distributions at low $x$ and high parton densities (in nuclei).

How exactly $G(x)$ saturates at low $x$ and high parton densities is subject of active theoretical studies (see previous talk!)

Signatures of saturation include suppressions of cross sections in $d$-$Au$ collisions compared to $pp$ at forward rapidity:
$R_{dA}(p_T)$, $R_{cp}(p_T)$, and suppression of di-hadron yields $I_{dA}(p_T)$
Suppression of Cross Sections in Forward Direction:

Sufficient Evidence for Saturation Effects in the Gluon Field in the Initial State of d-Au Collision at RHIC?
Quantify Nuclear Modification of Hadron Spectra in d-Au Collisions

Nuclear Modification Factor:

\[ R_{dA}(p_T) = \frac{d^2N^{dA}/dp_Td\eta}{T_{dA}d^2\sigma^{pp}/dp_Td\eta} \]

nucleon-nucleon cross section

\[ \frac{<N_{\text{binary}}>/\sigma_{\text{inel}}^{p+p}}{\sigma_{\text{inel}}^{p+p}} \]

CGC-based expectations


\[ y \]

\[ p_T \]
BRAHMS d+Au Cross Sections Decrease with Increasing Rapidity and Centrality

Hadron production is suppressed at large rapidity consistent with saturation effects at low $x$ in the Au gluon densities $\Rightarrow$ CGC
Similar Results from STAR, PHENIX and PHOBOS

Suppression in the d direction and enhancement in the Au fragmentation region

\[ D \rightarrow x_1 \quad \text{Au} \rightarrow x_2 \]

\[ x_1 \gg x_2 \quad \text{for forward particle, } x_g = x_2 \rightarrow 0 \]
Theory vs Data → CGC Inspired

A. Dumitriu, A. Hayashigaki, J. Jalilian-Marian

Not bad! However, large K factors, rapidity dependent.
Theory vs Data ➔ Cronin + Shadowing + E-loss

Not bad either!

⇒ $R_{dA}$ results alone do not demonstrate gluon saturation. More data & different observables will be needed!

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Rapidity Separated di-Hadron Correlations:

Idea + Forward Upgrades
First Results
Rapidity-Separated Hadron Correlations in d+Au

Idea:
Presence of dense gluon field in the Au nucleus leads to multiple scatterings and parton can distribute its energy to many scattering centers ➔ “Mono-jet signature”. D. Kharzeev, E. Levin, L. McLerran, Nucl.Phys.A748:627-640,2005

Experimental signature:
Observe azimuthal correlation between hadrons in opposing hemisphere separated in rapidity ➔ widening of correlation width of d-Au compared to pp?
➔ reduction in associated yield of hadrons on the away side

➔ Upgrades
Electromagnetic forward calorimeters added to STAR (FMS) and PHENIX (MPC) for 2008 d-Au run.
+ large acceptance forward calorimeter upgrade (FOCAL) planned in PHENIX.
New PHENIX Forward Calorimeters (MPC) for the Measurement of di-Hadron Correlations

PHENIX central spectrometer magnet

Muon Piston Calorimeter (MPC)

$d$ (North) →

Backward direction (South) ←

$\pi^0$ or clusters

$\pi^0$ or $h^\pm$–

Forward direction (North) →

Side View

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
PHENIX Muon Piston Calorimeter

Technology → ALICE(PHOS)

PbWO₄
avalanche photo diode readout

Acceptance:

\[ 3.1 < \eta < 3.9, \quad 0 < \phi < 2\pi \]
\[ -3.7 < \eta < -3.1, \quad 0 < \phi < 2\pi \]

d-Au data sampled:

Both detector were fully installed in PHENIX and commissioned for the d-Au run 2008 at RHIC.

PbWO₄ + APD + Preamp

MPC integrated in the piston of the muon spectrometer magnet.
The Correlation Measurements

- $\sqrt{s_{NN}} = 200$ GeV d-Au, pp collisions from 2008 at RHIC (30 x run 2003 !)
- Trigger particles are ($\pi^0$, $h^{\pm}$) with $|\eta| < 0.35$
- Associate particles are $\pi^0$, clusters with $3.1 < \eta < 3.9$
- One possible method to quantify the correlation:

$$N_{\text{pair}} = \frac{dN}{d\phi_{FG}} / \text{Acceptance} - \text{Background (wings)}$$

$$CY = \frac{N_{\text{pair}}}{N_{\text{trig}} \epsilon_{\text{assoc}}}$$

$$I_{dA} = \frac{CY_{dA}}{CY_{pp}}$$

- Peripheral d-Au Correlation Function

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Observations at PHENIX using the 2003 d-Au sample:

- Left: $I_{dA}$ for hadrons $1.4 < |\eta| < 2.0$, PHENIX muon arms. correlated with $h^{+/−}$ in $|\eta| < 0.35$, central arms.

- Right: Comparison of conditional yields with different trigger particle pseudo-rapidities and different collision centralities

→ No significant suppression or widening seen!


Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Correlation Functions from Run 9
Central arm trigger vs MPC
$h^{+/-}$ (trigger, central)/$\pi^0$ (associate, forward)

$1.0 < p_T^t < 2.0$ GeV/c for all plots

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
\(\pi^0\) (trigger, central)/cluster (associate, forward)

3.0 < \(p_T\) < 5.0 GeV/c for all plots

\(p_T^f\), \(p_T^a\), cluster

\(\Delta\phi\)

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Nuclear Effects in d-Au Collisions in PHENIX at RHIC

Forward/Central Correlation Widths

Trigger $\pi^0$: $|\eta| < 0.35$, $2.0 < p_T < 3.0$ GeV/c

- pp $\pi^0$
- dAu 0-20% $\pi^0$
- dAu 40-88% $\pi^0$
- pp Cluster
- dAu 0-20% Cluster
- dAu 40-88% Cluster

Correlated Systematic Error

Trigger $\pi^0$: $|\eta| < 0.35$, $3.0 < p_T < 5.0$ GeV/c

- pp $\pi^0$
- dAu 0-20% $\pi^0$
- dAu 40-88% $\pi^0$
- pp Cluster
- dAu 0-20% Cluster
- dAu 40-88% Cluster

Correlated Systematic Error

PHENIX PRELIMINARY
Forward/Central $I_{dA} \text{ vs } N_{\text{coll}}$

- Increasing suppression of $I_{dA}$ reaches a factor 2 for central events
- Model calculations are needed to distinguish between different models
  - Saturation (Color Glass Condensate)
  - Shadowing
  - Cronin
  - Others?

Associate $\pi^0$: 3.1 < $\eta$ < 3.9, 0.45 < $p_T$ < 1.6 GeV/c

Trigger Particle: |$\eta$| < 0.35
- $\pi^0$: pT = 2.0-5.0 GeV/c
- h'/: pT = 1.0-2.0 GeV/c

PHENIX PRELIMINARY

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Alternative Explanation of Rapidity-Separated di-Hadron correlations in d+Au

Complete (coherent + multiple elastic scattering) treatment of multiple parton scattering gives suppression of pairs with respect to singles for mid-rapidity tag!

However, small for forward trigger particle!


Expand analysis to backward MPC and forward + backward triggers. Update muon arm analysis from run 8.
Update from Ivan Vitev after QM 2009!!

Associate $\pi^0$: $3.1 < \eta < 3.9$, $pT = 0.45$-1.59 GeV/c

- Trigger Particle: $|\eta| < 0.35$
  - $\pi^0$: $pT = 2.0$-5.0 GeV/c
  - $h^+$: $pT = 1.0$-2.0 GeV/c

Expand analysis to backward MPC and forward + backward triggers. Update muon arm analysis from run 3!
Analysis Plan with 30 x ∫Ldt and the MPC

- $I_{dA}$ and $R_{dA}$ with **Forward Calorimeters** $3.1 < |\eta| < 3.9$ + High Statistics from 2008 d+Au Run. Update earlier muon arm measurement!

<table>
<thead>
<tr>
<th>Particle Detection</th>
<th>South MPC</th>
<th>South Muon Arm</th>
<th>Central Arm</th>
<th>North Muon Arm</th>
<th>North MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{\text{min}}$</td>
<td>$\pi^0$</td>
<td>$h^{+/}$</td>
<td>Identified hadrons</td>
<td>$h^{+/}$</td>
<td>$\pi^0$</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$</td>
<td>-3.7</td>
<td>-2.0</td>
<td>-0.35</td>
<td>1.4</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>-3.1</td>
<td>-1.4</td>
<td>+0.35</td>
<td>2.0</td>
<td>3.9</td>
</tr>
</tbody>
</table>


**Backward/Central**

**Forward/Central**

**Forward/Backward**
Conclusions

• First results from azimuthal angle correlations for rapidity separated di-hadrons with new forward MPCs:
  – The widths do not show appreciable variation for central/peripheral dAu vs pp within experimental precision.
  – Suppression of $I_{dA}$ is observed for central collisions.
  – Model calculations needed to differentiate possible explanations:
    • Saturation effects or shadowing
      – are we at low enough x to see this?
    • Cronin, other physics?
• Use 2008 d-Au sample + upgrade to evaluate $R_{dA}$ and $I_{dA}$ for different rapidity (gaps).
Backup Slides
The MPC can reliably detect pions (via $\pi^0 \rightarrow \gamma \gamma$) up to $E = 17\text{GeV}$.

To go to higher $p_T$, use single clusters in the calorimeter:
- Use $\pi^0$s for $7\text{GeV} < E < 17\text{GeV}$
- Use clusters for $20\text{GeV} < E < 50\text{GeV}$

Correlation measurements are performed using $\pi^0$s, clusters.

Use event mixing to identify pions:
- foreground $\rightarrow$ photons from same event
- background $\rightarrow$ photons from different events

**South MPC**

![Graph showing foreground and background yield](image)
Elliptic Flow $v_2$: Among Key Evidence for Formation of Partonic Matter at RHIC

- Early thermalization
- Strongly interacting
- Quark dofs, $v_2/n_q$ scales

Heavy quarks?
$l_{dA} \text{ vs } p_T^a$

$p_T^a = 0.55 \text{ GeV/c}$

Associate $z^d: 3.1 < \eta < 3.9$, $<p_T> = 0.55 \text{ GeV/c}$

Trigger Particle: $|y| < 0.35$

- $z^d$: $p_T = 2.0-3.0 \text{ GeV/c}$
- $z^d$: $p_T = 3.0-5.0 \text{ GeV/c}$
- $h^\pi$: $p_T = 1.6-2.0 \text{ GeV/c}$

Associate $p_T$ scale uncertainty 10%}

$p_T^a = 0.77 \text{ GeV/c}$

Associate $z^d: 3.1 < \eta < 3.9$, $<p_T> = 1.00 \text{ GeV/c}$

Trigger Particle: $|y| < 0.35$

- $z^d$: $p_T = 2.0-3.0 \text{ GeV/c}$
- $z^d$: $p_T = 3.0-5.0 \text{ GeV/c}$
- $h^\pi$: $p_T = 1.6-2.0 \text{ GeV/c}$

Associate $p_T$ scale uncertainty 10%}

$p_T^a = 1.00 \text{ GeV/c}$

Associate $z^d: 3.1 < \eta < 3.9$, $<p_T> = 1.00 \text{ GeV/c}$

Trigger Particle: $|y| < 0.35$

- $z^d$: $p_T = 2.0-3.0 \text{ GeV/c}$
- $z^d$: $p_T = 3.0-5.0 \text{ GeV/c}$
- $h^\pi$: $p_T = 1.6-2.0 \text{ GeV/c}$

Associate $p_T$ scale uncertainty 10%}
$I_{dA}$ with 3 Trigger Particle Bins

Associate $\pi^0$: $3.1 < \eta < 3.9$, $pT = 0.45-1.58$ GeV/c

PHENIX PRELIMINARY
\[ \pi^0 \text{ (trigger, central)}/\pi^0 \text{ (associate, forward)} \]

2.0 < \( p_T^t \) < 3.0 GeV/c for all plots

**Correlation Function**

- **pp**
- **dAu 0-20%**
- **dAu 60-88%**

\( p_T^t, \pi^0 \)

\( \Delta \phi \)

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
$\pi^0$ (trigger,central)/$\pi^0$ (associate,forward)

$3.0 < p_T^t < 5.0$ GeV/c

For all plots

$pp$

$d$Au 0-20%

$d$Au 60-88%

$p_T^t, \pi^0$

$p_T^a, \pi^0$

Nuclear Effects in d-Au Collisions in PHENIX at RHIC
Clusters vs $\pi^0$s

- MPC crystals are ~ 2.2 cm, and the detector sits $\Delta z = 220$ cm from $z = 0$
- From previous page, $\Delta r_{\text{min}}$ for two photons is 3.5 cm
- What is max pion energy we can detect?
  - For $\alpha = 0$, $E_{\gamma_1,\text{max}} = E_{\gamma_2,\text{max}}$
  - $E_{\gamma,\text{max}} = p_{T,\gamma}/\sin(\Delta \varphi/2) = m_\pi \Delta z/\Delta r_{\text{min}}$
  - $E_{\pi,\text{max}} = 2m_\pi \Delta z/\Delta r_{\text{min}} = 17$ GeV
- Able to identify pions up to 17 GeV for $\alpha = 0$
- Beyond this we need better cluster splitting
  - As of now, single clusters above this energy are likely to be $\pi^0$s, direct $\gamma$s, or background
- Use high energy clusters as well for correlations, $R_{cp}$, $R_{dA}$
MPC Pion Selection

- Cuts
  - Cluster Cuts
    - Cluster ecore > 1.0 (redundant w/ pion assym and energy cuts)
  - Pi0 pair
    - E > 6 GeV
    - Asym < 0.6
    - Separation cuts to match fg/bg mass distribution
    - Max(disp_x, disp_y) < 2.5

\[
\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} > 3.5 \text{cm}
\]

\[
\frac{\sqrt{(i x_1 - i x_2)^2 + (i y_1 - i y_2)^2}}{1.5}
\]

- Use mixed events to extract yields
  - Normalize from 0.25-0.4 presently
MPC/CA Cuts

- MPC pi0 ID
  - Mass window of 0.1-0.2 GeV + previously shown cuts
  - 7 – 17 GeV energy range
  - Max(dispx,dispy) \(\leq 2.5\)

- Charged Hadron ID Track Quality == 31 or 63
  - \(n_0 < 0\) Rich cut
  - \(p_T < 4.7\) GeV
  - pc3 sdz and sdphi matching < 3
  - -70 < zed < 70

- EMC pi0
  - Alpha < 0.8
  - PbGl min E = 0.1, PbSc min E = 0.2
  - Chi2 cut of 3, prob cut of 0.02
  - Sector matching
  - Mass window 0.1-0.18
  - Trigger bit check
$x_1$ and $x_2$ in Central Arm – MPC correlations

Central Arm

-0.35 < $\eta$ < 0.35

3.1 < $\eta$ < 3.9

$X_2$-range: 0.006 < $x$ < 0.1

Marco Stratman pQCD calculations for pp

$x_1 > x_2$