PHENIX study of the initial state with forward hadron measurements in 200 GeV p(d)+A and $^3$He+Au collisions

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On behalf of the PHENIX collaboration

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Small Systems: p+Au, p+Al and d+Au

• Distinguish cold nuclear matter (CNM) effects from final state effects
• Previous PHENIX measurement of forward charged hadron $R_{CP}$ (QM2017)
• Found backward enhancement and forward suppression
• New Result: $R_{pA}$ in 200 GeV p+Al, p+Au

Forward/Backward Physics

• Forward: small $x$, larger energy loss
• Backward: large $x$, higher multiplicity
• Future low-$x$ direct photon measurement will help constrain nuclear gluon distribution
New PHENIX Forward Hadron Measurements in Small Systems:

High Rapidity: \(-2.2 < \eta < -1.2, 1.2 < \eta < 2.4\)
- Forward and backward charged hadron \(R_{pA}\)
- Both in 200 GeV \(p+Au\) and \(p+Al\)
- Using Forward Vertex Detector (FVTX)

Very High Rapidity: \(3.1 < |\eta| < 3.8\)
- Upcoming forward \(\pi^0\) \(R_{CP}\)
- Future forward direct photons
- 200, 62, 39 and 20 GeV \(d+Au\) data sets
- Muon Piston Calorimeter Extension (MPC-EX)

<table>
<thead>
<tr>
<th>System</th>
<th>Species</th>
<th>(\eta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p+Al) 200 GeV</td>
<td>(h^\pm)</td>
<td>(1.2 &lt;</td>
</tr>
<tr>
<td>(p+Au) 200 GeV</td>
<td>(h^\pm)</td>
<td>(1.2 &lt;</td>
</tr>
<tr>
<td>(d+Au) 200 GeV</td>
<td>(\pi^0)</td>
<td>(3.1 &lt;</td>
</tr>
<tr>
<td>(d+Au) 200 GeV</td>
<td>(\gamma)</td>
<td>(3.1 &lt;</td>
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</tbody>
</table>
High Rapidity:

\[-2.2 < \eta < -1.2, \ 1.2 < \eta < 2.4\]
Forward Vertex (FVTX) Detector:

- $-2.2 < \eta < -1.2$, $1.2 < \eta < 2.4$
- FVTX: 4 layers of silicon planes placed close to the collision vertex on both PHENIX arms
- Precise measurements of $\eta$
- NIM A 755 (2014) 44-61
Hadron Analysis in the PHENIX Muon Arms

- $-2.2 < \eta < -1.2$, $1.2 < \eta < 2.4$
- Hadrons which pass through first absorber (3,4) can be detected in muon arms
- Low energy muons are rejected by cutting on longitudinal momentum, $p_z$
- High energy muons (2) are rejected by requiring tracks terminate in gap 2 or 3
- Requiring FVTX matching rejects secondary hadrons
$R_{pA}$ in $p+Al$ and $p+Au$

Centrality Dependence of $R_{pA}$ in p+Au

- Magnitude of Au-going enhancement and p-going suppression appear to depend on centrality.
Centrality Dependence of $R_{pA}$ in p+Al

- $R_{pA}$ in p+Al continues centrality trend
- Smaller systems show smaller backward enhancement
- Forward suppression similar to pAu results

![Graph showing centrality dependence of $R_{pA}$ in p+Al](image)

**Graph Details:**
- PHENIX preliminary
- p,d, Au,Al
- FVTX

**Legend:**
- 0-5% Central
- 5-10% Central
- 10-20% Central
- 20-40%
- 40-72%

**Equations:**
- $R_{pA}$
- $p_t$ (GeV/c)
- $\eta$

**Table:**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>p+Al → h^+X $\sqrt{s_{NN}}=$200 GeV</th>
</tr>
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<tbody>
<tr>
<td>0-5%</td>
<td>5-10%</td>
</tr>
<tr>
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<td>20-40%</td>
</tr>
<tr>
<td>40-72%</td>
<td></td>
</tr>
</tbody>
</table>
$R_{pA}$ vs. $N_{\text{part}}$

- Backward enhancement scales with $N_{\text{part}}$ across collision systems

$R_{pA}$ vs. $N_{\text{part}}$

- $-2.2 < \eta < -1.2$, $p+Au$ (Au-going)
- $-2.2 < \eta < -1.2$, $p+Al$ (Al-going)
- $1.2 < \eta < 2.4$, $p+Au$ (p-going)
- $1.2 < \eta < 2.4$, $p+Al$ (p-going)

$P_{h^\pm, 2.5<p_T<5 \text{ GeV/c}}$

$10\%$ global sys. uncertainty

$-2.2 < \eta < -1.2$, $p+Au$ (Au-going)

$-2.2 < \eta < -1.2$, $p+Al$ (Al-going)

$1.2 < \eta < 2.4$, $p+Au$ (p-going)

$1.2 < \eta < 2.4$, $p+Al$ (p-going)
η dependence of $R_{pA}$

- $R_{pA}$ vs $\eta$ integrated over $2.5 < p_T < 5$ (GeV/c)
- Larger enhancement in backward p+Au
$\eta$ dependence of $R_{pA}$

$R_{pA}$ of Charged Hadrons Compared to $\phi$, heavy flavor and $J/\Psi$ in 200 d+Au $R_{dA}$

- Similar backward enhancement seen in d+Au
- $h^\pm$ Enhancement and suppression consistent with $\phi$ and heavy flavor suppression in d+Au

PHENIX

Centrality Dependence of $R_{pA}$ vs. $\eta$ in p+Au

- Centrality dependent $R_{pA}$ vs $\eta$ integrated over $2.5 < p_T < 5$ (GeV/c)

Clear backward enhancement dependent on centrality
Centrality Dependence of $R_{pA}$ vs. $\eta$ in p+Al

- Centrality dependent $R_{pA}$ vs $\eta$ integrated over $2.5 < p_T < 5$
- Higher centrality exhibits stronger enhancement, peripheral $R_{pA}$'s closer to unity

<table>
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<tr>
<th>Centrality</th>
<th>$R_{pA}$ vs $\eta$ Integrated</th>
<th>$p_T$ Range</th>
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<tr>
<td>0-5%</td>
<td></td>
<td>2.5 &lt; $p_T$ &lt; 5 GeV/c</td>
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- $p/d$ Au, Al
- FVTX

- $-2.2 < \eta < -1.2$
- $1.2 < \eta < 2.4$

- p-going
- Forward
- Au, Al-going
- Backward
Very High Rapidity: $3.1 < |\eta| < 3.8$
Very Large Rapidity $3.1 < |\eta| < 3.8$
- Measure $\pi^0$ suppression out to high $p_T$ at large rapidity
- Use $\pi^0$ identification to measure direct photons

Nuclear Gluon Distribution
- Identifying and rejecting $\pi^0$s is necessary for measuring direct photons
- Direct photons directly access the underlying gluon distribution
- Allowing the nuclear gluon distribution at low-$x$ to be better understood

Gluon Saturation
- Several models including the CGC, predict strong gluon suppression at lower $x$ and higher centrality
- Measuring direct photons will allow the mapping of $Q$-$x$ space to better test the viability of CGC
Dihadron $J_{dA}$ in 200 GeV $d+Au$

- Forward-Forward dihadrons more suppressed than mid-forward
- Large suppression of dihadron correlation at low $x$ in central collisions
MPC-EX

- PHENIX has 2 detectors in the rapidity range $(3.1 < \eta < 3.8)$, the MPC and MPC-EX
- MPC: Electromagnetic calorimeter
- MPC-EX Upgrade: Preshower calorimeter located in front of the MPC
- Alternating tungsten plates and X-Y oriented micropattern silicon sensors called minipads
- 8 layers of 24 sensors with 128 minipads
MPC and MPC-EX

PHENIX has 2 detectors in the rapidity range \((3.1 < \eta < 3.8)\), the MPC and MPC-EX:

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**PHENIX Side View**

**MPC-EX Sensor with Minipads**

**Peak Finding in MPC-EX**

**Spatial Distribution of MPC-EX Shower Hits**

- Entries: 969425
- Mean: 2.467
- Std Dev: 1.245

\( h_{proj\ X} \) histogram:

- Entries: 969425
- Mean: 2.467
- Std Dev: 1.245
MPC Performance before Upgrade

- $\pi^0$s reconstructed with the MPC alone
- Limited to $p_T \sim 2$ GeV/c
- Adding MPC-EX upgrade improves the ability to distinguish photons up to $p_T \sim 6$ GeV/c
Uncorrected $\pi^0$ Spectrum

- Using MPC and MPC-EX
- Improving on the $p_T \sim 2$ GeV/c limitation of the MPC alone
- Extending the $p_T$ reach to $\sim 6$ GeV/c

![Uncorrected $\pi^0$ Spectra 3.1 < $\eta$ < 3.8](image)
Conclusions:
New Measurements with the PHENIX FVTX at $-2.2 < \eta < -1.2, 1.2 < \eta < 2.4$
- Forward and backward charged hadron $R_{pA}$ in $p+Au$
  - Low $p_T$ enhancement in Au-going and suppression in p-going
- Forward and backward charged hadron $R_{pA}$ in $p+Al$
  - Backward enhancements consistent with $p+Au$, but smaller in magnitude
  - Forward suppression similar to $p+Au$
- Enhancements scale with $N_{\text{part}}$
Measurements with the PHENIX MPC-EX at $3.1 < |\eta| < 3.8$ coming soon
- Upcoming forward $\pi^0 R_{CP}$ in 200, 62, 39, 20 GeV $d+Au$
  - Extending $p_T$ reach to 6 GeV/$c$
- Future forward direct photons in in 200 GeV $d+Au$
Backup Slides
FVTX ACC x EFF

- ACC x EFF determined by hadron cocktail simulation
- Initial hadron spectra extrapolated to forward rapidity from measured pT spectra in mid-rapidity based on pythia and hijing
- Embedding done to account for effects from background hits
- Uncertainty from selection of physics package is less than 5%, cancels out RpA, because hadron inside absorber is system independent
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$J_{dA}$ and $X_{Au}^{\text{frag}}$

- $R_{dA}^t$, nuclear modification factor for trigger particles
- $\sigma, \sigma^t, \sigma^{\text{pair}}$, cross sections for full event, trigger particle event and dihadron pair event selection
- $I_{dA}$, ratio of conditional hadrons yields $CY$
- $dN/d(\Delta \phi)$, the acceptance corrected dihadron correlation function
- $N^t$ number of trigger particles
- $\epsilon^a$, detection efficiency for the associated particle
- $b_0$, the level of uncorrelated pedestal in the correlation functions
- Integral taken over the Gaussian fit of the away side peak

$$J_{dA} = I_{dA} * R_{dA}^t = \frac{1}{N_{\text{coll}}} \frac{\sigma^{\text{pair}}}{\sigma_{dA}} \frac{\sigma_{dA}}{\sigma_{dA}}$$

$$R_{dA}^t = \frac{1}{N_{\text{coll}}} \frac{\sigma^t}{\sigma_{pp}} \frac{\sigma_{dA}}{\sigma_{dA}}$$

$$I_{dA} = CY = \int d(\Delta \phi) [dN/d(\Delta \phi) - b_0]$$

$$N^t * \epsilon^a * \Delta \eta^a * \Delta p_T^2$$

$$X_{Au}^{\text{frag}} = \frac{(\langle p_{T1} > e^{-\langle \eta1 >} + \langle p_{T2} > e^{-\langle \eta2 >})}{\sqrt{s_{\text{NN}}}}$$
FVTX ACC \times\ EFF

- Absorber: $\sim 7\lambda_I$
- Hadron rejection rate almost $\sim 1/1000$
FVTX Matching Cuts

- Matching cuts between Mutr and FVTX
MC Species Mix

- MC Species mix after track quality cuts