Cold nuclear matter effect measured with high $p_T$ hadrons and jets in 200GeV d+Au collisions in PHENIX

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For the PHENIX Collaboration
Why are we interested in d+Au collisions?

- In order to confirm that the high $p_T$ hadron suppression in Au+Au collisions is due to final state effect, and not cold nuclear matter (CNM) effect
  - Need system without additional effects from a hot medium.

- CNM effect include:
  - $\kappa$-broadening (Cronin enhancement at moderate $p_T$)
  - Shadowing of parton distributions
  - Cold nuclear matter energy loss
  - And possibly more…

- d+Au is more favorable for RHIC operation
  - $p$+Au becomes feasible now (M.Bai)
Nuclear PDFs are centrality dependent?

- Helenius, Eskola et al. published centrality dependent nuclear PDFs (arXiv:1205.5359)
- Compared to PHENIX $\pi^0$ $R_{dA}$ published in 2003
- Theory curves are scaled up/down within systematics
- New data can help better constraining nPDFs
PHENIX Detector

- Photon measurement
  - EMCal(PbSc, PbGl): Energy measurement and identification of real photons
  - Tracking(DC, PC): Veto to Charged particles

- Charged particle measurement
  - Tracking measure momentum
  - RICH: Identify electrons
  - EMCal add information on identifying electrons

- Event triggered by a coincidence of BBC South and BBC North
  - Sitting in 3.1<|\eta|<3.9
  - Centrality defined by BBC south charge (Gold going direction)

PHENIX recorded d+Au events of 80 nb\(^{-1}\) in 2008 (2.74 nb\(^{-1}\) in 2003)
\( \pi^0 \) and \( \eta \) reconstruction
How we measure $\pi^0$, $\eta$?

- Reconstruct hadrons via $2\gamma$ invariant mass in EMCal (example is in Au+Au)
  \[
  M^2 = (E_1 + E_2)^2 - (p_1 + p_2)^2 = 2E_1E_2(1 - \cos \theta)
  \]

- Subtract Combinatorial background
  - Compute Mass using $\gamma$s from different events. (mixed-event technique)

**Figure 3:** (Color online) Invariant mass spectrum of two photons (black) and the corresponding mixed events (red) at $7.0 < p_T < 7.5$ GeV/c in minimum bias collisions. Vertical lines indicate a $\pm 2.5 \sigma$ integration window.
Systematic errors

- **Type A**: point-by-point fluctuating errors
- **Type B**: $p_T$-correlated errors
- **Type C**: overall normalization errors

### $\pi^0$ Systematic Errors

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### $\eta$ Systematic Errors

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</tbody>
</table>

T. Sakaguchi, WWND2013@Squaw Valley

2013-02-07
$\pi^0$ and $\eta$ $p_T$ spectra in 200GeV d+Au collisions
\( \pi^0 R_{dA} \) by centrality

\[
R_{dA} = \frac{(1/ N_{evt}) (dN_{dAu} / dp_T)}{(T_{dAu}^AB) (d\sigma_{pp} / dp_T)}
\]

New \( \pi^0 R_{dA} \) from Run8

- Better statistics than Run 3
  - Extends \( p_T \) reach by 5 GeV/c
  - Better constraint for nPDFs

Peripheral is most enhanced

Central consistent with no modification at \( p_T > 2 \) GeV/c

How do we understand this?
Competing nuclear effects?
New $\eta R_{dA}$ from Run8

- Better statistics than Run 3
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How do we understand this?
Competing nuclear effects?
Jet reconstruction
Reconstruction of jets in p+p

- Gaussian Filter: Cone-like, but infrared and collinear safe

- Shape of the filter:
  - Optimizes the signal-to-background by focusing on the core of the jet
  - Stabilizes the jet axis in the presence of background

- Naturally handles isolated particles vs. collective background
Reconstruction of jets in p+p

- Gaussian Filter: Cone-like, but infrared and collinear safe

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  - Optimizes the signal-to-background by focusing on the core of the jet
  - Stabilizes the jet axis in the presence of background

- Naturally handles isolated particles vs. collective background

![Diagram of cone and filter]

\[
\int \mathcal{L} = 2.2 \text{ pb}^{-1}
\]

(Gaussian filter, \(\sigma = 0.3\)

Width not a \(p_T\) uncertainty

Run-5 p + p = 200 GeV/c

PHENIX Preliminary

PHENIX, \(\sigma = 0.3\)

PYTHIA, \(K = 2.5, \sigma = 0.3\)

NLO SCA, \(R = 0.3\) (Vogelsang)

STAR HT, \(R = 0.4\) (PRL 97, 252001)
Systematic errors

- Type B: $p_T$-correlated errors
- Type C: overall normalization errors
- Bin-by-bin unfolding to correct for $p_T$ increase from mild d+Au underlying events (evaluated with embedding analysis)
- Small residual fake rate (< 5%) above > 9 GeV/c

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Jet $p_T$ spectra in 200GeV d+Au collisions

$d^2N/dp_T^2$ for different centrality classes: 

- d+Au 0-20% ($\times 4$)
- d+Au 20-40% ($\times 2$)
- d+Au 40-60%
- d+Au 60-88%
- p+p
Jets $R_{dA}$

- Higher $p_T$ reach than $\pi^0$s

- Enhancement in peripheral, suppression in central.
  - Similar trend seen in $\pi^0$ and $\eta$
Comparison to \( \pi^0 \) and \( \eta \) \( R_{dA} \)

\( \pi^0 \), \( \eta \) and jets of same \( p_T \) sample slightly different parton scales, but let’s overlay them anyways…

Good agreement within uncertainties, and given the difference in observables.
Comparison to $\pi^0$ and $\eta \ R_{cp}$

$$R_{cp} = \frac{(1/ N_{cent}^{\text{coll}})(1/ N_{cent}^{\text{evt}})(dN_{cent}^{\text{coll}} / dp_T)}{(1/ N_{peri}^{\text{coll}})(1/ N_{peri}^{\text{evt}})(dN_{peri}^{\text{coll}} / dp_T)}$$

$\pi^0$, $\eta$ and jets of same $p_T$ sample slightly different parton scales, but let’s overlay them anyways…

Good agreement within uncertainties, and given the difference in observables.
Comparison with models
(Very basic) shadowing calculation uses EPS09 PDF modification* + Glauber MC + PYTHIA ($x, Q^2$) sampling for $\pi^0$.

Shadowing effects match reasonably well within the global scale uncertainties in central events (where modification is weak), but is not compatible with the $p_T$ shape in peripheral.

*nPDF modification assumed to scale linearly with longitudinal nuclear thickness.
Comparison to shadowing calculation (II)

(Very basic) shadowing calculation uses EPS09 PDF modification* + Glauber MC + PYTHIA ($x, Q^2$).

Shadowing effects match reasonably well within the global scale uncertainties in central events (where modification is weak), but is not compatible with the $p_T$ shape in peripheral.

*nPDF modification assumed to scale linearly with longitudinal nuclear thickness.
Interpretation of the results

- Strong centrality dependence of $R_{dA}$
  - $\pi^0$, $\eta$ and jets $R_{dA}$ are in very nice agreement in spite of completely different systematics
  - nPDF may be strongly centrality dependent

- Some thought
  - Before making the final conclusion, we would like to confirm some global things.
How we define centralities?

- Use Beam-Beam counter (BBC) installed in $3.1 < |\eta| < 3.9$
  - Centrality defined by BBC south charge (Gold going direction)
  - Participant region

- Compare with Monte Carlo simulations and determine $T_{AB}$
  - Glauber calculation folded with negative binomial distributions (NBD)
Possible dynamics in d+Au collisions

- We talk about *peripheral* collision case
- Soft- and hard-dominated events may produce different hit distributions in BBC
- In case that hardest jets are produced, less energy will be available for soft-production at high $\eta$
- There could be $p_T$ dependent effect?
  - We use BBC for event triggering as well as centrality definition
PYTHIA simulation

- Ran PYTHIA and look reconstructed jets in mid-rapidity
- PYTHIA sees a small anti-correlation effect
AMPT p+p simulation

- AMPT is a HIJING + hadron cascade event generator

- Plotted as a function of hadron $p_T$ in mid-rapidity
  - Jets are not reconstructed.
  - AMPT also sees similar effect in single hadrons

Number of hits in BBC vs hadron $p_T$ in mid-rapidity

Fraction of hadrons when requiring BBC trigger

Errors are RMS’s of dists
Conclusion

- Very solid results from $\pi^0$, $\eta$ and jets on $R_{dA}$ that would help constraining nuclear PDF from d+Au collision data
  - Very consistent each other even though the systematics are very different

- Huge enhancement in the yield in d+Au peripheral collisions compared to the one expected from p+p collisions

- We are making several global checks in preparation for publishing the results.
**$R_{dA}$ of Identified Hadrons**

Mesons follow similar trend w/ $p_T$ in all centralities.

Cronin enhancement at moderate $p_T$?

Or nPDF moving through antishadowing region into EMC region?

Proton enhancement still not explained by Cronin or shadowing models.

- R. Hwa, et al. reproduced $R_{CP}$ using recombination of shower + thermal(?) partons (nucl-th/0404066).
What is the merging effect?

- Because of limited granularity of the detector, two $\gamma$’s from $\pi^0$ can not be resolved at very high $p_T$ ($\gamma$’s merged. mass can not be reconstructed).
  - Opening angle: $\theta \sim \text{mass}/p_T$

- We corrected for the inefficiency due to merging, but also introduced a large systematic error.

![Diagram showing the merging effect with low and high $p_T$ for $\pi^0$ particles and the probability of detecting two $\gamma$’s from $\pi^0$.]
PHENIX Preliminary

$R_{dA}$ compared with the 2003 data (GeV/c)

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$R_{dA}$ compared with the 2003 data (GeV/c)

60-88%

0-20%

PHENIX Preliminary

0-20%

PHENIX Preliminary

60-88%
$\pi^0 R_{dA}$

![Graph showing $\pi^0 R_{dA}$ vs. $p_T$ for d+Au collisions at $\sqrt{s_{NN}}=200$ GeV](image)

PHENIX Preliminary
Enhancement of hadron production in heavy ion collisions

Usually modeled as multiple scattering of the incoming parton on the nucleus.

Most models don’t have any PID dependence...
- However, measured enhancement is larger for protons than pions/kaons.
- Originally thought to be due to steeper $p_T$ spectrum of protons and that it would go away at higher energies.

But proton enhancement is still much larger at RHIC energies!
Systematic errors

- **Type A:** point-by-point fluctuating errors
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Table 8: Error summary for $d+Au$ and $p+pyields$.

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Table 9: Error summary for $R_{dA}$ results.