Outstanding Results from the PHENIX Experiment at RHIC

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Nuclear Matter Under Extreme Conditions
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The PHENIX Experiment

**Midrapidity**
- $D, B \rightarrow e^\pm$
- $J/\psi \rightarrow e^+e^-$
- $\pi^0 \rightarrow \gamma\gamma$
- direct $\gamma$
- unidentified charged hadrons
- $-0.35 < y < 0.35$
- $\Delta \Phi = \pi$

Identified charge hadrons
- TOF & Aerogel

**Forward/backward rapidity**
- $D, B \rightarrow \mu^\pm$
- $J/\psi \rightarrow \mu^+\mu^-$
- $-2.2 < y < -1.2$  $1.2 < y < 2.4$
- $\Delta \Phi = 2\pi$

MPC/EX
- $\gamma, \pi^0$
- forward rapidity

High data rate, no Au+Au triggering
- Good triggers in $p+p, d+p+A$

2012
Use the total particle production at large rapidity as a measure of centrality in p+p, p+A, A+A

BBC detector covers $3.1 < |\eta| < 3.9$

Centrality corrected for bias due to autocorrelation between hard probe and particle multiplicity at BBC

• Studied by embedding Pythia hard process events in MB collisions
Small System Flow - $^3\text{He}+\text{Au}$

High multiplicity (i.e. very central) collisions in $^3\text{He}+\text{Au}$

Measure $v_2$ and $v_3$

Good agreement with SONIC
- Glauber MC initial conditions
- Viscous hydrodynamics $\eta/s = 0.08$
- Transition to hadronic cascade at $T = 170$ MeV

Supports initial geometry + hydrodynamic evolution as source of $v_n$

Perhaps not so surprising for $^3\text{He}$ projectile

Event plane determined by FVTX in Au going direction
Small System Flow - p,d,\(^3\)He+Au

High multiplicity (i.e. very central) collisions in p+Au, d+Au, \(^3\)He+Au

Consider \(v_2\) only (\(v_3\) not available for 2008 d+Au measurement)

Good agreement with SONIC:
- Glauber MC initial conditions
- Viscous hydrodynamics \(\eta/s = 0.08\)
- Transition to hadronic cascade at \(T = 170\) MeV

Supports initial geometry + hydrodynamic evolution as source of \(v_2\)

Indicates p+Au produces fireball also

Event plane determined by FVTX in Au going direction
Jets
Jets in d+Au

MB data (0-100% central) show no modification within uncertainties

\( R_{dAu} \) shows significant dispersion with centrality class
  - Suppression for 0-20%
  - Enhancement for peripheral classes
  - Separation increases with \( p_T \)

Jet modification in d+Au, or something else?

If it is jet modification, the effects have to **exactly cancel** when summed over centrality
  - Hmm .....

Is it the centrality measurement?

PHENIX, Phys. Rev. Lett. 116, 122301
Jets in d+Au - centrality characterization

Centrality category for an event is made from the soft particle production in a different rapidity range from the jet

\[ R_{p+A} = \frac{(dN_{p+A}/d\eta)}{(T_{p+A}d\sigma^{p+p}/d\eta)} \]

where the nuclear overlap factor \( T_{p+A} \) can be thought of as:

\[ T_{p+A} \frac{d\sigma^{p+p}}{d\eta} = \frac{(N_{\text{coll}}/\sigma_{NN})}{1/N_{\text{coll}}} \] \[ \frac{dN_{\text{central}}}{d\eta} \]

For comparison between data at different centralities, can eliminate some systematic uncertainties by using \( R_{CP} \):

\[ R_{CP} = \frac{R_{p+A}^{\text{central}}}{R_{p+A}^{\text{peripheral}}} = \frac{1/N_{\text{central}}}{1/N_{\text{peripheral}}} \] \[ \frac{dN_{\text{central}}}{d\eta} \]

\[ dN_{\text{peripheral}}/d\eta \]
Jets in (p,d)+A - centrality measurement?

Suggested effects on the centrality determination:


- Presence of large $x_p$ parton $\Rightarrow$ fewer than average number of partons (Brodsky, Farrar, PRL 31 (1973) 1153)
- $\Rightarrow$ Reduced average cross section
- $\Rightarrow$ Decrease in effective $N_{\text{coll}}$ for high $x_p$ collisions

Depletion of the longitudinal energy of the projectile remnant after the removal of a a high $x_p$ parton (Armesto, Gulhan, Milhano, PLB 747, 441 (2015))

Overall $x_p$ dependent suppression in the soft particle multiplicity per-N+N collision (Bzdak, Skokov, Bathe, (2014) arXiv:1408.3156)
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Jets in d+Au - proton color fluctuations?

McGlinchey, Nagle, Perepelitsa, PRC 94 (2016) 024915

MC - Glauber model study of p+Au, d+Au, $^3$He+Au $R_{CP}$

1-parameter description of $x_p$ dependent decrease of $\sigma_{NN}$

- Fit to $R_{CP}$ for jets

Convolve particle production with PHENIX centrality framework

Prediction for p+Au, $^3$He+Au

- data being analyzed now
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Coming at hard probes: new $^3$He+Au $\pi^0$ data, & comparison with this shrinking proton calculation
Jets in Cu+Au

Similar analysis to d+Au jets
Suppression of $x \times 2$ in central collisions
No significant $p_T$ dependence
Enhancement for peripheral events, but not much outside systematic uncertainties

Hot matter suppression
Quarkonia
In-medium Quarkonia Program

Study the screening length in hot matter via:
• Modifications to quarkonia production in A+A collisions
• Relative to the baseline production in p+p collisions
• Correcting for modifications due to production in a nucleus (p,d+A)
  • Traditionally called cold nuclear matter (CNM) effects

Physics is extracted from comparison with theory - so ideally, we would like to:

Vary the temperature of the medium in A+A
• Collision energy (RHIC vs LHC gives wide lever arm)
• Mass of colliding ions
• Collision centrality (but not easy to model)

Vary the type and strength of underlying CNM effects
• Depends on collision energy
• Depends on rapidity
Charmonia - $J/\psi$
J/\psi in Au+Au Collisions - Rapidity Dependence

PHENIX 2004 and 2007 data

The suppression is strongest at forward rapidity

- Energy density is slightly smaller at forward rapidity
- But cold nuclear matter effects are different
- Also, underlying charm is smaller at forward rapidity

Question on Saturday: is this caused by cold nuclear matter effects?

- next slide
Cold Nuclear Matter Effects

Processes that modify the quarkonia yield in a nuclear target are called **cold nuclear matter** (CNM) processes

**CNM effects include**
- **Gluon shadowing** – parton distributions modified in a nucleus
- **Breakup** of the precursor $J/\Psi$ by collisions with nucleons
- **Initial state energy loss** of partons in cold nuclear matter
- **Cronin effect** – multiple elastic scattering of partons

**Notes:**
- Gluon shadowing affects the underlying charm yield.
- Breakup reduces the **fraction** of charm forming bound charmonium.
- Initial state energy loss changes the rapidity distribution
- Cronin effect modifies only the $p_T$ distribution.
A Note on Time Scales

At 100 GeV/nucleon (200 GeV/nucleon center of mass) the colliding nuclei have γ = 100. Time scales are roughly (in the CM):

- Nuclear crossing time ~ 0.3 fm/c (0.001 fm/c at LHC). **CNM effects**
- J/Ψ meson formation time ~ 0.3 fm/c
- QGP thermalization time ~ 0.3 to 0.6 fm/c
- QGP lifetime ~ 5-7 fm/c
- J/Ψ lifetime (free space) ~ 2000 fm/c

The creation of the charm pair that evolves into the J/Ψ and its modification in the **hot** medium occur on different time scales. They are often taken as being factorizable.

If so, we can study the cold nuclear matter (CNM) effects using p+A to help understand the initial J/Ψ population in A+A.
PHENIX d+Au J/ψ data at 12 rapidities from 2008 run, plotted vs average impact parameter in the Au nucleus

Describe cross sections for d+A data with EPS09 shadowing plus absorption parameter $\sigma_{\text{abs}}$

- Vary $\sigma_{\text{abs}}$ in a Glauber MC study and compare with data using $\chi^2$

$\sigma_{\text{abs}}$ shows strength of cold nuclear matter suppression not due to shadowing
Combine PHENIX d+Au $J/\psi$ data at 12 rapidities, and $J/\psi$ data from 6 fixed target experiments

All cross sections parameterized with EKS98 or EPS09 shadowing plus absorption parameter $\sigma_{\text{abs}}$

Plot absorption parameter vs nuclear crossing time ($\tau$) for p+A or d+Au at 17.3A - 200A GeV CM collision energy

For Au + Au collisions: fold forward & backward rapidity CNM effects together in $1.2 < \eta < 2.2$
  - Stronger CNM suppression than at mid rapidity

Aside: What is the source of $\sigma_{\text{abs}}$?

Fit region above $\tau \sim 0.05 \text{ fm/c}$ with model of expanding color neutral meson

- Suggests we really have breakup at backward rapidity (large $\tau$), something else at forward rapidity (small $\tau$)

The suppression at forward rapidity seems to be well explained by energy loss in cold nuclear matter

J/ψ in Au+Au Collisions
(Early attempt to remove CNM Effects)

Use Glauber model to estimate $R_{AA}$ due to shadowing plus $\sigma_{abs}$ measured from d+Au data.

Divide measured Au+Au $R_{AA}$ at forward/backward and mid rapidity by $R_{AA}(CNM)$ to get estimate of hot matter effect.

Compare mid rapidity PHENIX Au+Au data with NA60 In+In and NA50 Pb+Pb data after correction for CNM effects.

Plot vs particle multiplicity at mid rapidity (used as proxy for energy density).


PHENIX PRC 84 054912 (2011)
J/ψ in Au+Au collisions - Energy Dependence

39, 62, 200 GeV at $1.2 < |\eta| < 2.2$

$R_{AA}$ values similar, lowest at 200 GeV

Similarity of $R_{AA}$ at these three energies in the model comes from balance between:

- Increased suppression due to higher energy density
- Increased coalescence due to larger charm production
The striking difference in suppression is mostly due to coalescence at LHC, partly due to stronger CNM effects at forward rapidity at RHIC energy.
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Where does coalescence start to dominate?

U+U collisions allow us to go to higher energy density at RHIC.

Central U+U collisions should have:
- 15-20% higher energy density than Au+Au collisions
- stronger color screening
- Increased charm production from ~ 25% larger $N_{\text{coll}}$ values
- stronger coalescence

$J/\psi$ production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production.
U deformation

Need $N_{\text{coll}}$ to get $R_{AA}$ for U+U. Requires a *deformed Woods Saxon* distribution of the nucleons in the U nucleus

$$\rho = \frac{\rho_0}{1 + \exp([r - R']/a)}$$

where

$$R' = R[1 + \beta_2Y_2^0(\theta) + \beta_4Y_4^0(\theta)]$$

We considered two parameterizations of the deformation of the U nucleus:

**Set 1** (Phys. Lett. B 679, 440 (2009)) - “conventional” description of the U deformation

• The mean radius and diffuseness are taken from electron scattering

**Set 2** (Phys. Lett. B 749, 215 (2015)) differs in 2 ways:

• Takes into account the finite radius of the nucleon
• Averages over all orientations of axis-of-symmetry
  • match average radius and diffuseness to values reported from electron scattering
Effect of U deformation model

The parameters for set 1 are significantly different in their surface diffuseness:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set 1</th>
<th>Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (fm)</td>
<td>6.81</td>
<td>6.86</td>
</tr>
<tr>
<td>a (fm)</td>
<td>0.6</td>
<td>0.42</td>
</tr>
<tr>
<td>β2</td>
<td>0.28</td>
<td>0.265</td>
</tr>
<tr>
<td>β4</td>
<td>0.093</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Larger surface diffuseness for set 1 results in a less compact nucleus, a larger reaction cross section by 12%, and $N_{coll}$ values that are smaller by 6 - 15%.

Set 2


Set 1
Take invariant yield ratio:
Curves show centrality dependence if J/ψ production scaled with
- \( N_{\text{coll}} \) (dashed lines)
- \( N_{\text{coll}}^2 \) (solid lines)
Set 1 (blue) Not much difference
set 2 (red) Favors \( N_{\text{coll}}^2 \) for central
Charmonia - $\psi(2S)$
d+Au $\psi'$ - mid rapidity

PHENIX $R_{dAu}$ data

PRL111 (2013) 202301

Too strong for CNM effects:
Interpreted as final state suppression due to effects of comoving matter on the weakly bound $\psi'$ state

Du & Rapp arXiv:1504.00670
Hadronic gas + QGP in final state

Ferreiro (PLB 749 (2015) 98)
“Comovers” in final state
d+Au $\psi'$ - comparison with p+Pb from ALICE

Double ratio has similar dependence on collision centrality at the two very different collision energies

Seems to be explained well by final state models

JHEP 06 (2016) 50
Add forward/backward rapidity p+Au and p+Al measurements from RHIC 2015 run - strong suppression at backward rapidity, consistent trend with midrapidity.
PHENIX p+Al, p+Au $\psi'$

Add forward/backward rapidity p+Au and p+Al measurements from RHIC 2015 run - strong suppression at backward rapidity, consistent trend with midrapidity

Coming at Hard Probes: Final $\psi(2S)/\psi(1S)$ ratios at forward/backward rapidity in
• p+p, p+Al, p+Au, $^3$He+Au
Upsilon
Statistics starved measurement for PHENIX due to

- small acceptance at midrapidity,
- small cross section at forward/backward rapidity

Described by the models, but the data do not provide a strong constraint.


PRC 91 (2015) 024913
Y(1S+2S+3S) comparisons at RHIC

Y(1S+2S+3S) for d+Au, U+U and Au+Au

Common trend with $N_{\text{part}}$ for suppression in Au+Au (200 GeV) and U+U (193 GeV)

[Graph showing Y(1S+2S+3S) vs. $N_{\text{part}}$ for different collision systems]
Open Heavy Flavor
Open Heavy Flavor in Au+Au Collisions

PHENIX uses semi-leptonic decays of heavy quarks
- VTX detector at mid-rapidity + electron ID in central arms
- FVTX detector at forward/backward rapidity + muon ID in muon arms

Heavy quark decays are identified by the displacement of the reconstructed electron track from the event vertex

First results so far only at mid-rapidity, from limited statistics 2011 data set
Open Heavy Flavor - procedure

Estimate background contributions

Generate decay matrices relating HF hadron $p_T$ to electron $p_T$ from Pythia
- Assumes rapidity distributions unmodified
- Assumes all ground state charm hadrons experience the same modification
- Assumes all ground state bottom hadrons experience the same modification

HF parent hadron distribution is integrated over all rapidity

Use a Bayesian unfolding technique to extract most likely HF parent hadron $p_T$ distributions from simultaneous fit to measured DCA distributions in 5 $p_T$ bins + HF $dN/dy$ vs $p_T$
Open Heavy Flavor - results

Extract ratio of $b/(c+b)$ contribution vs $p_T$ of electron, with uncertainty band

Convert to $R_{AA}$ of $c$ and $b$ using measured $R_{AA}$ of HF electrons
Open Heavy Flavor - Future

Mid-rapidity:
Run 14+16 data to come
  • ~ 30 times increase in statistics

Forward rapidity:
FVTX at forward rapidity (1.2 < |\eta| < 2.2)
  • b and c separation from unfolding single muons
PHENIX had its last run in 2016!

After 16 years of data taking, the PHENIX detector is no more (it is being dismantled this summer)
• Although we have a lot of data to analyze yet!

This is in preparation for the construction of a new experiment at RHIC in the 1008 hall

A new collaboration was formed in December 2015
• Currently known as sPHENIX

Planned to start data taking in 2022
**sPHENIX**

**Goal:** Compact, state of the art jet detector at RHIC

Physics program aimed at:
- Jets
- HF tagged jets
- Upsilon

Hermetic detector covering $-1.1 < \eta < 1.1$
- EM Calorimeter
- Hadronic calorimeter
- Precise vertexing
  - MAPS pixel inner barrel
- Precise tracking
  - intermediate Si strips
  - Compact TPC outer tracker

Uses BABAR superconducting solenoid $B = 1.5$ T
Data rate for Au+Au collisions = 15 kHz
Estimated precision of jet $R_{AA}$ vs $E_T$

Fraction of dijets in which both jets are within sPHENIX acceptance (red curve)
sPHENIX - b-tagged jets

One method for finding jets with a b quark (p+p collisions only so far)

MC study:
Use DCA measurement in the bend plane from inner barrel detector
Require 1, 2 or 3 tracks to be outside DCA cut
Use truth information to extract b-jet efficiency vs purity as DCA cut changes

3 track DCA cut can produce 30% b-jet efficiency at 70% purity
sPHENIX - Upsilon

Use **dielectrons**

Minimal mass of tracking detector (TPC)

\[ \sigma_{1S} = 80 \pm 1.4 \text{ MeV} \]

\[ p+p, 10 \text{ weeks} \]

\[ \Rightarrow \text{ good mass resolution} \]

\[ \Rightarrow \text{ minimal radiative tail} \]

Electron identification from EM + hadronic calorimeter \[ \Rightarrow \text{ E/p measurement} \]

**Expected statistics for** \( R_{AA} \) **assuming model suppression**

- 1 year \( p+p \) and 1 year \( Au+Au \) running