Key ingredient of **nuclear** physics: Change the **nucleus**
Spin physics
— $W A_L$ results
— $J/\psi A_N$ results
— $\eta A_N$ results
— $h^+ A_N$ results

Large systems
— Single particle $R_{AA}$ results, multiple species and collisions
— $\pi^0 - h$ correlations in Au+Au
— Spectra of charm and bottom in $p+p$
— $v_2$ of charm and bottom in Au+Au

Small systems
— $\phi$ meson nuclear modification factors
— Drell-Yan measurement in $p$+Au
— Longitudinal dynamics in small systems
— Small systems geometry scan
— Direct photon measurements in $p$+Au
Spin physics
W $A_L$

Sensitivity to light sea quarks

Consistency between PHENIX, STAR, global fits
$\eta A_N$ is consistent with zero (but noticeable structure)
\( \eta A_N \) is consistent with zero (but noticeable structure)

Dramatic improvement in statistical and systematic uncertainties over previous result
Nuclear target dependence on $J/\psi A_N$

What’s the origin of the asymmetry at low $p_T$ in $p+Au$?
Clear and strong dependence on nuclear target size $A^{1/3}$
Very similar dependence on $N_{\text{coll}}$

$\alpha = 1.21$

$\beta = 1.19$
Spin Summary

$W \ A_L$ now published

New results on $\eta \ A_N$
—Dramatic improvement in statistical and systematic precision over previous results
—Results consistent with zero

$J/\psi \ A_N$ now published
—Illustrates important of changing nuclear target in spin physics
—Why is $J/\psi \ A_N$ non-zero in $p+Au$?

$h^+ \ A_N$ just submitted to PRL
—Clear dependence of asymmetries on nuclear target, both $A^{1/3}$ and $N_{\text{coll}}$
Large Systems
Identified particle $R_{AA}$ in large systems

New!

$R_{AA}$

$\omega \to \pi^0 \gamma, A+A, |s_{NN}|=200 \text{ GeV}$

$|y| < 0.35$

- 20-60% Au+Au, $\langle N_{\text{part}} \rangle = 101.6$, PRC84, 044902
- 0-20% Cu+Cu, $\langle N_{\text{part}} \rangle = 85.9$, PRC84, 044902
- 20-40% Cu+Au, $\langle N_{\text{part}} \rangle = 80.4$

$\omega$ and $\phi$ mesons behave similarly in Cu+Cu, Cu+Au, Au+Au
Identified particle $R_{AA}$ in Cu+Au

$R_{AA}$ of identified neutral mesons $\pi^0$, $\eta$, $K_S^0$, $\omega$

Similar behavior for all species at high $p_T$

$R_{AA}$ in Cu+Au, $\sqrt{s_{NN}}=200$ GeV

$|y| < 0.35$

$\pi^0\rightarrow\gamma\gamma$

$\eta\rightarrow\gamma\gamma$

$K_S\rightarrow\pi^0\pi^0$

$\omega\rightarrow\pi^0\gamma$

New! $R_{AA}$ of identified neutral mesons $\pi^0$, $\eta$, $K_S^0$, $\omega$

$\pi^0(\eta)\rightarrow\gamma\gamma$ published in arXiv:1805.04389

PHENIX highlights at RHIC & AGS AUM 2019 Slide 12
Identified particle $R_{AA}$ in U+U

**New!**

$R_{AA}$ of identified neutral mesons $\pi^0$, $\eta$, $K_S^0$

Similar behavior for all species at high $p_T$
New!

Broadening of the away side for low $p_T$, similar width at high $p_T$
$c \to e$ and $b \to e$ in $\text{Au}+\text{Au}$ and $p+p$


HF electron spectra, all centralities and using all available data
c → e and b → e in Au+Au and p+p

Now published!


HF electron spectra, all centralities and using all available data
New p+p reference data; new publication with $R_{AA}$ on the way!
$c \rightarrow e$ and $b \rightarrow e$ in Au+Au

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
$p_T [\text{GeV/c}]$ & 0 & 0.5 & 1 & 1.5 & 2 & 2.5 & 3 & 3.5 & 4 & 4.5 & 5 \\
\hline
\end{tabular}
\end{center}

Charm $\nu_2 > 0$

Bottom $\nu_2 > 0$
$c \rightarrow e$ and $b \rightarrow e$ in $Au+Au$

Charm $v_2 > 0$
Bottom $v_2 > 0$
Both smaller than light flavor
Single particle $R_{AA}$ independent of collision species when selecting for similar $N_{\text{part}}$

Neutral mesons $R_{AA}$ very similar in Au+Au despite different strangeness content
—Strangeness very important at low $p_T$ but not at high $p_T$

Correlation measurements show away-side broadening
—Indicates large-angle radiation of high-$p_T$ partons

Measurement of $c \rightarrow e$ and $b \rightarrow e$ spectra in $p+p$
—Publication with new $R_{AA}$ coming soon

First measurement of bottom flow at RHIC
—Refinements and publication forthcoming
Small Systems
Identified hadron nuclear modification factors in $p+Au$

New!

$\phi$ meson in $p+Au$
Identified hadron nuclear modification factors in $p+Au$

New!

$\phi$ meson in $p+Au$

$\phi$ shows similar modification to $\pi^0$ in $p+Au$ despite different mass and strangeness content
Identified hadron nuclear modification factors in $^3\text{He}+\text{Au}$

New!

$\phi$ meson in $^3\text{He}+\text{Au}$
Identified hadron nuclear modification factors in $^3\text{He}+\text{Au}$

New!

$\phi$ meson in $^3\text{He}+\text{Au}$

$\phi$ shows similar modification to $\pi^0$ in $^3\text{He}+\text{Au}$ despite different mass and strangeness content.
Drell-Yan from angular correlations in $p+p$

Drell-Yan well-described by NLO pQCD & PYTHIA

arXiv:1805.04075 (PRD)
arXiv:1805.02448 (PRD)
Drell-Yan from angular correlations in $p+Au$

**New!**

Hints of modification to Drell-Yan in $p+Au$, though large uncertainties prevent a firm conclusion.
\( J/\psi \) nuclear modification in small systems

New!

Inclusive \( J/\psi \) \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

\(-2.2 < y < -1.2\) (A-going)

\( p + A \) \( R \)

0.5 1 1.5 2

\( p + \text{Al} \)

PHENIX preliminary

Inclusive \( J/\psi \) \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

\( 1.2 < y < 2.2 \) (p-going)

\( p + \text{Al} \)

PHENIX preliminary

New!
J/ψ nuclear modification in small systems

$\psi$ Inclusive J/ψ \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

-2.2<y<-1.2 (A-going)

=200 GeV

\( p+A \)

1.2<y<2.2 (p-going)

\( p+Al \rightarrow p+Au — \text{big change when increasing nuclear target size} \)

\( p+Al \rightarrow p+Au — \text{big change when increasing nuclear target size} \)

New!
J/ψ nuclear modification in small systems

New!

\[ \frac{d^2N}{dy \, dp_T^2} = \frac{N_{p+A}}{N_{p+A}} \times \frac{N_{p+Al}}{N_{p+Al}} \]

- \( p+\text{Al} \rightarrow p+\text{Au} \) — big change when increasing nuclear target size

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$J/\psi$ nuclear modification in small systems

New!

$\frac{d^2N}{dp_T^2dy} = \frac{N_{	ext{p+p}}}{N_{	ext{He+Au}}}$

Inclusive $J/\psi$ \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

$-2.2 < y < -1.2$ (A-going)

$1.2 < y < 2.2$ (p3He-going)

$p+Al \rightarrow p+Au$—big change when increasing nuclear target size

$p+Au \rightarrow ^3\text{He}+Au$—small change when increasing projectile size
Good agreement with wounded quark model
Good agreement with 3D hydro
Longitudinal dynamics in small systems

Now published!


$v_2$ vs $\eta$ in $p+\text{Al}$, $p+\text{Au}$, $d+\text{Au}$, and $^3\text{He}+\text{Au}$

Good agreement with 3D hydro for $p+\text{Au}$ and $d+\text{Au}$
Testing hydro by controlling system geometry

Now published!

Testing hydro by controlling system geometry

Now published!


\[ v_2 \text{ and } v_3 \text{ ordering matches } \varepsilon_2 \text{ and } \varepsilon_3 \text{ ordering in all three systems} \]
Testing hydro by controlling system geometry

\[ p + Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ \text{0-5\%} \]  \hspace{1cm} (a)

\[ d + Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ \text{0-5\%} \]  \hspace{1cm} (b)

\[ ^3\text{He} + Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ \text{0-5\%} \]  \hspace{1cm} (c)

\[ V_n \] vs \[ p_T \] (GeV/c)

Now published!


\[ v_2 \] and \[ v_3 \] vs \[ p_T \] described very well by hydro in all three systems
Testing hydro by controlling system geometry

Now published!

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \]

\( v_2 \) and \( v_3 \) vs \( p_T \) described very well by hydro in all three systems

Initial state model qualitatively agreed with data...

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Testing hydro by controlling system geometry

$v_2$ and $v_3$ vs $p_T$ described very well by hydro in all three systems.

Initial state model qualitatively agreed with data...

But recently discovered issue with calculation reduces $p_T$ scale by factor of 5

http://www.int.washington.edu/talks/WorkShops/int_19_1b/People/Mace_M/Mace.pdf
Testing hydro by controlling system geometry

Now published!


\[ \nu_2 \text{ Data} \]
\[ \nu_3 \text{ Data} \]
\[ \nu_n \text{ SONIC} \]
\[ \nu_n \text{ iEBE-VISHNU} \]

\( p+Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \)

\( d+Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \)

\( ^3\text{He}+Au \ \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \)

\( \nu_2 \) and \( \nu_3 \) vs \( p_T \) described very well by hydro in all three systems

\( p+Au \)

\( d+Au \)

\( ^3\text{He}+Au \)

http://www.int.washington.edu/talks/WorkShops/int_19_1b/People/Mace_M/Mace.pdf
Photons in small systems

$\sqrt{s_{NN}} = 200$ GeV, $|\eta| < 0.35$

$p+Au, 0-100\%$

PHENIX preliminary
Photons in small systems

Thermal photons in $p+Au$?

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$\sqrt{s_{\text{NN}}} = 200$ GeV, $|\eta| < 0.35$

- **p+Au, 0-100 %**

- **p+Au, 0-5 %**

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Photons in small systems

$\sqrt{s_{NN}} = 200 \text{ GeV, } |\eta| < 0.35$

- p+Au, 0-100 %
  - Thermal, Shen et al
  - pQCD, Shen et al

- p+Au, 0-5 %
  - Thermal, Shen et al
  - pQCD, Shen et al

Photon yields

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Common scaling for $Au+Au$ and $Pb+Pb$ at different energies; very different from $N_{coll}$-scaled $p+p$
Photon yields

Common scaling for Au+Au and Pb+Pb at different energies; very different from \(N_{\text{coll}}\)-scaled \(p+p\)

\(p+Au\) and \(d+Au\) in between
Modification of $\phi$ very similar to that of $\pi^0$ despite differences in mass and strangeness content

First measurement of Drell-Yan in small systems at RHIC
—Hint of enhancement but no firm conclusions

Comprehensive set of measurements of longitudinal dynamics
—Good support for wounded quark model and 3D hydro

Geometry scan results published in Nature Physics
—Only hydro can describe all the data

Photon enhancement in small systems
—Important additional evidence in support of QGP droplet formation in small systems
Additional Material
Identified hadron nuclear modification factors

New!

φ meson in U+U
Identified hadron nuclear modification factors

New!

\( \phi \) meson in U+U

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Identified hadron nuclear modification factors

New!

$\phi$ meson in U+U
Small systems flow

- Charged hadrons
  -2.0 < \( \eta < -1.4 \)
  \( \text{Sys}_{\text{Global}} = 1.9\% \)

- Charged hadrons
  1.4 < \( \eta < 2.0 \)
  \( \text{Sys}_{\text{Global}} = 1.9\% \)

Nonzero \( v_2 \) for heavy flavor in d+Au
Nonzero $v_2$ for heavy flavor in $d+Au$

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Small systems flow—heavy flavor

Nonzero $v_2$ for heavy flavor in $d+Au$

$3.22\sigma$, $2.16\sigma$ for $v_2 > 0$ at backward, forward (99.9%, 98.5% one-sided)
Identified particle $v_2$ vs $p_T$ in $p$+Au, $d$+Au, and $^3$He+Au — Mass ordering well-described by hydro
Measurement of $v_2$ in $d+Au$ at 200 GeV and $v_2$ in $d+Au$ at all energies.

Measurement of $v_2\{6\}$ in $d+Au$ at 200 GeV and $v_2\{4\}$ in $d+Au$ at all energies.
$d+Au$ beam energy scan


Event plane $v_2$ vs $p_T$ measured for all energies
**d+Au beam energy scan**

**200 GeV**

- $\sqrt{s_{NN}} = 200 \text{ GeV} 0-5\%$
- $|\eta| < 0.35$
- $v_2(\text{EP})$
- Global Sys. = ±0.3%

**62.4 GeV**

- $\sqrt{s_{NN}} = 62.4 \text{ GeV} 0-5\%$
- SONIC $v_2$
- superSONIC $v_2$
- Global Sys. = ±1.8%

**39 GeV**

- $\sqrt{s_{NN}} = 39 \text{ GeV} 0-10\%$
- PHENIX
- Global Sys. = ±3.6%

**19.6 GeV**

- $\sqrt{s_{NN}} = 19.6 \text{ GeV} 0-20\%$
- Extrapolated
- $\text{Res}(v_2^{1<|\eta|<3})$
- Global Sys. = ±35% -48%

Event plane $v_2$ vs $p_T$ measured for all energies

Hydro theory agrees with higher energies very well, underpredicts lower energies—nonflow?

**d+Au beam energy scan**

Select $10 < N_{\text{tracks}}^{\text{FVTX}} < 30$, integrate

AMPT sees similar trend

Fluctuations?

- Not Bessel-Gaussian
- Not small-variance limit
- Need to understand fluctuations better

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Forward modification consistent with nPDF effects (EPPS16)
Small systems nuclear modification

High-\(p_T\) modification consistent with nPDF effects (EPPS16)

- For p+Al → h^+ + X, 0-100% centrality
  - -2.2 < \(\eta\) < -1.2 (Al-going)
  - 1.2 < \(\eta\) < 2.4 (p-going)

- For p+Au → h^+ + X, 0-100% centrality
  - -2.2 < \(\eta\) < -1.2 (Au-going)
  - 1.2 < \(\eta\) < 2.4 (p-going)

PHENIX preliminary
Stronger effects in central collisions
Small systems nuclear modification

$p+Al \rightarrow h^+ + X \sqrt{s_{NN}}=200$ GeV
0-5% centrality

-2.2<\eta<-1.2 (Al-going)
1.2<\eta<2.4 (p-going)

Strong enhancement for backward at intermediate $p_T$—why?

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Small systems nuclear modification

Strong enhancement for backward at intermediate $p_T$—why?
Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

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Particle species dependence of “Cronin enhancement”

Small systems: $p+Al, p+Au, d+Au, ^3He+Au,$

Large systems: $Cu+Cu, Cu+Au, Au+Au, U+U,$
c\bar{c} and b\bar{b} from angular correlations in p+p

Pair creation at LO, flavor excitation and gluon splitting at NLO

PYTHIA suggests b\bar{b} dominated by pair creation
$b\bar{b}$ from angular correlations in $p+p$

$b\bar{b}$ cross-section consistent with previous measurements, larger than FONLL

arXiv:1805.04075 (submitted to PRL)
arXiv:1805.02448 (submitted to PRD)
Collectivity in large systems


\[ v_2^{2,|\eta|>2} \]

\[ v_2^{4} \]

\[ v_2^{6} \]

\[ v_2^{8} \]

1 < |\eta| < 3

\[ v_2^{2}, v_2^{4}, v_2^{6}, v_2^{8} \]
Collectivity in large systems


\[ \frac{\sigma_{v_2}}{\langle v_2 \rangle} \]

1 < |\eta| < 3

PHENIX

\[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \]

Au+Au

MC Glauber, cumulant based estimate
MC Glauber, direct calculation
AMPT

Data

Sys. Uncert. 2%
Collectivity in large systems


1 < |\( \eta \) | < 3

Cannot extract

\( \sigma_{v_3}/\langle v_3 \rangle \)
Collectivity in large systems

Can extract $\langle v_2 \rangle$ and $\sigma_{v_2}$ separately using forward-fold
Collectivity in large systems

\[ \langle v_3 \rangle \]

\[ \sigma_{v_3} \]

\[ \sigma_{v_3} / \langle v_3 \rangle \]

PHENIX Au+Au 200 GeV

Can extract \( \langle v_3 \rangle \) and \( \sigma_{v_3} \) separately using forward-fold