Data collected over 16 years of operations

Completed taking data in 2016
Many high impact analyses ongoing

<table>
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<tr>
<th>Run</th>
<th>Species</th>
<th>Energy $\sqrt{s_{NN}}$ (GeV)</th>
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Transverse single-spin asymmetry of midrapidity $\pi^0$ and $\eta$ mesons in $p+Au$ and $p+Al$ collisions at $\sqrt{s_{NN}} = 200$ GeV

The PHENIX collaboration, Abdulameer, N.J.; Acharya, U.; Aïdala, C.; et al.


Presented are the first measurements of the transverse single-spin asymmetries ($A_N$) for neutral pions and eta mesons in $p+Au$ and $p+Al$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the pseudorapidity range $|\eta| < 0.35$ with the PHENIX detector at the Relativistic Heavy Ion Collider. The asymmetries are consistent with zero, similar to those for midrapidity neutral pions and eta mesons produced in $p+p$ collisions. These measurements show no evidence of...

2 data tables

- Figure 2 (a) Data from Figure 2 (a) of the $\pi^0$ transverse single-spin asymmetry in $\sqrt{s_{NN}} = 200$ GeV $p^+1+A$ and $p^+1+Al$ collisions as a function of $p_T$.

- Figure 2 (b) Data from Figure 2 (b) of the $\eta$ transverse single-spin asymmetry in $\sqrt{s_{NN}} = 200$ GeV $p^+1+A$ and $p^+1+Al$ collisions as a function of $p_T$.

212/225 PHENIX papers on HEPData
Recent Papers

- arXiv:2406.08301 Jet modification via $\pi^0$-hadron correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- PRC109, 044912 (2024) Non-prompt $\gamma$ in Au+Au $\sqrt{s_{NN}} = 200$ GeV
- PRC109, 044907 (2024) Charm and bottom production in Au+Au $\sqrt{s_{NN}} = 200$ GeV
- PRC109, 054910 (2024) Identified charged hadron production in $p+Al$, $^3He+Au$, and Cu+Au at $\sqrt{s_{NN}} = 200$ and U+U at $\sqrt{s_{NN}} = 193$ GeV
- PRD108, 072016 (2023) Transverse spin asymmetry of $h^\pm$ in $p+p$, $p+Al$, and $p+Au \sqrt{s_{NN}} = 200$ GeV
- PRL130, 251901 (2023) Direct $\gamma$ cross section in $p+p \sqrt{s} = 510$ GeV
- PRD107, 112004 (2023) Transverse spin asymmetry of $\pi^0$, $\eta$ in $p+Al$ and $p+Au \sqrt{s_{NN}} = 200$ GeV
- PRD107, 052012 (2023) Transverse spin asymmetry of heavy flavor decay electrons
- PRC107, 024914 (2023) Low $p_T \gamma$ in Au+Au at $\sqrt{s_{NN}} = 39$ and 62.4 GeV
- PRC107, 024907 (2023) Flow in $p+p$, $p+Al$, $d+Au$, $^3He+Au \sqrt{s_{NN}} = 200$ GeV
- PRC107, 014907 (2023) $\phi$ in Cu+Au and U+U $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2303.12899 Suppression of high $p_T \pi^0$ relative to direct $\gamma$ in central $d+Au \sqrt{s_{NN}} = 200$ GeV
Yuri Mitrankov, *Highlights from the PHENIX experiment on flow measurements*  
— Tuesday Morning

Sanghoon Lim, *The small system flow measurements from the PHENIX experiment at RHIC*  
— Tuesday Afternoon

Devon Loomis, *Highlights from PHENIX Spin*  
— Tuesday Afternoon

Dan Richford, *Open Heavy-Flavor Physics - PHENIX*  
— Wednesday Morning

Ming Liu, *HF Quarkonium Physics - PHENIX*  
— Wednesday Afternoon
p+p
All of direct photons

\( \hat{p} + \hat{p} \rightarrow \gamma^{\text{ISO}} + X, \ \sqrt{s} = 510 \text{ GeV}, |\eta| < 0.25 \)

- Polarized gluon PDF \( \Delta g \) had sign ambiguity in previous results
  — JAM Collaboration, PRD105 074022 (2022)
  — JAM Collaboration, PRD106 L031502 (2022)
- PHENIX results indicate \( \Delta g > 0 \) at 2.8\( \sigma \) level
$A_N$ of hadrons

- $h^+$: large positive asymmetries
- $h^-$: mix of negative $\pi$ and positive $K$ asymmetries
- $\eta$: large (20-40%) asymmetries at high $x_F$
$p, d, ^3\text{He} + \text{Au}$
$A_N$ of identified particles in small systems

PHENIX, PRD 107, 112004 (2023)

- Midrapidity $\pi^0$ and $\eta$ $A_N$
- High precision measurements of $p^\uparrow+p$, $p^\uparrow+Al$, $p^\uparrow+Au$ all consistent with zero
$A_N$ of charged particles in small systems

PHENIX, PRD 108, 072016 (2023)

- Forward rapidity $h^\pm A_N$
- Strong nuclear size dependence seen for $h^+$
Reminder: $A_N$ of charged particles in small systems

PHENIX, PRL 123, 122001 (2019)

- Strong nuclear size dependence seen for $h^+$ previously
**J/ψ and ψ(2S) in small systems**

PHENIX, PRC 105, 064912 (2023)

-2.2 < y < -1.2, Inclusive

- J/ψ modification consistent with initial state effects alone at forward and backward rapidity
- ψ(2S) modification indicates presence of final state effects at backward rapidity

—Presence of co-movers? QGP?

R. Belmont

PHENIX highlights at RHIC & AGS AUM 2024
$J/\psi$ and $\psi(2S)$ in small systems

PHENIX, PRC 105, 064912 (2023)

Similar patterns for $J/\psi$ and $\psi(2S)$ found at RHIC and LHC
**$v_n$ in small systems**


- $v_2$ and $v_3$ vs $p_T$ predicted or described very well by hydrodynamics in all three systems
  - All predicted (except $v_2$ in $d+Au$) in J.L. Nagle et al, PRL 113, 112301 (2014)
  - $v_3$ in $p+Au$ and $d+Au$ predicted in C. Shen et al, PRC 95, 014906 (2017)
Flow decorrelations lead to larger $v_3$ for STAR, explaining $\sim 50\%$ of the difference between the experiments in this particular model.
Proton $R_{AB}$ at high $p_T$ not ordered by system size—largest in $d+Au$
When looking at $d+Au$ only, we do see clear $N_{\text{part}}$ dependence of proton enhancement, suggesting interplay between system size and collision type.
Since direct photons are not modified, we can use them to define $N_{\text{coll}}$ experimentally.

$$N_{\text{coll}}^{\text{EXP}} = \frac{Y_{\gamma_{\text{dir}}^{d+Au}}}{Y_{\gamma_{\text{dir}}^{pp}}}$$

PHENIX, arXiv:2303.12899
$\gamma^{\text{dir}}$ and $\pi^0$ spectra in $d+Au$

Suppression pattern not necessarily indicative of final state effects, see e.g. D.V. Perepelitsa arXiv:2404.17660
Au+Au
Direct photons in Au+Au

Photon yields proportional to \( (dN_{ch}/d\eta)^\alpha \)

The scaling of yields holds for various large systems

Large excess of direct photons relative to \( N_{coll}\)-scaled \( p+p \)
\( \nu_2 \) of direct photons in Au+Au

- Significant reduction in statistical and systematic uncertainties over previous measurement
- Results consistent with zero at high \( p_T \)
Medium response to jets in Au+Au

- Transition from enhancement for low $p_T$ to suppression for high $p_T$ associated hadrons
- Trend is reproduced with Hybrid model with medium response

\[ \Delta_{AA} = Y_{AA} - Y_{pp} \]
Open heavy flavor $v_2$ in Au+Au

- First-ever RHIC measurement of open heavy flavor elliptic flow at forward rapidity
- Mass ordering apparent
$J/\psi$ in Au+Au

- PHENIX $J/\psi$ $v_2$ consistent with zero, while clearly non-zero in ALICE data
- PHENIX $J/\psi$ shows stronger suppression compared to ALICE
- Regeneration seems to play a big role at LHC, not at RHIC
**c and b in Au+Au**

**PHENIX, PRC 109, 044907 (2024)**

- **Au+Au, min. bias**
  - $\sqrt{s_{NN}}=200$ GeV

- **Au+Au, 0-10%**
  - $\sqrt{s_{NN}}=200$ GeV

**Graphs:**
- $R_{AA}(c \rightarrow e, b \rightarrow e)$ vs $p_T^e$ [GeV/c]
- $R_{AA}(c \rightarrow e, b \rightarrow e)$ vs $p_T^e$ [GeV/c]

- Good agreement with STAR
- Good agreement with models (all \(p_T\) for \(c\), \(p_T > 4\) GeV/c for \(b\))
Evidence of final state effects in charmonium production in small systems at RHIC

Evidence of centrality determination bias in high-$p_T$ particle $R_{XA}$ in small systems, can use direct photons to correct for this bias
  — No enhancement in peripheral collisions
  — Suppression in central collisions

First measurement of open heavy flavor $v_2$ at forward rapidity in Au+Au

Zero $v_2$ for $J/\psi$ (and stronger suppression compared to LHC)
  — Regeneration less important RHIC energies

Comprehensive set of small systems measurements
  — Understanding the longitudinal dynamics is essential to understanding the measurements

Comprehensive set of direct photon measurements

More interesting and important measurements from PHENIX coming soon!
Small systems geometry scan


(a) 

\[ \langle \epsilon_2 \rangle \] 

\[ \langle \epsilon_3 \rangle \] 

(b) Temperature [GeV]

\[ \begin{align*} 
  t &= 1.0 \text{ fm/c} \\
  t &= 1.7 \text{ fm/c} \\
  t &= 3.2 \text{ fm/c} \\
  t &= 4.5 \text{ fm/c} 
\end{align*} \]
Small systems geometry scan

- $v_2$ and $v_3$ ordering matches $\varepsilon_2$ and $\varepsilon_3$ ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Small systems geometry scan

$\nu_2$ and $\nu_3$ vs $p_T$ predicted or described very well by hydrodynamics in all three systems
—All predicted (except $\nu_2$ in $d+Au$) in J.L. Nagle et al, PRL 113, 112301 (2014)
—$\nu_3$ in $p+Au$ and $d+Au$ predicted in C. Shen et al, PRC 95, 014906 (2017)
Can initial state effects explain the data?


\[ \frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d\Delta \phi} \]

CGC framework: glasma diagrams produce angular correlations like the ridge and $v_n$ purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?
Initial state effects cannot explain the data

Initial state effects important for theory, but make little contribution for central collisions.

Overestimation of data assumed to be related to fluid choice parameters and/or longitudinal dynamics.
How important are initial state effects?

For central $p+Au$, modest correlation between $\varepsilon_p$ and $v_2$

For central $d+Au$ and $^3He+Au$, no correlation between $\varepsilon_p$ and $v_2$

How important are initial state effects?

B. Schenke et al, Phys. Rev. D 105, 094023 (2022)

- The CGC/Glasma correlations appear to be too narrow in (pseudo)rapidity to have any significant impact on the data
  — The PHENIX data are measured with three detectors spanning $-3.9 < \eta < +0.35$
- We’ll talk more about the importance of the pseudorapidity acceptance of experiments soon
Good agreement between STAR and PHENIX for $v_2$
Comparisons with STAR

Good agreement between STAR and PHENIX for $v_2$

Large difference between STAR and PHENIX for $v_3$ in $p$+Au and $d$+Au

Large subnucleonic fluctuations can overwhelm the intrinsic geometry in some models, leading to similar $\varepsilon_3$ for all systems

STAR, Phys. Rev. Lett. 130, 242301 (2023)
PHENIX data update

PHENIX, Phys. Rev. C 105, 024901 (2022)

- PHENIX has completed a new analysis confirming the results published in Nature Physics
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
PHENIX data update

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- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It’s essential to understand the two experiments have very different acceptance in pseudorapidity
  —STAR-PHENIX difference actually reveals interesting physics
The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination — This is very different from the STAR analysis (TPC only)

We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR — Closer, and “balanced” between forward and backward, *but still different*
More STAR and PHENIX data comparisons

PHENIX, Phys. Rev. C 105, 024901 (2022)

Good agreement with STAR for $v_2$
—Similar physics for the two different pseudorapidity acceptances

Strikingly different results for $v_3$
—Rather different physics for the two different pseudorapidity acceptances
—Longitudinal effects apparently much stronger for $v_3$ than $v_2$
- Good agreement with STAR for $v_2$
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  —Longitudinal effects apparently much stronger for $v_3$ than $v_2$
Pseudorapidity dependence in small systems


- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of $v_3$ compared to $v_2$ is an essential ingredient in understanding different measurements
Flow vectors become decorrelated with increasing pseudorapidity separation
—The effect is much stronger for $v_3$ than for $v_2$

The hierarchy of the measured $v_n$ depends on that of the geometry and decorrelations
—Interesting that the decorrelation hierarchy matches that of the geometry...

W. Zhao et al, Phys. Rev. C 107, 014904 (2023)
Pseudorapidity dependence in small systems

W. Zhao et al, Phys. Rev. C 107, 014904 (2023)

Flow decorrelations lead to larger $v_3$ for STAR, explaining $\sim 50\%$ of the difference between the experiments in this particular model.
Intrinsic geometry likely persists over all pseudorapidity ranges.

Fluctuations in the geometry vary as a function of rapidity ($p$ from a $p+$Pb collision shown).

PHENIX data follow intrinsic geometry, STAR data follow subnucleonic fluctuations.
$J/\psi$ yield in $p+p$

- $J/\psi$ yield exhibits large dependence on local track multiplicity
  —Usually attributed to multi-parton interactions
$J/\psi$ yield in $p+p$

$J/\psi$ and tracks in the same rapidity

$J/\psi$ and tracks in the opposite rapidity

$J/\psi$ and tracks in the same rapidity, tracks from $J/\psi$ removed from track count

$J/\psi \rightarrow \mu^+ + \mu^-$

- $J/\psi$ yield vs multiplicity significantly reduced when
  - Looking at $J/\psi$ and multiplicity in separate rapidity windows
  - Looking at $J/\psi$ and multiplicity in the same rapidity window but removing the $\mu^+ \mu^-$ from the multiplicity

Important implications for MPI picture
Multiplicity-dependent studies can be used as test for onset of QGP-like signatures

PHENIX results match ALICE results, double ratio consistent with unity for all multiplicity
Measurements of intermediate mass dilepton pairs
Separation of semi-leptonic decay and prompt pairs
Enhancement of low $p_T$ hadrons quantified with $D_{AA} = Y_{AA} - Y_{pp}$

Hybrid model with wake consistent with PHENIX $\pi^0$-h correlations

Progressing towards $\gamma^\text{direct}$-h correlations in high statistics Au+Au data sets (2014 and 2016)
Multiplicity dependence of $v_2$ in different event categories in Au+Au

- Narrow selection in ZDC energy approximately fixes $N_{part}$
- Comparison of $v_2$ with same multiplicity but different ZDC energy allows study of geometry dependence—not the same as event-shape engineering, but a related idea
Multiplicity dependence of $v_2$ in different event categories in Au+Au

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- Comparison of $v_2$ with same multiplicity but different ZDC energy allows study of geometry dependence—not the same as event-shape engineering, but a related idea
Systematic study of $v_2$ in small systems
— $p+p$, $p+Au$, $d+Au$, $^3He+Au$
— Centrality dependence
— Multiple detector combinations

AMPT exhibits little or no collectivity but large $v_2$ due to non-flow correlations
Also shows similar relative pattern between backward-backward (BB) and backward-forward (BF)
**φ** meson in small systems


- **φ** similar to **π**^0^ with a few hints of a slight enhancement relative to **π**^0^
$\phi$ meson in small systems


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

- $p+Al$, 0% – 100%

- $p+Au$, 0% – 100%

- $d+Au$, 0% – 100%, PRC 83, 024909

- $^3He+Au$, 0% – 100%

$\phi$ nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed
\( \phi \) meson in small systems


\( \phi \) nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed

Also reasonably well-described by PYTHIA with nPDFs, but overall system size ordering is missed
Nuclear modification of $\pi^0$ in small systems


- Minimum bias collisions shown
- Cronin enhancement at intermediate $p_T$
  - Lighter target shows smaller enhancement ($p+\text{Al} < p+\text{Au}$)
  - Heavier projectile shows smaller enhancement ($\text{^3He+Au} < d+\text{Au} < p+\text{Au}$)
Nuclear modification of $\pi^0$ in small systems

Considerable centrality dependence—suppression in central, enhancement in peripheral

Peripheral enhancement not new, but still difficult to understand...
Systematic measurement of direct photons in various systems and beam energy in wide $p_T$ range
Direct photons in Au+Au

PHENIX, PRC 109, 044912 (2024)

\[ R_\gamma = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{decay}}} \]

- 10x higher statistics
- Agreement with previous results
- \( R_\gamma > 1 \) \( \rightarrow \) excess direct photons
c and b in Au+Au

Bottom shows less suppression than charm
Kaon femtoscopy in Au+Au

- Femtoscopy with $K^\pm$ and assuming Lévy source
- $\lambda$ describes strength of correlation
- $\alpha$ describes shape of distributions—$\alpha = 2$ is Gaussian, $\alpha = 1$ is Cauchy
- $R$ is width parameter (similar to but not same as standard Gaussian radius)
Femtoscopy with $K^{\pm}$ and assuming Lévy source
- $\lambda$ describes strength of correlation
- $\alpha$ describes shape of distributions—$\alpha = 2$ is Gaussian, $\alpha = 1$ is Cauchy
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