PHENIX Experiment Highlights

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The XXIV International Workshop on High Energy Physics and Quantum Field Theory
September 22 – September 29, 2019
Sochi, Russia
Huge amount of data collected by PHENIX

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<th>√s [GeV]</th>
<th>p+p</th>
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PHENIX at RHIC: 16 years of running, 9 collision species, 9 collision energies 196 papers published, 12 in the past year (2018)
Talk Outline

Spin physics (polarized proton beams)
- $h^+ A_N$ results: Just submitted (arXiv:1903.07422)
- $\eta A_N$ results: New!

Small systems (p/d/3He + A)
- Small systems geometry scan: Now published (Nature Physics 15, 214-220 (2019))
- $J/\psi$ in p+Al and p+Au and 3He+Au: New!
- $\phi$ meson nuclear modification factors: New!
- Drell-Yan measurement in p+p and p+Au: New!
- Direct photon measurements in p/d+Au: New!

Large systems (heavy ions)
- Single particle suppression: multiple species and collisions: New!
- Strangeness and nuclear modification factor: New!
- Flow of charm and bottom in Au+Au: New!
Proton spin is not just a sum of three valence quark spins

Jaffe-Manohar sum rule:  \[ S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

PHENIX @ RHIC aims at both longitudinal spin structure and transverse spin phenomena
$W^\pm$ longitudinal single-spin asymmetry $A_L$


$$A_L = \frac{\Delta \sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$A_L W^+ = \frac{-\Delta u(x_1) \bar{d}(x_2) + \Delta \bar{d}(x_1) u(x_2)}{u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)}$$

$$A_L W^- = \frac{-\Delta d(x_1) \bar{u}(x_2) + \Delta \bar{u}(x_1) d(x_2)}{d(x_1) \bar{u}(x_2) + \bar{u}(x_1) d(x_2)}$$

$$A_L W = \frac{1}{P} \frac{N_+ - RN_-}{N_+ + RN_-}$$

- $P$: avg. polarization of each beam
- $N_+$ ($N_-)$: yields in same (opposite) helicity
- $R = \frac{L^{++}}{L^{+-}}$: relative luminosity

$A_L$ sensitive to light sea quarks.

Consistency between PHENIX, STAR, global fits
Transverse single-spin asymmetry $A_N$

$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{p} \times \frac{N_L - N_R}{N_L + N_R}$, \hspace{1cm} $X_F = \frac{2p_z}{\sqrt{s}} \sim (x_1 - x_2)$

$A_N$ expected to be small in conventional pQCD calculations
Transverse single-spin asymmetry for $h^+$ in $p+A$

arXiv:1903.07422 (submitted to PRL)

Clear and strong dependence on nuclear target size $A^{1/3}$ ($\alpha = 1.21$)

Very similar dependence on $N_{\text{coll}}$ (centrality) ($\beta = 1.19$)

- PDF modification in nuclei (nuclear shadowing)
- Gluon saturation (CGC)
- Multiple scattering

A. Lebedev

PHENIX Experiment Highlights
J/ψ transverse single-spin asymmetry


Nuclear target dependence on J/ψ $A_N$

What's the origin of the asymmetry at low $p_T$ in p+Au?

A. Lebedev

PHENIX Experiment Highlights 8
$\eta$ transverse single-spin asymmetry

$\eta A_N$ is consistent with zero (but noticeable structure)
Dramatic improvement in statistical and systematic uncertainties over previous result
Spin Physics Summary

• $W^\pm$ $A_L$ now published

• $h^+$ $A_N$ just submitted to PRL
  - Clear dependence of asymmetries on nuclear target, both $A^{1/3}$ and $N_{\text{coll}}$

• New results on $\eta$ $A_N$
  - Dramatic improvement in statistical and systematic precision over previous results
  - Results consistent with zero with some noticeable structure

• $J/\psi$ $A_N$ now published
  - Illustrates importance of changing nuclear target in spin physics
  - Why is $J/\psi$ $A_N$ non-zero in p+Au?
Small Systems (p/d/\(^3\)He + A)
Intermission: some nuclear physics concepts

Nuclear Modification Factor $R_{AA}$

$$R_{AA} = \frac{dN_{AA}^{J/\psi}/dy}{N_{coll} \cdot dN_{pp}^{J/\psi}/dy}$$

Yield in nucleus-nucleus collisions divided by p+p yields and scaled by the appropriate number of binary collisions $N_{coll}$, which is calculated using Glauber model.

Centrality of collision is described by the number of participant nucleons $N_{PART}$ or number of binary collisions $N_{coll}$.
Intermission: some nuclear physics concepts

Collective Flow

In general, azimuthal distribution of the final state particles can be decomposed into Fourier series

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \langle p_T \rangle \cos (n (\phi - \psi_n))$$

Spatial asymmetry represented by eccentricity

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

translates into momentum flow described by Fourier coefficients $v_n$
Longitudinal dynamics in small systems \((dN_{\text{ch}}/d\eta)\)


\(p+\text{Al}, \ p+\text{Au}, \ d+\text{Au}, \ \text{and} \ 3\text{He}+\text{Au}\)

Good agreement with Wounded Quark Model

and 3-D Hydrodynamics
Longitudinal dynamics in small systems (flow)


$v_2$ agrees with 3-D hydro for $p+Au$ and $d+Au$.

In $^{3}$He+Au, 3-D hydro overpredicts the forward rapidity.
Testing hydrodynamic models by controlling geometry

p+Au, d+Au and 3He+Au collisions have different elliptic and triangular eccentricities ($\varepsilon_2$ and $\varepsilon_3$)


PHENIX Experiment Highlights

$v_2$ and $v_3$ ordering

- $v_2$ and $v_3$ ordering matches $\varepsilon_2$ and $\varepsilon_3$ ordering in all systems
- Regardless of the mechanism, the correlation is geometrical
Theory comparison

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

\begin{center}
\includegraphics[width=\textwidth]{theory_comparison.png}
\end{center}

$\text{iEBE-VISHNU: C. Shen et al., Phys. Rev. C 95, 014906 (2017).}$

J/$\psi$ in p+Al and p+Au

- Almost no modification in p+Al
- Significant suppression at low $p_T$ in p+Au in both directions.
J/$\psi$ in $^3\text{He}+\text{Au}$

No difference with increasing projectile size.
Despite mass difference and strangeness, in p+Au collisions φ shows similar modification to π⁰.
$\phi$ meson in $^3\text{He}+\text{Au}$

Again, $\phi$ shows similar modification to $\pi^0$
Drell-Yan in p+p from $\mu^-\mu^+$ angular correlations

Well described by PYTHIA and NLO

arXiv:1805.04075
arXiv:1805.02448
Drell-Yan in p+Au

Hint of modification of Drell-Yan in p+Au, although large uncertainties prevent a firm conclusion.
Direct Photon Yields in p+p and A+A


Common scaling independent of collision energy or centrality for Au+Au and Pb+Pb at different energies;

Very different from N_{coll}-scaled p+p
Direct Photons in p/d + Au

p+Au and d+Au data fill the gap smoothly between A+A and p+p collisions.

Thermal photons in p+Au?
Small systems summary

- 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

- $J/\psi$ in p/d/3He + A
  - Modification depends on target size, but not projectile size

- Modification of $\phi$ meson is 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

- Photon enhancement in small systems is an important additional evidence in support of QGP droplet formation in small systems
Heavy Ions
Summary of suppression in Au+Au

- Photons unmodified
- Baryons are not suppressed at intermediate $p_T$
- $\phi$ is an outlier at low $p_T$
Nuclear suppression in Cu+Au

Again $\phi$ is an outlier at low $p_T$, but $\omega$ and $K_S$ follow $\pi^0$ and $\eta$ trend at high $p_T$. 

For $|y| < 0.35$, the $R_{AA}$ values are shown, with $\sqrt{s_{NN}} = 200$ GeV. The graph highlights the PHENIX experiment's findings, with preliminary data published in arXiv:1805.04389.
Strangeness for different collision species

ω and φ mesons behave similarly in Cu+Cu, Cu+Au, and Au+Au when selecting for similar $N_{\text{part}}$. 
Strangeness in U+U

Suppression similar for all species including strange mesons at high $p_T$
c → e and b → e in p+p and Au+Au


HF electron spectra, all centralities and using all available data
New p+p reference data; new publication with R_{AA} on the way!
Charm and Bottom Flow in Au+Au

First bottom flow measurement at RHIC
Charm flows less than light-flavor hadrons, a hint of bottom flow
Heavy Ion Physics Summary

• Single particle $R_{AA}$ independent of collision species when selecting for similar $N_{\text{PART}}$

• Strangeness appears to be important at low $p_T$ but not at high $p_T$

• 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
Thank you!
Backup Slides
The PHENIX Experimental Setup

- **Central Arms** ($|\eta| < 0.35$, $\Delta \phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc

- **Muon Arms** ($1.2 < |\eta| < 2.2$ (S) or $2.4$ (N), $\Delta \phi = 2\pi$)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs

- **MPC/MPC-Ex** ($3.1 < |\eta| < 3.8$, $\Delta \phi = 2\pi$)
  - EMCal ($PbWO_4$) / Preshower by $W + $ Si minipads