Recent PHENIX results probing gluon dynamics in p+p and highly asymmetric nuclear collisions

Jin Huang (BNL)
For PHENIX Collaboration
Gluon dynamics in hadron collisions

- Dynamics of gluon fields play important roles in hadron collisions and can be accessed via multiple probes, that includes (not limited to) heavy flavor, hadron production, di-hadron correlation.
- Highly asymmetric collision also allow tune up the gluon densities in a controlled manner.

- Correlation with initial proton spin : unique handle.

Jin Huang <jhuang@bnl.gov>
Relativistic Heavy Ion Collider, NY, USA
The most versatile hadron collider in the world
World’s first and only spin-polarized proton collider
Multiple golden data sets (Coins), from decades of hard work

Highlighting four sets of recent results in this talk

1. \( p+p \rightarrow \text{HF and DY} \)
2. \( p+\text{Au} \rightarrow \text{hadron modification} \)
3. \( p+p, p+\text{Au} \rightarrow \text{di-hadron correlation} \)
4. \( p+p \rightarrow \text{hadron asymmetry} \)
Heavy flavor (HF) production in hadron collision provide a clean probe on parton interactions that originates from gluons

- Calculable by pQCD
- New measurement from PHENIX extract HF by decomposition di-muon production in the forward direction via fits on inv. mass-$p_T$ spectrums

$$g + g \rightarrow Q\bar{Q} \text{ channels}$$

$$p + p \rightarrow Q\bar{Q} \rightarrow \mu^+\mu^- \text{ in PHENIX experiment}$$
Decomposing di-muon cocktail

Opposite charge-sign di-muon pairs

Same charge-sign di-muon pairs

Charm highest S/B

DY highest S/B

Bottom highest S/B

Jin Huang <jhuang@bnl.gov>
Extract bottom cross section via fitting of mass-$p_T$ distributions
• Measured Cross section about 2x from central FONLL value
• Stay tuned: results coming for 510 GeV $p+p$ and 200 GeV $p+A$ collisions too
Angular corrections

- Decay muons’ azimuthal angle → parent heavy quark
- Azimuthal angular correlation sensitive to HF production channels in LO and NLO gluon interactions
- Qualitatively described by Pythia and NLO event generators
Drell-Yan process is sensitive to anti-quark distribution in proton

Drell-Yan cross section consistent with NLO calculations
Hadron production in the PHENIX central rapidity is dominated by $g+g/g+q$ interaction and described by NLO calculation for $p+p$ collisions [10.1103/PhysRevD.76.051106, arXiv:1501.01220]

Modification of hadron production in highly asymmetric collision system gives access to nuclear PDF
π⁰ production in asymmetric collisions

- Enhancement around $p_T \sim 5 \text{GeV/c}$
- The enhancement is system size dependent:
  $$R_{p+Au} > R_{d+Au} > R^{3\text{He}+Au}$$
Source of the enhancement

Comparing with models of cold nuclear energy loss
- Different loss scenario are comparable to data high $p_T$
- Collision system dependent is not described and location of low $p_T$ peak is shifted
- Insights from theoretical interpretation welcomed

Meanwhile, further exploring additional handles revealing interactions between hard parton probes and nuclear matter
- 2-h correlation and transverse spin asymmetry
New handle 1: 2-p correlation

- $p_{\text{out}}$: Transverse momentum correlation of two particles that is perpendicular to the trigger $p_T$
- Gauss-core width of $p_{\text{out}}$ sensitive nonperturbative effects
  - Much smaller ($\sigma \sim 0.5 \text{ GeV/c}$) than scales of $p_T$ and is sensitive to minute changes
- Comparing $p+A$ to $p+p$: probes interaction of parton in nuclear matter
  - e.g. soft gluon exchange and radiative energy loss

$\pi^0 \rightarrow \gamma\gamma$ ($p_T^{\text{trig}}$)

$p_{\text{out}}$ fit method see DOI: 10.1103/PhysRevD.95.072002
Near side correlation:
Sensitive to modification of fragmentation

Away side correlation:
Sensitive to initial $k_T$, initial radiation and modification to fragmentations
Observed away-side broadening of Gauss-core of $p_{\text{out}}$, but not for near side modification.

Suggest parton-nuclear interaction that leads to the broadening.

Consistent with picture that fragmentation outside nuclear and is not strongly modified in $p+A$ collisions.

**$p_{\text{out}}$ Gauss-core difference in pp and pA**

- Near side: $-\frac{\pi}{2} < \Delta \phi < \frac{\pi}{2}$
- Away side: $\frac{2\pi}{3} < \Delta \phi < \frac{4\pi}{3}$

![Graph showing $p_{\text{out}}$ difference between near and away sides in pp and pA collisions](attachment:image.png)
Further correlate the away-side broadening vs path length of parton in nuclear matter, approximated by $N_{\text{coll}}$

- Broadening of the Gauss-core of $p_{\text{out}}$ lines up in linear dependence of $N_{\text{coll}}$

Centrality and $N_{\text{coll}}$ in $p+A$ collisions:
PRC 90,034902

$p+A$ of $N_{\text{coll}}=1$ also consistent with $p+p$
New handle 2: Transverse spin asymmetry

- Hadron production is correlated with incoming proton transverse spin: observed as sine-modulation of transverse spin asymmetry, $A_N$
  - One way to generate $A_N$ is interference of parton through color field (Sivers effect)
- When parton traverse nuclear matter, $A_N$ may be modified
  - Sensitive to gluon exchange and small change of parton $p_T$ that is $\perp$ to spin direction
  - Suppress to $A_N$ presumably proportional to $1/A^{1/3}$ or $1/(\text{path length})$ in nuclear matter


Details see Apr 17
WG Spin: Jeongsu Bok
(New result for DIS18)
$A_N$ vs effective path length in nuclei

- Data is consistent with $A_N$ suppression of $1/<\text{path length}>$, which is approximated by $1/N_{\text{Coll}}$
- Strongly reject the scenario of no nuclear modification of $A_N$

Details see Apr 17 WG Spin: Jeongsu Bok
Summary 1: HF and $\pi^0$ production

- Measurement of HF production via di-muon production in p+p collisions
  - Favor 2x $b$-cross section of FONLL central cross section
  - Azimuthal correlation described by Pythia and NLO generators

- $\pi^0$ production in highly asymmetric $p/^{3}\text{He}+\text{A}$ collusions:
  - Constraints nPDF. Hints energy loss of in cold nuclear mater.
  - Observed ordering of enhancement with system dependence
Summary 2: new handles

- Additional handles on parton interaction of gluon field in $p+A$ collisions:
  - 2-particle correlation ($p_{out}$ width) and transverse-spin asymmetry ($A_N$)
- Data lines up as function of path-length in nuclear, approximated by $N_{coll}$
- Stay tuned: final results and more explorations on gluon dynamics to come from PHENIX!
S/B for di-muon azimuthal angular correction

Bottom region

Charm region
Mass-$pT$ fits

**Same sign**

**Opposite sign**
Pion production in $|\eta|<0.35$

Cross section

Production channels
Centrality dependence on $\pi^0$

- $p+$Au results show large centrality dependence
- $d+$Au results agree with $p+$Au at high-$p_T$
- $^3$He+$Au$ results agree with $p+$Au and $d+$Au at high-$p_T$
- At moderate $p_T$ an ordering is seen as a function of systems
**p\_out in p+p collisions**

Isolated $\gamma$

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

Relation with energy loss per unit length

DOI: 10.1016/j.physletb.2017.05.090

$$\langle \hat{q}L \rangle / 2 = \left[ \frac{\hat{x}_h}{\langle \hat{z}_t \rangle} \right]^2 \left[ \frac{\langle p_{out}^2 \rangle_{AA} - \langle p_{out}^2 \rangle_{pp}}{x_h^2} \right]$$

Di-hadron production

Large scale, $\sim Q^2$

Small scale, $\sim \Lambda_{QCD}$

Histogram $p_{out}$

Phys.Rev. D95 (2017) no.7, 072002
Wider Gauss core for $p_{\text{out}}$ in $p+A$ collisions: multiple scattering in $A$?

Stronger $p_T^{\text{trig}}$ dependence in peripheral $p+Au$: Ideas for interpretation?

See also: H. Ge (Tue), M. Skoby (Tue)
Access the Non-Abelian nature of gluon field

Example of TMD-factorized process:
DY in Pythia simulation
Positive width against scale (M)
As expected in CSS evolution

Non-TMD-factorized process: $\pi^0 + h, \gamma + h$
Data and Pythia simulation:
Both show negative width slope against scale ($p_T^{\text{trig}}$)
Opposite to CSS indicate impact from color flow

\[ \gamma/\pi^0 - h \] pairs in $p+p$ @ $\sqrt{s} = 510$ GeV
Centrality p+Au
PHENIX hall is being upgraded to sPHENIX

- Many detector preserved, reused in future exp.
- Thanks to the removal and repurposing crew!

Beam Pipe Removed

Summer 2016+

East Arm

South Muon Arm

2022+