PHENIX results in small collision systems

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Large Rapidity Coverage

BBC

FVTX

Muon arm

Central arm

FVTX

Muon arm

BBC

η=0
Study of small collision systems in PHENIX

Initial geometry

- p+Au
- d+Au
- 3He+Au

Target size

- p+Al

200 GeV

Event centrality

Au/Al going

p/d/3He going

Beam energy

- 200 GeV
- 62.4 GeV
- 39 GeV
- 19.6 GeV
Study of small collision systems in PHENIX

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- $p+Au$
- $d+Au$
- $^3He+Au$

Target size

- $p+Al$

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- 62.4 GeV
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- 19.6 GeV

Collectivity

Event centrality

- Au/Al going
- $p/d/^3He$ going

Central arm

BBC

FVTX Muon arm
Clearly different initial collision geometry in p/d/\(^3\)He+Au collisions

- Smaller \( \langle \varepsilon_2 \rangle \) in p+Au collisions
- Larger \( \langle \varepsilon_3 \rangle \) in \(^3\)He+Au collisions
Translation of geometry in hydrodynamics

Event display from SONIC

How about in data?

Smaller $\langle \varepsilon_2 \rangle$ in p+Au

Smaller $v_2$ in p+Au

Smaller $\langle \varepsilon_2 \rangle$ in p+Au

Smaller $v_2$ in p+Au

Larger $\langle \varepsilon_3 \rangle$ in $^3$He+Au

Larger $v_3$ in $^3$He+Au
Model description (Hydrodynamic model)

Good agreement with $v_2$ and $v_3$ from hydrodynamic models in all three systems

A model considering initial-state correlation from color domain claimed to describe the order of $v_2$ in three systems.
MSTV recently reported a bug such that the momentum scale is changed by $\hbar c$

With correction: $v_2$ in $p+Au > v_2$ in $d+Au$

Initial-state correlations are ruled out as the entire explanation

slides from Mark Mace: http://www.int.washington.edu/talks/Workshops/int_19_1b/People/Mace_M/Mace.pdf
Collectivity in $\eta$

$\nu_2(\eta)$ in $d+Au$ and $^3He+Au$ scales with $dN_{ch}/d\eta$

Sharp sudden rise in $\nu_2$ at backward in $p+Al$ and $p+Au$ likely from non-flow
Collectivity in $\eta$

$v_2(\eta)$ in $d+Au$ and $^3He+Au$ scales with $dN_{ch}/d\eta$

Sharp sudden rise in $v_2$ at backward in $p+Al$ and $p+Au$ likely from non-flow

Good agreement with 3D hydrodynamics model in $p+Au$ and $d+Au$

but overpredicts $v_2$ at forward in $^3He+Au$
Non-flow contribution is expected to be more significant in smaller collision systems
  - larger in p+Au than d+Au
PHENIX results using EP with $|\Delta \eta| > 2.5$
  - Systematic uncertainty on the non-flow contribution is evaluated using p+p data
- Non-flow contribution is expected to be more significant in smaller collision systems
  - larger in p+Au than d+Au
- PHENIX results using EP with |Δη|>2.5
  - Systematic uncertainty on the non-flow contribution is evaluated using p+p data
- STAR preliminary template fit results agree with PHENIX published results for p_T<2.5 GeV/c in d+Au
  for p_T<1.5 GeV/c in p+Au

Plots from Shengli Huang’s presentation at 2019 RHIC & AGS AUM
**Non-flow effect**

- On-going efforts in PHENIX to better understand the non-flow effect
  - Need careful studies because of the possibility of non-closure
  - Possible over-subtraction at higher $p_T$ based on the study with HIJING and AMPT

Plots from Shengli Huang’s presentation at 2019 RHIC & AGS AUM

**Template fit method**

| arXiv:1902.11290 | |

**Plots from Shengli Huang’s presentation at 2019 RHIC & AGS AUM**
Positive $c_2\{4\}$ in $p+Au$ and negative $c_2\{4\}$ in $d+Au$

Positive $c_2\{4\}$ in $p+Au$ from large fluctuation? remaining non-flow?

$v_2\{2\} = (c_2\{2\})^{1/2} \approx (\langle v_2^2 \rangle + \sigma^2)^{1/2}$

$v_2\{4\} = (-c_2\{4\})^{1/4} \approx (\langle v_2^2 \rangle - \sigma^2)^{1/2}$


Confirm positive $c_2\{4\}$ in $p+Au$ with sub-event method (ablab) and (aalbb)

More results in $d+Au$ beam energy scan data will come
Study of small collision systems in PHENIX

Particle production and modification

Initial geometry

- p+Au
- d+Au
- 3He+Au

Target size

- p+Al
- 200 GeV

Beam energy

- d+Au
- 200 GeV
- 62.4 GeV
- 39 GeV
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Event centrality

- Au/Al going
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Central arm

FVTX Muon arm

200 GeV

BBC

-4 -3 -2 -1 η=0 1 2 3 4

Particle production and modification
Particle production in small systems

\[ \frac{dN_{\text{ch}}}{d\eta} \text{ increases with system size} \]

Wounded quark model can describe the \( \frac{dN_{\text{ch}}}{d\eta} \) shapes in all centrality bins of different collision systems with a common wounded quark emission function extracted from PHOBOS d+Au data.
Clearly different modification of $p_T$ distribution for $p_T<7$ GeV/c in three systems
Stronger $p_T$ broadening in $p+Au$ where multiplicity is smallest

*Larger initial $k_T$ due to more $<N_{coll}>$ per projectile nucleon?*

$<N_{coll}>$: 9.7 in $p+Au$, 15.1 in $d+Au$, 22.3 in $^3He+Au$

*Final-state effects in $^3He+Au$?*
Modification of $\phi$ at forward and backward

Observed enhancement at backward and suppression at forward indicate different nuclear effects dominate in different $\eta$ ranges.
Modification of $\phi$ at forward and backward

Observed enhancement at backward and suppression at forward indicate different nuclear effects dominate in different $\eta$ ranges

Parton-$x$ in nucleus?
Sensitive to shadowing of low-$x$ (anti-shadowing of high-$x$) partons in Au at forward (backward)

Multiplicity effect?
Larger particle density at backward
In charged hadron production, very similar modification as the $\phi$ results

Modification based on nPDF sets can describe the forward results but underestimate the enhancement at backward
In charged hadron production, very similar modification as the $\phi$ results

Modification based on nPDF sets can describe the forward results but underestimate the enhancement at backward

In p+Al collisions, a clear A-dependence only at backward (A-going direction)

pQCD calculation considering incoherent multiple scattering can describe the difference between p+Au and p+Al collisions
At backward rapidity \((A\text{-going direction})\), \(R_{pA}\) in \(p+Au\) and \(p+Al\) follows the same trend of increasing with \(<N_{\text{part}}>\).
**A-dependent modification**

**At backward rapidity (A-going direction),**

$R_{pA}$ in $p+Au$ and $p+Al$ follows the same trend of increasing with $\langle N_{\text{part}} \rangle$

**At forward rapidity (p-going direction),**

$R_{pA}$ in $p+Au$ and $p+Al$ show their own trend of decreasing with $\langle N_{\text{part}} \rangle$

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To be on arXiv today

At backward rapidity (\textit{A-going direction}),

$R_{pA}$ in $p+Au$ and $p+Al$ follows the same trend of increasing with $<N_{\text{part}}>$

Dominated by final-state effects (multiplicity)?

At forward rapidity (\textit{p-going direction}),

$R_{pA}$ in $p+Au$ and $p+Al$ show their own trend of decreasing with $<N_{\text{part}}>$

Dominated by initial-state effects (impact parameter)?

To be on arXiv today

Comparison with heavy-flavor

Similar modification in charged hadrons and heavy-flavor muons (dominated by charm) both at forward and backward

Common nuclear effects for light and charm in small collision systems?

To be on arXiv today
Indication of modification in pair $p_T$ of dimuon from $bb$ at both forward and backward
**dimuons from bb**

Indication of modification in pair $p_T$ of dimuon from $b\bar{b}$ at both forward and backward

Similar with $p_T$ broadening of charged hadrons and heavy-flavor muons

Common nuclear effects in small collision systems for bottom as well?

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**Heavy-flavor muon**

**Charged hadron**

To be on arXiv today
PHENIX measurements of muon pairs from cc, bb, and Drell-Yan in p+p and p+Au at 200 GeV
  – Axel Drees (nPDF/CNM, June/25 TUE, PM 3:10)

Probing collision dynamics of small system collisions via high $p_T$ hadrons and direct photons by the PHENIX experiment at RHIC
  – Takao Sakaguchi (high $p_T$ probe of initial states, June/26 WED, PM 2:40)

Observation of collectivity in p+Au, d+Au, and $^3$He+Au collisions with PHENIX
  – Qiao Xu (Collectivity in small systems, June/26 WED, PM 4:50)

Thank you
Good agreement with $v_2$ and $v_3$ from hydrodynamic models in all three systems.

Hydrodynamic model with pre-flow (superSONIC) does not give as good agreement model without pre-flow (SONIC).
Clear mass dependent $v_2$ in all three systems

$p_T<1.5$ GeV: Higher pion $v_2$

$p_T>1.5$ GeV/c: Higher proton $v_2$

Hydrodynamic model describes the mass ordering in $p_T<1.5$ GeV/c
Clear mass dependent $v_2$ in all three systems

$p_T < 1.5$ GeV: Higher pion $v_2$

$p_T > 1.5$ GeV/c: Higher proton $v_2$

AMPT with hadronic rescattering also describes the mass ordering in $p_T < 1.5$ GeV/c

The splitting in $p_T > 1.5$ GeV/c is also described by AMPT from coalescence
Non-zero $v_2$ of muons from heavy-flavor decays (mostly charm) at forward and backward in d+Au collisions

Finite $v_2$ for charm in p+Pb
Non-zero $v_2\{4\}$ in d+Au collisions at all energies!

At 200 GeV, consistent $v_2\{2,|\Delta \eta|>2\}$, $v_2\{4\}$, and $v_2\{6\}$ indicate minimal non-flow effect.
Direct photon yield in 0-5% p+Au collision is higher than the scaled p+p yield.

Integrated yields in p+Au and d+Au collisions fill the gap between p+p and A+A.
No overall modification in $\Delta \phi$ between dimuon from $b\bar{b}$ both at forward and backward

Consistent with nPDF
Initial-state effects are expected to be similar for open and hidden heavy-flavor

Clear indication of final-state effects at A-going direction


Modification of $J/\psi$

Similar modification of $J/\psi$ in $p+Au$ and $^3He+Au$ both at forward and backward

No dependence on projectile
Different modification of $J/\psi$ in $p+Al$ and $p+Au$ both at forward and backward

**Clear dependence on target size**

Centrality dependence study in all small systems coming soon