Recent Results from PHENIX

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PHENIX at SQM22

- Rachid Nouicer, PHENIX Probing QCD Matter Through Heavy Flavor and Quarkonium at RHIC, PA-HF 2022-06-15 at 9am KST
- László Kovács, Charge kaon femtoscopy with Lévy sources in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at PHENIX, POS-BLK-21
- Krista Smith, $J/\psi$ in small systems with PHENIX, POS-HF-14

PHENIX papers recently submitted

- arXiv:2203.17058 Charm and bottom quark production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2203.17187 Non-prompt direct photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2203.09894 Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in $p+p$, $p+Au$, $d+Au$, and $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2203.06087 Study of $\phi$ meson production in in $p+Al$, $p+Au$, $d+Au$, and $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2202.03863 Measurement of $\psi(2S)$ nuclear modification at backward and forward rapidity in $p+p$, $p+Al$, and $p+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV
Jet substructure in $p+p$

- New analysis of jet substructure
  - $R = 0.3$
  - $12.0 \text{ GeV}/c < p_T < 14.5 \text{ GeV}/c$
- Analysis ongoing with $p+Au$, results coming soon!
Jet substructure in $p+p$

- New analysis of jet substructure
  - $R = 0.3$
  - $20.5 \text{ GeV}/c < p_T < 24.5 \text{ GeV}/c$
- Analysis ongoing with $p+Au$, results coming soon!
$c$ and $b$ in large systems


$\sqrt{s_{\text{NN}}}=200$ GeV

$\text{min. bias, } |y|<0.35$

$R_{AA}$

$c \rightarrow e$

$b \rightarrow e$

- Bottom shows less suppression than charm

$R_{\text{bottom}}$ shows less suppression than charm.

Recently submitted!
**c and b in large systems**


Recently submitted!

**PHENIX**

**Au+Au, min. bias**

$\sqrt{s_{NN}}=200$ GeV

- Green: PHENIX c → e
- Blue: PHENIX b → e
- Orange: STAR c → e
- Red: STAR b → e

- Good agreement with STAR
- Good agreement with models (all $p_T$ for c, $p_T > 4$ GeV/c for b)

**PHENIX**

**Au+Au, 0-10%**

$\sqrt{s_{NN}}=200$ GeV

- Various models depicted:
  - Yellow: D → e (DGLV)
  - Orange: B → e (DGLV)
  - Brown: D → e (SUBATECH)
  - Red: B → e (SUBATECH)
  - Red dashed: D → e (T-Matrix)
  - Orange dashed: B → e (T-Matrix)

R. Belmont, UNCG

SQM 2022, 13 June 2022 - Slide 5
$J/\psi$ $v_2$ in large systems

New preliminary!

$J/\psi$ $v_2$ is consistent zero at forward rapidity, different from the LHC results.

May indicate absence of charmonium regeneration in the forward rapidity region at RHIC energies.
**J/ψ and ψ(2S) in small systems**

Recently submitted!

-2.2 < y < -1.2, Inclusive
ψ(2S), p+Au √s_{NN}=200 GeV
J/ψ, p+Au √s_{NN}=200 GeV

1.2 < y < 2.2, Inclusive
ψ(2S) nCTEQ15 (Shao et al.)
ψ(2S) EPPS16 (Shao et al.)
ψ(2S) Transport Model (Du & Rapp)
J/ψ Transport Model (Du & Rapp)

- **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?
$J/\psi$ and $\psi(2S)$ in small systems

Recently submitted!

Similar patterns for $J/\psi$ and $\psi(2S)$ found at RHIC and LHC

$J/\psi$ 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

New preliminary!
The φ meson in small systems

Recently submitted!

\( \phi \) similar to \( \pi^0 \) with a few hints of a slight enhancement relative to \( \pi^0 \)
$\phi$ meson in small systems


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


Recently submitted!

*φ 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 ($p+$Al $< p+$Au)
  - Heavier projectile shows smaller enhancement ($^3$He+$+$Au $< d+Au < p+$Au)

Recently published!
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...
Long-known (and somewhat mysterious) centrality dependence of $R_{dA}$ of $\pi^0$

New measurement of direct photons shows similar centrality dependence, but should be unity—mean free path $\sim$50 times larger than nuclear size
Direct photons and $\pi^0$ in small systems

- Can use non-modification of photons to correct for bias in $N_{\text{coll}}$ determination
- Resolves a decade-long mystery of apparent enhancement in peripheral collisions
- Small but non-negligible suppression in central collisions
  —EMC effect? QGP?
\( \nu_n \) in small systems


- \( \nu_2 \) 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)
$v_n$ in small systems


- All new analysis using two-particle correlations with event mixing instead of event plane method used in Nature Physics publication
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- Uses same detector combination as used in Nature Physics publication

Recently published!
$\nu_n$ in small systems


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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)
Kaon femtoscopy in large systems

- 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
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- $R$ is width parameter (similar to but not same as standard Gaussian radius)
Jet substructure measurements done in $p+p$, $p+Au$ and $Cu+Au$ coming soon

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

Comprehensive set of small systems flow measurements

New results on femtoscopy with charged kaons

Many more interesting and important measurements from PHENIX coming soon!
Extra material
Particle species dependence of “Cronin enhancement”


Protons much more strongly modified than pions

$\phi$ mesons similar to pions
$v_n$ 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)
Initial state effects alone do not describe the data
Inclusion of initial state effects is important, but not a big contribution for central collisions
For central $p+$Au, modest correlation between $\varepsilon_p$ and $v_2$ but fairly strong correlation between $\psi_2^p$ and $\psi_2^{v_2}$

For central $d+$Au and $^3$He+Au, no correlation between $\varepsilon_p$ and $v_2$, modest correlation between $\psi_2^p$ and $\psi_2^{v_2}$

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$v_n$ in small systems

STAR, Quark Matter 2019

Good agreement between STAR and PHENIX for $v_2$
$v_n$ in small systems

STAR, Quark Matter 2019

Good agreement between STAR and PHENIX for $v_2$

Large discrepancy between STAR and PHENIX for $v_3$
The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination — Very different kinematic acceptance compared to STAR

We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR — Closer, and “balanced” between forward and backward
\(v_n\) in small systems

- Good agreement with STAR for \(v_2\)
  —Similar physics for the two different pseudorapidity acceptances
$v_n$ in small systems

- 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 much stronger for $v_3$ than $v_2$
\( v_n \) in small systems

- Good agreement with STAR for \( v_2 \)
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$v_n$ 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
Understanding the nonflow contribution: $v_2$ in $p+Au$ as a case study

- The large difference between the PHENIX published and STAR preliminary in this case is nonflow.
- PHENIX suppresses nonflow via kinematic selection.
Understanding the nonflow contribution: $v_2$ in $p+Au$ as a case study

The large difference between the PHENIX published and STAR preliminary in this case is nonflow.

PHENIX suppresses nonflow via kinematic selection.

STAR applies non-flow subtraction procedure.

One needs to be careful about the risk of over-subtraction methods—S. Lim et al, Phys. Rev. C 100, 024908 (2019)

| $p+Au$ at 200 GeV | $3\times2$PC: $-3.0<\eta<-1.0$, $0.35<|\eta|<1.0$ | $\eta<-1.0$, $|\eta|<3.0$ |
|------------------|-----------------------------------------------|--------------------------|
| STAR Preliminary, 2018 (sub, CMS-style) | | |
The large difference between the PHENIX published and STAR preliminary in this case is nonflow. PHENIX suppresses nonflow via kinematic selection.
Understanding the nonflow contribution: $v_2$ in $p+Au$ as a case study

- The large difference between the PHENIX published and STAR preliminary in this case is nonflow.
- PHENIX suppresses nonflow via kinematic selection.
- STAR applies non-flow subtraction procedure.
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX.
To enable additional study, the new PHENIX publication (Phys. Rev. C 105, 024901 (2022)) includes the complete set of $\Delta \phi$ correlations and extracted coefficients $c_1, c_2, c_3, c_4$

A new paper uses these data tables to explore non-flow subtraction of these data as well as to assess the degree of (non-)closure of non-flow subtraction methods
Additional non-flow studies using published data tables

The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn’t make too much difference
Additional non-flow studies using published data tables


- The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn’t make too much difference
- The FVTXS-CNT-FVTXN combination has more non-flow, and the subtraction does much more
- That the three different combinations all line up after non-flow subtraction seems to lend some credence thereto, but one must be careful...

- PHENIX p+Au 0-5%
- PHENIX d+Au 0-5%
- PHENIX 3He+Au 0-5%
The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn’t make too much difference

The FVTXS-CNT-FVTXN combination has more non-flow, and the subtraction does much more

That the three different combinations all line up after non-flow subtraction seems to lend some credence thereto, but one must be careful...
There’s a larger relative change for $v_3$ compared to $v_2$, but the smaller value of $v_3$ makes the non-flow subtraction more sensitive to non-closure.
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For the combinations with more non-flow, where the $v_3$ is imaginary in $p+Au$ and $d+Au$, the non-flow subtraction is completely uncontrolled.
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Additional non-flow studies using published data tables


Closure is considerably violated in AMPT
Additional non-flow studies using published data tables


Closure is considerably violated in AMPT and PYTHIA/Angantyr
Additional non-flow studies using published data tables

- Closure is considerably violated in AMPT and PYTHIA/Angantyr
- Since AMPT has too much non-flow and PYTHIA doesn't have any flow, the degree of overcorrection in real data is likely not as bad as it is with these generators

The standard PHENIX $v_3/v_2$ is lower than the ATLAS, while the non-flow corrected is above
The standard PHENIX $v_3/v_2$ is lower than the ATLAS, while the non-flow corrected is above.

The ratio is expected to be lower for lower collision energies in almost all physics scenarios—lower energy, shorter lifetime, more damping of higher harmonics.
Photons in small systems

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

| p+Au, 0-100 %

PHENIX preliminary

Photons in small systems

\[ p + Au, 0-100 \% ]

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

\[ \text{PHENIX preliminary} \]

- Thermal photons in \( p + Au \)?

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\[ p_T \text{ [GeV/c]} \]
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

PHENIX preliminary

Photon yields

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

\[ p(d,A) + p(A) \rightarrow \gamma_{\text{dir}} + X \]

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

\[ p+Au \text{ and } d+Au \text{ in between} \]