PHENIX insights into the inner workings of the quark-gluon plasma

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for the PHENIX collaboration
PHENIX scientific output in a nutshell

Close to 200 published papers
More than 25000 citations

Lessons learned about the inner workings of the QGP?
Outline

A brief account of what’ve learned through the years and some of the recent results

Concentrate on the two most prominent RHIC discoveries in Au+Au: jet quenching and perfect fluid

• High–p$_T$ hadrons

• Collectivity
  – Heavy flavor and electromagnetic probes will be covered partially as related to the storyline. For more complete presentations on these subjects see Rachid Nouicer’s, and Yorito Yamaguchi’s talks at this meeting
The discovery of jet quenching via hadron suppression

- Many measurements over the years of $\pi^0$ and $\eta$ production from several different collisions systems reaching $p_T = 20$ GeV/c
- Differential measurement with respect to the reaction plane
- Constraints on QGP transport coefficients and energy loss mechanism
At 200 GeV, suppression is independent of collision system, when compared at similar $N_{\text{part}}$. 

ArXiv:1805.04389
CAN WE TURN JET QUENCHING OFF?
Onset of suppression with energy

In central Cu+Cu at 22 GeV - $\pi^0$ are no longer suppressed. Turn off of QGP? Maybe, but Cronin enhancement also changes with energy.
Control experiment with a colorless probe

- Direct photons, unmodified at high $p_T$
- Both $\pi^0$ and $\eta$ are suppressed
- Important milestone confirming jet quenching

PRL 96, 202301 (2006)
2003: d+Au control experiment: cold nuclear matter expected

✓ Yes - no hadron suppression in d+Au
Closer look: Are all hadrons suppressed?

- Baryons are not suppressed at intermediate $p_T$
- Radial flow and hadronization by recombination

2005 “perfect liquid”

- Heavier particles boosted to higher momentum
  - Common flow field
- Agreement with ideal hydro
- RHIC experiments publish white papers

**RHIC Scientists Serve Up 'Perfect' Liquid**

New state of matter more remarkable than predicted — raising many new questions

Monday, April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom “smasher” located at the U.S. Department of Energy’s Brookhaven National Laboratory — say they’ve created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC’s heavy ion collisions appears to be more like a liquid.
Hadronization by recombination: Empirical scaling of elliptic flow

- Complicated dependence on mass and $p_T$
- Simplifies when plotted vs transverse kinetic energy
- Two groups: baryons and mesons

Now scale both axes with # of constituent quarks
- 2 for mesons
- 3 for baryons

Uniform behavior in flow/per quark
The history of refining perfection

- Two notable steps forward
  - 2007: development of viscous hydrodynamics
  - 2010: measurements of high-order harmonics, modeling of initial-state fluctuations event-by-event
- Confirms QGP is a very dense and strongly coupled system. => jet quenching and flow are related

\[ \eta/s \approx 0.12 \text{ at } \sqrt{s} = 0.2 \text{ TeV} \quad \eta/s \approx 0.2 \text{ at } \sqrt{s} = 2.76 \text{ TeV} \]
Discovery of heavy flavor suppression and flow


Au+Au 200 GeV
HF $e^+/-$ from charm and beauty decays
Suppressed

Flow with the light q

Si detector upgrades in 2011 and 2012 to provide b/c separation by DCA
In 0-10%, bottom and charm are more clearly separated

Charm more suppressed in 0-10% than MB for $p_T < 4.5\text{GeV/c}$

Run 11 min. bias results published in Phys. Rev. C93, 034904 (2016);
Charm and even beauty flow in Au+Au!

$\mathbf{v_2^c(c \rightarrow e)}$

- $v_2(c \rightarrow e)$ is positive and smaller than charged hadron $v_2$
- First $b \rightarrow e \ v_2(b \rightarrow e)$ measurement at RHIC
CAN WE TURN THE FLOW OFF?
• Mesons are not modified at mid-rapidity
• Huge centrality-dependent proton enhancement
• Similar behavior as in Au+Au. Is it of the same origin?
$R_{pA}$ at forward/backward rapidity

- Forward modification consistent with nPDF effects
- Enhancement at backward rapidity, where $dN_{ch}/d\eta$ is larger $\rightarrow$ suggestive of final state effects
\( R_{pA}(p_T) \) at forward/backward rapidity

No significant modifications at high \( p_T \)
$R_{pA}$ vs. $N_{\text{part}}$ at forward/backward rapidity

Strong $N_{\text{part}}$ dependence in intermediate $p_T$ hadrons, similar to observation for baryons at mid-rapidity
Closer look at the d+Au "control" experiment

- In 2013, prompted by discoveries at LHC, go back to 2008 data
- Viscous hydrodynamics with small shear viscosity provides reasonable description of the PHENIX measurement of $v_2(p_T)$ of pions and protons
New control experiments to solve the puzzle!

2016: d+Au
Beam energy scan
Turn the energy down: 200, 62.4, 39, 19.6 GeV
Does the flow disappear?

2014, 2015
Geometry engineering
to test the connection
between the initial-state
geometry of the possible hot spots and the translation to final-state particle distributions

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Flow signal present at all four energies

- Real-valued $v_2\{4\}$ at all four energies
- Nonflow increases at high-$p_T$ the lower energies, but not at low $p_T$
Test for evidence of a common velocity field

- Do we see a mass dependence in $v_2(p_T)$?
  - Yes, characteristic mass-splitting of pion and proton $v_2$ is seen, increasing with system size
  - Hydro captures the low $p_T$ behavior

*Phys. Rev. C 97, 064904 (2018)*
• Scaling $v_2$ with $n_q$ works reasonably well, especially in $^3\text{He}+\text{Au}$, where the multiplicity is larger
Geometry tests
$v_2(p_T)$ measurement in small systems

$\sqrt{s_{\text{NN}}}=200$ GeV 0-5%

$\nu_2^{p+Au} < \nu_2^{d+Au} \approx \nu_2^{3\text{He}+Au}$

$\langle \epsilon_2 \rangle$

$d+Au$ $v_2(p_T)$
- Updated from Run8 to Run16 data
- New nonflow estimate

arXiv:1805.02973
The measured $v_2$ and $v_3$ follow the initial eccentricity.

✓ Geometry control works!
\( v_n \) data and hydrodynamics in p/d/\(^3\)He+Au

- Hydrodynamics provides simultaneous quantitative description of these six measurements, as well as other measurements form small and large systems
- Indication of hot QGP droplets?
  - Can we see them glow, and what about heavy quarks and quenching of jets?

$R_{pAu}$ for direct photons: hot spots?

- Central p+Au collisions shows direct photon $R_{pAu} > 1$
- Data suggest thermal photon yields
Heavy flavor muons flow in d+Au!

First measurement at HF muon flow at RHIC
Significant non-zero heavy flavor $v_2$ in d+Au collisions !!
99.93% (98.61%) confidence level at backward (forward)
Is there jet queening in p/d/$^3$He+Au?

- Hints of suppression of high $p_T$ hadrons in central collisions
Alternatives?

- Reasonable description of $v_2(p_T)$, but misses the strong geometry dependence on $v_3(p_T)$
- Comparison to other observables?
Conclusions

• A wealth of data from PHENIX revealing the inner working of QGP in large systems
• Mounting evidence for QGP droplets in small systems
• Still to come:
  – Analyses of rare probes utilizing the large Au+Au data sets from Run 14 and Run16 not fully analyzed
  – Many ongoing analyses in small systems

Stay Tuned!
Golden datasets of PHENIX

<table>
<thead>
<tr>
<th>year</th>
<th>Beam, E(GeV)</th>
<th>Recorded data</th>
<th>upgrade</th>
<th>Physics</th>
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<tbody>
<tr>
<td>2016</td>
<td>AuAu 200 dAu 200</td>
<td>2.3/nb (90/pb) 1G &amp; 73/nb 0.6G 0.1G, 8M</td>
<td>VTX,FVTX MPC-EX</td>
<td>Heavy Flavor Gluon nPDF Small QGP</td>
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<td>dAu 62,39,20</td>
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<tr>
<td>2015</td>
<td>pp 200 pAu 200</td>
<td>23/pb 80/nb (16/pb) 275/nb (7.4/pb)</td>
<td>VTX, FVTX</td>
<td>Heavy Flavor Transverse spin CNM, small QGP</td>
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<tr>
<td></td>
<td>pAl 200</td>
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</tr>
<tr>
<td>2014</td>
<td>AuAu 200, 15 200</td>
<td>2.3/nb (90/pb) 25/nb (15/pb)</td>
<td>VTX, FVTX</td>
<td>Heavy Flavor Small QGP</td>
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<tr>
<td></td>
<td>³HeAu 200</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2013</td>
<td>pp 510</td>
<td>240/pb</td>
<td>W-trigger</td>
<td>Anti-quark spin Gluon spin</td>
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<tr>
<td>2012</td>
<td>pp 510</td>
<td>50/pb 9/pb 5/nb (60/pb) 0.17/nb (10/pb)</td>
<td>W-trigger VTX, FVTX</td>
<td>Anti-quark spin Transverse spin Heavy flavor Geometry</td>
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<td>pp CuAu 200 200</td>
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<td></td>
<td>UU 193</td>
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<tr>
<td>2011</td>
<td>pp 510 AuAu 200</td>
<td>28/pb 0.8/nb (32/pb)</td>
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<td>Anti-quark spin Heavy flavor BES-I</td>
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<td>AuAu 200</td>
<td>1.1/nb (44/pb)</td>
<td>HBD</td>
<td>Low mass ee BES-I</td>
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</table>

Many physics topics with variety of high statistics datasets
Up to 3 years to complete publication of major results
$p/d + Au$ at same $\langle dN_{ch}/d\eta \rangle$

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

- $p + Au$ 0-5\% (Phys.Rev. C95 (2017), 034910)
  $\langle N_{part} \rangle = 10.7 \pm 0.6$, $\langle dN_{ch}/d\eta \rangle = 12.3 \pm 1.7$

  $\langle N_{part} \rangle = 11.2 \pm 0.7$, $\langle dN_{ch}/d\eta \rangle = 12.2 \pm 0.9$

Same $\langle dN_{ch}/d\eta \rangle$
Charged hadron $R_{pA}$
V2 and dNch/dη

*Phys. Rev. C 96, 064905 (2017)*

![Image of data plots showing v2 and dNch/dη](PHENIX)
FIG. 4. Ratio of $v_2^{\pi}$ over $v_2^{proton}$ in central 0%-5% (a) $p+Au$, (b) $d+Au$, and (c) $^{3}\text{He}+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Theoretical calculations from SUPersonic and AMPT are also shown.

FIG. 3. Same as Fig. 1, but also shown are $v_2(p_T)$ transport model calculations using AMPT [23].
dAu BES: $v_2(p_T)$ and hydro models

- Nearly identical
- Well described by hydro
- No clear trend with preflow

Increase at high $p_T$? Nonflow?
Nonflow correlations: insights from AMPT

- Evidence for collective effects down to 39 GeV
- Nonflow correlations at 20 GeV require further studies
Nonflow correlations: insights from AMPT

200 GeV  62 GeV  39 GeV  20 GeV

Pure Flow  With Non-Flow  All Non-Flow

PHÖENIX preliminary

(d) d+Au \( \sqrt{s_{NN}} = 19.6 \text{ GeV} \) 0-20%
Extrapolated Res(\( v_2^{1st+3rd} \))
Global Sys (19.6 GeV) = -48%
**$v_2$ vs $\eta$**

- **Forward:** similar values at all $\sqrt{s_{NN}}$
- **Backward:** decrease with $\sqrt{s_{NN}}$

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**200 GeV**

**d+Au** $\sqrt{s_{NN}} = 200$ GeV 0-5%

- $v_2$\{EP\}

**62.4 GeV**

**d+Au** $\sqrt{s_{NN}} = 62.4$ GeV 0-5%

**39 GeV**

**d+Au** $\sqrt{s_{NN}} = 39$ GeV 0-10%

**PHENIX** preliminary

PHENIX preliminary

PHENIX preliminary

PHENIX preliminary

**20 GeV**

**Extrapolated Res($v_2^{33-35}$)**

Global Sys (19.6 GeV) = 35% - 48%
Insights from AMPT

- Forward: well described at all $\sqrt{s_{NN}}$
- Backward: AMPT deviates from data at low energy
Insights from AMPT

- Flow dominates at forward and middle pseudorapidity

**Flow dominates at forward and middle pseudorapidity**
Insights from AMPT

- Flow dominates at forward $\eta$

\[
\begin{align*}
\text{200 GeV} & \quad \text{d+Au } \sqrt{s_{NN}} = 200 \text{ GeV 0-5\%} \\
\text{62.4 GeV} & \quad \text{d+Au } \sqrt{s_{NN}} = 62.4 \text{ GeV 0-5\%} \\
\text{39 GeV} & \quad \text{d+Au } \sqrt{s_{NN}} = 39 \text{ GeV 0-10\%}
\end{align*}
\]