Collectivity in Small Systems
Measured with PHENIX at RHIC

Carlos E. Pérez Lara
(Stony Brook University)
Collective Phenomena

- Hot QCD matter is created in HIC: strongly interacting phase
- No direct experimental access to it
- One of the main probes is anisotropic flow
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What do we learn from $v_n$?

- Very low viscous fluid
- Increase with energy density
- Differential $v_2$ similar between LHC and RHIC
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- Increase with energy density
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Properties hold even for smaller systems
Collective Phenomena

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- One of the main probes is anisotropic flow

What do we learn from vn?

- Very low viscous fluid
- Increase with energy density
- Differential v2 similar between LHC and RHIC

All particle correlation even for pp?

Truth is in the details
Small Systems Results from PHENIX

- Correlations
- Nuclear Modification Factors
- Heavy Flavour
- Photons
PHENIX Detector

Central

Electromagnetic Calorimetry
- PbSc
- PbGl

Particle Identification
- TOF-W/E
- RICH

Tracking
- Drift Chamber
- Pad Chamber 1, 2, 3

Forward

Electromagnetic Calorimetry
- PbWO4

Particle Identification
- via DCA

Tracking
- Muon Chambers
- Silicon Strips
- Silicon Pads

|Eta| [2,4]

Phi Coverage TwoPi
CORRELATIONS
Correlation Function

Eta Gap  [0.65, 3.35]  [2.75, 4.25]  [2.00, 6.00]  [6.20, 7.80]

d+Au $\sqrt{s_{NN}} = 200\text{ GeV}$ 0-5%
CNT -- FVTXS
0.65 $< |\Delta \eta| < 3.35$
$1 + \sum_{n=3}^{3} 2C_n \cos(n\Delta \phi)$

PHENIX

FVTXN -- FVTXS
2.00 $< |\Delta \eta| < 6.00$
$1 + 2C_2 \cos(2\Delta \phi)$

d+Au $\sqrt{s_{NN}} = 200\text{ GeV}$ 0-5%
CNT -- BBCS
2.75 $< |\Delta \eta| < 4.25$
$1 + 2C_1 \cos(\Delta \phi)$

$\Delta \phi$

PHENIX

BBCN -- BBCS
6.20 $< |\Delta \eta| < 7.80$
$1 + 2C_3 \cos(3\Delta \phi)$

• Strong $C_1$ and $C_2$ coefficients present for most central d+Au collisions @ 200 GeV


200
Correlation Function

<table>
<thead>
<tr>
<th>sqrt(s)</th>
<th>200 GeV</th>
<th>62.4 GeV</th>
<th>39 GeV</th>
<th>19.6 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>d+Au ( \sqrt{s_{NN}} = 200 \text{ GeV} ) 0-5%</td>
<td>d+Au ( \sqrt{s_{NN}} = 62.4 \text{ GeV} ) 0-5%</td>
<td>d+Au ( \sqrt{s_{NN}} = 39 \text{ GeV} ) 0-10%</td>
<td>d+Au ( \sqrt{s_{NN}} = 19.6 \text{ GeV} ) 0-20%</td>
<td></td>
</tr>
<tr>
<td>FVTXN: ( 1.0 &lt; \eta^A &lt; 3.0 )</td>
<td>FVTX: ( -3.0 &lt; \eta^B &lt; -1.0 )</td>
<td>FVTX: ( -3.0 &lt; \eta^B &lt; -1.0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -1 + \sum_{n=1}^{3} 2C_n \cos(n\Delta \phi) )</td>
<td>( -1 + 2C_2 \cos(\Delta \phi) )</td>
<td>( -1 + 2C_2 \cos(2\Delta \phi) )</td>
<td>( -1 + 2C_3 \cos(3\Delta \phi) )</td>
<td></td>
</tr>
</tbody>
</table>

- Strong \( C_1 \) and \( C_2 \) coefficients present for most central d+Au collisions at different energies

$v_2(p_T)$ for Charged Particles @ 200 GeV

- $v_2$ signal present in all centralities
- $v_2$ reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

$v_2(p_T)$ for Most Central Low $p_T$

### $@200$ GeV
- $d+Au \, \sqrt{s_{nn}} = 200$ GeV 0-5%
  - $h_\star, |h_\star| < 0.35$
  - $v_2(EP)$
  - Global Sys. = ±0.3%
  - PHENIX

### $@62.4$ GeV
- $d+Au \, \sqrt{s_{nn}} = 62.4$ GeV 0-5%
  - $v_2(EP)$
  - Global Sys. = ±0.3%

### $@39$ GeV
- $d+Au \, \sqrt{s_{nn}} = 39$ GeV 0-10%
  - $v_2(EP)$
  - Global Sys. = ±3.6%

### $@20$ GeV
- $d+Au \, \sqrt{s_{nn}} = 19.6$ GeV 0-20%
  - Extrapolated
  - $Res(v_2^{1st+2nd})$
  - Global Sys. = +35%
  - -48%

---

$v_2(p_T)$ for Most Central Low $p_T$

- **@200 GeV**
  - $d+Au$ $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - $h_\perp$, $|h_\perp| < 0.35$
  - $v_2(EP)$
  - Global Sys. = ±0.3%
  - PHENIX

- **@62.4 GeV**
  - $d+Au$ $\sqrt{s_{NN}} = 62.4$ GeV 0-5%
  - $v_2(EP)$
  - Global Sys. = ±1.8%

- **@39 GeV**
  - $d+Au$ $\sqrt{s_{NN}} = 39$ GeV 0-10%
  - $v_2(EP)$ P. S.
  - AMPT $v_2(EP)$ H. S.
  - Global Sys. = ±3.6%

- **@20 GeV**
  - Extrapolated $\text{Res}(v_2^{1<|h_\perp|<2})$
  - Global Sys. = ±35% -48%

- **@200 and 62.4 GeV** well reproduced by Hydro


- All energies well reproduced by AMPT
Interesting scaling of $v_2$ and $v_3$ with system size
- $d+Au$ $v_2$ close to $^3He+Au$
- $d+Au$ $v_3$ close to $p+Au$

**v\_2, v\_3 \iff ? \iff Initial Eccentricity**

- Interesting scaling of v\_2 and v\_3 with system size
- Same scaling in initial eccentricity
- What is the mechanism behind this scaling?

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![Graphs showing scaling of \(v_2\) and \(v_3\) with system size.]
Hydro models reproduce the $p_T$ dependence quite well for all systems.

Supports that QGP droplet is created in these small systems.

Other models fail to describe all data simultaneously.

Particle Production Mechanism
\( v_2(p_T) \) Mass Dependence

- Large difference in \( v_2 \) for pions and protons.
- Hydro reproduces quite well low \( p_T \) data. Radial Flow push?

**PHENIX**

- \( p+Au \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \, 0\text{-}5\% \) (a)
- \( d+Au \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \, 0\text{-}5\% \) (b)
- \( ^3\text{He}+Au \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \, 0\text{-}5\% \) (c)

*Phys. Rev. C 97, 064904*
$v_2(p_T)$ Mass Dependence

- Large difference in $v_2$ for pions and protons.
- Hydro reproduces quite well low $p_T$ data. Radial Flow push?
- AMPT model suggests the difference could build up during hadronic scattering.

Phys. Rev. C 97, 064904  
$p$+Au  d+Au  $^3$He+Au  

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Partonic $v_2(p_T)$ Test

- Test of scaling with constituent quarks.
- Approximate quark scaling holds very well for the three different systems. Deconfinement?

**Phys. Rev. C 97, 064904**

<table>
<thead>
<tr>
<th>System</th>
<th>$s_{NN}$ (GeV/c)</th>
<th>$v_2/n_q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+Au</td>
<td>0-5%</td>
<td></td>
</tr>
<tr>
<td>d+Au</td>
<td>0-5%</td>
<td></td>
</tr>
<tr>
<td>$^3$He+Au</td>
<td>0-5%</td>
<td></td>
</tr>
</tbody>
</table>

$\pi^++\pi^-$

$++\pi^-$

$p+p$
Forward Rapidities

NUCLEAR MODIFICATION FACTOR
R_{AA} in Heavy Ion Collisions

- RAA is one of the (oldest) golden experimental observables in studying the physics of heavy ion collisions.

- It measures the relative yield found in AA to the respective scaled pp measurement, which helps characterise the role of in-medium modification.

- R_{pA} has been also used to study cold-matter effects, such as nuclear shadowing or gluon-saturation, specially at forward rapidities.
**$R_{pA}(\eta)$ for Charged Hadrons**

- **$p+Au$** → $h^\pm + X \sqrt{s_{NN}} = 200$ GeV
  - 0-100% centrality
  - $2.5 < p_T < 5$ GeV/c
- **$p+Al$** → $h^\pm + X \sqrt{s_{NN}} = 200$ GeV
  - 0-100% centrality
  - $2.5 < p_T < 5$ GeV/c

- PHENIX preliminary
- EPPS16+PYTHIA

- Enhancement found in Au-going direction not reproducible by EPPS16.

- Where does it come from?
**$R_{pA}(p_T)$ for Charged Hadrons**

$R_{pA}$

$p+Au \rightarrow h^\pm + X \sqrt{s_{NN}}=200$ GeV
0-100% centrality
- $-2.2<\eta<-1.2$ (Au-going)
- $1.2<\eta<2.4$ (p-going)

$p+Al \rightarrow h^\pm + X \sqrt{s_{NN}}=200$ GeV
0-100% centrality
- $-2.2<\eta<-1.2$ (Al-going)
- $1.2<\eta<2.4$ (p-going)

Where does it come from?

- Enhancement found in Au-going direction not reproducible by EPPS16.
- Enhancement mainly for $p_T<5$ GeV
Centrality Dependence of $R_{pA}(p_T)$

- Enhancement mainly for $p_T < 5$ GeV and centrality dependent.

Where does it come from?

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Particle Production Mechanism
\( N_{ch} \) vs Eta

- Both AMP and Hydro qualitatively predict an enhancement in the Au-going direction.

- AMPT describes also the measured trend in d+Au with collisional energy.


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\[ N_{ch} \text{ vs } \eta \]

- Both AMP and Hydro qualitatively predict an enhancement in the Au-going direction.

- AMPT describes also the measured trend in d+Au with collisional energy.

- Hydro describes quite well the data from different systems at all centralities

HEAVY FLAVOUR
Heavy Flavour in Heavy Ion Collisions

• In Heavy Ion Collisions, heavy flavour particles are expected to be produced mainly in the hard scattering.

• A large (comparable to ch-particles) azimuthal anisotropy has been found for HF-particles in several experiments, species and energies, which suggests some degree of sensitivity to the collective expansion.

• How about small systems, low energies?
$v_2$ of Muons from Heavy Flavour Decays

- Muons from heavy flavour decays are obtained from MC templates.
$v_2$ of Muons from Heavy Flavour Decays

- Muons from heavy flavour decays are obtained from MC templates.
- Large (comparable to charged hadrons) $v_2$ is found.

$0-20\%$ d+Au $\sqrt{s_{NN}}=200$ GeV
- $\mu^-$ from open heavy flavor decays
- $2.0 < \eta < 1.4$
- Systematic uncertainty $= 1.9\%$

$0-20\%$ d+Au $\sqrt{s_{NN}}=200$ GeV
- $\mu^-$ from open heavy flavor decays
- $1.4 < \eta < 2.0$
- Systematic uncertainty $= 1.9\%$
• Preliminary results for closed states hint to suppression even for Au-going direction.

• Are mechanisms responsible for enhancement of charged particles less effective with quarkonia?
PHOTONS
Photons in Heavy Ion Collisions

- Photons from Heavy Ion Collisions
  - Direct Photons
    - Initial State hard scattering (prompt) \( pQCD \)
    - Thermal \( \text{Temperature from Fireball (QGP)} \)
  - Hadronic Photons
    - Decay products \( \text{Underlying Event} \)
Direct Photon Yields @ 200 GeV in SS

A + B → γ + X

$\sqrt{s_{NN}} = 200$ GeV:
- \text{d+Au, 0-100 \%, Int. conv.}
- \text{p+Au, 0-100 \%, Ext. conv.}

- Small increase in photons production in d+Au wrt p+Au for minimum bias collisions
Direct Photon Yields @ 200 GeV in SS

\[ A + B \rightarrow \gamma + X \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV}: \]
- **d+Au, 0-100 %, Int. conv.**
- **p+Au, 0-100 %, Ext. conv.**
- **p+Au, 0-5%, Ext. conv.**

**PHENIX**

- **p+Au**
- **d+Au**

- **Small increase in photons production in d+Au wrt p+Au for minimum bias collisions**
- **Significant increase found at low \( p_T \) in most central p+Au Collisions wrt Minimum Bias**
Direct Photon Yields @ 200 GeV in SS

\[ A + B \rightarrow \gamma + X \]

\( \sqrt{s_{NN}} = 200 \) GeV:
- d+Au, 0-100 %, Int. conv.
- p+Au, 0-100 %, Ext. conv.
- p+Au, 0-5%, Ext. conv.

**PHENIX preliminary**

- Significant increase found at low \( p_T \) in most central p+Au Collisions wrt Minimum Bias
- Does it have a thermal origin?

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

- p+Au, 0-5 %
- Thermal, Shen et al
- pQCD, Shen et al

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Direct Photon Scaling in HIC

- Yield scales with \((N_{\text{ch}}/d\eta)^{1.25}\)
- Yield scaling holds over energies, systems, centralities.
Outlook

• Finite “flow-like” signals in Small Systems from 20 to 200 GeV and for different system sizes.
• Strong correlation between $v_n$ and initial (spatial) anisotropy.
• Hydrodynamics models (quark-gluon droplets) are only models able to reproduced the large variety of small systems.
• Sizable $v_2$ of heavy flavour probes
• Smooth scaling of direct photons from pp to Heavy Ions

Thanks!
BACKUP
$v_2(p_T)$ for Charged Particles @ 62.4 GeV

- $v_2$ signal present in all centralities. Also large for 62.4 GeV
- $v_2$ reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

$v_2(p_T)$ for Charged Particles @ 39 GeV

- $v_2$ signal present in all centralities. Also large for 62.4 and 39 GeV
- $v_2$ reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

Relative non-flow component higher for most peripheral centralities and higher $p_T$.
• Relative non-flow component higher for most peripheral centralities and higher $p_T$

• Same trend in all energies
Psi(2S) / Psi(1S) Ratios in SS

\( \frac{\sigma_{\psi(2S)}^{p^{3}He+Au}}{\sigma_{\psi(1S)}^{p+Au}} \)

PHENIX \( \sqrt{s_{NN}} = 200 \) GeV

- Sequential suppression of exited states also present is small systems?

PRC 95, 034904 (2017)

P+Au, d+Au, \(^{3}\)He+Au
A Transition?

PHENIX

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

$^3$He+Au

$p$+Au

$p$+Al

$\sqrt{s_{NN}} = 5.02$ TeV

$p$+Pb, LHCb

JHEP 1603 (2016) 133

$p$+Pb, ALICE

JHEP 1412 (2014) 073

$d+Au$ $^3He+Au$
Centrality Classification

More on dN/deta

\( v_2 \) at Forward Rapidities via MPC

- Why? By increasing the number of particles in the correlation, a progressive suppression of non-flow can be achieved.
Centrality Dependence of $R_{pA}(\eta)$

- Enhancement mainly for $p_T < 5$ GeV and centrality dependent.

Where does it come from?

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$v_2\{2\}$, $v_2\{4\}$ at Different Energies

$\sqrt{s_{\text{NN}}}$ (GeV)

PHENIX Data

AMPT

More on $v_2(\eta)$

More on v2(pt)
Hydro Evolution

Temperature [GeV]

Particle Systems:
- p+Au
- d+Au
- \(^3\)He+Au

Time Points:
- \(t = 1.0 \text{ fm}/c\)
- \(t = 1.7 \text{ fm}/c\)
- \(t = 3.2 \text{ fm}/c\)
- \(t = 4.5 \text{ fm}/c\)


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Photons in HIC

\[ \frac{d^3N}{dp_T^2 dy} \left( \frac{dN_{ch}}{dN} \right)^{1.25} \]

(a) \[ s_N = 62.4 \text{ GeV}, 0-86\% \]
(b) \[ s_N = 200 \text{ GeV} \]
(c) \[ s_N = 2760 \text{ GeV}, 0-20\% \]

\[ s = 62.4 \text{ GeV} \]

\[ s = 63 \text{ GeV} \]

\[ s = 200 \text{ GeV} \]

\[ s = 2760 \text{ GeV} \]

PHENIX

Photons in HIC

Fit: \[ \frac{1}{\text{SY}(\sqrt{s_{NN}})} \left( \frac{dN_{ch}}{d\eta} \right)^\alpha \]

\[ \eta = 1.25 \pm 0.02 \]

\[ \alpha = 1.25 \]

PHENIX

v2(eta) large rapidity coverage
v2(eta) system scan

PHENIX preliminary

Various plots showing v2 as a function of η for different reactions at 200 GeV 0-5%.
Where does it come from?

- Enhancement mainly from PT<5 GeV and centrality dependent.

**PHENIX preliminary**

-2.2<\(\eta\)<1.2, p+Au (Au-going)
-2.2<\(\eta\)<1.2, p+Al (Al-going)
1.2<\(\eta\)<2.4, p+Au (p-going)
1.2<\(\eta\)<2.4, p+Al (p-going)

- \(h^\pm, 2.5<p_T<5\) GeV/c
v2 Mass Dependence

- **(a)**: p+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - Data
  - $\pi^+\pi^-$ iEBE-VISHNU (no rescattering)
  - $p+\bar{p}$ iEBE-VISHNU (no rescattering)

- **(b)**: d+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - Data
  - $\pi^+\pi^-$ iEBE-VISHNU
  - $p+\bar{p}$ iEBE-VISHNU

- **(c)**: $^3$He+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - Data
  - $\pi^+\pi^-$ iEBE-VISHNU

*PHENIX*


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v2 Mass Dependence

$p+\text{Au}$ at $\sqrt{s_{NN}} = 200$ GeV 0-5% (a)

$d+\text{Au}$ at $\sqrt{s_{NN}} = 200$ GeV 0-5% (b)

$^3\text{He}+\text{Au}$ at $\sqrt{s_{NN}} = 200$ GeV 0-5% (c)

$p_T$ (GeV/c) vs. $v_2$

$\rm{PHENIX}$

$\pi^+\pi^-$ Data
$p+\bar{p}$ Data
$\pi^+\pi^-$ AMPT (no hadron rescattering)
$p+\bar{p}$ AMPT (no hadron rescattering)
$\pi^+\pi^-$ AMPT
$p+\bar{p}$ AMPT

Recent study extended the CFC effective theory to next to leading order couplings which also provide a scaling in the resulting $v_2$ and $v_3$ for asymmetric systems.

CFC EFT also reproduces quite well the $v_2 p_T$ trend for all systems, however overshoots $v_3$ in the smallest systems.

Supports that signals found are a result of the correlations created by gluons coupling in the initial state. No medium needed.