U+U and Cu+Au results from Phenix

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Outline

- Motivation
  - U+U and Cu+Au

- Measuring the bulk properties
  - Mid-rapidity global particle production
  - Mid rapidity identified flow
RHIC Run 12

- RHIC versatility – energy and species scans
- Allows for unique collision environments
  - First U+U collisions at 193 GeV
  - First Cu+Au at 200 GeV
- Recent Improvements
  - EBIS source
  - Horizontal stochastic cooling in both beams
    (small beam size, high luminosity, low beam loss rates)
Tests of initial geometry

Deformed nuclei

- Initial geometry changes event-by-event
  - Expect a higher energy density than Au+Au
- For tip-tip orientation

R_{long}/R_{perp} \sim 1.29

Studies

- Initial geometry – flow relation
- Path length – parton energy loss

Key point for this measurement – experimentally separate these configurations

PRL 94, 132301 (2005)
Tests of initial geometry

Asymmetric system

- Core: asymmetric density profile
- Corona: large on Au-side

Study

- Naturally arising odd harmonics
- Central collisions:
  - Cu completely swallowed
Global particle production
Charged particle multiplicity, $dN_{ch}/d\eta$

- Charged particle density
  - increases with increasing collision energy.
  - There is an increase for more central collisions at all collision energies.
  - Au+Au and U+U are similar.

- Note: centrality selection uses ZDC+BBC. Cut on central 1% (rightmost point) – no method to separate tip-tip events.
Charged particle multiplicity, $dN_{ch}/d\eta$

- Charged particle density
  - Increases with increasing collision energy.
  - There is an increase for more central collisions at all collision energies.
  - Au+Au and U+U are similar.

- No significant change in the shape of the centrality-dependence from 7.7 GeV Au+Au collisions up to 2.76 TeV Pb+Pb collisions.
The multiplicity per participant pair increases linearly with \( \log(\sqrt{s_{NN}}) \) to RHIC energies.

No significant excess particle production in very central U+U – Compared to Au+Au at the same energy.
Transverse energy density, $E_T$

- Transverse energy production
  - Increases with increasing collision energy.
  - Increases for more central collisions at all collision energies.
  - The Au+Au and U+U particle $E_T$ are similar
    - Small increase for most central data.
The transverse energy per participant pair increases linearly with $\log(\sqrt{s_{NN}})$ to RHIC energies.

- The Au+Au and U+U particle $E_T$ are similar
  - Small increase for most central data.

The red line is a logarithmic fit to all points excluding the ALICE point.
Bjorken Energy density, $\varepsilon_{BJ}$

- New RHIC energy density record in U+U collisions
  - $6.15$ GeV/fm$^2$/c.
- $\varepsilon_{BJ}$ increases by a factor of 3.8 when going from 7.7 to 200 GeV.
- Moderate increase from central Au+Au to very central U+U (20%).

Upper U+U point 1% most central, all other 5% centrality bins.
Bjorken Energy density, $\varepsilon_{\text{BJ}}$

- New RHIC energy density record in U+U collisions
  - 6.15 GeV/fm$^2$/c.
- $\varepsilon_{\text{BJ}}$ increases by a factor of 3.8 when going from 7.7 to 200 GeV.
- $\varepsilon_{\text{BJ}}$ increases by a factor of 11 when going from 7.7 GeV to 2.76 TeV.

Upper U+U point 1% most central, all other 5% centrality bins.
Cu+Au transverse energy density, $E_T$

- $E_T$ production is independent of the collision system
  - Similar $E_T$ in Cu+Cu and Au+Au at the same $N_{\text{part}}$
  - Higher $E_T$ in Cu+Au reflects larger core at the same $N_{\text{part}}$
Mid-rapidity identified flow
$v_2$ of identified hadrons

- $v_2$ is one of the main tests for U+U collisions.

- Comparison of $v_2$ of pions and protons in Au+Au and U+U
  - Shows mass ordering at low-$p_T$.
  - Similar behavior in peripheral collisions.
  - Slight difference in the slope of the proton $v_2$ in central collisions.
$v_2$ mass ordering and energy density

- Strong mass ordering is also observed at the LHC ($\varepsilon$ increases by 2.5 to RHIC)
  - At low-$p_T$ ($p_T<3$ GeV/c).
  - Qualitative agreement with Hydro (up to 3 GeV/c).

- RHIC energy scan
  - Increase of $\varepsilon$ by factor of 2 from 39 to 200 GeV.
  - Mass ordering holds at low $p_T$.
  - Proton slope same for all energies ($p_T<2$ GeV).

- $\text{Au+Au} \rightarrow \text{U+U}$?
0-2% central U+U

- Au+Au → very central U+U
  - Moderate increase of $\varepsilon$ by 20% form 0-10 Au+Au to 0-1% U+U.

- Mass ordering for pions and protons holds.

- Proton slope changes
  - Radial flow or geometry effect?
  - More studies underway.
Quark scaling, $n_q$

- $n_q$ scaling for $v_2$ of identified hadrons in Au+Au
  - Strong centrality dependence.
  - Holds to $K_{T_q} = 1.5$ GeV (0-10% central).
  - Breaks at $K_{T_q} > 0.7$ GeV (10-20% central).
- Qualitatively consistent with recombination model calculation.
Quark scaling, $n_q$

- $n_q$ scaling for $v_2$ of identified hadrons holds in U+U
  - For all centrality bins.

- Future measurement will extend the pion $v_2$ to lower $p_T < 0.5$ GeV/c.
\( v_n \) measurements in Cu+Au

- Asymmetric density profile will lead to asymmetric pressure gradient
  - Measure particle production relative to the Spectator(true) reaction plane.
- In data
  - Use the shower max in the ZDC (neutron).
  - Direction decided by the Au spectators.
  - \( \Psi_{1,SMD} \): combination of \( \Psi_{1,SMDSouth} \) with flipped \( \Psi_{1,SMDNorth} \).
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$\Phi_n$ or $p-\Psi_{\text{True}}$

$\Psi_{\text{True}}$

$\Psi_{1,\text{SMD}}$

south

north

Cu+Au

Cu

Au
• An asymmetric $dN/d\Delta \phi$ distribution is observed with $\Psi_{1, SMD}$
  - more particles emitted from the Au side than from the Cu side.
• Hadrons at mid-rapidity ($|\eta| < 0.35$) exhibit large $v_1$ and $v_2$
  (not observed in Au+Au).
• Not consistent with a large $v_3$.
Modeling $v_n$

- Comparison with AMPT at midrapidity
  - $v_2$ observed trends are expected.
  - Stronger $v_1$ (zero in AuAu)
    - Wrong sign.
    - Naively explained by the corona.

AMPT (v1.21) results calculated by H. Ruiz and J. Nagle with string melting cross section ($\sigma$) of 3 mb
Sizable positive pion $v_1$ is observed at $p_T > 1\text{GeV/c}$ at midrapidity
- Increases with $p_T$.
- Observed in all centrality bins.
- May be due to asymmetric density profile.
- Need more statistics for proton.
The $v_2$ of pions and protons are measured as a function of $p_T$ and centrality.

- The $v_2$ measured from $\Psi_1$ and $\Psi_2$ are consistent with each other ($\Psi_{BBC}$).
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- The $v_2$ measured from $\Psi_1$ and $\Psi_2$ are consistent with each other ($\Psi_{BBC}$).
- The $n_q$ scaling holds in Cu + Au collisions at 200 GeV.
Nuclear modification factor, $R_{AB}$

- Cu+Au comparable to Au+Au at the same Ncoll values.
Baryon to meson ratio

Cu+Au

- Significant baryon enhancement in central collisions
  - Magnitude similar for positive and negative ratios.
Baryon to meson ratio

- Significant baryon enhancement in central collisions
  - Magnitude similar for positive and negative ratios.
  - Different from Au+Au and Cu+Cu at the same energy.
Baryon to meson ratio

Cu+Au

- Pbar/p ratio *in symmetric systems* depends on root $s$ only, with small centrality and $p_T$ dependence
  - 200 GeV ~ 0.8
  - 62.4 GeV ~ 0.5
- Pbar/p ratio in Cu+Au at 200 GeV ~ 0.9
  - Why less protons?
  - Higher $\varepsilon$ at the same $N_{part}$ than in a symmetric system.
  - Need further measurements!
Summary

- First measurements at RHIC from two very unique systems.
- U+U at 193 GeV
  - The highest energy density reached at RHIC.
  - Exploring a way to separate tip-tip collisions.
- Cu+Au at 200 GeV
  - Non zero $v_1$ observed at mid-rapidity, no $v_3$.

- Many more results to come!
Backup
Transverse energy parametrization, LHC
U+U → Au+Au advantage

- Theoretical motivation
  - **Initial geometry (Eccentricity) – flow studies**
    - V2 driven by initial geometry
    - V2/e in central Au as predicted by ideal hydro
    - Crucial test: increase the en density, what happens to v2/e
  - Path length – parton energy loss studies

- The medium density in U+U is 35-55% higher than in Au+Au
  - Difference in the overlap area, S
    - b=0, S(tip-tip) same as S(Au+Au)
      - S(body-body) 24% higher than S(Au+Au)
    - Difference in Nch ~Npart

Transverse Nch density

- dNch/dy/S tip-tip 42.6 fm-2, Body-body 31.7 fm-2, Au_Au 31.5 fm-2
- PRC 73, 034911 (2006)
ALICE $v_2$

M. Krzewicki@ALICE QM2011

$\pi^\pm$, $v_2$ [SP, $|\Delta\eta|>1$]  
$\Lambda^0$, $v_2$ [SP, $|\Delta\eta|>1$]  
$\bar{p}$, $v_2$ [SP, $|\Delta\eta|>1$]  
hydro LHC  
(CGC initial conditions)  
($\eta/s=0.2$)

$\sqrt{s_{NN}} = 2.76$ TeV  
centrality 10%-20%

$nq(mT)$-scaling worse than at RHIC

$nq(pT)$-scaling at $pT > 1.2$ GeV/c violation 10–20%
3. Event plane correlation

1. The correlation between \( \Psi_{1,BBC}^{South} \), measured by the south BBC in the Au-going direction, and \( \Psi_{1,SMD}^{South} \) is stronger than the correlation between \( \Psi_{1,BBC}^{North} \) in the Cu-going direction and \( \Psi_{1,SMD}^{South} \). It indicates that \( \nu_1 \) is larger in the Au-going direction than that of Cu-going direction.

2. The raw correlation of \( \Psi_3 \) with \( \Psi_1 \) and \( \Psi_2 \) are pretty weak.

North: Cu-going
South: Au-going

Find a better plot A.Iordanova
Hadron $v_1$
Hadron $v_2$
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  - Collision geometry is driving the centrality dependence.
## Run 12 parameters

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<td>171.2 µb-1</td>
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<td>4.96 nb-1</td>
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C. B. Chiu, R. C Hwa et al. PRC.78.044903