Proving Quark Gluon Plasma via Baryon Production at RHIC

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Outline

1. Introduction
2. Overview of bulk properties at RHIC
3. Systematic study of baryon enhancement
4. What’s the origin of baryon enhancement?
5. Exploring the QCD phase diagram at RHIC
6. Summary
1. INTRODUCTION
Why baryons*?
(* protons and antiprotons in this talk)

- Heavier mass than the light mesons, sensitive to the **collective phenomena**, such as a radial flow.
- Sensitive to the **baryo-chemical property** of the matter.
- Different number of **constituent quarks** from that for mesons, test of recombination models.
A lots of data and publications on baryons from RHIC experiments; 1
(spectra, yields, and jet correlations)

- **BRAHMS**

- **PHENIX**
  - Nuclear effects on hadron production in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV revealed by comparison with $p + p$ data, *PRC* 74, 024904 (2006). [(TC)]
  - Particle-Species Dependent Modification of Jet-Induced Correlations in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV, *PRL* 101, 082301 (2008).
  - Au+Au 62.4 GeV (preliminary) [TC], Cu+Cu 200 GeV (preliminary),
  - Cu+Cu 22.5, 62.4 GeV (preliminary) [TC], $p+p$ 62.4 GeV (preliminary) [TC]
  - $p+p$ 200 GeV (new data)

* note: not the complete list.
A lots of data and publications on baryons from RHIC experiments; 2
(spectra, yields, and jet correlations)

• **PHOBOS**

• **STAR**
  - Identified Baryon and Meson Distributions at Large Transverse Momenta from Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV, *PRL* 97, 152301 (2006).
  - Energy dependence of $\pi^{\pm}$, p and p-bar transverse momentum spectra for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, arXiv:nucl-ex/0703040.

* note: not the complete list.
A recent STAR publication
(systematic study of PID spectra in p+p (200 GeV), d+Au (200 GeV),
Au+Au (62, 130, 200 GeV), arXiv:0808.2041)

- $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$ $p_T$ spectra (low $p_T$ region only, dE/dx by TPC).
- A nice full paper (60 pages)!
2. BULK PROPERTIES AT RHIC
What are the bulk properties (EOS)?

- Energy density ($\varepsilon$)
- Temperature ($T$):
  - critical temperature ($T_c$), initial temperature ($T_{ini}$), chemical freeze-out temperature ($T_{ch}$), kinetic freeze-out temperature ($T_{kin}$)
- Chemical potential ($\mu$):
  - baryon chemical potential ($\mu_B$), strangeness chemical potential ($\mu_s$), strangeness suppression factor ($\gamma_s$)
- Collective flow velocity ($\langle \beta_T \rangle$)
- Pressure gradient ($\Delta P$), particle emission anisotropy ($v_2$)
- Particle multiplicity (dN/dy, N)
- Transverse energy (dE$_T$/dy, E$_T$)
- Transverse momentum distribution (E$^3$dN/dp$^3$)
- Particle abundance and ratio
- Average transverse momentum ($\langle p_T \rangle$)
- HBT radii ($R_{out}$, $R_{side}$, $R_{long}$, $\lambda$)
- Velocity of sound ($v_s$)
- Shear viscosity – entropy ratio ($\eta/s$)

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... red: directly measured by $p_T$ spectra
... pink: indirectly measured by $p_T$ spectra

How the bulk properties change as a function of centrality, system and beam energy?
Charged particle multiplicity at RHIC

PHOBOS

Cu+Cu
Preliminary
3-6%, N_{part} = 100

Au+Au
35-40%, N_{part} = 99

• Same number of participants, ~same number of charged particle density at RHIC.

• Focus at the mid-rapidity to study the multiplicity scaling of bulk properties.
Average $p_T$ vs. $N_{ch}$

- $<p_T>$ scales with $\sqrt{(dN_\pi/dy)/S}$, p+p 200 GeV, Au+Au 62.4, 130, 200 GeV data.
- Suggests that the kinetic freeze-out properties in Au+Au collisions are energy independent.
- CGC (gluon saturation): small x gluons overlap and recombine, reducing the total number of gluons and increasing their transverse energy.
  - Predicts a lower particle multiplicity and larger $<p_T>$.
  - In CGC, $<p_T>$ scales with $\sqrt{(dN_\pi/dy)/S}$.
  - Data is consistent with CGC picture.

$S_T$: Transverse overlap area [fm$^2$]

STAR, arXiv:0808.2041

factor ~2

Heavy Ion Café, Univ. of Tokyo (Dec. 6, 2008)  T. Chujo
Antiparticle-to-Particle Ratios vs. $N_{ch}$

$\pi^-/\pi^+$: Flat and unity.

$p\bar{p}/p$:
- A slight decrease with centrality (130, 200 GeV)
- **Considerable drop** with centrality (62 GeV)

→ indicating that **larger baryon stopping in central collisions**
Hum…

pbar/p ratio: seems decreasing with \( N_{\text{part}} \) in PHENIX data too.

DNP2004 (TC)
**Bulk properties vs. $N_{ch}$ (1)**

- $T_{ch}$, $T_{kin}$
- $<\beta_T>$

$T_{ch}$: constant with $dN_{ch}/dy$.
- close to the lattice QCD: $T_c \approx 160$ MeV.
- universality at RHIC energies.

$T_{kin}$: decreasing with $dN_{ch}/dy$.
- same trend for all systems at RHIC (with $dN_{ch}/dy$)
- indicating strong expansion and cooling?

$<\beta>$: increasing with $dN_{ch}/dy$. 

STAR, arXiv:0808.2041
**Bulk properties vs. N\textsubscript{ch} (2)**

- $\mu_{B,s}$: finite value, weak centrality dependence (baryon stopping at central)
- $\mu_s$: close to zero.

- $\gamma_s$: approaching to unity with $dN_{ch}/dy$.

Strangeness production is strongly suppressed in p+p, dAu, peripheral Au+Au. In central Au+Au, implying that strangeness is as equally equilibrated as light quarks.
Bulk properties vs. $N_{ch}$ (3)

**HBT**

**$v_2/\varepsilon$**
Bulk properties vs. $N_{\text{ch}}$ (4)

“Only” $N_{\text{ch}}$ (or initial energy density) determines the bulk properties at RHIC?

STAR, arXiv:0808.2041
### 3. SYSTEMATIC STUDY OF BARYON ENHANCEMENT

<table>
<thead>
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<th>Run</th>
<th>Year</th>
<th>Species</th>
<th>( \sqrt{s_{NN}} ) (GeV)</th>
<th>( f/L dt )</th>
<th>( N_{\text{coll}} )</th>
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<td>01</td>
<td>2000</td>
<td>Au+Au</td>
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<td>1.0 ( \text{pb}^{-1} )</td>
<td>100M</td>
<td>3 Tpb</td>
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<td>10 Tpb</td>
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**Comments**

- **2009**
  - 500 GeV p+p: Assuming ~April 1 start, about 3-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet RIKEN milestone.

- **2010**
  - 200 GeV p+p: ~12 physics weeks to complete 200 GeV A_A measurements — could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009. STAR DAQ1000 fully operational.

- **2011**
  - Cu+Cu at associated low E: 1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (not least prototype).
  - 200 GeV U+U: 1st U+U run with EBBS, to increase energy density coverage.

- **2012**
  - 500 GeV p+p: 1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb⁻¹ for substantial statistics on W production and AG measurements.

- **2013**
  - 500 GeV Au+Au: Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II goals: heavy flavor, \( \gamma \)-jet, kaon, multi-particle correlations.

- **2014**
  - 200 GeV Au+Au or 2nd low-E, scan: To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX VTX and NCC and full STAR HFT.
  - Run option not chosen for 2013 run — low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (\( \gamma \)-jet) and 2016 (identified heavy flavors) milestones. Proof of principle test of coherent electron cooling.
Baryon enhancement at RHIC

In Au+Au $\sqrt{s_{NN}} = 200$ GeV central collisions:

- $R_{CP}$ (or $R_{AA}$)
  - Pions: Strong suppression of yields above $p_T \sim 2$ GeV/c, due to jet quenching.
  - Protons: No suppression at intermediate $p_T$ (2-5 GeV/c).

- $p/\pi$ and $pbar/\pi$ ratios
  - Factor $\sim 3$ more (anti) protons than pions at intermediate $p_T$ (2-5 GeV/c).
  - Strong centrality dependence.
Systematic study of PID spectra: Au+Au, Cu+Cu, p+p at $\sqrt{s_{NN}} = 22.5, 62.4, 200$ GeV

Cu+Cu $\rightarrow \bar{p}+X$ @ $\sqrt{s_{NN}} = 22.5$ GeV

Cu+Cu $\rightarrow \bar{p}+X$ @ $\sqrt{s_{NN}} = 62.4$ GeV

Heavy Ion Café, Univ. of Tokyo (Dec. 6, 2008)
\( \sqrt{s} \) dep. of \( \bar{p}/\pi^- \) ratio (central)

- No weak decay feed-down correction applied.

p+p 62.4 GeV, set the baseline for HI data. PHENIX data agrees with ISR data.
$\sqrt{s}$ dep. of pbar/$\pi^-$ ratio (central)

Cu+Cu 22.5 GeV, pbar/$\pi^-$ ratio in central agrees with p+p.
$\sqrt{s}$ dep. of $\bar{p}/\pi^-$ ratio (central)

Cu+Cu $62.4$ GeV, $\bar{p}/\pi^-$ ratio larger than those in $p+p$ and Cu +Cu $22.5$ GeV.

Cu+Cu $62.4$ GeV, $\bar{p}/\pi^-$ ratio larger than those in $p+p$ and Cu +Cu $22.5$ GeV.
$\sqrt{s}$ dep. of pbar/$\pi^-$ ratio (central)

Cu+Cu 200 GeV, similar to those in Cu+Cu 62.4 GeV.
\[ \sqrt{s} \text{ dep. of } p_{\bar{\text{b}}}/\pi^- \text{ ratio (central)} \]

\[ \text{Au+Au 62 GeV, } p_{\bar{\text{b}}}/\pi^- \text{ is unchanged from } \\
\text{Cu+Cu 200 GeV} \]
$\sqrt{s}$ dep. of $p_{\bar{b}/\pi^-}$ ratio (central)

Au+Au 200 GeV, $p_{\bar{b}/\pi^-}$ is enhanced.
$\sqrt{s}$ dep. of pbar/$\pi^-$ ratio (peripheral)

Peripheral collisions for all systems
Conversing to the same line
• In 22.5 GeV Cu+Cu: weak centrality dependence, \( \frac{\bar{p}}{\pi^-} \) ratios are \( \sim 0.3-0.4 \) at \( p_T = 2 \) GeV/c, which is close to the value in p+p.

• In 62.4 GeV Cu+Cu: \( \frac{\bar{p}}{\pi^-} \) ratio in central collisions reaches \( R \approx 0.6 \) at \( p_T = 2 \) GeV/c, decreasing towards the peripheral events.

* No weak decay feed-down correction applied.
Comparison with SPS data

T. Schuster, A. Laszlo (NA49)
nucl-ex/0606005

SPS Pb+Pb: consistent with Cu+Cu 22.5 GeV pbar/π.
**pbar/π⁻ ratio (central): summary**

- Increasing as a function of $\sqrt{s}$.
- Indicates the onset of baryon enhancement is in between 22 GeV and 62 GeV.

* No weak decay feed-down correction applied.
$\pi^0$ $p_T$ spectra in Cu+Cu and p+p at 22.4, 62.4, 200 GeV

$\pi^0 R_{AA}$ in Cu+Cu: energy dep.

- Enhancement at 22 GeV.
- Consistent with no energy loss model.
4. WHAT’S THE ORIGIN OF BARYON ENHANCEMENT?
Jet induced baryon enhancement?

Near side
Away side
Away side two peaks (shoulder)

2.5 - 4 GeV/c x 2 - 3 GeV/c, All Charge

J (∆φ)

∆φ(rad)

Centrality: 0 - 10%
Centrality: 30 - 40% x 0.33
Centrality: 60 - 92% x 0.048

Away side two peaks (shoulder)

Sonic shock wave? Baryon/Meson effect?
Jet-pair distribution for associated M/B


- **Trigger particle**: charged hadron (2.5 \( < p_T^{\text{trig}} < 4.0 \) GeV/c)
- **Associate particle**: meson or baryons (1.0 – 2.0 GeV/c).
- **Near side**: substantially weaker for associated baryons.
- **Away side**: similar for associated mesons and baryons.

"Shoulder" structure appeared.
Conditional jet yields for M/B


**Mesons:**
- exponential decrease with increasing $p_T$, assoc.
- Yield increase from peripheral to central, with different slope
- Incompatible with in-vacuum fragmentation
- Due to contribution from correlated soft partons, softening of FF, recombination, energy loss, etc…?

**Baryons:**
- different strongly from those for mesons.
- Not exponential shape.
- Yield (away) > Yield (near).
- Much stronger increase with centrality than those for mesons.
- Might be due to the correlated soft parton recombination.
Baryon/meson ratios associated with high $p_T$ hadron trigger ($2.5 < p_T < 4\text{GeV/c}$)

- Peripheral ratios ~ vacuum fragmentation
- In-jet ratios ~ inclusive $p/($π+K$)$

Away-side “shoulder”, and baryon enhancement in single spectra: might be the common origin.

* Recombination of correlated soft partons induced via strong parton medium interactions?
Intermediate $p_T$ ridge & Jet
(near side only)
(from SQM08, O. Barannikova, STAR)

- $p_T^{\text{trig}} > 4.0$ GeV/c
  $2.0 < p_T^{\text{Assoc}} < p_T^{\text{trig}}$

- Au+Au: $2 < p_T^{\text{trig}} < 3$ GeV/c
  Cu+Cu: $3 < p_T^{\text{trig}} < 6$ GeV/c

- Jet+ridge yields follow similar trend in $p_T$ for all trigger types
  (left bottom)

- Production mechanisms for jet and ridge are different ($p/\pi$, $\Lambda/K$)

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Heavy Ion Café, Univ. of Tokyo (Dec. 6, 2008)  
T. Chujo
5. EXPLORING THE QCD PHASE DIAGRAM AT RHIC
**Excitation functions of freeze-out properties**

- **$\mu_B$**: falls monotonically.
- **$T_{ch}$**: rapidly rises at SIS and AGS energy, saturates at SPS and RHIC energies (a unique $T_{ch} \sim T_c$ from lattice QCD).
- **$T_{kin}$**: decoupled at $\sqrt{s_{NN}} \sim 10$ GeV from $T_{ch}$. Due to the strong collective flow, matter is cooled $\rightarrow$ prolong period of chemical freeze-out and kinetic freeze-out.
- **$<\beta_T>$**: rapid increase from SIS to AGS, increasing slowly from SPS to RHIC.

Q: Freeze-out properties changes from AGS to SPS (e.g. $\sqrt{s_{NN}} \sim 10$ GeV)?
“hone” at SPS is true?

- $K^−/π^−$ ratio: steadily increases with $\sqrt{s_{NN}}$, while $K^+/π^+$ sharply increases at low energies.
- A maximum $K^+/π^+$ value is reached at about $\sqrt{s_{NN}} \approx 10$ GeV.
- $K^+/K^−$ vs sqrt(s): smooth decrease (log scale).

- using the functional forms for $K^+/K^−$ and $K^−/π^−$, then make the function for $K^+/π^+$.
  - Generates a maximum at 10 GeV ("horn").
- More detail energy scan is needed.
Yet another onset at RHIC

Cu+Cu

Emergence of opacity

Approach to constant $v_2$ and hydrodynamic limit?

Au+Au

Onset of Quark Number Scaling?

Where is the onset of quark number scaling?
Relationship to quark DOF?
• Increasing as a function of $\sqrt{s}$.

• Indicates the onset of baryon enhancement is in between 22 GeV and 62 GeV.

* No weak decay feed-down correction applied.
Search for QCD Critical Point (QCP)

Where is the QCP?

Lattice QCD, Effective models...

Stephanov, hep-lat/0701002

From C. Nonaka (JPS2008 fall)
Focusing Effect

Isentropic trajectories on $T$-$\mu_B$ plane

With QCD critical point

Bag Model + Excluded Volume Approximation (No Critical Point)

= Usual Hydro Calculation

Focused

Not Focused

Chiho NONAKA
Toward Quantitative Analyses

Realistic Dynamical Model
- 3D Hydro + UrQMD Model

The QCD Critical Point
- Focusing effect near the QCD critical point in isentropic trajectories on the $T-\mu_B$ plane

Emission Time Dependence
- High $P_T$ particles emit at earlier time
Observable: look at $\text{pbar}/p$ vs. $p_T$. 

$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$

- decreases (FO,C0)
- increases (QCP)

with QCP steeper $\bar{p}$ spectra at high $P_T$
6. Summary

- Baryons (protons and antiprotons) has a unique role to characterize the many bulk properties of matter, hadronization mechanism, and medium response.

- Bulk properties at RHIC (at mid-rapidity): governed by the charged particle multiplicity
  - Relevant to the CGC gluon saturation picture.

- Systematic study of baryon enhancement:
  - Qualitative difference between 22 GeV and 62.4 GeV on the property of baryon enhancement (while freeze-out properties seems to be already changed at 10 GeV).
  - Jet correlation: indicating the jet induced baryon enhancement.

- Towards the understanding of QCD phase diagram and QCP search.
Backup Slides
$\sqrt{s_{NN}}$ dep. of $p/\pi^+$ ratio (central)

- decreasing as a function of $\sqrt{s}$.

* No weak decay feed-down correction applied.
$\pi^0 R_{AA}$ vs. $\sqrt{s_{NN}}$

Suppression at $p_T = 4$ GeV/c:
- Pb+Pb $\rightarrow \pi^0+X$ 0-7% central [WA98]
- Pb+Au $\rightarrow \pi^0+X$ 0-5% central [CERES]
- S+Au $\rightarrow \pi^0+X$ 0-8% central [WA80]
- Au+Au $\rightarrow \pi^0+X$ 0-10% central [PHENIX]

X.N. Wang jet quenching:
- Non-Abelian energy loss: $\Delta E_g/\Delta E_g = 9/4$
- "Non-QCD" energy loss: $\Delta E_g = \Delta E_g$

D. d’Enterria, nucl-ex/0504001
High $p_T$ Results for proton Spectra

$p+p$ collisions at RHIC: pQCD based calculations provide a reasonable fit to data
STAR p+p 200 GeV data 
(x_T scaling)


- In p+p collisions, x_T (=2p_T/√s) scaling works for both inclusive charged hadrons and identified hadrons (pions, protons, and antiprotons).

- Invariant cross sections can be expressed as the following equation:

\[ E \frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}} G(x_T) \]

- The power “n” = 6.3-6.5 showed a good scaling in p+p collisions (c.f. PPG023).

- Indicates soft and hard transition by data.
\[ \sqrt{s_{NN}} \text{ dep. } R_{AA} \text{ for antiprotons (by ISR fit)} \]

Nuclear Modification Factor
\[ R_{AA}(p_T) = \frac{\text{yield}(AuAu)}{N_{coll}} \frac{\text{yield}(pp)}{\text{yield}(pp)} \]

- Used ISR data at 23 GeV and 63 GeV (Alper. NPB 100, 237) for p+p reference.

- Similar \( R_{AA} \) for all three systems.

* Note:
p+p 62.4 GeV p+p data has been measured by PHENIX, still working on the trigger bias and cross section seen in the detector. Here we use ISR fit to obtain \( R_{AA} \).

* No weak decay feed-down correction applied.
$\sqrt{s_{NN}}$ dep. $R_{AA}$ for charged pions (by ISR fit)

- Used ISR fit (nucl-ex/0411049, D. d’Enteria) for p+p parameterization.

- Moderate suppression for Au+Au 62.4 GeV.

- Greater than unity for Cu+Cu 62/22 GeV ($p_T > 2.0$ GeV/c).

* No weak decay feed-down correction applied.