What pA (may) tell us about AA

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Brookhaven National Laboratory
& Duke University

International Conference on the Initial Stages of High Energy Nuclear Collisions
Illa de Toxa, Spain
8-14 September 2013
Disclaimers

I doubt that I will be able to answer the “charge” for my talk
but
I also doubt that this is what the organizers expected :-)
The common view before 2013

p+A (d+A) collisions serve as a control experiment to separate initial-state effects from final-state effects in A+A collisions

Flashback to 2003:
Collisions of small with large nuclei were always foreseen as necessary to quantify cold nuclear matter effects.

Recent theoretical work on the “Color Glass Condensate” model provides alternative explanation of data:

- Jets are not quenched, but are a priori made in fewer numbers.

Small + Large distinguishes all initial and final state effects.
Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.

Jet Suppression is clearly a final state effect.
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T.K. Hemmick

“PHENIX Preliminary” results, consistent with PHOBOS data in submitted paper.
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T.K. Hemmick

Wednesday, September 11, 13
The p+Pb shock

PbPb $\sqrt{s_{NN}} = 2.76$ TeV
120 $\leq N_{\text{offline}} < 150$
$\text{CMS Preliminary } 150 \leq N_{\text{offline}} < 185$
$165 \leq N_{\text{offline}} < 220$
$220 \leq N_{\text{offline}} < 260$

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

pPb
"Initial state" effects

\[ \frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d\Delta \phi} \]

Initial state correlations

Soft "minijets" back-to-back correlation

Dusling & Venugopalan 1211.3701, 1302.7018
Continuity \( pp \rightarrow pA \rightarrow AA \)
The ultimate train wreck?
Claiming that pA (dA) collisions can probe cold nuclear matter effects does not imply that there are no hot matter effects present in pA (dA).

But it does require that we understand where hot nuclear matter effects show up and where they are negligible!

This is our present challenge.
Final-state effects were not completely unanticipated, even in p+p(bar) collisions....
Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai (a) and Berndt Müller

Department of Physics, Duke University, Durham, North Carolina 27706
(Received 1 March 1991)

In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from $p + \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

E735 - T. Alexopoulos, PRD84, 984 (1993)

Ambiguity:
Instead of being caused by collective flow, the increase of $<pt>$ with hadron mass could be the result of a minijet production mechanism (Xin-Nian Wang)
E735 claims QGP!

Evidence for hadronic deconfinement in $\bar{p}-p$ collisions at 1.8 TeV


arXiv:hep-ex/0201030v1 18 Jan 2002

Abstract

We have measured deconfined hadronic volumes, $4.4 < V < 13.0$ fm$^3$, produced by a one dimensional (1D) expansion. These volumes are directly proportional to the charged particle pseudorapidity densities $6.75 < dN_c/d\eta < 20.2$. The hadronization temperature is $T = 179.5 \pm 5$ (syst) MeV. Using Bjorken's 1D model, the hadronization energy density is $\epsilon_F = 1.10 \pm 0.26$ (stat) GeV/fm$^3$ corresponding to an excitation of $24.8 \pm 6.2$ (stat) quark-gluon degrees of freedom.

$n_{\pi}^{\text{exp}} = 1.6$/fm$^3 \gg n_{\pi}^{\text{th}}$
Experimental cross checks: d+Au ($^3$He+Au ?)
d+Au has larger $v_2$
p vs. d vs. $^3$He

$^3$He should generate a large $\varepsilon_3$
RHIC could do it!
Bozek & Broniowski
arXiv:1304.3044

Assumptions about spatial location of the interactions make a difference

Two particle correlations resemble data
Guangyou Qin & BM (arXiv:1306.3439) using E-by-E initial state + hydro model developed for Au+Au collisions at RHIC (ideal fluid!) find remarkable agreement
The nagging question

Can it really be hydrodynamics?

The standard folklore (before 2012): Protons are small.

But are they really? Compared to what?
The nagging question

*Can it really be hydrodynamics?*

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But are they really? Compared to what?

\[ \frac{\eta}{s} = \frac{1}{4\pi} \text{ together with kinetic theory } \eta = n_p \lambda/3 \text{ implies} \]

\[ \lambda = \frac{3s}{(4\pi n_p)} \approx \frac{1}{p} \approx \frac{1}{(3T)} \approx 0.2 \text{ fm} \]
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We know that protons are fluctuating quantum systems. When they are tiny, we call it “color transparency.” But what can be tiny, also can be “fat”!
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We know that protons are fluctuating quantum systems. When they are tiny, we call it “color transparency.”
But what can be tiny, also can be “fat”!

How to catch “fat” protons? A heavy nucleus acts as a net.
**σ_{NN} fluctuations**

Blättel, Baym, Frankfurt, Heiselberg & Strikman
PRD47, 2761 (93)

Alvioli & Strikman
1301.0728:
Large $N_{WN}$ picks out large $\sigma$
Fat proton “net”

Some models of $P(\sigma)$:

- Gaussian
- Gamma
- Alvioli

$N_{\text{part}}$ depends on $\sigma$:

$$W(N, \sigma) = e^{-\overline{\sigma}(\sigma)} \frac{\overline{n}(\sigma)^N}{N!}$$

$$\sigma_{\text{eff}}(N_{\text{part}}) = \frac{\int \sigma \, d\sigma \, W(N_{\text{part}}, \sigma) \, P(\sigma)}{\int d\sigma \, W(N_{\text{part}}, \sigma) \, P(\sigma)}$$

C. Coleman-Smith & BM, 1307.5911
Fat proton “net”

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C. Coleman-Smith & BM, 1307.5911

$N_{\text{part}}$ serves as a “net” catching “fat” protons
What does a “fat” proton look like?
“Obese” protons

Two extreme models
“Obese” protons

Two extreme models

The “stringy” proton
“Obese” protons

Two extreme models

The “stringy” proton

The “cloudy” proton
The “stringy” proton

*Thanks to Chris Coleman-Smith
The “stringy” proton

The “cloudy” proton

*Thanks to Chris Coleman-Smith
pion cloud: exp. evidence

R.S. Towell et al. (E866/NuSea Collaboration), PRD64, 052002 (2001)

\[
\int dx (\bar{d} - \bar{u}) = 0.118 \pm 0.012
\]
Pion cloud models

Kumano, PRD 43, 59 (1991)

\[ f_\pi(y) \sim \frac{g_{\pi NN}^2}{(4\pi)^2} y \int_{-\infty}^{t_{\text{max}}} dt \frac{-t}{(-t + m_{\pi}^2)^2} F_{\pi NN}(t)^2 \]

\[ P_N = \text{probability for a proton to be accompanied by } N \text{ virtual pions} \]

\[ N_Q = \text{number of “valence” quarks} \]

<table>
<thead>
<tr>
<th>( N )</th>
<th>( P_N )</th>
<th>( N_Q/3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.89</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0.104</td>
<td>1.67</td>
</tr>
<tr>
<td>2</td>
<td>0.0062</td>
<td>2.33</td>
</tr>
<tr>
<td>3</td>
<td>( 2.4 \times 10^{-4} )</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>( 7.2 \times 10^{-6} )</td>
<td>3.67</td>
</tr>
</tbody>
</table>
We have estimated the probability of finding a fat “cloudy” proton. Can we estimate the probability of finding a fat “stringy” proton?

\[ \sim 10^{-4} \]
Stringy proton model

\[
\begin{align*}
    u &= x_2 - x_1 \\
    v &= (x_2 + x_1)/2 - x_3 \\
    V(x_1, x_2, x_3)^2 &= k^2(u^2 + v^2) \\
    \langle r^2 \rangle &= \frac{2.285}{k} \\
    k &\approx 1 \text{ GeV/fm} = 5 \text{ GeV}^{-2}
\end{align*}
\]
Stringy proton model

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\[ v = (x_2 + x_1)/2 - x_3 \]
\[ V(x_1, x_2, x_3)^2 = k^2(u^2 + v^2) \]
\[ \Psi(u, v) = N \exp \left( -\frac{k u^2}{2\sqrt{2}} - \frac{k v^2}{\sqrt{6}} \right) \]
\[ \langle r^2 \rangle = 2.285/k \quad k \approx 1 \text{ GeV/fm} = 5 \text{ GeV}^{-2} \]

\[ \rho(L) = \int \Psi^2 \delta(u + v - L) u^2 v^2 du dv \]

\[ L = \text{total length of flux tube} \]
Experimental checks?
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- Fat protons have more “soft” partons, and valence quarks are shifted to smaller values of $x$. 
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- This should lead to a suppression of very high-pt mesons in high-multiplicity p+A and d+A events, and hard di-jets should be shifted downstream (towards $y_A$) in c.m. rapidity.
Wounded nucleon (MC-Glauber) model vs. IP-Glasma (CGC) model
IP Dipole model

Nucleon thickness function:

\[ T(b) = \int_{-\infty}^{\infty} d\zeta \rho(b, \zeta) \]

Gaussian model:

\[ T_G(b) = \frac{1}{2\pi B_G} \exp\left(-\frac{b^2}{2B_G}\right) \]

\[ B_G = 4.25 \text{ GeV}^{-2} \]

Kowalski & Teaney, hep-ph/0304189

Bzdak, Schenke, Tribedy, Venugopalan
arXiv:1304.3403
IP-Glasma model

Wednesday, September 11, 13
Energy deposition in the MC-"Glauber" model is conceptually uncertain.
WNM vs. CGC?

Wounded nucleon model: \( N_{ch}^{pA} \sim N_{part} \)

CGC/Glasma: \( N_{ch}^{pA} \sim \ln(N_{part}) \)

Problem: Fluctuations in \( N_{ch} \) in the CGC model are large!

Problem: How to determine \( N_{part} \) experimentally?
Core questions
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- What is the structure of “fat” nucleons?
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- Can initial state explanation of double ridge be excluded?
Final thoughts
### Tentative Run Schedule for RHIC

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>• 510 GeV pol p+p</td>
<td>• Sea quark and gluon polarization</td>
<td>• upgraded pol'd source</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• STAR HFT test</td>
</tr>
<tr>
<td>2014</td>
<td>• 200 GeV Au+Au • 15 GeV Au+Au</td>
<td>• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies</td>
<td>• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• QCD critical point search</td>
<td></td>
</tr>
<tr>
<td>2015-2016</td>
<td>• p+p at 200 GeV • p+Au, d+Au, ³He+Au at 200 GeV • High statistics Au+Au</td>
<td>• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor</td>
<td>• PHENIX MPC-EX • Coherent electron cooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>studies • Sphaleron tests</td>
<td>test</td>
</tr>
<tr>
<td>2017</td>
<td>• No Run</td>
<td></td>
<td>• Electron cooling upgrade</td>
</tr>
<tr>
<td>2018-2019</td>
<td>• 5-20 GeV Au+Au (BES-2)</td>
<td>• Search for QCD critical point and deconfinement onset</td>
<td>• STAR ITPC upgrade</td>
</tr>
<tr>
<td>2020</td>
<td>• No Run</td>
<td></td>
<td>• sPHENIX installation</td>
</tr>
<tr>
<td>2021-2022</td>
<td>• Long 200 GeV Au+Au w/ upgraded detectors • p+p, p(d)+Au at 200 GeV</td>
<td>• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism •</td>
<td>• sPHENIX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Color screening for different QQ states</td>
<td></td>
</tr>
<tr>
<td>2023-24</td>
<td>• No Runs</td>
<td></td>
<td>• Transition to EIC (eRHIC)</td>
</tr>
</tbody>
</table>
EIC will be a QCD laboratory
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Gluon and sea quark structure of the proton, or what gives matter (most of) its mass?
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Is there a universal saturated gluon ocean (CGC) at low x?
pA versus eA?
When RHIC shuts down and transitions to eRHIC (as we hope), the opportunity to explore polarized pA physics experimentally is
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Input from theoretical (and experimental) community is needed as we plan and justify the future physics program of RHIC.
Back-up slides
e-RHIC overview

Add an electron accelerator to the existing RHIC accelerator complex:

5-10 GeV e-beam accelerated with an Energy Recovery Linac (ERL) inside the existing RHIC tunnel and colliding with RHIC beams (250 GeV polarized protons or 100 GeV/n heavy ions)

ERL provides fresh electron bunches for each collision resulting in high luminosity ($10^{33}$ cm$^{-2}$ s$^{-1}$) and high electron polarization over a wide kinematic range

Preliminary cost estimate for 5 GeV e-beam: $550M (FY12$) w/o detector. Work on a design that will allow us to reach 10 GeV electron energy for similar cost is ongoing.

STAR and PHENIX will soon submit LoI for e-RHIC Day-1 upgrades.

Comprehensive e-RHIC design document by year-end 2013.
The 2013 NSAC Subcommittee on Future Facilities identified the physics program for an Electron-Ion Collider, as it was described in the 2013 EIC White Paper, as absolutely central to the U.S. nuclear science program in the next decade.