(Unintended) Consequences of the Glauber Initial State

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Acknowledgments

Glauber Modeling in High-Energy Nuclear Collisions

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Geometric properties of nuclear collision
(what could involve earlier times?...)

Simple model of matter creation
What is a Nucleus?

An average density distribution of nucleon positions
Nuclear Distributions

Distributed according to a Fermi distribution (or Hulthen, for d+Au)
Optical Limit Approach

\[ \sigma_{AB} = \int d^2b \left\{ 1 - [1 - \sigma_{inel}^{NN} T_{AB}(b)]^{AB} \right\} \]

everything based on smooth, averaged densities
What is a Nucleus?

A bound state of nucleons, with positions chosen according to the Fermi distribution
Glauber Monte Carlo (GMC)

\[ \sigma_{\text{inel}}^{AB} = \int d^2b \int d^2s_A^1 \cdots d^2s_A^A d^2s_B^1 \cdots d^2s_B^B \times \]
\[ \hat{T}_A(s_A^1) \cdots \hat{T}_A(s_A^A) \hat{T}_B(s_B^1) \cdots \hat{T}_B(s_B^B) \times \]
\[ \left\{ 1 - \prod_{j=1}^{B} \prod_{i=1}^{A} \left[ 1 - \hat{\sigma}(b - s_A^i + s_B^j) \right] \right\} \]

1. Fermi distribution density
2. straight line trajectories
3. interaction via \( d < \sqrt{\sigma_{NN}/\pi} \)

800 dimensional integral w/ 20 lines of code.
Glauber Monte Carlo (GMC)

- Can calculate geometric features event-by-event (and nucleon-by-nucleon)
  - Participants, collisions
  - Collisions per participant (e.g. nuclear thickness)
  - Eccentricity
  - Cold nuclear effects (onia suppression)

Collisions on “surface” are quasi-p+p. How can \( R_{AA} \) go below geometric limit?
Effect on Total Cross Section

Total cross section systematically larger in optical approach
Recent measurements of nucleon attenuation at 1.4 Bev (where $\lambda = 0.1 \times 10^{-18}$ cm) seem, on the contrary, to reveal a substantial lack of additivity of the neutron and proton cross sections, in deuterium. Measurements with incident protons and incident neutrons both indicate that the deuteron cross section is less than the sum of the free-particle cross sections. The measured differences, although obviously subject to uncertainty, amount to 9 mb and 6 mb respectively, values to be compared with $\sigma(n,p) = 42$ mb and $\sigma(p,p) = 48$ mb.

Some simple considerations may be of help in indicating the nature of the effect. At these energies the attenuation of the incident amplitude by incoherent processes such as meson production may be schematically represented as due to a certain amount of absorption of the incident wave by the nucleons. Since the incident wavelengths in these cases are evidently much smaller than the ranges of interaction, the nucleons may be thought of as casting fairly well-defined shadows. It is then clear that absorption or scattering by either nucleon is reduced when it enters the shadow of the other. Astronomers have long been familiar with a time-reversed analog of this effect; the decrease in luminosity of binary star systems during eclipses.
Effect on Centrality

Centrality bins are relative to total cross section: even with a few % difference, expect systematic effects.

nucl-ex/0701025
Generically, optical limit (no fluctuations) leads to underestimating $N_{\text{part}}$ in peripheral events.
Effect on Observables

\[ \frac{(h^+ + h^-)}{2} \]

Kharzeev-Nardi

\[ n_{pp} = 2.25 \]

hard = 0.11 ± 0.005

EKRT

\[ C = 0.89 ± 0.01 \]

\[ a = 0.92 \]

\[ s = 0.40 \]

(2/\langle N_{part} \rangle) dN_{ch}/d\eta

Interpretation of data can be changed by using optical (wrong!) or MC Glauber approach

**STAR, nucl-ex/0311017**
Role of Glauber @ Early Times

- The inelastic cross section shows that Glauber matters as to whether anything happens at all!
  - Do CGC-shadowed calculations give $\sigma_{\text{tot}}$?

- It can also give us a hint as to how and where matter was produced
  - No longer a means to do an integral, but a quasi-“model”
let us also assume that the matter is created where the interactions occur, following the participants.

If it thermalizes suddenly, then this is the initial state for hydrodynamic evolution (less sudden $\rightarrow$ less local).
SPLAT
Sources are Participants, Localized At Thermalization
Total Multiplicity

Total produced entropy scales **linearly** with $N_{part}$

No information on where matter was created
Eccentricity

Overlap zone where matter thermalizes has a particular “shape” vs. impact parameter

\[ \epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \]

Generically, hydro predicts complete transfer of spatial anisotropy into momentum anisotropy! (Heinz, Ollitrault,)

\[ \nu_2 \propto \epsilon \]

Hydro is sensitive to where the matter was (and not what!)
Hydro @ RHIC

\[ \begin{align*}
\tau_0 &\sim 0.6 \text{ fm/c} \\
\epsilon &\sim 30 \text{ GeV/fm}^3
\end{align*} \quad \leftrightarrow \quad
\begin{align*}
\tau_0 &\sim 1 \text{ fm/c} \\
\epsilon &\sim 500 \text{ MeV/fm}^3
\end{align*} \]
The Edge of Liquidity

Heatlalization
Time
Length scale
Longitudinal Dynamics

Theory

Data

Near-Perfect Fluid?

Energy
Geometry
Rapidity

nucl-ex/0702020

Hotter, Denser, Faster, Smaller...and Nearly-Perfect: What's the matter at RHIC?
“Scaling Behavior”

integrated “pressure” $\frac{v_2}{\epsilon}$ is a simple function of $\frac{dN/dy}{S}$ “transverse density”

Is this hydrodynamic equilibration, or just the approach to it? In any case, it seems to be universal.
Does $v_2$ follow $\epsilon$?

$v_2$ does not go to zero when eccentricity should (b~0)
Something wrong...
Participants trace out overlap zone, but include

1. Fluctuations (finite number per event)
2. Correlations (it takes two to tango...)

(NB: these are snapshots of nucleon configurations, not stable nuclear states!)
Fluctuations can significantly deviate from nominal overlap zone for small numbers of nucleons
Cu+Cu

\[ \epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \]

“Standard eccentricity”
Cu+Cu

Principal axes make sense if $v_2$ depends on shape of produced matter (in SLP), not the reaction plane

$$\epsilon_{part} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} = \sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\left(\sigma_{xy}^2\right)^2} \over \sigma_y^2 + \sigma_x^2$$

“Participant eccentricity”
Participant vs. Standard

PHOBOS MC
nucl-ex/0610037

Eccentricity vs. Number of participants for different collision systems:
- \( \langle \varepsilon_{\text{part}} \rangle \) Cu+Cu
- \( \langle \varepsilon_{\text{std}} \rangle \) Cu+Cu
- \( \langle \varepsilon_{\text{part}} \rangle \) Au+Au
- \( \langle \varepsilon_{\text{std}} \rangle \) Au+Au

The graph shows the comparison of eccentricity with the number of participants for different collision systems, highlighting the differences between participant and standard conditions.
Something wrong...

![Graph showing $\frac{V_2}{\langle \varepsilon_{\text{std}} \rangle}$ versus $N_{\text{Part}}$ for Au+Au and Cu+Cu collisions. The graph includes data points labeled 'Hits' and 'Tracks' for PHOBOS QM2006 R. Nouicer.](image)
...leads to scaling

![Graph showing the relationship between $V_2/\langle \varepsilon \rangle_{\text{part}}$ and $N_{\text{Part}}$ for PHOBOS data. The graph includes data points for both Au+Au and Cu+Cu collisions, with different markers for hits and tracks.](image)
vs. Areal Density

PHOBOS QM2006

PHOBOS preliminary

- 200 GeV, Au+Au, tracks
- 200 GeV, Au+Au, hits
- 130 GeV, Au+Au, hits
- 62.4 GeV, Au+Au, hits
- 19.6 GeV, Au+Au, hits
- 200 GeV, Cu+Cu, tracks
- 200 GeV, Cu+Cu, hits
- 62.4 GeV, Cu+Cu, hits
- 22.4 GeV, Cu+Cu, hits
- 130 GeV, STAR
- 17 GeV, NA49
- 4 GeV, E877

$V_2 / \left< \xi_{\text{part}} \right>$

$\frac{1}{\langle S \rangle} \left< \frac{dN_{\text{ch}}}{dy} \right> [\text{fm}^{-2}]$

statistical errors only
Transverse Momentum

Choose two bins with same $N_{\text{part}}$ (~same density)
Transverse Momentum

Unity of geometry, system, energy, $p_T$ at same $N_{\text{part}}$

PHOBOS QM2006 R. Nouicer

200 GeV

$N_{\text{part}} = 82$

$V_2 / \langle \xi_{\text{part}} \rangle$

$0 < \eta < 1.6$

Au+Au 35-50%
Cu+Cu 3-20%

PHOBOS Preliminary
Generally, ϵ not sensitive to \((N_{\text{part}}, N_{\text{coll}})\) if variable is local
(smear matter by 1-2fm to mock-up thermalization time?...TBD)

CGC models “throw away” information and get large eccentricities (Adil, et al)
“Freeze-in”

Configuration established early and preserved: substantial viscosity or long thermalization times generates entropy under different geometric conditions.
Energy/geometry systematics at $\eta=0$ suggest small $\tau_0$. Near-Perfect Fluid?
What about “the rest” of particle production, $\eta \neq 0$?
Longitudinal Scaling

\[ \eta' = \eta - y_{beam} \]

In “limiting fragmentation” frame, one sees that entire angular distribution changes with centrality, in an energy-independent way.

N.B. \( N_{\text{part}} \) scaling of total mult. from global modification of \( dN/d\eta' \)
Elliptic flow is invariant when viewed in the same “limiting fragmentation” frame.
Unity of Response

v₂ seems to respond ~linearly to particle density at all energies, rapidities, & centralities
Eccentricity is Global

Participant eccentricity unifies different systems at same $N_{\text{part}}$, at all pseudorapidity: source shape does not change with $\eta$
Eccentricity is Global

Participant eccentricity unifies different systems at same $N_{\text{part}}$, at all pseudorapidity: source shape does not change with $\eta$
Same $N_{\text{part}}$

Unity of geometry, system, energy, rapidity at same $N_{\text{part}}$
Different $N_{\text{part}}$

At same fraction of cross section ($\sim b/2R$), observe longitudinal scaling, but system dependence
Cross Section Scaling

Curious, since longitudinal distributions of particle multiplicities are similar when matching fraction of cross section...

PHOBOS QM2006
Au+Au vs. Cu+Cu

Same nuclear thickness? Same total particle density?

or, transverse observables: $N_{\text{part}}$

longitudinal observables: cross section?
Flow Fluctuations

Configuration is transmitted to particles at all rapidities and (observed) $p_T$. Does this hold event-by-event?

strong assumption: $v_2 \propto \epsilon_{part}$

\[
\frac{\sigma v_2}{v_2} = \frac{\sigma \epsilon_{part}}{\epsilon_{part}}
\]
$v_2$ Fluctuations in GMC

MC approach makes definite prediction for event-by-event fluctuations of $\epsilon_{\text{part}} \sim 40\%$ (robust against variation in Glauber MC parameters)
Flow fluctuations directly suggest SLP approach: configuration established early by participants, and preserved.

B. Alver
Wednesday
Conclusions

Sudden, localized participant (SLP) matter unifies a substantial amount of experimental data.

What does this imply about early time dynamics in \textcolor{red}{\text{HIC}}?

thermalization time? viscosity (dynamical length scales)?
2+1D vs. 3+1D? initial velocity gradients?
long-range rapidity correlations?
Thermalization Scenarios

**Landau**

Total stopping, immediate thermalization & longitudinal re-expansion

\[ \tau_0 \sim \frac{1}{\sqrt{s}} fm/c \]

**Bjorken**

Partial stopping, “boost-invariant” expansion

\[ v = \frac{z}{t} \]

\[ \tau_0 \sim 1 fm/c \]

Same hydro, different initial conditions
(e.g. very different initial velocity gradients)!
$\frac{dN}{dy}$

$\sigma_y \sim \sqrt{\log(ENN)}$

These initial conditions naturally (& rapidly) propagate initial configuration to large $y$ (explains $N_{ch}$, $dN/dy$, limiting fragmentation):

$\rightarrow$ long-range rapidity correlations

Complete stopping in initial state (local “freeze-in”)

Landau

Longitudinal Physics
Separation of Scales

\[ \Delta r \sim O(R) \]

\[ \Delta z \sim O\left(\frac{1}{\sqrt{s}}\right) \]

Longitudinal physics (dN/dy) develops on much shorter time scales than transverse physics (dN/dp_T, v_2): \( \tau_0 = 0.1 \text{ fm/c} \) is “initial conditions” to \( \tau_0 = 0.6 \text{ fm/c} \).
RHIC has a lot of data, covering a large region of phase space & geometry:
please try and use all of it, and simultaneously!
“Hello, Nobel Prize Committee?
No...it’s not for the initial state at RHIC...”
Extra Slides
Just a Moment

If:

$$v_2 \propto \epsilon$$

then an n-particle $v_2$ measurement is really measuring a higher moment of the eccentricity distribution

$$v_2 \{n\} \sim \langle \epsilon^n \rangle^{1/n}$$

(argument applies to moments & cumulants)
Which Moment?

- Moment of event-plane (EP) method depends on $v_2$ resolution
  J.Y. Ollitrault - private communication

- Good resolution: $\langle v_2 \rangle$

- Poor resolution: $\sqrt{\langle v_2^2 \rangle}$

- Experiment-dependent
  - Different resolutions, different moment!
Mean vs. RMS vs. Fluctuations

\[ \sigma_\epsilon \langle \epsilon \rangle = \alpha \]

\[ \langle \epsilon^2 \rangle = (1 + \alpha^2) \langle \epsilon \rangle^2 \]

MC calculations suggests that Mean and RMS of eccentricity differ by \( \sim 8\% \)

→ Small effect on areal density plot
Elliptic flow shows strong pseudorapidity dependence, not entirely dissimilar to particle density.
Longitudinal Scaling

\[ \Delta z \sim \frac{1}{\sqrt{s}} \]

\[ \sigma_y = \sqrt{\frac{1}{2} \ln \left( \frac{s}{4M_P^2} \right)} \]

\[ \frac{dN}{dy} = K s^{1/4} \frac{1}{\sqrt{2\pi L}} \exp \left( -\frac{y^2}{2L} \right) \]

\[ L = \ln \left( \frac{\sqrt{s}}{2m_P} \right) \quad y' = y + y_{\text{beam}} = y + e^L \]

\[ \frac{dN}{dy'} \sim \frac{1}{\sqrt{L}} \exp \left( -\frac{y'^2}{2L} - y' \right) \]

Landau Hydro is an example of Longitudinal Scaling

\[ \sqrt{s} = 200 \text{ GeV} \]
\[ \sqrt{s} = 130 \text{ GeV} \]
\[ \sqrt{s} = 62 \text{ GeV} \]
\[ \sqrt{s} = 20 \text{ GeV} \]
How Small is “Small”?

A+A: Large, hydrodynamic ↔ e⁺e⁻: small, perturbative
Rethink 2-component model

Change at midrapidity can be seen as a consequence of $N_{\text{part}}$ scaling & broadened $\eta$ distribution.
d+Au Distributions

Thin+Thin ~ several p+p collisions
Thin+Thick ~ minbias p+A
Shifting CM in d+Au

Dividing by $N_{\text{part}}$ shows distributions “shift” backwards
Central Events

Central collisions involve highly symmetric longitudinal configurations
Peripheral events involve asymmetric collisions in local regions of transverse overlap.

Convolution of local “d+Au” collisions will widen integrated $dN/d\eta$. 