Why is the radial flow in high multiplicity pA stronger than in AA?

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based on 4 papers with I. Zahed and T. Kalaydzhyan

1. **High-multiplicity pp and pA collisions: Hydrodynamics at its edge**
   
   
   Published in *Phys.Rev. C88* (2013) 4, 044915
   
   e-Print: [arXiv:1301.4470](https://arxiv.org/abs/1301.4470)

2. **New Regimes of Stringy (Holographic) Pomeron and High Multiplicity pp and pA Collisions**
   
   
   e-Print: [arXiv:1311.0836](https://arxiv.org/abs/1311.0836)

3. **Self-interacting QCD strings and String Balls**
   
   

4. **Early stages of high multiplicity pA collisions**
   
outline

- hydro of small systems: scaling, role of viscosity
- reminder of min.bias pp/pA: strings, spaghetti, Lund model
- high multiplicity pA is different (hydro: radial flow etc)
- QCD strings and their interaction
- spaghetti collapses at large string multiplicity, their sigma field collectivizes and creates QGP fireball
- QCD string balls
the radial (Gubser’s) flow is higher for smaller systems, (assuming the same $T_f=150$ MeV)

Gubser’s solution of ideal relativistic hydrodynamics, for the transverse velocity and the energy density reads

$$v_{\perp}(t,r) = \frac{2tr}{1+t^2+r^2} \quad (10)$$

$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}0^{28/3}}{t^{4/3} \left[1 + 2(t^2+r^2) + (t^2-r^2)2^{4/3}\right]}$$

$$t = q^{\tau}, \quad r = q^p$$

$$q_{AA}^{-1} = 4.3, \quad q_{pA}^{-1} = 1, \quad q_{pp}^{-1} = 0.5 \quad (fm)$$

my guesses of the system’s size
central PbPb 400
pA: 15-20 participants
pp 2

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High-multiplicity $pp$ and $pA$ collisions: Hydrodynamics at its edge
Edward Shuryak and Ismail Zahed

$\mathbf{v_{\perp}^{max}[AA, pA, pp]} = [0.69, 0.83, 0.95]$
We predicted the radial flow in pp/pA to be even stronger than in central AA.

Not the Mt scaling at large \( N_{\text{tr}} \) => not a large \( Q_s \) but a collective flow: \( p=m \nu \)

``straightforward hydro'' (Epos) or cascade (AMPT) predict very weak radial flow.
brief history of QCD strings

- 1960’s: Regge phenomenology, Veneziano amplitude. Strings have exponentially growing density of states $N(E)$
- 1970’s Polyakov, Susskind => Hagedorn phenomenon near deconfinement
- 1980’s: Lund model (now Pythia, Hijing): string stretching and breaking
- 1990-now lattice studies. Dual Abrikosov flux tubes. (Very few) papers on string interaction
- 2013 Zahed et al: holoraphic Pomeron and its regimes (cannot speak about it in few min’s)
the simplest multi-string state: the spaghetti

$2N_p$

$N(\text{strings}) = 2N(\text{Pomerons})$

in small multiplicity bins strings are dilute and thus broken independently (the Lund model),

but one should obviously think about their interaction if string number grows

area in pA (from cross section) is about 100 mb = 10 fm$^2$, (inner) area of one string is 0.1 fm$^2$:
so 30 strings (16 pomerons in central pA) still make diluteness about 0.3 < 1
and sigma fields not collectivized
2 flux tubes on the lattice attract each other

string interaction via sigma meson exchange

our fit uses the sigma mass 600 MeV

\[
\frac{\langle \sigma(r_{\perp}) W \rangle}{\langle W \rangle \langle \sigma \rangle} = 1 - CK_0(m_\sigma \tilde{r}_\perp)
\]

\[
\tilde{r}_\perp = \sqrt{r_{\perp}^2 + s_{\text{string}}^2}
\]

FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with \( C = 0.26, s_{\text{string}} = 0.175 \) fm.

So the sigma cloud around a string is there!
2d spaghetti collapse

Basically strings can be viewed as a 2-d gas of particles with unit mass and forces between them are given by the derivative of the energy (8), and so

\[ \ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{F}_{ij}}{\vec{F}_{ij}} (g_{N \sigma_T}) m_\sigma 2K_1(m_\sigma \vec{r}_{ij}) \]  \hspace{1cm} (19)

with \( \vec{r}_{i*} = \vec{r}_i - \vec{r}_j \) and "regularized" \( \vec{r} \) (9).

\[ E_{\text{tot}} = \sum_i \frac{v_i^2}{2} - 2g_{N \sigma_T} \sum_{i>j} K_0(m_\sigma r_{ij}) \]

FIG. 4. (Color online) The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 6, as a function of time \( t(\text{fm}) \). The horizontal line with dots is their sum, namely \( E_{\text{tot}} \), which is conserved.
peripheral AA contraction in x first (and only: limited time scale)

string stretching - about 1fm/c

1/4 period of yo-yo - another 0.5
so too small coupling does not work

gₙσₙ = 0.01, 0.02, 0.03, 0.05, 0.08, 0.10, 0.20.
Collective sigma field

Field gradient at the edge leads to quark pair production: QCD analog of Hawking radiation
Our lattice model for string balls

$$Z \sim \int dL \exp \left[ \frac{L}{a} \ln(2d - 1) - \frac{\sigma_T L}{T} \right],$$

and hence the Hagedorn divergence happens at

$$T_H = \frac{\sigma_T a}{\ln(2d - 1)}.$$  

(19)

Setting $T_H = 0.30 \text{ GeV}$, according to the lattice data mentioned above and the string tension, we fix the 3-dimensional spacing to be

$$a_3 = 2.73 \text{ GeV}^{-1} \approx 0.54 \text{ fm}.$$  

(20)

The most compact (volume-filling or Hamiltonian) string wrapping visits each site of the lattice. If the string is closed, then the number of occupied links is the same as the number of occupied sites. Since in $d = 3$ each site is shared among 8 neighboring cubes, there is effectively only one occupied link per unit cube, and this wrapping produces the maximal energy density,

$$\frac{\epsilon_{\max}}{T_c^3} = \frac{\sigma_T a}{a^3 T_c^4} \approx 4.4$$  

(22)

(we normalized it to a power of $T_c$, the highest temperature of the hadronic phase). It is instructive to compare it to the energy density of the gluonic plasma, for which we use the free Stefan-Boltzmann value

$$\frac{\epsilon_{\text{gluons}}}{T^4} = (N_c^2 - 1) \frac{\pi^2}{15} \approx 5.26$$  

(23)

Example of non-interacting strings
Metropolis algorithm, updates, T(x) instead of a box Yukawa self-interaction.

we observe a new regime: the entropy-rich self-balanced string balls separated by 2 phase transitions.

**FIG. 7:** Upper plot: The energy of the cluster E (GeV) versus the length of the string L/a. Lower plot: The energy of the cluster E (GeV) versus the “Newton coupling” g\(\nu\) (GeV\(^{-2}\)). Points show the results of the simulations in setting \(T_0 = 1\) GeV and size of the ball \(s_T = 1.5a, 2a\), for circles and stars, respectively.
Jet quenching during the mixed phase

It has however been pointed out long ago [24] that large experimental values of $v_2$ are difficult to explain by any simple model of quenching, in particular, they were in a strong contradiction with the simplest assumption (30). One possible solution to this puzzle has been suggested few years ago in Ref. [6]: the $v_2$ data can be reproduced, if $\hat{q}$ is significantly enhanced in the mixed phase. More

$$\hat{q} = \frac{d(p_{1\perp}^2)}{dl}, \quad (p_{1\perp}^2) \approx (gE r_s)^2,$$

$$\hat{q} \approx \frac{16}{3} \alpha_s \sigma_T \frac{\bar{L} r_s}{\text{fm}^3}.$$  

The string length inside $1$ fm$^3$ across the mixed phase, to be compared with values by the Jet coll. at Tc

$$\hat{q}_{\text{min}} = 0.028, \quad \hat{q}_{\text{max}} = 0.10 \left(\frac{\text{GeV}^2}{\text{fm}}\right).$$

Here we want to point out that a natural explanation for the enhanced $\hat{q}$ in the mixed phase can be provided by the strings. As far as we know, the “kicks” induced by the color electric field inside the QCD strings has been ignored in all jet quenching phenomenology: only the fields of “charges” (quarks and gluons in QGP, hadrons alternatively) were included, in the spherical Dukhe approxima-

$$E(x) = \frac{\Phi_n}{2\pi r_s^2} K_0(x/r_s)$$

the string radius $r_s = 1/(1.3\text{GeV}) = 0.15$ fm.

$$\hat{q}_{\text{min}} = 0.025, \quad \hat{q}_{\text{max}} = 0.15 \left(\frac{\text{GeV}}{\text{fm}}\right).$$

But in high entropy self-supporting balls it can be up to one order of magnitude larger!
Summary

- pA has stronger radial flow then AA (and then straightforward hydro predicts) why?

- because spaghetti (multiple strings) collapses and makes denser fireball

- string balls are known from string theory to interpolate toward black holes (size, entropy)

- we studied QCD string balls and found that their QCD analog —> self supporting high entropy balls in the mixed phase
intro into pA collisions

Multiplicity distribution in pPb

maximal mean number of participants is along the Pb diameter, about 16
blue line is Poisson with $\langle N_p \rangle = 16$
red with $\langle N_p \rangle = 20$

geometry — columns with smaller $N_p$ - explains well the left side (Bozek 2011)

the large tail to the right is not explained by the “wounded nuclei model”
(= independent string fragmentation, Lund model)

the two sides are very different:
to the right of it one needs to explain extra multiplicity, and — more importantly — appearance of radial, elliptic and triangular flows