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

Edward Shuryak
Stony Brook

Talk at Quark Matter 2014, Darmstadt

based on 4 papers with

I.Zahed and T. Kalaydzhyan

Hydro:
viscous effects
in small systems

1.**High-multiplicity pp and pA collisions: Hydrodynamics at its edge**
Edward Shuryak, Ismail Zahed (SUNY, Stony Brook). Jan 2013. 13 pp.
Published in **Phys.Rev. C88 (2013) 4, 044915**
arXiv:1301.4470

2.**New Regimes of Stringy (Holographic) Pomeron and High Multiplicity pp and pA Collisions**
Edward Shuryak, Ismail Zahed Nov 4, 2013. 24 pp.
e-Print: **arXiv:1311.0836**

Stringy holograpic Pomeron

3. **Self-interacting QCD strings and String Balls**
Tigran Kalaydzhyan, Edward Shuryak. Feb 28, 2014.
e-Print: **arXiv:1402.7363**

QCD strings
and their
collectivization

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

Tigran Kalaydzhyan and Edward Shuryak arXiv:1404.1888

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

presented at Busza meeting May 2013

PHYSICAL REVIEW C 88, 044915 (2013)

High-multiplicity pp and pA collisions: Hydrodynamics at its edge

Edward Shuryak and Ismail Zahed

the radial (Gubser's) flow is higher for smaller systems,

(assuming the same Tf=150 MeV)

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

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

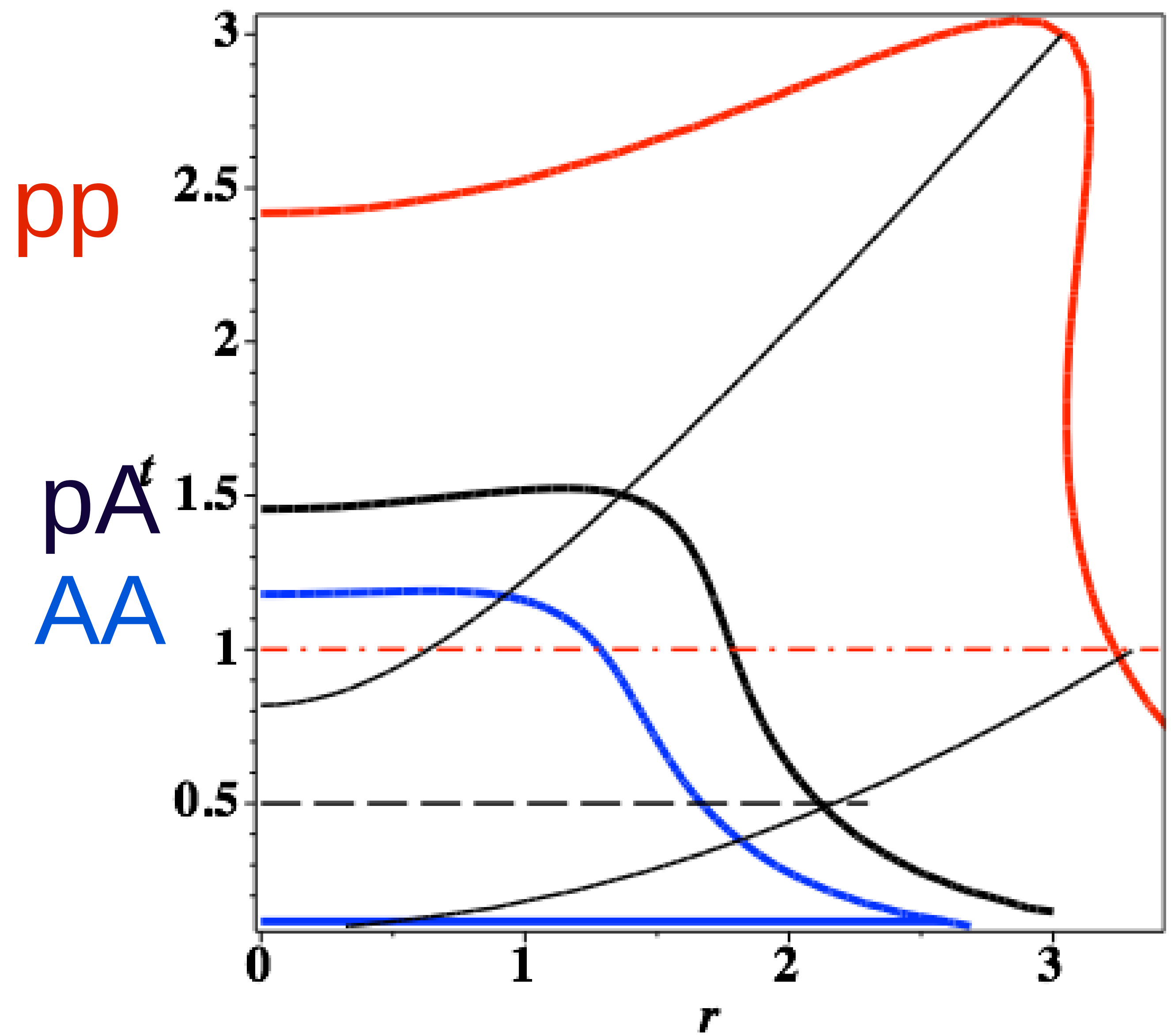
$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}_0 2^{8/3}}{t^{4/3}\left[1+2(t^2+r^2)+(t^2-r^2)^2\right]^{4/3}}$$

$$t = q\tilde{\tau}, \quad r = q\tilde{r}$$

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

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

$$v_\perp^{max}[AA, pA, pp] = [0.69, 0.83, 0.95]$$



PHYSICAL REVIEW C 88, 044915 (2013)

High-multiplicity pp and pA collisions: Hydrodynamics at its edge

Edward Shuryak and Ismail Zahed

We predicted the radial flow in pp/pA to be even stronger than in central AA

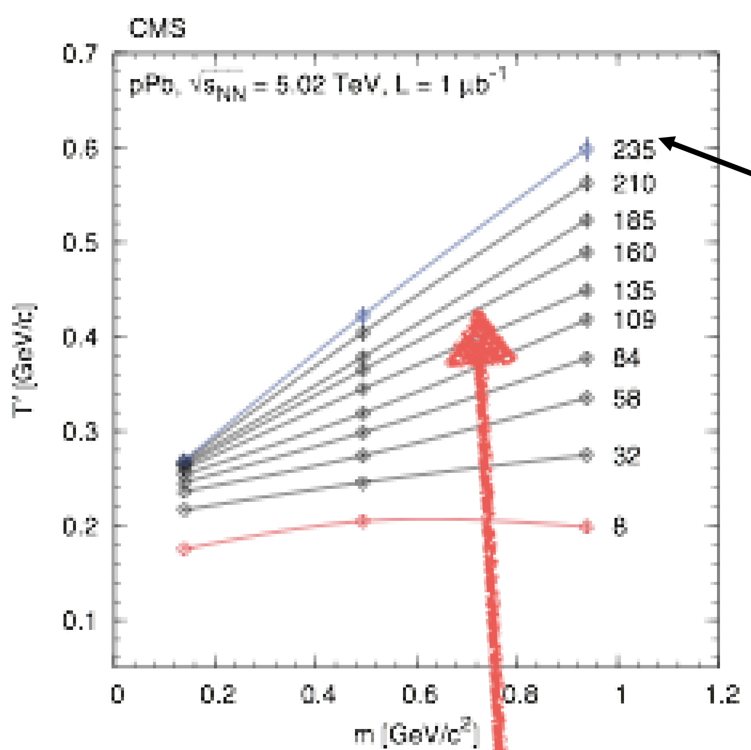


FIG. 8. (Color online) The slopes of the $m_\perp$ distribution T' (GeV) as a function of the particle mass, from [13]. The numbers on the right

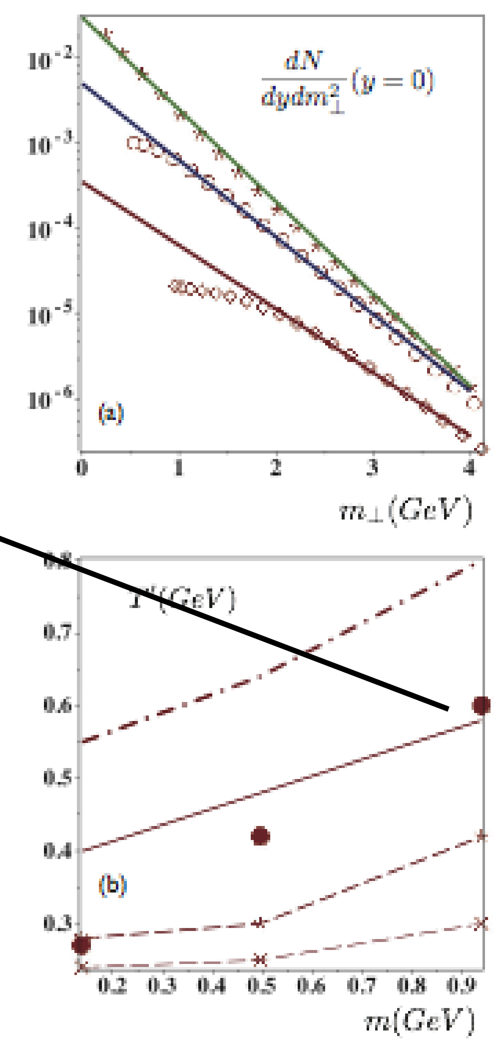
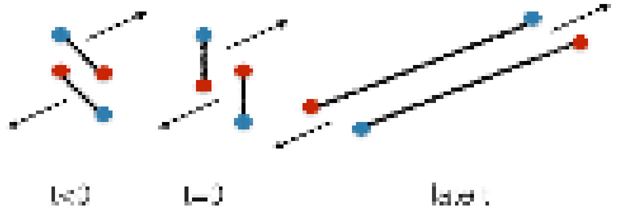


FIG. 9. (Color online) (a) A sample of spectra calculated for π, K, p, top-to-bottom, versus $m_\perp$ (GeV), together with fitted exponents.(b) Comparison of the experimental slopes $T'(m)$ versus the particle mass m (GeV). The solid circles are from the highest multiplicity bin data of Fig. 8, compared to the theoretical predictions. The solid and dash-dotted lines are our calculations for freeze-out temperatures $T_f = 0.17, 0.12$ GeV, respectively. The asterisk-marked dashed lines are for Epos LHC model, diagonal crosses on the dashed line are for AMTP model.

``straightforward hydro" (Epos) or cascade (AMPT) predict very weak radial flow

Not the Mt scaling at large Ntr => not a large Qs but a collective flow: p=m v

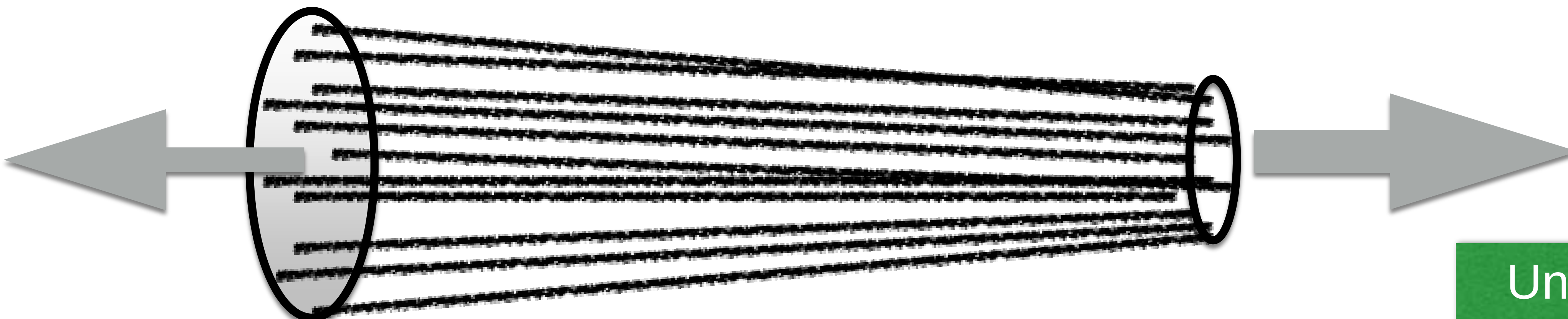
brief history of QCD strings



- **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

$2N_P$



Under the hood of Pythia and Hijing

N(strings)=2N(Pomerons)

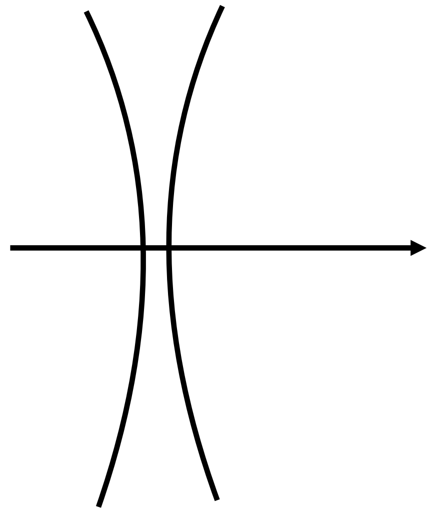
in small multiplicity bins strings are dilute and thus broken independently (the Lund model),

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

attractive sflux tubes; we live inside the type-1 superconductor



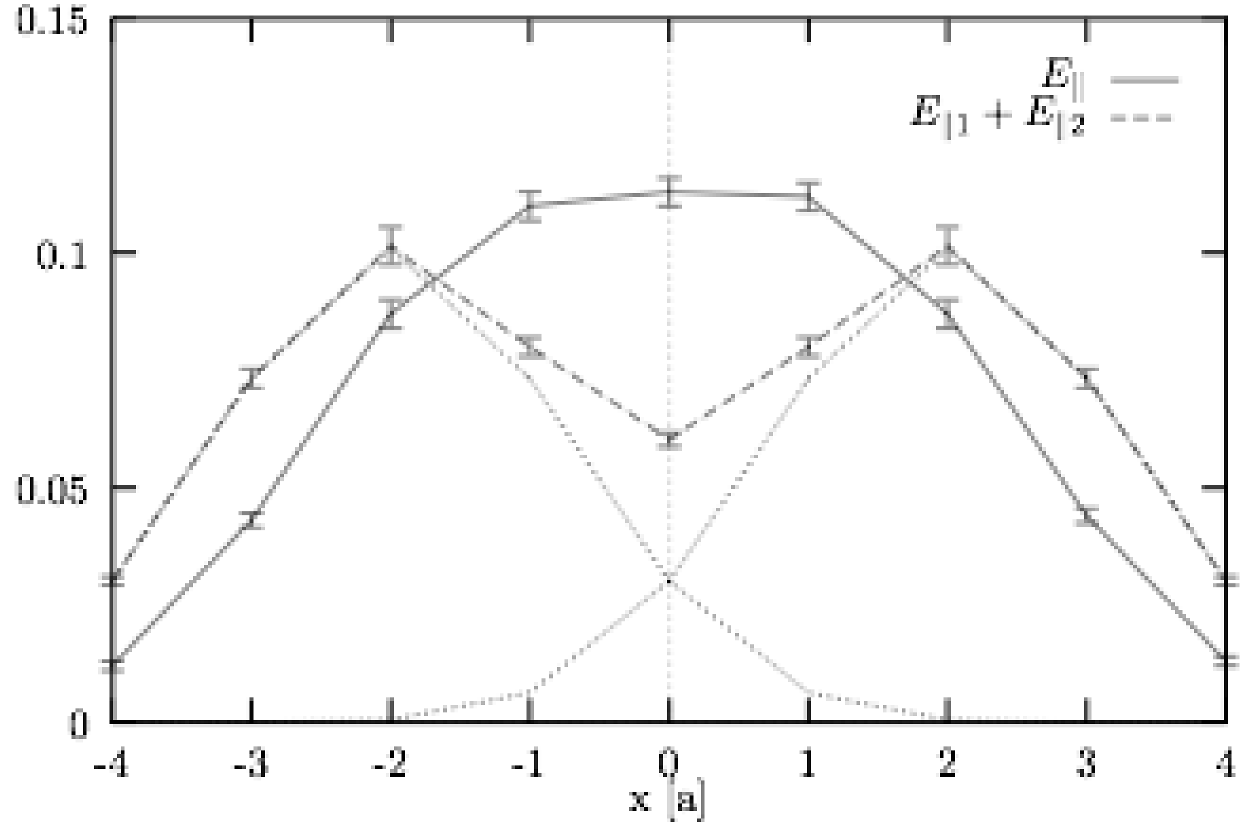


Figure 12: Longitudinal electric field profile of two interacting flux tubes in the symmetry plane ($E_{||}$, solid line). The length of flux tubes is $d = 22a$, the transverse distance of equal charges is $4a$. For comparison, the dotted lines show the results for single flux tubes at $x = -2a$ and $x = +2a$, and the dashed line corresponds to the superposition $E_{||1} + E_{|2}$ of these two non-interacting flux tubes.

Interaction strongly grows near Tc

M. Zach, M. Faber and P. Skala, Nucl. Phys. B 529, 505 (1998) [hep-lat/9709017].

string interaction via sigma meson exchange

our fit uses
the sigma mass
600 MeV

$$\frac{\langle \sigma(r_\perp) W \rangle}{\langle W \rangle \langle \sigma \rangle} = 1 - C K_0(m_\sigma \tilde{r}_\perp)$$

$$\tilde{r}_\perp = \sqrt{r_\perp^2 + s_{string}^2}$$

T. Iritani, G. Cossu and S. Hashimoto, arXiv:1311.0218

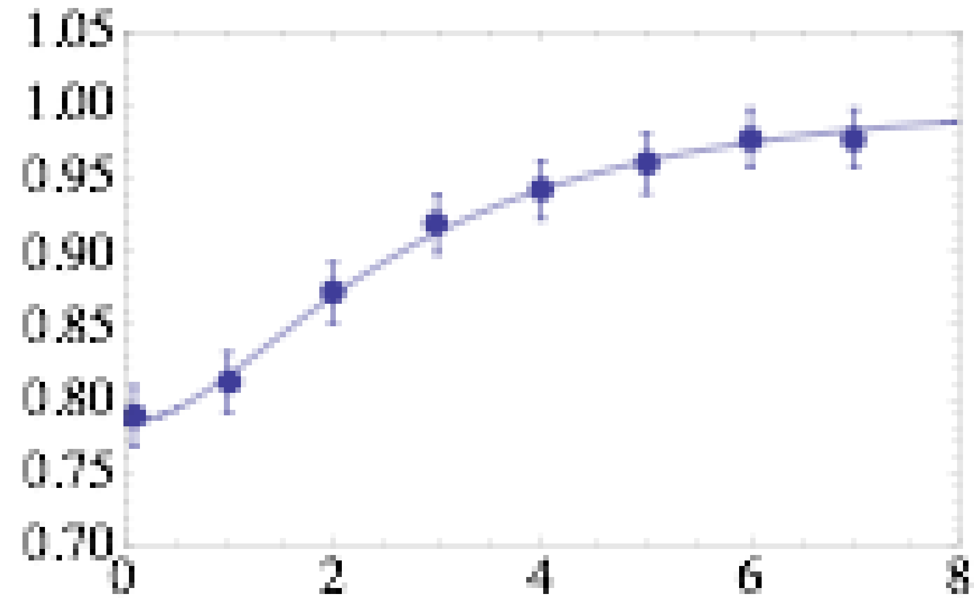


FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with $C = 0.26$, $s_{string} = 0.176$ fm.

So the sigma cloud around a string is there!

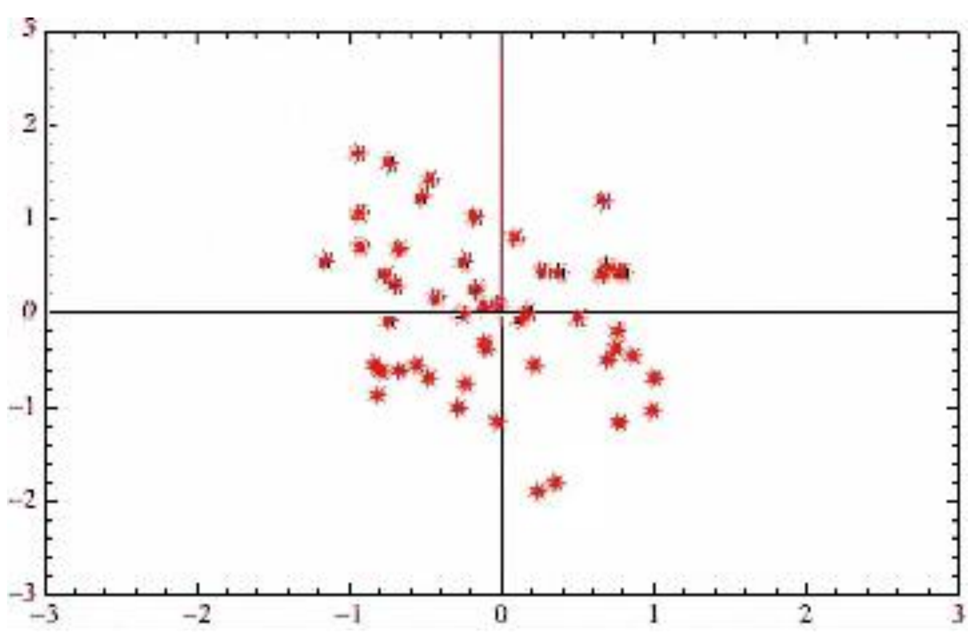
2d spaghetti collapse

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

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N\sigma_T)m_\sigma 2K_1(m_\sigma \tilde{r}_{ij}) \qquad (19)$$

$$E_{tot} = \sum_i \frac{v_i^2}{2} - 2g_N\sigma_T \sum_{i>j} K_0(m_\sigma r_{ij})$$

with $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and "regularized" $\tilde{r}$ (9).



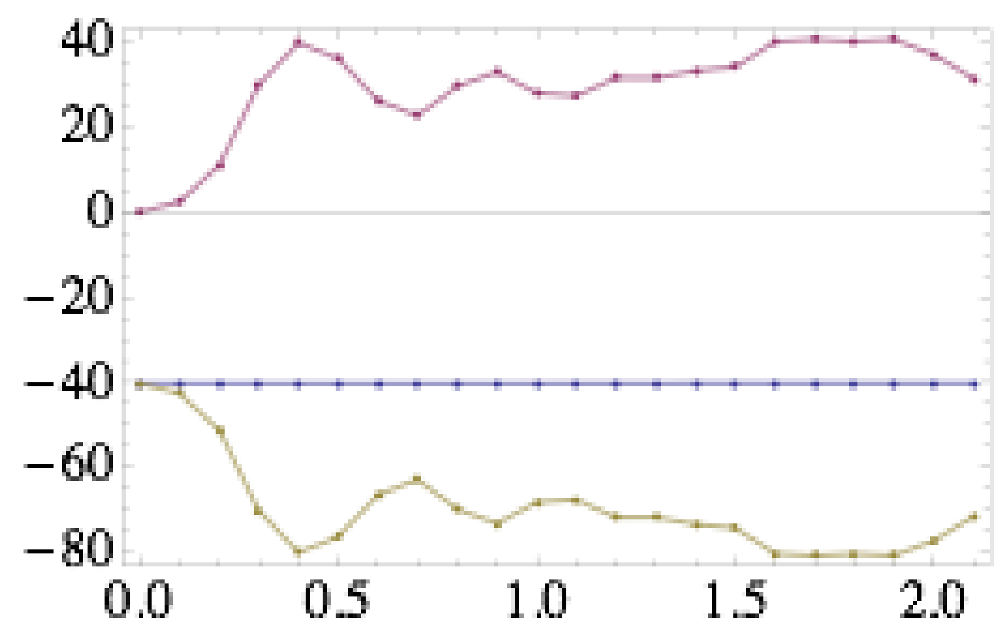
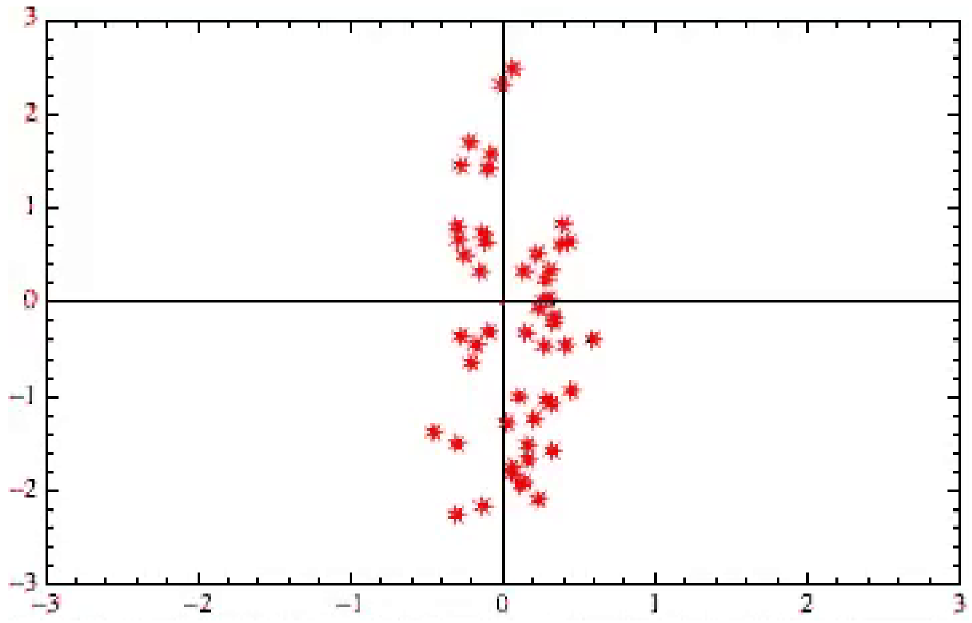
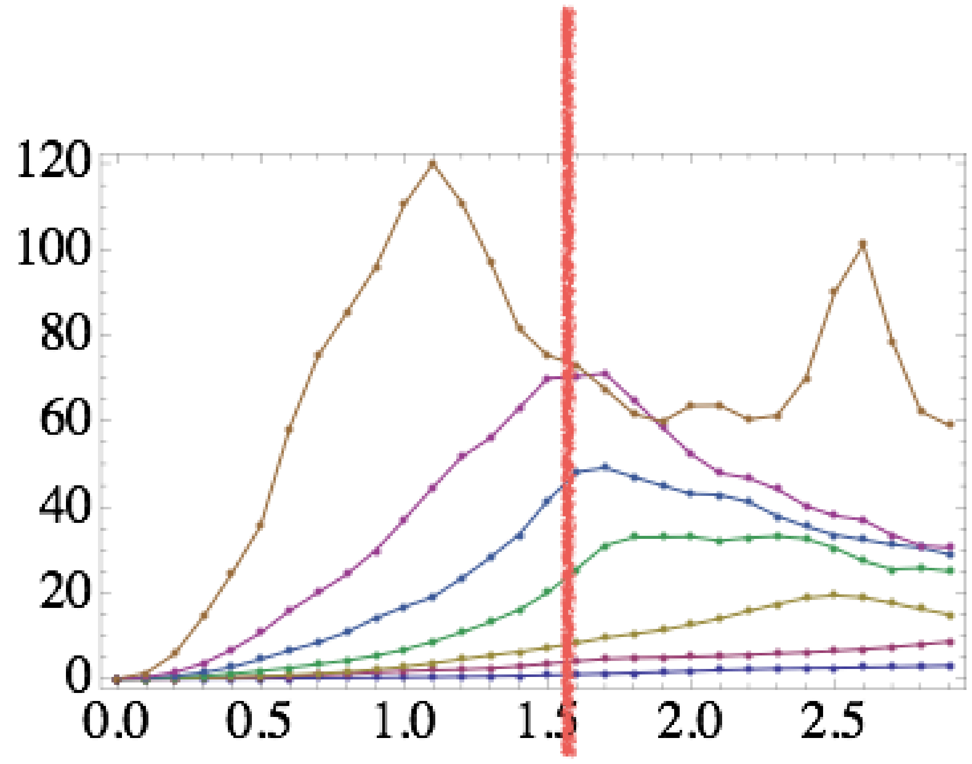


FIG. 4. (Color online) The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 6, as a function of time t(fm). The horizontal line with dots is their sum, namely E_{tot}, which is conserved.



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

$g_N \sigma_T$ =0.01,0.02,0.03,0.05,0.08,0.10,0.20.

collective sigma field

before and after collapse

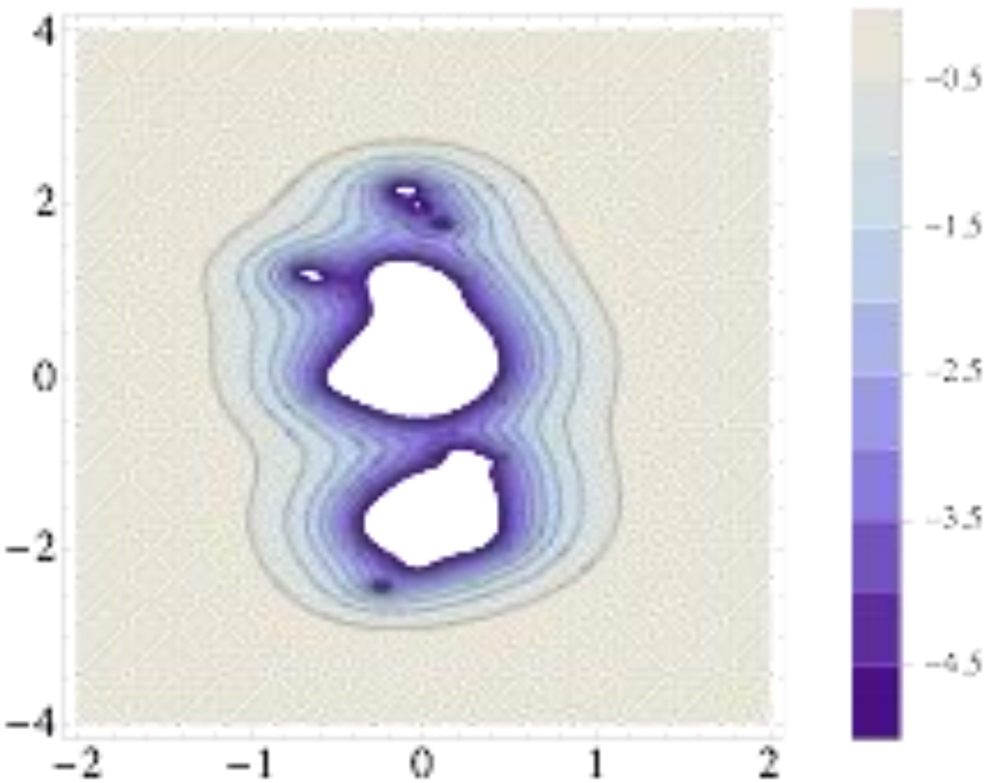


FIG. 10: Instantaneous collective potential in units $2g_N\sigma_T$ for an AA configuration with $b = 11$ fm, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment of time $\tau = 1$ fm/c. White regions correspond to the chirally restored phase.

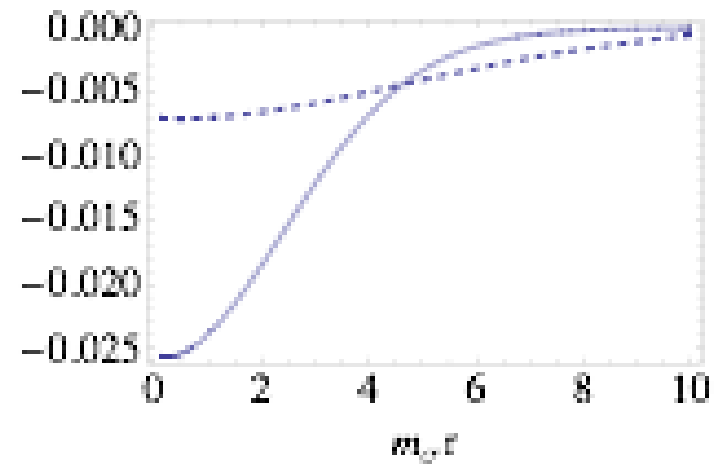


FIG. 4: The mean field (normalized as explained in the text) versus the transverse radius in units of inverse m_σ. The dashed and solid curves correspond to the source radii $R = 1.5$ and 0.7 fm, respectively.

Field gradient at the edge
leads to quark pair production:
QCD analog of Hawking radiation

Our lattice model for string balls

$$Z \sim \int \mathrm{d}L \exp\left[\frac{L}{a}\ln(2d-1) - \frac{\sigma_T L}{T}\right], \qquad (18)$$

and hence the Hagedorn divergence happens at

$$T_H = \frac{\sigma_T a}{\ln(2d-1)}. \qquad (19)$$

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

$$a_3 = 2.73\,\mathrm{GeV}^{-1} \approx 0.54\,\mathrm{fm}. \qquad (20)$$

$$E_{plaquette} = 4\sigma_T a \approx 1.9\,\mathrm{GeV}, \qquad (21)$$

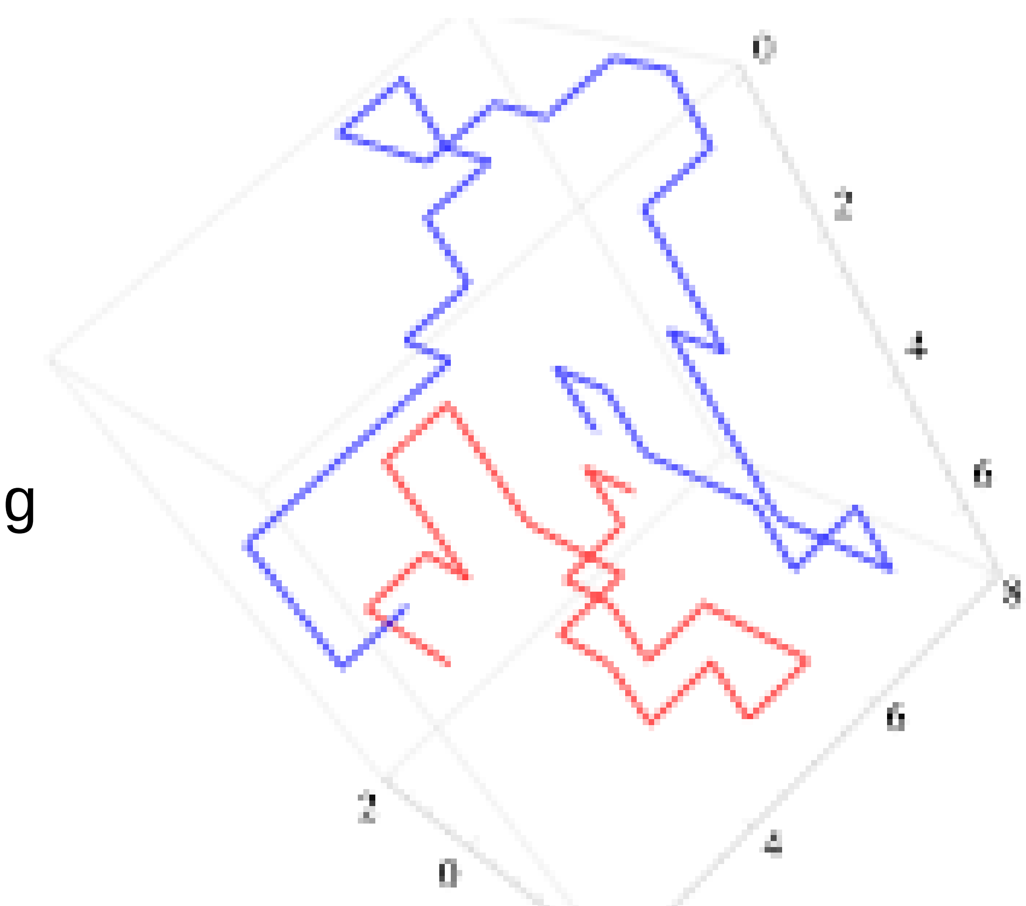
is amusingly in the ballpark of the lowest glueball masses of QCD. (For completeness: the lowest "meson" is one link or mass 0.5 GeV, and the lowest "baryon" is three links – 1.5 GeV of string energy – plus that of the "baryon junction".)

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,

$$\frac{\epsilon_{max}}{T_c^4} = \frac{\sigma_T a}{a^3 T_c^4} \approx 4.4 \qquad (22)$$

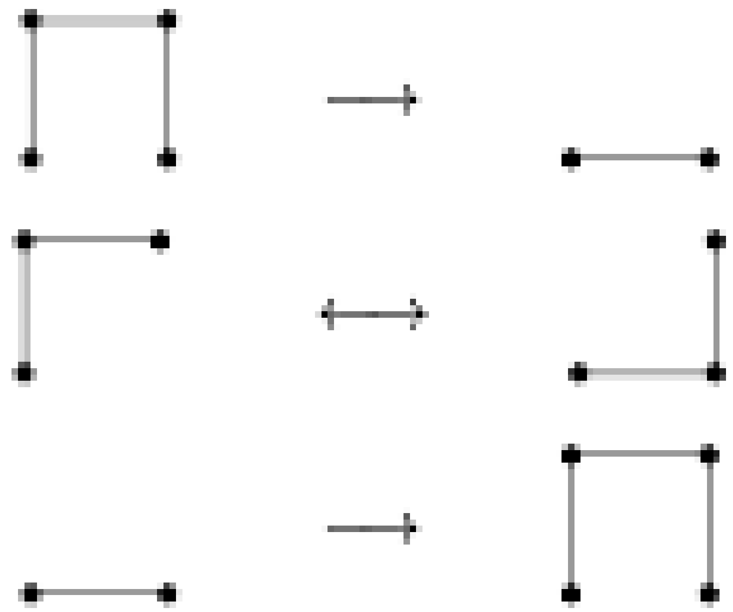
(we normalized it to a power of T_c, the highest temperature of the hadronic phase). It is instructive to compare it to the energy density of the gluonic plasma, for which we use the free Stefan-Boltzmann value

$$\frac{\epsilon_{gluons}}{T^4} = (N_c^2 - 1)\frac{\pi^2}{15} \approx 5.26 \qquad (23)$$



Example of non-interacting strings

Self-interacting string balls



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

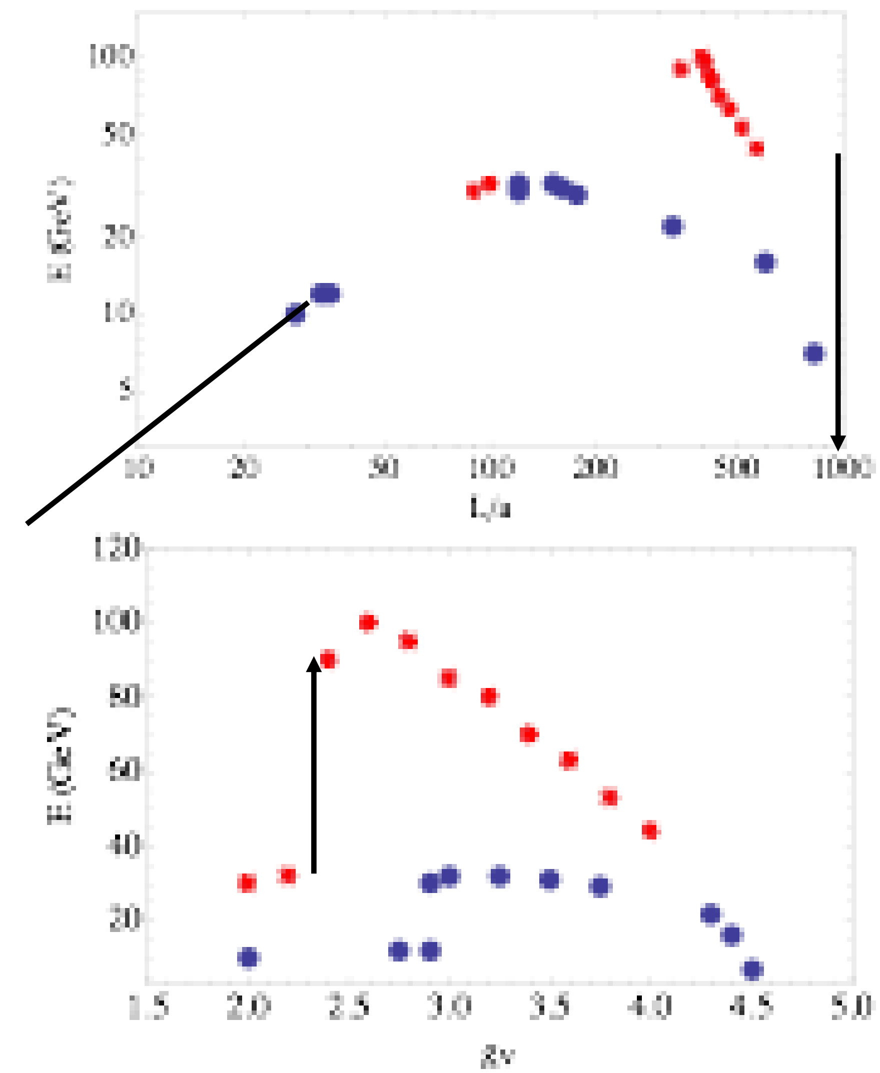


FIG. 7: Upper plot: The energy of the cluster E (GeV) versus the length of the string L/a. Lower plot: The energy of the cluster E (GeV) versus the "Newton coupling" g_N (GeV^{-2}). Points show the results of the simulations in setting $T_0 = 1\,\mathrm{GeV}$ and size of the ball $s_T = 1.5a, 2a$, for circles and stars, respectively.

$\frac{\hat{q}}{s} \approx const$?

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

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 Debye approxima-

$$\hat{q} = \frac{d\langle p_\perp^2 \rangle}{dl},$$

$$\langle p_\perp^2 \rangle \approx (gEr_s)^2;$$

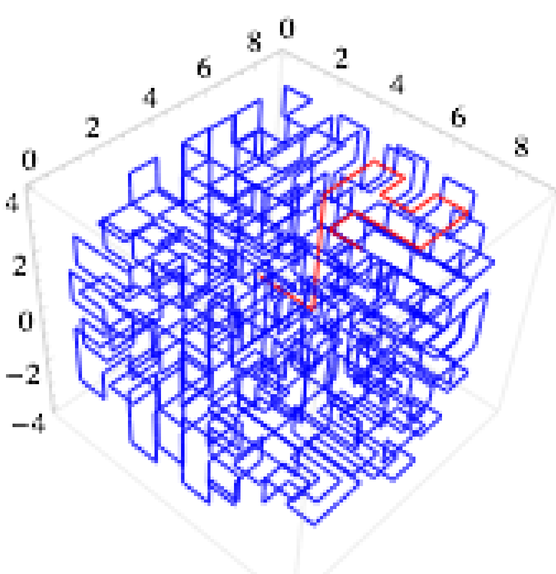
$$E(x) = \frac{\Phi_e}{2\pi r_s^2} K_0(x/r_s)$$

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

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

string length inside 1 fm^ 3

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



across the mixed phase, to be compared with values by the Jet coll. at Tc $\hat{q}_{min} = 0.025, \quad \hat{q}_{max} = 0.15 \left(\frac{\mathrm{GeV}^2}{\mathrm{fm}}\right).$

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

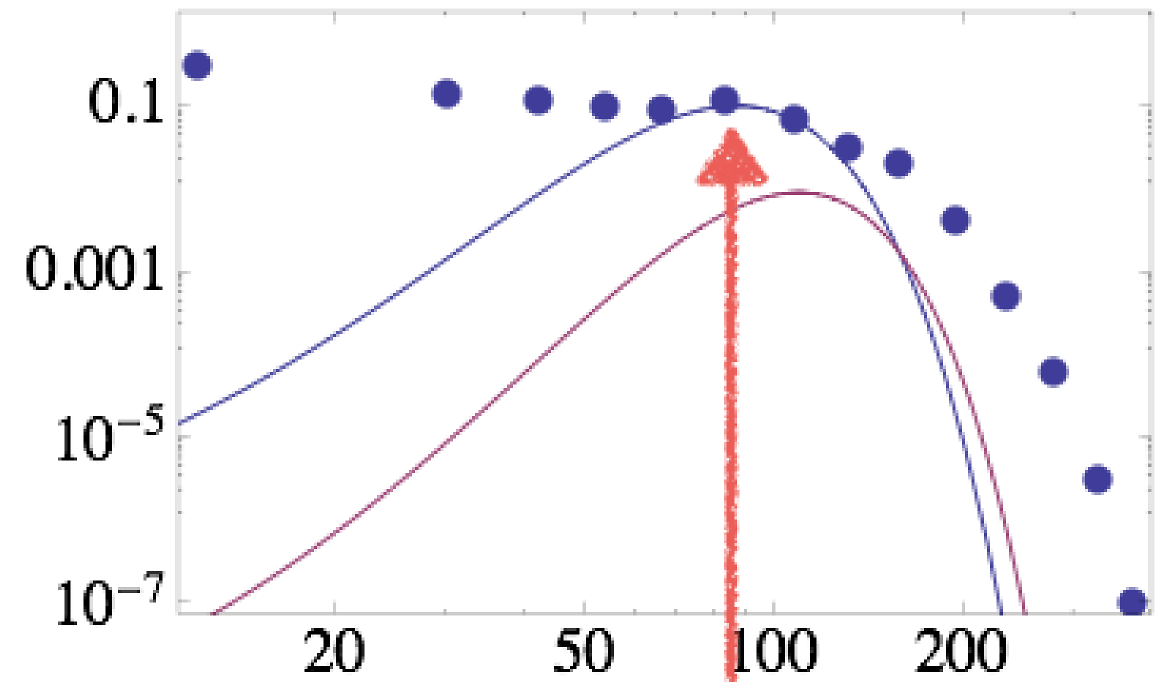
intro into pA collisions

Multiplicity distribution in pPb

maximal mean number of participants is along the Pb diameter, about 16
blue line is Poisson with <Np>=16
red with <Np>=20

geometry — columns with smaller Np - 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)



CMS charged
|eta|<2.4,p_t>.4

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