QCD strings and collective phenomena in AA, pA and pp collisions

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1407.3270: Explosive regime should dominate collisions of UHECR

1404.1888: Collective interaction of QCD strings and early stages of high multiplicity pA collisions

1402.7363: Self-interacting QCD strings and string balls

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December 3, 2014. McGill University, Montreal, Canada.

What systems do we consider?

- **AA collision and QCD in the mixed phase**
- **high multiplicity pA collisions**
- **peripheral AA collisions**
- **ultra-high energy cosmic rays**
- **high multiplicity pp collisions**
- **early universe (if there is an interest)**

Spaghetti

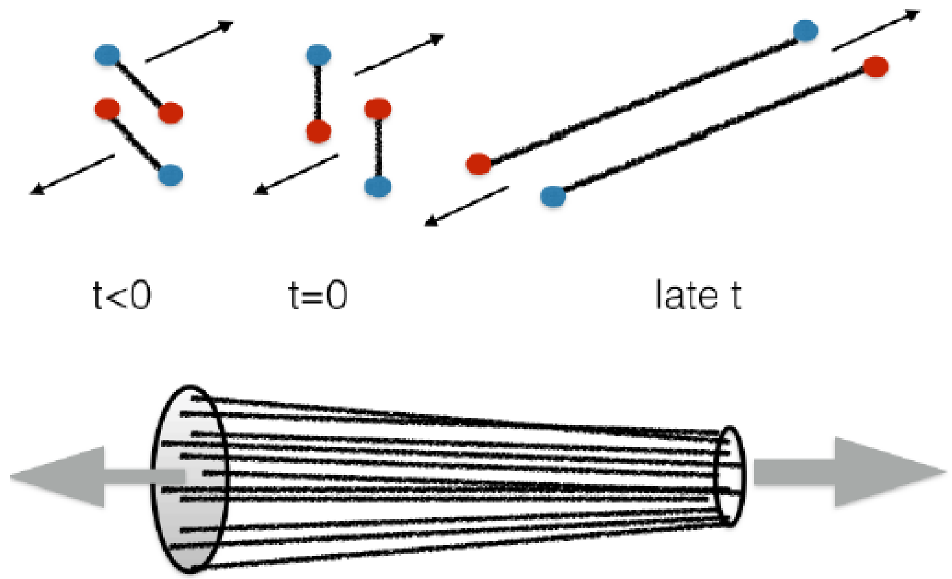


FIG. 1: The upper plot reminds the basic mechanism of two string production, resulting from color reconnection. The lower plot is a sketch of the simplest multi-string state, produced in pA collisions or very peripheral AA collisions, known as "spaghetti".

Motivation: multiplicity in pA

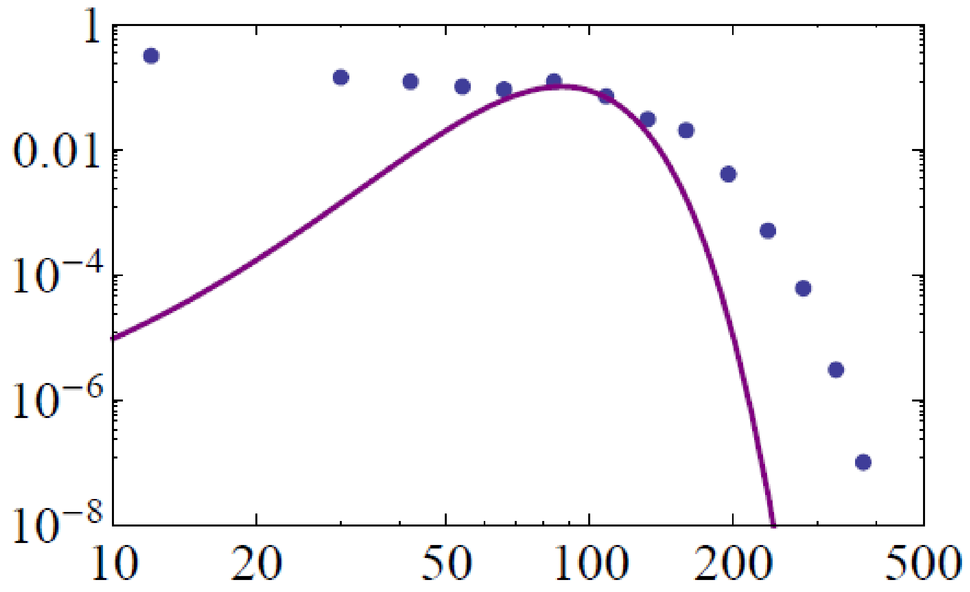
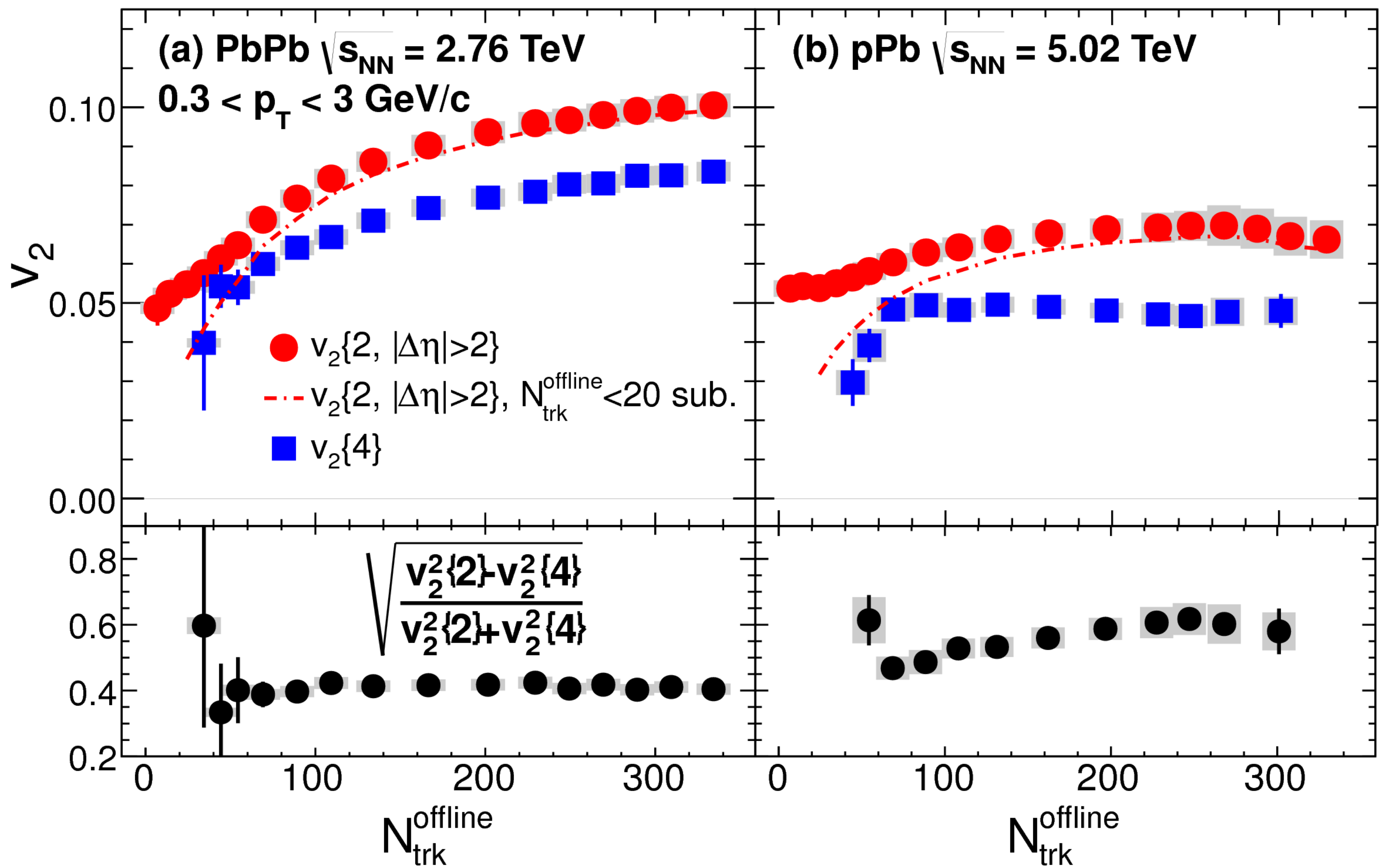


FIG. 2: (Color online). Probability distribution over the number of charged tracks in the CMS detector acceptance $P(N_{tr})$ [13]. The (purple) line is the Poisson distribution with $\langle N_p \rangle = 16$, arbitrarily normalized to touch the data points.

Also (Poisson ○ Poisson) ≠ Negative Binomial

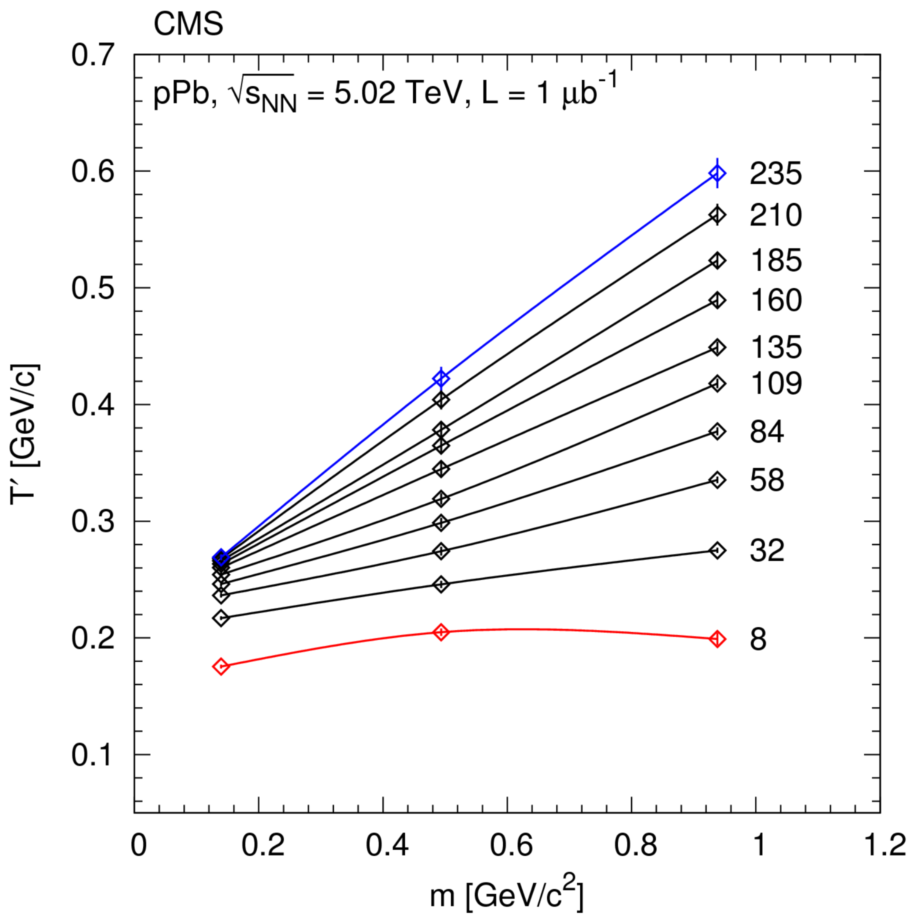
CMS: 1305.0609

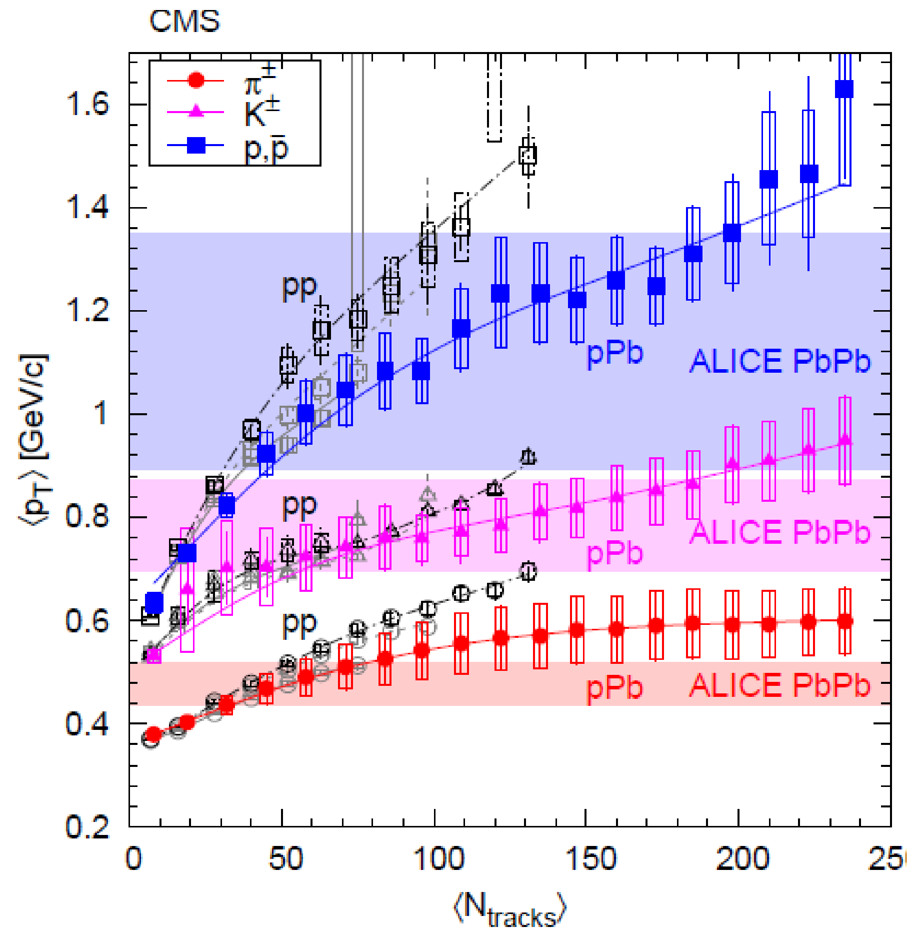
Motivation: elliptic flow in pPb



CMS: 1305.0609

Motivation: radial flow in pPb





$$\frac{dN}{dy\,dp_\perp^2} \sim \exp\left(-\frac{\sqrt{m^2+p_\perp^2}}{T'}\right)$$

Inverse slope parameters T' from fits of pion, kaon, and proton spectra (both charges)

CMS: 1307.3442, E. Shuryak and I. Zahed: 1301.4470

History: collapse to a black hole

Susskind; Horowitz and Polchinski; Damour and Veneziano.

Free string:

$$S_{string} \sim M/M_s \qquad \frac{R_{ball,r.w.}}{l_s} \sim \sqrt{M}$$

Black hole:

$$S_{BH} \sim Area \sim M^{\frac{d-1}{d-2}} \qquad R_{BH} \sim (M)^{\frac{1}{(d-2)}}$$

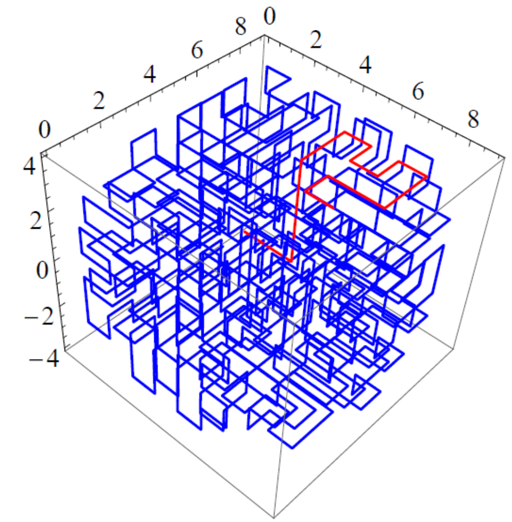
String ball:

$$S(M,R) \sim M \left(1 - \frac{1}{R^2}\right)\left(1 - \frac{R^2}{M^2}\right)\left(1 + \frac{g^2 M}{R^{d-2}}\right)$$

S(string)=S(BH) only at some special mass.

Temperature T=T_H.

But the sizes don't match, so we need self-interaction.



Something like this in QCD?

Hagedorn phenomenon

Partition function for strings on a lattice

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

Hagedorn phenomenon

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

Energy

Entropy factor

Hagedorn transition temperature (zero effective tension of the string)

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

Bringoltz & Teper '06: $T_H/T_c = 1.11$

What happens with the string at the critical temperature? Let's put in on a lattice.

$$a \simeq 0.54\,\mathrm{fm} \qquad E_{pl} = 4\sigma_T a \simeq 1.9\,\mathrm{GeV} \qquad \frac{\epsilon_{max}}{T_c^4} = \frac{\sigma_T a}{a^3 T_c^4} \approx 4.4$$

$$\sigma_T = (0.42\,\mathrm{GeV})^2 \qquad E_m = \sigma_T a \simeq 0.5\,\mathrm{GeV} \qquad \frac{\epsilon_{gluons}}{T^4} = (N_c^2 - 1)\frac{\pi^2}{15} \approx 5.26$$

String on a lattice

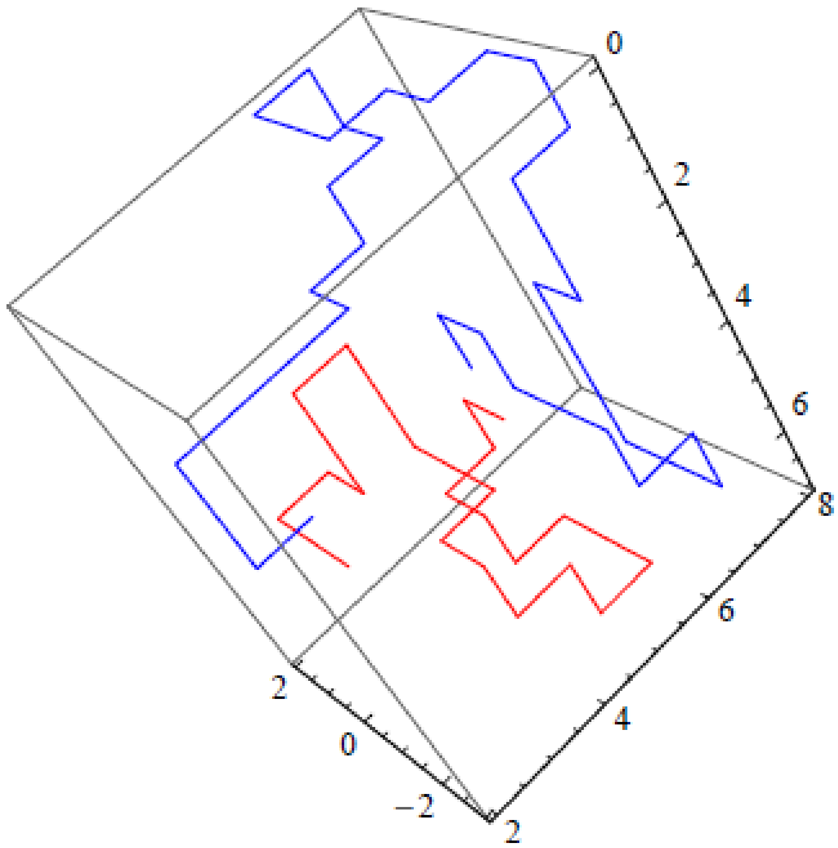


FIG. 4: (Color online) Example of a two-string configuration (a sparse string ball): two strings are plotted as blue and red.

Sigma-cloud

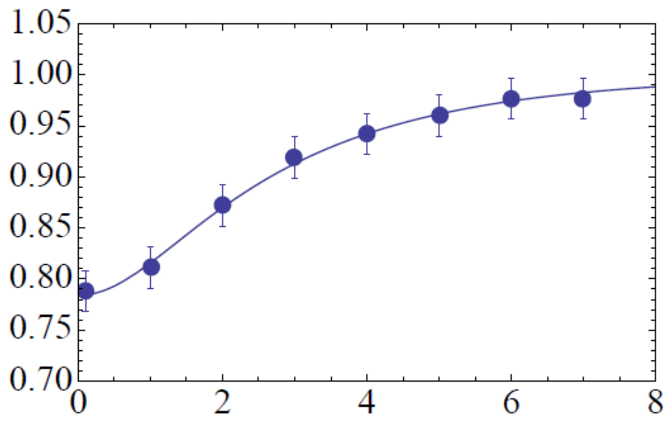
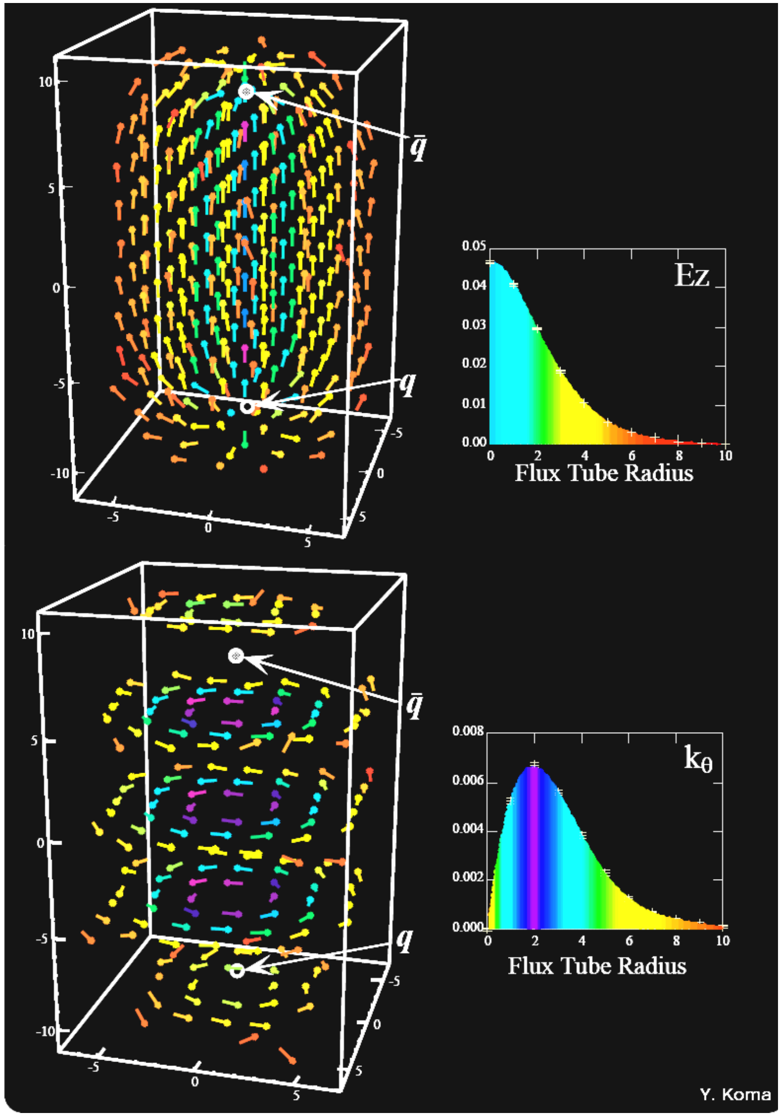


FIG. 3: (Color online). Points are from the lattice data for the chiral condensate [16]. The curve is expression (7) with $C = 0.26$, $s_{string} = 0.176\,\mathrm{fm}$.

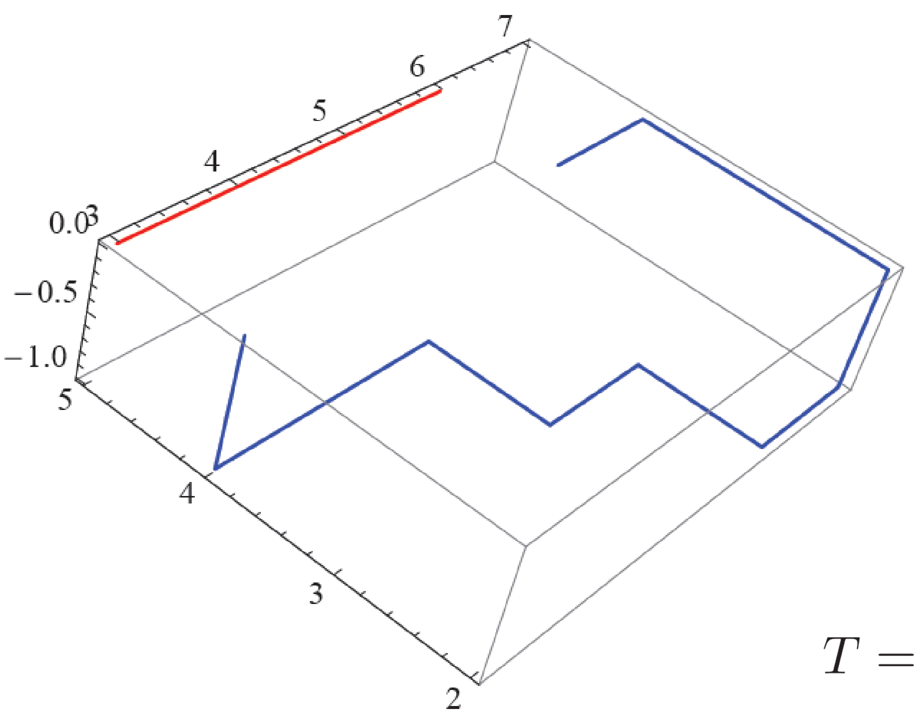
$$\frac{\langle \bar{q}q(r_\perp)W\rangle}{\langle W\rangle\langle \bar{q}q\rangle} = 1 - CK_0(m_\sigma \tilde{r}_\perp)\,,$$

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



Type I dual superconductor

Interacting strings

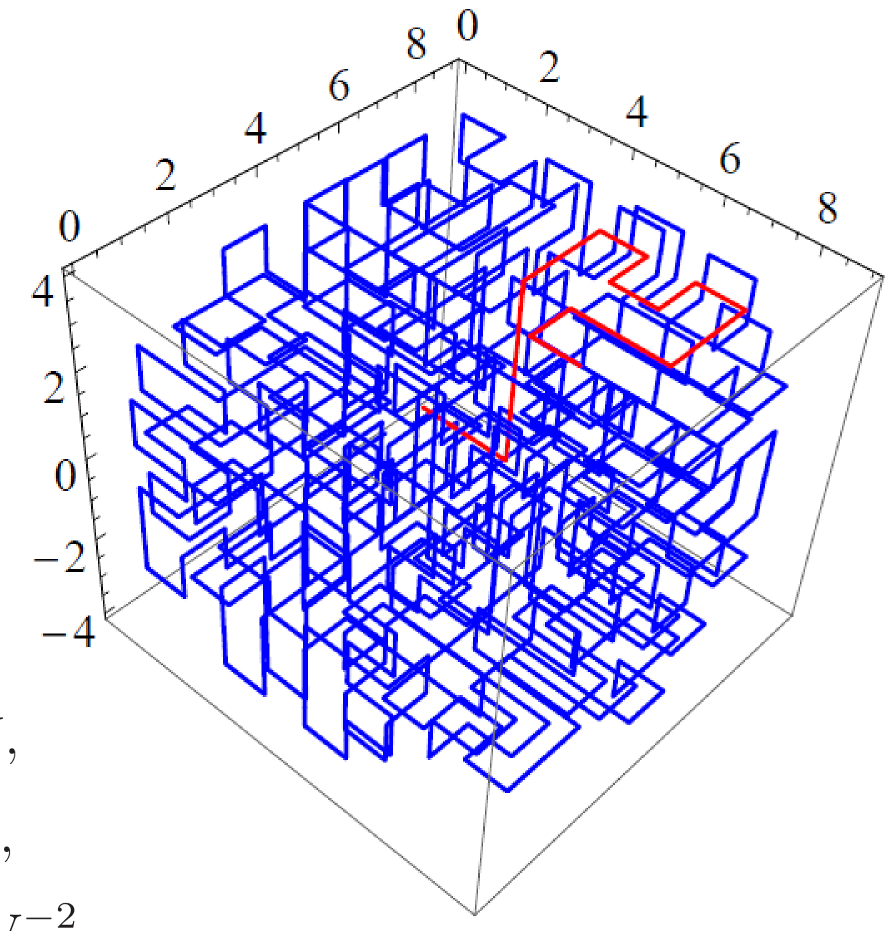


Without self-interaction

$$T = 1\,\mathrm{GeV},$$

$$s_T = 1.5a,$$

$$g_N = 4.4\,\mathrm{GeV}^{-2}$$



With self-interaction

String balls

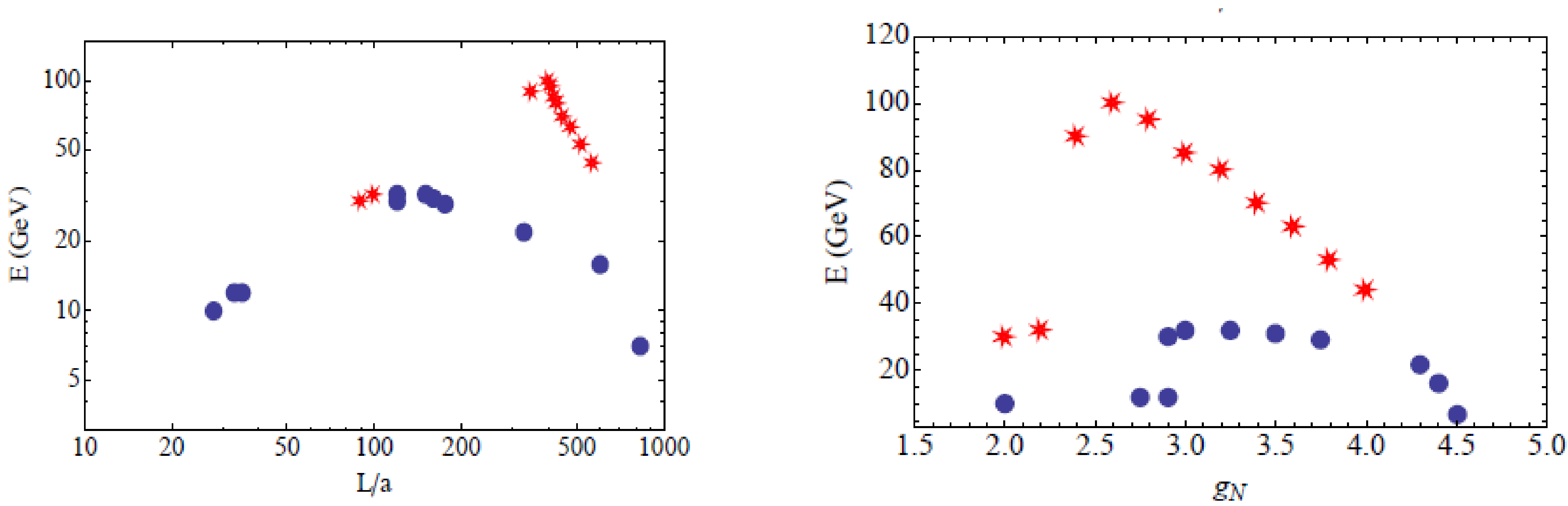


FIG. 7: Upper plot: The energy of the cluster E (GeV) versus the length of the string L/a. Lower plot: The energy of the cluster E (GeV) versus the "Newton coupling" g_N (GeV^{-2}). Points show the results of the simulations in setting $T_0 = 1\,\mathrm{GeV}$ and size of the ball $s_T = 1.5a, 2a$, for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

Applications:

1. Jet queching

2. Angular correlations

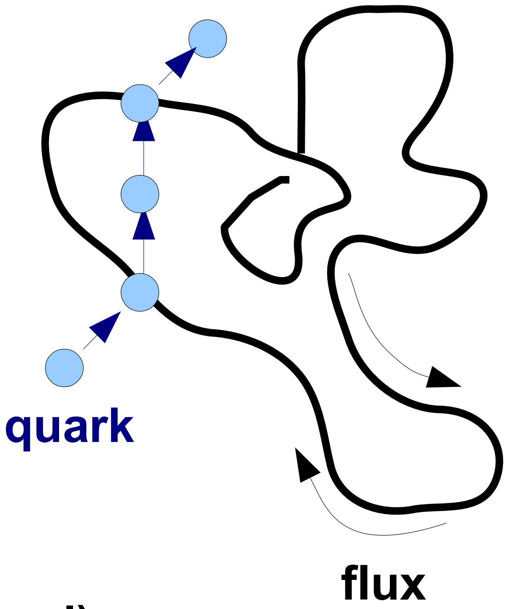
Jet quenching

Jet queching parameter, by definition

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}l}$$

in our case (due to „kicks“ by the color force)

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



In numbers, in the mixed phase
(min-max are because of the string density per qubic fermi):

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

Compare to the data of JET collaboration (1312.5003):

Can be up to 1 GeV²/fm for a string ball!

$$\hat{q}_{min} = 0.025, \qquad \hat{q}_{max} = 0.15 \left(\frac{\mathrm{GeV}^2}{\mathrm{fm}} \right)$$

Angular correlations

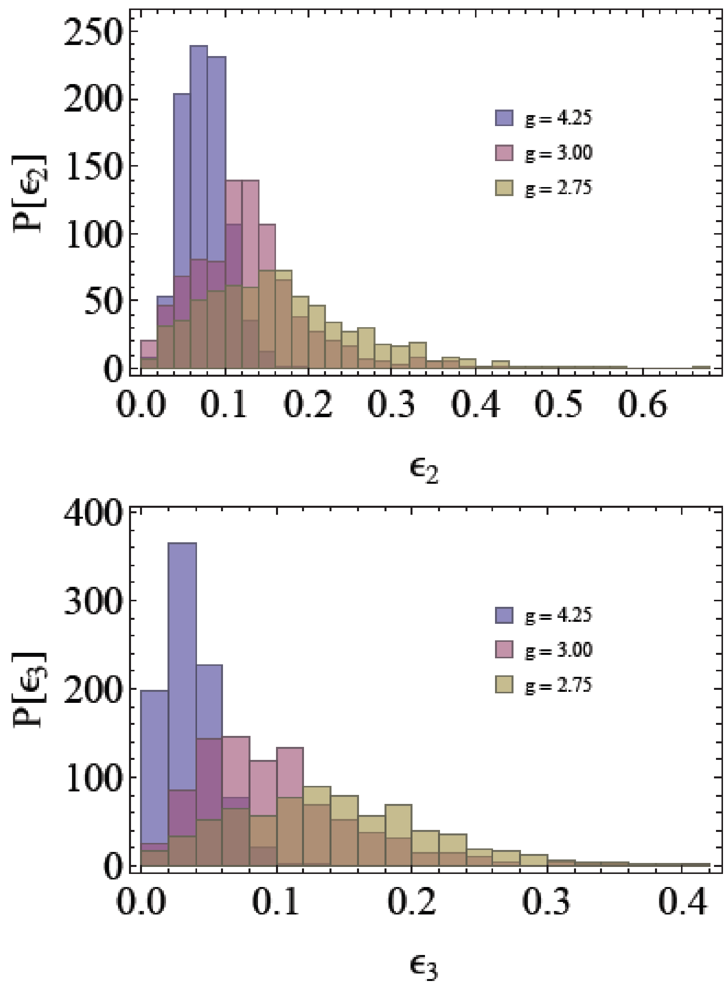


FIG. 10: The distributions over ϵ_2 and ϵ_3 (upper and lower plots), for several values of the "Newton coupling" g_N [GeV^{-2}].

$$\epsilon_n = \frac{\int d^2 r_\perp \cos(n\phi) r_\perp^n (dN/d^2 r_\perp)}{\int d^2 r_\perp r_\perp^n (dN/d^2 r_\perp)}$$

$$(\epsilon_n\{2\})^2 = \langle \epsilon_n^2 \rangle ,$$
$$(\epsilon_n\{4\})^4 = 2\langle \epsilon_n^2 \rangle^2 - \langle \epsilon_n^4 \rangle ,$$
$$(\epsilon_n\{6\})^6 = \frac{1}{4}\left[\langle \epsilon_n^6 \rangle - 9\langle \epsilon_n^2 \rangle\langle \epsilon_n^4 \rangle + 12\langle \epsilon_n^2 \rangle^3\right] ,$$

$$\epsilon_2\{2\} = 0.0759, \quad \epsilon_2\{4\} = 0.0621,$$
$$\epsilon_2\{6\} = 0.0636, \quad \epsilon_2\{8\} = 0.0635$$

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

Spaghetti

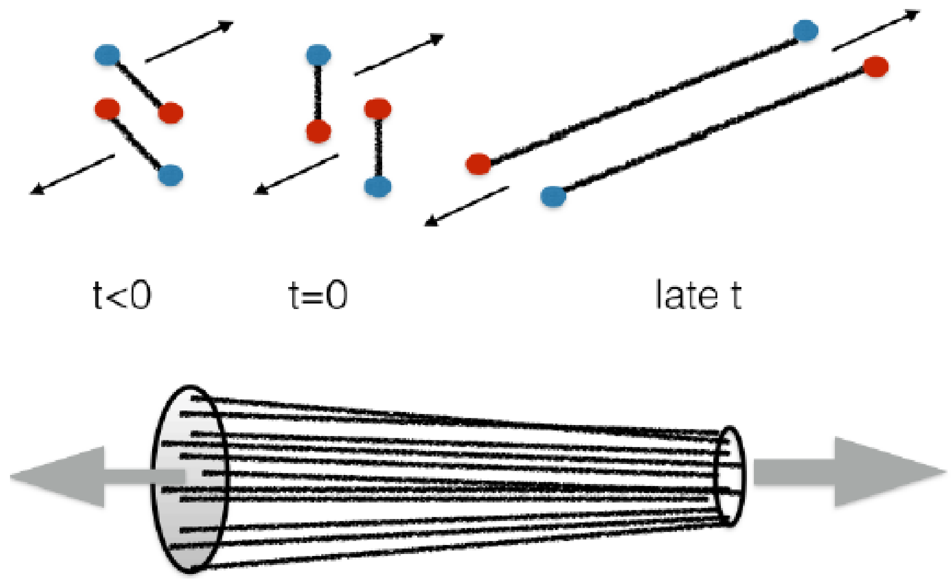


FIG. 1: The upper plot reminds the basic mechanism of two string production, resulting from color reconnection. The lower plot is a sketch of the simplest multi-string state, produced in pA collisions or very peripheral AA collisions, known as "spaghetti".

2D Yukawa gas

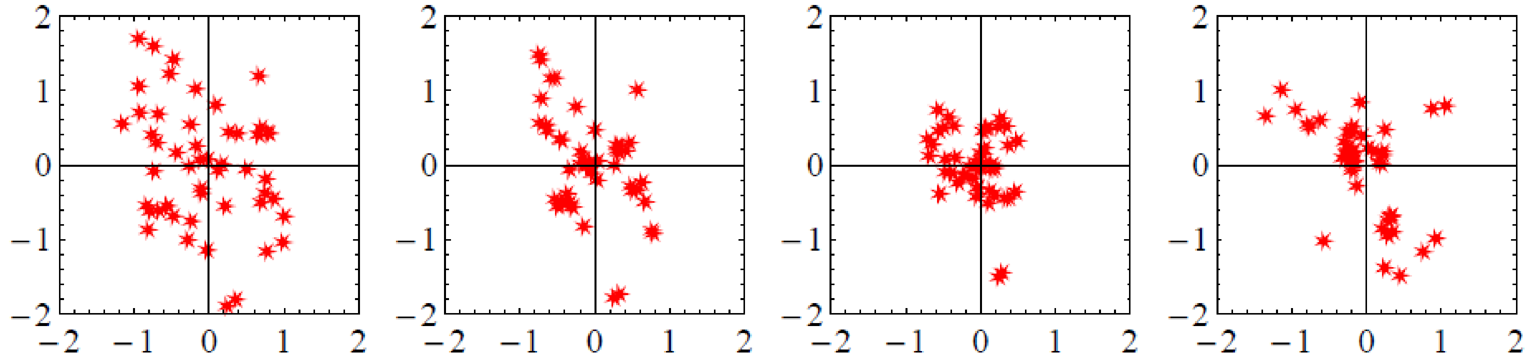


FIG. 7: (Color online) Example of changing transverse positions of the 50 string set: four pictures correspond to one initial configuration evolved to times $\tau = 0.1, 0.5, 1, 1.5\,\text{fm}/c$. The distances are given in fm, and $g_N \sigma_T = 0.2$.

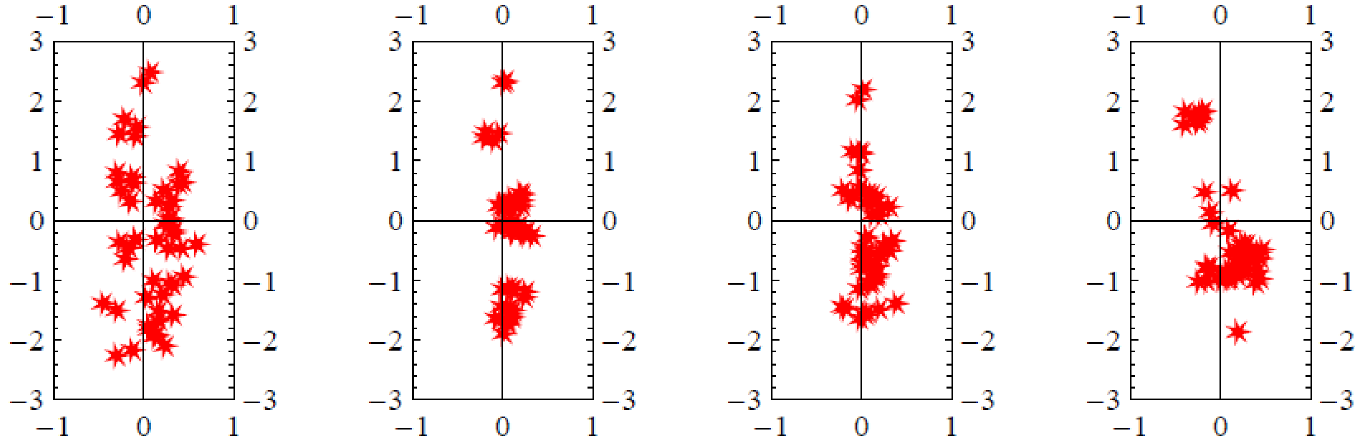


FIG. 8: (Color online) Example of peripheral AA collisions, with $b = 11\,\text{fm}$, $g_N \sigma_T = 0.2$, and the 50 string set. Four snapshots of the string transverse positions x, y (fm) correspond to times $\tau = 0.1, 0.5, 1., 2.6\,\text{fm}/c$.

Energy and energy density

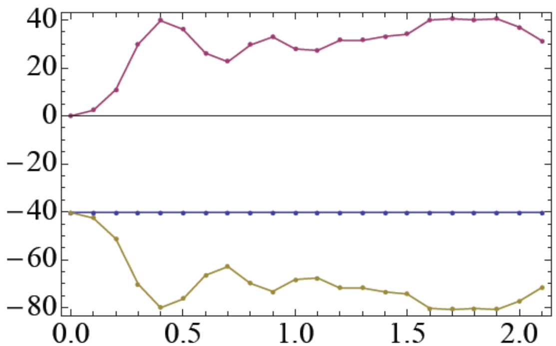


FIG. 5: (Color online). The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 7, as a function of time $t\,(\mathrm{fm}/c)$. The horizontal line with dots is their sum, E_{tot}, which is conserved.

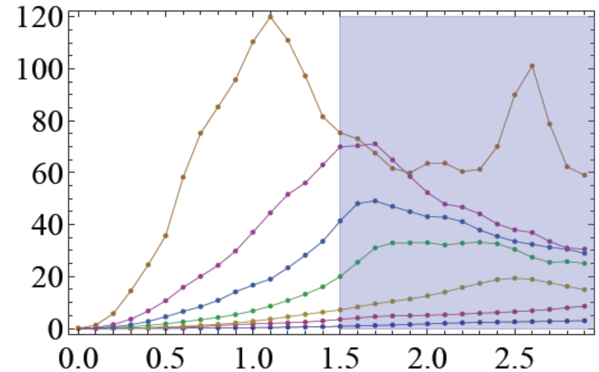


FIG. 6: (Color online). Kinetic energy (dimensionless) versus the simulation time (fm/c), for few pA $N_s = 50$ runs. Seven curves (bottom-to-top) correspond to increasing coupling constants $g_N\sigma_T = 0.01, 0.02, 0.03, 0.05, 0.08, 0.10, 0.20$.

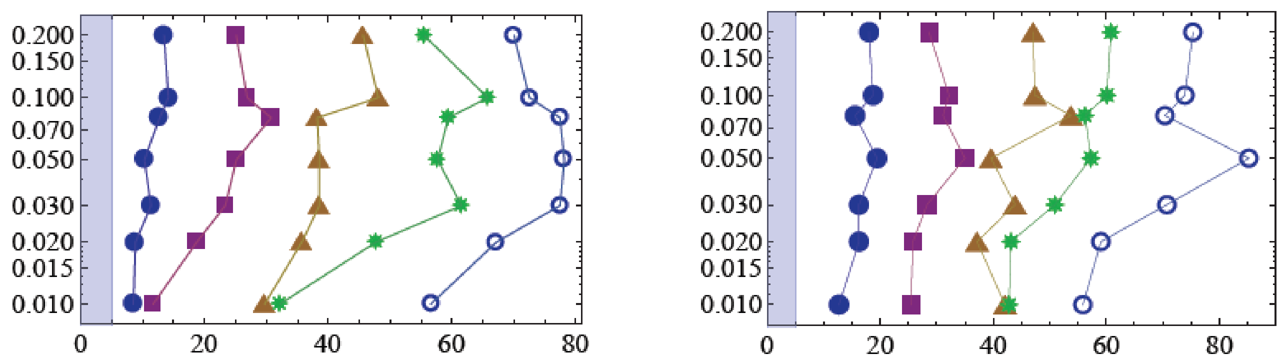


FIG. 9: (Color online) The left plot is for central pA, the right one – for peripheral AA collisions. The vertical axis is the effective coupling constant $g_N\sigma_T$ (dimensionless). The horizontal axis is the maximal energy density ϵ_{max} (GeV/fm^3) defined by the procedure explained in the text. Five sets shown by different symbols correspond to string number $N_s = 10, 20, 30, 40, 50$, left to right respectively.

Elliptic flow

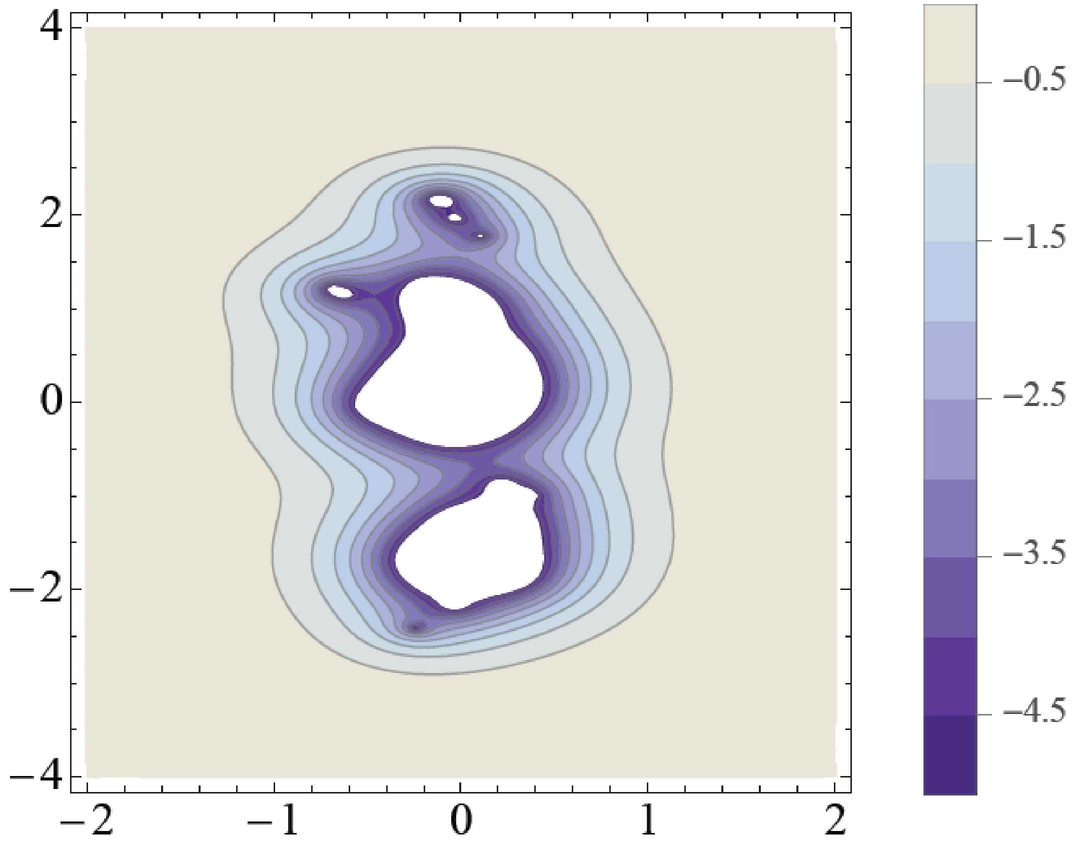
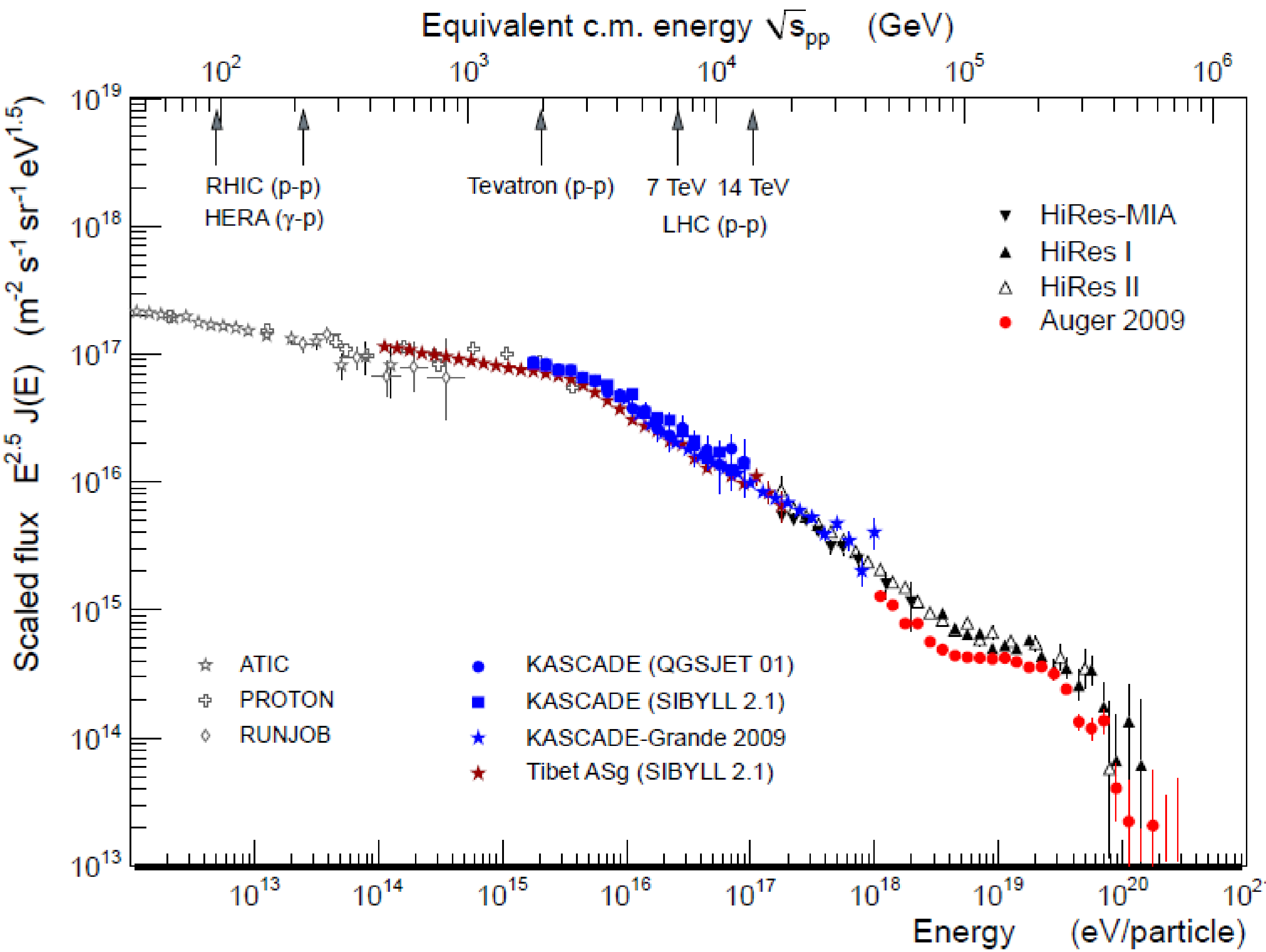
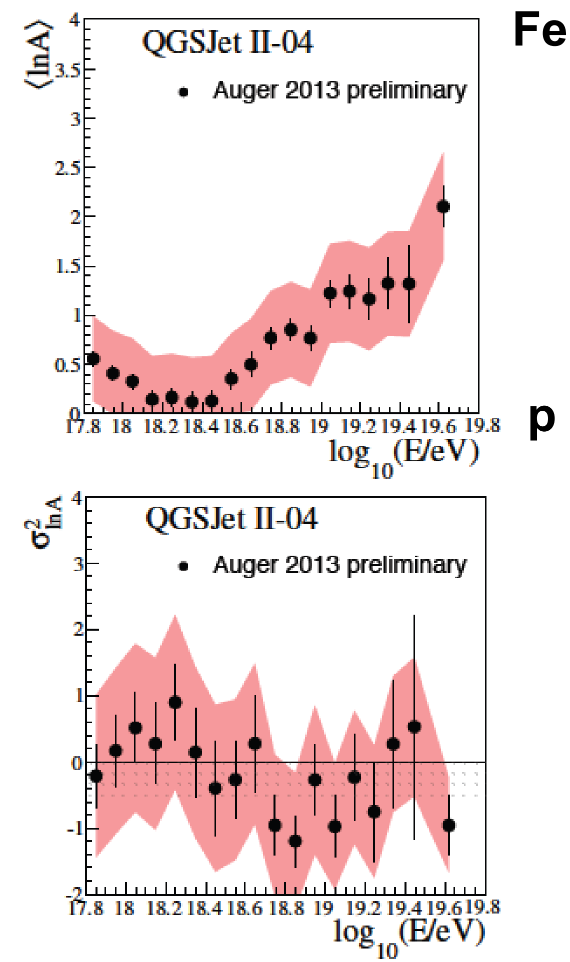


FIG. 10: Instantaneous collective potential in units $2g_N\sigma_T$ for an AA configuration with $b = 11$ fm, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment of time $\tau = 1$ fm/c. White regions correspond to the chirally restored phase.

Cosmic rays





1101.5596

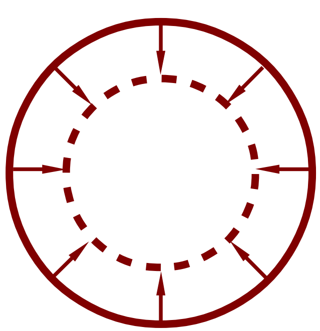
1310.4620

Freezeout surfaces

p O

Fe O

Pb Pb



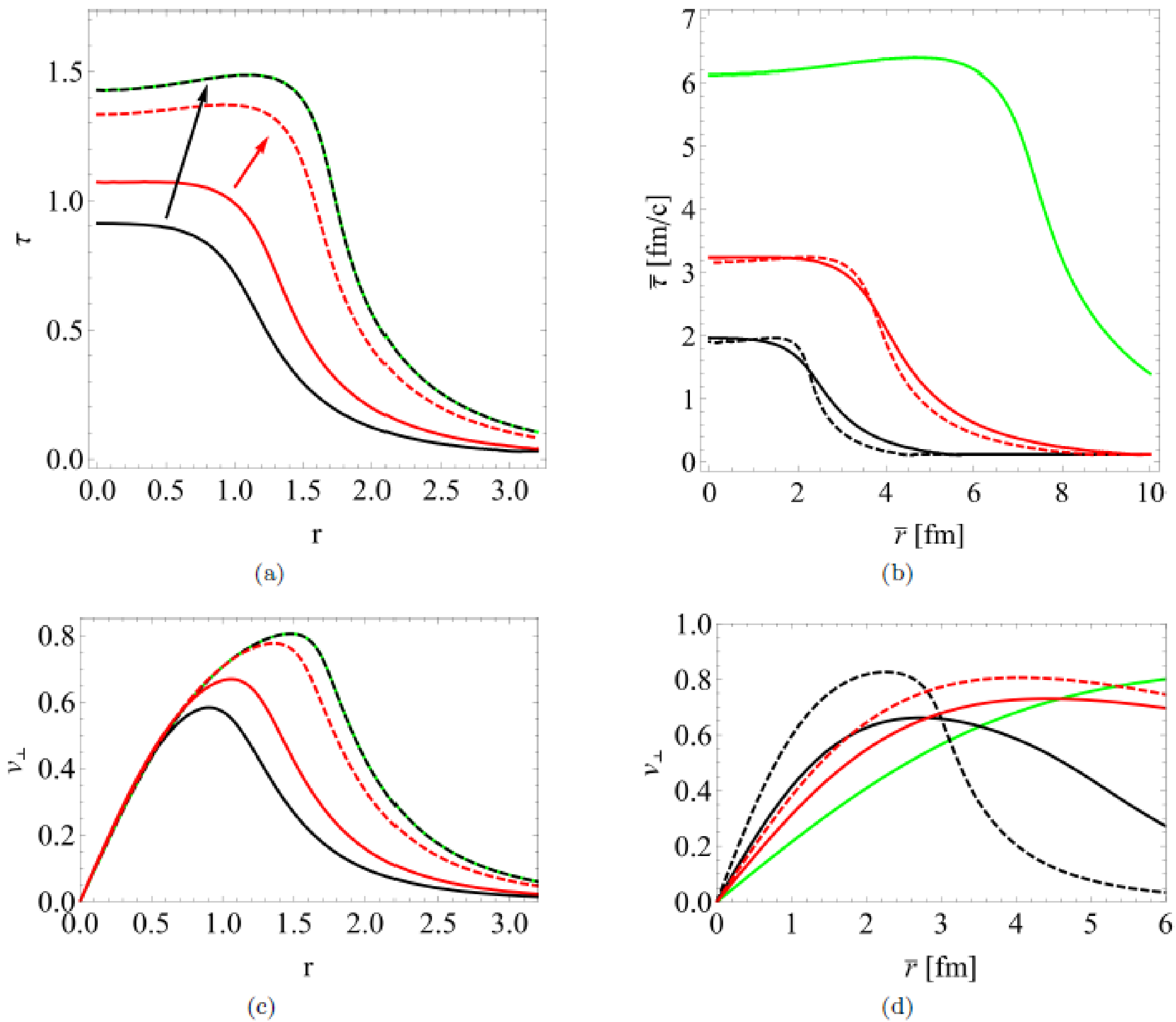


FIG. 2: (color online) (a) The freezeout surfaces in the (τ, r) plane and (c) the distribution of the transverse flow velocity on those surfaces. In both plots the green solid curve at the top is our "benchmark", the central *PbPb* collisions at LHC. Black solid line is for light-light collisions, black dashed (coincident with green by chance) are light-light collisions with the size compression. Similarly, red solid and red dashed are heavy-light collisions without and with the size compression, respectively.

Particle spectra

From Cooper-Frye formula and freezeout curves

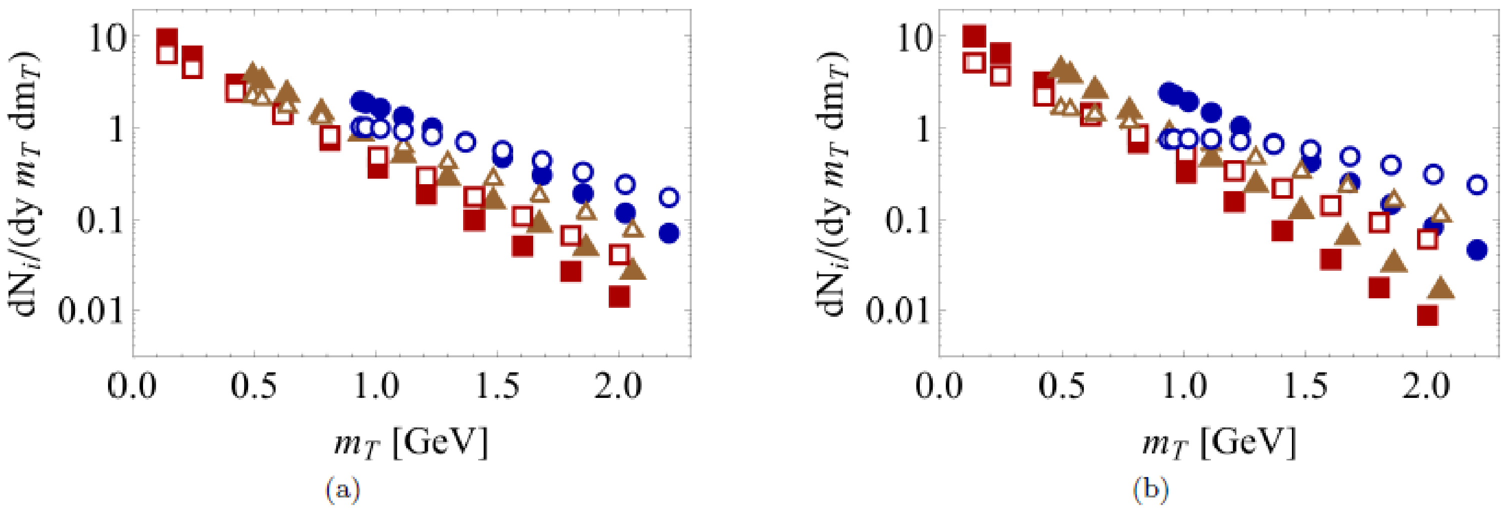


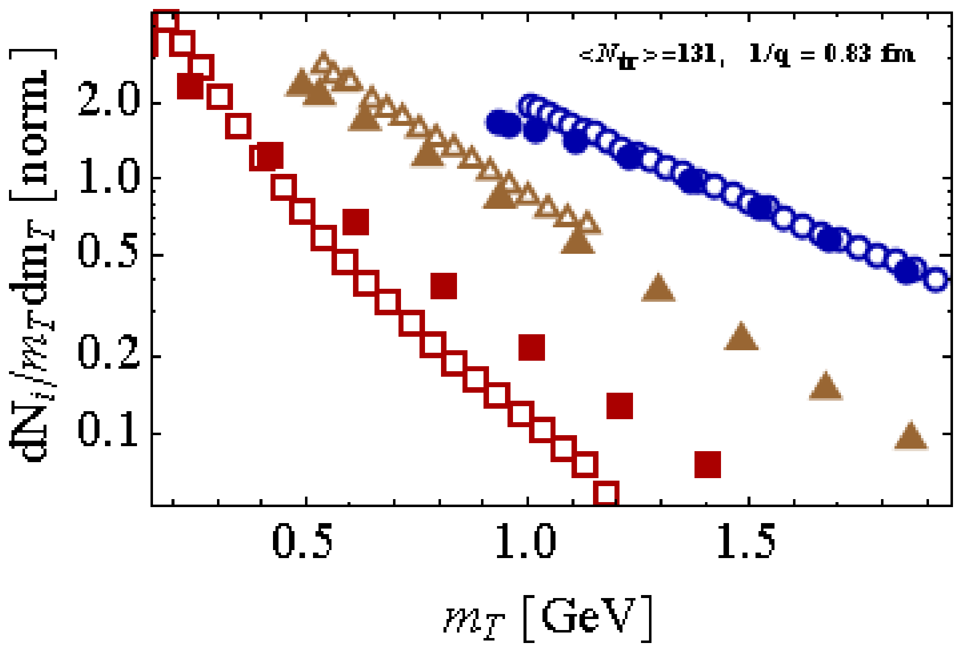
FIG. 3: (color online) Normalized spectra of pions (squares), kaons (triangles) and protons (discs) for the (a) heavy-light (e.g. FeO) and (b) light-light (e.g. pO) collisions. Open symbols correspond to the "compressed" cases, explained in the text.

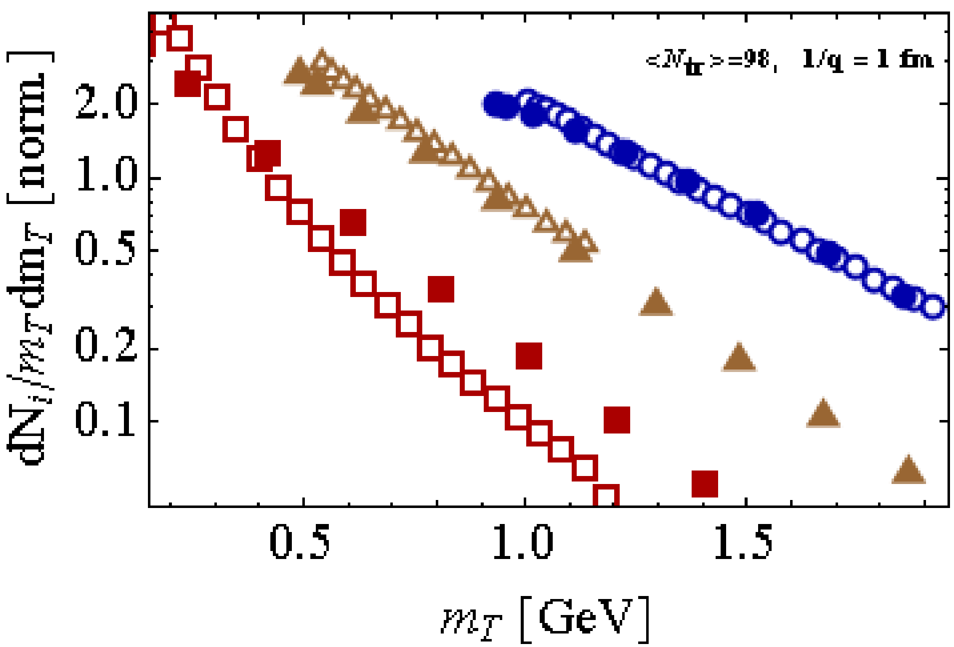
Mean p_T :

particles	FeO	FeO comp.	pO	pO comp.	PbPb
$\pi^{\pm}$	0.56	0.69	0.53	0.76	0.73
$K^{\pm}$	0.71	0.88	0.66	0.96	0.92
$p, \bar{p}$	0.90	1.09	0.83	1.17	1.13

pp with Gubser's flow

From Cooper-Frye formula and freezeout curves





The data (open symbols) are from CMS, 7 TeV,
fit done by the system size parameter q in the Gubser's flow solution.
protons, kaons, pions

How to make a transition to QGP/hydro? String balls?

Conclusions

- **One should reconsider the QCD string phenomenology taking into account the interaction between strings. More lattice data are needed.**
- **Jet quenching in the inhomogeneous phases.**
- **One should implement the interaction in order to describe the collective effects in pA collisions. The Lund model based approaches may be improved.**
- **Naive energy extrapolation of the LHC results (and Monte-Carlo generators) for ultra-high-energy cosmic rays should be corrected.**
- **Stay tuned.**

Thank you for the attention!