Rapidity long range correlations, parton percolation and color glass condensate.

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Abstract. The similarities between string percolation and Glasma results are emphasized, special attention being paid to rapidity long range correlations, ridge structure and elliptic flow. As the string density of high multiplicity pp collisions at LHC energies has similar value as the corresponding to Au–Au semi-central collisions at RHIC we also expect in pp collisions long rapidity correlations and ridge structure, extended more than 8 units in rapidity.

Keywords: Long range correlations, percolation of strings, Color Glass Condensate.

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The mechanisms of parton saturation, string fusion and percolation have been quite successful in describing the basic facts, obtained mostly at RHIC, of the physics of QCD matter at high density. Here we would like to emphasize the similarities between both approaches string percolation [1][2] and color glass condensate (CGC) or glasma [3][4] and to show some predictions on rapidity long range correlations ridge structures [5][6][7][8], width of the normalized multiplicity distributions and elliptic flow [9].

In string percolation the relevant parameter is the transverse string density $\eta$, $\eta \equiv N_s \pi r_0^2/\pi R^2$ where $N_s$ is the number of strings, $r_0^2$ the radial size of a single string and $\pi R^2$ the transverse size of the collision. $\eta$ behaves like $N_s^{2/3}$ and $s^3$. String percolation leads to reduction of particle density at mid-rapidity, and because of energy-momentum conservation, to an increase of the rapidity length of the effective strings. The basic formulae are, for particle density and for $<p_T^2>$

$$\frac{dn}{dy} = F(\eta) N_s \mu$$

and

$$<p_T^2> = <p_T^2>_1 / F(\eta)$$

where $F(\eta)$ is the color reduction factor, $F(\eta) = \sqrt{(1 - e^{-\eta})/\eta}$, and $\mu$ and $<p_T^2>_1$ are the particle density and the averaged transverse momentum squared of the single string ($<p_T^2> > r_0^2 \simeq \frac{1}{4}$), $r(\eta)$ or more specifically in the large $\eta$ limit, $\sqrt{\eta}$, plays the role of the saturation scale of CGC. Indeed, from (1), the transverse size correlation is $r_0^2 F(\eta)$ and $1/Q_s^2$ the corresponding one in CGC.

As far as color electric field is concerned the effective strings can be identified with the flux tubes of the Glasma picture. In fact the area occupied by the strings divided by the area of the effective string gives the number of effective strings [5][6],

$$<N> = \frac{(1 - e^{-\eta})R^2}{F(\eta) r_0^2} = (1 - e^{-\eta})^{1/2} \sqrt{\eta}(R/r_0)^2$$

which in the high density limit is equivalent to $Q_s^2 R^2$ the number of flux tubes of the Glasma.

In the process of fusion of strings one has to take care of the energy momentum conservation, which implies an increase in the length in rapidity of the string, thus the length of a cluster of $N_s$ strings is given by

$$\Delta Y_N = \Delta Y_1 + 2 N_s$$

One further notes that overall conservation of energy/momentum regimes for the number of strings to behave as

$$N_s \simeq s^{\lambda} \simeq e^{2\lambda Y}$$

where $Y$ is the beam rapidity, $Y = \ln(\sqrt{s}/m)$ and $\lambda = 2/7$. Therefore

$$\Delta Y_{NS} \simeq 2 \lambda \Delta Y$$

As in the CGC the length in rapidity of the classical fields is $1/\alpha_s(Q_s^2)$ and as the saturation scale is power behaved in $Y$, we end up in a formula of the kind of (5). Therefore longitudinal extension of the cluster of strings in string percolation as in the CGC, increases with energy as $\log(s)$, giving rise to long range rapidity correlations, even for pp at LHC. Notice that the transverse
string density for \( pp \) and \( AA \) collisions are related by 
\[
\eta_{AA} = \eta_{pp} N_{AA}^{2/3}.
\]
Comparing \( AA \) collisions at RHIC with \( pp \) collisions at LHC, the factor \( N_{AA}^{2/3} \) can be balanced with the larger energy of LHC and the selection of high multiplicity \( pp \) collisions. In fig 1, we show our predictions for the parameter \( b, b = \langle n_f n_B > - \langle n_f \rangle < n_B > \rangle / \langle n_f^2 \rangle \) as a function of the rapidity gap \( \Delta \eta \), for \( pp \) at LHC energies, and for a forward on rapidity bins of 0.2. We observe large rapidity correlations, covering 8 units of rapidity. The CMS collaboration has reported large rapidity correlations has to do with the ridge structure observed at RHIC for \( A - A \) collisions [5][10]. In fact, the quantity measured, \( \Delta \rho / \sqrt{\rho_{ref}} \) is the density of particles correlated with a particle emitted at zero rapidity. The quantity \( \Delta \rho \) is the difference in densities between single events and mixed events, \( \rho_{ref} \) coming from mixed samples. It has been shown that [7]
\[
\frac{\Delta \rho}{\sqrt{\rho_{ref}}} = R \frac{dn}{dy} F(\phi)
\]
where \( F(\phi) \) describes the azimuthal dependence taken from an independent model, and \( R \) is the normalized 2-particle correlation given by
\[
R = \frac{\langle n^2 \rangle - \langle n \rangle >}{\langle n \rangle} = \frac{\langle n^2 \rangle - \langle n \rangle >}{\langle n \rangle} = \frac{1}{k}
\]
being \( 1/k \) the normalized fluctuations of the number of effective strings (color flux tube in the Glasma distribution). If the particle distribution is negative binomial with a \( NB \) parameter \( k_{NB} \) as in string percolation or in glasma, then \( k \equiv k_{NB} \).

In the low density regime the particle density is essentially Poisson and we have
\[
\eta \to 0, k \to \infty
\]
(8)
In the large \( \eta \), large \( < N > \) limit, if one assumes that the N-effective behave like a single string, with \( < N^2 > = < N >^2 \simeq < N > \), one obtains
\[
\eta \to \infty, k \to < N > \to \infty
\]
(9)
An important consequence of (7) and (9), if one assumes that the effective strings in the high energy limit emit particles as independent sources, is that \( k_1 \) for the single effective string is given by
\[
k_1 \equiv \frac{k}{< N >} \simeq 1
\]
(10)
corresponding to Bose-Einstein distribution. That behaviour was predicted out before in the Glasma [6], as an amplification of the intensity of multiple emitted gluons.

A parametrization for \( k \) satisfying (8) and (9) is
\[
k \simeq \frac{< N >}{(1 - e^{-\eta})^{3/2}}
\]
(11)
(In the CGC, \( k = < N > \), being implicit that the relation only works for the high density regime). Then
\[
\frac{dn}{dy} = \frac{1}{k} \frac{dn}{dy} = (1 - e^{-\eta})^{3/2} \mu
\]
(12)
On the other hand as
\[
1/k = \frac{1}{b - 1}
\]
(13)
the range in rapidity of the correlation observed in \( b \), is the same of the rapidity range of the ridge structure. In this way, it was predicted at LHC a ridge structure for high multiplicity \( pp \) collisions [5][9][10], extended 8 units of rapidity. The CMS collaboration has reported recently such ridge structure [11].

From (7), \( 1/k \) is the width of the distribution \( < n > \) as a function of \( n/ < n > \). The curve \( k \) as a function of \( \eta \) shows a minimum at \( \eta \simeq 1.2 \). At low density we have \( k \) decreasing with \( \eta \) and a larger density we have \( k \) increasing with \( \eta \). This change of behavior of \( k \) can be reached for \( pp \) at the highest energy of LHC and therefore the distribution \( < n > \) will start to be narrower [10].

Finally, let us mention that string percolation describes rightly the observed elliptic flow, and its dependence on \( p_t \), rapidity and centrality [9]. In percolation are obtained close analytical expressions for a \( v_2(p_t) \). For instance for the \( p_t \) integrated elliptic flow \( v_2 \) we obtain [9]
\[
v_2 \equiv \frac{e^{-\eta} - F(\eta)^2}{2F(\eta)^3} \frac{R}{R - 1} \int_0^{\pi/2} \cos(2\varphi)(\frac{R_\varphi}{R})^2
\]
(14)
where
\[
R_\varphi = R \frac{\sin(\varphi - \alpha)}{\sin \varphi}
\]
(15)
\[
\alpha = \sin^{-1}(\beta \sin \varphi)
\]
(16)
and \( \beta = \frac{b}{\sqrt{R}} \), being \( b \) the impact parameter. In fig 2 we compare our results for \( Au - Au \) collisions at \( \sqrt{s} = 200 \) GeV, for \( N_{part} = 211 \) with the experimental data for the full range of pseudorapidity \( \eta \). In fig. 3 we show our prediction for \( Pb - Pb \) collision at \( \sqrt{s} = 5.5 \) TeV.

Summarizing up, string percolation and glasma, which have been quite successful in describing the basic experimental facts obtained at RHIC, give defined predictions for LHC energies on rapidity long range correlations,
FIGURE 1. The normalized forward-backward dispersion $b$ as a function of the rapidity gap, $\Delta \eta$, between the forward and backward bins, for $pp$ collisions. The bins are of 0.2 units of rapidity. Solid line, $\sqrt{s} = 14$ TeV; dashed line $\sqrt{s} = 7$ TeV.

FIGURE 2. $v_2$ as a function of pseudorapidity for $N_{\text{part}} = 211$ in Au-Au collisions at $\sqrt{s} = 200$ GeV. Dots are our results, and the data is taken from reference [12].

Such predictions, which are valid not only for AA collisions but also for $pp$ high multiplicity collisions, if confirmed by the experimental data, can help to establish the existence of a highly coherent state formed of strong color field extended several units of rapidity.

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REFERENCES

1. N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Rev. Lett. 77 (1996) 3736 M. Nardi and H. Satz, Phys. Lett. B 442, 14 (1998)
2. J. Dias de Deus, E. G. Ferreiro, C. Pajares and R. Ugoccioni, Eur. Phys. J. C 40, 229 (2005) C. Pajares, Eur. Phys. J. C 43, 9 (2005)
3. L. D. McLerran and R. Venugopalan, Phys. Rev. D 49, 3352 (1994)
4. T. Lappi and L. McLerran, Nucl. Phys. A 772, 200 (2006)
5. P. Brogueira, J. Dias de Deus and C. Pajares, Phys. Lett. B 675, 308 (2009)
6. N. Armesto, L. McLerran and C. Pajares, Nucl. Phys. A 781, 201 (2007) Y. V. Kovchegov, E. Levin and L. D. McLerran, Phys. Rev. C 63, 024903 (2001)
7. K. Dusling, F. Gelis, T. Lappi and R. Venugopalan, Nucl. Phys. A 836, 159 (2010)
8. F. Gelis, T. Lappi and L. McLerran, Nucl. Phys. A 828 (2009) 149. S. Gavin, L. McLerran and G. Moschelli, Phys. Rev. C 79, 051902 (2009)
9. K. Aamodt et al. [ALICE Collaboration], Eur. Phys. J. C 65, 111 (2010)
10. C. Pajares, arXiv:1007.3610 [hep-ph].
11. J. D. de Deus and C. Pajares, arXiv:1011.1099 [hep-ph]. Submitted to Phys Lett B.
12. CMS collaboration arXiv 1009.4122 hep-ex
13. B. B. Back et al. [PHOBOS Collaboration], Phys. Rev. C 72, 051901 (2005) B. B. Back et al. [PHOBOS Collaboration], Phys. Rev. Lett. 97, 012301 (2006)