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Gluonic hot spots and spatial correlations inside the proton

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Abstract

In this work, largely based on [1, 2], we present a novel initial state geometry for proton-proton interactions. We rely on gluonic hot spots as effective degrees of freedom whose transverse positions inside the proton are correlated. We explore the impact of these non-trivial spatial correlations on the eccentricity and triangularity of the system following a Monte Carlo Glauber approach.

Keywords: initial state, proton-proton, hot spots, correlations

1. Introduction

Recent experimental results of high multiplicity p+p interactions at the LHC ($\sqrt{s} = 7, 8$, and 13 TeV) have revealed the existence of a non-negligible value of the elliptic flow (v_2) as well as the triangular flow (v_3) [3]. These findings initiated a lively debate in the heavy-ion physics community about wether these collective effects should be attributed to the initial state dynamics, to the hydrodynamic evolution or to a combination of both. It has been recently shown [4] that a good description of the measured values of v_2 on p+p, p+A and A+A can be achieved using a single choice for the fluid parameters within a hydrodynamical calculation. From the initial state perspective taking into account subnucleonic d.o.f and their fluctuations has been realized in several conceptually different approaches: from the wounded quark Glauber model [5, 6, 7] to the IP-Glasma framework based on the impact parameter dependent CGC saturation model [8] or EKRT [9] where the initial condition is generated combining pQCD and saturation. Especially, within the IP-Glasma approach, the proton shape fluctuations turn out to be essential to reconcile

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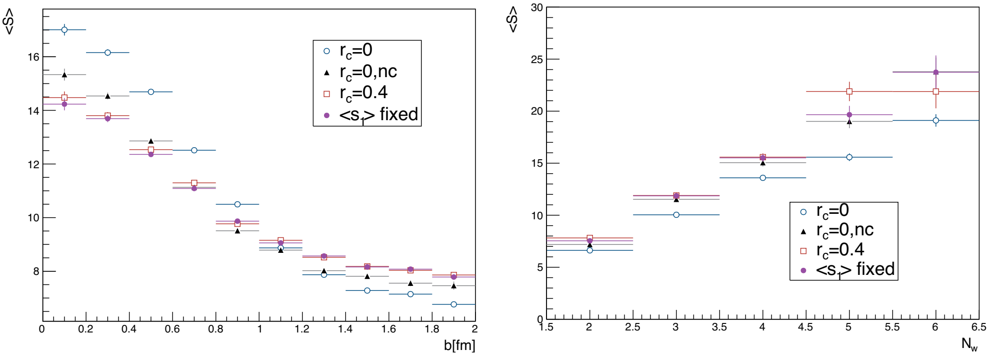

Fig. 1. Average entropy deposited vs. the impact parameter (left) and the number of wounded hot spots (right) for $r_c = 0$ (blue open circles), $r_c = 0.4$ fm (red open squares), $r_c = 0$,nc (grey filled triangles) and $\langle s_1 \rangle$ fixed (purple filled circles).

the theoretical predictions with the experimental data on v_2 in p+A at LHC energies [10]. Further constraints on the initial conditions can be extracted using Bayesian statistical techniques [11]. Nevertheless, while the previously mentioned initial condition models differ in many aspects all assume that the subnucleonic components of each colliding proton are completely independent from each other in coordinate space. This assumption may be challenged after the analysis of the p+p elastic differential cross section data from the TOTEM experiment at $\sqrt{s} = 7$ TeV [12]. The inelasticity density of the collision reaches its maximum at a non-zero value of the impact parameter i.e. $b \neq 0$. This new, i.e. not observed at lower energies, and counterintuitive phenomenon, i.e. it implies that peripheral collisions are more effective producing new particles than head-on ones at LHC energies, has been referred to as the hollowness effect in the literature [13, 14]. A microscopic realization of the hollowness effect considering the proton to be constituted by 3 gluonic hot spots within the Glauber multiple scattering theory was presented in [1]. One of the main results of that study and the most remarkable for the initial state community is the necessity to consider spatial correlations between proton constituents in order to explain the onset of the hollowness effect. The natural question arises: what is the influence of spatial correlations among the subnucleonic d.o.f on the properties of the initial state in proton-proton interactions?

2. Model ingredients

In order to tackle the latter question we have developed a Monte-Carlo Glauber event generator with event-by-event fluctuations in the hot spots positions in the transverse plane and in their entropy deposition [2]. For each p+p event several steps are followed:

- The impact parameter is chosen randomly from the distribution $\mathrm{d}N_{\mathrm{ev}}/\mathrm{d}b \propto b$ up to $b_{\max} = 2$ fm $\gtrsim 2R_p$. Other possibilities have been explored in [15].
- Once the colliding protons are located at $(x, y) = (-b/2, 0)$ and $(b/2, 0)$ we generate the transverse positions of the gluonic hot spots $(\vec{s}_1, \vec{s}_2, \vec{s}_3)$ sampling the distribution

$$D(\vec{s}_1, \vec{s}_2, \vec{s}_3) = C \prod_{i=1}^{3} e^{-s_i^2/R^2} \delta^{(2)}(\vec{s}_1 + \vec{s}_2 + \vec{s}_3) \times \prod_{\substack{i<j \\ i,j=1}}^{3} \left(1 - e^{-\mu|\vec{s}_i - \vec{s}_j|^2/R^2}\right). \tag{1}$$

The constant C ensures that $\int \{\mathrm{d}^2 s_i\} D(\{s_i\}) = 1$. The δ-function fixes the centre of mass of the hot spots system in the center of the proton. The last term is the main novelty of this work:

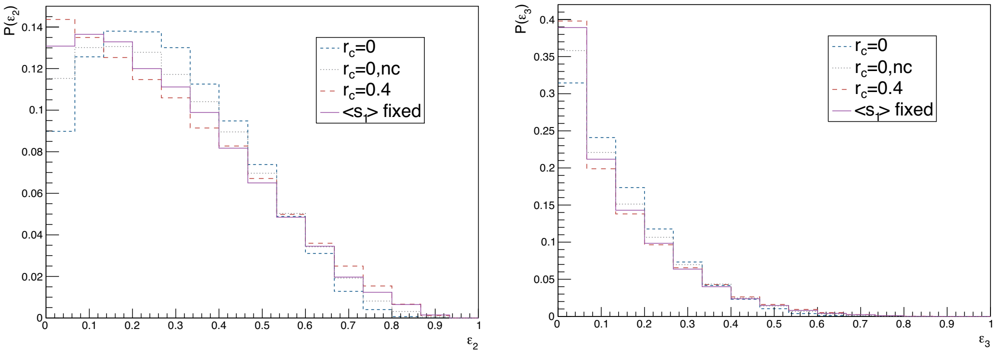

Fig. 2. Probability distributions of the eccentricity (left) and triangularity (right) for $r_c = 0$ (blue short-dashed line), $r_c = 0.4$ fm (red long-dashed line), $r_c = 0$,nc (grey dotted line) and $\langle s_1 \rangle$ fixed (purple solid line).

it implements repulsive short-range correlations between all pairs of hot spots controlled by an effective repulsive core $r_c^2 \equiv R^2/\mu$. In the limit $\mu \to \infty$, or equivalently $r_c = 0$, the uncorrelated case is recovered. Regarding the correlation structure of the hot spots, Eq. 1, we have considered two extreme scenarios: the uncorrelated case labeled as $r_c = 0$ and a repulsive core of 0.4 fm labeled as $r_c = 0.4$. A third situation, $r_c = 0$,nc, is considered where we set $r_c = 0$ but choose the values of $\{R_{hs}, R, \rho_{hs}\}$ as in the $r_c = 0.4$ case. In order to avoid the artificial swelling of the proton radius due to the repulsive correlations we have considered "$\langle s_1 \rangle$ fixed", in which $\{R_{hs}, r_c, \rho_{hs}\}$ are the same as in the $r_c = 0.4$ case but R is chosen to reproduce the $\langle s_1 \rangle \equiv \int s_1 \mathrm{d}\vec{s}_1 \mathrm{d}\vec{s}_2 \mathrm{d}\vec{s}_3 D(\vec{s}_1, \vec{s}_2, \vec{s}_3)$ of the correlated distribution.

- The probability of two hot spots to collide is sampled from

$$G_{\mathrm{in}}(d) = 2e^{-d^2/2R_{hs}^2} - (1 + \rho_{hs}^2)e^{-d^2/R_{hs}^2} \quad (2)$$

  where d is the transverse distance between a pair of hot spots with radius R_{hs}, and ρ_{hs} is the ratio of real and imaginary parts of the hot spot-hot spot scattering amplitude. We refer to a hot spot as *wounded*, if it has suffered at least one collision.

Only the wounded hot spots take part in the participant plane eccentricity calculation. Thus, ε_n are defined on an event-by-event basis. The entropy deposited by each wounded hot spot located at (x_w, y_w) is chosen to be a fluctuating quantity s_0 smeared by a Gaussian of width R_{hs}. s_0 fluctuates independently for each wounded hot spot according to a Γ-distribution with the same parameters as the negative binomial distribution that yield a precise description of the measured multiplicity [7]. The behavior of the average entropy deposited, $\langle S \rangle$, as a function of the impact parameter and the number of wounded hot spots is depicted in Fig. 1. We found a similar trend in the four cases considered in this work: $\langle S \rangle$ decreases as a function of the impact parameter as it should be by construction in our model i.e. the more central the collision (smaller impact parameter or equivalently larger number of wounded hot spots) the larger the entropy deposited. We see that the difference between "$r_c = 0.4$" and "$\langle s_1 \rangle$ fixed" cases is small in Fig. 1. Thus, we find a strong correlation on average between basic elements of the Monte Carlo Glauber approach such as impact parameter, entropy deposited and number of wounded hot spots.

3. Spatial eccentricities and Outlook

In small systems such as a p+p interactions the eccentricities are essentially driven by fluctuations in the initial state and not so much by the geometry of the collision. In Fig. 2 we show the probability distributions for ε_2 and ε_3. In our opinion this is the most general and unbiased way of showing the results from our calculation in the sense that the message is very neat: after including all the possible fluctuations of our model (impact parameter, hot spots positions and entropy deposition) the probability of having smaller eccentricities and triangularities is increased with the inclusion of correlations between the hot spots. We expect this effect to be smaller in the A+A case as there the nucleon-nucleon collisions are predominant. It should be noted that our model admit a broad range of values for ε_2 and ε_3 due to its large amount of fluctuations. This can be inferred from the broadness of the probability distributions.

In future studies we would like to address the impact of correlated constituents on more sophisticated observables of the initial state such as the symmetric cumulants, recently measured by the CMS Collaboration at $\sqrt{s} = 13$ TeV [16], that give access to the correlations among the ε_n.

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