Multiplicity dependent $p_T$ distributions of identified particles in pp collisions at 7 TeV within HIJING/$B\bar{B}$ v2.0 model

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Effects of strong longitudinal color fields (SCF) on the identified (anti)particle transverse momentum ($p_T$) distributions in pp collision at $\sqrt{s} = 7$ TeV are investigated within the framework of the HIJING/$B\bar{B}$ v2.0 model. The comparison with the experiment is performed in terms of the correlation between the mean transverse momentum ($\langle p_T \rangle$) and multiplicity ($N_{ch}$) of charged particles at central rapidity, as well as the ratios of the $p_T$ distributions to the one corresponding to the minimum bias (MB) pp collisions at the same energy, each of them normalized to the corresponding charged particle density, for high multiplicity (HM, $N_{ch} > 100$) and low multiplicity (LM, $N_{ch} < 100$) class of events. The theoretical calculations show that an increase of the strength of color fields (characterized by the effective values of the string tension $\kappa$), from $\kappa = 2$ GeV/fm to $\kappa = 5$ GeV/fm from LM to HM class of events, respectively, lead to a ratio at low and intermediate $p_T$ (i.e., $1\text{GeV}/c < p_T < 6\text{GeV}/c$) consistent with recent data obtained at LHC by the ALICE Collaboration. These results point out to the necessity of introducing a multiplicity (or energy density) dependence for the effective value of the string tension. Moreover, the string tension $\kappa = 5$ GeV/fm, describing the $p_T$ spectra of ID (anti)particle in pp collisions at $\sqrt{s} = 7$ TeV for high charged particle (HM) multiplicity event classes, has the same value as the one used in describing the $p_T$ spectra in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Therefore, we can conclude that at the LHC energies the global features of the interactions could be mostly determined by the properties of the initial chromoelectric flux tubes, while the system size may play a minor role.

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I. INTRODUCTION

Relativistic and ultra-relativistic heavy-ion experimental data evidenced global features such as flow, baryon-meson anomaly, (multi)strange enhancement, jet quenching which support the interpretation within theoretical (phenomenological) models as originating from a deconfined, strongly interacting thermalised phase, coined Quark-Gluon Plasma (sQGP). A recent review was presented at the Quark Matter Conference 2017 \cite{1,2}. In contrast, no similar effects were observed in proton-proton (pp) and proton-nucleus ($p - A$) collisions, these results being considered of interest only as reference data for nucleus-nucleus ($A - A$) collisions. Recently, features reminiscent from heavy-ion phenomenology have been found also in such reactions at the LHC energies, \textit{i.e.}, long range near side ridge in particle correlations observed in high multiplicity events \cite{3,4}, collective flow \cite{5,6}, or strangeness enhancement \cite{7}. The nature of these similarities is still an open question. Do they originate from a deconfined phase following a hydrodynamic evolution like in nucleus-nucleus ($A - A$) collisions or are they a consequence of the initial state dynamics manifested in the final state observables \cite{7,11,13}? Most probable the two processes coexist, with a dense thermalised central core and an outer corona. Such a picture is successfully implemented in the EPOS model (Energy sharing Parton based theory with Off-shell remnants and ladder Splitting) \cite{14,16}. The core-corona interplay in the light flavor hadron production for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was recently discussed in Ref. \cite{17}. Therefore, the study of of pp, $p - A$ and $A - A$ collisions as function of charged particle multiplicity has gathered recently much attention \cite{1,12,13,18,23}.

The non-perturbative particle creation mechanisms in strong external fields has a wide range of application not only in the original $e^+e^-$ pair creation on quantum electrodynamics (QED) problems \cite{24}, but also for pair creation (fermions and bosons) in strong non-Abelian electromagnetic fields \cite{25,30}. In a high-energy heavy-ion collision, strong color fields are expected to be produced between the partons of the projectile and target. Theoretical descriptions of particle production in high energy pp and $A - A$ collisions are based on the introduction of chromoelectric flux tube (strings) models \cite{37,39}. String breaking picture \cite{37} is a good example of how to convert the kinetic energy of a collisions into field energy. Therefore, Schwinger mechanism \cite{24} for non-perturbative particle production in strong color fields is assumed to play an important role in the dynamics of the pp and nucleus-nucleus ($A - A$) collisions.

In a string fragmentation phenomenology, it has
been proposed that the observed strong enhancement of strange particle production in nuclear collisions could be naturally explained via strong longitudinal color field effects (SLCF) 26. Recently, an extension of color Glass Condensate (CGC) theory has proposed a more detailed dynamical model of color ropes “GLASMA” 40–42.

In the string models, strong longitudinal fields (flux tubes, effective strings) decay into new quark anti-quark (qq) or diquark anti-diquark (qq̅, q̅q) pair production and subsequently hadronize to produce the observed hadrons. Due to confinement, the color of these strings is restricted to a small area in transverse space 30. With increasing energy of the colliding particles, the number of strings grows and they start to overlap, forming clusters. This can introduce a possible dependence of particle production on the energy density 43. The effect of modifying the string tension due to local density has been studied in Monte Carlo models, which are used primarily for heavy-ion collisions 44–49. In the Partons String Models (PSM) string fusion and percolation effects on strangeness and heavy flavor production have also been discussed in Refs. 50–52. A similar model with string fusion into color ropes is considered in the Dipole evolution in Impact Parameter Space and rapidity (DIPSY) 14, 54, 55. String collective effects were also introduced in a multi-pomeron exchange model to improve the production of hadrons in pp collisions at the LHC energies 56–58.

Heavy Ion Jet Interacting (HIJING) type models such as HIJING1.0 38–39, HIJING2.0 59, 60 and HIJING/BB v2.0 61–71, have been developed to study hadron productions in pp, p - A and A - A collisions. These models are based on a two-component geometrical model of mini-jet production and soft interaction and has incorporated nuclear effects such as shadowing (nuclear modification of the parton distribution functions) and jet quenching, via final state jet medium interaction. In the HIJING/BB v2.0 model 63, 64 we introduced new dynamical effects associated with long range coherent fields (i.e., strong longitudinal color fields, SCF), including baryon junctions and loops 65, 66. At RHIC energies we have shown 61–63 that the dynamics of strangeness production deviates considerably from calculations based on Schwinger-like estimates for homogeneous and constant color fields 24, and points to a possible contribution of fluctuations of transient strong color fields (SCF). These fields are similar to those which could appear in a GLASMA 41 at initial stage of the collisions. In a scenario with QGP phase transitions the typical field strength of SCF at ultra-relativistic energies was estimated to be about 5-12 GeV/fm 72.

The HIJING/BB v2.0 model has successfully described the global observables and identified particle (ID) data, including (multi)strange particles production in pp 65, 66, 67, p - Pb 68, 70, 71 and Pb - Pb collisions 67 at the LHC energies. However, correlations among different measurable quantities in multi-particle production offer a better way to constrain the models. In this paper we extend our study to identified particle (i.e., π, K, p, Λ, Ξ, Ω and their anti-particle) produced in the collisions of the small system. We will perform a detailed analysis of correlations between average transverse momenta (pT) and charged particles multiplicity (Nch) and for the ratio of double differential cross sections normalized to the charged particle densities (dNch/dη) versus multiplicity, i.e.,

\[ R_{mb} (cen) = \left( \frac{d^2N}{dydp_T} \right)_{i}^{cen} / \left( \frac{d^2N}{dydp_T} \right)_{i}^{ppMB} \]

where i = identified particle in pp collisions, “cen” stand for multiplicity event classes. We will consider high multiplicity (HM; Nch > 100), and low multiplicity (LM; Nch < 100 ) classes. MB stand for minimum bias events. The charged particle densities dNch/dη are integrated values at mid-pseudo-rapidity |η| < 0.5 for that class of events. The pT distributions of ID particle were recently measured in pp collisions at √s = 7 TeV for different multiplicity classes of events by ALICE Collaboration 74–76.

II. OUTLINE OF HIJING/BB V2.0 MODEL.

A. Strong color field. String tension.

In this paper we present the results of calculations for different observables measured in pp, p - Pb and Pb - Pb collisions at the LHC energies. Therefore, we consider useful for the reader to include a summary of the main input parameters which have been determined in Refs. 63, 64 and that are used in the present analysis.

For a uniform chromoelectric flux tube with field (E), the production rate for a quark pair (qq̄), per unit volume is given by 24, 72, 73

\[ \Gamma = \frac{\kappa^2}{4\pi^3} \exp \left( -\frac{\pi m_q^2}{\kappa} \right) . \]

A measurable rate for spontaneous pair production requires strong chromoelectric fields, such that \( \kappa/m_q^2 > 1 \). Introducing strong longitudinal electric field within string models, results in a highly suppressed production rate of heavy QQ̄ pair (γQQ̄) related to light quark pairs (qq). From Eq. 2 one obtains the suppression factor γQQ̄ 74:

\[ \gamma_{QQ} = \frac{\Gamma_{QQ}}{\Gamma_{qq}} = \exp \left( -\frac{\pi(m_Q^2 - m_q^2)}{\kappa} \right) . \]

The suppression factors are calculated for Q = qq (diquark), Q = s (strange), Q = c (charm), or Q = b (bottom) (q = u, d stand for light quarks).
The current quark masses are: \( m_s = 0.12 \text{ GeV}, \) \( m_c = 1.27 \text{ GeV}, \) \( m_q = 4.61 \text{ GeV} \) \cite{79}, and for di-quark \( m_{qq} = 0.45 \text{ GeV} \) \cite{80}. The constituent quark masses of light non-strange quarks are \( M_{qq,d} = 0.23 \text{ GeV}, \) of the strange quark is \( m_s = 0.28 \text{ GeV}, \) \( M_q = 0.17 \text{ GeV} \) \cite{31}, and of the diquark is \( M_{qq} = 0.55 \pm 0.05 \text{ GeV} \) \cite{80}. In our calculations, we use \( M_{qq} = 0.5 \text{ GeV}, \) \( M_s = 0.28 \text{ GeV}, \) \( M_q = 1.27 \text{ GeV}. \) Therefore, for the vacuum string tension value \( \kappa_0 = 1 \text{ GeV/fm}, \) the above formula from Eq. \ref{eq:3} results in a suppression of heavier quark production according to \( u_i : d : q_{QQ} : s : c \approx 1 : 1 : 0.02 : 0.3 : 10^{-11} \) \cite{63}. For a color rope, on the other hand, if the effective string tension value \( \kappa_0 \) increases to \( \kappa = f_{eef} \kappa_0 \) (with \( f_e > 1 \)) the value of \( \gamma_{QQ} \) increases. Equivalently, a similar increase of \( \gamma_{QQ} \) could be obtained by a decrease of quark mass from \( m_q \) to \( m_q/\sqrt{f_e} \). We have shown that this dynamical mechanism improves considerably the description of the strange meson/hyperon data at the Tevatron and at LHC energies \cite{65}. The flux tubes used to simulate \( A - A \) collisions may have a string tension almost one order of magnitude larger than the fundamental string tension linking a mesonic quark-antiquark pair \cite{52, 53}. The initial energy densities in the collisions (\( \epsilon_{ini} \)) are computed from the square of the field components \cite{50}. Within our phenomenology \( \epsilon_{ini} \) is proportional to mean field values \( < E^2 > \), and using the relation \( \kappa = \epsilon_{eff} E \), results \( \epsilon_{ini} \propto \kappa^2 \). Using Bjorken relation the \( \epsilon_{ini} \) is proportional with charged particle density at mid-rapidity and therefore \( \kappa^2 \propto \langle dN_{ch}/d\eta \rangle_{\eta=0} \). A similarity with the phenomenology embedded in the CGC model is obvious, and we obtain \( \kappa \propto Q_{sat,p} \) as discussed in Ref. \cite{62}. In Ref. \cite{66}, in order to describe the energy dependence of the charged particle density at mid rapidity in \( pp \) collisions up to the LHC energies, we used a power law dependence:

\[
\kappa(s) = \kappa_0 \left( \frac{s}{s_0} \right)^{0.04} \text{ GeV/fm}, \tag{4}
\]

consistent (within the error) with the value deduced also in CGC model for \( Q_{sat,p} \) \cite{82}. Equation \ref{eq:4} leads to an increasing value for the effective string tension value from \( \kappa = 1.5 \text{ GeV/fm} \) at \( \sqrt{s} = 0.2 \) TeV (top RHIC energy) to \( \kappa = 2.0 \text{ GeV/fm} \) at \( \sqrt{s} = 7 \) TeV. The sensitivity to the string tension values (\( \kappa \)) for different observables have been studied in previous papers \cite{62, 63, 67, 69}. Our phenomenological parametrizations Eq. \ref{eq:4} is strongly supported by data on charged particle densities at mid-rapidity \( < dN_{ch}/d\eta \rangle_{\eta=0} \). Within the error the \( \sqrt{\langle dN_{ch}/d\eta \rangle_{\eta=0}} \) shows a power law dependence proportional to \( s^{0.05} \) for inelastic \( pp \) interactions and to \( s^{0.055} \) for non-single diffractive effects \cite{83, 84}. In addition, in \( A - A \) collisions the effective string tension value could also increase due to in-medium effects \cite{67}, or dependence on the number of participants. This increase is quantified in our phenomenology by an analogy with CGC model. We consider for the mean value of the string tension an energy and mass dependence, \( \kappa(s,A) \propto Q_{sat,A}(s,A) \propto Q_{sat,p}(s,A^{1/6}) \). Therefore, we use in the present analysis for \( A - A \) collisions a power law dependence \( \kappa = \kappa(s,A) \)

\[
\kappa(s,A)_{LHC} = \kappa(s)A^{0.167} = \kappa_0 \left( \frac{s}{s_0} \right)^{0.04} A^{0.167} \text{ GeV/fm}, \tag{5}
\]

Eq. \ref{eq:5} leads to \( \kappa(s,A)_{LHC} \approx 5 \text{ GeV/fm} \), in \( Pb - Pb \) collisions at c.m. energy per nucleon \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). Note that the suppression factors \( \gamma_{QQ} \) approach unity in \( Pb - Pb \) collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \, \text{for the string tension values} \kappa \geq 5 \text{ GeV/fm}. \)

The mean effective values of the string tension \( \kappa(s) \) for \( pp \) collisions (Eq. \ref{eq:4} and \( \kappa(s,A) \) for \( Pb - Pb \) collisions (Eq. \ref{eq:5}) are used in the present calculations. These lead to an increase of the various suppression factors, as well as an enhancement of the intrinsic (primordial) transverse momentum \( k_T, \) i.e. : i) the ratio of production rates of diquark-quark to quark pairs (diquark-quark suppression factor), \( \gamma_{qq} = \Gamma(qq)/\Gamma(qq); \) ii) the ratio of production rates of strange to non-strange quark pairs (strangeness suppression factor), \( \gamma_s = \Gamma(s)/\Gamma(qq); \) iii) the extra suppression associated with a diquark containing a strange quark compared to the normal suppression of strange quark (\( \gamma_s \)), \( \gamma_{uu} = \Gamma(uu)/\Gamma(uu)/\Gamma(qq); \) iv) the suppression of spin 1 di-quarks relative to spin 0 ones (in addition to the factor of 3 enhancement of the former based on counting the number of spin states), \( \gamma_{qq}; \) and v) the (anti)quark (\( \sigma''_{qq} = \sqrt{\kappa/\kappa_0} \cdot \sigma_q \) and (anti)diquark (\( \sigma''_{qq} = \sqrt{\kappa/\kappa_0} \cdot f \cdot \sigma_{qq} \)) Gaussian width of primordial (intrinsic) transverse momentum \( k_T. \) In the above formula for \( \sigma''_{qq} \) and \( \sigma_q \) we use \( \sigma_q = \sigma_{qq} = 0.350 \text{ GeV/c} \) as default values (in absence of SCF effects) for Gaussian width of quark (diquark) intrinsic transverse momentum distribution. Note, that the factor \( f = 3 \), has been discussed in Ref. \cite{65, 66}. Moreover, for a better description of the baryon/meson anomaly seen in data at RHIC and LHC energies, a specific implementation of JJ loops, had to be introduced (for details see Refs. \cite{67, 69}). The absolute yield of charged particles, \( dN_{ch}/d\eta \) is also sensitive to the low \( p_T < 2 \text{ GeV/c} \) non-perturbative hadronization dynamics that is performed via LUND \cite{85} string JETSET \cite{86} fragmentation as constrained from lower energy \( ee, ep, pp \) data. The conventional hard pQCD mechanisms are calculated in HIJING/BB v2.0 via the PYTHIA \cite{57} subroutines. Nuclear shadowing and jet quenching are discussed in Ref. \cite{66}.

The main advantage of HIJING/BB v2.0 over PYTHIA 6.4 is the ability to include novel SCF color rope effects that arise from longitudinal fields amplified by the random walk in color space of the high x valence partons in \( A - A \) collisions. This random walk could induce a very broad fluctuation spectrum of the effective string tension. In the present work we will study only the effect of a larger effective value \( \kappa > 1 \text{ GeV/fm} \) on the production of identified particles measured in \( Pb - Pb, p - Pb \) and \( pp \) collisions at LHC energies. The model is based on the time-independent strength of color field while in reality the production of \( QQ \) pairs is a far-from-equilibrium.
time and space dependent complex phenomenon. Therefore, we can not investigate in details possible fluctuations which could appear due to these more complex dependencies.

III. NUMERICAL RESULTS AND DISCUSSION

A. The average transverse momentum \( \langle p_T \rangle \) versus \( N_{ch} \) correlations

The HIJING/BB v2.0 model predicts many experimental observables (charged hadron pseudo-rapidity distributions, transverse momentum spectra, identified particle spectra, baryon-to-meson ratios) using the above values for the effective string tension, \( \kappa \) (see Sec. II) [65, 66, 68–70].

The ALICE Collaboration has reported measurements of the average transverse momentum \( \langle p_T \rangle \) versus charged particles \( N_{ch}^* \) at central rapidity in \( pp \) at \( \sqrt{s} = 7 \) TeV, \( pp - Pb \) at \( \sqrt{s_{NN}} = 5.02 \) TeV, and \( Pb - Pb \) collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV [88]. The analysis range was restricted to a \( NN \) range of \( 5.02 \) TeV, and \( Pb - Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV (left panel) and \( p - Pb \) at \( \sqrt{s_{NN}} = 5.02 \) TeV (right panel). As we can see in Fig. 1 a continuous increase of \( \langle p_T \rangle \) with \( N_{ch}^* \) is observed for both reactions. Therefore, to calculate the correlation \( \langle p_T \rangle_{N_{ch}} \) vs \( N_{ch}^* \), we first investigate in a model of hadronizing strings if the above increase could be attributed to the effects of SCF and the results are given for different strength of color fields quantified by an effective value of the string tension from \( \kappa = 1 \) GeV/fm (default value) up to \( \kappa = 5 \) GeV/fm. As we could remark, the calculations with the default value \( \kappa = 1 \) GeV/fm, describe better the \( pp \) data. An alternative explanation of the increase of \( \langle p_T \rangle \) with \( N_{ch}^* \) should be naturally given in the context of the fragmentation of multiple minijets embedded in HIJING type models [88] and was discussed in the early 90s for \( pp \) collisions at \( \sqrt{s} = 1.8 \) TeV [92]. The large multiplicity events are dominated by multiple minijets while low multiplicity events are dominated by those of no jet production. Few partons are enough to explain the increase of \( \langle p_T \rangle \) with \( N_{ch}^* \). We may also conclude that these correlations in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV are not sensitive to the soft fragmentation region, where we expect that SCF effects are dominant. In contrast, for \( pp - Pb \) collisions the theoretical calculations compared to data [88] in Fig. 11 (right panel) show better agreement if the value of \( \kappa \) is increased from \( \kappa = 1 \) GeV/fm to \( \kappa = 3 \) GeV/fm.

We will study now the effect of an enhanced value of the effective string tension \( \kappa \) on the correlation of \( \langle p_T \rangle \) versus \( N_{ch}^* \) for ID particle in \( pp \) and \( p - Pb \) collisions at \( \sqrt{s} = 7 \) TeV, and \( \sqrt{s_{NN}} = 5.02 \) TeV, respectively. Shown in Fig. 12 are our theoretical calculations (open symbols) in comparison with data [74, 75] on the \( \langle p_T \rangle \) of \( \pi^+ + \pi^- \), \( K^+ + K^- \), \( p + \bar{p}, \Xi^- + \bar{\Xi}^+ \), and \( \Omega^- + \bar{\Omega}^+ \) for \( 0 < p_T < 10 \) GeV/c and mid-rapidity |\( y \)| < 0.5 versus charged particle multiplicity \( N_{ch}^* \) (selected in the |\( y \)| < 0.5 range) for \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. The results (open symbols) are given for two values of the effective string tension \( \kappa = 2 \) GeV/fm (left panel) and \( \kappa = 5 \) GeV/fm (right panel). The data show an increase of \( \langle p_T \rangle \) with increased multiplicity and with the particle mass, facts fairly well described by the model. Note, that for clarity we did not include here the results for \( \Lambda + \bar{\Lambda} \). Since the mass difference between lambda and proton is very small, the results are almost the same [74]. The \( \langle p_T \rangle \) increases with increasing multiplicity as the effect of the strong color field (SCF) embedded in our model. A modified string fragmentation using \( \kappa = 2 \) GeV/fm increase the production rate for heavier particle production. Moreover an increase of the width of the primordial (intrinsic) transverse momentum \( (k_T) \) distribution from the default value of the Gaussian \( \sigma_q = \sigma_{q\bar{q}} = 0.350 \) GeV/c to larger values for the (anti)quark \( \sigma_q = \sqrt{\kappa/\kappa_0} \cdot \sigma_q \) and (anti)diquark \( \sigma_{q\bar{q}} = \sqrt{\kappa/\kappa_0} \cdot f \cdot \sigma_{q\bar{q}} \), where \( f = 3 \) [63, 62], contribute also to an increases of the heavier particle production rate. This provides a consistent evidence that modified fragmentation obtained by an enhanced \( \kappa \) from the default value \( \kappa = 1 \) GeV/fm and minijet production as implemented in HIJING/BB v2.0 model lead to a fairly good description of these observables. However, the model give only partial agreement of \( \langle p_T \rangle \) values for ID particle at high multiplicity. The model describes well \( \langle p_T \rangle \) of \( \pi^+ + \pi^- , p + \bar{p}, \Lambda + \bar{\Lambda} \), but the results strongly underestimate the \( \langle p_T \rangle \) of (multi)strange particles as \( K^+ + K^- \), and \( \Xi^- + \bar{\Xi}^+ \), and \( \Omega^- + \bar{\Omega}^+ \). We studied if one can find a scenario that would give a larger enhancement of the \( \langle p_T \rangle \) of (multi)strange particles. We consider the effect of a further increase of the string tension to \( \kappa = 5 \) GeV/fm and the results are presented in Fig. 2 (right panel).

Note that a value \( \kappa \approx 5 \kappa_0 \) GeV/fm is also supported by the calculations at finite temperature \( (T) \) of potentials associated with a \( q\bar{q} \) pair separated by a distance \( r \) [89]. The finite temperature \( (T) \) form of the \( q\bar{q} \) potential has been calculated by means of lattice QCD [90]. At finite temperature, there are two potentials associated with a \( q\bar{q} \) pair separated by a distance \( r \): the free energy \( F(T, r) \) and internal energy \( V(T, r) \). The free and internal energies actually correspond to slow and fast (relative) motion of the charges, respectively. Infrared sensitive variables such as string tension are very helpful to identify specific degrees of freedom of the plasma. Since the confinement of color in non-Abelian theories is due to the magnetic degree of freedom, the magnetic component is expected to be present in the plasma as well. In the presence of the chromo-magnetic scenario it was shown that the effective string tension of the free energy \( \kappa = \kappa_F \) decreases with \( T \) to near zero at critical temperature \( (T_c) \). In contrast, the effective string tension of the internal energy (corresponding to a fast relative motion of the charges) \( \kappa = \kappa_V \) remains nonzero below \( T_c \approx 1.3 T_c \) with a peak value at \( T_c \) about 5 times the vacuum tension.
FIG. 1. Open symbols-HIJING/B ¯B v2.0 predictions for the average transverse momentum ($\langle p_T \rangle$) of charged particles as a function of multiplicity at mid-pseudo-rapidity $N^\ast_{ch}$. Left panel-pp collisions at $\sqrt{s} = 7$ TeV for $0.15 < p_T < 10$ GeV/c and mid-pseudo-rapidity $|\eta| < 0.3$; Right panel-p- Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $0.15 < p_T < 10$ GeV/c and mid-rapidity $|\eta| < 0.3$. The theoretical results are obtained for different effective string tensions increasing from $\kappa = 1$ GeV/fm (default) up to $\kappa = 5$ GeV/fm. The ALICE data (filled circles) are from Ref. [88]. The errors represent systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

FIG. 2. Open symbols-HIJING/B ¯B v2.0 predictions for the average transverse momentum ($\langle p_T \rangle$) of identified particle for $0 < p_T < 10$ GeV/c and mid-rapidity $|y| < 0.5$ as function of charged particle multiplicity, $N^\ast_{ch}$ in pp collisions at $\sqrt{s} = 7$ TeV. The results are obtained with an effective string tension value, $\kappa = 2$ GeV/fm (left side) and $\kappa = 5$ GeV/fm (right side). For clarity we do not include the results for $\Lambda$. The ALICE preliminary data (filled symbols) are from Ref. [74, 75]. Only statistical error bars are shown.

The above calculations for $\kappa \approx 5\kappa_0$ GeV/fm result in only a modest increase of the $\langle p_T \rangle$ of kaons ($K^+ + K^-$) by 10-15% and a better description of $\langle p_T \rangle$ of multi-strange particles ($\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$) only at low multiplicity ($N_{ch} < 15$). In our calculations the discrepancy obtained for $\langle p_T \rangle$ of kaons does not appear to turn over for $\kappa = 5$ GeV/fm as expected. This discrepancy may be related to the kaon enhancement reported first in Ref. [93] at Tevatron energies and confirmed now at LHC energies [74, 75]. Note, that new PYTHIA8 model which include a specific increase of the string tension values [12], also could not describe better the $\langle p_T \rangle$ of kaons in pp collisions at $\sqrt{s} = 7$ TeV. Further analysis are necessary in order to draw a definite conclusion.

In the HIJING/B ¯B v2.0 model the collective behavior is a consequence of the confining strong color fields, resulting in an interaction between strings that is without diffusion or loss of energy [13]. Therefore, for values of string tension between 5 and 10 GeV/fm (the calculations are not included here) a saturation seems to set in, possibly as an effect of energy and momentum conservation, as well as due to a saturation of strangeness suppression factors. Similar conclusions could be drawn for $\langle p_T \rangle$ of ID particles versus charged particle multiplicity, $N^\ast_{ch}$ measured in p- Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
such conclusions can be drawn from measurements of hydrodynamic evolution like in Pb - Pb collisions, or they are a function of multiplicity could be a signal for the occurrence of a phase transition in hadronic matter, i.e., formation of a mini quark-gluon plasma (mQGP). The long range near side ridge in particle correlations observed in high multiplicity events is collective flow and strangeness enhancement were evidenced in pp collisions at the LHC energies and suggest such hypothesis.

However, a fundamental question remains, are such correlation of \( p_T \) vs \( N_{ch}^* \) for ID particle in small systems (pp, p - Pb collisions) of collective origin, attributed to a hydrodynamic evolution like in Pb - Pb collisions, or they are a natural consequence due to initial state dynamics that show-up in the final state observables.

Collective hydrodynamic flow as a signature of sQGP is well established in Pb - Pb collisions at LHC energies. Such conclusions can be drawn from measurements of the invariant yields of identified particles in central Pb - Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. In Fig. 1 we consider the results for light identified charged hadrons in Pb - Pb collisions (solid histograms) in comparison with those produced in pp collisions (dashed histograms) at \( \sqrt{s} = 2.76 \) TeV. The experimental data are from ALICE Collaboration Ref. [10]. The calculation are performed taking an effective value of the string tension \( \kappa \) an energy and mass dependence as in Eq. 5, i.e.,

\[ \kappa(s, A)_{LHC} = \kappa(s) A^{0.167} = \kappa_0 (s/s_0)^{0.04} A^{0.167} \text{ GeV/fm}. \]

This formula leads to \( \kappa(s, A)_{LHC} \approx 5 \text{ GeV/fm} \) in Pb - Pb collisions at c.m. energy per nucleon \( \sqrt{s_{NN}} = 2.76 \) TeV. In pp collisions we consider only variation with energy, i.e., \( \kappa(s) = \kappa_0 (s/s_0)^{0.04} \text{ GeV/fm} \), which gives a value of \( \kappa \approx 1.9 \text{ GeV/fm} \). The results obtained within our model show a partial agreement with data, since a larger pressure in the initial state, leading to flow especially for (anti)protons, is not considered in string fragmentation models.

**B. Ratio of normalized transverse momentum distributions**

The measured transverse momentum distributions for ID particles for different multiplicity bins have been recently reported by ALICE Collaboration in pp collisions at \( \sqrt{s} = 7 \) TeV [42, 76]. The transverse momentum spectra of the identified hadrons (ID) were measured for several event multiplicity classes from the highest (class I) to the lowest (class X) multiplicity classes, corresponding to approximately 3.5 and 0.4 times the average value in the integrated sample \( \langle dN_{ch}/d\eta \rangle^{MB} \approx 6.0 \), respectively. In experiment the multiplicity classes are defined based on the total charge deposited in the V0A and V0C detectors located at forward \( (2.8 < \eta < 5.1) \) and backward \( (-3.7 < \eta < -1.7) \) pseudorapidity regions, respectively. The event multiplicity estimator is taken to be the sum of V0A and V0C signals denoted as V0M. The average charged particle density \( \langle dN_{ch}^{CP}/d\eta \rangle \), is estimated within each multiplicity class by the average of the tracks distribution in the region \( |\eta| < 0.5 \) [42, 76].

Based on these spectra and minimum bias results we will study here the ratio of double differential cross sections normalized to the charged particle densities...
$dN_{ch}^{th}/d\eta$ versus multiplicity, i.e., the ratio $R_{mb}$ defined in Eq. 11.

For theoretical calculations within HIJING/BB v2.0 model we will chose different classes of event activity cutting on the total multiplicity ($N_{ch}$) for each $10^6$ set of events generated using two effective string tension values, i.e., $\kappa = 2.0$ GeV/fm and an enhanced value to $\kappa = 5.0$ GeV/fm. Moreover, the average charged particle density, is estimated (for both set of events) within each multiplicity class of events, by the integrated value of $dN_{ch}^{th}/d\eta$ at mid-pseudorapidity ($|\eta| < 0.5$). In addition, we generate also $10^6$ minimum bias (MB) events for $\kappa = 2.0$ GeV/fm. Note, that for this selection theoretical calculations give an integrated charged particle density at mid-pseudorapidity ($|\eta| < 0.5$), $(dN_{ch}^{th}/d\eta)^{MB} = 5.7$, close to the experimental value $<dN_{ch}/d\eta>_{MB} \approx 6.0$ quoted above.

We will consider six classes of event activity defined as:

- class I: $200 \leq N_{ch} < 300; dN_{ch}^{th}/d\eta = 30.9$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 25.2$ (for $\kappa = 5$ GeV/fm).
- class II: $120 \leq N_{ch} < 200; dN_{ch}^{th}/d\eta = 18.6$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 15.1$ (for $\kappa = 5$ GeV/fm).
- class III: $100 \leq N_{ch} < 120; dN_{ch}^{th}/d\eta = 12.5$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 10.3$ (for $\kappa = 5$ GeV/fm).
- class IV: $80 \leq N_{ch} < 100; dN_{ch}^{th}/d\eta = 9.7$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 7.8$ (for $\kappa = 5$ GeV/fm).
- class V: $60 \leq N_{ch} < 80; dN_{ch}^{th}/d\eta = 7.1$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 5.7$ (for $\kappa = 5$ GeV/fm).
- class VI: $30 \leq N_{ch} < 60; dN_{ch}^{th}/d\eta = 4.7$ (for $\kappa = 2$ GeV/fm); $dN_{ch}^{th}/d\eta = 3.9$ (for $\kappa = 5$ GeV/fm).

For comparison to data from Refs. [75, 76] we show in Fig. 5, Fig. 6 and Fig. 7 the results of the HIJING/BB v2.0 predictions for transverse momentum distributions at mid-rapidity for light hadrons, i.e., $\pi, K, p$ and their anti-particles in two multiplicity classes, class I (panels a, b) and class V (panels c, d). The model estimates are represented by solid (dashed) histograms for $\kappa = 2$ GeV/fm and $\kappa = 5$ GeV/fm, respectively. For comparison with data, the experimental spectra (open stars) are chosen for an average value of $<dN_{ch}^{exp}/d\eta>$ similar with those obtained in the model, $dN_{ch}^{th}/d\eta$ (see the above six classes of event activity). The results for minimum bias $pp$ collisions obtained for $\kappa = 2$ GeV/fm and represented by dotted histograms). Data for MB are from Ref. [52] (open circles) and Ref. [97] (open squares).

The ratio of double differential cross sections normalized to the charged particle densities, $R_{mb}$ (calculated by us) is plotted for high (class I) and low (class V) multiplicity classes in panels e, f by dashed and solid histograms, respectively. This ratio is based on average $p_T$ spectra (preliminary) of particle and anti-particle measured (open stars) by ALICE Collaboration [72, 76]. In the calculations we take into account the variation of strong color (electric) field with energy. The assumed effective value of the string tension is $\kappa = 2$ GeV/fm (panel e) corresponding to $\kappa(s) = \kappa_0 (s/s_0)^{0.04}$ GeV/fm (see Eq. 3). Since we expect in high multiplicity proton-proton collisions features that are similar to those observed in Pb-Pb collisions [1, 3, 8, 13], we consider also the results obtained for an enhanced value of effective string tension to $\kappa = 5$ GeV/fm (see panel f). The agreement with the data is fairly good in the limit of the error bars, except for very low $p_T < 1$ GeV values. The experimental spectra show a small depletion at high multiplicity at very low $p_T$, indicating possible influence of the radial flow. The transverse momentum spectra of identified particles carrying light quarks and their azimuthal distributions are well described by hydrodynamical models [14, 15] at very low $p_T$. However, as far as in the string model the pressure is not considered, it is
We will explore here dynamical effects including (multi)strange particles production in the global observables and identified particle (ID) data, (multi)strange particles in p + p collisions at \( \sqrt{s} = 7 \) TeV. The effect is more evident for an enhanced effective value of string tension \( \kappa = 5 \) GeV/fm, and within experimental errors we can not rule out any of them. These calculations does not show any sensitivity to possible dependence on multiplicity of the event. Since we expect higher sensitivity to SCF effects for (multi)strange than for bulk particles, measurements of \( R_{\text{mb}} \) distributions at mid-rapidity as well as the ratio \( R_{\text{mb}} \) could help to evidentiate these effects, within the phenomenology embedded in HIJING/BB v2.0 model.

Figure 5 show the ratios of the normalized \( p_T \) distributions, \( R_{\text{mb}} \) of \( \Lambda + \bar{\Lambda} \) produced in \( p + p \) collisions at \( \sqrt{s} = 7 \) TeV. The results for six multiplicity classes (class I to class VI) based on average \( p_T \) spectra of particle and anti-particle are included. From top to bottom the calculations correspond to highest (class I) to lowest (class VI) multiplicity events. Left (Right) panels are the results obtained with \( \kappa = 2 \) GeV/fm (\( \kappa = 5 \) GeV/fm) respectively. We remark a clear hardening of the \( p_T \) spectra of particle and anti-particle measured (open stars) by ALICE Collaboration \([72,73]\). Only statistical error bars are shown.

The HIJING/BB v2.0 model has successfully described the global observables and identified particle (ID) data, including (multi)strange particles production in \( p + p \) \([65,69]\) - Pb \([68,70]\) and Pb - Pb collisions \([67]\) at the LHC energies. We will explore here dynamical effects associated with long range coherent fields (i.e. strong color fields, SCF, with emphasis on the novel observables (ratio \( R_{\text{mb}} \)) and their multiplicity dependence for (multi)strange particles in \( p + p \) collisions at \( \sqrt{s} = 7 \) TeV. Due to strange quark content of (multi)strange particle the study of the ratio \( R_{\text{mb}} \) is of particular interest. Since we expect higher sensitivity to SCF effects for (multi)strange than for bulk particles, measurements of \( R_{\text{mb}} \) distributions at mid-rapidity as well as the ratio \( R_{\text{mb}} \) could help to evidentiate these effects, within the phenomenology embedded in HIJING/BB v2.0 model.

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The experimental fact that $pp$ collisions manifest features similar with Pb - Pb collisions [3–10, 99] point out to the necessity to modify $\kappa$, in describing observables in $pp$ collisions for HM class of events. The calculations with SCF contributions assume an effective string tension value $\kappa = 2$ GeV/fm, obtained from an energy depend $\kappa$, see Sec. II, while the results with $\kappa = 5$ GeV/fm are obtained based on the above experimental fact. Note, that a specific size dependent $\kappa = \kappa(r)$ was considered recently in PYTHIA 8 model, with $r$ a new parameter fixed to fit data [12].

Therefore, in Fig. 9 (Λ and $\bar{\Lambda}$), Fig. 10 (Ξ$^-$ and $\bar{\Xi}^+$), and Fig. 11 (Ω$^-$ and $\bar{\Omega}^+$) we show the results obtained for

near side long range two-particle correlation reported by CMS Collaboration [3]. However, there is no mechanism that produces a ridge in our model.
FIG. 8. The HIJING/B̅B v2.0 model predictions for Λ + ̅Λ produced in pp collisions at √s = 7 TeV. The ratios of the normalized p_T distributions, R_{mb} (see Eq. 1) for six multiplicity classes (see text for explanation) based on average p_T spectra of particle and anti-particle. From top to bottom the calculations correspond to class (I) to class (VI) multiplicity events. Left-the results obtained with κ = 2 GeV/fm; Right- the results obtained with (κ = 5 GeV/fm).

FIG. 9. The same as in Fig. 8 for events of high (class II) and low (class VI) multiplicity. The calculations are for Λ and ̅Λ. The results for minimum bias pp collisions obtained with κ = 2 GeV/fm (dotted histograms) are included and compared to data from CMS Collaborations [97] (open squares). Only statistical error bars are shown.

p_T distributions at mid-rapidity for (multi)strange particles in two event classes, corresponding to high (HM) and low (LM) multiplicity. The calculations for minimum bias events are included and compared to data from Refs. [74, 75, 97]. As in the previous calculations comparison to data for HM and LM events, is made for p_T spectra obtained for a class of multiplicity events which give a value of dN_{ch}^exp/dη similar with those obtained in the experiment < dN_{ch}^{ch}/dη > . Theoretical predictions for the p_T dependence of R_{mb} for Λ + Λ, Ξ^− + ̅Ξ^−, and Ω^− + ̅Ω^+ are presented for two scenarios: using κ = 2 GeV/fm (panel c) and an increased value to κ = 5 GeV/fm (panel f). The results show a clear hardening of p_T spectra in case of HM class of events. Moreover, in case of the LM class of events, the R_{mb} ratio of (multi)strange particles are better described using κ = 2 GeV/fm. In contrast, an increase of effective value κ to κ = 5 GeV/fm better describes class with HM events. The remark is true for strange Λ + ̅Λ as well as for multi-strange (Ξ^− + ̅Ξ^−, Ω^− + ̅Ω^+) particle in pp collisions at √s = 7 TeV.

To conclude, for a better description of (multi)strange particle productions we have to consider an increase of
effective string tension value from $\kappa = 2$ GeV/fm to $\kappa = 5$ GeV/fm, which is strongly supported by data. The fact that an effective value $\kappa = 5$ GeV/fm describes better the $R_{mb}$ ratio in $pp$ collisions at $\sqrt{s} = 7$ TeV, reveal features similar with those observed in chromoelectric flux configurations used to describe some experimental observables in Pb - Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [66]. The enhancement of (multi)strange hadron yields as function of multiplicity have been associated with the creation of a strongly interacting medium, sQGP [91]. Recently, a similar behavior was also observed for (multi)strangeness production in the LM event classes. A better description is obtained for an enhanced effective string tension value $\kappa = 5$ GeV/fm which point out to the necessity of a new dependency on multiplicity (or $\epsilon_{ini}$ ) for the effective string tension value, $\kappa$.

IV. SUMMARY AND CONCLUSIONS

In summary, we studied in the framework of the HIJING/BB v2.0 model, the influence of possible strong homogeneous constant color electric fields on new experimental observables measured by ALICE Collaboration, especially for identified particle in $pp$, $p - Pb$, and Pb - Pb collisions at $\sqrt{s} = 7$ TeV, $\sqrt{s_{NN}} = 5.02$ TeV, and $\sqrt{s_{NN}} = 2.76$ TeV, respectively. The effective string tension $\kappa$, control QQ pair creation rates and the suppression factors $\gamma_{QQ}$. The measured average transverse momentum and ratio $R_{mb}$ of ID particle help to verify our assumptions and to set the strangeness suppression factor. We assume in our calculations an energy and possible system dependence of the effective string tension, $\kappa$.

For Pb - Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV all nuclear effects included in the model, e.g., strong color fields, shadowing and quenching should be taken into account. However, partonic energy loss and jet quenching process as embedded in the model achieve a reasonable description of the $p_{T}$ distributions of light hadrons ($\pi$, $K$, $p$). The discrepancy could be explained by an initial condition with a large pressure and therefore a large collective flow, which is not embedded in our model.

For identified particle in $pp$ collisions at $\sqrt{s} = 7$ TeV we compute correlation between mean transverse momentum and multiplicity of charged particles ($N_{ch}^{*}$) at central rapidity as well as the ratio of double differential cross sections normalized to the charged particle densities versus multiplicity, $R_{mb}$. In the calculations we
take into account the variation of strong color (electric) field with energy but not with the multiplicity (or initial energy densities, \( \epsilon_{\text{ini}} \)) of the colliding system. The assumed effective string tension is \( \kappa = 2 \text{ GeV/fm} \), corresponding to \( \kappa(s) = \kappa_0 (s/s_0)^{0.04} \) GeV/fm (see Eq. 4). Since we expect in high multiplicity proton-proton collisions features that are similar to those observed in Pb-Pb collisions [1, 3, 8, 18], we consider also the results obtained with an enhanced value of the effective string tension, from \( \kappa = 2 \text{ GeV/fm} \) to \( \kappa = 5 \text{ GeV/fm} \). This increase of the strength of color fields lead to a ratio \( R_{\text{mb}} \) consistent with recent data for HM class of events, while in the LM class of events \( R_{\text{mb}} \) is better described using a lower effective string tension value \( \kappa = 2 \text{ GeV/fm} \). These results show that the above increase of the strength of color fields could be an important dynamical mechanisms. New measurements with high statistics at low and intermediate \( p_T < 6 \text{ GeV/c} \) of the ratio \( R_{\text{mb}} \) in \( pp \) collisions at LHC energies, could help to disentangle between different model approaches and/or different dynamical mechanisms, especially for high multiplicity event classes.

Note, that the HIJING/B slices model is based on a time-independent strength of color field, while in reality the production of QQ pairs is more complex being far-from-equilibrium, time and space dependent phenomenon. To achieve more quantitative conclusions, such time and space dependent mechanisms [34, 78] should be considered in future generations of Monte Carlo codes.

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