Strong colour fields and cosmic ray showers at ultra-high energies

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Abstract

We argue that the increase of the ratio baryon/meson due to the presence of strong colour fields and percolation in ultra-high energy hadronic collisions, helps to explain some of the global features of ultra-high energy cosmic ray cascades at $E > 10^{18}$ eV and, in particular the observed excess in the number of muons with respect to current models of hadronic interactions. A reasonable agreement with the small value and slope of the average depth of shower maximum $\langle X_{\text{max}} \rangle$ vs shower energy – as seen in data collected at the Pierre Auger Observatory – can be obtained with a fast increase of the p-Air production cross-section compatible with the Froissart bound.

Key words: Strong color fields, percolation, high energy cosmic rays, extensive air showers, muons, elongation rate

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The largest source of uncertainty in the prediction of observables of cosmic-ray induced atmospheric showers at ultra-high energy (UHE) – above $\sim 10^{17} - 10^{18}$ eV – stems from our limited knowledge of the features of hadronic interactions in this energy range. QCD-inspired models of multi-particle production need to be extrapolated to energies far beyond those reached in terrestrial accelerators, and in regions of phase space of the collisions usually not covered in collider or accelerator experiments. On the other hand inferring the properties of the hadronic interactions at UHE in cosmic ray experiments is not an easy task which is hampered by the low luminosity of the primary beam, and by the unknown nature of its constituents. Furthermore, data are relatively scarce at such high energies.

The composition of cosmic rays at high energies is still a matter of controversy,
mainly because direct measurements are only possible up to $E \sim 10^{15}$ eV [1].

Above this energy, attempts to infer the mass number $A$ of the primary particle are based on measured shower variables and are rather indirect [2]. Observables such as the number of muons at ground level $N_\mu$, or the depth at which the maximum in shower longitudinal development occurs $X_{\text{max}}$, are sensitive to both the nature of the primary and the hadronic interaction model [3]. In particular, the muon component of the shower is a powerful tool for the validation of hadronic interaction models.

Very recently an analysis of the data collected with the hybrid detector of the Pierre Auger Observatory [4], indicated that the number of muons produced in UHE showers is about 1.5 times larger than that predicted by the QGSJETII [5] model assuming proton primaries. This conclusion seems to be rather independent of the primary cosmic ray composition. This “deficit of muons” in the hadronic interaction models is consistent with the one found in the recent analysis of more direct data on muons collected with the Yakutsk array [6].

The Pierre Auger Collaboration has also reported that the arrival directions of 20 out of the 27 most energetic detected events above 57 EeV (1 EeV = $10^{18}$ eV) correlate with the positions in the sky of nearby Active Galactic Nuclei (AGN) [7], which are candidate sources of cosmic-ray production and acceleration to ultra-high energies. It has been pointed out [7] that this result together with the observed suppression of the cosmic-ray flux above 60 EeV [8,9], is consistent with the hypothesis that most of the cosmic rays reaching the Earth are protons from nearby astrophysical sources [7].

There are also measurements of the average depth of maximum shower development as a function of energy [10,11]. The measured $\langle X_{\text{max}} \rangle$ is smaller than what is predicted by current hadronic models assuming a proton dominated composition, and moreover it increases with energy slower than expected [10].

In this work under the assumption of proton primaries, we show that the presence of strong colour fields in UHE collisions increases the ratio of baryons to mesons ($B/M$) with respect to hadronic models currently used in the simulation of atmospheric showers. This has the effect of increasing the number of muons, following the tendency seen in data. We also find that the behaviour of $X_{\text{max}}$ is not strongly affected by strong colour fields, and conclude that available data can be explained with a rapid increase of the p-Air production cross section, but still compatible with the Froissart bound.

The global features of particle production in hadron-hadron (hh), hadron-nucleus (hA) and nucleus-nucleus (AA) collisions seem to be well described by models where particles are produced in the decay of longitudinal strings formed in the initial stage of the interaction [13,14,16,17,18,19]. However, in order to explain some effects observed at SPS and RHIC energies, such as
the limited growth of the rapidity particle density in the central region, or
the increase of the average transverse momentum and strangeness with the
number of participant nucleons [20], one requires the introduction of fusion
of strings [21,22] or more generally percolation of strings [24,25]. One should
mention here that the results obtained within the string percolation model
coincide to a large extent with those of the Colour Glass Condensate model
[26-27].

The key idea in the present work is that fusion and percolation of strings
lead to the formation of strings with higher string tension, and this implies
that mass effects – formation of strange quarks, di-quarks, etc... – become less
important. In the Schwinger model of string fragmentation [28], the probability
of generating a set $S$ of quarks and anti-quarks and a conjugate set $\bar{S}$ out of
the vacuum, each one with mass $M$, is

$$P_M \sim \exp\left(-\frac{\pi}{\kappa} M^2\right)$$

where $\kappa$ is the string tension. As $\kappa$ tends to infinity the probability (1) becomes
less and less dependent on $M$. The role of strong colour fields to increase the
fraction of heavier particles has also been emphasized in [21,22,23,29,30,31].

If we consider a single $q-\bar{q}$ ($3-\bar{3}$) string, with $m$ being the mass of the
$u$ and $d$ quarks ($m \simeq 0.23$ GeV), and $\kappa$ the 3-representation string tension
$\kappa \simeq 0.2$ GeV$^2$, and neglect strangeness and higher mass flavours, we have that
the probability $B$ of producing a baryon is given by

$$B \sim \exp\left(-\frac{\pi}{\kappa} 4m^2\right)$$

and the corresponding probability $M$ for meson production is

$$M \sim \exp\left(-\frac{\pi}{\kappa} m^2\right),$$

so that the ratio $B/M$ is

$$B/M \sim \exp\left(-\frac{\pi}{\kappa} 3m^2\right) \simeq 0.083.$$  

This is our reference value for the ratio $B/M$ at low energies.

We shall next consider the effect of exchanging a quark by a diquark, as in
Eqs. (2) and (3), in more complex systems. In ($q-\bar{q}$) ($q-\bar{q}$) fused strings, if
they are in the SU(3) 6-representation with \( \kappa_6 = 5\kappa/2 \), we obtain

\[
\exp \left( -\frac{\pi}{\kappa} 2m^2 \right) \simeq 0.19. \tag{5}
\]

which is larger than Eq. (4). Furthermore, if we consider \((q - \bar{q})(q - \bar{q})\) in the 8-representation with \( \kappa_8 = 9\kappa/4 \), one obtains

\[
\exp \left( -\frac{\pi}{\kappa} \frac{20}{9}m^2 \right) \simeq 0.16 \tag{6}
\]

which is again larger than Eq. (4).

In general, if we consider \( N \) quarks in \((m,n)\) representations of SU(3) (see for instance [32]), the highest dimension representation corresponds to \( N = m+2n \) with \( m \simeq 2n \simeq N/2 \), and \( \kappa_{(m,n)} \simeq \alpha \kappa N^2 \) with \( \alpha \) being a number of the order of \( \sim 1/260 \) such that for the quark diquark interchange we obtain,

\[
\exp \left( -\frac{\pi}{\kappa} \frac{(N+1)^2}{N^2} m^2 \right) \exp \left( -\frac{\pi}{\kappa} \frac{m^2}{N} \right) \tag{7}
\]

and, in the \( N \to \infty \) limit,

\[
\exp \left( -\frac{\pi}{\kappa \alpha} \frac{2m^2}{N} \right) \to 1 \tag{8}
\]

We take this result as an indication for the increase of the ratio \( B/M \) as the energy or centrality of the collision increases.

It is also worth emphasizing that the enhancement of baryons or antibaryons over mesons is not only due to a mass effect as explained above. In fact in addition to the larger color and string tension in the percolation model, the way the cluster formed from the overlapping of individual strings decays, favours the increase of the ratio \( B/M \) with energy and/or density of strings. Consider a cluster formed by several \( q - \bar{q} \) strings. This cluster behaves as a \( Q - \bar{Q} \) string, where \( Q \) is composed of the different flavours of the individual \( q - \bar{q} \) strings. The fragmentation of a cluster occurs through the successive creation of \( Q - \bar{Q} \) complexes [23]. Clearly this mechanism leads to an enhancement in the production of baryons over mesons, because the large number of quarks in the cluster of strings favours the formation of particles with higher number of constituents [33]. Coalescence and recombination models [34] proposed similar mechanisms to explain the suppression of pion yields relative to baryons and antibaryons observed in relativistic heavy-nuclei collisions [20].
The increase with energy of $B/M$ helps to explain the excess of muons in data when compared to existing hadronic interaction models. In fact, increasing the number of baryons and anti-baryons more muons are produced. This effect has been shown with a simple toy model and also in the framework of the EPOS model of hadronic interaction in [30]. Increasing the number of baryons decreases the number of neutral pions $\pi^0$ which decay into $\gamma\gamma$ and initiate electromagnetic sub-showers in which muon production is typically very small. Moreover a decrease in the amount of shower energy going into $\pi^0$s increases the total number of hadronic interactions in the shower, in which copious muon production typically occurs. Also $\pi^0$s tend to stretch shower development due to the production of electromagnetic sub-showers with comparatively larger $X_{\text{max}}$ than hadronic sub-showers of the same energy. As a consequence one would expect that decreasing the number of $\pi^0$s – increasing the $B/M$ ratio – would limit the rate of increase of $X_{\text{max}}$ with energy, a tendency seen in cosmic ray data. It is important to note that an increase of the $B/M$ ratio also leads to a reduction in the number of charged pions, but as a first approximation charged pions play the same role as baryons in shower development and hence this has no consequences for either pion production or the behaviour of $X_{\text{max}}$.

In order to test these effects in a more quantitative way and make contact with Auger data, we have simulated sets of 100 proton induced showers at energies ranging from $E = 10^{15}$ eV up to $10^{20}$ eV. The hybrid, one-dimensional shower simulation described in [37] was used to obtain the average number of muons at Auger ground level $\langle N_{\mu} \rangle$, and the average depth of shower maximum $\langle X_{\text{max}} \rangle$. Firstly, we used the SIBYLL 2.1 hadronic interaction model described in [38] which includes a ratio $B/M \sim 0.075$ constant with energy. Then we modified the SIBYLL 2.1 model and implemented a value of $B/M$ according to the following relation

$$B/M = 0.1 \log_{10} \frac{E}{\text{eV}} - 1.3$$

(normalized to the SIBYLL 2.1 value at low energy $E \sim 10^{14}$ eV where accelerator data exists.

In Fig. [1] we show the relative increase in the number of muons when increasing the ratio $B/M$. The relative difference between the average number of muons at ground predicted by SIBYLL 2.1 with $B/M \sim 0.075$, and the number of muons predicted by SIBYLL 2.1 but with $B/M$ following Eq. (9) is shown as a function of shower energy. One can see that at the highest energies the number of muons can increase by as much as 50% in agreement with Auger data [4]. It is important to remark that the choice of the underlying hadronic model is not relevant for our results, since we are only interested in the relative change of the number of muons when increasing the ratio $B/M$. 


Fig. 1. Solid line: Relative difference between the average number of muons at Auger ground obtained in proton-initiated showers simulated with the SIBYLL 2.1 model, with a ratio $B/M \sim 0.075$ constant with energy $\langle N_{\mu}(\text{SIB}) \rangle$, and with the SIBYLL 2.1 model but with a modified ratio $B/M$ following Eq. (9) $\langle N_{\mu}(B/M) \rangle$. The relative difference is calculated as $\left[\langle N_{\mu}(B/M) \rangle - \langle N_{\mu}(\text{SIB}) \rangle\right]/\langle N_{\mu}(\text{SIB}) \rangle$ and is shown as a function of shower energy. The lines joining the points are just to guide the eye.

In Fig. 2 we show the behaviour of $X_{\text{max}}$ with energy as obtained in proton-induced showers with the SIBYLL 2.1 model, and with the SIBYLL 2.1 model with the ratio of $B/M$ modified according to Eq. (9). As explained above, increasing the ratio $B/M$ decreases the slope of $\langle X_{\text{max}} \rangle$ vs $E$ curve and the value of $\langle X_{\text{max}} \rangle$ due to the decrease in the production of $\pi^0$, which would otherwise induce electromagnetic subshowers evolving deep into the atmosphere. One can see that the decrease of $\langle X_{\text{max}} \rangle$ is not large enough to explain the trend observed in the data collected at the Pierre Auger Observatory [10] also shown in Fig. 2.

Another important consequence of the presence of strong colour fields in the region where the interaction occurs is the percolation of strings. More details on the percolation model can be found in [39,40]. Of special importance for shower development is the prediction of the percolation model on the inelasticity $K$, defined as one minus the fraction of momentum carried by the fastest (leading) particle. Essentially, all existing high energy strong interaction models based on QCD and QCD evolution, predict an increase with energy of the inelasticity [41]. The same is true for the hadronic generators SIBYLL [38].
Fig. 2. Solid line with empty circles: Behaviour of the average depth of shower maximum $\langle X_{\text{max}} \rangle$ with energy as obtained in proton-initiated showers simulated with the SIBYLL 2.1 model with ratio $B/M \sim 0.075$ constant with energy. Dashed line with empty squares: $\langle X_{\text{max}} \rangle$ with the SIBYLL 2.1 model but with a modified ratio $B/M$ following Eq. (9). Dotted line with empty circles: $\langle X_{\text{max}} \rangle$ predicted by the SIBYLL 2.1 model but with a modified ratio $B/M$ following Eq. (9), using the inelasticity $K$ predicted by the percolation model and with the p-Air and $\pi^{-}$Air cross section modified according to Eq. (10). The filled squared points without lines are the data on $\langle X_{\text{max}} \rangle$ collected at the Pierre Auger Observatory [10], and QGSJET [5], widely used in the analysis of cosmic ray data. However as shown in [10], above the percolation threshold the inelasticity decreases with energy. This has important consequences for shower development as studied in [40, 12], among them a decrease of the inelasticity tends to propagate the primary energy deeper into the atmosphere and increase $X_{\text{max}}$ in contrast to what is seen in Auger data. Note that the observed decrease of $\langle X_{\text{max}} \rangle$ with energy [10] is at odds with the reported reduction of $A$ at high energies [7]. As we shall see next, the behaviour of $X_{\text{max}}$ with energy may be accommodated with an increase of the p-Air cross section compatible with the Froissart bound.

We have implemented the inelasticity predicted by the percolation model [40] in the SIBYLL 2.1 hadronic generator. Also we decreased the position of the first interaction and subsequent hadronic collisions by increasing the p-Air and $\pi^{-}$Air production cross section in a similar manner as was done in [12]. In particular we have changed the SIBYLL 2.1 energy dependence of the
production cross section $\sigma_{p-Air}^{SIBYLL}$ using the relation

\[ \sigma_{p-Air} = \sigma_{p-Air}^{SIBYLL} \left( 1 + 0.2 \log_{10} \frac{E}{10^{15} \text{eV}} \right) \quad (10) \]

which we apply for $E \geq 10^{15}$ eV, so that at lower energies one reproduces accelerator data. Moreover, since the SIBYLL cross section behaves as $\log E$ the modified cross section in Eq. (10) clearly behaves as $\log^2 E$, saturating the Froissart bound but not violating it. The p-Air cross section in Eq. (10) and the SIBYLL 2.1 p-Air cross section are shown in Fig. 3.

![Graph showing the comparison of SIBYLL 2.1 p-Air cross section to the modified p-Air cross section in Eq. (10). The graph plots p-Air cross section (mb) against Proton energy (eV). The SIBYLL 2.1 cross section is shown in red, and the modified cross section in Eq. (10) is shown in blue. The graph shows that at lower energies, the SIBYLL cross section behaves as $\log E$, while the modified cross section behaves as $\log^2 E$, saturating the Froissart bound but not violating it.](image)

Fig. 3. The SIBYLL 2.1 p-Air cross section (solid line) compared to the modified p-Air cross section (dashed line) in Eq. (10). Note that the SIBYLL cross section behaves as $\log E$, while the modified cross section behaves as $\log^2 E$, saturating the Froissart bound but not violating it.

Our results for $\langle X_{max} \rangle$ are shown in Fig. 2 where a fair agreement with Auger data can be seen. This is mainly due to the changes implemented in the SIBYLL 2.1 cross-section, while modifying the inelasticity and the $B/M$ ratio according to what strong colour fields induce, affects $\langle X_{max} \rangle$ much less. It is also interesting to note that an increase of the p-Air cross section also induces a decrease of the RMS of the $X_{max}$ distribution with respect to what current models of hadronic interaction predict for proton-initiated showers.

Also we have checked in our shower simulations, that the increase in the number of muons is fairly insensitive to both the decrease of inelasticity due to
percolation of strings, and to the increase of the p-Air and $\pi-$Air cross-section, the dominant effect being the increase of the ratio $B/M$.

We have shown that strong colour fields associated to high dimension representations of $Q - \bar{Q}$ strings, together with the $Q - \bar{Q}$ string breaking mechanism, lead to the increase of the $B/M$ ratio with respect to current hadronic models in which the $B/M$ ratio is $\sim 0.1$ and constant with energy. For UHE cosmic ray-induced showers this results in an increase of the average number of muons in the shower at ground level, and in a (small) decrease of $\langle X_{\text{max}} \rangle$. In order to further decrease $\langle X_{\text{max}} \rangle$ and approximately agree with data, a large, but still compatible with the Froissart bound increase of the p-Air and $\pi$-Air cross sections with energy is required.

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