The LHC inclusive results and interaction model extrapolatins to the UHECR domain.

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Abstract: The pseudorapidity measurements at LHC, although in the central region only, allows to perform preliminary tests of the multiparticle production extrapolation formula inspired by the recent cosmic ray data analysis. We have shown that the rapidity distributions measured by LHC experiments follow the some universal high energy distribution scaled respectively in a way proposed in 70s by Wdowczyk and Wolfendale. The high degree of Feynman scaling violation is confirmed. The decrease of the very high energy interaction inelasticity suggested by cosmic ray data analysis is found to be consistent with LHC measurements up to 7 TeV.

Keywords: high-energy interactions, LHC, scaling violation

1 Introduction

The inclusive description of minimum bias LHC events is not as spectacular as, e.g., Higgs hunting, but is essential for other very important scientific endeavours. One of them is the Ultra High-Energy Cosmic Ray (UHECR) problem and the answer to the question of an existence of Greizen-Zatsepin-Kuzmin (GZK) cut-off [1]. The origin and nature of cosmic rays is studied for almost exactly 100 years. The great experimental effort has been taken recently by two groups: the Pierre Auger Observatory [2] and the Hi-Res experiment [3]. The progress is observed, but the answers are still not decisive. The cosmic rays of energies of about 10^{20}eV, if they are protons, should not reach us from cosmological distances. On the other hand anisotropy measurements show that they probably actually do. Our knowledge about the nature of UHECR is based on observation of giant Extensive Air Showers (EAS) - cascades of secondary particles created in the atmosphere when the single atomic nucleus (proton in a simplest case) enters from above. It is expected that the EAS initiated by protons and iron nuclei should differ. This difference is determined by the rate of energy dissipation. Thus it depends strongly on the distribution of secondaries produced in the forward direction and on the nature of primary particle: its atomic mass. The long-lasting discussions on the primary cosmic ray mass composition at the very end of the cosmic ray energy spectrum, in the so-called "ankle" region ($E_{\rm lab} > 10^{18}$ eV), could not be conclusive also because of the lack on the more exact knowledge of the very high energy interaction physics, what makes the importance of the high energy proton fragmentation even greater for cosmic ray physicist, astronomers and cosmologists.

Searching for regularities and phenomenological description of the multiparticle production model is as old as the modeling in high-energy physics itself. Starting from simple Fermi thermodynamical model, to the first parton (quark) model propositions by Feynman, the model extrapolation to much higher, cosmic ray energies was one of the most important and most wanted model predictions. It is usually in the form of a kind of scaling. The idea of limited fragmentation applied to the quark-jet hadronization led to introduction of the Feynman scaling variable of x_F and the universal fragmentation function $f(x_F,\ s) = f_F(x_F)$ [4]. This brilliant idea works well for the first collider experiments up to $\sqrt{s}\ \sim\ 60$ GeV. However, when applied to cosmic ray EAS development, it was questioned already at the "knee" energies of $E_{lab} \sim 10^{15}$ eV. The SPS ($\sqrt{s} \sim 200-900$ GeV) experiments allow to quantify the scaling violation. The scale-breaking model of Wdowczyk and Wolfendale has been proposed to described the CR data at the beginning of '70 [5]. It is, in a sense, a generalization of the Feynman scaling idea introducing the one scaling violation parameter.

In Ref. [6] we have shown that the light composition suggested by the studies of the anisotropy and the average depth of the shower maximum ($x_{\rm max}$) does not contradict other results, mainly the width of the $x_{\rm max}$ distribution, only if one assume strong Feynman scaling violation.

The rapidity (pseudorapidity) distributions were measured by LHC experiments: ALICE[7], CMS[8, 9] and ATLAS [10] (the last for $p_\perp > 0.5$ GeV only) in the central rapidity region $|\eta|\ \leq\ 2.5$ for c.m.s. energies of 900 GeV, 2.3

TeV and 7 TeV. Narrow range of a rapidity (pseudorapidity) at first sight does not allow to study important characteristics of very forward particle production. To study the fragmentation region new measurements, specially by much forward detectors (LHCf), are welcome. But, as it is shown below, the existing data can be used to test the scaling violation picture found in UHECR physics domain.

2 Rapidity distribution

Rapidity distributions measured in LHC experiments cover the central region where the produced particles are dynamically separated from the valence quarks of colliding hadrons. The central rapidity density $\rho(0) = 1/\sigma\ (\mathrm{d}\sigma/\mathrm{dy})|_{y=0}$ is the variable describing the particle production there. The original Feynman scaling preserves the value of the central rapidity density. The plateau in rapidity is characteristic feature of independent jet fragmentation model as well as statistical models with limited transverse momentum phase space. Unfortunately, it is known for long, that such simple picture does not work.

2.1 Feynman scaling

Feynman scaling [4] can be expressed introducing one universal function f_F of the variable $x = p_\parallel/p_{\max}$ which describes the invariant momentum (longitudinal $p_\parallel$) distribution of particles crated in the high-energy inelastic (and non single diffractive) interaction

$$\frac{E}{\sqrt{s}/2}\,\frac{1}{\sigma}\,\frac{d^3\sigma}{dx\,d^2p_\perp} \;=\; f(x,\,p_\perp,\,s) \;=\; f_F(x,\,p_\perp) \quad (1)$$

where $\sqrt{s}$ is the interaction c.m.s. energy, E, $p_\parallel$ and $p_\perp$ are energy, and longitudinal and transverse momenta of outgoing particles. Changing of variable from Feynman x to rapidity y and using an approximate relation $\sqrt{p_\perp^2+m^2}\sinh(y) \;\approx\; p_\perp\sinh(\eta)$ and introducing the very convenient variable: pseudorapidity ηafter the integration over all $p_\perp$ (assuming uncorrelated $p_\perp$ and $p_\parallel$ and the universality of the $p_\perp$ distribution) we obtaine

$$\frac{1}{\sigma}\,\frac{d\sigma}{d\eta} \;=\; F_F\left(\frac{2\langle p_\perp\rangle}{\sqrt{s}}\sinh(\eta)\right) \quad . \qquad (2)$$

The factor $\langle p_\perp\rangle$ is a constant related to the transverse momentum scale.

The original Feynman scaling implies that the inelasticity of proton-proton interaction, defined as a fraction of incoming energy carried by newly created particle, is universal, the same for all interaction energies. The first observations suggested an attractive value of 0.5. The rise of some characteristics of the interactions (like, e.g., average $p_\perp$ or central rapidity density we mentioned above) makes the assumption about the constancy of the inelasticity not quite well justified. Introducing the multiplicative factor proportional to the observed rise of the rapidity plateau to the right-hand side of Eq.(2) we can try to recover a form of scaling. Applying this procedure the simplicity of the original Feynman idea is lost and the next correction for the rise of the average transverse momentum could be introduced here as well. We have used in the present work the average transverse momentum rise shown in Fig. 4 of Ref. [9]. The additional inelasticity control parameter is an index α_F in a power law multiplicative factor. These two modifications lead according to Eq.(2) to only slightly more complicated scaling formula

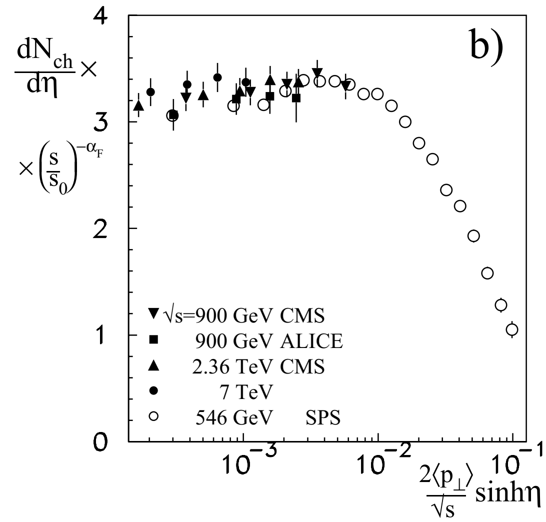

Figure 1: Pseudorapidity distributions shifted and transformed respectively adjusting α_F measured by LHC experiments at energies from 900 GeV to 7 TeV compared with SPS $\sqrt{s} = 546$ GeV UA5 result.

$$\frac{1}{\sigma}\,\frac{d\sigma}{d\eta} \;=\; \left(\frac{s}{s_0}\right)^{\alpha_F} F_F\left(\frac{2\langle p_\perp\rangle}{\sqrt{s}}\,\sinh(\eta)\right) \quad . \qquad (3)$$

We have used the UA5 data measured at $\sqrt{s_0} = 546$ GeV c.m.s. energy [11] as a datum. The very accurate measured NSD pseudorapidity distribution have been used as a definition of the universal F_F function. We adjusted the α_F parameter value to minimize the discrepancy between Eq.(3) scaling prediction and the distributions of pseudorapidity measured at different energies: from ISR to 7 TeV of LHC. The LHC fit results are given in Fig. 1.

Values of α_F increase from ~ 0.05 found for ISR 53 GeV to ~ 0.11 at LHC 7 TeV. The increase is statistically not very significant, at least for the overall inelasticity, what will be discussed later. The accuracy of the data scaling according to Eq.(3) can be estimated with the help of statistical tests. The χ^2 values for the ISR and SPS are of about $\chi^2/NDF \approx 40/20$. The systematic uncertainties of the Tevatron and LHC results makes the χ^2/NDF smaller but the overall tendency seen in Fig. 1 suggests strongly that proposed modification of the Feynman scaling is not a right solution for the extrapolation of interaction properties to the very high interaction energies.

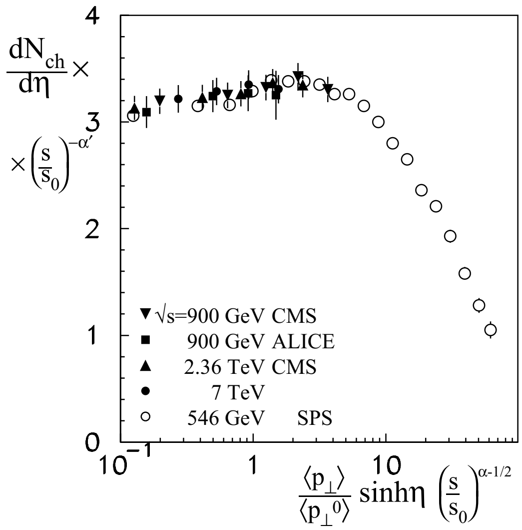

Figure 2: Wdowczyk and Wolfendale scaling results with α set to the UHECR analysis data.

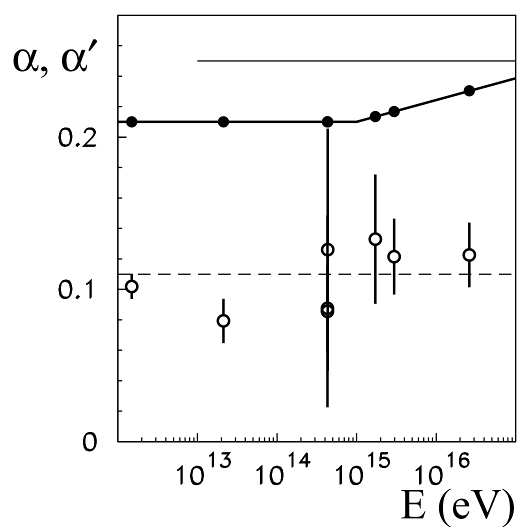

Figure 3: W&W scaling parameters predictions from the UHECR analysis [6] for α (solid symbols and solid lines) and for α' (open symbols and dashed line) adjusted.

2.2 Wdowczyk and Wolfendale scaling

It was shown in Ref. [6] that the forty years old modification known as Wdowczyk and Wolfendale (WW) scaling [5] could be still used to scale the interaction properties to the ultra high ($> 10^{19}$ eV) cosmic ray energies.

The original idea of the WW scaling

$$f\,(x,\,p_\perp,\,s) \;=\; (s/s_0)^\alpha\, f_{WW}\,(x\,(s/s_0)^\alpha,\,p_\perp) \qquad (4)$$

is an extension of the Feynman fragmentation formula of Eq. (1) (the limit for $\alpha = 0$) with the possibility to get the 'thermodynamical limit' of $\langle n \rangle \sim s^{1/4}$ with $\alpha = 0.25$.

The WW model in its version of mid '80 has been successfully used for the EAS studies around 'the knee'. Its extension introducing partial inelasticities (energy fraction carried by specific types of particles), and the transverse momentum rise with interaction energy dependencies, as discussed above, gave better description of the production of different kinds of secondaries. As a result of this improvements the first power-law factor index was released and gave an extra model parameter. This more flexible formula was applied, e.g., in Ref. [11] where the agreement of the WW model predictions and the UA5 measured rapidity distributions was shown.

In the present work we explore the WW scaling of the form

$$\frac{1}{\sigma}\,\frac{d\sigma}{d\eta} \;=\; \left(\frac{s}{s_0}\right)^{\alpha'} F_{WW}\left(\frac{\langle p_\perp \rangle}{\langle p_\perp^0 \rangle}\,\sinh(\eta)\left(\frac{s}{s_0}\right)^{\alpha-1/2}\right)\,, \qquad (5)$$

where $\langle p_\perp^0 \rangle$ is the average transverse momentum at the datum interaction energy ($\sqrt{s_0} = 546$ GeV).

The parameter α' is in fact a 'modified' α taking into account central (pseudo)rapidity density change responsible for the normalization (average multiplicity) of the inclusive distribution. We have adjusted first both α and α' parameters.Although the large uncertainties, which are result of limited rapidity range as well as possible systematics, do not allow for any definite conclusions. We can say only that the predictions of Ref. [6] and the LHC data are consistent (as well as a lack of any energy dependence depicted in Ref. [11] fits). We can, however, use the UHECR data analysis predictions for the values of α and test if results of the fit, with such reduced free parameter space, remains consistent with the WW scaling. It can be seen in Fig. 2. The data description is not much worst than the one obtained with the α parameter released.

The constancy of the α' suggested by WW original papers still holds as presented as in Fig. 3. Horizontal lines show results from Ref. [11] (solid for α and dashed for α', respectively). The thick solid broken line is the result for α of our UHECR analysis [6].

We can thus conclude that the data from LHC can be described by the WW scaling formula with the parameters taken from Refs. [11], and (α') [6] (α).

3 Inelasticity

In Ref. [6] it is found quite unexpected high-energy behaviour of interaction inelasticity coefficient. It was obtained as a result of the experimental suggestion that the composition of the UHECR is quite light, contains a significant proton fraction. The WW model with the strong Feynman scaling violation leads to continuous decrease of the energy fraction released to the secondaries produced in very high energy interactions. Eq.(5) gives the inelasticity

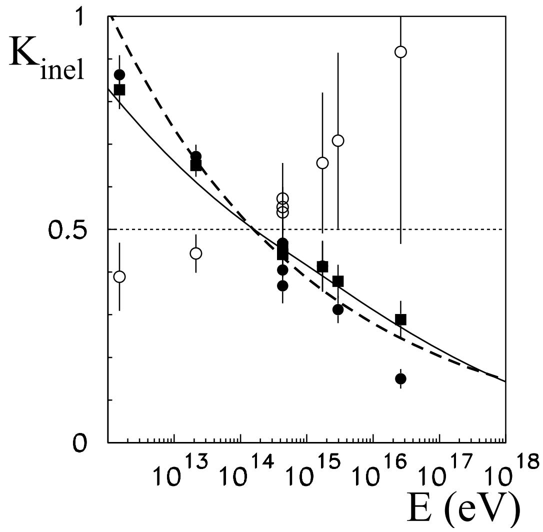

Figure 4: Inelasticity calculated with WW scaling assumption (filled symbols - circles for both α and α' adjusted and squares for UHECR inspired α.The open symbols are for the modified Feynman scaling with α_F parameter. Solid line shows the UHECR data analysis prediction from Re-f. [6]. Dashed line is the inelasticity fit from Ref. [11]. The 'canonical' value 0.5 – normalization point at energy of 10^{14}eV – is shown by short-dashed line.

energy dependence

$$K(s) \;=\; K_0 \, \left(\frac{s}{s_0}\right)^{(\alpha'-\alpha)} \quad , \tag{6}$$

while for the modified Feynman scaling formula Eq.(3)

$$K(s) \;=\; K_0 \, \left(\frac{s}{s_0}\right)^{\alpha_F} \quad . \tag{7}$$

In the Fig. 4 we have shown results of our analysis. Open symbols show the fast rise of the inelasticity for modified Feynman scaling formula. Even if the α_F follow the lower energy, smaller value, in the UHECR domain the saturation is expected. Filled symbols were obtained for WW scaling. The solid line gives the predictions from Ref. [6] obtained using UHECR data. The dashed line is the fit from Re-f. [11] of the WW scaling parameters to SPS data. The value of 0.5 is also shown.We normalize prediction of both models to this value at energy of 10^{14}eV.

4 Summary

We have shown that the minimum bias pseudorapidity distributions measured by LHC experiments can be very well described with the scale-breaking Wdowczyk and Wolfendale formula.

The scaling violation observed for the energies up to SPS $\sqrt{s} = 900$ GeV and 1800 GeV in Tevatron was uphold recently in the analysis of new UHECR data.

The phenomenological model of Wdowczyk and Wolfendale introduces two model parameters. One of them (α') is mostly related to the overall normalization. Its value of 0.11 sugested in Ref. [11] is confirmed by new data. The value of the second (α), which is responsible for the degree of the Faynman scaling violation was originally found to be equal to 0.13 using interpolation of the $x_F = p_\parallel/p_{\max}$ distributions between $\sqrt{s} \approx 10$ GeV and ISR energies. Later interpolations including SPS data gave the value of 0.18 and finally the effective value of 0.25 was found in Ref. [11]. The increase of the central rapidity density reported also in Ref. [11] suggests $\alpha = 2 \times 0.105 = 0.21$. This value gives the Extensive Air Showers development maximum position $x_{\max}$ for proton initiated showers not far from measured [2, 3] as it is shown in Ref. [6].

The UHECR data suggests further smooth rise of the scale-breaking parameter. The first measurements at LHC up to 7 TeV c.m.s. energy agree with the trend observed at lower energies and seems to smoothly bridge accelerator results and these on very high energy interaction of cosmic ray protons. The limited range of measured pseudorapidities does not allow for a stronger statement. The more forward particle production data is highly welcome.

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