

# Leading cluster approach to simulations of hadron collisions with GHOST generator

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**Abstract.** The model HDPM of CORSIKA has been updated and developed on the base of the recent measurements by ALICE, CMS, TOTEM, LHCb, LHCf... The new model, GHOST, involving a four-source production reproduces correctly the pseudo-rapidity distributions of charged secondaries and has been tested with the data in the mid and forward rapidity region, especially in the complex case of TOTEM, and also with the recent measurements of CMS, up to  $\sqrt{s} = 13$  TeV ( $9.0 \cdot 10^{16}$  eV in laboratory system). Special calculations have been devoted to the semi-inclusive data playing an important role in the cosmic ray simulation (fluctuations in earliest collisions, individual cascades measured at high altitude with high energy emulsion chambers). Taking into account the violation of KNO scaling, the negative binomial distribution (NegBin-expressed in terms of scaled elements)  $z = n/\bar{n}$  ( $n$  is the number of charged secondaries) has been used pointing out a possible asymptotic behaviour of total charged multiplicities at primary energies exceeding 40 TeV ( $8.5 \cdot 10^{17}$  eV). Thus, larger reduction of the energies devoted to the leading cluster and very large multiplicity of secondary particles could suggest for EAS generated by primary protons a larger production of muons and a shower maximum at higher altitude.

## 1 Introduction

The clear evidence was demonstrated for the violation of KNO scaling by the UA5 collaboration after presentation of their results at  $\sqrt{s} = 546$  GeV in 1984 [1]. The exception from Feynman scaling was also underlined in 1983 [2]. This unexpected situation generated the employment of the negative binomial distribution (see section 3.1) and the experimental observations of the CERN  $p\bar{p}$  at c.m. energies  $\sqrt{s} = 53 - 900$  GeV. The largest energies became important here for contacts with the cosmic ray data (EAS at mountain altitude and at sea level, high energy events observed in emulsion chambers installed on balloons around 35 km altitude (for instance with the JACEE Collaboration), around altitude 18 km of supersonic Atlantic flights with Concorde and also with important stations at 3000-5500 m altitude (Chacaltaya, Tian Shan, Pamir, Mt Aragats-Armenia...)).

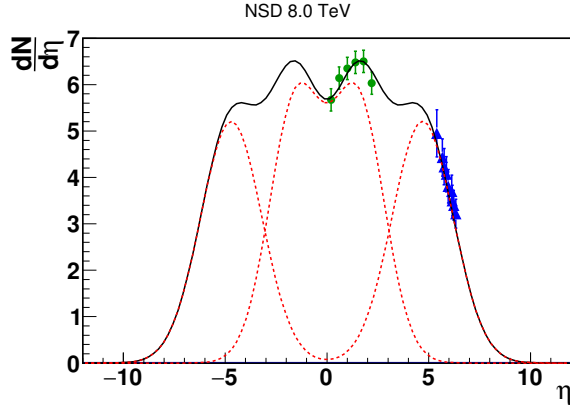
Taking into account the comparison with the “milestones” reached by the CERN proton-antiproton collider in 1985 at center of mass energy  $\sqrt{s} = 546$  GeV, four decades (1970-2010) were necessary to adapt the physics and the technology for the LHC.

## 2 GHOST, LHC and COSMIC RAY SIMULATION

The cosmic ray generator GHOST has been improved taking into account phenomenological models describing a large part of LHC results up to  $\sqrt{s} = 13$  TeV, concerning rapidity and pseudo-rapidity in all types of collision ND (Non Diffractive), NSD (Non Single Diffractive), SD (Single Diffractive), DD (Double Diffractive), Inelastic, for  $p\text{-}p$ ,  $p\text{-}\bar{p}$  and  $n\text{-}n$  collisions, as well as for  $p\text{-}A$  and  $A\text{-}A$  collisions. Unfortunately for charged particles, up to now, the LHC data published are limited at  $\sqrt{s} = 13$  TeV with rapidity or pseudo-rapidity lower than 2.2 units. More favorable limits were used at  $\sqrt{s} = 7\text{--}8$  TeV, reaching nearly units in the “agreement”, (arrangement Totem-CMS). The violation of KNO scaling is increasing with energy when compared to CERN data, as illustrated hereafter.

A large number of models tested up to Fermilab maximal energy  $\sqrt{s} = 11.8$  TeV have reproduced very well the pseudo-rapidity densities measured in the LHC up to  $\sqrt{s} = 2.2$  TeV in central rapidity region. The preliminary topological approach of the profile of the NSD distributions of CMS and TOTEM at  $\sqrt{s} = 8$  TeV is shown in Fig. 1 assuming the superposition of 4 Gaussian functions symmetric in CMS frame. Only the distributions of rapidity of high energy secondaries are approximately similar to the pseudo-rapidity distributions for the region of  $y$ ,  $\eta$  much greater than 0. Therefore, the Gaussian adjustment in forward region centered at  $\eta = \pm 4.7$  with a width 1.5

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**Figure 1.** Non Single Diffractive data at  $\sqrt{s} = 8$  TeV [11] described by four Gaussian functions. Green points represents results from CMS experiment, blue are related to the TOTEM experiment.

(amplitude 5.21) suggests the profile of the rapidity distribution above 4 units of pseudorapidity. The Gaussian functions centered at  $\eta = \pm 1.53$  with a width 1.3 (amplitude 5.6) remains different from the actual behaviour of the rapidity distribution, but altogether the profile of one plateau with Gaussian wings looks unlikely. We published more precise description of NSD and Inelastic data at  $\sqrt{s} = 8$  and 13 TeV using GHOST model in [22].

### 2.1 Charged multiplicity in limited pseudorapidity intervals

The most useful distributions obtained by CMS and TOTEM are separated by large gap, for instance between 0-2 units of pseudo rapidity for CMS and 5.3-6.4 units for TOTEM, this gap could suggest that the total distribution would be more easily described by multi cluster models than in the case of a perfect continuity with a single maximum above one wide plateau followed by Gaussian wings (for instance GENCL for UA5 in CERN). A tolerable scaling agreement was obtained in central region for  $\eta \leq 1.3$  or  $\eta \leq 1.5$  in the case of ISR, UA5 and UA1 for instance.

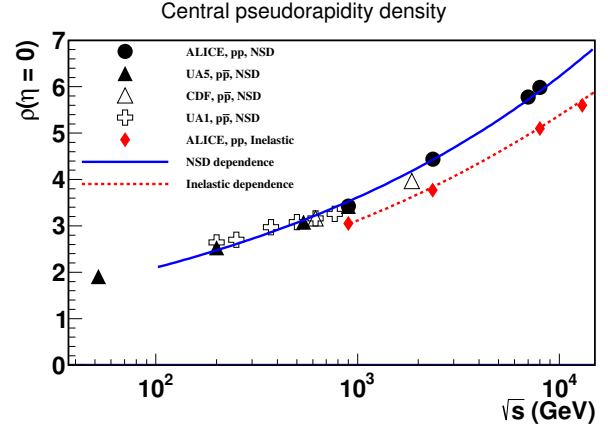
### 2.2 Central pseudo-rapidity densities at LHC

The dependence  $\rho(0)$  on  $\sqrt{s}$  exhibits an unexpected enhancement at the most recent energies attained by the LHC with CMS [11] and Alice at 13 TeV [19]. Therefore, we have first fitted the energy dependence of central pseudo-rapidity densities (here for NSD, only)  $\rho(0)$  and perform a numerical extrapolation as follows in the energy range  $E_0 = 10^{12}$ -  $10^{17}$  eV:

$$\rho(0) = 0.708 s^{0.118} \quad (1)$$

$$\rho(0) = \rho_1(0) = 0.24 \ln(s) + 0.1 \quad (\sqrt{s} \leq 1.292 \text{ TeV}) \quad (2)$$

$$\rho(0) = \rho_2(0) = 0.666 \ln(s) - 6 \quad (\sqrt{s} \geq 1.292 \text{ TeV}) \quad (3)$$



**Figure 2.** Central pseudorapidity density dependence on  $s$  for  $E_0 = 10^{13}$ - $10^{17}$  eV (solid line for NSD component, dashed line with diamonds devoted to the inelastic component is approximately  $0.8695 \cdot \rho(0)$  NSD)

## 3 VHE interactions up to $\sqrt{s} = 13$ TeV

The extension from HDPM is carried as follows with the four sources GHOST model [6]:

- $p_t$  distribution conserved from HDPM
- Rapidity distribution with 4 Gaussian functions
- Fluctuation of total multiplicity with the negative binomial distribution as in UA5 and in HDPM
- Composition of secondaries (pions, kaons,  $\eta'$ s, baryons) conserved from HDPM
- Conservation of longitudinal and transverse momenta, conservation of total energy

### 3.1 Use of Negative Binomial Distribution

Following UA5 [10] and considerations in CORSIKA user's guide [14], the fluctuations of  $\langle N_{ch} \rangle$  for a fixed primary energy can be reproduced at very high energy by a more simple relation corresponding to the negative binomial distribution (NBD); this simple function represents in terms of KNO reduced variables  $z = \frac{n}{\bar{n}}$  the fluctuations as:

$$\Psi(z, k) = \bar{n} P_n = \frac{k^k}{\Gamma(k)} z^{k-1} e^{-kz} \quad (4)$$

$$k^{-1} = a + b \ln \sqrt{s} \quad (5)$$

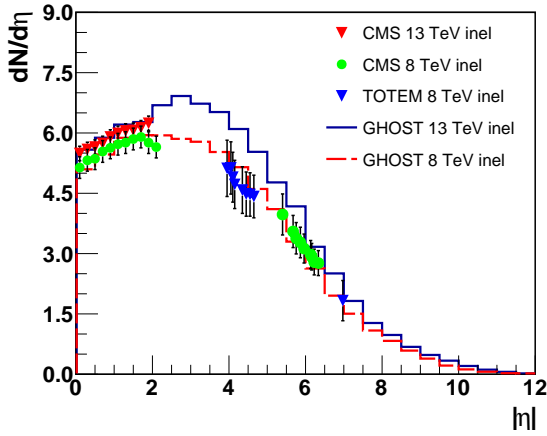
$$(a = -0.104, b = 0.058) \quad (6)$$

Thanks to the function  $\zeta$ , the semi-inclusive data can be governed by the integro-differential system:

$$\frac{dN}{dy}_{y=0} = m_r \frac{dN}{d\eta}_{\eta=0} = m_r \zeta \bar{\rho}(0) \quad (7)$$

$$\int \frac{dN}{dy} dy = z < n > \quad (8)$$

where  $m_r$  is the ratio of central mean rapidity density and mean central pseudo rapidity density derived from the



**Figure 3.** Inelastic data of CMS and Totem for  $\sqrt{s} = 8\text{TeV}$  and  $13\text{TeV}$  described using GHOST model.

"dip" existing in the centre of the pseudorapidity distribution, resulting from the mass  $m$  and the transverse mass  $m_T$  of the secondaries as  $m_r = \sqrt{1 - \frac{m^2}{m_T^2}}$ . With,

$$\frac{dN}{dy} = \sum_{i=1}^{i=2} a_i (e^{-0.5u_i} + e^{-0.5v_i}) \quad (9)$$

$$u_i = \left(\frac{y - y_i}{\sigma_i}\right)^2, \quad v_i = \left(\frac{y + y_i}{\sigma_i}\right)^2 \quad (10)$$

it is possible to use the opportunity of the scaling of function  $\zeta$  in the relation between the center  $y_i$  and the width  $\sigma_i$  of each Gaussian function as

$$y_i = \sigma_i \left( 2 \ln \left( \frac{z < n >}{\sqrt{(2\pi) \zeta \sigma_i}} \right) \right)^{0.5}$$

### 3.2 Average pseudo rapidity distributions up to $\sqrt{s} = 13 \text{ TeV}$

Both semi-inclusive and inclusive data have been calculated with the previous equations and the results of GHOST for charged inelastic distributions are shown here in Fig. 3 to compare the results at  $\sqrt{s} = 8 \text{ TeV}$  and  $\sqrt{s} = 13 \text{ TeV}$ . Unfortunately the measurements of LHC at 13 TeV are limited to 2 units of rapidity, when the limitation for 8 TeV is close of 8 units of rapidity.

Some measurements with LHCf experiment to separate charged and neutral secondaries at very large distance from the centre of collision can give information above 10 units of rapidity.

## 4 Leading clusters, common properties of proton collisions up to 40 TeV, EAS behaviour at high altitude

### 4.1 Leading clusters and LHC data

In a simple approach, we have compared the situation of the leading clusters using a small part of our data at  $\sqrt{s} = 8 \text{ TeV}$ :

1. In the first group of 10000 events, the leading cluster contains the last quantity of energy remaining after production of all secondaries (produced randomly) obtained after about 50% of rejections,

2. In the second group of 10000 events, all the secondaries generated are distributed randomly and classified later starting in the order of decreasing individual energies; the leading cluster is recognized in the most energetic group of 10 particles. In both cases NSD data and central pseudorapidity area are considered. We tabulated hereafter the distributions of charged secondaries and also the distributions of charged central pseudo-rapidity: the group of charged secondaries is explored and compared for multiplicities up to 400 particles, whereas the central pseudorapidities are observed up to 10. units of pseudorapidity.

The central pseudorapidity distributions for the same  $N_{ch}$  are collected hereafter for  $\rho_0$  up to 10 units of rapidity. A comparison with the next results of the LHC at  $\sqrt{s} = 13 \text{ TeV}$  and at distances for charged secondaries at least above 7-8 units rapidity (instead of 2 units up to now) are needed. The distance in the Tab. 1. represents the width of the multiplicity distribution.

### 4.2 A possible convergence at 40 TeV

One new prediction from the negative binomial distribution was compared by SSC collaboration with one exact KNO-scaling for  $\sqrt{s} = 40 \text{ TeV}$  [20]. The cross sections for high multiplicities increases drastically and becomes acceptable with the shape parameter  $k$  rising with energy ( $1/k = a + b\sqrt{s}$  with  $a = -104$  and  $b = 0.0058$  in GeV-square) as given at lower energy in last section (but up to 40 TeV). The asymptotic form at very high energy (40 TeV) in the abandoned project of the Superconducting Super Collider (SSC 1986) is then the most enlarged variation with the expression  $\Psi(z) = 4z e^{-2z}$ .

The probability in p-p collision to receive randomly very small  $N_{ch}$  or very large  $N_{ch}$  increases at very high energy following the tendencies at energies larger than  $\sqrt{s} = 8 \text{ TeV}$  up to 40 TeV. The effect could be important for EAS with production of secondaries at higher altitudes, larger production of pions, kaons.. and consequently of muons, higher altitude of the shower origin and maximum of the shower also at higher altitude.

### 4.3 LHC energy domain and cosmic ray domain

The larger number of gamma ray families remaining in Pamir and Mt Fuji emulsion chambers are not consistent with the intensity of the primary cosmic ray spectrum. Some properties of gamma ray families (coplanar emission, halo emission...) at mountain altitudes or in events recorded in the low stratosphere are still not explained. The integral energy spectrum of very high energy gammas recorded was exhibiting during a Concorde Atlantic flight a steeper decrease than expected with the QGSJET model [21]. A similar steepness enhanced above

**Table 1.** Charged secondaries in two groups

distance	10	20	40	60	80	100	120	140	160	200	250	300
$N_{ch}$ 1st in 2	177	403	495	402	337	254	184	116	83	50	15	6
$N_{ch}$ free in 1	170	384	419	380	333	269	203	133	108	43	12	3

**Table 2.** Central pseudorapidity distribution for the same  $N_{ch}$

Units of rap.	0.1	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
$\eta$ 1st in 2	6.05	6.24	6.46	6.31	5.99	5.26	3.88	2.38	1.19	0.47	0.14	0.03
$\eta$ free in 1	6.20	6.40	6.60	6.20	6.70	6.27	5.01	3.30	1.90	0.94	0.40	0.12

$\sqrt{s} = 4.6$  TeV has been also observed in the integral distributions of gammas measured up to 15 TeV with the Tien Shan experiment. Several questions remains also in EAS data such as the the age parameter of the lateral electron distribution increasing above  $10^{16}$  eV, different primary cosmic ray spectrum obtained from electron size spectrum or muon size spectrum or also different primary spectrum and knee position from EAS recorded at very high altitude or at sea level. Remarkable events such as coplaner emission or "spikes" have been compared at mountain altitude and stratosphere at energies between 1 PeV and 100 PeV in laboratory frame. Very small (40 cm x 50 cm) emulsion X-ray chambers with high resolution have collected data in the stratosphere (ballons in JACEE, Siberian flights above 30 km altitude, Concorde supersonic flights at 17 km altitude...). In parallel very heavy Emulsion X ray chambers were also installed in Pamir and in Tibet above 4 km to collect events exceeding  $10^{17}$  eV. Similarly to Pamir registration, near and above  $\sqrt{s} = 5$  TeV, the unexpected alignment of secondaries has been observed in two independant stratospheric flights.

## 5 Conclusion

The four sources model of GHOST is a very efficient Monte Carlo collision generator capable to reproduce inelastic as well as ND (Non Diffractive) or NSD data up to  $\sqrt{s} = 13$  TeV, allowing a more refined analysis of cosmic ray data above the "knee" at 3-5  $10^{15}$  eV in laboratory system. A complete extension of GHOST possibilities will be done as soon as the LHC (at  $\sqrt{s} = 13$  TeV) will produce at least pseudo-rapidity densities up to 8 units or more and even data of LHCf for pseudo-rapidities exceeding partly 11 units. Those results at 7-8 TeV and 13 TeV will give complete values of primary energy behaviour in continuity in cosmic ray data up to 13 TeV to  $\sqrt{s} = 13$  TeV ( $9.2 \cdot 10^{16}$  eV in laboratory system).

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