PROCEEDINGS OF SCIENCE

The MC collision generator GHOST at LHC energies

Jean-Noel CAPDEVIELLE*†

APC, CNRS-IN2P3, Paris E-mail: capd@apc.in2p3.fr

Zbigniew Plebaniak

National Centre for Nuclear Research, BP4 - Łódź, Poland

An extension of the model HDPM of CORSIKA has been developed taking the opportunity of the measurements performed presently by CMS, LHCb, TOTEM ... The new model GHOST involving a 4-source production is presented here. It reproduces correctly the pseudo-rapidity distributions of charged secondaries and can help the approach of the inclusive and semi-inclusive data in the mid and forward rapidity region, especially in the complex case of TOTEM. An important enhancement of both mean multiplicity and central pseudorapidity density is pointed out.

Short range extrapolations up to $\sqrt{s} = 13$ TeV suggest important consequences in the interpretation of cosmic ray measurements up to 10^{17} eV. In parallel, simulation of cascades and EAS are also carried out in order to understand unexpected results in energy distributions of very high energy γ's, collected with X-ray emulsion chambers. If confirmed by the present and next measurements of the LHC at $\sqrt{s} = 13-15$ TeV, the enhancement of multiplicities will generate new developments of EAS simulation, amended to take into account adequate guidelines of extrapolation; this will give the opportunity of a new interpretation of the cosmic ray results up to 10^{20} eV.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

*Speaker.

†we are indebted to the support of the France-Poland collaboration COPIN

PoS(ICRC2015)536

1. Introduction

The second run of the LHC at an energy of $\sqrt{s} = 13$ TeV was carried successfully in June 2015 and we can expect now a complete description of the multiple production up to energies close to 10^{17} eV needed in the interpretation of cosmic ray measurements. In the sections that follow, we shall discuss the new improvements in cosmic simulation suggested by the most recent results of the LHC, especially the data of ALICE, ATLAS, CMS, TOTEM, LHCb ... up to $\sqrt{s} = 8$ TeV selected to elaborate the new Monte Carlo collision generator suitable for cosmic ray simulations.
Section 2 is devoted to the new tendencies observed from S$p\bar{p}$S to LHC in important features of high energy interactions. It concerns the dependence on primary energies of the total multiplicity of charged secondaries as well as the central pseudorapidity density.
Section 3 is focused on the new four component model GHOST (Generator Hadronic Oversteering Secondary Treatment) [1] used to explore the fluctuations of multiplicity and the violation of KNO (Koba-Nielsen-Olsen) scaling. The extension of the generator HDPM [2] previously inserted in CORSIKA [3] is described in [1].
Section 4 recalls a few measurements not explained in cosmic ray data above $\sqrt{s} = 5$ TeV, especially in the case of very high energy spectra of secondaries measured in EAS and γ-ray families.

2. Basic features of VHE interactions

The earliest results of the multiple production derived from cosmic ray measurements introduced an energy dependence of the mean multiplicity as important as $s^{0.25}$. This was probably a consequence of the relativistic hydrodynamical model of Landau devoting all the available energy to the mass production. This was ruled out by the results of the ISR and the models taking into account Feynman scaling, the main part of the energy being distributed to a small number of particles in the leading cluster. The last results of the LHC indicate a more complex multiple production than it was assumed in the models tuned to fit the accelerator data under $\sqrt{s} = 1.5$ TeV.

2.1 Enhancement of the total charged multiplicity and central pseudo-rapidity density

The energy dependence in Fig. 1 -a of the total mean charged multiplicity (NSD component) is shown hereafter adding to the S$p\bar{p}$S collider measurements [5] the data of CMS and TOTEM at $\sqrt{s} = 8$ TeV. An important enhancement is thus appearing when we take into account the multiplicity estimated using GHOST [1] after integration of the density of rapidity in the best agreement with the pseudo rapidity measured at $\sqrt{s} = 8$ TeV by CMS and TOTEM [4].

We note a large discrepancy of the asymptotic behaviour (dashed line) with the previous tendency (solid line) expected from UA5 data [5]. The first estimation of the total average multiplicity $< N_{ch-UA5} >$ by a power law has to be updated as we suggest above $\sqrt{s} = 1$ TeV introducing another power law for $< N_{ch} >$ as follows:

$$< N_{ch-UA5} > = -7.0 + 7.2 \, s^{0.127} \quad (2.1)$$

$$< N_{ch} > = -0.74 + 2.59 \, s^{0.191} \quad (2.2)$$

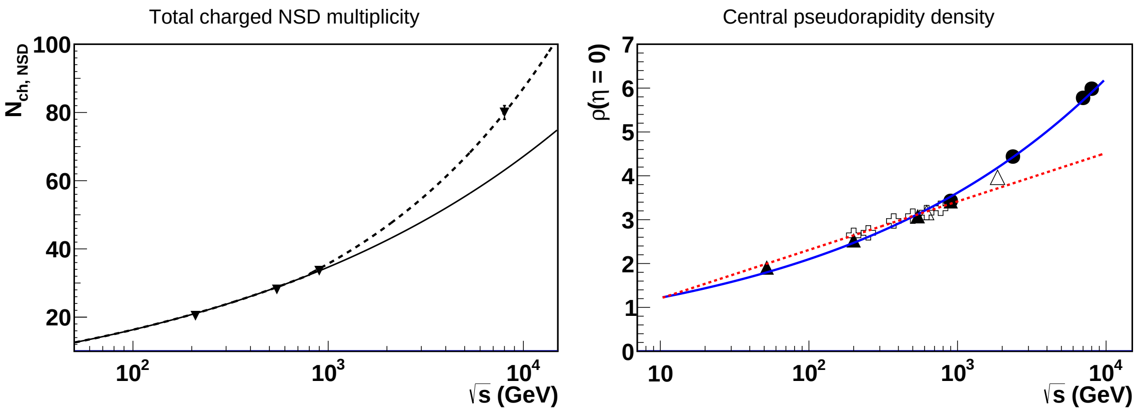


Figure 1: Fig.1a (left): Total charged multiplicity (NSD) dependence on s for $E_0 = 10^{13}$-10^{17} eV following UA5 (solid line – eq. 2.1) and the asymptotic tendency using GHOST (dashed line – eq. 2.2). 3 lower points are from UA5, the upper point is estimated with GHOST (subsection 2.2).
Fig.1b (right): Central pseudorapidity density dependence on s for $E_0 = 10^{13}$-10^{17} eV.

There is also an important rise of multiplicity in the central region characterized by the average central pseudo rapidity density $\bar{\rho}(0)$ with a power law dependence on s: the description with the logarithmic dependence $\bar{\rho_1}(0)$ of UA5 replaced by $\bar{\rho}(0)$ as follows is shown in Fig. 1b.

$$\bar{\rho_1}(0) = 0.24\, ln(s) + 0.1 \tag{2.3}$$

$$\bar{\rho}(0) = 0.708\, s^{0.118} \tag{2.4}$$

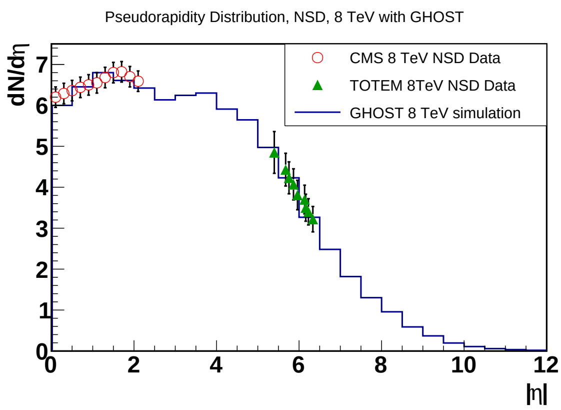
The results from LHC show multiplicity enhancement in central rapidity region as well as in mid-rapidity region. For still higher energies, at $\sqrt{s} = 15$ TeV, the average total charged multiplicity can be close to 100.

2.2 Pseudorapidity distribution and mean multiplicity

The average pseudorapidity distribution data were obtained from non single diffraction (NSD) events. At present the combined results of CMS and TOTEM for charged density measurements at $\sqrt{s}$ = 8 TeV cover central and mid-rapidity region and are limited to 6.5 units of rapidity. Comparison of a profile generated with the double gaussian generator GHOST is shown in Fig. 2.

This result takes into account the generation of individual multiplicities following the histogram of Fig. 2a for the relation $3-1$ with $\sqrt{s}$ = 8 TeV included in GHOST. The procedure is the same than the generation introduced in CORSIKA [2]. For each random value of N_{ch} one complete set of rapidities is generated by GHOST for all secondaries (as indicated is subsection $3-3$). During a next step (generation of transverse momenta for each secondary), the couple (rapidity-p_t) is used to get the individual energies of secondaries and also individal pseudo-rapidities. If all the conditions of conservation are fulfilled in the interaction (transverse momenta, longitudinal momenta and energy) the interaction is conserved and a next N_{ch} is generated.
The distribution of pseudo-rapidity averaged using 10000 collisions is reproduced by the histogram of Fig. 2a and compared with the inclusive distribution of pseudorapidity of CMS and TOTEM.

The data of this simulation contains also the parameters of initialization with relation $3-6$ as well as the distribution of the original average rapidity, the distribution of the transverse energy



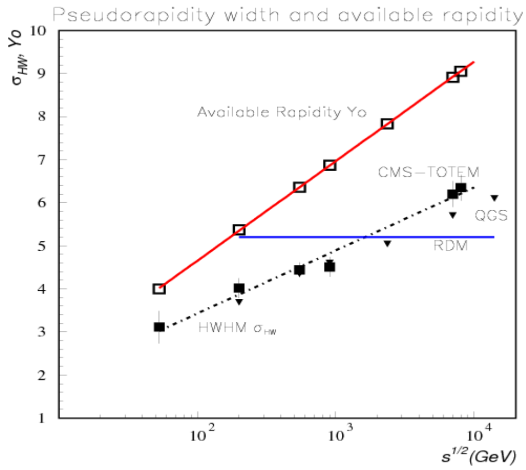


Figure 2: Fig.2a (left): Average pseudorapidity density simulated with GHOST compared with CMS and TOTEM measurements.
Fig.2b (right): Energy dependence of the available rapidity Y_0 and of the FWHM, σ_{HW}, respectively, open squares, solid line and dashed line from GHOST, dark squares from CMS-TOTEM, triangles from QGSJET01 model, horizontal line from the relativistic diffusion model RDM [7].

and a large number of characteristics of the inclusive data. About 20 histograms are conserved from GHOST reproducing the average multiplicity distribution, rapidity, pseudorapidity (of course with central densities), energy, inelasticity for charged and neutral secondaries. Those histograms contains average values and other statistical momenta of the distributions. Among them $< N_{ch} >$ which can be also obtained by the simple integration of the simulated distribution inside the physical limits in agreement with the data on average densities of rapidity $< N_{ch} > \; = \; \int \frac{dN_{ch}}{dy} \, dy$ gives for $\sqrt{s} = 8$ TeV an average total multiplicity $< N_{ch} > \; = \; 80 \; \pm 2$. The direct integration of one distribution fitting directly the inclusive measurements $< N_{ch} > \; = \; \int \frac{dN_{ch}}{d\eta} \, d\eta$ suggests also for an average totalmultiplicity close of $< N_{ch} > \; = \; 80$, but the evaluation is approximate as there are no densities measured in the fragmentation region close to the leading cluster. This difficuly was underlined in the UA5 cluster Monte Carlo simulation program [6] using also for rapidity the shape advocated by Feynman i.e.the "plateau" followed by a gaussian descent, adapted to pseudorapidity taking into account a central "dip" of kinematical nature and followed again by a gaussian tail [8]. As far as the gaussian shape could be adjusted to the data, they introduced the full width at half maximum FWHM to describe the growth of the pseudorapidity NSD inclusive distribution with energy in parallel with the central pseudorapidity linked to the height of the plateau.

We can observe also in Fig. 2 the different behaviour of the full width at half maximum (FWHM), σ_{HW}, on the one hand, and the rise of the available rapidity range (or rapidity Y_o of the center of mass in the laboratory system) on the other hand. Even if slightly approximated, Yo here is just $y_{beam} \; = \; \frac{\sqrt{s}}{m}$, m being the mass of the proton. A similar approach is done using in addition the shape of Fig. 2 above 6.5 pseudorapidity units.

Both dependences on s reflect a logarithmic increase with always a smaller growth for the FWHM than the available rapidity range.

$$\sigma_{HW} = 0.3182\, ln(s) + 0.5 \tag{2.5}$$
$$Y_o = 0.502\, ln(s) + 0.3 \tag{2.6}$$

3. Total multiplicity distribution and violation of KNO scaling

The KNO variable $z = n/\bar{n}$ is the normalized multiplicity. To facilitate the correspondence between collider notations and theoretical notations from KNO, in the case of Non Single Diffraction (NSD), we don't distinguish hereafter N_{ch} or n employed considering a single interaction, as well $< N_{ch} >$ or $\bar{n}$ average multiplicities for a large group of collisions.

3.1 Fluctuations of multiplicity

The violation of Koba Nielsen Olsen (KNO) scaling describing correctly the fluctuations of multiplicity at ISR energies was pointed out by UA5 ..3 decades ago. The validity of KNO scaling being limited at ISR, we have used in CORSIKA one relation reproducing at very high energy the properties of the negative binomial distribution following [9]. In terms of reduced variables $z = \frac{n}{\bar{n}}$, a particular simple expression describes the fluctuations as:

$$\Psi(z,k) = \bar{n}P_n = \frac{k^k}{\Gamma(k)} z^{k-1} e^{-kz} \tag{3.1}$$
$$k^{-1} = a + b \cdot ln\sqrt{s}$$
$$a = -0.104\ ,\ b = 0.058$$

The values of the parameters correspond here to $\bar{n} =< N_{ch} >$ for the charged NSD component, P_n being the probability of an incoming multiplicity N_{ch}. The evolution of those fluctuations of N_{ch} is plotted in Fig. 3a at ISR and UA5 energies, the histogram illustrating the calculation with GHOST at $\sqrt{s} = 8$ TeV. The asymptotic form at very high energy (40 TeV) in the unfulfilled project of the Superconducting Super Collider (SSC 1986) is 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 as shown in Fig. 3a. Such contrast changes the statistical treatment of the earliest interactions in hadronic cascades at UHE and we underline the neighborhood of the histogram at $\sqrt{s} = 8$ TeV with the asymptotic expression of the SSC.

3.2 Empirical scaling

An interesting property of the normalized central density of pseudorapidity has been observed also in the semi-inclusive data in colliders and accelerators [6]. A new kind of empirical scaling has been pointed out in the relation $\rho(0)/\bar{\rho}(0) = f(z)$ instead of $f(z,s)$ independent of $\sqrt{s}$ where $\rho(0)$ is the central density for a given charged multiplicity n, $\bar{\rho}(0)$ the average central density. The KNO variable $z = n/\bar{n}$ is the normalized multiplicity. The general dependence on z is shown in Fig. 3a. Following our adjustment, we propose for $f(z)$ the numerical representation:

$$\zeta = f(z) = 0.11499\, z^2 + 1.0231\, z - 0.1319 \tag{3.2}$$

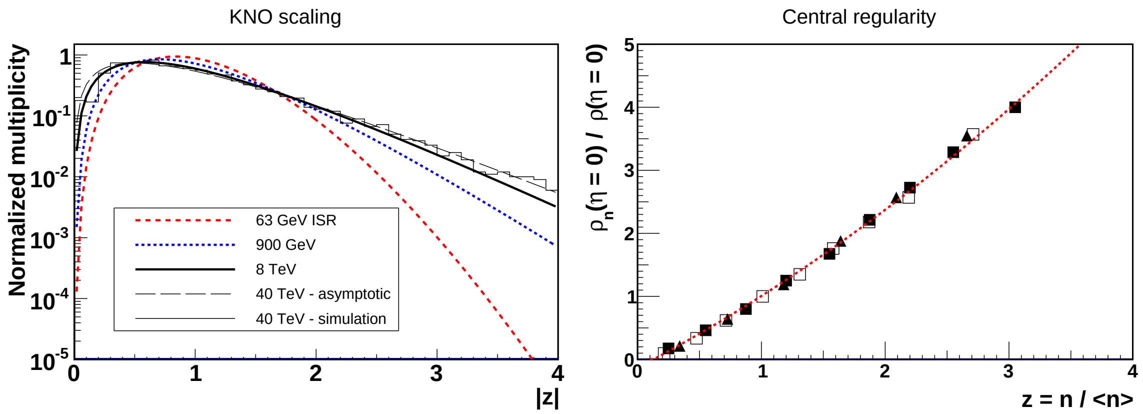


Figure 3: Fig.3a. Fluctuations of total charged NSD multiplicity.
Fig.3b. Empirical scaling function ζ = f(z) for $\sqrt{s}$ = 200, 546 and 900 GeV for NSD collisions.

This kind of scaling is not yet confirmed in LHC data as the semi-inclusive measurements are performed only in small windows of pseudorapidity, but it remains present in models extrapolations at larger energies.

3.3 Semi-inclusive data

The semi-inclusive data is governed by the integro-differential system:

$$\frac{dN}{dy}_{y=0} = m_r \frac{dN}{d\eta}_{\eta=0} = m_r \, \zeta \, \bar{\rho}(0) \tag{3.3}$$

$$\int \frac{dN}{dy} dy = z < n > \tag{3.4}$$

m_r is the ratio of central mean rapidity density and mean central pseudo rapidity density derived from the "dip" existing in the centre of the pseudorapidity distribution, resulting from the mass m and the transverse mass m_T of the secondaries as $m_r = \sqrt{1 - \frac{m^2}{m_T^2}}$. In the case of the 4 gaussian generation (one pair of functions in each hemisphere, symmetrics around the center of mass,

$$\frac{dN}{dy} = \sum_{i=1}^{i=2} a_i (e^{-0.5u_i} + e^{-0.5v_i}) \tag{3.5}$$
$$u_i = (\frac{(y-y_i)}{\sigma_i})^2, \; v_i = (\frac{(y+y_i)}{\sigma_i})^2$$

it is possible to use the opportunity of the scaling $3-2$ in the relation between the center y_i and the width σ_i of each gaussian function as

$$y_i = \sigma_i \; (2ln(\frac{z < n >}{\sqrt{(2\pi)} \; \zeta \; \sigma_i}))^{0.5} \tag{3.6}$$

After introducing one proportion χ of the multiplicity distributed to the pair of gaussian centered in central region and in mid-rapidity region, it is possible to obtain with a minimal Monte Carlo generation of random deviates the total original rapidity distribution source of the distribution of pseudorapidity shown in Fig. 2a (respectively $\chi = 20\%$ and 80%). The couples rapidity-transverse momentum (y, p_t) are generated using the same p_t distribution than in CORSIKA [3]. The total

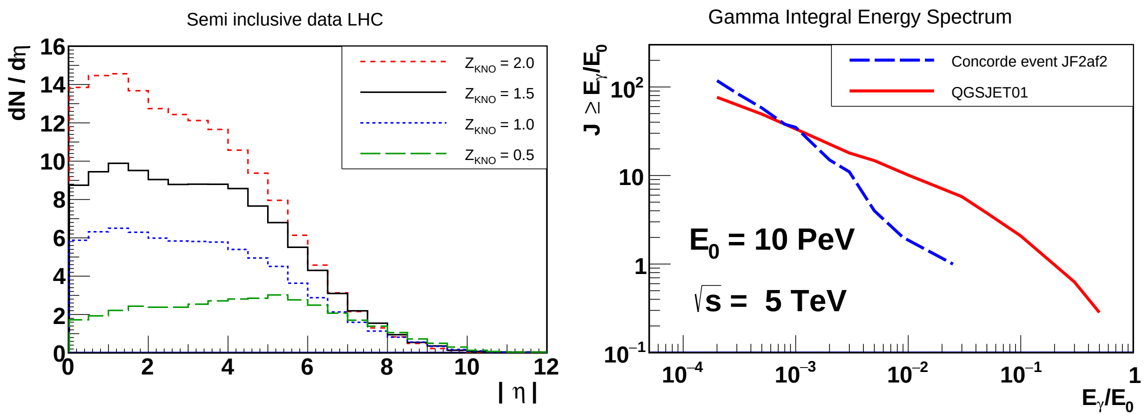


Figure 4: Fig.4a (left): Semi-inclusive NSD pseudo-rapidity distribution, z= 0.5, 1., 1.5, 2 correspond respectively to relative intervals of N_{ch} $[0.25-0.75], [0.75-1.25], [1.25-1.75], [1.75-2.25]$.
Fig.4b (right): Integral energy spectrum of very high energy γ's near $\sqrt{s} = 2$ TeV compared with QGSJET01 simulation.

average inelasticity of the NSD collisions calculated with GHOST is 0.71 indicating a larger proportion of the primary energy distributed to the secondaries. The generator GHOST can be used to appreciate the elements provided by semi-inclusive measurements which will be distributed in the next month by the LHC. One possible behaviour is shown in Fig. 4a in parallel with the fluctuations of multiplicity (histogram of Fig. 2a) for $\sqrt{s} = 8$ TeV. The different density distributions correspond to behaviour very contrasted with larger probability than at lower primary energies; the total multiplicity is enlarged with a shorter "plateau" for z=1.5 or 2; on the opposite the central "plateau" is enlarged with smaller total multiplicity in the case of z= 0.5. The Fig. 2a is the average result of 10000 collisions generated for all possible N_{ch} illustrated in Fig. 3a. The consequences up to now have been underestimated in the simulation of EAS development. The convolution of the probabilities coming the enlarged fluctuations of Fig. 3a with the primary cosmic ray energy spectrum can turn according to the conditions of trigger (different altitude, zenith angle, muon or electron components..) to identify proton initiated showers which were previously classified as resulting from heavier primary nuclei [10].

4. Cosmic ray data in the LHC energy domain

In the energy band covered now by the LHC, the models widely used in simulation cannot explain completely non expected observations [1]. The large 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 events..) at mountain altitude or in events recorded in the low stratosphere are also not explained. We show in Fig. 4b the integral energy spectrum of very high energy γ's recorded during a Concorde flight exhibiting a steeper decrease than expected with QGSJET model. A similar steepness enhanced above $\sqrt{s} = 4.6$ TeV has been also observed in the integral energy distributions of γ's measured up to $\sqrt{s} = 15$ TeV in the Tian Shan experiment [11]. Several questions remain also in EAS data such as 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.

5. Conclusion

The 4 sources model GHOST is a very fast Monte Carlo collision generator able to reproduce the NSD data up to $\sqrt{s} = 8$ TeV.

The semi-inclusive data can be reproduced with the same multi-source generator as well as the single diffractive component (using only one pair of gaussian functions in one hemisphere). As soon as the measurements at $\sqrt{s} = 13$ TeV will be performed, the definition of the guidelines $(\bar{n}(s), \bar{\rho}(0)(s), \sigma(s)$... will be achieved and the generator GHOST will be available in the LHC energy range and also for improved extrapolations up to energies $\geq 10^{19}$ eV. This circumstance allows a more refined analysis of cosmic ray data at energies above the "knee" at $3-5 \cdot 10^{15}$ eV. The enhancement of multiplicity suggests in EAS simulation a larger abundance of muons and a maximum of development at higher altitude than with previous models. Alltogether an abundance of heavy primaries lower than with previous models can be expected above the knee. Furthermore, the energy guidelines derived from the complete data of the LHC shall provide new elements in the polemics on GZK cut-off.

References

[1] J.N. Capdevielle, **Eur. Phys. J**, Proceedings ISVHECRI 2014 (in press)

[2] J.N. Capdevielle et al., J. Phys. G **36**, 075205 (1989).

[3] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw, FZK A report-6019 ed. FZK *T*he CORSIKA Air Shower Simulation Program, Karlsruhe (1998).

[4] CMS and TOTEM collaborations, **Eur. Phys. J**, C (2014) 74:3053

[5] G.J. Alner et al., UA5 collaboration, Nucl. Phys. **B291**, 445, (1987)

[6] G.J. Alner et al. (UA5 Collaboration), Physics Reports **154**, No 5&6, 247-383 (1987)

[7] G. Wolschin , Phys. Lett. **B698**, 411 (2011)

[8] R. P. Feynman , **PRL 23**, 1415 (1969)

[9] P. Carruthers and C.C. Shih, Phys. Lett. **B127**, 242 (1983)

[10] J.N. Capdevielle, Proc.31th ICRC, Lodz, **icrc0118**, (2009)

[11] S.I. Nikolski Nuclear Physics B **39A**, 228 (1998)