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EPOS LHC-R : up-to-date hadronic model for EAS simulations

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The hadron production in the simulation of extensive air showers is a long standing problem and the origin of large uncertainties in the reconstruction of the mass of the high energy primary cosmic rays. Hadronic interaction models re-tuned after early LHC data give more consistent results among each other compared to the first generation of models, but still can't reproduce extended air shower data (EAS) consistently. Ten years after the first LHC tuned model release, much more detailed data are available both from LHC, SPS and hybrid air shower measurements allowing to understand some deficiencies in the model. Properly taken into account in the new EPOS LHC-R, it leads to a change in both X_{max} and the muon production by air showers. A better treatment of the hadronization according to LHC data is important for the muon production while an update of cross-section and nuclear fragmentation is changing the X_{max} distribution. The detailed changes introduced in EPOS LHC-R will be addressed and their consequences on EAS observable.

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1. Introduction

Despite all the efforts made to take into account the first results of proton-proton collisions at the LHC in hadronic interaction models used for air-shower simulations, the observed number of muons, their height of production, or even the depth of shower maximum are still not reproduced consistently by the models [1]. Furthermore, the differences among model predictions introduce uncertainties in cosmic-ray data analysis, which are currently smaller than in the past but still exceed the experimental uncertainties in certain cases [2]. Nevertheless before claiming the need for “new physics”, it is important to guarantee that all the standard QCD physics is properly taken into account in these models. For that, it is necessary to go beyond the simplest observables which are usually used to test them. After ten years of running, the various LHC experiments provided a large amount of complex data to analyze and understand, in particular, thanks to the correlations between different observables, which are not yet fully investigated.

Among the hadronic interaction models used for air-shower analysis, only Epos LHC [3] includes all the features needed to have a detailed description of the correlation between various observables [1]. Indeed, the core-corona approach in this model, which allows the production of a collective hadronization phase, appears to be a key element to reproduce LHC data. Before LHC, it was usually accepted that hydrodynamical phase expansion, for instance due to the formation of a quark-gluon plasma, was possible only in central heavy-ion collisions. Proton-nucleus (pA) collisions were then used as a reference to probe the effect of such collective behavior (final state) but with some nuclear effect at the initial state level, while proton-proton (pp) interactions were free of any nuclear effects. With the LHC operated in pp, pPb and PbPb mode, it is now possible to compare high-multiplicity pp or pPb events with low-multiplicity PbPb events (which correspond to the same number of particles measured at mid-rapidity) and surprisingly, the very same phenomena are observed [4, 5] concerning the soft-particle production.

At the same time, the recent results compiled by the Working group on Hadronic Interactions and Shower Physics (WHISP) [6] clearly indicate that the discrepancy between the muon production in simulations and data gradually increases with energy. It is a strong indication of a different hadronization than the one used in the current hadronic models [7, 8], including Epos LHC, which does not have enough core contribution according to data [4] published after the release of the model in 2012.

But before any claim based on the core-corona model, it is important to fully understand the corona part (based on string fragmentation) and check all possible sources of uncertainty which could lead to a change in muon production. In Section 2, we will check the uncertainty on the ρ resonance production in data and its impact on the muon production.

Furthermore, other studies showed some deficiencies of Epos LHC and other models not only for the number of muons but also for $X_{\max}$ measurements [9]. Since this is the most important observable for the mass composition of cosmic rays, one should check the model against the latest LHC data in terms of cross-section and multiplicity distributions which are key factors for the shower development [10]. This will be done in Section 3 using a preliminary version of the new tune of Epos, called Epos LHC-R, presented here in a setting without core formation. Finally, a summary is given in Section 4.

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2. Hadronization and air-shower physics

The dominant mechanism for the production of muons in air showers is via the decay of light charged mesons. The vast majority of mesons are produced at the end of the hadron cascade, after typically five to ten generations of hadronic interactions (depending on the energy and zenith angle of the cosmic ray). The energy carried by neutral pions, however, is directly fed into the electromagnetic shower component and is not available for further production of more mesons and subsequently muons. Thus, the energy carried by hadrons other than neutral pions is typically available to produce more hadrons and ultimately muons in following interactions and decays. As explained in Ref. [7, 11], the ratio of the average electromagnetic to average hadronic energy, called R, and its dependence on center-of-mass energy, are thus related to the muon abundance in air showers: if this energy ratio is smaller (larger), more (less) energy is available for the production of muons at the end of the hadronic cascade and ultimately more (fewer) muons are produced.

In a simplified world where all hadrons in air shower would be reduced to pions and considering perfect isospin symmetry, the ratio R would be fixed to 0.5. It was already shown [11] that when more particles species are considered (baryons, kaons) this value is reduced and then depends on the hadronization type [7] (string fragmentation in corona or statistical decay in core). But since the pions are dominating, it is difficult to change R alot. In fact, the pions them-selves can be either produced directly or via the decay of higher mass resonances such as ρ mesons. With perfect isospin symmetry, where the same number of ρ^0, ρ^+ and ρ^- are produced, the same fractions 1:1:1 are obtained for the pions. Using this theoretical constrain, hadron production from $e^+ - e^-$ collisions can be reproduced within the uncertainties. In the following we will call this hadronization “noIB” standing for “no Isospin Breaking”. In [12] it is shown that an ad-hoc replacement of π^0 by ρ^0 has a strong influence on muon production because ρ^0 decays into charged pions changing significantly the value of R. But this would break the isospin symmetry, which is based on the assumption that light mesons are massless, which is not the case. So the symmetry could be broken and this can be done at in string fragmentation simply allowing more ρ^0 production than charged ρ by about 20% for instance in Epos LHC-R. The rest of the $e^+ - e^-$ data can be equally well reproduced in both cases. The result can be seen in three examples on Fig. 1, where the “noIB” hypothesis is shown with dashed-dotted lines while Epos LHC-R is represented by a dotted lines. It appears that the photon number is actually better reproduced allowing isospin symmetry violation in $e^+ - e^-$ data, and that the direct measurement of ρ^0 in low energy $p + p$ interaction can not really disentangle the two scenarii. Furthermore recent LHC data [13] would actually favor an even larger production of ρ^0. Other data set such as recent NA61 data [14] are indicating a large fraction of ρ^0. There is very few charged ρ measurements, but they exclude the possibility to keep isospin symmetry for ρs using a large fraction of this resonances in the hadronization process.

Having about 20% more ρ^0 without changing charged ρ is decreasinging R by about 17% and as a consequence the number of muons is increased by about 25% as shown on Fig. 3 left-hand side (open square for “noIB” and open circle for Epos LHC-R). Since at the same time the baryon production has been reduced compared to Epos LHC, reducing the number of muons, the two effect can compensate each other and for this particular configuration the number of muons appear to be the same. But this are preliminary results and more data should be taken into account including the core-corona model to predict more accuratly the number of muons and be able to reproduce hybrid

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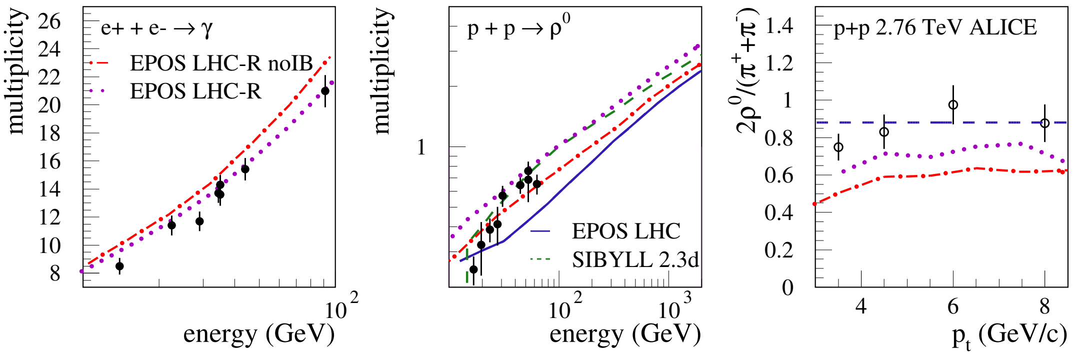

Figure 1: Left-hand side: photon production in $e^+ - e^-$ interactions as a function of the center-of-mass energy. Middle: ρ^0 production in $p + p$ interactions as a function of the center-of-mass energy. Right-hand side: ρ^0 to charged pion ratio as measured by the ALICE collaboration at 2.76 TeV in $p + p$ interactions [13] as a function of the transverse momentum. Simulations are done with Epos LHC-R (dotted line), Epos LHC (full line), Epos LHC-R with no isospin breaking “noIB” (dash-dotted line), and Sibyll 2.3d (dashed line).

air shower measurement consistently.

3. Latest LHC data and X_{max}

Using the simple Heitler-Matthews model [15] or studying Monte-Carlo simulations [10], it is well known that the inelastic cross-section, the elasticity and the multiplicity of hadronic interactions, together with the mass and energy of the primary cosmic rays are the most important factors which determine the position of the maximum air shower development X_{max}. For Epos LHC, this was fixed using the early data of different LHC experiments at 7 TeV center-of-mass energy. Since then, new and more precise data have been released at 13 TeV or using lead as a projectile giving new constraints to the models which should be taken into account to give proper X_{max} predictions

3.1 pp cross-sections

The various pp cross-sections (inelastic, elastic and total) are key ingredients to tune the model parameters. As described in [3], the amplitude of the elementary scattering in Epos LHC can be used directly to compute these cross-sections via the profile function. Really recently, the ATLAS Collaboration, using its ALFA detector, published a very precise measurement at 13 TeV [16], which is a few millibarn lower than the TOTEM measurements published early on and on which the models were tuned [17]. These new data are chosen to define the cross-sections in the new Epos LHC-R and lead to a reduction of about 10% of the inelastic cross-section at the highest energy. These reduced cross-sections in the new model will have a direct impact on the depth of the shower maximum X_{max}.

3.2 Multiplicity and elasticity in pA

The elasticity is important for the shower development but is complicated to measure at LHC. There is no direct measurement, but some other distributions could be sensitive to the energy

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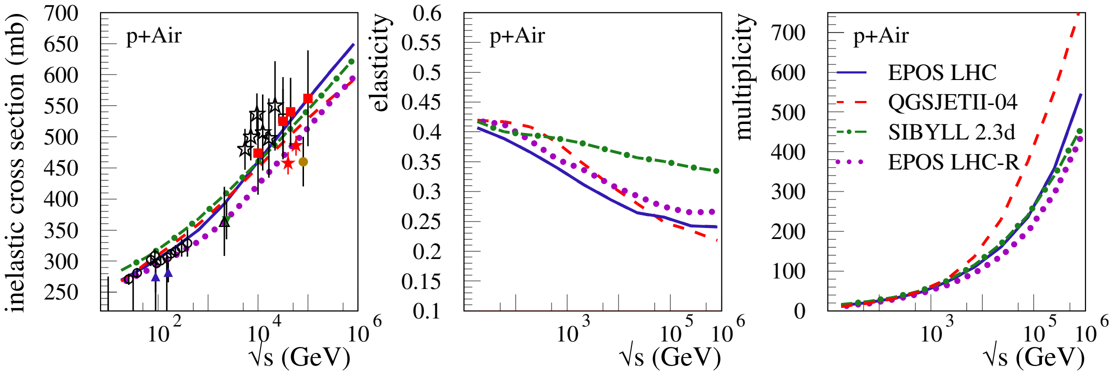

Figure 2: Inelastic cross-section (left-hand side), elasticity (energy fraction of the leading particle) (middle) and multiplicity (right-hand side) for p-air interactions as a function of center of mass energy. Simulations are done with Epos LHC-R (dotted line), Epos LHC (full line), QGSJetII.04 (dashed line), and Sibyll 2.3d (dash-dotted line). Points are data from [21].

fraction of the leading particle. The average multiplicity of pp and pPb interactions, another important measurement for $X_{\max}$, is well described by the hadronic models. In the meantime, the fluctuations of the multiplicity in pPb collision have been published and is, in fact, not so well reproduced by the two models which can run with lead projectile Epos LHC and QGSJetII.04. In fact, the latter is linked to the elasticity because the frequency of low multiplicity events is related to highly elastic events while the high multiplicity events are linked to low elasticity. So, a better description of the fluctuations of the multiplicity should improve the elasticity prediction.

In Epos LHC-R without core formation, the nuclear effects have been increased to lower the multiplicity and the cross-section to be in better agreement with CMS data [18] on the multiplicity distribution of Pb-p interactions at 5.02 TeV and with the p-Air cross-section as measured by air shower experiment like the Pierre Auger observatory [19, 20]. This will lead to a further reduction of the cross-section and the multiplicity, and an increase of the elasticity (more event with low multiplicity).

3.3 Nuclear fragmentation

As stated in [22], the fluctuations of $X_{\max}$ for nuclear primaries are underestimated in Epos LHC because of an error in the generation of wounded nucleons which were produced first by the model itself, which is based on the list of nucleons, and then again by the subroutine creating the nuclear fragment from the list of the remaining nucleons, which includes some evaporation which was not necessary. Hence, the produced fragments are too light with too many free nucleons. Furthermore a new process to produce medium size fragments from the heavy fragments as been introduced and tuned to the available data. After these corrections in Epos LHC-R, the RMS of $X_{\max}$ for iron showers is increased from 20 g/cm^2 to 24 g/cm^2 while other models have 25 g/cm^2. The remaining small difference is coming from the fact that there is still a bit more free nucleons in Epos LHC-R than in the other models, but this is actually supported by the data available at low energy. Unless Epos LHC, Epos LHC-R has now a realistic distribution of nuclear fragments and slow nucleons.

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3.4 Hadronic interactions in Air and $X_{\max}$

In order to understand the impact of these modifications on the $X_{\max}$ predictions by Epos LHC-R we can first check the p-air cross-section and elasticity. In Fig. 2, the inelastic p-air cross-section is shown on the left-hand side, the elasticity on the middle panel and the multiplicity is on the right-hand side. The lines are for Epos LHC-R (dotted line), Epos LHC (full line), QGSJetII.04 (dashed line), and Sibyll 2.3d (dash-dotted line), and the points are data from [21]. Epos LHC-R has a cross-section about 10% lower than Epos LHC on the full energy range, an elasticity which is increased by around 10%, and a multiplicity decreased by about 10% too.

These are not huge differences but all going into the same direction, and as shown in Fig. 3 right-hand side, it is only a 2% increase of $X_{\max}$ for proton-induced showers. Nevertheless this represents already around 15 g/cm^2 which was the difference between Epos LHC (line with full stars) and Sibyll 2.3d (line with full triangles). So, in fact, Epos LHC-R (line with open circles) predicts around the same $X_{\max}$ values than Sibyll 2.3d, much deeper than the predictions from QGSJetII.04 (line with open squares) and even deeper than Sibyll 2.3d for iron induced showers.

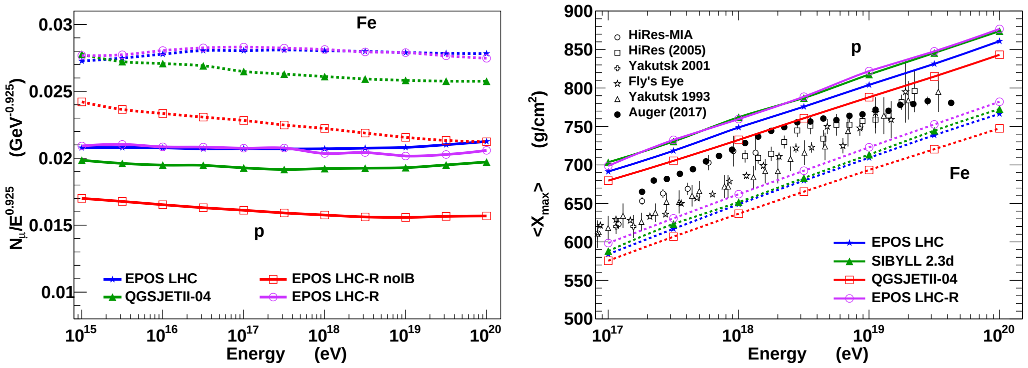

Figure 3: Number of muons normalized by $E^{0.925}$ (left-hand side) and $\langle X_{\max}\rangle$ (Right-hand side) for proton- and iron-induced showers as a function of the primary energy. Predictions of different high-energy hadronic interaction models are presented with full lines for proton and dashed lines for iron with full triangles for Sibyll 2.3d, open circles for Epos LHC-R, open squares for QGSJetII.04, full stars for Epos LHC. Refs. to the data can be found in [23] and [24].

In terms of mass composition, it means that the mean logarithmic mass deduced from $X_{\max}$ measurements using Epos LHC-R will also be around 15% larger, hence reducing the muon deficit in simulation compared to data. It will probably be very similar to Sibyll 2.3d, or actually heavier since the muon line is deeper for Epos LHC-R, but these are still preliminary results.

4. Summary

The better description of the collective hadronization and, in particular, the fact that the core is produced earlier than predicted by Epos LHC can have very important consequences for the muon production in air showers. But before studying such effect, it is important to first properly define the corona hadronization.

In string fragmentation used for the corona part, the pions can be generated directly or using ρ resonances as intermediate step. If there was a perfect isospin symmetry, the ratio between neutral and charged pions would be the same in both cases and there will be no impact on the muon production. But we demonstrated here that various data set favor a sligth isospin symmetry breaking with up to 20% more ρ^0 than charged ρ. As a consequence, the number of muons would be increased by almost 25% as shown in here and in [12]. The lack of precise data do not allow a definitive answer on the exact amount of ρ^0 in string fragmentation. In Epos LHC-R the number of muons is not increased compared to Epos LHC because at the same time, the number of forward baryon has been reduced in accordance to NA61 data. Furthermore, using updated cross-sections from LHC and air shower measurement in Epos LHC-R, $X_{\max}$ is now 15 g/cm^2 deeper, very close to Sibyll 2.3d predictions, leading to an heavier composition for a given measured $X_{\max}$.

These preliminary results do not include yet the effect of the core-corona model which is necessary to fully reproduce LHC data, but they demonstrate that all the details of the hadronic interactions are important and should be carefully studied. Simplified models cannot account for all complex hadronization scheme which are observed at the LHC and which can play an important role for the air shower development. This is why a complete model like Epos is important and should be compared and constrained by a large variety of data.

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