Current Concepts in Theory and Modelling of High Energy Hadronic Interactions

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We discuss some key observations of cosmic ray experiments. It will be shown that prediction from air shower simulation using different hadronic interaction models differ by large amounts. We try to understand this by investigating the theoretical concepts behind these models.

The interpretation of the results of air shower experiments depends heavily on simulations. Whereas the electromagnetic part of an air shower (the so-called electromagnetic cascade) is well under control, the hadronic part is not accessible from first principles, and is therefore treated via phenomenological hadronic interaction models.

We will focus in this article on two "key" observables of air showers: the number of muons and the number of electrons at the observation level (defined by the geographical location of the detector array of the corresponding experiment).

It has been a longstanding problem in air shower physics that the number of muons obtained from air shower simulations has always been too low compared to the measurements. Any attempt to modify the hadronic interaction models in order to get more muons created other problems. In 2006, non of the existent models (QGSJET [1], SIBYLL [2]) could consistently describe all cosmic ray air shower data.

Starting to use EPOS [3, 4, 5] as interaction model, it was found that one gets significantly more muons, without changing observables like $X_{\max}$ too much, see [6]. As an example, we show in Fig. 1 the muon density at a fixed distance from the core, as measured by the MIA collaboration [7], compared to simulations based on QGSJET and EPOS. Significantly more muons are produced in the EPOS simulations. Similar results have been obtained more recently from the AUGER collaboration [8].

Why are there more muons produced in EPOS ? Because EPOS produces more baryons! In Fig. 2, we plot the antiproton over pion ratio in p+Air collisions for EPOS, QGSJET, and SIBYLL, as a function of the energy. Knowing that the pion rate in the three models is similar, we can see that the antiproton production increases much more in EPOS compared to the other models. This fact is also observed for other baryons.

The particular role of the baryons concerning muon production is easily understood. The main property of the baryon, in this context, is the fact that it is not a π^0. The latter particle decays immediately into two photons, its energy is given to the corresponding electromagnetic cascade, no muons can be produced in the following. On the contrary, a baryon can still interact, producing charged pions, which then decay into muons. Also, baryons have a softer pion spectrum than pions in the next generation, leading to less energy lost in the electromagnetic

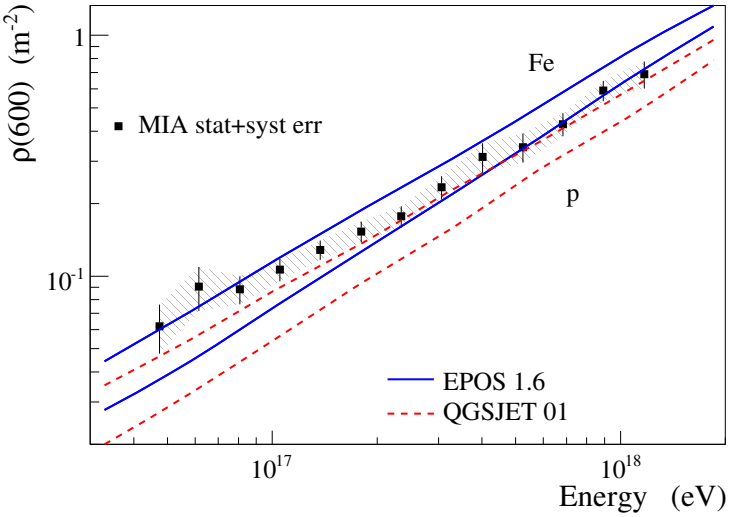

Figure 1: The muon density at a fixed distance from the core, as measured by the MIA collaboration [7], compared to simulations based on QGSJET and EPOS.

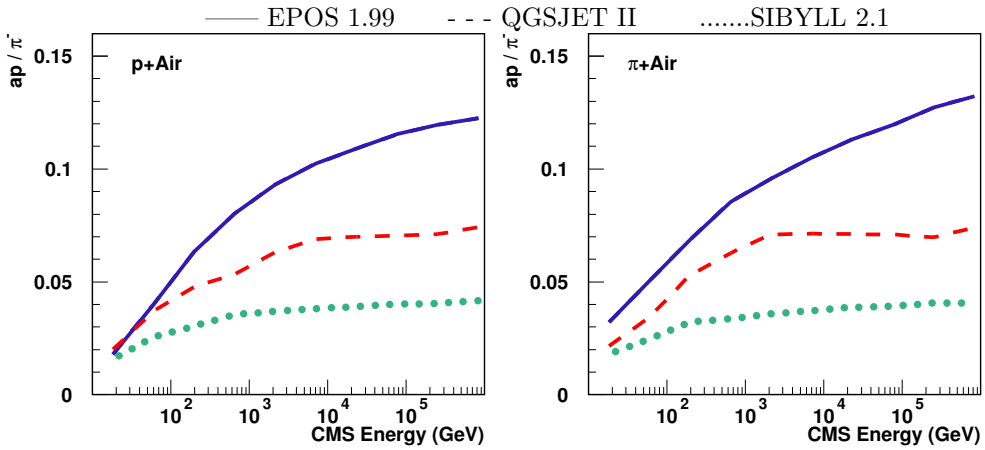

Figure 2: The antiproton over pion ratio in p+Air collisions for EPOS, QGSJET, and SIBYLL, as a function of the energy.

channel in case of π^0 production in the next collision with air. So although baryons are not the most abundant particles in the cascade, their role is very important concerning the muon rate.

EPOS has been designed (and optimised) to understand ALL types of hadrons by carefully studying baryon production in accelerator experiments, without thinking about CR applications. In Fig. 3(upper panel), we plot the yields of different kinds of baryons in proton-proton collisions at 158 GeV, from EPOS calculations, compared to data from SPS/NA49 [9]. An enor-

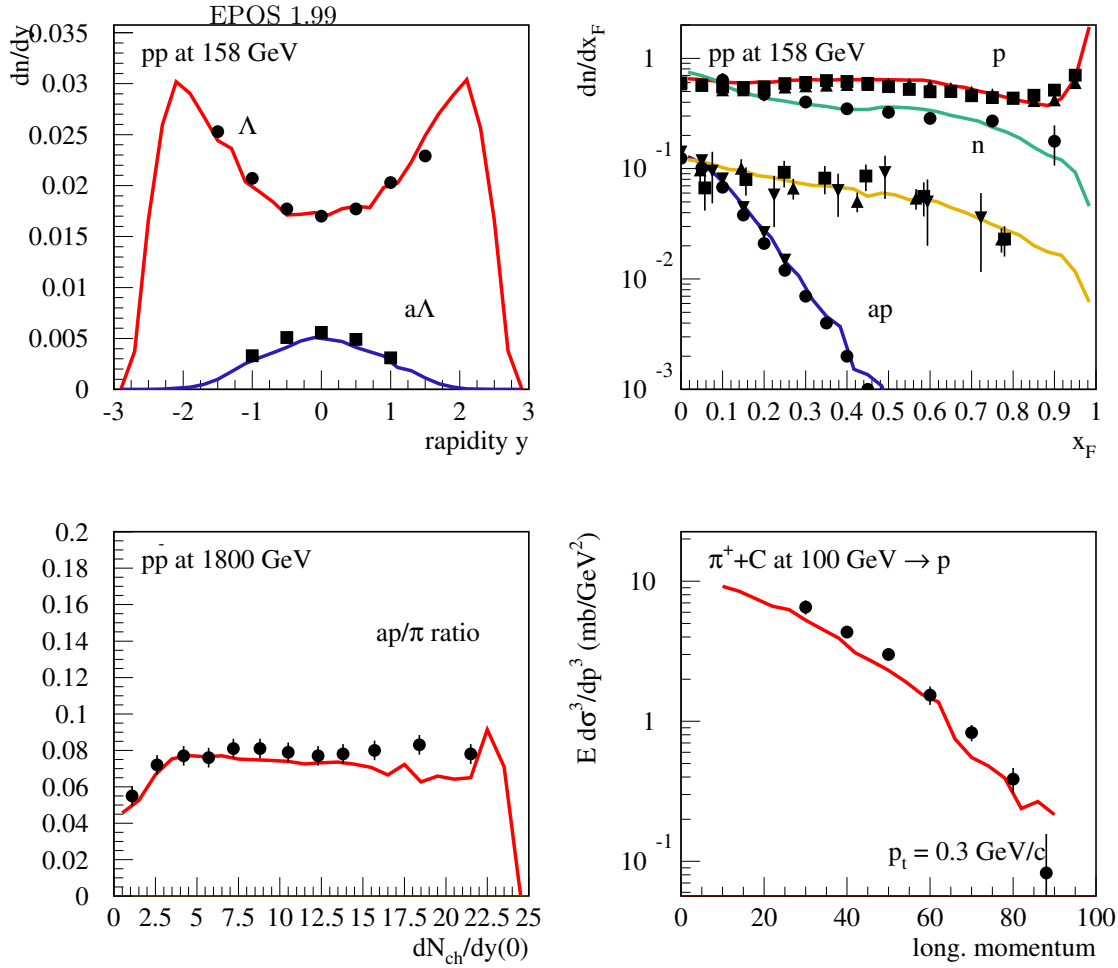

Figure 3: Upper panel: The yields of different kinds of baryons in proton-proton collisions at 158 GeV, compared to data from SPS/NA49 [9]. Lower panel: Antiproton over pion ratio as a function of the multiplicity density, in pp scattering at 1800 GeV (left), and proton production in pion carbon scattering at 100 GeV (right). We compare EPOS calculations with data [10, 11].

mous amount of pp ($p\bar{p}$) data has been considered, at SPS, ISR, RHIC, TEVATRON, also πp, pA and πA collisions. As another example, we show in Fig. 3 (lower panel) the antiproton over pion ratio in pp scattering at 1800 GeV (left), and proton production in pion carbon scattering at 100 GeV (right).

If we compare EPOS to QGSJET and SIBYLL, we find similar results concerning pions, but big differences concerning baryons, see Fig. 4, where we show pion production (left) and proton production (right) in pion carbon scattering at 100 GeV. We compare calculations from different models with data [11]. Clearly visible the large difference between EPOS and the other

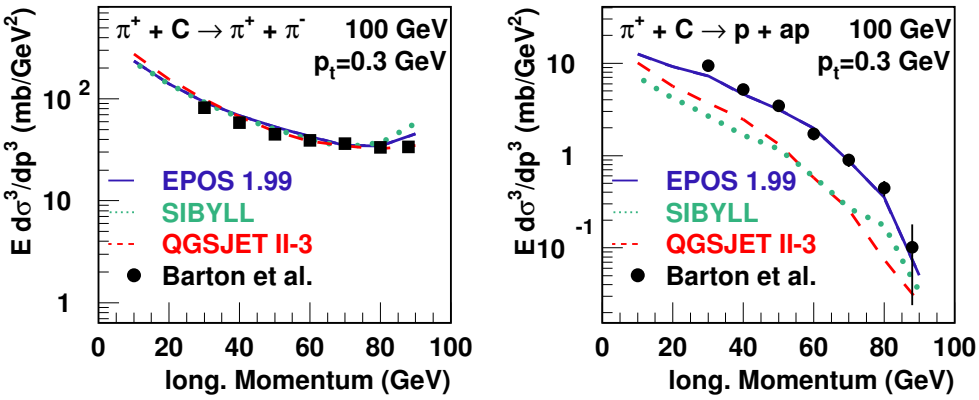

Figure 4: Pion production (left) and proton production (right) in pion carbon scattering at 100 GeV.

models, in case of protons. Whereas EPOS is close to the data, the other models are lower by as much as a factor of 2-3.

Having increased the muon number without affecting too much the electrons leads, however, to some contradictions. The problems comes from KASCADE data [12], where the number of muons is correlated with the number of electrons. Here, QGSJET and SIBYLL seem to work, so increasing the muons and not the electrons will give a wrong electron-muon correlation. The solution is related to a completely different subject: non-linear effects (already considered for particle production) should also be taken into account for cross section calculations (which has not been done in earlier EPOS versions). Introducing non-linear effects as discussed in [1] also for cross section calculations, we obtain the results as shown in Fig. 5. Both cross sections

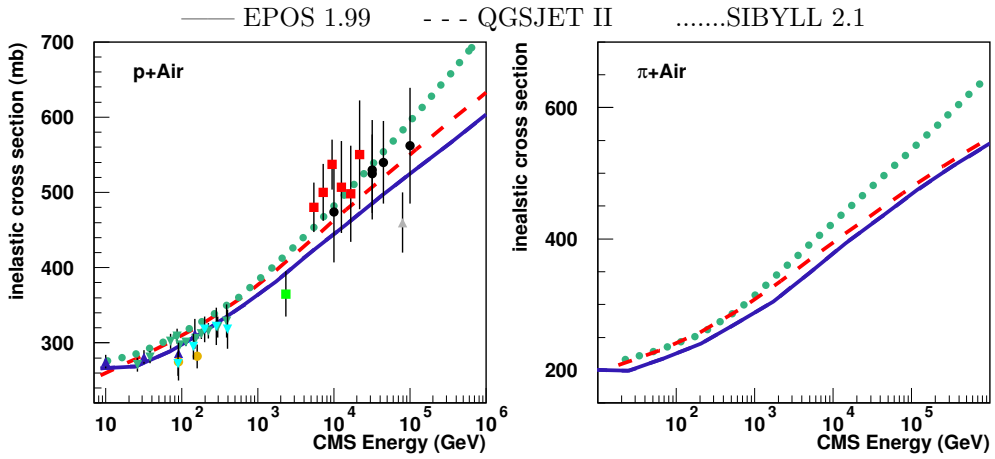

Figure 5: The inelastic cross section in p-Air and π-Air collisions, for different models.

from EPOS calculations are below the results from the other models. There is also a trend in the data towards lower values, in more recent measurement compared to older data. Using our new results (with lower cross sections compared to other models), we get more electrons at ground, since the shower gets deeper into the atmosphere. We seem to be in agreement with the KASCADE muon-electron correlations, but having both more electrons and more muons compared to the other models. Studies are under way to make precise comparisons between the new EPOS and KASCADE.

Having a smaller inelastic cross section compared to earlier calculations (and other models) has also an impact on Xmax: it will be bigger, see Fig. 6.

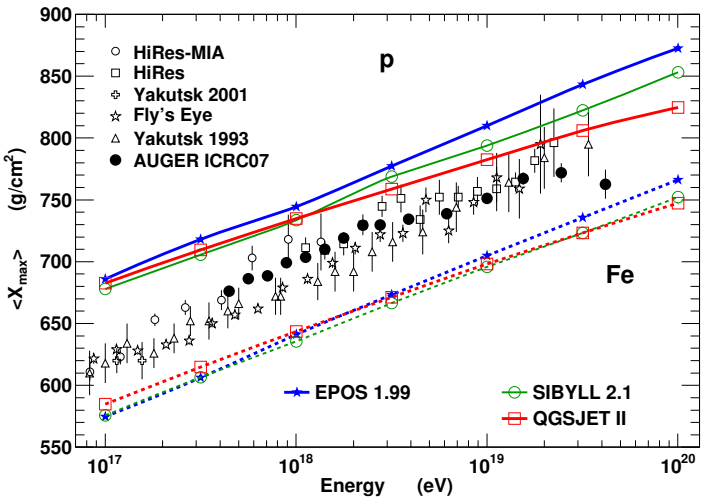

Figure 6: Xmax from different models compared to data.

In the following, we will discuss very briefly the physics of the interaction models.

EPOS and QGSJET are multiple scattering model in the spirit of the Gribov-Regge approach, see Fig. 7 (left). Here, one does not mean simply multiple hard scatterings, the elementary processes corresponds to complete parton ladders, which means hard scatterings plus initial state radiation. In this case, this elementary process carries an important fraction of the available energy. This is why in EPOS one treats very carefully the question of energy sharing in the multiple scattering process. Particle production comes from remnants and string decay. In SIBYLL, one distinguishes between a primary interaction leading to two $q-qq$ string, and subsequent scatterings of the type $g+g$, leading to $\bar{q}-q$ strings after splitting of the gluons, see Fig. 7 (right).

All there models treat in some way so-called non-linear effects due to high parton densities. In EPOS one first parameterises the numerically obtained results for an elementary interaction (more precisely: the imaginary part of the corresponding amplitude in $b-$space) as $\alpha(x^+)^\beta(x^-)^\beta$, which is then changed into $\alpha(x^+)^{\beta+\epsilon_P}(x^-)^{\beta+\epsilon_T}$, where ϵ_P, ϵ_T mimic the effect of rescattering of ladder partons (or Pomeron-Pomeron interactions), see Fig. 8 (left), and the corresponding screening effects. Here, x^+, x^- are the light cone momentum fractions of the first ladder partons. The exponents ϵ_P, ϵ_T depend on $\log s$ and the number of participating nucleons in case of pA or AA scattering. So high density effects are treated in an effective fashion, but

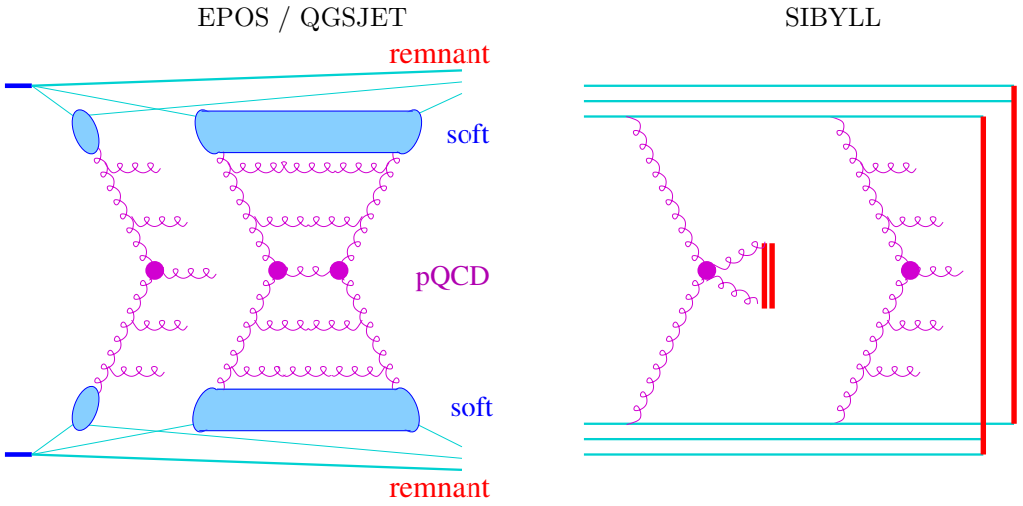

Figure 7: Multiple scattering diagram in EPOS, QGSJET (left) and SIBYLL (right).

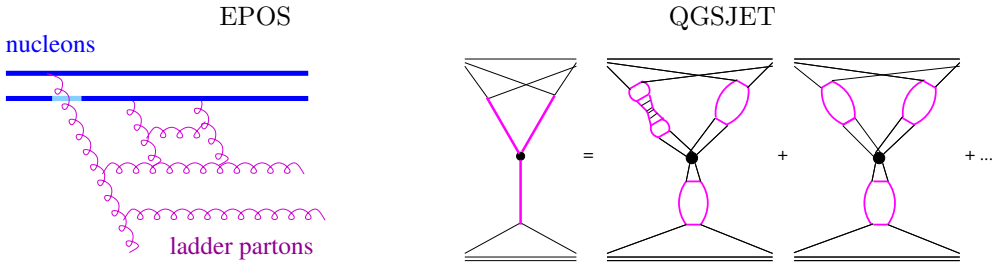

Figure 8: Non-linear effects: effective treatment of rescattering of ladder partons (Pomeron-Pomeron interactions) in EPOS (left); explicit treatment of triple Pomeron graphs (and higher orders) in QGSJET (right).

energy is perfectly conserved (the only model which does so). In QGSJET, Pomeron-Pomeron interactions are taken into account to all orders, see Fig. 8 (right), but in this case energy conservation for multi-Pomeron diagrams is no longer imposed. In SIBYLL, an energy dependent saturation scale is introduced, which serves as a p_t cutoff. Energy conservation is not imposed either.

Finally, based on the experience with heavy ion collisions, EPOS treats high density proton-proton events collectively, via a three-dimensional hydrodynamical evolution of a quark-gluon plasma / hadron gas, with subsequent freeze out.

To summarise: air shower simulations with EPOS provide more muons, due to more baryon production, compared to QGSJET and SIBYLL, which is due to more baryon production in the former model. Despite the large differences in their predictions, the basic theoretical concepts of the three models are similar (multiple scattering of Gribov-Regge type, strings, non-linear effects). But the practical implementation is quite different.

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