Test of hadronic interaction models via accelerator data

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Abstract
At high energy, cosmic rays can only be studied by measuring the extensive air showers they produce in the atmosphere of the Earth. Although the main features of air showers can be understood within a simple model of successive interactions, detailed simulations and a realistic description of particle production are needed to calculate observables relevant to air shower experiments. Currently hadronic interaction models are the main source of uncertainty of such simulations. We will study how accelerator data can constrain the different hadronic models available for extensive air shower simulations.

1 Cosmic rays and hadronic interactions

Due to the steeply falling energy spectrum of cosmic rays, direct detection by satellite- or balloon-borne instruments is only possible up to about $\sim 10^{14}$ eV. Fortunately, at such high energy, the cascades of secondary particles produced by cosmic rays reach the ground and can be detected in coincidence experiments. The cascades are called extensive air showers (EAS) and are routinely used to make indirect measurements of high energy cosmic rays.

As a consequence of the indirect character of the measurement, detailed simulations of EAS are needed to extract information on the primary particle from shower observables. Whereas electromagnetic interactions are well understood within perturbative QED, hadronic multiparticle production cannot be calculated within QCD from first principles. Differences in modeling hadronic interactions, which cannot be resolved by current accelerator data, are the main source of uncertainty of EAS predictions [1, 2]. In this article, we will discuss the relation between hadronic multiparticle production and EAS observables and the constrains given by accelerator data.

2 Heitler's Model

Thanks to a simple Heitler model generalized for hadronic showers [3, 4], one can extract the main observables of hadronic interactions needed to understand the development of air showers.

In this kind of toy model, a hadronic interaction of a charged particle with energy E will produce $N_{\rm tot}$ new particles with energy $E/N_{\rm tot}$, with $N_{\rm EM}$ particles (π^0 mainly) transferring their energy to the electromagnetic channel. Introducing a characteristic energy ($E_0 = 150\,$GeV), where pions are assumed to decay into muons, the number of muons for a shower with primary energy E_0 after n generations is given as [5]

$$N_\mu = \{N_{\rm tot} - N_{\rm EM}\}^n = \left(\frac{E_0}{E_{\rm dec}}\right)^{1+\ln R/\ln N_{\rm tot}}, \qquad (1)$$

with $R = (N_{\rm tot} - N_{\rm EM})/N_{\rm tot}$. The muon number depends therefore strongly on R, which is understandable since $N_{\rm EM}$ counts particles giving all their energy to the electromagnetic channel – not producing muons.

Usually these kind of toy models consider only pions as secondary particles resulting in $R = 2/3$. In this case the muon number depends only on $N_{\rm tot}$, as does $\rm X_{max}$ [5], as

$$X_{\rm max} = \lambda_{\rm had} + \lambda_{\rm EM} \cdot \ln\left(\frac{E_0}{N_{\rm tot} E_c}\right), \tag{2}$$

with $\lambda_{\rm had}$ being the hadronic interaction path length, and with $E_c = 85$ MeV being the critical energy (where particles disappearing from the shower). Let us now be a bit more realistic, and consider all kinds of hadrons, including (anti)baryons. Particle production in hadronic interactions is model dependent, and so is the precise value of R. With R being less than 1 and $N_{\rm tot} >> 1$, the muon number depends very sensitively on the ratio R.

Thus this simple approach allows us to extract the main observables which lead the EAS development, namely:

- cross section
- multiplicity (and inelasticity)
- (anti)baryon production

We will compare the commonly used hadronic interaction models for EAS simulations to accelerator data for these observables.

3 Accelerator data

Hadronic interaction models

There are several hadronic interaction models commonly used to simulate air showers. For high energy interactions ($E_{\rm lab} \gtrsim 100$ GeV), the models studied here are EPOS 1.6 [6,7], QGSJET 01 [8], QGSJET II [9,10], and SIBYLL 2.1 [11–13]. The physics models and assumptions are discussed in, for example, [14].

Cross section

As seen Sec. 2, the cross section is very important for the development of air showers and in particular for the depth of shower maximum. As a consequence, the number of electromagnetic particles at ground is strongly correlated to this observable (if the shower maximum is closer to ground, the number of particles is higher).

The proton-proton scattering total cross section is typically used as an input to fix basic parameters in all hadronic interaction models. Therefore, as shown in Fig. 1 lefthand-side, it is very well described by all the models at low energy, where data exist. And then it diverges above 2 TeV center-of-mass (cms) energy because of different model assumptions. In all the figures EPOS 1.6 is represented by a full (blue) line, QGSJET II by a dashed (red) line, QGSJET 01 by a dash-dotted (black) line and SIBYLL 2.1 by a dotted (green) line.

From p-p to proton-air interactions, the Glauber model is used in all models but with different input parameters depending on nuclear effects (none in SIBYLL 2.1, strong in QGSJET II).

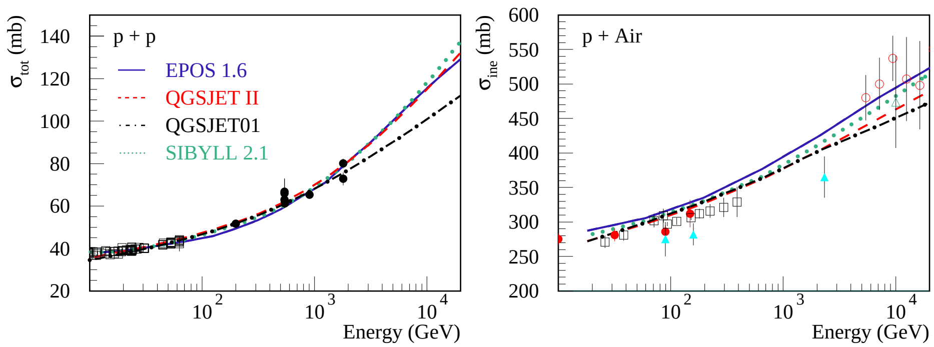

Fig. 1: Total cross section of p-p collision (lefthand-side) and inelastic proton-air cross section (righthand-side) as calculated with EPOS 1.6 (full line), QGSJET II (dashed line), QGSJET 01 (dash-dotted line) and SIBYLL 2.1 (dotted line). Points are data from accelerator [15] and cosmic ray experiment [16–19].

So comparing the models to each other Fig. 1 righthand-side, differences appear even at low energy where the p-p cross section are similar. And at high energy the spread is again larger. Furthermore, the simulated cross sections seem all to increase faster than the measured one, even at low energy ($<$ 1 Tev) where direct measurement of single hadrons from cosmic rays can be done at ground [16–19] (almost accelerator like measurement since proton flux is known).

Multiplicity

According to eq. 2, the multiplicity plays a similar kind of role as the cross section, but with a weaker dependence (log). On the other hand, the predictions from the models have much larger differences.

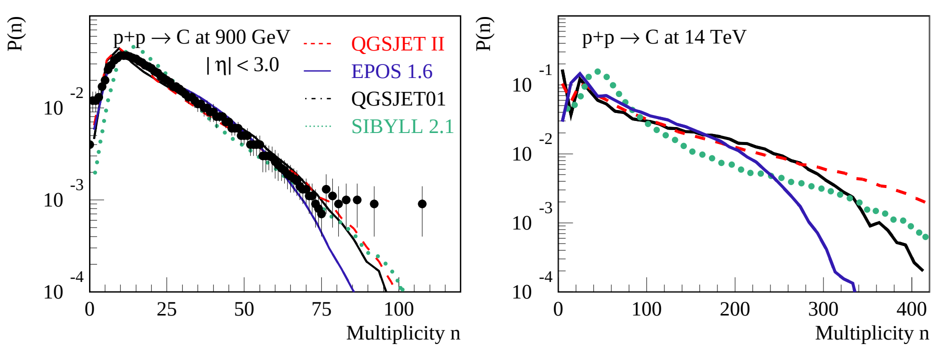

Fig. 2: Multiplicity distribution of $\overline{p}$-p collision at 900 GeV cms energy (lefthand-side) and 14 TeV (righthand-side) as calculated with EPOS 1.6 (full line), QGSJET II (dashed line), QGSJET 01 (dash-dotted line) and SIBYLL 2.1 (dotted line). Points are data [20].

As shown in Fig. 2, going from 900 GeV cms energy (lefthand-side), where models agree with the UA5 data [20], to 14 TeV (LHC) (righthand-side), the discrepancy can be larger than a factor of 2 in the tail of the distribution (and the shape is different). The EPOS model predicting much smaller multiplicity than QGSJET II.

The multiplicity distribution of charged particles is a very good test of the fundamental property of the hadronic interaction models and it should be one of the first result of the LHC experiments.

(Anti)Baryon production

In the forward region, the number of (anti)baryons is very important for the number of muons produced in EAS, because it changes the ratio R of eq. 1. The process is well described in [21], where it is also shown that the number of antiprotons on the projectile side of π-carbon collision can only be reproduced correctly by the EPOS model. This is due to a more sophisticated remnant treatment in this model which allows baryon number transfer between the inner part of the collision and the forward (or backward) region. This can be tested with other data like the lambda rapidity distribution published by the NA49 collaboration [22] and shown on the lefthand-side of Fig. 3. We can see that in EPOS a large number of lambdas are in the central region and not at large rapidity any more (cf QGSJET 01).

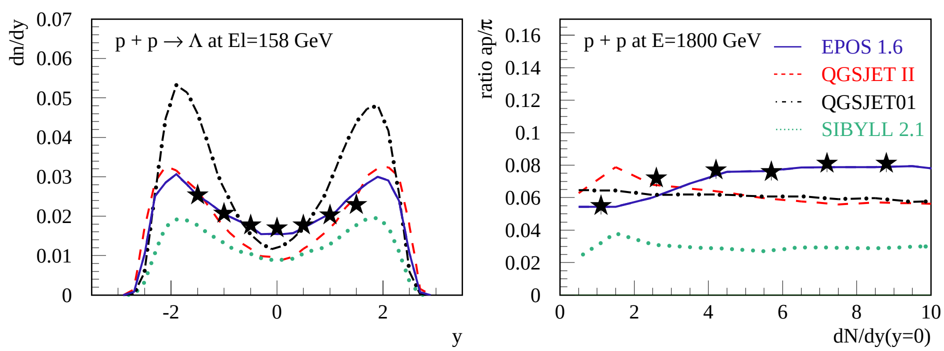

Fig. 3: Lambda rapidity distribution of p-p collision at 158 GeV lab energy (lefthand-side) and ratio of anti-proton over pion in $\overline{p}$-p scattering at 1.8 TeV cms energy as a function of the plateau height (righthand-side) as calculated with EPOS 1.6 (full line), QGSJET II (dashed line), QGSJET 01 (dash-dotted line) and SIBYLL 2.1 (dotted line). Points are data [22, 23].

Another particularity of the (anti)baryons is that their production increase faster with the energy that the pion production. In other words, the ratio $\overline{p}/\pi$ increase with energy. At the highest measured energy (TEVATRON [23]), we can see on the righthand-side of Fig. 3, that only EPOS described correctly this ratio as a function of the event multiplicity. Other models are too low. This explain why air showers simulated with EPOS contain more muons. Measurement of (anti)baryon distributions at LHC will be very important to constrain muon number in air showers.

4 Summary

Using a simple toy model, it was shown that EAS development is driven by a limited number of fundamental observables like the proton (and pion) air cross section, the multiplicity (and inelasticity) and the number of (anti)baryon in proton (and pion) air interactions. Unfortunately these quantities are well measured only at low energy ($\sim$100 GeV lab) in proton (or pion) nucleus scattering. The cross section and multiplicity are measured up to 2 TeV cms energy in (anti)proton-proton collisions, but nevertheless the hadronic models commonly used for EAS simulations show big differences in their extrapolation already at LHC energies. The discrepancy is even larger if we consider hadron-nucleus collisions. Situation is even worth for the forward distributions of (anti)baryons (important for muons), which are not measured at all at collider energies. In that case, the models disagree with each other already at low energy. This probably explain why none of these hadronic interaction models can consistently reproduce all results from an experiment like KASCADE [24], even if the energies involved are in the range of accelerator data.

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