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Comparison of Hadronic Interaction Models with LHC data

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Abstract: The uncertainty in the prediction of shower observables for different primary particles and energies is currently dominated by differences between hadronic interaction models. Since the end of 2009, LHC data has become available for proton-proton scattering at different energies, extending to the reach of collider data. The LHC data on minimum bias measurements can be used to test Monte Carlo generators and these new constrains will help to reduce the uncertainties in air shower predictions. In this contribution, we will show the results of the comparison between the currently used high energy hadronic interaction models and LHC data. Implications for air shower simulations will be discussed.

Keywords: LHC, hadronic, model

1 Introduction

Knowing the elemental composition of cosmic ray particles arriving at Earth is of crucial importance to understand the production and propagation of cosmic rays. Unfortunately, cosmic rays can be measured only indirectly above an energy of 10^{14} eV through the cascades of secondary particles, called extensive air-showers (EAS), that they produce in the atmosphere (for a recent review, see [1]). Only by simulating the generation of EAS and comparing the predictions with measurements one can draw conclusions on the primary mass composition of the arriving particles [2]. With the operation of modern large-scale experiments the reliability of air-shower simulations has become the source of the largest systematic uncertainty in the interpretation of cosmic-ray data [3, 4, 5, 6, 7, 8]. While the electroweak interaction processes are reasonably well understood, modeling of hadronic multiparticle production is subject to large theoretical uncertainties that are, moreover, difficult to estimate [9, 10, 11].

The Large Hadron Collider (LHC) at the CERN laboratory allows us to access, for the first time, the energy region above the knee in the laboratory. Therefore an analysis of inclusive particle data taken at the LHC is particularly interesting for constraining existing hadronic interaction models and for testing possible new mechanisms of hadron production [12]. Data from LHC experiments published so far have mostly been taken with detectors covering the central phase space region in pseudorapidity ($|\eta| \lesssim 2.5$). This region is most easily accessible in collider experiments and is also the region of the highest rapidity-density of produced particles. The first data have been compared to cosmic ray models in [13]. On the other hand, since the number of particles in an air-shower is roughly proportional to the energy of the primary particle, the most energetic outgoing particles of an interaction, emitted in the very forward region of a collider experiment – such as in diffractive interactions – are the most important ones for understanding air-showers. This data are now available with the first LHCf results [14]. In addition the first cross section measurements by ATLAS [15] have been published.

In this paper we compare the predictions of several representative hadronic interaction models, EPOS 1.99 [16, 17], SIBYLL 2.1 [18, 19, 20], QGSJET01 [21, 22] and QGSJETII-03 [23, 24, 25] with the inelastic cross section and single-particle inclusive observables measured at midrapidity and at very large pseudorapidity at the LHC. Implications on air shower development will be discussed.

2 LHC Data

A large number of minimum bias distributions has been published by the different experimental collaboration at the LHC. It is not possible to report them all in this proceeding, but we can focus on a few distributions which are most important for the description of air shower development [26].

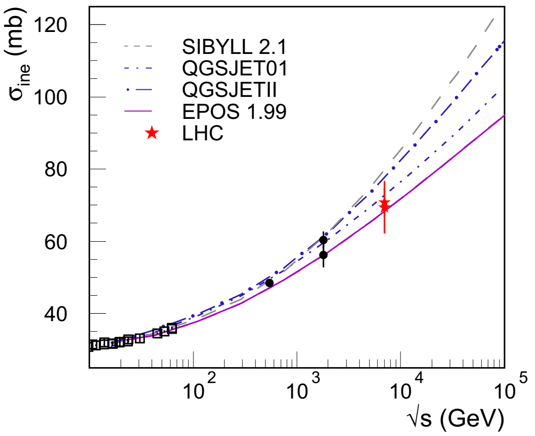

Figure 1: Inelastic cross section as a function of center-of-mass energy. The star point indicates the last ATLAS measurement [15] compared to the predictions of QGSJET01 and II-03, SIBYLL 2.1, and EPOS 1.99.

2.1 Cross Section and Average Multiplicity

One of the most important parameter for EAS simulation is the inelastic cross section. It drives the entire shower development and reflects in both shower maximum measurement and as a consequence in the number of electromagnetic particles at ground.

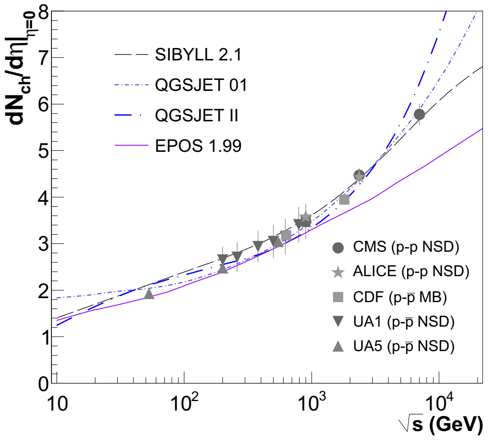

Figure 2: Collision-energy dependence of the midrapidity charged hadron invariant yields in non single-diffractive (NSD) p-p and p-$\bar{p}$ collisions compared to the predictions of QGSJET01 and II-03, SIBYLL 2.1, and EPOS 1.99.

Since more than a decade their was a large uncertainty concerning the cross section because two measurements at the highest energy (1.8 TeV) had a difference of more than one sigma. As shown on Fig. 1, the ATLAS collaboration recently published a value of the inelastic cross section at 7 TeV which seems to validate a slowly rising cross section as in EPOS and QGSJET01. The uncertainty is still relatively large because of the correction needed to extract the data, but in a near future the TOTEM [27] experiment should improve a lot this measurement.

On the other hand, we show on Fig. 2 that the evolution of the multiplicity at midrapidity of non-single diffractive (NSD) interaction seems to be relatively fast following the trend of the QGSJET01 model, but not as fast as QGSJETII-03. The slope of the multiplicity increase in the EPOS 1.99 model is too low.

2.2 Pseudorapidity and Multiplicity Distribution

Even if this observables at mid-rapidity are not simple parameters of the EAS development, they are very good test for the hadronic models. On Fig. 3 is shown one of the pseudorapidity distributions measured by ATLAS [28]. Unlike the result shown on Fig. 2 where the data were corrected by a model to represent NSD events, these data are based on a hadron level trigger only (more than 2 charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$). It gives a not biased comparison with the hadronic models and we actually see that here SIBYLL is not any more in perfect agreement with the data. In fact, looking at all the distributions published by ATLAS, none of the tested models is in perfect agreement with the data.

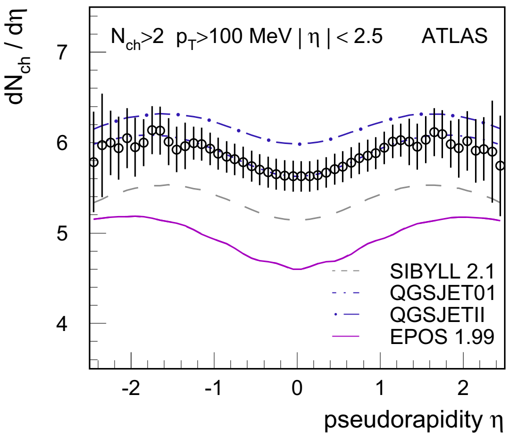

Figure 3: Pseudorapidity distributions of charged hadrons, measured in p-p events with more than 2 charged particles with $p_T > 100$ MeV at the LHC (7 TeV) by ATLAS [28], compared to the predictions of QGSJET01 and II-03, SIBYLL 2.1, and EPOS 1.99.

One illustration can be seen in Fig. 4. The multiplicity distributions published by ALICE collaboration [29] are compared to the models. Even if the general shape is well described, none of the models is able to fit the tail of the distributions correctly. In [13] it can be seen that the maximum is not very well described neither.

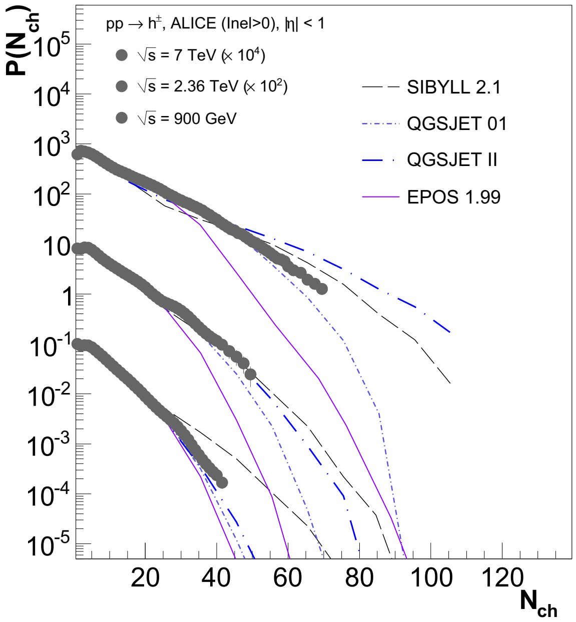

Figure 4: Multiplicity distributions of charged hadrons, $P(N_{ch})$, measured by ALICE in Inel>0 p-p events at 0.9, 2.36 and 7 TeV [29] compared to the predictions of QGSJET01 and II-03, SIBYLL 2.1, and EPOS 1.99.

2.3 Transverse Momentum Distribution

In air shower development, the p_{T} distribution is mostly relevant for secondaries with relatively low energy when the boosted longitudinal momentum is not too large compared to the transverse momentum. So at the LHC, it is not a critical measurement. Nevertheless it is a good test of the physics implemented in the hadronic models. Comparing on Fig. 5 the p_{T} distribution measured by the CMS collaboration [30] at 7 TeV with the model predictions, we can see that again the data are well bracketed by the models used in CR physics. As shown in [13], we notice that the low p_{T} range is over estimated by the QGSJET models, but on the other hand the tail at high p_{T} is better reproduce than in EPOS. The SIBYLL model who has a good $\langle p_{\perp} \rangle$ in fact underestimates the intermediate range p_{T} and overestimates the high p_{T}.

2.4 Forward Energy Distribution

For the first time in a hadron collider experiment, it is possible to the measure energy spectrum of γ at very large pseudorapidities. This is a key quantity for air shower development since the forward γ coming from π^0 decay drive the transfer of energy from the hadronic core to the electromagnetic cascade.

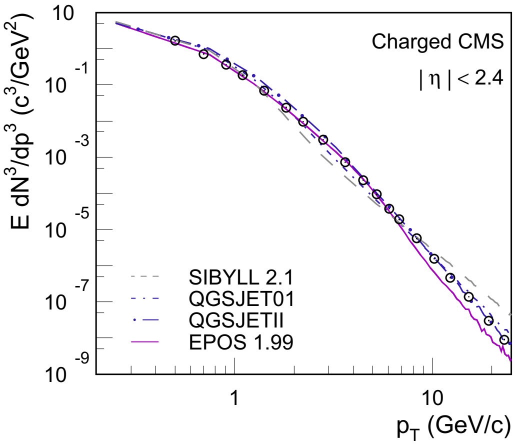

Figure 5: Transverse momentum (p_{T}) distribution of charged hadrons measured by CMS in p-p events at 7 TeV [30] compared to the predictions of QGSJET01 and II-03, SIBYLL 2.1, and EPOS 1.99.

The LHCf collaboration published the first results on γ spectra in two pseudorapidity windows [14]. On Fig. 6, the measured γ spectrum for $\eta > 10.94$ is compared to the model simulations. To a large extent simulations are in relatively good agreement with the data within the systematics (not shown here) and bracket again the data (EPOS slightly harder than the data, QGSJET softer). Looking into the details, the slope of the data seems to be smaller in the data than in all the models for γ energy below 1.5 TeV. This can have an effect on air shower development and will be investigated in future study.

3 Conclusions

The quality of the LHC data description varies from model to model and differs for different observables. A first general observation is that none of the models considered provides a very good description of all the LHC data considered here. Yet, the CR models bracket both the LHC cross section, the central rapidity densities, the multiplicity probabilities and the forward γ spectrum. As a consequence the LHC measurements at $\sqrt{s} = 7$ give strong support to the conventional interpretation that the break in the power-law index of the observed CR spectrum at $10^{15.5}$ eV is indeed due to a feature of the primary cosmic ray flux. Alternative interpretations of the knee being a side-effect of rapidly changing properties of hadronic interactions above $\sqrt{s} \approx 2$ TeV are strongly disfavored. Similarly the LHC measurements support the interpretation of air shower data in the knee energy range as reflecting a change from a light to a more heavy mass composition. No

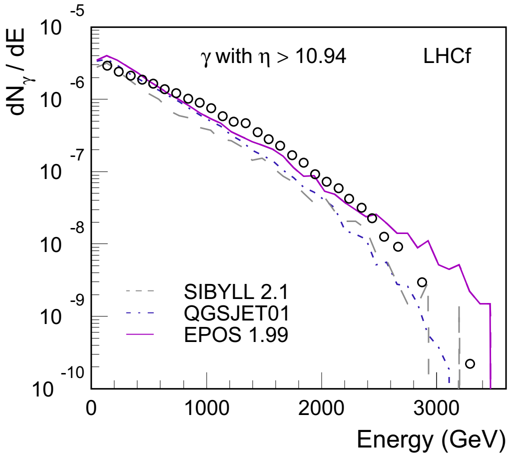

Figure 6: Energy distributions of γ with $\eta > 10.94$ measured by LHCf in p-p events at 7 TeV [14] compared to the predictions of QGSJET01, SIBYLL 2.1, and EPOS 1.99.

new or exotic physics assumptions or extrapolations are needed for describing the overall event features measured in the central pseudorapidity region at the LHC. While re-tuning of model parameters to match LHC data will improve the reliability of air shower simulations, there is no indication from the LHC results that the extrapolations have to be changed significantly. At the highest CR energies of $\mathcal{O}(10^{20}$ eV) – i.e. more than twenty times higher than those c.m. energies reachable in p-p at the LHC – the current wide range of predictions for the particle densities, $dN_{ch}/d\eta|_{\eta=0} \approx 10$ (EPOS, SIBYLL) – 50 (QGSJETII), as well as for the mean hadron transverse momentum, $\langle p_\perp \rangle \approx 0.6$ (SIBYLL, QGSJET01) – 1 (EPOS) GeV/c, justify today the concurrent use of all MCs to gauge the uncertainties linked to the underlying hadronic interactions in the interpretation of the cosmic ray data at the highest energies.

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