Air shower development: impact of LHC data

S. OSTAPCHENKO[1,2]
[1]*Institutt for fysikk, NTNU, 7491 Trondheim, Norway*
[2]*D. V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119899 Moscow, Russia*
DOI: 10.7529/ICRC2011/V02/0681

Abstract: A new version of the QGSJET-II model is presented and the differences with the previous version are analyzed in view of recent LHC data on soft multi-particle production. The calculated air shower characteristics are compared. The impact on the interpretation of experimental cosmic ray data is discussed.

Keywords: cosmic rays, extensive air shower, hadronic interactions, LHC.

1 Introduction

High energy cosmic rays (CR) are traditionally studied on the basis of extensive air shower (EAS) measurements. Using the atmosphere of the Earth as the target allows one to cope with the steeply falling down CR spectrum and to detect significant numbers of primary cosmic rays even at ultra-high energies, using ground-based detectors covering a sufficiently large area or measuring EAS fluorescence signal [1]. However, the price to pay is that the results obtained depend on the correctness of the description of air showers by EAS simulations employed. This is especially true for studies of CR composition, which prove to be very sensitive to predictions of hadronic interaction models applied for modeling hadronic cascades in the atmosphere.

During the last two decades, there has been a significant progress in the development of hadronic Monte Carlo (MC) generators for cosmic ray applications. Contemporary models are based on microscopic treatment of the interaction dynamics and provide detailed information on final states produced in high energy hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. In particular, the QGSJET model [2, 3] has been successfully used in the CR field, being succeeded 5 years ago by QGSJET-II [4, 5], the latter being characterized by a much more advanced description of the underlying physics.

However, there is quite a bit of phenomenology involved in the treatment of hadronic interactions by present-day MC generators. Hence, model updates related to improving the underlying theoretical description and to recalibrating model parameters with new accelerator data are always desirable. In the following, the new version of the QGSJET-II model (QGSJET-II-04) [6] will be discussed. In particular, the impact of first data from the Large Hadron Collider (LHC) on the recalibration of model parameters will be illustrated by comparing with the previous version (QGSJET-II-03) and the consequences for the interpretation of high energy CR data will be outlined.

2 QGSJET-II model: physics update

The physics content of the QGSJET-II model has been discussed in some detail in Refs. [5, 6, 7]. Like the original QGSJET, the model treats soft and (semi-)hard parton processes in hadronic collisions in the framework of the Reggeon Field Theory (RFT) [8], applying the "semihard Pomeron" approach [9, 10, 11] to match the phenomenological Pomeron description of soft parton cascades with the DGLAP treatment of hard parton evolution, with a virtuality cutoff Q_0^2 being used to separate the two regimes. The unique feature of QGSJET-II is the microscopic treatment of nonlinear interaction dynamics – based on all-order resummation of the corresponding (so-called enhanced) RFT graphs which describe Pomeron-Pomeron interactions [5, 12]. While the previous model version took into account the dominant contributions of "net"-like enhanced diagrams, the full resummation procedure [13, 14], including also contributions of "Pomeron loops", has been employed in QGSJET-II-04.

Being formally subleading, "loop" diagrams provide important screening corrections to hadron-hadron scattering amplitude at large impact parameters, thus influencing model predictions for total, elastic, and diffractive cross sections [14, 15, 16]. As a consequence, taking such contributions into account, one has to adjust some basic model parameters when calibrating to respective collider observations. In particular, this resulted in a twice smaller value for the main parameter which governs the mag-

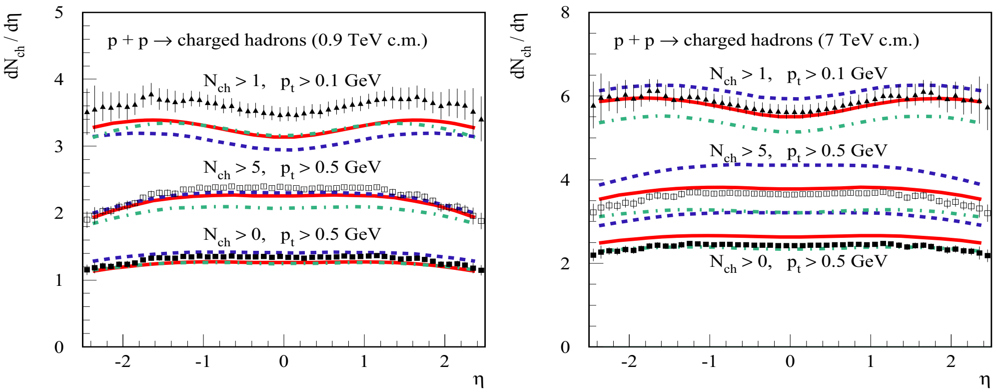

Figure 1: Psedorapidity density of charged hadrons at $\sqrt{s} = 0.9$ TeV (left) and $\sqrt{s} = 7$ TeV (right) as calculated using QGSJET-II-04 (solid), QGSJET-II-03 (dashed), and SIBYLL (dot-dashed) compared to ATLAS data [18] for different event selections (for $|\eta| < 2.5$): $N_{\rm ch} \geq 1$, $p_t > 0.5$ GeV – filled squares, $N_{\rm ch} \geq 2$, $p_t > 0.1$ GeV – filled triangles, $N_{\rm ch} \geq 6$, $p_t > 0.5$ GeV – empty squares.

nitude of nonlinear effects – the triple-Pomeron coupling – in QGSJET-II-04 compared to QGSJET-II-03. In turn, this led to a significantly smaller high mass diffraction in hadron-hadron collisions and to smaller screening effects in hadron-nucleus and nucleus-nucleus interactions [15, 16].

Still, when calibrating the new model version to the same set of accelerator data as used previously, the differences in the predicted air shower development proved to be rather insignificant [15]. As the next step, the model parameters have been adjusted to match better the data measured at LHC. These changes are discussed in the next Section and illustrated by comparing the results of the two model versions with each other and with experimental observations.

3 Comparison with LHC data

As demonstrated in [17], CR interaction models met the first LHC measurements of multi-particle production relatively well. The experimental results appeared to be well bracketed by model predictions, with most of the models being in a reasonable agreement with the data. However, certain trends revealed by experimental observations are worth a particular attention, as discussed in the following.

The analysis in Ref. [17] indicated that QGSJET-II-03 predicts a too quick energy-rise of the multiplicity of charged secondaries $N_{\rm ch}$ in pp-collisions. This may be potentially related to saturation effects being important for parton virtualities $|q^2|$ above the cutoff value $Q_0^2 = 2.5\,{\rm GeV}^2$ used in the model. As the saturation is reached (in the "dense" limit of high energies and small impact parameters) in QGSJET-II only for "soft" partons ($|q^2| < Q_0^2$), increasing Q_0^2 to 3 GeV^2 allowed the mechanism to operate over a larger kinematic space and to slow down the multiplicity rise. The calculated pseudorapidity density of charged particles for the old and new versions of QGSJET-II is compared to recent data of the ATLAS and CMS collaborations in Figs. 1, 2; the results of the SIBYLL model [20, 21] are also shown.As a side effect, the discussed modification, together with additional screening corrections due to "Pomeron loop" contributions, resulted in a slower energy rise of total and inelastic pp cross sections in QGSJET-II-04 compared to the previous model version.

	QGSJET-II-04	QGSJET-II-03	SIBYLL	exp. [23]
$\rm MBTS_{AND}$	54.1	62.3	68.4	51.9 ± 5.7
$\rm MBTS_{OR}$	60.8	69.8	74.7	58.7 ± 6.5

Table 1: Model predictions for "visible" cross sections (in mb) for pp inelastic collisions at $\sqrt{s} = 7$ TeV for ATLAS minimum-bias trigger selections: at least one charged hadron at $-3.84 < \eta < -2.09$ and at $2.09 < \eta < 3.84$ ($\rm MBTS_{AND}$) or in either of the two intervals ($\rm MBTS_{OR}$).

	QGSJET-II-04	QGSJET-II-03	SIBYLL	exp. [25]
2.76 TeV	47.4	52.5	56.2	47.2 ± 3.3
7 TeV	55.1	63.6	69.1	54.2 ± 3.8

Table 2: Model predictions for "visible" cross sections (in mb) for pp inelastic collisions at $\sqrt{s} = 2.76$ and 7 TeV for the ALICE $\rm MB_{AND}$ trigger selection: at least one charged hadron at $-3.4 < \eta < -1.7$ and at $1.7 < \eta < 5.1$.

Apart from that, it appeared that QGSJET-II-03 underestimated the production of strange particles, as shown in Fig. 3, which required an adjustment of the respective parameters of the hadronization procedure.

Recently, the ATLAS collaboration performed measurements of "visible" cross sections at $\sqrt{s} = 7$ TeV for different event selection criteria [23]. As discussed in [24], such studies can be very powerful in discriminating between various model approaches to the treatment of soft multi-particle production, being in particular sensitive to model predictions for inelastic diffraction. The measured values compiled in Table 1 appeared to be in a good agreement with respective predictions of QGSJET-II-04 [6],

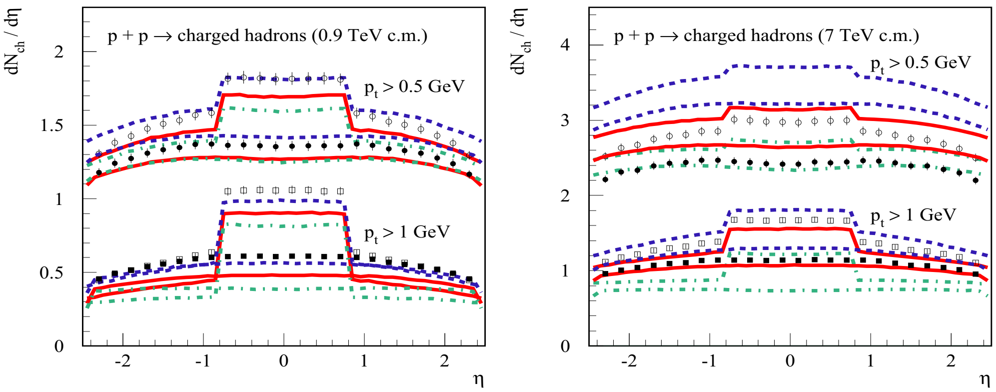

Figure 2: Psedorapidity density of charged hadrons at $\sqrt{s} = 0.9$ TeV (left) and $\sqrt{s} = 7$ TeV (right) as calculated using QGSJET-II-04 (solid), QGSJET-II-03 (dashed), and SIBYLL (dot-dashed) compared to CMS data for events with at least one charged hadron with $p_t > 0.5$ GeV at $|\eta| < 2.4$ or $|\eta| < 0.8$ – respectively filled and open circles, and with $p_t > 1$ GeV at $|\eta| < 2.4$ or $|\eta| < 0.8$ – respectively filled and open squares [19].

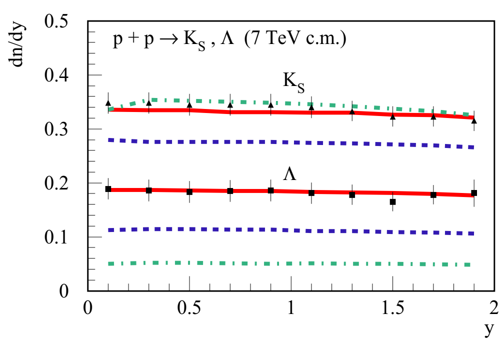

Figure 3: CMS data on rapidity density of K_S^0 (triangles) and Λ (squares) in inelastic pp interactions at $\sqrt{s} = 7$ TeV [22] compared to calculations: QGSJET-II-04 (solid), QGSJET-II-03 (dashed), and SIBYLL (dot-dashed).

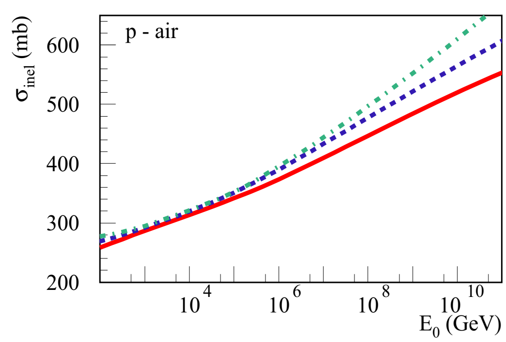

Figure 4: $\sigma^{\rm inel}_{p-{\rm air}}$ as calculated by QGSJET-II-04 (solid), QGSJET-II-03 (dashed), and SIBYLL (dot-dashed).

while being significantly smaller than the corresponding results of QGSJET-II-03 and SIBYLL. Similar conclusions follow from the comparison with "visible" cross sections measured by ALICE over a wider energy range [25], as illustrated in Table 2, while the values measured by CMS [26] are slightly higher, favoring the high energy extrapolation somewhat in between the QGSJET-II-03 and QGSJET-II-04 predictions. It should be stressed, however, that a reconstruction of $\sigma^{\rm inel}_{pp}$ on the basis of "visible" cross sections measured with minimum-bias triggers is strongly model-dependent [27] (see also the discussion in [16]).

4 Impact on EAS characteristics

The predictions of the new model version for EAS development are affected by the improved treatment of the interaction mechanism and by the recalibration of model parameters with LHC data. As discussed in some detail in [15], including "Pomeron loop" diagrams in the scheme, one obtains smaller screening corrections for hadron-nucleus and nucleus-nucleus collisions – when the same set of experimental data on hadron-hadron interactions is used for the model calibration. This leads to an enhancement of the multiplicity of hadron-air collisions in QGSJET-II-04 compared to QGSJET-II-03 [15], and results in some 10% increase of the calculated EAS muon number N_μ (> 1 GeV) at $E_0 \sim 10^{15} \div 10^{19}$ eV. It is noteworthy that the recalibration of the predicted multiplicity rise with LHC data, illustrated in Figs. 1 and 2, has no effect here – as the corresponding changes are at a fine-tuning level. On the other hand, a part of the obtained increase of N_μ is due to the enhanced production of strange particles in QGSJET-II-04, which channels more energy into hadronic cascade.

Another consequence of "Pomeron loops" is an enhancement of screening corrections in peripheral hadronic collisions [15], which results in a reduction of total and inelastic cross sections. Moreover, this reduction is enhanced by parton shadowing effects now operating over a larger kinematic space – due to the increase of the virtuality cutoff Q_0^2 between soft and hard processes. As illustrated in Tables 1 and 2, the slower energy rise of $\sigma^{\rm inel}_{pp}$ matches better

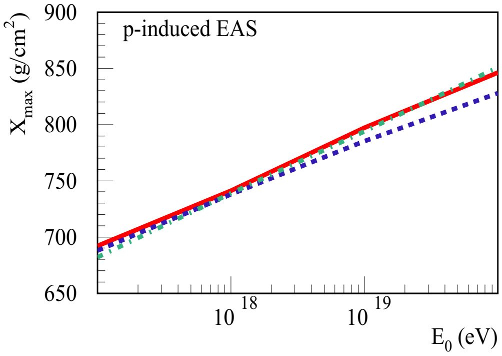

Figure 5: Shower maximum position $X_{\max}$ for p-induced EAS as calculated with QGSJET-II-04 (solid), QGSJET-II-03 (dashed), and SIBYLL (dot-dashed).

the LHC measurements. In turn, this leads to a substantial reduction of the predicted proton-air cross section – Fig. 4. As a consequence, QGSJET-II-04 predicts a deeper shower maximum position $X_{\max}$, as shown in Fig. 5. It is noteworthy that even larger increase of the predicted $X_{\max}$ may be expected for SIBYLL if the latter is recalibrated with the LHC data – as its present version largely overestimates "visible" cross sections at $\sqrt{s} = 7$ TeV (Tables 1 and 2).

5 Conclusions and outlook

We discussed here the new version of the QGSJET-II model, including both the corresponding physics update and the recalibration of model parameters with LHC data. The most essential difference with the previous model version is a noticeable reduction of the energy rise of $\sigma^{\rm inel}_{p-{\rm air}}$, which is both due to screening corrections induced by "Pomeron loop" graphs and due to the increased virtuality cutoff $Q_0^2 = 3$ GeV^2 between soft and hard processes, the latter change inspired by the comparison with LHC measurements. The smaller $\sigma^{\rm inel}_{p-{\rm air}}$ resulted in a larger shower elongation rate at $E_0 \sim 10^{18} \div 10^{20}$ eV in QGSJET-II-04 compared to QGSJET-II-03. Additionally we obtained a slight ($\sim 10\%$) increase of N_μ over a wide energy range $E_0 \sim 10^{15} \div 10^{19}$ eV, which is both due to the discussed changes in the interaction mechanism and due to enhanced production of strange particles (as dictated by LHC data).

Overall, the predicted EAS characteristics had only minor changes at $E_0 \sim 10^{15} \div 10^{18}$ eV. Hence, no revision of present interpretations of CR data in this energy range, notably by KASCADE [28] and KASCADE-Grande [29], is required in view of LHC observations.

At higher energies ($E_0 \gtrsim 10^{18}$ eV), the small changes of the predicted $X_{\max}$ and N_μ are unable to resolve current contradictions between different sets of CR data, notably by the Auger collaboration. As discussed in [30], Auger results on the EAS muon content and on the width of $X_{\max}$ distribution indicate a heavy-dominated composition at $E_0 \gtrsim 10^{18}$ eV, while the observed $X_{\max}$ is consistent with a light (predominantly p-dominated) composition at $E_0 \sim 10^{18} \div 10^{19}$ eV. As the present LHC data give no hint towards a much stronger than currently predicted energy rise of the multiplicity or of the inelastic cross section for pp interactions, the mentioned contradiction is very likely to be a purely experimental challenge.

Acknowledgment The author acknowledges a fellowship from the program Romforskning of Norsk Forsknigsradet.

References

[1] M. Nagano and A. A. Watson, Rev. Mod. Phys., 2000, **72**: 689
[2] N. N. Kalmykov and S. S. Ostapchenko, Phys. Atom. Nucl., 1993, **56**: 346
[3] N. N. Kalmykov, S. S. Ostapchenko and A. I. Pavlov, Nucl. Phys. Proc. Suppl., 1997, **52B**: 17
[4] S. Ostapchenko, Nucl. Phys. Proc. Suppl., 2006, **151**: 143
[5] S. Ostapchenko, Phys. Rev. D, 2006, **74**: 014026
[6] S. Ostapchenko, Phys. Rev. D, 2011, **83**: 014018
[7] S. Ostapchenko, AIP Conf. Proc., 2007, **928**: 118
[8] V. N. Gribov, Sov. Phys. JETP, 1968, **26**: 414
[9] N. N. Kalmykov, S. S. Ostapchenko and A. I. Pavlov, Bull. Russ. Acad. Sci. Phys., 1994, **58**: 1966
[10] H. J. Drescher et al., J. Phys. G, 1999, **25**: L91
[11] S. Ostapchenko et al., J. Phys. G, 2002, **28**: 2597
[12] S. Ostapchenko, Phys. Lett. B, 2006, **636**: 40
[13] S. Ostapchenko, Phys. Rev. D, 2008, **77**: 034009
[14] S. Ostapchenko, Phys. Rev. D, 2010, **81**: 114028
[15] S. Ostapchenko, Nucl. Phys. Proc. Suppl., 2009, **196**: 90
[16] S. Ostapchenko, arXiv:1103.5684 [hep-ph].
[17] D. d'Enterria et al., arXiv:1101.5596 [astro-ph.HE]
[18] G. Aad et al. (ATLAS Collaboration), New J. Phys., 2011, **13**: 053033
[19] CMS Collaboration, CMS PAS QCD-10-024
[20] R. S. Fletcher et al., Phys. Rev. D, 1994, **50**: 5710
[21] E.-J. Ahn et al., Phys. Rev. D, 2009, **80**: 094003
[22] V. Khachatryan et al. (CMS Collaboration), JHEP, 2011, **1105**: 064
[23] G. Aad et al. (ATLAS Collaboration), Eur. Phys. J. C, 2011, **71**: 1630
[24] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Phys. Lett. B, 2009, **679**: 56
[25] M. Poghosyan for the ALICE Collaboration, talk at "Quark Matter 2011", 2011, Annecy, France
[26] M. Marone for the CMS Collaboration, talk at "DIS-2011", 2011, Newport (VA), USA
[27] G. Aad et al. (ATLAS Collaboration), arXiv:1104.0326 [hep-ex]
[28] T. Antoni et al. (KASCADE Collaboration), Astropart. Phys., 2005, **24**: 1
[29] A. Haungs for the KASCADE-Grande Collaboration, these proceedings
[30] S. Ostapchenko, arXiv:1010.0137 [astro-ph.HE].