PROCEEDINGS OF SCIENCE

Validation of Electromagnetic Showers in CORSIKA 8

Alexander Sandrock,[a,*] **Jean-Marco Alameddine**[b] **and Felix Riehn**[c] **for the CORSIKA 8 collaboration**

[a] *Bergische Universität Wuppertal, Fakultät für Mathematik und Naturwissenschaften, Gaußstraße 20, 42119 Wuppertal, Germany*

[b] *Technische Universität Dortmund, Fakultät Physik, Otto-Hahn-Straße 4a, 44227 Dortmund, Germany*

[c] *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Rúa de Xoaquín Díaz de Rábago s/n, 15705 Santiago de Compostela, Galicia, Spain*

E-mail: asandrock@icecube.wisc.edu, jean-marco.alameddine@tu-dortmund.de, friehn@lip.pt

The air shower simulation code CORSIKA has served as a key part of the simulation chain for numerous astroparticle physics experiments over the past decades. Due to retirement of the original developers and the increasingly difficult maintenance of the monolithic Fortran code of CORSIKA, a new air shower simulation framework has been developed over the course of the last years in C++, called CORSIKA 8. Besides the hadronic and muonic component, the electromagnetic component is one of the key constituents of an air shower. The cascade producing the electromagnetic component of an air shower is driven by bremsstrahlung and photoproduction of electron-positron pairs. At ultrahigh energies or in media with high densities, the bremsstrahlung and pair production processes are suppressed by the Landau-Pomeranchuk-Migdal (LPM) effect, which leads to more elongated showers compared to showers without the LPM suppression. Furthermore, photons at higher energies can produce muon pairs or interact hadronically with nucleons in the target medium, producing a muon component in electromagnetic air showers. In this contribution, we compare electromagnetic showers simulated with the latest Fortran version of CORSIKA and CORSIKA 8, which uses the library PROPOSAL for the electromagnetic component. While earlier validations of CORSIKA 8 electromagnetic showers focused on showers of lower energy, the recent implementation of the LPM effect, photo pair production of muons, and of photohadronic interactions allows now to make a physics-complete comparison also at high energies.

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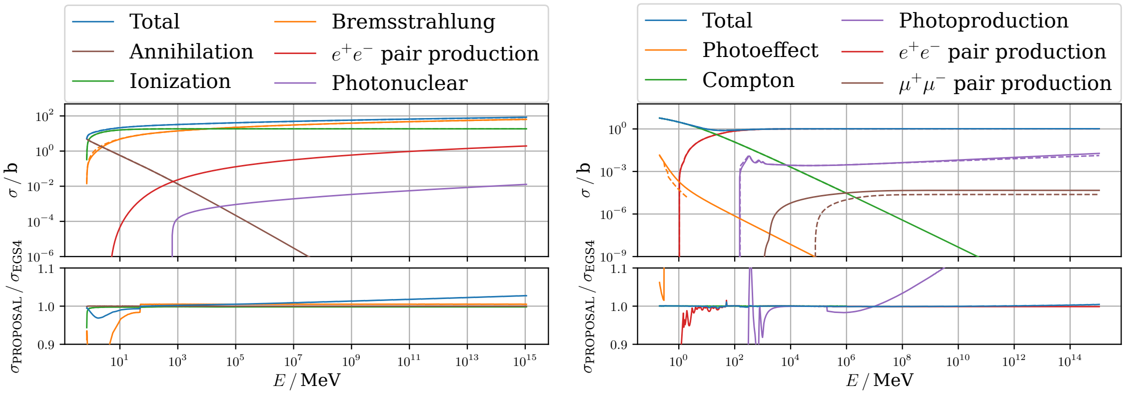


(a) Positron cross-sections compared between C7 and C8. **(b)** Photon cross-sections compared between C7 and C8.

Figure 1: Total stochastic cross-sections for positrons and photons in air. The losses smaller than 0.2 MeV are treated continuously to obtain a finite cross-section. The dashed lines refer to cross-sections from C7, the solid lines show the implementation in C8.

1. Introduction

Many astroparticle physics experiments have relied on CORSIKA [1] for the simulation of extensive air showers. The Fortran version, originally developed for the KASCADE experiment, is currently at version 7.7500 and still has an excellent performance. However, its monolithic design and hand-optimized code make its further development and the addition of new features increasingly difficult. To overcome these limitations, a new modular simulation framework for extensive air showers called CORSIKA 8 has been developed in C++ over the course of the last years (cf. also [2]).

The electromagnetic component of air showers is formed as the result of a cascade of bremsstrahlung and pair production processes. In the Fortran versions of CORSIKA (C7 for short) the processes responsible for this shower component were simulated by a customized version of EGS4 [3], which is deeply integrated in the CORSIKA source code. In its place, in CORSIKA 8 (C8) this task is carried out using the particle propagation library PROPOSAL [4–7], a modular C++14 library with Python bindings that can be used for the propagation of electrons, positrons, muons, tau leptons as well as photons. The current version of PROPOSAL is 7.6.2.

PROPOSAL offers several parametrizations for the cross-sections of the pertinent processes; the default choice for C8 differs only in a few minor details from the parametrizations used in C7: Rayleigh scattering is not implemented in CORSIKA 8, triplet production $e^{\pm} \to e^{\pm}e^{+}e^{-}$ is not implemented in CORSIKA 7, and the parametrization of the photoelectric effect and the calculation of secondary particles in photohadronic interactions are different. The cross-sections implemented differ at most by a few percent, and that only at the lowest or extremely high energies or in regions where the contribution of the process is very small (cf. Fig. 1 for exemplary comparisons of positron and photon cross-sections between C7 and C8).

2. Recent improvements to the electromagnetic shower simulation

Since the last ICRC, we have implemented several enhancements in C8. The most important ones are the treatment of photohadronic interactions, the photo-pairproduction of muons, and the implementation of the Landau-Pomeranchuk-Migdal (LPM) effect. Furthermore, the new improved implementation of the Molière multiple scattering in PROPOSAL allowed to use this more precise treatment instead of the faster approximation by Highland used earlier in C8 for speed reasons.

Photohadronic interactions are a subdominant interaction process of high-energy photons, since the cross-section is about 1% of the pair production process. However, the decay products of the produced hadrons constitute the dominant amount of the muon content in electromagnetic showers and a non-negligible portion in hadronic showers via electromagnetic sub-showers [8]. In C7, the photohadronic interaction was treated with routines for single-pion or two-pion production at resonances and the hadron dual-parton model at low energies below 80 GeV, and with the chosen high-energy hadronic interaction model at higher energies. In C8, the low-energy portion is treated by the code SOPHIA [9], while at higher energies the high-energy hadronic interaction model is called as well. Nuclear effects in the photohadronic interaction are neglected in both C7 and C8, apart from a shadowing correction to the total cross-section.

The remaining part of the muon content in electromagnetic air showers is due to photopair production of muons by photons. As in C7, the cross section from [10] has been implemented with an additional term in analogy to [11] to take into account the production of muon pairs on atomic electrons.

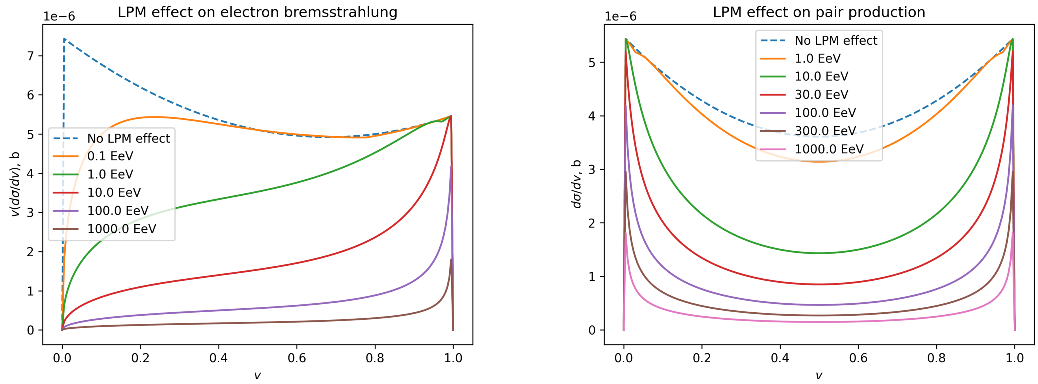
The LPM effect is a density-dependent effect which suppresses the emission of bremsstrahlung photons with energies small compared to the electron energy, as well as the production of pairs with a roughly equal distribution of energy between electron and positron at high energies (cf. Fig. 2). In the Monte Carlo particle shower simulation, the LPM suppression is treated with a Neumann rejection method: after an interaction has been sampled, an additional random number is drawn and if the random number is larger than the ratio between the cross-section with and without LPM suppression, the interaction is rejected (for the description in C7 see [12]).

3. Validation of electromagnetic showers

To validate the simulation of electromagnetic showers in C8, we compare against C7 showers with an initial electron at various primary energies and particle cuts as a widely used reference. The atmosphere is the US standard atmosphere, the chosen low- and high-energy hadronic interaction models are FLUKA [13] and Sibyll 2.3d [14], respectively. We compare the longitudinal profiles of particle numbers and charge excess, as well as the lateral distributions and energy spectra of the showers near the shower maximum.

3.1 100 TeV showers

In Fig. 3, we show the longitudinal profiles of 1000 showers with an 100 TeV e^- as primary particle and 1 MeV particle cut energy. The charged particles and photon longitudinal profiles agree to within better than 5%, and the charge excess to better than 3%; the longitudinal profiles of muons



(a) Bremsstrahlung cross section in air with and without the LPM effect.

(b) Pair production cross section in air with and without the LPM effect.

Figure 2: Differential cross-sections of bremsstrahlung and pair production at very high energies in air at sea level pressure to illustrate the LPM effect. v denotes the fraction of the primary particle energy going into the secondary photon or positron, respectively.

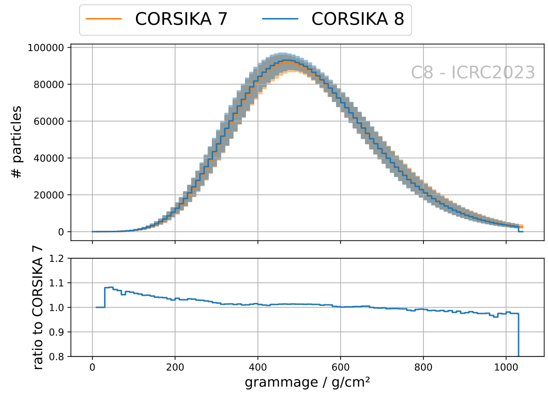
and hadrons show about 10% more particles, and the shower maxima are earlier by about $2\,\mathrm{g/cm^2}$. The shaded area around the profiles denotes the inter-quartile range on the histograms.

In Fig. 4, we show energy spectra and lateral distributions of particles near the shower maximum. Overall a good agreement is observed, except in the lowest and highest bins the differences amount to no more than 5%; the lateral distribution functions agree within 3% except for the bins nearer than about 1 m from the shower core.

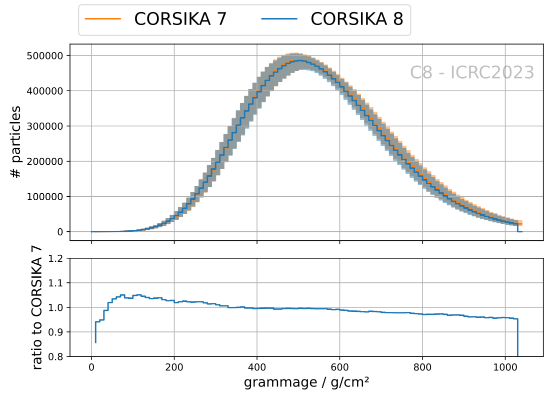
The ratio between the two-dimensional distributions in radius and energy near the shower maximum of these showers for charged particles and photons with C7 and C8 are shown in 5. These distributions show some small differences in low-energy charged particles in addition to the disagreement between C7 and C8 at small radii visible in the one-dimensional lateral distributions.

3.2 100 EeV showers and the LPM effect

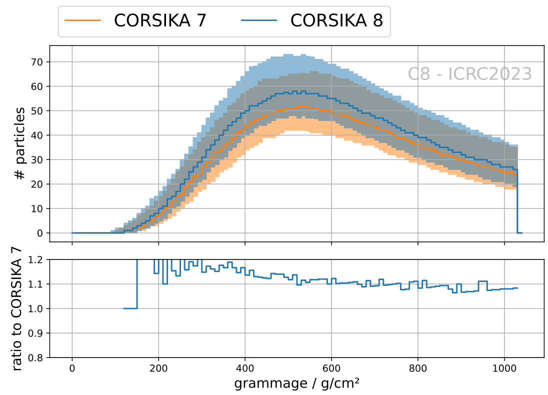
In Fig. 6, the longitudinal profiles of charged particles and photons for 5000 electromagnetic showers with a primary energy of 100 EeV and a particle cut of 100 TeV are shown with and without the LPM effect option. This high particle cut was chosen for performance reasons, as only the highest energy interactions are expected to be influenced sufficiently strongly by the LPM effect to change the global behaviour of the showers. As expected, LPM showers develop slower and reach their maximum later. The agreement is not as good as at the lower energies investigated above, but the deviations in the profiles are not worse than 5–10%. The somewhat larger number of charged particles in C8 could be due to the increasing role of triplet pair production at these extremely high energies, since this process is not taken in to account in C7.



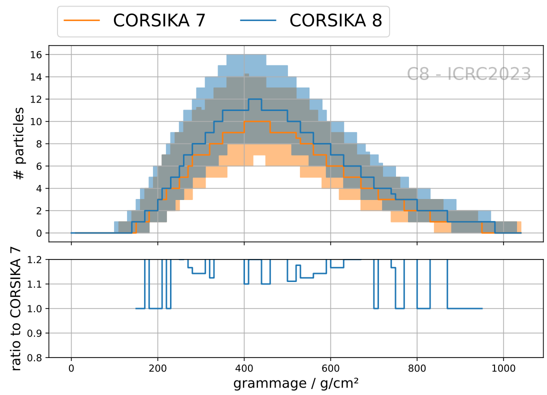
(a) Longitudinal profile of charged particles.



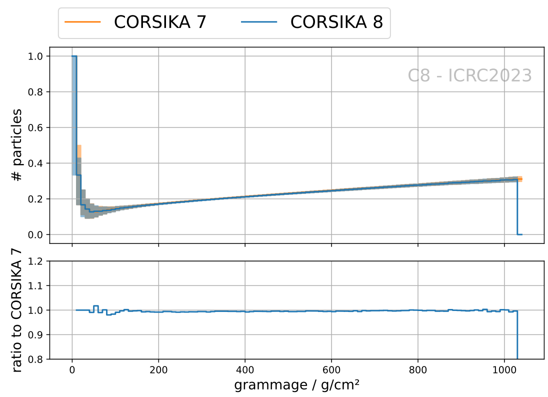
(b) Longitudinal profile of photons.



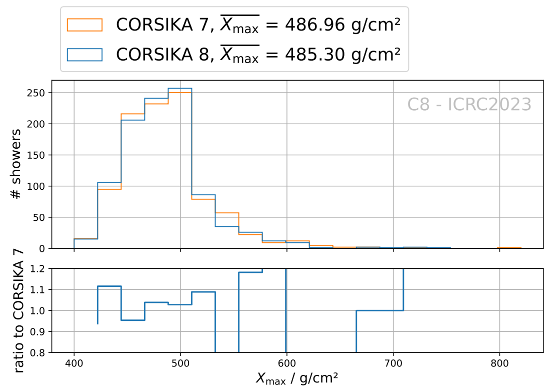
(c) Longitudinal profile of muons.



(d) Longitudinal profile of hadrons.

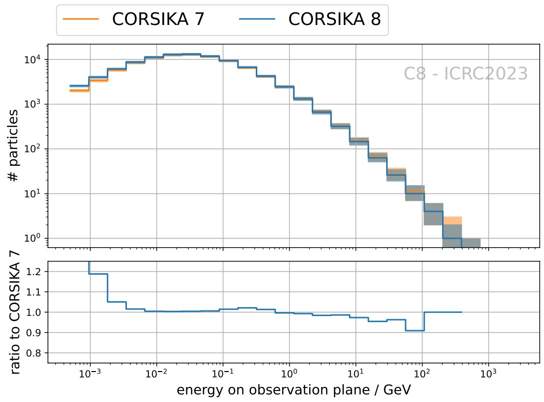


(e) Longitudinal profile of the charge excess.

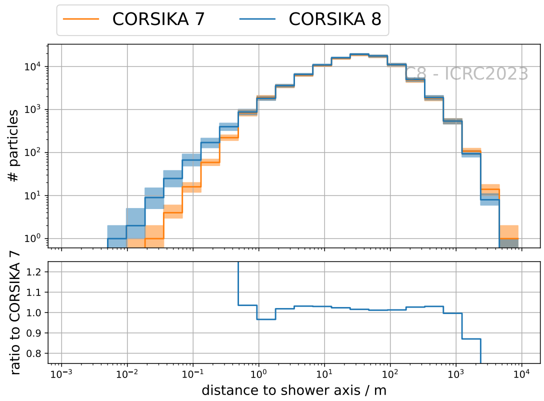


(f) Distribution of shower maxima.

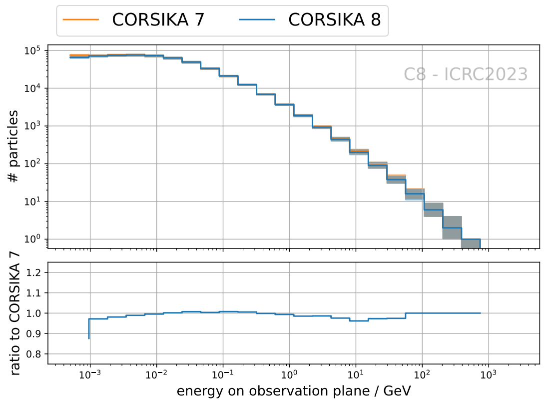
Figure 3: Longitudinal profiles and X_{max} distribution for 100 TeV showers with 1 MeV particle cut



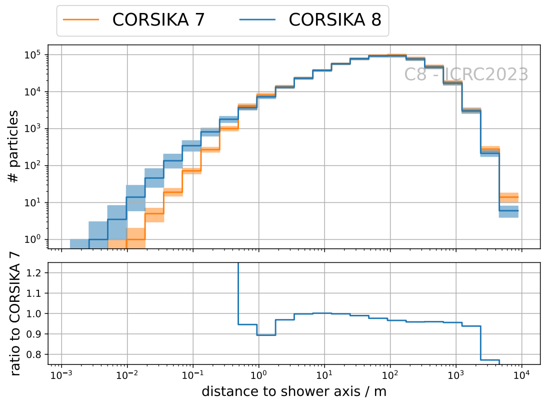
(a) Energy spectrum of charged particles.



(b) Lateral distributions of charged particles.

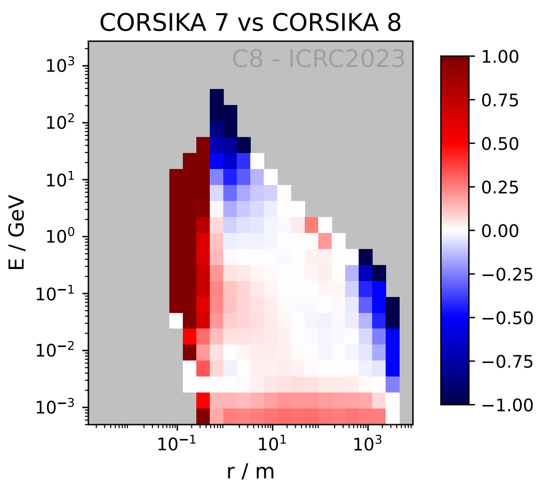


(c) Energy spectrum of photons.

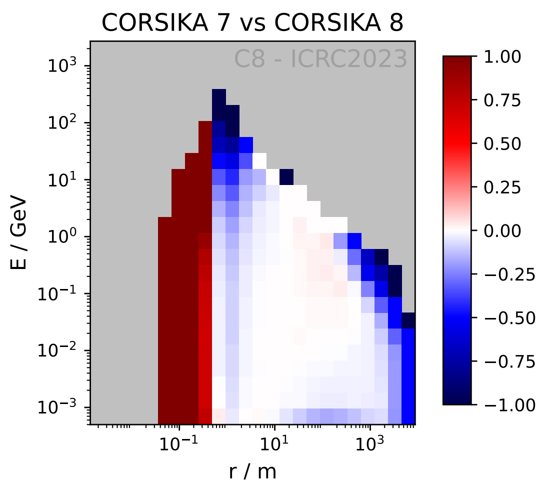


(d) Lateral distributions of photons.

Figure 4: Energy spectra and lateral distributions of 100 TeV showers near the shower maximum.

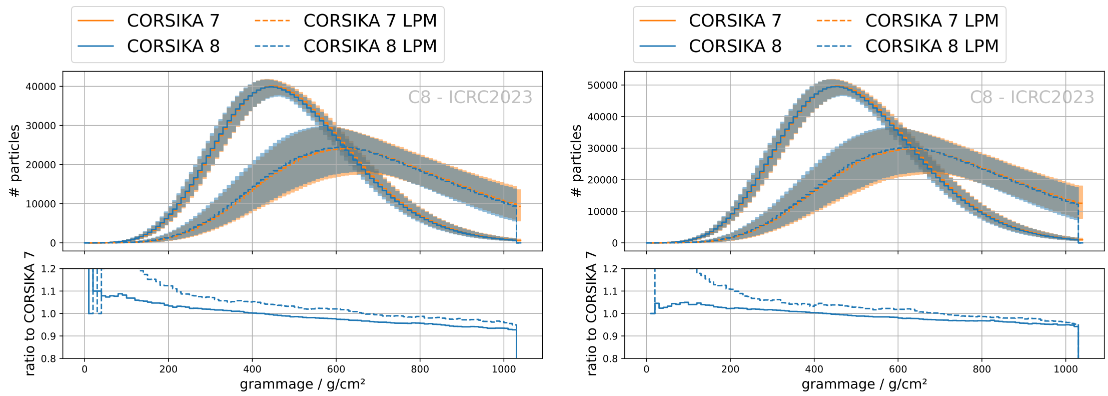


(a) Charged particles.



(b) Photons.

Figure 5: Deviation from unity of the ratio of two-dimensional distributions in energy and radius near the shower maximum.



(a) Longitudinal profile of charged particles.

(b) Longitudinal profile of photons.

Figure 6: Longitudinal profiles for 100 EeV electromagnetic showers with a particle cut of 100 TeV. The showers without the LPM effect are shown in solid lines, while the showers with LPM Effect are shown in dashed lines.

4. Conclusions

In this contribution, the electromagnetic shower simulation in CORSIKA 8 was validated by comparison to simulated showers from CORSIKA 7. The implementation of photohadronic interactions, photo pair production of muons, and the Landau-Pomeranchuk-Migdal effect allowed to extend earlier comparisons at lower energies [15] to higher energies. The charge excess and longitudinal profiles agree to better than 3–5%, the energy spectra and lateral distribution functions near the shower maximum show good agreement except very near the shower core in a logarithmic plot, and the longitudinal profiles of LPM showers agree within not worse than about 10%.

Some disagreement between C7 and C8 is to be expected, since the code bases are disjunct except for the externally provided hadronic interaction models, and some rarer processes are treated in only one of the codes. Since the electromagnetic physics implemented is the essentially same, these comparisons also serve as a validation of C7. Overall, the electromagnetic showers simulated in C8 agree well with C7, including both the electrons, positrons, and photons as well as muons and hadrons not studied in earlier validations.

Acknowledgments

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Full Authors List: CORSIKA 8 Collaboration

J.M. Alameddine[1], J. Albrecht[1], J. Alvarez-Muñiz[2], J. Ammerman-Yebra[2], L. Arrabito[3], J. Augscheller[4], A.A. Alves Jr.[4], D. Baack[1], K. Bernlöhr[5], M. Bleicher[6], A. Coleman[7], H. Dembinski[1], D. Elsässer[1], R. Engel[4], A. Ferrari[4], C. Gaudu[8], C. Glaser[7], D. Heck[4], F. Hu[9], T. Huege[4,10], K.H. Kampert[8], N. Karastathis[4], U.A. Latif[11], H. Mei[12], L. Nellen[13], T. Pierog[4], R. Prechelt[14], M. Reininghaus[15], W. Rhode[1], F. Riehn[16,2], M. Sackel[1], P. Sala[17], P. Sampathkumar[4], A. Sandrock[8], J. Soedingrekso[1], R. Ulrich[4], D. Xu[12], E. Zas[2]

[1] Technische Universität Dortmund (TU), Department of Physics, Dortmund, Germany
[2] Universidade de Santiago de Compostela, Instituto Galego de Física de Altas Enerxías (IGFAE), Santiago de Compostela, Spain
[3] Laboratoire Univers et Particules de Montpellier, Université de Montpellier, Montpellier, France
[4] Karlsruhe Institute of Technology (KIT), Institute for Astroparticle Physics (IAP), Karlsruhe, Germany
[5] Max Planck Institute for Nuclear Physics (MPIK), Heidelberg, Germany
[6] Goethe-Universität Frankfurt am Main, Institut für Theoretische Physik, Frankfurt am Main, Germany
[7] Uppsala University, Department of Physics and Astronomy, Uppsala, Sweden
[8] Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
[9] Peking University (PKU), School of Physics, Beijing, China
[10] Vrije Universiteit Brussel, Astrophysical Institute, Brussels, Belgium
[11] Vrije Universiteit Brussel, Dienst ELEM, Inter-University Institute for High Energies (IIHE), Brussels, Belgium
[12] Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, Shanghai, China
[13] Universidad Nacional Autónoma de México (UNAM), Instituto de Ciencias Nucleares, México, D.F., México
[14] University of Hawai'i at Manoa, Department of Physics and Astronomy, Honolulu, USA
[15] Karlsruhe Institute of Technology (KIT), Institute of Experimental Particle Physics (ETP), Karlsruhe, Germany
[16] Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisboa, Portugal
[17] Fluka collaboration