Opportunities and Future directions for Astroparticle Physics: the case of ultra-high-energy cosmic rays

(Input from: R. Conceição)

Ultra-high-energy cosmic rays are the most energetic particles ever observed. Due to their extremely low flux—approximately one particle per square kilometer per century—the detection of these particles is only feasible by measuring the extensive air showers (EAS) they produce when interacting with atoms in the Earth's atmosphere. The center-of-mass energy in these initial interactions can reach up to 400 TeV. However, accurately interpreting the primary particle's mass composition and the properties of the first interaction relies heavily on the precision of high-energy hadronic interaction models.

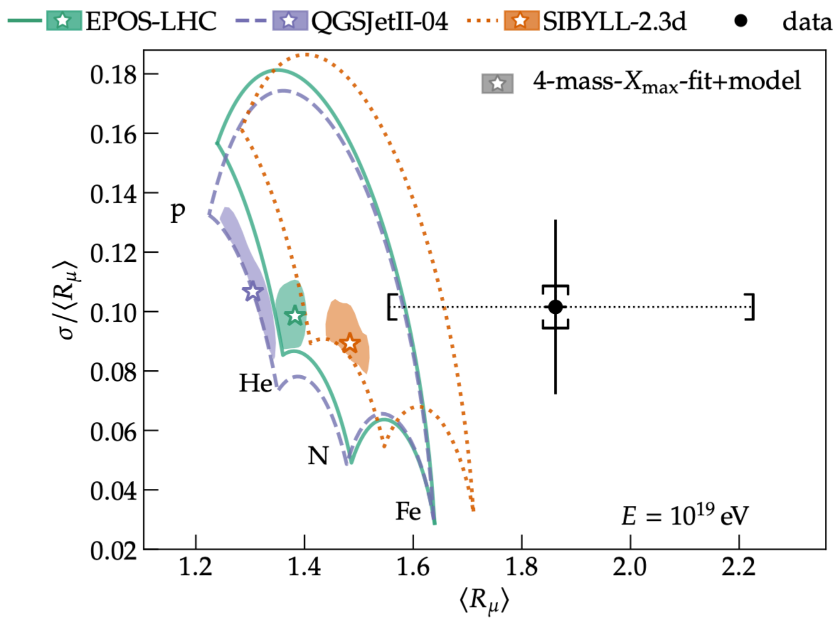

Figure 1 - Data (black, with error bars) compared to models for the fluctuations and the average number of muons for showers with a primary energy of 10^{19} eV. Fluctuations are evaluated in the energy range from $10^{18.97}$ eV and $10^{19.15}$ eV. The statistical uncertainty is represented by the error bars. The total systematic uncertainty is indicated by the square brackets. The expectation from the interaction models for any mixture of the four components p, He, N, Fe is illustrated by the coloured contours. The values preferred by the mixture derived from the Xmax measurements are indicated by the star symbols. The shaded areas show the regions allowed by the statistical and systematic uncertainties of the Xmax measurement. - Taken from [2].

The Pierre Auger Observatory has demonstrated in [1] that none of the current post-LHC-tuned hadronic interaction models can consistently explain the observed shower data in terms of primary mass composition. Specifically, the measurements indicate an excess of muons compared to model predictions, commonly known as the "Muon Puzzle."

Further analysis in [2] suggests that this apparent muon excess is likely due to deficiencies in the description of lower-energy hadronic interactions, which dominate the later stages of the shower cascade. This contrasts with the expectation that higher-energy interactions should exhibit greater deviations due to the absence of direct accelerator data at these energy scales.

The High-Luminosity upgrade of the LHC (HL-LHC) will enhance pseudo-rapidity coverage and introduce new collision systems, such as proton-oxygen and oxygen-oxygen, which are more analogous to the interactions occurring during extensive air shower development. Furthermore, studies [3,4] have demonstrated a strong correlation between the low-muon-number distribution tail and the energy spectrum of neutral pions produced in the first cosmic ray interaction (see Fig. 2).

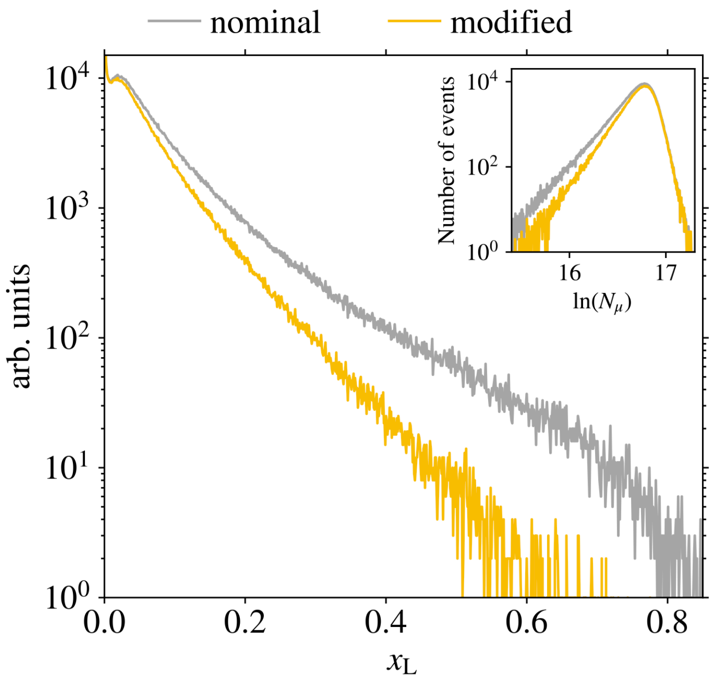

FIG. 2 - Distribution of the fraction of energy in the laboratory frame carried by the highest energy π^0 in the first interaction of a proton with 10^{19} eV. The gray distribution is the standard distribution in SIBYLL 2.3c while the yellow is for a modified neutral pion energy spectrum. The corresponding muon-number distributions for the air showers are shown in the inset plot.

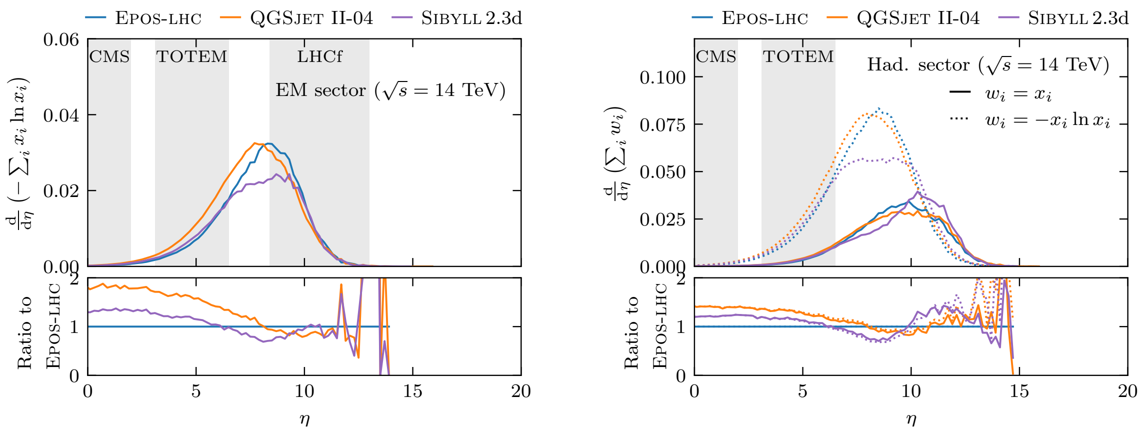

Fig. 3 - (Left) Upper panel: Contribution of each particle of the electromagnetic sector to the values of ζEM as a function of the particle's pseudo-rapidity, that is the ζ-flow, for different hadronic interaction models. Lower panel: ratio to the energy and ζ flows predicted by Epos-lhc. Proton-air interactions were simulated with E0 = 1018.7 eV corresponding to √s = 97 TeV. The shaded grey bands represent the pseudo-rapidities covered by CMS, TOTEM and LHCf.
(Right) Upper panel: Contribution of each particle to the values of αhad (solid lines) and ζhad (dotted lines) as a function of the particle's pseudo-rapidity, that is, the energy and ζ-flows respectively, for different hadronic interaction models. Lower panel: ratio to the energy and ζ flows predicted by EPOS-LHC. Proton-air interactions were simulated with E0 = 1017 eV corresponding to √s = 14 TeV. The shaded grey bands represent the pseudo-rapidities covered by CMS and TOTEM.

While efforts are ongoing to extract this information from cosmic ray data, measuring the neutral pion energy spectrum at the HL-LHC using forward experiments would provide valuable constraints on hadronic interaction models at $\sim 10^{17}$ eV. These energies are also accessible to experiments like the Pierre Auger Observatory, enabling detailed cross-calibration between astroparticle and accelerator experiments.

In a study nearing submission for publication [5], it has been shown that the depth of the shower maximum, Xmax, can be fully characterized by a new set of multi-particle production variables that depend solely on the first cosmic ray interactions. As illustrated in Figure 3, the contributions of secondary particle energies to these variables, as a function of pseudo-rapidity, can be used to constrain and potentially exclude certain state-of-the-art hadronic interaction models.

While some models could already be discriminated using HL-LHC data, Figure 4 reveals that the functional forms of these proposed variables remain indistinguishable across models within the current pseudo-rapidity range. Consequently, further constraints on these critical distributions would need to come from ultra-high-energy cosmic ray (UHECR) experiments.

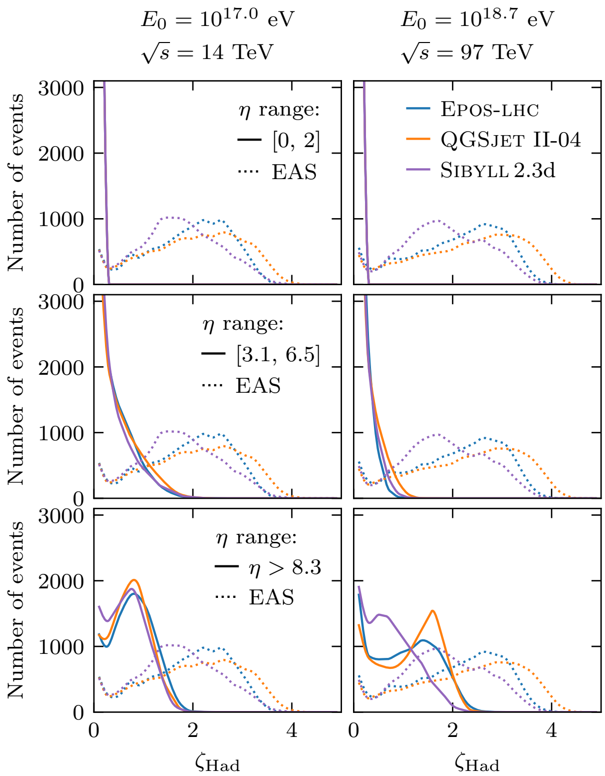

Fig. 4 - Distribution of ζhad restricted to the rapidity regions covered by central (upper panels), forward (middle panels) and very-forward (lower panels) detectors, represented by the solid lines, for different hadronic interaction models. For reference, the distributions of ζhad integrated over rapidity, as accessible in Extensive Air Showers, are depicted by dotted curves. The left panels correspond to proton-air interactions at √s = 14 TeV (LHC) and the right panels to √s = 97 TeV (roughly FCC-hh).

Looking ahead, the proposed Future Circular Collider (FCC-hh), which aims to reach a center-of-mass energy of √s = 100 TeV, corresponding to a cosmic-ray proton-air collision energy of approximately $10^{18.8}$ eV, would provide a unique opportunity to probe the significant differences between hadronic interaction models at these energies. These discrepancies stem from the distinct physical treatments employed by each model, which diverge further due to uncertainties in energy extrapolations.

[1] Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001
[2] Pierre Auger Coll., Phys.Rev.Lett. 126 (2021) 15, 152002
[3] L. Cazon, R. Conceição, M. M. Martins, Phys.Rev.D 103 (2021) 2, 022001
[4] L. Cazon, R. Conceição, M. M. Martins, Phys.Lett.B 859 (2024)
[5] L. Cazon, R. Conceição, M. M. Martins, F. Riehn, to be submitted to Phys.ReV.D