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CORSIKA 8: A modern and universal framework for particle cascade simulations

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CORSIKA 8 represents a significant update in the simulation of particle showers, building on the well-established foundation of CORSIKA 7. It has been entirely rewritten as a modular and modern C++ framework, addressing the limitations of its predecessor to provide a flexible platform designed to satisfy current and novel use cases. This allows for application beyond pure air-shower scenarios such as cross-media particle cascades and an advanced calculation of the radio emission. A first official "physics-complete" version has already been released that supports the treatment of hadronic interactions with Sibyll 2.3d, QGSJet-II.04, and EPOS-LHC and the treatment of the electromagnetic cascade with PROPOSAL 7.6.2. In this presentation, we will discuss the design principles, current functionality, and validation efforts of CORSIKA 8, emphasizing its potential applications for future experiments.

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1. Introduction

Monte Carlo simulations are essential in the field of astroparticle physics for the interpretation of measured data. CORSIKA (latest version 7.7550) has been widely used for more than 20 years to simulate air showers initiated by ultra-high-energy cosmic rays in the Earth's atmosphere. While CORSIKA 7 has served the community well, its design is limited to atmospheric showers, making it unsuitable for simulations in other media such as water or ice, which are crucial for modern experiments. To meet these evolving needs, the development of CORSIKA 8 was launched in 2018 as a complete rewrite within a flexible and modular C++ framework. CORSIKA 8 not only extends the simulation capabilities beyond air showers to include particle cascades in arbitrary media but also enables the simulation of cross-media showers, a key feature for a broader range of current and future experiments. The CORSIKA 8 code is considered "physics complete" and a first expert version of it was released at the end of 2024 [1]. We are now focused on making CORSIKA 8 more accessible by developing a containerized version that users can easily run out of the box. We are also working on enhancing aspects such as performance, simulation steering, and documentation to improve the overall user experience.

The general design of CORSIKA 8 is described in reference [2]. In this proceeding, we present the latest developments in CORSIKA 8, focusing on the validation of air showers against CORSIKA 7, the inclusion of radio emission calculations, and new functionality such as cross-media shower simulations. Additionally, we introduce new tools, a Python library for reading CORSIKA 8 output and a graphical interface for visualizing simulations, designed to enhance usability for the community.

2. Air shower validation

To ensure the reliability of CORSIKA 8, we validate its simulation results against those of CORSIKA 7. As a first step, we compare electromagnetic showers initiated by a 100 TeV primary electron, cf. reference [3] for details. Examining the longitudinal and lateral shower profiles as well as the energy distribution, the differences typically remain within 10 %. This level of agreement is remarkable given that different codes are used to describe the electromagnetic cascade: PROPOSAL [4–6] in CORSIKA 8 versus a customized version of EGS4 in CORSIKA 7.

We now extend our comparison to hadronic showers. CORSIKA 8 employs a modular framework that integrates state-of-the-art hadronic interaction models. At high energies, it currently supports EPOS-LHC [7], Sibyll 2.3d [8], and QGSJet-II.04 [9], as well as a preliminary implementation of Pythia 8 [10–12]. Ongoing efforts also focus on integrating updated models such as EPOS LHC-R [13] and QGSJet-III [14]. Low-energy interactions are handled using FLUKA [15].

In Fig. 1, we showcase the average longitudinal profile and lateral distribution of electrons plus positrons and muons for 300 vertical proton-induced air showers with an energy of 10^{17} eV, cf. reference [16] for details on the exact simulation setup. We observe a typical agreement for various particle species on the ~10 % level. The observed differences seem to be dependent on the high-energy interaction model. However, reaching agreement between completely independent codes at this level is a notable accomplishment and further investigations will be conducted to better understand the origin of these discrepancies.

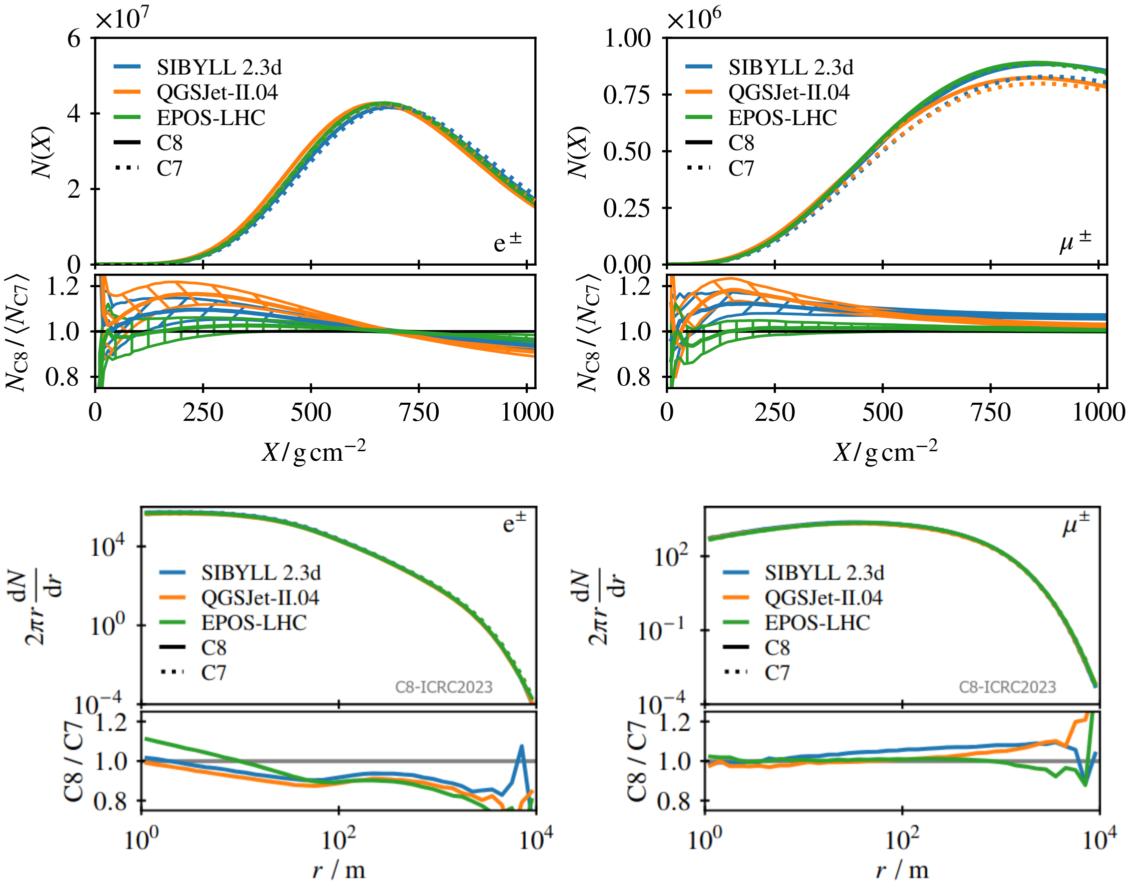


Figure 1: Average longitudinal profile (top) and lateral distributions (bottom) of electrons plus positrons (left) and muons (right) at ground for 300 vertical proton-induced air showers with a primary energy of 10^{17} eV. The hatched area shows the standard deviation of the mean. Figures from [16].

3. Radio emission calculations

Radio-emission calculation has been a key driver in the development of CORSIKA 8, primarily due to the radio-detection community's need for flexibility in handling more complex scenarios, such as radio emission from air showers crossing into ice for in-ice detection experiments, cf. following section. To address this, CORSIKA 8 decouples the emission calculation from the signal propagation. This design enables easy integration of specific use cases required by the community. CORSIKA 8 can perform concurrent simulation of the radio emission for the identical particle cascade with two established formalisms: the endpoint formalism as originally implemented in the CORSIKA 7 extension CoREAS [17] and the ZHS formalism available in ZHAireS [18].

A comparison of radio-emission predictions between CORSIKA 8 using both formalism and the established CoREAS and ZHAireS codes showed very good qualitative agreement, particularly in the symmetry and polarization of the energy fluence footprints. For high-precision simulations, the difference in the radiation energy, the energy emitted by charged particles in the form of electromagnetic waves, reaches less than 10 % in the 30 MHz to 80 MHz band currently used by many experiments and becomes negligible in the 50 MHz to 350 MHz band. A detailed explanation

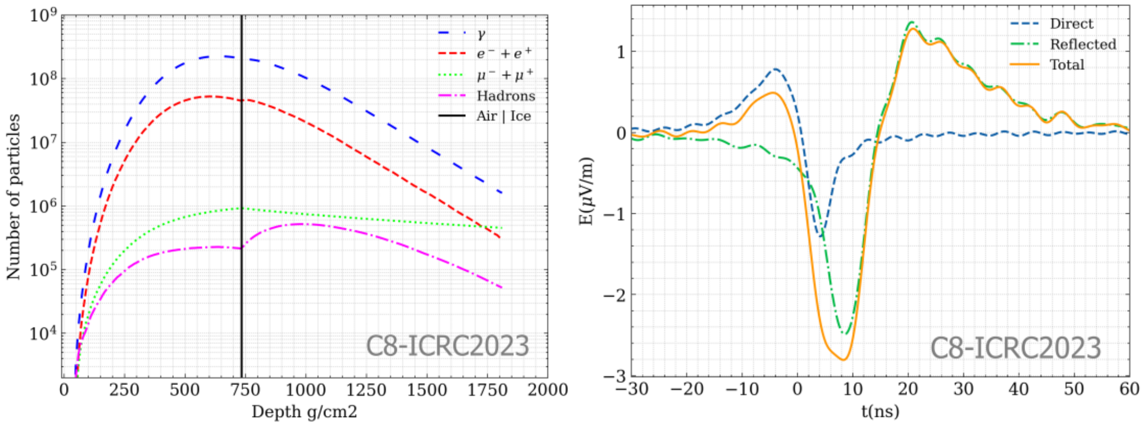


Figure 2: Comparison of a 100 PeV proton shower propagating through the atmosphere and intersecting an ice core at 2.4 km. On the left, the longitudinal profile simulated with CORSIKA 8 is shown, and on the right, the radio emission from the in-ice portion of the shower, considering direct and reflected optical paths. Figures from [20].

of the implementation of the radio process in CORSIKA 8 and an in-depth analysis of the predicted radio emission is presented in reference [19].

4. Cross-media showers

One of the most significant advancements in CORSIKA 8 is its ability to simulate cross-media showers, a functionality that previously required the use of multiple tools. In the past, simulating particle cascades that transition between different media, such as air into ice or water, was a complex task involving the combination of CORSIKA 7 for atmospheric showers and GEANT for simulating interactions in dense media. This approach was cumbersome and limited by the need to manually integrate results from different codes, each with its own set of assumptions and interfaces. CORSIKA 8 now brings everything into a single, unified framework, making it possible to simulate showers that span multiple media seamlessly. The modular structure of CORSIKA 8 allows users to define complex environments where different materials can interact with incoming high-energy particles, providing a more accurate and consistent picture of the particle cascade process. This capability is crucial for current and future experiments, such as ultra-high energy neutrino detection.

As an example, we compare a 100 PeV proton shower propagating through the atmosphere and intersecting an ice core at an altitude of 2.4 km, cf. reference [20] for details. The agreement between CORSIKA 8 (shown in Fig. 2 (left)) with previous work using CORSIKA 7 and GEANT4 is generally good, with the key difference being that CORSIKA 8 accounts for the hadronic interactions in the ice. This rehadronization process in CORSIKA 8 leads to an increase in hadrons and a small bump in electron and photon profiles as neutral pions decay into photons after the interface.

We now explore the simulation of radio emission from the in-ice part of the shower. The radio emission can travel via two possible optical paths: directly through the ice or reflected at the ice surface. The results are shown in Fig. 2 (right). This application is made possible by the flexibility of CORSIKA 8's radio module, which allows for the treatment of complex media transitions. We note that this is a simplified treatment for the purpose of testing the radio interface. At this stage, the simulation only accounts for the basic signal paths, without incorporating more complex effects like phase shifts that might occur at the reflections.

Additional applications of simulating in-ice radio emissions from air showers using CORSIKA 8 are discussed in [21].

5. Python library and the C8 viewer

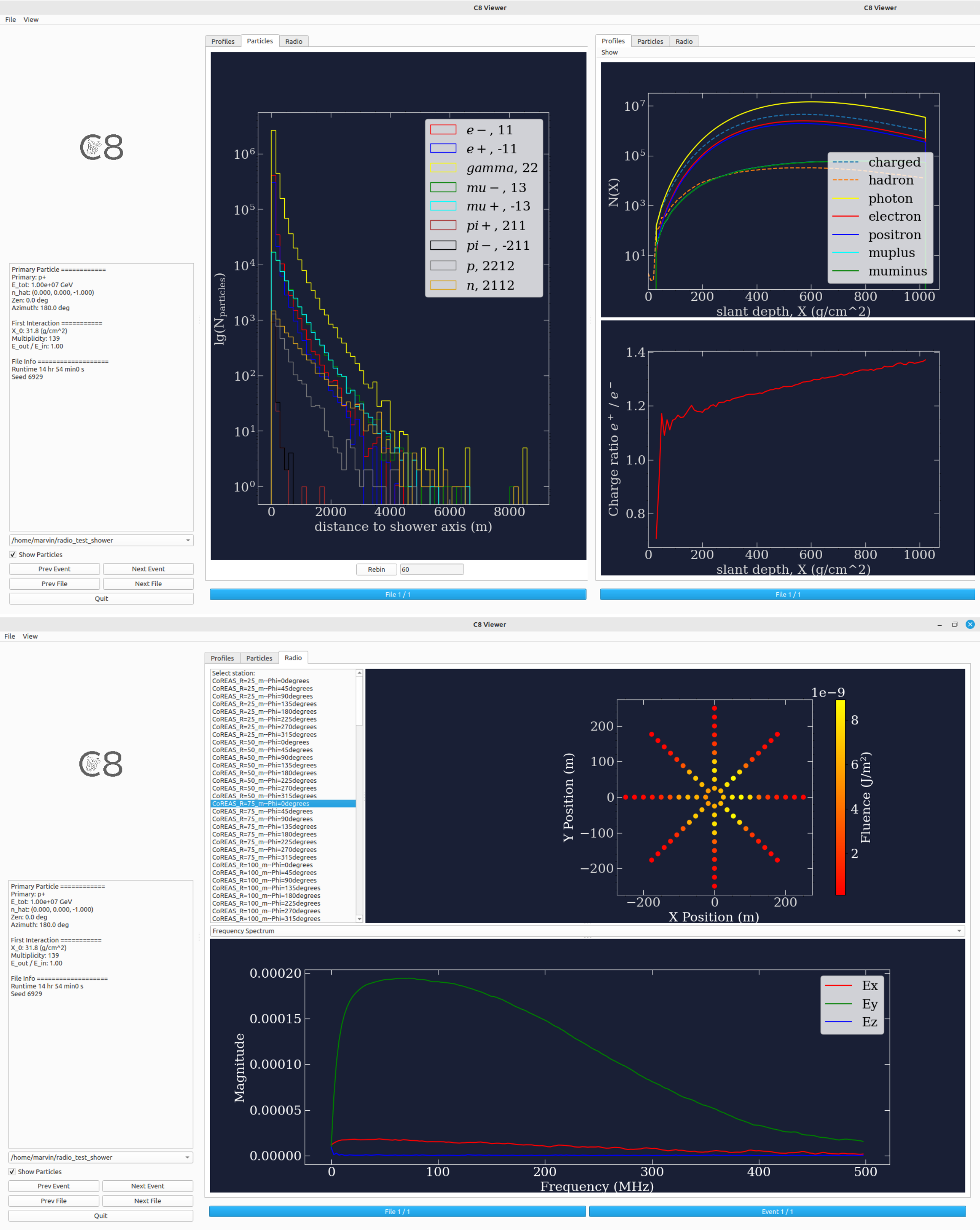
The CORSIKA 8 output is organized into separate directories for each observing process. At the top level, human-readable YAML files store configuration details and summary information, both globally and for each observing process. The global YAML file includes details such as the CORSIKA 8 version, exact steering parameters, random seed, and runtime. Observer-specific YAML files provide additional metadata, such as the units used or, in the case of radio simulations, the locations where radio emission was calculated. The primary data from each observing process is stored in a Parquet file. Although these files can be read manually, we recommend using the dedicated Python library included with CORSIKA 8. This library serves as an abstraction layer, ensuring that analysis scripts remain functional and independent of specific output formatting, even if the structure evolves in future versions. In addition, example scripts are provided that demonstrate how to use the library for data analysis to help users get started.

To further enhance user experience, CORSIKA 8 will be accompanied by the “C8 Viewer”, a graphical tool designed for intuitive and interactive visualization of simulated events, as shown in Fig. 3. This GUI-based application enables users to explore various aspects of particle cascades in detail. General information about the primary particle, the first interaction, and simulation runtime is displayed in a dedicated text panel on the left. On the right, multiple tabs provide information on key aspects of the shower development: the longitudinal profile, lateral particle distributions, and radio emission characteristics.

The “Profiles” tab presents the number of particles as a function of amospheric depth for different particle types, the energy deposited along the shower axis, and the electron-to-positron ratio. The “Particles” tab visualizes the lateral distribution of various particle species at the ground, including the lateral footprint of the shower and the distribution of particle weights from the thinning. The “Radio” tab provides a list of all simulated pulse locations, displaying the time-domain signal and its frequency spectrum for individual stations. Additionally, it computes and visualizes the distribution of energy fluence, the energy carried by radio waves per unit area, for all observer positions. For specialized star-shape simulations in the shower plane, the energy fluence map allows interpolation of the full radio footprint, revealing the expected emission features. These include the interplay between geomagnetic and charge-excess contributions and the characteristic Cherenkov-like compression of the radio signal into a ring around the shower axis [22].

6. Conclusion

Over the past years, CORSIKA 8 has made significant progress, reaching a stage where it is considered “physics-complete.” This means that the fundamental physical processes governing particle shower development and the calculation of the radio emission are fully implemented. Extensive validation against CORSIKA 7 has demonstrated agreement at the ~10 % level, with



Primary Particle ============
Primary: p+
E_tot: 1.00e+07 GeV
n_hat: (0.000, 0.000, -1.000)
Zen: 0.0 deg
Azimuth: 180.0 deg

First Interaction ===========
X_0: 31.8 (g/cm^2)
Multiplicity: 139
E_out / E_in: 1.00

File Info ===================
Runtime 14 hr 54 min0 s
Seed 6929

/home/marvin/radio_test_shower

Primary Particle ============
Primary: p+
E_tot: 1.00e+07 GeV
n_hat: (0.000, 0.000, -1.000)
Zen: 0.0 deg
Azimuth: 180.0 deg

First Interaction ===========
X_0: 31.8 (g/cm^2)
Multiplicity: 139
E_out / E_in: 1.00

File Info ===================
Runtime 14 hr 54 min0 s
Seed 6929

/home/marvin/radio_test_shower

Select station:
CoREAS_R=25_m--Phi=0degrees
CoREAS_R=25_m--Phi=45degrees
CoREAS_R=25_m--Phi=90degrees
CoREAS_R=25_m--Phi=135degrees
CoREAS_R=25_m--Phi=180degrees
CoREAS_R=25_m--Phi=225degrees
CoREAS_R=25_m--Phi=270degrees
CoREAS_R=25_m--Phi=315degrees
CoREAS_R=50_m--Phi=0degrees
CoREAS_R=50_m--Phi=45degrees
CoREAS_R=50_m--Phi=90degrees
CoREAS_R=50_m--Phi=135degrees
CoREAS_R=50_m--Phi=180degrees
CoREAS_R=50_m--Phi=225degrees
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CoREAS_R=50_m--Phi=315degrees
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CoREAS_R=100_m--Phi=270degrees
CoREAS_R=100_m--Phi=315degrees

Frequency Spectrum

Figure 3: Screenshots of the “C8 Viewer”. On the left hand side general information on the simulated air shower are displayed. The top plot contains a combination of the “Profile” and “Particles” tab visualizing the lateral distribution and longitudinal profile of different particle types as well as the ratio of electrons and positrons. The bottom figure contains the “Radio” tab, showing the time trace or frequency spectrum of simulated pulses and a view of the distribution of the radio emission in the shower plane.

remaining differences under active investigation. An expert version of it was released at the end of 2024 to obtain broader feedback from the community [1]. For the simulation of particle showers developing in dense media or crossing from air into dense media, we consider CORSIKA 8 the code of choice already now. However, CORSIKA 7 remains the recommended choice for standard air-shower applications at this time.

References

[1] *CORSIKA 8 - Release v1.0-beta1*, `https://gitlab.iap.kit.edu/AirShowerPhysics/corsika/-/tags/corsika8-v1.0-beta1`.

[2] R. Engel, D. Heck, T. Huege et al., Comput. Softw. Big Sci. **3** (2019) 2.

[3] A. Sandrock, J-M. Alameddine and F. Riehn for the CORSIKA 8 collaboration, PoS(ICRC2023)393.

[4] J.-H. Koehne, K. Frantzen, M. Schmitz et al., Comput. Phys. Commun. **184** (2013) 2070.

[5] J.-M. Alameddine, M. Dunsch, L. Bollmann et al., *tudo-astroparticlephysics/PROPOSAL: Zenodo* (2020).

[6] M. Dunsch, J. Soedingrekso, A. Sandrock et al., Comput. Phys. Commun. **242** (2019) 132.

[7] T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko and K. Werner, Phys. Rev. C **92** (2015) 034906.

[8] F. Riehn, R. Engel, A. Fedynitch, T.K. Gaisser and T. Stanev, Phys. Rev. D **102** (2020) 063002.

[9] S. Ostapchenko, Phys. Rev. D **83** (2011) 014018.

[10] T. Sjöstrand and M. Utheim, Eur. Phys. J. C **82** (2022) 21.

[11] C. Gaudu, M. Reininghaus, and F. Riehn for the CORSIKA 8 collaboration, arXiv:2412.15094 (2024).

[12] C. Gaudu for the CORSIKA 8 collaboration, PoS(UHECR2024)089.

[13] T. Pierog and K. Werner, PoS(ICRC2023)230.

[14] S. Ostapchenko, arXiv:2410.23465 (2024).

[15] F. Ballarini, et al., EPJ Nucl. Sci. Technol. **10** (2024) 16.

[16] T. Huege and M. Reininghaus for the CORSIKA 8 collaboration, PoS(ICRC2023)310.

[17] T. Huege, M. Ludwig and C.W. James, AIP Conf. Proc. 1535 (2013) 128.

[18] J. Alvarez-Muñiz, W.R. Carvalho Jr. and E. Zas, Astropart. Phys. 35 (2012) 325.

[19] J.M. Alameddine, et al., Astropart. Phys. **166** (2025) 103072.

[20] J. Ammerman-Yebra for the CORSIKA 8 collaboration, PoS(ICRC2023)442.

[21] A. Coleman, C. Glaser, R. Rice-Smith, et al., arXiv:2410.08615 (2024).

[22] T. Huege, Physics Reports, **620** (2016) 1.