Bayesian Reconstruction of Air-Shower Component Energy Spectra with Multi-Hybrid Detector Stations

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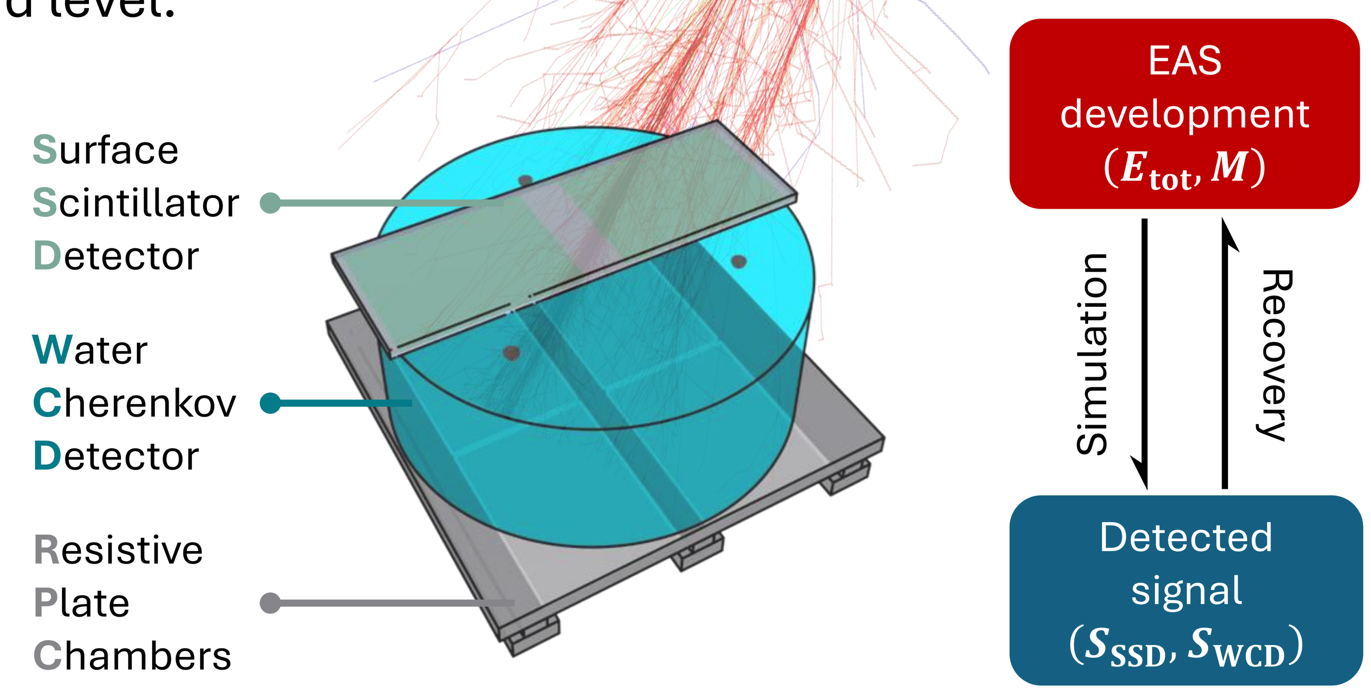
1. Introduction: cosmic rays in the *AugerPrime* Era

The **most energetic cosmic rays** interact with the atmosphere initiating **extensive air-showers (EAS)** composed of a myriad of secondary particles.

Their detection is done by sampling the shower components in **large ground-based detector arrays**, such as the Pierre Auger Observatory [1] in Malargüe, Argentina.

Discrepancies between the experimental measurements and air-shower simulations, particularly concerning the muonic component, the **Muon Puzzle** [2], strongly motivate a more detailed investigation of the particle content of air-showers at ground level.

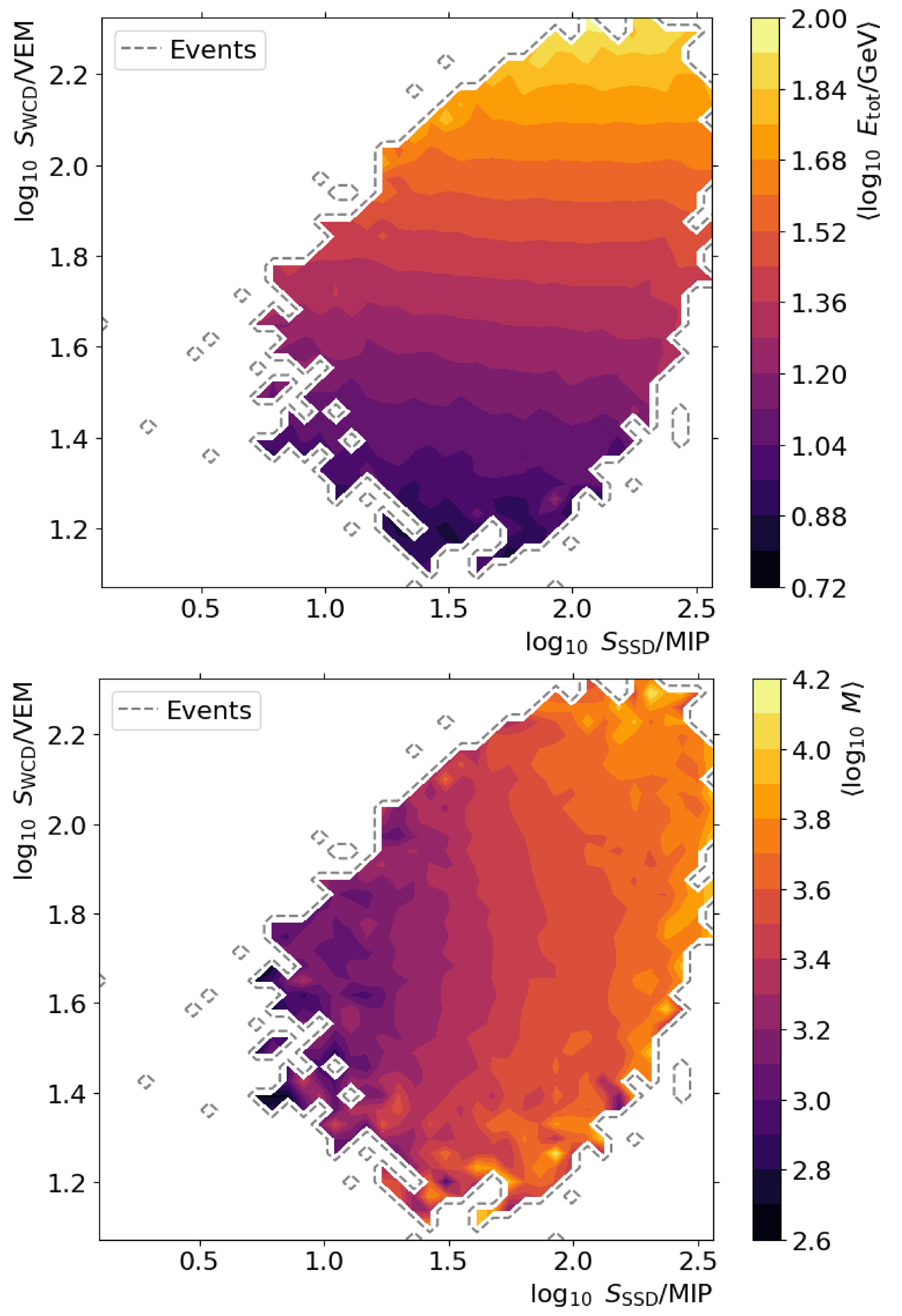


Station scheme from [3]. EAS visualization from [4].

2. Objective: measuring EAS ground component energy

We explore the physically motivated relationship between the **surface scintillator** (S_{SSD}) and **water Cherenkov** (S_{WCD}) signals, and **total particle energy** (E_{tot}) and **EM particle multiplicity** (M).

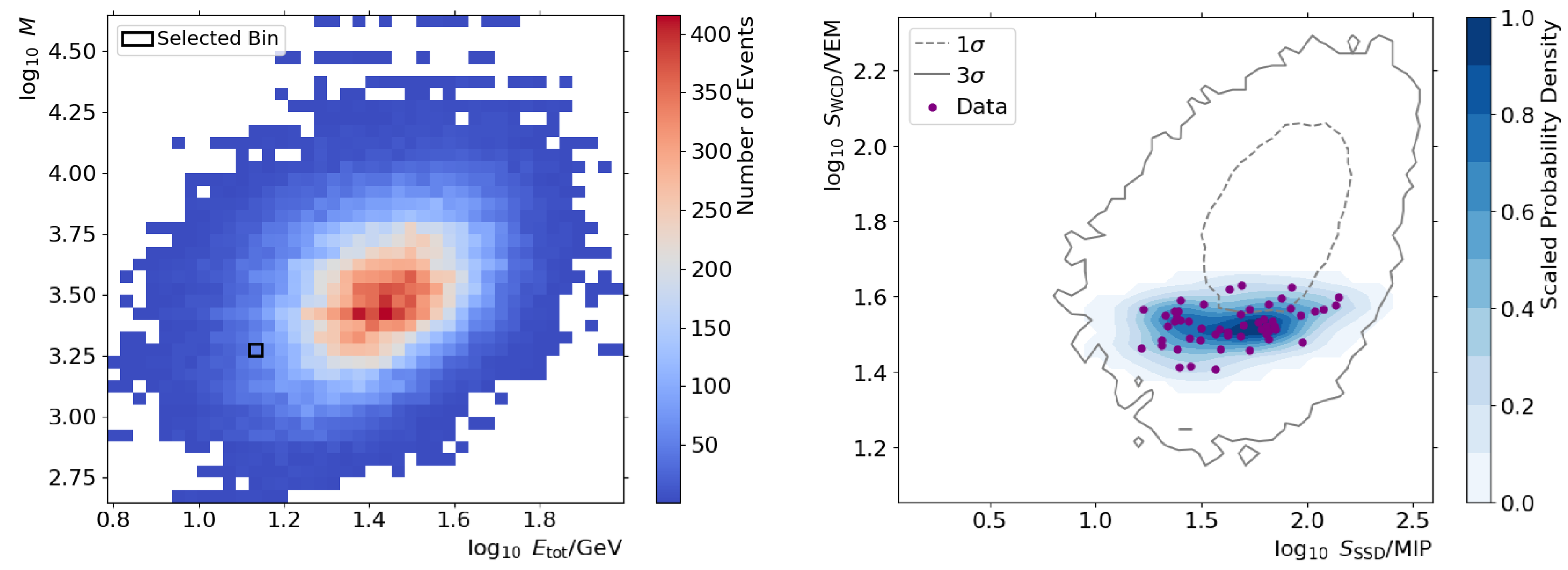
$$\underbrace{S(t)}_{\text{Detector Signal}} = \sum_{\text{species}} \left[\underbrace{\int dE\, d\Omega\, d^2x\, dt'}_{\text{Energy, geometry and time dependance}} \underbrace{\phi(t', E, \Omega, \mathbf{x})}_{\text{Particle Flux}} \underbrace{D(t-t', E, \Omega, \mathbf{x})}_{\text{Detector Response}} \right] + \underbrace{n(t)}_{\text{Noise}}$$



KDE to construct the response + **Bayesian inference** to predict

3. Results: spectral properties inference from detector signals

From the signal and spectral phase spaces, we constructed a method to exploit their one-to-one mapping.

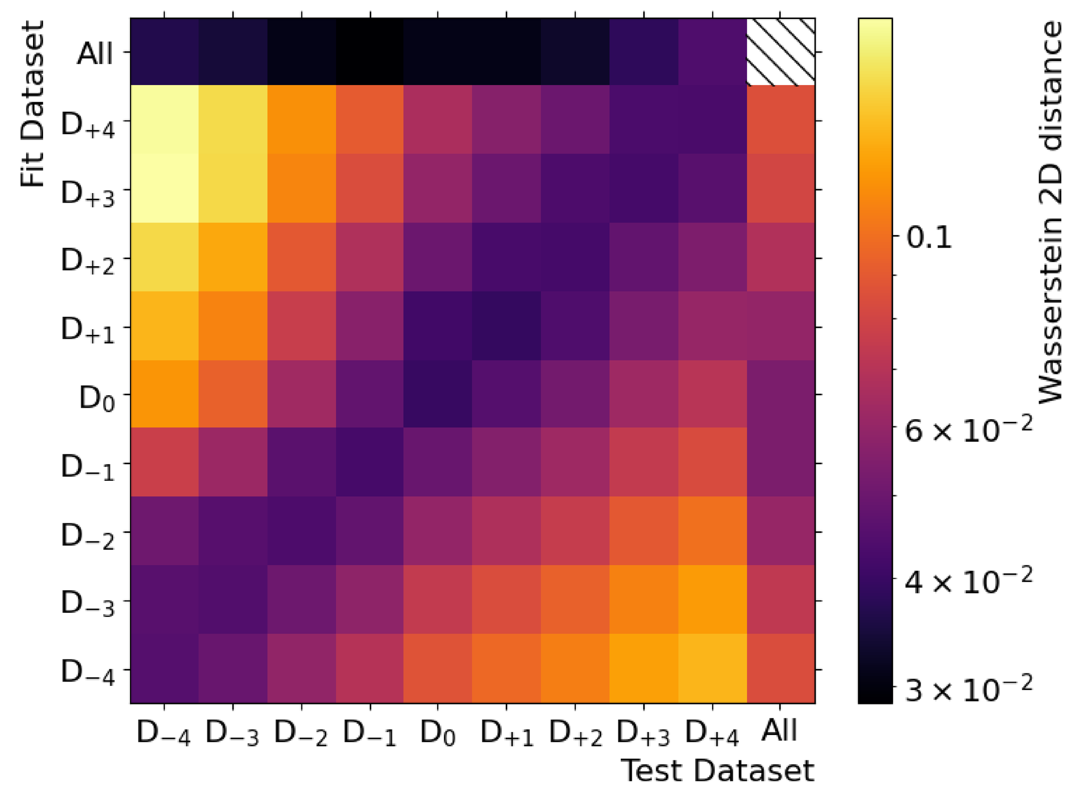


Simulation
Phenomenological modifications of the energy spectra.

Method
KDE on signal space.
Bayes' Theorem to infer spectral distribution.

Fixing the joint signal (S_{SSD}, S_{WCD}) allows to infer the **most probable** (E_{tot}, M) values, estimating their distribution in the **spectral phase space**.

The **dissimilarity** between predicted and true distributions is quantified by the **Wasserstein distance** [5].



Smaller values indicate a better agreement.

Increasing the fit events improves inference across most spectral modifications.

4. Conclusions and outlook

Proof-of-concept: signal-spectral mapping

The complementary modules of a multi-hybrid detector station enable the inference of event-by-event spectral properties, opening the door to unprecedented tests to hadronic interaction models.

Disentangling the muonic component & controlling detector systematics

Taking advantage of the RPCs installed beneath the WCD – the R&D MARTA station – the muonic component of the shower could be separated from the remaining shower components. Additionally, a 3rd detector module would allow for consistency checks on the method, mitigating the impact of detector-related effects.

References

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