Reconstructing Air-Shower Observables Using a Universality-Based Model

7th International Symposium on
Ultra High Energy Cosmic Rays
2024 Malargüe, Argentina

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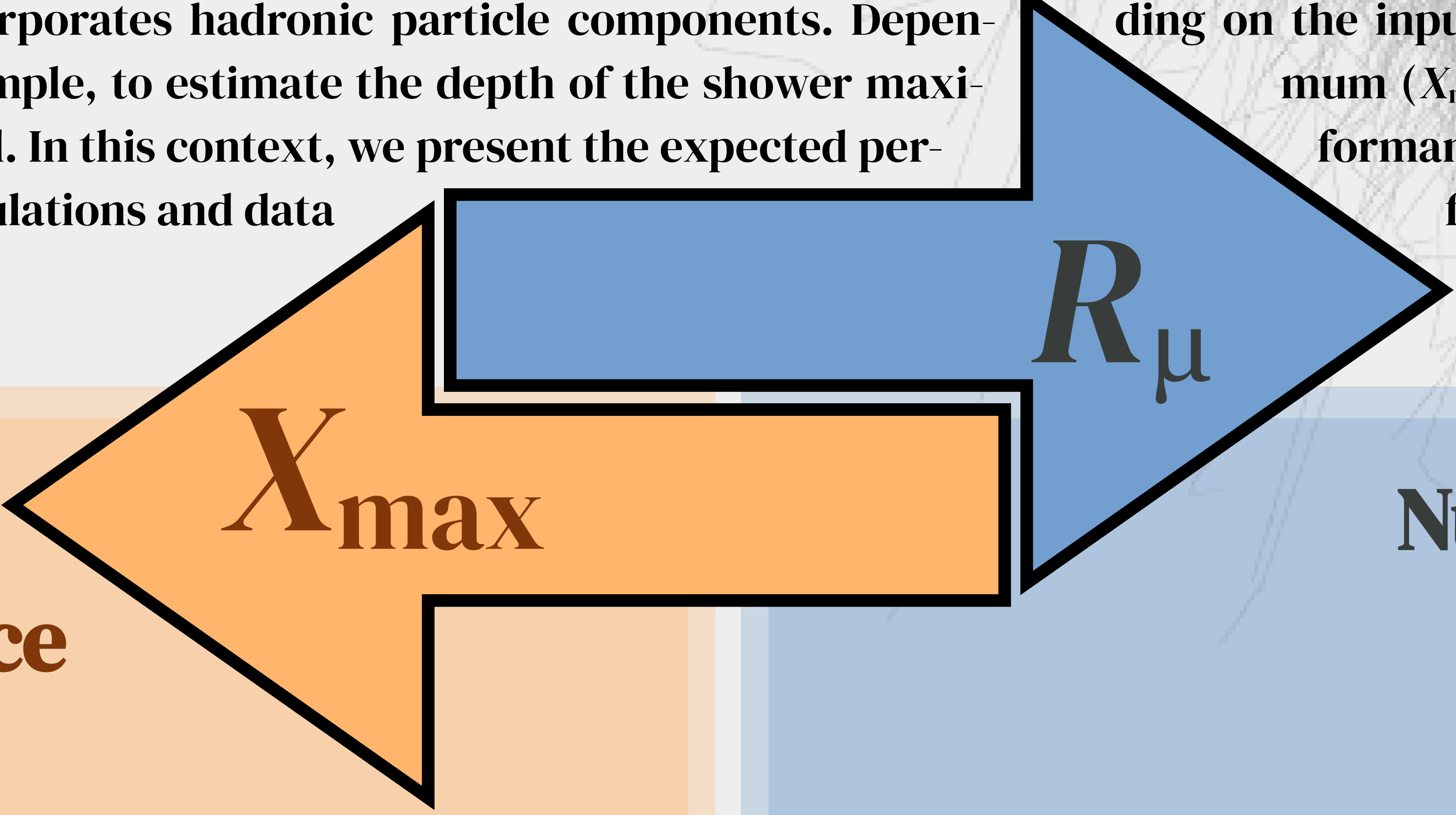
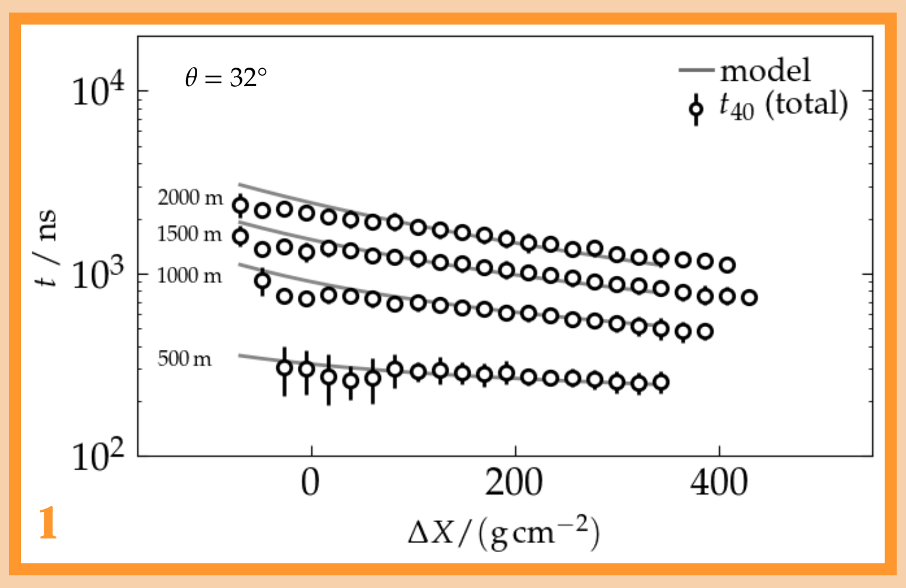
Air-Shower universality describes the regularity in the longitudinal, lateral, and energy distributions of electromagnetic shower particles, as motivated by solutions of the cascade equations. To reconstruct air-shower observables from ultra-high-energy cosmic rays, we employ a universality-based model of shower development that incorporates hadronic particle components. Depending on the input parameters, the model can be used, for example, to estimate the depth of the shower maximum (X_{max}) or the number of muons ($\sim N_\mu$) on event level. In this context, we present the expected performance for the reconstruction using air-shower simulations and data from the Pierre Auger Observatory.



Depth of the shower maximum using surface detector data

Shower cascades induced by heavy/light primary particles reach their maximum earlier/later due to superposition effects, elasticity of the first interaction, and due to the differences in the cross sections of the primary particles.

The **depth of the shower maximum is directly influencing the shape of the signal traces** in the detector stations. Using a universality-based model of the ideal signal trace, **this fact can be exploited to estimate X_{max} from surface detector data.**



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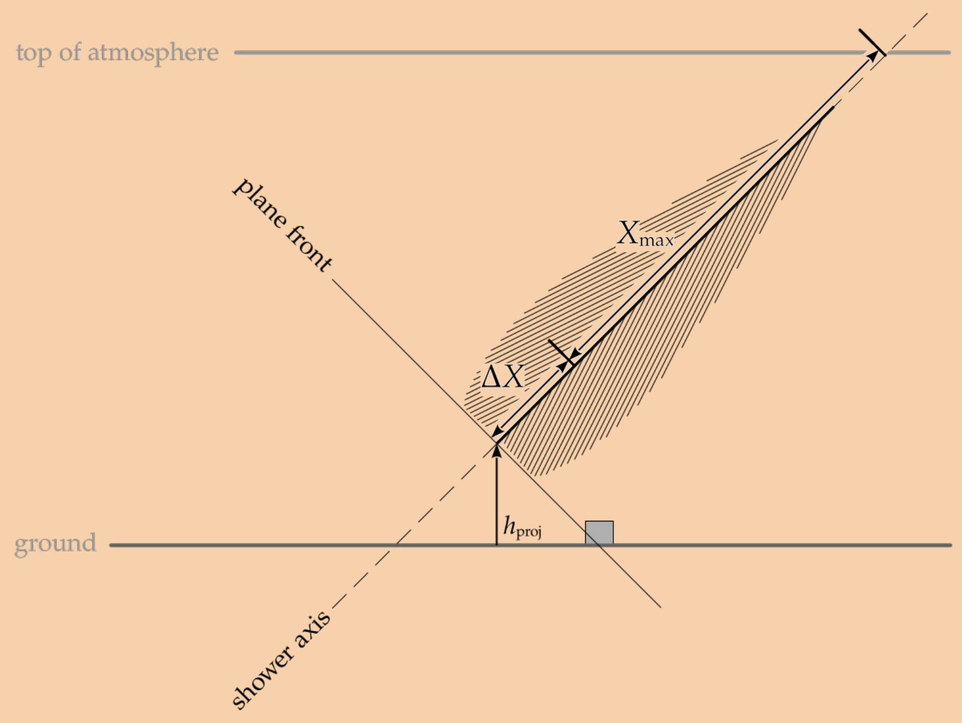

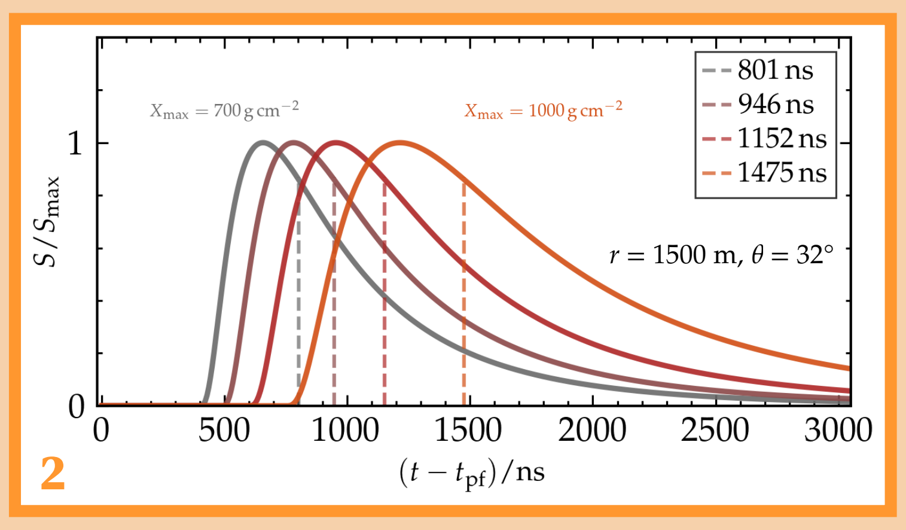

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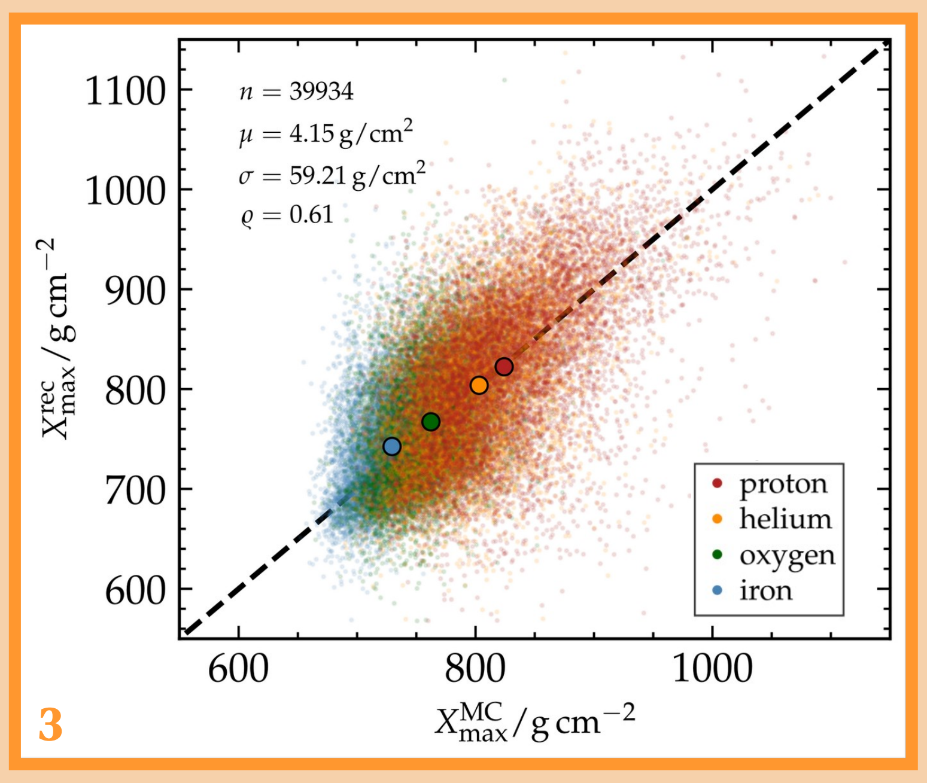
Particles reaching the detector at around the point in time in which 40% of the total signal have been deposited (t_{40}) are expected to be created around the shower maximum. Thus, t_{40} is parametrized as a function of the distance of the detector to the shower maximum. Before fitting to the model, traces are normalized to avoid artificial correlation with the number of muons and to minimize the influence of the muon puzzle on the X_{max} results.

Figure 1 shows the model of t_{40}, and Figure 2 shows ideal detector traces for an example detector station responding to showers with different depths of the shower maximum.

From simulations, we find promising results, with the estimations of the depth of the shower maximum being strongly correlated with the simulated values, see Figure 3. Using fluorescence detector data, the method can be calibrated and validated; in Figure 4 we present the comparison of direct measurements and estimates from the universality reconstruction.



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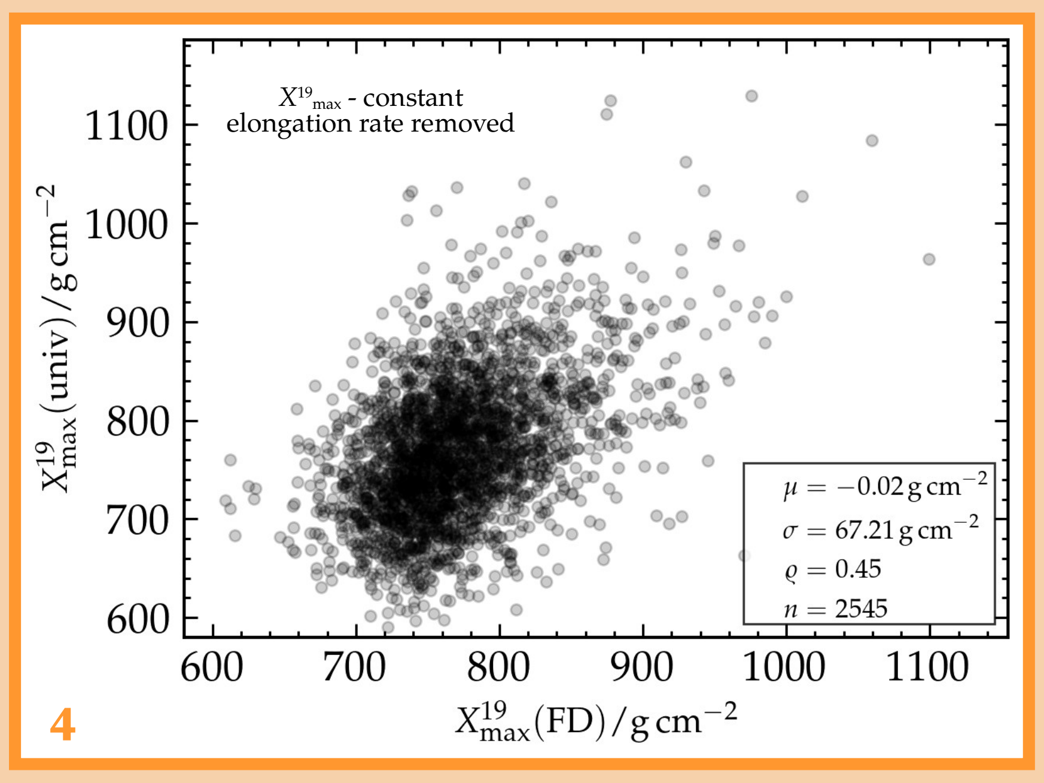

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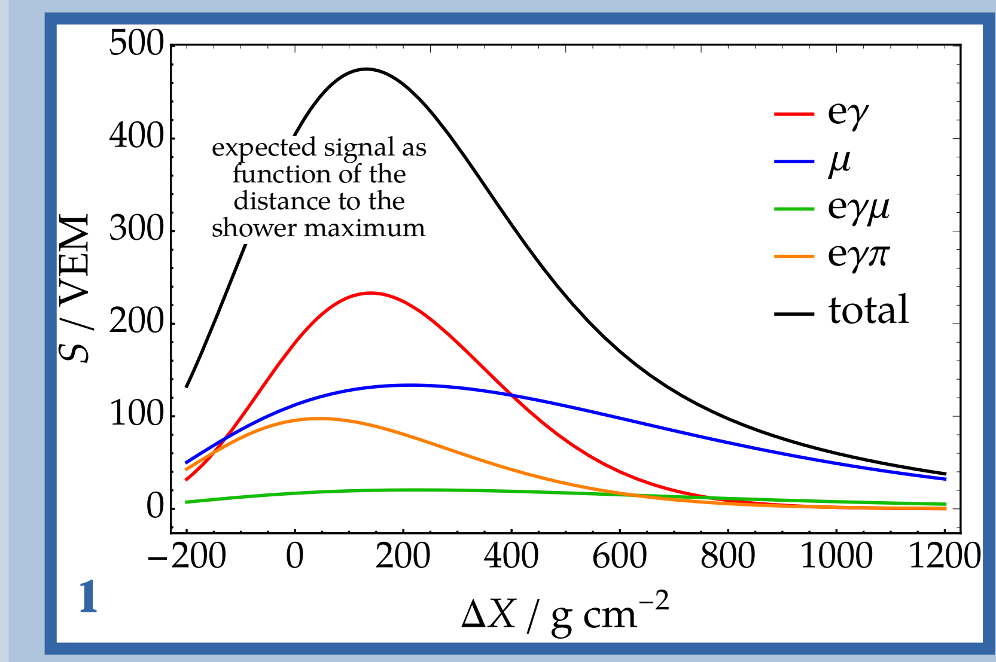
Number of muons using Golden Hybrid data

The number of muons produced in extensive air showers is a reliable proxy for the amount of hadronic multi-particle production happening in the first interactions. We utilize a four-component universality shower model, see Figures 1 and 2, with the **energy and X_{max} as input from the fluorescence detector measurements to examine the footprint of air showers.** In this way, we can fit the number of muons relative to proton expectations as a free parameter, $R_\mu \equiv N_\mu/{<}N_\mu{>}_\text{p}$. Figures 1 and 2 show the model for $R_\mu = 1$.



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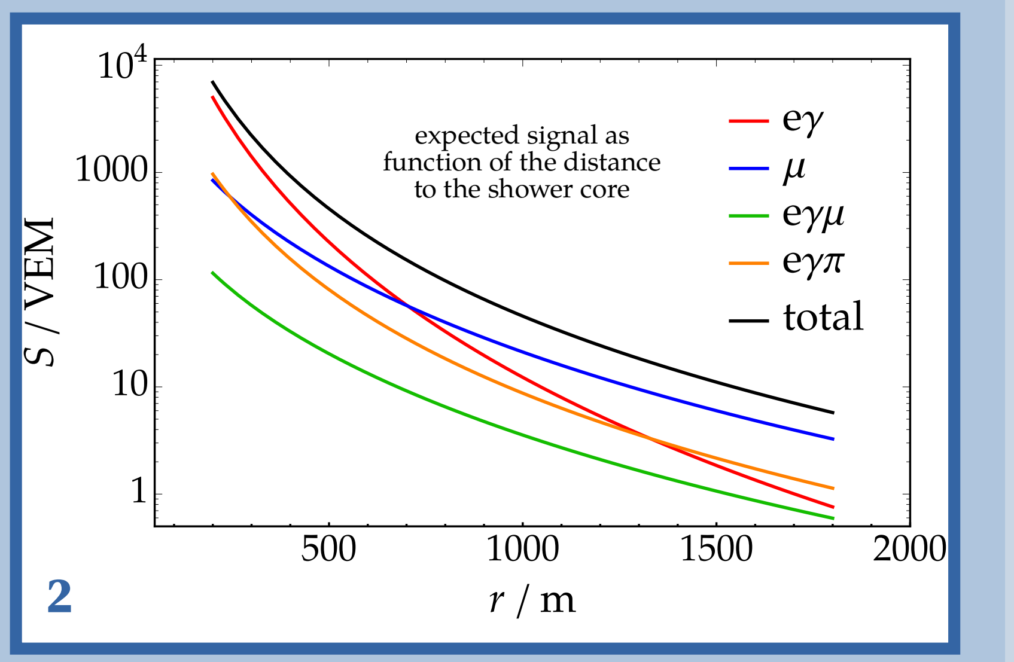
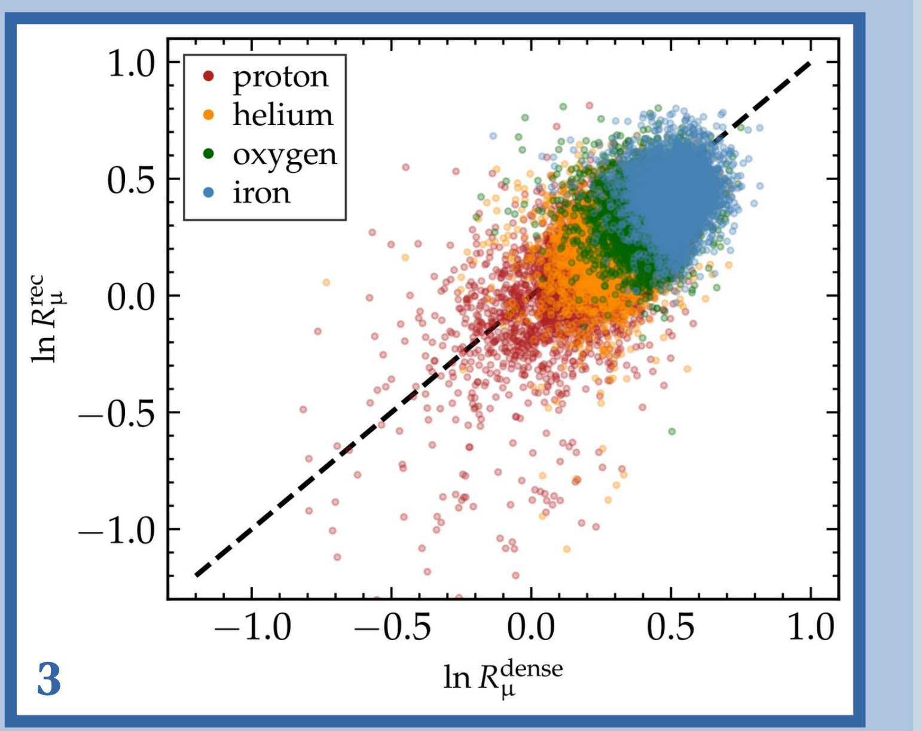


2

The contribution of the hadronic shower components is scaled linearly with the number of muons, so that the total signal can be written as

$$S = S_{\text{e}\gamma} + R_\mu\,(S_\mu + S_{\text{e}\gamma\mu} + S_{\text{e}\gamma\pi})\,.$$

From simulations we expect good performance of the method, see Figure 3. In the Golden Hybrid data, the number of muons is correlated with the measurements of X_{max}, as expected from a mixed composition; see Figure 4. Unfortunately, **no consistent interpretation of the data is possible with any modern hadronic interaction model,** since more muons are measured than expected for any scenario, see Figure 5.



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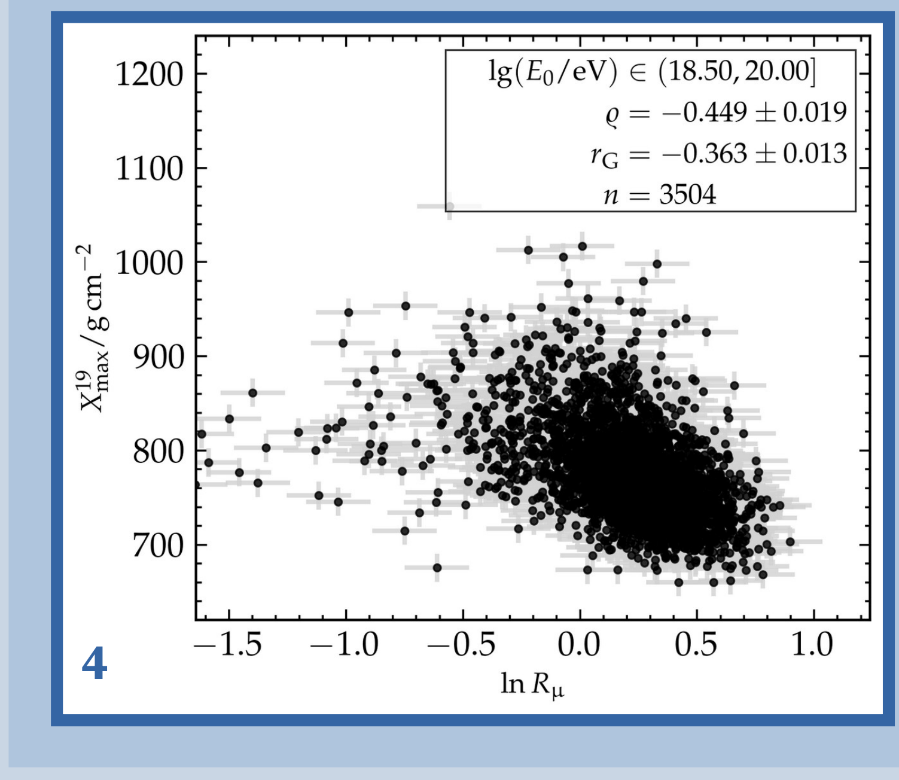

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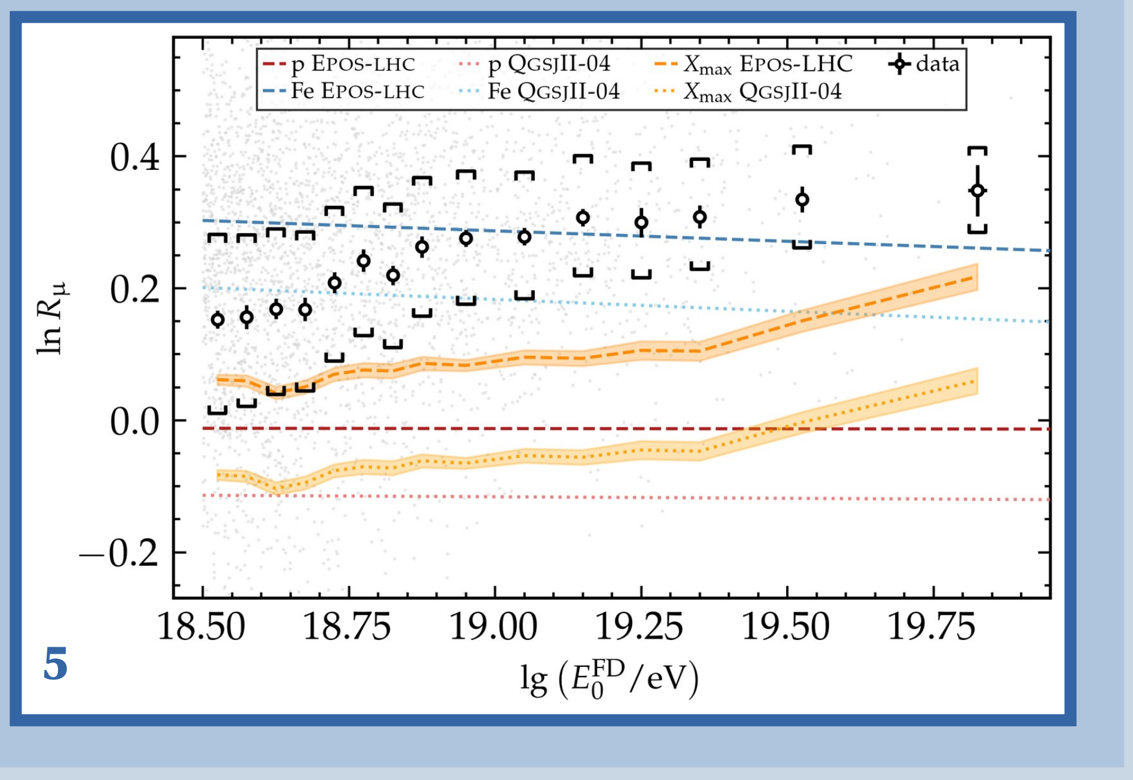

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For references, see
Stadelmaier et al., PRD **110** (2024) 2, 023030
PAO collaboration, PoS **ICRC2023** (2023) 339
and cited references therein