Machine learning-based analyses using surface detector data of the Pierre Auger Observatory

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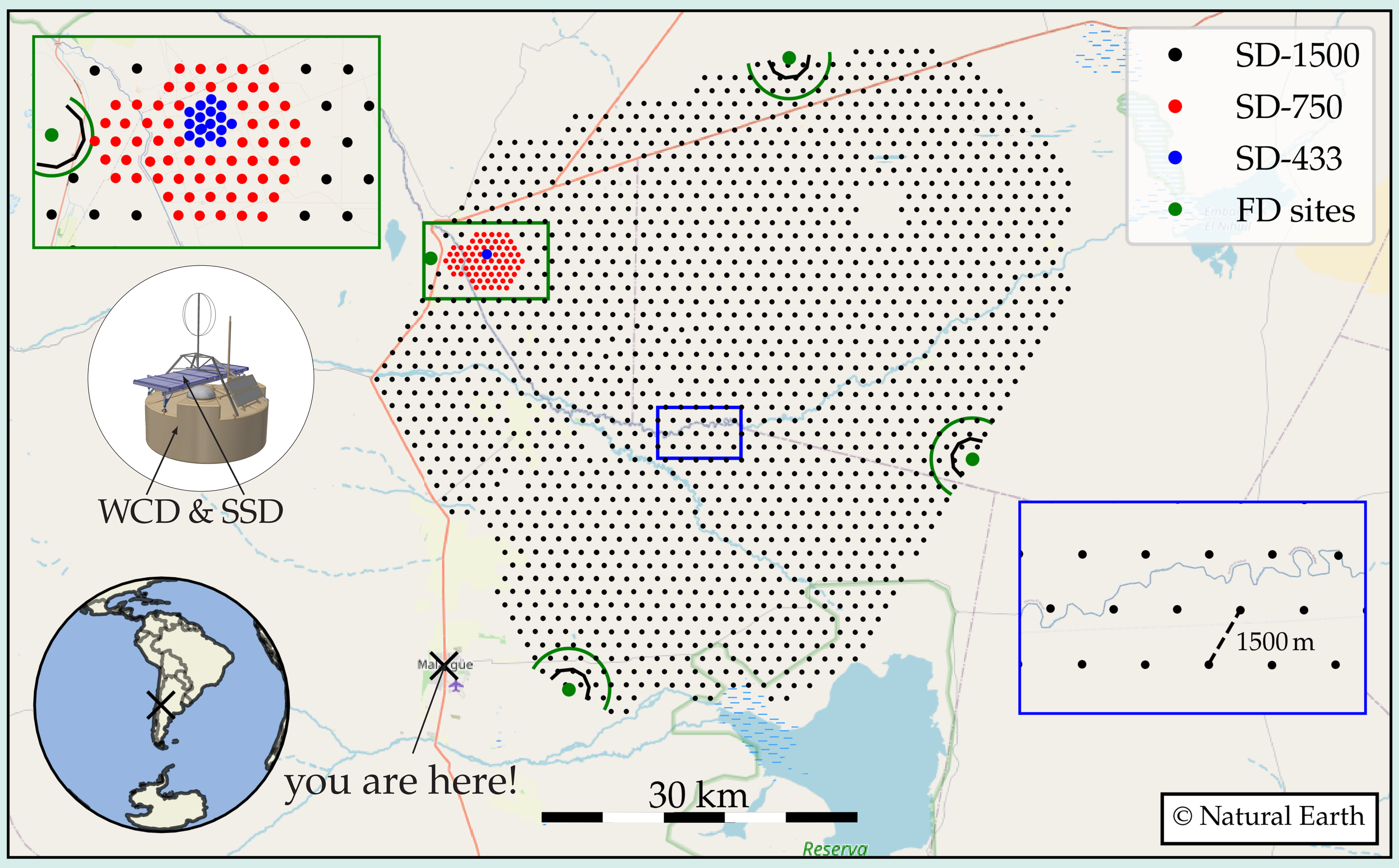
Shortend abstract

To analyze the complex spatio-temporal data from air shower footprints detected by the Pierre Auger Observatory, machine learning-based algorithms are used to complement traditional methods. These algorithms help extract mass-sensitive observables, such as the number of secondary muons and the (atmospheric) depth of the shower maximum, from the surface detectors, improving the precision of UHECR mass estimates with an uptime of nearly 100%. The machine learning-based analyses perform exceptionally well in simulations and show, after calibration, excellent results when applied to measurements.

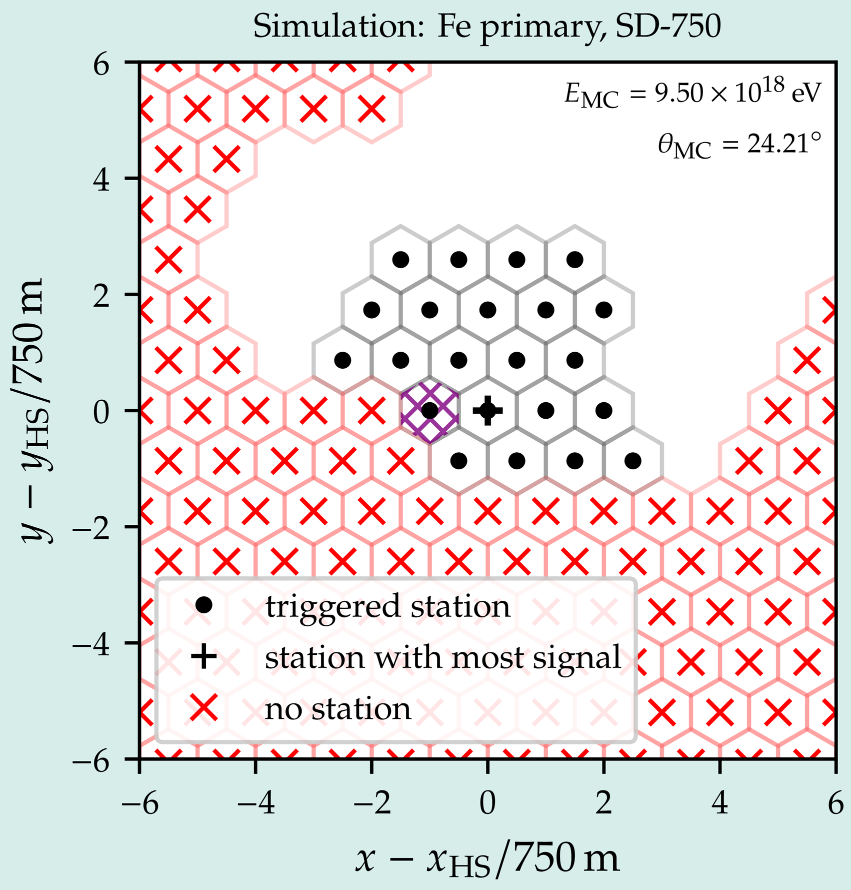
Surface detector arrays (SDs) of the Pierre Auger Observatory

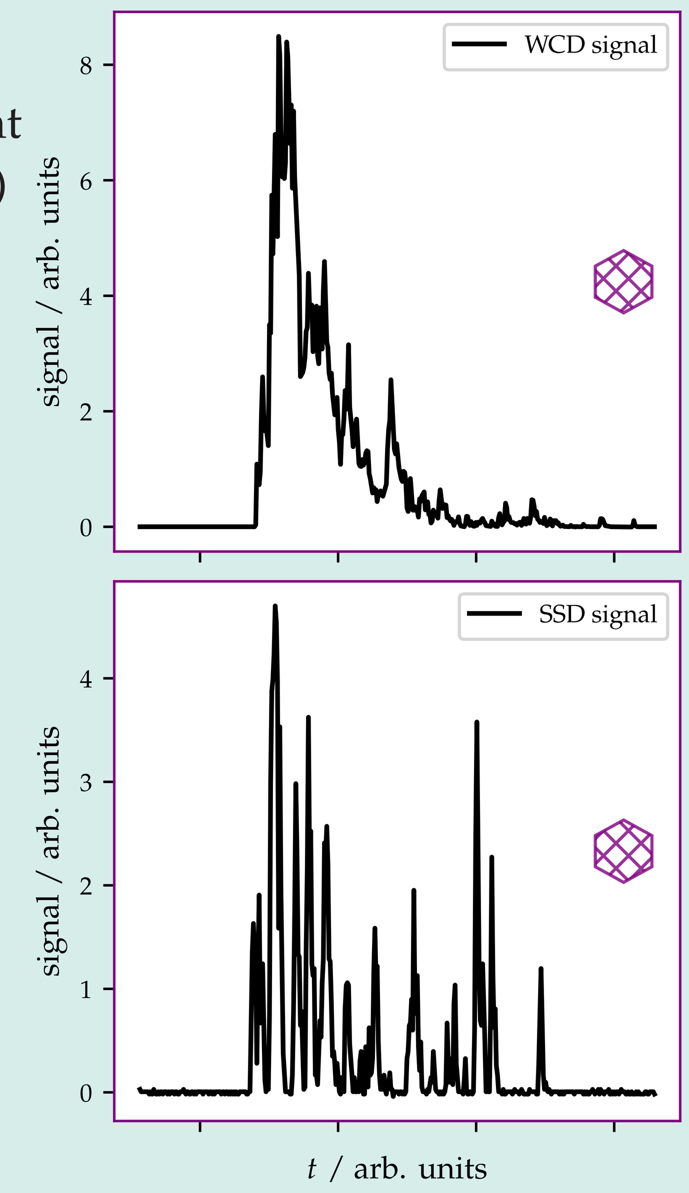


- 1660 water-Cherenkov detectors (WCD) with nearly 100% uptime
- upgrade *AugerPrime*: new surface scintillator detectors (SSD)

Spatio-temporal information contained in the shower footprint

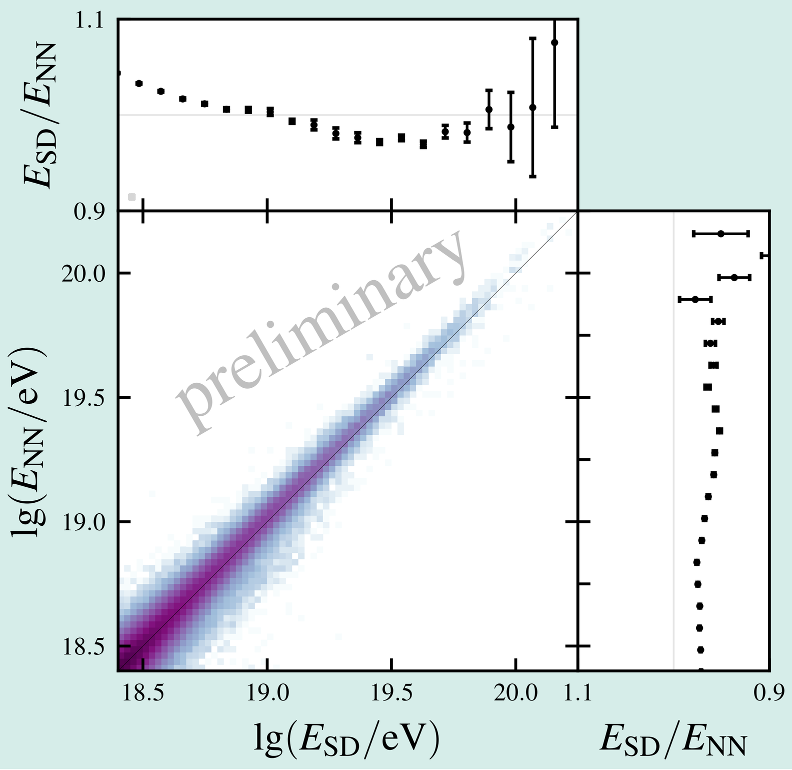
- each shower triggers multiple stations in one of the SDs yielding a distinct footprint
- each SD station detects time-signal (trace) of the passing shower front

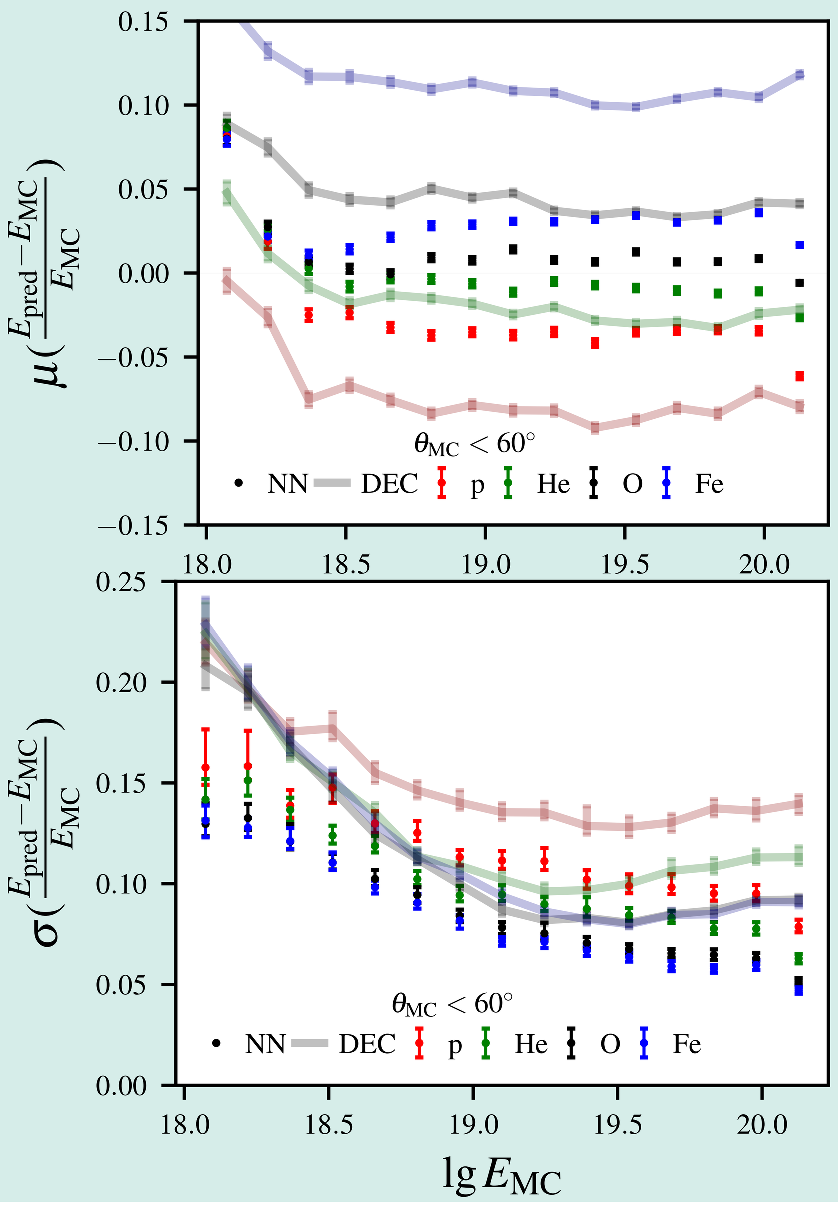




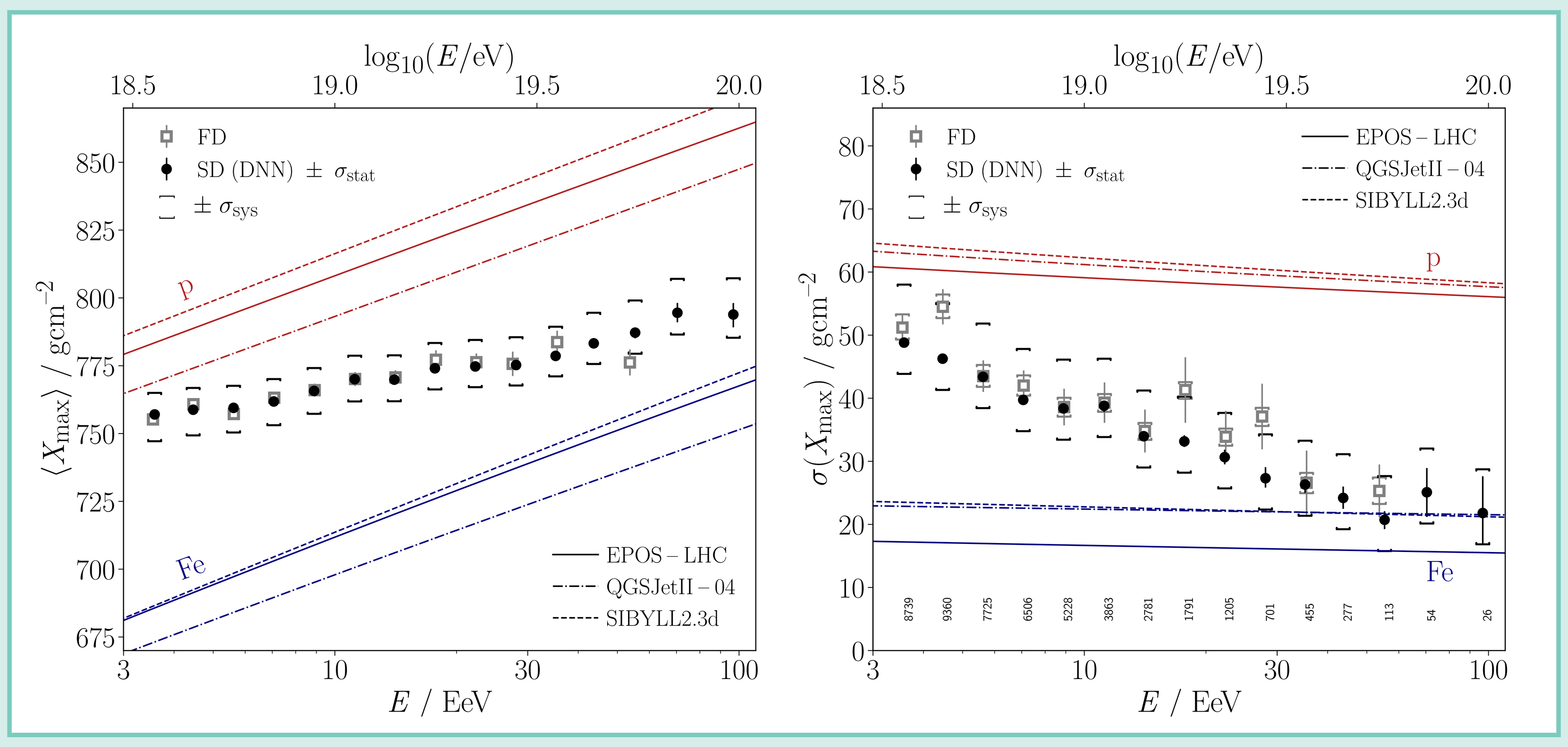
Direct comparison to classical reconstruction: energy estimation [1]

- two-step (trace, footprint) CNN
- clear reduction of inter-primary bias and improved resolution on simulations
- after calibration with FD-SD events, predictions comparable to standard SD reconstruction





Indirect measurement of shower depth of shower maximum [2]

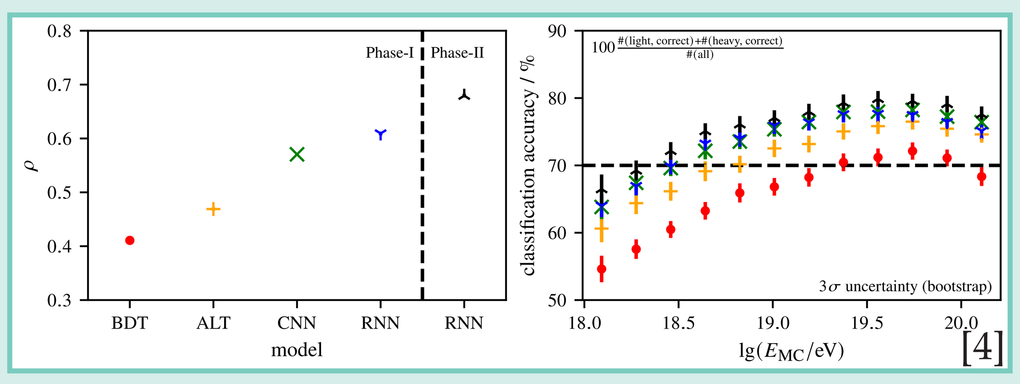


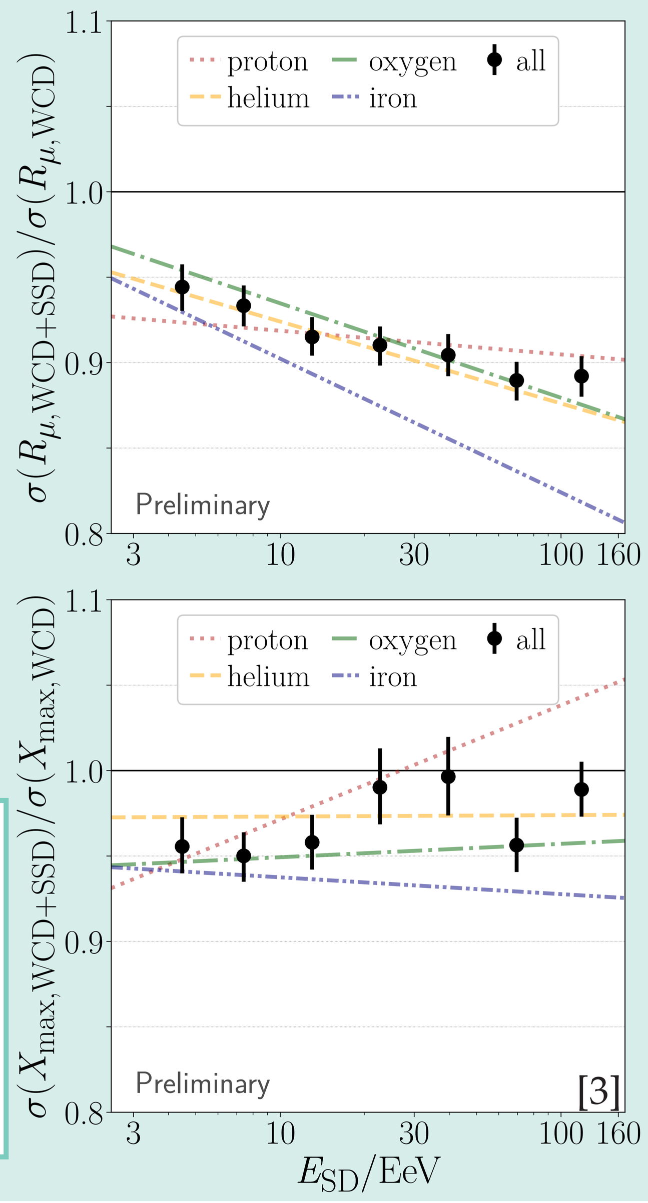
- LSTMs to extract features from time traces sharing weights for all traces
- hexagonal group convolutions to analyze spatial information taking SD symmetry into account
- predictions of shower depth of the shower maximum X_{max} calibrated with FD-SD events
- NN predictions reproduce 1st and 2nd moment of X_{max} (measured by FD) extending the energy range due to higher SD statistics

Prospects of AugerPrime

- number of muons normalized to expected number of muons of protons R_μ is proportional to mass of primary
- proof of concept: Transfomers and CNNs/RNNs trained on detector simulations of AugerPrime (WCD, SSD) to predict R_μ and X_{max}
- the information from the improved sampling rate and additional traces of the SSD improve the prediction of these mass-sensitive observables

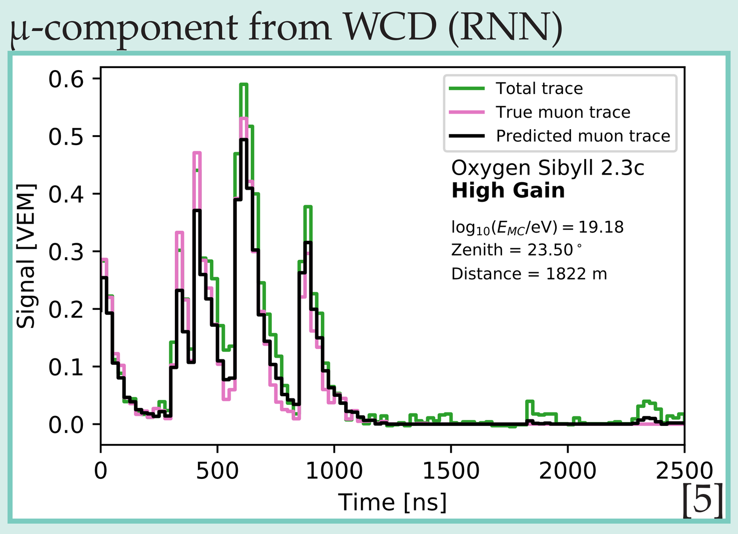
⇒ the mass separation also improves



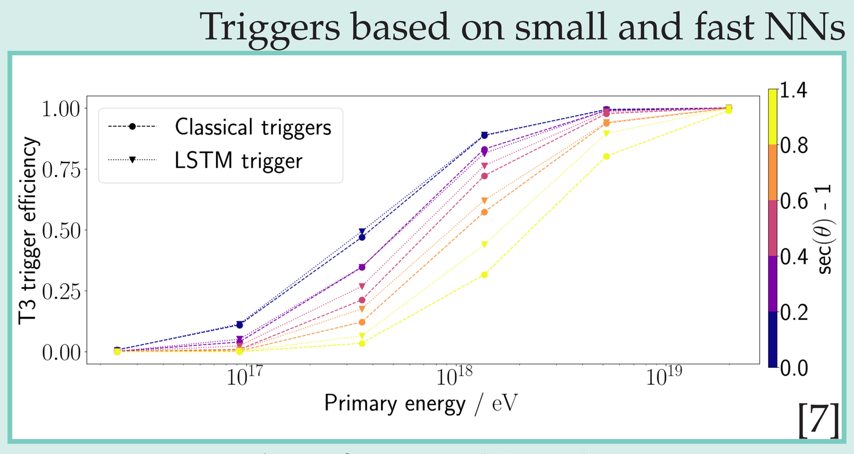


Many studies on potential use cases...

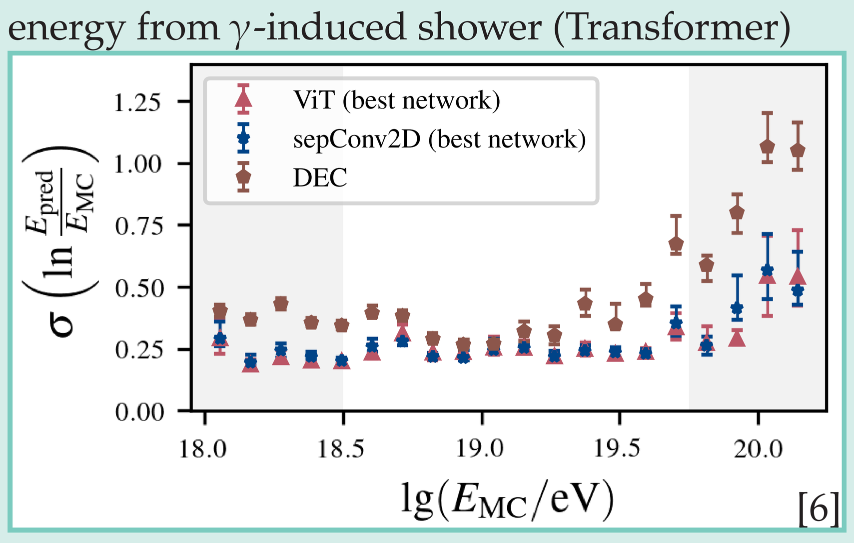
μ-component from WCD (RNN)



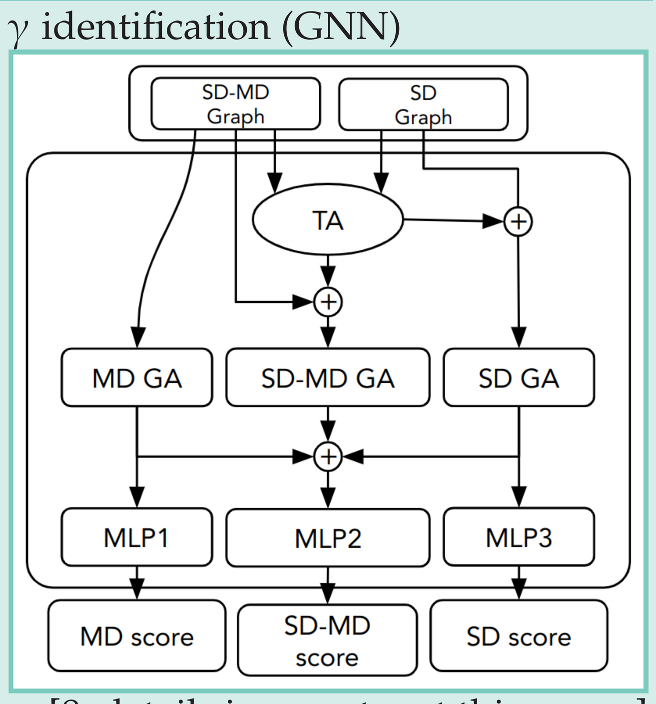
Triggers based on small and fast NNs



energy from γ-induced shower (Transformer)



γ identification (GNN)



[8, details in a poster at this venue]

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[1] F. Ellwanger, PoS ICRC2023, 275 (2023)
[2] Auger Collab., ArXiv, 2406.06315 (2024)
Auger Collab., ArXiv, 2406.06319 (2024)
[3] N. Langner, PoS ICRC2023, 371 (2023)
[4] S. T. Hahn. PoS ICRC2023, 318 (2023)
[5] Auger Collab., JINST 16, P07016 (2021)
M. Majerčáková, master's thesis (2022)
[6] D. Rech, master's thesis (2024)
[7] P. Filip, master's thesis (2023)
[8] E.E. Rodriguez, priv. com. (2024)

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