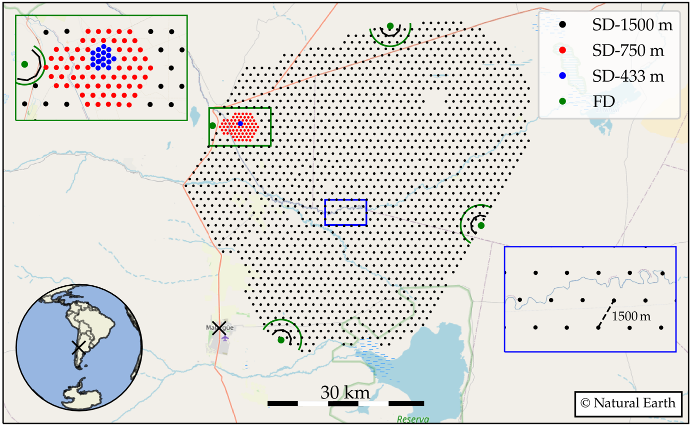
Estimation of cosmic ray mass by correlating muon signals extracted from surface detector stations of the Pierre Auger Observatory using neural networks

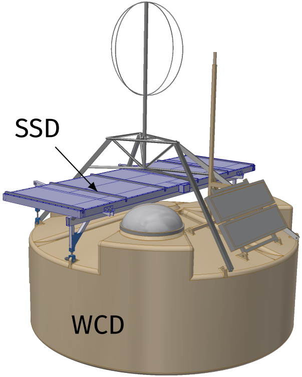
S. Hahn, F. Heizmann, M. Roth, D. Schmidt, D. Veberič for the Pierre Auger Collaboration | 04.03.2024

KIT - IAP/ETP

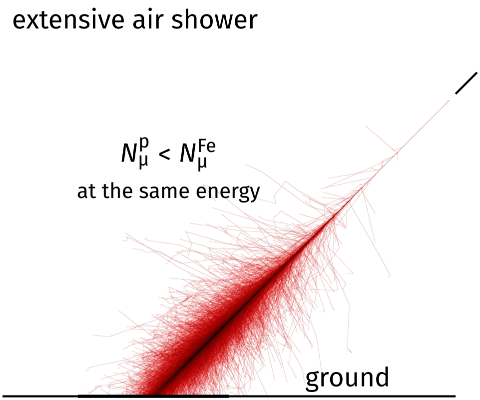
Pierre Auger Observatory

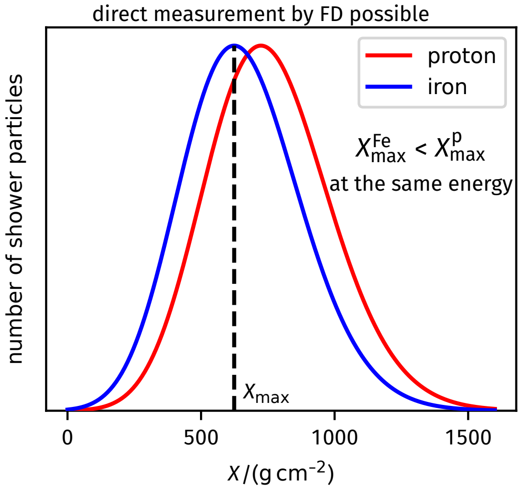


Upgraded SD station



Mass sensitive observables



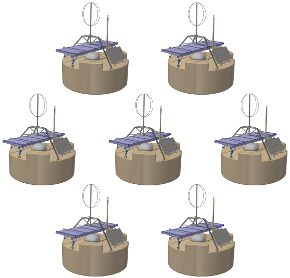


Approach

Artificial Neural Networks

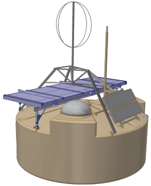
event level: "top-down"

e.g., $X_{\max}$, N_{μ}, $\ln A$



station level: "bottom-up"

e.g., S_{μ}, f_{μ}, $\ln A$



Approach

Artificial Neural Networks

!

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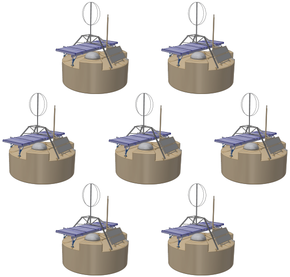
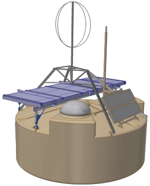


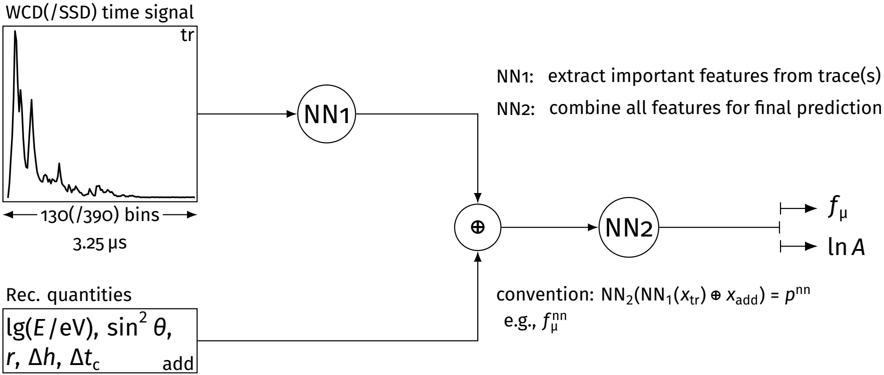
station level: “bottom-up”

e.g., S_{μ}, f_{μ}, $\ln A$

...  ...

many predictions
for one event

Sketch of architecture (station-level approach)



input quality selection removes (~ 80 %) of station-level data

$\lg(E/\mathrm{eV})$	log. energy	Δh	up/downstream parameter
θ	shower inclination	Δt_c	trigger time vs. core time
r	distance to shower axis		

How to go from muon fraction to mass? / station level to event level?

Ansatz

$$f_\mu^{\mathrm{g}}(\sec\theta, r, \Delta h, \lg\hat{S}, \ln A) = \beta_1\sec\theta + \beta_2 r + \beta_3\ln A + \beta_4\Delta h\sec\theta + \beta_5 + \beta_6\lg\hat{S} + \beta_7\Delta h + \beta_8 r^2$$

Idea

1. fit f_μ^{g} to MC (using rec. obs.)
2. compute $\hat{f}_\mu^{\mathrm{g}} = f_\mu^{\mathrm{g}}(\ldots, \lg\hat{S}, 0)$
3. use $f_\mu^{\mathrm{p}} - \hat{f}_\mu^{\mathrm{g}} = \beta_3 \ln A$

Strong assumption

$$\ln A \simeq \langle \ln A[p^{\mathrm{nn}}]\rangle_{\mathrm{ev}},$$

where

$$\langle\cdot\rangle_{\mathrm{ev}} \equiv \frac{1}{N_{\mathrm{tr}}}\sum\cdot$$

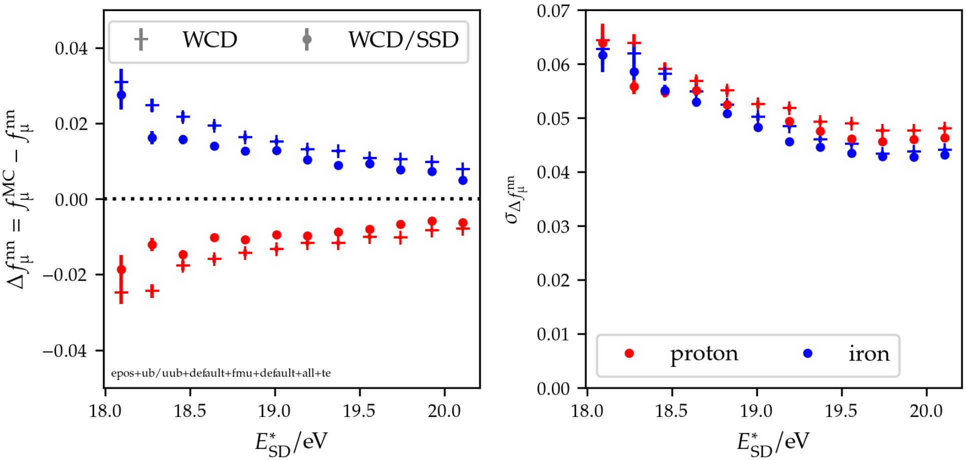
and N_{tr} num. of trig. SD stations.

Test for “separation” of primaries

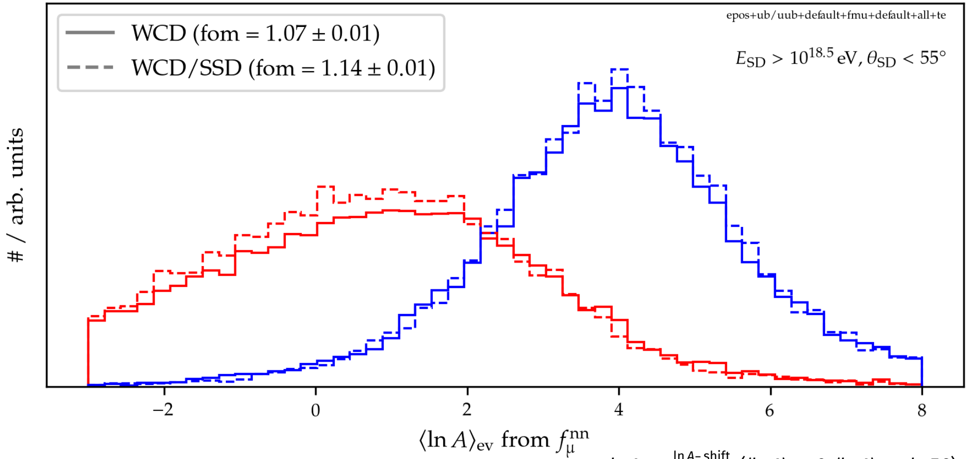
$$\mathrm{fom}(x) = \frac{\left|\langle x\rangle_{\mathrm{p}} - \langle x\rangle_{\mathrm{Fe}}\right|}{\sqrt{\sigma_{\mathrm{p}}^2 + \sigma_{\mathrm{Fe}}^2}}$$

p - proton, Fe - iron

Station level – WCD vs. WCD/SSD

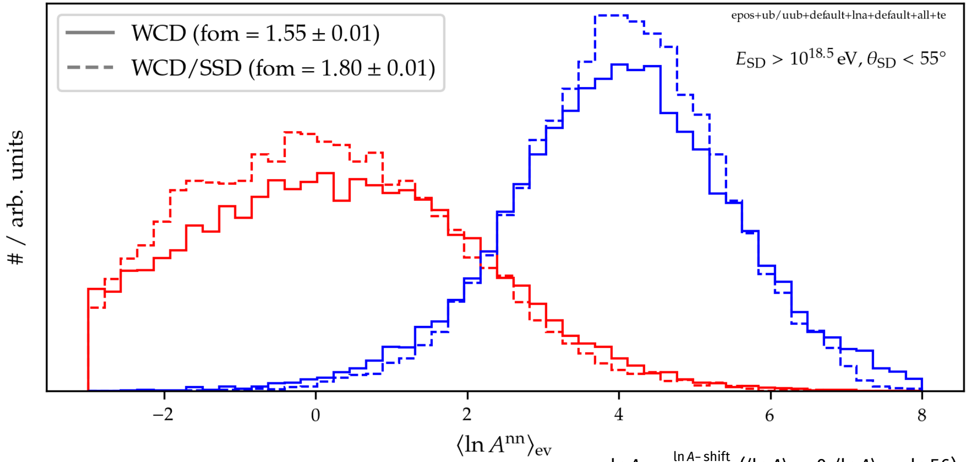


Event level - WCD vs. WCD/SSD (from muon fraction)



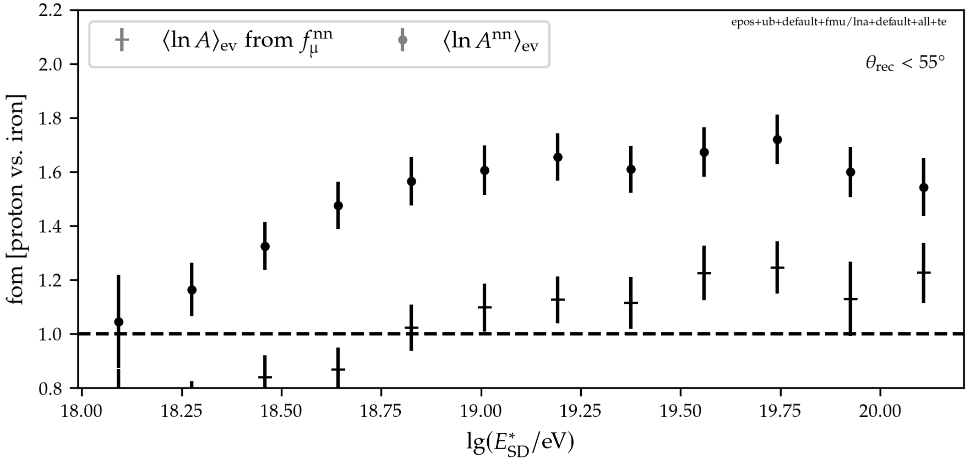
$\ln A \rightarrow \frac{\ln A - \text{shift}}{\text{scale}}$ $(\langle \ln A \rangle_p = 0, \langle \ln A \rangle_{Fe} = \ln 56)$

Event level - WCD vs. WCD/SSD (from direct prediction)

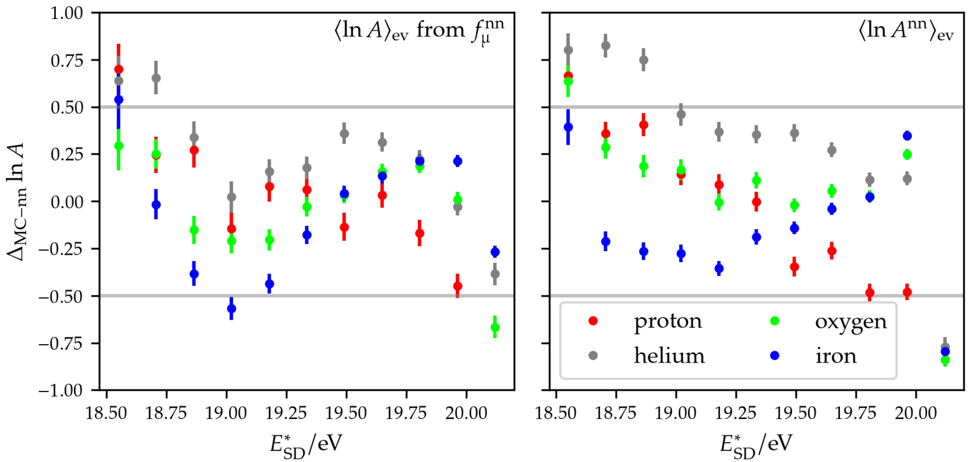


$\ln A \rightarrow \frac{\ln A - \text{shift}}{\text{scale}}$ $(\langle \ln A \rangle_p = 0, \langle \ln A \rangle_{Fe} = \ln 56)$

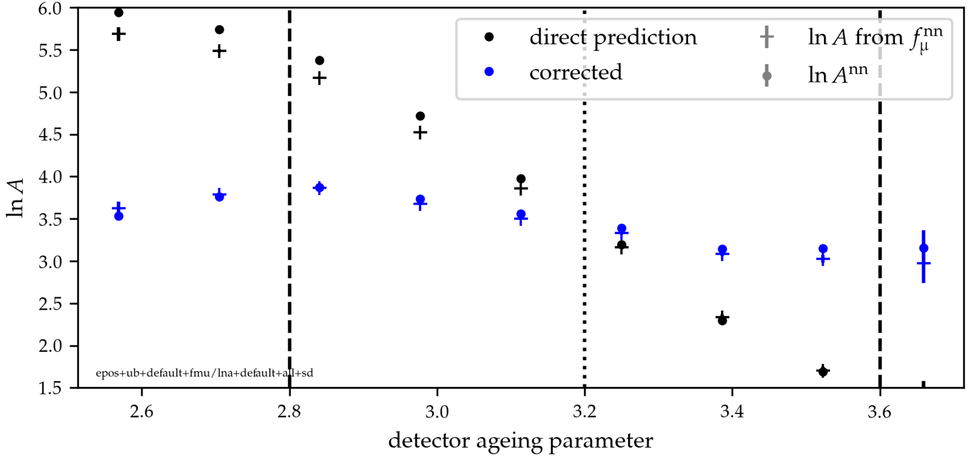
Event level – MC separation for predictors



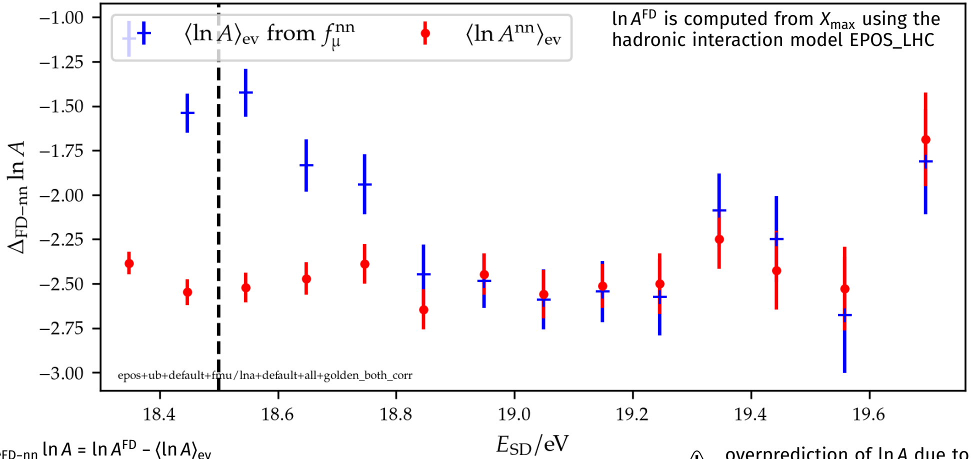
Event level – MC bias



Station level – removing non-physical biases



Event level - constant value calibration

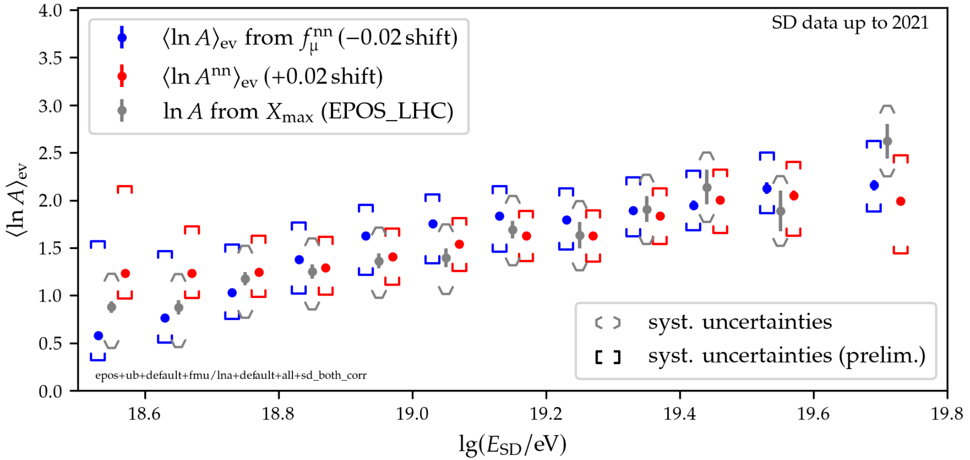


$\ln A^{FD}$ is computed from X_{max} using the hadronic interaction model EPOS_LHC

$\Delta_{\text{FD-nn}} \ln A = \ln A^{FD} - \langle \ln A \rangle_{ev}$

⚠ overprediction of $\ln A$ due to lack of muons in MC

Event level - SD data until 2021

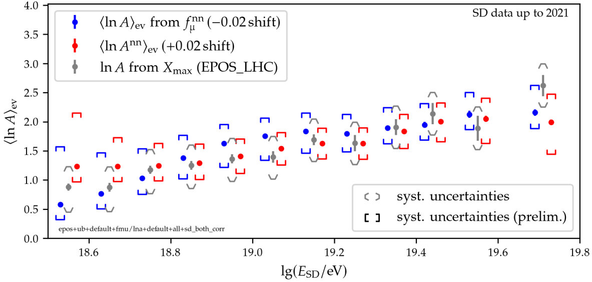


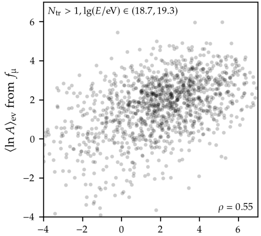
Conclusion

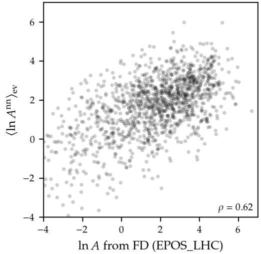
Karlsruhe Institute of Technology

Takeaway

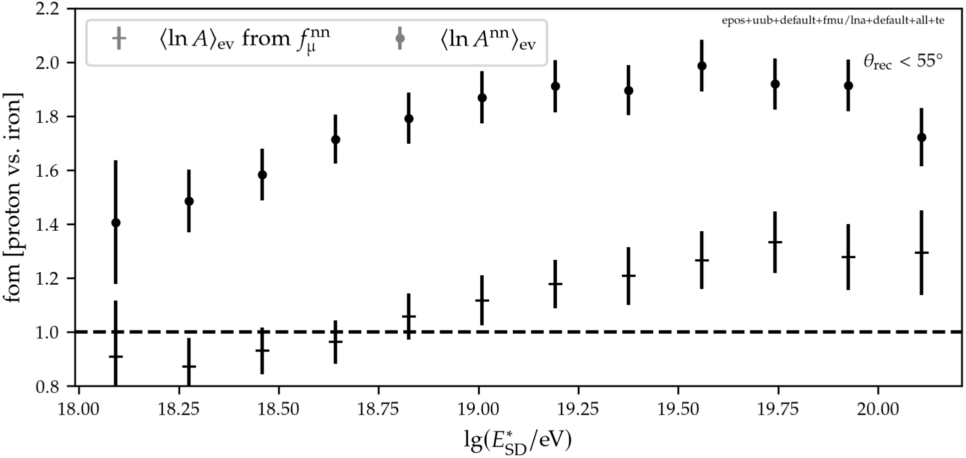
- prediction of mass-sensitive observables using station-level predictors is feasible
- using signals from SSD improves predictors significantly







Ev.lvl. – separation (WCD/SSD)



Qualtiy selection (QS)

Pre-selection (fraction of MC data removed)

- $\theta_{SD} < 60°$ (11.1 %)
- not low-gain saturated (2.5 %)
- $S_{ldf}(r_{rec}) > 30$ VEM (76.5 %)

$S_{ldf}(r_{rec})$ is the expected signal (using the LDF) at r_{rec} (distance to the shower axis).

Dataset(s) - MC

Interaction models

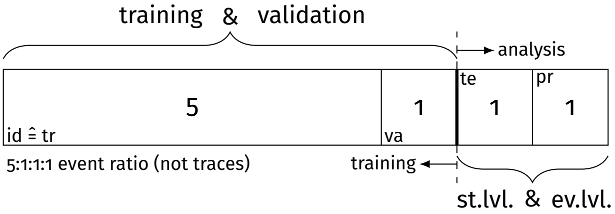
- QGSJet-II.04 (qgsj)
- EPOS_LHC (epos)

Electronics

- UB (ub)
- UUB (uub)

# events	ub	uub
qgsj	688934	721450
epos	686276	691140

Splitting procedure (after basic QS)



E.g., events (traces)

- epos-ub-te: 85784 (291992)
- qgsj-uub-va: 90181 (300937)

} No events are split!