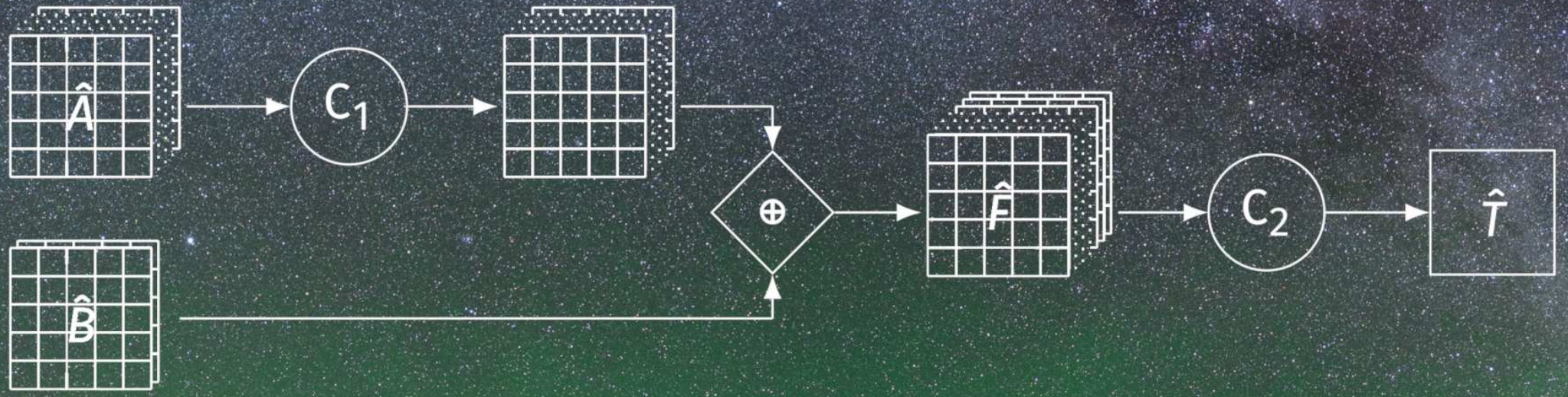


Applications of Machine Learning at the Pierre Auger Observatory

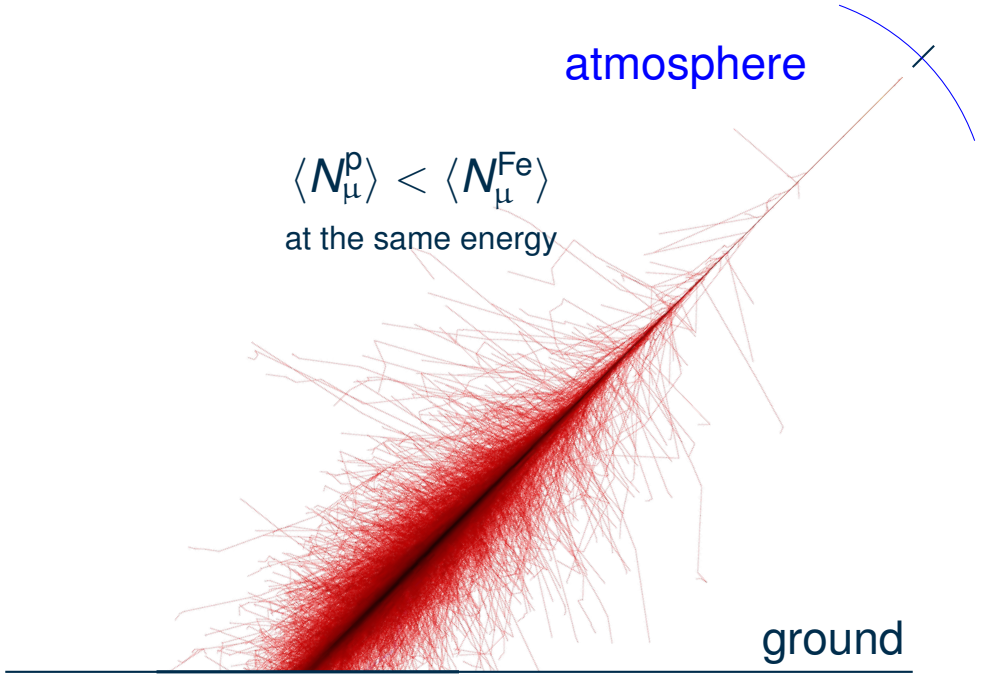
Past, present, and future

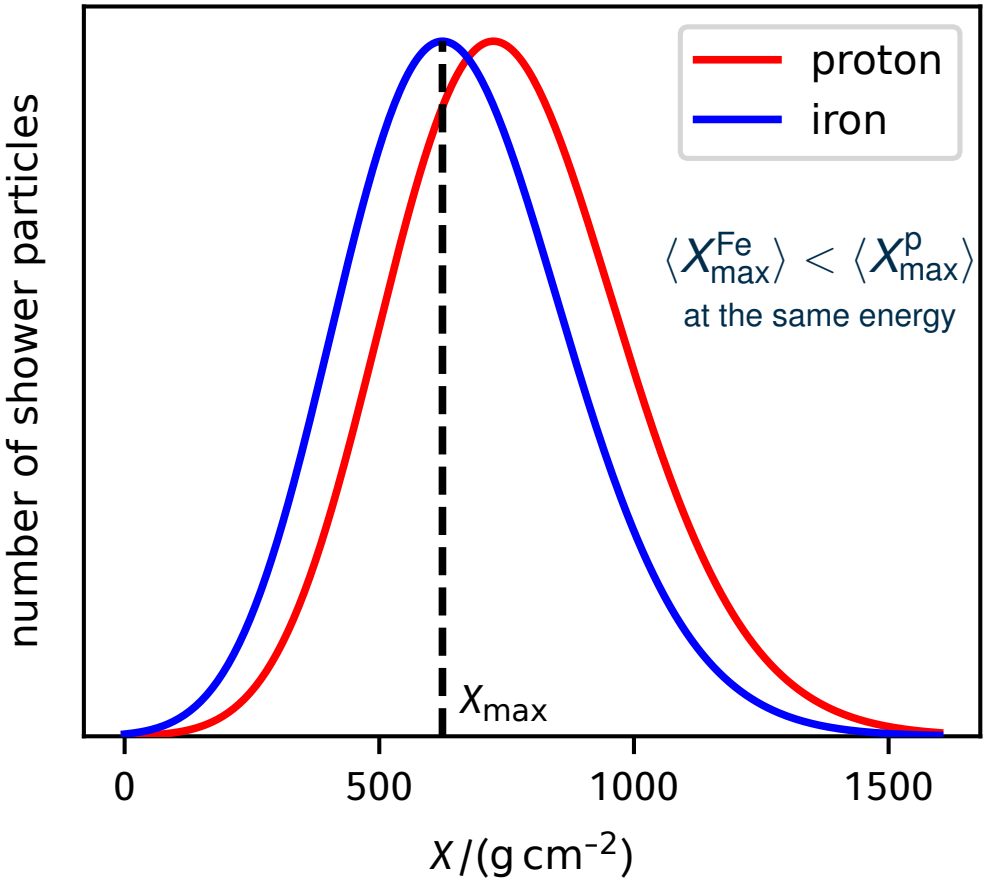
S. Hahn | November 13, 2025 | Campus Miguelete, Buenos Aires

Institute for Astroparticlephysics (IAP)

Motivation

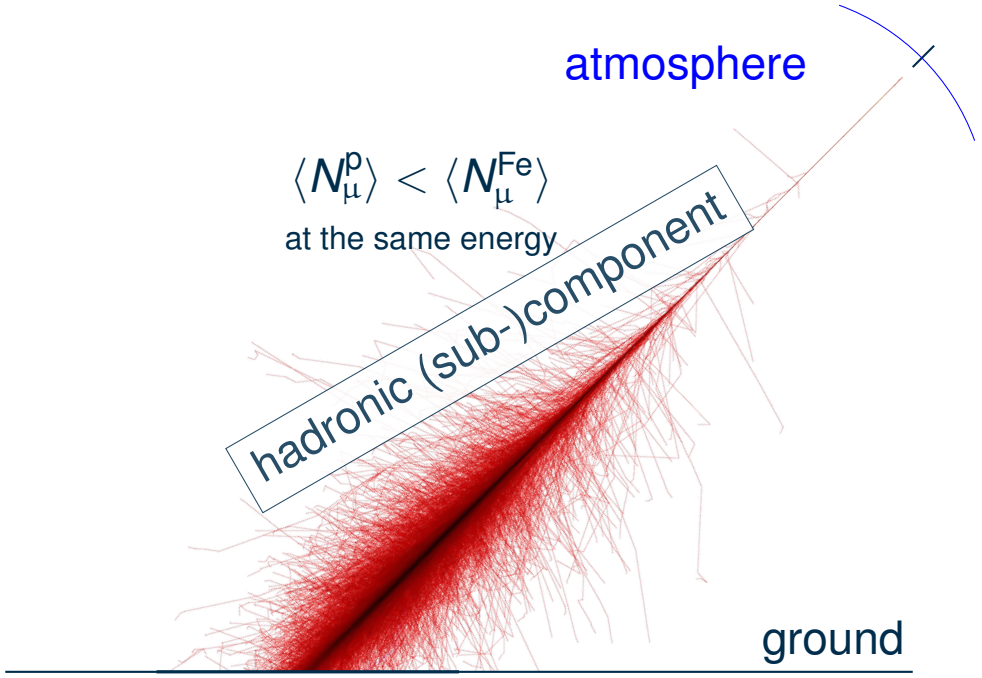
Mass-sensitive observables

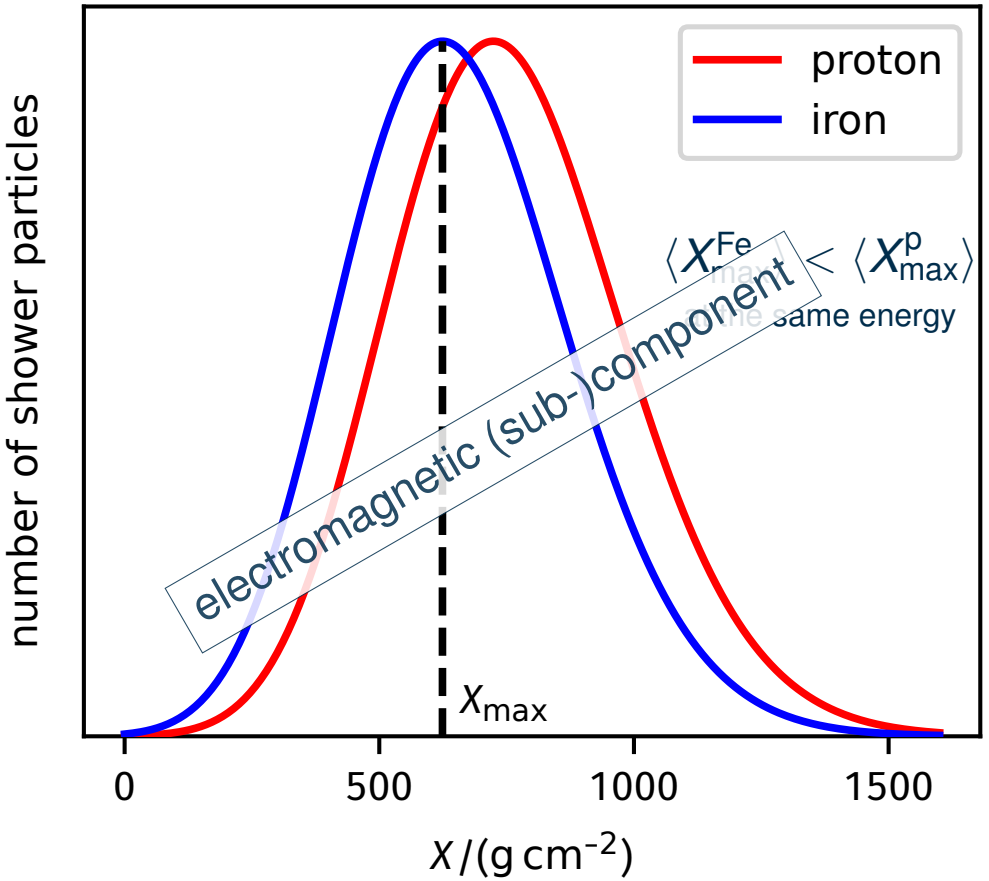




Motivation

Mass-sensitive observables





Motivation

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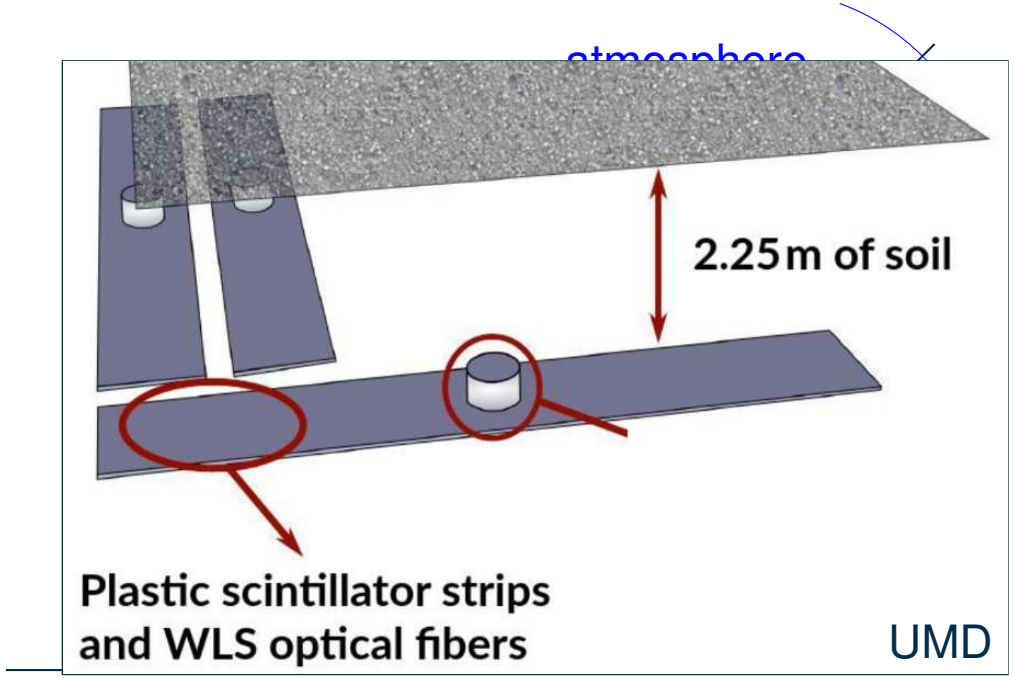
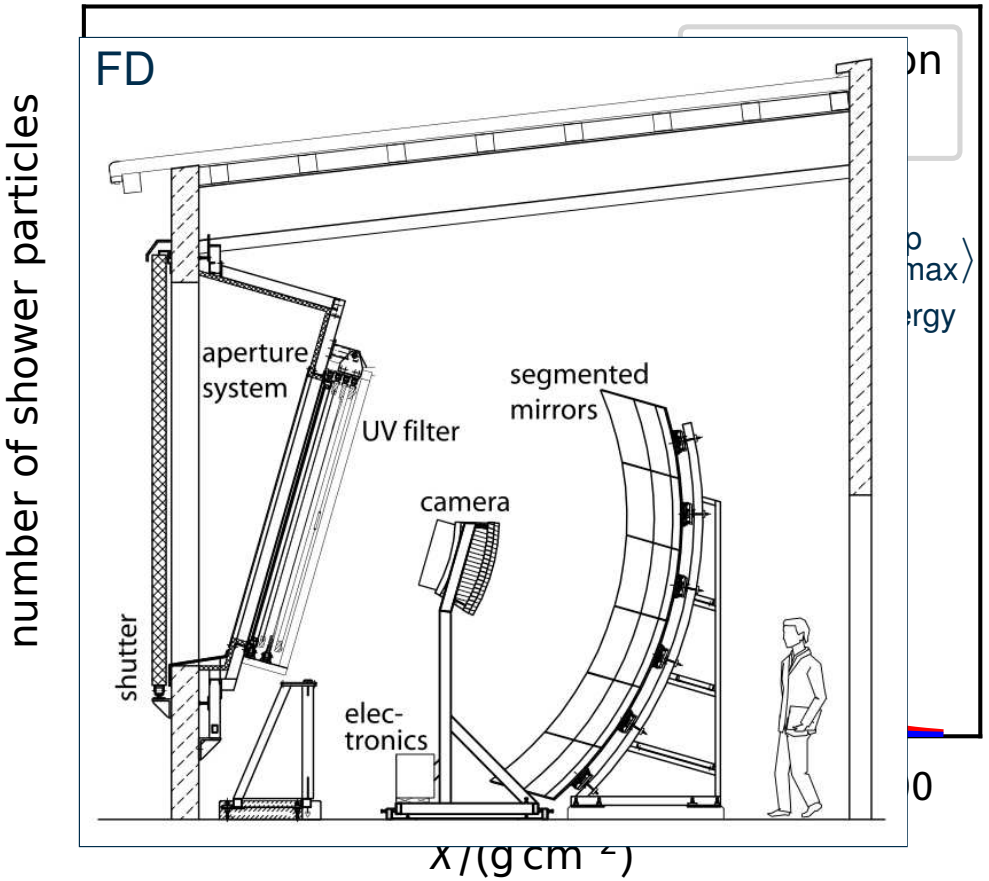
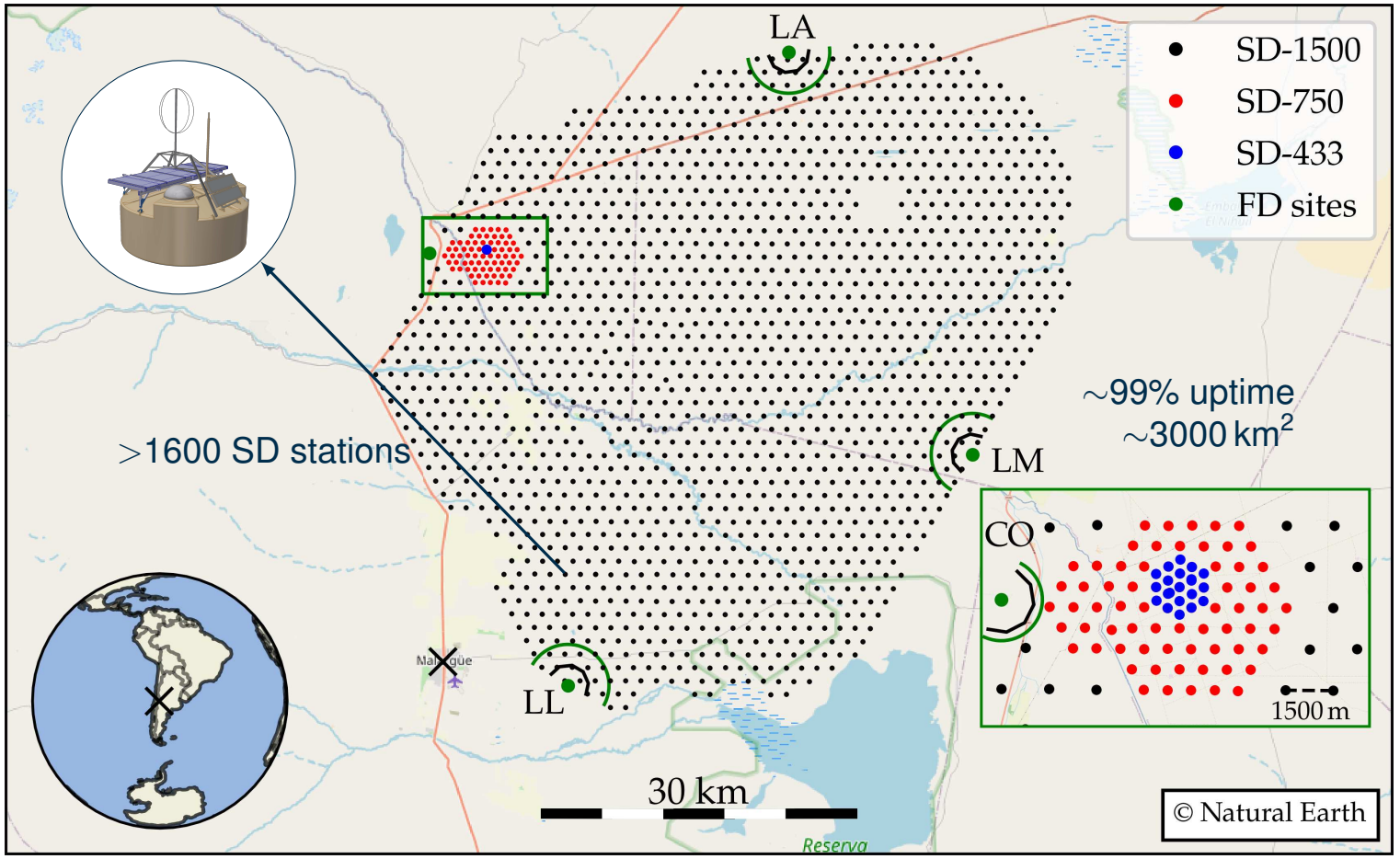
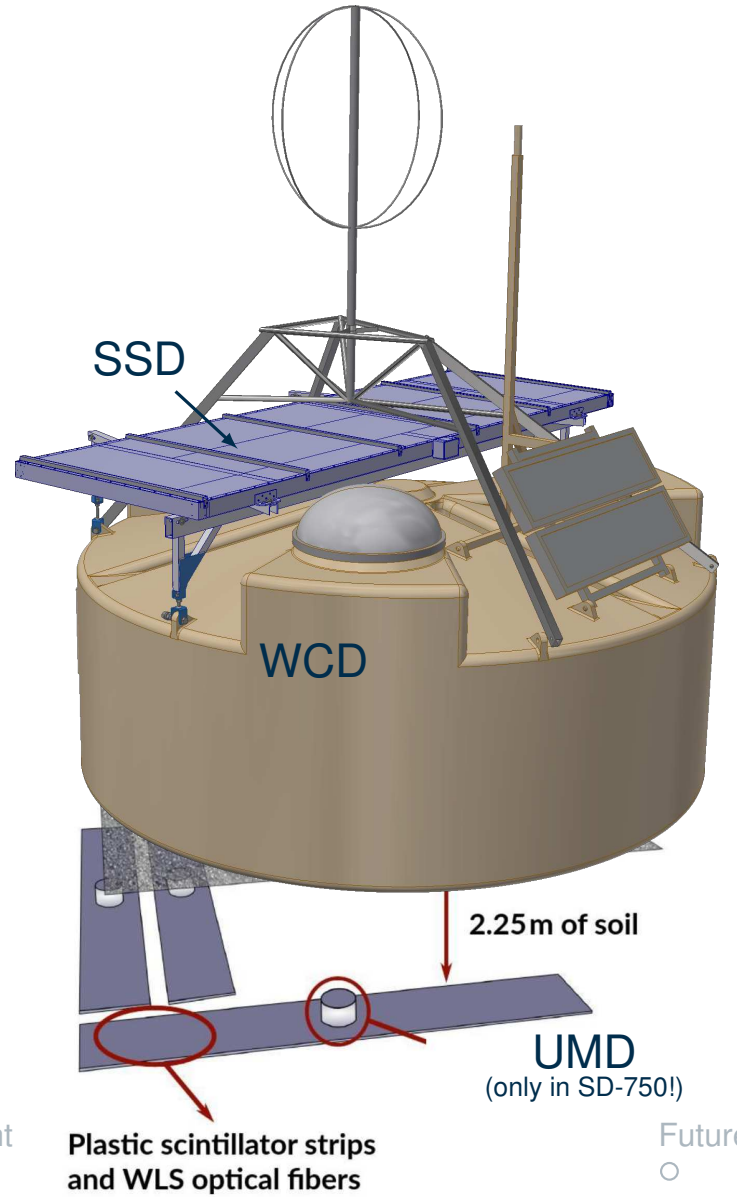




Motivation

Indirect reconstruction (?)





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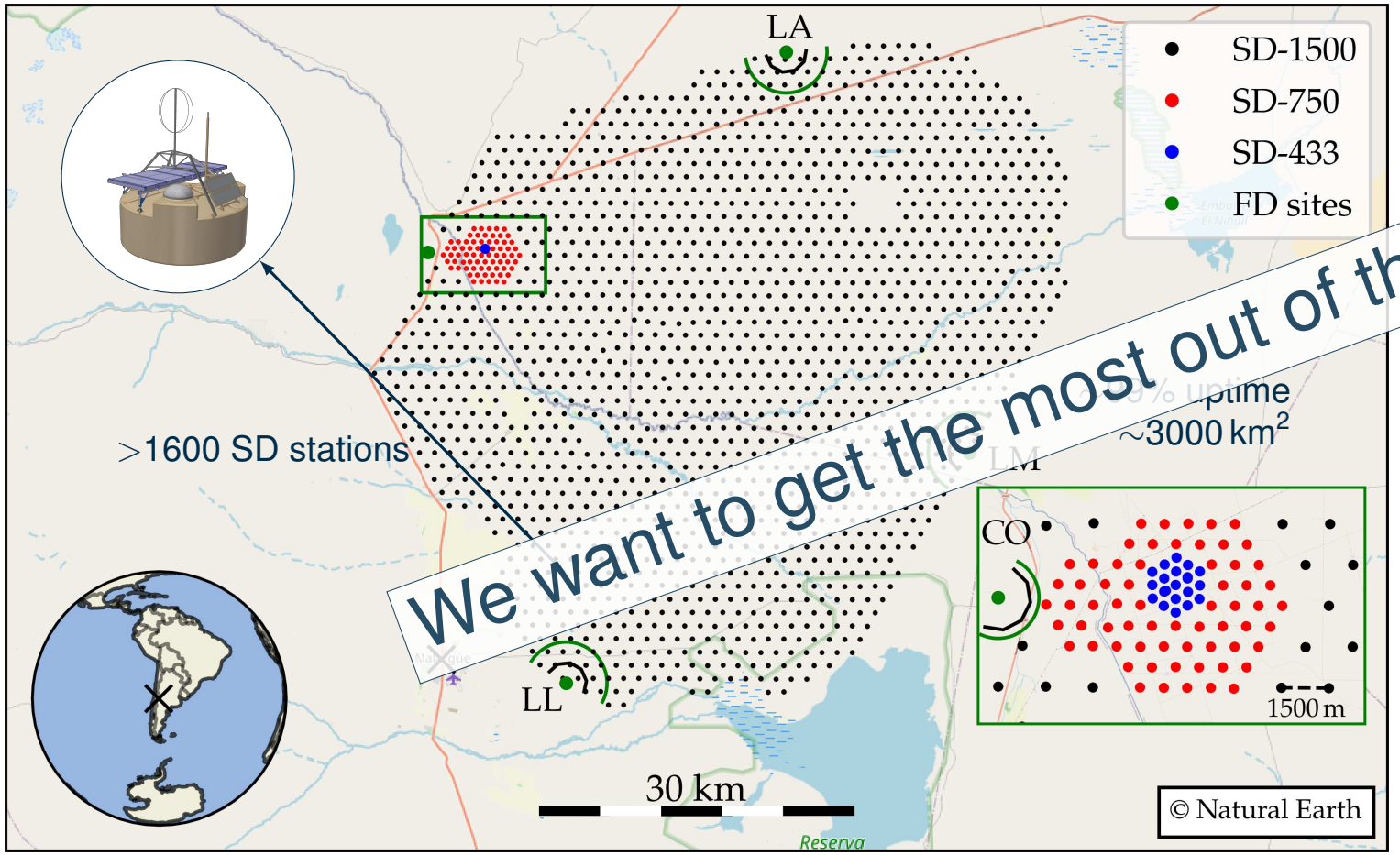
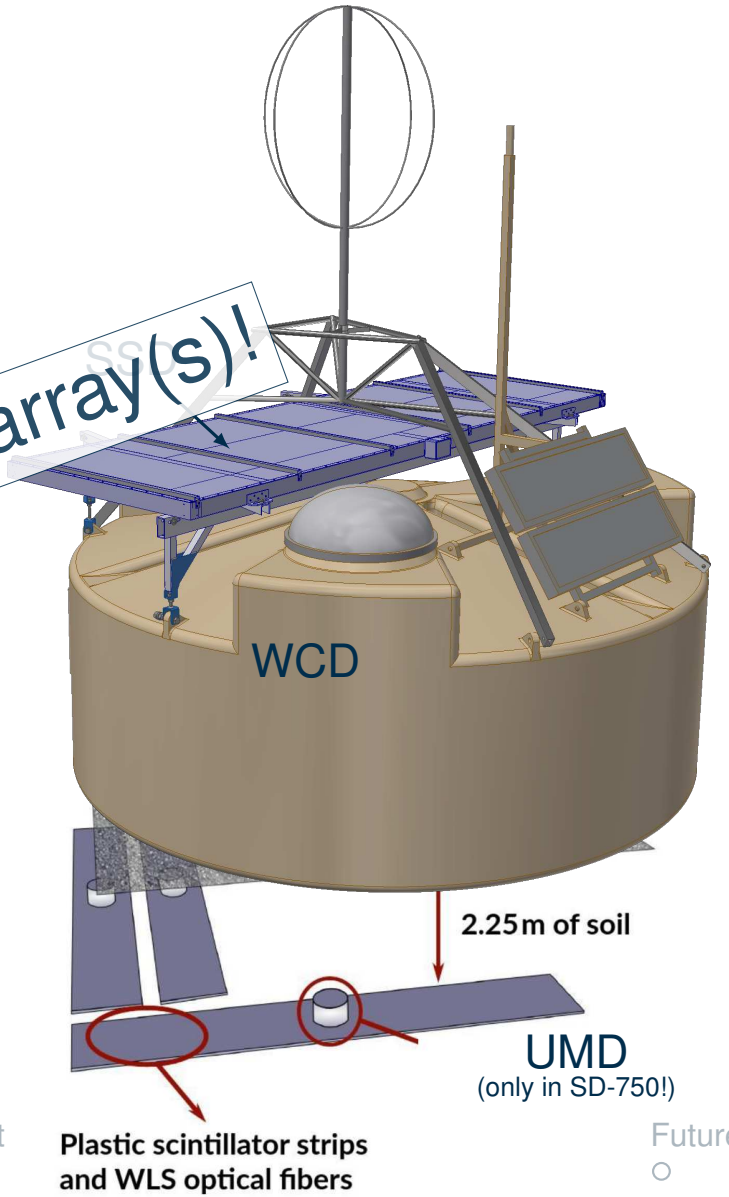
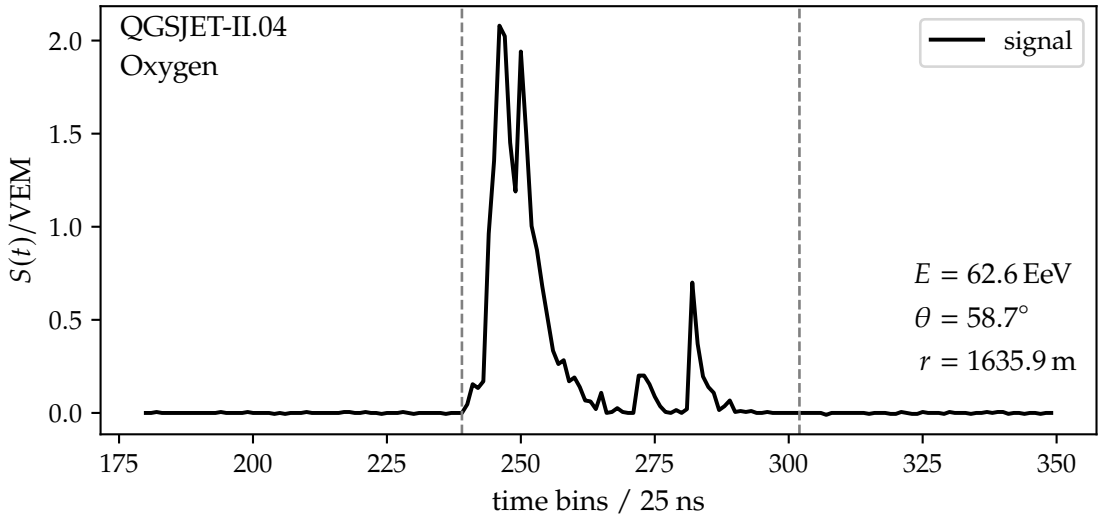
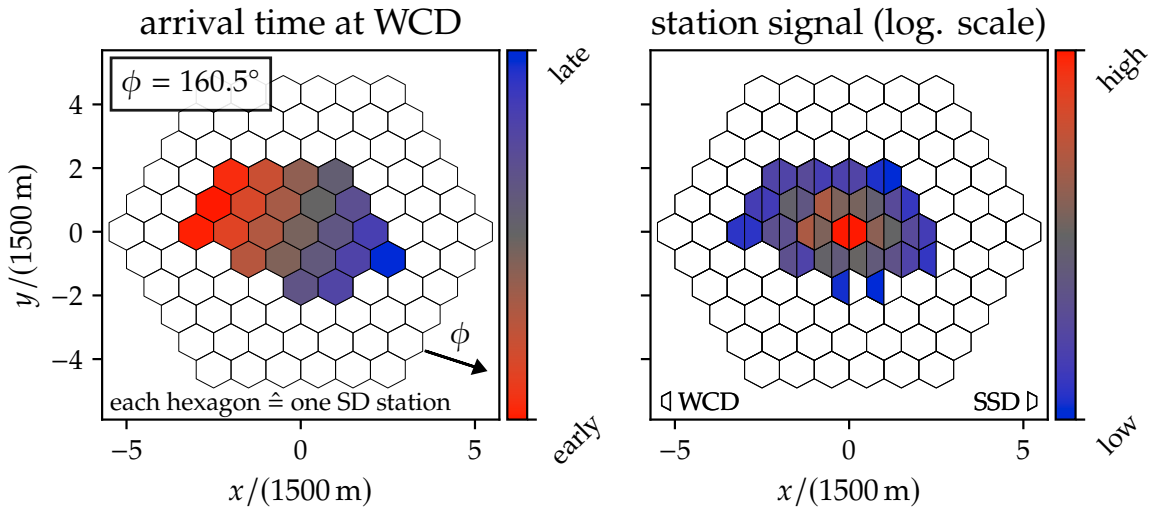




Motivation

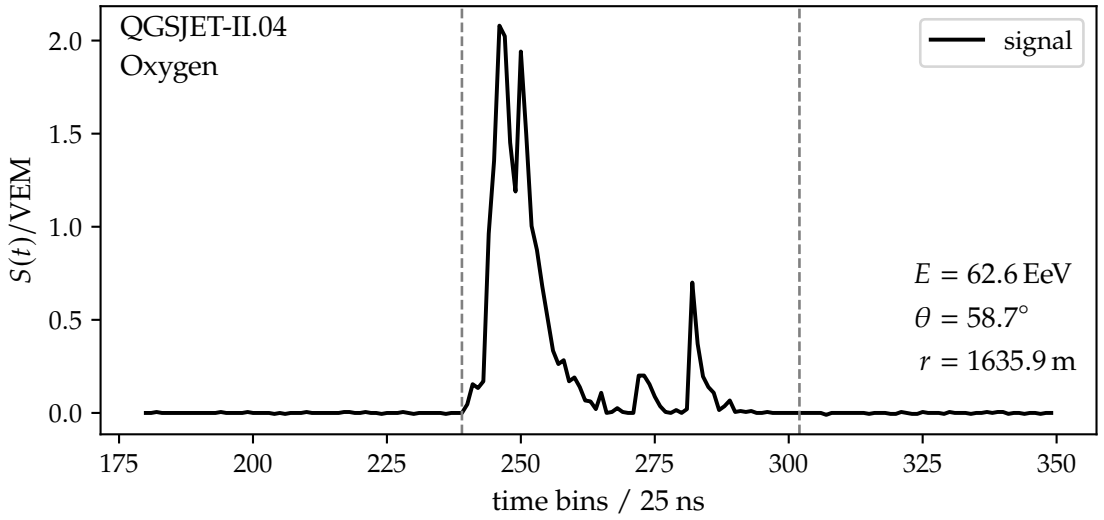
SD measurement





Motivation

SD measurement

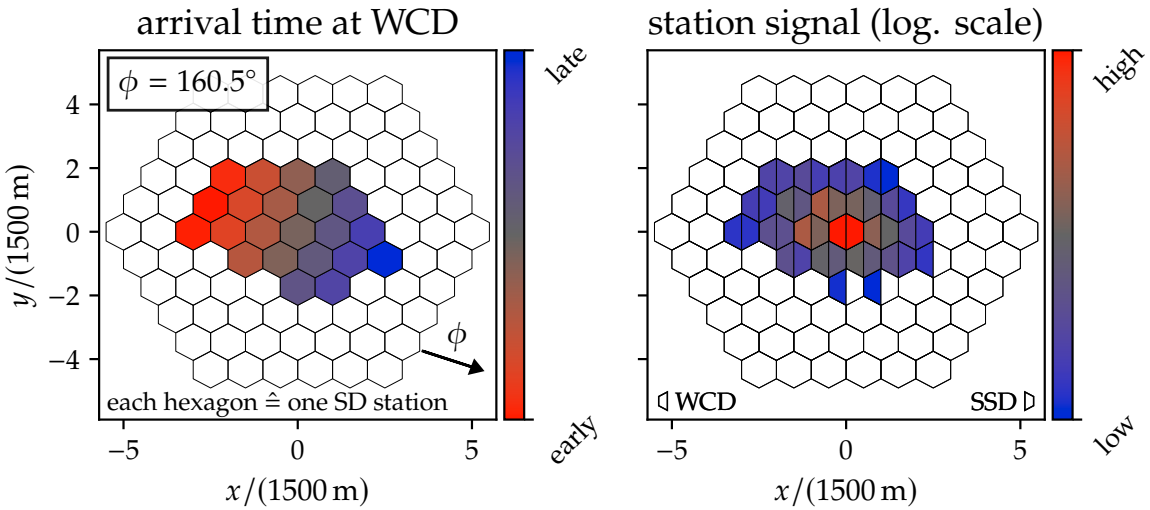


event structure $\Longleftrightarrow$ 2D information

e.g., CNN, GNN, Transformer...

time structure $\Longleftrightarrow$ 1D information

e.g., CNN, RNN, ...



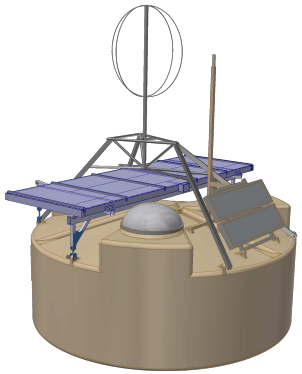
NN in Auger

Neural Networks

1.

station-level: “bottom-up”

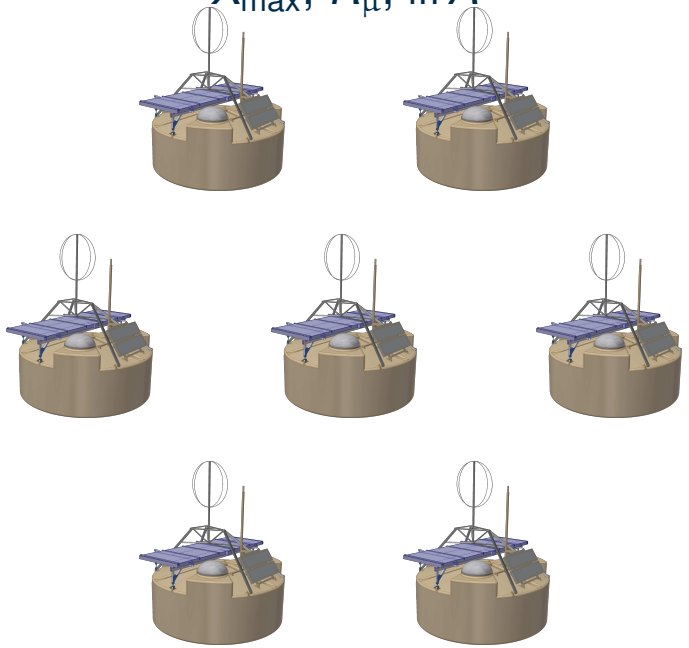
$S_\mu(t)$, $f_\mu = S_\mu / S_{\text{tot}}$



2.

event-level: “top-down”

X_{max}, R_μ, $\ln A$

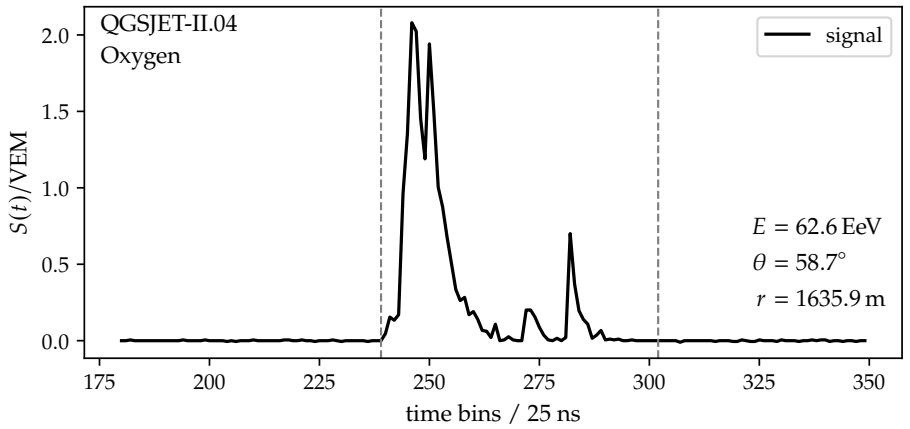


NN in Auger

Neural Networks

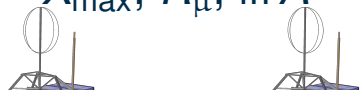
1. station-level: “bottom-up”

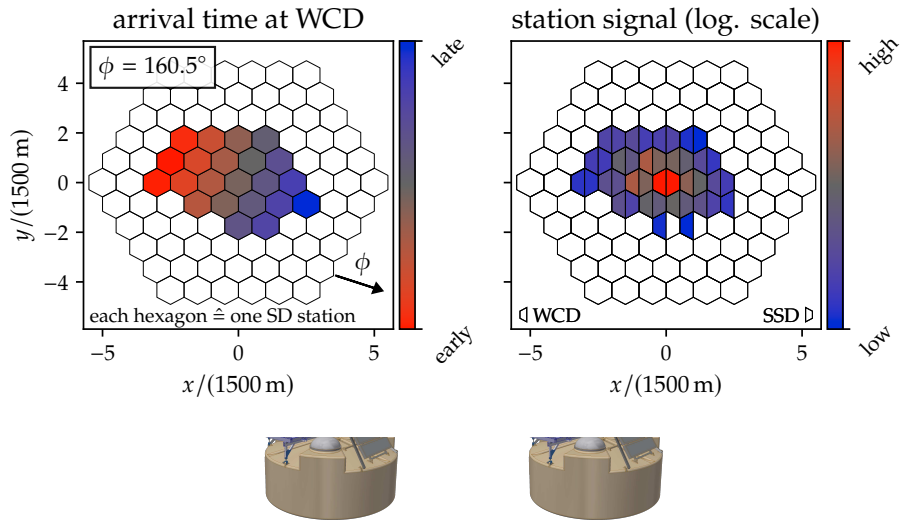
$S_\mu(t)$, $f_\mu = S_\mu / S_{\text{tot}}$



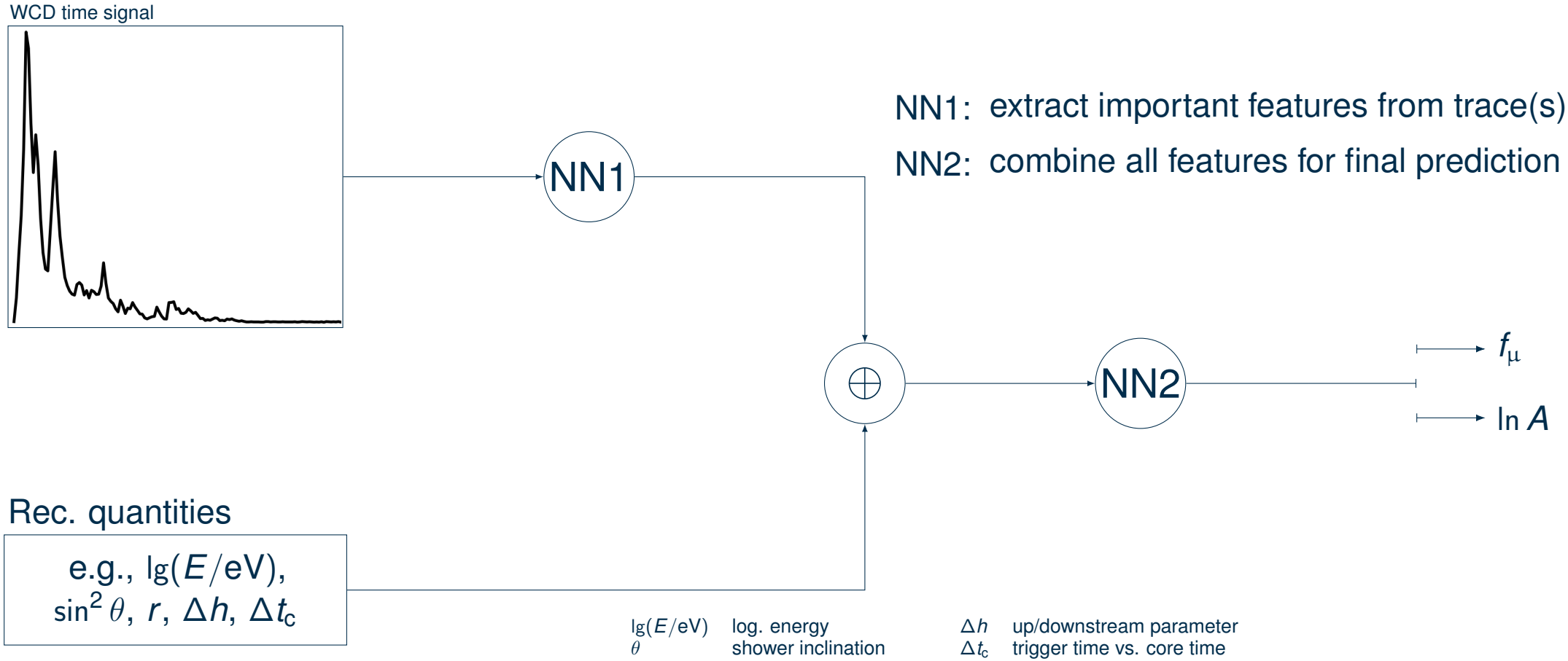
2. event-level: “top-down”

X_{max}, R_μ, ln A

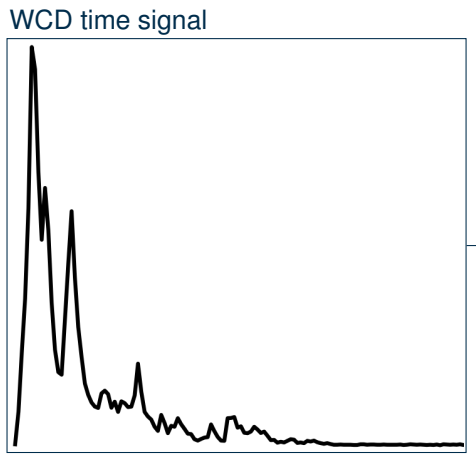




NNs for (SD) station-level



NNs for (SD) station-level



NN1

NN1: short-time correlations

NN2: ‘build up’ final trace

NN2

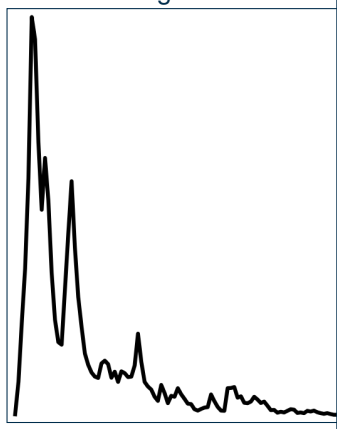
$S_\mu(t)$

Rec. quantities

$\sec\theta,\ r$

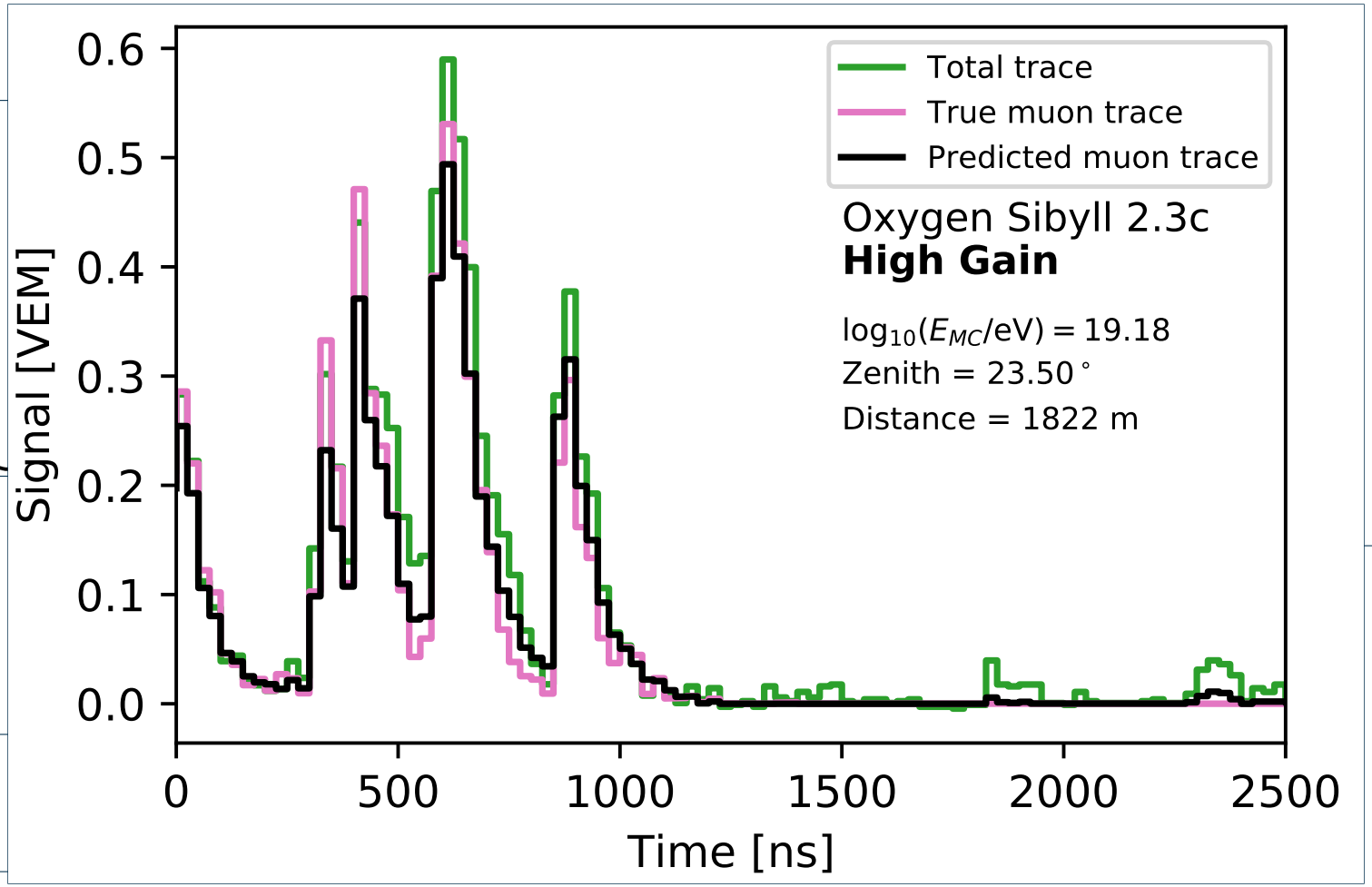
NNs for (SD) station-level

WCD time signal



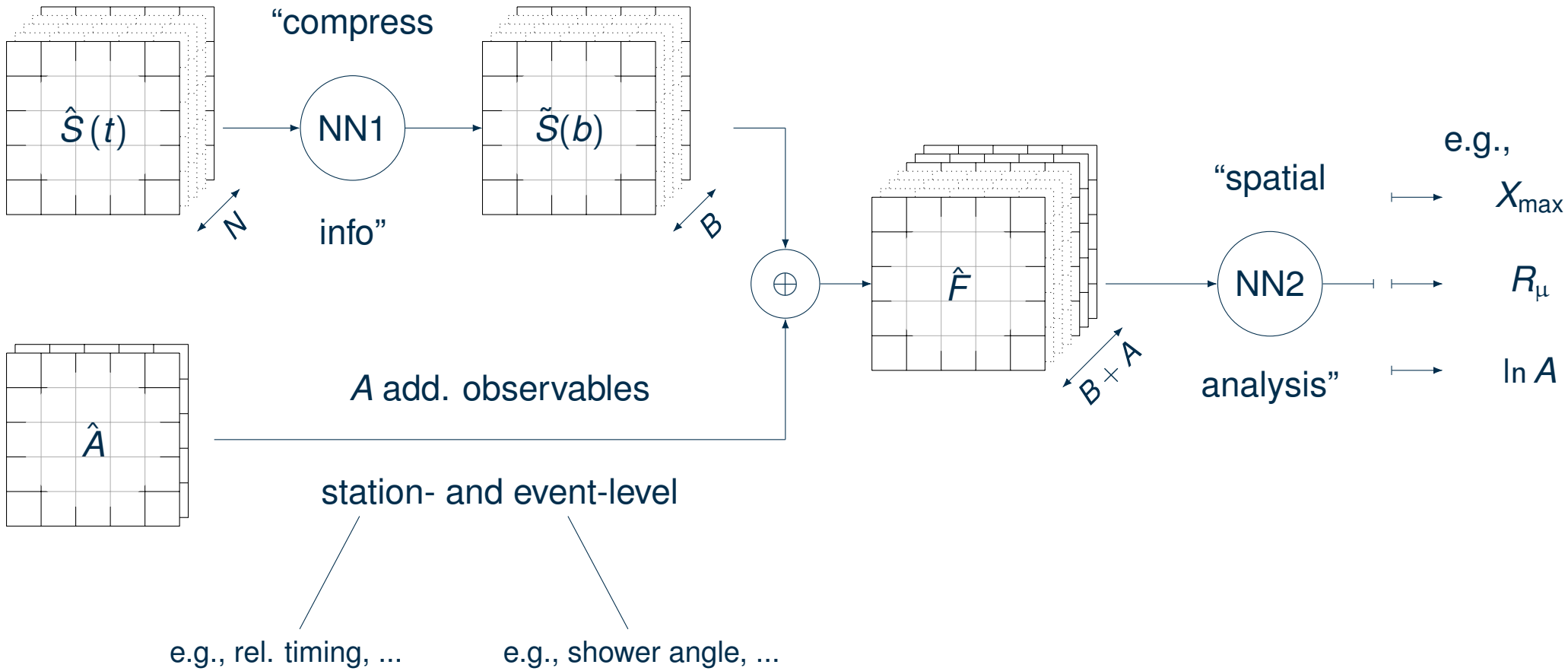
Rec. quantities

$\sec\theta,\ r$

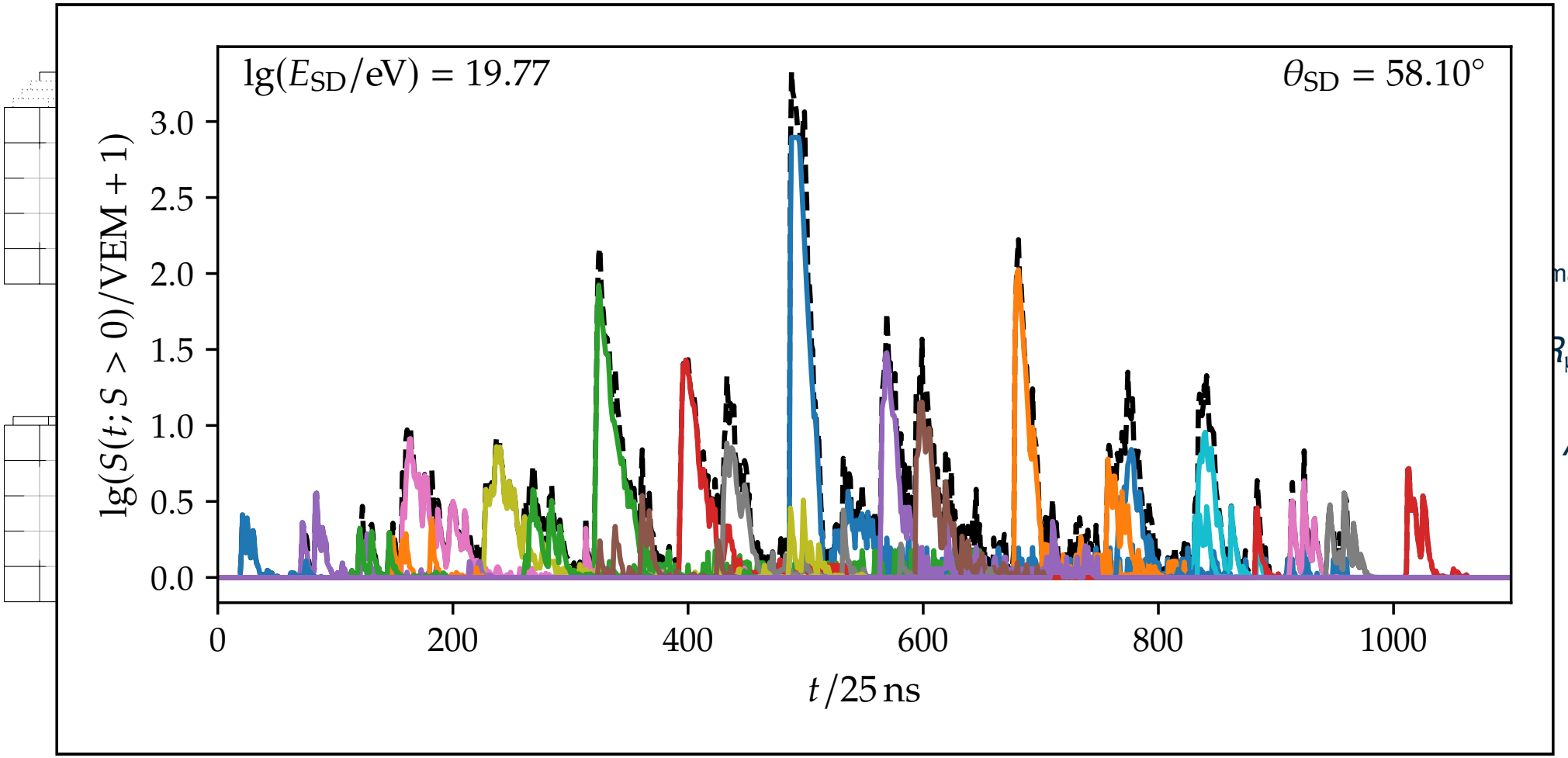


$S_\mu(t)$

NNs for (SD) event-level



NNs for (SD) event-level



max

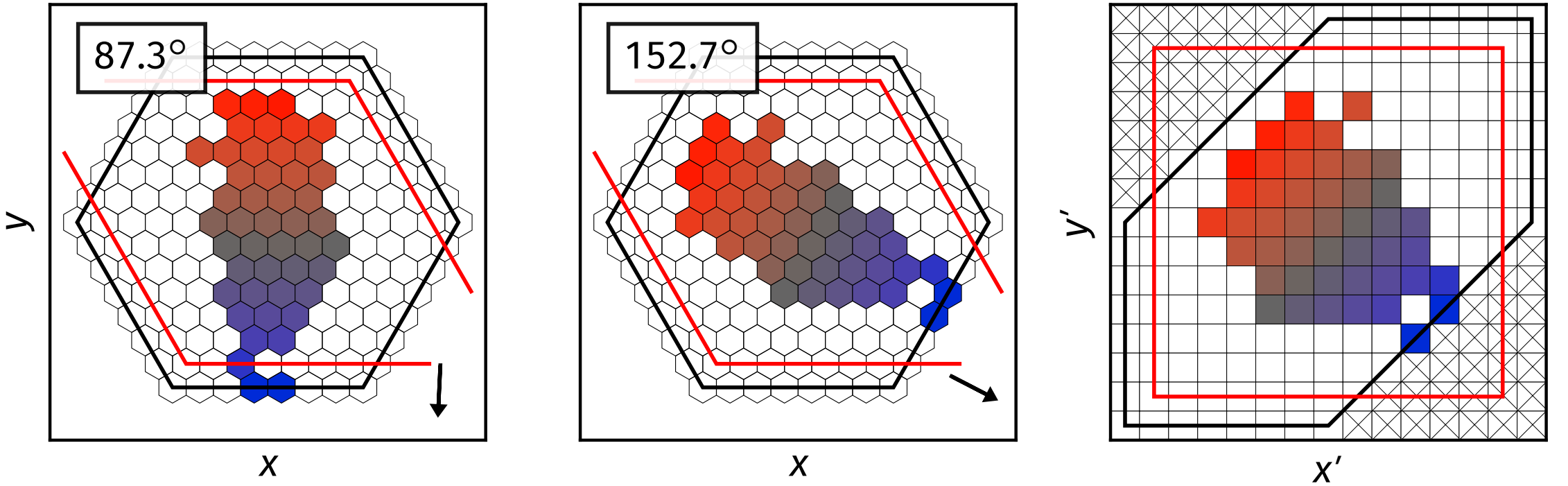
R_μ

A

Symmetries

Transform data

axial coordinates



12 unique transformations $\Rightarrow \phi_{SD} \in [0°, 360°) \rightarrow \phi'_{SD} \in [\phi_0, \phi_0 + 30°)$

Symmetries

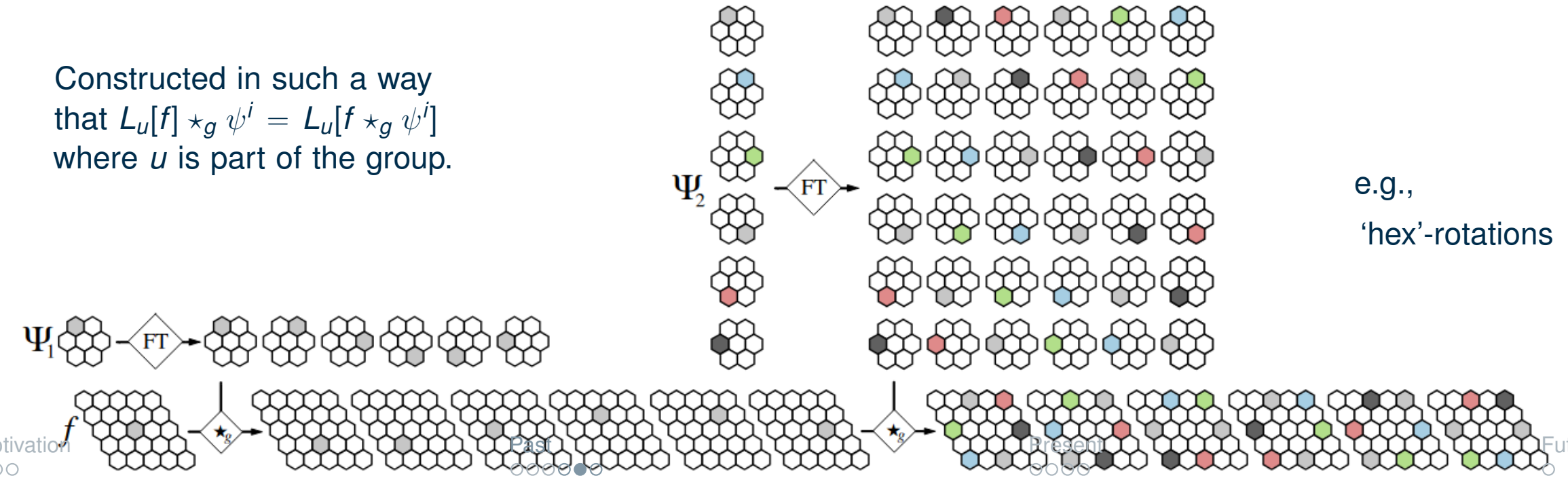
Encode in NN

Essentially, generalized convolutions:

filter i — inverse transformation

$$[f \star \psi^i](x) = \sum_y \sum_{k=1}^{K} f_k(y)\psi^i(x-y) \rightarrow [f \star_g \psi^i](x) = \sum_{h \in X} \sum_{k=1}^{K} f_k(h)\psi^i(g^{-1}h)$$

Constructed in such a way that $L_u[f] \star_g \psi^i = L_u[f \star_g \psi^i]$ where u is part of the group.

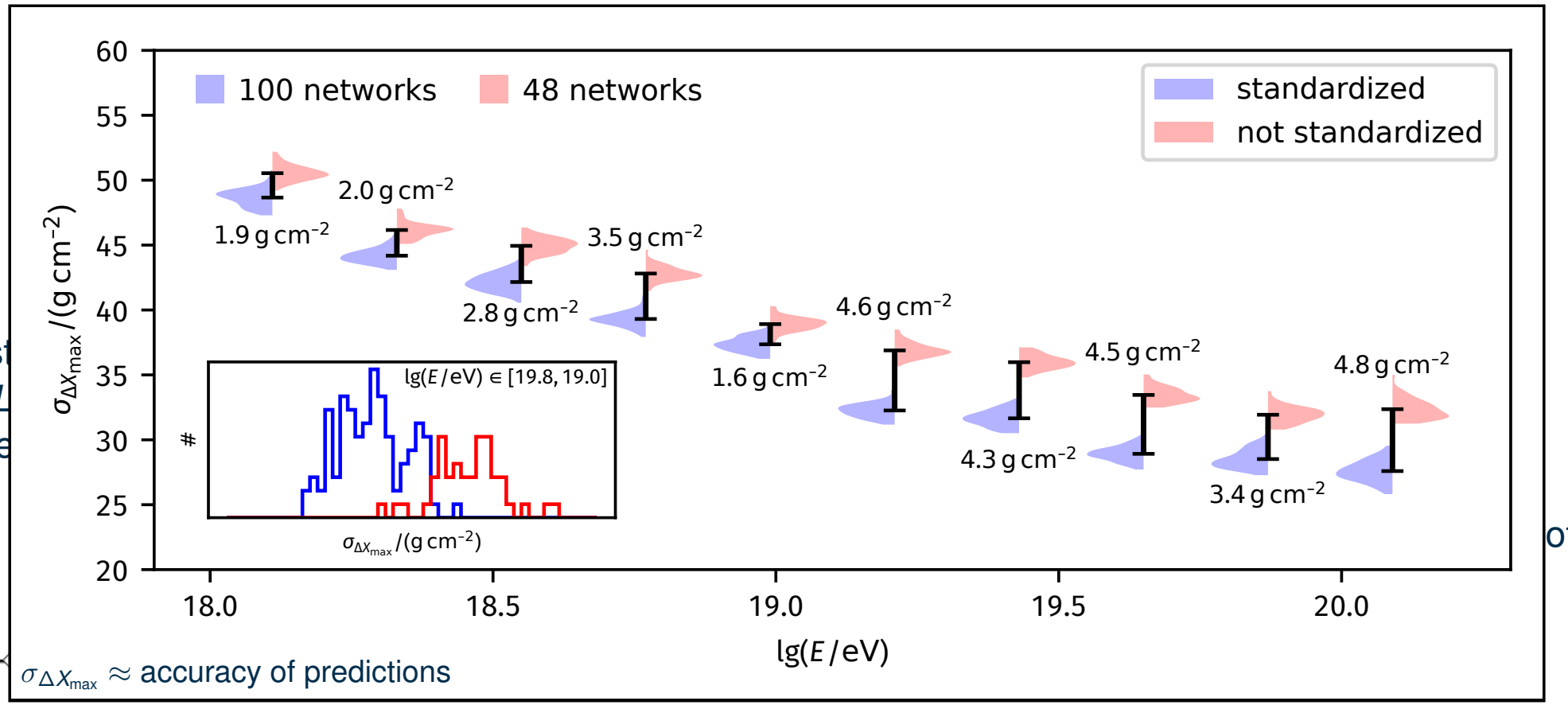


Symmetries

Encode in NN

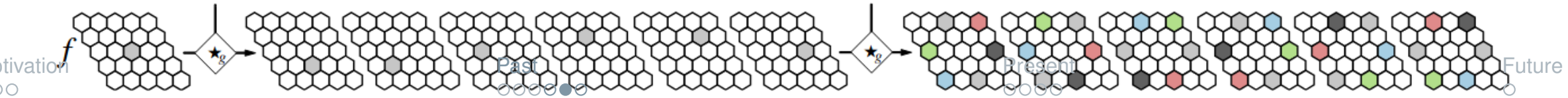
Essentially,

Const
that L
where

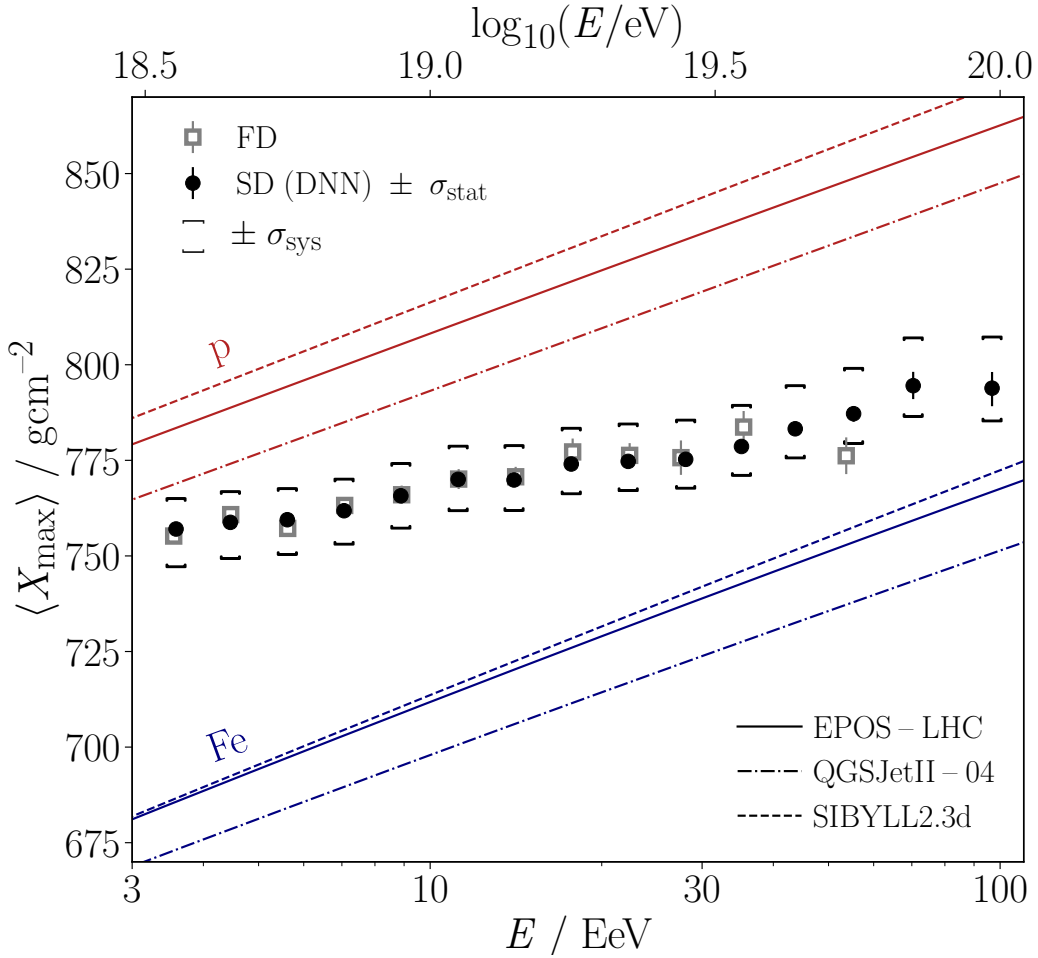


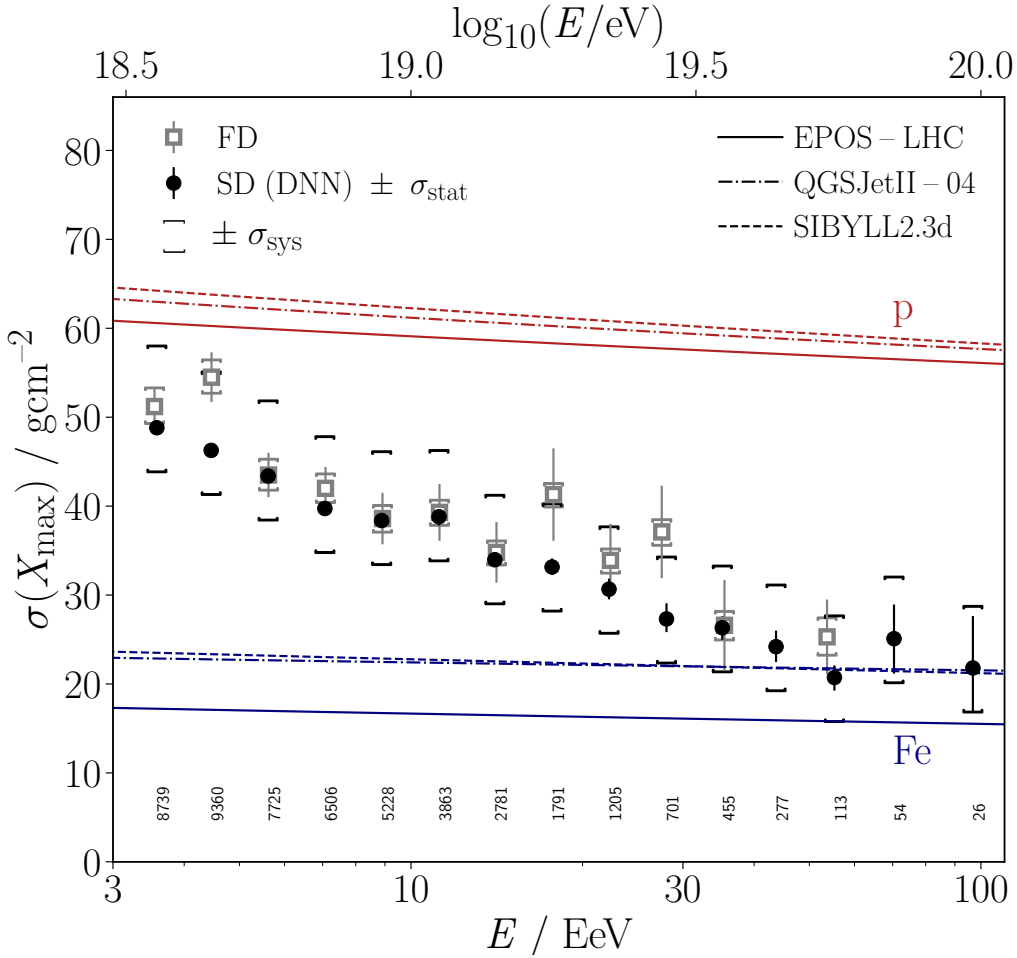
otations

$\sigma_{\Delta X_{max}} \approx$ accuracy of predictions



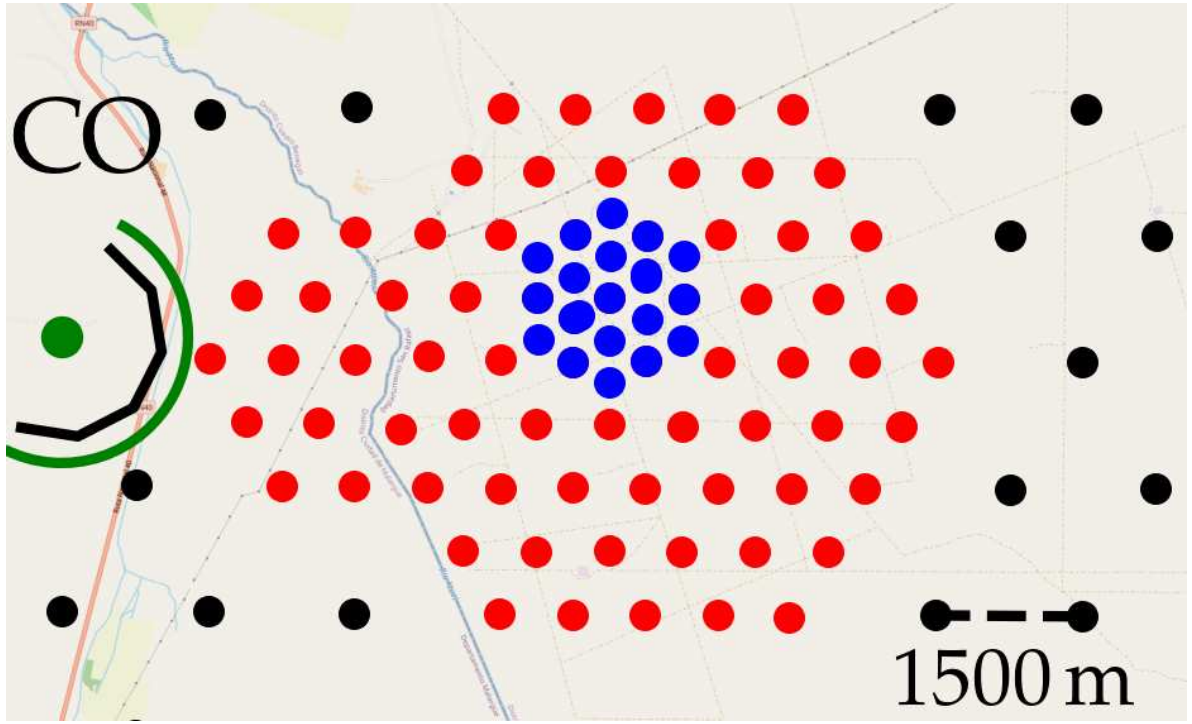
Shower depth on SD-1500

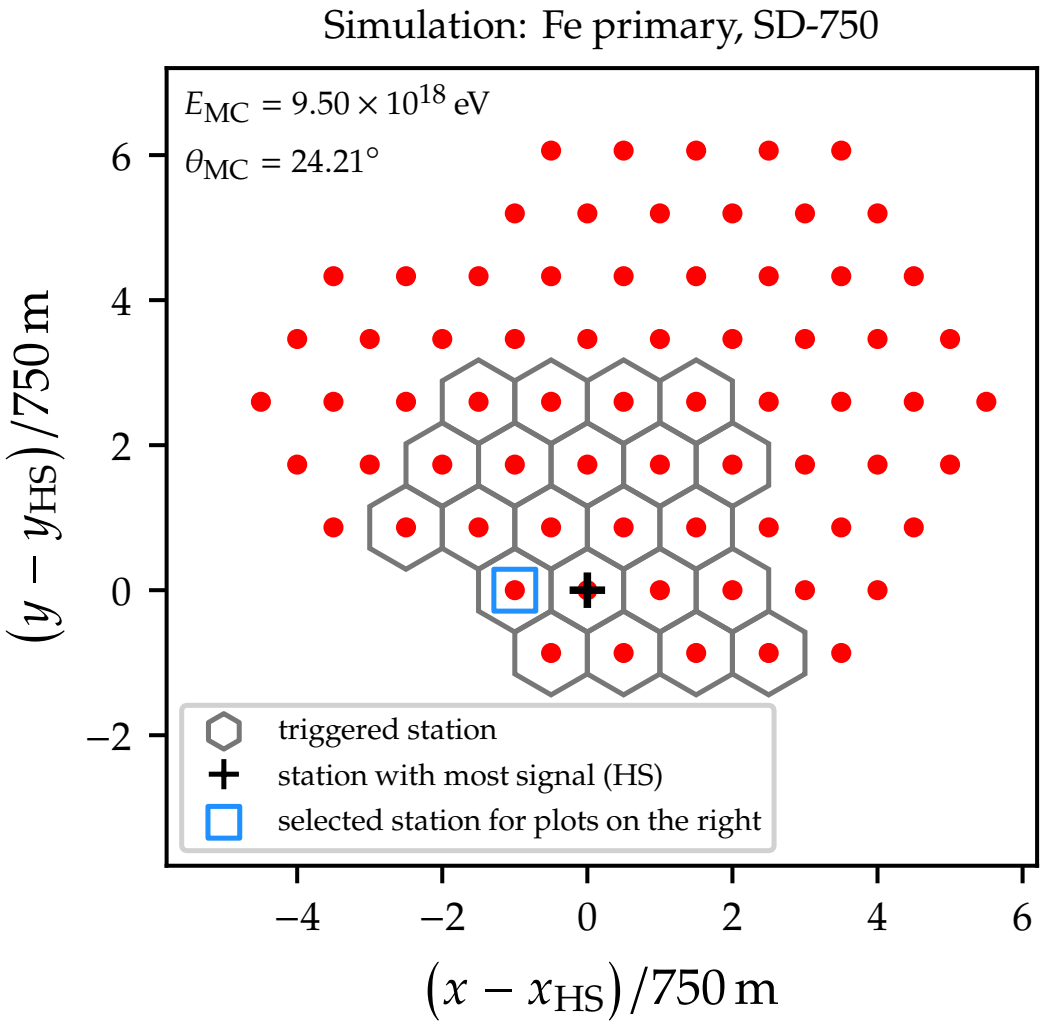




After corrections, after quality selection, after calibration

Border conflicts at the SD-750





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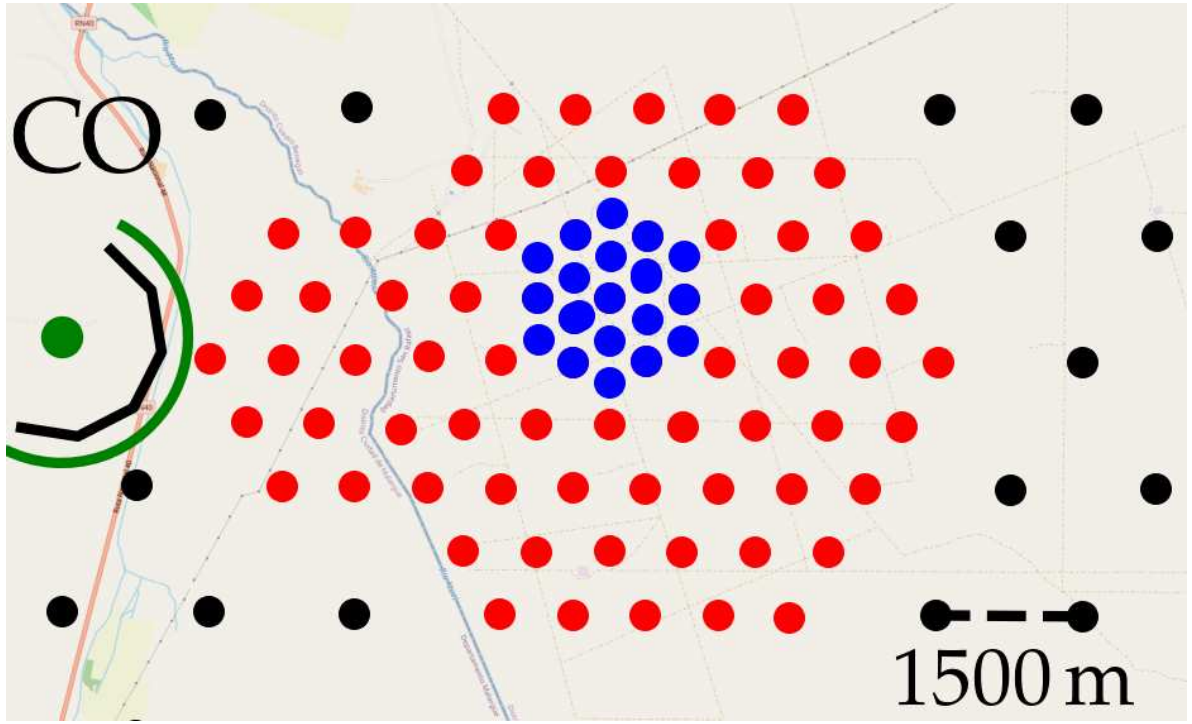

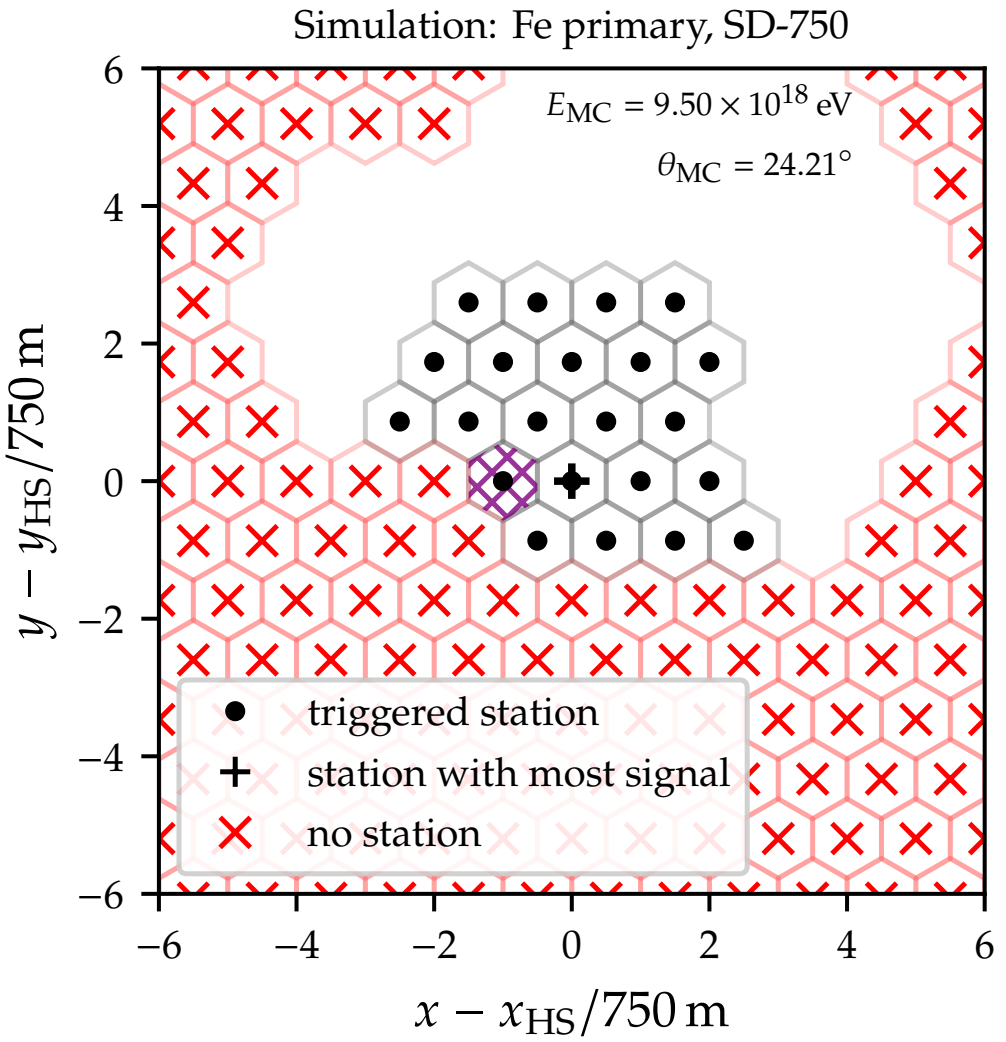

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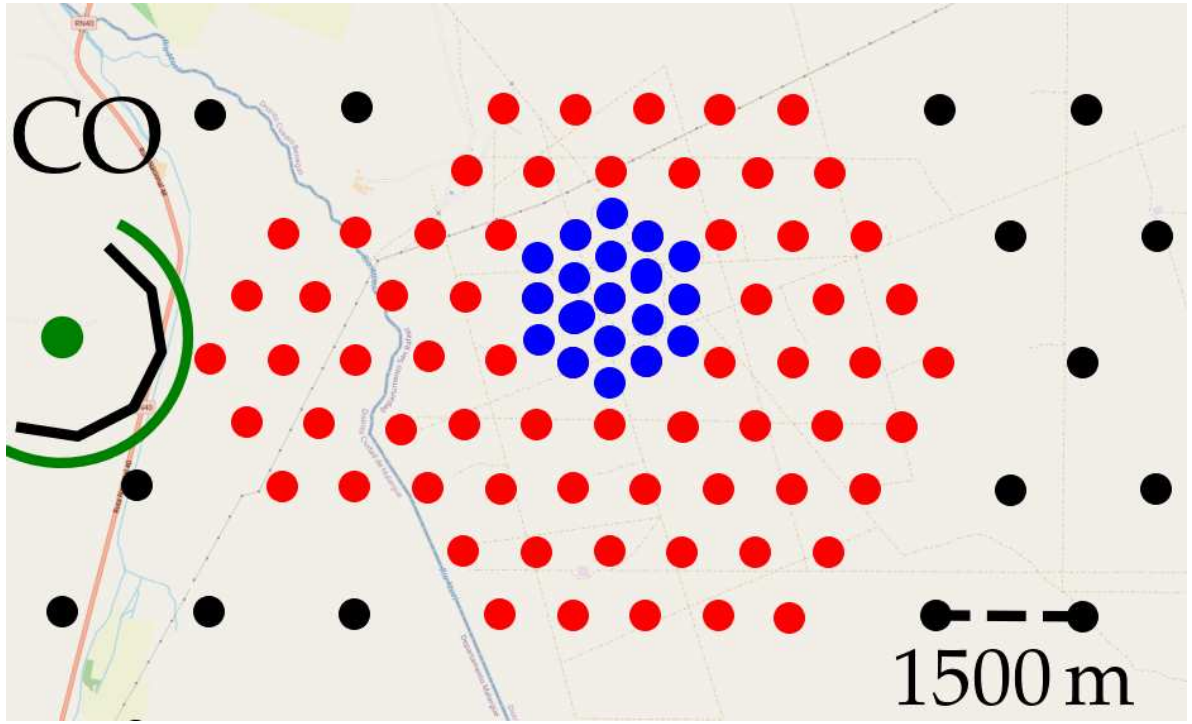

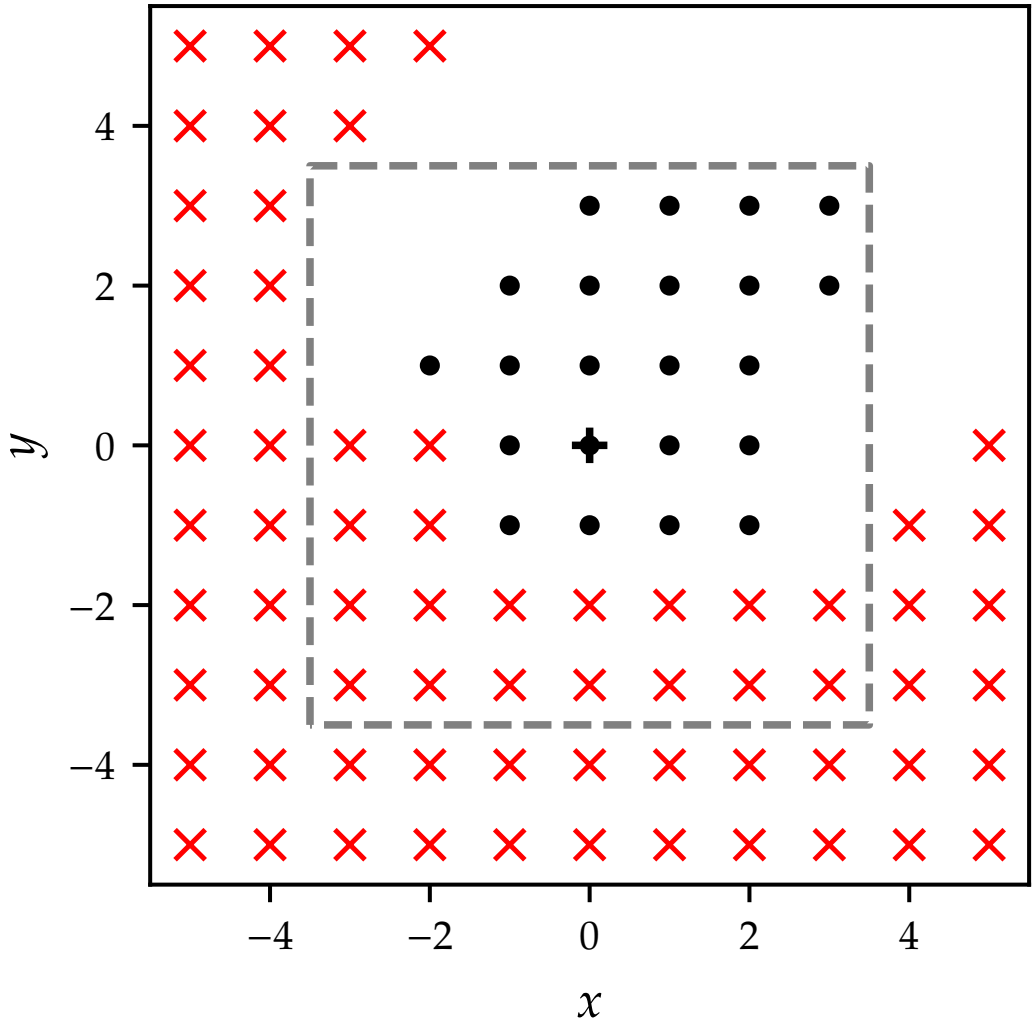

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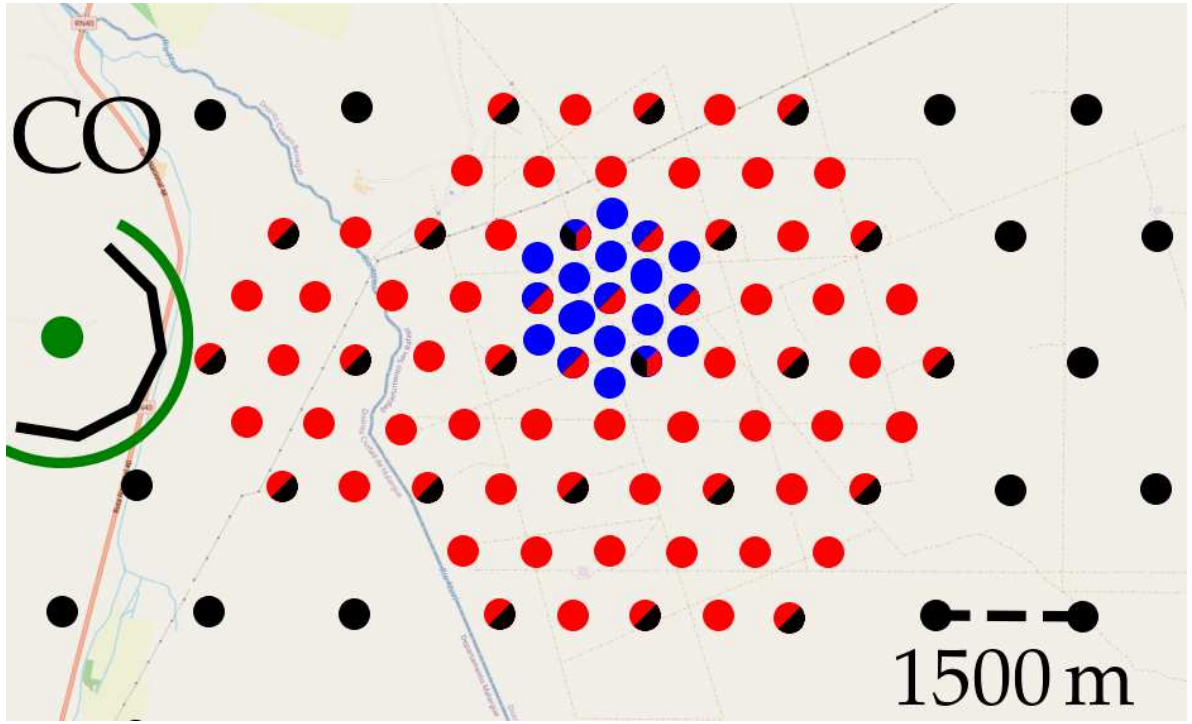
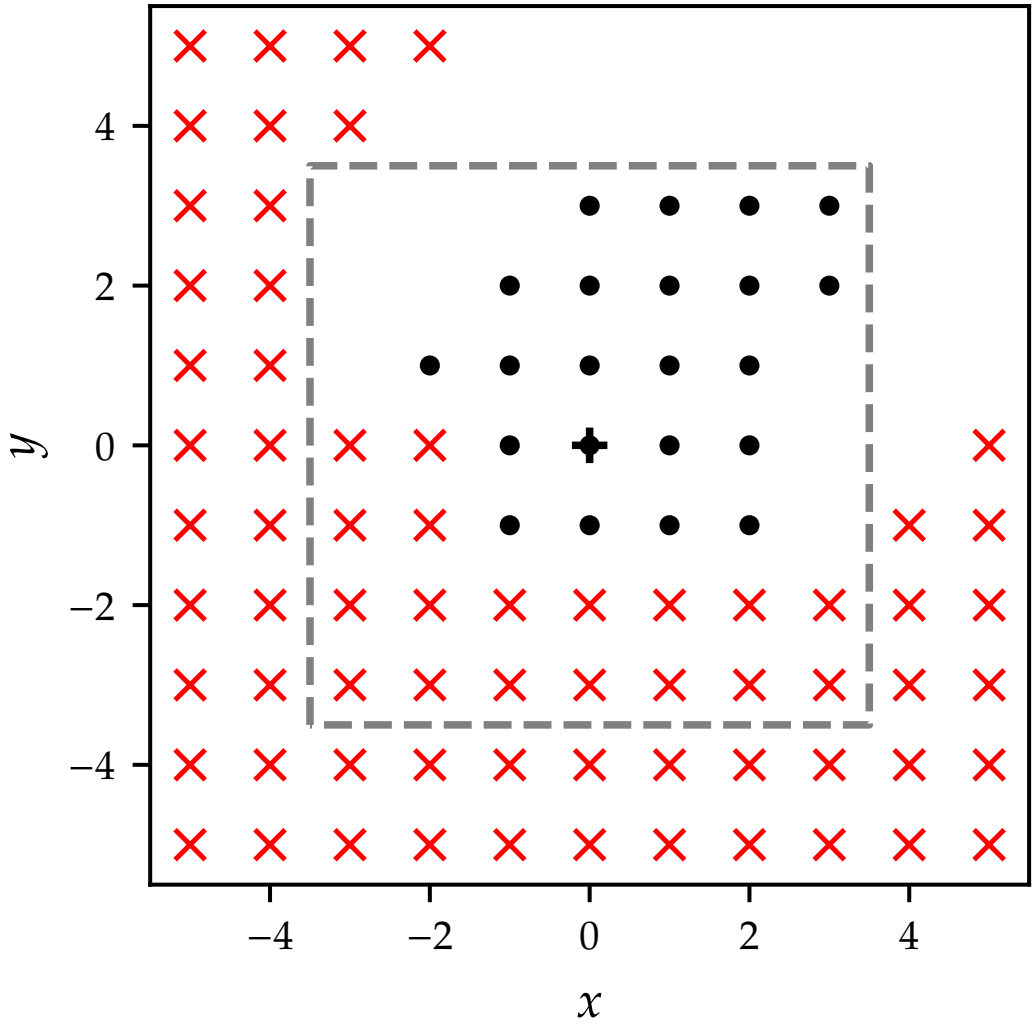
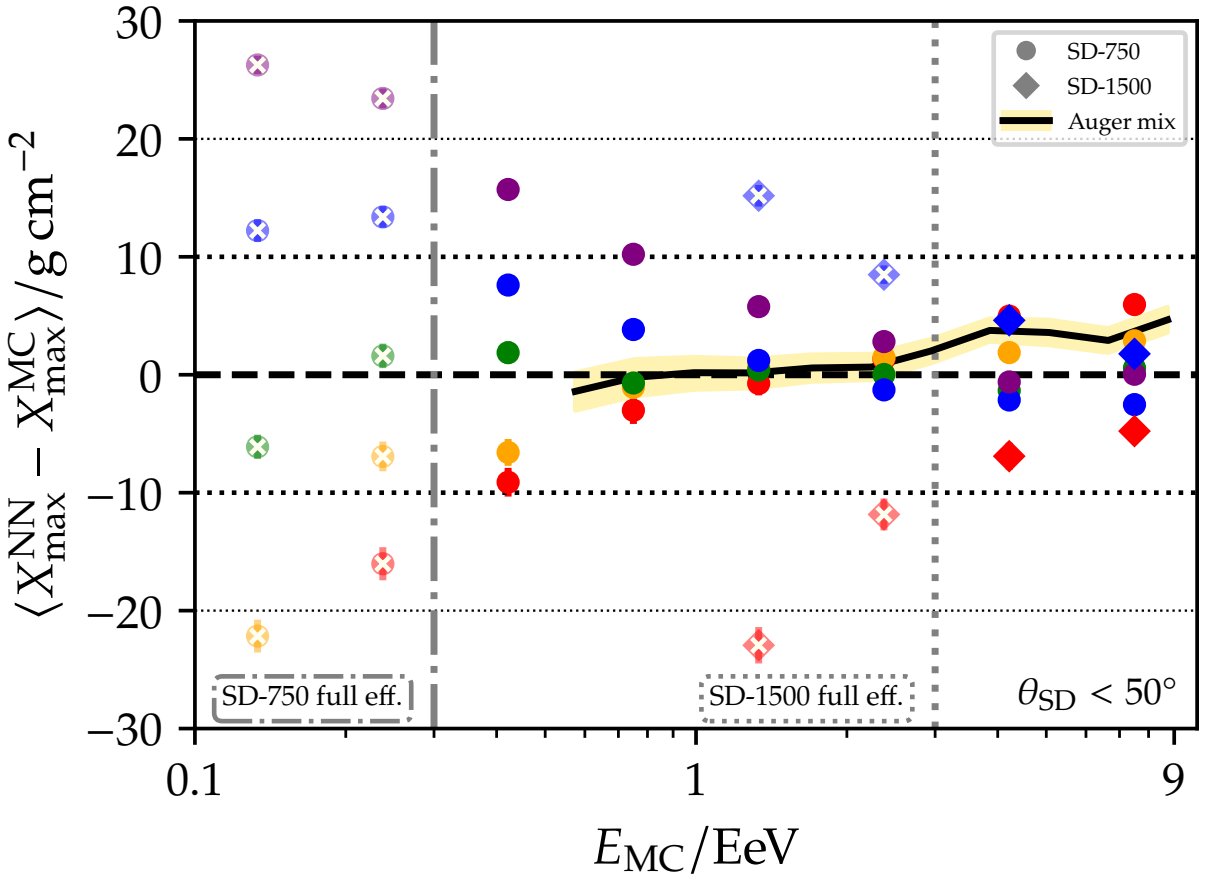
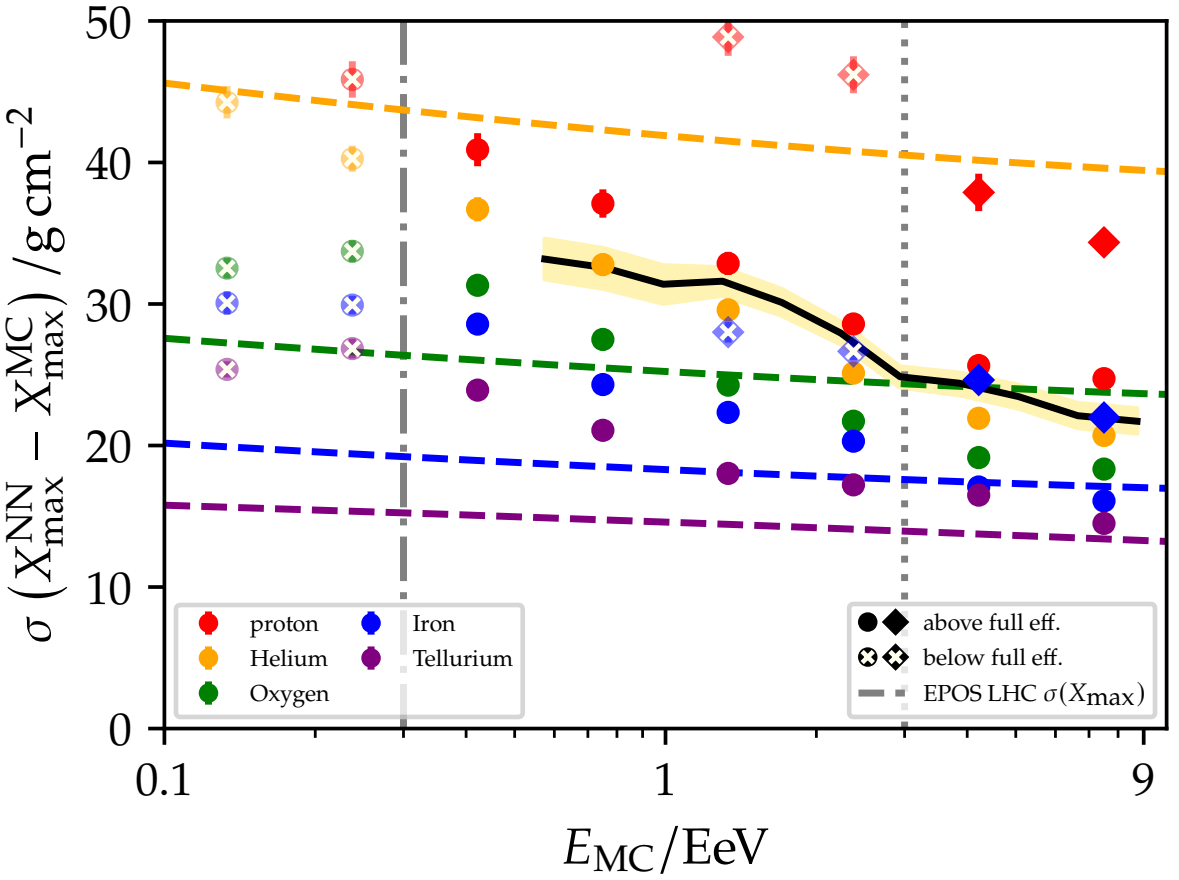




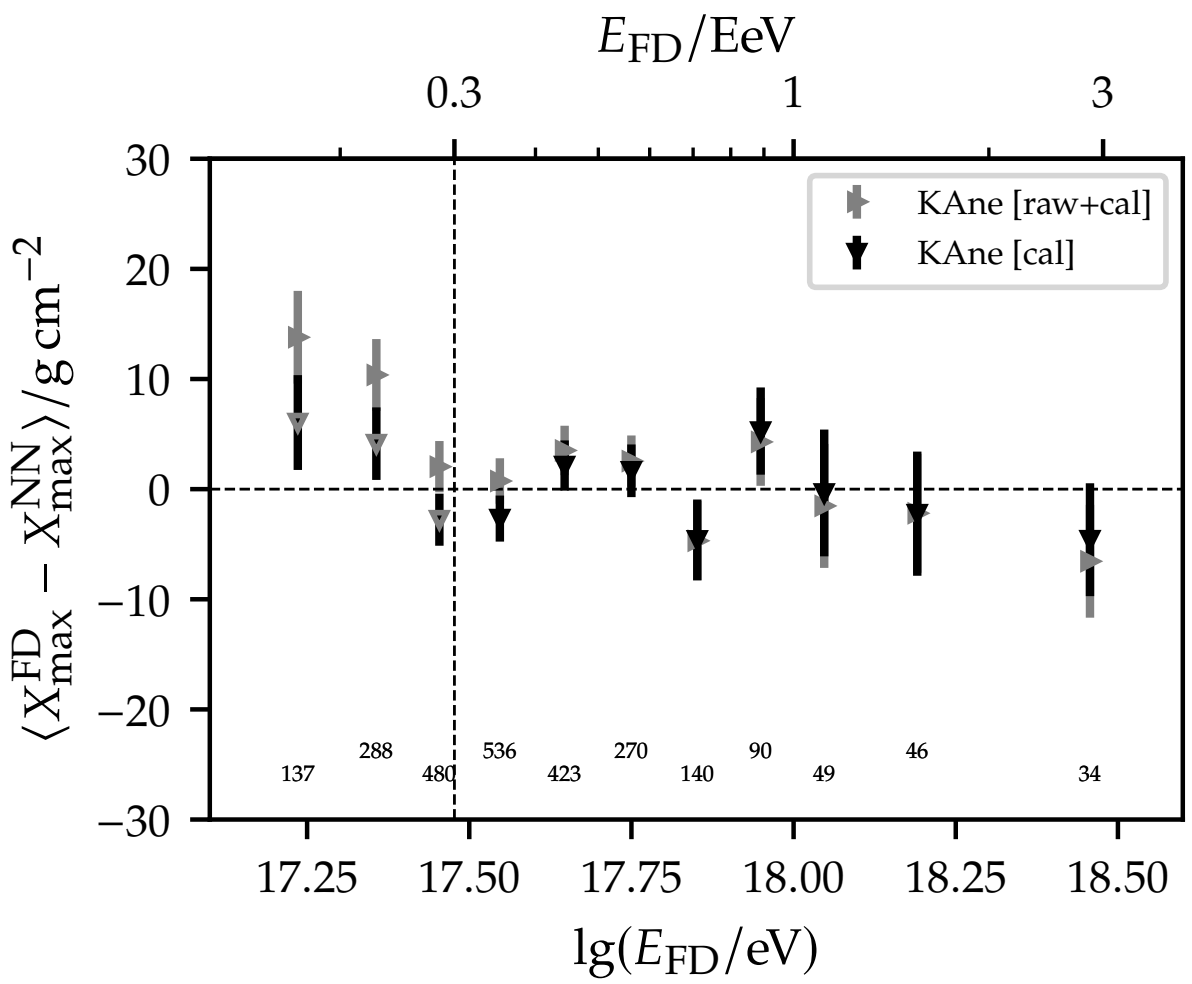
⇒ cross-calibration via SD-1500/SD-750 events

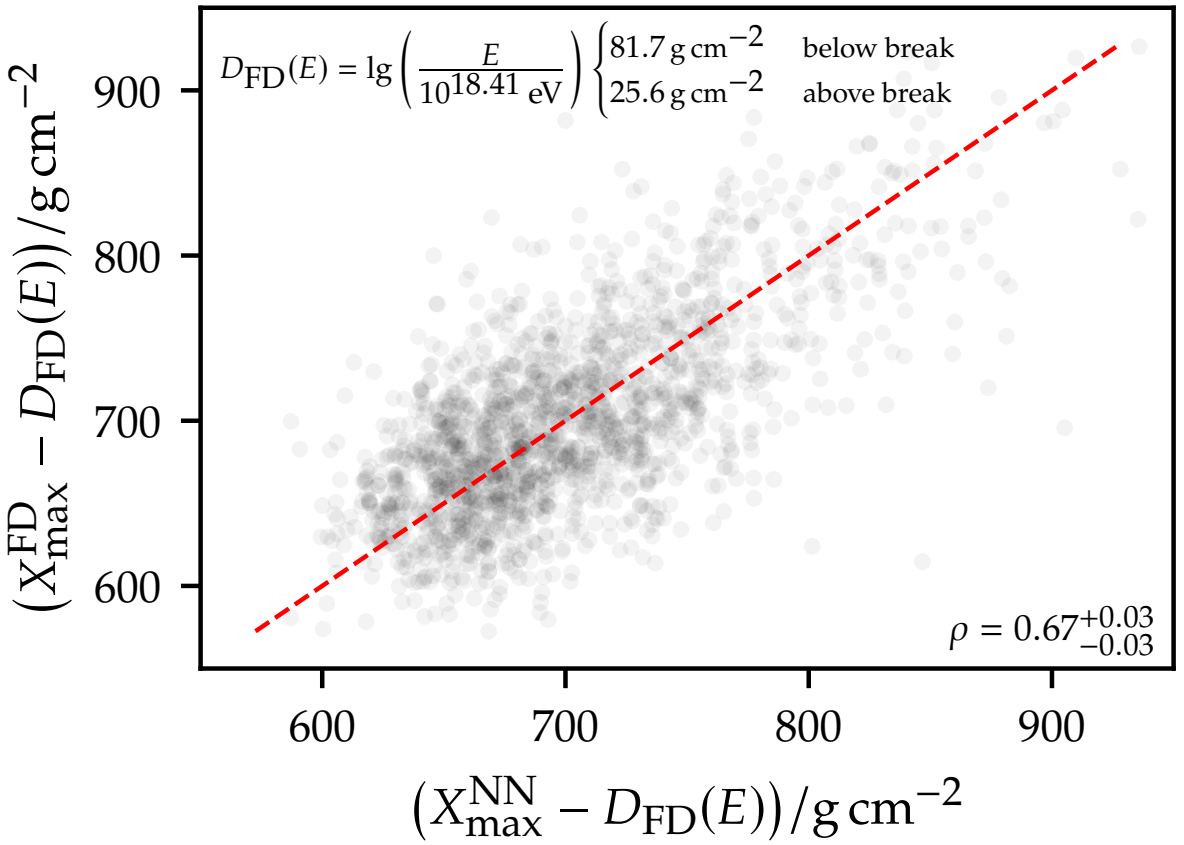
Shower depth on SD-750



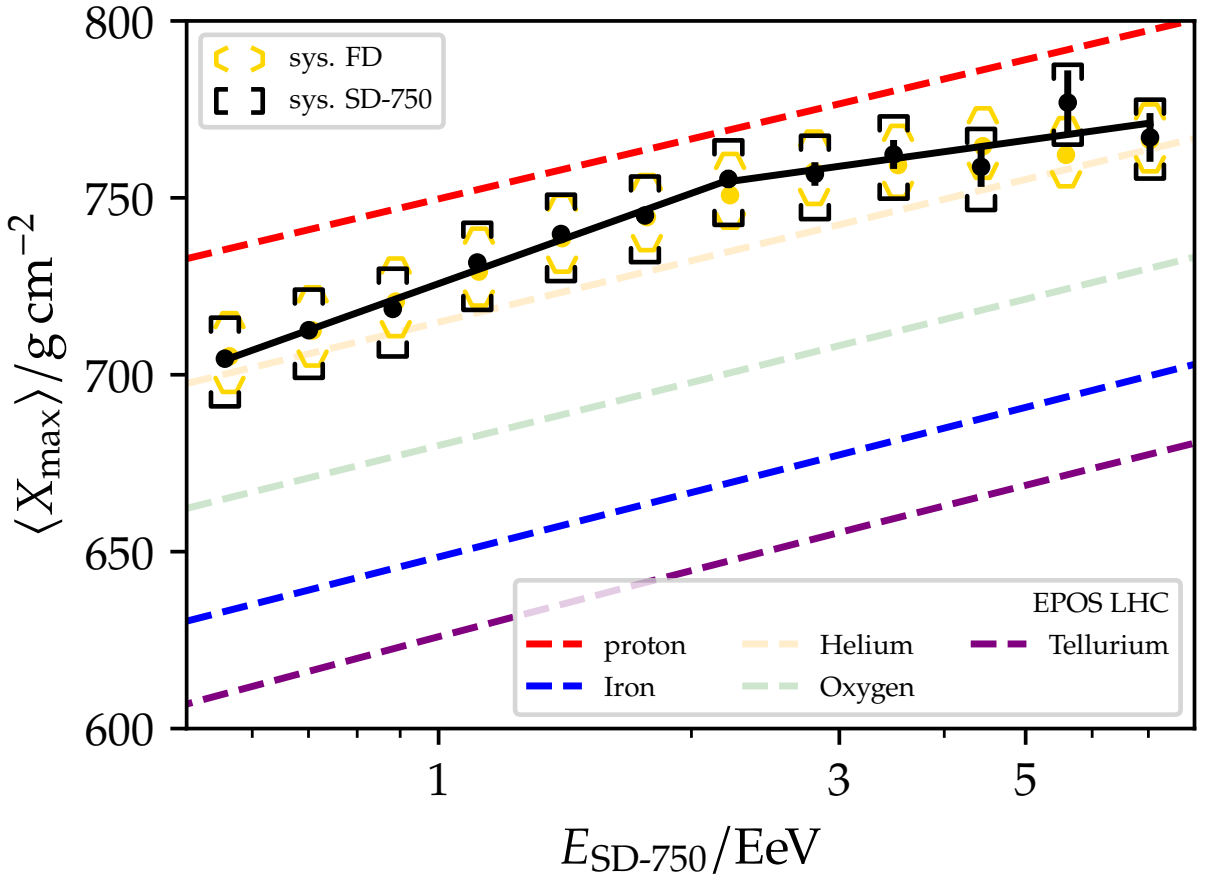


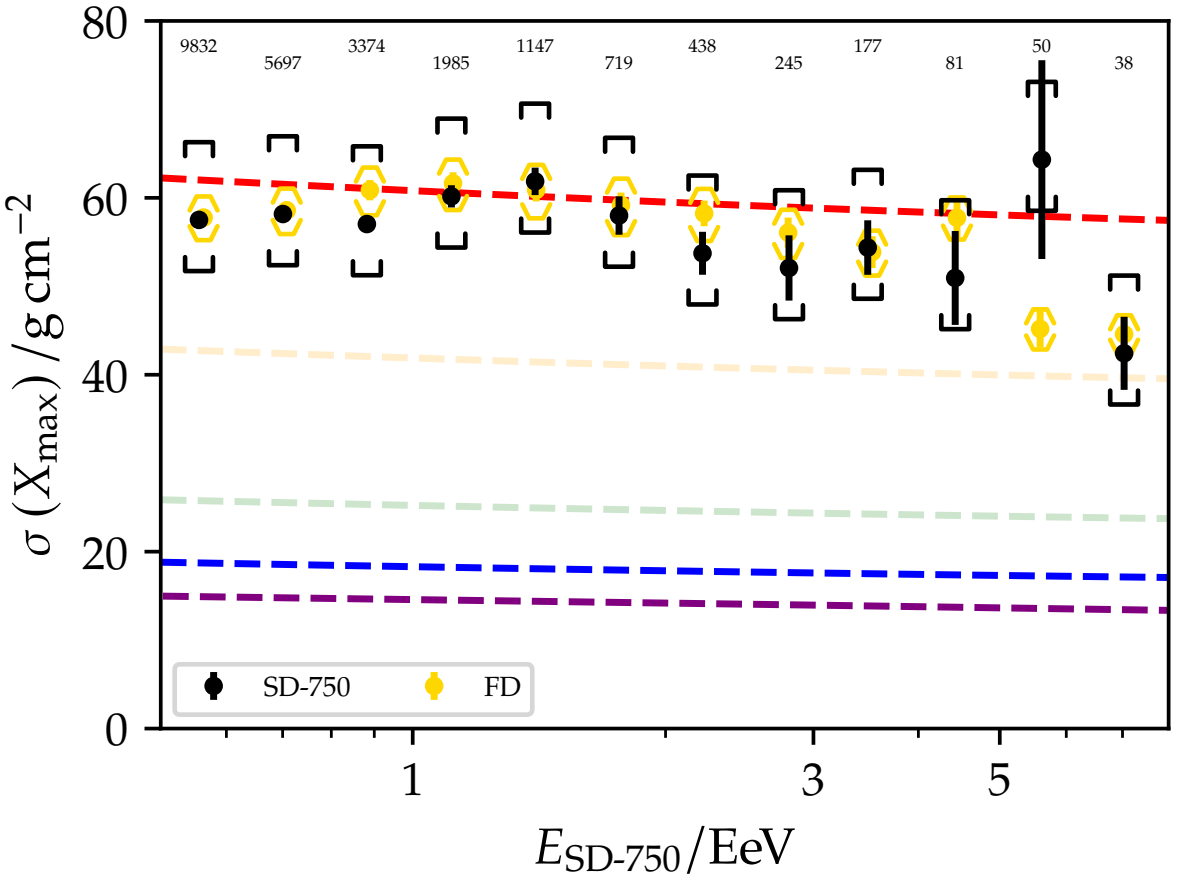
Shower depth on SD-750





Shower depth on SD-750





Relative muon content & z-scale

Reminder

Let x be an observable that depends on the amount of muons in the shower footprint, then the relative muon number is

$$R_\mu[x_\mu] = \frac{x_\mu}{\langle x_\mu \rangle_\mathrm{p}}.$$

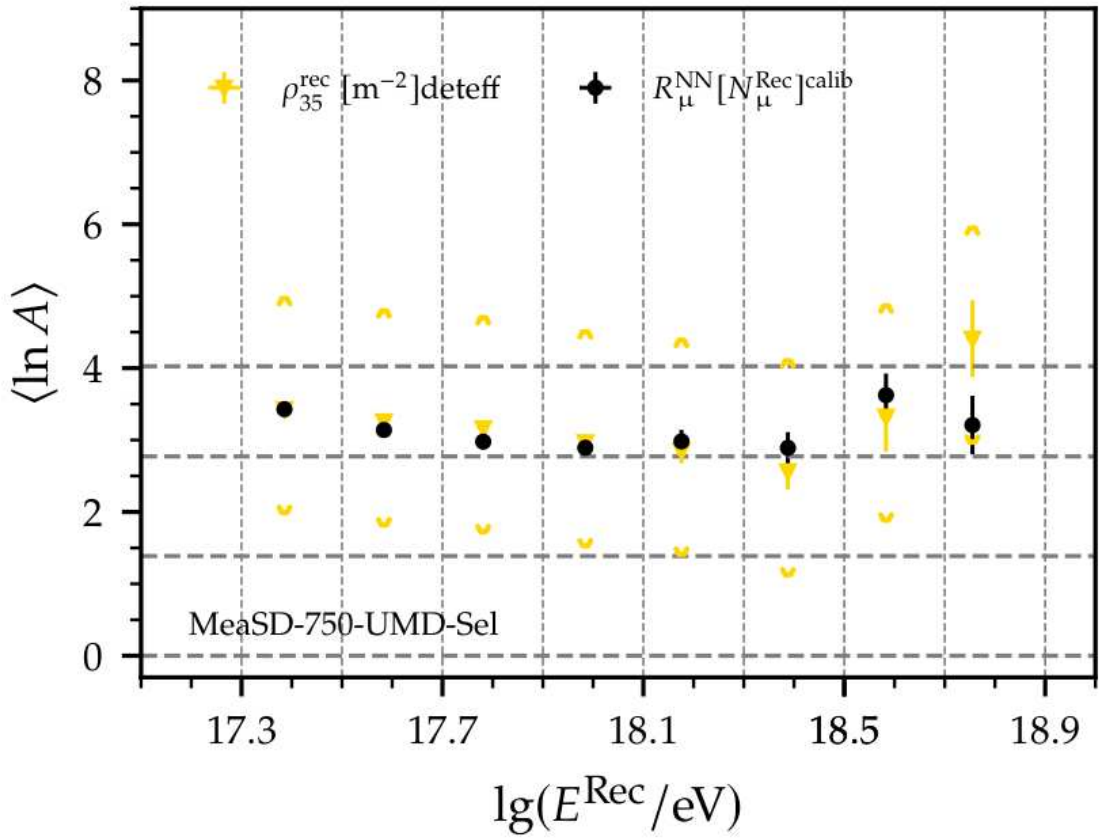
z-scale

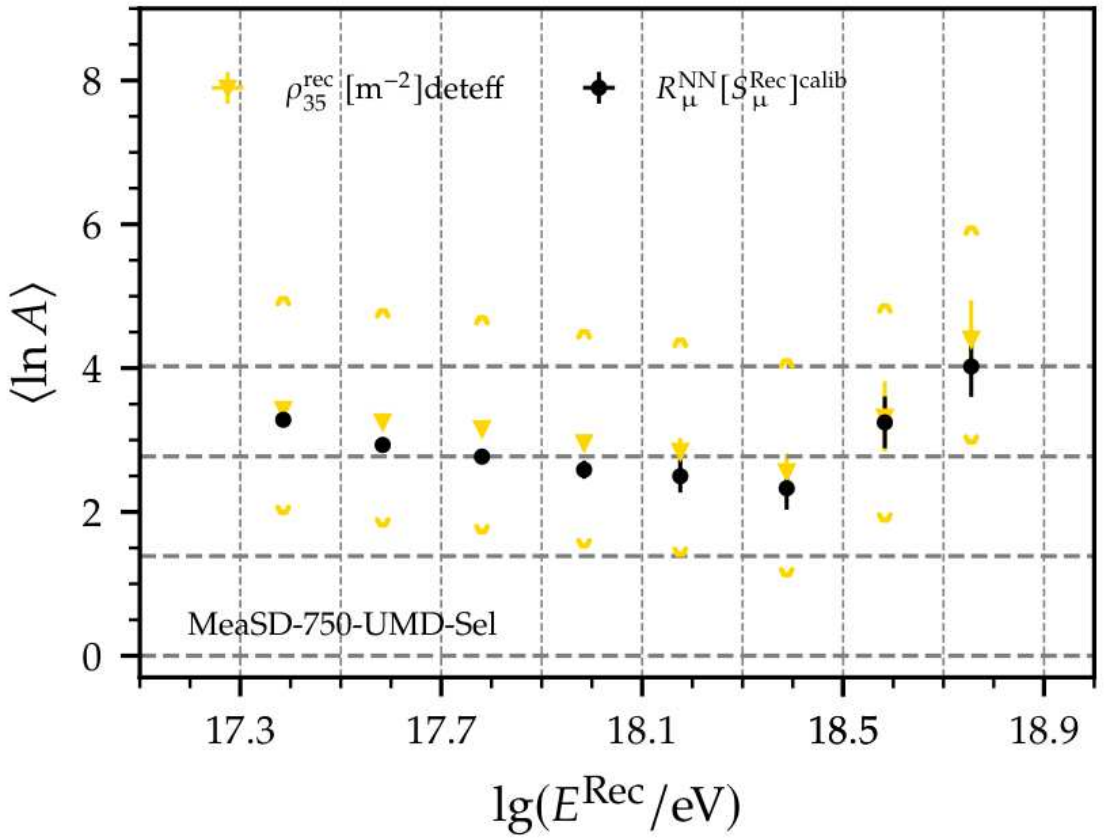
$$z[y] = \frac{y - \langle y \rangle_\mathrm{p}}{\langle y \rangle_\mathrm{Fe} - \langle y \rangle_\mathrm{p}},$$

where $y \propto \ln A$, e.g., $\ln R_\mu$.

Muon content on SD-750

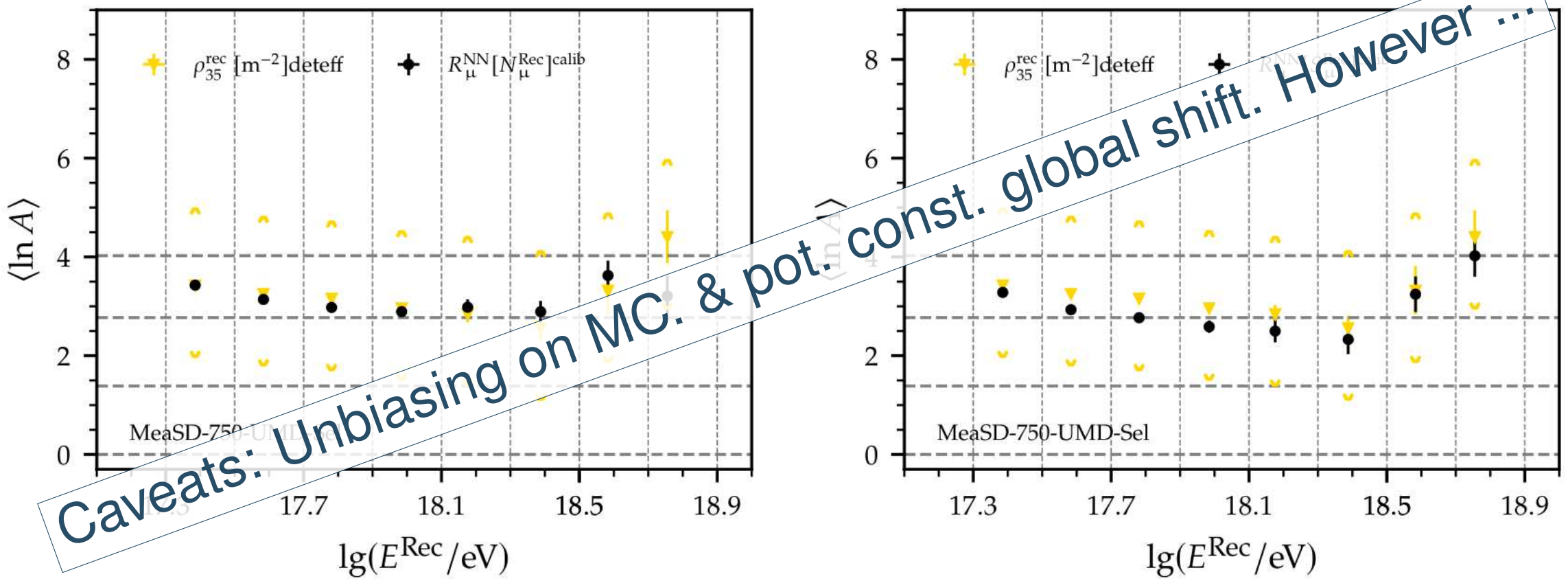
Sneak peek





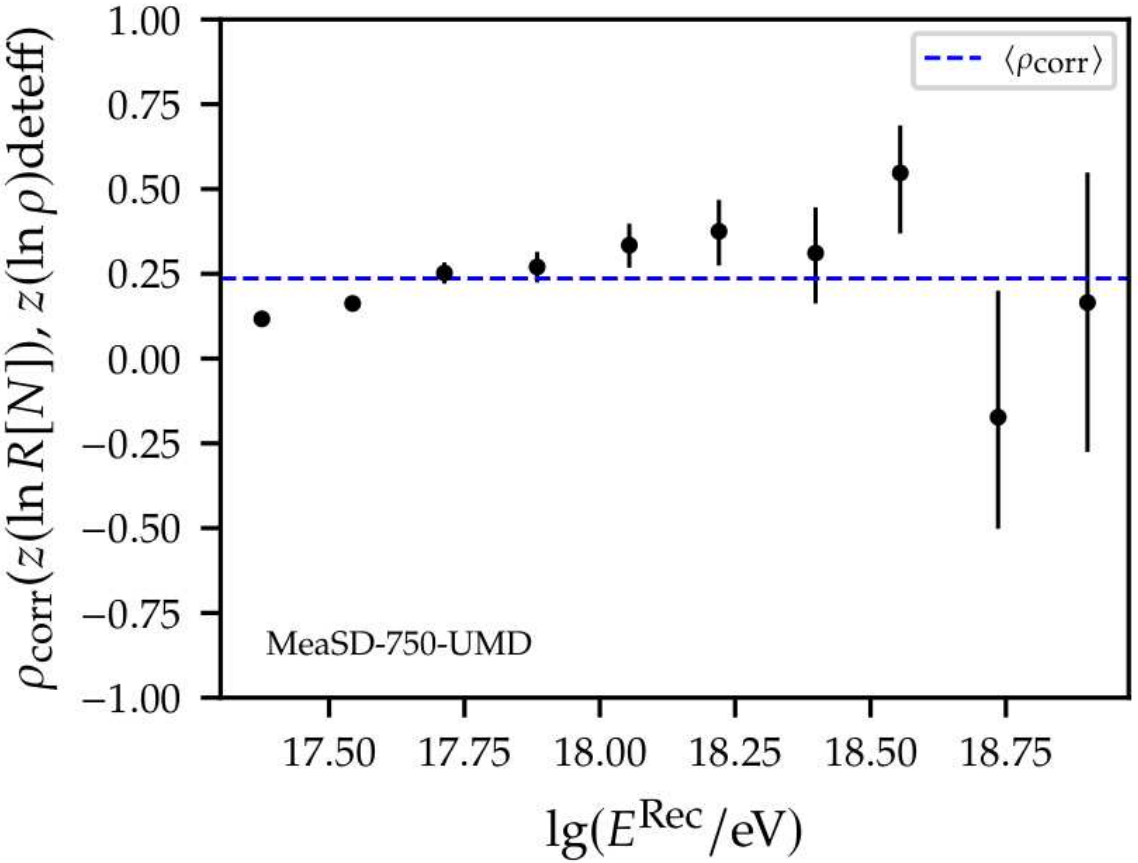
Muon content on SD-750

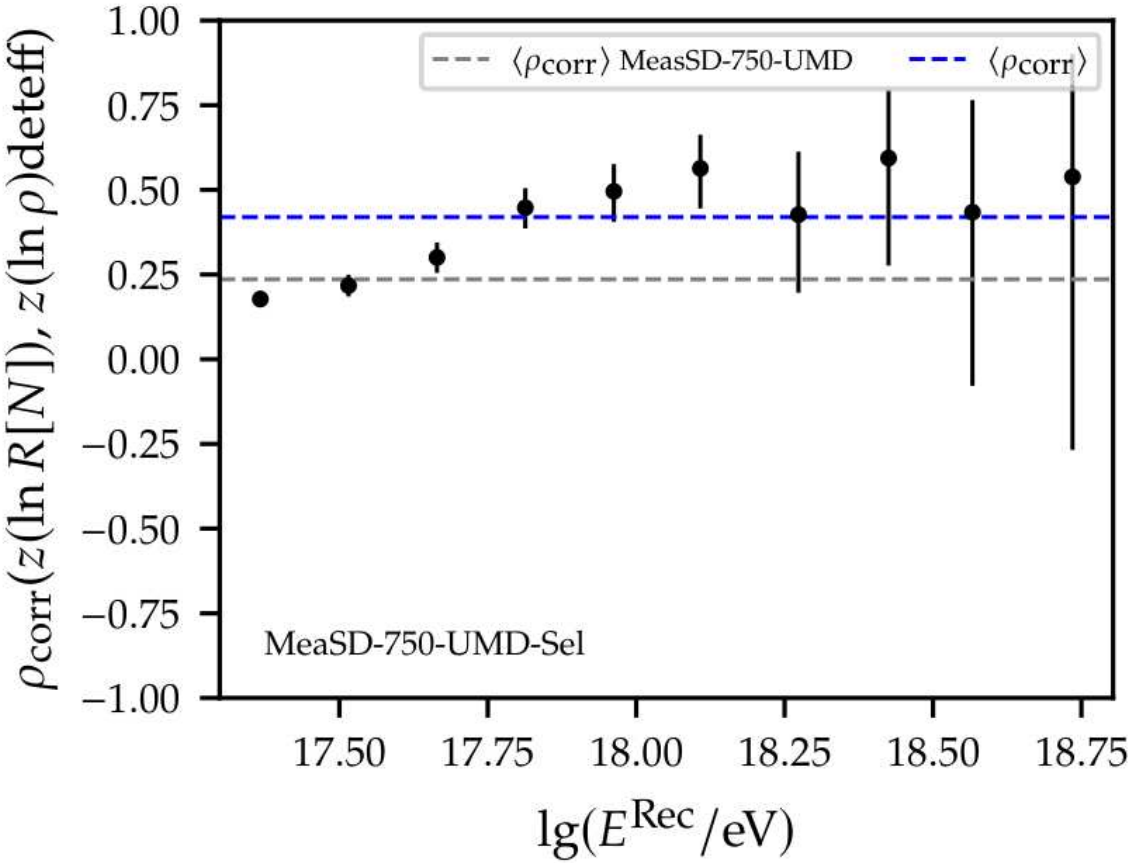
Sneak peek



Muon content on SD-750

Sneak peek





Future

Disclaimer

The focus was on ‘classical’, event-level predictors. There are other applications:

- NN-based station-level muon trace for SD-750
- NN-based energy estimators
- (G)NN-based photon search
- ...

Future

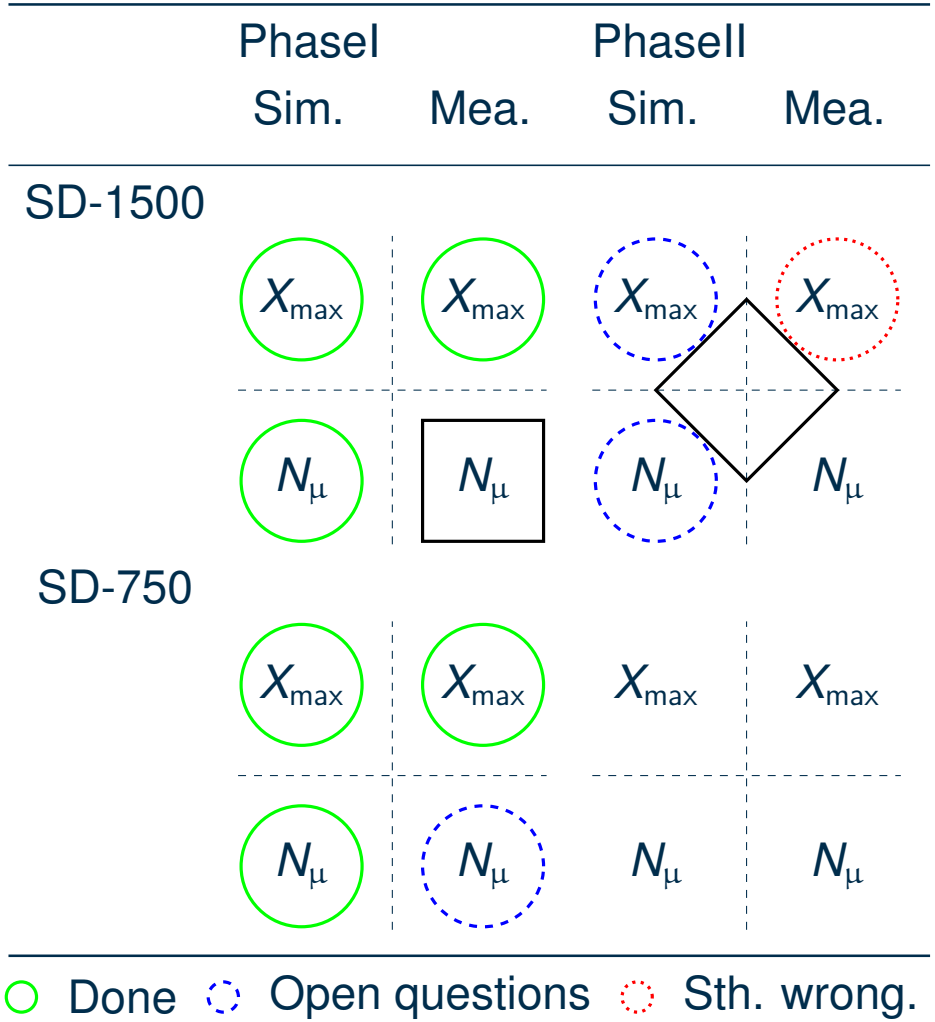
Disclaimer

The focus was on ‘classical’, event-level predictors. There are other applications:

- NN-based station-level muon trace for SD-750
- NN-based energy estimators
- (G)NN-based photon search
- ...

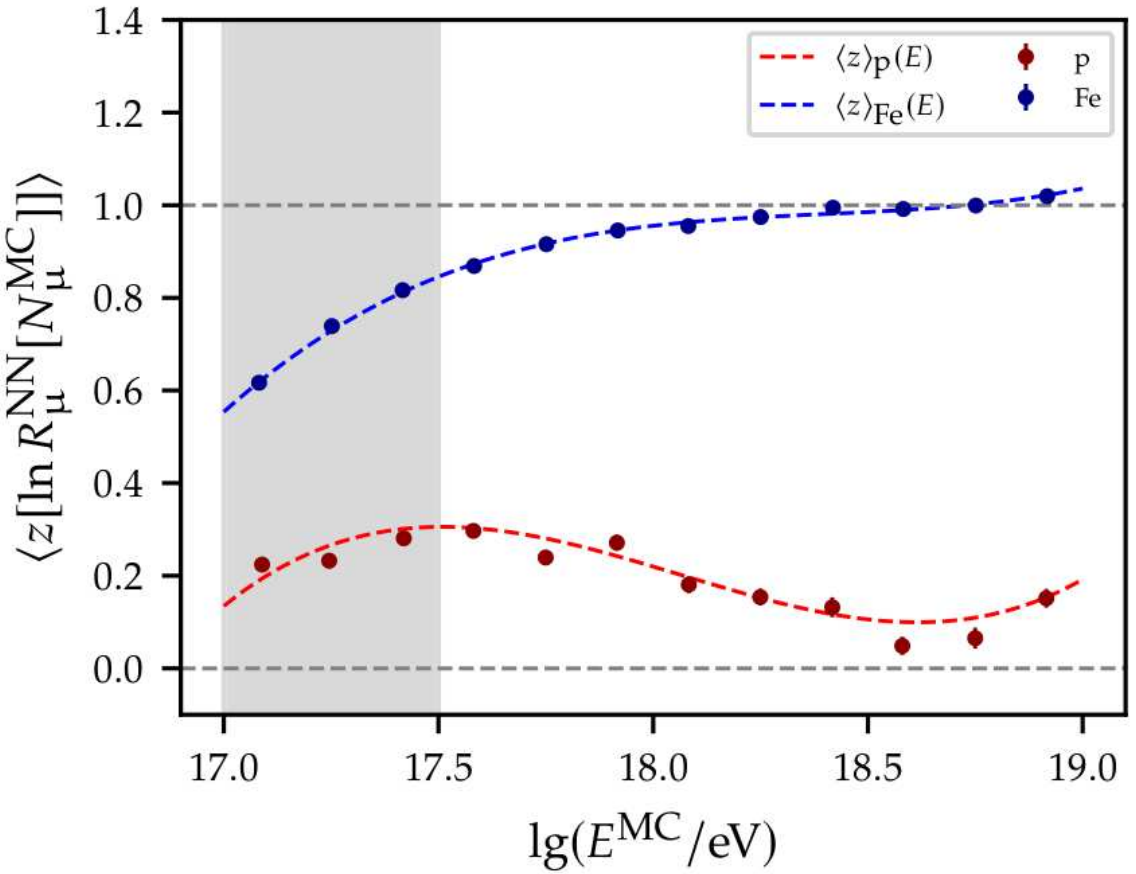
Next steps

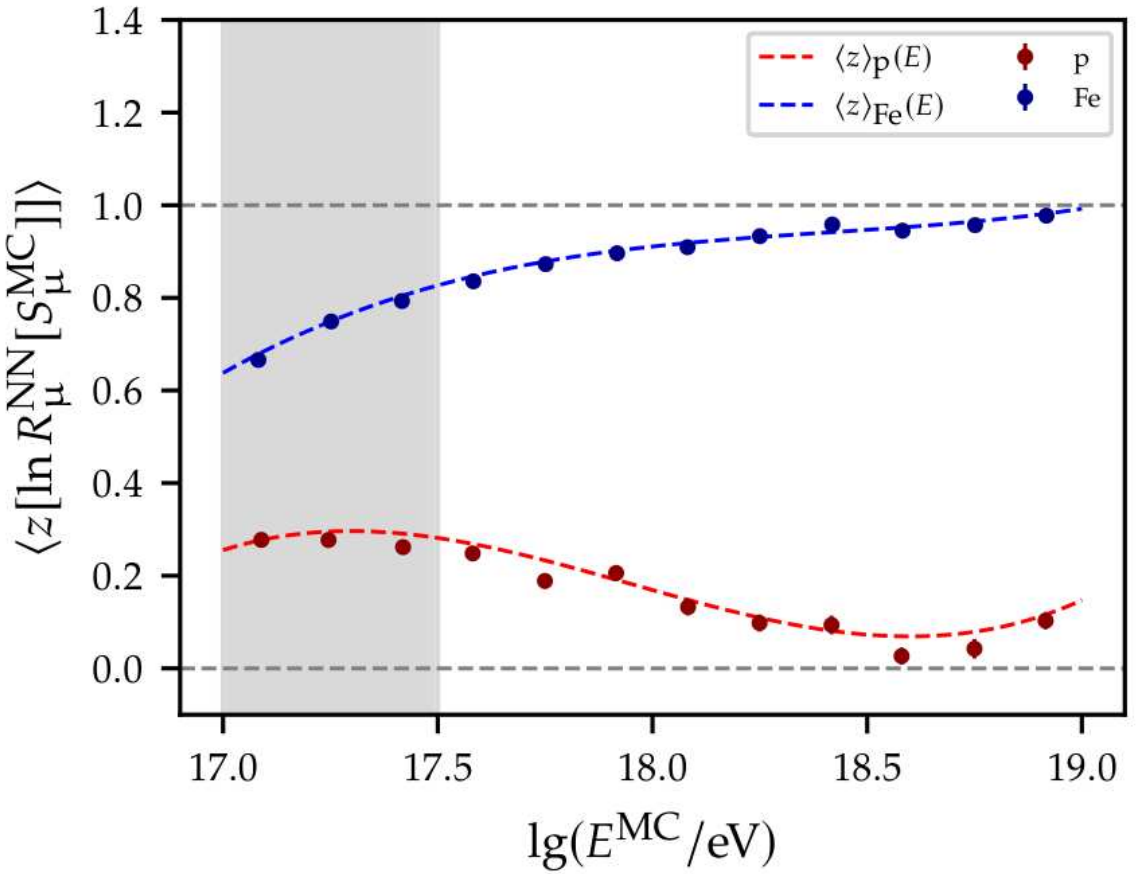
- cross-calibration of N_μ on SD-1500 (□)
- transition to PhaseII (SD-1500) (◇)

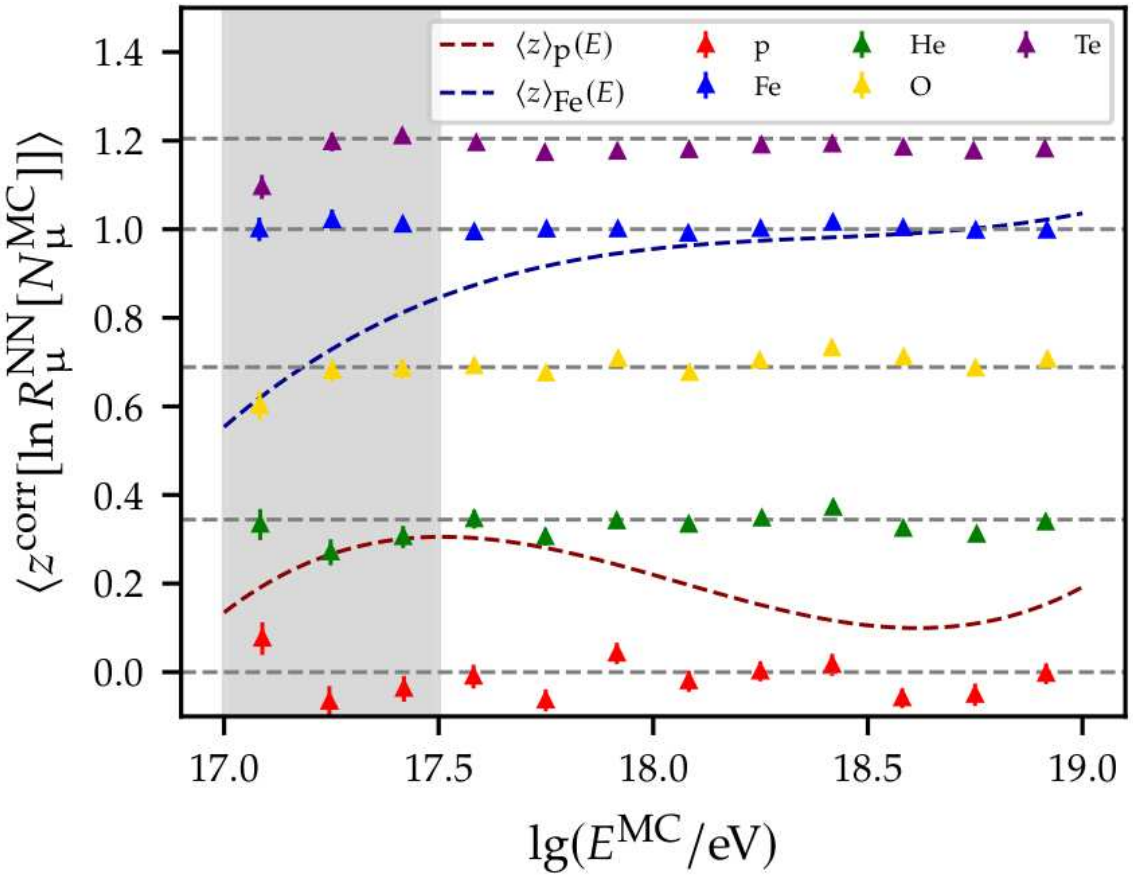
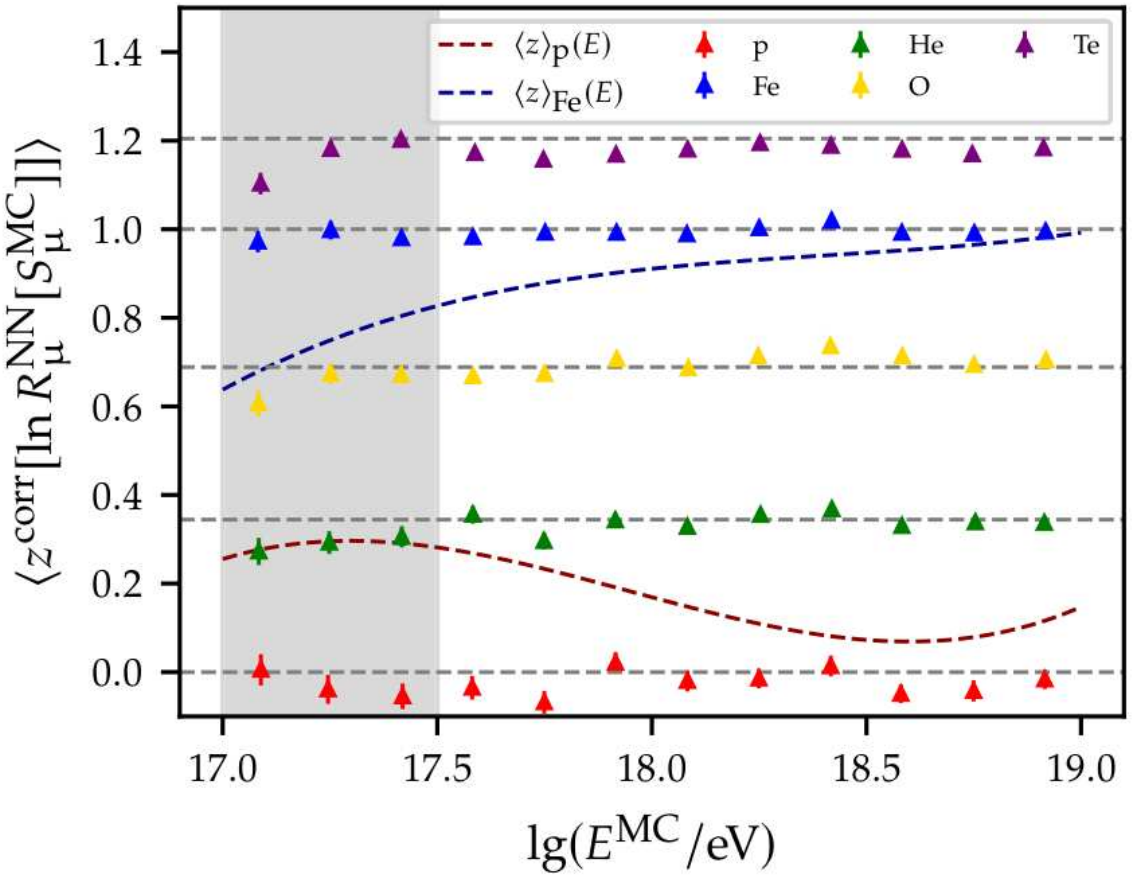


Muon content on SD-750

Unbiasing of first moment





Muon content on SD-750

Unbiasing of first moment