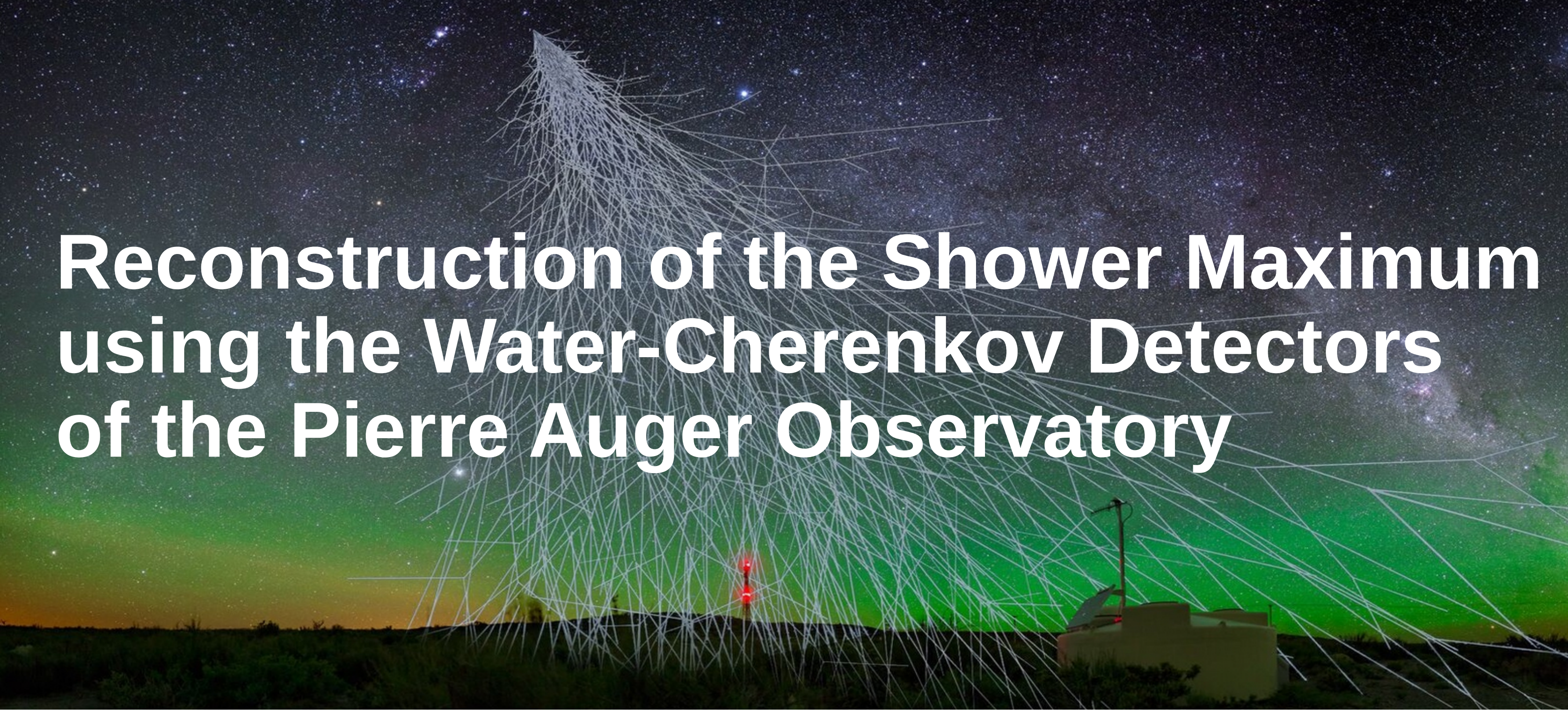
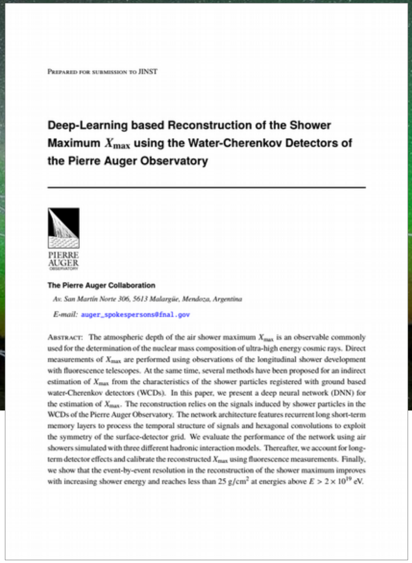
Reconstruction of the Shower Maximum using the Water-Cherenkov Detectors of the Pierre Auger Observatory




Prepared for submission to JINST

Deep-Learning based Reconstruction of the Shower Maximum $X_{\max}$ using the Water-Cherenkov Detectors of the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

The Pierre Auger Collaboration

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Abstract: The atmospheric depth of the air shower maximum $X_{\max}$ is an observable commonly used for the determination of the nuclear mass composition of ultra-high energy cosmic rays. Direct measurements of $X_{\max}$ are performed using observations of the longitudinal shower development with fluorescence telescopes. At the same time, several methods have been proposed for an indirect estimation of $X_{\max}$ from the characteristics of the shower particles registered with ground based water-Cherenkov detectors (WCDs). In this paper, we present a deep neural network (DNN) for the estimation of $X_{\max}$. The reconstruction relies on the signals induced by shower particles in the WCDs of the Pierre Auger Observatory. The network architecture features recurrent long short-term memory layers to process the temporal structure of signals and hexagonal convolutions to exploit the symmetry of the surface-detector grid. We evaluate the performance of the network using air showers simulated with three different hadronic interaction models. Thereafter, we account for long-term detector effects and calibrate the reconstructed $X_{\max}$ using fluorescence measurements. Finally, we show that the event-by-event resolution in the reconstruction of the shower maximum improves with increasing shower energy and reaches less than 25 g/cm^2 at energies above $E > 2 \times 10^{19}$ eV.

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ArXiv/2101.02946

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ErUM-Data IDT

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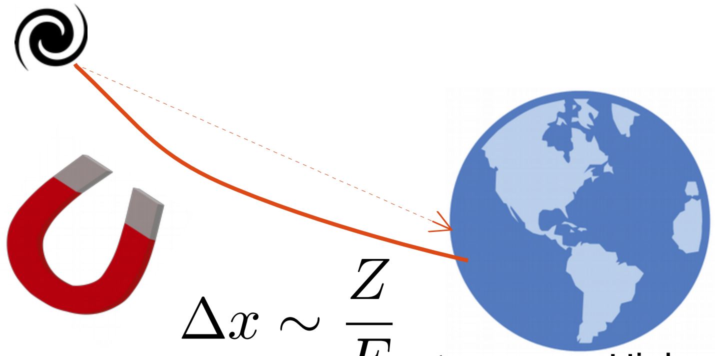
Cosmic Rays

- Charged nuclei from astronomical origins
  - **10 orders** of magnitude energy range

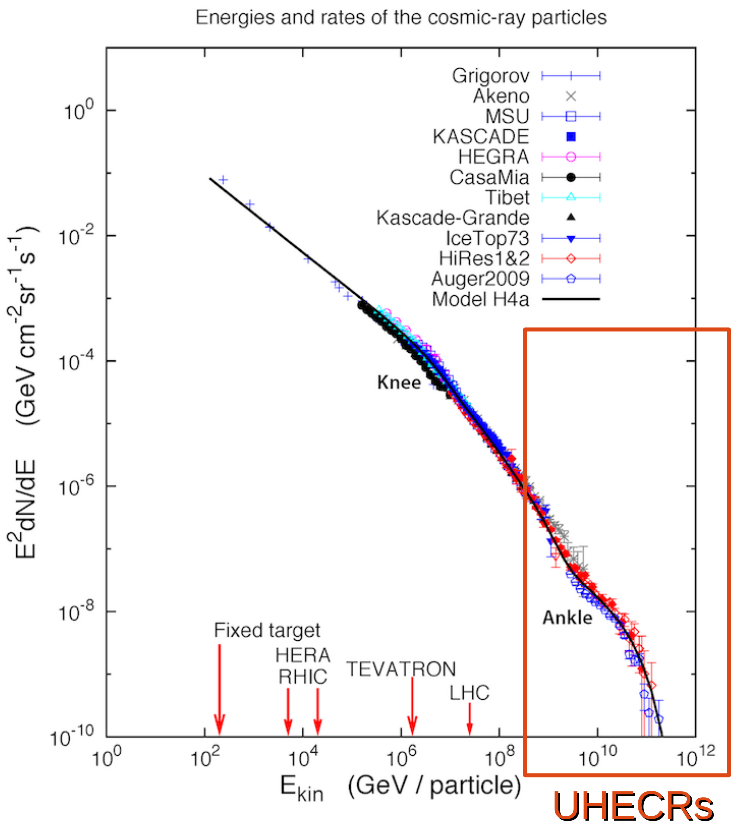
Ultra-high energy cosmic rays (UHECRs)

- Energies > 10^{18} eV
- manageable deflection by magnetic fields
  - Search for extra-galactic origins



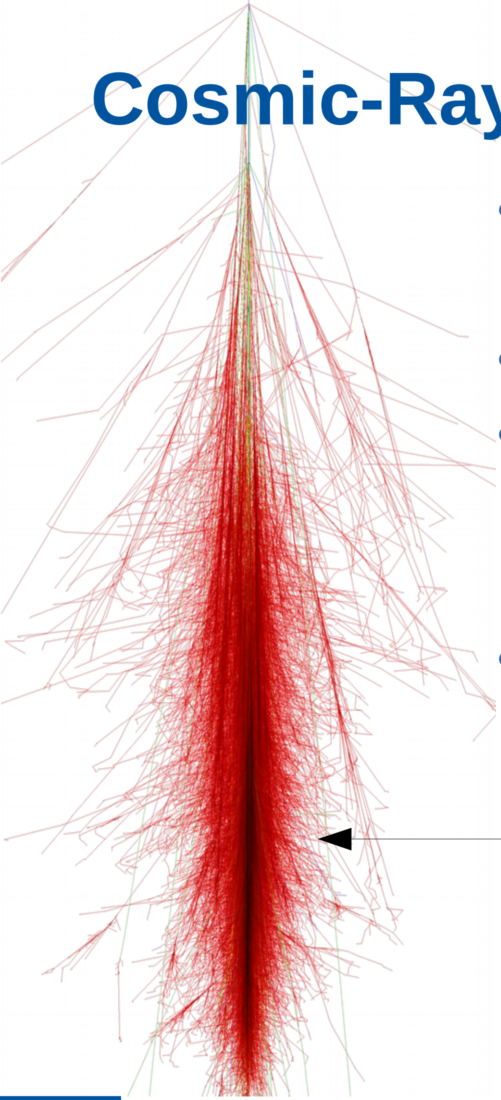
$$\Delta x \sim \frac{Z}{E}$$

← High energies



10.1103/PhysRevD.88.042004

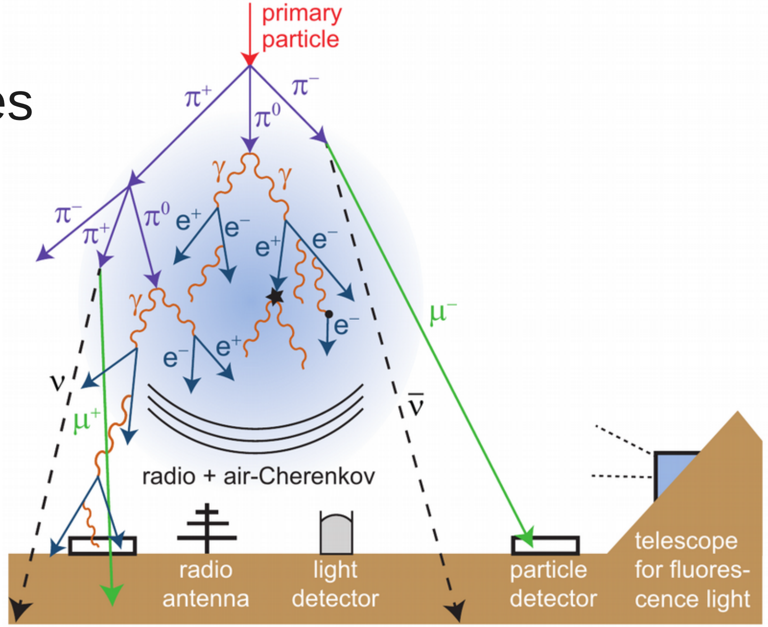
Cosmic-Ray induced Air Showers



- Cosmic rays interact with Earth's atmosphere
  - Induce extensive particle cascade
- Particle shower reach size of several km² at Earth's surface
- Particle mass determines shower structure
  - Low mass, deep penetration → late maximum
  - Heavy mass, early maximum
- Many different detection techniques

Xmax

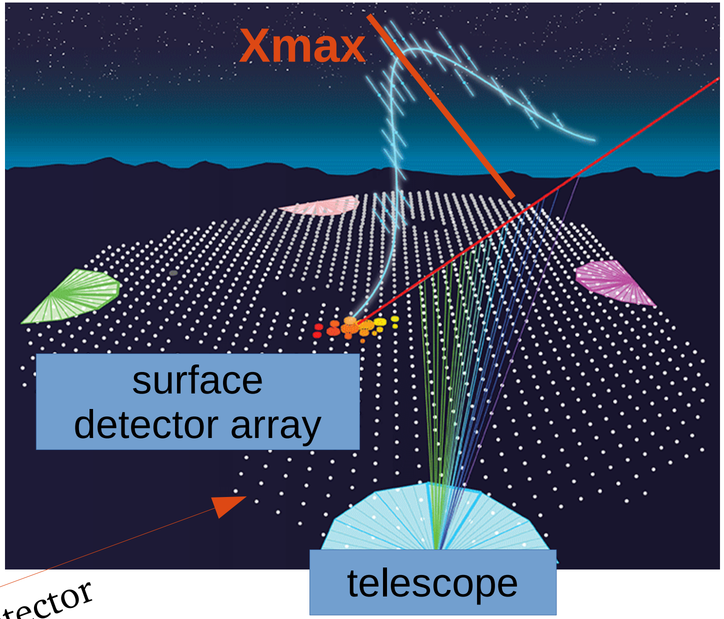
Shower maximum correlates with primary mass

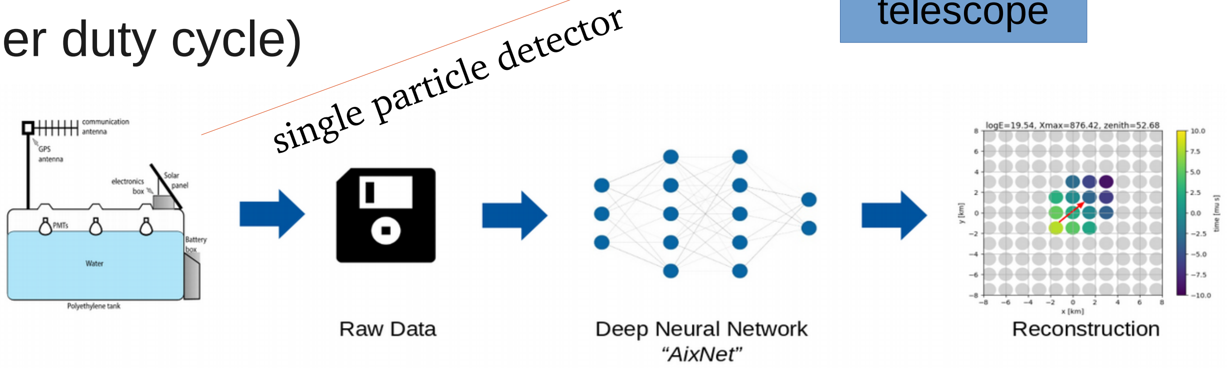


Air-Shower Reconstruction

- shower maximum (Xmax) of cosmic-ray-induced air showers contains mass information
  - directly observed by fluorescence telescopes
    - limited observations (only during dark nights)
  - challenging to measure with surface detector

- use deep learning to reconstruct Xmax
  - use surface detector data only
  - enlarge statistics (much higher duty cycle)





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Deep-Learning based reconstruction of Cosmic-Ray induced Air Showers

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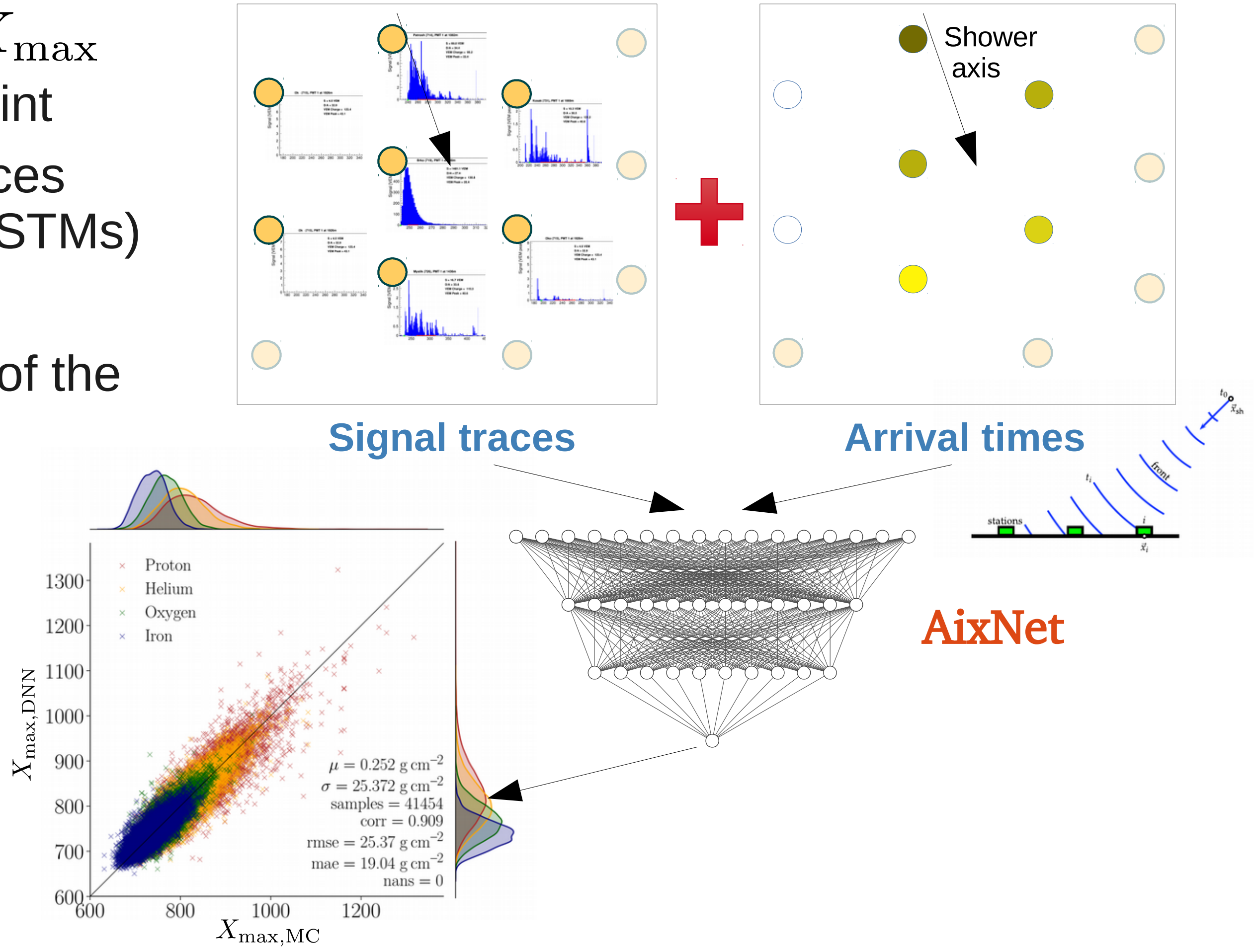
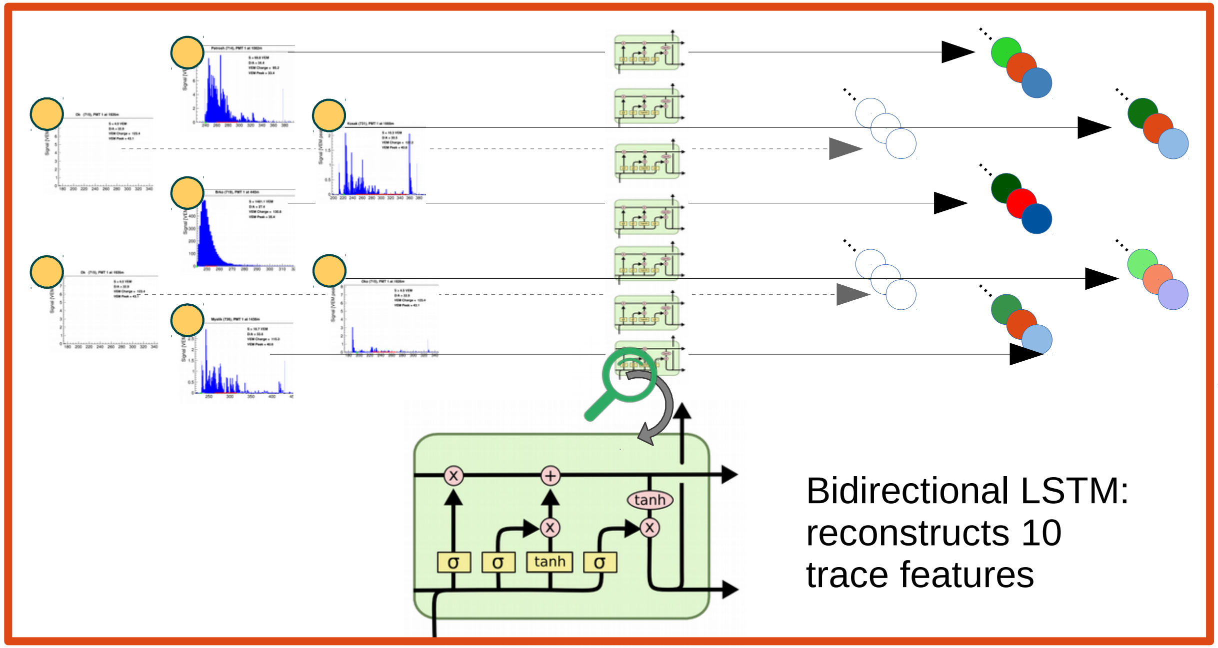
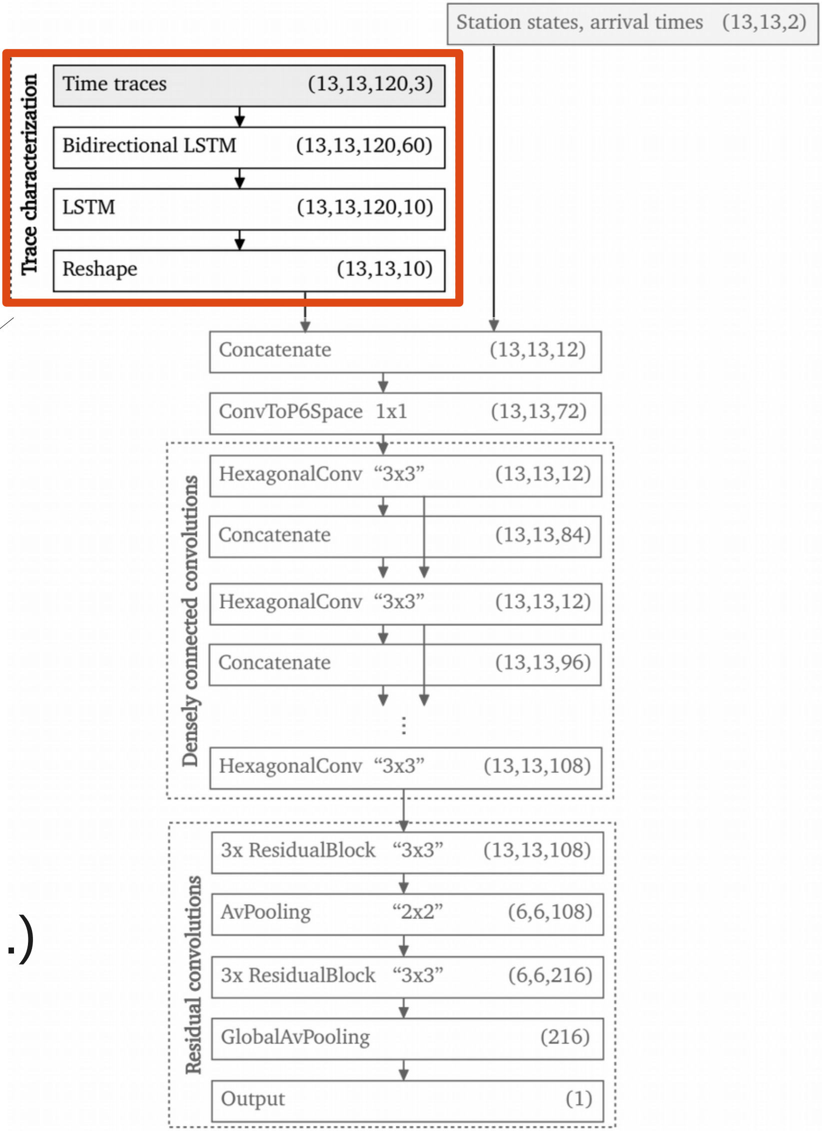
- deep learning to reconstruct $X_{\max}$
- use geometry of shower footprint
  - analyze measured signal traces
    → use recurrent networks (LSTMs)
  - measured arrival times
  - exploit hexagonal symmetry of the surface-detector grid
    → hexagonal convolutions







RNN part extracts trace features

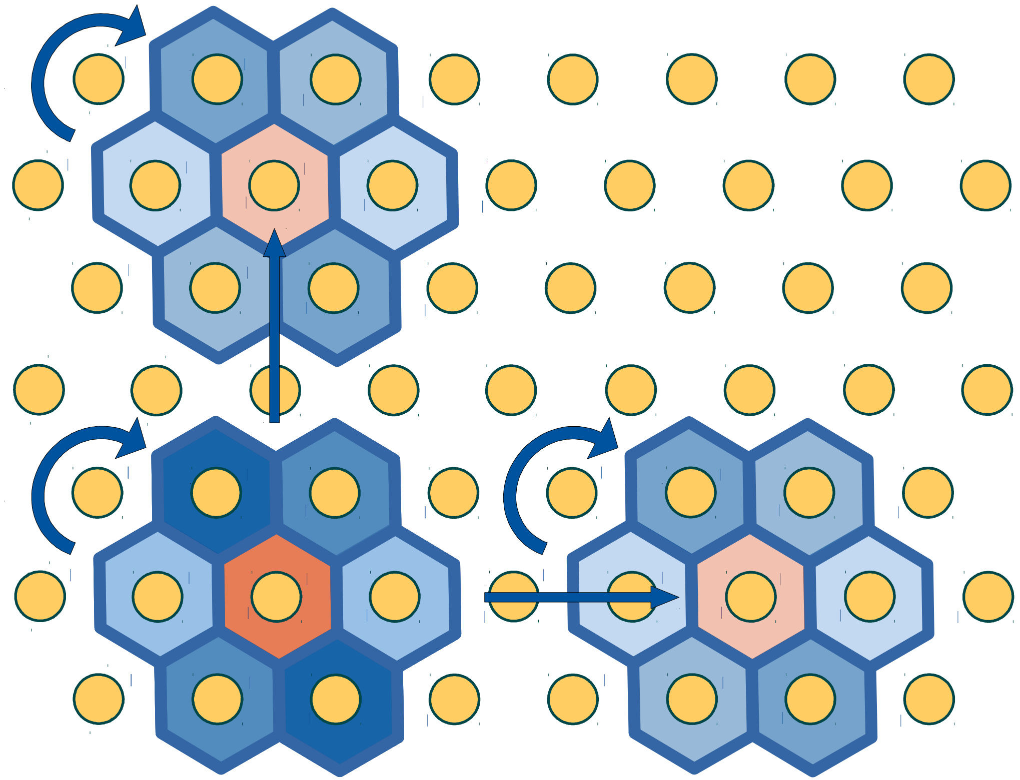
- **same network** (same weights) for each station
  - same kind of features (same color) per station (features e.g.: rising edge, falling edge, peaks ...)
  - but different characteristic → different strength

Erdmann, Glombitza, Walz
https://doi.org/10.1016/j.astropartphys.2017.10.006

Hexagonal Convolutions

measured air-shower footprint differs from image

➔ Cartesian vs. Hexagonal grid



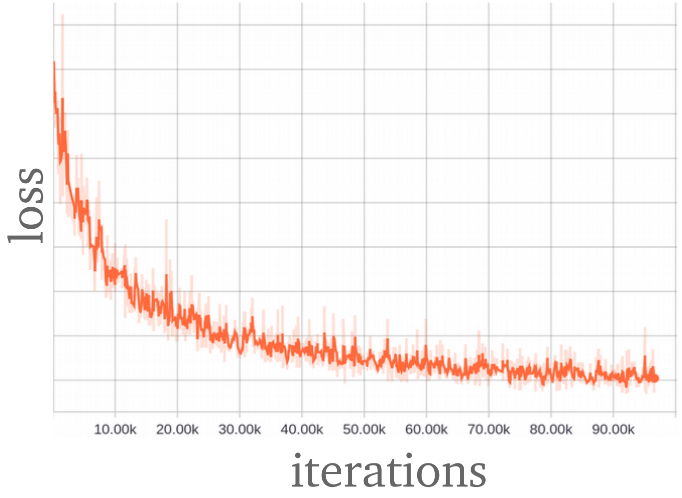
use symmetry of hexagonal grid

- find hexagonal clusters
- use **translational invariance**
  - similar patterns at different grid positions
- use **rotational invariance**
- similar patterns for showers from different arrival directions

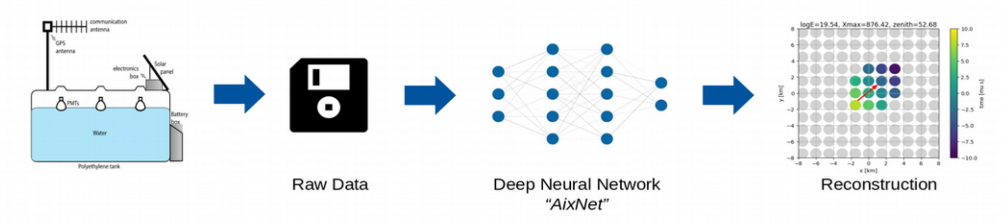
Hoogeboom, Peters, Cohen, Welling
ArXiv/1803.02108

AixNet

- ~ 1.5 million parameters
- training on GPU ~ 1-2 days
- *mimic different detector states*
  - *broken stations, broken PMTs*
  - *different saturation values*



Simulated shower data	**Epos LHC**
# Showers	800,000
Training	700,000
Validation	10,000
Test	90,000
Energy	18.0 – 20.2
Spectrum	E^{-1}
Composition	25% proton 25% helium 25% oxygen 25% iron
Zenith	0 – 65°



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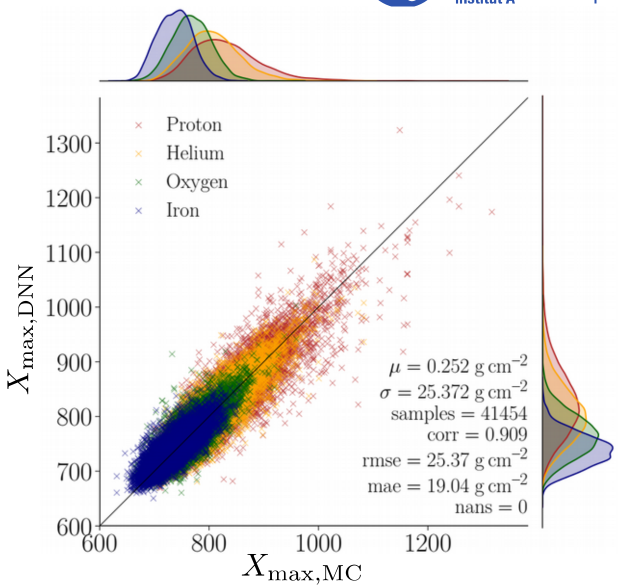
Evaluation – EPOS LHC

DNN trained using EPOS LHC

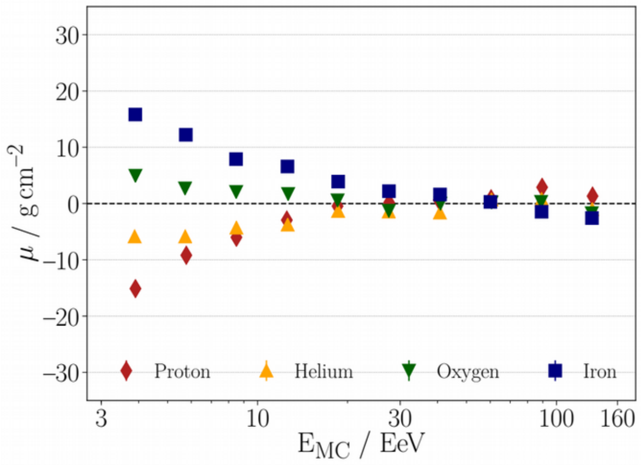
- evaluation using EPOS LHC

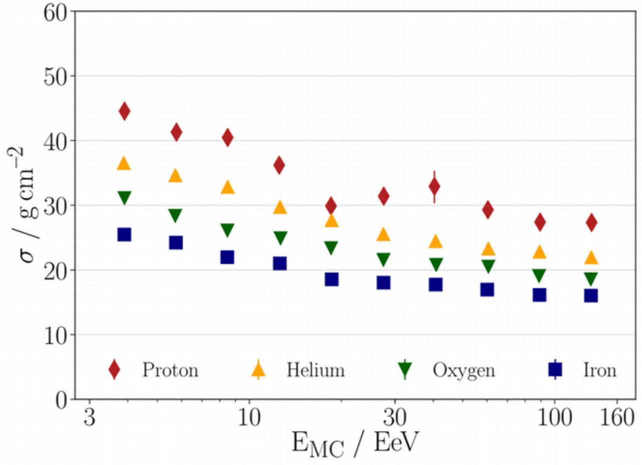
- performance improves with energy
- above 10-20 EeV
  - bias vanishes
  - proton resolution ~30 g/cm²
  - iron resolution ~20 g/cm²



Comparison:

- delta method
  - based on signal rise times
  - resolution of 45 g/cm²





Evaluation – Additional Interaction Models

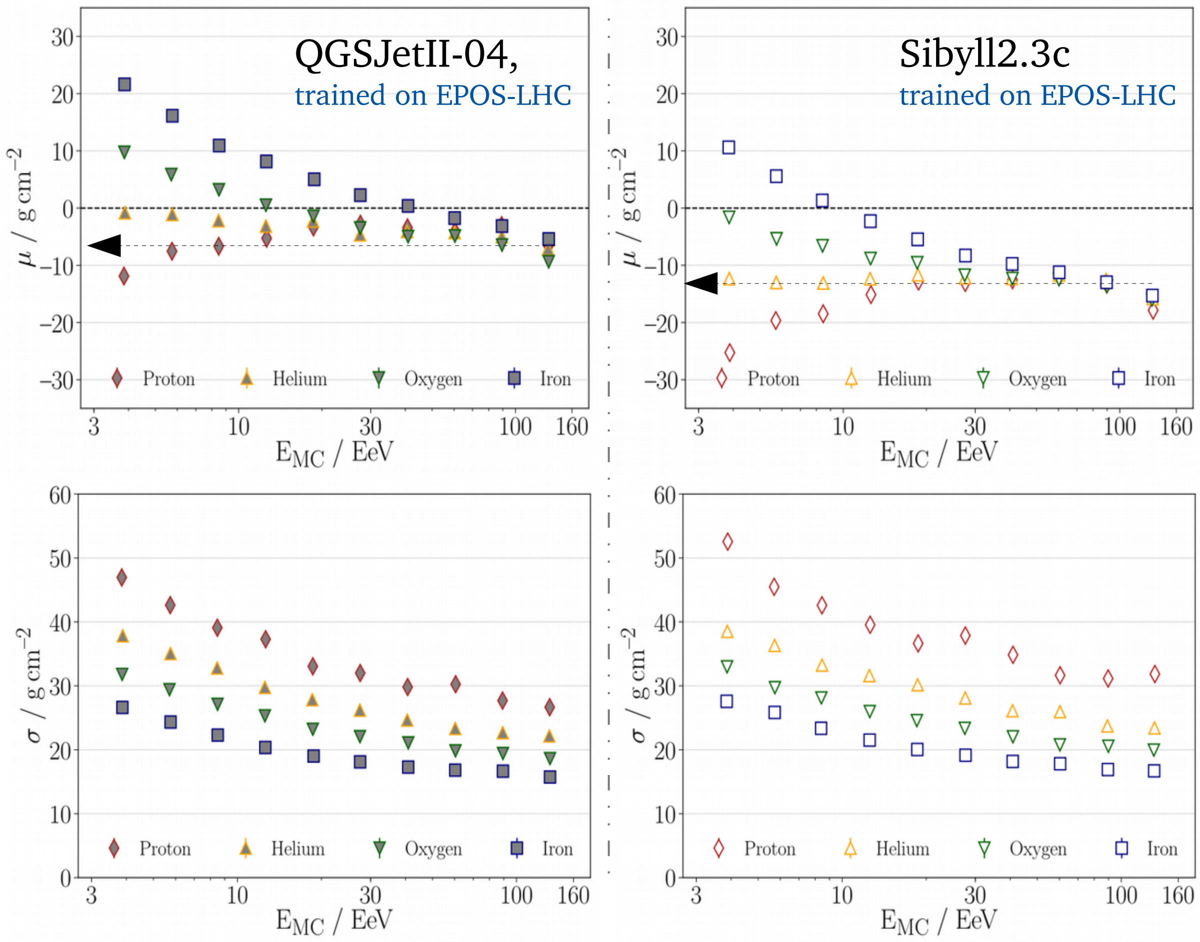
DNN trained using EPOS LHC

Evaluation using:

- QGSJET-II.04
- SIBYLL2.3c

- similar resolution
  - interaction model independent

- bias different
  - negative for both models
  - depends on interaction model



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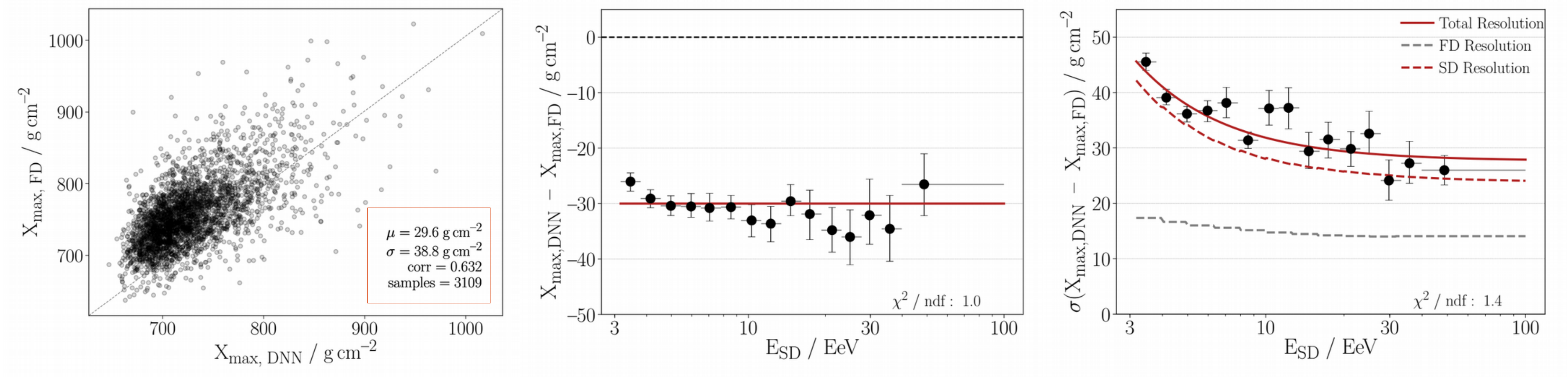
Application to Hybrid data

Golden Hybrids (absolute Xmax calibration)

- **correlation 0.63** (0.61 when corrected for elong. rate)
- **resolution matches** expectations, at 10 EeV below 30 g/cm²
- **-30 g/cm² bias** (hadronic models, detector simulation)
  - independent from energy! → perform calibration



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Summary

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(ArXiv/2101.02946)

Deep Learning at the Pierre Auger Observatory:

- extract mass-sensitive information using the SD → unprecedented statistics
- develop network that exploits symmetries of underlying structure (RNNs + CNN)
- dedicated data augmentation used, considering realistic-operation characteristics

- performance investigated on simulation (various interaction models)
  - resolution independent of used model
  - scale depends on used hadronic model
- method verified and calibrated using Fluorescence Detector observations
  - resolution matches expectations, at 10 EeV below 30 g/cm²
  - shift of -30 g/cm² bias (larger than expected, removed by calibration)

- **promising results to determine UHECR composition to the highest energies**

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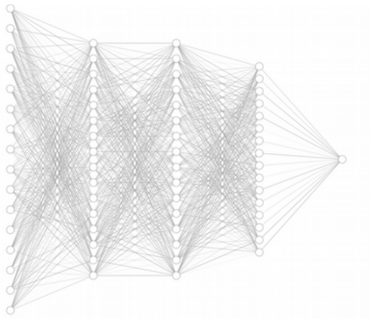
AixNet

Reconstruction of the Shower Maximum using the Water-Cherenkov Detectors of the Pierre Auger Observatory

Backup



Jonas Glombitza

May 11, 2021

Mass composition using Xmax

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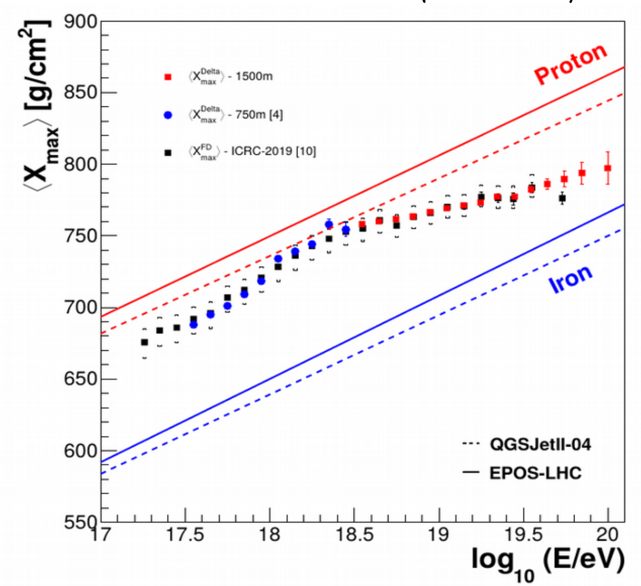
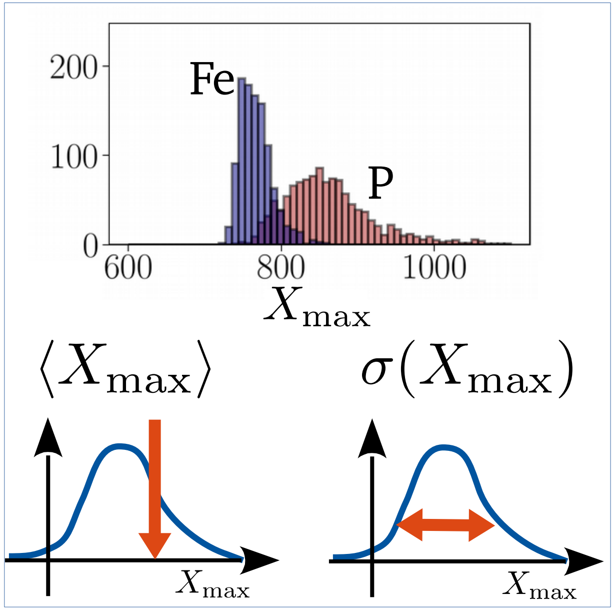
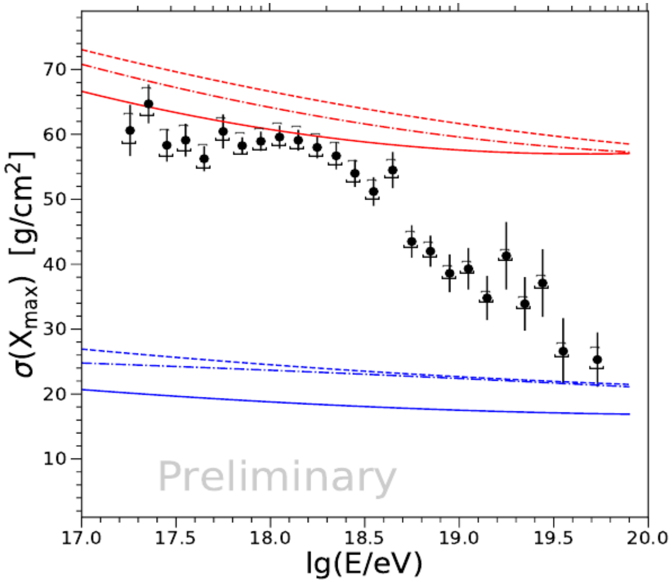
1st moment $\langle X_{\max} \rangle$



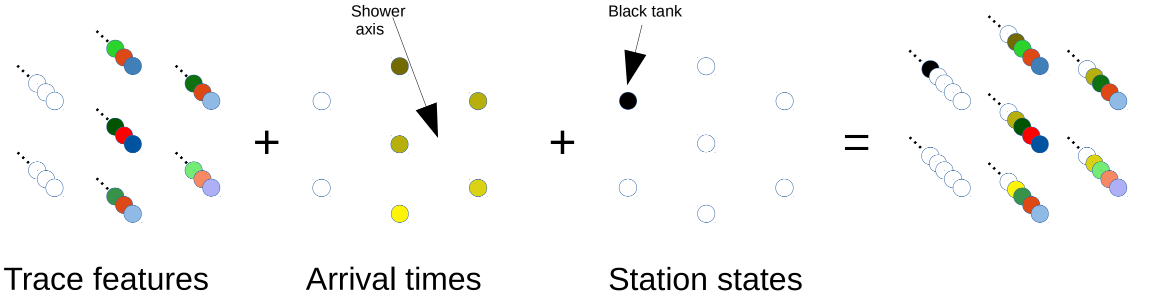


2nd moment $\sigma(X_{\max})$

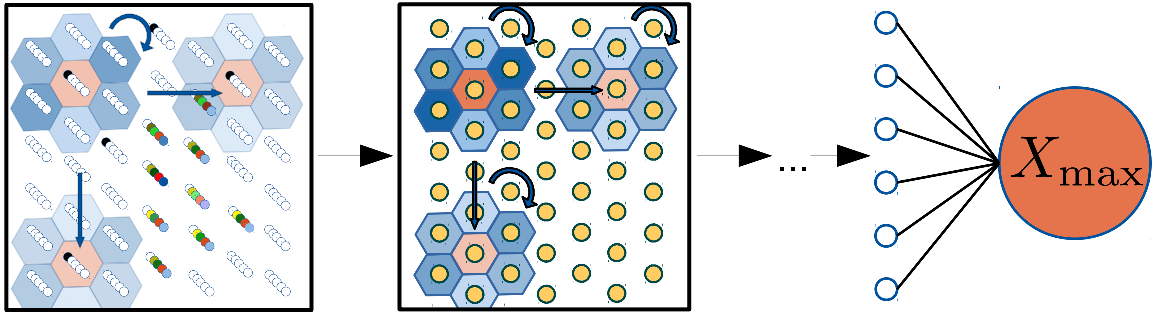


- measure average composition
  - reconstructed by delta method, FD
- distance P, Fe ≈ 100 g/cm²
- systematic ≈ 10 g/cm² >> statistical uncert.

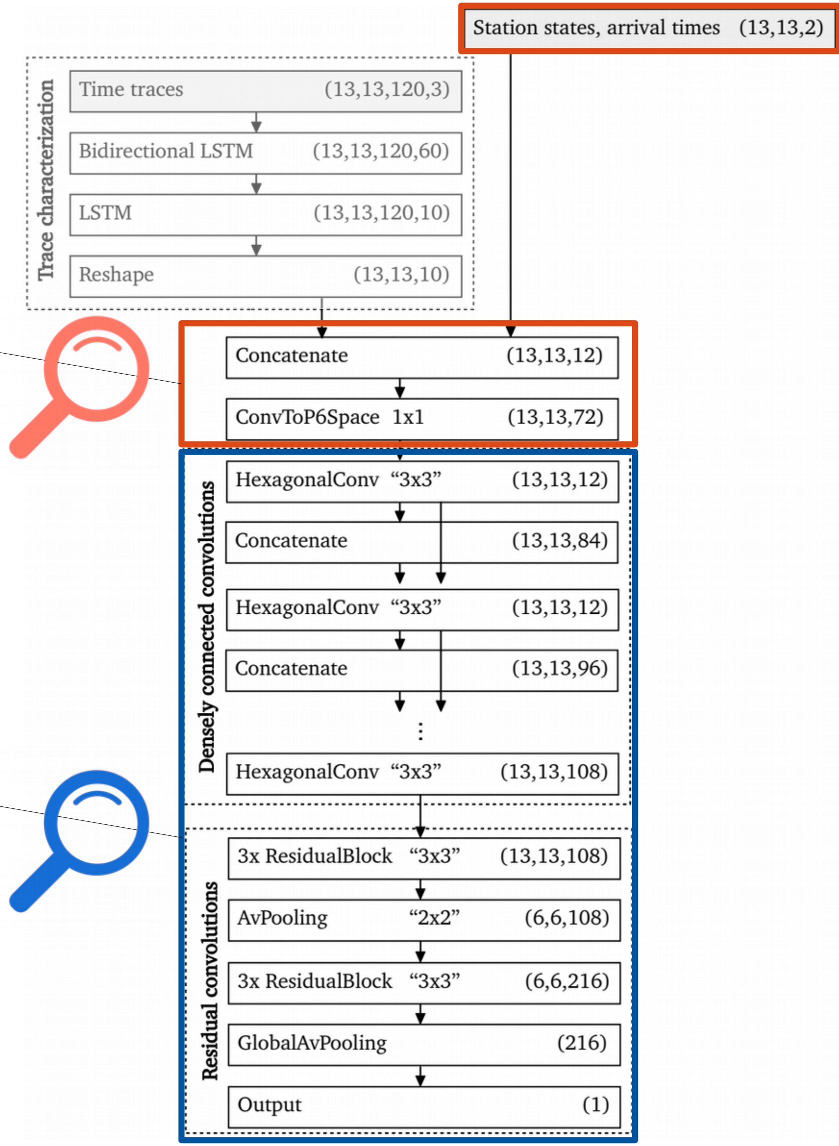
- measure composition mix
  - reconstructed using FD
- fluctuations 20-60 g/cm²
- uncert. statistically dominated



- add station states and arrival times to trace features



- hexagonal convolutions to combine features in space and time (DenseNet, ResNet)
- finally predict single Xmax value

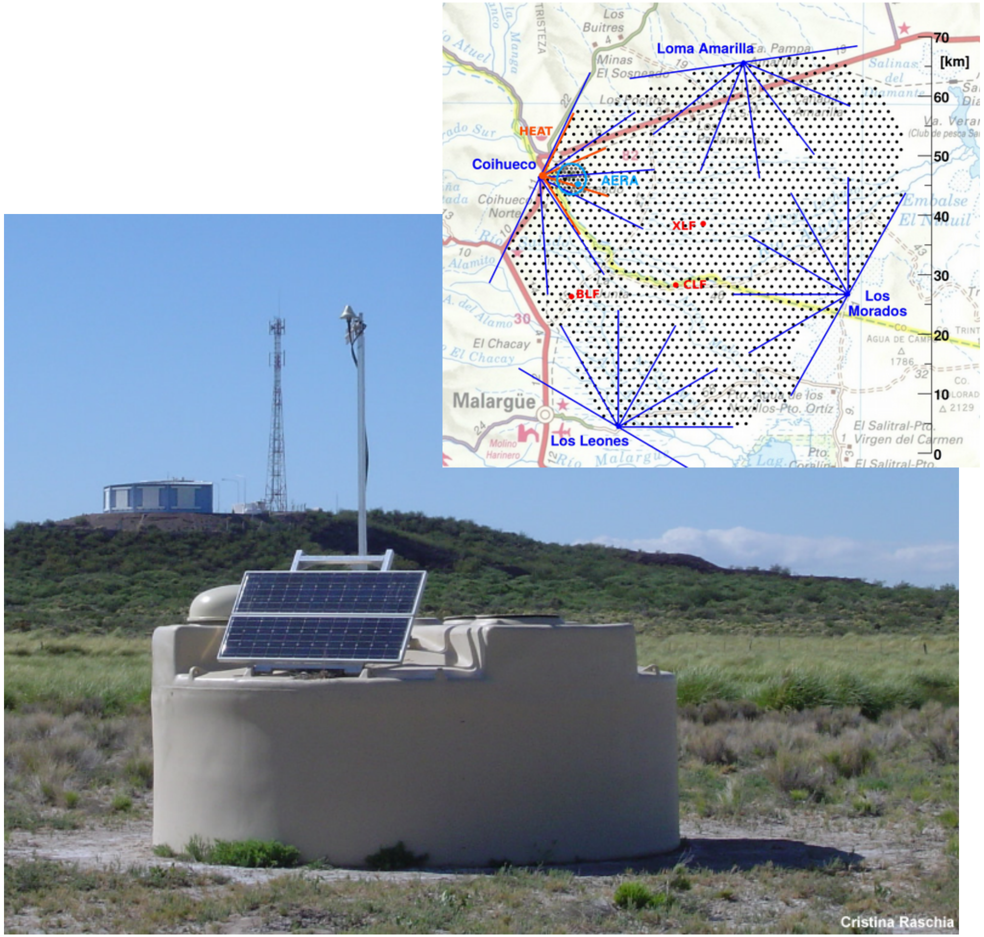


The Pierre Auger Observatory

- world largest cosmic-cay observatory
- placed in Argentina
- measure high-energetic particles
  - energy > 10^{17} eV
- study composition of cosmic rays
- search for cosmic-ray origins

hybrid measurements of UHECRs

- 27 fluorescence telescopes at 4 sites
  - 15% duty cycle
- 1660 water-Cherenkov stations
  - 3000 km² array, ~100% duty cycle



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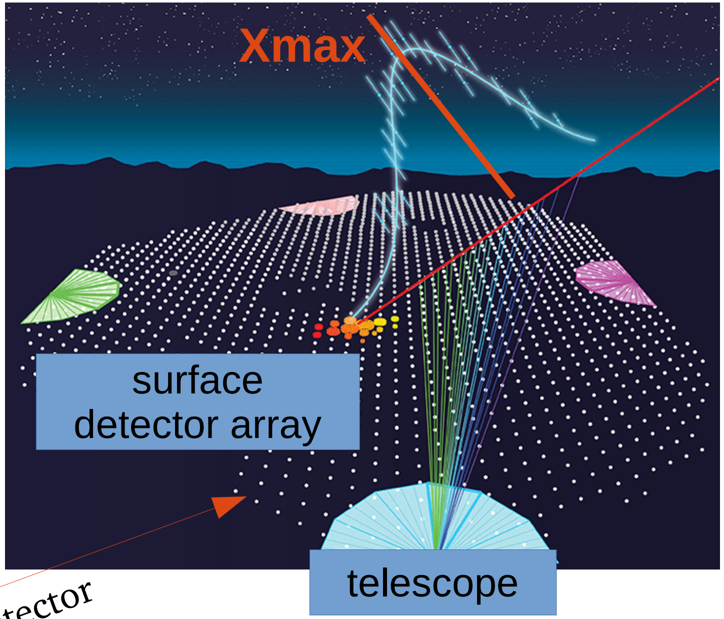

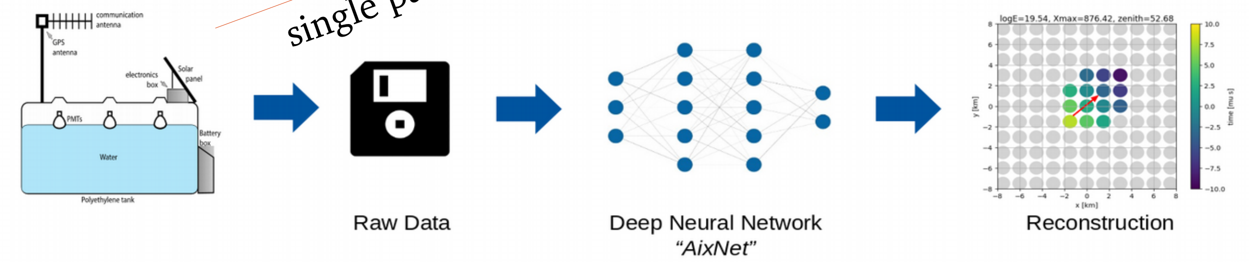

ArXiv:2101.02946

Training and Verification of the Network

- neural network trained on simulated air showers
  - utilizes LSTMs to process time-dependent signals
  - analyzes pattern of triggered detectors
    using hexagonal convolutions
  - trained by considering real-operation characteristics
- performance extensively investigated
  - studied on simulations (various interaction models)
  - verified and calibrated using observations of the Fluorescence Detector (FD)
- promising results to determine UHECR composition to the highest energies using deep learning

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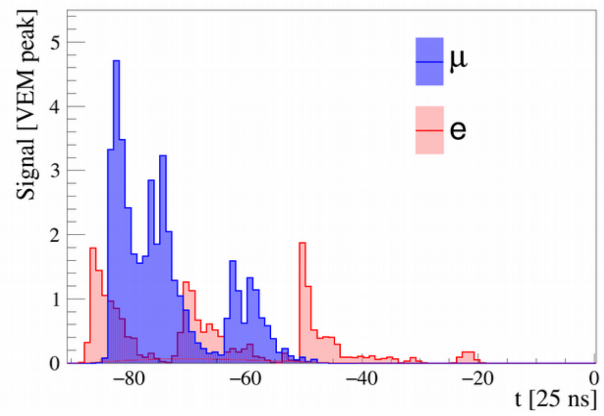
signal measured at single station



verification using fluorescence observations