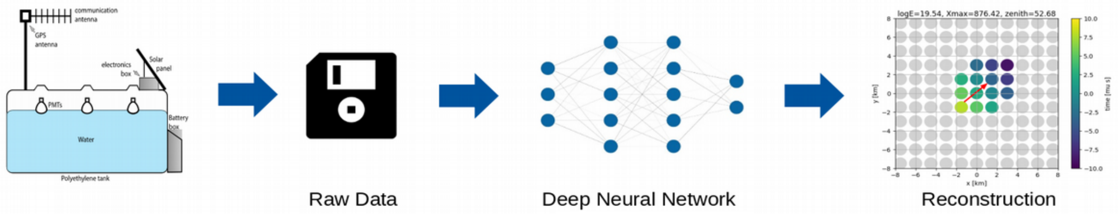
Cosmic Ray Indirect – Contribution 915

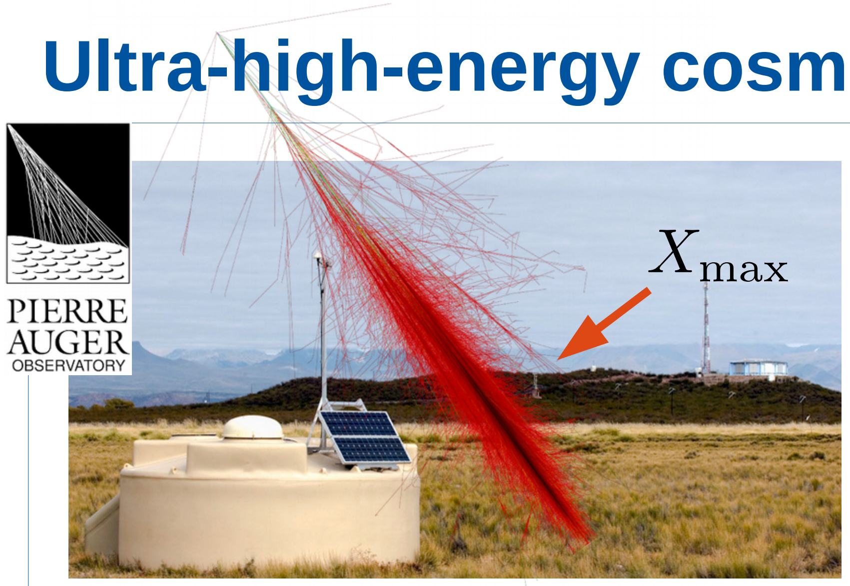
Event-by-event reconstruction of Xmax with the Surface Detector of the Pierre Auger Observatory using deep learning



Jonas Glombitza on behalf of the Pierre Auger Collaboration

PoS(ICRC2021)359

Ultra-high-energy cosmic rays (UHECRs)

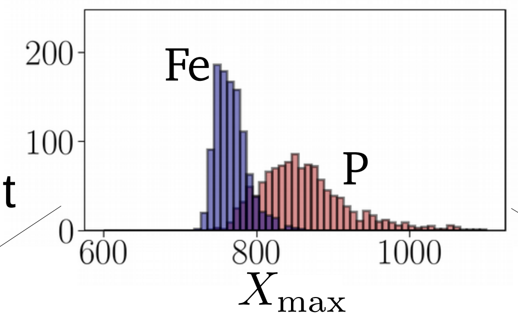


The Pierre Auger Observatory

- world's largest observatory to study ultra-high-energy cosmic rays
- hybrid detection of air showers
  - 1,660 water-Cherenkov detectors
  - 27 fluorescence telescopes

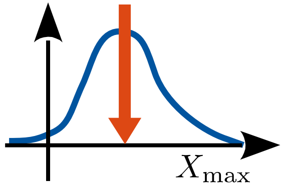
Mass composition of UHECRs

- currently: most precise mass estimate by reconstructing shower maximum $X_{\max}$
- determine composition by studying the measured $X_{\max}$ distributions



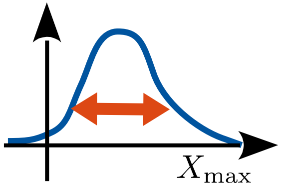
1st moment

$\langle X_{\max} \rangle$



2nd moment

$\sigma(X_{\max})$



Reconstructing the shower maximum Xmax

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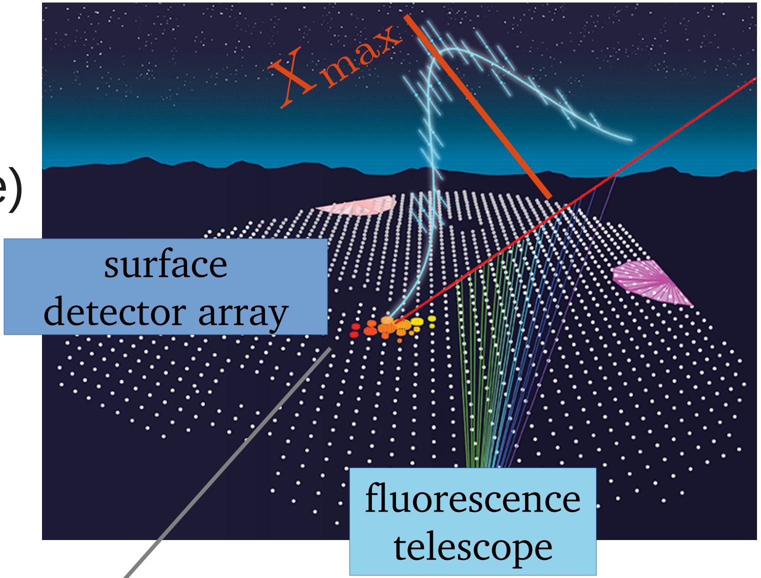
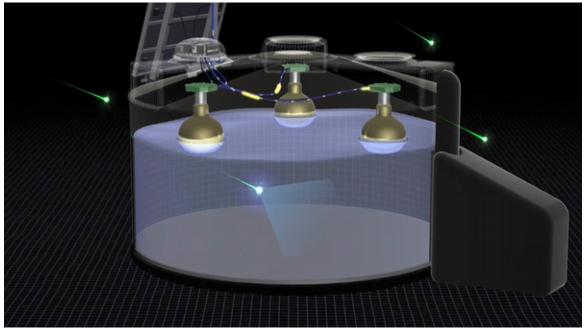
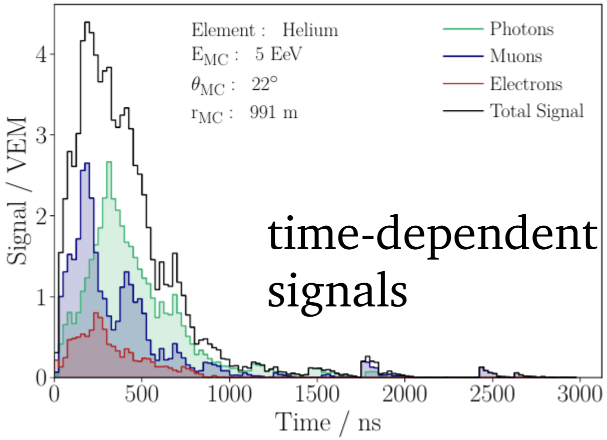
- precise observation of X_{max} using fluorescence telescopes
  - observations confined to dark nights (15% duty cycle)
- challenging to measure with surface detector (SD)
  - no direct observation of X_{max} possible
  - measured time-dependent signals encode information about air-shower development
  - → use deep learning to estimate X_{max}





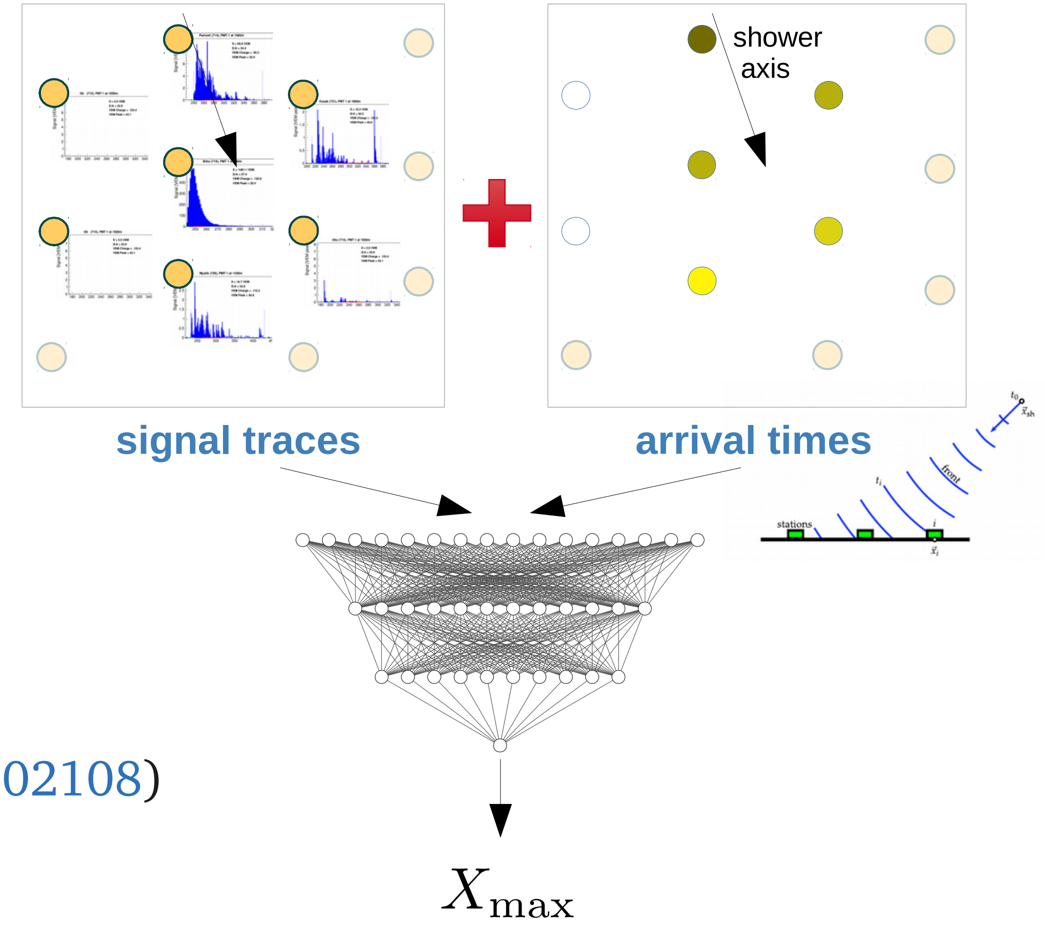


Deep-learning based reconstruction of Xmax using the Surface Detector

SD provides measurement of:

- time-dependent signals
- arrival time of first shower particles

➔ use deep neural network to reconstruct shower maximum



Reconstruction strategy:

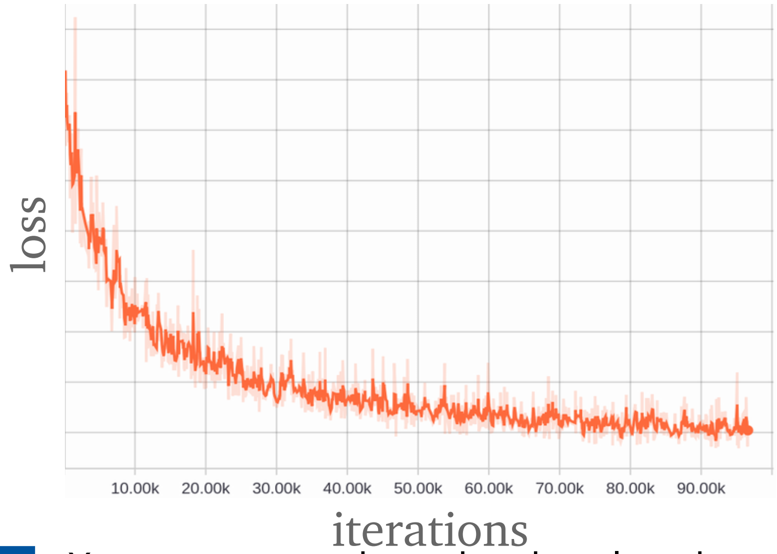
(1) process time-dependent signal traces using recurrent networks (LSTMs)

(2) process shower footprint

➔ exploit symmetry of the SD using hexagonal convolutions (ArXiv/1803.02108)

Network training

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



	Epos LHC
# Showers	800,000
Training	700,000
Validation	10,000
Test	90,000
Energy $\log_{10}(E/\mathrm{ev})$	18.0 – 20.2
Spectrum	E^{-1}
Composition	25% proton 25% helium 25% oxygen 25% iron
Zenith	0 – 65°

DNN trained on EPOS-LHC only!

Validate on EPOS-LHC, QGSJetII-04, Sibyll2.3c

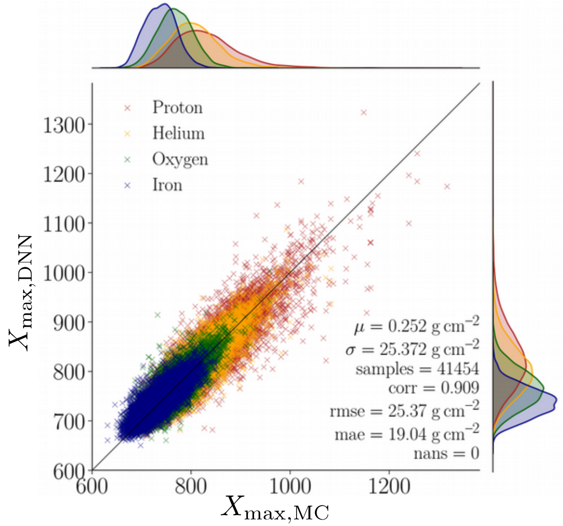
Evaluation – EPOS-LHC

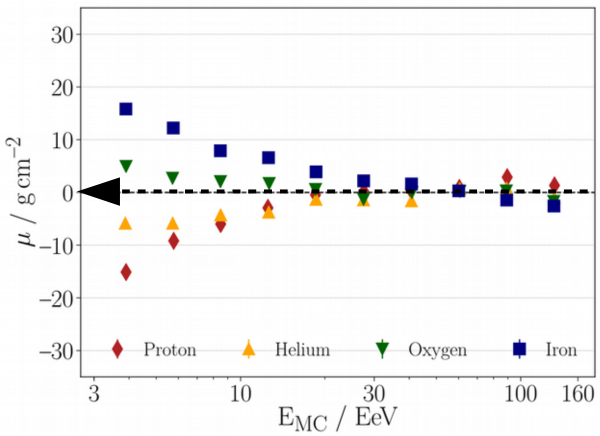
DNN trainined using EPOS-LHC

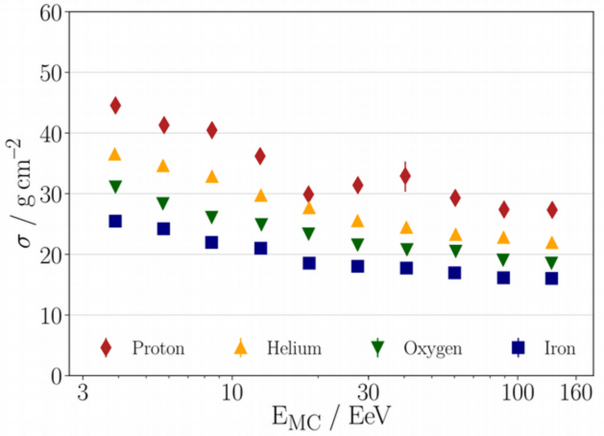
- evaluation using EPOS-LHC

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

- averaged among compositions
  - overall bias ~ 0 g/cm²







Evaluation - additional interaction models

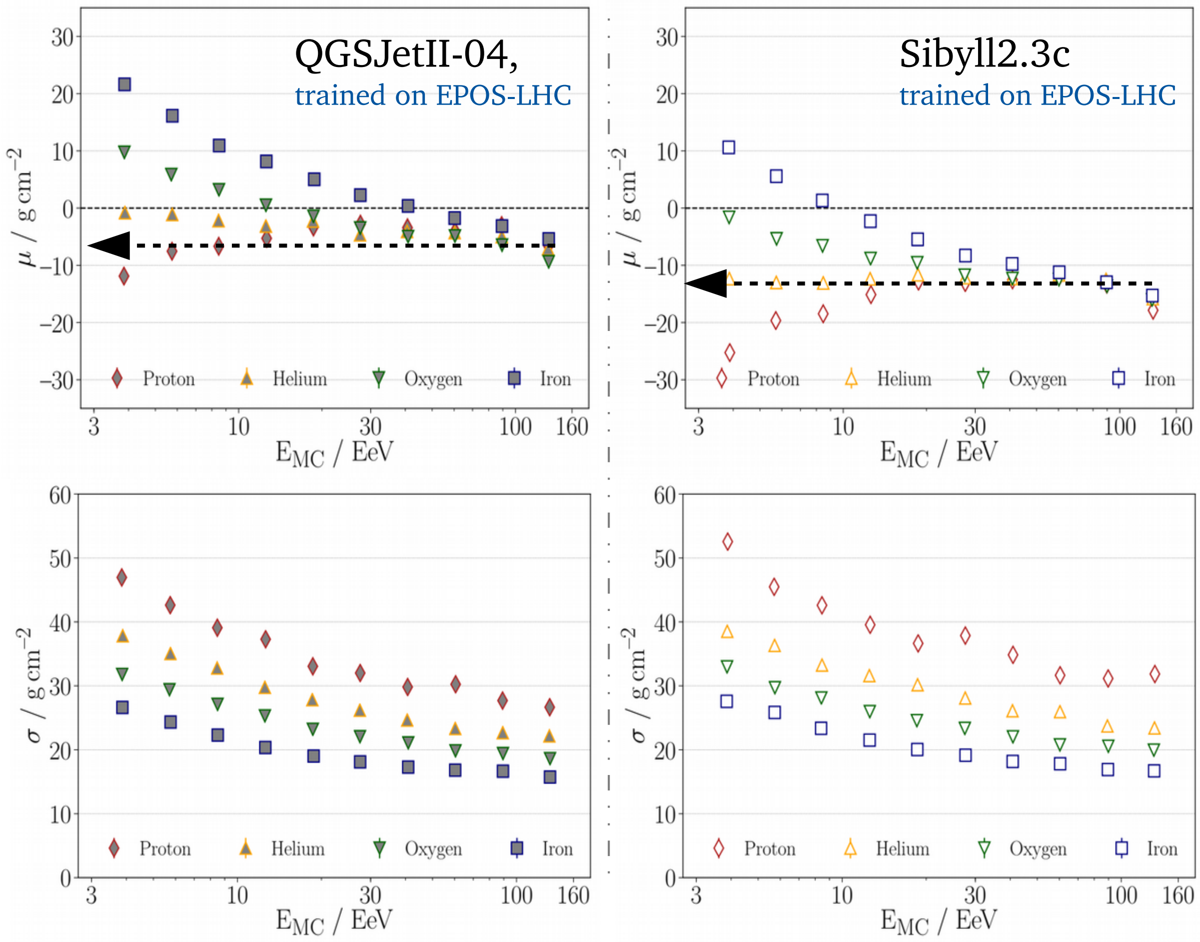
DNN trained using EPOS-LHC

Evaluation using:

- QGSJET-II.04
- SIBYLL2.3c

- similar resolution
  - interaction model independent

- bias different
  - mean negative for both models
  - Xmax scale of the DNN depends on interaction model



Reconstructed Xmax distributions

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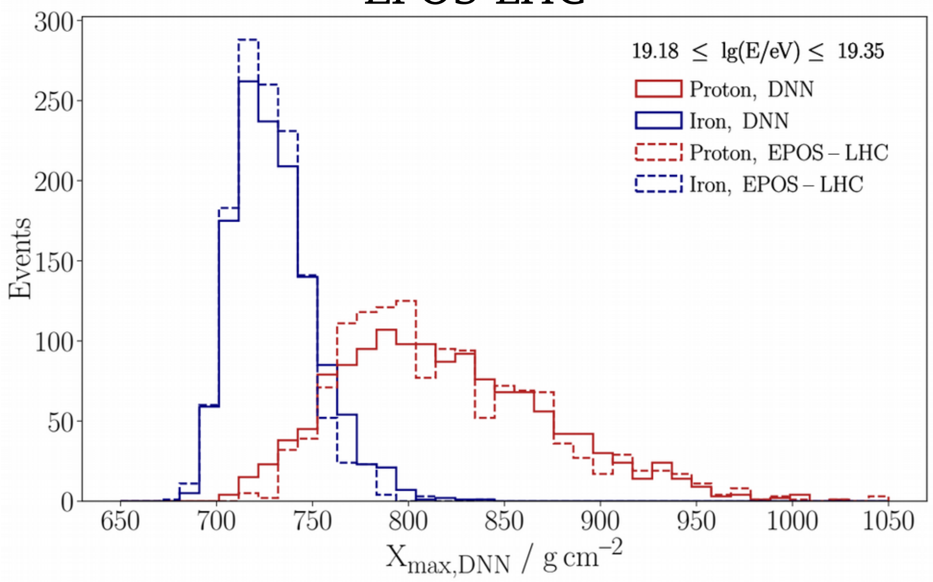
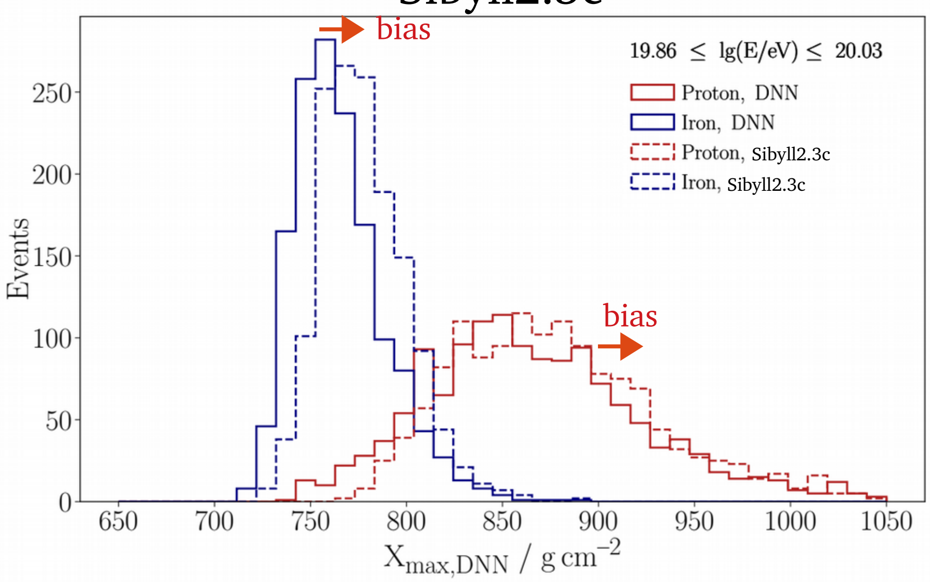
- check reconstructed Xmax distributions for various hadronic models
- absolute bias clearly visible, as expected (Sibyll2.3 = -15 g/cm²)
- overall shape reconstructed correctly

➔ calibration to X_{max}-scale of the FD needed for measuring X_{max} distributions

EPOS-LHC



Sibyll2.3c

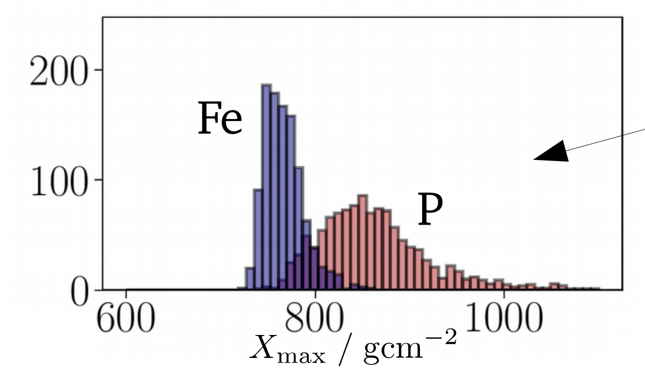


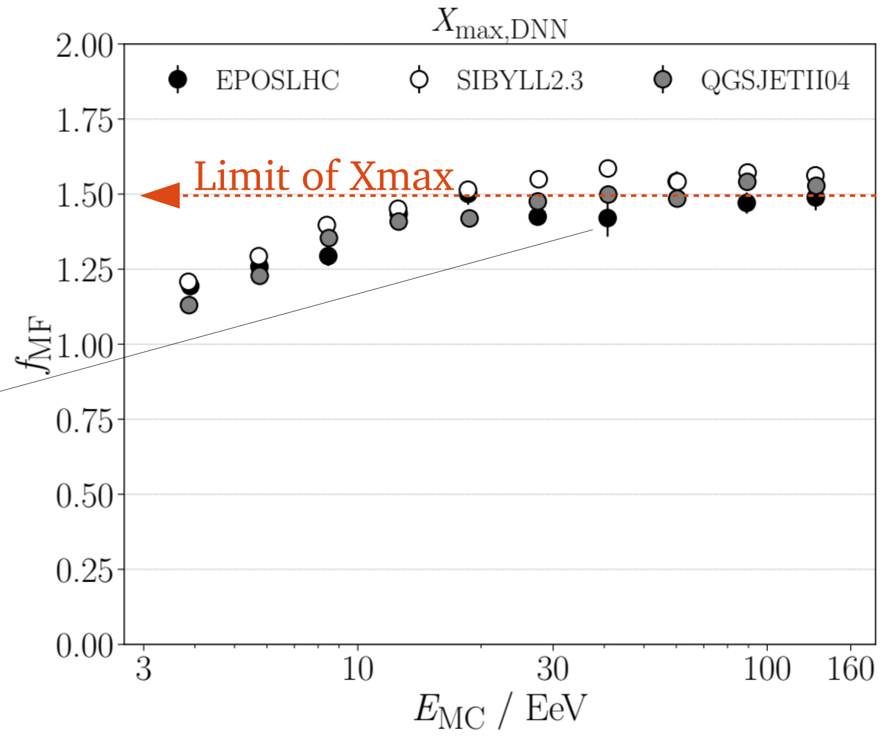
Event-wise composition measurements

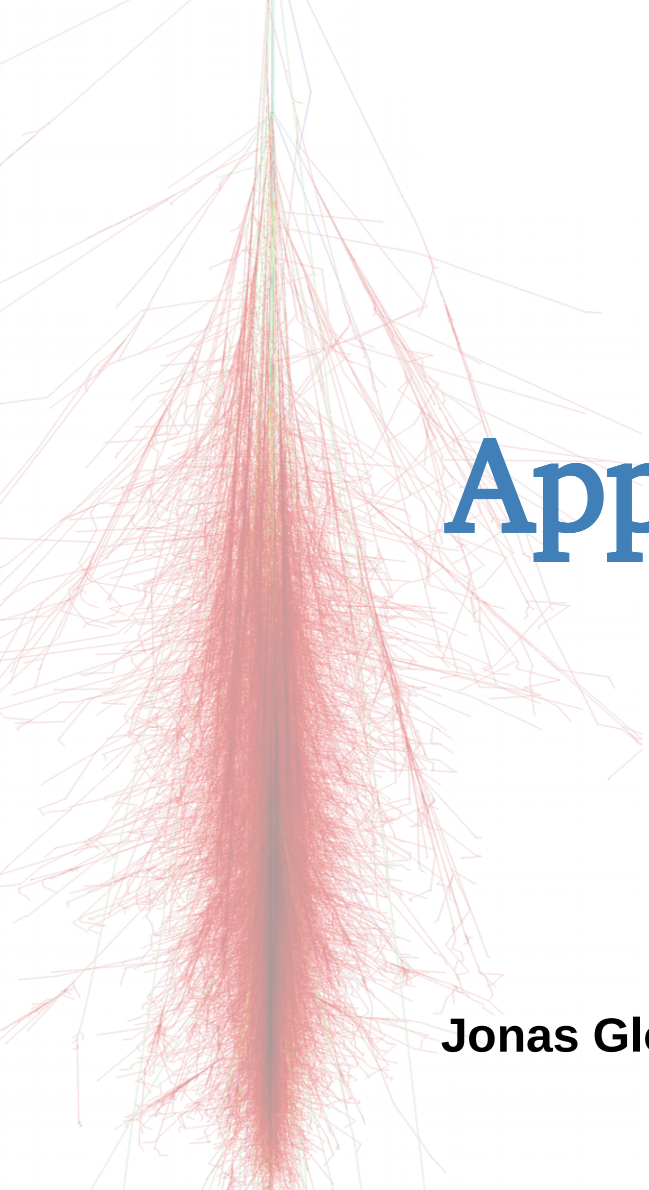
Merit factor for discriminating between proton and iron

$$f_{\mathrm{MF}} = \frac{|\langle X_{\mathrm{max,P}}\rangle - \langle X_{\mathrm{max,Fe}}\rangle|}{\sqrt{\sigma^2(X_{\mathrm{max,P}}) + \sigma^2(X_{\mathrm{max,Fe}})}}$$

- merit factor of simulated $X_{\mathrm{max,MC}}$ ~ 1.5
- DNN merit factor increases with energy
  - above 10 EeV, merit factor = 1.5
  - good separation for all interaction models







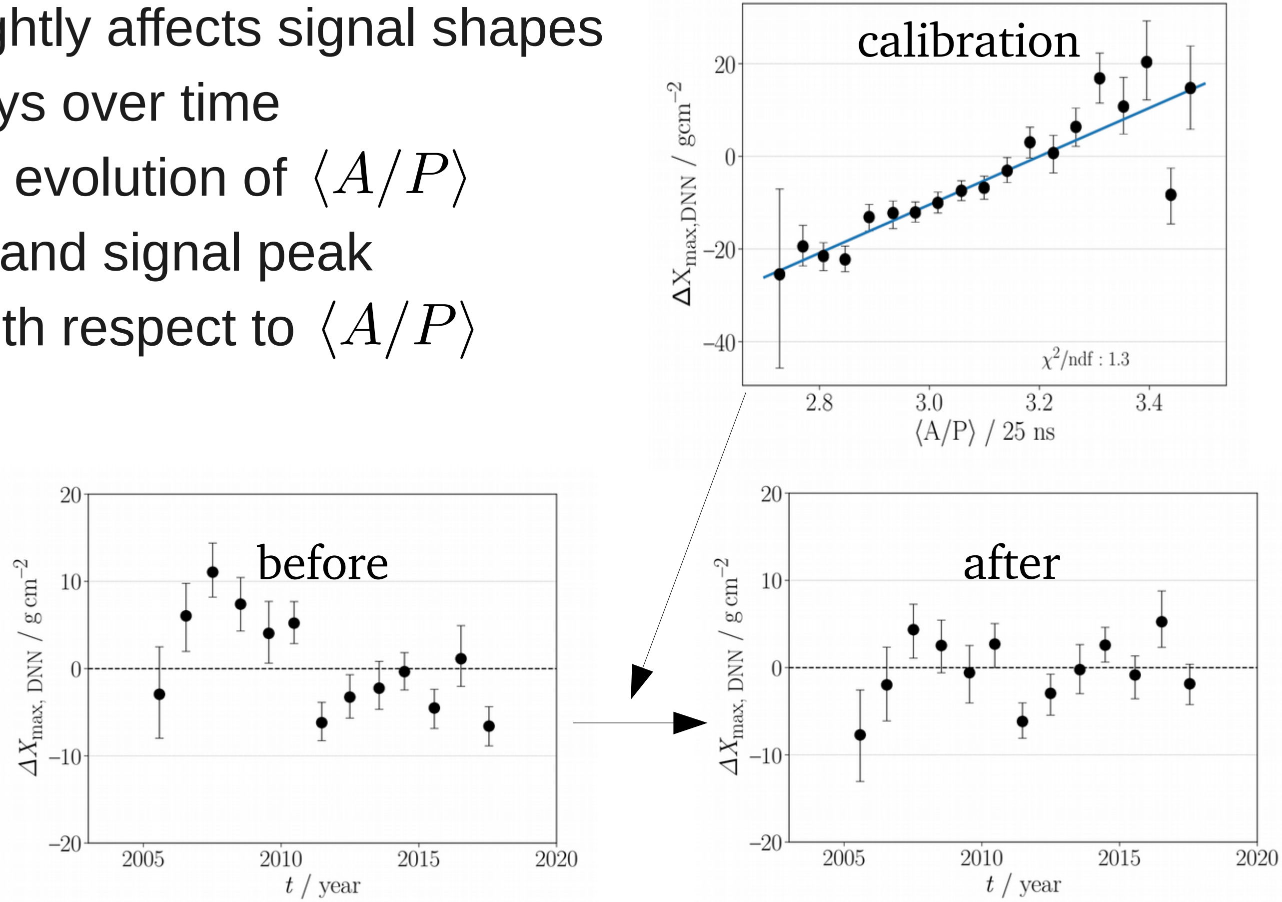
Application to hybrid data

Jonas Glombitza on behalf of the Pierre Auger Collaboration

Calibration to account for detector ageing

Ageing of detector stations slightly affects signal shapes

- width of muon signals decays over time
- detector monitoring records evolution of $\langle A/P \rangle$
  - ratio between signal area and signal peak
- perform linear calibration with respect to $\langle A/P \rangle$
  - ageing effect removed

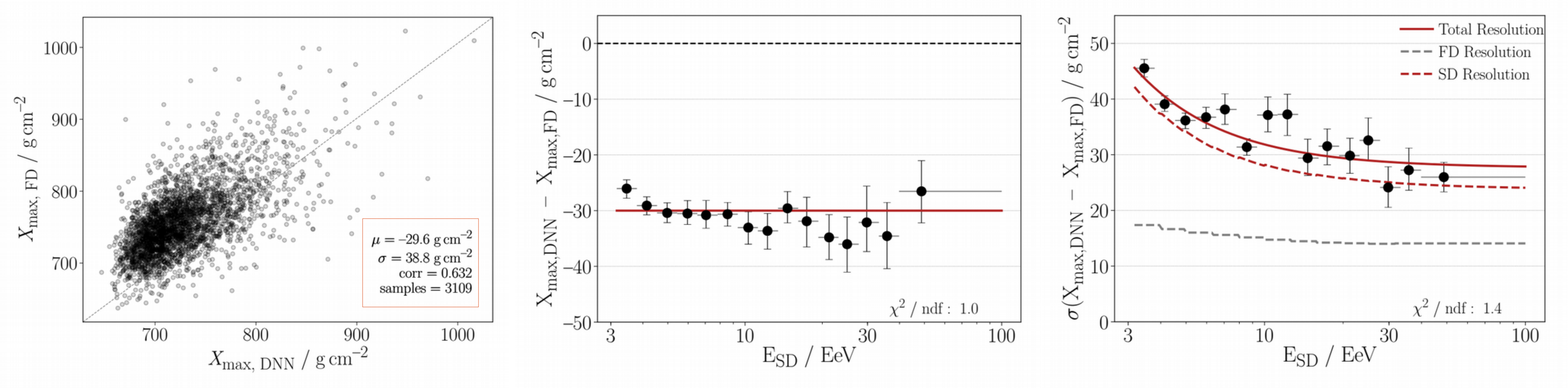


Long Term Performance of the Pierre Auger Observatory
https://doi.org/10.22323/1.358.0222

Application to measured hybrid data

Use hybrid events to perform calibration to the FD $X_{\max}$ scale

- **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 of energy → perform calibration



ArXiv/2101.02946

Conclusion

Deep-learning based reconstruction of $X_{\max}$ using the SD (ArXiv/2101.02946)

- reconstruction extensively studied on various hadronic interaction models
  - $X_{\max}$-bias depends on interaction model used
- event-by-event resolution independent of interaction model
- performance validated on golden hybrids
  - bias of -30 g/cm² observed → DNN calibrated to the FD $X_{\max}$ scale
  - observed resolution meets expectations from simulation studies

- very promising results to measure $X_{\max}$ -distributions to the highest energies
  - → new insights into the UHECR composition at highest energies!
  - → new prospects for analyses requiring event-by-event estimation of primary mass

- AugerPrime will allow for additional cross-checks and improvements

PIERRE AUGER OBSERVATORY

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany 37th International Cosmic Ray Conference 12–23 July 2021

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Event-by-event reconstruction of Xmax with the Surface Detector of the Pierre Auger Observatory using deep learning

Backup

Jonas Glombitza on behalf of the Pierre Auger Collaboration

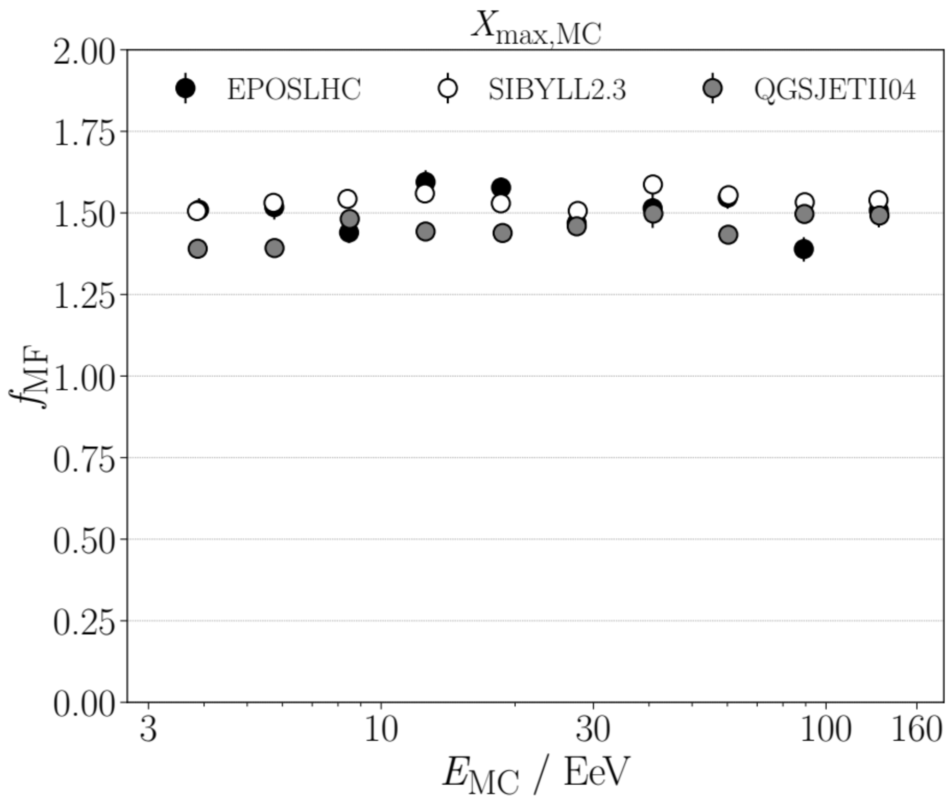
Data

- Data from 01.01.2004 till 31.8.2018

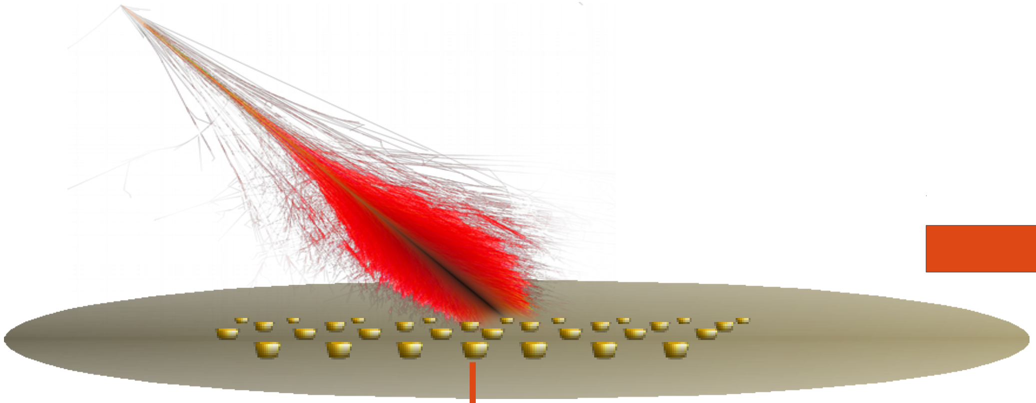
- **SD selection**
  - $\log_{10}(E/eV) > 18.5$
  - Zenith angles below 60 degrees
  - Only events in which the station with the highest signal is surrounded by a hexagon of operating stations
  - include events with saturated stations
- **FD selection**
  - Same as used for the X_{max} measurements with the FD

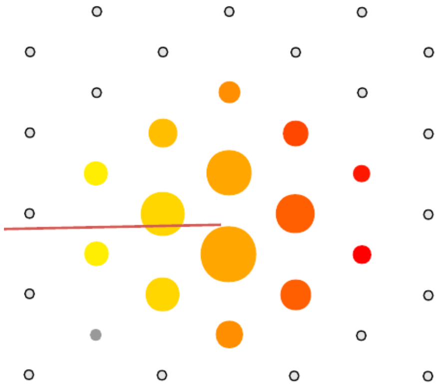
➔ Full sample: 3124 events

Merit factor for the simulated Xmax

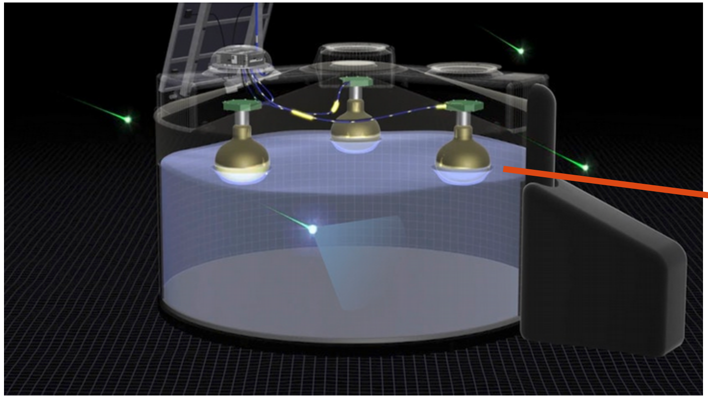


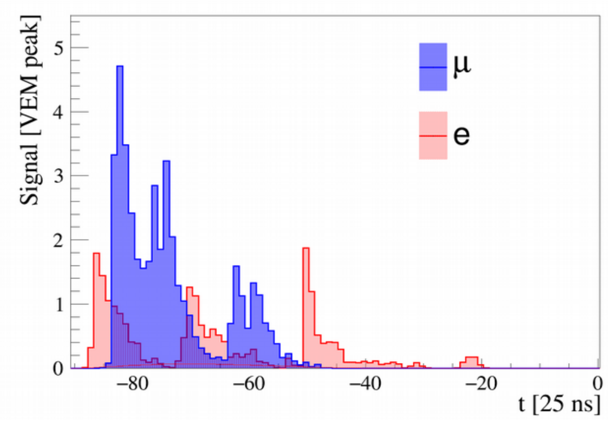
Air-Shower Detection





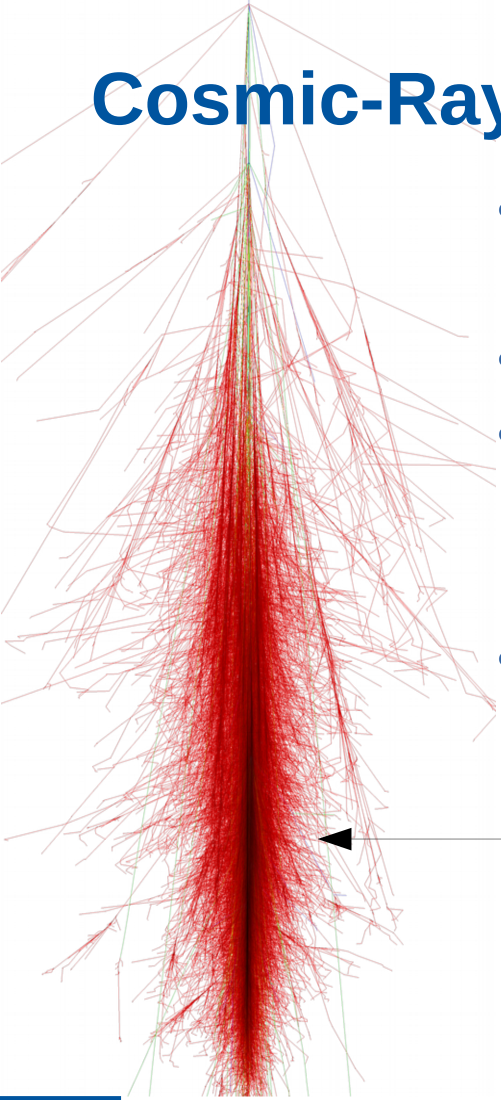
air-shower footprint





signal traces → time series (audio)

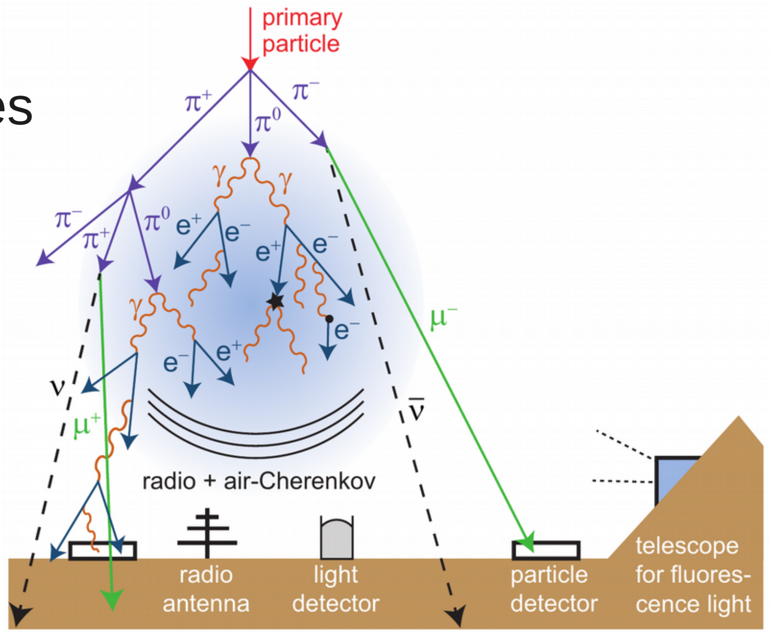
Cosmic-Ray induced Air Showers



- 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

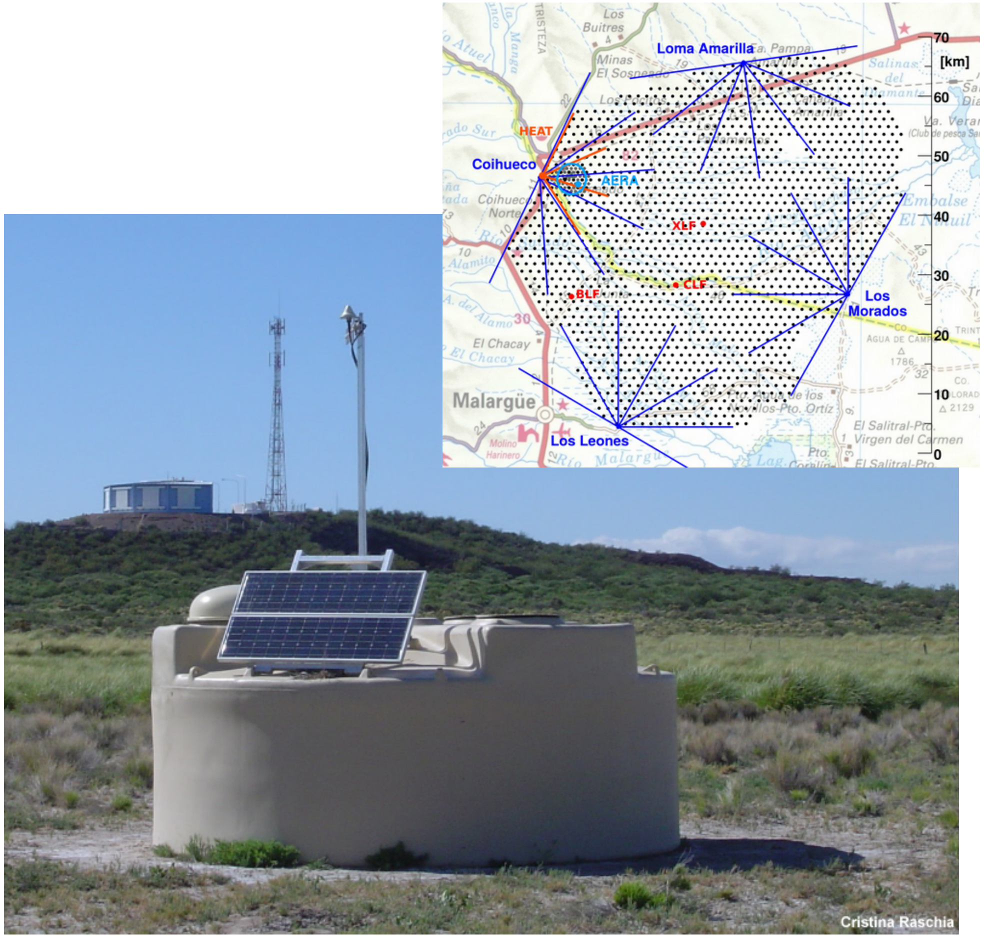
shower maximum correlates with primary mass

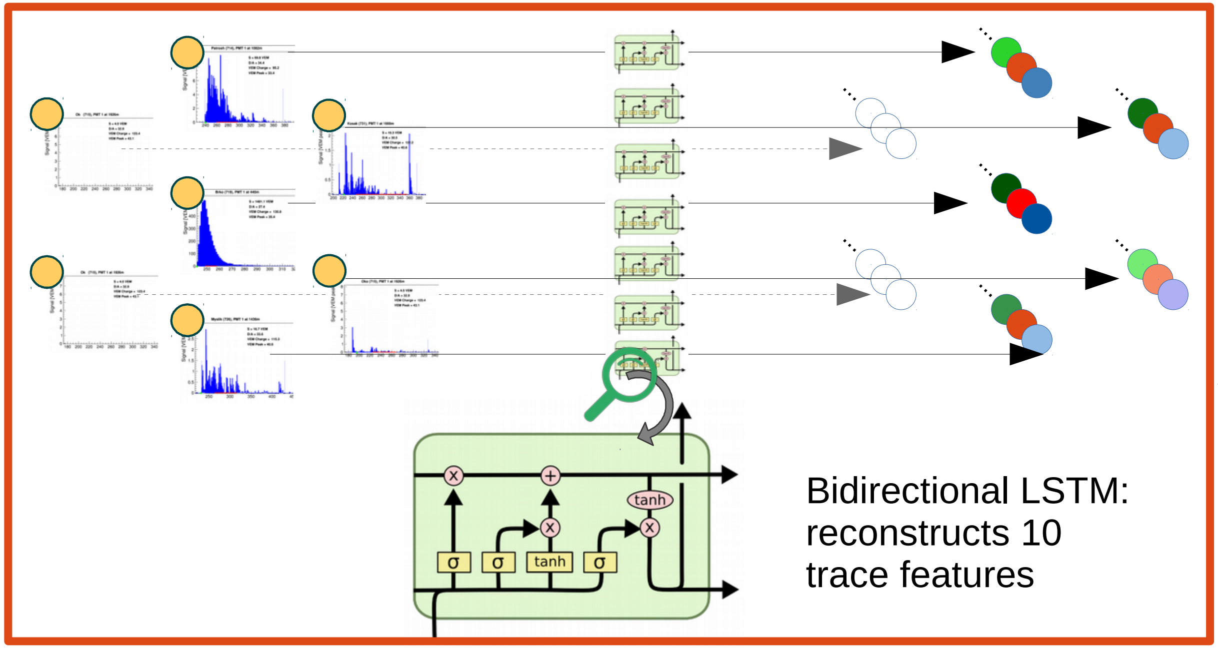


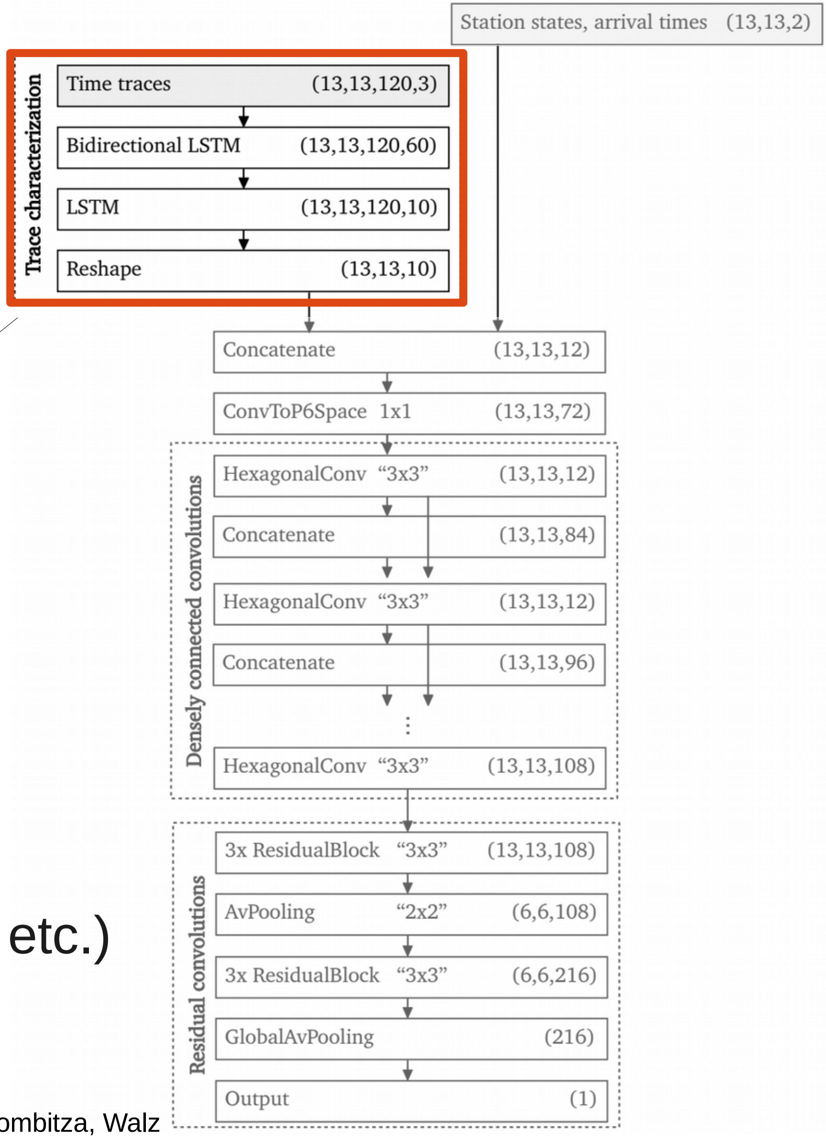
The Pierre Auger Observatory

- world's 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



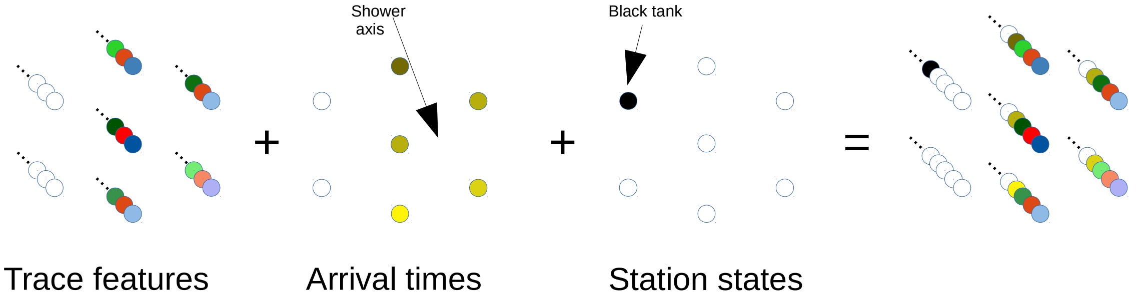




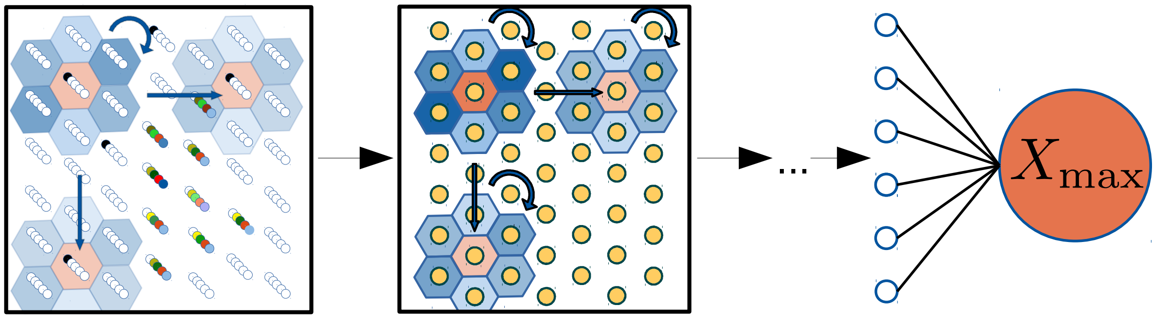
RNN part extracts trace features

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

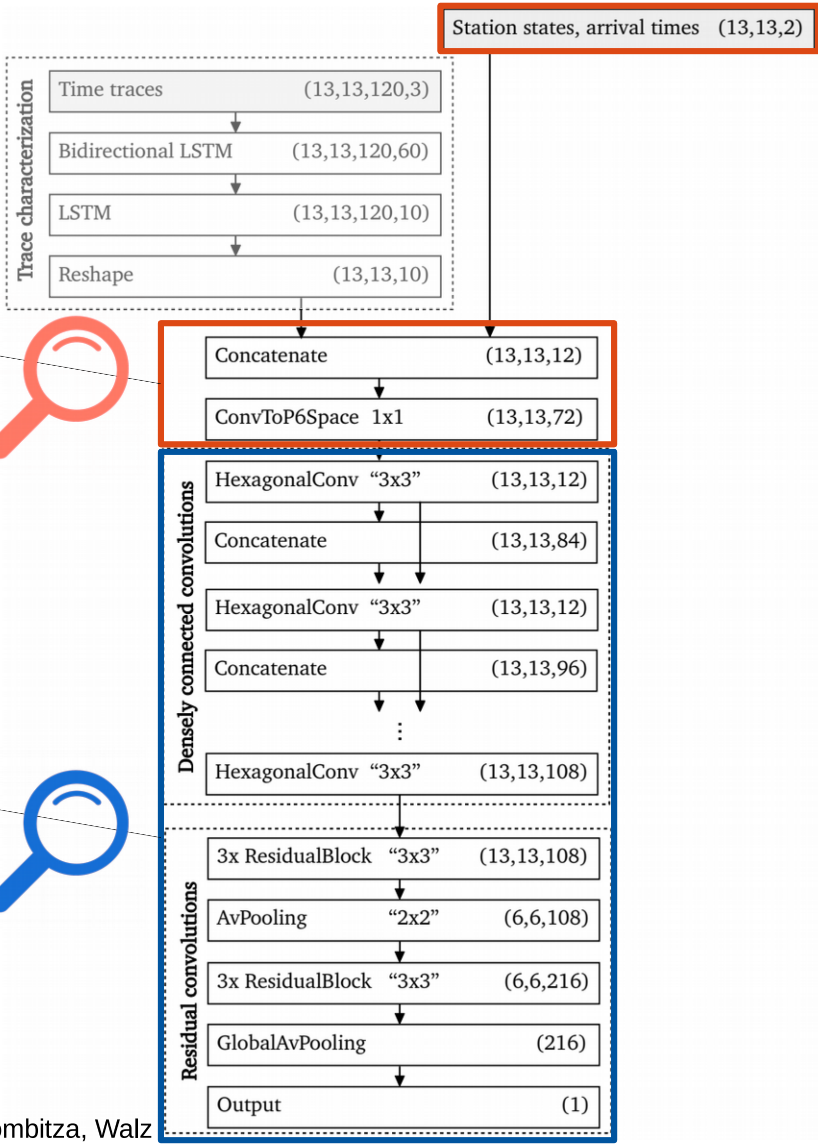
Erdmann, Glombitza, Walz
https://doi.org/10.1016/j.astropartphys.2017.10.006



- add station states and arrival times to trace features



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



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