Extraction of the Muon Signals Recorded with the Surface Detector of the Pierre Auger Observatory Using Recurrent Neural Networks

Juan Miguel Carceller[a] on behalf of the Pierre Auger Collaboration[b]

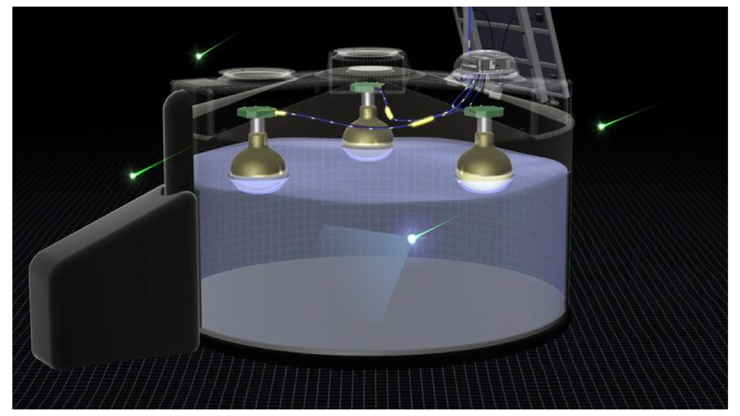
[a] University of Granada, Granada, Spain

[b] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

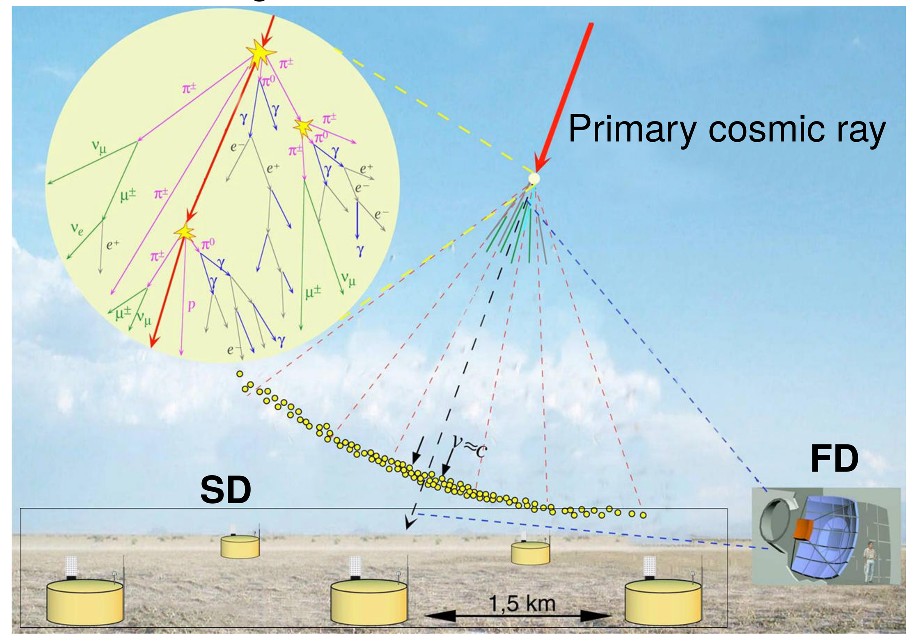
CRI-229
PoS(ICRC2021)

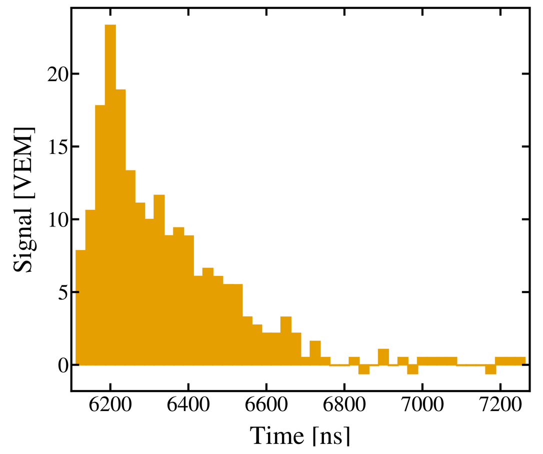
Ultra-High Energy Cosmic Rays with The Pierre Auger Observatory

- **Hybrid detector**: Combined measurements of the particle density with the Surface Detector (SD) and longitudinal shower profiles with the Fluorescence Detector (FD)
- SD: More than 1600 surface detectors covering an area of 3000 km^2 that measure Cherenkov radiation emitted by particles of the extensive air shower
- FD: 27 fluorescence telescopes measure the light emitted by atmospheric nitrogen



- Each SD station has three photomultiplier tubes looking into the water

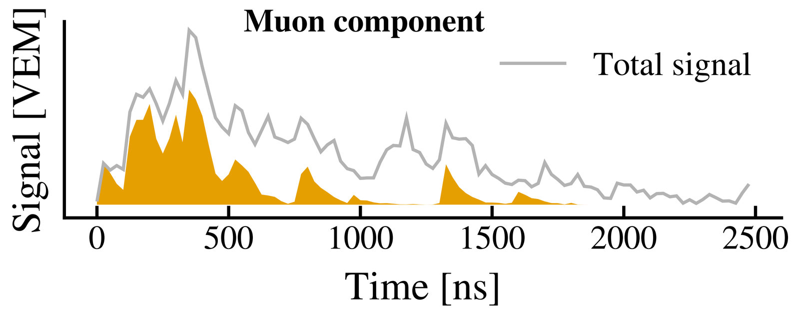




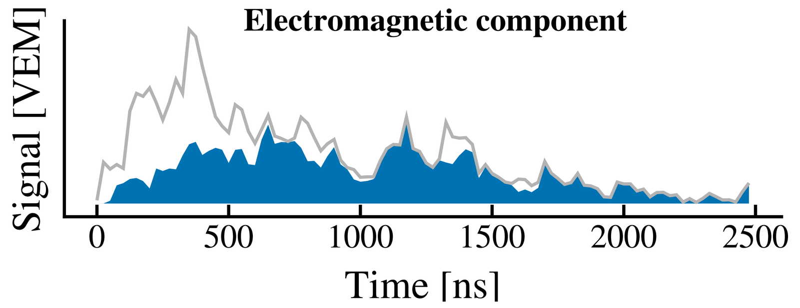
- The signal is measured in VEMs (Vertical Equivalent Muons)

The Muon Component

- With the baseline design of the SD, the muon component cannot be separated efficiently for all events
- The muon component is an interesting physical observable because it gives us **hints about the mass** of the primary cosmic ray



- Muon component in an SD station from a simulated shower

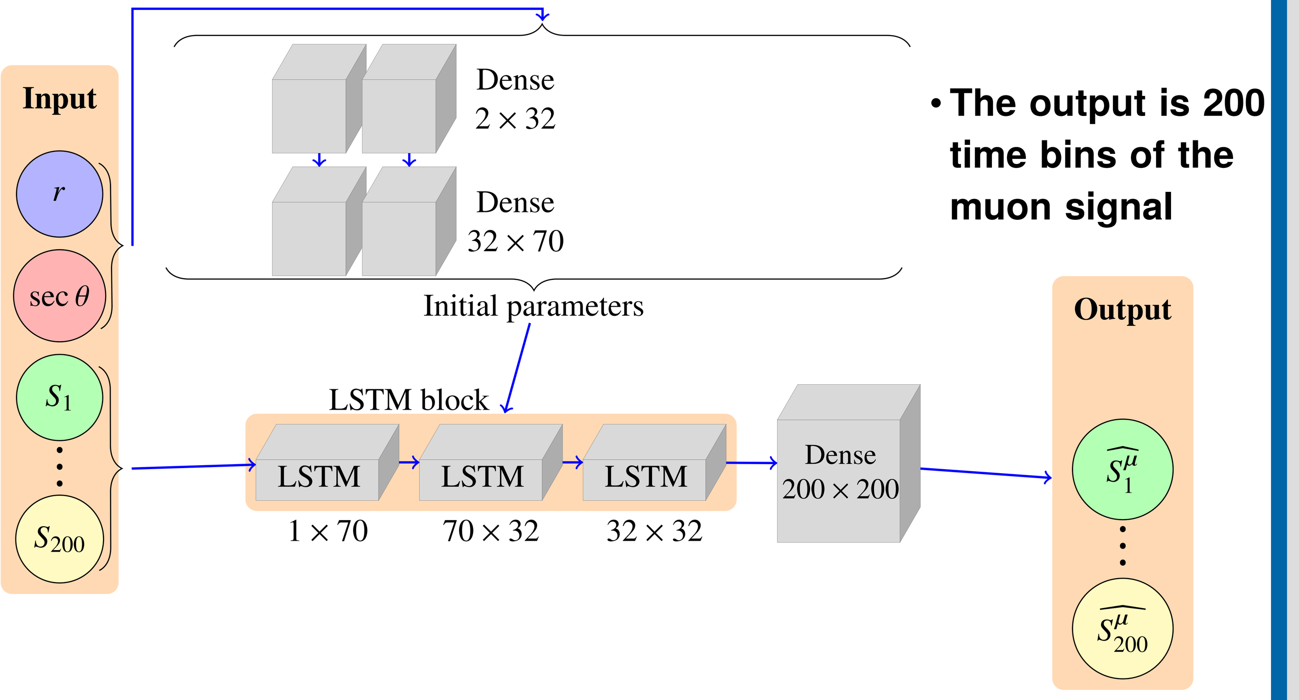


- Electromagnetic component (signal from photons, electrons and positrons) in an SD station from a simulated shower

What do we do? We train a neural network on simulations done with EPOS-LHC to predict the muon signal

The Neural Network

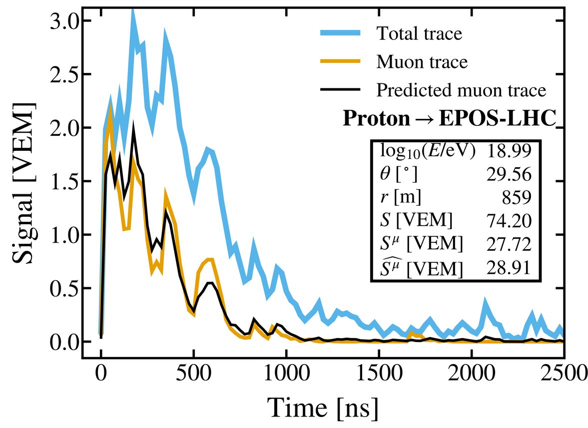
- The Neural Network is based on a Recurrent Neural Network (RNN)
- RNNs have a memory mechanism which makes them well suited for time series
- The input is a time series of 200 time bins of the total signal
- The distance to the shower axis of each station r and the secant of the zenith angle are also used



- **The output is 200 time bins of the muon signal**

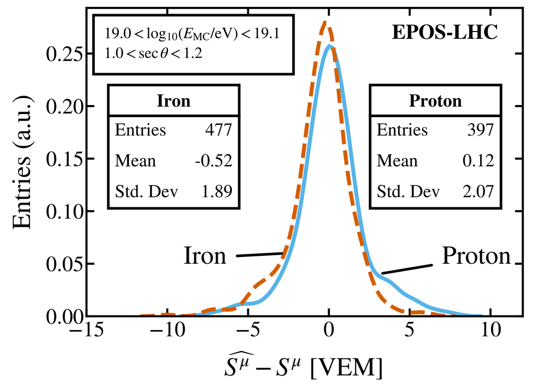
Long Short-Term Memory (LSTM) cells process the temporal input

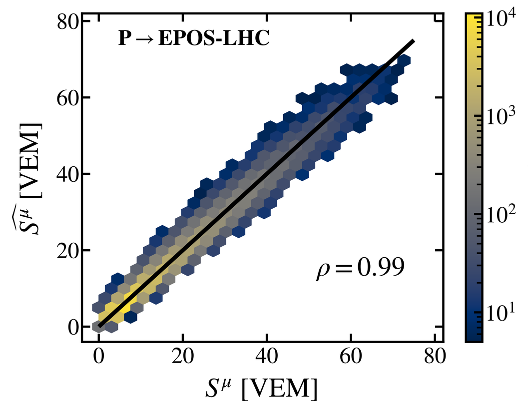
Results on Simulations

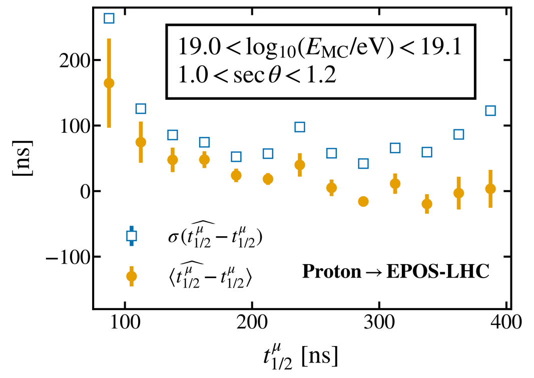


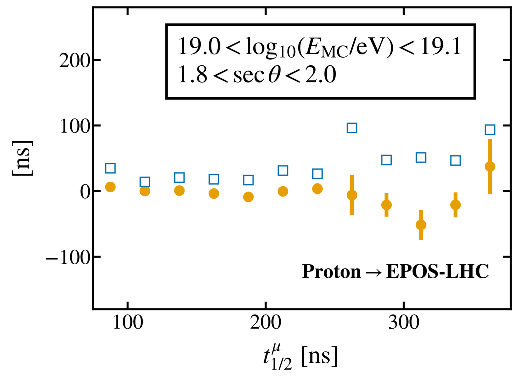
- The results are tested on simulations that the neural network has not seen before
- The neural network has learnt to predict the key features of the muon signal: early arrival and a spiky structure

- The integral of the predicted signal $\widehat{S^\mu}$ is compared to its value from the simulation S^μ
- The predictions reach a resolution of 10-20% of the total signal depending on the energy and zenith angle





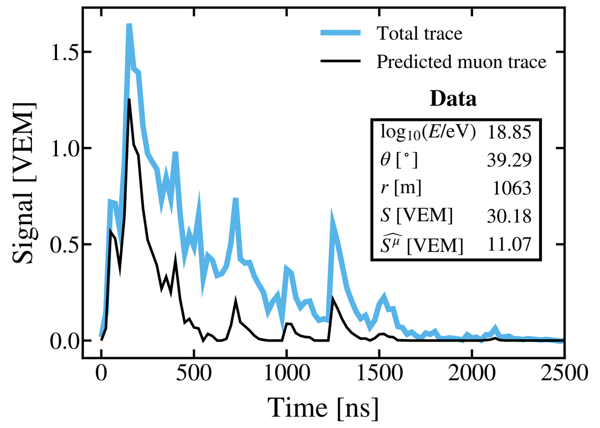




- The risetime of the muon signal, related to the shape of the signal, can be predicted within 100 ns for most values of the true risetime $t^\mu_{1/2}$

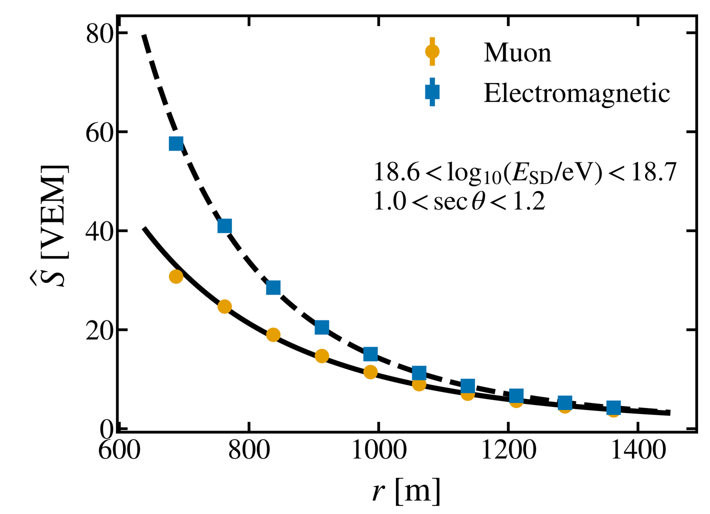
Application to data

Example of a predicted signal in data

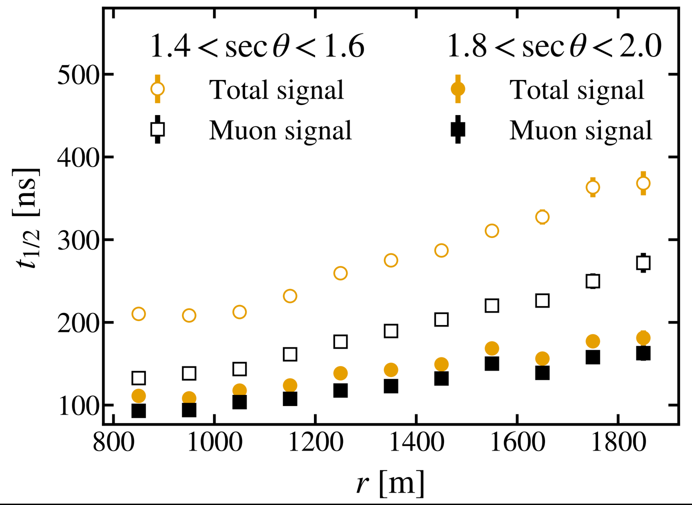


- The expected features are also reproduced in data: early arrival and a spiky structure

Data crosschecks



- The muon and electromagnetic signal (total - muon) are fitted using functions obtained by the AGASA collaboration, leaving only the normalization of the function free
- The fits are in very good agreement with the signals predicted by the neural network from the measurements done by the Pierre Auger Observatory



- The risetime of the signal follows the expected behaviour from physics principles
  - It increases with r
  - It decreases with $\sec\theta$

Summary and conclusions

- Using a Recurrent Neural Network, the muon signal can be predicted for each water-Cherenkov detector of The Pierre Auger Observatory
- The neural network is trained with simulations but the predictions are independent of the hadronic model used
- The **resolution** of the integrals of the predicted signals is **between 10 and 20% of the total signal**, and the muon risetime
- **Lateral distributions** of muon and electromagnetic signals obtained with the DNNs from the Auger data **agree well with the parameterizations obtained by AGASA**
- The combination of neural networks with the upgraded detectors of AugerPrime will have an unprecedented performance regarding the estimation of the primary mass on an event-by-event basis

The details of this work can be fonud in arXiv:2103.11983 (accepted for publication in JINST)