Workshop on Machine Learning for Analysis of High-Energy Cosmic Particles

Monday 27 January 2025 - Friday 31 January 2025

University of Delaware

Book of Abstracts

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Talks / **1**

Application of graph networks to a next generation wide-field gamma-ray observatory in the southern sky

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Water-Cherenkov detectors have long proven their importance for the research of high energetic gamma rays in numerous experiments in the Northern Hemisphere.
The Southern Wide-field Gamma-ray Observatory (SWGO) will be the first observatory using this technology in the Southern Hemisphere to observe gamma-ray emission in an energy range of 100s of GeV up to the PeV scale.
The proposed layout will enable observations of the galactic center with a wide field of view and a very high-duty cycle, complementing the Cherenkov Telescope Array (CTA).
The challenge of precision observation lies in rejecting cosmic-ray backgrounds and accurately reconstructing primary energy, using only the air shower footprint captured by the detector.
With new machine-learning techniques advancing in recent times, we propose a novel approach based on graph neural networks (GNNs) to improve background rejection and energy reconstruction for a next-generation observatory.
We selected a GNN-based approach to leverage the capabilities of convolutional neural networks while offering the flexibility needed for event reconstruction across the extensive energy range of SWGO.

In this talk, we introduce the design of the proposed GNN, describe the details of the application to different test configurations of SWGO, and present the obtained results for γ / hadron separation and energy reconstruction.
Comparing our results to current state-of-the-art approaches, we find that our proposed algorithm outperforms hand-designed classification algorithms and observables in background suppression, and improves the energy resolution compared to state-of-the-art methods.

Type of Contribution:

talk

Talks / **2**

Towards improving efficiency of machine learning techniques in neutrino telescopes

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Neutrino telescopes detect rare interactions of particles produced from some of the most extreme environments in the Universe. Given the rate of backgrounds, these telescopes amass an enormous quantity of large variance, high-dimensional data. These attributes create substantial challenges for analyzing and reconstructing neutrinos, particularly when utilizing machine learning (ML) techniques. In this talk, I will present methods to efficiently manage and process these events using ML techniques, while preserving as much information as possible. These methods include employing autoencoder networks to generate compact representations of high-dimensional data associated to neutrino events and utilizing sparse networks to substantially reduce memory usage and runtime.

The ultimate aim of these efforts is to enable high-quality ML-based reconstructions during the earlier stages of data processing.

Type of Contribution:

talk

Talks / **3**

Optimizing a Cosmic-ray Energy Estimator with Machine learning for the HAWC observatory (Remote)

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Situated at an elevation of 4,100 meters a.s.l. in Puebla, Mexico, the High-Altitude Water Cherenkov (HAWC) gamma-ray observatory detects TeV gamma-rays from astrophysical sources. Additionally, it gathers substantial data on hadronic air showers, expanding HAWC's research capabilities to explore cosmic rays with energies from 1 TeV to 1 PeV. The initial energy estimation method optimized for cosmic rays enabled the analysis of the anisotropy and composition of the cosmic rays. However, recent improvements in HAWC reconstruction algorithms have pointed out the need for an improved energy estimator of hadronic EAS. To this end, it is important to explore more sophisticated methods for cosmic-ray energy reconstruction. In this work, we present preliminary results of the implementation of machine learning techniques for predicting the energy of cosmic-ray-induced events in HAWC.

Type of Contribution:

talk

Talks / **4**

Direction and energy reconstruction with uncertainty quantification for GRAND using graph neural network (Remote)

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For experiments such as GRAND, a distributed radio-antenna array for ultra-high-energy neutrino detection, a precise direction and energy reconstruction is essential. Machine-learning methods and in particular graph neural networks (GNN) appear to be an interesting solution given their ability to use localised and variable-size inputs. In this contribution, we will present and summarize the ongoing work within the GRAND collaboration using GNNs in reconstruction efforts, and show that by adding physical inputs to our networks, we achieved better accuracy than existing maximum likelihood methods without increasing the inference time. We also implemented methods to estimate the uncertainty of our predictions under certain conditions.

Type of Contribution:

talk

Talks / **5**

Mass composition study with machine learning on KASCADE archival data (Remote)

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Despite many experiments in the 1–100 PeV range, accurately measuring mass component spectra in this energy region remains challenging. Discrepancies between experiments are attributed to factors including the choice of the hadronic interaction model used.
In this study, we present a reanalysis of archival data from the KASCADE experiment, which recorded extensive air showers from 1996 to 2013. This analysis uses a novel approach to measure the energy spectra of five mass components (protons, helium, carbon, silicon, and iron), based on event-by-event mass-type reconstruction using a convolutional neural network.
The systematic uncertainties, which were lower than in the last original KASCADE study, as well as the corresponding uncertainties of the IceTop and TALE experiments, were also investigated. Furthermore, the uncertainties associated with the use of different post-LHC hadronic interaction models (QGSJet-II.04, EPOS-LHC, Sibyll 2.3c) were examined.
Our findings show a marked excess of the proton component flux compared to the latest original KASCADE results. We demonstrate, with the highest statistical significance, a knee in the proton (~4.4 PeV) and helium (~11 PeV) components. Additionally, we observe a hint of hardening (~4.5 PeV) in the iron spectrum, which can be interpreted as analogous to the proton hardening (~166 TeV) observed in the GRAPES-3 experiment.

Type of Contribution:

talk

Talks / **6**

A graph neural network reconstruction for the IceAct telescopes

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Situated at the geographic South Pole, the imaging air shower telescopes IceAct observe the atmosphere above the IceCube Neutrino Observatory. Therefore, the IceAct telescopes measure the electromagnetic air-shower development complementary to the air shower at the surface with IceTop and the high-energetic muonic component measured by the in-ice detector. Currently, three IceAct telescopes are installed and have shown to operate in the harsh conditions at the South Pole

successfully. The telescope camera consists of 61 silicon photomultipliers (SiPMs) with a hexagonal light guide glued to each SiPM. A graph neural network is used to reconstruct the air-shower properties of the camera images. The graph gives great flexibility to do a combined analysis of several telescopes and other detector components. The current status of the reconstruction method is presented.

Type of Contribution:

talk

Talks / 7

Gamma/Hadron Separation using Machine Learning Methods with the IceAct Telescopes

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The IceCube Neutrino Observatory, located at the South Pole, is a multi-component detector array capable of observing cosmic-rays on the TeV to EeV scale. In addition to the InIce component, and the surface component IceTop, three new Imaging Air Cherenkov Telescopes, called IceAct, were installed. One of the primary goals of the IceAct telescopes is to search for high-energy photons in the Southern Sky. To do so, Gamma/Hadron separation is done by using modern machine learning methods alongside a hybrid Hillas analysis which uses both the Hillas parameters alongside InIce parameters. This approach geometrically parameterizes the ellipse formed by the images on the IceAct cameras alongside the total charge deposition at various layers in ice, as well as using reconstructed muon bundle energy loss as model features. Various classification and regression models are used to reconstruct the energy and type of the primary cosmic-ray, as well as a final meta-modeling approach that aggregates the predictions from all used models in a so-called "stacking method".

This contribution will provide a preliminary look into the sensitivity of the current machine learning model/ stacking method, used for distinguishing photons from the cosmic ray background.

Type of Contribution:

talk

Talks / 8

Machine learning-based analyses using surface detector data of the Pierre Auger Observatory

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The Pierre Auger Observatory, the world's largest detector for studying ultra-high-energy cosmic rays (UHECRs), employs multiple detection techniques to observe the different components of extensive air showers. In order to accurately understand the physics of UHECRs, it is essential to determine their mass composition. Since UHECRs can only be measured indirectly, it is necessary to study mass-sensitive observables, such as the number of muons reaching the ground and the atmospheric depth of the shower maximum. One way to estimate these observables is by analyzing spatio-temporal patterns in the shower footprint recorded by the surface detector (SD) of the Observatory. Given the complexity of this information, the Pierre Auger Collaboration utilizes machine learning (ML) to complement the traditional analytical techniques. With the SD operating nearly 100% of the time, ML algorithms enable the analysis of events with an unprecedented precision. In this work, we summarize the ML-driven analyses conducted at the Pierre Auger Observatory to identify and reconstruct mass-sensitive observables and explores potential applications of ML in other areas. Special emphasis is placed on techniques that utilize the different sub-detector systems of the SD, including the newly installed scintillator detectors from AugerPrime, highlighting their potential for advancing UHECR studies.

Type of Contribution:

Talks / 9

IceTop gamma-hadron separation and angular error estimation using machine learning techniques

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The IceCube Neutrino Observatory, located at the South Pole, combines two detector systems to study high-energy cosmic-ray events. The surface array, called IceTop, indirectly detects cosmic rays within the 100 TeV to EeV range through ice-Cherenkov tanks, providing reconstructed observables such as primary energy and direction. The in-ice optical array detects high-energy muonic components of air showers. Together, these detectors could enhance particle-type discrimination, though at the cost of a narrower field of view for source searches. This work in progress aims to differentiate between photon- and cosmic-ray-induced air showers detected by IceTop. This is done using a Convolutional Neural Network (CNN) that processes time, charge, and lateral distance distributions. The resulting classification results are then compared against previous methods incorporating data from both detectors. Furthermore, to support gamma-ray source searches, we apply a boosted decision tree for estimating directional reconstruction errors. These tree-based models excel in regression and classification tasks, where we use numerous reconstruction fit parameters as inputs to obtain the angular error on an event-by-event basis.

Type of Contribution:

talk

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In-situ pulser depth reconstruction for RNO-G using Neural Network

Authors: Sanyukta Agarwal[1]; David Besson[1]

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Radio Neutrino Observatory in Greenland (RNO-G) aims to detect Askaryan emission from ultra-high energy astrophysical and cosmogenic neutrinos above 10 PeV. Situated at Summit Station, it is proposed to have 35 stations of which 7 stations have been installed so far. Search for neutrinos and their direction reconstruction using interferometry requires precise control of parameters such as antenna positions and an accurate ice model. Various known sources are available in and around the RNO-G stations which can be used in calibration of the observatory. In-situ calibration pulsers deployed on helper strings in each station along with pulser drops performed for some stations allow us to constrain the uncertainty in antenna position and test the accuracy of our ice model.

In my poster I assume a simple straight line, plane wave approximation and ignore ray-bending as an initial guess to reconstruct the depth of the stationary pulsers in 14 helper strings across 7 stations. The station geometry allows this simple model to be a good approximation and I use the stationary pulser data to train my neural network, allowing me to reconstruct pulser depths in cases where ray-bending effects might be more significant (such as pulser drops). This method is preferred as it's much faster than analytical raytracing or simulating radio propagation.

Type of Contribution:

poster / flash talk (for work in progress)

Talks / **11**

Generative Neural Networks for Simulating Radio Emission from Air Showers (Remote)

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The simulations of radio emission from EAS are essential for reconstructing various shower parameters from the measured radio signals. As bigger experiments use more and more antennas, the computational cost of these simulations gets prohibitively large. These simulations also scale exponentially with higher primary energies and linearly with the number of antennas. Thus there is a need to interpolate and generate radio signals across various energy ranges and antenna positions.

In this work, we present a novel neural network which can predict radio pulses for the AERA setup using several shower parameters and antenna positions as input. The results which showcase the pulses generated by the network compared to the CoREAS simulations, are presented. The network's ability to also get the fluence pattern and the total radiation energy is shown along with its performance benchmarks. Finally, the network is used in a simplistic Xmax reconstruction procedure to show the viability of these generated pulses for Xmax reconstruction.

Type of Contribution:

talk

Talks / **12**

AI Agents for Ground-Based Gamma Astronomy (Remote)

Authors: Dmitriy Kostunin[1]; Vladimir Sotnikov[2]; Sergo Golovachev[2]; Strube Alexandre[3]

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The next generation instruments for ground-based gamma-ray astronomy are marked by a substantial increase in complexity with dozens of telescopes. This leap in scale introduces significant challenges in managing system operations and offline data analysis. The methods, which depend on advanced personnel training and sophisticated software, become increasingly strained as the system's complexity grows, making it more challenging to effectively support users in such a multifaceted environment.

To address these challenges, we propose the development of AI agents based on instruction-finetuned large language models (LLMs). These agents align with specific documentation and codebases, understand the environmental context, operate with external APIs, and communicate with humans in natural language. Leveraging the advanced capabilities of modern LLMs, which can process and retain vast amounts of information, these AI agents offer a transformative approach to system management and data analysis by automating complex tasks and providing intelligent assistance.

We present two prototypes aimed at integrating with the Cherenkov Telescope Array Observatory pipelines for operations and offline data analysis. The first prototype automates data model implementation and maintenance for the Configuration Database of the Array Control and Data Acquisition (ACADA). The second prototype is an open-access code generation application tailored for data analysis based on the Gammapy framework.

Type of Contribution:

talk

Talks / **13**

Convolutional Neural Network Processing of Radio Emission for Nuclear Composition Classification of Ultra-High-Energy Cosmic Rays (Remote)

Authors: Cosmina Mihoreanu[1]; Paula Gina Isar[2]; Tudor Alexandru Calafeteanu[1]; Emil Ioan Slusanschi[1]

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Ultra-high-energy cosmic rays (UHECRs) are the most mysterious particles in the Universe originating from extragalactic sources, which yet rise a couple of fundamental open questions, such as where do they come from, how do they propagate, and how do they reach the energies they exhibit. Due to the very low flux, i.e. one particle per km2 per century at about 1020 eV, UHECRs are detected indirectly from the Earth, through their developed air showers, by modern detection techniques in frame of hybrid and large-scale experiments. Radio detectors have proven to be a competitive method for reconstructing the properties of EASs, such as the shower's incoming direction, its energy, and its maximum development (Xmax).
Concurrently, data science has become indispensable in physics. By applying statistical, computational, and deep learning methods to large databases, researchers can extract insights and make predictions efficiently and accurately, in conjunction with traditional analysis methods.
We introduce a convolutional neural network (CNN) architecture designed to classify simulated CoREAS air shower events to process the radio emission for several types of primary cosmic rays' nuclei. For the classification of the primary particle, we use metrics like Accuracy or MCC to indicate the prediction capability for mass-composition based on data that can be gathered by the

Radio Detector (RD) at the world's largest cosmic ray experiment on Earth, the Pierre Auger Observatory.

Type of Contribution:

talk

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Machine Learning Techniques for Neutrino Reconstructions in IceCube

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Advancements in machine learning have improved event reconstruction in the analyses of IceCube data, providing fast and accurate estimations of neutrino properties. These methods typically use pulse series data and the spatial information of digital optical modules as inputs to neural networks. I will discuss current reconstruction techniques in IceCube and their applications to physics analyses. Increasingly more complex models like graph neural networks and transformers are being explored as improvements over convolutional neural network-based reconstructions. I will introduce state space models as a promising approach for efficiently reconstructing very long data sequences, removing the need for compression techniques and avoiding the quadratic complexity of attention. Additionally, efforts are ongoing to integrate these new models into the open-source reconstruction framework GraphNeT, which could extend these techniques to other experiments.

Type of Contribution:

talk

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Machine Learning at Telescope Array (Remote)

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Telescope Array is a large-scale cosmic-ray observatory studying ultra-high-energy cosmic rays. Its Surface Detector array consists of 507 scintillation stations arranged in a rectangular grid covering approximately 700 km^2. This talk presents our deep learning approach to reconstructing cosmic ray properties from Telescope Array Surface Detector data. We demonstrate how combining multiple data representations with various neural architectures (convolutional, recurrent, and transformer networks) enhances reconstruction accuracy of primary particle properties, including arrival direction and energy. Finally, we present post-processing techniques developed for searching for rare event, such as ultra-high-energy photons.

Type of Contribution:

talk

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Denoising Radio Pulses from Air Showers Using Machine Learning Methods (Remote)

Author: Zhisen Lai[1]

Co-authors: Aurélien Benoit-Lévy [2]; Oscar Macias [3]; Claire Guepin ; Arsene Ferriere [4]

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The Giant Radio Array for Neutrino Detection (GRAND) aims to detect radio signals from extensive air showers caused by ultra-high-energy cosmic particles. Galactic, instrumental, and anthropogenic noise are expected to contaminate these signals.
To address this problem, we propose training an unsupervised convolutional network known as an autoencoder. This network is used to learn a coded representation of the data and remove specific features from it. This denoiser is trained using realistic air-shower simulations generated by CoREAS and ZHAireS, which are specifically designed to closely resemble the signals detected by GRAND. In this talk, we will present details about our machine-learning model and preliminary results on the sensitivity gain obtained when our denoising algorithm is applied to realistically simulated noisy GRAND signals of varying signal-to-noise ratios.

Type of Contribution:

poster / flash talk (for work in progress)

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Reconstructing the Direction of Ultra-High-Energy Cosmic Rays Using a Simulation-Based Inference Method

Author: Zach Mason[1]

Co-authors: Oscar Macias [2]; Aurélien Benoit-Lévy [3]; Matthew Ho

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GRAND (Giant Radio Array for Neutrino Detection) is a proposed next-generation observatory designed to detect ultra-high-energy (UHE) cosmic particles. It aims to accomplish this by identifying the radio signals generated when these particles interact with the atmosphere and Earth's magnetic field. We present a novel pipeline utilizing simulation-based inference (SBI) methods to reconstruct the incoming direction of UHE cosmic rays. By training the SBI algorithm using realistic simulations produced with CoREAS and ZHAireS, which include electric field amplitudes, antenna positions, and trigger times, we demonstrate how our algorithm learns the posterior probability of the Bayesian model given the data. This approach enables us to access robust error estimates in the reconstructed direction. Additionally, we show that, in contrast to standard "black box" machine learning methods, our SBI technique allows us to evaluate the statistical rigor of our results.

Type of Contribution:

poster / flash talk (for work in progress)

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A Simulation-Based Inference Method for Electric Field Reconstruction (Remote)

Author: Thomas McKinley[1]

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The primary goal of the Giant Radio Array for Neutrino Detection (GRAND) is to uncover the mysterious sources of ultra-high-energy cosmic rays (UHECRs). GRAND aims to achieve this by detecting electric fields generated by UHECR interactions with Earth's atmosphere and magnetic field. Reconstructing the electric field from measured antenna voltages is difficult due to the need for a detailed model of the antenna's response and background noise.
We will present a simulation-based inference model trained to learn the likelihood ratio using realistic simulations from CoREAS and ZHAireS. The model incorporates a realistic antenna response and Galactic background noise to accurately reconstruct the electric field. Additionally, we will introduce various statistical tests, such as coverage tests, to demonstrate the statistical validity of our findings.

Type of Contribution:

poster / flash talk (for work in progress)

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Modeling IACT Gamma-ray Background using Singular Value Decomposition

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Extended γ-ray sources, such as TeV halos, evolved pulsar wind nebulae, and star clusters, impose a challenge to analyses of Imaging Atmospheric Cherenkov Telescope (IACT) data due to the difficulty in estimating irreducible background originating from cosmic-ray-induced γ-ray-like events in the source regions. A background estimation method is necessary to address IACT analyses in the cases when the source angular size exceeds or occupies a significant part of the field-of-view. The proposed new method analyzes the distribution of cosmic-ray-like events in the coordinate of γ-ray camera using singular value decomposition (SVD) to derive the irreducible background estimation. This

data-driven method significantly reduces the systematic uncertainty on the background estimation, and the method performance is evaluated using VERITAS archival observations.

Type of Contribution:

talk

Talks / **20**

Improving Gamma-ray Angular Resolution with Convolutional Neural Network De-noiser

Author: Ruo-Yu Shang[1]

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Imaging Atmospheric Cherenkov Telescopes (IACT) reconstruct the locations of gamma-ray sources using stereo analysis of images of gamma-ray air showers. The images of gamma-ray showers suffer from the noise fluctuation arises from night-sky brightness. Understanding the quality of an image is crucial for estimating the uncertainty of the gamma-ray arrival direction. In this presentation, we show how to improve the gamma-ray angular resolution by denoising the gamma-ray shower images with a Convolutional Neural Network (CNN) and estimating the direction uncertainty of a gamma-ray event by propagating the location uncertainties of single photoelectrons in the gamma-ray camera frame.

Type of Contribution:

talk

Talks / **21**

Fast Generation of Realistic Data-Driven Stereoscopic Shower Images using Generative Adversarial Networks (Remote)

Authors: Kameswara Bharadwaj Mantha[1]; Deivid Ribeiro[1]; Lucy Fortson[1]; Hugh Dickinson[2]; Ramanakumar Sankar[3]; Samuel Spencer[4]

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Effective identification and characterization of particle showers captured by ground-based cherenkov telescopes is critical for very high energy gamma-ray astrophysics. A common step employed in the field is to use synthetic gamma-ray and hadronic events generated based on computationally-expensive simulations and use them for downstream analyses. Leveraging the power of generative deep learning, various studies have developed fast emulators that can generate synthetic simulated events that mimic the simulation outputs. However, they still carry the intrinsic assumption that the emulated/simulated data is representative of the observations. In an attempt to address the aforementioned challenges, in this work, we designed and trained on real data a fully-unsupervised

Wasserstein Generative Adversarial Network on stereoscopic shower images (Stereo-wGAN) from the VERITAS gamma-ray observatory. In this presentation, we highlight our model's ability to generate realistic stereoscopic events that are self-consistent in their quantitative image-wise moments (Hillas parameters) and overall reconstructed shower parameters. We also showcase the utility of our model-learnt internal feature representations in exploring the diversity of shower events as a way towards enabling future unsupervised characterization of gamma-ray and hadronic events, which is another challenging task in the field of gamma-ray astrophysics.

Type of Contribution:

talk

Talks / **22**

Graph Neural Networks for Photon Search with the Underground Muon Detector of the Pierre Auger Observatory (Remote)

Author: Ezequiel Rodriguez[1]

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Ultra-high-energy (UHE) photons are expected as by-products of cosmic-ray acceleration, propagation, or decay of super-heavy dark matter particles. Predicted diffuse photon fluxes are usually several orders of magnitude below the UHE cosmic-ray flux. This contribution presents a method for discriminating photon-initiated air showers in the overwhelming cosmic-ray background with the Pierre Auger Observatory. The method leverages information from both the Surface Detector (SD), consisting of water-Cherenkov detectors (WCDs) and the Underground Muon Detector (UMD). We use graph neural networks, that allow the encoding of the input information acquired by the SD and UMD. The approach is particularly suitable for handling the irregular geometries of the SD and UMD arrays, where stations may be temporarily missing due to technical issues. Using simulations, the performance estimates indicate that the method has a strong potential for identifying photons at UHE.

Type of Contribution:

talk

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Stereograph: stereoscopic event reconstruction using graph neural networks applied to CTAO (Remote)

Authors: Thomas Vuillaume[1]; Hana Ali Messaoud[1]; Tom Francois[1]

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The CTAO (Cherenkov Telescope Array Observatory) is an international observatory currently under construction. With more than sixty telescopes, it will eventually be the largest and most sensitive ground-based gamma-ray observatory.

CTAO studies the high-energy universe by observing gamma rays emitted by violent phenomena (supernovae, black hole environments, etc.). These gamma rays produce an atmospheric shower upon entering the atmosphere, which emits faint blue light, observed by CTAO's highly sensitive cameras. The event reconstruction consists of analyzing the images produced by the telescopes to retrieve the physical properties of the incident particle (mainly direction, energy, and type).

A standard method for performing this reconstruction consists of combining traditional image parameter calculations with machine learning algorithms, such as random forests, to estimate the particle's energy and class for each telescope. A second step, called stereoscopy, combines these monoscopic reconstructions into a global one using engineered weighted averages.

In this work, we explore the possibility of using Graph Neural Networks (GNNs) as a suitable solution for combining information from each telescope. The "graph" approach aims to link observations from different telescopes, allowing analysis of the shower from multiple angles and producing a stereoscopic reconstruction of the events. We apply GNNs to CTAO-simulated data from the Northern hemisphere and show that they are a very promising approach to improving event reconstruction, providing a more performant stereoscopic reconstruction. In particular, we observe better energy and angular resolutions and enhanced separation between gamma photons and protons compared to the Random Forest method.

Type of Contribution:

talk

Talks / **24**

Deep Learning applied to CTAO LST-1 and the difficulty to go from simulated to real data (Remote)

Authors: Thomas Vuillaume[1]; Michaël Dell'aiera[1]; Alexandre Benoit[2]

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GammaLearn is a project developing deep learning solutions for the Cherenkov Telescope Array Observatory (CTAO) data analysis. Its first application is event reconstruction based on images acquired by the Large-Sized Telescope (LST-1), currently under commissioning at La Palma.
In this talk, we present a review of the project: the architecture γ-PhysNet we have developed to tackle this multi-task problem, the results obtained on simulated and real data, as well as solutions developed to compensate for some of the issues arising from data vs simulation discrepancies.

Type of Contribution:

talk

Talks / **25**

A Hybrid Approach to Event Reconstruction for Atmospheric Cherenkov Telescopes Combining Machine Learning and Likelihood Fitting (Remote)

Authors: Georg Schwefer[1]; Robert Parsons[2]; Jim Hinton[1]

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The imaging atmospheric Cherenkov technique currently provides the highest angular resolution achievable in astronomy at very high energies. High resolution measurements provide the key to progress on many of the key questions in high energy astrophysics. The huge potential of the next generation Cherenkov Telescope Array Observatory (CTAO) in this regard can be realised with the help of improved algorithms for the reconstruction of the air-shower direction and energy. Hybrid methods combining maximum-likelihood fitting techniques with neural networks represent a particularly promising approach.
Here, we present the FreePACT algorithm, a hybrid machine-learning likelihood reconstruction method for IACTs. In this, the analytical likelihood used in traditional image-likelihood fitting techniques is replaced by a neural network that approximates the charge probability density function for each pixel in the camera. The performance of this improved algorithm is demonstrated using simulations of the planned CTAO Southern array.

Type of Contribution:

talk

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Interpretable Deep Learning for Event Reconstruction in IceCube

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Event reconstruction is a critical step in the analysis of data at the IceCube Neutrino Observatory. Traditional maximum-likelihood methods, while provably optimal under certain conditions, can be computationally expensive and infeasible in practice. A reconstruction method is presented that combines the statistical rigor of maximum-likelihood estimation with the powerful representation learning capabilities of deep neural networks. By leveraging domain knowledge and exploiting inherent symmetries in the problem, a highly interpretable deep learning model is developed that improves event reconstruction accuracy and computational efficiency. The model not only achieves state-of-the-art performance but also provides robust generalization along built-in symmetries.

Type of Contribution:

Talks / **27**

IceTop-CNN: Cosmic-Ray Reconstruction in IceTop using a Convolutional Neural Network with Low-Level Inputs (Remote)

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We present on the development of an application for training and evaluating convolutional neural networks for use with high-statistics, minimally-cut cosmic-ray anisotropy studies. This application has been built to utilize computing resources from the IceCube Observatory using the HTCondor workload management system. Our goal is to streamline the creation of lightweight models that can successfully reconstruct well-captured and uncontained events over a large zenith range using only low-level charge and time information as inputs. By doing this, we aim to minimize systematic uncertainty in our models while maintaining the accuracy of models trained on higher-level parameters. Our current baseline model is capable of estimating the energies of 68% of unfiltered simulations in our dataset within 15% of their true values. The application is intended to be accessible to novices in machine learning and data science with guides for installation and creating and assessing models available. We hope to see improvement in both the reconstructions of additional event characteristics and accessibility of our application to beginners in programming and research.

Type of Contribution:

talk

Talks / **28**

Evaluation of energy reconstruction performance of the Telescope Array surface detector using a deep neural network and hybrid data (Remote)

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Accurate reconstruction of Ultra-High-Energy Cosmic Ray (UHECR) properties is crucial for studying their origins and composition. In this work, we introduce a Deep Neural Network (DNN) model based on the AixNet architecture to reconstruct UHECR parameters using data from the Telescope Array surface detector (SD). The DNN predicts key parameters, such as energy, arrival direction, core position, Xmax, and primary mass, by analyzing both time traces and spatial correlations in the data. Monte Carlo simulations for four mass groups (proton, helium, CNO, and iron) indicate that the DNN enhances the resolution of energy, direction, and core position compared to standard methods. This improvement is expected to hold even with relaxed data quality criteria, potentially increasing the number of usable events. We present resolution estimates, systematic studies based on simulations, and validate the DNN's performance with hybrid data.

Type of Contribution:

talk

Talks / **29**

Deep Learning in Astroparticle Physics

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Deep Learning in Astroparticle Physics

Algorithms based on machine learning have been extraordinarily successful across many domains, including computer vision, machine translation, engineering, and science.
Moreover, in the field of physics, the importance of machine learning is growing quickly, driven by the need for precise and efficient algorithms that can effectively handle vast amounts of complex and high-dimensional data.
Recently, with the help of these novel algorithms, providing improved reconstructions, new insights into astroparticle physics could be gained.
Could it even become a new paradigm for data-driven knowledge discovery?

In this review, we explore the current state of machine learning in astroparticle physics after introducing its fundamental concepts.
We outline the immense potential of this emerging technology, illustrate the wide variety of possible applications in the context of astroparticle physics, and debate the latest breakthroughs.
Finally, we present novel approaches and techniques and discuss future applications and challenges in the field.

Type of Contribution:

Talks / 30

Detection of Radio Signals from Cosmic Rays Using Convolutional Neural Networks with Data from SKALA antennas at IceTop

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Cosmic rays colliding with atmospheric particles produce cascades of secondary particles known as extensive air showers. These showers emit electromagnetic radiation whose radio component is detectable by radio antennas. At the surface of the IceCube Neutrino Observatory in Antarctica, a prototype station equipped with three antennas has been collecting background and air-shower data since 2020. Traditionally, we have employed Signal-to-Noise Ratio (SNR) cuts to select candidate radio events, which discarded valuable measurements of air showers at lower SNR levels. However, Convolutional Neural Networks (CNNs) can outperform traditional methods in classification and denoising radio pulses from air showers. Such CNNs have been trained on the waveforms resulting from combining South Pole background data with simulated cosmic-ray signals generated by the CoREAS software.The CNNs can identify additional air-shower events that do not pass traditional SNR cuts, while also improving the accuracy of pulse power and timing measurements. Recently, we have also started to explored the impact of upsampled waveforms on the accuracy of CNN-based classifiers and denoisers. These networks will contribute to achieving the science goals envisioned for radio arrays for air-shower detection, such as the IceCube-Gen2 Surface Array.

Type of Contribution:

talk

Talks / 31

UHE Cosmic Ray Candidate Identification in RNO-G Deep Antennas Using Machine Learning

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Ultra-high-energy cosmic rays (UHECRs) are believed to originate from the universe's most cataclysmic events, yet their sources remain unidentified. Composed primarily of protons and nuclei ranging from light elements to iron, these charged particle emissions are deflected en route to Earth by magnetic fields, obscuring their true source directions. The Radio Neutrino Observatory in Greenland (RNO-G) addresses this issue by targeting UHE neutrinos, as many of the mechanisms hypothesized to produce UHECRs are also expected to unleash UHE neutrinos. Neutrinos, due to their neutrality, near-zero mass, and weak interactions, can traverse the cosmos unhindered and undeflected. While these characteristics make neutrinos invaluable for tracing their origins, they also make them incredibly difficult to detect.

RNO-G overcomes this challenge by leveraging the Askaryan effect: when UHE neutrinos interact within a dense, dielectric medium, they produce showers that emit broadband electromagnetic radiation which coherently sums in the radio regime. This phenomenon allows for a massive effective detection volume due to the long attenuation lengths of radio waves in ice. However, UHECR showers can produce impulsive emissions that closely mimic neutrino-induced showers, making them a critical background to account for in neutrino searches. This work presents methodology and preliminary results from a linear discriminant analysis, along with plans for other classification methods, applied to a subset of RNO-G data to identify cosmic ray candidate events in its deep in-ice antennas.

Type of Contribution:

talk

Talks / 32

Reconstruction of energy and arrival directions of UHECRs registered by fluorescence telescopes with a neural network (Remote)

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Fluorescence telescopes are important instruments widely used in modern experiments for registering ultraviolet radiation from extensive air showers (EASs) generated by cosmic rays of ultra-high energies. We present a proof-of-concept convolutional neural network aimed at reconstruction of energy and arrival directions of primary particles using model data for two telescopes developed by the international JEM-EUSO collaboration. We also demonstrate how a simple convolutional encoder-decoder can be used for EAS track recognition. The approach is generic and can be adopted for other fluorescence telescopes.

Type of Contribution:

talk

Talks / 33

Machine learning using NuDot

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NuDot is a ton-scale liquid scintillator research and development testbed. It aims to develop techniques to reduce one of the dominant backgrounds in large modern and future liquid scintillator neutrinoless double beta decay ($0\nu\beta\beta$) searches: the solar neutrino background. With the help of machine learning and high-speed electronics, NuDot will demonstrate the ability to extract directional information by separating the prompt Cherenkov radiation within the isotropic scintillation emission. This separation is done using low time-transit-spread photomultiplier tubes. We are using U-Net architecture, a convolutional neural network originally developed to perform image segmentation that aims to find the hit time of the photon and extract the charge. In addition, efforts are underway to integrate these machine learning models into the front-end data acquisition systems, such as RFSoC platforms, to enable real-time processing and decision-making.

Type of Contribution:

poster / flash talk (for work in progress)

Talks / 34

The Radar Echo Telescope for Cosmic rays

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The Radar Echo Telescope for Cosmic Rays (RET-CR) was deployed this year at the high-altitude Summit Station in Greenland. Its primary goal is to detect in-ice continuations of high-energy cosmic-ray-induced air showers using the radar echo method. Successfully detecting in-ice cosmic-ray signals through this technique would provide significant insights and serve as a foundation for the establishment of the Radar Echo Telescope for Neutrinos (RET-N).
This talk will focus on the radar echo technique, analysis of RET-CR surface station data for reconstruction of key parameters, including primary energy, arrival direction, and core positions. It would also involve studying the combined askaryan and radar signals.

Type of Contribution:

poster / flash talk (for work in progress)

Opening Session / 35

Machine Learning Educational Talk

Type of Contribution:

Opening Session / 36

Welcome

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Talks / 37

Searching for Rare Astrophysical Events with Rare AI

Rare event searches are fundamental to our understanding of crucial astrophysical phenomena, including neutrinoless double beta decay, dark matter detection, and binary black hole mergers. While artificial intelligence has revolutionized many scientific fields, its application to rare event searches presents unique challenges due to the inherent scarcity of training data. This talk presents two innovative AI solutions specifically developed for rare event searches in physics and astronomy. First, we introduce a Rare Event Surrogate Model, initially designed for optimizing neutrinoless double-beta decay detectors, with planned extensions to binary black hole merger simulations. Second, we discuss our AI-ready data release from a cutting-edge axion dark matter detector, demonstrating significant improvements in dark matter search sensitivity through AI-driven analysis. These developments showcase how carefully tailored AI approaches can overcome the challenges of limited data availability while enhancing our capability to detect and analyze rare astrophysical events.

Type of Contribution:

Opening Session / 39

Teaching AI and ML to phsyics students

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Artificial Intelligence (AI) is pervading all aspects of our society, and can be leveraged to support and facilitate scientific discovery. However, teaching AI in the rapidly evolving AI landscape is difficult. I will cover the essential tools and concepts that physics students should familiarize with in their course work to be on track to master AI applications in physics and astronomy, and methods for teaching them, including leveraging AI when writing code.

Type of Contribution:

talk