

I. IDENTIFIKAČNÍ ÚDAJE

Název práce:	Rekonstrukce mionové produkční hloubky v atmosférických sprškách kosmického záření
Jméno autora:	Antonín Kravka
Typ práce:	Diplomová práce
Fakulta:	Fakulta jaderná a fyzikálně inženýrská (FJFI)
Katedra:	Katedra fyziky
Vedoucí práce:	Eva Maria Martins dos Santos
Pracoviště vedoucího práce:	Fyzikální ústav AV ČR, v. v. i. Na Slovance 1999/2 182 00 Praha 8

II. HODNOCENÍ JEDNOTLIVÝCH KRITÉRIÍ

Zadání a motivace k jeho vypsání	náročnější
<i>Hodnocení náročnosti zadání závěrečné práce a krátké průvodní slovo k motivaci pro zadání práce.</i>	
<p>The thesis aimed to extend the existing method to reconstruct the muon production depth of muons in extensive air showers tuned to work for zenith angles around 60 degrees to a complementary region, where the current reconstruction performs poorly.</p> <p>The muon detectors of AMIGA - Auger Muons and Infill for the Ground Array, currently being deployed at the Pierre Auger Observatory, covering this lower zenith angle region is the only one allowing for direct measurement of the muon content of extensive air showers. Furthermore, AMIGA covers a lower energy region of the cosmic ray spectrum, allowing for a slight overlap with the nominal energy of the LHC, where we expect lower systematic uncertainties from current hadronic interaction models used in cosmic-ray physics. Such specificities also call for a significant decrease of the classical radial cut, from 1000 m to only 200 m, due to statistical constraints at the lower energy region around $E = 0.1$ EeV and showers with zenith angles close to 0 degrees, which cover smaller areas at the ground.</p> <p>Our approach was to use Machine Learning instead of the classical algorithm, where an overall parametrization of the kinematic delay of muons, resorting to a spline fit, was made. To</p>	

fulfill the proposed objectives, Antonín had to learn machine learning from scratch and wholly by himself and decide which algorithm best fit his purposes. Ultimately, he proposed an algorithm with a better reconstruction of the Muon Production Depth (MPD). For the first time, he showed the accuracy and precision of the MPD reconstruction made on a muon-by-muon basis. His method has better accuracy and an almost unbiased reconstruction than the classical approach for muons reaching 2.3m depth, equivalent to 1 GeV energy cut for vertical incidence using a strict radial cut of 200 m, and improved reconstruction for very low zenith angles. His thesis results are mature enough to be implemented in a real detector, AMIGA-like, if a Ph.D. in the same topic is pursued.

Splnění zadání

splněno

Posuďte, zda předložená závěrečná práce splňuje zadání. V komentáři případně uveďte body zadání, které nebyly zcela splněny, nebo zda je práce oproti zadání rozšířena. Nebylo-li zadání zcela splněno, pokuste se posoudit závažnost, dopady a případně i příčiny jednotlivých nedostatků.

Antonín has excelled at fulfilling the proposed objectives.

Aktivita a samostatnost při zpracování práce

výborná

Posuďte, zda byl student během řešení aktivní, zda dodržoval dohodnuté termíny, jestli své řešení průběžně konzultoval a zda byl na konzultace dostatečně připraven. Posuďte schopnost studenta samostatně tvůrčí práce.

Antonín is a very independent student. He actively shared the progress of his work and adhered to the proposed deadlines and tasks. He was always very critical and demanding of his results. Antonín proposed all the proposed Machine Learning algorithms used in his thesis. The Machine Learning algorithm described in Chapter 3 of his thesis was not his first choice but a decision taken after several months of research on constantly improving my proposed assignment. During our meetings, Antonín sought counseling. Nonetheless, he always actively looked for the solution to the problems faced during his work almost on an equal foot. He should be fully credited for the work presented in his thesis.

Odborná úroveň

výborná

Posudte úroveň odbornosti závěrečné práce, využití znalostí získaných studiem a z odborné literatury, využití podkladů a dat získaných z praxe.

Antonín is an avid, hard-working, and motivated student who strives for constant improvement. The bibliography present in his thesis is pertinent and adequate. After carefully reading the proposed bibliography, he also read relevant papers and books referenced by the initial sources. Antonín also searched for other articles that could be relevant to his work. Throughout the whole time, Antonín was always very motivated and found all the tools and methods to achieve the proposed goals through a permanent consultation of new bibliographical references.

Formální a jazyková úroveň

průměrná

Posudte správnost používání formálních zápisů obsažených v práci. Posudte typografickou a jazykovou stránku.

As typical of many researchers and even more senior scientists, writing scientific documents poses many challenges, and it is very time-consuming. When reading Antonín's thesis, I found that this was where he noticeably had more difficulty. Nonetheless, I have witnessed a significant improvement in his writing since his research project. As an evaluator of many abstracts and proceedings submitted to conferences, I can verify that his English is already at the level of even more advanced students.

I consider that the scientific jargon was not employed, particularly in Chapter 4, as I would have wished for. However, even with elementary language, he could accurately describe and interpret his results independently. On this topic, I want to stress that Antonín has little experience writing scientific texts and is not a native English speaker. Therefore, I expect him to improve his writing in the forthcoming years if he becomes a scientist.

I did not notice a typography and a language page in the thesis, which I also find very useful, particularly during this hectic time

when many students have defenses on many topics. Nonetheless, Antonín introduces all the acronyms before using them systematically throughout the thesis. I hope that the absence of this page does not significantly hamper the reading of his thesis.

Výběr zdrojů, korektnost citací

výborné

Vyjádřete se k aktivitě studenta při získávání a využívání studijních materiálů k řešení závěrečné práce. Charakterizujte výběr pramenů. Posuďte, zda student využil všechny relevantní zdroje. Ověřte, zda jsou všechny převzaté prvky řádně odlišeny od vlastních výsledků a úvah, zda nedošlo k porušení citační etiky a zda jsou bibliografické citace úplné a v souladu s citačními zvyklostmi a normami.

During the supervision of the thesis, I observed that Antonín adhered to all ethics and good practice norms when developing his work. All the breakthroughs were achieved by consultation with the adequate bibliography cited in his thesis and by attending a Machine Learning school and a more general IDPASC school where he also had a Machine Learning subject. Antonín has also sought advice from the task coordinator of the Pierre Auger Collaboration by presenting his work at one task meeting. All work carried out by Antonín is original and was made by himself, under my supervision, and with further counseling from the Machine Learning task coordinator of the Pierre Auger Collaboration.

Další komentáře a hodnocení

Vyjádřete se k úrovni dosažených hlavních výsledků závěrečné práce, např. k úrovni teoretických výsledků, nebo k úrovni a funkčnosti technického nebo programového vytvořeného řešení, publikačním výstupům, experimentální zručnosti apod.

In work carried out by Antonín for his thesis, we extended the current method of reconstructing the Muon Production Depth (MPD) in extensive air showers for low zenith angles, a complementary region to the one proposed in the previous papers. We opted to use a Machine Learning algorithm employing Boost Decision Trees to parametrize the kinematic delay of muons, which are the main source of systematic uncertainty of the MPD reconstruction. We also managed to significantly reduce the

applied radial cut from ~ 1000 m to only 200 m. Such achievement enables us to use the current method for a much wider range of events, highly increasing the statistical sample of showers to which we can apply the MPD reconstruction with regard to the original method. Antonín has also done exploratory research on whether we could apply a second Neural Network to estimate the kinetic energy of muons from the reconstruction of the MPD using the first Neural Network. Even though he barely had time to develop this method, he could lay the foundations for achieving it.

The work presented in this thesis was presented at the second most important conference in cosmic-ray physics in 2022, and the full results will be presented this year at the International Cosmic Ray Conference, the reference conference in cosmic rays. In both conferences, we will have conference proceedings published, and later this year, we aim at a paper to be published in the *Astroparticle Physics* journal or similar.

III. CELKOVÉ HODNOCENÍ A NÁVRH KLASIFIKACE

Shrňte aspekty závěrečné práce, které nejvíce ovlivnily Vaše celkové hodnocení. Případně uveďte otázky, které by měl student zodpovědět při obhajobě závěrečné práce před komisí.

The reasons which lead me to evaluate Antonín's work as excellent are:

- The objective of Antonín's work was to extend the existing method of the reconstruction of the Muon Production Depth to an array of buried scintillator detectors, which was achieved.**
- The main results of Antonín's thesis can now be applied to the case of a real detector array by including the effects of the detector time resolution and collection area.**
- We opted to use Machine Learning, particularly Gradient Boosted Decision Trees, to reconstruct the Muon Production Depth**

instead of applying an overall spline fit over the kinetic energy of muons predicted by Monte Carlo simulations.

- Antonín has also worked on a proof of concept, from which we can apply a second Machine Learning algorithm, again a Gradient Boosted Decision Tree, to estimate the kinetic energy of muons. A quantity that cannot be measured directly in typical cosmic ray experiments but that can now be assessed by combining the two Gradient Boosted Decision Trees. We can successfully apply these two algorithms to cosmic ray data and improve the current hadronic model predictions.

- The work is entirely original and was developed by Antonín with great independence. He had to search the correct literature and forums to find the Machine Learning algorithm with the best performance in reconstructing the MPD.

- For the reasons stated above, I hope that I could show that Antonín is already to work independently and search for the correct or most adequate sources of how to conduct original research while knowing to work in a small group.

- Antonín showed all the necessary skills to pursue a career in physics if that is his wish.

- His work has attracted the attention of several members of the Pierre Auger Collaboration, who would like to have him as a Ph.D. student.

Předloženou závěrečnou práci hodnotím klasifikačním stupněm **A - výborně**.

Datum: 23.5.2023

Podpis: *Eva Santos*