Colombian Network on High Energy Physics
Input on Experimental HEP

Abstract:

The Colombian High Energy Physics community has steadily been growing in the last decade, with young scientists taking leading positions at local universities and more students joining this field of research. The reach of the Colombian groups working on particle physics experiments has also been extended, with participation in the ATLAS, CMS, LHCb and ALICE experiments of the LHC at CERN, in the NOvA and DUNE neutrino experiments, and in the AUGER and LAGO observatories. This document summarises the current status and interests of the different groups working on Experimental High Energy Physics in Colombia, and their perspectives for the future.

<u>Participation in the LHC experiments</u>

Scientific context

The scientific cooperation between Colombia and the European Organization for Nuclear Research CERN has brought big benefits in training of PhD students, engineers and postdoc researchers; enhancement of postgraduate programs; increasing the scientific production indicators and building bridges for the development of Physics and technology transference in Colombia.

Currently the Large Hadron Collider at CERN is the only collider that is exploring the high energy particle physics frontier. With its four Experiments ATLAS, CMS, LHCb and Alice, it is possible to explore any evidence of new physics at energy scales never reached before.

The participation of different Colombian groups in the four Experiments of the Large Hadron Collider dates from many years ago and it has been fruitful and successful:

The High Energy Physics group (HEP) of Universidad de Los Andes, Colombia (UNIANDES), has been a full member of the CMS collaboration since March 2006, contributing both in the detector operation and Physics analysis. The group has been involved in the operation and upgrades of the Resistive plate chambers and Gas electron multiplier detectors used for muon identification and triggering. About 30 engineers from UNIANDES have been part of the international team in charge of the computing and data operations, through the GRID system, of the CMS experiment, some of the engineers have been stationed for about two years at CERN, others at FERMILAB. The group has been also heavily involved and leading searches of supersymmetric signatures and physics beyond the Standard Model, few of them focused on the experimentally challenging compressed mass spectra scenarios, which require special physics tools such as jets from initial state radiation or Vector Boson Fusion Topology. The UNIANDES HEP group has graduated seven Phd students who have performed their research theses on CMS physics analyses. The group has also incorporated master degree students in their hardware and software activities, with more than a dozen MSc theses already completed. As a bridge for technology transfer to Colombia, the group has setup an instrumentation laboratory in their university campus, in Bogota, where interdisciplinary applications of semiconductor and gaseous radiation detectors are being investigated.

The experimental High Energy group of Universidad Antonio Nariño has been part of the ATLAS Collaboration since 2007. In these years, the group has been part of different activities including detector performance studies and its calibration, physics analysis as well as activities related to the

ATLAS detector maintenance and operation. The group is interested in searches for Beyond the Standard Model Higgs Bosons, supersymmetric signatures and physics BSM. The group is currently composed by two professors and two engineers, but many researchers and students have been associated with the group during these years.

In July 2014, the agreement between LHCb Experiment and Universidad Nacional de Colombia (UNAL) was signed and the UNAL was accepted to participate as an associated group of LPNHE (Laboratoire de physique nucléaire et de haute énergies) in the LHCb Collaboration. The group is composed by two professors, three undergraduate students, four master students and one PhD student. Their members are collaborating in physics of Charm quark and quarkonia and exotic states analyses.

The Group of Phenomenology of Fundamental Interactions of Universidad de Antioquia (UDEA) has been working for several years in phenomenology. Since 2019 the group is a member of the CMS Collaboration. They have been working on searches for physics beyond the Standard Model. Currently, three professors, one post-doc, two Phd students, one master student and two undergraduate students, members of the group are associated to CMS projects.

Current status and expected challenges:

The Large Hadron collider (LHC) at CERN is currently the world's largest and most powerful particle accelerator in operation which allows to explore the high energy particle physics frontier. Four detectors are placed along its 27 km-circumference: ATLAS, CMS, LHCb and Alice. After four years of successful data taking (2015-2018), the so-called Run 2 has finished and the second long technical stop (LS2) has started to prepare the accelerator and detectors for the conditions of the third data taking period (Run 3).

The LHC has shown an extraordinary performance during the first and second data taking periods. During Run 2, the LHC has delivered about 150 fb^-1 to the ATLAS and CMS experiments and about 2 fb^-1 to the LHCb experiment.

The ATLAS and CMS Experiments have delivered a large amount of results of physics analysis using a first set of Run 2 data, which include precise measurements of the Standard Model (SM) properties, top quark physics, Higgs Boson properties, the observation of the production of the Higgs Boson in association with W or Z bosons decaying into a pair of bottom quarks and the observation of the Higgs boson production in association with the top quark.

Despite the success of the SM in describing the nature at high energy scale, we know it is not a fundamental theory of nature as it cannot explain some phenomena like the origin of the neutrino mass, Dark matter and Dark energy, and it does not include gravity. Both Collaborations have also produced a big amount of searches for Beyond the Standard Physics signatures, including Supersymmetry, evidence of Dark Matter presence, among others. Also many analyses with the total amount of Run 2 dataset have been delivered and many more are in progress.

The most important results achieved by the LHCb Experiment are the precise measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix parameters, the observation of tetra and pentaquark resonances and the observation of CP violation in particles composed by charm quarks for the first time.

The accelerator is currently in a technical stop LS2, aiming at preparing the accelerator and the detectors for the Run 3 foreseen conditions. When data taking resumes in 2021, the peak luminosity is expected to reach 2-3 $\times 10^{34}$ cm^{-2} s^{-1} corresponding to 55 to 80 interactions per crossing (pile-up) with 25 ns bunch spacing, well beyond the initial design goals. Also it is expected to reach the designed collision energy of 14 TeV. All the LHC experiments will upgrade their parts. ATLAS and CMS will upgrade their components in order to improve the granularity, acceptance and longevity of their detectors. The LHCb experiment will be replaced with faster detector components and Alice will upgrade the technology of its tracking detectors.

Run 3 is scheduled between 2021 and 2023, to then give way to a new Long Shutdown (LS3), between 2024 and 2026, leading to the High-Luminosity LHC (HL-LHC) era. The HL-LHC will collide beams at up to seven times the luminosity for which the ATLAS detector was designed, resulting in about 200 simultaneous collisions per beam crossing. This will greatly increase the potential for the Experiments to find new or rare physics processes – but necessitates the development and installation of new detectors with radiation-hard elements, finer granularity and faster readout.

Construction and operational costs:

Institutes joining the different Collaborations are expected to contribute to the Operation and Maintenance (M&O), to operation tasks, to the physics programme and the upgrade programmes for the operation at the High-Luminosity LHC of the detectors.

To enter as a full member, a financial contribution must be paid. This contribution could, in part, be delivered “in kind”, by providing deliverables in technical areas.

There is a yearly share of M&O costs of around 10 kCHF per author signing the Collaborations publications and holding a PhD.

Participation in DUNE Experiment

Scientific context

The Deep Underground Neutrino Experiment (DUNE) is one of the most ambitious and promising experiments currently under construction. The experiment's main focus lies in the area of neutrino physics as well as nucleon decay. In the neutrino sector, DUNE will look for signs of CP violation, put constraints on the neutrino mass hierarchy, and improve some of the parameters related to neutrino physics. For proton decay, DUNE will have unprecedented sensitivity to the decay of a proton into a charged kaon and an antineutrino, although it is possible to study some other nucleon decay modes as well.

DUNE has an ancillary program that goes beyond the aforementioned goals. Due to the great potential of the experiment, it is possible to study and constrain physics beyond the Standard Model (BSM). For instance, DUNE could be sensitive to deviations of the neutrino standard interactions, which arise from BSM physics. Moreover, due to the high-intensity proton beam used by the experiment, it is possible to produce BSM particles that could then be detected in the near detector, those particles could be part of a dark sector or could be dark matter candidates themselves. Colombian institutions are also working on this front, developing models as well as effective theories to understand the experiment’s sensitivity to new physics signals.

At today, four colombian institutions belong to the DUNE collaboration. The institutions are Universidad del Atlántico, Universidad Escuela de Ingeniería de Antioquia (EIA), Universidad Antonio Nariño (UAN) y Universidad Sergio Arboleda. From the already mentioned institutions EIA and UAN are working directly in the design of the digitalization boards. It is expected that the Universidad de Antioquia joint this efforce in near future.

Colombian institutions participating in the DUNE Experiment are interested in investigating the experiment's capability to find or constrain physics BSM. For this, the groups propose to introduce new physics models that have the potential of being explored in DUNE. Such models could focus on non-standard interactions (NSI) or on a dark sector such as the one that could arise from the presence of new symmetries and/or particles. It is important to study DUNE's sensitivity to the new particles or interactions of the model in order to perform these analyses.

Current status and expected challenges:

Latin America in general and in particular Colombia is involved in the photon detector system design, for that reason this part of the document will describe the current status of that system.

The PDS includes a light collection system, light sensors, readout electronics and monitoring system. The light Collection is based on the so-called ARAPUCA concept which consist on the trapping of photons in a box with highly reflective internal surfaces. Inside of each ARAPUCA, 48 Silicon Photomultipliers (SiPM) will be connected together to detect the trapped photons. The exact type of SiPM, mounting and connection scheme is under investigation.

In order to read the SiPMs signals, digitalization at room temperature will be performed by electronics boards currently under designing by Colombian engineers in collaboration with Fermilab. The boards are known as DAPHNE (Detector Electronic for Acquiring Photons from Neutrinos) and will be in charge of the digitalization, initial processing and communication of the PDS with the DAQ system.

DUNE is the first science project of this scale in the USA that will be built under an international collaboration scheme. This opens a series of opportunities for countries around the world to participate in the design and construction of specific components gaining experience and strengthen relationships with the local industry. In particular, Colombia is working in the designing of the digitalization boards of the Photon Detector system. As a result of this work at the beginning of the year 2020 the production of a small number of prototypes board is planned. The prototypes will be tested at different facilities around the world with the close collaboration between Colombian, Peruvian and Paraguayan engineers.

Construction and operational costs:

The final design of the DUNE experiment is still under discussion. In particular the Photon detection system is planned to have a total cost of production of 17 millions U.S dollars. The digitalization electronics of the photon detector system is calculated of the order of 400000 US Dollars.

Discussion about a common fund are ongoing a fee per member and for a to be determined scale of time is considered. Initial proposal is the 10000 US Dollar yearly per member.

Participation in Lago and Auger Experiments

The Universidad Industrial de Santander (UIS) is part of the LAGO collaboration since 2010, working on the development, construction and operation of Water Cherenkov detectors for the site in Bucaramanga, as well as the development of a new electronic readout, a DAQ custom system, and also the modelling and simulation of the signal.
The UIS group also participates in the Auger experiment since 2014, together with the recently formed group at Universidad de Medellín (2018). Their involvement in the collaboration covers high quality data for analysis, Cosmic ray Air showers modelling and simulation, and Atmospheric phenomena, correlation with solar activity and space weather.
The work done by the UIS group on cosmic ray detection has led to other projects such as the Muon Telescope (MuTe) for muon volcanography and the RACIMO initiative as a citizen network for environmental monitoring.

Participation in NOVA Experiment

Neutrinos are the only solid evidence of physics beyond the Standard Model to date. They are massless within the Standard Model as they only seem to exist in one chiral state. However, neutrinos exhibit oscillations among their three known flavors. Such behavior is only feasible if neutrinos are massive. Their mass, although small, has profound implications in cosmology. Neutrinos are the second most abundant known particle in the universe after photons. Moreover, their oscillation pattern opens a possibility of CP violation in the lepton sector. The oscillation matrix that relates the two bases -mass and flavor- is constructed from at least seven parameters: three rotation angles, three mass squared differences and a CP phase (δCP), whose values are only known through experiments. All the angles and all the mass differences have been measured experimentally with varying uncertainties, and the possibility of a CP violating phase is still under investigation by various experiments. The sign of the mass difference between the heaviest and lightest neutrinos is currently unknown.

Knowledge of the seven parameters is key to understanding the workings of neutrinos in the aftermath of the Big Bang, and hence, their influence in cosmology. A non-zero δCP could explain an ancient asymmetry between neutrinos and antineutrinos that might be responsible for the current matter-dominated universe. The ambiguity in the mass difference’s sign (neutrino mass hierarchy problem), and the value of δCP have other implications in ideas related to GUTs, flavor physics, and the nature of neutrino masses, i.e. Dirac or Majorana.

Other neutrino-related topics are of paramount importance to HEP, e.g., the possible existence of sterile neutrinos, neutrino magnetic moment and neutrino cross sections. Sterile neutrinos could be major contributors to dark matter; non-zero magnetic moment is present in many ideas of physics beyond the Standard Model and improved accuracy in measurements of neutrino interactions are necessary to better test novel HEP models and to reduce uncertainty in neutrino oscillations.

Colombia has member institutions in two major neutrino oscillations experiments: NOvA (Universidad del Atlántico and Universidad del Magdalena) and DUNE (Universidad Antonio Nariño, Universidad del Atlántico, Universidad EIA and Universidad Sergio Arboleda). NOvA is an international collaboration hosted by Fermilab that is currently taking data, aiming to establish 2 or 3σ

measurements on the δCP and the neutrino mass hierarchy, among other scientific targets. NOvA's data run is scheduled to end in 2025, with possible extensions, contingent on DUNE's starting date.

1. Neutrino oscillations
   NOvA has the capability to take neutrino and antineutrino data and combine them to produce competitive measurements on the previously mentioned quantities. The latest results exclude most values near $\delta CP = \pi/2$ for the inverted mass hierarchy (one light neutrino and two heavy neutrinos) by more than 3σ and favor the normal neutrino mass hierarchy (two light neutrinos and one heavy neutrino) by 1.9σ and θ23 (one of the rotation angles) values in the upper octant by 1.6σ (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.151803). NOvA's oscillation results provide strong bases to discriminate between competing theories on physics beyond the Standard Model; particularly those related to the origins of mass, GUTs, See-Saw mechanism, and leptogenesis.

2. Sterile neutrinos
   NOvA is currently searching for sterile neutrinos to strengthen its oscillation searches. Latests results on sterile neutrinos show no evidence of oscillations between Standard Model neutrinos and sterile ones. Nonetheless, the collaboration places constraints on the values of mixing angles in the extended oscillation matrix: θ24 < 20.8° and θ34 < 31.2° at the 90% C.L. for 0.05eV^2 ≤ Δm^2_41 ≤ 0.5 eV^2, the range of mass splittings that produce no significant oscillations over NOvA's Near Detector baseline (https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.072006). The search continues and new results are expected to be released within the next two years.

3. Neutrino cross sections
   NOvA's neutrino program is rich, and is currently producing results in various fronts such as cosmic rays (https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.122004), gravitational waves (under collaboration review), *machine learning* (https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.073005) and neutrino cross sections, among others. NOvA's cross sections program uses the near detector to examine neutrino interactions. The program covers inclusive and exclusive channels, seeking results that mainly benefit the community of carbon-based detectors and the HEP theoretical community. The results are presented as differential and total cross sections. The differential cross sections are presented as functions of neutrino kinematic variables. Each result focuses on a type of neutrino: either electron or muon, the charge of the interaction mediator: charged or neutral, and the kind of the neutrino: matter or antimatter. An inclusive result encompasses a neutrino: type and kind, as well as the charge of the mediating boson. An exclusive result focuses on the final state of the interaction, e.g. N charged/neutral mesons (N = 0, 1, 2, ...), N nucleons and/or N hadrons. NOvA results are important to the HEP community to help pinpoint the validity of popular neutrino interaction models. The more stringent neutrino cross section results to date include 2 to 20% systematic uncertainties related to: axial masses, final state interactions, random phase approximation and the 2p2h model. These effects are related to cross section modeling, and reducing their uncertainties is rather important for the understanding of neutrino interactions. Current and future experiments willing to measure neutrino cross section parameters need to address the reduction of such uncertainties. Results that have been socialized by NOvA on neutrino cross sections address the neutral-current coherent pi-zero production (https://arxiv.org/abs/1902.00558). This particular result is the most precise measurement of neutral-current coherent pi-zero production in the few-GeV neutrino energy region. Results that are under current collaboration review address: muon neutrino charged current inclusive interactions, electron neutrino charged current inclusive interactions and muon neutrino charged current interactions with a pi-zero in the

final state. Other analyses under investigation address interactions, both charged and neutral, with final states containing: no pi-mesons, one charged pi-meson and more than one charged pi-mesons.

List of the interested scientists in the community:

- Mario A. Acero Ortega (Universidad del Atlántico)
- Enrique Arrieta Díaz (Universidad del Magdalena)
- Carlos Ávila (Universidad de los Andes)
- Amalia Betancur (Universidad EIA)
- Andres Castillo (Universidad Sergio Arboleda)
- Andrés Flórez (Universidad de los Andes)
- Luz Stella Gomez (Universidad Sergio Arboleda)
- Jhovanny Andrés Mejía Guisado (Universidad de Antioquia)
- Diego Milanés (Universidad Nacional de Colombia)
- Deywis Moreno (Universidad Antonio Nariño)
- Gabriela Navarro (Universidad Antonio Nariño)
- Luis Nuñez (Universidad Industrial de Santander)
- Jairo Alexis Rodriguez (Universidad Nacional de Colombia)
- José David Ruiz Álvarez (Universidad de Antioquia)
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- Nelson Vanegas (Universidad de Antioquia)