České vysoké učení technické v Praze
Fakulta jaderná a fyzikálně inženýrská

Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering

Dr. Jesús Guillermo Contreras Nuño

Highlights from ALICE results during RUN1 at the LHC

Výběr nejvýraznějších výsledků experimentu ALICE z RUN1 na LHC

Summary

The ALICE Collaboration has designed and built a complex detector system, which is installed around one of the interaction points of the Large Hadron Collider (LHC). The aim is to study the properties of a new state of matter, called the Quark Gluon Plasma, which is expected to be created in the collisions of lead ions at the LHC.

This detector system has been in operation since 2009. By October 2015, more than 100 articles have been published by the ALICE Collaboration. Some highlights of this extensive production are described below. They include the quantification of the suppression in the yield of particles at high momentum due to the created medium and the measurement of collective motion of this medium. Another topic discussed here is the surprising observation of long range correlations in collisions of protons with lead ions, which suggests that the QGP could also be created in systems smaller then previously thought. The final highlight to be presented is the study of the energy evolution of the gluon structure of the proton using photon-production processes, which at the LHC reach energies beyond twice what has been achieved before. Furthermore, the impact on the operation of the ALICE detector system of two of its components, the VZERO and the AD detectors, is briefly described. A few words on the near future plans of the ALICE Collaboration conclude this work.

Souhrn

Instituce spolupracující na experimentu ALICE navrhly a postavily komplexní detektorový systém, který je umístěn na jednom z několika interakčních bodů urychlovače Large Hadron Collider (LHC). Posláním experimentu ALICE je studium vlastností nového stavu hmoty, zvaného Kvark-gluonové plasma. Ve srážkách iontů olova na LHC se předpokládá vytvoření tohoto stavu hmoty.

Detektorový systém ALICE je v provozu od roku 2009. Do října 2015 bylo publikováno více než 100 vědeckých článků z experimentu ALICE. Níže jsou popsány výrazné body tohoto velkého objemu vědeckých prací. Tyto výrazné body zahrnují kvantifikaci potlačení výtěžku částic s velkou hybností kvůli vytvoření média a měření kolektivního pohybu v tomto médiu. Jiné zde diskutované téma je překvapivé pozorování korelací na velkých vzdálenostech ve srážkách protonů s ionty olova, což naznačuje vytvoření kvark-gluonového plazmatu i v menších systémech než se uvažovalo dříve. Posledním výrazným bodem o kterém je nutno se zmínit je studium energetické evoluce gluonové struktury protonu s použitím fotoprodukčních procesů, ve kterých LHC dosáhl energií dvojnásobně větších než při předchozích měřeních. Dále je stručně popsán vliv dvou částí experimentu ALICE na provoz celého detektorového systému ALICE, a to detektorů VZERO a AD. Závěrem této práce je stručný popis plánů experimentu ALICE pro blízkou budoucnost.

Klíčová slova:

Kvark-gluonové plasma, potlačení jetů, kolektivní pohyb, saturace, detektor ALICE, LHC

Key words:

Quark Gluon Plasma, Jet suppression, Collective motion, Saturation, ALICE detector, LHC

Contents

1 Introduction

One of the most fascinating aspects of Nature is that it forms so different types of matter with the same building blocks. An everyday instance of this phenomenon is that of H_2O molecules forming ice, water and vapour. Something similar is expected to happen with QCD matter.

As far as we know there are four fundamental forces: gravitation, electromagnetism and the weak and strong forces. The latter are responsible for the stability of nuclear matter keeping the protons together inside the nuclei in spite of the electromagnetic repulsion. These force is described by QCD, a theory of relativistic quantum fields. The fields in question are quarks and gluons. These are the building blocks of hadrons which include the protons, the neutron and other not so familiar particles as the pions, kaons and many more. The full list includes several hundred particles and resonances [1]. All of them form what is known as hadronic matter or Cold Nuclear Matter (CNM). Numerical solutions of QCD in a time-space lattice [2] pointed out, already in 1980, that a different form of matter could be created with the QCD fields, the so called Quark Gluon Plasma (QGP).

One possibility to create a QGP in the laboratory to study its properties is to collide heavy ions at ultra relativistic velocities. The basic idea is that heavy ions, composed of several tens or even hundreds of nucleons, would have enough QCD material to work with. Being ions, they could be accelerated with electromagnetic fields. Their collisions would have to achieve the high energy densities and temperatures needed to ”melt” the standard CNM.

One machine capable of producing such interactions is the Large Hadron Collider (LHC), which is described in detail in [3]. The period of operation from 2009 to 2013 is called the RUN1. Currently, after a pause of almost two years for updates and improvements, the LHC is in operation again in the so called RUN2, which will last, according to the current schedule, until 2018. During RUN1 the LHC collided nuclei of lead at centre-of-mass energies $\sqrt{s_{\rm NN}} = 2.76$ TeV per nucleon pair. There were two data taking periods in this mode in the autumn of 2010 and 2011, respectively. During RUN1 the LHC also collided protons at different centre-of-mass energies: 0.9 TeV, 2.76 TeV, 7 TeV and 8 TeV. Currently, these collisions are at 13 TeV. Furthermore, the LHC also produced collisions of protons against lead ions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The combination of results of these three types of collisions are needed to separate effects of QGP from those of CNM.

ALICE is a Collaboration of some 1500 scientists, engineers and students from 37 countries that has designed and built a complex system of detectors called also ALICE [4]. Both, Cinvestav (MEX) and CVUT (CZ) are among the participating institutes. Using data from RUN1 the ALICE Collaboration has published more than 100 scientific articles, which have contributed to our understanding of hadronic matter as well as the new state of matter created in heavy-ion collisions.

In the following sections we present some highlights of the physics results and of the detector system used to obtain them. This work is concluded with a brief description of the near and middle term plans of the ALICE Collaboration.

2 Physics highlights

As mentioned before the scientific production of the ALICE Collaboration is quite large and impossible to present in a few pages. For that reason, we have selected four physics topics, to present a representative sample of the work of the Collaboration.

2.1 Suppression of high-momentum particles

One important aspect of Relativistic Quantum Mechanics is that processes require some time to happen. In the collision of heavy ions the formation of the QGP takes longer than the formation of so called hard probes. In this case, quarks or gluons with large momentum in the plane transverse to the direction of the incoming projectiles. As the hard probes are formed faster, they can be used to test the response of the created medium, that they will have to transverse, to different probes.

It has to be mentioned that these type of experiments do not sample one point in the phase space of matter, but a trajectory. That is, the incoming ions are in the state CNM, their collision produces the QGP, which expands, cools and revert to hadrons, which then reach our detectors.

Fast quarks or gluons are hard probes which are abundantly created in the most energetic collisions of lead-ions. They transverse the medium and interact with it through QCD forces and later, create particles that are measured in the detector. The creation of particles with high momentum is well understood within QCD in the case of proton-proton collisions.

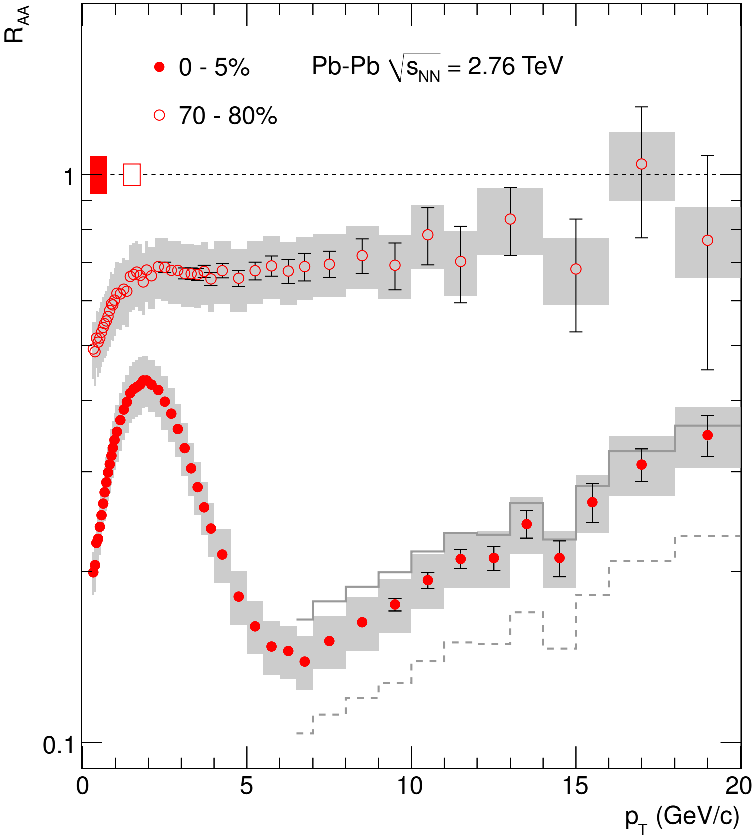

Figure 1: R_{AA} in central (0–5%) and peripheral (70–80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as measured by ALICE. Figure taken from [5].

The basic idea of is then to measure the momentum spectra of hadrons both in proton-proton and in lead-lead collisions and compare them through a normalised ratio of these spectra, called R_{AA}. The normalisation takes into account the geometry of the nuclei in terms of protons and neutrons, so that a ratio of one would mean the same behaviour on both types of collisions. In case of the formation of a QGP it is expected that the fast quarks and gluons will lose energy while traversing the medium and thus the ratio would be below one.

Figure 1 (from [5]), shows R_{AA} against the transverse momentum of the hadron for two cases. So called central collisions where the nuclei collide head-on and peripheral collisions where only part of the nuclei interact. These cases are labeled in the figure as 0-5% and 70-80%, respectively. It is observed that peripheral collisions have an R_{AA} closer to one that central collisions, which are suppressed by more than a factor of five. This figure also shows a strong dependence on transverse momentum. This behaviour is qualitatively compatible with the formation of a QGP. These early results have been confirmed by more precise and detailed measurements performed later by ALICE. See for example [6, 7, 8].

2.2 Collective motion

From the results presented in the previous section, it seems that there is a created medium that interacts with the hard probes such that the yield of high-momentum particles is suppressed. To understand further the properties of this medium the momentum spectra is expanded in a Fourier expansion in the transverse plane using the azimuth angles of the detected particles. For an azimuthally symmetric system it is expected that the odd coefficients vanish. Furthermore, in the case of an asymmetric collision, for example between the central and peripheral cases, it is expected that pressure gradients are formed. These gradients push differently the medium depending on the azimuthal angle and the geometrical asymmetry is transferred to a momentum asymmetry. The peculiarities of this process shed light on the properties of the created medium.

The ALICE Collaboration has performed a series of measurements in this field; e.g., [10, 11, 12, 13]. The main findings are, as in the case of hadron suppression, in agreement with expectations from the formation of QGP in these collisions. The second harmonic coefficient, called flow, exhibits a dependence in the mass of the measured hadron as expected from theoretical models. Higher order harmonics have been measured

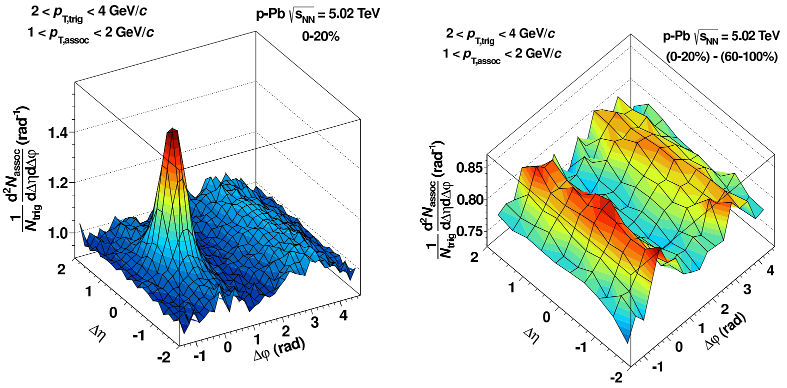

Figure 2: Angular correlations of triggered and associated particles for central collisions (left panel). Subtraction of the angular correlations in the peripheral case from the central case (right panel). Figures taken from [9].

and confirm this picture. These observations have also been made in very central collisions, which point out to the presence of fluctuations in the initial conditions existing at the time of the QGP formation. This view is reinforced by the observation of non-zero odd coefficients. The fluctuations needed to explain this observation are at the sub-nucleon level, an open a window of opportunity to study so called saturation effects in perturbative QCD. This is, to study configurations where the distribution of gluons in a hadron fluctuates so that they occupy all the available phase space and saturate the hadron. This is one of the most interesting topics nowadays in QCD. We will return to it in Section 2.4.

2.3 Long-range correlations

One of the more surprising results from the LHC is the observation of QGP-like behaviour in collisions of protons and in proton-lead collisions. These behaviour has been observed through the study of long-range angular correlations. The procedure is as follows. One selects a particle in the event with a given momentum and measures its angular correlation with all other particle in the event within a given momentum interval.

Figure 2 shows, in the left panel, one such correlation where the selected particles is named the trigger and all the rest the associated particles. (This figure is from [9].) One can see a strong peak around (0,0), which correspond to all particles that are produced from one fast quark or gluon. The wave at a distance of π in azimuth is expected due to momentum conservation, but one can also see some unexpected waves along azimuth distance centred around zero. To have a better view to this unexpected behaviour the same correlation function is computed for central and peripheral events and the later is subtracted from the former. The result is shown in the right panel of Figure 2., where two such long range structures are seen.

This means that somehow particles very separated in phase space are correlated. One possible explanation is that the particle production comes from one single medium. And the properties of the QGP are compatible with the observation. This was completely unexpected and it has caused that the study of proton-proton and proton-lead collisions are even more important than before. For example, ALICE has studied the same correlations, but for identified particles [14], where, in the case of QGP, one expects a given mass dependence of these long-range effects. The results are again compatible with the formation of QGP, but the picture is not yet completely clear and alternative explanations, based on properties and fluctuations of the initial state of the incoming hadrons have been also used to describe quantitatively these observations.

2.4 The gluon in the proton

As explained before, the observation of long-range correlations in small systems has an alternative explanation based on a saturated gluon distribution in the projectile. One of the cleanest measurements of the gluon distribution in a hadron is to shed light on it and observe how the light scatters.

As the lead ions accelerated in the LHC are charged, the electric field of the fast particle is Lorentz contracted and its Fourier transform can be interpreted as a beam of quasi-real photons. The energy of this beam is given by the boost of the charged particles, and thus at the LHC can reach values higher than ever measured before. As the photons are quasi-real when they scatter they may produce instead of a photon a vector meson, which upon decay can be measured by the detector. For a recent review see [16].

The ALICE Collaboration has measured the photoproduction of vector mesons in Pb-Pb [17, 18, 19, 20] and in p-Pb collisions [15]. In this last case, as the intensity of the quasi-real photon beam depends on

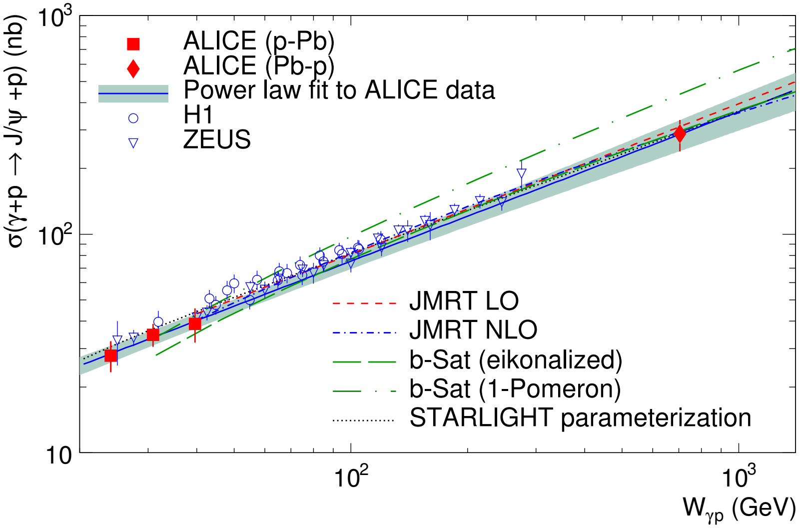

Figure 3: Energy dependence of the exclusive J/ψ photoproduction cross section. Figure taken from [15].

the square of the electric charge of the accelerated particle, the source of the photon is almost always the lead ion and the gluon distribution in the proton is sampled. It is a big challenge to perform these measurements with an accelerator and a detector that were optimised for a different kind of physics.

Figure 3, taken from [15] shows the cross section, as a function of the centre-of-mass energy in the photon-proton system, measured in ALICE and compared to previous measurements and to models. It is remarkable that ALICE has reached an energy more than two times larger than the maximum energy reached before. This process is proportional to the square of the gluon distribution in the target, and precisely at large energies is where one expects to see some effects of a gluon-saturated proton. As the behaviour of the cross section does not change with energy, it is a power law with an exponent around 0.7 all over the measured range, one can conclude that, with the present precision, one has not yet seen saturation in the proton.

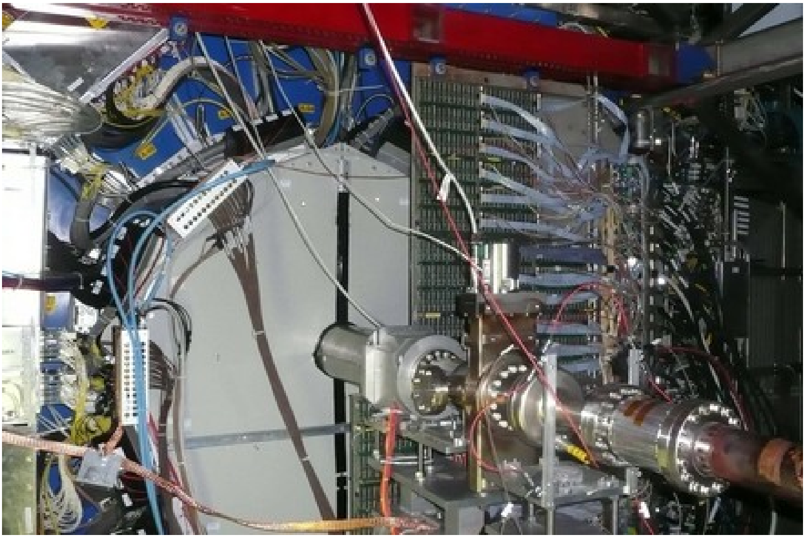

Figure 4: The VZERO-A detector installed inside the ALICE detector system. The beam pipe is clearly seen as well as some of the read-out electronics and cables carrying the electric power to the different components.

3 Detector highlights

The measurements described in the previous sections are not possible without detectors. But the detectors are not only needed to measure the events, but also, in a previous phase called triggering, to select those events that will be analysed later on. This is so, because the amount of data produced by the LHC is orders of magnitude larger than the data that can be processed by the experiment. The importance of the trigger detectors cannot be overemphasised. Below we describe two detectors, which are relatively simple from the technological point of view, but vital for the data taking process of the experiment.

3.1 The VZERO detector

The VZERO detector [21] consists of two arrays of plastic-scintillator detectors called VZERO-A and VZERO-C. The VZERO-A array was designed and built in Mexico, while the VZERO-C in France. A photo of the VZERO-A detector as installed inside ALICE is shown in Figure 4. Each array is segmented in four rings in the radial direction and 8 azimuthal sectors. The plastic is BC404 from Bicron and has a 2.5 cm (2.0 cm) thickness in the VZERO-A (-C). The arrays use WLS fibres, which conduct the light, produced by particles traversing the plastic, to R5946-70 photomultiplier tubes (PMT) from Hamamatsu.

The signal from the PMT is split into two signals. One is amplified and used to obtain timing information with a TDC. The other is not amplified and it is used to obtain charge information with an ADC. The timing information can be used to trigger for the presence of activity in either a beam-beam time window or in a beam-gas time window. These windows are defined setting the time of the collision at the nominal interaction point to zero. Particles produced by the collision arrive at positive time to the detectors. Particles coming to the detectors from behind, i.e., produced by a beam-gas interaction downstream of the nominal interaction point, arrive at one of the arrays before time zero. The charge information can be used to trigger on the amount of activity in a given event and thus they are the basis of a centrality class trigger.

The arrays are placed in opposite sides of the nominal interaction point and cover the pseudo-rapidity ranges (2.8,5.1) and (-3.7,-1.7) for the VZERO-A and VZERO-C respectively. This large rapidity coverage is very useful for measurements of diffraction events [22] as well as to exclusive photoproduction processes as described in Section 2.4.

This detector is at the basis of the trigger system of ALICE and its importance is manifested by the fact that it has been used, as necessary detector, in each one of the physics publications of the ALICE Collaboration to date.

3.2 The AD detector

The AD detector is similar to the VZERO detector in philosophy and construction. It is also made of scintillator plastic read out by optical fibres and PMTs. The electronics and data acquisition system are also similar to that from VZERO. The AD detector was integrated in ALICE during the LHC shutdown before Run 2 to enhance the capabilities of the experiment to tag diffractive processes and events with low transverse momentum. It consists of two double layers of scintillation counters placed far from the interaction region, on both sides: one in the ALICE cavern at 17.0 m and one in the LHC tunnel at -19.5 m.

Its good time resolution and large coverage in pseudorapidity, extending up (down) to 6.3 (7.0) units will be very useful to tag the pres-

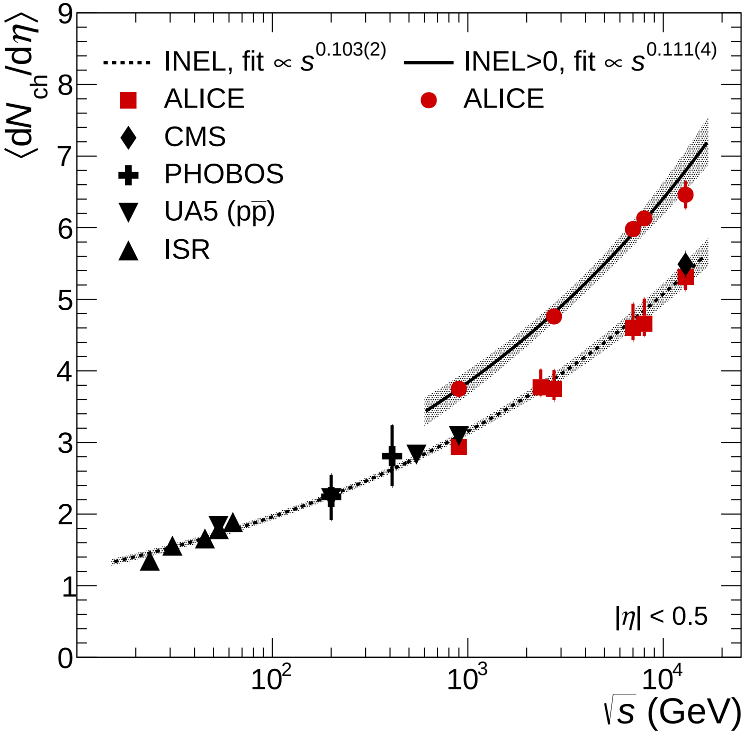

Figure 5: Charged-particle pseudorapidity density measured in the central pseudorapidity region. The lines are power-law fits of the energy dependence of the data and the grey bands represent the standard deviation of the fits. Figure taken from [23].

ence of inelastic collisions, to select events with large forward rapidity gaps, like central diffraction production or exclusive photoproduction processes as described in Section 2.4.

It has already been used, along with the VZERO and other detectors, in the first ALICE publication with results from RUN2 at the LHC [23].

4 Perspectives for RUN2

The RUN2 has already started at the LHC with collisions of protons at 13 TeV. The first results have already been published. The ALICE Collaboration has measured the pseudorapidity and transverse momentum distribution of charged particles [23]. Figure 5 shows the density of charged particles at mid rapidity at different energies for two processes inelastic and inelastic with at least one particle produced at mid rapidity. These results are very important to understand the bulk of particles produced. This observable cannot be computed with perturbative methods within QCD and has to be described with phenomenological models, which require data to fix their parameters.

During RUN2, ALICE expects to measure in detail the appearance of QGP-like effects in small systems, taking advantage of the increase in energy and in statistics. In what respects to lead-ion collisions there will also be a factor of two increase on the total energy available for the interactions and a large increase in the number of available events to be analysed. In some cases the expected increase is a factor of 10, which will allow very detailed studies, with smaller experimental uncertainties in all topics covered in this work. The next few years will be full of new data, and hopefully they will bring with them some more unexpected observations.

References

[1] **Particle Data Group** Collaboration, K. A. Olive et al., *Review of Particle Physics*, *Chin. Phys.* **C38** (2014) 090001.

[2] M. Creutz, *Monte Carlo Study of Quantized SU(2) Gauge Theory*, *Phys. Rev.* **D21** (1980) 2308–2315.

[3] L. Evans and P. Bryant, *LHC Machine*, *JINST* **3** (2008) S08001.

[4] **ALICE Collaboration** Collaboration, K. Aamodt et al., *The ALICE experiment at the CERN LHC*, *JINST* **3** (2008) S08002.

[5] **ALICE** Collaboration, K. Aamodt et al., *Suppression of Charged Particle Production at Large Transverse Momentum in Central Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys.Lett.* **B696** (2011) 30–39, [`arXiv:1012.1004`].

[6] **ALICE** Collaboration, J. Adam et al., *Measurement of charged jet production cross sections and nuclear modification in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*, *Phys. Lett.* **B749** (2015) 68–81, [`arXiv:1503.0068`].

[7] **ALICE** Collaboration, B. B. Abelev et al., *Production of charged pions, kaons and protons at large transverse momenta in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =2.76 TeV*, *Phys. Lett.* **B736** (2014) 196–207, [`arXiv:1401.1250`].

[8] **ALICE** Collaboration, B. Abelev et al., *Measurement of charged jet suppression in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*, *JHEP* **03** (2014) 013, [`arXiv:1311.0633`].

[9] **ALICE** Collaboration, B. Abelev et al., *Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys.Lett.* **B719** (2013) 29–41, [`arXiv:1212.2001`].

[10] **ALICE** Collaboration, K. Aamodt et al., *Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV*, *Phys.Rev.Lett.* **105** (2010) 252302, [`arXiv:1011.3914`].

[11] **ALICE** Collaboration, K. Aamodt et al., *Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV*, *Phys.Rev.Lett.* **107** (2011) 032301, [`arXiv:1105.3865`].

[12] **ALICE** Collaboration, B. B. Abelev et al., *Elliptic flow of identified hadrons in Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, *JHEP* **06** (2015) 190, [`arXiv:1405.4632`].

[13] **ALICE** Collaboration, B. Abelev et al., *D meson elliptic flow in non-central Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76 TeV$, *Phys. Rev. Lett.* **111** (2013) 102301, [`arXiv:1305.2707`].

[14] **ALICE** Collaboration, B. B. Abelev et al., *Long-range angular correlations of* π*, K and p in p-Pb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, *Phys.Lett.* **B726** (2013) 164–177, [`arXiv:1307.3237`].

[15] **ALICE** Collaboration, B. B. Abelev et al., *Exclusive* J/ψ *photoproduction off protons in ultra-peripheral p-Pb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, *Phys. Rev. Lett.* **113** (2014), no. 23 232504, [`arXiv:1406.7819`].

[16] J. Contreras and J. Tapia Takaki, *Ultra-peripheral heavy-ion collisions at the LHC*, *Int.J.Mod.Phys.* **A30** (2015) 1542012.

[17] **ALICE** Collaboration, J. Adam et al., *Coherent ?*^{0} *photoproduction in ultra-peripheral Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, *JHEP* **09** (2015) 095, [`arXiv:1503.0917`].

[18] **ALICE** Collaboration, E. Abbas et al., *Charmonium and* e^+e^- *pair photoproduction at mid-rapidity in ultra-peripheral Pb-Pb collisions at* $\sqrt{s_{\rm NN}}$=*2.76 TeV*, *Eur. Phys. J.* **C73** (2013), no. 11 2617, [`arXiv:1305.1467`].

[19] **ALICE** Collaboration, B. Abelev et al., *Coherent J/*ψ *photoproduction in ultra-peripheral Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Phys. Lett.* **B718** (2013) 1273–1283, [`arXiv:1209.3715`].

[20] **ALICE** Collaboration, J. Adam et al., *Coherent* ψ*(2S) photo-production in ultra-peripheral Pb-Pb collisions at* $\sqrt{s}_{\rm NN} = 2.76$ *TeV*, `arXiv:1508.0507`.

[21] **ALICE** Collaboration, E. Abbas et al., *Performance of the ALICE VZERO system*, *JINST* **8** (2013) P10016, [`arXiv:1306.3130`].

[22] **ALICE** Collaboration, B. Abelev et al., *Measurement of inelastic, single- and double-diffraction cross sections in proton–proton collisions at the LHC with ALICE*, *Eur. Phys. J.* **C73** (2013), no. 6 2456, [`arXiv:1208.4968`].

[23] **ALICE** Collaboration, J. Adam et al., *Pseudorapidity and transverse-momentum distributions of charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV*, `arXiv:1509.0873`.

Dr. Jesús Guillermo Contreras Nuño

Professional experience

- Full professor, Applied Physics Department, Cinvestav Merida, Mexico. From 1998 to date. (On leave of absence since 2012.)
- Scientific associate, CERN, 2005.
- Invited professor (through Navrat project) FJFI-ČVUT, Prague, Czech Republic. From 2012 to date.

Research interests

- Experiment: DIS, Relativistic heavy ion collisions.
- Phenomenology: High energy limit of QCD.

Thesis supervised

- Ph. D.: 8 finished, 3 in process.
- M. Sc.: 10 finished, 1 in process.
- B. Sc.: 10 finished, 2 in process.

Scientific production

- Articles outside big collaborations: 12 (one is a review).
- Articles with the H1 Collaboration: 204.
- Articles with the ALICE Collaboration: 98.
- Books edited: 5 (conference proceedings).
- Outreach articles: 21.
- Presentations in international conferences: more than 30.
- Conferences organized: 8 (as Chair or co-Chair).

Scientific leadership

- Member of the IHEPCCC panel of ICFA (2007-2008).
- Vice-President (2008-2009) and President (2009-2011) of the Particles and Fields Division of the Mexican Physics Society.

- Member of executive committee of the Mexican Network on High Energy Physics (2008-2010).
- Member of the executive committee of the H1 Collaboration (2009-2011).
- Convener of the UPC and Diffraction Section of the European Network Sapore Gravis (2012-2014).
- Convener of the UD group of the ALICE Collaboration (2014-2016).
- Member of the Physics Board of the ALICE Collaboration (2014-2016).

Honours and recognitions

- Member of the Mexican Academy of Science (since 1998).
- Best Mexican young scientist in Exact Science 2005. (Award presented by the President of Mexico).
- Level III (highest) of the Mexican System of Researchers (since 2009).