Contribution to the European Strategy for Particle Physics Update

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The Nuclear Physics European Collaboration Committee is an Expert Committee of the European Science Foundation

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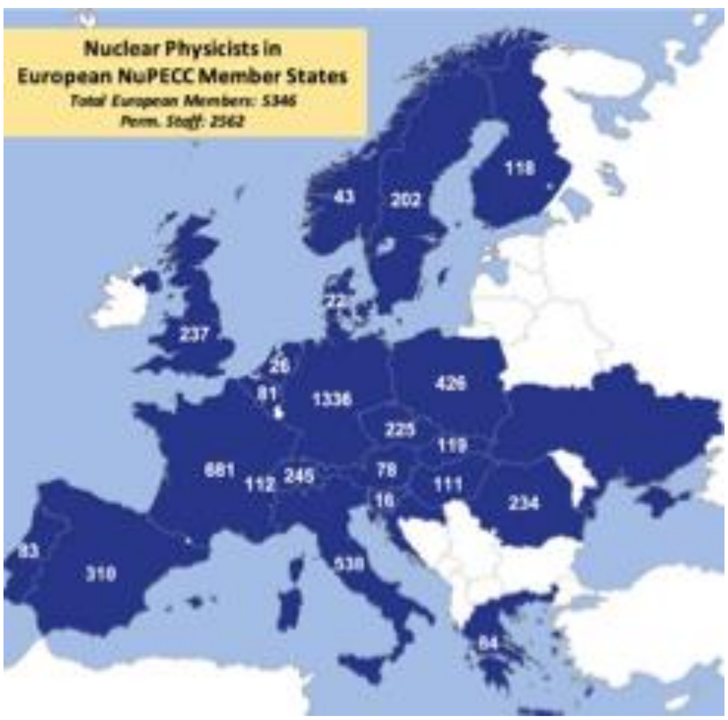


Caption: Nuclear Physicists in the European NuPECC Member countries
and Associate Member CERN
(source: NuPECC survey 2021 and 2023)

In this presentation I will closely follow the nuclear physics European agenda, as organized in the NuPECC Long Range Plan 2024 for European Nuclear Physics.

Nuclear Physics is embedded in the landscape of the European Research Area (ERA). Close collaboration with related fields of science, as particle and astroparticle physics in the framework of Joint ECFA-NuPECC-APPEC activities are necessary and should increasingly continur Research in nuclear physics an international sustainable effort, for even stronger European nuclear physics scientific programmes.

These programmes revolve around the main challenges in Nuclear Physics for the next decade, and their challenges are the search for the answers to the following questions:

1. How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
2. What is the role of nuclear correlations?
3. How can we probe the equation of state with nuclear structure observables, such as resonances?
4. How does the major part of the visible mass of the universe emerge from the almost massless quarks?
5. Can massless gluons form massive, exotic matter?
6. What is the role of strong interactions in stellar objects?

Given the European comparison of expedinture in R&D shown below, nuclear physicists affiliated in Portuguese institutions, in close collaboration with funding bodies and knowledge institutions stakeholders, need to strengthen the resources and support the training of young nuclear scientists. Broad skills, across experimental and theoretical nuclear physics research, need to be guaranteed. Many industries rely on the expertise and techniques from the nuclear science. The health and enviroment sectors, are just two where nuclear physics has very large societal impact. The solution, as NuPECC recommends, is to create new opportunities for increased international mobility and short-term exchange of early-career and technical personnel across institutions.

Distribution, by execution sector, of expenditure in R&D (%GDP)

Source: https://www.pordata.pt/pt

In **Portugal**, Nuclear Physics Research runs mainly across across **3** Units:

- **LIP**

Laboratory of Instrumentation and Experimental Particle Physics

- **CFisUC**

Centre for Physics of the University of Coimbra

- **CTN**

Campus Tecnológico e Nuclear IST (Applications)

I will focus on the two first Units in this presentation. The reason for this choice is that the research they conduct is fundamental physics oriented, and therefore more prone to have cuts of funding in the present historic context. On the other hand, it is more limited in scope than the vast domain of possible applications, allowing for a brief presentation. Nevertheless, their research programs stem from the vastness of the 6 questions above.

LIP

Nuclear Reactions, Instrumentation and Astrophysics **(NUC-RIA)**

Nuclear Physics and Strong Interaction Group **(NPStrong; pQCD)**

Staff 21 PhD students 11

CFisUC

Centre for Physics of the University of Coimbra

Staff 12 PhD students 8

Explored Domains

Nuclear Structure and Reactions **NSR**

Nuclear Astrophysics **NAP**

Hadronic Physics **HAD**

Highlights of Theoretical Nuclear Physics

NAP

Group is member of **MUSES** collaboration supported by NSF.

Support from several institutions: DOE, GSI Helmholtz Centre for Heavy-ion Research, São Paulo Research Foundation (FAPESP), MIT, Princeton, …

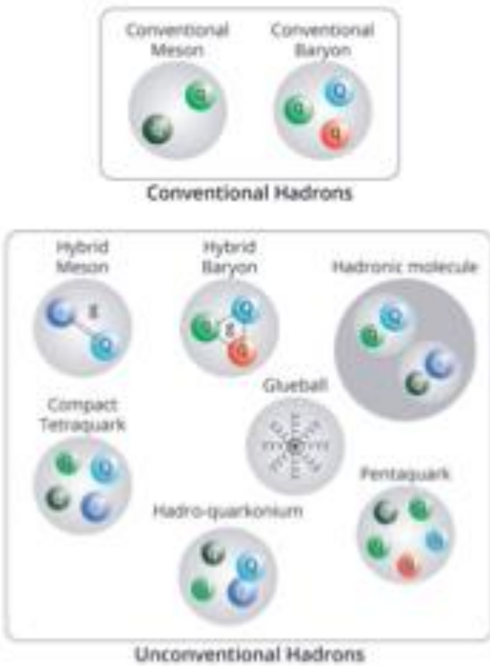
Modular Unified Solver of the Equation of State (EoS)

Merges lattice QCD, nuclear physics, gravitational wave astrophysics, relativistic hydrodynamics, and computer science in programming and front-end development.

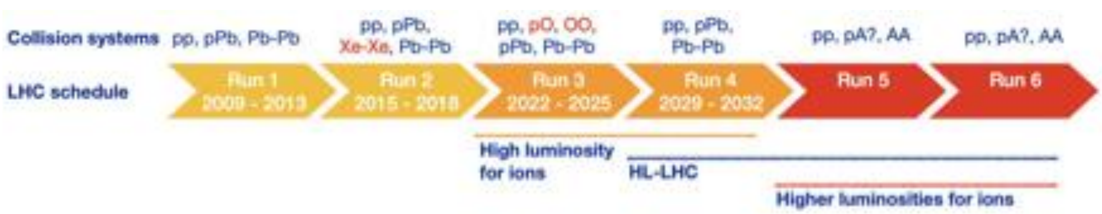
HAD

Group Members are Portuguese representatives in PRACE, the Partnership for Advanced Computing in Europe.

I specially highlight in my contribution here the Portuguese Research in Hadron Physics.
The main reason is that we are living a new era, where theory based on QCD principles is making an old dream come true: hadrons, nucleons and the nuclear interaction considered together in a unified manner as different manifestations of the structure formation of QCD. The 3 driving forces of this dream are the LHCb, Belle, BES III discoveries of Exotic Hadrons which call for theoretical interpretation, the game-changing computing power and algorithms, and the inspiring planned experiments as the FAIR2028 complex and HL-LHC.



In the future, the copious production of beauty and charm quarks in HL-LHC collisions offers golden opportunities for QCD studies in exotic hadrons, and will provide dramatic spectroscopic discoveries chartering new states that can be bound in QCD.

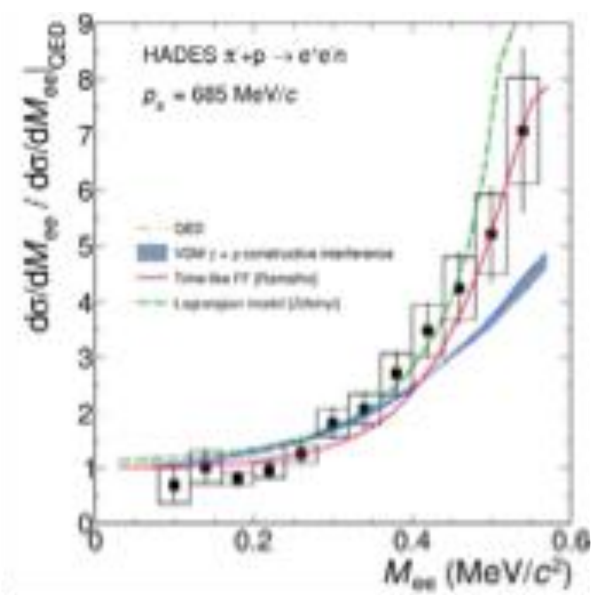


Caption: Timeline of current LHC experiments and upgrades

If ground-state tetraquarks containing beauty and charm or double beauty (Tbc or Tbb), are more tightly bound, they may be stable to strong decays. If so, they would decay only via the weak interaction and hence have lifetimes comparable to those of ground state beauty and charm hadrons. It is also possible that Pcc, Pbc and Pbb pentaquarks could be detected, with the appropriate analysis strategy depending on whether or not they are stable against strong decay.

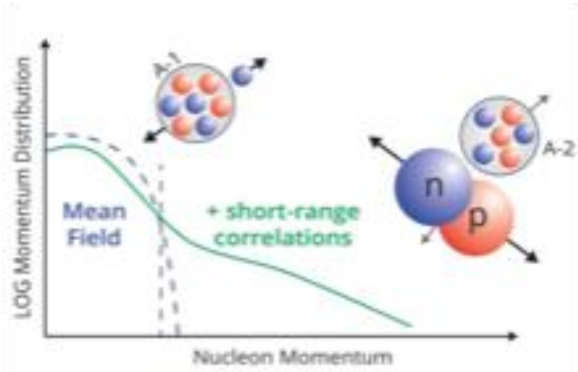
Furthermore, it is plausible (albeit speculative) that six quark, dibaryon states containing at least two beauty or charm quarks may be measurable. Altogether these discoveries will not only revolutionize our knowledge of the hadron spectrum.

However, spectroscopy alone is not enough. Only by unravelling the structure of hadrons in terms of quarks and gluons ("parton") we understand the strong interaction.
The new spectroscopical findings will motivate and guide hadron structure studies (as measurements of electromagnetic or gravitational form factors giving information on size, charge and mass distributions, dilepton production in the unphysical resonance region) in other facilities, namely FAIR-GSI, BESIII and JLAB, which will impact our understanding of the effective nuclear interactions by informing us about, for example, on the role of diquarks in baryon structure and the internal arrangements of hexaquark systems.



Caption: Dilepton excess yield in the low invariant mass region identified as the modified ρ- spectral function. The red line shows a prediction from the Portuguese tehoretical LIP-IST group is compared to the data measured by HADES in AuAu collisions at = 2.42 GeV, HADES, Nature Phys. 15, 1049, 2019.

In the low energy nuclear physics regime, the strong interaction between proton and neutrons originates close-proximity nucleon pairs in nuclei, named short-range correlations, with high relative momentum and low centre-of-mass momentum, deviating from the momentum distribution in a mean-field picture. SRC were measured in (e,e') experiments. Nucleon-Nucleon collisions at relativistic energies offer the chance to study the isospin dependence of this phenomenon with higher cross sections, for an understanding of effects of SCRs on the evolution of nuclear structure, the properties of nuclear matter, and also of the connection between nuclear physics and QCD. More precise investigations can be carried out at CERN/HIE-ISOLDE and at the FAIR/R3B facility.



Given

- the impact of the recent discoveries of the LHCb, new QCD bound states that escape the conventional standard quark model explanation,
- the established know-how, leadership and volume of the Hadron Physics expert community in Portugal,
- the possibilities of the HL-LHC,
- the guidelines of the NuPECC Long Range Plan 2024 for European Nuclear Physics,

it is recommended a consistent and predictable funding for the activities in the scientific domain of Hadron Physics, by the Portuguese Fundação para a Ciência e Tecnologia (FCT) to support

- sustainable theoretical projects,
- international collaborations with CERN and also with complementary facilities allowing complementary structure studies, going beyond spectroscopical data analysis
- PhD grants, interfacing Nuclear and Particle Physics.
- renewal and capture of talent.

Summarizing and concluding,

- nuclear physics opportunities at **CERN** are a pillar of a world-leading hadron physics research programme, but for structure studies they need to be complemented by the FAIR2028 complex.
- radioactive beam facilities in Europe (in particular the Super-FRS at FAIR, the upgrade of **ISOLDE** and **SPIRAL2**) are not only needed to study exotic nuclei involved in explosive stellar events; they also measure short-range correlations that will enale us to link QCD and low energy nuclear physics; customised instrumentation and beam time availability should be guaranteed for fundamental tests at facilities like **ISOLDE.**

https://indico.cern.ch/event/1238718/contributions/5433705/attachments/2690330/4668483/NuPECC%20LRP.pdf

https://www.nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf