LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

09/01/2025

Individual Contribution to the European Strategy for Particle Physics

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The Large Hadron Collider (LHC) has played a pivotal role in confirming the Standard Model of Particle Physics as the most robust framework for describing fundamental interactions in nature. Since its inception, the LHC has enabled precision measurements and groundbreaking discoveries, including the historic detection of the Higgs boson in 2012, which confirmed the mechanism of mass generation through electroweak symmetry breaking. These results, along with rigorous tests of quantum chromodynamics (QCD), the electroweak force, and rare particle decays, have provided unparalleled evidence supporting the Standard Model's predictions.

Despite its remarkable success, the Standard Model of Particle Physics leaves several fundamental questions unanswered, pointing to the need for new physics and further experimental investigation. One major mystery is the nature of dark matter, which constitutes approximately 27% of the universe's mass-energy content but has no explanation within the Standard Model. Another is the observed matter-antimatter asymmetry, as the Standard Model's predictions for CP violation, encoded in the CKM matrix, are insufficient to account for the dominance of matter in the universe. Additionally, the origin of the Higgs potential, which is central to the mechanism of electroweak symmetry breaking, remains unexplained. The Standard Model also offers no insight into why there are exactly three families of quarks and leptons or why their masses span such an enormous range.

The answers to some of these fundamental questions may lie in the discovery of new particles or fundamental interactions that exist beyond the Standard Model, emerging at high energies that exceed the reach of the LHC. Exploring these phenomena requires access to energy scales where the effects of such new physics might become apparent. The curiosity and drive to uncover how the universe truly operates should compel us to build a new particle collider beyond the LHC, one capable of probing uncharted energy regimes and testing revolutionary theoretical ideas. The most cost-effective and comprehensive option in Europe to achieve this is through the FCC integrated program.

At a future higher energy particle collider beyond the LHC, the goal is to achieve precision measurements of a vast array of elementary particle reactions, with many observables to be measured at percent-level accuracy. Such high-precision data would allow scientists to probe deeper than ever before into the limitations of the Standard Model, as even small deviations from its predictions could reveal the effects of new physics. By providing an unprecedented level of detail, this data could uncover subtle discrepancies, offering insights into phenomena like dark matter, the hierarchy of particle masses, or unknown forces, paving the way for breakthroughs in our understanding of the universe. However, to interpret and utilize this data for uncovering new discoveries in particle physics, the theoretical description of the measured quantities must be equally accurate.

Theoretical predictions with greater precision than we currently have are challenging, as they require extremely difficult calculations of scattering amplitudes and cross sections within quantum field theory. However, these predictions are of great relevance, as the success of discovering new physics can depend on our ability to distinguish its effects from the large QCD background in multi-particle processes at the FCChh. Similarly, at the FCCee, the description of the physics across the proposed four stages will require breakthroughs in the computation of electroweak (EW) and QCD corrections to higher-perturbative orders.

To this end, the aim of this contribution to the national input for the ESPP is to maintain and further develop a leading line of research in precision QCD within the phenomenology group hosted at LIP. This group is already well-established and internationally recognized for its expertise in this field. By maintaining and consolidating research activities in this area, it will ensure a continuous national contribution to the successful exploitation of the future physics programs at upcoming colliders.

Opportunities to be explored in this context, using the current expertise, include the QCD physics program at the FCCee, namely:

- **Strong Force at High Energies**: With its clean environment, the FCCee will allow detailed studies of QCD at higher energy scales, leading to better measurements of strong coupling constants and the study of multi-jet events.
- **Hadronization and Fragmentation**: The program will explore how quarks and gluons transition into observable hadrons, which is a critical aspect of QCD but remains a complex and poorly understood process.
- **QCD Corrections:** The program will also focus on calculating higher-order QCD corrections to various processes with high accuracy, which is crucial for the precise comparison of theory and experiment.

When moving to the physics program at the FCChh care is needed, as effects that are negligible at LHC energies may become significant at a 100 TeV hadron collider. The physics opportunities to be explored, using the current expertise include,

- **Parton Distribution Functions**: Parton Distribution Functions, an essential ingredient of present and future phenomenology studies at hadron colliders, currently represent the dominant theoretical uncertainty in the description of Higgs boson production processes and limit the reach of searches for new physics in high-mass final states. Making use of dijet observables at the FCChh will allow new PDF determinations across a broad kinematic range, particularly in the regions of very high-*x* (close to 1) and very low-*x* (approaching 10^(-5) or lower). The benefits of improving Parton Distribution Functions at the FCChh include increased sensitivity in new physics searches, as deviations from Standard Model predictions could be identified with greater confidence.
- **ttH production:** at the FCChh Top-antitop quark pair production in association with the Higgs boson (ttH) production becomes the third most important Higgs production mechanism. By studying ttH production at the unprecedented energy of 100 TeV, one can achieve highly precise measurements of the Higgs boson's Yukawa coupling to the top quark, which is the strongest coupling in the Standard Model and crucial for understanding the mechanism of mass generation. This precision enables the detection of subtle deviations from Standard Model predictions, potentially signalling the presence of new physics phenomena such as extended Higgs sectors or interactions involving undiscovered particles. By analyzing differential cross sections and rare decay modes, using the Monte Carlo tools in development at the LIP pheno group one can test the limits of quantum chromodynamics (QCD) and electroweak theory, while also constraining effective field theories that describe possible new interactions at the unprecedented energy of 100 TeV.

In conclusion, the FCC integrated program offers unparalleled opportunities with unprecedented precision to address fundamental open questions in particle physics. In this context, QCD studies are essential to the search for new physics at the FCC, as they provide the theoretical framework necessary for interpreting high-precision data. Refining our understanding of the strong interaction will enable more accurate predictions of Standard Model (SM) processes, which form the foundation for identifying deviations that could signal new physics. At the FCC, where energy and luminosity levels will far exceed current limits, the complexity of QCD phenomena increases, presenting a unique opportunity for the further development of precise theoretical calculations, which will be indispensable to the success of the physics program.