



Il Colle di
Galileo

Exploring the energy frontier with muon beams

Florence, 30 June–1 August 2025

Organizers: SCOTT BERG (BNL, USA), DARIO BUTTAZZO (INFN Pisa), ROBERTO FRANCESCHINI (ROMA TRE U. AND INFN), TOVA HOLMES (U. TENNESSEE, USA), PATRICK MEADE (STONY BROOK, USA), FABIO MALTONI (LOUVAIN, BOLOGNA AND INFN), FEDERICO MELONI (DESY, DE)

Abstract. The workshop brought together international experts working on the physics of muon beams and on the physics of a multi-TeV muon collider. For five weeks, scientists explored new theoretical avenues as well as novel detection strategies and accelerator technologies. The event benefited from the presence of Simons Fellows, who led discussions on well-motivated theories and on the status of current experimental and machine technologies. The whole program was characterized by lively discussion, leading to new interactions across theoretical and experimental particle physics, including accelerator and beam physics.

Keywords: Muon Collider, Beyond the Standard Model, New Physics, High-energy phenomenology, Accelerator Physics.

Scientific context and motivations

What lies beyond the Standard Model? This simple question lies at the heart of one of the most urgent open problems in fundamental physics. While the discovery of the Higgs boson marked a milestone, confirming the mechanism of electroweak symmetry breaking, many questions remain unanswered. The nature of dark matter, the origin of flavor and the hierarchy problem demand new physics at the TeV scale level and beyond.

The aim of the workshop was to critically assess the status of the hunt for new physics using muon beams. Muon beams up to multi-TeV energies would lead to a transformative change in the way that the energy frontier can be explored. Such a paradigm shift requires a corresponding leap in the development of theoretical methods and accelerator technologies. The workshop brought together international experts in these fields to address these important questions, with a specific focus on the synergy between theory, experiment and accelerator physics.

Regular workshop activities

During the first four weeks, the workshop activities consisted of a combination of pedagogical lectures, focused seminars and hands-on working groups. To stimulate profitable discussions, each week focused on a specific topic, so that participants who were experts on a specific subject could make sure to visit GGI at the right time.

The first week was devoted to Training, with a focus on PhD students and senior researchers new to the field. Renowned experts delivered lectures on accelerator physics (Luca Bottura, Anton Lechner, Daniel Schulte, Chris Rogers), particle detectors (Kevin Black) and particle theory (Hitoshi Murayama, Davide Pagani). A key highlight of this week was the organization of hands-on working groups focused on simulation tools essential to the muon collider program. Specifically, experimental physicists and machine physicists collaborated closely on the use of FLUKA, for simulating radiation transport and shielding requirements, and GEANT4, for detailed detector response modeling. These sessions allowed the immediate exchange of expertise between those designing the accelerator lattice and those building the detectors, addressing critical challenges such as beam-induced backgrounds and neutrino radiation hazards in real-time. This interaction led to discussions on the possible use of machinery to source muons also as a possible kaon source, which would further broaden the physics application of muon beam and related technologies.

The second and third weeks were Focus Weeks. The second week concentrated more on Standard Model topics, such as the use of factorization and collinear PDFs in high energy muon collider calculations, electroweak symmetry restoration and radiative corrections. The third week was more focused on the exploration of topics for new physics, including direct and indirect reach, exotic signatures (long-lived particles), and the relevance of beam-induced backgrounds.

Week four was devoted to Synergy, covering several branches of high-energy physics with a substantial interest in muon beams. After an introductory day with general talks, we discussed lepton flavor with muons, dark sectors, neutrinos and dark matter portals. Every day there were between two and four long talks aimed at bringing everyone up to speed on the topics of the day and exploring the connections with the physics of muons and the apparatus needed to source and handle them.

Conference

During the fifth week, the program turned its attention to the specialist conference, entitled “Physics at the Highest Energies with Colliders.” There were morning and afternoon sessions from Monday to Thursday and a final morning

session on Friday. The topics of the sessions spanned different aspects of future collider physics: the landscape of theoretical models for the TeV scale, the feasibility of various accelerator technologies towards an “Ultimate Collider,” the connection with cosmology and gravitational wave physics, and the new detector and computing challenges necessary to carry out experiments using a machine of this kind. The discussion also raised new questions about the possible role of intermediate scales between the Fermi scale and the Planck scale.

A total of more than 100 scientists from all over the world came to GGI to attend the workshop and the conference, which featured invited talks by renowned accelerator experts, theorists and detector physicists.

Simons Fellows

Three eminent scientists in the field spent a significant amount of time at GGI and played a central role in the workshop activities. They helped organize the daily seminars, delivered seminars on their research activities and led discussions. The Simons Fellows involved in this GGI workshop were Michael Peskin (SLAC, USA), who visited for two weeks, Chris Quigg (Fermilab, USA), who visited for three weeks, and David Neuffer (Fermilab, USA), who visited for four weeks.

Summary

The workshop program proved remarkably varied, spanning multiple branches of physics from accelerator technology to detector development to particle theory. It brought together a variety of different communities - from flavor physics to neutrinos, dark matter and collider physics - creating fertile ground for the cross-pollination of ideas. The program offered a comprehensive outlook on the use of muon beams across three continents: in Europe, with a muon collider and related experiments; in North America, with Fermilab’s plans for a muon collider cooling demonstrator and other muon beam applications; and in Asia, where KEK is pursuing new R&D to achieve muon beams with low emittance and high intensity.

Overall, the workshop presented an informative cross-section of muon beam applications for fundamental physics, with the muon collider being the ultimate goal of this development. Beyond the scientific content, the event served as an incubator for collaboration and synergy among different subfields of particle physics.

GGI proved to be an excellent host for fostering communication among experimental, theoretical and accelerator communities. Many participants will remember this event specifically for this cross-disciplinary collaboration. The organizers are grateful to GGI for accepting this proposal and enabling this unique opportunity for scientific exchange. As we stand at the threshold of new pos-

sibilities with muon beams, gatherings of this kind generate the connections and ideas that may ultimately lead to breakthrough discoveries in the years to come.

Acknowledgements

The organizers would like to thank the administrative staff of GGI for their invaluable help and assistance, both before the event and during the workshop. It is a real and sincere pleasure to thank Annalisa Anichini, Alessio Attardi, Mauro Morandini and Mirella Ridi.