Acronym and title: FLOMOTION, **F**lexible **LO**w **MO**mentum **T**racker in **ION**-ion collisions

Development of a track reconstruction framework for low momentum particles in a high multiplicity environment for HEP experiments, with implementation of a flexible geometry.

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1. Research objectives

The FLOMOTION project aims to develop a software framework for particle tracking in high-energy physics (HEP) experiments specialised to handle the low-momentum tracks in a high multiplicity environment, with high reconstruction efficiency, including secondary particles from weak decays. The system aims for flexible geometry of the tracking detector, to accommodate evolving geometrical layouts during the design phases of any experimental setup, and will include a dedicated suite of tools to reconstruct complex decay topologies.

State of the art: fast, efficient, and fully parallelised tracking codes are now available for HEP experiments. A prominent example of an experiment-independent toolkit for track reconstruction currently used in HEP is ACTS (A Common Tracking Software), developed by members of the ATLAS Collaboration. All the available tracking codes can cope with a large pile-up of pp collisions in the detectors, and are able to quickly reconstruct high rigidity tracks. For the reconstruction of ion-ion collisions down to low transverse momentum, specialised codes exist that are tailored to the needs of each specific experiment geometry.

All the available implementations are subject to some limitations that restrict their usage by any new experiment targeted to ion-ion collisions and/or to low-momentum physics:

1. Lack of streamlined and simplified procedures for modifying detector and service geometries to facilitate rapid prototyping and testing of alternative detector layouts during the research and development phases
2. Suboptimal computing and reconstruction performance for low-momentum tracks and in high-multiplicity environments, such as those of ion-ion collisions
3. No reconstruction of ultralow-momentum particles spiralling multiple times in the magnetic field (loopers) and complex decay topologies
4. Missing particle identification information in the tracking process

Such limitations were particularly evident when trying to use ACTS to study the performance of the ALICE 3 experiment in heavy-ion collisions. With our project, we aim to develop targeted solutions to the identified shortcomings and deliver a modular, portable software framework capable of supporting both new and existing experiments — from the design phase through to full operation — while potentially integrating with the existing ACTS framework. In particular, the work of the FLOMOTION project will be structured around four core scientific pillars:

1. *Flexible simulation and geometry architecture:* supporting rapid detector design iterations, with particular attention to the material budget implementation, and fully compatible with state-of-the-art particle transport codes such as GEANT4. This will enable the software to be used for different HEP and ion-ion experiments without major modifications.
2. *Performance-oriented design for high multiplicity and low momentum tracking:* to effectively process data characterised by extreme detector occupancy - such as high-rate ion-ion collisions - while maintaining accurate reconstruction of low-momentum tracks across a wide rapidity range, the design of conventional tracking algorithms must be fundamentally rethought. This challenge is especially critical in scenarios with multiple overlapping ion-ion collisions (pile-up) within the detector read-out frame. Addressing these challenges will require algorithmic innovations tailored to cope with such dense environments, as well as efficient parallel implementations. To this end, the development will include GPU-based processing, capitalising on the broad availability of modern heterogeneous computing infrastructure in high-performance computing centres.
3. *Advanced topology reconstruction*: incorporating the reconstruction of loopers significantly enhances the sensitivity of ion-ion experiments to low-mass dilepton signals, opening the door to precise studies of chiral symmetry restoration — a major milestone in understanding QCD matter. While such low-momentum, spiralling tracks are often fragmented into multiple segments by standard reconstruction methods, novel algorithms that stitch these segments into coherent trajectories have proven successful in low-energy experiments like Mu3e. Adapting and extending these approaches to high-multiplicity environments represents a challenging but exciting frontier, with significant potential to advance the reconstruction of complex decay topologies, such as weak decays and decays with undetected final-state particles (e.g. neutrinos or neutral hadrons), which are central to the search for heavy baryons in ion-ion collisions.
4. *Particle-ID aware tracking*: FLOMOTION introduces tracking methods that incorporate particle identification (PID) early in the reconstruction process. The framework will include the ability to use detectors providing specific energy loss and timing information. In addition, the framework implements dE/dx estimation by analysing momentum loss along the helical paths of loopers. This allows early-stage PID, improving the identification of pions, kaons, and protons, especially when particles don't reach detectors with PID capabilities.

The project structure offers strong training opportunities for early-career researchers, providing hands-on experience in high-performance computing and algorithm development for complex data environments - skills that are also highly transferable across both academia and industry.

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

The nature of the project requires substantial Virtual Access to heterogeneous high-performance computing (HPC) infrastructures. We plan to actively utilise resources such as the ALICE EPN farm at CERN and the CNAF facilities at INFN, both of which are well suited to our computational and data analysis needs. These infrastructures also represent strong candidates for the development of new Virtual Access services, as they are not yet broadly available to external institutes.

A key objective of our work is to develop containerised and possibly interactive computing environments based on Jupyter notebooks that will enable efficient, reproducible workflows across these HPC platforms. All software developed will be released as open source and made publicly available to the broader community, with the explicit aim of supporting future experimental efforts. In this way, the project not only leverages existing computational resources but also actively contributes to building sustainable, FAIR-aligned Virtual Access services.

3. Estimated budget request

The estimated budget includes the personnel costs for one PhD student (€75.000) and one two-year postdoctoral researcher (€90.000). These costs are calculated based on Italian salary levels or under the assumption of a co-funding arrangement with the Austrian research institute involved in the collaboration. In addition, an amount of €35.000 is allocated to cover indirect costs associated with institutional overheads and project administration. The total budget request amounts to €200.000 for the entire 4-year funding period.

4. Participating and partner institutions: INFN (Bari, Padova, Trieste), CERN, Austrian Academy of Sciences (Stefan Meyer Institute)