LETTER OF INTENT: Partons2Hadrons

Name of the project leaders: Pier Monni (CERN), Simon Plätzer (University of Graz), Andrzej Siodmok (Jagiellonian University)

1. State-of-the-art

The particle-physics program at modern colliders relies on the precise description of scattering events across a wide range of energy scales. These span from the hard momenta probed in the collisions, reaching up to Q ~ O(few TeV) at the LHC, down to small scales around Λ ~ O(1 GeV), at which partons confine into hadrons. This large hierarchy of scales gives rise to logarithmically enhanced radiative corrections at all orders in the strong coupling constant αs, that can be systematically predicted either through analytic resummation techniques or via parton-shower (PS) algorithms. While resummation can achieve high perturbative accuracy, its applicability is typically restricted to specific classes of observables. Moreover, incorporating a complete description of non-perturbative effects in these calculations remains a significant challenge. In contrast, PS algorithms, implemented in Monte Carlo event generators, provide fully exclusive event simulations and include phenomenological models for non-perturbative effects such as hadronization, hadron decays, and color reconnection. As a result, although resummed predictions offer greater formal accuracy, it is ultimately Monte Carlo simulations that play a central role in the interpretation of experimental data.

2. Research objectives:

This project aims at enhancing the performance of Monte Carlo parton-shower (MCPS) simulations by refining the modelling of non-perturbative QCD effects in scattering events. State-of-the-art PS algorithms are designed to describe the radiation of soft and collinear partons with next-to- (or next-to-next-to-) leading-logarithmic accuracy, N(N)LL. Achieving such theoretical precision is essential to match the accuracy of current measurements at the LHC and those anticipated at future lepton colliders. While the analytic and algorithmic development of MCPS has reached an advanced level, realistic simulations of hadronic and leptonic collisions still require a proper treatment of hadronization and other non-perturbative final-state interactions.

The goal of this project is to reliably model the transition from perturbative to non-perturbative dynamics in state-of-the-art MCPS simulations. This will be entail two complementary key aspects. The first is the calibration of existing models by tuning the output of cutting-edge MCPS simulations against a wide range of hadronic final-state observables measured in high-energy leptonic and hadronic collisions. These observables include quantities such as event shapes, jet substructure observables, fragmentation functions, and hadron multiplicities and spectra. The second aspect concerns the development of novel models of hadronization. These models will blend elements inspired by theoretical advancements in the field of logarithmically-accurate PS and by the treatment of colour via colour-evolution equations with cutting-edge Machine-Learning (ML) technology to provide a robust parameterisation of QCD dynamics in this key stage of MCPS simulations.

The overarching aim is to enhance the predictive power of MCPS simulations, reduce their theoretical uncertainties, and improve the accuracy of signal and background modelling in precision Standard Model studies and in searches for new physics at current and future collider experiments.

Detailed plan:

(1) Foster collaborations and discussions across the theoretical and experimental community on the state-of-the-art modelling of non-perturbative aspects in MCPS for leptonic and hadronic collisions. This stage will help outline the landscape of exiting non-perturbative models and their interface with public MCPS tools.

(2) Analysis of publicly available LEP and Belle-II measurements and reanalysis of archived LEP (ALEPH) e+e- data (and, potentially, of clean exclusive final states in photon-photon collisions at the LHC, collected in low-pileup measurements) with a range of observables and jet substructure tools.

(3) Tuning of existing non-perturbative models interfaced with state-of-the-art MCPS generators to the data collected in (2) using Bayesian optimisation methods. The study will focus on the models implemented in public MC tools (e.g. Herwig 7, Pythia 8, Sherpa 3) interfaced with public NLL and NNLL PS algorithms, such as the Alaric, Apollo, Deductor, FHP dipole-shower and PanScales shower plugins. The resulting tunes will be publicly released for use in experimental analyses.

(4) Development and implementation of novel hadronization models in MCPSs, expected to provide a more robust description of the parton-to-hadron transition in collider events. The new models will build on insights originating from the development of PS with higher logarithmic accuracy and will exploit ML technology trained on experimental data to achieve a more faithful parameterisation of the hadronization process.

The project is designed to advance both theoretical and phenomenological aspects of collider physics, as well as aspects of computing and AI technologies through the development of machine learning–based hadronization models. Moreover, the project will provide training for a postdoctoral researcher within a highly dynamic and stimulating scientific environment.

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

TA infrastructure: The participating institute, CERN, is the world's largest particle physics laboratory. It is currently the host for the LHC experiments, and it is the designated host for future e+e- projects (FCC), currently under active development and consolidation.
VA infrastructure: The project will make extensive use of computing resources available at the host and partner institutions participating in the proposal. The use of computing infrastructure from other pQCD-oriented VAs would be a benefit.

4. Estimated budget request

Total: 100kEUR (accounting also for 25% administrative overheads and conversion rate to PLN)

- Personnel:
  100kEUR for a two-years postdoc position at Jagiellonian University (including overheads).

- Others: We would kindly request, if possible, an allocation of 20kEUR from CERN TA to support key collaborative activities essential to this proposal. This amount is based on an estimated of 150 kEUR/person-day × 30 person-days/year × 4 years. The funding would enable EXP/TH users to attend collaboration meetings, conduct on-site studies, and participate in topical workshops at CERN, as well as cover short stays of the project postdoctoral researcher and principal investigators, Simon Plätzer (University of Graz) and Andrzej Siodmok (Jagiellonian University). Their presence at CERN is vital to ensure effective coordination and smooth execution of the project.

5. Participating and partner institutions:

CERN EP and TH Departments (Switzerland), University of Graz (Austria), Jagiellonian University (Poland). The project might involve, at different stages, the institutions involved in the development of MCPS: Institut de Physique Théorique Saclay, IPPP Durham, Karlsruhe Institute of Technology, Lund University, Monash University, NIKHEF, Universidad de Granada, University of Göttingen, University of Manchester, University of Oxford, University of Vienna, Fermilab.