Heavy quark production at e^+e^- colliders and at the LHC

Introduction

In the Spring of 2022 the Large Hadron Collider (LHC) at CERN started its Run 3 data taking period. In the subsequent three years it will produce as many events as those collected since its turn-on eleven years ago. Then, starting in 2027 and during the subsequent decade, the upgraded “high luminosity” LHC will further increase tenfold the amount of data collected and studied by the experimental collaborations. A high energy e+e- collider, complementary to the LHC, is also likely to see the light during this timeframe.

Such a large increase in the amount of available data will be accompanied by an increased accuracy of experimental measurements, and must be met by an equally improved precision of theoretical predictions.

Heavy quarks (charm, bottom and top) are copiously produced at the LHC, usually in the form of hadrons. Because of their large mass, their total cross sections can be predicted in perturbative Quantum Chromodynamics (QCD). In particular, production at intermediate and very large (i.e. much larger than the heavy quark mass) transverse momentum distributions can be predicted with high accuracy, and used as a probe of phenomena taking place at very small distance scales.

The ultimate objective of this project is to improve the precision of theoretical predictions for heavy hadron production at very large transverse momentum at the LHC and at a future high energy e+e- collider. Deliverables will include public codes able to evaluate these predictions, and extractions from experimental data of non-calculable non-perturbative ingredients, similar in spirit to the Parton Distribution Functions, that are needed to finalise the phenomenological predictions.

Method

Perturbative predictions for heavy quark production at large energy or transverse momenta (i.e. >> m) include large terms of the kind log(E/m) and log(pT/m) that can spoil the convergence of the series. A technique allowing for resummation to all perturbative orders of these terms is that of perturbative fragmentation functions, first developed in the 1990s to next-to-leading logarithmic (NLL) level. Resummation to all orders of soft-gluon emission effects can also be included

The project

Building on the recently completed calculation of heavy quark production in e+e- collisions at next-to-next-to-leading order plus next-to-next-leading logarithmic (NNLO+NNLL) level using the perturbative fragmentation functions technique (https://arxiv.org/abs/2312.12519), the project aims at 1) studying in more details the interface of this calculation with the non-perturbative region, and 2) predicting heavy quark production in pp collisions at large transverse momentum at NNLO+NNLL.

For part 1), the question to which an answer is sought is how to best complement the calculated perturbative prediction (a perturbative fragmentation function) with a non-perturbative component describing the transformation of a heavy quark into a hadron (i.e. a real, observed particle) containing the heavy quark. Various techniques exist (effective theories, effective running coupling, renormalons,...) and have been applied to this problem in the past, albeit at lower perturbative accuracy. The student will become proficient in at least one of these techniques, and apply it in the context of a NNLO+NNLL calculation to obtain phenomenological results.

The student will then consider the problem of heavy quark production in e+e- collisions, and develop and use the C++ code from arXiv:2312.12519 to perform fits to experimental data to extract the non-perturbative contribution describing the hadronization of the heavy quark into heavy hadrons. This contribution will then be needed for part 2) of the project.

For part 2), most of the ingredients that are needed are already available in the literature, as is the numerical code from arXiv:2312.12519. The only missing ingredient, the short-distance coefficient functions for single parton production in proton-proton collisions to NNLO, is presently being developed by the group of Thomas Gehrmann in Zurich, and should be available within a year or two.

The student will start considering existing results for heavy quark production in proton-proton collisions. Presently, the NLL resummation of the log(pT/m) terms and the full NNLO massive, fixed order calculation, are known. We are therefore in the position to check explicitly that the prediction of the NLL resummation matches the explicit NNLO massive calculation. This exercise, to be performed in collaboration with the group of Massimiliano Grazzini in Zurich, author of the NNLO calculation, will represent an introduction to the broader problem of heavy quark production in proton-proton collisions.

Finally, when the proton-proton coefficient functions will become available the student will work on their interfacing with the heavy quark perturbative fragmentation functions and the non-perturbative component, and on the production of phenomenological predictions for the LHC.

Requirements: particle physics, analytical and numerical skills. C++ and Python knowledge is not immediately necessary, but working proficiency in the two languages will very soon be needed, at least at low level.

Note: parts of the project, namely the analytical study of the interface between perturbative and non-perturbative component, or fits to the non-perturbative component, or the cross-check of the NLL terms in the NNLO massive proton-proton calculation, can be initiated during a Master 2 stage.

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