PhD project:
Calculating the Shape of Events

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1 Introduction and motivation

The Large Hadron Collider (LHC) at CERN is the most powerful accelerator ever built and it is currently investigating particle interactions at the tiniest distances. At the LHC, protons are accelerated to 13.6 TeV and then collide together. These high-energy interactions give rise to events, characterised by hundreds, if not thousands, of particles. Research in particle physics aims to understand and model these complex final states so that interesting events can be separated from an overwhelming background, which is often orders of magnitude bigger than the signal we are looking for. To achieve this goal, sophisticated techniques are continuously developed, building both on our theoretical understanding of particle physics and on state-of-the-art statistical analysis tools.

A key question we want to answer may be phrased in very simple terms. In order to classify events, we would like to be able to tell whether two events look similar or not. A good way to characterise events is through their *energy flows*, which essentially measure how much energy the collision produces in a given spatial direction. From an experimental viewpoint, this makes perfect sense as it is precisely what is measured by calorimetric cells. Furthermore, it turns out that energy flows are directly linked to the basic building blocks of our theoretical framework, such as the energy-momentum tensor.

It is then natural to think about two events as being similar if their energy flows are not too different. This idea can be made rigorous by equipping the space of energy flows, i.e. of events, with a metric. The Authors of Refs [1, 2], introduced such a metric by taking inspiration from the theory of optimal transport. The Energy Mover's Distance (EMD) between two events measures the amount of "work" required to rearrange one event to the other. Its value can be obtained by solving an optimal transport problem between energy flows $\mathcal{E}$ and $\mathcal{E}'$. It can be shown that the EMD is positive, symmetric, $\text{EMD}(\mathcal{E}, \mathcal{E}) = 0$ and, under a few additional hypotheses, it satisfies the triangle inequality. It is therefore a metric. In such a case, the EMD, coincides with the Wasserstein distance [3, 4], which is widely used in the context of optimal transport.

Equipping collider events with a metric allows us to explore interesting geometric ideas in the space of events. In a metric space, we can introduce manifolds, i.e. sets of events with some defined properties. Thanks to this observation, it is possible to rephrase many concepts and techniques that have been developed in the context of jet physics [5] in a geometrical language. For instance, the event shape *thrust* [6] can be seen as the EMD between an event and the manifold of idealised events with just two back-to-back particles. In the same spirit, *event isotropy* [7, 8] is defined as the EMD between an event and an idealised event with uniform radiation. This novel event shape has potential applications in searches for particles beyond the Standard Model that decay isotropically, as well as in the context of mitigating the background noise due to multiple proton interactions per bunch crossing, i.e. pileup.

Event isotropy has been recently measured by the ATLAS collaboration [9] and the experimental data have been compared to standard Monte Carlo event generators, finding decent agreement, with a few discrepancies. However, to date, no first-principle theoretical predictions for event isotropy exist. This is in contrast, for instance, with thrust, which is one of the most studied observables in perturbative QCD.

2 Objectives of this proposal

The research proposed develops into four main objectives. The first three constitute the bulk of this PhD project. The fourth point is more speculative but has a broader scope. Points 1, 2 and 4 can be started almost simultaneously, allowing the student to immediately acquire experience with both analytical and numerical calculations, and with machine learning techniques. For some time, progress along the three axes can be uneven, and be adapted to the student's needs and preferences. Point 3 instead will necessarily follow completion of points 1 and 2.

1. We will provide a first-principle description of observables inspired by event geometry. To achieve this, we will exploit all-order perturbative techniques (resummation) in QCD. We will start with a fresh look at observables for which the perturbative behaviour is known, e.g. thrust, to move then to new observables such as event isotropy.

2. We also study event-geometry observables using numerical simulations obtained with standard Monte Carlo event generators, which are ubiquitously used in particle physics phenomenology. We will assess the role of effects beyond perturbation theory such as the hadronisation process.

3. We will compare our first-principle theoretical predictions to the Monte Carlo ones and to the experimental data collected by the ATLAS collaboration [9].

4. We will explore the broader consequences of our analytic understanding of the EMD to more general classification problems that use the Wasserstein distance. This last, more speculative, point will naturally allow us to investigate the relation between artificial intelligence techniques and expert knowledge, a research field often referred to as physics-informed machine learning.

The successful completion of the research points above will require developing skills in analytic calculation in perturbative field theory (point 1), traditional programming (points 2 and 4) and machine-learning techniques (point 4).

3 Context of the project and co-supervisions

The successful execution of this project requires a broad set of expertises that spans from analytic resummation to numerical simulation of particle interactions. Therefore, it will be developed in the context of an international collaboration which includes Matteo Cacciari (Université Paris Cité, LPTHE), Gregory Soyez (IPhT Saclay), and Simone Marzani (Universià di Genova, Italy). The expertise of the supervisors, which ranges from analytic resummation in QCD, jet physics, and the construction and numerical implementation of novel Monte Carlo event generators, complement each other. On the one hand, this ensures that the proposed research lays on solid foundations. On the other hand, the presence of three supervisors will enrich the student experience, allowing them to be part of an international team from the very beginning of their PhD programme. We foresee multiple research visits during the course of this PhD and we expect to set up a formal co-tutelle between Genoa and Université Paris Cité. Finally, because this research project builds on the work done by the group of Prof. Jesse Thaler at MIT, we will also envisage exchanges and possible collaborations with them.

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References

[1] P.T. Komiske, E.M. Metodiev and J. Thaler, *Metric Space of Collider Events*, *Phys. Rev. Lett.* **123** (2019) 041801 [1902.02346].

[2] P.T. Komiske, E.M. Metodiev and J. Thaler, *The Hidden Geometry of Particle Collisions*, *JHEP* **07** (2020) 006 [2004.04159].

[3] L.V. Kantorovich, *On the translocation of masses*, *C. R. (Doklady) Acad. Sci. URSS (N. S.)* **37** (1942) 199.

[4] R.L. Wasserstein, *Markov processes over denumerable products of spaces, describing large systems of automata*, *Problemy Peredachi Informatsii* **5** (1969) 64.

[5] S. Marzani, G. Soyez and M. Spannowsky, *Looking inside jets: an introduction to jet substructure and boosted-object phenomenology*, vol. 958, Springer (2019), 10.1007/978-3-030-15709-8, [1901.10342].

[6] E. Farhi, *A QCD Test for Jets*, *Phys. Rev. Lett.* **39** (1977) 1587.

[7] C. Cesarotti and J. Thaler, *A Robust Measure of Event Isotropy at Colliders*, *JHEP* **08** (2020) 084 [2004.06125].

[8] C. Cesarotti, M. Reece and M.J. Strassler, *The efficacy of event isotropy as an event shape observable*, *JHEP* **07** (2021) 215 [2011.06599].

[9] ATLAS collaboration, *Measurements of multijet event isotropies using optimal transport with the ATLAS detector*, *JHEP* **10** (2023) 060 [2305.16930].