Popular Summary

This thesis is the culmination of my four and a half years of research in theoretical particle physics at Lund University (with a short stay at UC Louvain, in Belgium, included). For the majority of this thesis I describe a new method called chirality flow, which I developed along with my supervisor and collaborators to calculate the scattering probabilities of colliding fundamental particles at high energies more efficiently and transparently. Additionally, I optimised a part of the computer program `MadGraph5_aMC@NLO` which calculates these scattering probabilities. But what does this mean? Why did I do this? And how successful were these methods?

To answer the first two questions, we must first understand the basics of particle physics. The aim of theoretical particle physics is to find and study the smallest, most fundamental building blocks which make up our universe. That is, if you were to take an object around you and break it into ever smaller and smaller pieces, would you eventually find some fundamental particle which cannot be further broken up? If so, what would these particles look like, and how would they behave? To the best of our knowledge so far, it appears as if everything can be created by a set of 17 distinct particles which interact with each other via gravity, and at least one of the other three fundamental forces of nature: electrodynamics (QED), responsible for electricity and magnetism; the weak force, which is partially responsible for radioactivity and radioactive decay; and the strong force, also called quantum chromodynamics (QCD), which binds together protons and neutrons in the atom. Together, these 17 particles, their properties, and their interactions, make up the Standard Model of particle physics.

In the opening paragraph, I said that I calculated scattering probabilities, that is, the probability of two fundamental particles colliding and creating some final set of particles with a given set of momenta. Notice that I said scattering *probabilities*, not *the* outcome of a given scattering event. This is because fundamental particles are extremely small and obey the laws of quantum mechanics. Therefore, they are probabilistic rather than deterministic. That is, given a single starting point, there are multiple possible things which may happen, each with a certain probability to occur, rather than one single possible outcome.

To understand what these particles look like and how they behave, we have to first break up some object to both create them and to make them interact with each other. The best tool we have to do so today is the Large Hadron Collider (LHC) at CERN, which smashes together protons at extremely high energy and measures what is created. Since what is created follows a probabilistic distribution, we need to smash together very many protons to obtain enough statistics to determine the probability of a certain outcome. Next, we compare this distribution to the distribution calculated according to the rules of the Standard Model. If the experimental and theoretical distributions match, we say that the result confirms the

Standard Model, and if there is a discrepancy, we must find a new explanation, possibly involving new types of particles.

In order to calculate the theoretical prediction, we calculate the scattering probability of two protons becoming some final state with some momenta, and repeat this process possibly millions of times with different random final-state particles and momenta. For complicated final states, this requires a great deal of (expensive) computer power, and optimising it is very desirable. In this thesis, we attempted to optimise this task in several ways, including developing the chirality-flow formalism.

The third question, was how successful were the methods? Using chirality flow with pen and paper, we were able to do known calculations in less time than using previous methods, and it became much easier to see what part of the calculation led to what part of the result. When implementing chirality flow in the computer program `MadGraph5_aMC@NLO`, we found significant speed-ups in simulation time, thus proving chirality flow to be a success. Additionally, I optimised an unrelated component of `MadGraph5_aMC@NLO` called the colour sum, successfully making it two times faster than before. This is important, because the colour sum often uses the most computer resources in a given calculation.

There are five papers in this thesis. In the first two papers, I, along with my supervisor and collaborators, developed a formalism called chirality flow which requires less work and is more transparent than standard calculation methods. We developed this for the most basic approximation possible, known as tree-level. We did the calculations with pen and paper rather than on a computer, marvelling in the beauty, simplicity, and transparency of chirality flow compared to standard methods. Then, in paper III, we implemented this method in the computer program `MadGraph5_aMC@NLO`, making its QED calculations up to 10 times faster than before. In paper IV we extended the previous papers, developing chirality flow for the next-to-most-basic approximation, called one-loop level. Finally, in paper V, I sped up the leading bottleneck of `MadGraph5_aMC@NLO` by about a factor of 2, and while doing so learned enough about the program to complete paper III.

In addition to the work included in this thesis, over the four and a half years of my PhD I worked on several things not included in this thesis, including talks, seminars, proceedings, co-supervising a bachelor student, work for the student unions, and representing students and postdocs in the Monte Carlo network (MCnet) board, a funding agency and international collaboration working on simulations in particle physics. I also have ongoing work, in which I, along with the other authors of paper III and some master students, are working to implement chirality flow for the rest of the Standard Model in `MadGraph5_aMC@NLO`. While not directly a part of this thesis, these works were still an important part of my time in this PhD.