



*Top Quark Spin and QCD Corrections in Event Generation*  
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# Summary

*Particle physics* aims to discover, understand and describe the elementary particles that are the building blocks of all matter present in the universe. Constituents of matter are most easily found by demolition, and our universe would not look the way it does if elementary particles would reveal themselves easily. This forces scientists to an aggressive approach, colliding (composite) stable particles at the highest energy available by accelerating them to nearly the speed of light. The most powerful accelerator built so far, the *Large Hadron Collider* (LHC) has become operable in 2009. The LHC is designed to collide protons at approximately 14 TeV, equivalent to the kinetic energy present in a flying mosquito. The LHC squeezes this energy into a proton, an object which is approximately  $10^{14}$  times smaller. The energy determines the masses of the particles that are created in the collisions as can be seen in Einstein's law of  $E = mc^2$ .

Before the LHC became operational, its predecessors had already discovered a variety of elementary particles. These particles are grouped into families whose members behave similarly in interactions with other particles. Three main groups can be distinguished: the leptons, quarks and bosons. The existence of an omnipresent Higgs field with associated *Higgs boson*, was predicted during the construction of the *Standard Model* (SM), the theory describing all these particles and their interactions. Only by postulating the existence of a new unseen particle, were theorists able to allocate masses to observed particles in the model. The discovery of the Higgs boson in 2012 comes 48 years after its prediction in 1964, characterizing the large time scales related to the construction of big accelerator experiments.

The Standard Model has been tested to impressive accuracy which leaves little room for unknown physics at minute length scales explored so far. However, tests of the Standard Model's validity are also provided at extremely large length scales: the movement of large scale objects in the universe studied by astrophysicists. For instance, the movement of galaxies governed by gravity, implies the existence of unseen *dark matter*, as the amount of the visible matter alone cannot explain it. Dark matter must also be made of particles, however the Standard Model does not provide a candidate particle. This motivates among other reasons, the development of more theories. One such idea is *supersymmetry*, a theory that postulates the existence of superpartners to all known Standard Model particles and that does provide a dark matter candidate. The supersymmetric particles

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must have masses beyond currently explored limits, otherwise they would have already been observed in accelerator experiments. The supersymmetry can therefore only exist at very high energies, allowing a lower energy scale mechanism to break the symmetry in the particle masses. Other models are also interesting, as long as they contain the Standard Model supplemented with ideas that provide answers or insights to open questions. Collectively such theories are therefore often referred to as *Beyond the Standard Model (BSM)* theories .

While the development of increasingly large accelerator experiments requires some tens of years before they collect data, theoretical work on BSM theories continues. One of the LHC's tasks will be to exclude, or confirm, as much as possible of BSM physics and simultaneously perform precision measurements that test the Standard Model's validity. The development of strategies that *distinguish between the Standard Model and BSM theories* is thus of crucial importance for the LHC. This translates to isolating parts of the BSM that deviate from SM behavior. A very interesting approach is based on a property of subatomic particles called spin.

*Spin* is quantum property of a particle that relates to the physical conservation law of angular momentum. This law is comparable to Einstein's  $E = mc^2$ , where in this case the angular momentum of a particle is transferred elsewhere when the spin is changed. Spin was discovered by two Dutch physicists Uhlenbeck and Goudsmit in Leiden in 1925. Leptons and quarks have spin  $\frac{1}{2}$ , commonly referred to as fermions, while bosons have spin 0 or 1. Bosons and fermions behave very differently. For instance bosons can be in the same state while fermions always need to be in different states (when they are in one place with the same velocity). Spin relates peculiarly to our general interpretation of measuring. The type of particle (boson or fermion) determines the amount of spin to be either  $\frac{1}{2}$  or 1 times the unit of spin (spin 0 is a trivial measurement). It is a quantum property that the spin is always found along the measuring axis either in the *up or down* direction, even if the measurement is followed by a measurement in perpendicular direction. Spin is thus always pointing in either way of your measuring axis regardless of the direction of your measuring axis.

Both the Standard Model and BSM theories produce particles with up and down spin (along some axis), but models can differ in their preference to produce spin up or spin down type particles. This difference can be exploited to distinguish between Standard Model and BSM theories. The asymmetry in spin is measured with *polarization*, which effectively compares the amount of particles produced with up spin, to the amount of particles produced with spin down. Interestingly, this difference is most notable when spin is measured along the direction of movement (longitudinal polarization). We use the top quark to study polarization in this thesis, as this quark immediately decays into other elementary particles instead of forming a bound state as lighter quarks do. The decay allows for the tracing of spin information. The *angular distributions* of the the top quark decay products can easily be correlated with polarization in the top rest frame. This is more complicated in the laboratory frame, where the top quark is moving, which focusses

the decay products towards the top quark direction of movement. As a result the trace of polarization in the angular distributions of the top quark decay products is weakened in the laboratory frame. It is interesting to study polarization in the laboratory frame as this relates more obviously to LHC data. The main goal of chapter 3 and 4 is to investigate the sensitivity of the angular distributions of the top decay product, to the polarization of a top quark produced in the Standard Model and a BSM theory in the laboratory frame. This approach is supplemented with a study of the correlation between polarization and the energy of the top decay product for cases where it is difficult to accurately measure the emission angle of the decay particle.

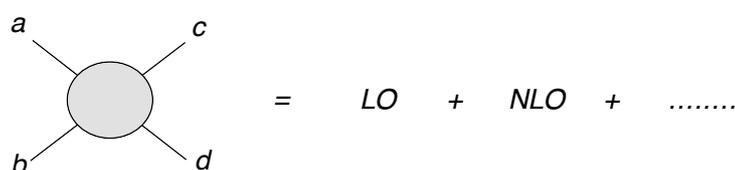


Figure D.1: Graphical representation of the prediction of a particle scattering calculated in perturbation theory.

The above approaches require accurate *theoretical predictions*, based on Standard Model and BSM theories, to test the robustness of polarization. For this we use perturbation theory, an approach that makes successively better predictions. The simplest approximation is called *Leading Order (LO)* and the first correction to it the *Next-to-Leading-Order (NLO)* term and so on. To use perturbation theory wisely requires thorough knowledge on the precision of calculations. Predictions of Standard Model observables are known to increase up to 30% when higher order corrections to the simplest approximation are taken into account. Lacking a thorough investigation of the influence of higher order terms for Standard Model observables can cause measurements to be mistaken for Standard Model deviations (and deviations are interpreted as signs for BSM). While the benefit of NLO predictions might be obvious, the calculations become increasingly complicated with each step in the perturbative series.

The idea of using polarization as a probe to distinguish between the Standard Model and BSM theories was already known. Though it had not been investigated prior to the work in this thesis, how the inclusion of NLO corrections influenced the usefulness of such approaches. Chapter 2 examined the effect of higher order corrections for producing a top quark in the Standard Model and a Two Higgs Doublet Model, a BSM with a larger Higgs sector. We found that the inclusion of *NLO weakens the signal of polarization slightly*, but that it remains sufficiently strong to distinguish between the Standard Model and BSM and provide information on the BSM parameters. A similar result was found for the energy distributions, although relating these distributions usefully to the BSM parameters was found to be more challenging and dependent on the model's parameters. This result

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motivated the work in the next chapter to be carried out, at LO, where we investigated how supersymmetric parameters influence the polarization of a top quark in the context of a supersymmetric BSM. As supersymmetry has not yet been discovered, these parameters can take a wide range of values. We found that polarization can be a *useful probe for supersymmetric parameters* when the masses of sparticles are known.

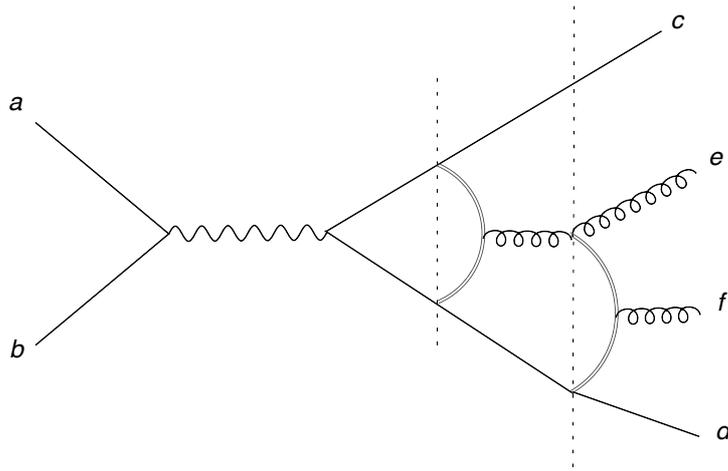


Figure D.2: Simulation of an event with an antenna shower. Initial particles  $a$  and  $b$  form a new particle that decays into particle  $c$  and  $d$ . The latter two particles then form an antenna and radiate off particle  $e$ . At the point illustrated by the second dotted line, there are two competing antennae  $c - e$  and  $e - d$ . A computer algorithm will decide which antenna will win the competition and is allowed to radiate a particle. The line type indicates the type of particle, straight for a quark and wiggly and curly lines denote different gauge bosons.

The polarization studies have used computer simulations of particle collisions (*event simulation*). A very fast way to simulate events is by building up the collision iteratively. The starting point is a LO calculation of a particle scattering denoted in fig. D.4 by particles  $a$  and  $b$  scattering into particle  $c$  and  $d$  through a short lived particle. Additional final state particles are generated by forming an antenna between particles  $c$  and  $d$ , that together radiate a third particle  $e$ . The next evolution step has two antennae to choose from, and a computer algorithm will decide which competing antenna will win the right to radiate off another particle. The evolution is guided by a timelike parameter that terminates the shower at a preset time. In order for the generated event to behave according to what the prediction of the Standard Model or BSM theory predicts requires an additional step called matching. We have discussed the VINCIA antenna shower including its matching procedure in detail in chapter 5. The shower already contained a LO matching prescription, and the work in this thesis generalized this to a *NLO matching procedure* in chapter 6 for an electron and positron (anti-electron) decaying into three massless particles. Our approach shows impressive results on speed in comparison to existing generators.