Synopsis

The Standard Model (SM) of particle physics is our present understanding of Nature. It is a framework in which properties and behavior of the fundamental particles and forces can be studied. It offers a unified description of the electromagnetic and weak forces along with the strong force in the microscopic domain. At the fundamental level, these forces act among quarks and leptons (the matter particles) through gauge bosons (the mediator particles). The model has been remarkably successful in explaining a huge amount of data collected so far at various high energy particle collider experiments throughout the world. Despite its success, there are direct as well as indirect evidences which indicate that the SM cannot be a complete story of the Universe. It does not include the fourth force of Nature, the Gravity. It does not account correctly for the dominance of matter over antimatter as observed in the Universe. It does not have any suitable candidate for the proposed Dark matter particles.

Apart from these direct evidences, there are certain theoretical inconsistencies associated with the model. It predicts the existence of a fundamental scalar, the Higgs boson as a result of the electroweak symmetry breaking (EWSB) through the SU(2) doublet of scalar fields. The recent discovery of a fundamental boson ($\sim 125$ GeV) at the Large Hadron Collider (LHC) experiments might confirm the existence of this last missing piece of the SM particle jungle soon. Within the model, the quantum correction to the Higgs mass is not stable; it is quadratically divergent and requires a very fine tuning of parameters. This is known as a fine tuning or naturalness problem in the literature. Another problem, more of a philosophical nature and closely related to the naturalness problem, is the unexplained hierarchy between the electroweak symmetry breaking scale ($\sim 100$ GeV) and the fundamental scale of Gravity in 4 dimensions, the Planck scale ($\sim 10^{19}$ GeV). The desirable unification of the fundamental forces is also not feasible within the model. All these lead
us to believe that the SM is only a low energy description of a deeper reality. We expect new physics and new particles to appear at higher energy scales (∼ TeV), where the SM predictions are not yet tested.

There are many candidates for new physics, with their own merits and demerits, which address many of the above mentioned problems. Models based on supersymmetry, models of new forces and models of extra dimensions are few among many. Their predictions can be tested at the present day high energy colliders such as the LHC and this requires calculations to be done in both the SM and new physics models. Any deviation from the SM predictions is a signature of new physics. The problem of large hierarchy between the electroweak and the Planck scales can be addressed within the models of extra space dimensions. Among various models of extra dimensions, the ADD model of large extra dimensions is one of the very first successful attempts in this direction. In the ADD model, the number of space-time dimensions is taken 4 + δ. The SM degrees of freedom live on a (3 + 1)-dimensional brane, while the Gravity can access the full 4 + δ dimensions. The extra space dimensions are supposed to be compact. In this model, the 4-dimensional Planck scale is only an effective scale and the fundamental scale of Gravity, $M_S$ can be near TeV scale. In 4 dimensions, the 4 + δ dimensional graviton appears as an infinite tower of Kaluza-Klein (KK) modes and it couples to the energy-momentum tensor ($T_{\mu\nu}$) of the SM fields. The direct production of the KK-gravitons gives rise to missing energy signals in the detector.

At hadron colliders the fundamental interactions take place among its constituents, the quarks and the gluons. Collectively these are called partons and they carry a certain momentum fraction of the parent hadron. Although the coupling of the strong interaction ($\alpha_s$) acting among the partons is quite large at low energies, due to the property of asymptotic freedom it is possible to apply perturbative methods at the parton level at higher energies. The color confinement forces the partons not to be seen as free particles and therefore, perturbative calculations at the parton level may appear meaningless. The factorization theorem provides a means to calculate hadronic cross sections in terms of partonic ones. Predictions obtained this way have been verified at the hadron colliders such as the Tevatron and the LHC. The $p\bar{p}$ collider facility at the Tevatron has been recently shutdown. The
LHC is a proton-proton collider with the centre-of-mass (c.m.) energy in the multi-TeV range. It is presently running at 8 TeV c.m. energy and more than $10 fb^{-1}$ of data has been collected so far at the two general purpose detectors, the ATLAS (A Toroidal LHC Apparatus) and the CMS (Compact Muon Solenoid). At higher energies the gluon distribution functions are quite important, and therefore, gluon fusion processes can contribute significantly towards the SM as well as new physics predictions.

In this thesis, I have studied certain gluon fusion processes at the hadron colliders. We have considered the di-vector boson production in association with a jet via gluon fusion within the SM. We have also considered the direct production of the KK-gravitons in association with a boson via gluon fusion in the ADD model. All these processes share a common feature that they proceed via the quark loop diagrams at the leading order (LO) itself and being LO contributions these are expected to be finite. Total cross sections and phenomenologically relevant kinematic distributions constitute the main results of these studies. The amplitude calculation is done at the parton level. One of the most difficult parts of the calculation is the reduction of one-loop tensor integrals into a suitable set of one-loop scalar integrals. In our projects, we have one-loop five-point tensor integrals of rank five as the most complicated tensor structures. We have worked with two different codes for the one-loop tensor reduction in $n$ dimensions. An analytical tensor reduction code in FORM was developed during the ADD model projects. It is based on the reduction method suggested by Denner-Dittmaier, and the reduction of any one-loop tensor integral up to four-rank, four-point function can be performed using it. We have used it successfully in our ADD model projects to make various checks on amplitudes. For actual numerical calculations we have used a numerical code written in FORTRAN following the one-loop tensor reduction method of Oldenborgh-Vermaseren. Any one-loop amplitude in 4 dimensions, after the tensor reduction, can be expressed in terms of the scalar integrals of box, triangle, bubble and tadpole types and an additional piece called the Rational part. Thus the singularity structure of any one-loop amplitude is dictated by those of the scalar integrals. The rational part is an artifact of the regularization of ultra-violet (UV) divergences of one-loop tensor integrals. We have derived the one-loop scalar integrals, required in this thesis, following the method of ’t Hooft-Veltman. UV singularities are regularized in $4 - 2\epsilon$ dimensions while infra-red (IR) singularities are regularized by giving a small mass to the
quarks in the loop. Due to the numerical instability these scalar integrals are used only for making finiteness checks on amplitudes. Actual numerical results are obtained using the scalar integrals from the LoopTools and the OneLOop packages.

In the ADD model, the process $gg \rightarrow BG_{KK}$ contributes to $pp \rightarrow BG_{KK} + X$ at the next-to-leading order (NLO) in $\alpha_s$. These processes proceed via quark loop diagrams of the triangle and the box types. We work with all the six quark flavors and except the top quark all others are treated as massless. We find that the amplitude for $gg \rightarrow \gamma G_{KK}$ vanishes at the LO. This can be shown using Furry’s Theorem and the charge conjugation property of the graviton. Due to the same reason the vector part of the $gg \rightarrow Z G_{KK}$ amplitude does not contribute. Since the axial part of the amplitude is proportional to the $T^3_q$ value, it does not receive any contribution from the first two generations. We find that due to the nature of the graviton coupling with the quarks, both the triangle and box diagrams are linearly divergent and give rise to the anomaly. We have studied the intricate relationship between the anomaly and the rational terms in linearly divergent fermion loop amplitudes. We find that in fermion loop amplitudes (including those plagued with the chiral anomaly), correct rational terms can be obtained utilizing the Decoupling theorem. The process $gg \rightarrow HG_{KK}$ receives dominant contribution from the top quark in the loop. It is a leading non-zero contribution to $pp \rightarrow HG_{KK} + X$, if we neglect the bottom quark mass. In all these cases, we have studied the variation of the total cross section with respect to the collider c.m. energy. We observe a significant cancellation between the triangle and the box contributions at the amplitude level. We find that at the typical LHC energy the cross section is only few fb. We give the transverse momentum ($p_T$) and the rapidity ($\eta$) distributions of the bosons ($Z/H$) and examine the effect of changing the renormalization and the factorization scales. In the direct production processes of the KK-gravitons, all the kinematically allowed modes are produced and therefore we also discuss their distribution. We have studied changes in our results as the ADD model parameters $\delta$ and $M_S$ are varied. We have also checked the effect of choosing different sets of the parton distribution functions (PDFs).

In the SM, the process $gg \rightarrow VV'g$ contributes to $pp \rightarrow VV'j + X$ at the next-to-next-to-leading order in $\alpha_s$. Like the corresponding di-vector boson production cases, these are important backgrounds to the Higgs boson production as well as new physics scenarios.
In particular, we have considered the production of $\gamma \gamma g$, $\gamma Z g$, $ZZ g$ and $W^+ W^- g$ at the LHC. The process $gg \rightarrow \gamma \gamma g$ has been calculated in the past. We have updated its cross section and have reconfirmed the importance of this processes at the LHC. In the $ZZ g$ and $W^+ W^- g$ cases, we have ignored the Higgs boson interference effects. These proceed via the quark loop diagrams of the box and the pentagon types. The box diagrams give only the vector contribution while the pentagon diagrams give both the vector and the axial-vector contributions. We work in the limit of the decoupling of the top quark. We have studied the variation of the hadronic cross section with respect to the collider c.m. energy for all the four processes. We find that these one-loop contributions are in the range of $4 - 15\%$ of the corresponding tree-level contributions. We also give some important kinematic distributions common to all the four processes.

In a more complete study of the $\gamma Z g$ production process, we explicitly check the decoupling of the top quark at the amplitude level as well as at the level of the total cross section. We have quantified the contributions of the vector and the axial-vector parts of the amplitude towards the total cross section. We also study the effects of changing the renormalization and the factorization scales and the effect of choosing the PDF sets. We have considered the decay of the $Z$ boson, and a comparison with the corresponding LO and NLO calculation is also made. We briefly discuss the method adopted to deal with the numerical instabilities in our calculations.