Title: Scattering Amplitudes in the Yang-Mills sector of Quantum Chromodynamics

Author: Hiren Kakkad

Abstract

Scattering amplitudes are one of the most crucial objects in Quantum Field Theories because they are the building blocks for computing cross sections measured at the particle colliders. Traditionally, amplitudes were computed using the Feynman diagram technique. However, in field theories that involve self-interactions, like the Yang-Mills sector of Quantum Chromodynamics (QCD) which describes pure gluonic interactions, this technique becomes impractical because the number of diagrams grows factorially with the number of external gluons.

We derive a new classical action for the pure gluonic sector of QCD that implements new interaction vertices (local in the light-cone time) with at least four legs and fixed helicities, which makes it efficient in calculating tree-level pure gluonic scattering amplitudes. We demonstrated this by computing several tree-level amplitudes up to 8-point and the maximum number of planar diagrams we got was 13 (in the Feynman diagram technique, an 8-point tree amplitude requires tens of thousands of diagrams). The new action was obtained by performing a canonical field transformation on the light-cone Yang-Mills action such that it eliminates both the triple point interaction vertices from the latter. The transformation replaces the fundamental gluon fields of the Yang-Mills theory with the Wilson line degrees of freedom – geometric objects facilitating parallel transport of vectors in curved spaces. The new action extends the so-called MHV action, i.e. the action implementing the Cachazo-Svrcek-Witten method that utilizes the Maximally Helicity Violating (MHV) scattering amplitudes as interaction vertices.

At the loop level, both the MHV action and the new classical action turn out to be incomplete because the eliminated triple gluon vertices with helicity $(++-)$ and $(+--)$ contribute to loops. To systematically develop loop corrections to the MHV action first, we used the one-loop effective action approach where we start with constructing it for the Yang-Mills action and then perform the field transformation to obtain the classical MHV action plus loop contributions. We verified that there are no missing loop contributions by computing four-point one-loop amplitudes where all the gluons have plus helicity $(++++)$ and where one of them has a minus helicity $(+++-)$. These could not be computed in the MHV theory. A major advantage of this approach is that the transformation accounts for all the tree level connections one could make by connecting the $(++-)$ triple gluon vertex with the external legs of the loop contributions. As a result, the number of diagrams required to compute one-loop amplitudes is way less when compared with the one-loop effective Yang-Mills action.

Next, we extend this approach to develop loop corrections for our new Wilson line-based action. We start with the one-loop effective Yang-Mills action and then perform the transformation to obtain the new classical action plus loop corrections. In this case, the number of diagrams required to compute a higher multiplicity one-loop amplitude is lesser than in the one-loop effective MHV action. This is because the transformation accounts for all the tree level connections one could make by connecting both the $(++-)$ and $(+--)$ triple gluon vertices with the external legs of the loop contributions. To validate the one-loop action we computed one-loop amplitudes with helicities $(++++)$, $(+++-)$, $(++--)$, $(----)$

and $(---+)$.

Although one-loop complete (no missing loop contribution), a major drawback of this approach is that it uses Yang-Mills vertices inside the loop and the new efficient vertices of our action outside the loops only. We, therefore, re-derive the one-loop actions via a different approach, where we first perform the canonical transformation to the Yang-Mills action transforming also the current dependent terms, and then integrate the field fluctuations to derive the one-loop effective actions. This way the new interaction vertices of our action are explicit in the loop. We test this approach first for the MHV action and demonstrate that the one-loop effective MHV action, derived this way, is both one-loop complete and has MHV vertices explicit in the loop. Since there are "bigger" interaction vertices when compared with the Yang-Mills vertices in the loop, the efficiency of computing higher multiplicity one-loop amplitude further increases in this approach. We finally extend the new approach to our action and derive the one-loop action such that the interaction vertices of our action are manifest in the loop. Since our interaction vertices are even bigger when compared to the MHV vertices, computing one-loop amplitude requires even fewer diagrams.

The research done in this thesis provides a new field-theory action-based method to efficiently calculate pure gluonic scattering amplitudes up to one loop.

27/06/2023