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Bootstrapping two-loop six-gluon amplitudes in QCD

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The maximally transcendental, or "most complicated", terms of gauge-theory scattering amplitudes have long been singled out, following Lipatov and collaborators, as those parts of a QCD amplitude that most closely mirror maximally supersymmetric Yang–Mills theory. We report on a programme that turns this observation into a practical computational tool. We show that the rational prefactors multiplying the highest-weight special functions of planar QCD amplitudes are governed by four-dimensional leading singularities, which can be classified and evaluated using on-shell diagrams. The resulting prefactors are manifestly conformally invariant and admit compact spinor-helicity expressions that hold for arbitrary multiplicity. Combining this input with the recently established two-loop six-particle function space, we set up a symbol bootstrap and determine, for the first time, the maximal-weight symbol of the planar two-loop six-gluon amplitude in massless QCD, first for the $--++++$ helicity configuration and subsequently for all MHV configurations. The answer is fixed uniquely by physical consistency conditions, requires a reduced alphabet of only 137 symbol letters, and yields as a byproduct previously unknown two-loop triple-collinear and double-soft splitting functions. We summarise the method and the results, and outline the directions they open up.

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1. Introduction

Scattering amplitudes connect the Standard Model Lagrangian to collider measurements and have repeatedly exposed hidden structures of quantum field theory. The phenomenological demand for precision at the Large Hadron Collider keeps pushing computations to higher loop order and multiplicity, while each new frontier reveals an analytic structure that is far richer, and often far simpler, than a brute-force calculation would suggest [1, 2].

For massless five-particle scattering, the past decade has seen dramatic progress: the relevant two-loop Feynman integrals are known analytically and complete two-loop amplitudes are available for a range of $2 \to 3$ processes of phenomenological interest. The natural question is what happens at six particles. There the obstacles are of two qualitatively different kinds. On the one hand, the special functions become genuinely more complicated: the planar (leading-colour) two-loop six-particle function space consists of iterated integrals in seven independent kinematic variables, with up to 167 symbol letters at weight four [3, 4]. On the other hand, and more subtly, the rational prefactors multiplying these functions proliferate. Already at five gluons their explicit form is highly non-trivial [5, 6], and a naive treatment quickly becomes prohibitive at six points.

It is useful to recall the schematic structure of a perturbative QCD amplitude,

$$\mathcal{A} \;=\; \sum_{i,j} c_{ij}\, R_i\, f_j\,, \tag{1}$$

with transcendental special functions f_j, rational (or algebraic) prefactors R_i, and kinematic-independent rational numbers c_{ij}. Bootstrapping such an amplitude requires detailed control of *both* the function space and the prefactors. The six-point function space was recently obtained by traditional means [3, 4]; the prefactors are the missing ingredient supplied here.

We are guided by the principle of maximal transcendentality. Kotikov, Lipatov and collaborators observed that the maximally transcendental parts of certain QCD quantities, such as the twist-two anomalous dimensions, coincide with those of maximally supersymmetric Yang–Mills theory (sYM), since gluons dominate the BFKL equation [7, 8]; see also [9]. The correspondence is not exact for amplitudes—already the one-loop $-+-+$ configuration is richer than its sYM counterpart [12, 13]—but the maximally transcendental part stays strikingly simple. We compute precisely these "most complicated terms" for two-loop six-gluon amplitudes and argue that, in their coefficients, they are the *simplest* part of the amplitude. The material is based on refs. [14, 15].

2. The strategy: hard functions, maximal weight, and on-shell diagrams

Our approach combines five ideas: we work with leading-colour six-gluon amplitudes (because of the available function space); we study infrared-finite hard functions; we project onto the maximally transcendental, "most complicated" terms; this exposes a hidden conformal symmetry and a direct connection to on-shell diagrams; these simplifications make a symbol bootstrap feasible, with physical constraints fixing the answer uniquely. We develop each in turn.

2.1 Hard functions

We compute helicity amplitudes in the leading-colour approximation, keeping the leading term in the large-N_c limit while retaining fermion loops by holding the ratio N_f/N_c fixed. Rather than

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the amplitude itself we study the infrared-finite hard function obtained by subtracting the universal infrared poles,

$$\mathcal{H}^{(2)} = \lim_{\epsilon\to 0}\left[\mathcal{A}^{(2)} - I^{(1)}\,\mathcal{A}^{(1)} - I^{(2)}\,\mathcal{A}^{(0)}\right], \tag{2}$$

where $\mathcal{A}^{(L)}(\epsilon)$ are the colour-stripped L-loop amplitudes and $I^{(1)}, I^{(2)}$ are the universal infrared subtraction operators [10, 11]. Hard functions are less sensitive to the spurious effects of dimensional regularisation than "naive" finite remainders; in five-particle scattering this was reflected in cancellations within the relevant function space [16]. Crucially, the hard function can be analysed with genuinely four-dimensional methods, for both its functions and its coefficients.

2.2 The maximal-weight projection

At maximal transcendental weight (weight four at two loops) the prefactors simplify dramatically. The maximal-weight part of a Feynman integral is conjecturally computed from its "$d\log$" integrand, the corresponding prefactors—the leading singularities—being given by the maximal residues of the integrand [17, 19]. The same circle of ideas, relating uniform transcendental weight to $d\log$ forms, has been instrumental in understanding how to obtain canonical differential equations for Feynman integrals [18]. The leading singularities can be computed for a suitably defined infrared-finite part, namely the hard function. They are determined by generalised unitarity cuts; the expectation that, at maximal weight, these cuts can be evaluated in four dimensions was argued for in ref. [19]. Our first target is therefore the weight-four part of the planar QCD amplitudes.

3. Prefactors from on-shell diagrams

The decisive simplification concerns the prefactors multiplying the maximal-weight functions. It is expected—and argued for in ref. [19]—that these prefactors are four-dimensional leading singularities. What can in addition be shown is that such leading singularities are expressible in terms of on-shell diagrams. These diagrams are built by gluing together three-point on-shell vertices, and the resulting on-shell functions are easy to classify and to evaluate [20]. A central observation is that this gluing procedure preserves conformal invariance [22]: the leading singularities are annihilated by the conformal generator

$$k^{\alpha\dot\alpha} = \sum_{i=1}^{n} \frac{\partial}{\partial\lambda_{i\,\alpha}}\,\frac{\partial}{\partial\tilde\lambda_{i\,\dot\alpha}}\,, \tag{3}$$

in line with the classical conformal invariance of massless QCD [21]. Here we use the spinor-helicity formalism, in which massless momenta are written as $p_i^{\alpha\dot\alpha} = \lambda_i^\alpha\tilde\lambda_i^{\dot\alpha}$ and the holomorphic spinor brackets are denoted by $\langle ij\rangle = \epsilon_{\alpha\beta}\lambda_i^\alpha\lambda_j^\beta$. The conformal invariance is already manifest for the tree-level amplitude, which for the $--+\cdots+$ configuration is given by the Parke–Taylor factor

$$\mathrm{PT}_{1,2} = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 56\rangle\langle 61\rangle}\,. \tag{4}$$

We focus on the $--++++$ six-gluon configuration. At one loop, the known amplitudes confirm that the coefficients of the highest-weight terms are simply given by (4), consistent with evaluating

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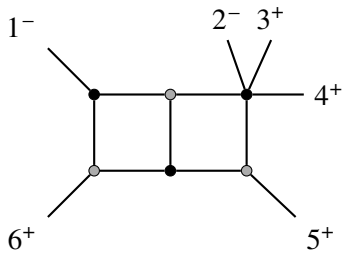

Figure 1: A representative two-loop on-shell diagram, of double-box topology, giving the non-trivial leading singularity $R_{5,6}$ for the $--++++$ helicity configuration (after ref. [14]). Black and grey nodes denote the two types of trivalent on-shell vertex. All six leading singularities $R_{i,j}$ $(2 < i < j \leq 6)$ arise from analogous diagrams; together with the Parke–Taylor term R_1 they are evaluated in four dimensions.

the relevant on-shell box diagrams. At two loops, the Parke–Taylor prefactor $R_1 = \mathrm{PT}_{1,2}$ is supplemented by six new leading singularities $R_{i,j}$, associated with the two-loop double-box topologies shown in figure 1. The on-shell diagrams there represent maximal cuts of these double boxes, on which all internal propagators are put on shell. A maximal cut of the double box leaves a single residual integration, i.e. a one-form, whose residue defines the leading singularity. Remarkably, a single closed formula captures all of them,

$$R_{i,j}/R_1 \;=\; -1 + 12\,u_{i,j} - 30\,u_{i,j}^2 + 20\,u_{i,j}^3\,, \qquad u_{i,j} := \frac{\langle 1i\rangle\langle 2j\rangle}{\langle 12\rangle\langle ij\rangle}\,. \tag{5}$$

Since (5) is expressed in terms of holomorphic spinors only, its conformal invariance is manifest. The same expression with $2 < i < j \leq n$ moreover captures all two-loop leading singularities of $--+\cdots+$ amplitudes for arbitrary multiplicity n. As a consistency check, the known maximal-weight coefficients of the five-particle two-loop amplitudes [23, 24] reduce precisely to these expressions. Although they look lengthy in the literature, at maximal weight they collapse to the simple formula (5), a simplification due in part to the use of spinor-helicity variables.

4. The symbol bootstrap

With the prefactors in hand, we can bootstrap the weight-four symbol of the two-loop hard function. The *symbol* of a transcendental function records the sequence of differentials defining it as an iterated integral [29], turning functional identities into linear algebra. Symbol bootstraps have been powerful in planar $\mathcal{N} = 4$ sYM [30, 31]. Here we apply them for the first time to two-loop QCD amplitudes. We make an ansatz directly for the hard function of eq. (2), expanded on the seven leading singularities,

$$\mathcal{H}^{(2)}_{\mathrm{YM}} \;=\; R_1\,G_1 \;+\; \sum_{2<i<j\leq 6} R_{i,j}\,G_{i,j}\,, \tag{6}$$

where the $G_1, G_{i,j}$ are weight-four symbols from the space of planar two-loop six-point functions, closed under cyclic permutations [3, 4]. Only G_1 is affected by the infrared subtraction (the tree-level and one-loop amplitudes involve only R_1), which we implement by adding products of $I^{(L)}$ and lower-loop amplitudes. The discrete flip symmetry $(123456) \leftrightarrow (216543)$ then leaves 2412 unknowns.

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The ansatz is then constrained by a sequence of physical consistency requirements. First, the symbol entries of G must be dimensionless. Second, the rational prefactors $R_{i,j}$ contain spurious poles $1/\langle ij\rangle^3$ (for non-adjacent i, j) and higher-order poles $1/\langle i\,i{+}1\rangle^4$ (for adjacent momenta, understood cyclically), each of which must be cancelled by the vanishing of the accompanying symbol at the corresponding locus. Third, the amplitude must reproduce the known behaviour in the collinear and triple-collinear limits, in which the hard function factorises into lower-point hard functions and (infrared-subtracted) splitting functions, for all the relevant helicity configurations. These conditions reduce the initial 2412 unknowns to a unique solution. Remarkably, they are also mutually consistent—a non-trivial cross-check—and as a bonus they determine the previously unknown triple-collinear and double-soft splitting functions that enter them.

To reach full QCD we include fermion loops. In the planar limit the two-loop hard function organises as

$$\mathcal{H}^{(2)}_{\rm QCD} \;=\; \mathcal{H}^{(2)}_{\rm YM} + \frac{N_f}{N_c}\,\mathcal{H}^{[1]} + \left(\frac{N_f}{N_c}\right)^2 \mathcal{H}^{[2]}\,. \tag{7}$$

The fermionic sectors are simpler: the $--++++$ configuration receives no maximal-weight contribution from $\mathcal{H}^{[2]}$, while $\mathcal{H}^{[1]}$ is controlled by six leading singularities of the same form,

$$S_{i,j}/R_1 \;=\; -2 + 12\,u_{i,j} - 21\,u_{i,j}^2 + 11\,u_{i,j}^3\,, \tag{8}$$

and is fixed by the first groups of conditions alone, without the triple-collinear input.

5. Novel results for scattering amplitudes and splitting functions

The bootstrap delivers the complete QCD answer for the maximal-weight symbol of the planar two-loop $--++++$ amplitude, and in subsequent work [15] for all six-gluon MHV helicity configurations. Three features deserve emphasis.

First, though the most complicated in terms of special functions, the maximal-weight part is the simplest in its coefficients: its prefactors are the few conformally invariant leading singularities of eqs. (5) and (8). That an answer consistent with all physical limits exists at all is strong evidence for the result, and for the conjecture that these prefactors are four-dimensional leading singularities.

Second, the symbol alphabet is reduced. Of the 245 letters of the full two-loop alphabet, 167 can appear up to weight four, yet only 137 occur in the final answer. The same 137-letter set governs all MHV configurations and has independently appeared in studies of six-point Wilson loops with a Lagrangian insertion. This reduction is at present unexplained and hints at deeper structure—as in planar $\mathcal{N} = 4$ sYM, where cluster adjacency and the (extended) Steinmann relations proved instrumental in pushing the bootstrap to high loop orders [30]—with first steps connecting some of the six-particle letters to cluster-algebraic and flag-variety descriptions [25, 26]. The QCD function space is, however, far more complicated than its sYM counterpart—with many more letters and less symmetry—so the analogy concerns structure rather than the size of the problem.

Third, the calculation yields genuinely new physical data. Enforcing consistency with the triple-collinear and double-soft limits determines the corresponding two-loop splitting functions at maximal weight, extending results previously known only at one loop: the maximal-weight double-soft function (for two gluons of the same helicity taken to be soft) coincides with its $\mathcal{N} = 4$ sYM counterpart, while the triple-collinear functions involve a genuinely new weight-four ingredient.

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These feed directly into higher-point amplitudes—the $g \to ggg$ symbol, for example, predicts part of the leading-colour two-loop $gg \to Hgg$ amplitude—and are provided in the ancillary files of refs. [14, 15].

6. Conclusions and outlook

The take-home message is twofold: the coefficients of the maximal-weight part of QCD amplitudes are on-shell diagrams evaluable systematically in four dimensions; and, with the symbol bootstrap, this fixes the planar six-gluon MHV amplitudes at maximal weight—the "most complicated" terms proving the simplest to organise.

Several directions are now open.

- *From symbols to functions.* Repeating the bootstrap for iterated integrals rather than symbols poses no technical obstacle: it requires only the boundary behaviour at function level, which is standard, while the necessary expansions can conveniently be obtained via the defining differential equations of the functions, see e.g. [33].

- *Non-planar and NMHV.* The leading-singularity method extends naturally to non-planar contributions and, via prescriptive unitarity, to a reduced set of integrals and to the NMHV sector [27].

- *Bypassing the integrals.* In the present work we relied on the explicitly known two-loop six-particle Feynman integrals. Combining the bootstrap with a Landau-equation analysis of the singularity structure may remove this prerequisite, eventually bypassing the explicit computation of Feynman integrals altogether.

- *Below maximal weight.* The hardest question lies below maximal weight, where there are far fewer functions but many more coefficients: characterising the prefactors needed for QCD amplitudes—and how much four-dimensional information suffices—is already worth revisiting at one loop [28, 34].

- *Approximate and numerical connections.* It would be interesting to connect this bootstrap philosophy to approximate numerical methods. If a candidate function reproduces the true amplitude in all relevant limits, by how much can it differ numerically elsewhere? One could envisage effective approximations in the spirit of the Padé and conformal-mapping techniques developed for the Higgs-gluon form factor [32], possibly exploiting recently discussed Stieltjes properties of perturbative expansions [35].

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