

A complete solution for scattering in a kind of quiver gauge theory

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April 21st 2025

1 Preliminary

2 Scattering in quiver gauge theory

A brief introduction to BCFW

BCFW recursion relation is a method to compute scattering amplitude, especially in Yang-Mills theory and gravity.

- Ruth Britto
- Freddy Cachazo
- Bo Feng
- Edward Witten

From real to complex – Analytic Continuation

Why is analytic continuation valid?

- Tree level scattering amplitudes are rational functions of Lorentz invariants, such as $p_{i\mu}p_j^\mu$, $p_{i\mu}\epsilon_j^\mu$.
- **Locality** tells us that any pole of a tree-level amplitude must correspond to a on-shell propagating particle.
- There's only single pole, no branch cuts (logs, square roots, etc) at tree level.



Amplitudes can be shifted to complex plane

Momentum Shift in BCFW

What did BCFW do to make the shift?

Here we consider the case in which all particles are massless, $p_i^2 = 0$ for all $i = 1, 2, \dots, n$. Then introduce n complex-valued vectors r_i^μ .

- (i) $\sum_{i=1}^n r_i^\mu = 0$,
- (ii) $r_i \cdot r_j = 0$ for all $i, j = 1, 2, \dots, n$. In particular $r_i^2 = 0$,
- (iii) $p_i \cdot r_i = 0$ for each i (no sum).

These vectors r_i are used to define n shifted momenta

$$\hat{p}_i^\mu \equiv p_i^\mu + z r_i^\mu \quad \text{with } z \in \mathbb{C}$$

Note that,

- (A) By property (i), momentum conservation holds for the shifted momenta: $\sum_{i=1}^n \hat{p}_i^\mu = 0$,
- (B) By (ii) and (iii), we have $\hat{p}_i^2 = 0$, so each shifted momentum is on-shell,
- (C) For a non-trivial subset of generic momenta $\{p_i\}_{i \in I}$, define $P_I^\mu = \sum_{i \in I} p_i^\mu$.

Then, \hat{P}_I^2 is **linear** in z :

$$\hat{P}_I^2 = \left(\sum_{i \in I} \hat{p}_i \right)^2 = P_I^2 + 2z P_I \cdot R_I \quad \text{with} \quad R_I = \sum_{i \in I} r_i,$$

because the z^2 term vanishes by property (ii). We can write

$$\hat{P}_I^2 = -\frac{P_I^2}{z_I} (z - z_I) \quad \text{with} \quad z_I = -\frac{P_I^2}{2P_I \cdot R_I}$$

Fantastic result from Cauchy Theorem

As a result of (A) and (B) (momentum conservation and on-shell), we can consider amplitude A_n in terms of shifted momentum \hat{p}_i^μ instead of original real momentum.

$$A_n \longrightarrow \hat{A}_n(z)$$

and we have known the possible positions of single poles, z_I , different propagators give us different single poles in the z -plane.

If we consider the meromorphic function $\frac{\hat{A}_n(z)}{z}$ in the complex plane, pick a contour that surrounds the simple pole at the origin. ★ The most important point here is that

$$\text{Res}|_{z=0} \frac{\hat{A}_n(z)}{z} = \hat{A}_n(0) = A_n$$

It means that the original amplitude equals to the residue at origin.

From Cauchy Theorem, we can obtain

$$A_n = - \sum_{z_I} \text{Res}|_{z=z_I} \frac{\hat{A}_n(z)}{z} + B_n,$$

where B_n is the residue of the pole at $z = \infty$, called boundary term.

Then, at a z_I pole, the propagator \hat{P}_I^2 goes to on-shell. In that limit, the shifted amplitude **factorizes** into to on-shell parts (Unitarity)

$$\hat{A}_n(z) \xrightarrow{z \text{ near } z_I} \hat{A}_L(z_I) \frac{1}{\hat{P}_I^2} \hat{A}_R(z_I) = - \frac{z_I}{z - z_I} \hat{A}_L(z_I) \frac{1}{P_I^2} \hat{A}_R(z_I)$$

This makes it easy to evaluate the residue at $z = z_I$

$$- \text{Res}|_{z=z_I} \frac{\hat{A}_n(z)}{z} = \hat{A}_L(z_I) \frac{1}{P_I^2} \hat{A}_R(z_I) =$$

Little Group

In the context of relativistic QFT, particles are classified according to the unitary irreducible representations of the Poincaré group.

A crucial concept in this classification is the

Little Group: The subgroup of Lorentz transformations that leaves a given four-momentum invariant.

- **Massless Case**

For a massless particle with representative momentum

$$p^\mu = (E, 0, 0, E)$$

the little group is $SO(2) \simeq U(1)$.

In terms of spinor-helicity variables, the massless momentum can be written as

$$p_{\alpha\dot{\alpha}} = \lambda_\alpha \tilde{\lambda}_{\dot{\alpha}}$$

The action of the little group is:

$$\lambda \rightarrow t^{-1}\lambda, \quad \tilde{\lambda} \rightarrow t\tilde{\lambda}, \quad t \in \mathbb{C}^*$$

same as

$$|\lambda\rangle \rightarrow t|\lambda\rangle, \quad |\lambda] \rightarrow t|\lambda]$$

The scattering amplitudes should transform covariantly under little group scaling:

$$\mathcal{A}_n(\{|1\rangle, |1], h_1\}, \dots \{t_i^{-1}|i\rangle, t_i|i], h_i\}, \dots) = t_i^{2h_i} \mathcal{A}_n$$

■ Massive Case

It can also be handled in terms of spinor-helicity variable, see also arXiv:1709.04891 [hep-th] (Nima Arkani-Hamed, Tzu-Chen Huang, Yu-tin Huang).

3-point can be completely determined

- 3-particle special kinematics determines an on-shell 3-point amplitude with massless particles depends only on either angle or square brackets of the external momenta.

Let us suppose that it depends only on angle brackets, then we can write down the general ansatz

$$A_3(1^{h_1}, 2^{h_2}, 3^{h_3}) = c \langle 12 \rangle^{x_{12}} \langle 13 \rangle^{x_{13}} \langle 23 \rangle^{x_{23}},$$

Little group scaling tells us that

$$t_1^{2h_1} A_3(1^{h_1}, 2^{h_2}, 3^{h_3}) = c t_1^{-x_{12}} t_1^{-x_{13}} \langle 12 \rangle^{x_{12}} \langle 13 \rangle^{x_{13}} \langle 23 \rangle^{x_{23}}.$$

We can obtain

$$2h_1 = -x_{12} - x_{13}$$

Similarly, we can also obtain

$$2h_2 = -x_{12} - x_{23}, \quad 2h_3 = -x_{13} - x_{23}.$$

Then all index can be solved from this system of equations, so that

$$A_3^{h_1 h_2 h_3} = c \langle 12 \rangle^{h_3 - h_1 - h_2} \langle 31 \rangle^{h_2 - h_1 - h_3} \langle 23 \rangle^{h_1 - h_2 - h_3} \quad h_1 + h_2 + h_3 < 0.$$

Also for square brackets case, we can obtain

$$A_3^{h_1 h_2 h_3} = c' [12]^{h_1 + h_2 - h_3} [23]^{h_2 + h_3 - h_1} [31]^{h_3 + h_1 - h_2} \quad h_1 + h_2 + h_3 > 0.$$

Example: 3-gluon amplitude

$$A_3(g_1^-, g_2^-, g_3^+) = g \frac{\langle 12 \rangle^3}{\langle 23 \rangle \langle 31 \rangle}$$

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Introduction to quiver gauge theory

The lagrangian can be written like

$$\mathcal{L} = - \sum_{i=1}^k \frac{1}{2} \text{Tr}(F_i)^2 + \sum_{i=1}^{k-1} \text{Tr}[(D_\mu \Phi_i)^\dagger (D^\mu \Phi_i)],$$

here F_i refers to the i th field strength, scalar field Φ_i transformed under the **bi-fundamental** representation and the covariant derivative equals to

$$D_\mu \Phi_i = \partial_\mu \Phi_i - ig_i V_{i\mu} \Phi_i + ig_{i+1} \Phi_i V_{i+1\mu}.$$

It is easy to confirm that this theory is invariant under $SU(N_1) \times SU(N_2) \times \cdots \times SU(N_k)$.

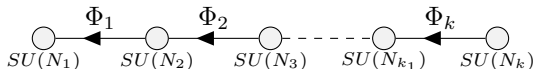


Figure: Quiver gauge theory

Classification of scattering amplitude

For the simplicity, we started from the two-site gauge theory, means that there are only two gauge fields and one scalar field. The amplitudes in this theory can be classified to many types

- 3-point

- $V_1 \Phi \Phi^\dagger$
- $V_2 \Phi \Phi^\dagger$
- $V_1 V_1 V_1$
- $V_2 V_2 V_2$

- 4-point

- $V_1 V_1 V_1 V_1$
- $V_2 V_2 V_2 V_2$
- $\Phi^\dagger V_1 V_1 \Phi$
- $\Phi V_2 V_2 \Phi^\dagger$
- $\Phi \Phi^\dagger \Phi \Phi^\dagger$