

Scattering of massless particles: scalars, gluons and gravitons

Freddy Cachazo, Song He, Ellis Ye Yuan

Su Yingze

Nagoya University

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1 Why the S -matrix is so important?

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Locality and Unitarity

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Gauge theory color structure

At tree level, with particles in the adjoint representation of gauge group $SU(N)$, the amplitude can be decomposed as

$$\mathcal{A}_n^{tree}(1, 2, 3, \dots, n) = \sum_{\mathcal{P}(2,3,\dots,n)} \text{Tr}[T^{a_1} T^{a_2} T^{a_3} \dots T^{a_n}] A_n^{tree}[1, 2, 3, \dots, n]$$

here we omit the coupling constant g , and A_n^{tree} is called tree-level color-ordered partial amplitude. Notice that this basis includes $(n-1)!$ independent amplitudes.

Color-ordered partial amplitudes satisfy a set of well-known properties,

- Cyclic:

$$A_n^{tree}[1, 2, 3, \dots, n] = A_n^{tree}[2, 3, \dots, n, 1]$$

- Reflection:

$$A_n^{tree}[1, 2, 3, \dots, n] = (-1)^n A_n^{tree}[n, \dots, 3, 2, 1]$$

- "photon" decoupling:

$$\sum_{\sigma \in \text{cyclic}} A_n^{tree}[1, \sigma(2, 3, \dots, n)] = 0$$

- KK(Kleiss-Kuijf) relation:

$$A_n^{tree}[1, \alpha, n, \beta] = (-1)^{n_\beta} \sum_{\{\sigma\}_i \in OP(\{\alpha\}, \{\beta\}^T)} A_n^{tree}[1, \{\sigma\}_i, n]$$

where the OP means ordered permutations, that is all permutations of $\{\alpha\}, \{\beta\}^T$ that maintains the order of individual elements of each set.

For example, a five point amplitude $A_n^{tree}(1, \{2, 3\}, 5, \{4\})$, we have

$$A_n^{tree}[1, 2, 3, 5, 4] = -A_n^{tree}[1, 2, 3, 4, 5] - A_n^{tree}[1, 2, 4, 3, 5] - A_n^{tree}[1, 4, 2, 3, 5]$$

The other five point relations can be obtained by permuting legs 2,3,4 and using cyclic and reflection properties.

This means that the six amplitudes $A_n^{tree}(1, \mathcal{P}\{2, 3, 4\}, 5)$ form a basis of remaining five-point partial amplitudes. **More generally, for multiplicity n , the KK relation can be used to rewrite any color-ordered partial amplitude in terms of only $(n-2)!$ basis partial amplitudes, where two legs are fixed (usually choose 1 and n).**

A Similar Structure

It can be proved that tree level amplitudes can also be decomposed like

$$\mathcal{A}_n^{\text{tree}} = \sum_{\sigma \in S_{n-2}} \tilde{f}^{a_1 a_{\sigma_1} b_1} \tilde{f}^{b_1 a_{\sigma_2} b_2} \dots \tilde{f}^{b_{n-3} a_{\sigma_{n-2}} a_n} \tilde{A}_n(1, \sigma_1, \sigma_2, \dots, \sigma_{n-2}, n)$$

It is easy to realize that the number of basis amplitudes is also $(n-2)!$.

How can we realize the existence of this basis?

We just need to notice the contribution from ladder diagram

$$\begin{array}{c}
 \sigma_1 \quad \sigma_2 \quad \dots \quad \sigma_{n-2} \\
 | \quad | \quad \dots \quad | \\
 \hline
 1 \quad \quad \quad n
 \end{array}
 \rightarrow
 \tilde{f}^{a_1 a_{\sigma_1} b_1} \tilde{f}^{b_1 a_{\sigma_2} b_2} \dots \tilde{f}^{b_{n-3} a_{\sigma_{n-2}} a_n}$$

And any (three vertex) diagram, by using the Jacobi identity like

$$\begin{array}{c} 2 \\ \diagdown \\ \text{---} \\ \diagup \\ 3 \end{array} \begin{array}{c} 4 \\ | \\ \text{---} \\ | \\ 5 \end{array} = - \begin{array}{c} 2 \\ | \\ \text{---} \\ | \\ 1 \end{array} \begin{array}{c} 3 \\ | \\ \text{---} \\ | \\ 5 \end{array} \begin{array}{c} 4 \\ | \\ \text{---} \\ | \\ 5 \end{array} - \begin{array}{c} 2 \\ \diagdown \\ \text{---} \\ \diagup \\ 3 \end{array} \begin{array}{c} 4 \\ | \\ \text{---} \\ | \\ 5 \end{array}$$

can be transformed to the ladder diagram. It has been proved that $\tilde{A}_n(\dots)$ here is identical to $A_n^{tree}[\dots]$ in the trace basis.

Color-Kinematics Duality and BCJ Relation

The Color-Kinematics Duality here is not the complete version, but we can sketch some point from lower point case

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Scattering equations

It has been proposed that there is connection between the scattering data of n massless particles and the n -punctured sphere from a rational map

$$k_{\mu}^a = \frac{1}{2\pi i} \oint_{|z-\sigma_a|} dz \frac{p^{\mu}(z)}{\prod_{b=1}^n (z - \sigma_b)}$$

To describe the n -punctured sphere more properly, we can introduce the Riemann sphere as

$$\mathbb{CP}^1 \cong \mathcal{S}^2 \cong \mathbb{C} \cup \{\infty\}$$

and n -punctured Riemann sphere can be described by $SL(2, \mathbb{C})$ affine coordinates $\sigma_1, \sigma_2, \dots, \sigma_n$, that is to say we have a equivalence relation

$$\{\sigma_1, \sigma_2, \dots, \sigma_n\} \sim \{\psi(\sigma_1), \psi(\sigma_2), \dots, \psi(\sigma_n)\},$$
$$\psi(\sigma) := \frac{\alpha\sigma + \beta}{\gamma\sigma + \delta}, \quad \alpha, \beta, \gamma, \delta \in \mathbb{C}, \alpha\delta - \beta\gamma = 1$$

because of the redundancy of

From this map, we can easily obtain the main ingredients of this report

Scattering equations

$$\sum_{b \neq a} \frac{s_{ab}}{\sigma_a - \sigma_b} = 0, \quad a \in \{1, \dots, n\}$$

It has been proved that the number of solutions in any dimension is $(n-3)!$, and only $n-3$ of the equations are independent, so we can rewrite the scattering equations as following

$$\sum_{b \neq a} \frac{s_{ab}}{\sigma_a - \sigma_b} = 0, \quad a \in \{4, 5, \dots, n\} \quad \text{and} \quad \sigma_1 \rightarrow \infty, \sigma_2 = 0, \sigma_3 = 1$$

KLT Relation

So-called KLT relation, in the language of field theory, refers to the decomposition of **gravity amplitudes** to **two gauge theory amplitudes**.

\mathcal{N}	Factors	Supergravity
8	$\mathcal{N} = 4SYM \otimes \mathcal{N} = 4SYM$	pure $\mathcal{N} = 8SG$
6	$\mathcal{N} = 4SYM \otimes \mathcal{N} = 2SYM$	pure $\mathcal{N} = 6SG$
5	$\mathcal{N} = 4SYM \otimes \mathcal{N} = 1SYM$	pure $\mathcal{N} = 5SG$
4	$\mathcal{N} = 4SYM \otimes (\mathcal{N} = 0YM + n_\nu scalars)$	$\mathcal{N} = 4SG, n_\nu$ vector multiplets
4	$\mathcal{N} = 2SYM \otimes \mathcal{N} = 2SYM$	$\mathcal{N} = 4SG, 2$ vector multiplets
3	$\mathcal{N} = 2SYM \otimes \mathcal{N} = 1SYM$	$\mathcal{N} = 3SG, 1$ vector multiplet
2	$\mathcal{N} = 2SYM \otimes (\mathcal{N} = 0YM + n_\nu scalars)$	$\mathcal{N} = 2SG, n_\nu$ multiplets + 1 vector multiplets
2	$\mathcal{N} = 1SYM \otimes \mathcal{N} = 1SYM$	$\mathcal{N} = 2SG, 1$ hypermultiplet
1	$\mathcal{N} = 1SYM \otimes (\mathcal{N} = 0YM + n_\nu scalars)$	$\mathcal{N} = 1SG, n_\nu$ vector and 1 chiral multiplet

- KLT orthogonality is a striking property of the solutions to scattering equations.

Proposition 1

$$\frac{(i, j)}{(i, i)^{\frac{1}{2}}(j, j)^{\frac{1}{2}}} = \delta_{ij}$$

First we need to define the Jacobian matrix associated to the scattering equations

$$\Phi_{ab} \equiv \partial \left(\sum_{c \neq a} \frac{s_{ac}}{\sigma_a - \sigma_c} \right) / (\partial \sigma_b) = \begin{cases} \frac{s_{ab}}{(\sigma_a - \sigma_b)^2}, & a \neq b, \\ -\sum_{c \neq a} \Phi_{ac}, & a = b \end{cases}$$

As mentioned above only $n-3$ of the scattering equations are independent so the matrix Φ has **rank $n-3$** . (This matrix was first encountered in the gravity amplitudes constructed from gauge theory using KLT relation)

Consider a generalization of Φ_{ab}

$$\Psi_{ab, a \neq b} \equiv \frac{s_{ab}}{(\sigma_a - \sigma_b)(\sigma'_a - \sigma'_b)}, \quad \Psi_{aa} \equiv - \sum_{c \neq a} \Psi_{ac}.$$

Proposition 2

$$\text{rank } \Psi(\{\sigma\}, \{\sigma'\}) = \begin{cases} n - 4, \{\sigma\} \neq \{\sigma'\} \\ n - 3, \{\sigma\} = \{\sigma'\} \end{cases}$$

σ and σ' are assumed to be solutions to scattering equation.

Prove of KLT orthogonality

For the purpose of proving KLT orthogonality, we can construct a $n!$ dimension vector for each solution

$$\frac{1}{(\sigma_{\omega(1)} - \sigma_{\omega(2)})(\sigma_{\omega(2)} - \sigma_{\omega(3)}) \cdots (\sigma_{\omega(n)} - \sigma_{\omega(1)})}$$

Not so obvious is the fact that we can fix the position of 3 labels, which we choose 1, $n-1$, n , give rise to the KK relation and BCJ relation.

Now the vectors become $(n-3)!$ dimension, and even after selecting three labels, we still have the freedom of where to put them. Here we only use two choices :

$$(1, \omega(2), \dots, \omega(n-2), n-1, n) \quad \text{and} \quad (1, \omega(2), \dots, \omega(n-2), n, n-1)$$

The corresponding two vectors are

$$V(\omega) = \frac{1}{(\sigma_1 - \sigma_{\omega(2)}) \cdots (\sigma_{\omega(n-2)} - \sigma_{n-1})(\sigma_{n-1} - \sigma_n)(\sigma_n - \sigma_1)},$$

$$U(\omega) = \frac{1}{(\sigma_1 - \sigma_{\omega(2)}) \cdots (\sigma_{\omega(n-2)} - \sigma_n)(\sigma_n - \sigma_{n-1})(\sigma_{n-1} - \sigma_1)}.$$

In this language, we can construct a bilinear form

$$S[\alpha|\beta] = \prod_{i=2}^{n-2} \left(s_{1,\alpha_i} + \sum_{j=2}^{i-1} \theta(\alpha(j), \alpha(i))_{\beta} s_{\alpha(j),\alpha(i)} \right)$$

where $\alpha, \beta \in S_{n-3}$, $\theta(i, j)_{\beta} = 1$ if the order of i, j is the same in both permutations $\alpha(2, 3, \dots, n-2)$ and $\beta(2, 3, \dots, n-2)$, and 0 otherwise. S is usually called **Momentum Kernel**.

Given any two solutions of scattering equations,

$$\{\sigma_1^{(i)}, \sigma_2^{(i)}, \dots, \sigma_n^{(i)}\} \quad \text{and} \quad \{\sigma_1^{(j)}, \sigma_2^{(j)}, \dots, \sigma_n^{(j)}\}$$

define two vectors, $V(\alpha)^{(i)}$ and $U(\beta)^{(j)}$, i, j are choices of solutions and α, β are the choices of permutations, the number of both is $(n-3)!$.

A natural inner product can be defined as

$$(i, j) := \sum_{\alpha, \beta \in S_{n-3}} V^{(i)}(\alpha) S[\alpha|\beta] U^{(j)}(\beta)$$

Knowing all definitions above, we can proceed to prove KLT orthogonality.

The starting point is to notice that

$$\frac{(i, j)}{(i, i)^{\frac{1}{2}}(j, j)^{\frac{1}{2}}} = \delta_{ij}$$

is clearly invariant under $SL(2, \mathbb{C}) \times SL(2, \mathbb{C})$. Partially fixing both $SL(2, \mathbb{C})$ redundancies with convenient choice $\sigma_{n-1}^{(i)} = \sigma_n^{(j)} = \infty$ and $\sigma_n^{(i)} = \sigma_{n-1}^{(j)} = 1$ and define

$$K_n(\{\sigma\}, \{\sigma'\}) \equiv \sum_{\alpha, \beta \in S_{n-3}} \frac{1}{\sigma_{1, \alpha(2)} \cdots \sigma_{\alpha(n-3), \alpha(n-2)}} S[\alpha|\beta] \frac{1}{\sigma'_{1, \beta(2)} \cdots \sigma'_{\beta(n-3), \beta(n-2)}}$$

The motivation for this definition is that K_n appears in the numerator of KLT orthogonality.

It is also convenient to define an auxiliary co-rank one $(n-2) \times (n-2)$ matrix $\psi^{(n)}$

$$\psi_{ab, a \neq b} = \frac{s_{ab}}{\sigma_{ab} \sigma'_{ab}}, \quad \psi_{aa} = - \sum_{b \neq a} \psi_{ab}, \quad a, b = 1, \dots, n-2$$

It can be proven that any $(n-3) \times (n-3)$ minors of $\psi^{(n)}$ are the same, and we denote such a minor as $\det' \psi^{(n)}$, that is to say, the determinant of the matrix after removing any row and column.

Proposition 3

The two functions defined above are identical up to a sign.

$$K_n(\{\sigma\}, \{\sigma'\}) = (-1)^n \det' \psi^{(n)}$$

The final step is put all pieces together. With the choice $\sigma_{n-1}^{(i)} = \sigma_n^{(j)} = \infty$ and $\sigma_n^{(i)} = \sigma_{n-1}^{(j)} = 1$, we have

$$\frac{(i, j)}{(i, i)^{\frac{1}{2}}(j, j)^{\frac{1}{2}}} = \frac{K_n(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})}{K_n^{\frac{1}{2}}(\{\sigma^{(i)}\}, \{\sigma^{(i)}\})K_n^{\frac{1}{2}}(\{\sigma^{(j)}\}, \{\sigma^{(j)}\})}$$

In addition, one finds that the minor of ψ obtained by removing the first row and column is identical to that of $\Psi(\{\sigma\}, \{\sigma'\})$ after removing rows and columns $\{1, n-1, n\}$. We denote them respectively $|\psi^{(n)}|_1^1$ and $|\Psi|_{1, n-1, n}^{1, n-1, n}$. Then,

$$\begin{aligned} \frac{(i, j)}{(i, i)^{\frac{1}{2}}(j, j)^{\frac{1}{2}}} &= \frac{K_n(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})}{K_n^{\frac{1}{2}}(\{\sigma^{(i)}\}, \{\sigma^{(i)}\})K_n^{\frac{1}{2}}(\{\sigma^{(j)}\}, \{\sigma^{(j)}\})} \\ &= \frac{(-1)^n |\psi^{(n)}|_1^1}{(-1)^n |\psi^{(n)}|_1^{\frac{1}{2}} |\psi^{(n)}|_1^{\frac{1}{2}}} \\ &= \frac{|\Psi(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})|_{1, n-1, n}^{1, n-1, n}}{(|\Psi(\{\sigma^{(i)}\}, \{\sigma^{(i)}\})|_{1, n-1, n}^{1, n-1, n})^{\frac{1}{2}} (|\Psi(\{\sigma^{(j)}\}, \{\sigma^{(j)}\})|_{1, n-1, n}^{1, n-1, n})^{\frac{1}{2}}} \end{aligned}$$

Fianlly, we just need to use Proposition 2.

- If $i = j$, the rank of matrix Ψ is $n - 3$ and the minor is nonzero, we obtain

$$\frac{(i, i)}{(i, i)^{\frac{1}{2}} (i, i)^{\frac{1}{2}}} = \frac{|\Psi(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})|_{1, n-1, n}^{1, n-1, n}}{|\Psi(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})|_{1, n-1, n}^{1, n-1, n}} = 1$$

- If $i \neq j$, the rank of matrix is $n - 4$, so any minor with volume more than $n - 4$ equals 0.

$$|\Psi(\{\sigma^{(i)}\}, \{\sigma^{(j)}\})|_{1, n-1, n}^{1, n-1, n} = 0 \Rightarrow \frac{(i, j)}{(i, i)^{\frac{1}{2}} (j, j)^{\frac{1}{2}}} = 0$$

Up to now, we conclude the proof of KLT orthogonality.

Attempt to construct S-matrix — Towards CHY

Thanks to the excellent properties of scattering equations, it is very tempting to propose that the solutions to scattering equations should be used to construct scattering amplitudes.

The first two constructed are YM and gravity amplitudes in any dimensions

$$M_n^{\text{YM}}(1, 2, \dots, n) = \int \frac{d^n \sigma}{\text{vol SL}(2, \mathbb{C})} \prod_a' \delta \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_{ab}} \right) \frac{E_n(\{k, \epsilon, \sigma\})}{\sigma_{12} \dots \sigma_{n1}},$$
$$M_n^{\text{gravity}} = \int \frac{d^n \sigma}{\text{vol SL}(2, \mathbb{C})} \prod_a' \delta \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_{ab}} \right) E_n(\{k, \epsilon, \sigma\})^2$$

The measure is defined as following

$$\prod_a' \delta \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_{ab}} \right) := \sigma_{ij} \sigma_{jk} \sigma_{ki} \prod_{a \neq i, j, k} \delta \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_{ab}} \right)$$

The reason we extract 3 indices from delta equation is the fact that only $n - 3$ scattering equations are independent. This from can be proved to be **independent of choice of i, j, k** , therefore permutaion invariant. We also have

$$\sigma_a \rightarrow \frac{\alpha\sigma_a + \beta}{\gamma\sigma_a + \delta} : \quad d\mu_n \rightarrow \prod_{a=1}^n (\gamma\sigma_a + \delta)^{-4} d\mu_n$$

$E_n(\{k, \epsilon, \sigma\})$ itself is permutaion invariant with resprct to σ_a, k_a^μ and ϵ_a^μ . The $SL(2, \mathbb{C})$ invariance of amplitude also constraints the form of $E_n(\{k, \epsilon, \sigma\})$

$$\sigma_a \rightarrow \frac{\alpha\sigma_a + \beta}{\gamma\sigma_a + \delta} : \quad E_n(\{k, \epsilon, \sigma\}) \rightarrow E_n(\{k, \epsilon, \sigma\}) \prod_{a=1}^n (\gamma\sigma_a + \delta)^2$$

The form of measure

It is worth to compute the measure explicitly. After "gauge fixing" the $SL(2, \mathbb{C})$ redundancy, one finds

$$\int \prod_{c \neq p, q, r} d\sigma_c (\sigma_{pq} \sigma_{qr} \sigma_{rp}) (\sigma_{ij} \sigma_{jk} \sigma_{ki}) \prod_{a \neq i, j, k} \delta \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_{ab}} \right)$$

The delta functions completely localize all integrals and the answer is evaluating a Jacobian defined above.

$$\Phi_{ab} \equiv \partial \left(\sum_{c \neq a} \frac{s_{ac}}{\sigma_a - \sigma_c} \right) / (\partial \sigma_b) = \begin{cases} \frac{s_{ab}}{(\sigma_a - \sigma_b)^2}, & a \neq b, \\ -\sum_{c \neq a} \Phi_{ac}, & a = b \end{cases}$$

Then, we obtain the measure

$$\sum_{\{\sigma\} \in \text{solutions}} \frac{(\sigma_{pq} \sigma_{qr} \sigma_{rp}) (\sigma_{ij} \sigma_{jk} \sigma_{ki})}{|\Phi|_{pqr}^{ijk}}$$

Always denoted by

$$\det' \Phi := \frac{|\Phi|_{pqr}^{ijk}}{(\sigma_{pq}\sigma_{qr}\sigma_{rp})(\sigma_{ij}\sigma_{jk}\sigma_{ki})}$$

$|\Phi|_{pqr}^{ijk}$ means that we need to delete the rows $\{i, j, k\}$ and the columns $\{p, q, r\}$, of course it is free to choose which index refers to row or column (Φ is a symmetric matrix).

The form of $E_n(\{k, \epsilon, \sigma\})$

In order to present the explicit form of $E_n(\{k, \epsilon, \sigma\})$, first define the following $2n \times 2n$ antisymmetric matrix

$$\Psi = \begin{pmatrix} A & -C^T \\ C & B \end{pmatrix}$$

where A, B and C are $n \times n$ matrices, defined as

$$A_{ab} = \begin{cases} \frac{s_{ab}}{\sigma_a - \sigma_b} & a \neq b, \\ 0 & a = b, \end{cases} \quad B_{ab} = \begin{cases} \frac{\epsilon_a \cdot \epsilon_b}{\sigma_a - \sigma_b} & a \neq b, \\ 0 & a = b, \end{cases}$$

$$C_{ab} = \begin{cases} \frac{\epsilon_a \cdot k_b}{\sigma_a - \sigma_b} & a \neq b, \\ -\sum_{c \neq a} \frac{\epsilon_a \cdot k_c}{\sigma_a - \sigma_c} & a = b. \end{cases}$$

The first important observation is that while the Pfaffian of Ψ is 0, but after removing any rows i, j and columns i, j with $1 \leq i < j \leq n$, the new matrix Ψ_{ij}^{ij} have nonzero Pfaffian and we define the corresponding reduced Pfaffian as

$$\text{Pf}'\Psi := \frac{(-1)^{i+j}}{(\sigma_i - \sigma_j)} \text{Pf}(\Psi_{ij}^{ij})$$

It can be proved that the reduced Pfaffian is invariant under permutation of **particle labels**.

Pfaffian

Pfaffian is defined for antisymmetric matrix, usually in two ways as following



$$\text{Pf}(A)^2 = \det A$$



$$\text{Pf}(A) = \frac{1}{2^n n!} \sum_{\sigma \in S_{2n}} \text{sgn}(\sigma) \prod_{i=1}^n a_{\sigma(2i-1), \sigma(2i)}$$

Write down the proposal

$$E_n(\{k, \epsilon, \sigma\}) = \text{Pf}' \Psi(k, \epsilon, \sigma)$$