

## Black Hole Information Paradox

## Amplitudes 2022 Gong Show

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- We have already seen how Cachazo, He, and Yuan found how to construct  $d$ -dimensional scattering amplitudes from

$$\mathcal{A}(1, \dots, n) = \int d\Omega_{\text{CHY}} \mathcal{I}_L \times \mathcal{I}_R \quad (1)$$

with measure  $d\Omega_{\text{CHY}} = z_{rs}^2 z_{st}^2 z_{tr}^2 \prod_{\substack{i=1 \\ i \neq r, s, t}} dz_i \delta(S_i)$ .

- $S_i$ 's are the scattering equations

$$S_i(z) \equiv \sum_{\substack{j=1 \\ j \neq i}} \frac{2k_i \cdot k_j}{z_i - z_j} = 0, \quad i = 1, \dots, n. \quad (2)$$

- Left and right integrands depend on specific theory, but often contain a Pfaffian.



Can be expanded to include massive particles.

$$E_i(z) \equiv \sum_{\substack{j=1 \\ j \neq i}} \frac{2k_i \cdot k_j + 2\Delta_{ij}}{z_{ij}} = 0, \quad i = 1, \dots, n, \quad (3)$$

with

$$\Delta_{ij} = \Delta_{ji}, \quad \sum_{\substack{i=1 \\ i \neq j}}^n \Delta_{ij} = m_j^2. \quad (4)$$



- Two particles  $m_1 = m_n = m$ .
- Sufficient to consider  $\Delta_{1n} = \Delta_{n1} = m^2$ .
- If Pfaffian is reduced by 1 and  $n$

$$\text{Pf}'_{\text{massive}} \Psi_{1n} = \text{Pf}'_{\text{massless}} \Psi_{1n}. \quad (5)$$



# Color/kinematics duality

## Introduction

- Using double copy in the DDM-basis leads to expansion of CHY Pfaffian

$$\text{Pf}'(\Psi_{1n}) = \sum_{\beta \in S_{n-2}} N(1, \beta, n) \text{PT}(1, \beta, n), \quad (6)$$

- 1 and  $n$  can be massive due to the reduction of the Pfaffian.



# Color/kinematics duality

## Increasing tree algorithm

- Increasing tree algorithm to calculate numerators.
- Need the following quantities for spin one

$$f_i \equiv f_i^{\mu\nu} = p_i^\mu \epsilon_i^\nu - p_i^\nu \epsilon_i^\mu, \quad (7)$$

$$B_{s=1}(1, \rho, n) = \epsilon_1 \cdot f_{\rho(b_1)} \cdot f_{\rho(b_2)} \cdots f_{\rho(b_{|B|})} \cdot \epsilon_n. \quad (8)$$

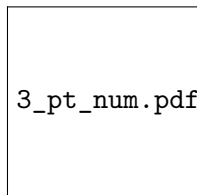
- Rules are most easily shown from example



# Color/kinematics duality

## Increasing tree algorithm

Diagrams contributing to three-point numerator



(9)

The numerator is

$$N_{\{2\}}(1^1, 2^1, 3^1) = -(\epsilon_1 \cdot \epsilon_3)(\epsilon_2 \cdot k_1) + (\epsilon_1 \cdot f_2 \cdot \epsilon_3) \quad (10)$$

