# Black Hole Information Paradox

## Amplitudes 2022 Gong Show

Taro Valentin Brown

Center for Quantum Mathematics and Physics (QMAP), Davis

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# CHY

## Recap

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

$$\mathcal{A}(1,\ldots,n) = \int \mathrm{d}\Omega_{\mathsf{CHY}}\, \mathcal{I}_L \times \mathcal{I}_R \tag{1}$$

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

- $S_i$'s are the scattering equations

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

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

# CHY

## Massive particles

Can be expanded to include massive particles.

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

with

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

# CHY

## Massive particles

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

$$\mathsf{Pf}'_{\mathsf{massive}}\Psi_{1n} = \mathsf{Pf}'_{\mathsf{massless}}\Psi_{1n}. \tag{5}$$

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

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

- $1$ 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

$$f_i \equiv f_i^{\mu\nu} = p_i^{\mu} \epsilon_i^{\nu} - p_i^{\nu} \epsilon_i^{\mu}, \tag{7}$$

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

- Rules are most easily shown from example

Diagrams contributing to three-point numerator

3_pt_num.pdf (9)

The numerator is

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