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Compton Scattering and Kerr Black Holes

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Based on: **2107.14779**

November 22, 2021



Review

Higher Spin Theory

Results

Conclusion



Kerr energy-momentum tensor contracted into on-shell graviton [Vines (2017)]

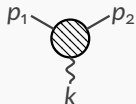
$$\varepsilon_{\mu\nu}(k)T^{\mu\nu}(k) = (\varepsilon_k \cdot p)^2 \exp\left(-i \frac{k_\mu \varepsilon_{k\nu} S^{\mu\nu}}{\varepsilon_k \cdot p}\right)$$



Kerr energy-momentum tensor contracted into on-shell graviton [Vines (2017)]

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Massive spinning three-point amplitude: [Arkani-Hamed, Huang, Huang (2017)]


$$= (\varepsilon_k \cdot p_1)^2 \left(\frac{[12]}{m}\right)^{2S}$$



Kerr energy-momentum tensor contracted into on-shell graviton [Vines (2017)]

$$\varepsilon_{\mu\nu}(k)T^{\mu\nu}(k) = (\varepsilon_k \cdot p)^2 \exp\left(-i \frac{k_\mu \varepsilon_{k\nu} S^{\mu\nu}}{\varepsilon_k \cdot p}\right)$$

Massive spinning three-point amplitude: [Arkani-Hamed, Huang, Huang (2017)]

$$\begin{aligned} \begin{array}{c} p_1 \quad p_2 \\ \diagdown \quad / \\ \text{---} \text{---} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \text{---} \text{---} \\ \text{---} \\ k \end{array} &= (\varepsilon_k \cdot p_1)^2 \left(\frac{[12]}{m}\right)^{2s} \\ &= (\varepsilon_k \cdot p_1)^2 \varepsilon_2^s \cdot \exp\left(-i \frac{k_\mu \varepsilon_{k\nu} \hat{S}^{\mu\nu}}{\varepsilon_k \cdot p}\right) \cdot \varepsilon_1^s \end{aligned}$$

[Guevara, Ochirov, Vines (2018); Huang,...(2018); Guevara, Bautista(2019); ...]



Classical observables in terms of amplitudes: [Bjerrum-Bohr,...; Guevara,...; Haddad,...; Luna,...; ...]

$$\Delta\mathcal{O} \sim \begin{array}{c} \diagup \quad \diagdown \\ \text{shaded circle} \\ \diagdown \quad \diagup \\ \text{wavy line} \\ \diagup \quad \diagdown \\ \text{shaded circle} \\ \diagdown \quad \diagup \end{array} + \begin{array}{c} \diagup \quad \diagdown \\ \text{shaded circle} \quad \text{shaded circle} \\ \diagdown \quad \diagup \\ \text{wavy line} \\ \diagup \quad \diagdown \\ \text{shaded oval} \\ \diagdown \quad \diagup \end{array} + \dots$$



Classical observables in terms of amplitudes: [Bjerrum-Bohr,...; Guevara,...; Haddad,...; Luna,...; ...]

$$\Delta\mathcal{O} \sim \text{[Diagram 1]} + \text{[Diagram 2]} + \dots$$

The diagram shows two terms in a sum. The first term is a shaded circle with two straight external lines on the left and two wavy external lines on the right. The second term is a shaded circle with two straight external lines on the left and two wavy external lines on the right, with a horizontal line connecting the two top vertices.

Compton amplitude needed at NLO. BCFW results: [Arkani-Hamed,...; Johansson,...]

$$\begin{aligned} \text{[Diagram 1]} &= \frac{[4|p_1|3]^{4-2s}([41]\langle 32\rangle + [42]\langle 31\rangle)^{2s}}{s_{12}(s_{13} - m^2)(s_{14} - m^2)} \\ \text{[Diagram 2]} &= \frac{\langle 12\rangle^{2s}[34]^4}{m^{2s-4}s_{12}(s_{13} - m^2)(s_{14} - m^2)} \end{aligned}$$

The diagrams are Feynman diagrams for Compton scattering. The first diagram has external legs labeled 1, 2, 3, 4 with helicities 4+, 3-, 3-, 4+ respectively. The second diagram has external legs labeled 1, 2, 3, 4 with helicities 4+, 3+, 3+, 4+ respectively.



Classical observables in terms of amplitudes: [Bjerrum-Bohr,...; Guevara,...; Haddad,...; Luna,...; ...]

$$\Delta\mathcal{O} \sim \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \diagdown \quad \diagup \\ \text{---} \end{array} + \begin{array}{c} \text{---} \quad \text{---} \\ \diagdown \quad \diagup \\ \text{---} \quad \text{---} \end{array} + \dots$$

Compton amplitude needed at NLO. BCFW results: [Arkani-Hamed,...; Johansson,...]

$$\begin{array}{c} 1 \\ \diagup \quad \diagdown \\ \text{---} \\ \diagdown \quad \diagup \\ 4^+ \quad 3^- \end{array} = \frac{[4|p_1|3]^{4-2s}([41]\langle 32\rangle + [42]\langle 31\rangle)^{2s}}{s_{12}(s_{13} - m^2)(s_{14} - m^2)}$$

$$\begin{array}{c} 1 \\ \diagup \quad \diagdown \\ \text{---} \\ \diagdown \quad \diagup \\ 4^+ \quad 3^+ \end{array} = \frac{\langle 12\rangle^{2s}[34]^4}{m^{2s-4}s_{12}(s_{13} - m^2)(s_{14} - m^2)}$$

Spurious pole appearing for $s > 2$!



Classical observables in terms of amplitudes: [Bjerrum-Bohr,...; Guevara,...; Haddad,...; Luna,...; ...]

$$\Delta\mathcal{O} \sim \text{[Diagram 1]} + \text{[Diagram 2]} + \dots$$

The diagram shows two Feynman diagrams for Compton scattering. The first diagram is a tree-level exchange of a scalar particle between two incoming particles and two outgoing particles. The second diagram is a tree-level exchange of a scalar particle between two incoming particles and two outgoing particles, with a different internal structure.

Compton amplitude needed at NLO. BCFW results: [Arkani-Hamed,...; Johansson,...]

$$\begin{aligned} \text{[Diagram 1]} &= \frac{[4|p_1|3]^{4-2s}([41]\langle 32\rangle + [42]\langle 31\rangle)^{2s}}{s_{12}(s_{13} - m^2)(s_{14} - m^2)} \\ \text{[Diagram 2]} &= \frac{\langle 12\rangle^{2s}[34]^4}{m^{2s-4}s_{12}(s_{13} - m^2)(s_{14} - m^2)} \end{aligned}$$

The diagrams are labeled with external legs 1, 2, 3, and 4. The first diagram has legs 1 and 2 incoming, and 3 and 4 outgoing. The second diagram has legs 1 and 2 incoming, and 3 and 4 outgoing.

Spurious pole appearing for $s > 2$!

Meaning: BCFW does not work for higher spin.



Current constraint

$$P \cdot J = \mathcal{O}(m), \quad J^\mu \equiv \text{diagram}$$

The diagram for J^μ shows a horizontal line with a wavy line attached to its right end. The horizontal line is labeled with P below it. The wavy line is labeled with μ above it. The diagram is enclosed in a light blue rounded rectangle.



Current constraint

$$P \cdot J = \mathcal{O}(m), \quad J^\mu \equiv \text{diagram}$$

The diagram shows a horizontal line representing a particle with momentum P . From its right end, two lines branch out upwards and to the right, and a wavy line extends downwards and to the right, representing a photon emission vertex.

- ▶ Kerr three-point amplitudes fixed uniquely up to $s = 5/2$.



Current constraint

$$P \cdot J = \mathcal{O}(m), \quad J^\mu \equiv \text{diagram}$$

The diagram shows a horizontal line with a wavy line extending downwards from its right end. A double line extends upwards and to the right from the same vertex. The label P is positioned below the horizontal line, and the label μ is positioned above the vertex.

- ▶ Kerr three-point amplitudes fixed uniquely up to $s = 5/2$.
- ▶ Four-point contact terms partially fixed. Physically-motivated constraints fix the leftover ambiguity.



Current constraint

$$P \cdot J = \mathcal{O}(m), \quad J^\mu \equiv \text{diagram}$$

The diagram shows a horizontal line with a wavy line extending downwards from its right end. A double line extends upwards from the right end of the horizontal line. The label μ is placed above the horizontal line, and the label P is placed below it.

- ▶ Kerr three-point amplitudes fixed uniquely up to $s = 5/2$.
- ▶ Four-point contact terms partially fixed. Physically-motivated constraints fix the leftover ambiguity.
- ▶ Unique Compton up to $s = 5/2$:

$$\frac{[41]\langle 32 \rangle + [42]\langle 31 \rangle}{[4|p_1|3]} \left(\frac{([41]\langle 32 \rangle + [42]\langle 31 \rangle)^4}{s_{12}(s_{13} - m^2)(s_{14} - m^2)} - \frac{([14][24]\langle 13 \rangle \langle 23 \rangle)^2}{m^6} \right).$$



Current constraint

$$P \cdot J = \mathcal{O}(m), \quad J^\mu \equiv \text{diagram}$$

The diagram shows a horizontal line representing a particle with momentum P . From the right end of this line, two lines branch out upwards and to the right, and a wavy line extends downwards and to the right, representing a photon.

- ▶ Kerr three-point amplitudes fixed uniquely up to $s = 5/2$.
- ▶ Four-point contact terms partially fixed. Physically-motivated constraints fix the leftover ambiguity.
- ▶ Unique Compton up to $s = 5/2$:

$$\frac{[41]\langle 32 \rangle + [42]\langle 31 \rangle}{[4|p_1|3]} \left(\frac{([41]\langle 32 \rangle + [42]\langle 31 \rangle)^4}{s_{12}(s_{13} - m^2)(s_{14} - m^2)} - \frac{([14][24]\langle 13 \rangle \langle 23 \rangle)^2}{m^6} \right).$$

- ▶ **Caveat:** Not a proof that this will match Kerr, need explicit checks.

Higher Spin Theory

Example: $s = 1$ gauge



Massive spin-1 field coupled to photon:

$$\mathcal{L} = 2D_{[\mu}\bar{W}_{\nu]}D^{[\mu}W^{\nu]} - m^2\bar{W}_\mu W^\mu + ie\alpha F_{\mu\nu}\bar{W}^\mu W^\nu$$



Massive spin-1 field coupled to photon:

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Compton Ingredients

Three-point current (P off-shell, p_1 and k on-shell; $f_k \equiv k\varepsilon_k - \varepsilon_k k$):

$$J(P, p_1, k) = \varepsilon_P \cdot \varepsilon_1 \varepsilon_k \cdot (p_1 - P) - \varepsilon_1 \cdot \varepsilon_k \varepsilon_P \cdot p_1 + \varepsilon_k \cdot \varepsilon_P \varepsilon_1 \cdot P - \alpha f_k^{\mu\nu} \varepsilon_{1\mu} \varepsilon_{P\nu}$$

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Spin-1 propagator:

$$\Delta_{\mu\nu}(P) = \frac{1}{P^2 - m^2} \left(\eta_{\mu\nu} - \frac{P_\mu P_\nu}{m^2} \right)$$



Massive spin-1 field coupled to photon:

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Compton amplitude **diverges** in the $P/m \rightarrow \infty$ limit, unless $P \cdot J = \mathcal{O}(m)$

$$\Rightarrow \alpha = 1$$



Massive spin-1 field coupled to photon:

$$\mathcal{L} = 2D_{[\mu}\bar{W}_{\nu]}D^{[\mu}W^{\nu]} - m^2\bar{W}_\mu W^\mu + ie\alpha F_{\mu\nu}\bar{W}^\mu W^\nu$$

Compton Ingredients

Three-point current (P off-shell, p_1 and k on-shell; $f_k \equiv k\varepsilon_k - \varepsilon_k k$):

$$J(P, p_1, k) = \varepsilon_P \cdot \varepsilon_1 \varepsilon_k \cdot (p_1 - P) - \varepsilon_1 \cdot \varepsilon_k \varepsilon_P \cdot p_1 + \varepsilon_k \cdot \varepsilon_P \varepsilon_1 \cdot P - \alpha f_k^{\mu\nu} \varepsilon_{1\mu} \varepsilon_{P\nu}$$

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Compton amplitude **diverges** in the $P/m \rightarrow \infty$ limit, unless $P \cdot J = \mathcal{O}(m)$

$$\Rightarrow \alpha = 1$$

Kerr three-point and Compton matched!

Higher Spin Theory

$s = 3/2$ gauge



Massive spin-3/2 field coupled to photon:

$$\mathcal{L} = \bar{\psi}^\mu \gamma_{\mu\nu\rho} \left(iD^\nu - \frac{1}{2} m \gamma^\nu \right) \psi^\rho - \frac{ie}{m} \left(l_1 \bar{\psi}_\mu F^{\mu\nu} \psi_\nu + l_2 \bar{\psi}_\mu F_{\rho\sigma} \gamma^\rho \gamma^\sigma \psi^\mu \right. \\ \left. + l_3 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi + \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) + l_4 \bar{\psi} \cdot \gamma F_{\rho\sigma} \gamma^\rho \gamma^\sigma \gamma \cdot \psi + i l_5 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi - \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) \right)$$



Massive spin-3/2 field coupled to photon:

$$\mathcal{L} = \bar{\psi}^\mu \gamma_{\mu\nu\rho} \left(iD^\nu - \frac{1}{2} m \gamma^\nu \right) \psi^\rho - \frac{ie}{m} \left(I_1 \bar{\psi}_\mu F^{\mu\nu} \psi_\nu + I_2 \bar{\psi}_\mu F_{\rho\sigma} \gamma^\rho \gamma^\sigma \psi^\mu \right. \\ \left. + I_3 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi + \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) + I_4 \bar{\psi} \cdot \gamma F_{\rho\sigma} \gamma^\rho \gamma^\sigma \gamma \cdot \psi + i I_5 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi - \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) \right)$$

Spin-3/2 propagator:

$$\Delta^{\mu\nu}(P) \sim \left(\eta^{\mu\nu} - \frac{P^\mu P^\nu}{m^2} \right) (\not{P} + m) + \frac{1}{3} \left(\frac{P^\mu}{m} + \gamma^\mu \right) (\not{P} - m) \left(\frac{P^\nu}{m} + \gamma^\nu \right)$$



Massive spin-3/2 field coupled to photon:

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Impose current constraint

$$P \cdot J = \mathcal{O}(m) \Rightarrow l_1 = -2, l_2 = 1/2, l_3 = 1, l_5 = 0$$



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Impose current constraint

$$P \cdot J = \mathcal{O}(m) \Rightarrow l_1 = -2, l_2 = 1/2, l_3 = 1, l_5 = 0$$

Note: l_3 and l_5 are four-point contact terms, since $\gamma \cdot \psi = 0$ on-shell.



Massive spin-3/2 field coupled to photon:

$$\mathcal{L} = \bar{\psi}^\mu \gamma_{\mu\nu\rho} \left(iD^\nu - \frac{1}{2} m \gamma^\nu \right) \psi^\rho - \frac{ie}{m} \left(l_1 \bar{\psi}_\mu F^{\mu\nu} \psi_\nu + l_2 \bar{\psi}_\mu F_{\rho\sigma} \gamma^\rho \gamma^\sigma \psi^\mu \right. \\ \left. + l_3 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi + \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) + l_4 \bar{\psi} \cdot \gamma F_{\rho\sigma} \gamma^\rho \gamma^\sigma \gamma \cdot \psi + i l_5 F^{\mu\nu} (\bar{\psi}_\mu \gamma_\nu \gamma \cdot \psi - \bar{\psi} \cdot \gamma \gamma_\mu \psi_\nu) \right)$$

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Note: l_3 and l_5 are four-point contact terms, since $\gamma \cdot \psi = 0$ on-shell.

Kerr three-point matched!

Higher Spin Theory

$s = 3/2$ gauge



Leftover ambiguity:

- ▶ F^2 contact terms: $m^{-3}F_{\mu\nu}F^{\mu\nu}\bar{\psi}^{\mu}\psi_{\mu}$, etc

Higher Spin Theory

$s = 3/2$ gauge



Leftover ambiguity:

- ▶ F^2 contact terms: $m^{-3}F_{\mu\nu}F^{\mu\nu}\bar{\psi}^\mu\psi_\mu$, etc
- ▶ Higher-derivative terms that trivially satisfy the current constraint:
 $m^{-3}D_{[\mu}\bar{\psi}_{\nu]}D^{[\mu}\psi^{\rho]}F_\rho^\nu$

Higher Spin Theory

$s = 3/2$ gauge



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- ▶ Higher-derivative terms that trivially satisfy the current constraint:
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These can appear also in lower spin theories.

Higher Spin Theory

$s = 3/2$ gauge



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Solutions:

Higher Spin Theory

$s = 3/2$ gauge



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These can appear also in lower spin theories.

Solutions:

- ▶ Look for the lowest-derivative solution to the current constraint.

Higher Spin Theory

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These can appear also in lower spin theories.

Solutions:

- ▶ Look for the lowest-derivative solution to the current constraint.
- ▶ Require the smallest divergence possible in the $p_i/m \rightarrow \infty$ limit.

Higher Spin Theory

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Leftover ambiguity:

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- ▶ Look for the lowest-derivative solution to the current constraint.
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Outcome: either approach singles out the Lagrangian shown previously as the only solution!

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- ▶ Known same-helicity Compton reproduced.



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These can appear also in lower spin theories.

Solutions:

- ▶ Look for the lowest-derivative solution to the current constraint.
- ▶ Require the smallest divergence possible in the $p_i/m \rightarrow \infty$ limit.

Outcome: either approach singles out the Lagrangian shown previously as the only solution!

- ▶ Known same-helicity Compton reproduced.
- ▶ New, spurious-pole-free opposite-helicity expression computed.



Spin-3/2 Gauge Theory

$$\mathcal{L} = \mathcal{L}_{min} + \bar{\psi}_\mu \left(F^{\mu\nu} - \frac{i}{2} \gamma_5 \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \right) \psi_\nu$$

$$\mathcal{A}_4 = \frac{[41]\langle 32 \rangle + [42]\langle 31 \rangle}{[4|p_1|3]} \left(\frac{([41]\langle 32 \rangle + [42]\langle 31 \rangle)^2}{(s_{13} - m^2)(s_{14} - m^2)} - \frac{[14][24]\langle 13 \rangle \langle 23 \rangle}{m^4} \right)$$



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Spin-5/2 Gravity

$$\mathcal{L} = \mathcal{L}_{min} + \bar{\psi}_{\mu\rho} \left(R^{\mu\nu\rho\sigma} - \frac{i}{2} \gamma_5 \epsilon^{\rho\sigma\alpha\beta} R^{\mu\nu}_{\alpha\beta} \right) \psi_{\nu\sigma}$$

$$\mathcal{M}_4 = \frac{[41]\langle 32 \rangle + [42]\langle 31 \rangle}{[4|p_1|3]} \left(\frac{([41]\langle 32 \rangle + [42]\langle 31 \rangle)^4}{s_{12}(s_{13} - m^2)(s_{14} - m^2)} - \frac{([14][24]\langle 13 \rangle \langle 23 \rangle)^2}{m^6} \right)$$



Summary

- ▶ Current constraint \Rightarrow Kerr three-point amplitude up to spin-5/2



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- ▶ Current constraint + special high-energy properties \Rightarrow unique Compton amplitude up to spin-5/2



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Outlook



Summary

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- ▶ Classical limit: check agreement with Kerr observables (e.g. Teukolski equation)
- ▶ Beyond spin-5/2: current constraint and derivative counting are not enough to fix the answer uniquely
- ▶ Compare to other theories that satisfy high-energy unitarity (e.g. strings)

The image features a complex, multi-layered spiral pattern that resembles a galaxy or a nebula. The pattern is composed of numerous concentric, slightly irregular rings that spiral inward from the edges towards the center. The color palette is primarily light blue and grey, with a soft, ethereal glow. In the very center of the spiral, there are two bright, glowing yellow spheres, one slightly above and to the right of the other, which serve as a focal point. Overlaid on the lower-middle portion of the spiral is the text "Thank you!" in a bold, black, sans-serif font. The overall composition is balanced and visually appealing, with a sense of depth and movement.