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Compton Scattering and Kerr Black Holes

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Content

Review: Three-point

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

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

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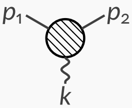

$$= (\varepsilon_k \cdot p_1)^2 \left(\frac{[12]}{m}\right)^{2s}$$

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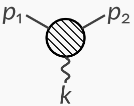


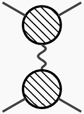
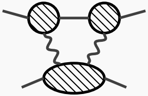
$$= (\varepsilon_k \cdot p_1)^2 \left(\frac{[12]}{m}\right)^{2s}$$

$$= (\varepsilon_k \cdot p_1)^2 \varepsilon_2^s \cdot \exp\left(-i\frac{k_\mu \varepsilon_{k\nu} \hat{S}^{\mu\nu}}{\varepsilon_k \cdot p}\right) \cdot \varepsilon_1^s$$

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

Review: Compton

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

$\Delta\mathcal{O} \sim$  $+$  $+ \dots$

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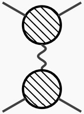
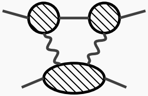


$$+$$



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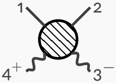
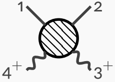
Compton amplitude needed at NLO. BCFW results: [Arkani-Hamed,...;Johansson,...]



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



$$= \frac{\langle 12\rangle^{2s}[34]^4}{m^{2s-4}s_{12}(s_{13}-m^2)(s_{14}-m^2)}$$

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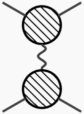
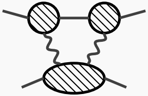
$\Delta\mathcal{O} \sim$  $+$  $+ \dots$

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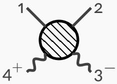

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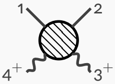

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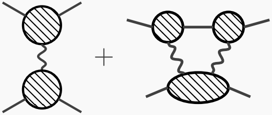

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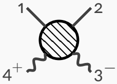

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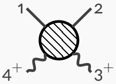

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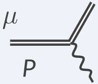
Meaning: BCFW does not work for higher spin.

Results (Preview)

Current constraint

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



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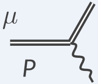

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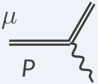

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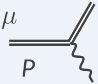

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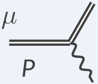

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- **Caveat:** Not a proof that this will match Kerr, need explicit checks.

Higher Spin Theory

Example: s = 1 gauge

Massive spin-1 field coupled to photon:

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

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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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Kerr three-point and Compton matched!

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s = 3/2 gauge

Massive spin-$3/2$ field coupled to photon:

$$\mathcal{L} = \bar{\psi}^{\mu}\gamma_{\mu\nu\rho}\left(iD^{\nu} - \frac{1}{2}m\gamma^{\nu}\right)\psi^{\rho} - \frac{ie}{m}\Big(l_1\bar{\psi}_{\mu}F^{\mu\nu}\psi_{\nu} + l_2\bar{\psi}_{\mu}F_{\rho\sigma}\gamma^{\rho}\gamma^{\sigma}\psi^{\mu}$$
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Spin-3/2 propagator:

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These can appear also in lower spin theories.

Higher Spin Theory

s = 3/2 gauge

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Higher Spin Theory

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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.

# 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: $m^{-3}D_{[\mu}\bar{\psi}_{\nu]}D^{[\mu}\psi^{\rho]}F^{\nu}_{\rho}$

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 $p_i/m \to \infty$ 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.

Results

Spin-3/2 Gauge Theory

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

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

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Spin-5/2 Gravity

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

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

Conclusion

Summary

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- Classical limit: check agreement with Kerr observables (e.g. Teukolski equation)

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

Outlook

- 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)

Thank you!