A Universal Bound on the Strong Coupling Scale of a Gravitationally Coupled Massive Spin-2 Particle

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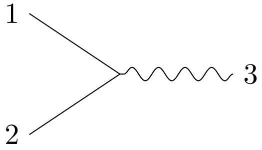
Universal gravitational interactions

S-matrix equivalence principle

- Every particle that interacts with Einstein gravity must have a minimal coupling vertex with a universal coupling constant Weinberg:

$$\mathcal{V}_{\text{cubic}} = \frac{2i}{M_p} \left(\epsilon_3 \cdot p_1\right)^2 \left(\epsilon_1 \cdot \epsilon_2\right)^s .$$

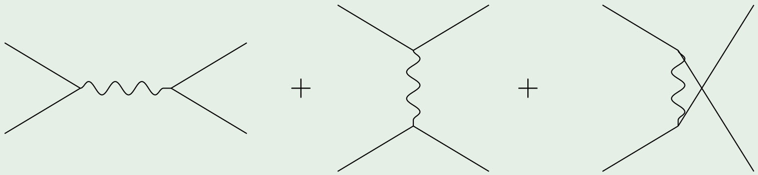


Low spin particles

Simple scalar example

- Consider a scalar minimally coupled to gravity,

$$S = \frac{1}{2} \int d^4x \sqrt{-g} \left(M_p^2 R - \partial_\mu \phi \partial^\mu \phi - m^2 \phi^2 \right).$$



- For $E \gg m$, the four-point amplitude is

$$\mathcal{A} = \frac{1}{4M_p^2} \frac{\left(\mathbf{s}^2 + \mathbf{t}^2 + \mathbf{u}^2\right)^2}{\mathbf{stu}}.$$

Massless higher-spin particles

- For massless particles with $s > 2$, the S-matrix equivalence principle is incompatible with gauge invariance:

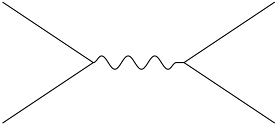
$$p_1 \cdot \frac{\partial}{\partial \epsilon_1} \left(\frac{2}{M_p} \left(\epsilon_3 \cdot p_1\right)^2 \left(\epsilon_1 \cdot \epsilon_2\right)^s + \ldots \right) \neq 0.$$

No-go result

Massless higher-spin particles cannot couple directly or indirectly to Einstein gravity in flat spacetime.

Massive higher-spin particles

- Massive higher-spin particles can couple to gravity, e.g. QCD and string theory.
- However, isolated massive particles with $m \ll M_p$ and $s > 1$ cannot remain fundamental point-like particles up to M_p.



$$\sim \quad \frac{E^{2k}}{M_p^2 m^{2k-2}}$$

- The local effective field theory violates perturbative unitarity at some scale $\Lambda_k \equiv \left(m^{k-1} M_p\right)^{1/k} \ll M_p$.
- Contact terms can partially cancel the bad high-energy behaviour and raise the strong coupling scale.

Bounding the strong coupling scale

- How large can Λ_k be for a given spectrum of particles?

Strategy:

1. Classify all cubic and quartic vertices
2. Construct the general four-point amplitude consistent with locality, unitarity, Lorentz invariance, gauge invariance, and crossing symmetry.
3. Find the amplitude with the highest strong coupling scale.

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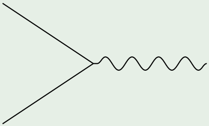
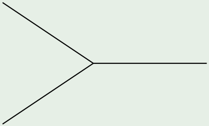
- Here we look at massive spin 2 coupled to gravity.

Example

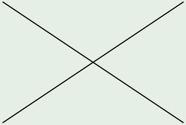
Classifying spin-2 vertices



5 structures,



4 structures,



95 structures.

RESULTS

- The highest strong coupling scale for a unitary gravitationally coupled massive spin-2 particle is $\Lambda_3 = \left(m^2 M_p\right)^{1/3}$.

IMPLICATIONS

- Lower bound on the mass of an isolated light massive spin-2 particle: if $\Lambda_3 \gtrsim 10^{-3}\,\mathrm{eV}$ then $m \gtrsim 10^{-18}\,\mathrm{eV}$.
- Large-N QCD: if the lightest glueball has spin 2, then the next lightest state cannot be heavier than Λ_3.

Examples

Λ_3 theories: saturating the bound

- Ghost-free bigravity Hassan & Rosen, a generalization of ghost-free massive gravity de Rham, Gabadadze, & Tolley.
- A gravitationally coupled pseudotensor—no known theory. Uses two-derivative parity-odd vertex and exists only in $4d$.
- Pseudo-linear theory with massive and massless spin-2 particles (no gravity) JB, Hinterbichler, & Johnson.

Examples

M_p theory

- If we allow imaginary cubic couplings, i.e. ghosts, then the maximum strong coupling scale is M_p.
- The unique amplitude is generated by quadratic curvature gravity,

$$S = M_p^2 \int d^4x \, \sqrt{-g} \left(\frac{1}{2} R + \frac{1}{4m^2} C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} \right).$$

- This amplitude is also contained in the bigravity amplitude Paulos & Tolley.

Higher-spin generalisation

- Porrati & Rahman: for a charged massive spin-s particle the strong coupling scale satisfies

$$\Lambda \leq \frac{m}{q^{1/(2s-1)}}.$$

- Assume the lightest state satisfies the weak gravity conjecture:

$$q \geq \frac{m}{M_p} \implies \Lambda \leq \left(m^{2s-2} M_p\right)^{1/(2s-1)}.$$

Conjecture

The maximum strong coupling scale for a gravitationally coupled massive spin-s particle is Λ_{2s-1} Rahman.

- This is true for $s \in \{1, \frac{3}{2}, 2\}$.

Conclusions

- Effective field theories of gravitationally coupled massive higher-spin particles can exist, but they have low strong coupling scales.
- For spin-s, the maximum strong coupling scale is conjectured to be Λ_{2s-1}.
- We have proven this for $s = 2$ by studying the four-point scattering of massive particles with graviton exchange.

Future directions

Open question

- Can we raise the cutoff to M_p by adding a finite number of additional particles?

- This works for $s = \frac{3}{2}$, e.g. addition of scalar and pseudoscalar gives broken $\mathcal{N} = 1$ supergravity.
- For $s = 2$, we can get to $\Lambda_{3/2} = \left(m M_p^2\right)^{1/3}$ with a Kaluza-Klein reduction of $5d$ gravity.