Title: The Calculus of Observables in Perturbative Quantum Gravity

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Abstract:

Spacetime fluctuations can invalidate usual notions of distance, time, and even what it means to perform an experiment. This raises a simple question: when spacetime fluctuates, how do we describe what happens? Few detailed answers exist, even in the low-energy effective field theory of quantum gravity. In this talk, we present a study of geometric and detector observables in perturbative quantum gravity. Geometric observables—elapsed proper time, proper distance, area, and Shapiro time delay—can be defined in relation to observer worldlines. Proper time observables capture quantum gravity effects in interferometers, leading to predictions for experiments that probe the interface between quantum mechanics and gravity. Several geometric observables display a quantum version of memory. Realistic detector observables—modelled by local operators inserted along worldlines—describe measurements more directly. We compute correlators of worldline-dressed scalars at tree level with an external on-shell graviton. The worldline dressing is hardly innocuous and can, in fact, induce enormous corrections. Gravitational effects can either open or close light cones, as captured by the commutator of dressed scalars. Finally, we discuss the broader landscape of observables now within closer reach in effective field theory and holography.

The Calculus of Observables in Perturbative Quantum Gravity

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January 8, 2026

Based mainly on
2409.03894: Carney, Karydas, AS
2506.16109: AS
To appear: Daniel Carney, Manthos Karydas, Murat Kologlu , AS
Clifford Cheung, AS, Jordan Wilson-Gerow, Lihang Zhou

Observables in Quantum Gravity

- Physics on a fixed background described by geometry (time, distance, subregions) and detectors (correlators of quantum fields, currents). When spacetime fluctuates, how do we describe what happens?

- Low-energy EFT of quantum gravity: metric perturbations quantized via usual QFT rules

- Observables are generically metric-valued, therefore depend on spacetime fluctuations

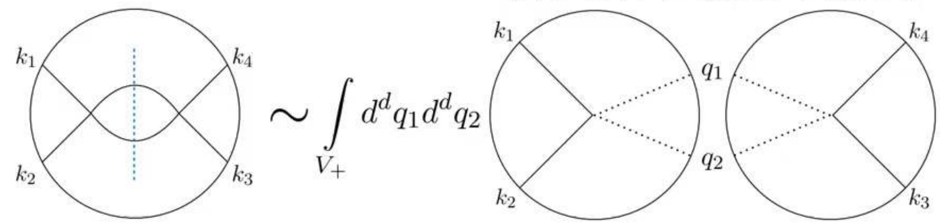
- This talk: a general approach to constructing, computing observables
  - Define fully relativistic observables using path integrals and worldline dressing
  - Compute correlators of times, distances, and scalars; learn properties of QG

- Some EFT observables have been proposed, fairly unexplored via computation. (But see work by Donnelly, Giddings, Perkins, Frob…)

Prologue: many tools for correlators

- Optical theorem: $2\ \mathrm{Im}(\mathcal{T}) = \mathcal{T}^\dagger \mathcal{T}$

$$2\ \mathrm{Re}\,\langle T[\phi(k_1)\phi(k_2)\phi(k_3)\phi(k_4)]\rangle = \langle \overline{T}[\phi(k_3)\phi(k_4)]T[\phi(k_1)\phi(k_2)]\rangle$$
$$= \langle [\phi(k_3),\phi(k_4)]_A[\phi(k_1),\phi(k_2)]_R\rangle$$



Meltzer, AS

Off-shell (Feynman) propagators: $\Box_x G_F(x,y) = \delta^{(d)}(x,y)$ Minkowski: $G_F(x,0) = \langle T[\phi(x)\phi(0)]\rangle = \int d^d k\ \frac{-i}{k^2+m^2-i\epsilon} e^{ik\cdot x}$
On-shell (Wightman) functions: $\Box_x G^\pm(x,y) = 0$ Minkowski: $G^\pm(x,0) = \langle \phi(\pm x)\phi(0)\rangle = \int d^d k\ 2\pi\theta(\pm k^0)\delta(k^2+m^2)e^{ik\cdot x}$

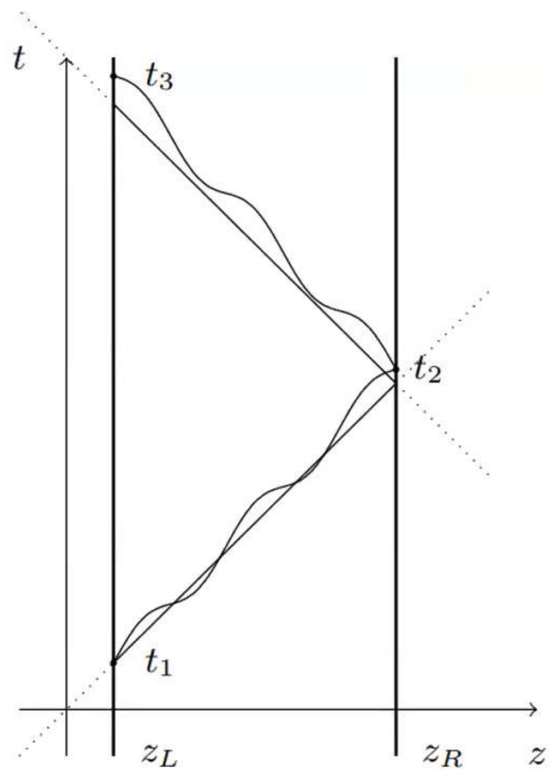
- Unitarity and on-shell kinematics. Tested in AdS/CFT, implements color-kinematics duality in curved space. **Comfortably compute correlators**

  Caron-Huot; Alday and Caron-Huot; Simmons-Duffin, Stanford, Witten; Perlmutter, Meltzer, AS; Meltzer, AS; Cheung, Parra-Martinez, AS; Diwakar, Herderschee, Roiban, Teng; Herderschee, Roiban, Teng

Worldline Model of Observer

- Endpoints?
- Quantum or classical observer?
- Measurements invariant under (which?) diffs?
- **Many observables in theory & experiment are worldline observables: directly connect measurement to conceptual features of QG**
- **Will study geometric, detector observables**

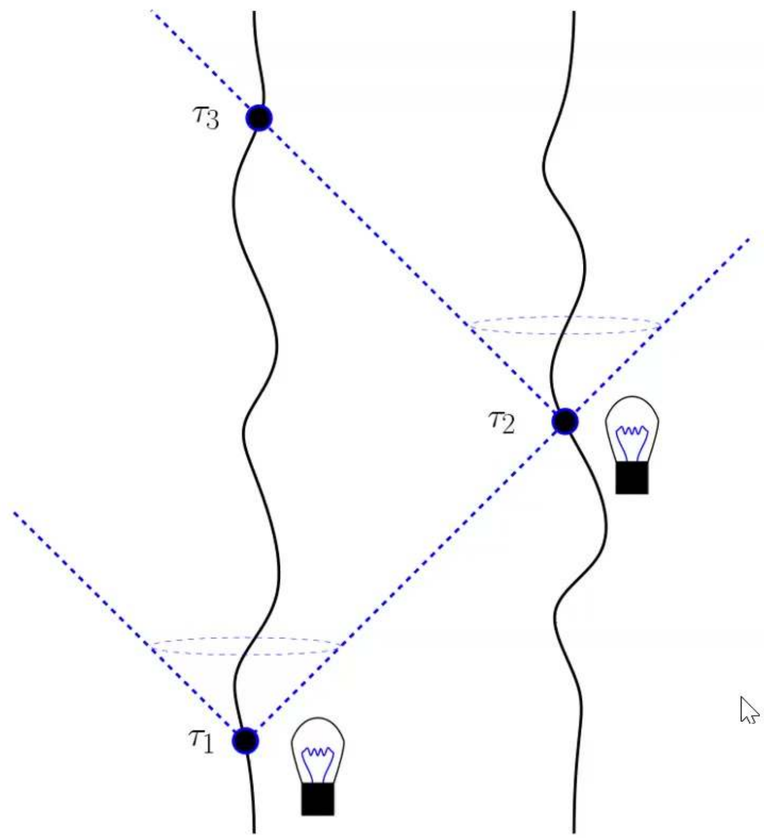
Idealized interferometer



- To understand experimental results, consult theory. To understand theory, consult experimental results.
- Worldlines separated by L
- Phase is $\varphi = 2L/\lambda = \tau\omega_\ell/2\pi$
- Experiment measures $\langle\varphi(t_1)\varphi(0)\rangle$
- Let's study $\langle\tau(t_1)\tau(0)\rangle$
- Good place to start: is an experiment that gives an operational meaning to distance and/or time
- For our approach, we'll also need the curved space generalization, which is less clear

Carney, Karydas, AS

A "lightbulb" clock in curved space: diff-invariantly specify worldline segments



AS

Proper Time Correlator

- Compute $\tau_3(\tau_1)$ in synchronous gauge for off-shell *h*

$$ds^2 = -dt^2 + (\delta_{ij} + h_{ij})dx^i dx^j, \qquad h^{0\mu} = 0$$

$$\tau(t_1) = 2L + \frac{1}{2}\int_{t_1}^{t_1+2L} dt\, h_{zz}(t, z(t)) + O(h^2)$$

- The approach: compute off shell, then perform path integral

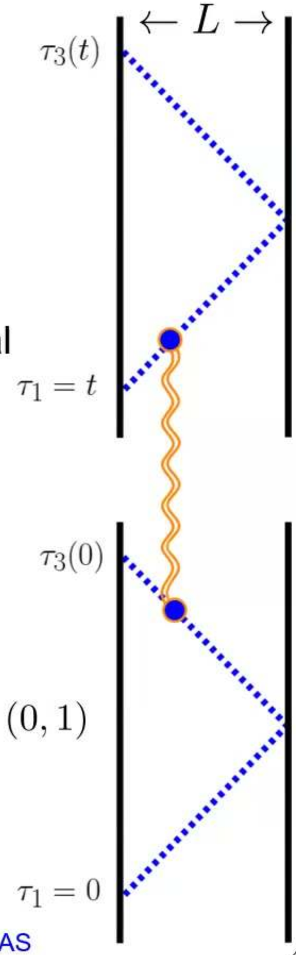
$$\boxed{\langle \tau_3(\tau_1)\tau_3(\tau_1')\rangle = \int \mathcal{D}[h]\tau_3(\tau_1, h)\tau_3(\tau_1', h)e^{-iS[h]}}$$

$$\langle \tau(t)\tau(0)\rangle_c = \frac{1}{4}\int_t^{t+2L} dt' \int_0^{2L} dt'' \, \langle h_{zz}(t', z(t'))h_{zz}(t'', z(t''))\rangle_c$$

$$\langle[\tau(t), \tau(0)]\rangle = -i\frac{8}{3}G_N(3 - 12u + 18u^2 - 8u^3), \quad u = t/2L \in (0, 1)$$

- For arrival time, specify τ_2. Exact synchronization fails!

$$\langle[\tau_3(t), \tau_3(0)]\rangle = i\frac{16G_N}{3}(u-1)^3$$



Carney, Karydas, AS; AS

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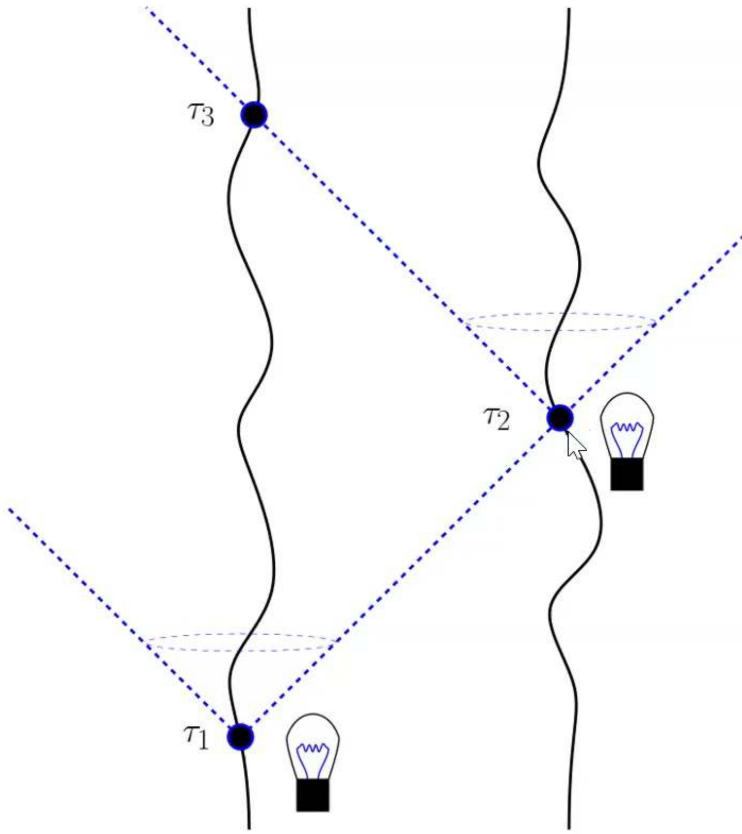
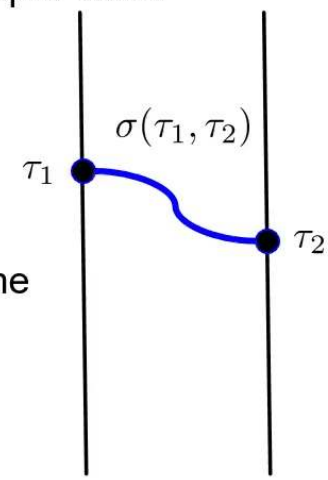


AS

Proper distance

- Geodesic length between two geodesics at specified proper times

$$\langle \sigma(t,t)\sigma(0,0)\rangle_c = \frac{1}{4}\int d\lambda d\lambda' \, \langle h_{zz}(t,\lambda)h_{zz}(0,\lambda')\rangle$$



- Distance fails to commute, and is not equal to proper time

$$\langle [\sigma(t,t), \sigma(0,0)]\rangle = \frac{i\pi^2 G_N (L-t)^3(3L+t)}{3L^3 t}$$

- Reproduces PSD of observable in realistic interferometer setup with standing waves in a cavity. But to clarify, need to better understand the classical observable for arbitrarily high frequency gravitational waves

Carney, Karydas, Kologlu, AS

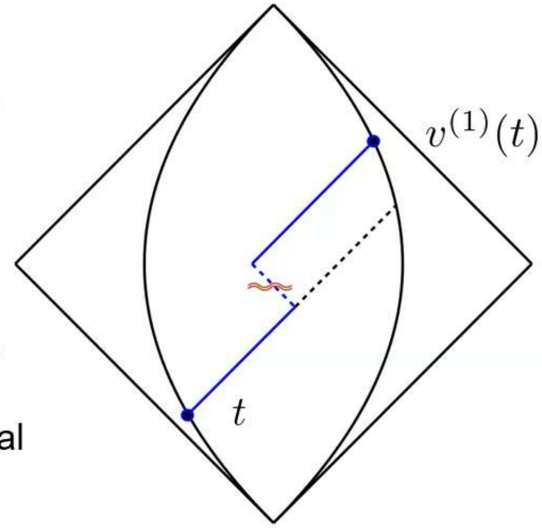
Shapiro time delay, IR divergences, memory

- Arrival time in large-L limit gives limiting definition of Shapiro time delay $v^{(1)}$, which is actually a proper time delay

- Two-point function of arrival time is IR divergent

$$\langle v^{(1)}(t)v^{(1)}(0)\rangle_c(\Lambda) = it\Lambda + \log(t\Lambda) + \text{finite}$$

- However, only elapsed or differences in arrival times are observable, whose two-point functions are indeed IR finite.



$$\left\langle \left(v^{(1)}(t+T) - v^{(1)}(t)\right)\left(v^{(1)}(T) - v^{(1)}(0)\right)\right\rangle_c = 2i\pi - 4\log T + 2\log(T^2 - t^2)$$

- Classically, memory captured by e.g. $\sigma_m(T,0) = \sigma(T,T) - \sigma(0,0), \quad T \to \infty$
- Vacuum fluctuations provide a **quantum analogue of memory** e.g.

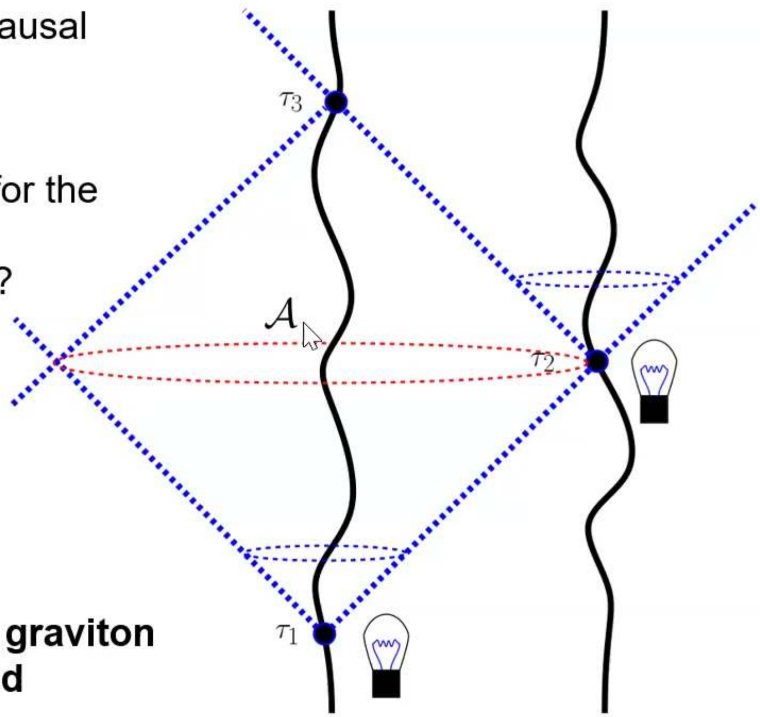
$$\lim_{T/t\to\infty} \langle \sigma_m(T+t,t)\sigma_m(T,0)\rangle_c \approx 2\langle \sigma(t,t)\sigma(0,0)\rangle_c \neq 0.$$

Carney, Karydas, Kologlu, AS

Area fluctuations of the corner

- Lightbulb clock defines a causal diamond, subregion
- What is the area operator for the corner? Are subregions perturbatively well-defined?
- Can compute!
- Also $\langle \mathcal{A}(\tau_1)\mathcal{A}(\tau_1')\rangle$
- **Area operator crucial for graviton corrections to generalized entropy; currently murky**

Colin-Ellerin, Lin, Penington



WIP: Chen and AS

Detector observables at finite distance: why we need dressing

- Local fields defined naively using coordinates aren't diff-invariant

$$\phi(x) \to \phi(f(x))$$

- By analogy with gauge theory, fields transform nontrivially under gauge transformation, and x is like an uncontracted index

- What goes wrong? Consider a matrix element with an (off-shell) bulk leg,

$$\langle 0|\phi(p_1)|\phi(p_2)h(p_3)\rangle = -\frac{\epsilon_{3\mu\nu}p_1^\mu p_2^\nu}{p_1^2}\delta^{(D)}(p_1+p_2+p_3)$$

- To make sense, must be invariant under diffeomorphism,

$$\epsilon_3^{\mu\nu} \to \epsilon_3^{\mu\nu} + p_3^\mu \xi^\nu + p_3^\nu \xi^\mu, \qquad p_3 \cdot \xi = 0$$

$$\langle 0|\phi(p_1)|\phi(p_2)h(p_3)\rangle \to \langle 0|\phi(p_1)|\phi(p_2)h(p_3)\rangle - p_1 \cdot \xi$$

- Not invariant unless first operator is soft/fully smeared, $p_1 = 0$

Cheung, AS, Wilson-Gerow, Zhou

Relational/dressed observables

- Resolution: define operators in relation to (or dressed to) something else in the system: asymptotic boundary, values of clock/ruler field, **proper time along geodesics:**

$$\Phi(x_i) = \phi(x_i(\tau_i)), \qquad \ddot{x}_i^\mu + \Gamma^\mu_{\rho\sigma}\dot{x}_i^\rho \dot{x}_i^\sigma = 0$$

- Insertion location is now metric-dependent but diffeomorphism invariant. Fields now manifestly diff invariant. Proper time earlier was dynamical and a metric-valued operator, while here is a specified number

- Matrix elements with external gravitons aren't manifestly diff invariant, so are a more non-trivial check of "relationality implies diff invariance".

$$\langle\Omega|\phi(x_1)\phi(x_2)|h(k)\rangle = -i\kappa \int \frac{d^4p_1}{(2\pi)^4}\frac{d^4p_2}{(2\pi)^4}\, e^{-ip_1x_1}e^{-ip_2x_2}\,\frac{(p_1\epsilon p_2)}{p_1^2p_2^2}\,\delta(p_1+p_2-k)$$

Cheung, AS, Wilson-Gerow, Zhou

Dressed matrix element

- Upon dressing, x now depends on h, which generates additional terms when we perform a diff. These fix diff invariance
- Solving the geodesic equation perturbatively, keeping τ_i implicit,

$$x_i = x_i^{(0)} + x_i^{(1)} + \mathcal{O}(h^2)$$

- To leading order in h,

$$\langle\Omega|\Phi(x_1)\Phi(x_2)|h^{\mu\nu}(k)\rangle$$
$$= \int \frac{d^dp_1}{(2\pi)^d} \int \frac{d^dp_2}{(2\pi)^d} \langle\Omega|e^{-i(x_1^{(0)}+x_1^{(1)})p_1 - i(x_2^{(0)}+x_2^{(1)})p_2}\phi(p_1)\phi(p_2)|h^{\mu\nu}(k)\rangle$$

- Expanding yields undressed correlator plus two additional terms

$$\langle 0|\Phi(x_1)\Phi(x_2)|h^{\mu\nu}(k)\rangle = e^{-ix_2k}\int \frac{d^dp}{(2\pi)^d} e^{-i(x_1-x_2)p}$$
$$\times \left(\frac{\mathcal{V}^{\mu\nu}(p,k-p,k)}{p^2(k-p)^2} + \langle 0|\phi(p)\phi(-p)|0\rangle \langle 0|(-ip(x_1^{(1)} - x_2^{(1)}))|h^{\mu\nu}(k)\rangle\right)$$

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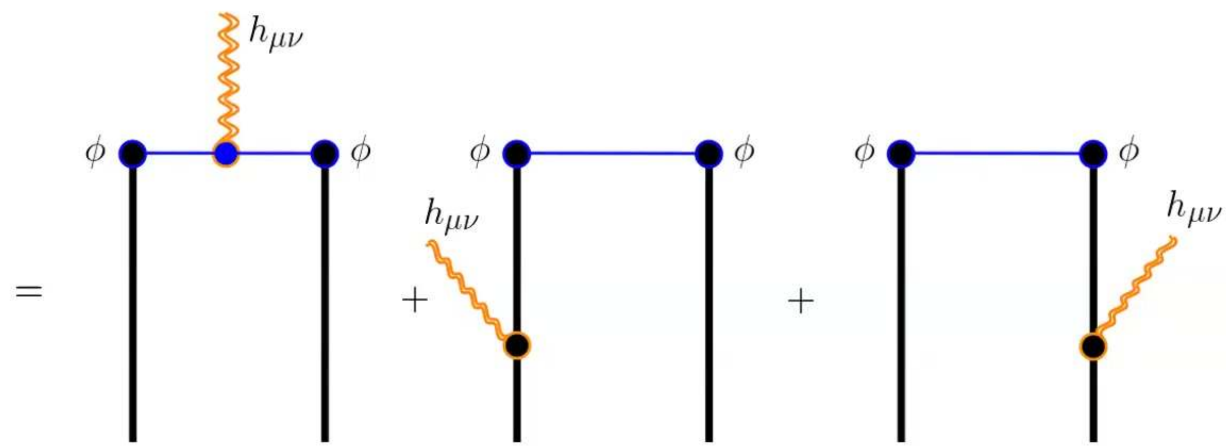
Dressed matrix element

- Two extra terms correspond to graviton hitting the dressing!

$$\langle 0|\Phi(x_1)\Phi(x_2)|h^{\mu\nu}(k)\rangle = e^{-ix_2 k}\int \frac{d^d p}{(2\pi)^d} e^{-i(x_1-x_2)p}$$
$$\times\left(\frac{\mathcal{V}^{\mu\nu}(p,k-p,k)}{p^2(k-p)^2} + \langle 0|\phi(p)\phi(-p)|0\rangle\,\langle 0|(-ip(x_1^{(1)}-x_2^{(1)}))|h^{\mu\nu}(k)\rangle\right)$$



Cheung, AS, Wilson-Gerow, Zhou

Standard momentum integrals, doable Fourier transforms, and at worst, ${}_2F_1$'s at one loop

Lessons from tree, loop-level results

- **Dressing is physical**. Large when k soft, or nearly collinear with x_{12} e.g.

$$\langle\Omega\big|\phi(x_1)\phi(x_2)\big|h(k)\rangle = \kappa\,\frac{e^{-ik\cdot x_1}-e^{-ik\cdot x_2}}{4\pi^2(x_{12}^2)^2}\,\frac{(x_{12}\epsilon x_{12})}{k\cdot x_{12}}$$

  - Choice of dressing matters; what dressing does experiment choose?
- **Dressing as gauge fixing**: can "straighten" worldline using gauge that enforces $\Gamma^{\mu}_{\rho\sigma}\dot{x}^{\rho}\dot{x}^{\sigma}=0$, analogous to axial gauge trivializing Wilson lines.
  - In practice, merely compute the undressed diagram but in new gauge, which amounts to adding projectors to the polarizations. Simple! For example,

$$\epsilon_{\mu\nu}\to P^{\alpha}_{\mu}P^{\beta}_{\nu}\epsilon_{\alpha\beta}, \qquad P_{\alpha\mu}=\eta_{\alpha\mu}-\frac{k_{\alpha}\dot{x}_{\mu}}{k\cdot\dot{x}}$$

- **Light cones can bend in any direction**: in the state $|\Psi\rangle=|\Omega\rangle+i\,|h(k)\rangle$, the commutator is

$$\langle\Psi|[\Phi(x_1),\Phi(x_2)]|\Psi\rangle = c_1\delta(-x_{12}^2)+c_2\kappa f(kx_1,kx_2)P^{\alpha}_{\mu}P^{\beta}_{\nu}\epsilon_{\alpha\beta}\partial^{\mu}_{x_1}\partial^{\nu}_{x_1}\delta(-x_{12}^2)$$

  - The location of the singularity in τ_{12} has perturbatively shifted, and the direction of the shift is determined by the sign of the correction term above. Expect the same from the geometric quantity $\langle\Psi|\tau_3(0)|\Psi\rangle$

Cheung, AS, Wilson-Gerow, Zhou

Landscape of gravitational observables

- General questions:
  - Including quantum fluctuations of observer, clock, quantum reference frames
  - Clarify framework and rigorous experimental predictions (e.g. Aziz & Howl, Nature (2025)) for interface between quantum mechanics and gravity
  - **Quantum gravity phenomenology**: what do various gravity quantization approaches predict for observables?
  - **What are the properties of quantum gravity?** Investigate positivity, e.g. ANEC, generalized entropy, null rays, bootstrap conditions perturbatively
  - Observers, measurements in closed universes

- Holography
  - Observer/subregion holography: how is quantum gravity holographic? Are subregions well-defined? Edge modes? Bulk reconstruction from observer d.o.f.?
  - Recover timelike observers from holographic correlators
  - Probe black hole singularity from the CFT

Almost no perturbative computations of fully relativistic, fully diffeomorphism-invariant QG observables that directly probe local physics, yet we largely learned about quantum field theory from calculations like these! Here, we calculated various observables and even these initial calculations reveal intriguing properties of QG.

Some first steps into the wild, but we have excellent boots!