TOWARDS A SPACETIME DESCRIPTION OF HARD PARTON EVOLUTION IN THE QGP

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INTRODUCTION

Typical energy loss calcuations in AdS/CFT simulations use an initial condition of pairs of quarks placed in the Quark Gluon Plasma (QGP), but a precise and theoretically motivated description of configuration does not exist. Quark virtuality can have noticable effects on the rate of energy loss so a first principles calculation is needed for the early time behaviour of virtual particles soon after production [1].

Hard partons (which result in jets) are created during the initial collision of the nuclei, and are governed by perturbative QCD. We use the Schwinger Keldysh formalism applied to an interacting scalar field theory to study the Energy Momentum Tensor of hard partons in real time, and propose this as a foundational model to use as an initial condition in jet energy loss calculations.

SET UP AND DESCRIPTION

We create two distinguishable scalar particles given by $|\psi\rangle = |\psi_1\psi_2\rangle$ at $t_0 = -\infty$. We evolve $|\psi\rangle$ and $\langle\psi|$ to time t and apply the $T_{\mu\nu}(x)$ operator, defining the Schwinger Keldysh contour which we expand solve diagrammatically.

$$\langle\hat T_{\mu\nu}(x)\rangle = \langle\psi|T_C\left(e^{-i\int_C d^4z\,\hat H_I}\hat T_{I\mu\nu}(x)\right)|\psi\rangle$$

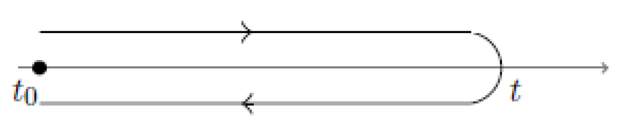


Figure 1: Schwinger-Keldysh contour used to find expectation values.

RESULTS SUMMARY

We found the following:

- $P_\mu = \int d^3x\,\hat T_{\mu 0}(x)$ is conserved for all time at each order, which is crucial for the consistency of the diagrammatic expansion.
- $\langle\hat T_{\mu\nu}(x)\rangle$ is related to the cross-section at late times.
- We studied $\langle\hat T_{\mu\nu}(x)\rangle$ for a back-to-back parton pair.
- We have started formulating a finite time numerical solution for the $\langle\hat T_{\mu\nu}(x)\rangle$ of colliding partons.

RESULTS

To study the **kinematics** of the system, we demonstrate our results with a simple model of 2 uncharged scalar fields,

$$\mathcal{L} = \sum_{i=1,2}\left(\frac{1}{2}(\partial_\mu\psi_i)^2 - \frac{1}{2}m^2\psi_i^2\right) + \lambda\psi_1^2\psi_2^2. \quad (1)$$

Late time Solution

We found that in general we should expect that in the center of mass frame the late time total momentum would be given by

$$\lim_{t\to\infty}\int d^2b\,\langle\hat P\rangle = \int d\Pi_{p_f}\left(\sum_f \vec p_f\right)\frac{d\sigma}{d\Pi_{p_f}}^{(\mathrm{in}\to\{\vec p_f\})}, \quad (2)$$

where $\frac{d\sigma}{d\Pi_{p_f}}^{(\mathrm{in}\to\{\vec p_f\})}$ is the cross section to fall into a $\prod_f \frac{d^3p_f}{E_f}$ region of phase space. We verified Equation 2 for the toy model given by Equation 1. Performing the calculation for $\psi_1\psi_2 \to \psi_1{}'\psi_2{}'$, we find that for late times

$$\int d^2b\frac{dP^\mu}{d\Pi} \sim \sum_f \frac{P_f{}^\mu P_f{}^0}{E_{p_f}}\lambda^2\delta^4(p_{\mathrm{in}} - \sum_f p_f).$$

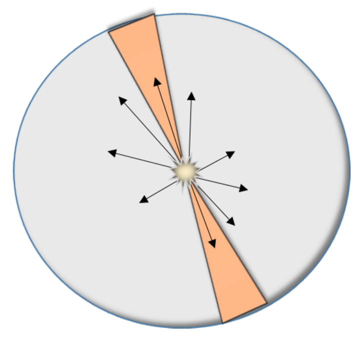


Figure 2: Visualization of the Expectation Value (blue) and Conditional Expectation Value (Red). The expectation value will be a sum over the possible final states, but the conditional expectatio value will be restricted.

Conditional Expectation Value

For an initial density matrix ρ at $t = -\infty$, and projection operator $M_R(\Delta)$ at $t = \infty$ we define the conditional expectation value (visualized in Figure 2) of the operator Θ as

$$E^c(\hat\Theta) = \frac{\mathrm{Tr}\{\rho M_R(\Delta)\hat\Theta(t)M_R(\Delta)\}}{\mathrm{Tr}\{\rho M_R(\Delta)\}}, \quad (3)$$

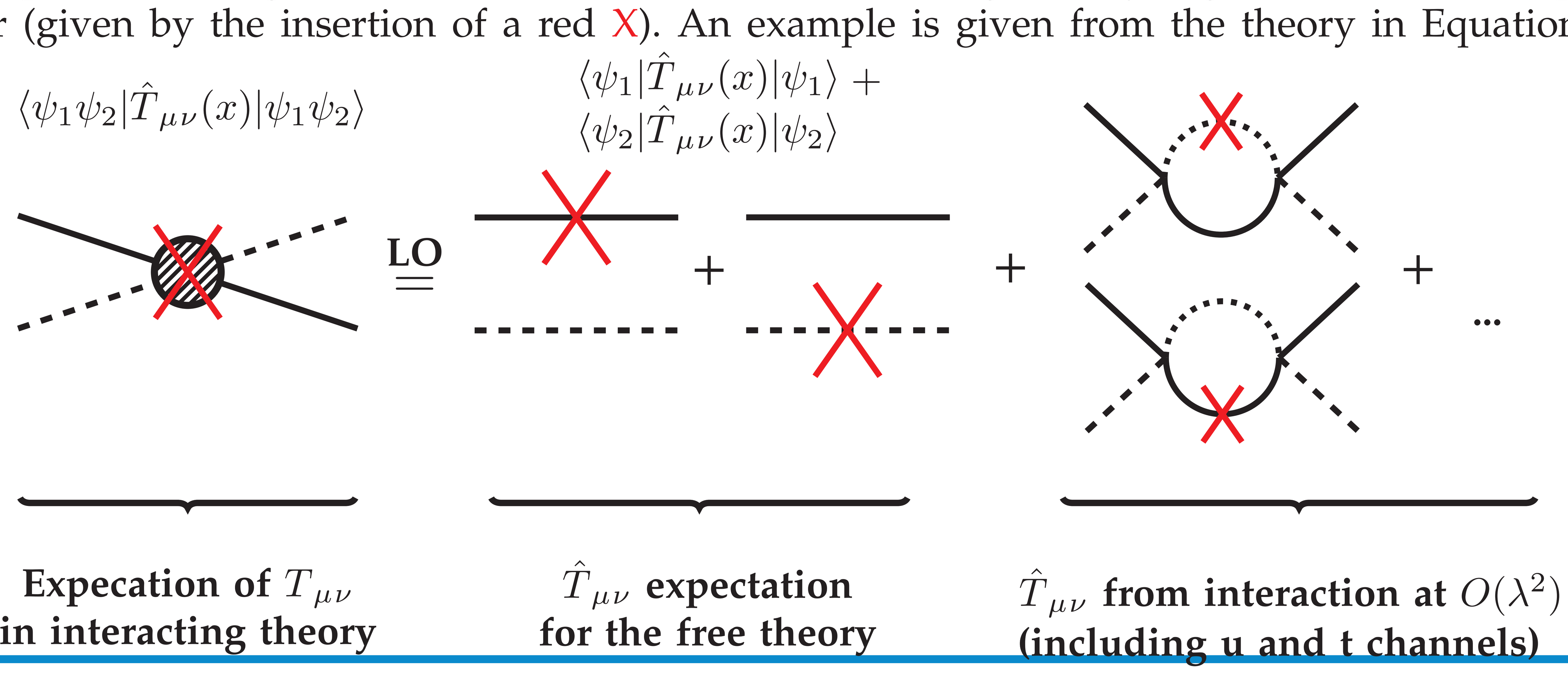
which gives us the expectation value of the operator Θ given an initial condition ρ and a final state which can project onto $M_R(\Delta)$. A derivation of Equation 3 is given in [2].

In the model given by Equation 1 we choose an initial state of two distinguishable particles, and calculate the expectation value of the energy momentum tensor of particle ψ_1, given that particle ψ_2 is detected in a region of phase space determined by the projection operator $M_R(\Delta) = \int \frac{d^3s}{(2\pi)^3 2E_s}\theta_s\,|s\rangle\langle s|_{\psi_2}\otimes\mathbb{1}_{\psi_1}$. For a projection of particle ψ_2 onto a small region of phase space centered around momentum $\mathbf{q}$, we find the conditional expectation value of the energy momentum tensor of particle ψ_1 to be

$$E^c \approx \left(\frac{p_\mu p_\nu}{E_p}\right)\Bigg|_{\mathbf{p}=-\mathbf{q}}. \quad (4)$$

The Diagrammatic Expansion

The expansion of diagrams in the Schwinger-Keldysh formalism carries similar meaning to squares of diagrams in the "in/out" formalism, weighted by eigenvalues of the operator (given by the insertion of a red X). An example is given from the theory in Equation 1.



FUTURE WORK: NUMERICAL SOLUTION

We have found sensible analytic solutions in the late time limit of $\langle P_\mu\rangle = \langle\int d^3x\,T_{\mu 0}(x)\rangle$. We can perform reliable numerical simulations for $\langle T_{\mu\nu}(x)\rangle$. We can use the conditional expectation value to cut away unnecessary final states that would have ordinarily existed in a sum over final states as given by the expectation value. We expect a numerical output to replication the process given by Figure 3.

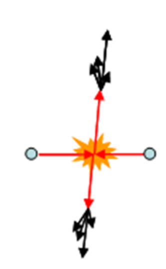


Figure 3: Visualization of Back-to-back hard parton evo-

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REFERENCES

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[2] Meiring B and Horowitz W A 2015 *J. Phys. Conf. Ser.* **623** 012019