Universal corrections to entanglement entropy of local quantum quenches

Surbhi Khetrapal

Indian Institute of Science, Bangalore

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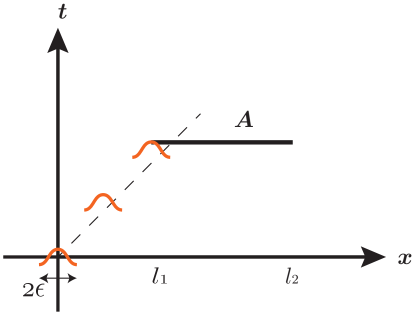
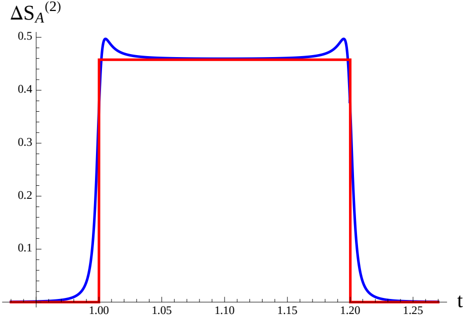
Introduction

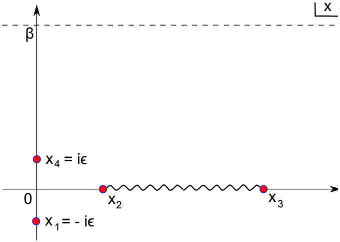
- Consider an excited state at origin, at zero time. As time progresses, it propagates along the light cone.
- For times $l_1 < t < l_2$ leads to a step function jump in entanglement entropy of this interval.
- This magnitude of the jump is the quantum dimension of the excited state.



- For finite width quench, $\epsilon \neq 0$, it is expected that the step function will be smoothed out.
- Shape of smoothening depends on details of the CFT.
- However, we show that time dependence of the correction to Renyi and entanglement entropy at order ϵ^2 is universal.



Excited state density matrix



- Excited state density matrix,

$$\hat{\rho} = \mathcal{N} e^{-iHt} \mathcal{O}(0) |\beta\rangle\langle\beta| \mathcal{O}^\dagger(0) e^{iHt}$$
$$|\beta\rangle\langle\beta| = \rho_\beta = e^{-\beta H}$$

$\mathcal{N}$ is normalisation such that $\mathrm{Tr}\,\hat{\rho} = 1$.

- Using regularisation parameter, ϵ, width of excitation

$$\hat{\rho}_\epsilon = \mathcal{N} e^{-iHt} \left(e^{-\epsilon H} \mathcal{O}(0) e^{\epsilon H}\right) \rho_\beta \left(e^{\epsilon H} \mathcal{O}^\dagger(0) e^{-\epsilon H}\right) e^{iHt}$$

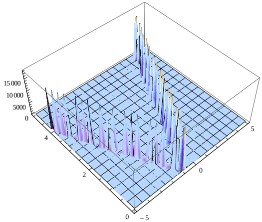
- Holomorphic and anti-holomorphic co-ord, $(x, \bar{x}) = (l - t, l + t)$,

$$\hat{\rho}_\epsilon = \mathcal{N} e^{-iHt} \mathcal{O}(x_1, \bar{x}_1) \rho_\beta\, \mathcal{O}^\dagger(x_4, \bar{x}_4)\, e^{iHt}$$
$$x_1 = -i\epsilon, \quad \bar{x}_1 = +i\epsilon, \quad x_4 = +i\epsilon, \quad \bar{x}_4 = -i\epsilon.$$

Energy density

Energy density in the excited state is

$$
\begin{aligned}
\mathrm{Tr}\hat{\rho}T_{tt} &= \langle T_{tt}(x,\bar{x})\rangle_{\mathcal{O}} \\
&= \frac{\langle \mathcal{O}^{\dagger}(x_1,\bar{x}_1)T_{tt}(x,\bar{x})\mathcal{O}(x_4,\bar{x}_4)\rangle_{R_1}}{\langle \mathcal{O}^{\dagger}(x_1,\bar{x}_1)\mathcal{O}(x_4,\bar{x}_4)\rangle_{R_1}} \\
&= \frac{\pi^2 c}{3\beta^2} + \frac{4\pi^2\Delta_{\mathcal{O}}}{\beta^2}\sin^2\left(\frac{2\pi\epsilon}{\beta}\right)\times
\end{aligned}
$$



$$
\left(\left(\cosh\left(\frac{2\pi(-t+x)}{\beta}\right)-\cos\left(\frac{2\pi\epsilon}{\beta}\right)\right)^{-2}+\left(\cosh\left(\frac{2\pi(-t+x)}{\beta}\right)-\cos\left(\frac{2\pi\epsilon}{\beta}\right)\right)^{-2}\right)
$$

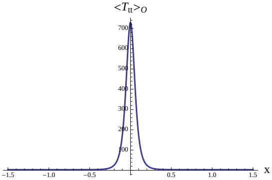


Figure: $t = 0$

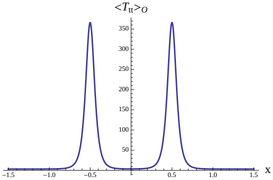


Figure: $t = 0.5$

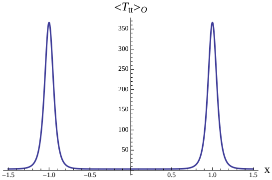
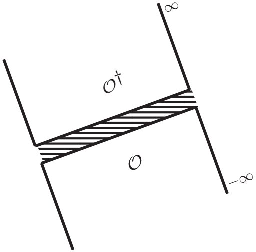


Figure: $t = 1$

Reduced density matrix

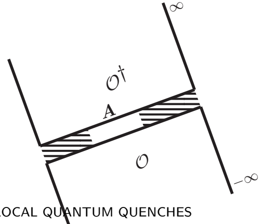
- Trace of excited state density matrix is a two point function.

$$\begin{aligned}\mathrm{Tr}\,\hat{\rho} &= \mathcal{N}^{-2}\sum_i \langle i|e^{\tau H}\mathcal{O}(-i\epsilon,0)|\beta\rangle\langle\beta|\mathcal{O}^\dagger(i\epsilon,0)e^{-\tau H}|i\rangle \\ &= \mathcal{N}^{-2}\sum_i \langle\beta|\mathcal{O}(-i\epsilon,0)e^{-\tau H}|i\rangle\langle i|e^{\tau H}\mathcal{O}^\dagger(i\epsilon,0)|\beta\rangle \\ &= \mathcal{N}^{-2}\langle\beta|\mathcal{O}^\dagger(-i\epsilon,0)\mathcal{O}(i\epsilon,0)|\beta\rangle\end{aligned}$$



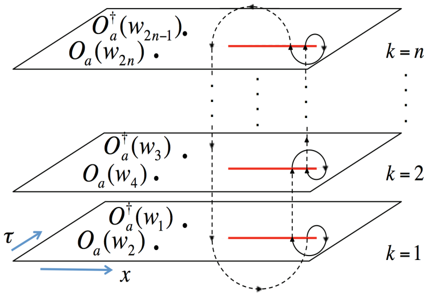
- Reduced density matrix of excited state,

$$\begin{aligned}\rho_A &= \mathrm{Tr}_B\hat{\rho} \\ &= \mathcal{N}^{-2}\langle\beta|\mathcal{O}^\dagger(-i\epsilon,0)\mathcal{O}(i\epsilon,0)|\beta\rangle_1\end{aligned}$$



n sheeted Riemann surface

$$\mathrm{Tr}\,\rho_A^n = \mathcal{N}^{-2}\langle\beta|\mathcal{O}^\dagger(i\epsilon^0,0)\mathcal{O}(-i\epsilon^0,0)\mathcal{O}^\dagger(i\epsilon^1,0)\dots\mathcal{O}(-i\epsilon^{n-1},0)|\beta\rangle_n$$



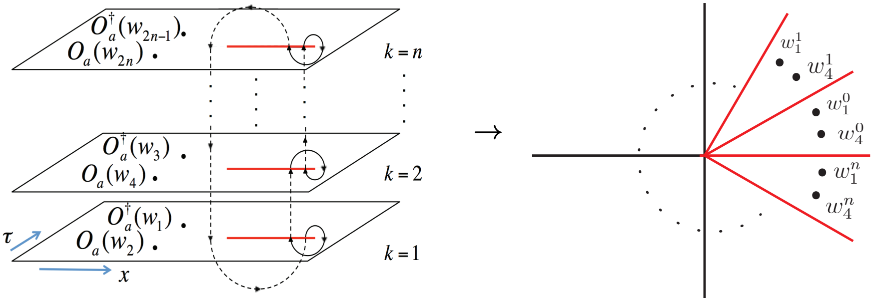
Note that on every copy $\mathcal{O}^\dagger$, $\mathcal{O}$ is present.

Uniformisation map

Uniformisation map, $$w(x) = e^{\frac{i(x_2 - x_3)}{n}} \left(\frac{\sinh(x - x_2)}{\sinh(x - x_3)} \right)^{\frac{1}{n}}$$

$$\mathrm{Tr}\,\rho_A^n \propto \langle \mathcal{O}^\dagger(w_4^0, \bar{w}_4^0)\mathcal{O}(w_1^0, \bar{w}_1^0)\mathcal{O}^\dagger(w_4^1, \bar{w}_4^1)\ldots\mathcal{O}(w_1^{n-1}, \bar{w}_1^{n-1})\rangle$$

n-th Renyi entropy, $$S_A^{(n)} = \frac{1}{1-n} \ln \frac{\mathrm{Tr}\rho_A^n}{\mathrm{Tr}(\rho_A^{(0)})^n}$$



Uniformisation map contd..

Defining the cross-ratios,

$$z \equiv \left(\frac{w_1}{w_4}\right)^n \xrightarrow{\epsilon\to 0} 1 + 2i\epsilon \frac{\pi \sinh\left(\frac{\pi}{\beta}(l_2 - l_1)\right)}{\beta \sinh\left(\frac{\pi}{\beta}(l_1 - t)\right) \sinh\left(\frac{\pi}{\beta}(l_2 - t)\right)}$$

$$\bar{z} \equiv \left(\frac{\bar{w}_1}{\bar{w}_4}\right)^n \xrightarrow{\epsilon\to 0} 1 - 2i\epsilon \frac{\pi \sinh\left(\frac{\pi}{\beta}(l_2 - l_1)\right)}{\beta \sinh\left(\frac{\pi}{\beta}(l_1 + t)\right) \sinh\left(\frac{\pi}{\beta}(l_2 + t)\right)}$$

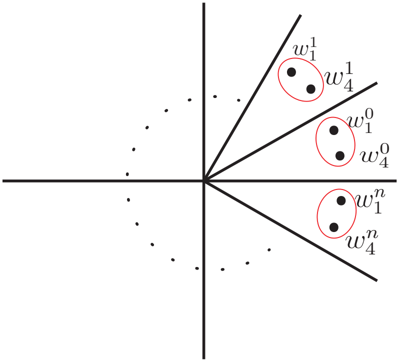
$$z \xrightarrow{\epsilon\to 0} \begin{cases} 1 & t < l_1, t > l_2 \\ e^{2\pi i} & l_1 < t < l_2 \end{cases} \Rightarrow \lim_{\epsilon\to 0} \frac{w_1}{w_4} = z^{\frac{1}{n}} = \begin{cases} 1 & t < l_1, t > l_2 \\ e^{\frac{2\pi i}{n}} & l_1 < t < l_2 \end{cases}$$

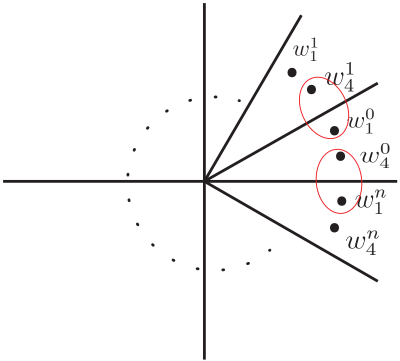
$$\bar{z} \xrightarrow{\epsilon\to 0} 1 \qquad \text{for all times} \quad \Rightarrow \lim_{\epsilon\to 0} \frac{\bar{w}_1}{\bar{w}_4} = \bar{z}^{1/n} = 1 \quad \text{for all times}$$

In the limit, $\epsilon \to 0$, two branches of the holomorphic cross-ratio.

$$z \to 1$$
$$w_1^{(0)} \to w_4^{(0)}$$
$$t < l_1 \ \& \ t > l_2$$

$$z \to e^{2\pi i}$$
$$w_1^{(0)} \to e^{\frac{2\pi i}{n}} w_4^{(0)} = w_4^{(1)}$$
$$l_1 < t < l_2$$





2nd Renyi entropy

$$\Delta S_A^{(2)} = -\ln\left(\frac{\langle\mathcal{O}^\dagger(x_4^{(0)},\bar{x}_4^{(0)})\mathcal{O}(x_1^{(0)},\bar{x}_1^{(0)})\mathcal{O}^\dagger(x_4^{(1)},\bar{x}_4^{(1)})\mathcal{O}(x_1^{(1)},\bar{x}_1^{(1)})\rangle_2}{\langle\mathcal{O}^\dagger(x_4^{(0)},\bar{x}_4^{(0)})\mathcal{O}(x_1^{(0)},\bar{x}_1^{(0)})\rangle_1^2}\right)$$

$$= \begin{cases} 0, & t < l_1 \text{ and } t > l_2 \\ -\ln F_{00}[\mathcal{O}], & l_1 < t < l_2 \end{cases} \quad + \epsilon^2\,\Delta S_{A,0}^{(2;2)}$$

The universal correction at $O(\epsilon^2)$ is,

$$\Delta S_{A,0}^{(2;2)} = \frac{\Delta_{\mathcal{O}}}{4}\left[\mathcal{S}_{l_1 l_2}(t)^2 + \mathcal{S}_{l_1 l_2}(-t)^2\right]$$

$$\mathcal{S}_{l_1 l_2}(t) = \frac{\pi}{\beta}\frac{\sinh\frac{\pi}{\beta}(l_2 - l_1)}{\sinh\frac{\pi}{\beta}(l_1 - t)\sinh\frac{\pi}{\beta}(l_2 - t)}$$

$F_{00}[\mathcal{O}]$ is the quantum dimension of the operator $\mathcal{O}$.

Conformal block argument

$$\Delta S_A^{(2)} = -\ln\left[|u|^{4h}|1-u|^{4h}G_{\mathcal{O}}(u,\bar{u})\right]$$

where $u = -\frac{(\sqrt{z}-1)^2}{4\sqrt{z}}$, $\bar{u} = -\frac{(\sqrt{\bar{z}}-1)^2}{4\sqrt{\bar{z}}}$

$$G_{\mathcal{O}}(u,\bar{u}) \;=\; \sum_b (C_{\mathcal{O}}^{\mathcal{O}_b})^2\, F_{\mathcal{O}}(\mathcal{O}_b|u)\, \bar{F}_{\mathcal{O}}(\mathcal{O}_b|\bar{u})$$

Vacuum, $b=0$, $h_b = 0, C_{\mathcal{O}}^{\mathcal{O}_0} = 1, \quad F_{\mathcal{O};\mathrm{vac}} = u^{-2h}\left(1 + \frac{2h^2}{c}u^2 + \dots\right)$

For time $t < l_1$ and $t > l_2$, $(z,\bar{z}) \to (1,1)$, hence $(u,\bar{u}) \to (0,0)$,

$$\Delta S_A^{(2)} = \Delta_{\mathcal{O}}(u+\bar{u}) + O(\epsilon^4)$$

$$u = \frac{\epsilon^2}{4}\mathcal{S}_{l_1 l_2}(t)^2, \quad \bar{u} = \frac{\epsilon^2}{4}\mathcal{S}_{l_1 l_2}(-t)^2$$

- To obtain entropy for $l_1 < t < l_2$, i.e., in the limit $(z, \bar{z}) \to (e^{2\pi i}, 1)$, which corresponds to $(u, \bar{u}) \to (1, 0)$.
- The following fusion transformation rule of conformal blocks is used,

$$F_{\mathcal{O}}(\mathcal{O}_b|u) = \sum_c F_{bc}[\mathcal{O}] F_{\mathcal{O}}(\mathcal{O}_c|1-u).$$

  which for vacuum becomes,

$$F_{\mathcal{O};\text{vac}}(u) = F_{00}[\mathcal{O}] F_{\mathcal{O};\text{vac}}(1-u) + \dots$$

- Hence,

$$\Delta S_A^{(2)} = -\ln F_{00}[\mathcal{O}] + \Delta_{\mathcal{O}}(1 - u + \bar{u}) + O(\epsilon^4)$$

$$u = 1 - \frac{\epsilon^2}{4} \mathcal{S}_{l_1 l_2}(t)^2, \quad \bar{u} = \frac{\epsilon^2}{4} \mathcal{S}_{l_1 l_2}(-t)^2.$$

n-th Renyi entropy - OPE argument

Using $\mathcal{O}\mathcal{O}$ OPE, in a theory without conserved $U(1)$ current,

$$\mathcal{O}^\dagger(x_4, \bar{x}_4)\mathcal{O}(x_1, \bar{x}_1) \sim |x_4 - x_1|^{-2\Delta_{\mathcal{O}}} \times \left[1 + \frac{\Delta_{\mathcal{O}}}{c}\left((x_4 - x_1)^2\, T(x_1) + (\bar{x}_4 - \bar{x}_1)^2\, \overline{T}(\bar{x}_1)\right) + \cdots\right]$$

The $2n$-point function,

$$\left\langle \prod_{j=1}^{n} \mathcal{O}^\dagger(x_4^{(j)}, \bar{x}_4^{(j)})\, \mathcal{O}(x_1^{(j)}, \bar{x}_1^{(j)}) \right\rangle_n \sim \frac{1}{(2\epsilon)^{2n\Delta_{\mathcal{O}}}} \left[1 - \frac{4\epsilon^2\, \Delta_{\mathcal{O}}}{c} \sum_{j=1}^{n} \left\{ \left\langle T(x_1^{(j)}) \right\rangle_n + \left\langle \bar{T}(\bar{x}_1^{(j)}) \right\rangle_n \right\} \right]$$

$\Rightarrow$ correction to Renyi entropy at $\mathrm{O}(\epsilon^2)$ is given by the expectation value of the stress tensor on the n-sheeted surface.

$$\boxed{\Delta S_A^{(n;\,2)} \;=\; 4\,\frac{\Delta_{\mathcal{O}}}{c}\,n\,\frac{\langle T(0)\rangle_n \;-\; \langle T\rangle_\beta}{n-1} \;+\; (t\to -t)}$$

Transformation to the uniformised plane,

$$T(x) \;=\; w'(x)^2\,T(w) \;+\; \frac{c}{12}\,\{w,\,x\}$$

$\langle T(w)\rangle = 0$, hence only the schwarzian derivative contributes,

$$\frac{c}{12}\,\{w,\,x\} \;=\; c\frac{(n^2-1)}{24\,n^2}\;\left[\mathcal{S}_{l_1 l_2}(t+x)\right]^2 \;-\; \frac{c\,\pi^2}{6\beta^2}$$

Hence,

$$\Delta S_A^{(n)} = \Delta S_A^{(n;0)} + \epsilon^2 \Delta_{\mathcal{O}}\frac{1+n}{6n}\left[\mathcal{S}_{l_1 l_2}(t)^2 + \mathcal{S}_{l_1 l_2}(-t)^2\right] + O(\epsilon^4)$$

Large interval large time limit

- Taking $l_2 \to \infty$ followed by $t \gg l_1$.

$$\langle T \rangle_n \big|_{l_2 \to \infty, t \gg l_1} = \langle T \rangle_{n\beta}$$

- Using the thermal expectation value of the stress tensor,

$$\langle T \rangle_\beta = -\frac{c\,\pi^2}{6\beta^2}$$

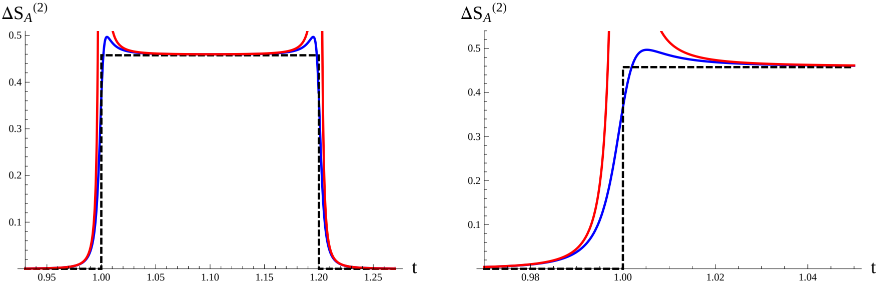
$$\boxed{\Delta S_A^{(n;\,2)}\,\big|_{l_2 \to \infty,\, t \gg l_1} = 4\frac{\Delta_{\mathcal{O}}}{c}\, n\, \frac{\langle T \rangle_{n\beta} - \langle T \rangle_\beta}{n-1} = \Delta_{\mathcal{O}} \frac{2(n+1)}{3n} \frac{\pi^2}{\beta^2}}$$

Example: Minimal model

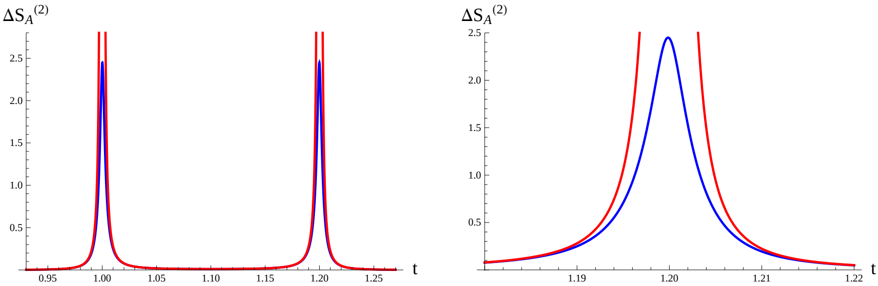
- (p, p') minimal model CFT with $p > p'$, with central charge $c = 1 - 6\frac{(p-p')^2}{pp'}$.
- The 4-point function, $G(u, \bar{u})$, is known in terms of hypergeometric functions.
$$\Delta S_A^{(2)} = -\ln\left[|u|^{4h}|1-u|^{4h}\, G(u,\bar{u})\right]$$
- Consider operator $\phi_{2,1}$ of conformal dimension, $h = \frac{3}{4}\frac{p}{p'} - \frac{1}{2}$.

$$\Delta S_A^{(2;\,0)} = \begin{cases} 0, & t < l_1 \quad \text{or} \quad t > l_2 \\ \ln\left(-2\cos\frac{\pi p}{p'}\right), & l_1 < t < l_2\,, \end{cases}$$

$$\epsilon^2 \Delta S_A^{(2;\,2)} = \epsilon^2 \frac{h}{2}\left[\mathcal{S}_{l_1 l_2}(t)^2 + \mathcal{S}_{l_1 l_2}(-t)^2\right]\,.$$



The exact result (blue curve), the step jump at order ϵ^0 (dashed black), and the approximation at order ϵ^2 (in red). $p/p' = 1.21$, $\beta = 1, l_1 = 1, l_2 = 1.2$ and $\epsilon = 0.005$.



- The exact result (blue curve) and the leading approximation at order ϵ^2 (in red) for $p/p' = 10/3$, $\beta = 1$, $l_1 = 1$, $l_2 = 1.2$ and $\epsilon = 0.005$.

- For this value of p/p', the jump $\sim \ln(-2\cos(\pi p/p'))$ at order ϵ^0 is vanishing.

Agreement with Holographic EE

- A CFT perturbed by heavy operator ($\mathcal{O}_\Delta$) is dual to AdS with a massive point particle ($m \propto \Delta$), which starts its motion a distance ϵ from the boundary and falls towards bulk blackhole horizon as time progresses.

- The presence of massive particle leads to a backreacted geometry in the bulk. [Takayanagi, Caputa, et. al. '10]

- The geodesic length ($\mathcal{L}$) of a geodesic with end points at l_1 and l_2 on the boundary is evaluated. The prescription to obtain entanglement entropy, $S_A = \frac{\mathcal{L}}{4G_N}$

$$\Delta \hat{S}_A = \epsilon^2 \Delta_{\mathcal{O}} \frac{1}{3} \left[\mathcal{S}_{l_1 l_2}(t)^2 + \mathcal{S}_{l_1 l_2}(-t)^2 \right].$$

Deformation by chemical potential for spin-3 current

- Consider CFT with non-zero spin-3 chemical potential, μ, disturbed with a local quantum quench of finite width.
- We show that leading μ-dependent correction to Renyi entropy of excited state occurs at $\mathrm{O}(\mu^2\epsilon^2)$.
- The step function at ϵ^0 is unaffected by chemical potential at order μ^2.
- The time dependence of the correction at order $\epsilon^2\mu^2$ is universal and is determined by the three-point function of the stress tensor with the higher spin currents on the n-sheeted cylinder.

Correction at $O(\mu^2\epsilon^2)$

$$\epsilon^2\mu^2\Delta S_A^{(n;\,2,\,2)} = \epsilon^2\mu^2 2\frac{\Delta_{\mathcal{O}}}{c}\,\frac{n}{n-1}\times$$
$$\int d^2y_1 d^2y_2\left[\langle T(0)W(y_1)W(y_2)\rangle_n - \langle T(0)W(y_1)W(y_2)\rangle_\beta\right] + (t\to -t)$$

We have found the full analytic form of the time dependent correction at this order for deformation by chemical potential of spin-3 operator.

$$\mu^2\epsilon^2\,\Delta S_A^{(n;\,2,\,2)}\,\big|_{l_1=0,\,l_2\to\infty} = \mu^2\epsilon^2\,\Delta_{\mathcal{O}}\,\frac{\widetilde{\mathcal{N}}}{c}\,\frac{\pi^6}{\beta^4}\,\frac{(n+1)}{2n}\,\frac{1}{(1-e^{-2\pi t/\beta})^6}\times$$
$$\Big[-\tfrac{160}{3} - \tfrac{128}{3}\left(\tfrac{2\pi t}{\beta} - 11\right)e^{-2\pi t/\beta} + 64\left(\tfrac{16\pi^2t^2}{\beta^2} - \tfrac{32\pi t}{\beta} - 7\right)e^{-4\pi t/\beta} +$$
$$+\tfrac{128}{3}\left(\tfrac{36\pi^2t^2}{\beta^2} + \tfrac{42\pi t}{\beta} - 7\right)e^{-6\pi t/\beta} + \tfrac{32}{3}\left(\tfrac{32\pi t}{\beta} + 31\right)e^{-8\pi t/\beta} +$$
$$+\frac{(n^2-4)}{30n^2}\Big\{320 + 256\left(\tfrac{4\pi^2t^2}{\beta^2} - \tfrac{14\pi t}{\beta} + 1\right)e^{-2\pi t/\beta} +$$
$$128\left(\tfrac{32\pi^2t^2}{\beta^2} + \tfrac{16\pi t}{\beta} - 11\right)e^{-4\pi t/\beta} + 768\left(\tfrac{2\pi t}{\beta} + 1\right)e^{-6\pi t/\beta} + 64\,e^{-8\pi t/\beta}\Big\}\Big]\,.$$

Plots: correction at $O(\mu^2\epsilon^2)$

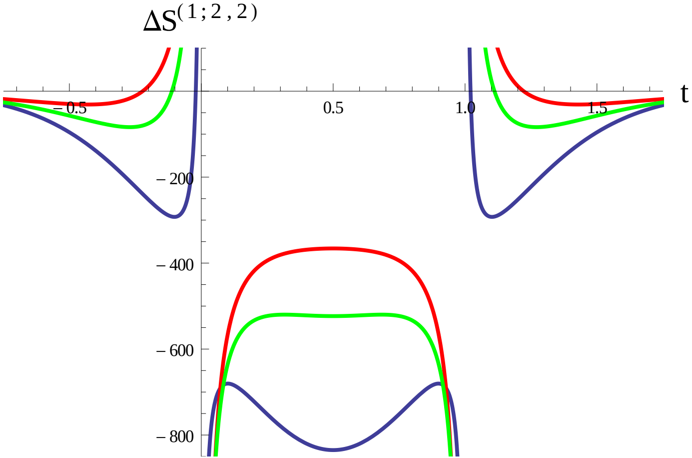


Figure: Plot of $S^{(1;2,2)}_{(0,1)}$, the $\mu^2\epsilon^2$ correction to entanglement entropy as a function of time for the entanglement interval, $l_1 = 0$, $l_2 = 1$. The plots from bottom to top are for increasing values of $\beta = 1.8$, 2.1, 2.4, respectively.

Large interval late time result at $O(\epsilon^2\mu^2)$

$$\Delta S_A^{(n;\,2,\,2)} \sim 2\frac{\Delta_{\mathcal{O}}}{c}\,\frac{n}{n-1}\int d^2y_1 d^2y_2\,\langle T(0)W(y_1)W(y_2)\rangle_n + \ldots$$

- In the large interval, large time limit,

$$\langle T(0)W(y_1)W(y_2)\rangle_n\,|_{l_2\to\infty,\,t\gg l_1} \;\to\; \langle T(0)W(y_1)W(y_2)\rangle_{n\beta}\,.$$

  need to evaluate TWW correlator on cylinder of period $n\beta$.
- This is obtained by using Ward identity on the following,

$$\langle W(y_1)\,W(y_2)\rangle_\beta \;=\; \frac{\widetilde{\mathcal{N}}\,\pi^6}{\beta^6\,\left[\sinh\frac{\pi}{\beta}(y_1-y_2)\right]^6}$$

$$\Delta S_A^{(n;\,2,\,2)}\,|_{l_2\to\infty,\,t\to\infty} \;=\; -\,\Delta_{\mathcal{O}}\,\frac{\widetilde{\mathcal{N}}}{c}\,\frac{64\,(n^2+1)(n+1)}{3n^3}\,\frac{\pi^6}{\beta^4}$$

General higher spin, s, result

- Result for general higher spin, s is obtained in $l_2 \to \infty$, followed by $t \to infty$ limit.

- Obtained by acting with Ward identity on the following correlator,

$$\langle W(y_1)\, W(y_2)\rangle_\beta \;=\; \frac{\widetilde{\mathcal{N}}\,\pi^{2s}}{\beta^{2s}\,\left[\sinh\frac{\pi}{\beta}(y_1-y_2)\right]^{2s}}$$

- The following correction at $O(\epsilon^2\mu^2)$ is obtained

$$\Delta S_A^{(n;\,2,\,2)}\,\Big|_{l_2\to\infty,\,t\gg l_1} \;=\; 8\,\Delta_{\mathcal{O}}\left(\frac{\widetilde{\mathcal{N}}}{c}\right)\left(\frac{\pi^{2s}}{\beta^{2s-2}}\right)\frac{n(n^{2-2s}-1)}{(n-1)}\,(2s-1)\,\mathcal{R}(s)$$

where $\quad \mathcal{R}(s) \;=\; -(-1)^s\,\dfrac{\Gamma(s)\,\Gamma\left(\frac{3}{2}\right)}{\Gamma\left(s+\frac{1}{2}\right)}$

Summary and future direction

- We study time evolution of RE/EE following local quantum quench in 2d CFT at finite temperature, finite width.
- Time dependence of RE/EE at order ϵ^2 is universal, and determined by expectation value of stress tensor on n-sheeted cylinder.
- Checked ϵ^2 result matches with holographic EE, for $t < l_1$.
- Consider CFT deformed by chemical potential, μ, of spin-3 field. We find the time dependent correction at $\mathrm{O}(\epsilon^2\mu^2)$, and show that it is universal.
- Future direction: Holographic check of the universal time dependent correction at $\mathrm{O}(\epsilon^2\mu^2)$. Requires formulation of dual to quench in Chern-Simons higher spin theory.

Thank You!

Surbhi Khetrapal
surbhi@chep.iisc.ernet.in

Indian Institute of Science, Bangalore

Quantum Mechanics analog

- Consider the state ψ, where $|\uparrow\rangle, |\downarrow\rangle$ corresponds to $e^{i\alpha\phi}, e^{-i\alpha\phi}$, respectively.

$$\mathcal{O}(x,\bar{x}) = e^{i\alpha(\phi(x)+\phi(\bar{x}))} + c\, e^{-i\alpha(\phi(x)+\phi(\bar{x}))}$$

$$|\psi\rangle = \frac{1}{\sqrt{1+|c|^2}}\left(|\uparrow\rangle_R|\uparrow\rangle_L + c\,|\downarrow\rangle_R|\downarrow\rangle_L\right)$$

- Operators at $x = l - t$ and $\bar{x} = l + t$ are analogous to right and left moving states, respectively.

$$\rho_R = \mathrm{Tr}_L|\psi\rangle\langle\psi| = \frac{1}{1+|c|^2}\left(|\uparrow\rangle_R\langle\uparrow|_R + |c|^2|\downarrow\rangle_R\langle\downarrow|_R\right)$$

$$\rho_R^2 = \frac{1}{(1+|c|^2)^2}\left(|\uparrow\rangle_R\langle\uparrow|_R + |c|^4|\downarrow\rangle_R\langle\downarrow|_R\right)$$

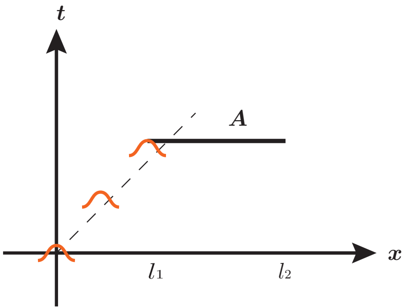
$$S_R^{(2)} = -\ln \mathrm{Tr}\rho_R^2 = -\ln\frac{1+|c|^4}{(1+|c|^2)^2}$$

- For small values of μ, ϵ, presence of chemical potential of spin 3 current, decreases the entanglement entropy in the entanglement region.

- Finite width ϵ of the excitation makes the discontinuous jump smoother.

Some region is excluded because we have kept only the ϵ^2 correction for the plots. The expansion is valid when

$$\frac{N\epsilon^2}{(l-t)} << 1 \Rightarrow t << l - \epsilon^2 N$$



We find that keeping all orders in ϵ renders the jump completely smooth.