Hadronisation of the QGP as a Quench

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Hadronisation of the QGP

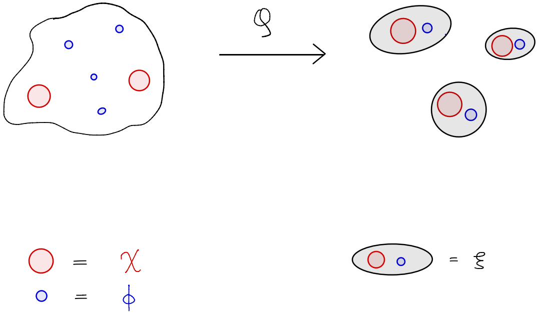
- The quark-gluon plasma (QGP): An exotic state of matter formed in AA or pA HICs. A hot soup of quarks and gluons.
- Once formed, QGP expands and cools.
- Eventually, it evaporates into colourless objects (hadrons), which are what we see in our detectors.
- Hadronisation of the QGP: Packaging of the coloured degrees of freedom in the QGP into colourless (hadron) final states.

Aim and motivation

- **Aim:** In a toy model: Calculate 'heavy flavour (HF) meson' number distributions in the final state, given the initial number distributions of constituent 'heavy and light quarks' in the pre-hadronisation phase.
- **Why?**
  - HF meson yields are known experimentally.
  - Using the formula calculated, we may deduce the distributions of heavy and light quarks in the pre-hadronisation phase of this toy model.
  - Such a formula can thus 'probe' the QGP in this toy model.
- May provide insights into already existing hadronisation models like Instantaneous Coalescence and Fragmentation. [Zhao et al., arXiv 2311.10621]

A toy model

- **Pre-hadronisation phase**: A fundamentally $U(N)$ coloured complex scalar field $\chi^a(x)$ (a 'heavy quark') immersed in a bath of another fundamentally $U(N)$ coloured complex scalar field $\phi^a(x)$ (a 'light quark'). No gluons.
- **Post-hadronisation phase**: A colourless complex scalar field $\xi(x)$ (a 'HF meson').
- **Hadronisation**: A heavy quark χ picks out a light antiquark ϕ^* from the bath and emerges out as a HF meson $\xi \sim \chi\,\phi^*$. We will call this a 'quench' and denote it by $\mathcal{Q}$.



Toy model (continued)

- Within this toy model, the aim is to calculate correlators between the number distributions of the HF meson ξ and light/heavy quarks (ϕ,χ):

$$\mathcal{C}\,(t_+\,,\,t_-)\,=\langle\,\mathbf{N}_\xi\,(t_+)\,\mathbf{N}_\phi(t_-)\,\mathbf{N}_\chi(t_-)\,\rangle_{\mathcal{Q}}\,,$$

  with t_- being a pre-hadronisation time and t_+ a post-hadronisation time.
- Convoluting $\mathcal{C}\,(t_+\,,\,t_-)$ with any given number distributions of light and heavy quarks in the pre-hadronisation phase, we get HF meson number distributions in the post-hadronisation phase.
- The function $\mathcal{C}$: Exactly like the recombination probabilities used in hadronisation models.

The quench $\mathcal{Q}$

- The quench is a superoperator with the action:

$$\mathcal{Q}\left[\rho_{\phi\,,\,\chi}\,(t=0^{-})\right]=\rho_{\xi}\,(t=0^{+})\,.$$

- $\mathcal{Q}$ instantaneously takes an initial density matrix made up of only the 'heavy quark' χ and the 'light quark' ϕ to a final density matrix made up of only the 'HF meson' ξ.
- $\mathcal{Q}$: A special limit of *quantum collision models* in open quantum systems. [Ciccarello et al., Phys. Rep. 954 (2022)]
- In our context, $\mathcal{Q}$ can be thought of in 2 ways: i) An open EFT, ii) a generalisation of the S-Matrix.

Quench = Open EFT

- $\mathcal{Q}$: Effect induced by integrating out the complicated environment surrounding ϕ and χ (e.g gluons, photons, leptons, et cetera).
- These effects can be accounted for by systematically adding couplings between ξ, ϕ and χ in the quench superoperator.
- This is like setting up an open EFT to describe hadronisation in this toy model.

- $\mathcal{Q}$: A generalisation of the S-Matrix for open systems.
- S-Matrix: Asymptotically free states come in, interact in a complicated way at an instant and then go away as asymptotically free states again.
- However, the S-matrix is *unitary*: Always takes pure states to pure states.
- $\mathcal{Q}$ too converts in-states to out-states, but can also describe non-unitary processes; can take pure states to mixed states, mixed states to other mixed states.

The Schwinger-Keldysh generating functional

- The central object to calculate is the Schwinger-Keldysh (SK) generating functional with a quench insertion:

$$Z_{\mathcal{Q}}\left[\, J^{\xi}_{2R/2L}\,,\; J^{\phi}_{1R/1L}\,,\; J^{\chi}_{1R/1L}\,\right]$$

$$= \mathrm{Tr}\left[\; U[J^{\xi}_{2R}]\;\mathcal{Q}\left\{U[J^{\phi}_{1R},J^{\chi}_{1R}]\;\rho_{\phi,\chi}(t_i)\;U^{\dagger}[J^{\phi}_{1L},J^{\chi}_{1L}]\;\right\}\;U^{\dagger}[J^{\xi}_{2L}]\;\right].$$

- Input needed: A model for the superoperator $\mathcal{Q}$.
- EFT inspired model - In $\mathcal{Q}$, add all possible terms upto a certain degree, consistent with symmetries dictated by the problem.

Hermiticity and trace-preservation

- Calculation best done in the coherent basis of the fields.
- Expressed in this basis, $\mathcal{Q}$ assumes the form:

$$\mathcal{Q} \equiv \mathcal{Q}\left(\xi^*_{fR}, \tilde{\xi}^*_{fR}, \xi_{fL}, \tilde{\xi}_{fL} \,\middle|\, \phi_{iR}, \tilde{\phi}_{iR}, \chi_{iR}, \tilde{\chi}_{iR}, \phi^*_{iL}, \tilde{\phi}^*_{iL}, \chi^*_{iL}, \tilde{\chi}^*_{iL}\right).$$

  We call the above the quench kernel.
- To start, a couple of reasonable demands on the quench:

  Hermiticity-preservation: Given a Hermitian density matrix as input, it should take it to another Hermitian density matrix:

$$\mathcal{Q} = [\mathcal{Q}]^*_{L\leftrightarrow R}.$$

  Trace-preservation: It should preserve the trace of the density matrix it acts on (conservation of probability).

Imposing symmetries on $\mathcal{Q}$

- **U(N) colour symmetry:** Invariance under fundamental U(N) colour rotations:

$$\phi^a \mapsto U^a{}_b\, \phi^b \ \ , \ \ \tilde{\phi}_a \mapsto (U^*)_a{}^b\, \tilde{\phi}_b,$$

$$\chi^a \mapsto U^a{}_b\, \chi^b \ \ , \ \ \tilde{\chi}_a \mapsto (U^*)_a{}^b\, \tilde{\chi}_b,$$

$$\xi \mapsto \xi \ \ , \ \ \tilde{\xi} \mapsto \tilde{\xi}.$$

- **U(1) heavy flavour symmetry:** Invariance under U(1) rotations of the heavy quark coherent variable:

$$\chi^a \mapsto e^{-i\theta}\, \chi^a \ \ , \ \ \tilde{\chi}_a \mapsto e^{i\theta}\, \tilde{\chi}_a,$$

$$\xi \mapsto e^{-i\theta}\, \xi \ \ , \ \ \tilde{\xi} \mapsto e^{i\theta}\, \tilde{\xi}.$$

- **U(1) light flavour symmetry:** Invariance under U(1) rotations of the light quark coherent variable:

$$\phi^a \mapsto e^{-i\alpha}\, \phi^a \ \ , \ \ \tilde{\phi}_a \mapsto e^{i\alpha}\, \tilde{\phi}_a$$

$$\xi \mapsto e^{i\alpha}\, \xi \ \ , \ \ \tilde{\xi} \mapsto e^{-i\alpha}\, \tilde{\xi}.$$

Quench at quadratic level

- For a clear understanding, think of the complex scalar fields ξ, χ and ϕ as being complex SHOs for the moment.
- In this simpler SHO model, the quench kernel at quadratic level:

$$\mathcal{Q}^{(2)} = N_{\mathcal{Q}} \; \exp\Big[\, \phi_{iR}\, \phi^*_{iL} + \tilde{\phi}_{iR}\, \tilde{\phi}^*_{iL} + \chi_{iR}\, \chi^*_{iL} + \tilde{\chi}_{iR}\, \tilde{\chi}^*_{iL} + \sigma_\xi\, \xi_{fL}\, \tilde{\xi}_{fL} + \sigma^*_\xi\, \xi^*_{fR}\, \tilde{\xi}^*_{fR} + \lambda_\xi\, \xi_{fL}\, \xi^*_{fR} + \tilde{\lambda}_\xi\, \tilde{\xi}_{fL}\, \tilde{\xi}^*_{fR} \Big],$$

- **Hermiticity-preservation:** $\{\, N_Q\,,\, \lambda_\xi\,,\, \tilde{\lambda}_\xi \,\} \in \mathbb{R}$.
- **Trace-preservation:**
    - 4 couplings are simply 1.
    - $N_{\mathcal{Q}} = (1 - \lambda_\xi)(1 - \tilde{\lambda}_\xi) - |\sigma_\xi|^2$.

$\mathcal{Q}^{(3)} = \exp\left[\, q^{(3)} \,\right]$ with the terms in $q^{(3)}$ being:

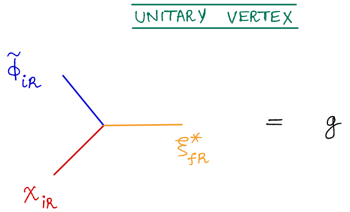
UNITARY COUPLINGS

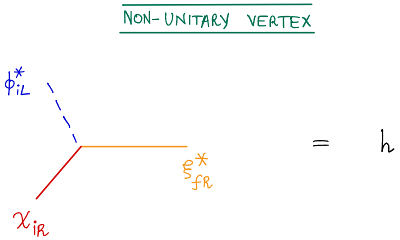
SNO.	TERM
1	$g\, \xi^*_{fR}\, \tilde{\phi}_{iR}\, \chi_{iR} + h.c$
2	$\tilde{g}\, \tilde{\xi}^*_{fR}\, \phi_{iR}\, \tilde{\chi}_{iR} + h.c$

NON-UNITARY COUPLINGS

SNO.	TERM
1	$h\, \xi^*_{fR}\, \phi^*_{iL}\, \chi_{iR} + h.c$
2	$\tilde{h}\, \tilde{\xi}^*_{fR}\, \tilde{\phi}^*_{iL}\, \tilde{\chi}_{iR} + h.c$
3	$\kappa\, \xi^*_{fR}\, \tilde{\phi}_{iR}\, \tilde{\chi}^*_{iL} + h.c$
4	$\tilde{\kappa}\, \tilde{\xi}^*_{fR}\, \phi_{iR}\, \chi^*_{iL} + h.c$
5	$y\, \xi^*_{fR}\, \phi^*_{iL}\, \tilde{\chi}^*_{iL} + h.c$
6	$\tilde{y}\, \tilde{\xi}^*_{fR}\, \tilde{\phi}^*_{iL}\, \chi^*_{iL} + h.c$

Examples of some Feynman diagrams:





Relations between couplings

- Trace-preservation imposes a set of coupled, non-linear equations linking the cubic couplings.
- **Example:** Continuing with the simpler complex SHO model:

$$(1-\tilde{\lambda}_\xi)\,|g|^2 + \sigma_\xi\, g\,\tilde{y} + \sigma_\xi^*\, g^*\,\tilde{y}^* + (1-\lambda_\xi)\,|\tilde{y}|^2 = 0,$$

$$(1-\tilde{\lambda}_\xi)\, g\, y^* + \sigma_\xi\, g\,\tilde{g} + \sigma_\xi^*\, y^*\,\tilde{y}^* + (1-\lambda_\xi)\,\tilde{g}\,\tilde{y}^* = 0,$$

$$(1-\tilde{\lambda}_\xi)\,|h|^2 + \sigma_\xi\, h\,\tilde{\kappa} + \sigma_\xi^*\, h^*\,\tilde{\kappa}^* + (1-\lambda_\xi)\,|\tilde{\kappa}|^2 = 0$$

$$\vdots$$

- Total: 6 complex equations and 4 real equations.

Ongoing and future work

- **Ongoing:** Calculating the SK generating functional perturbatively in the cubic couplings of the quench.
- **Future:**
  - Relate this toy model to other hadronisation processes (instantaneous coalescence, fragmentation).
  - Refine the model towards actual QCD.
  - 'Bootstrapping' the quench: Can we reconstruct the quench couplings from the recombination probabilities $\mathcal{C}$? Would be another way to 'probe' the QGP.
- **Aside:** In another work, have succeeded in reconstructing a Gaussian quench which instantaneously takes a complex scalar field from the state (β_1, μ_1) to (β_2, μ_2) purely from field correlators across the quench.

Summary

- **Motivation**: In a toy model, calculate 'HF meson' number distributions in the final states for given 'heavy quark' and 'light quark' distributions in the pre-hadronisation phase - a probe into the QGP.
- **Strategy:**
  - Modelled hadronisation via a quench superoperator $\mathcal{Q}$.
  - Adopted an EFT approach to model $\mathcal{Q}$: Added terms to a certain degree (cubic) obeying general principles (hermiticity and trace-preservation) and symmetries ($U(N)_c$, $U(1)_H$, $U(1)_L$).
- **Ongoing:** Calculating the SK generating functional perturbatively in the cubic couplings.
- **Future:**
  - Refine and relate this toy model calculation to other hadronisation approaches like instantaneous coalescence and fragmentation.
  - 'Bootstrapping' the quench: Can we reconstruct $\mathcal{Q}$ in terms of $\mathcal{C}$? If yes, that too would be a 'probe' into the QGP.