Strong and Electro-Weak Matter 2026
17–21 Aug 2026
Helsinki, Finland

Technische Universität München

Transport coefficients for Lindbladian quarkonium evolution in quark–gluon plasma

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Based on: JHEP08(2025)219 + ongoing work

T30f
Theoretische Teilchen- und Kernphysik

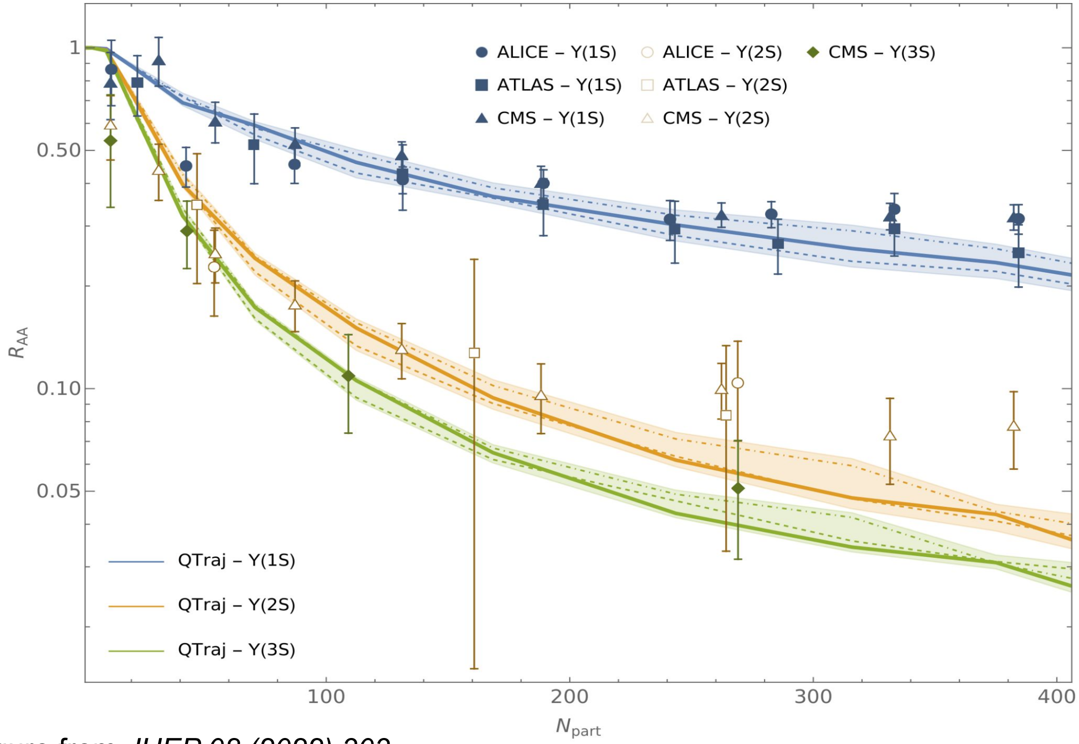
ORIGINS Excellence Cluster

Advanced Grant
EFT-XYZ

Quarkonium in QGP

Matsui and Satz (1986): Quarkonium is an ideal probe of quark-gluon plasma (QGP) → Formed early in a heavy ion collision → sensitive to the medium → Decays to dileptons. [*Phys. Lett. B178, 416 (1986)*]

Measurement of interest: Nuclear modification factor



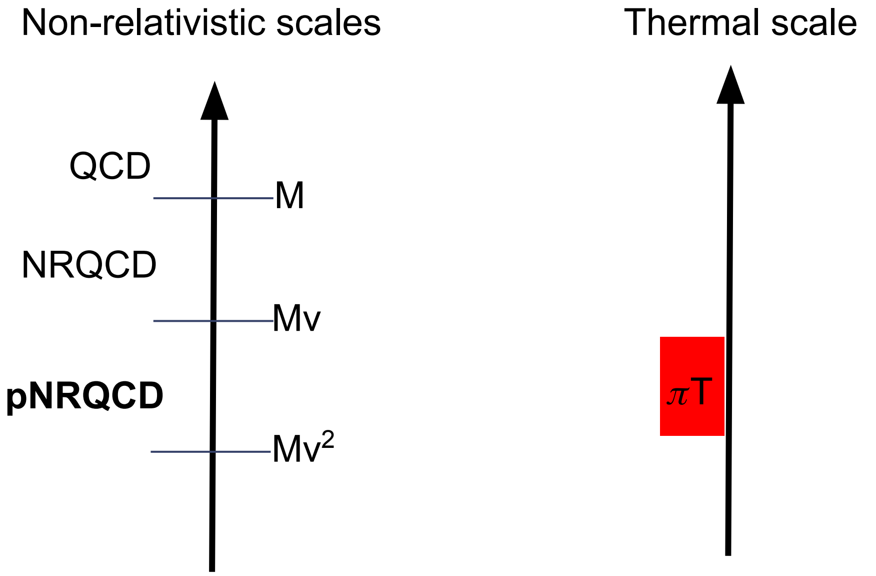
How does the QGP enter the real-time evolution of quarkonium?

Figure from *JHEP 08 (2022) 303*

Theory I: pNRQCD

A first principles treatment is **very** difficult: **Quarkonium** in **QGP** → several scales involved

A **hierarchical** separation of scales → Effective field theory (for Bottomonium (Υ))



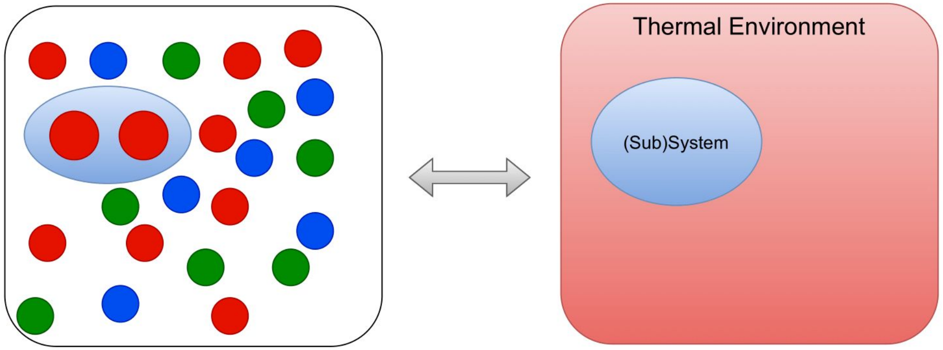
pNRQCD: Quarkonium in Singlet (S) or an Octet (O) configuration

Here interested in: $M \gg Mv \sim 1/r \gg T \gg Mv^2 \sim E, gT$ ➡ **Weakly-**coupled QGP

[*Phys.Lett.B 167 (1986) 437-442, Phys.Rev.D 51 (1995) 1125-1171 , Nucl.Phys.B 566 (2000) 275, Rev.Mod.Phys. 77 (2005)*]

Theory IIa: Lindladian Evolution

Out-of-equilibrium evolution of quarkonium in QGP, treated in Open quantum systems (OQS) framework



Interested in the evolution of quarkonium density matrix.
Leads to a **Lindblad** (real-time) equation:

$$\frac{\mathrm{d}\rho_S(t)}{\mathrm{d}t} = -i\left[H_S + \Delta H_S, \rho_S(t)\right] + \kappa_X \left(L_{ai}\rho_S(t)L_{ai}^\dagger - \left\{L_{ai}^\dagger L_{ai}, \rho_S(t)\right\}\right)$$

with $\Delta H_S \propto \gamma_X$

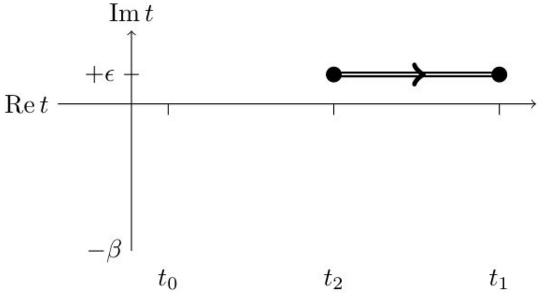
[*Brambilla et al,Phys.Rev.D 96 (2017) 3, Yao et al.,Phys.Rev.D 108 (2023) 5, 054024,Phys.Rev.D 109 (2024) 9, 099902 (erratum)*]

Theory IIb: Transport Coefficients

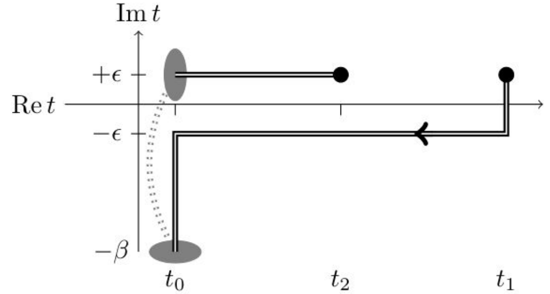
Medium modifications to quarkonium evolution is quantified by **transport coefficient $\boldsymbol{\kappa}_X$** governing the transition rates and its dispersive counterpart γ_X are written in terms of real time correlators

$$\boxed{\frac{g^2}{6N_c} r_i \int_0^\infty \mathrm{d}s\, D_X^{>\dagger}(s) = \kappa_X + i\gamma_X}$$

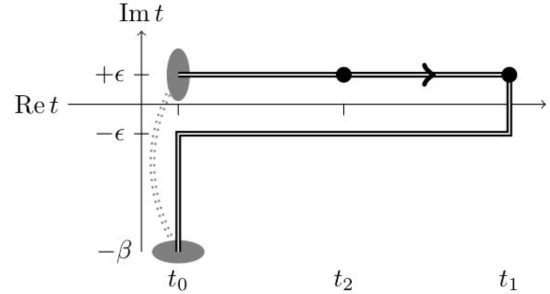
where X identifies the **three different channels.**



Singlet → Octet [1]



Octet→ Singlet* [2]



Octet→ Octet [3]

Octet sector $\rho_E^{ab} \propto W^{ab}(t_0 - i\beta, t_0)$
→ Motivates normalisation necessary for lattice computations

*[*Yao et al JHEP 02 (2021) 062*]
[*Brambilla, Escobedo,* ***P. P.****, Vairo, Vander Griend, to appear soon*]

Theory IIc: Euclidean Correlators

Can be analytically continued to Imaginary time [*Brambilla, Escobedo,* ***P. P.****, Vairo, Vander Griend, to appear soon*]
→ Three distinct gauge invariant **Euclidean** chromoelectric correlators → Allow for direct contact with Lattice QCD

We focus on:

[1] $$\langle EE\rangle_U \equiv -\langle g_s E_i^a(0) U^{ab}(0,\tau) g_s E_i^b(\tau)\rangle$$

[2] $$\langle EE\rangle_L \equiv -\langle g_s E_i^b(0) g_s E_i^a(\tau) U^{ab}(\tau,1/T)\rangle$$

[3] $$\langle EE\rangle_S \equiv -\langle g_s E_i^{ab}(0) U^{bc}(0,t) g_s E_i^{cd}(\tau) U^{da}(\tau,1/T)\rangle$$

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$$U^{ab}(t,t') \equiv \left[\mathrm{P}\exp\left(-ig_s\int_t^{t'}\mathrm{d}t''A_0(t'')\right)\right]^{ab}$$

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We focus on:

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[2] $\langle EE \quad \ldots \quad)\rangle$

[3] $$\langle EE\rangle_S \equiv -\langle g_s E_i^{ab}(0)U^{bc}(0,t)g_s E_i^{cd}(\tau)U^{da}(\tau,1/T)\rangle$$

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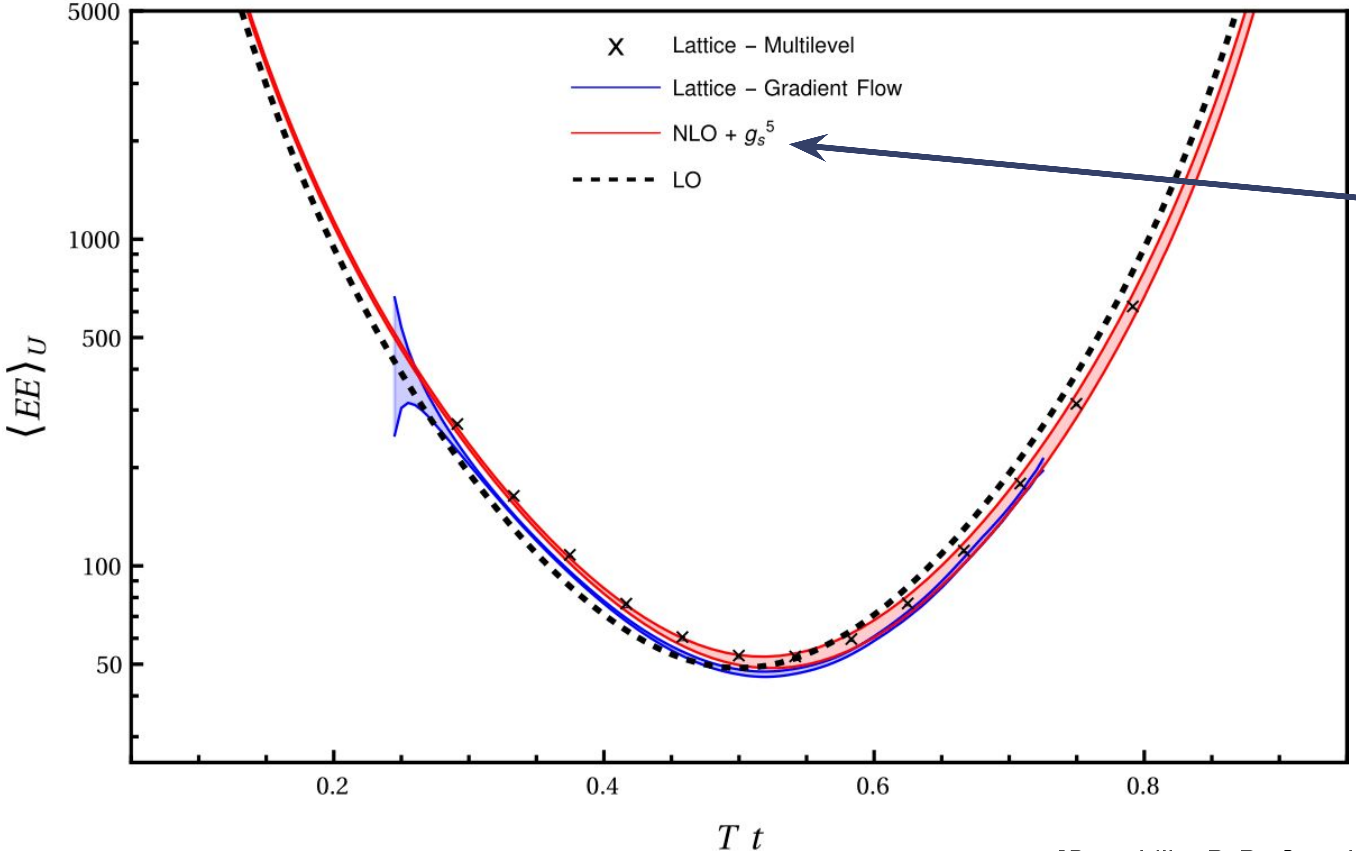
<EE> correlator also on the Lattice

Comparing **upper** correlator at a **very high** Temperature $T = 10^4\,T_c,\ \ N_f = 0$ [*TUMQCD 2505.16603*]



Our Result

[*Brambilla, **P. P.**, Säppi, Vairo, JHEP08(2025)219*]

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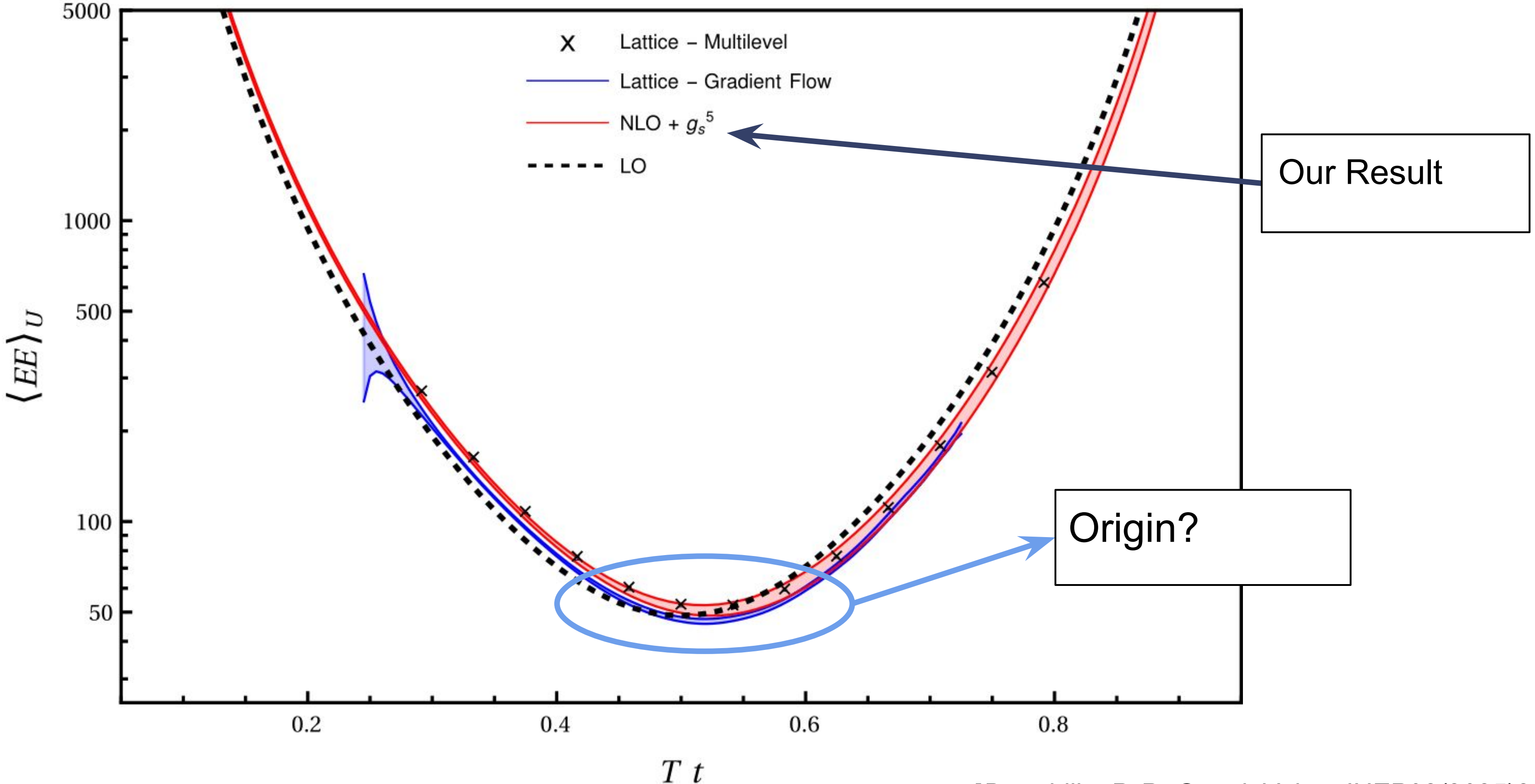
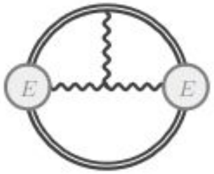


[*Brambilla*, ***P. P.***, *Säppi, Vairo, JHEP08(2025)219*]

Asymmetry and its impact

Key result: Two loop integrals can be **factorised….**
[See *Davydychev and Schröder JHEP 12 (2022) 047, Davydychev et al., JHEP 02 (2024) 104*]

… but **one** non-factorizable integral contains term proportional to **length of Wilson line**



Spectral function:
Upper and Lower correlators can be split into a symmetric and antisymmetric part

$$\langle EE\rangle_U = \langle EE\rangle_U^{\mathrm{Asym}} + \langle EE\rangle_U^{\mathrm{Sym}}$$

The symmetric part equivalent to *Burnier et al., JHEP 08 (2010) 094* up to color factors.
Antisymmetric part gives an **even** contribution

$$\boxed{\rho^{Asym} \propto |\omega|^3}$$

Consequence: Up to color scaling, heavy quarkonium diffusion coefficients, are all the same up to **NLO**

$$\kappa_X = \lim_{\omega\to 0} \frac{2T\rho}{\omega}$$

Quarkonium Mass shift – **Preliminary!**

In-medium Quarkonium mass shift: Definition through γ_U in pNRQCD+OQS

$$\delta M(1S) = \frac{3}{2} r^2 \gamma_U$$

Can be formally expressed in terms of the spectral function

$$\gamma_U = -\frac{g^2}{6N_c} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{\pi} \mathcal{P} \frac{1+n_B(\omega)}{\omega} \rho(\omega)$$

Sensitive to the even part of the spectral function! Difference, $\Delta\gamma$,first found in
[*Eller et al, Phys.Rev.D 99 (2019) 9, 094042,Phys.Rev.D 102 (2020) 3, 039901 (erratum)*]

But: Using relations between moments of correlators and spectral function at **NLO(!)** we can write:

$$\gamma_U = -\frac{1}{6N_c} \int_0^{1/T} \langle EE \rangle_U^{\mathrm{Sym}}(\tau) \mathrm{d}\tau + \frac{1}{6N_c} \int_0^{1/T} 2T\tau \langle EE \rangle_U^{\mathrm{Asym}}(\tau) \mathrm{d}\tau$$

Can this be generalised beyond NLO? Is it useful for lattice?

[*Brambilla, **P. P.**, Säppi, Vairo, to appear*]

Conclusions

A) Three distinct gauge-invariant correlators arise from Lindblad evolution.

B) At NLO, two are asymmetric over the thermal circle, but the asymmetry does not modify κ.

C) The asymmetry contributes to γ, which at NLO can be expressed through moments of the Euclidean correlator.

Conclusions

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Thank you!

BACKUP SLIDES

Quarkonium as an open quantum system I

There are **timescales** involved associated with

- System: $\tau_S \sim \frac{1}{E}$
- Environment: $\tau_E \sim \frac{1}{(\pi)T}$
- Interaction of (Sub)system with environment $\tau_I \sim \frac{1}{a_0^2\left((\pi)\,T\right)^3}$

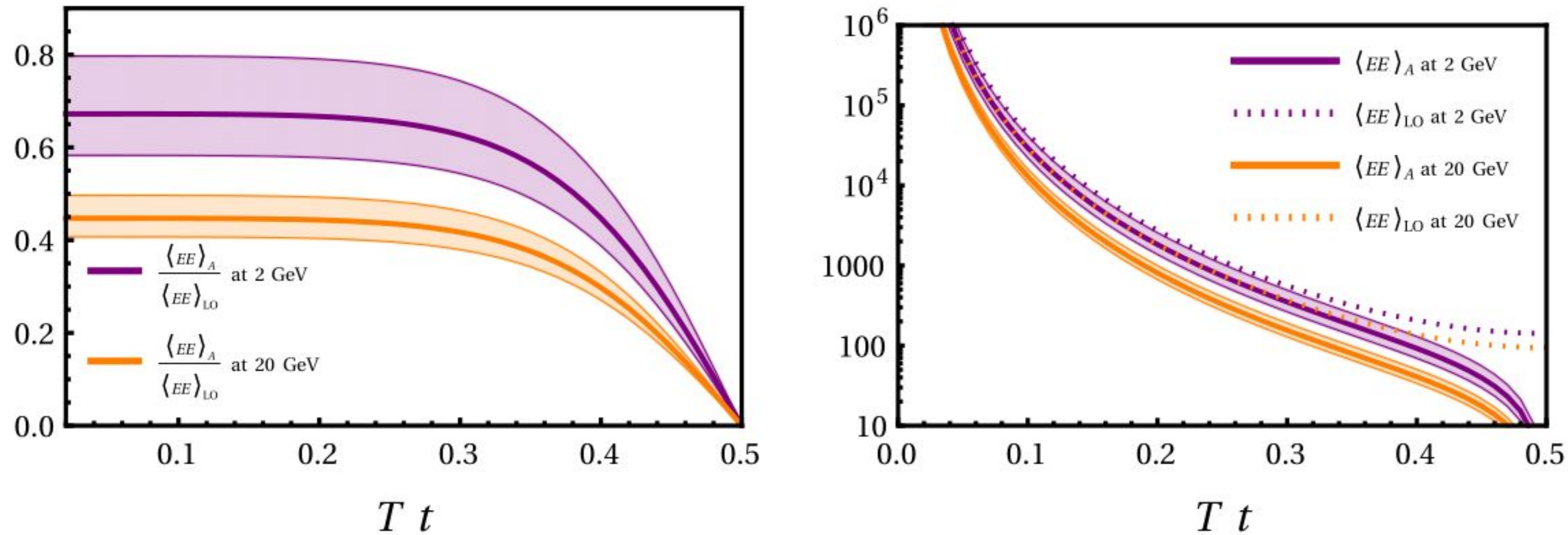
Interplay between timescales plays a role. Set by chosen hierarchy of scales

$$\tau_I \gg \tau_E \qquad \tau_S \gg \tau_E$$

Known as Quantum Brownian limit.

Adjoint correlator is asymmetric

Left Panel: Normalised asymmetric contribution at T = 2, 20 GeV
Right Panel: Comparison of LO and asymmetry at T = 2, 20 GeV



$N_f = N_c = 3$

Real-time Correlators and normalization

Total density matrix has unit trace → Provides necessary normalization for $Z_{s/o}$

$$Z_o = \langle W^{aa}(t_0 - i\beta t_0)\rangle Z_s$$

This leads to real-time correlators

[1] $$\langle EE\rangle_U(t) = \mathrm{e}^{-i\delta h_\Lambda t}\left\langle E_i^a(t) W^{ab}(t,0) E_i^b(0)\right\rangle$$

[2] $$\langle EE\rangle_L(t) = \frac{\mathrm{e}^{i\delta h_\Lambda t}\left\langle W^{da}(-\infty - i\beta, -\infty) W^{ab}(-\infty, t) E_i^b(t) E_i^c(0) W^{cd}(0,-\infty)\right\rangle}{\langle W^{aa}(-\infty - i\beta, -\infty)\rangle}$$

[3] $$\langle EE\rangle_S(t) = d^{bcd} d^{efg} \frac{\left\langle W^{ha}(-\infty - i\beta, -\infty) W^{ab}(-\infty, t) E_i^c(t) W^{de}(t,0) E_i^f(0) U^{gh}(0,-\infty)\right\rangle}{\langle W^{aa}(-\infty - i\beta, -\infty)\rangle}$$