

Strong dynamics without approximation

Anthony Francis

Introduction

Theoretical High Energy Physics - Anthony Francis

Particle Physics, Lattice Gauge Theory and Quantum Computing



@NYCU since 2022

QCD is the theory of the strong force. It has the most unsolved problems in PP.
But, to understand the theory we have to run QCD simulations on the world's largest super computers - or perhaps soon quantum computers.

Research profile:

1. curious about the sub-atomic world and what all these quarks and gluons do.
2. interested in theoretical physics and computer science.
-> some knowledge of (at least python) programming or the will to learn it.

PP, LGT, QC and HPC:

- 博鈞張 - Could Dark Matter be like a dark QCD?
- 蘇川璋 - Can we develop a better (thermalization) algorithm for fine lattices?
- 盧泓均 - Is there a better (AI) algorithm for spin system simulations?
- 陳昱璋 - Can we get a quantum advantage for QCD problems at LHC?

Current members and projects:

Alumni projects:

Can scalar fields form resonances? Answer: Yes!
Are there diquarks in protons? Answer: Still open.

Your project?

Come by and say hi! The group is open to new members.

The big picture

Research statement in one sentence:

Research purely non-perturbative phenomena without approximation and their manifestation in the creation and interaction of matter.

Let's disentangle this a bit:

- Purely non-perturbative phenomena
 - Dynamics that cannot be addressed using perturbation theory.
 - That means physics were the **only alternative** is to use phenomenological or model building approaches.
 - Typically these are **strong dynamics** where $\alpha_{theory} = \mathcal{O}(1)$.
 - These is typically the physics of hadrons. That is, **well-defined** observables.
- Without approximation
 - Dynamics that **cannot be adequately described** using phenomenological or model building approaches.
 - **No compromises** on the description of the dynamics.
 - Methodological limitations need to be **systematically improvable**.
 - The only consistent theories where no approximations need to be made are usually **non-Abelian quantum gauge field theories**.
 - Lattice QFT is usually the only method that fulfills the criteria.

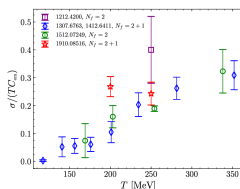
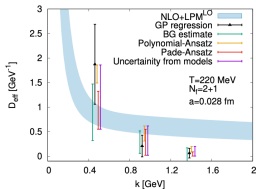
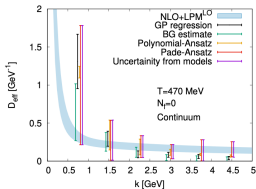
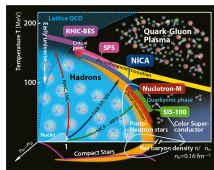
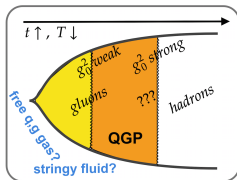
Research statement in one sentence:

Research purely non-perturbative phenomena without approximation and their manifestation in the creation and interaction of matter.

Let's disentangle this a bit:

o Manifestation in creation of matter

- Physics of the early universe, i.e. at **high temperatures** but not necessarily with a chemical potential or external fields.
- Connection to *Heavy-Ion Collision physics, cosmology and astrophysics*.

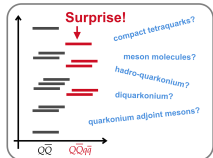
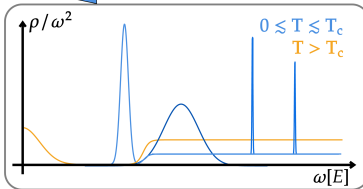
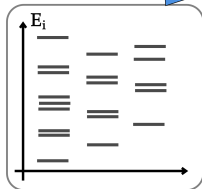
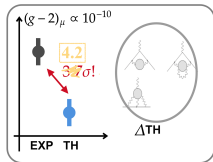
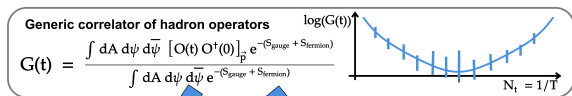


Research statement in one sentence:

Research purely non-perturbative phenomena without approximation and their manifestation in the creation and interaction of matter.

Let's disentangle this a bit:

- o Manifestation in the interaction of matter
 - High-energy, medium-energy and low-energy particle physics.
 - Connections to *Heavy hadrons and exotica, bound states and resonances, precision tests of the SM.*



Among the physics in this broad category my research focuses on:

Research that will **significantly impact** the community so that more research becomes possible **without further help from expensive lattice calculations**.

Calculations that can **confirm/exclude a phenomenological concept**. Enabling a more focused search for the community in future.

To not do everything on the lattice. That is not practical for several reasons, conceptual and logistical.

Precision calculations for which there is no other way of obtaining them and their impact would enable a **leap in knowledge**.

Four physics crises

In this subset of research problems, there are four main "crises" that I am working on:



Hard probes

- Transport coefficients (diffusion, conductivities) across the QCD phase transition.
- Dilepton and photon production rates in high temperature QCD.
- Formation and dissociation of hadrons across the QCD phase transition.



Bound states and resonances

- Heavy and exotic hadrons, especially doubly heavy tetraquarks.
- Multi-hadron states, e.g. dibaryons or, also, tetraquarks, and two-particle scattering states like the ρ -meson.



Precision tests

- Anomalous magnetic moment of the muon (coming to an end?).
Will skip this here. In short: Very closely related to the inverse problem.



Lattice technology

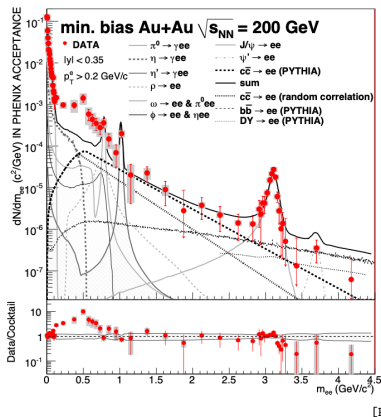
- Critical slowing down and masterfields.
- Availability of modern gauge ensembles in the public domain.



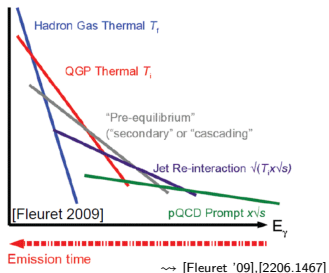
Identifying the problems - Hard probes

Probes of the quark gluon plasma

- Dileptons and photons are produced at all stages of Heavy-Ion Collisions.
- Weak coupling to QGP constituents
→ they decouple after production
→ probes of the full thermal medium evolution



Sketch of different photon sources



Thermal QCD goals

- thermal dileptons: understand contribution for $m_{ee} \sim 0.5$ GeV
- thermal photons: understand dominant contribution for $p_T \in [1 : 2]$ GeV



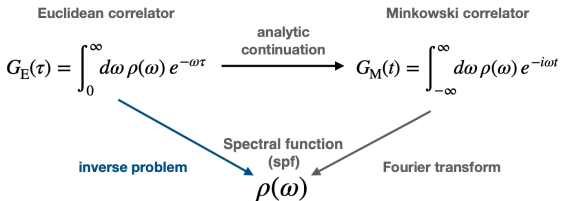
We are interested in three properties of the vector spectral function:



- conductivity: $\sigma_{el} \sim \rho^i_i(0, 0)$
- dilepton rate: $d\Gamma_{\ell^+\ell^-}(\mathcal{K}) \sim -\rho^\mu_\mu(\mathcal{K}) \rightsquigarrow \rho^\mu_\mu(\omega, \mathbf{k} = 0)$
- photon rate: $d\Gamma_\gamma(\mathbf{k}) \sim -\rho^\mu_\mu(k, \vec{k}) \rightsquigarrow \rho^\mu_\mu(\omega = k, \mathbf{k} \neq 0)$

note: $\rho^0_0(0, 0) = \text{const.} =: \chi_q$

The most interesting are in the low-energy, non-perturbative regime of QCD.



We want to extract the spf from the Euclidean correlator calculated in lattice QCD/
 \Rightarrow This is an **ill-conditioned/posed inverse problem**.



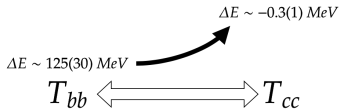
The T_{cc} discovery and the T_{QQ} family

- o At the time, lattice QCD and phenomenology discussion* on doubly heavy tetraquarks like:

$$T_{QQ} \rightsquigarrow \bar{q}q'QQ, J^P = 1^+ \text{ or } 0^-$$

- o Motivated binding mechanism in $J^P = 1^+$.
- o **Phenomenology:** indications of bound T_{bb}^{ud} .
- o **Lattice:** indications of bound T_{bb}^{ud} and T_{bb}^{us} .

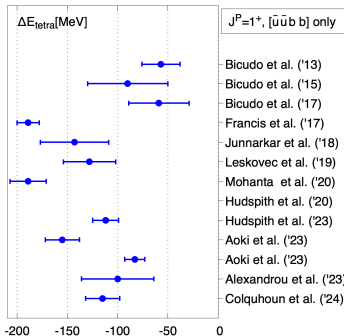
But: +++ How do we get from T_{bb} to T_{cc} ? +++



- How and does the binding mechanism change?
- What are the relevant dynamics?
- What are the other family members?
- What are their properties?

⇒ Use the freedom of the lattice to dial through different quark masses!

Current T_{bb} status



Recently gathered in: PPNP 140 (2025) 104143

*Discussion in pheno and lattice: Pheno: *Karliner, Rosner ('17); Eichten, Quigg ('17); Czarnecki, Leng, Voloshin ('18); Mehen ('17); Maiani ('19)*, Lattice: *AF ('16-'24); Bicudo, Wagner ('11-'22); Mathur ('18); Prelovsek, Manugopalan ('22), and more...*

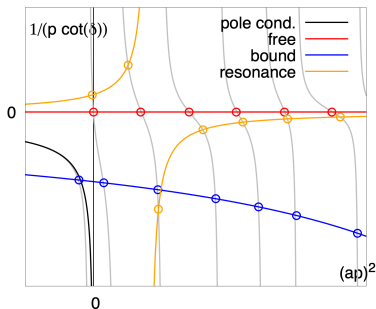
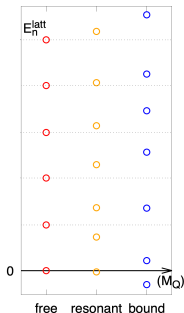


Absolutely mandatory for T_{QQ} studies

Finite volume / Scattering analysis

Limitation: Small GEVP without f.vol analysis ok for deeply bound states.
 Insufficient to tell apart free, resonant or virtual bd. states.

Extension: Connect energies to scattering phase shifts via finite volume quantisation conditions (Lüscher-formalism).



- o connect (many) f.vol states to scattering parameters (sketch: BW)
- o resonance: extra state(s) appear, lowest state close to threshold



Identifying the problems - Lattice technology

Lattice QCD as an engine to progress

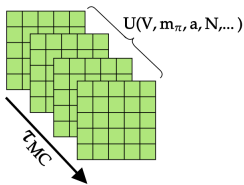
with impacts on (selection)

- | | |
|--------------------|--------------------|
| - HVP and HLBL, | - QCD Spectrum, |
| - Resonances, | - 2-,3-Scattering, |
| - Decay Constants, | - Exotic Hadrons, |
| - Form Factors, | - Matrix elements, |
| - CKM Matrix, | - BSM / DM, ... |



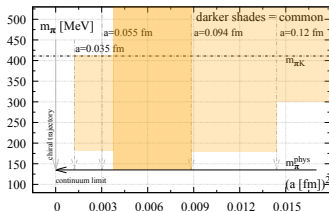
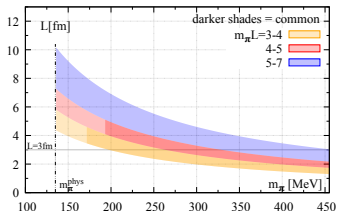
Successes have been possible due to:

- Improved theoretical tools and understanding.
- Gauge configurations that enable controlled extrapolations for:
 - chiral / quark mass effects
 - finite size / volume effects
 - discretisation effects and continuum limit



- Configurations generated via Markov Chain Monte Carlo:
 - Many samples to reduce *statistical uncertainties*
 - Long trajectories to control *auto-correlations*
- "New physics": With a good set of configurations more research areas open up.

The quantity and quality of the set of configurations drives the accessible precision.



With a good set of configurations precision becomes accessible. **But:**

(1.) Discretisation / Volume effects: Continuum extrapolation not always clear.

- Cost bound on finest $[a]$ due to lower bound V constraints. ($L=3$ fm and $m_\pi L \sim 4$ hard to fulfil)
- Cost bound on largest V . ($m_\pi L \geq 6$ hard to reach)

(2.) Stability issues: $m_\pi \rightarrow m_\pi^{\text{phys}}$ increases numerical problems associated with generation as fluctuations go with $\mathcal{O}(1/m_\pi, a)$.

- Algorithmic bound on m_π at given $[a]$. (Coarse $[a]$ = hard to go light)
- Smearing? Not a silver bullet.

(3.) Critical slowing down: As $[a] \downarrow$ the topology tunneling probability drops.

- Topology bound on $[a]$. (Topology freezes \rightarrow autocorrelation explodes)
- Frozen topology induces $\propto Q/V$ contamination of observables.

\rightsquigarrow some dependence on action for these statements.



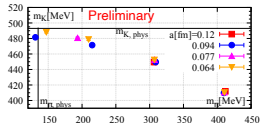
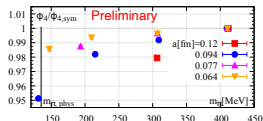
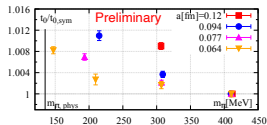
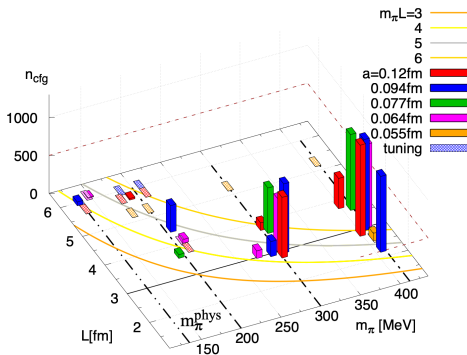
Open lattice initiative - Est. 2019

Motivation:

- Quantity and quality of ensembles drives precision.

OpenLat: Generate and share configurations with community.

- ⇒ Develop new, complementary, actions and algorithms.
- ⇒ Use and benefit from (and be ready for) new developments in the community.
- ⇒ Provide all the basic auxiliaries (rwf, m_π , f_π , Z_A , ...) for broad use in ILDG.

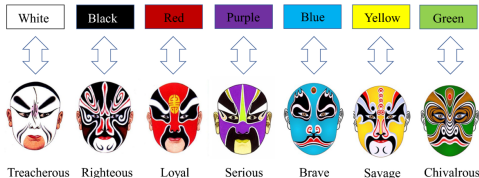


Pushing boundaries

My interests are in non-perturbative dynamics without approximation.

Lattice QFT poses some unique limitations:

- MCMC cannot deal with complex valued actions.
- This forbids studies at finite baryon density.
External \vec{B} fields and similar are possible, but finite μ_B is more important.
- It is also not possible to study real-time evolution.
This is at the root of the inverse problem.
- The calculations are numerical, in a finite volume at finite lattice spacing.
Need to control many systematics. (But: The dynamics is the dynamics.)



Yan et al. (2023), "Intelligent generation of Peking opera facial masks with deep learning frameworks".

Pushing boundaries

My interests are in non-perturbative dynamics without approximation.

How can I improve? Several active paths:

On the side of the observable and systematics:

- Actively searching for better methods for the inverse problem.
- Looking for observables that avoid it. (Good example is the skipped a_{μ}^{HLO} .)
- Can machine learning be used to improve the covariance estimators?
- Multi-level methods improve the signal as expected? (Hung-Chun Lu, TPS 2026)
- Machine learning for heavy quark parameters? (Thamyris de Oliveira, →Wed.)

On the side of lattice technology:

- Better thermalization strategies for fine lattices? (Chuan-Wei Su)
- Multi-scale methods? Improved actions and update setups?
- OpenLat ensemble generation and planning.

Outside of lattice technology:

- Quantum Machine Learning for data generation?
- Quantum Computing for classification problems? (Yu-Zhang Chen, grad. 2025)

謝謝
Thank you!

