Using Lattice QCD to search for physics beyond the standard model

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Graduate Students

- Mackenzie Barton-Rowledge (Nelson/Sanjay Reddy): neutron stars
- John Fuini (Yaffe): studying quark-gluon plasma using “applied string theory”
- Akshay Ghalsasi (Nelson): cosmological applications of particle theory
- Kira Hicks (Nelson): (just starting)
- Derek Horkel (Sharpe): effective field theory applied to lattice QCD, ...
- Brandon Robinson (Karch): applied string theory=holography, wormholes
Postdocs

* David McKeen: Beyond the Standard Model Phenomenology & Cosmology
* Christoph Uhlemann: string theory, holography
Standard model is successful ...

Particles of the Standard Model (a quantum field theory)
... but many questions remain

Why the pattern of masses & mixings?
What lies beyond the SM, at the TeV+ scale?
How can gravity & QM be combined?
...particularly in cosmology

- What are dark matter & dark energy?
- What is the mechanism of baryogenesis (which requires new sources of CP violation)?
Bottom-up approach

✦ Search for new physics by looking for small deviations from the Standard Model
✦ E.g. CP violation in $D \rightarrow \pi \pi$

Does experiment (future LHCb) agree with SM prediction (future lattice QCD)?
Theorist's task

- Understand & calculate properties of strongly coupled theories, e.g. QCD

![Diagram showing the behavior of \( \alpha(\mu) \) as a function of \( \mu/\Lambda \).](chart)

- Quarks confined in hadrons
- quark & gluon jets

Perturbation theory fails at strong coupling

\( \mu = 1 \text{ GeV} \)
\( \mu = 300 \text{ GeV} \)

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\( \mu = 1 \text{ GeV} \)

\( \mu/\Lambda \)

\( \alpha(\mu) \)

SF scheme, \( N_f=2 \)

-3-loop

ALPHA collaboration
Only first-principles method: Lattice QCD

- Use Feynman path integral implemented by Monte-Carlo
- Requires supercomputers and a lot of auxiliary QFT calculations
- My present focus: developing finite-volume QFT tools for extracting multiparticle decays, e.g. $D \rightarrow \pi \pi$, $4\pi$, $KK$, $\eta$, ...

Finite box ~3-6 fm across “femto-world”
Postdiction: hadron spectrum

Lattice QCD results have \(\sim\)percent accuracy, and reproduce experimentally measured spectrum (and many other quantities)
Example of my present research

Ongoing projects with ex-student Max Hansen & others

* How can we calculate three (or more) particle interactions and decay rates ($K \rightarrow 3\pi$) using LQCD?

* LQCD can calculate numerically energies of multiple particles in a finite box (3-6fm across!), but how do we go from these results to scattering amplitudes?

* This is a finite-volume QFT problem
Example of my present research

✦ Long solved for 2 particles, and now used in practice
✦ We solved for 3 identical spinless particles

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Relativistic, model-independent, three-particle quantization condition

Expressing the three-particle finite-volume spectrum in terms of the three-to-three scattering amplitude

Perturbative results for two and three particle threshold energies in finite volume

Maxwell T. Hansen* and Stephen R. Sharpe†

✦ Now we need to generalize, remove simplifying assumptions, and turn into a practical tool
✦ Numerical results are ahead of theory—much to do!
Example of my present research

Requires all-orders analysis of finite-volume Feynman diagrams, separating off volume dependence

\[ C_L(E, \tilde{P}) = \cdots \]
Example of my present research

Final result looks pretty simple

The finite-volume spectrum is determined by

$$\det \left[ 1 + F_3 \mathcal{K}_{df,3} \right] = 0,$$

where the determinant is over the direct product space just introduced. The matrix $F_3$ is

$$F_3 \equiv \frac{F}{2\omega L^3} \left[ -\frac{2}{3} + \frac{1}{1 + [1 + \mathcal{K}_{2G}]^{-1} \mathcal{K}_{2F}} \right],$$

where

$$\left[ \frac{1}{2\omega L^3} \right]_{k',\ell',m';k,\ell,m} \equiv \delta_{k',k} \delta_{\ell',\ell} \delta_{m',m} \frac{1}{2\omega_k L^3},$$

$$G_{p,\ell',m';k,\ell,m} \equiv \left( \frac{k^*}{q_p^*} \right)^\ell' \frac{4\pi Y_{\ell',m'}(\bar{p})H(\bar{k})H(\bar{k})Y_{\ell,m}(\bar{p}^*)}{2\omega_{kp}(E - \omega_k - \omega_p - \omega_{kp})} \left( \frac{p^*}{q_k^*} \right) \frac{1}{2\omega_k L^3},$$

$$F_{k',\ell',m';k,\ell,m} \equiv \delta_{k',k} F_{\ell',m';\ell,m}(\bar{k}),$$

$$F_{\ell',m';\ell,m}(\bar{k}) = F_{\ell',m';\ell,m}(\bar{k}) + \rho_{\ell',m';\ell,m}(\bar{k}),$$

$$F_{\ell',m';\ell,m}(\bar{k}) = \frac{1}{L^3} \sum_{\bar{a}} - \int_{\bar{a}} \frac{4\pi Y_{\ell',m'}(\bar{a}^*)Y_{\ell,m}(\bar{a}^*)H(\bar{k})H(\bar{a})H(\bar{b}_{ka})}{2\omega_a 2\omega_{ka}(E - \omega_k - \omega_a - \omega_{ka} + i\epsilon)} \left( \frac{a^*}{q_k^*} \right)^{\ell + \ell'},$$
A typical student timeline in PT

- **Year 1**: PT Journal club in spring & independent study in summer
- **Year 2**: Take QFT, particle physics, group theory,...; continue indep studies (try several faculty?); warm up research project towards end of year/summer;
- **Year 3**: (hopefully) start of partial RA support, research kicks into high gear; take general exam
- **Year 4**: key year for research productivity as applications for postdocs occur in the fall of...
- **Year 5**: give seminars, get a postdoc offer in January, write thesis in spring, graduate in spring/summer
If you are interested, please note:

* Faculty & research jobs are scarce in PT

  Do you like theory so much to put up with job insecurity for the next ~10 years, with possible postdocs in distant places?

  However, PT PhDs who leave the field find interesting gainful employment (finance, bioinformatics, teaching,...)

* Need to love the field, be inspired by it, and “let the chips fall where they may”

  Great place to dip your toe into the field is to attend the (student run) PT Journal Club next quarter or in the spring. Can sit and listen. Once in the PT group, you’ll typically give one self-taught talk each quarter.

* Expect a mix of pen-paper and numerical calculations in most projects
Openings? Who is graduating?

2016: Fuini (Yaffe), Ghalsasi (Nelson) & Horkel (Sharpe)
2017: Robinson (Karch), Barton-Rowledge (Nelson)?

I am looking for a new student now!
Where do students go?

* 2015: Seyda Ipek (Nelson) → postdoc at FermiLab
* 2015: Bridget Bertoni (Nelson/Reddy) → postdoc at Stanford
* 2014: Han-Chih Chang (Karch) → postdoc at U. Virginia
* 2014: Max Hansen (Sharpe) → postdoc at U. Mainz
* 2014: Stefan Janiszewski (Karch) → postdoc at U. Victoria
* 2013: Jakub Scholtz (Ellis/Nelson) → postdoc at Harvard
* 2010: Kristen Jensen (Karch) → U. Victoria → Stony Brook → SFSU (faculty)
* 2010: Andrew Lytle (Sharpe) → Southampton (UK) → Tata Inst. (Mumbai) → Glasgow
* 2010: Steve Paik (Strassler/Karch) → faculty, Santa Monica College
* 2010: Ethan Thompson (Strassler/Karch/Yaffe) → Inst. of Systems Biology
* 2010: Chris Vermillion (Ellis) → U. Louisville → tech. start-up company
* 2010: Jon Walsh (Ellis/Nelson) → LHC postdoc at Berkeley