Redefining B-Physics Precision: A Continuum Limit Strategy for Improved Standard Model Predictions

B-physics from the continuum limit of lattice gauge theory observables

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In Short

- Develops a new strategy to compute B-meson observables with controlled uncertainties.
- Interpolates between relativistic simulations and static effective theory in the continuum.
- Targets two key quantities: the b-quark mass and $B \to \pi\ell\nu$ form factors relevant for extracting $|V_{ub}|$.
- Relies on fine lattice spacings and large physical volumes, achievable only on HPC systems.
- Results will inform LHC and B-factory experiments, setting a new standard in lattice B-physics.

The Standard Model (SM) of particle physics has proven extraordinarily successful in describing the behaviour of fundamental particles and interactions. Yet, some of its key predictions—such as those involving the b-quark, a building block of B mesons—are currently limited by our ability to perform precise theoretical calculations. Such calculations rely on Quantum Chromodynamics (QCD), the theory of strong interactions. At the low-energy regime relevant for hadronic physics, QCD is dominated by non-perturbative dynamics, rendering traditional perturbative methods inapplicable.

This is where lattice QCD becomes essential: by formulating QCD on a discretized space-time lattice, it becomes possible to determine physical observables from first principles via numerical simulations. However, reaching the precision required for high-impact predictions—like the mass of the b-quark or the decay properties of B mesons—remains a challenge. Our project addresses this challenge with a new computational strategy that combines two complementary approaches and is designed from the ground up to control all major sources of uncertainty.

What are we trying to achieve?

We aim to approach percent-level predictions for two quantities of fundamental importance:

- The mass of the b-quark (m_b), which is essential for precision tests of the SM and for predicting Higgs boson decays at the Large Hadron Collider (LHC) at CERN.
- The form factors describing $B \to \pi\ell\nu$ decays, essential for extracting the CKM matrix element $|V_{ub}|$, a fundamental parameter encoding the strength of quark flavor transitions in the SM.

Both observables are central to interpreting experiments at B factories and the LHC, and both are currently limited by systematic uncertainties in theoretical input.

What is new about our method?

Previous lattice QCD studies have often relied on effective theories that are challenging to control systematically, or on relativistic simulations that approach the limits of numerical reliability for the heavy b-quark. In contrast, we propose a strategy that combines results from:

1. A relativistic theory with heavy quark masses below that of the b-quark, where lattice calculations are under good control.
2. The static approximation of QCD, where the heavy quark is treated as infinitely massive—avoiding the large lattice artefacts that usually arise when simulating heavy particles.

By interpolating between these two regimes, we can reach the physical b-quark mass without directly simulating it at full mass, where discretisation effects would be too large. In contrast to an extrapolation, this interpolation in more rigorously controlled, yielding more reliable predictions.

Why do we need high-performance computing?

To control all sources of systematic uncertainty, we must simulate QCD on extremely fine lattices (as small as 0.05 fm spacing) and large physical volumes. Such calculations are computationally intensive and require modern HPC infrastructure. Each configuration of the gauge fields requires the solution of large linear systems, repeatedly and with high precision.

To achieve our target statistical and systematic accuracy, we will perform simulations on multiple ensembles with varying quark masses and lattice spacings, analyse a large number of measurements

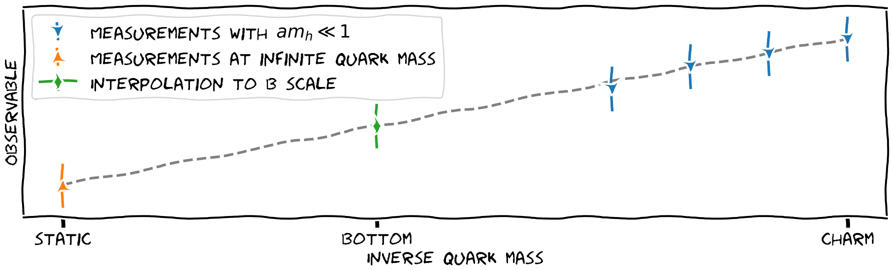

Figure 1: *Sketch of the interpolation strategy: combining continuum results from static theory and relativistic theory to reach the physical b-quark mass. Realistic examples of this interpolation procedure are provided in references cited below.*

of correlation functions, and conduct fits across data sets to extract physical predictions.

What is the expected impact?

Our project represents the first full-scale application of this new strategy for B-physics on the lattice. By demonstrating its viability in key observables, m_b and $|V_{ub}|$, we aim to redefine the standard approach to heavy-quark physics in lattice QCD. The resulting predictions will directly inform experimental analyses at LHCb, Belle II, and future flavour experiments, as well as Higgs boson decays studies at the LHC and next-generation colliders.

Moreover, the methodology is broadly applicable: once validated, it can be extended to a wide range of observables in the heavy-quark sector. It provides a sustainable and scalable framework that other groups can adopt, helping to reduce uncertainties in the global picture of flavour physics.

Outlook

In this computing time proposal, we will target measurements on fine lattices and at quark masses approaching the physical point on ensembles that are perfectly suited for ZIB. In a next step, we plan to extend and combine these results with data at physical quark masses and additional lattice spacings—some of which are already available or underway.

Simulations directly at the physical point or with finer lattice spacings require even larger computing resources than those available at ZIB and will be carried out at leadership-class facilities, building on the foundational work planned in this proposal. The combination of all results will enable continuum and chiral extrapolations that meet the precision standards required by modern particle physics.

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More Information

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Project Partners

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