# Matthew **Black**

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## Statement of Research

My research interests primarily focus on lattice QCD simulations in the context of particle physics phenomenology, with a focus on heavy quark physics. Further interests are in QCD sum rules, BSM phenomenology, and quantum computing.

My academic research began during my Master's project, supervised by Prof. Dr. Alexander Lenz, where I delved into the Two Higgs Doublet model (2HDM), and this work extended into the start of my PhD, where I performed comprehensive analyses using almost 300 observables to constrain 2HDMs. The outcome of this research has resulted in three publications directly related to the 2HDM and its parameter space. Additionally, this work inspired further research into BSM phenomenology which lead to a fourth publication, exploring methods to enhance negligible decays to observable levels; this research invoked dialogue with experimental colleagues and further motivated LHCb researchers to look for such processes. My involvement in BSM physics has significantly shaped the foundation of my research career, preparing me with vital skills which I apply in my ongoing work. It has also imparted me with a profound understanding of phenomenology at the LHC and other colliders, a knowledge base I consider essential to recognising physical meaning, context, and importance to my research. In particular, many of the observables analysed in these studies came from $B$ meson processes, and it was in this context that I learned to appreciate the rich phenomenology inherent to $B$ physics and the importance of understanding the hadronic physics at play in this sector.

My PhD commenced in March 2021, focusing on lattice QCD for heavy quark flavour physics under the mentorship of Dr. Oliver Witzel. $B$ physics on the lattice represents an interesting challenge due to the heavy mass of the $b$ quark. In order to keep discretisation effects under control for fully dynamical quarks, the mass must obey $am_q < 1$ and practically this limit can be even stricter. While some newer lattices are beginning to reach the scale needed ($a^{-1} \gtrsim 4$ GeV), most lattices in production are not yet fine enough to treat the $b$ quarks similarly to lighter quarks. To circumvent this problem on current lattices, there are two main methods, both of which I have dealt with in my research: the effective action, namely the Relativistic Heavy Quark (RHQ, based on the Fermilab) action, or the fully relativistic approach where one simulates heavier than the charm quark mass with e.g. domain wall quarks and extrapolates towards $m_b$.

Initial research focused on the calculation of pseudoscalar and vector $B^{(*)}$, $B_s^{(*)}$, and $B_c^{(*)}$ meson decay constants as part of the RHQ project of the RBC/UKQCD collaboration. I also played a pivotal role in implementing the RHQ operators for $O(a)$ improvement in general leptonic and semileptonic decays within the C++ codebase `Hadrons` utilising the `Grid` lattice QCD software package. This involved working with and advising a Bachelor's student, whose thesis work focused on this code implementation and validation. The developed RHQ code is now being used in large scale production runs by RBC/UKQCD for semileptonic $B$ decays.

This early research into heavy quark dynamics on the lattice using RHQ has continued throughout my PhD with interest in studying new types of decays on the lattice and the calculation of form factors for both pseudoscalar-to-pseudoscalar and pseudoscalar-to-vector transitions. Future plans include the continuation of the RHQ project for these processes and eventually aiming for finer lattices and all-domain-wall setups where only minor extrapolations to physical $m_b$ will be needed.

The primary research objective of my PhD has been developing techniques aimed at calculating the four-quark dimension-six $\Delta B = 0$ matrix elements for $B$ meson lifetimes within lattice QCD. A key challenge for these matrix elements is the issue of operator mixing in standard renormalisation procedures. To address this, I have been working on a novel non-perturbative renormalisation scheme, leveraging the gradient flow and the "short flow time expansion" in which operator mixing is largely suppressed. The gradient flow has become an important tool in lattice simulations for e.g. scale setting, however of interest here is the evolution of four-quark matrix elements along the positive gradient flow whereby these matrix elements are removed of UV divergences and thus renormalised in a gradient flow scheme. The "short flow time expansion" is the key step in matching gradient flow renormalised matrix elements to the $\overline{\mathrm{MS}}$ scheme to deliver phenomenologically-relevant results. For this final step, I work in collaboration with Prof. Dr. Robert Harlander and his group who focus on calculating the matching

to $\overline{\mathrm{MS}}$ in high-order perturbation theory. These perturbative coefficients can be combined with the non-perturbative result where, using both the non-perturbative and perturbative expertise of our collaboration, the final step is to understand the zero-flow-time extrapolation and deliver a final $\overline{\mathrm{MS}}$-scheme result.
The preliminary work testing this method considers $\Delta F = 2$ four-quark matrix elements governing neutral meson mixing such that we can compare to literature. We first start at the charm quark scale before any additional extrapolations towards the bottom quark are to be considered using an all-domain-wall approach. The highly-promising first results for this project were presented at Lattice 2023. With this innovative approach, we aim to provide full lattice QCD predictions of the vital $\Delta B = 0$ four-quark matrix elements for the first time, working towards more accurate and precise predictions for the lifetimes of $B$ mesons.
Using knowledge gained from my work in the RHQ project, a first milestone for this research was also implementing the necessary code for the gradient flow in `Hadrons`. To perform the early simulations of this project, I made use of computation time on the large-scale High Performance Computing clusters `HAWK` and `LUMI-G`, where I have been in charge of compiling code, benchmarking, and running the simulations as well as the subsequent analysis. In particular on `LUMI-G`, the use of GPU nodes made optimal compilation and benchmarking crucial before performing measurements. Furthermore, for future use of `LUMI-G` with larger-volume simulations, I contributed to the writing of a grant proposal for this needed computation time.

In parallel to my lattice research, I have also engaged in exploring alternative non-perturbative methodologies, namely QCD sum rules, for the computation of $\Delta B = 0$ lifetime and $\Delta B = 2$ mixing matrix elements similarly to my lattice studies, however here for BSM operators. The QCD sum rules approach is quite different to lattice simulations, technically involving three-loop integrals, and this interdisciplinary approach has broadened my research horizon and enabled me to acquire a comprehensive understanding of diverse computational techniques in non-perturbative calculations.

Outside of my core research, I have been a driving force in a quantum computing initiative within the Siegen physics community, bringing together the theoretical particle physics group with experimental quantum computing to learn the prospects of using quantum computing for particle physics. While our research experience in this field is still limited, I have actively pushed to learn more, as evidenced for example by my participation in the MIAPbP program "Quantum Computing Methods for High Energy Physics".

In conclusion, I am eager to apply my extensive expertise and interdisciplinary knowledge to contribute to cutting-edge and innovative research in lattice QCD simulations and heavy quark physics, while also exploring novel computational methodologies. My research experience so far has covered several different aspects of lattice QCD, such as code implementation, simulation running, and data analysis, and as such I am strongly suited to continue researching within this field with the flexibility and aptitude to perform in the many roles that can be required. I am committed to leveraging my diverse skill set and comprehensive understanding to make significant contributions to the academic community and push the boundaries of our understanding of particle physics phenomenology.

Thank you for your time and consideration, I look forward to hearing from you.
Sincerely,

**Matthew Black**