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Summary of Doctoral Thesis

Name in Full：Kellermann, Ryan

Title：Lattice QCD studies of inclusive semileptonic decays of charmed mesons

The Standard Model of Particle Physics (SM) is a framework combining the current understanding of the field of particle physics. Nevertheless, inexplicable discrepancies between theoretical predictions and experimental measurements indicate that the SM is not complete, motivating the search for New Physics and extensions of the SM.

One such discrepancy is the long standing tension between inclusive and exclusive determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ub}|$ and $|V_{cb}|$. Since it is imperative to have precise predictions of the SM in order to search for New Physics, this discrepancy provides theorists and experimentalists alike with the challenge of further deepening their understanding on these types of decays.

Focusing on the inclusive decays, while analytical techniques to analyze this class of decays exist, i.e., Operator Product expansion (OPE), a prediction with full control over all systematic effects requires nonperturbative methods. Lattice QCD fulfills those requirements, although it comes with its own sets of challenges. One major challenge, and one of the main reasons why it was thought impossible to apply lattice techniques towards inclusive decays, is the sheer number of potential states, possibly containing multi hadron states, which contribute to this class of decays. It is clear that identifying all the amplitudes for each contribution and summing them up over the whole phase space seems like a daunting task. This is combined with the fact that the extraction of spectral densities from hadron correlators remains an intractable task.

In view of this, a new technique, extending the application of lattice QCD towards the inclusive description, was recently developed. The basic idea is to consider smeared spectral densities to calculate an approximation for the energy integral appearing in the definition of the inclusive decay rate, where the role of the smearing is fulfilled by the phase space integral. In doing so, the problem of determining the inclusive rate is reduced to one where a suitable polynomial approximation for the kernel function of the energy integral has to be found. The approach utilized in this work is the approximation through Chebyshev polynomials.

This work studies the application of the aforementioned technique towards the inclusive semileptonic decay of the charmed D_s meson from lattice correlators using a full and flexible setup. We choose the charm sector instead of the bottom sector, where the discrepancy is observed, due to inherent problems on the lattice when it comes to the treatment of the bottom sector. The main two challenges that have to be addressed are the large discretization errors expected for the b quark mass, as well as the challenge of simulating the physical b quark mass on the lattice. These systematic effects are under better control for the charm sector, hence why this application provides a good way to prove the concept whether the proposed method is applicable.

We employ the Chebyshev polynomials to analyze the inclusive decays, introducing a trade-off between the data and the Chebyshev matrix elements, taking into account the bounds on which the Chebyshev polynomials are defined. Although we are limited to polynomial orders of $N = 10$, we confirm that the Chebyshev approximation provides an accurate and efficient way to determine the inclusive rate. Although we only include the statistical error in this work, a comparison with experimental data from the BESIII collaboration confirms that our prediction for the CKM matrix element $|V_{cs}|$ appears to be in the right ballpark when compared to available values from the PDG. We further improved the approximation through Chebyshev polynomials by introducing a set of generic shifted polynomials in terms of $e^{-\omega}$. As an important cross-check of the results obtained from the inclusive analysis strategy, we compare the results under the assumption of a ground state dominance in the inclusive decay with the prediction from the form factors determined for the exclusive decay mode, confirming a good agreement between the two determinations. While we observe increasing discrepancies between the values for higher values of $\boldsymbol{q}^2$, these can be attributed to the decreasing phase space and the hence higher polynomial order required in the approximation, in addition to systematic effects such as discretization or cut-off effects.

Additionally, we present a first study into understanding and estimating systematic effects contributing to the inclusive decay analysis from lattice data. We address the error introduced from the smearing applied to the kernel function in combination with the limited polynomial order in the Chebyshev approximation as well as the error associated with the presence of finite volume effects. In case of the former, we combine the two required limits, namely the $N \to \infty$ and $\sigma \to 0$ limits, and employ properties of the Chebyshev polynomials, to obtain a conservative estimate on the expected corrections. To estimate corrections due to finite volume effects, we develop a modeling strategy based on the production of multi-hadron states, specifically two-body states. We derive the spectral density in the infinite and finite volume. The information is then combined with the lattice data and after confirming that our model reproduces the behavior of the data, we estimate the corrections based on the infinite volume extrapolation.

To summarize, this work builds a solid foundation in applying the introduced techniques towards the inclusive decay. We advanced the analysis by presenting first steps into understanding and estimating systematic effects origination from the Chebyshev polynomial approach and finite volume effects. By extending this analysis towards the bottom sector it will be possible to obtain a new and independent determination of the CKM matrix elements and advance the understanding of the still unresolved discrepancy mentioned at the beginning.

（別紙１ Separate Sheet 1）

Results of the doctoral thesis defense

博士論文審査結果

氏　名（Name in Full） Kellermann, Ryan

論文題目（Title） Lattice QCD studies of inclusive semileptonic decays of charmed mesons

出願者は、格子量子色力学（格子 QCD）の数値シミュレーションにより、チャームクォークを含む中間子のセミレプトニック崩壊の包括的崩壊率を計算する手法に関する研究を行った。包括的崩壊とは、終状態に現れるすべてのハドロン状態に関して崩壊率の和をとったもので、実験では終状態を指定しないですべての事象を数えることに相当する。格子 QCD では通常、終状態を指定した崩壊形状因子（および崩壊率）の計算が行われる。終状態が複数のハドロンを含む場合は散乱状態の計算が必要となるために格段に難しく、かつ多数の可能性があるために必要な計算が膨大になってしまうためである。Kellermann 氏が行った計算は、最近開発された包括的崩壊を最初からすべて足し上げる手法にもとづくものである。ハドロンのエネルギーに関する積分を近似的に行うことでこれを実現する。まだ新しい手法であるため、今回の研究は、その最初の詳細な研究のうちの一つとなる。

Kellermann 氏が主に研究したのは、包括的崩壊に関するこの手法にともなう系統誤差に関するもので、特にエネルギー積分における系統誤差と、多体ハドロンの終状態における有限体積効果である。エネルギー積分に関しては、特に崩壊の運動学的な制限によってエネルギー積分の範囲が小さくなる場合が問題となる。Kellermann 氏は、エネルギー積分の近似において無視した高次項を厳密な数学的な制限を用いて評価する方法を示し、問題となる運動学的領域では誤差が大きくなって基底状態だけを考える別の評価と矛盾しないことを示した。有限体積効果に関しては、支配的になる二体崩壊の場合の模型を構築して崩壊率の体積依存性を評価した。模型の妥当性は格子データから得られる別の情報（エネルギー積分の上限に関する依存性）を用いて示した。これにより無限体積極限での評価が可能になった。これらの知見はこれまで研究されたことがなく、Kellermann 氏によるオリジナルな貢献となる。包括的崩壊率の最終的な決定と系統誤差の評価の詳細はさらなる研究が必要だが、これまでの成果も十分に学位に値するものと評価される。

Kellermann 氏は、この研究に関して格子場の理論国際会議において２度発表し、プロシーディングス論文も発表している。また､密接に関連する論文が査読付き論文誌(Journal of High Energy Physics)に掲載されている。学位論文は、関連分野の状況を基礎からまとめたうえで自身の研究について詳細に述べたもので、明快かつ正確に書かれている。英語による研究発表能力は非常に高い。

これらのことを総合し、審査委員会は、委員全員の賛成により本論文が学位の授与に値すると判断した。