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Abstract: My main research interest is non-perturbative physics relevant to the Large Hadron Collider (LHC). This is reflected in two main research avenues that I am pursuing, namely the scenario of electroweak symmetry breaking via strongly-coupled quantum field theories at TeV scale, and physics of Λ_b baryon. The former is directly linked to the chief experimental goal of the LHC, and the latter is the subject of the LHC-b experiments. The tool that I am using is large-scale numerical calculations with lattice gauge theory. In this article, I summarise the progress from August 2010 to October 2013 in this research direction, funded by the NSC through grant 102-2112-M-009-002-MY3.

I. BACKGROUNDS AND GOALS

On the fourth of July, 2012, it was announced at CERN that a Higgs-like boson was discovered. Amidst the triumph of the Standard Model (SM), various questions still remain to be answered. In particular, the following issues have become imminent:

- Can the scalr Higgs boson be a composite state composed of new fermions beyond the SM?
- If the Higgs boson turns out to be a fundamental scalar particle, then how would the electroweak scale be stabilised without fine-tuning? This problem is particularly important, given that supersymmetric extensions of the SM are moribund.
- What is the origin of flavours and masses of the fermions in the SM?

To address these issues, I have been working on projects in non-perturbative scenarios for electroweak symmetry breaking. These include a research programme in lattice caluclations for walking technicolour model building (in collaboration with my student, Cynthia Huang, and a few postdocs in Japan and Germany), and a project in strong-Yukawa models on the lattice (in collaboration with Karl Jansen at DESY Zeuthen and George Hou at NTU). To investigate flavour physics in the LHC era, I have been performing lattice computation for the Λ_b baryon spectrum and decay amplitudes (in collaboration with Will Detmold and Stefan Meinel at MIT, as well as Matt Wingate at Cambridge University).

A. Summary of Publications from August 2010 to October 2013

1. Refereed journal papers

1. W. Detmold, C.-J.D. Lin, S. Meinel, M. Wingate,
   "$\Lambda_b \to p l^- \bar{\nu}$ form factors from lattice QCD with static b quarks",
   arXiv:1306.0446 [hep-lat],
   Phys. Rev. **D88**, 014512 (2013).

2. W. Detmold, C.-J.D. Lin, S. Meinel, M. Wingate,
   "$\Lambda_b \to \Lambda l^+ l^-$ form factors and differential branching fraction from lattice QCD",
   arXiv:1212.4827 [hep-lat],
   Phys. Rev. **D87**, 074502 (2013).

3. J. Bulava, P. Gerhold, K. Jansen, J. Kallarackal, B. Knippschild, C.-J.D. Lin, K.-I. Nagai, A. Nagy, K. Ogawa,
   "Higgs-Yukawa models in chirally-invariant lattice field theory",
   arXiv:1210.1798 [hep-lat],
   Adv. High Energy Phys. **2013** (2013) 875612.

4. C.-J.D. Lin, K. Ogawa, H. Ohki, E. Shintani
   "Lattice study of infrared behaviour of SU(3) gauge theory with twelve massless flavours",
   arXiv:1205.6076 [hep-lat],
   JHEP **1208** (2012) 096.

5. W. Detmold, C.-J.D. Lin, S. Meinel,
   "Calculation of the heavy-hadron axial couplings g_1, g_2 and g_3 using lattice QCD.",
   arXiv:1203.3378 [hep-lat],
   Phys. Rev. **D85**, 114508 (2012).

6. C. Aubin, C.-J.D. Lin, A. Soni,
   "Possible lattice approach to $B \to D\pi(K)$ matrix elements",
   arXiv:1111.4686 [hep-lat],
   Phys. Lett. **B710**, 164 (2012).

7. W. Detmold, C.-J.D. Lin, S. Meinel,
   "Axial couplings and strong decay widths of heavy hadrons",
   arXiv:1109.2480 [hep-lat],
   Phys. Rev. Lett. **108**, 172003 (2012) .

8. W. Detmold, C.-J.D. Lin, S. Meinel,
   "Axial couplings in heavy hadron chiral perturbation theory at the next-to-leading order",
   arXiv:1108.5594 [hep-lat],
   Phys. Rev. **D84**, 094502 (2011).

2. Conference papers

1. P. Hegde, K. Jansen, C.-J.D. Lin, A. Nagy,
"Stabilizing the electroweak vacuum by higher-dimensional operators in a Higgs-Yukawa model',
arXiv:1310.6260,
PoS LATTICE2013 (2013).

2. P. Hegde, G.W.-S. Hou, K. Jansen, B. Knippschild, C.-J.D. Lin, K.-I. Nagai, A. Nagy, K. Ogawa,
"The phase structure of a chirally-invariant Higgs-Yukawa Model",
arXiv:1310.5922,
PoS LATTICE2013 (2013).

3. W. Detmold, C.-J.D. Lin, S. Meinel, M. Wingate,
"Form factors for $\Lambda_b \to \Lambda$ transitions from lattice QCD",
arXiv:1211.5127 [hep-lat],
PoS LATTICE2012 (2012) 123.

4. J. Bulava, P. Gerhold, G.W.-S. Hou, K. Jansen, B. Knippschild, C.-J.D. Lin, K.-I. Nagai, A. Nagy, K. Ogawa,
Investigation of the phase structure of a chirally-invariant Higgs-Yukawa model,
arXiv:1210.8249 [hep-lat],
PoS LATTICE2012 (2012) 253.

5. W. Detmold, C.-J.D. Lin, S. Meinel,
"Axial couplings of heavy hadrons from domain-wall lattice QCD",
arXiv:1203.3600 [hep-lat],
PoS LATTICE2011 (2011) 166.

6. C. Aubin, C.J.D. Lin, A. Soni,
"Chiral expansion for lattice' computations of $B^+ \to D^0 K^+(\pi^+)$ and $B^+ \to \bar{D}^0 K^+(\pi^+)$ amplitudes",
arXiv:1111.5891 [hep-lat],
PoS LATTICE2011 (2011) 330.

7. J. Bulava, P. Gerhold, G.W.-S. Hou, K. Jansen, B. Knippschild, C.-J.D. Lin, K.-I. Nagai, A. Nagy, K. Ogawa, B. Smigielski,
"Study of the Higgs-Yukawa theory in the strong-Yukawa coupling regime",
arXiv:1111.4544 [hep-lat],
PoS LATTICE2011 (2011) 075.

8. K. Ogawa, T. Aoyama, H. Ikeda, E. Itou, M. Kurachi, C.-J.D. Lin, H. Matsufuru, H. Ohki, T. Onogi, E. Shintani, T. Yamazaki,
"The infrared behaviour of SU(3) $N_f = 12$ gauge theory - about the existence of conformal fixed point",
arXiv:1111.1575 [hep-lat],
PoS LATTICE2011 (2011) 081.

9. E. Itou, T. Aoyama, M. Kurachi, C.-J.D. Lin, H. Matsufuru, H. Ohki, T. Onogi, E. Shintani, T. Yamazaki,
"Search for the IR fixed point in the Twisted Polyakov Loop scheme (II)",
arXiv:1011.0516 [hep-lat],
PoS LATTICE2010 (2010) 054.

10. H. Ohki, T. Aoyama, E. Itou, M. Kurachi, C.-J.D. Lin, H. Matsufuru, T. Onogi, E. Shintani, T. Yamazaki,
"Study of the scaling properties in SU(2) gauge theory with eight flavors",
arXiv:1011.0373 [hep-lat],
PoS LATTICE2010 (2010) 066.

II. SUMMARY OF RESEARCH PROGRESS AND RESULTS

A. Walking technicolour on the lattice

1. Infrared behaviour of SU(3) gauge theory with 12 flavour

With my collaborators, we have performed a lattice study of infrared behaviour in SU(3) gauge theory with twelve massless fermions in the fundamental representation. Using the step-scaling method, we compute the coupling constant in this theory over a large range of scale. The renormalisation scheme in this work is defined by the ratio of Polyakov loops in the directions with different boundary conditions. We closely examine systematic effects, and find that they are dominated by errors arising from the continuum extrapolation. Our investigation suggests that SU(3) gauge theory with twelve flavours contains an infrared fixed point.

2. SU(2) gauge theory with 8 flavours

This is a new project that we initiated in 2013. The first stage is to study the phase structure of the this theory. According to our current results, we have found evidence for first-order phase transitions in this theory in the strong bare-coupling regime. Such phase transitionns have been conjectured to be connected to the conformal phase transition in the continuum limit.

B. Higg-Yukawa models on the lattice

1. The phase structure of a chirally symmetric Higgs-Yukawa model

My collaborators and I have obtained new results from our investigation of the phase structure of the Higgs-Yukawa model at small and large bare Yukawa couplings. The critical exponents of the second order bulk phase transitions of this model are determined from finite-size analyses and compared to the pure O(4)-model to test for triviality and the possibility of having a non-Gaussian fixed point. In addition, we will present a first study of Higgs boson masses and fermion correlation functions.

2. *Stabilising the electroweak vacuum by higher dimensional operators in a Higgs-Yukawa model*

The Higgs boson discovery at the LHC with a mass of approximately 126 GeV suggests, that the electroweak vacuum of the standard model may be metastable at very high energies. However, any new physics beyond the standard model can change this picture. We want to address this important question within a lattice Higgs-Yukawa model as the limit of the standard model (SM). In this framework we will probe the effect of a higher dimensional operator for which we take a $(\phi^\dagger\phi)^3$ term. Such a term could easily originate as a remnant of physics beyond the SM at very large scales. As a first step we investigate the phase diagram of the model including such a $(\phi^\dagger\phi)^3$ operator. Exploratory results suggest the existence of regions in parameter space where first order transitions turn to second order ones, indicating the existence of a tri-critical line. We will explore the phase structure and the consequences for the stability of the SM, both analytically by investigating the constraint effective potential in lattice perturbation theory, and by studying the system non-perturbatively using lattice simulations.

C. Physics of the Λ_b baryon

1. *Axial couplings in heavy hadron chiral perturbation theory at the next-to-leading order*

Will Detmold, Stefan Meinel, and I performed calculations of axial-current matrix elements between various heavy-meson and heavy-baryon states to the next-to-leading order in heavy hadron chiral perturbation theory in the p-regime. When compared with data from lattice computations or experiments, these results can be used to determine the axial couplings in the chiral Lagrangian. Our calculation is performed in partially-quenched chiral perturbation theory for both SU(4|2) and SU(6|3). We incorporate finite-size effects arising from a single Goldstone meson wrapping around the spatial volume. Results for full QCD with two and three flavours can be obtained straightforwardly by taking the sea-quark masses to be equal to the valence-quark masses. To illustrate the impact of our chiral perturbation theory calculation on lattice computations, we analyse the SU(2) full QCD results in detail. We also study one-loop contributions relevant to the heavy hadron strong-decay amplitudes involving final-state Goldstone bosons, and demonstrate that the quark-mass dependence of these amplitudes can be significantly different from that of the axial current matrix elements containing only single hadron external states.

2. *Axial couplings and strong decay widths of heavy hadrons*

Wit Will Detmold and Stefan Meinel, we calculate the axial couplings of mesons and baryons containing a heavy quark in the static limit using lattice QCD. These couplings determine the leading interactions in heavy hadron chiral perturbation theory and are central quantities in heavy quark physics, as they control strong decay widths and the light-quark mass dependence of heavy hadron observables. Our analysis makes use of lattice data at six different pion masses, 227 MeV $< m_\pi <$ 352 MeV, two lattice spacings, a=0.085, 0.112 fm, and a volume of $(2.7\ \mathrm{fm})^3$. Our results for the axial couplings are g_1=0.449(51), g_2=0.84(20), and g_3=0.71(13), where g_1 governs the interaction between heavy-light mesons and pions and $g_{2,3}$ are similar couplings between heavy-light baryons and pions. Using our lattice result for g_3, and constraining $1/m_Q$ corrections in the strong decay widths with experimental data for $\Sigma_c^{(*)}$ decays, we obtain $\Gamma[\Sigma_b^{(*)} \to \Lambda_b \pi^\pm] = 4.2(1.0), 4.8(1.1), 7.3(1.6), 7.8(1.8)$ MeV for the Σ_b^+, Σ_b^-, Σ_b^{*+}, Σ_b^{*-} initial states, respectively. We also derive upper bounds on the widths of the $\Xi_b^{\prime(*)}$ baryons.

3. Calculation of the heavy-hadron axial couplings g_1, g_2, and g_3 using lattice QCD

Together with Will Detmold and Stefan Meinel, we discuss important details of the calculation and give further results. To determine the axial couplings, we explicitly match the matrix elements of the axial current in QCD with the corresponding matrix elements in HHχPT. We construct the ratios of correlation functions used to calculate the matrix elements in lattice QCD, and study the contributions from excited states. We present the complete numerical results and discuss the data analysis in depth. In particular, we demonstrate the convergence of SU(4|2) HHχPT for the axial-current matrix elements at pion masses up to about 400 MeV and show the impact of the nonanalytic loop contributions. Finally, we present additional predictions for strong and radiative decay widths of charm and bottom baryons.

4. $\Lambda_b \to \Lambda l^+ l^-$ form factors and differential branching fraction from lattice QCD

Will Detmold, Stefan Meinel, Matt Wingate and I performed the first lattice QCD determination of the $\Lambda_b \to \Lambda$ transition form factors that govern the rare baryonic decays $\Lambda_b \to \Lambda l^+ l^-$ at leading order in heavy-quark effective theory. Our calculations are performed with 2+1 flavors of domain-wall fermions, at two lattice spacings and with pion masses down to 227 MeV. Three-point functions with a wide range of source-sink separations are used to extract the ground-state contributions. The form factors are extrapolated to the physical values of the light-quark masses and to the continuum limit. We use our results to calculate the differential branching fractions for $\Lambda_b \to \Lambda l^+ l^-$ with $l = e, \mu, \tau$ within the standard model. We find agreement with a recent CDF measurement of the $\Lambda_b \to \Lambda \mu^+ \mu^-$ differential branching fraction.

5. $\Lambda_b \to p l^- \bar{\nu}$ form factors from lattice QCD with static b quarks

Will Detmold, Stefan Meinel, Matt Wingate and I performed a lattice QCD calculation of form factors for the decay $\Lambda_b \to p \mu^- \bar{\nu}$, which is a promising channel for determining the CKM matrix element $|V_{ub}|$ at the Large Hadron Collider. In this initial study we work in the limit of static b quarks, where the number of independent form factors reduces to two. We use dynamical domain-wall fermions for the light quarks, and perform the calculation at two different lattice spacings and at multiple values of the light-quark masses in a single large volume. Using our form factor results, we calculate the $\Lambda_b \to p\mu^-\bar{\nu}$ differential decay rate in the range 14 GeV$^2 \leq q^2 \leq q^2_{max}$, and obtain the integral $\int_{14GeV^2}^{q^2_{max}}[d\Gamma/dq^2]dq^2/|V_{ub}|^2 = 15.3\pm4.2\ ps^{-1}$. Combined with future experimental data, this will give a novel determination of $|V_{ub}|$ with about 15% theoretical uncertainty. The uncertainty is dominated by the use of the static approximation for the b quark, and can be reduced further by performing the lattice calculation with a more sophisticated heavy-quark action.

D. Other projects

1. *Possible lattice approach to B to D pi (K) matrix elements*

With Christopher Aubin and Amarjit Soni, we proposed an approach for computing the real parts of the nonleptonic B to DP and B to D-bar P (P=K,pi) decay amplitudes by using lattice QCD methods. While it remains very challenging to calculate the imaginary parts of these matrix elements on the lattice, we stress that their real parts play a significant role in extracting the angle gamma in the b-d unitarity triangle of the CKM matrix. The real part on its own gives a lower bound to the absolute magnitude of the amplitude which is in itself an important constraint for determining gamma. Also the relevant phase can be obtained by using B-decays in conjunction with relevant charm decay data. Direct four-point function calculations on the lattice, while computationally demanding, does yield the real part as that is not impeded by the Maiani-Testa theorem. As an approximation, we argue that the chiral expansion of these decays is valid in a framework similar to that of hard-pion chiral perturbation theory. In addition to constructing the leading-order operators, we also discuss the features of the next-to-leading order chiral expansion. These include the contributions from the resonance states, as well as the generic forms of the chiral logarithms.