Charm physics with physical light and strange quarks using domain wall fermions

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Charm phenomenology

test the Standard Model:
• SM provides correlation between processes
• experiment + theory → over constrain SM

\[ \Gamma_{\text{exp.}} = V_{\text{CKM}}(\text{WEAK})(\text{EM})(\text{STRONG}) \]

e.g tree level leptonic D decay

\[ \mathcal{B}(D_s \rightarrow l\nu_l) = \frac{G_F^2 |V_{cq}|^2 \tau_{D(s)}}{8\pi} f_{D(s)}^2 m_l^2 m_{D(s)} \left(1 - \frac{m_l^2}{m_{D(s)}^2}\right)^2 \]

Experimental measurement + theory prediction allows for extraction of CKM MEs
Motivation for (more) charm on the lattice

Lattice + experiment → CKM matrix elements: e.g. leptonic D and Ds decay

\[ f_D |V_{cd}| = 46.40(1.98) \text{MeV}, \quad f_{Ds} |V_{cs}| = 253.1(5.3) \text{MeV} \]  
(Stone, Rosner in PDG)

similar for semi-leptonic decay...

**Status:**

- "state-of-the-art results":
  - very few
  - staggered, twisted mass
  - phenomenologically important
  - tensions?
Motivation for (more) charm on the lattice

- $|V_{cs}|$ from leptonic decays is slightly larger than from semileptonic decays
- $|V_{cs}|$ from leptonic decays is at tension with CKM-unitarity by 1.9σ (→HPQCD)

| $|V_{cd}|$       | $|V_{cs}|$       |
|-----------------|-----------------|
| our average for $N_f=2+1$ |  |
| HPQCD 12A/10A  | lepton         |
| FNAL/MILC 11   |                |
| HPQCD 11/10B   | semi-lepton    |

<table>
<thead>
<tr>
<th>$N_f=2$</th>
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<td>our average for $N_f=2$</td>
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<td>ETM 13B</td>
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- **neutrino scattering**
- **CKM unitarity**
Our strategy - setup

• **Domain wall fermions** as light and charm quark discretisation
  • automatically $O(a)$-improved
  • good chiral properties

• use **RBC/UKQCD $N_f = 2+1$ DWF ensembles**
  • $a^{-1}=1.7, 2.3$ GeV readily available
  • $m_\pi$ physical ensembles in large volumes

• complementary to ongoing RBC/UKQCD B-physics program

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see talks by Witzel and Ishikawa in session 5G, Wednesday 9:20 ff
Our strategy

• **Quenched pilot study**
  • $a^{-1} \sim 2, 3, 4, 6$ GeV $\rightarrow$ scaling study
  • small volume $L=1.6\text{fm}$
  • parameter tuning
  • map out range of applicability
  • qualitative picture should apply also to dynamical case

• **$N_f= 2+1$ DWF charm project (RBC/UKQCD)**
  • strategy: simulate several ‘charm’ masses
  • inter/extrapolate to charm (and beyond?)
  • heavy-light, heavy-strange, heavy-heavy
  • leptonic/semileptonic decays, mixing (BSM), $g-2$, …
Quenched DWF pilot study

- small volume L=1.6fm
- $a^{-1} \sim 2, 3, 4, 6 \text{ GeV}$
- DWF maintain its properties up to $a m_q \leq 0.45$
- parameter tuning ($M_5, L_s, \text{largest } a m_h, \ldots$)
Quenched DWF pilot study

- small volume \( L = 1.6 \text{fm} \)
- \( a^{-1} \sim 2, 3, 4, 6 \text{ GeV} \)
- DWF maintain its properties up to \( am_q \leq 0.45 \)
- parameter tuning (\( M_5, L_s, \text{largest } am_h, \ldots \))
- beautiful \( a^2 \)-scaling
- properties expected to carry over to dynamical case
Dynamical case: simulation parameters

RBC/UKQCD DWF $N_f=2+1$ ensembles:
(Shamir/Moebius + Iwasaki)

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<th>$L$</th>
<th>$a$</th>
<th>$m$</th>
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<tr>
<td></td>
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</table>
Dynamical case: simulation parameters

- add Moebius `charm quarks` with $a m_h$ in the range 0.2-0.45
  (Brower, Neff, Orginos, arXiv:1206.5214, P. Boyle’s talk on Monday)
- limited to below charm on 1.7GeV lattices $\rightarrow$ extrapolation in $m_h$
- optimal domain wall height from quenched run: $M_5=1.6$
- 48 random $Z_2$ noise wall sources per config (one-end trick)
- monitor heavy quark CG-convergence via time-slice residual

$$r(t) = \frac{|A\psi - \eta|_t}{|\psi|_t}$$
Does DWF mechanism work for charm?

Observation in quenched study:
nice properties of DWF break down for too heavy quark masses ($am_q \approx 0.4-0.5$)

monitor Axial Ward Identity:
\[
\langle \partial_\mu A_\mu(x) P(0) \rangle = 2m \langle P(x)P(0) \rangle \\
+ 2 \langle J_{5q}(x)P(0) \rangle \\
\]

\[
m_{\text{res}} \equiv \frac{\left\langle \sum_x J_{5q}(x)P(0) \right\rangle}{\left\langle \sum_x P(x)P(0) \right\rangle}
\]
data so far
Analysis

1. interpolate observables on all ensembles to reference heavy quark masses
2. interpolate to the physical light quark mass
3. extrapolate to the continuum limit
4. extrapolate results in the continuum limit to the physical charm quark point
Results interpolated to common $\eta_{cc}$-masses

1st STEP: interpolation to common $\eta_{cc}$-masses

- $m_{\eta_{cc}} \approx 2.2, 2.4, 2.6, 2.8$ GeV
- polynomial ansatz, data benign
- interpolation points mostly close to data points
- solid vertical line: charm
Results interpolated to common heavy quark masses

**$D_s$**

**$D$**
Light quark mass dependence

2nd STEP: light quark mass interpolation
- Data on 1.7GeV covers $m_\pi$ down to physical point - NO curvature seen!!
  → linear interpolation to physical point
- outlook: physical point on 2.3GeV lattice coming soon

D_s

D
Continuum limit

3rd STEP: continuum limit:
- so far only 1.7 and 2.3GeV and therefore very preliminary
- quenched study suggests linear dependence on $a^2$
- but clearly need 3rd lattice spacing for reliable predictions
  → we are working on it

![Graphs of $D_s$ and $D$](image.png)
3rd STEP: extrapolation to charm
• looks quite linear but will study systematics
• already at this early stage astonishingly good statistical precision
This was the first shot at it:

• additional data coming in (48cube stats, 2.3GeV physical pt., ~3GeV ensemble, …)
• need to check impact of alternative fit-ansaetze
  (interpolation in \(m_h\) at finite lattice spacing, extrapolation to \(m_c\) in the continuum →systematics)

Results so far:

• no curvature in \(m_\pi\) seen down to the physical point
• benign mass-dependence, polynomial parameterisations should work well
• charm not far away → short extrapolation to charm, good statistical properties
• all results very preliminary, too early to provide numbers
• DWF excellent for charm!

Outlook:

• look into ratio method, interpolate to static, …
• other observables: quark masses, mixing, HVP, semi-leptonics
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