SPC Flavor Summary

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USQCD All Hands Meeting
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Caveat: This has not been reviewed by the SPC, so please don’t blame the rest of the SPC for anything you do not like.

Goals:
- Brief summary of 2017 B physics proposals
- Discussion of some of the physics opportunities to pin down the CKM matrix, test the Standard Model, search for evidence of new physics
Proposals

- Determination of $|V_{cb}|$ from Semi-leptonic Decays $B \to D^{(*)} \ell \nu$ using the Oktay-Kronfeld Action; PI: Gupta, 26 M J-Psi core-hr

- Investigation of $B \to K \pi \ell^+\ell^-$ Decays with Lattice QCD; PI: Leskovec, 18.9 M J-Psi core-hr

- Standard Model Parameters and the Search for Physics Beyond the Standard Model with HISQ; PI: Mackenzie, 87.4 M J-Psi core-hr + 5.7 M BG/Q core-hr

- Semi-leptonic $B$ and $B_S$-decays with charming hadronic final state; PI: Soni, 17.6 M J-Psi core-hr

- The following slides will summarize the goals of each proposal.
Uses Oktay-Kronfeld heavy quark action for $b$ and $c$ quarks

MILC HISQ ensembles: three lattice spacings and three values of pion mass at each lattice spacing.

$a=0.15, 0.12$ fm done on local clusters. Time is for 250 configurations of $a=0.09$ fm $m_l/m_s=0.1$ and physical mass ensembles.

- 2016 allocation used for $m_l/m_s=0.2$ ensemble

Use truncated solver method

Aim for 1.0% (1.1%) error for $B \rightarrow D^* \, l \nu$ ($B \rightarrow D \, l \nu$) form factors. Currently, 1.4% (1.2)%.

More about $|V_{cb}|$ later…
Leskovec

- Studying rare flavor changing neutral current decay $B \rightarrow K \pi \ell^+ \ell^-$ in region of $K^*(892)$
- Uses 2+1 flavor dynamical clover ensemble with $a=0.114$ fm and $m_\pi=317$ MeV
- LHCb found anomalous angular dependence at low $q^2$.
- Sensitive probe of beyond standard model physics.
- Previously $K^*$ treated as a stable particle
- Use one large volume $(32^3 \times 96)$ and several moving frames
- Continuation: about 285 configurations will be analyzed this year. Would like to get to 800 with new allocation.
Use 2+1+1 flavor HISQ ensembles; HISQ light valence quarks, Wilson/clover (w. FNAL interp.) $b,c$ quarks; $c$ quarks treated with HISQ as well for some projects

Six lattice spacings: $a \approx 0.15, 0.12, 0.09, 0.06, 0.042, 0.03$ fm

Physical light quark mass except for 0.03 fm ensemble

Test CKM unitarity with broad range of decays:

- $B \rightarrow \pi \ell \nu, B \rightarrow D^{(*)} \ell \nu, B_s \rightarrow D_s^{(*)} \ell \nu, K \rightarrow \pi \ell \nu, D \rightarrow \pi(K) \ell \nu$
- neutral B meson mixing
- $B \rightarrow \tau \nu, B \rightarrow D^{(*)} \tau \nu, B \rightarrow K^{(*)} \ell^+\ell^-$
- Decay constants for pseudoscalar and vector mesons
- charm and bottom quark masses, $\alpha_s$

Aim for better precision than asqtad results
Using Mobius domain-wall 2+1 flavor ensembles

Seven ensembles with 0.114 fm > a > 0.711 fm, one with physical mass pion

Relativistic heavy quark (RHQ) action

$B \rightarrow D^{(*)} \, l \, \nu$, $B_s \rightarrow D_s^{(*)} \, l \, \nu$ to determine $|V_{cb}|$

Light and strange quark propagators are already archived.

Will run on two $48^3 \times 96$ ensembles with $a=0.11$ and 0.07 fm, with pion mass 138 and 234, respectively.

Three other ensembles already analyzed.

Will later compute B meson mixing, & decay constants
Kobayashi & Maskawa

- Won 2008 Nobel prize for realization that with three (or more) generations can have CP violation, which might explain baryon asymmetry of Universe.

KEK photo from nobelprize.org
CKM Matrix

- Some relevant processes listed under each element

\[ 
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
\pi \rightarrow l\nu & K \rightarrow \pi l\nu & B \rightarrow \pi l\nu \\
V_{cd} & V_{cs} & V_{cb} \\
D \rightarrow \pi l\nu & D \rightarrow K l\nu & B \rightarrow D^{(*)} l\nu \\
V_{td} & V_{ts} & V_{tb} \\
\langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & \\
\end{pmatrix} \]
CKM Matrix II

✧ CKM matrix is unitary.
  • Each row and column is a (complex) unit vector.
  • Each row (column) is orthogonal to the other rows (columns).
✧ Violations of unitarity are evidence of non-standard model physics.
✧ If two different processes are used to determine an element of the matrix and they do not agree, that is evidence for new physics.
✧ LQCD input for decay constants and form factors is needed to determine elements of CKM matrix

\[
\mathcal{B}(D_{(s)} \rightarrow \ell \nu_\ell) = \frac{G_F^2 |V_{cq}|^2 \tau_{D_{(s)}}}{8\pi} f^{D_{(s)}}_D m^2_\ell m_{D_{(s)}} \left(1 - \frac{m^2_\ell}{m^2_{D_{(s)}}}\right)^2
\]

S. Gottlieb, USQCD AHM, 4/28/17
Processes involving only light quarks test first row unitarity.

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
\pi \rightarrow l\nu & K \rightarrow \pi l\nu & B \rightarrow \pi l\nu \\
V_{cd} & V_{cs} & V_{cb} \\
D \rightarrow \pi l\nu & D \rightarrow K l\nu & B \rightarrow D^{(*)} l\nu \\
D \rightarrow l\nu & D_s \rightarrow l\nu \\
V_{td} & V_{ts} & V_{tb} \\
\langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle \\
\end{pmatrix}
\]
• Light decay constants as summarized by FLAG

• Some calcs. use $f_\pi$ to set the scale so fewer results on left

• Ratio of decay constants is easy to calculate and used to test unitarity

$\pi$ and $f_K$
• Light decay constant ratio summarized by FLAG

• From experimental measurement:

\[
\frac{V_{us}}{V_{ud}} \cdot \frac{f_{K}^\pm}{f_{\pi}^\pm} = 0.2758(5)
\]
K semileptonic decay

Semileptonic decays have three-body final states, so there is one kinematic variable, usually denoted $q^2$, which is momentum transfer to the leptons.

\[ p_K = p_\pi + q_\ell + q_\nu \]
\[ q = q_\ell + q_\nu \]

To extract $|V_{us}|$ we just need $f_+(0)$ as experiment tells us

\[ |V_{us}| f_+(0) = 0.2163(5) \]

From FNAL/MILC with 2+1+1 flavors PRL 112, 112001 (2014), arXiv:1312.1228 (0.34 % error)

\[ f_+(0) = 0.9704(24)(22) \]
• FLAG averages for Kaon decay constant at $q^2 = 0$
• Only one value for $N_f = 2, 2+1+1$
• Two values for $N_f = 2$
• Next, we look at unitarity test

**f+(0) for Kaon Decay**

![Graph showing FLAG averages for Kaon decay at different $N_f$ values.](image)
First Row Unitarity Test

- Black line is unitarity
- Vertical band is from nuclear $\beta$ decay (LQCD independent)
- Angled band is from leptonic decays
- Horizontal band is from semileptonic K decay
- Some tension between the two types of decay for 2+1+1.
- Can we reduce semileptonic error?

1611.04188

• Preliminary FLAG3 results for 2+1 and 2+1+1 flavors
• Matrix elements not squared here
• Dotted line is unitarity
• 2+1 flavors has larger error and consistent with unitarity
• plot from FLAG
• squares leptonic
• triangles semileptonic
• good agreement w. 2+1 flavors, some tension for 2+1+1
• note tension between $\tau$ decay results and $\pi$ and $K$ decays
Processes involving charm quark test second row unitarity

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
\pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\
& K \to l\nu & \\
V_{cd} & V_{cs} & V_{cb} \\
D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\
& D \to l\nu & D_s \to l\nu \\
V_{td} & V_{ts} & V_{tb} \\
\langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & 
\end{pmatrix}
\]
Charm Decay Constants

- Note improvement of precision from initial 2005 2+1 flavor results to current 2+1+1 flavor results.

\[ f_{D^+} = 212.6(0.4)^{+1.0}_{-1.2} \, \text{MeV} \]

\[ f_{D_s} = 249.0(0.3)^{+1.1}_{-1.5} \, \text{MeV} \]

- FLAG3 averages should be quite similar with slightly smaller errors

\[ f_{D^+} \]
\[ f_{D_s} \]

- Electronic address: S. Gottlieb, USQCD AHM, 4/28/17

Charm Decay Constant Ratio

- Once again, note remarkable improvement over the past decade

\[ \frac{f_{D_s}}{f_{D^+}} = 1.1712(10)(^{+29}_{-32}) \]

• Once again, note remarkable improvement over the past decade

\[ f_{D_s}/f_{D^+} = 1.1712(10)(^{+29}_{-32}) \]

• FLAG 1.1716(32) for 2+1+1 flavors
Extraction of $V_{cd}$ & $V_{cs}$

✧ The experimental results for charm meson leptonic decays are summarized by the Heavy Flavor Averaging Group (HFAG):

\[ f_D |V_{cd}| = 46.40(1.98) \text{MeV}, \quad f_{D_s} |V_{cs}| = 253.1(5.3) \text{MeV} \]

✧ Experimental error is 2.1-4.3%.

✧ Using decay constants from LQCD, we get CKM matrix elements:

\[ |V_{cd}| = 0.217(1)(5)(1), \quad |V_{cs}| = 1.010(5)(18)(6) \]

✧ Errors are lattice, experiment, and structure dependent electromagnetic, respectively.
Second Row Unitarity

- Black line is unitarity
- Horizontal blue band is $D_s$ leptonic decay
- Vertical green band is $D^+$ leptonic decay
- Note the $\approx 1.8 \sigma$ tension with unitarity
- Fajfer et al., PRD91, (2015) 094009 bound new physics
- Fewer results for semileptonic $D$ meson decays
- Expt. error dominant now.

Interestingly, there is a new BaBar paper, PRD91, 052022(2015), on semileptonic D decay that uses HPQCD result.

It yields $|V_{cd}| = 0.206 \pm 0.007_{\text{exp}} \pm 0.009_{\text{LQCD}}$.

Adding errors in quadrature 0.206 (11) compared with our leptonic decay result of 0.217(5).

Their central value is two of our sigma below our result, but our result is only one of their sigmas high.
B Meson Decays

✧ Leptonic and semileptonic decays studied in LQCD
✧ Rare decays involving flavor changing neutral currents (FCNC) also studied
  • FCNC vanish at tree level in Standard Model, so a good place to look for new physics
  • Some tension between recent SM prediction from LQCD and LHCb measurements
  • Alternative to B meson mixing for determining $|V_{td}|$ and $|V_{ts}|$
B Meson Leptonic Decays

- FLAG3 will have only minor updates to these results
- RBC/UKQCD 2+1
- ETM 2+1+1 (plotted)
- both have large errors
- For 2+1 and 2+1+1 flavors errors about 2%
- $f_B = 190.5(4.2) \text{ MeV}$, $f_{B_s} = 227.7(4.5) \text{ MeV}$ for 2+1 flavors (2013)
|Vub| from FLAG2

- Large errors for leptonic decays from experiment (25%)
- Semileptonic decays give smaller value
- Tension between exclusive and inclusive results
- Plot from T. Vladikas arXiv:1509.01155
- Belle II will improve $B \rightarrow \tau \nu$ measurement (5% error expected)
Exclusive B Decay Update


- FLAG:

  \[ |V_{ub}| = 3.37(21) \times 10^{-3}, \quad N_f = 2 + 1; \text{BaBar} \]

  \[ |V_{ub}| = 3.47(22) \times 10^{-3}, \quad N_f = 2 + 1; \text{Belle} \]

- New FNAL/MILC result

  \[ |V_{ub}| = 3.72(16) \times 10^{-3}, \quad N_f = 2 + 1; \text{BaBar&Belle} \]

- This result decreases, but does not eliminate tension between exclusive and inclusive results.

- Next slide also includes Lambda baryon decay result
Lattice error now comparable to experimental error.

This work + BaBar + Belle, $B \rightarrow \pi l\nu$
Fermilab/MILC 2008 + HFAG 2014, $B \rightarrow \pi l\nu$
RBC/UKQCD 2015 + BaBar + Belle, $B \rightarrow \pi l\nu$
Imsong et al. 2014 + BaBar12 + Belle13, $B \rightarrow \pi l\nu$
HPQCD 2006 + HFAG 2014, $B \rightarrow \pi l\nu$
Detmold et al. 2015 + LHCb 2015, $\Lambda_b \rightarrow pl\nu$
BLNP 2004 + HFAG 2014, $B \rightarrow X_u l\nu$
UTFit 2014, CKM unitarity

Exclusive calculations of $B \rightarrow D^* \ell \nu$ and $B \rightarrow D \ell \nu$ yield $V_{cb}$

Experimental error dominant for $B \rightarrow D \ell \nu$ (3.9% vs 1.4%)

Again, tension between exclusive and inclusive results


But two exclusive decay modes consistent

Fermilab/MILC ’15 + BaBar ’09, $B \rightarrow D$, $w \geq 1$

Fermilab/MILC ’15 + HFAG ’14, $B \rightarrow D$, $w = 1$

Fermilab/MILC ’14 + HFAG ’14, $B \rightarrow D^*$, $w = 1$

Gambino & Schwanda ’13, $B \rightarrow X_c$ inclusive
• Two results with 2+1 flavors both on MILC asqtad ensembles.
**$V_{ub}$ and $V_{cb}$: exclusive vs inclusive**

- **Exclusive:**
  
  $|V_{ub}|_{B\to\pi\ell\nu} = 3.73(14) \times 10^{-3}$ [FLAG]
  
  $|V_{ub}|_{B\to\tau\nu} = 4.33(72) \times 10^{-3}$ [PDG+FLAG]
  
  $|V_{cb}|_{B\toD\ell\nu} = 40.1(1.0) \times 10^{-3}$ [FLAG]
  
  $|V_{cb}|_{B\toD^{*}\ell\nu} = 39.27(56)(49) \times 10^{-3}$ [FLAG]
  
  $|V_{ub}/V_{cb}|_{\Lambda_{b}\to(p,\Lambda_{c})\ell\nu} = 0.083(6)$ [PDG]

- **Inclusive [PDG]:**
  
  $|V_{ub}|_{B\toX_u\ell\nu} = 4.49(16)(^{+16}_{-18}) \times 10^{-3}$
  
  $|V_{cb}|_{B\toX_c\ell\nu} = 42.2(0.7) \times 10^{-3}$

- The overall tension between all these determinations is 3.2 $\sigma$

- **Future progress**

  - $B\toD^{*}$ form factor: $q^2$ dependence and use of BCL/BGL parametrization [Berlochner et al. 1703.05330]
  
  [Bigi, Gambino, Schacht 1703.06124]
  
  [Grinstein, Kobach 1703.08170]

  - $B_s\toK\nu$
Ken Lane’s List from LHCb

- \( B^+ \rightarrow K^+\mu^+\mu^- / B^+ \rightarrow K^+e^+e^- \) 25%< SM (2.6\(\sigma\))
- Independently, \( B^+ \rightarrow K^+\mu^+\mu^- \) branching ratio 30% <SM (2\(\sigma\))
- Earlier results for electron mode consistent with SM
  - Lepton nonuniversality may not demand much more from LQCD, i.e., BSM physics will change Wilson coefficients. (pheno ms.)
- \( B^0 \rightarrow K^{*0}\mu^+\mu^- \) angular distribution differs from SM by 2.9\(\sigma\) in two bins. Theoretical error questioned.
  - We have not done this decay. (Not gold plated…)
- \( B_{(s)} \rightarrow \mu^+\mu^- \) branching ratios jointly measured by CMS and LHCb …
$B_{(s)} \rightarrow \mu^+ \mu^-$

- Nature: doi:10.1038/nature14474 (we’re cited)
2D contour plot of branching ratios

- $B_s$ too small by $1\sigma$
- $B$ too big by $\approx 2\sigma$
Individual contour plots
Rare B Decays

✧ FNAL/MILC has recently calculated form factors needed for several rare decays that require flavor changing neutral current.
✧ Good place to look for new physics
✧ Some tension between SM prediction and recent LHCb measurement
Rare B Decays II

- LHCb measurement is smaller than SM prediction in 3 of 4 bins. 1.7σ tension.
- arXiv:1510.02349
Rare decays depend on $|V_{tq}|$ with $q=d$ or $s$

$$|V_{td}| = 7.45(69) \times 10^{-3}, \quad |V_{ts}| = 35.7(1.5) \times 10^{-3}$$

The same elements of CKM matrix can be determined from B-meson mixing

$$|V_{td}| = 8.4(6) \times 10^{-3}, \quad |V_{ts}| = 40.0(2.7) \times 10^{-3}$$

New $|V_{ts}|$ is 1.4 $\sigma$ below that from mixing with smaller error

Values of $|V_{td}|$ are comparable

LQCD will help improve both determinations
• BaBar: PRD88, 072012 (2013)
• FNAL/MILC: PRL109, 071802, (2012)
• $R(D)$: 2.0σ
• $R(D^*)$: 2.7σ
• Together: 3.4σ
• all BaBar’s values
• However, no agreement is 2H model
• BaBar's comparison with two Higgs doublet model predictions
• $x$-axis should be $\tan(\beta)/M_H$
• We slightly improve agreement between BaBar result and standard model.
Introduction

✦ Goal is quick summary of some of the places where there is a hint of beyond the standard model physics.
  • Emphasis on where lattice QCD might have an impact.
  • Many graphs from our recent papers.

✦ Obvious non-lattice:
  • neutrino masses and mixing
  • dark matter
  • dark energy

✦ Muon g-2
  • Many talks on this subject, so just point out it is one of the most significant anomalies.