The Fermilab/MILC Quark Flavor Physics Program

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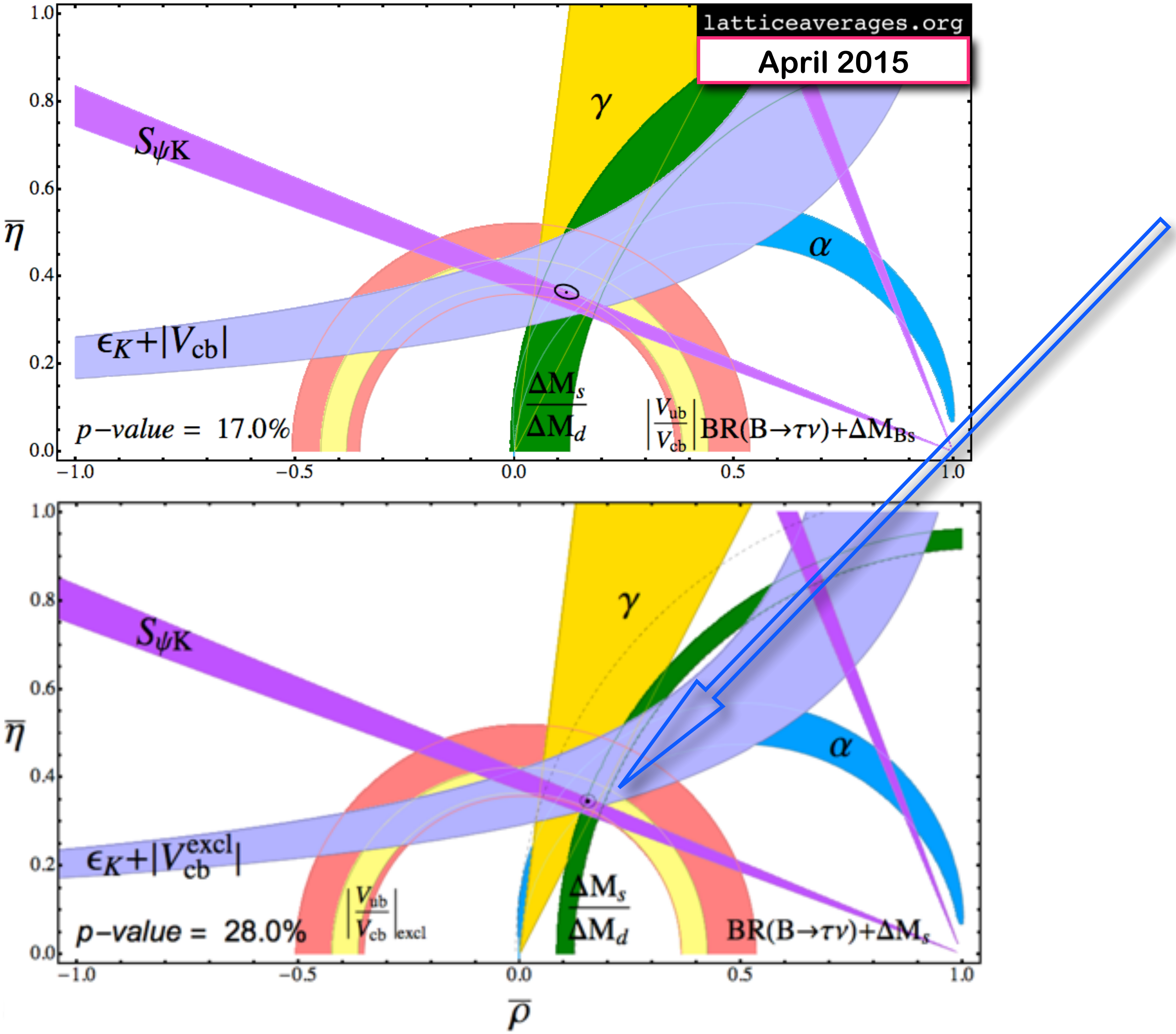
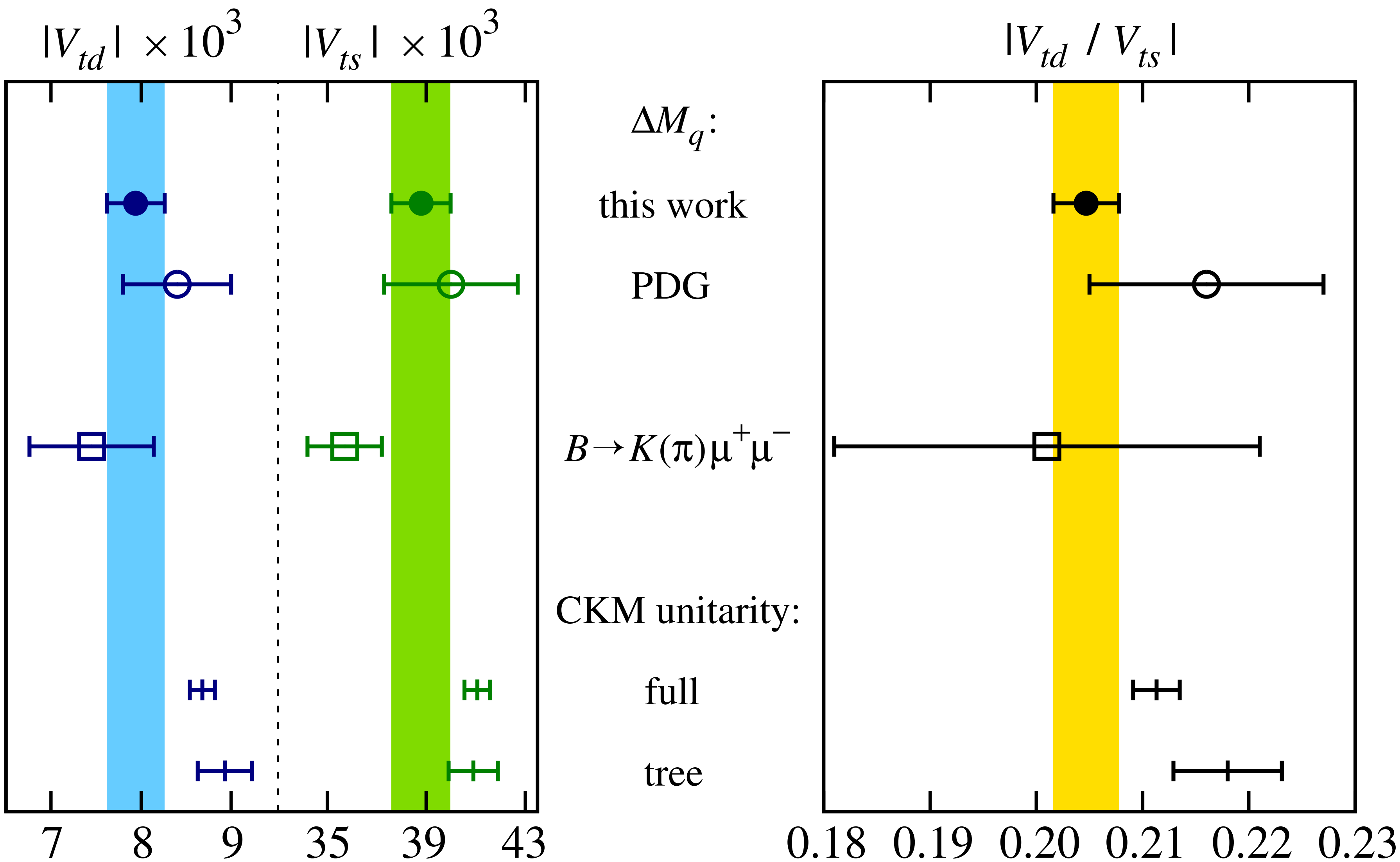
Quark flavor physics

- Still critically important in the program of lattice gauge theory.
- Experimental uncertainties are still much smaller than theory for many important quantities



Our new xi result has 1.5% errors, but experiment has 0.5% errors.
Future lattice calculations have the potential to push the search for BSM effects in flavor physics much further still.

CKM matrix elements from recent B mixing



- There has been a pattern in our recent results that CKM matrix elements obtained from loop processes (colored bands) are a little below those obtained from fits to tree process only.
- Since loop processes are expected to be more sensitive to BSM effects than tree processes, this is an interesting trend to keep an eye on.

Recent results

Our B-physics program on the MILC asqtad ensembles is nearing completion. In the past year, we have published the most precise (and in some cases only) three-flavor results for several interesting B-physics processes:

- for the B->Dlnu form factor at nonzero recoil
  - (PRD92, 034506 (2015)),
- the B->pi and B->K semileptonic form factors
  - (PRD92, 014024 (2015);
  - PRL115, 152002 (2015);
  - PRD93 (2016) no.2, 025026)),
- and the neutral B-meson mixing matrix elements for both the Standard Model and BSM theories
  - (arXiv:1602.03560).

Final results for the B- and D-meson decay constants expected this year.

HISQ physics program

An expanded list of goals:

With Fermilab heavy quarks:

- $B \to D^{(*)}\ell\nu$ and $B_s \to D_s^{(*)}\ell\nu$ (non-zero recoil), with Fermilab b and c quarks, HISQ s and l quarks.
- $B \to \pi\ell\nu$, $B_s \to K\ell\nu$, $B \to Kl^+l^-$, and $B_s \to D_s\ell\nu$, with Fermilab b, HISQ c, s and l quarks.
- f_B, f_{B_s}, f_D, f_{D_s}, with Fermilab b and c, HISQ s and l quarks.
- f_B^*, $f_{B_s}^*$, f_D^* and $f_{D_s}^*$ with Fermilab b and c, HISQ s and l, with vector and tensor currents.
- B mixing, B_s mixing, with Fermilab b, HISQ s and l quarks.

In addition, all HISQ program for charm leptonic and semileptonic decays.
Eventually, b quarks with HISQ .too.

Basically, the entire CKM matrix.

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell\nu & B \to \ell\nu \\ & K \to \pi\ell\nu & B \to \pi\ell\nu \\ \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d|\bar{B}_d\rangle & \langle B_s|\bar{B}_s\rangle & \\ B \to \pi\ell\ell & B \to K\ell\ell & \end{pmatrix}$$

MILC HISQ ensemble generation program

β m_l/m_s	size	N_{lats}	a(fm)	L(fm)	$m_\pi L$	m_π
6.30 1/5	$32^3 \times 96$	1011	0.09242(21)	2.95	4.5	301
6.30 1/10	$48^3 \times 96$	1000	0.09030(13)	4.33	4.7	215
6.30 1/27	$64^3 \times 96$	1047	0.08773(08)	5.62	3.7	130
6.72 1/5	$48^3 \times 144$	1016	0.06132(22)	2.94	4.5	304
6.72 1/10	$64^3 \times 144$	1246	0.05938(12)	3.79	4.3	224
6.72 1/27	$96^3 \times 192$	701*	0.05678(06)	5.44	3.7	135
7.00 1/5	$64^3 \times 192$	1167	0.04333(09)	2.77	4.3	309
7.00 1/27	$144^3 \times 288$	278*	0.04257(04)	6.13	4.17	134
7.30 1/5	$96^3 \times 288$	378*	0.03222(10)	3.09	4.8	309

Improvements in HISQ program

- Charm quark loops
  - Probably small error in asqtad results, but least well quantified.
- Physical light-quark masses.
  - Chiral extrapolation to the physical light-quark masses is the largest source of uncertainty in our recent calculations of the the B->Dlnu form factor at nonzero recoil and the B->pi and B->K semileptonic form factors, and is among the largest uncertainties in our B-mixing matrix element results.
  - Use of the physical-mass HISQ ensembles will render the chiral extrapolation unnecessary and eliminate the associated systematic uncertainty.

- Finer lattice spacings.
    - Discretization errors from the heavy-quark action and heavy-light current are the dominant source of systematic uncertainty in our recent calculations of the B->D*lnu form factor at zero recoil and B-mixing matrix elements, and are also important for the B->Dlnu form factor.
    - Use of the HISQ ensemble with a=0.03 fm now in production will reduce these heavy-quark discretization errors. (The finest ensemble used in the asqtad program was 0.045 fm.)
    - Further, the a~0.03 fm lattice-spacing ensemble will enable, for the first time, the use HISQ valence quarks with a mass close to the physical b-quark mass.
        - Our calculations of D-meson decay constants with HISQ charm quark are currently the world's most precise (PRD90 (2014) no.7, 074509),
        - We expect our results for B-meson decay constants using the "heavy HISQ" approach to have smaller uncertainties than our calculation with Fermilab b quarks on the HISQ ensembles.

LQCD-ext II proposal, 2013

TABLE I: History, status, and future of selected lattice-QCD calculations needed for the determination of CKM matrix elements. Forecasts from the 2008 LQCD-ext proposal (where available) assumed computational resources of 10–50 TF years. Most present lattice results are taken from latticeaverages.org [33]. Other entries are discussed in the text. The quantity $\xi = f_{B_s} B_{B_s}^{1/2} / f_B B_B^{1/2}$.

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2018 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.5%	0.5%	0.15%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	–	0.5%	0.2%
f_D	$\lvert V_{cd}\rvert$	4.3%	5%	2%	$< 1\%$
f_{D_s}	$\lvert V_{cs}\rvert$	2.1%	5%	2%	$< 1\%$
$D \to \pi \ell \nu$	$\lvert V_{cd}\rvert$	2.6%	–	4.4%	2%
$D \to K \ell \nu$	$\lvert V_{cs}\rvert$	1.1%	–	2.5%	1%
$B \to D^* \ell \nu$	$\lvert V_{cb}\rvert$	1.3%	–	1.8%	$< 1\%$
$B \to \pi \ell \nu$	$\lvert V_{ub}\rvert$	4.1%	–	8.7%	2%
f_B	$\lvert V_{ub}\rvert$	9%	–	2.5%	$< 1\%$
ξ	$\lvert V_{ts}/V_{td}\rvert$	0.4%	2-4%	4%	$< 1\%$
ΔM_s	$\lvert V_{ts}V_{tb}\rvert^2$	0.24%	7–12%	11%	5%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	$< 1\%$

For some quantities, lattice precision is ahead of experiment.

For most, it is a factor of 2 or 3 behind experiment.

For some, it is way behind experiment.

Many of the most important quantities in B physics have come from USQCD only.

HISQ program uncertainty goals

Example asqtad uncertainties.

ASQTAD

	stat	chiral+cont	HQ disc	combined*	matching	scale	other	charm sea	total
f0(B -> D)	0.7	0.7	0.4	(1.1)	0.7	0.2	-	-	1.2
B -> D*	0.4	0.5+0.3(g_pi)	1.0	(1.2)	0.4	0.1	-	-	1.4
B mix O1	4.8	2.3+0.7	3.6	(6.5)	2.3	3.4	1.6	2	8.1
xi	0.9	0.4+0.1	0.5	(1.1)	0.3	0.6	0.5	0.5	1.5
fB**	2.4	1.2+0.4	1.8	(3.3)	1.2	1.7	-	0.7 (PDG)	3.9
f+(B -> pi)		(in combined)		(3.1)	1.1	0.5	0.6	-	3.4

- "Combined error" is the quadrature sum of the statistical, chiral-continuum extrapolation, and HQ discretization errors and should not be included twice in the total.

- First, we estimate our uncertainty achievable, assuming fixed statistics, but the three HISQ improvements discussed above.

HISQ

	stat	chiral+cont	HQ disc	combined*	matching	scale	other	charm sea	total
f0(B -> D)	0.7	0	0.3	(0.8)	0.7	0.2	0	0	1.1
B -> D*	0.4	0	0.7	(0.8)	0.4	0.1	0	0	0.9
B mix O1	4.8	0+0.2	2.5	(5.4)	2.3	3.4	1.6	0	7.0
xi	0.9	0+0.0	0.4	(1.0)	0.3	0.6	0.5	0	1.3
fB	0.3	1.1	(in chiral+cont)	(1.1)	(in stat)	0	0.2	0	1.1

- Once chiral-extraplation error is eliminated and HQ discretization errors are reduced, statistics and other sources of uncertainty become important.
- We do not yet know how the statistical errors will change on these new ensembles for the heavy-light quantities.
  - Larger volumes and random wall sources→better statistics,
  - but physical light-quark mass ensembles are noisier.
- Several options for reducing the statistical errors without adding more configurations to our existing ensembles if needed:
  - more time sources per configuration or
  - more nonzero-momentum permutations.

Finally, same improvements as previous, plus halved statistical errors.

HISQ (full statistics)

	stat	chiral+cont	HQ disc	combined*	matching	scale	other	charm sea	total (*asqtad*)
f0(B -> D)	0.4	0	0.3	(0.8)	0.7	0.2	0	0	0.9 *(1.2)*
B -> D*	0.2	0	0.7	(0.8)	0.4	0.1	0	0	0.8 *(1.4)*
B mix O1	2.4	0+0.2	2.5	(5.5)	2.3	3.4	1.6	0	5.6 *(8.1)*
xi	0.5	0+0.0	0.4	(1.0)	0.3	0.6	0.5	0	1.1 *(1.5)*
fB	0.2	< ~1	(in chiral+cont)	<~ 1	(in stat)	0	0.2	0	< ~1 *(1.1)*

- Quantities for scale setting more direct and precise than the Sommer scale r1.
  - Recently obtained results for the gradient-flow parameters t0 and \sqrt{w0} on a number of the HISQ ensembles (arXiv:1503.02769).
- Finally, we are exploring approaches to reduce the uncertainty associated with matching the lattice operators to the continuum by, for example, computing ratios with respect to absolutely normalized or nonperturbatively renormalized quantities.

Summary of uncertainty goals

with Fermilab b quarks.

- B->D and B->D* form factors: <1%.
- B->pi and B->K form factors: <3%.
    - Ultimately, believe we will be able to b quarks with HISQ fermions, enabling still greater accuracy for semileptonic decays.
    - For B decay constants, it is already clear that HISQ b quarks will be significantly.
- B-mixing matrix elements: <5%,
- SU(3)-breaking ratio xi: <1%.

We're pretty much on track to meeting the uncertainty goals in the 2013 hardware proposal!