Precision Lattice QCD in Support of BSM Searches

LOI RF/SNOWMASS21-RF1_RF0-EF5_EF0-TF5_TF0-CompF2_CompF0_DeTar-047 Fermilab Lattice & MILC (POC = Carleton DeTar)
w/ soupçon of LOI EF/SNOWMASS21-EF5_EF2-RF1_RF0-TF5_TF2-CompF2_CompF0_Kronfeld-257 Fermilab Lattice, MILC, & TUMQCD (POC = A.S.K.)

Andreas S. Kronfeld
Fermilab Lattice and MILC Collaborations

Rare Processes and Precision Frontier
Townhall Meeting
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Tension with SM

- $|V_{cb}|$ and $|V_{ub}|$, inclusive vs. exclusive
- $R(D)$, $R(D^*)$
- $B \to Kll$, $B \to K^*ll$; $B \to \pi ll$, $B \to \rho ll$
- $B_s \to \mu\mu$
- $B_s \leftrightarrow \bar{B}_s$, $B^0 \leftrightarrow \bar{B}^0$
- $D_s \to \mu\nu$, $\tau\nu$
- R_K, R_{K^*}

High Precision Gateway

- Heavy-light meson masses and decay constants:

$$f_D = 212.7(0.6)\ \text{MeV} \qquad M_{D_{(s)}}(m_c) \Rightarrow \qquad m_c(3\ \text{MeV}) = 983.7(5.6)\ \text{MeV}$$

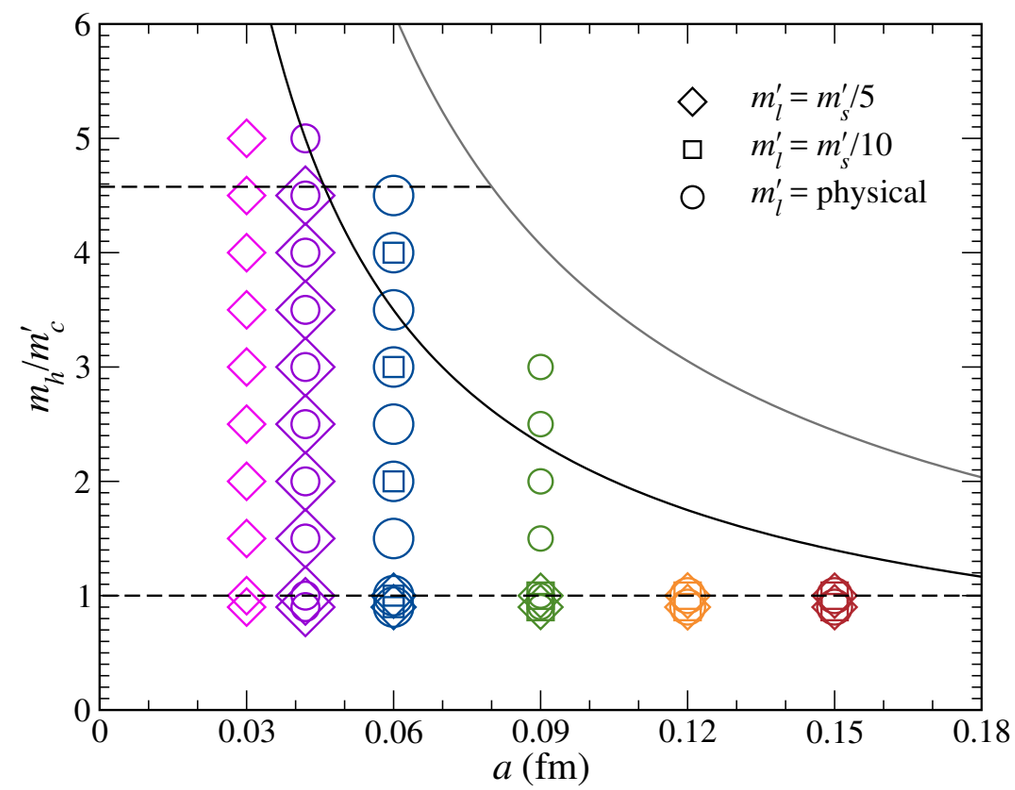
$$f_B = 189.4(1.4)\ \text{MeV} \qquad M_{B_{(s)}}(m_b) \Rightarrow \qquad m_b(m_b) = 4195(14)\ \text{MeV}$$

with two other similarly precise m_c calculations in the literature.

- Charm quark has same lattice action (HISQ) as strange, down, and up.

- Quarks with $0.9m_c < m_Q < m_b$ and $m_Q a \leq 0.9$.

- Huge slab of parameter space (a, L, m_l, m_q, m_Q) fit via EFTs to physical QCD.



High Precision Frontier

- Fermilab Lattice and MILC collaborations have next-gen and next-to-next-gen analysis campaigns underway.

- Next-gen semileptonic form factors Fermilab heavy quarks on HISQ ensembles:

  - for $B \to D$, $B \to K$, $B \to \pi$, including the tensor form factor, and corresponding D decays ("soon");

  - all four SM form factors for $B \to D^*$ ("soon-ish"; on asqtad *very* soon).

- Next-to-next-gen semileptonic form factors, *i.e.*, follow the all-HISQ strategy used for sub-percent decay constants: D "soon", B "later".

- New ideas for neutral $B_{(s)}$ mixing being developed: 4-quark matrix elements with few permille uncertainty!?!

HISQ Ensembles: 2+1+1

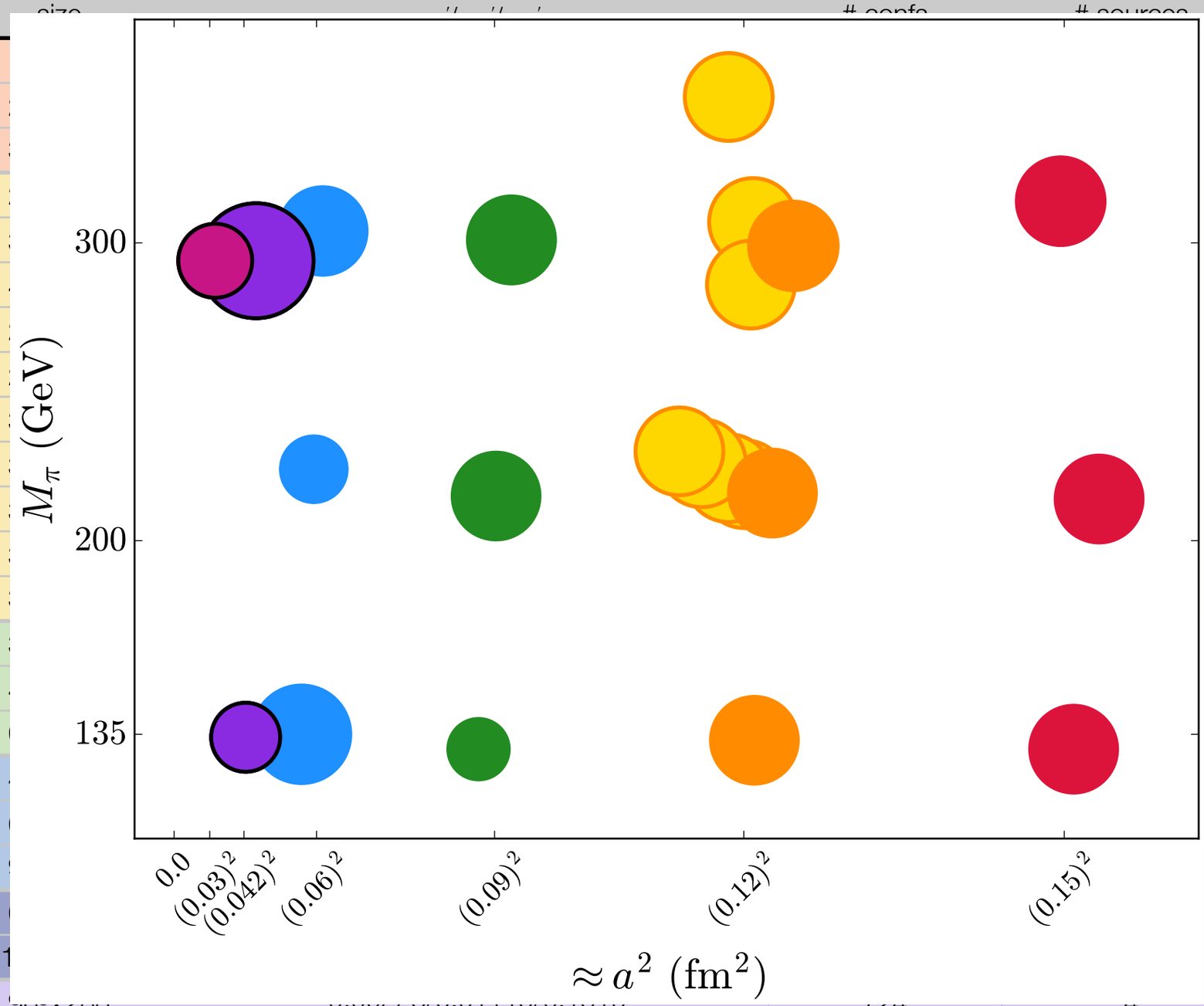
MILC, arXiv:1212.4768, arXiv:1712.09262

a (fm)	size	$am'_l/am'_s/am'_c$	# confs	# sources	notes
≈ 0.15	$16^3\times 48$	0.0130/0.065/0.838	1020	4	
≈ 0.15	$24^3\times 48$	0.0064/0.064/0.828	1000	4	
≈ 0.15	$32^3\times 48$	0.00235/0.0647/0.831	1000	4	physical
≈ 0.12	$24^3\times 64$	0.0102/0.0509/0.635	1040	4	
≈ 0.12	$32^3\times 64$	0.00507/0.0507/0.628	1020	4	also 24^3, 40^3
≈ 0.12	$48^3\times 64$	0.00184/0.0507/0.628	999	4	physical
≈ 0.12	$24^3\times 64$	0.0102/0.03054/0.635	1020	4	$m'_s < m_s$
≈ 0.12	$24^3\times 64$	0.01275/0.01275/0.640	1020	4	$m'_s = m'_l$
≈ 0.12	$32^3\times 64$	0.00507/0.0304/0.628	1020	4	$m'_s < m_s$
≈ 0.12	$32^3\times 64$	0.00507/0.022815/0.628	1020	4	$m'_s < m_s$
≈ 0.12	$32^3\times 64$	0.00507/0.012675/0.628	1020	4	$m'_s \ll m_s$
≈ 0.12	$32^3\times 64$	0.00507/0.00507/0.628	1020	4	$m'_s = m'_l$
≈ 0.12	$32^3\times 64$	0.0088725/0.022815/0.628	1020	4	$m'_s < m_s$
≈ 0.09	$32^3\times 96$	0.0074/0.037/0.440	1005	4	
≈ 0.09	$48^3\times 96$	0.00363/0.0363/0.430	999	4	
≈ 0.09	$64^3\times 96$	0.0012/0.0363/0.432	484	4	physical
≈ 0.06	$48^3\times 144$	0.0048/0.024/0.286	1016	4	
≈ 0.06	$64^3\times 144$	0.0024/0.024/0.286	572	4	
≈ 0.06	$96^3\times 192$	0.0008/0.022/0.260	842	6	physical
≈ 0.042	$64^3\times 192$	0.00316/0.0158/0.188	1167	6	
≈ 0.042	$144^3\times 288$	0.000569/0.01555/0.1827	429	6	physical
≈ 0.03	$96^3\times 288$	0.00223/0.01115/0.1316	724	4	

HISQ Ensembles: 2+1+1

MILC, arXiv:1212.4768, arXiv:1712.09262

a (fm)	size			# confs	# sources	notes
≈ 0.15						
≈ 0.15						
≈ 0.15						physical
≈ 0.12						
≈ 0.12						also 24^3, 40^3
≈ 0.12						physical
≈ 0.12						$m_s' < m_s$
≈ 0.12						$m_s' = m_l'$
≈ 0.12						$m_s' < m_s$
≈ 0.12						$m_s' < m_s$
≈ 0.12						$m_s' \ll m_s$
≈ 0.12						$m_s' = m_l'$
≈ 0.12						$m_s' < m_s$
≈ 0.09						
≈ 0.09						
≈ 0.09						physical
≈ 0.06						
≈ 0.06						
≈ 0.06						physical
≈ 0.042						
≈ 0.042						physical
≈ 0.03						



High Difficulty Frontier

- QED corrections are now crucial: structure at radial and hyperfine scales, Λ and $\Lambda^2/2m_Q$, respectively.

- "Gold-plated" matrix elements have pseudoscalar mesons, but many key flavor-violating processes contain a vector meson,† such as K^* or ϱ.

- These are resonances—can be controlled rigorously through careful monitoring of finite-volume dependence ("toroidal" harmonics)—

  - JLab rho resonance parameters

  - RBC/UKQCD $K \to \pi\pi$;

  - theory for $B \to K^*$ and inclusive B decays (W. Jay talk, next).

†D^* is special, because $m_{D^*} = m_D + m_\pi$

High Performance Frontier

- Support from DOE.ASCR via the Exascale Computing Project (ECP) is helping us (= Fermilab/MILC and other U.S. lattice-QCD groups) develop software for the coming exascale machines (Perlmutter, Aurora, Frontier).

- Continued support is essential (and expected but not certain) post-ECP, *i.e.*, after June 30, 2023.

- Intellectual innovations, such as multi-grid algorithms for quark propagators (recently) or Markov algorithms accelerated with machine learning (future), will continue to be needed.

- Compute architectures are not going to get simpler—need to develop and maintain expertise to get the most out of future supercomputers.

Personal Observations

- Community support for (computing for) lattice QCD has been essential to the success of lattice-QCD *B* & *D* Physics,
  - along with a stream of excellent students & postdocs and improvements in algorithms & computers.
- For a long time, the bang/buck of quark-flavor physics was unique;
  - now (*cf.*, )
    - muon *g*–2;
    - parton distribution functions;
    - nucleon charges and form factors;
    - exotic spectroscopy;
  - have similar bang/buck (with very different $\frac{B}{\$}(t)$ for *g*–2).