Lattice QCD @ Fermilab:

"What are we doing for precision science?"

Ruth Van de Water

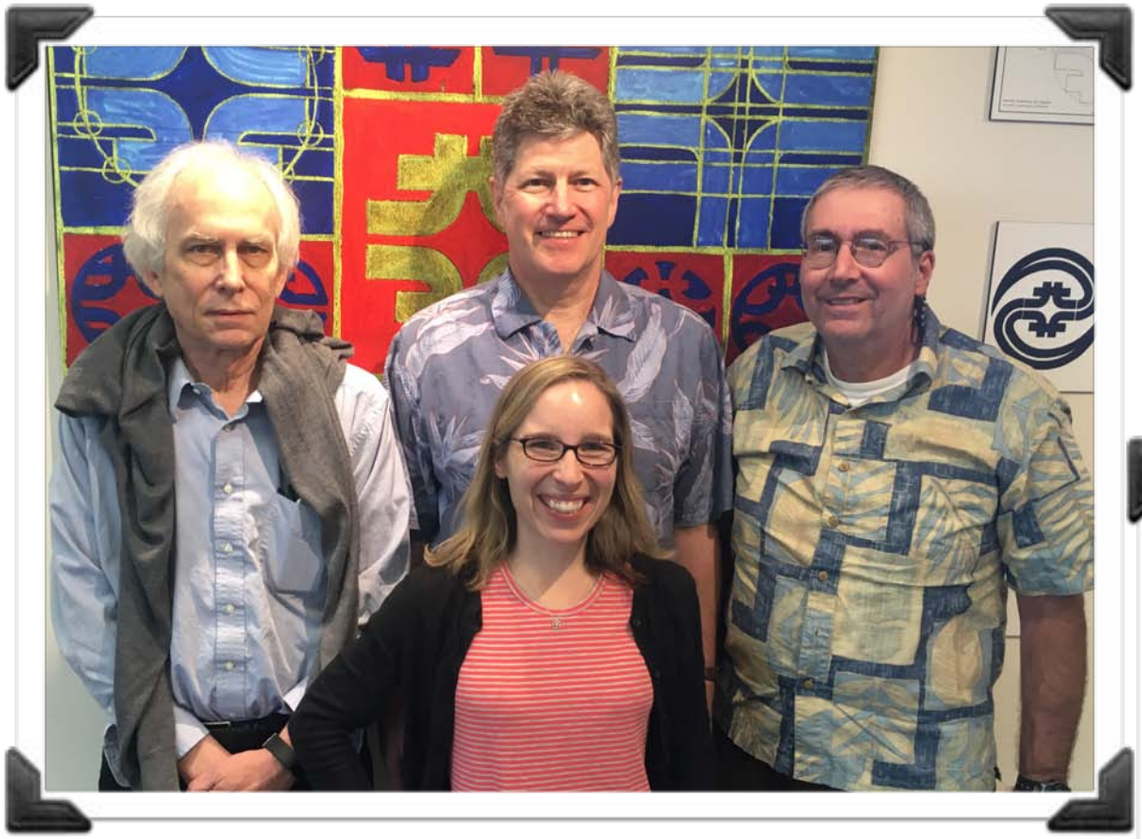
Fermilab Precision Science Retreat

October 27, 2017

Fermilab lattice gauge theorists

- Lead **Fermilab Lattice Collaboration**, with collaborators at UIUC & other institutions
- Outstanding record in all aspects of lattice gauge theory: developing theory & algorithms, pioneering applications to high-energy physics, and building hardware & software

Scientists



Research associates

Graduate students

Fermilab distinguished scholar

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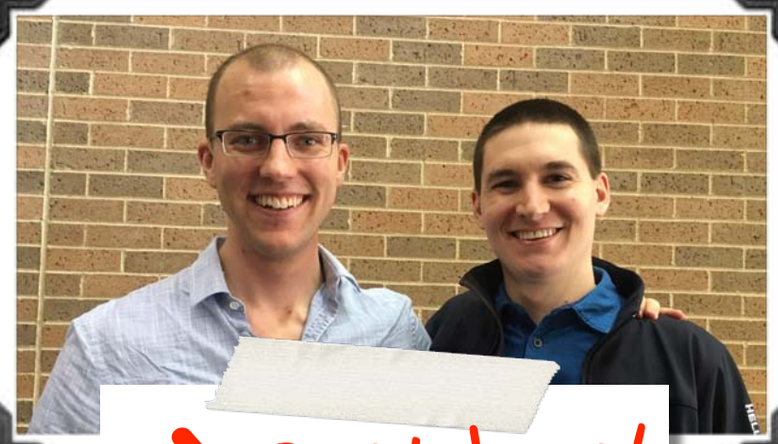

Fermilab distinguished scholar

Lattice QCD for precision measurements

- **QCD is ubiquitous throughout experimental program**, e.g.:
  - Scattering off of *nuclear detector material* in neutrino / DM experiments
  - Observation of *hadronic final states* in collider experiments
  - Quark masses & CKM matrix elements parametric inputs to theoretical predictions

- Discovery of new physics requires reliable QCD calculations on same time scale as measurements with commensurate uncertainties

quark flavor

- decay constants
- form factors
- mixing matrix elements

neutrinos

- nucleon axial-vector form factor

Higgs physics

- b, c-quark masses
- strong coupling (α_s)

muon g-2

- hadronic vacuum polarization contribution

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LHCb · BESIII · Belle II

Fermilab lattice-QCD effort targeting key hadronic parameters needed to interpret current & future experiments as Standard-Model tests & new-physics searches

…form factor…

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Higgs physics

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strong coupling (α_s)

ILC · FCC TLEP

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muon g-2

- hadronic vacuum polarization contribution

FY17 highlights

"In the last five years lattice QCD has matured into a precision tool. ... *The ultimate aim of lattice-QCD calculations is to reduce errors in hadronic quantities to the level at which they become subdominant either to experimental errors or other sources of error."*

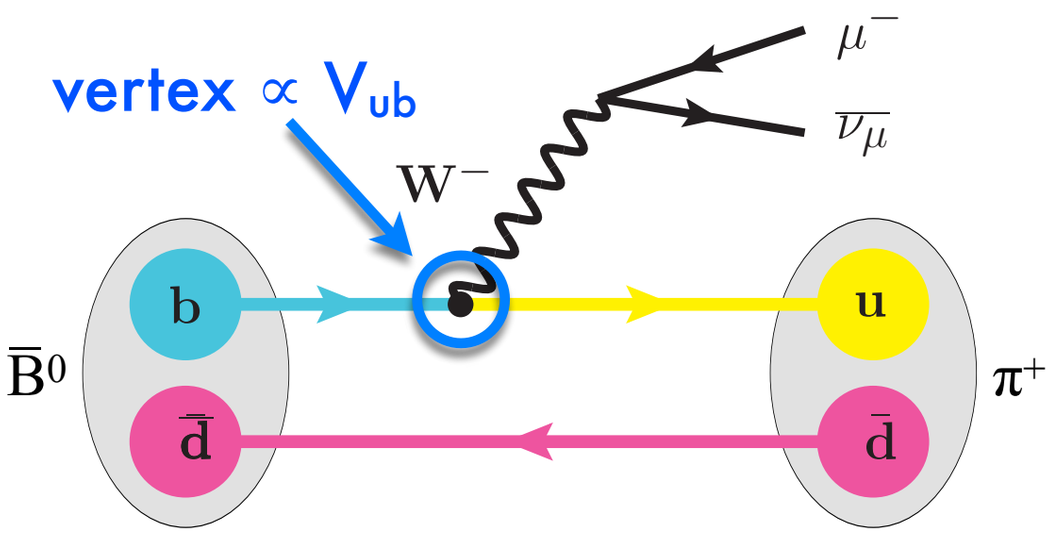
— **Snowmass 2013 Quark-flavor WG report (1311.1076)**

Quark-flavor physics

- Most Standard-Model extensions have additional sources of flavor & CP violation in the quark sector
- Fermilab lattice effort has two main thrusts:

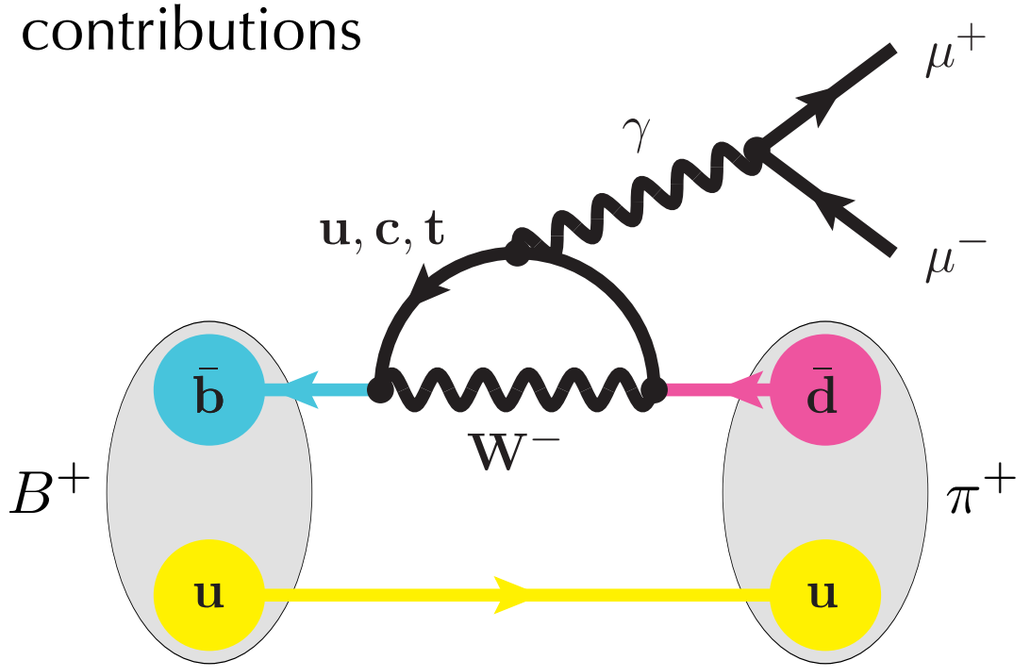
(1) Determination of CKM quark-mixing matrix elements

- Use tree-level decays unlikely to receive substantial new-physics contributions



(2) New-physics searches in rare decays & mixing

- Study (primarily) loop-level processes sensitive to beyond-the-Standard-Model contributions



Recent publications

Cabibbo-Kobayashi-Maskawa quark-mixing matrix

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

- Fermilab Lattice Collaboration world leaders in quark-flavor physics, with most precise results for hadronic matrix elements needed to obtain 7/9 CKM elements

In 2016/17:

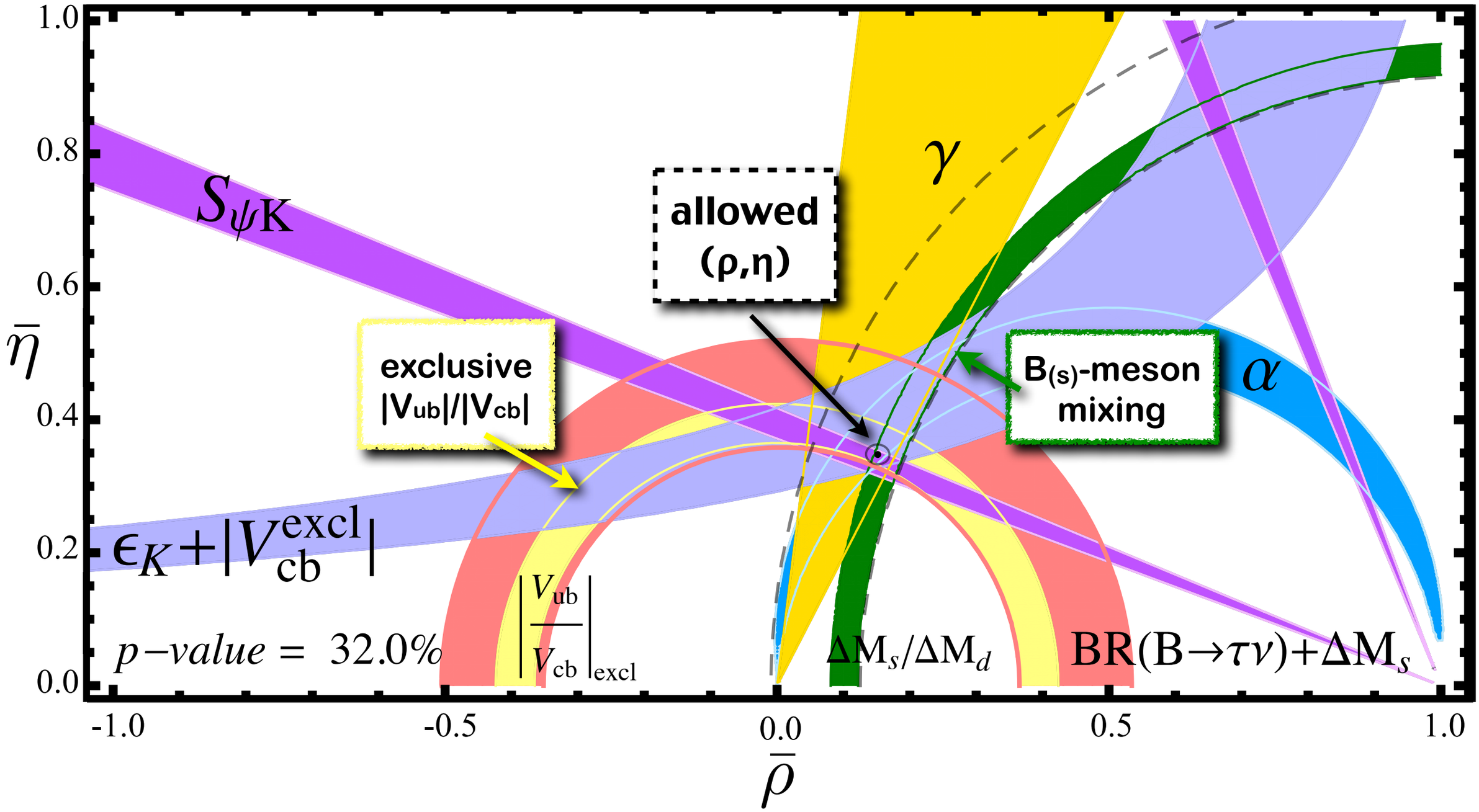
(1) First complete 3-flavor calculation of neutral $B_{d,s}$-mixing matrix elements for all five local Δ(B)=2 four-quark operators that arise in Standard Model and new-physics theories [Fermilab/MILC, Phys.Rev. D93 (2016) no.11, 113016]

(2) First 3-flavor calculation of short-distance matrix elements of Δ(C)=2 four-quark operators that contribute to neutral D-mixing matrix elements both in and beyond the Standard Model [Fermilab/MILC, arXiv:1706.04622]

Impact on CKM unitarity-triangle fit

[Fermilab/MILC, PRD93, 113016]

[plot from E. Lunghi]

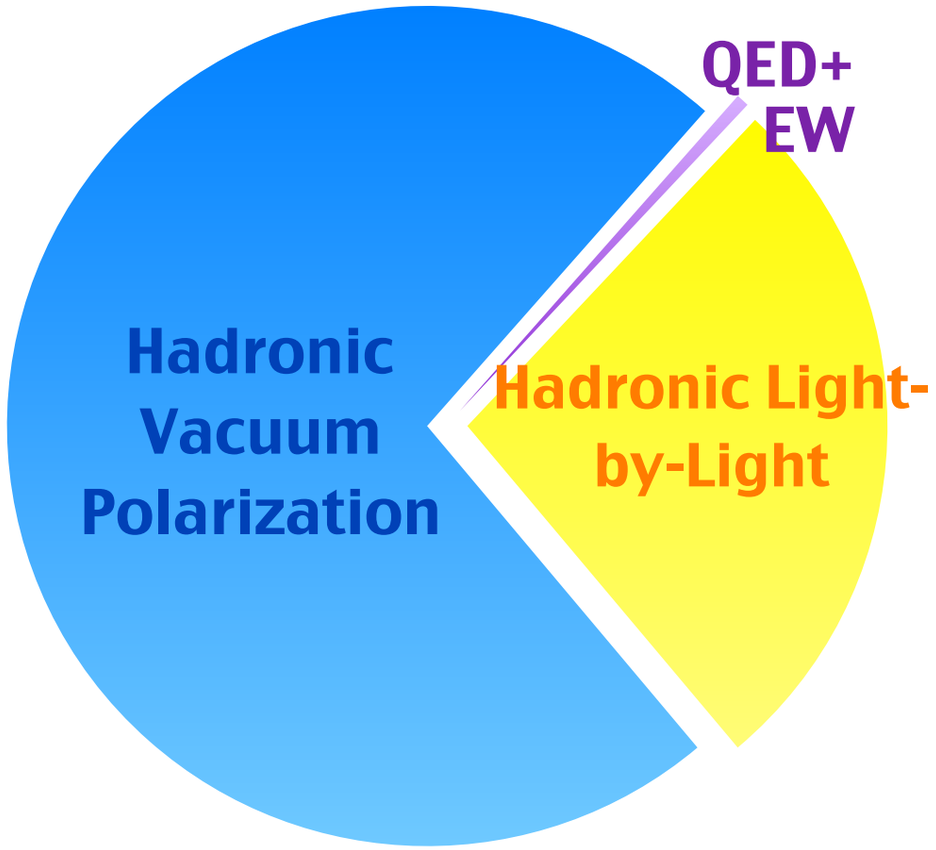


Muon anomalous magnetic moment

- Muon g-2 Experiment running (!), & anticipates final measurement error of ~0.14 ppm

➡ **Must reduce theory error to commensurate level to identify definitively whether any deviation observed between theory and experiment is due to new physics**

Standard-Model Error Budget

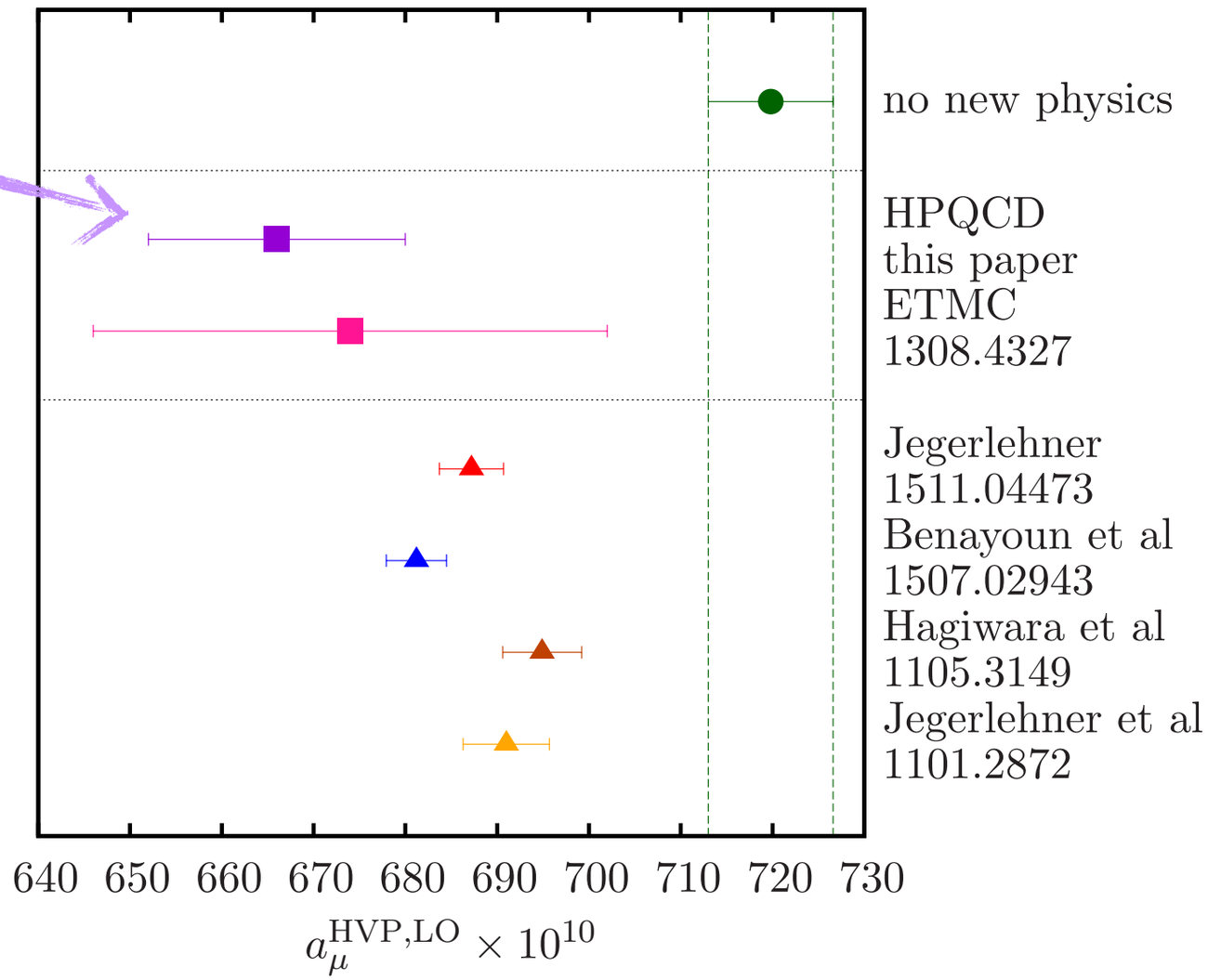


$O(\alpha_{EM}^2)$ Hadronic Vacuum Polarization Contribution

- Fermilab Lattice Collaboration calculating HVP contribution, which is largest source of theory error

First g-2 publication

- First complete lattice-QCD calculation of a_μ^{HVP} to reach precision needed to observe significant deviation from experiment [HPQCD Collaboration with Van de Water, Phys. Rev. D96 (2017) no.3, 034516]
- **Fermilab Lattice, HPQCD, & MILC Collaborations** together addressing leading sources of error in earlier result from omission of **isospin-breaking [arXiv:1711.XXXXX]**, electromagnetism, and quark-disconnected contributions

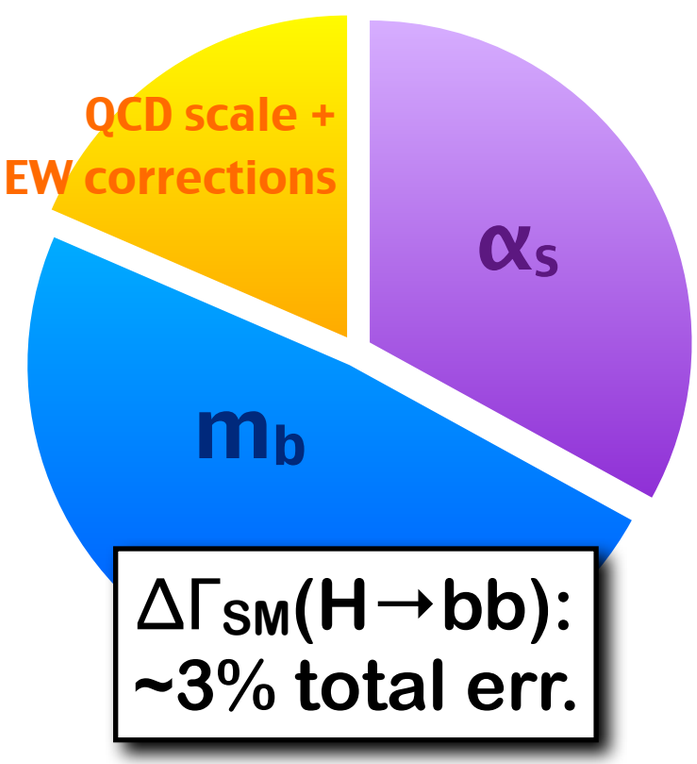


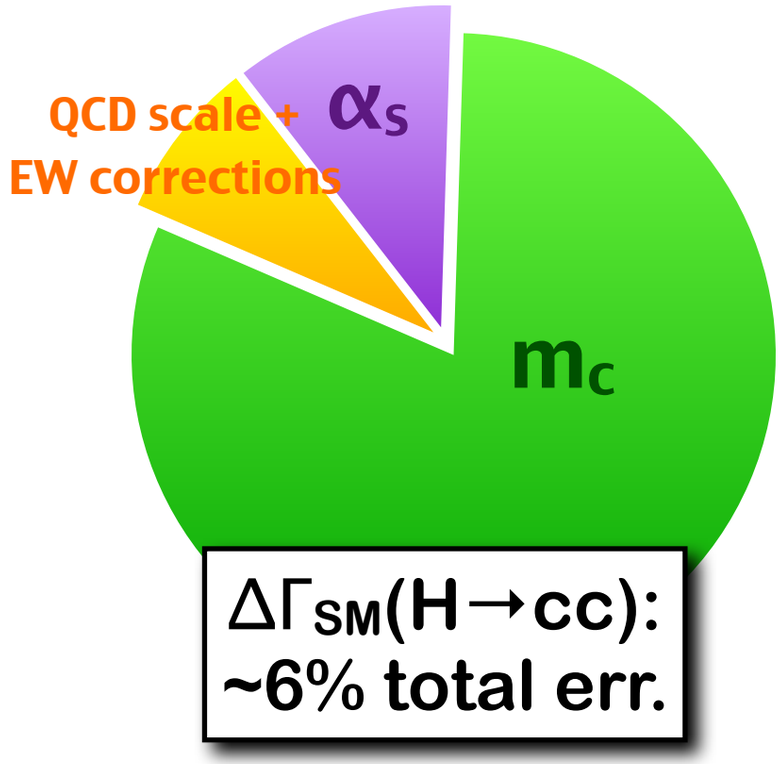
- Anticipate reaching sub-percent precision before first experimental result next Spring

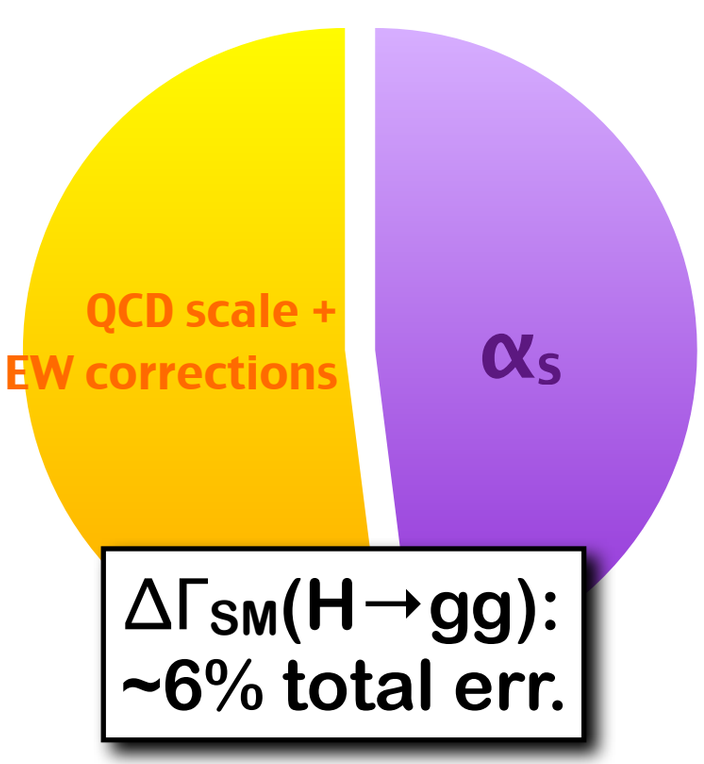
$$a_\mu^{\mathrm{HVP,LO}} \times 10^{10} = 666(11)_{u,d}(1)_{s,c,b}(9)_{\mathrm{disc.}}$$

Precision Higgs physics

- **Next-generation high-luminosity colliders will measure Higgs partial widths to sub-percent precision** to look for deviations from Standard-Model expectations
  - *Full exploitation of measurements needs theory predictions with same precision*
- **Parametric errors from quark masses (m_c, m_b) & strong coupling constant (α_S) are largest sources of uncertainty in SM Higgs partial widths** for many decay modes [LHCHXSWG-DRAFT-INT-2016-008]
  - **QCD parameters can be calculated to needed precision with lattice methods**

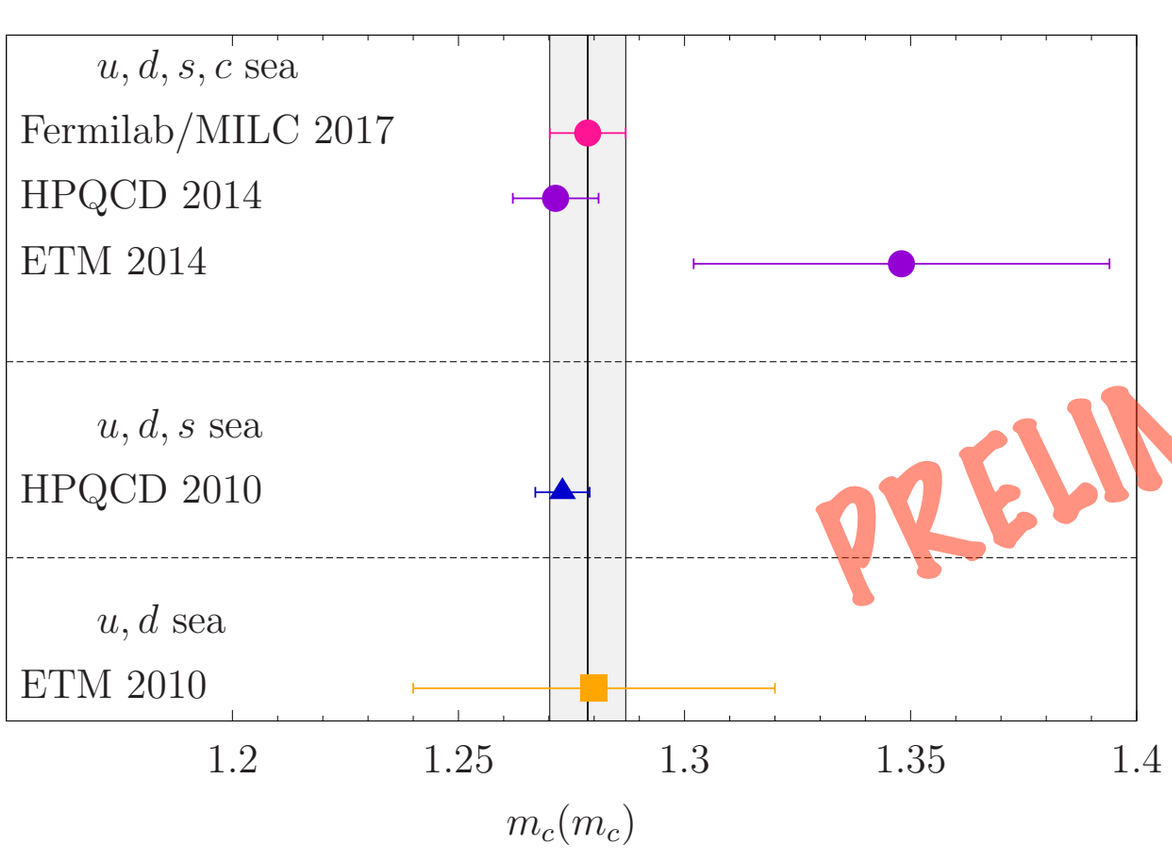


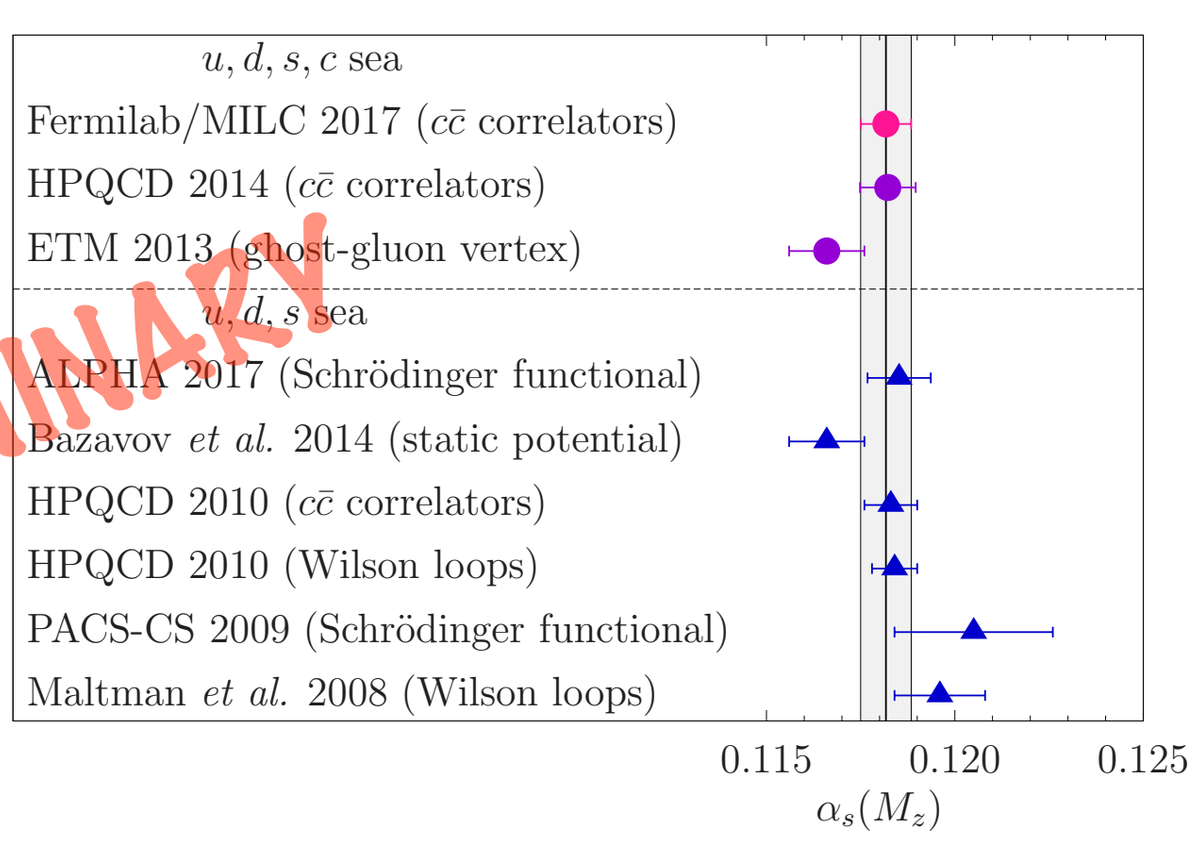




Work in progress

- Postdoc Aarti Veernala spearheading Fermilab effort to compute heavy-quark masses quantities on state-of-the-art four-flavor QCD lattices with finer lattice spacings than ever before
  - **Presented first preliminary results for charm-quark mass & QCD coupling in June** @ Lattice 2017





Plans for FY18

"Progress in science is based on the interplay between theory and experiment, between having an idea about nature and testing that idea in the laboratory. Neither can move forward without the other." — **Snowmass 2013 Executive Summary**

"Lattice QCD has [already] become an important tool in flavor physics. ...*The full exploitation of the experimental program requires continued support of theoretical developments.*" — **Snowmass 2013 Quark-flavor WG report**

Anticipated publications

- **Paper drafts complete or nearing completion for:**
  - $D_{(s)}$- and $B_{(s)}$-meson leptonic decay constants (2 papers) [u,d,s,c sea quarks, arXiv:1711.xxxxx; u,d,s sea quarks, 1801.xxxxx]
  - $B_s \to Klv$ semileptonic form factors and determination of $|V_{ub}|$ [arXiv:1803.xxxxx]
  - ***Strong-isospin-breaking correction to hadronic-vacuum-polarization contribution to muon g–2*** [arXiv:1711.xxxxx]
  - Up, down, strange, and charm-quark masses from heavy-light meson masses + heavy-quark effective theory [arXiv:1712.xxxxx]
  - Charm-quark mass and αs from charmonium correlator moments [arXiv:1712.xxxxx]
- **Other projects may also be finished in FY18, e.g.:**
  - $B \to D^* lv$ semileptonic form factors at nonzero recoil and determination of $|V_{cb}|$

Summary & outlook

- Fermilab theorists have strong record of lattice-QCD calculations of hadronic parameters needed to interpret precision measurements as Standard-Model tests & new-physics searches
  - ☑ In recent years, produced many of world's best lattice-QCD results in **K, B, & D physics and for muon g-2**
  - ☐ In coming years, will continue quark-flavor and muon g-2 efforts to probe present tensions and exploit future measurements
  - ☐ Also pursing new calculations for planned **high-luminosity lepton colliders**

Lab activities Research	**Primary Lab Objective**
Lattice QCD	Calculate leading-order hadronic-vacuum-polarization contribution to muon g-2 with total error below 1%.
(Lepton-flavor model building)	*(See Roni Harnik)*

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Want to provide needed theoretical support to enable Fermilab's experimental program to be successful. Please come talk to us!

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