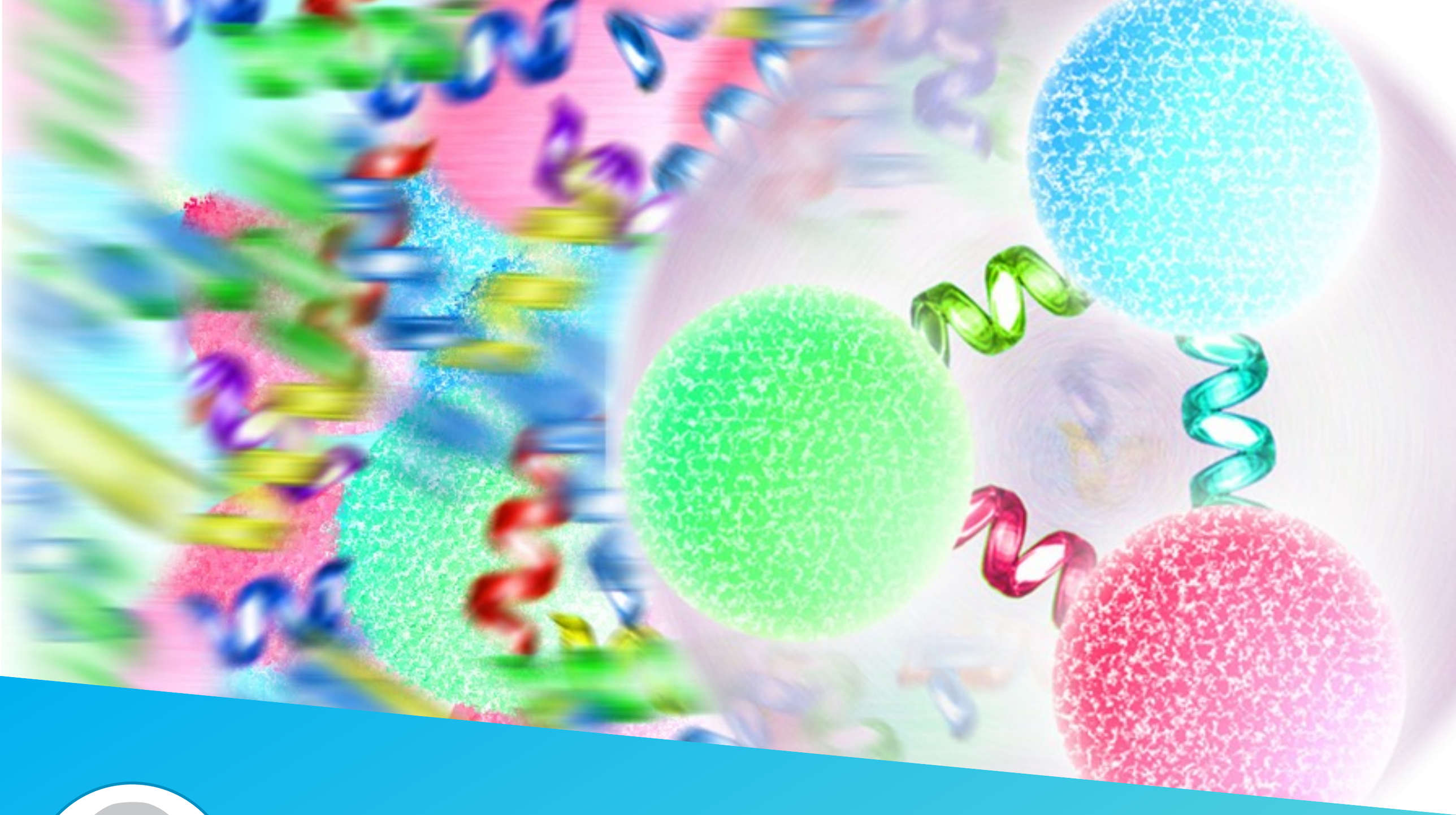


Quark & lepton flavor physics

Ruth Van de Water, Fermilab

LQCD-Ext III review

9 July, 2019

Scientific motivation

What is needed by quark- & lepton-flavor experiments?

Track record

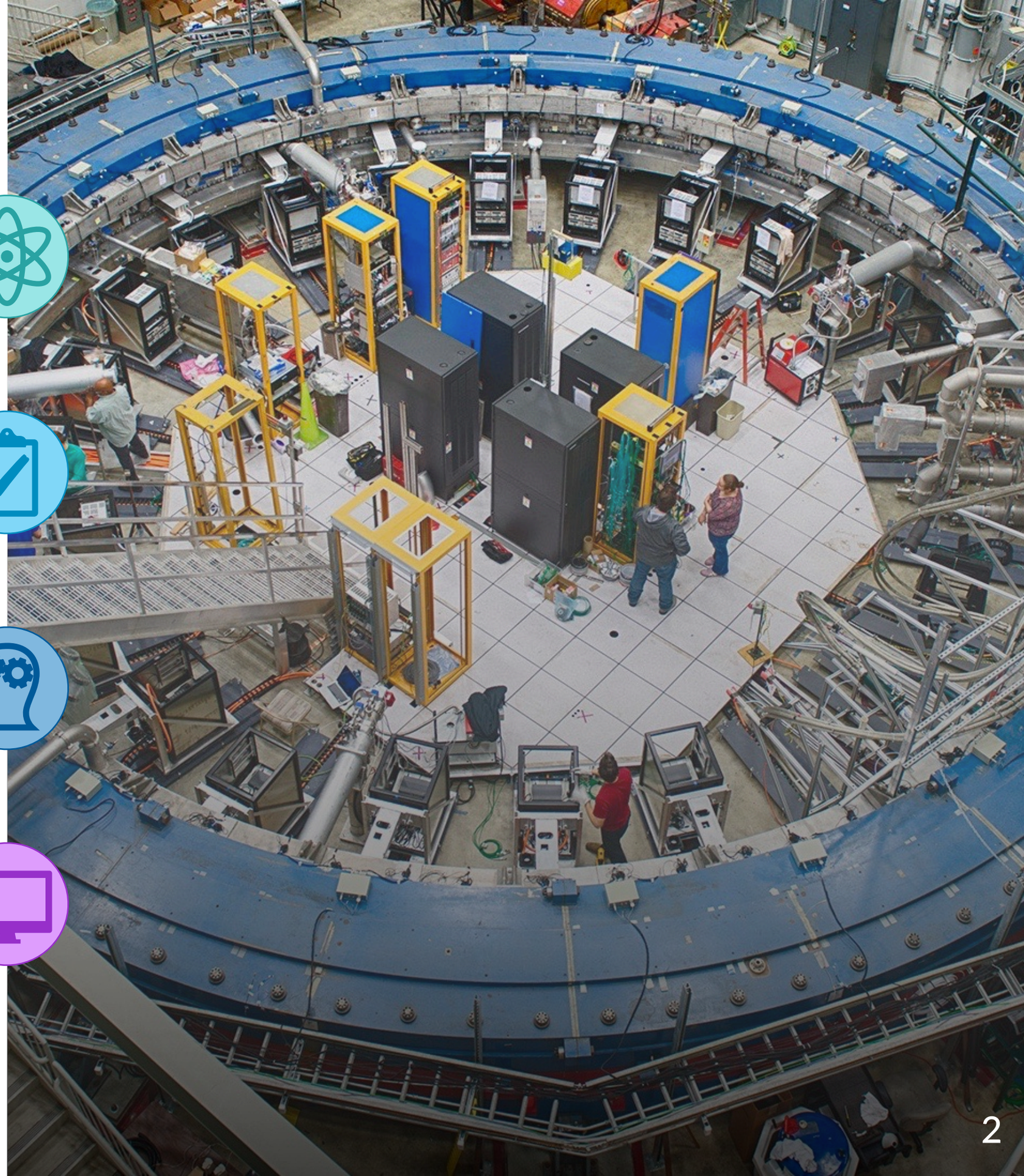
What has the U.S. lattice-QCD community done for flavor-physics experiments?

Plans and priorities

What will USQCD do for flavor-physics experiments in the future?

Computing needs

Why is dedicated hardware crucial for achieving USQCD's scientific objectives?



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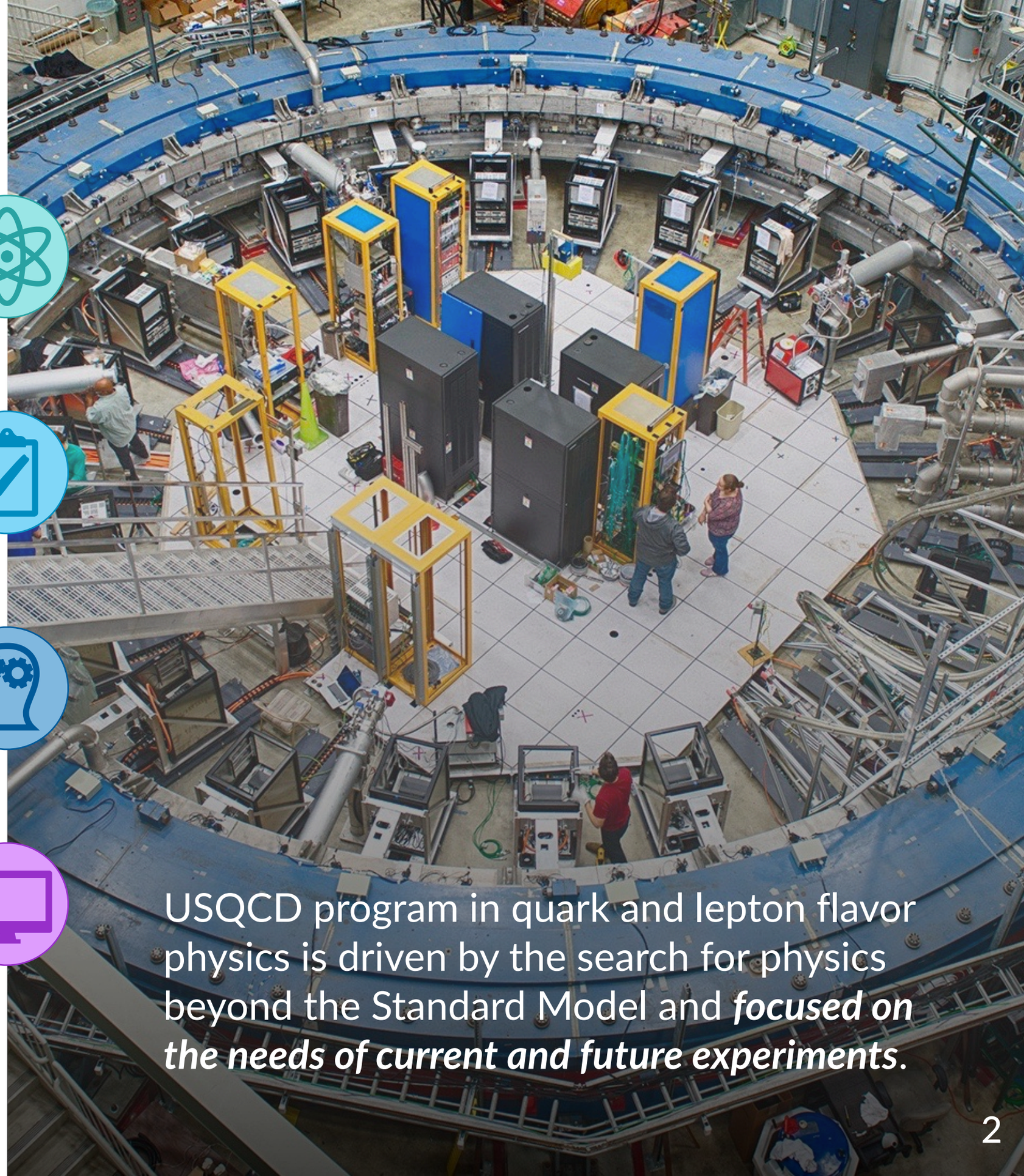
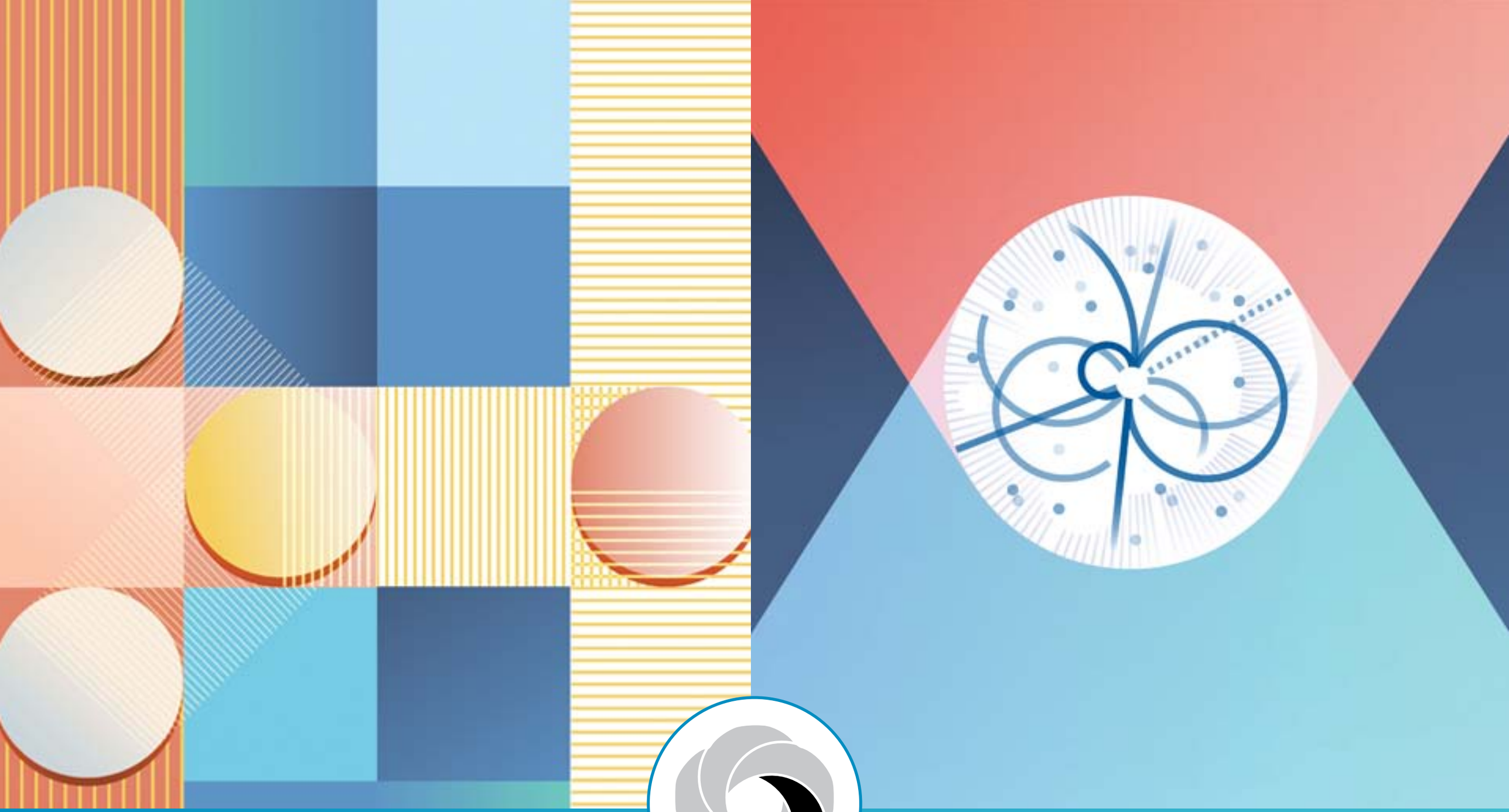


USQCD program in quark and lepton flavor physics is driven by the search for physics beyond the Standard Model and ***focused on the needs of current and future experiments***.

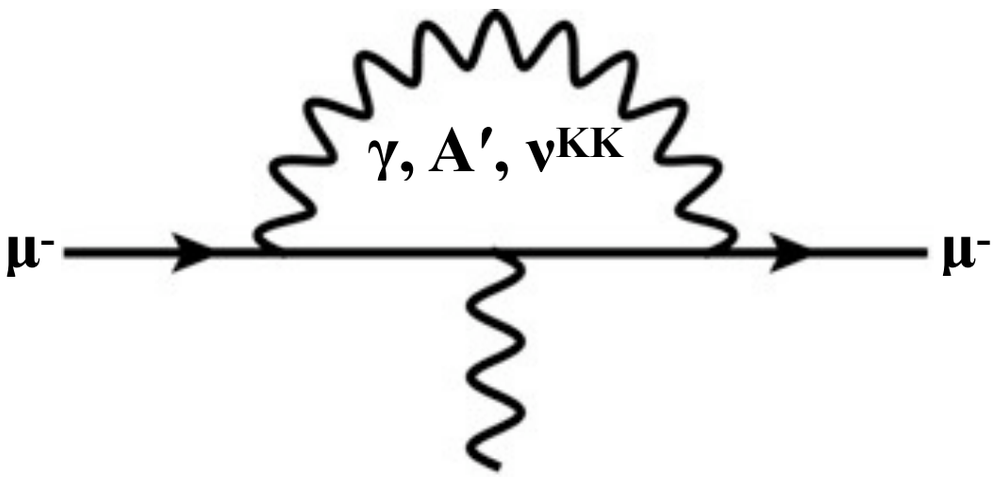


Exploring the unknown

Where is the new physics?

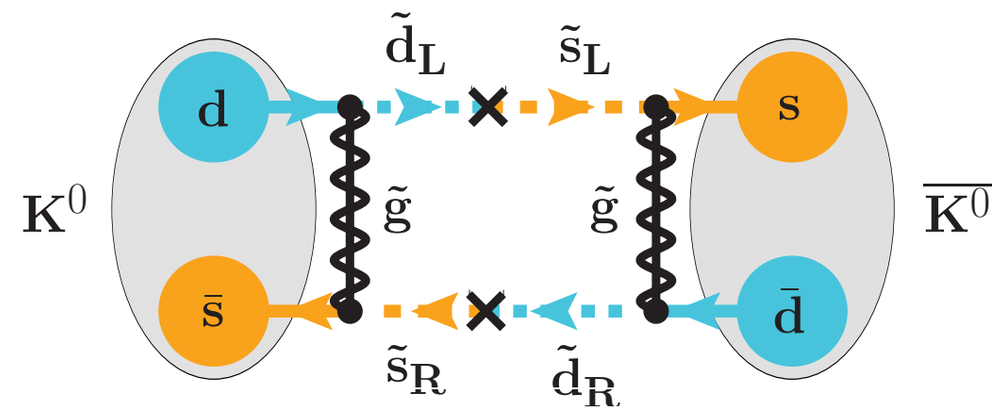
muon anomalous magnetic moment (g-2)

sensitive to supersymmetry (SUSY), extra dimensions, dark photons, ...



s→d & b→d,s flavor-changing neutral currents

sensitive to SUSY, flavor-changing Z', leptoquarks, 4th generation, composite Higgs, ...



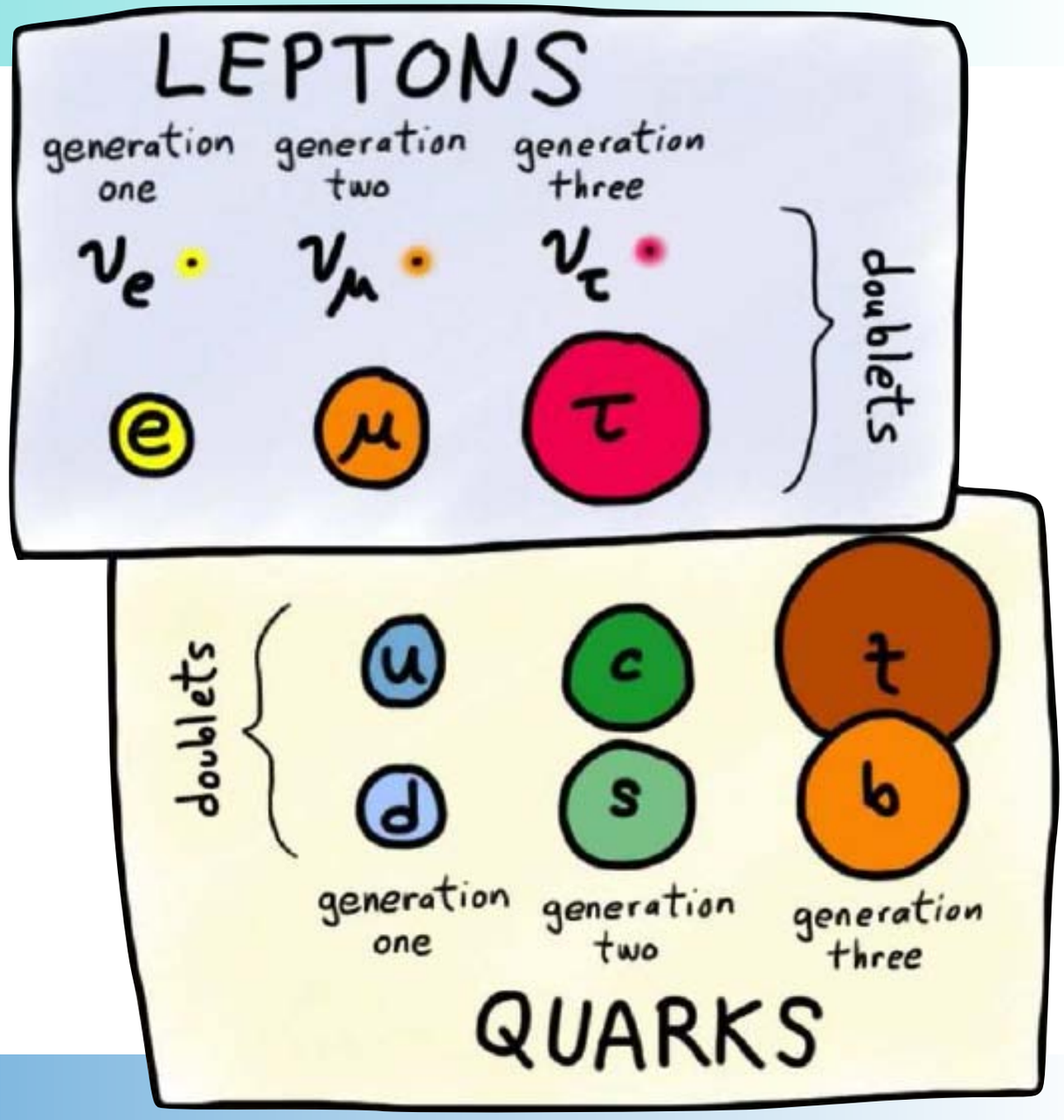
- Experimental particle-physics community searching broadly for new particles and forces over wide range of energy scales and areas within particle physics
- Low-energy flavor observables sensitive to quantum-mechanical effects of new particles that would give rise to tiny deviations from Standard-Model expectations
- Indirect searches probe energy scales beyond direct reach of foreseeable colliders

▶ *Revealing new physics requires very precise measurements and equally precise (and reliable) theory!*

Flavor-physics overview

Charged leptons come in 3 flavors

➤ Charged-lepton flavor violation forbidden in Standard Model



Quarks come in 6 flavors

➤ Can change flavor via the charged weak interaction

Flavor-physics overview

- Study processes in which quarks or leptons change flavor, or observables that may depend upon the particle's flavor
- In the lepton sector, electron's and muon's anomalous magnetic moments provide some of the most stringent tests of QED and limits on new physics
- Flavor physics in the quark sector has *proven track record of new discoveries of fundamental physics*

  e.g., observation of CP-violation in kaon decays necessitated existence of third generation of quarks

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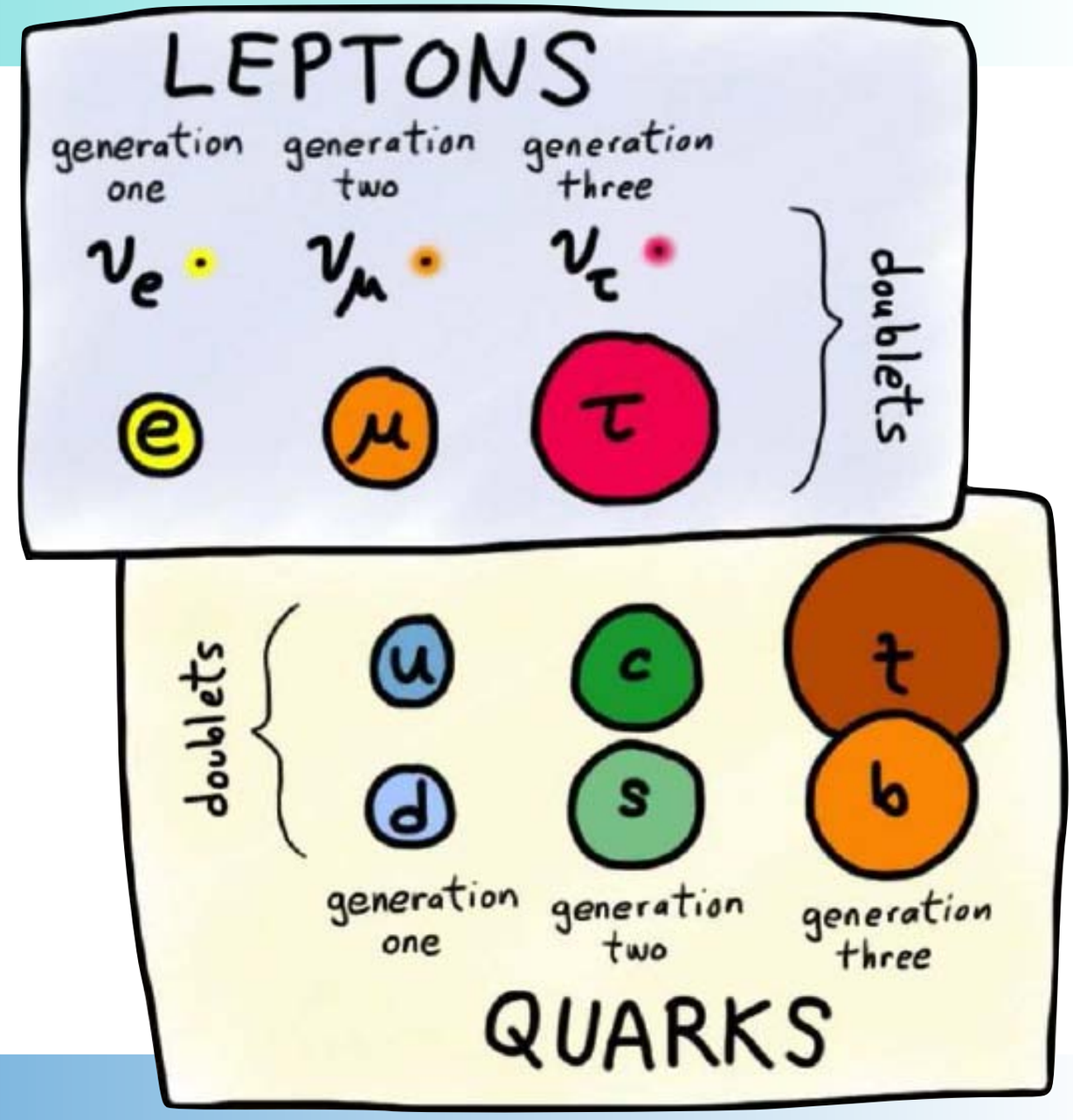

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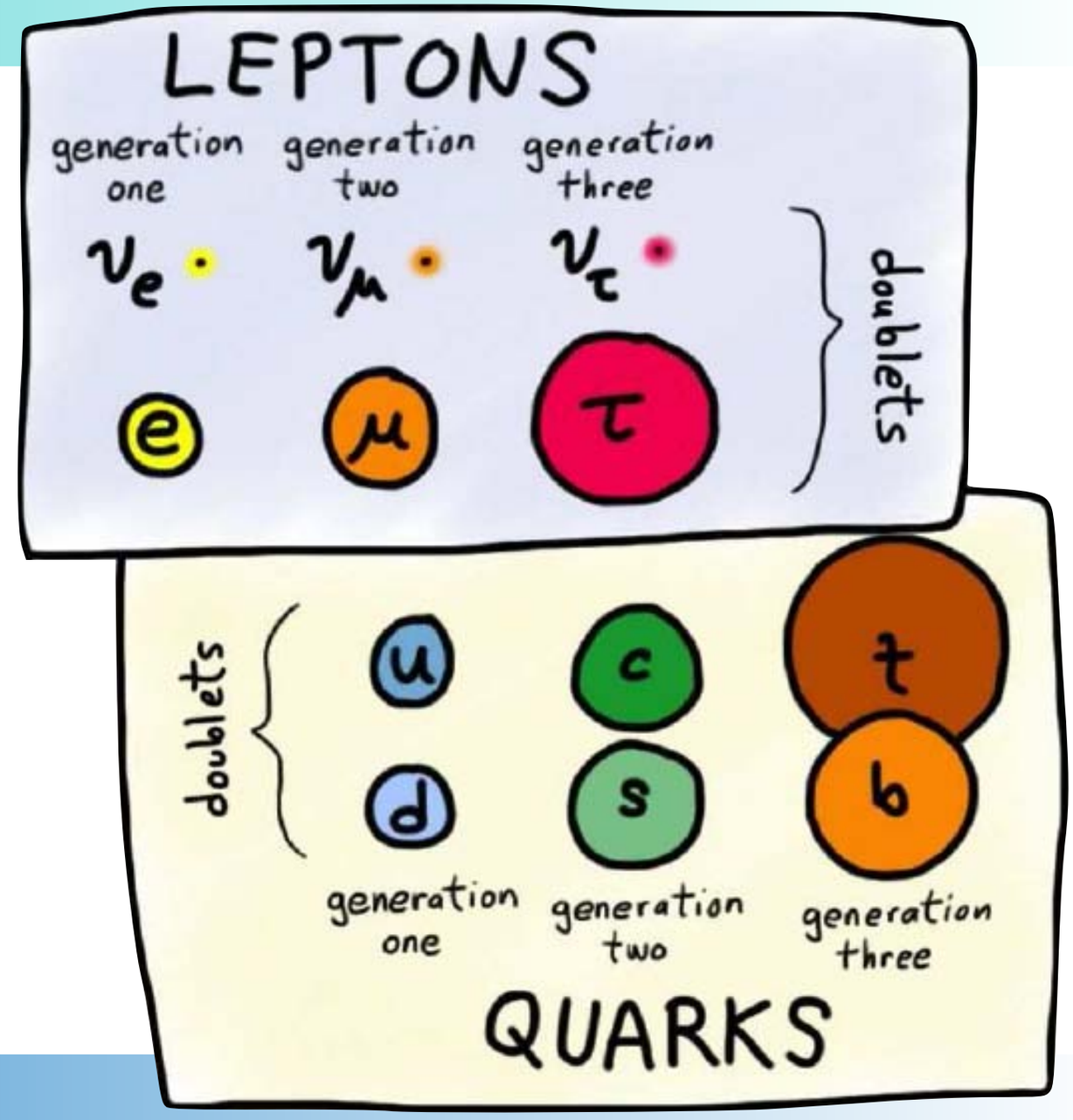

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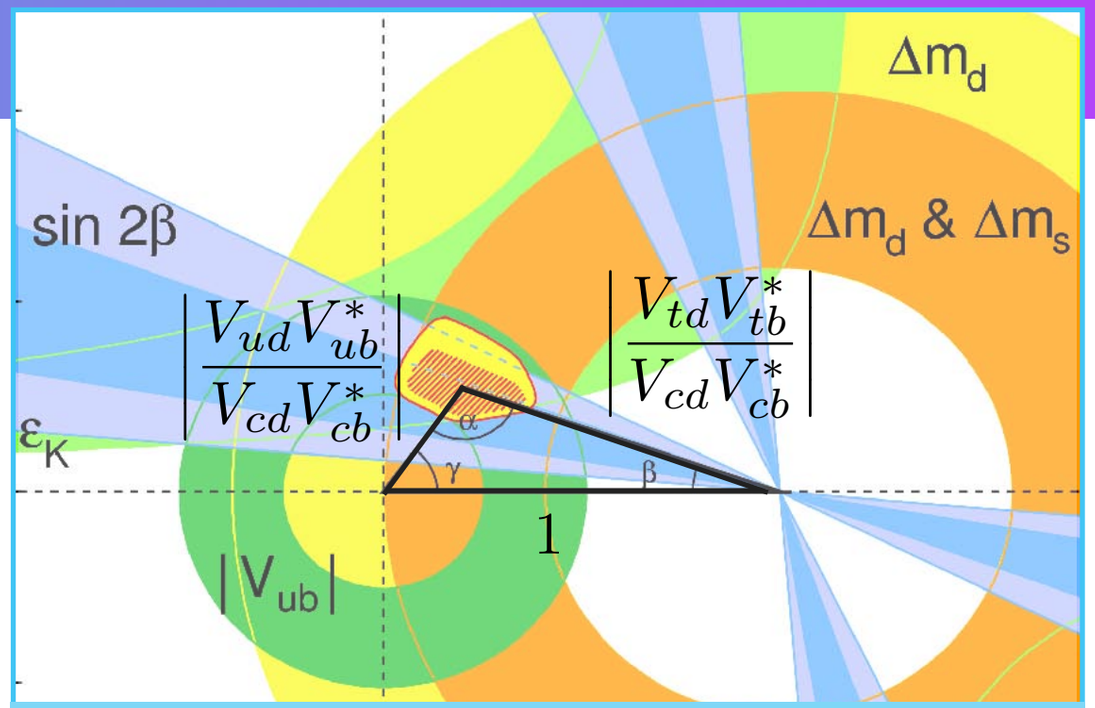
Interplay between theory and experiment crucial!

The CKM quark-mixing matrix

$$V_{\mathrm{CKM}} \approx \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{bmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{bmatrix} \end{array} \begin{array}{c} u \\ c \\ t \end{array}$$

$$\lambda \approx 0.22$$

Interactions between quarks of different flavors under charged weak interaction governed by **Cabibbo-Kobayashi-Maskawa matrix**



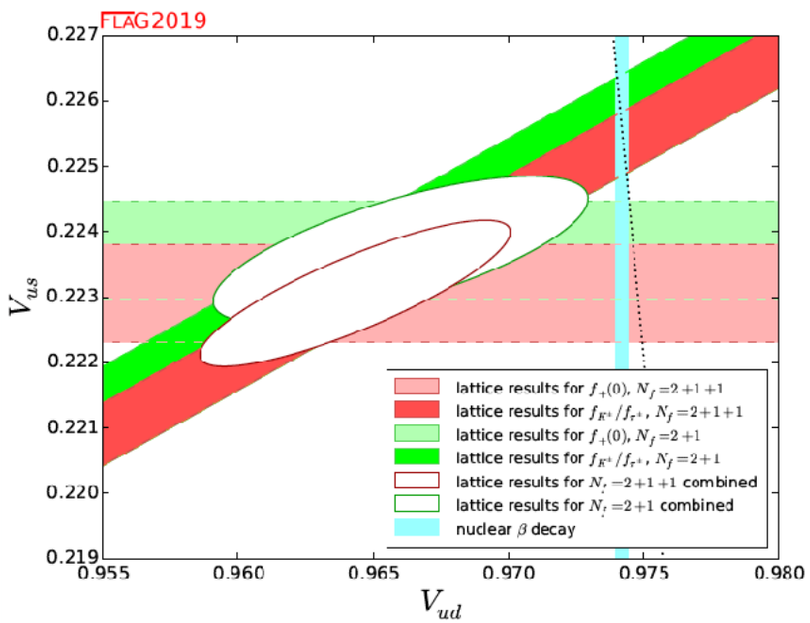
CKM unitarity triangle provides graphical representation of constraints on the CKM matrix from different processes

- Changes basis between flavor/mass and weak eigenstates
- Obtain entries of CKM matrix by comparing measurements of flavor-changing processes to theoretical Standard-Model predictions

▶ *CKM matrix is unitarity*, *i.e.* $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = \mathbb{1}$

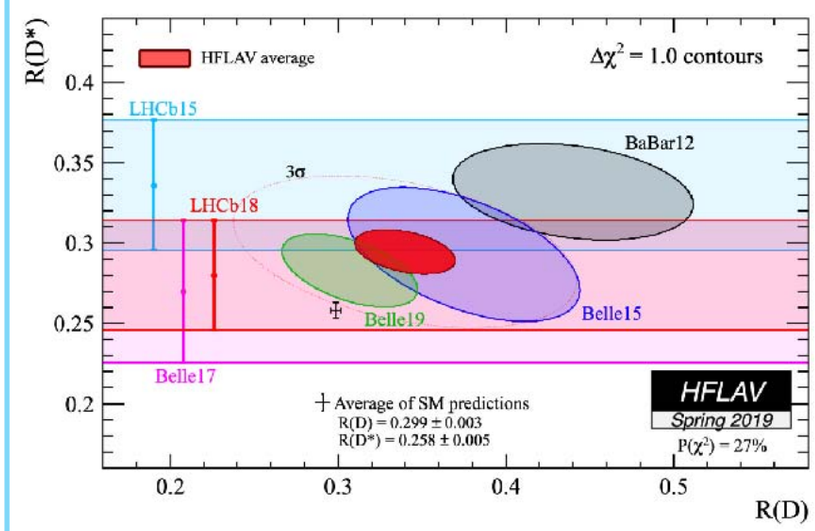
Hints of new physics?

[Flavor Lattice Averaging Group, arXiv:1902.08191]



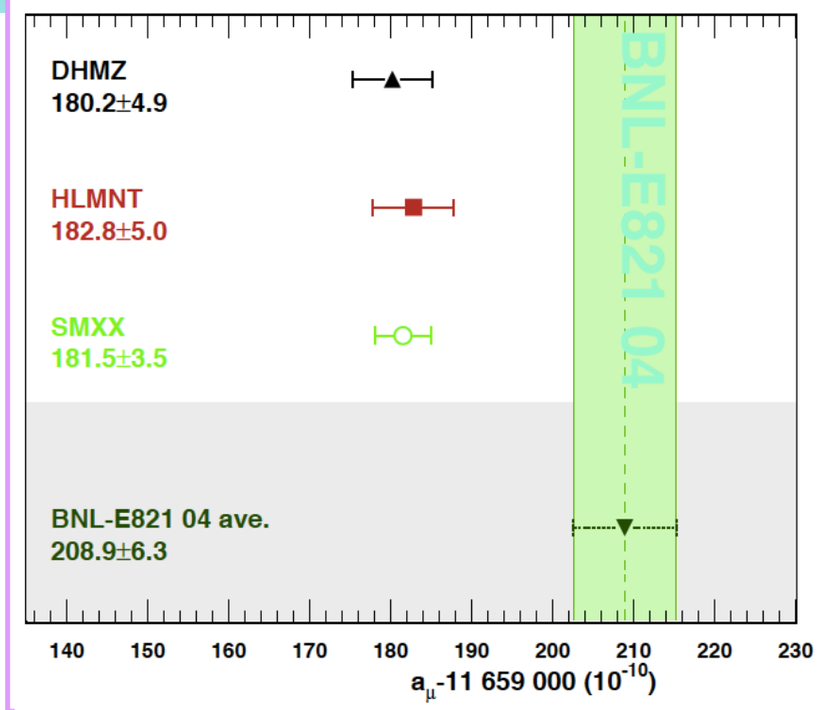
First row of CKM quark-mixing matrix violates unitarity by **~3-5σ**

[Heavy Flavor Averaging Group, https://hflav.web.cern.ch]



Semileptonic B→D(*) decays violate lepton-flavor universality by **>3σ**

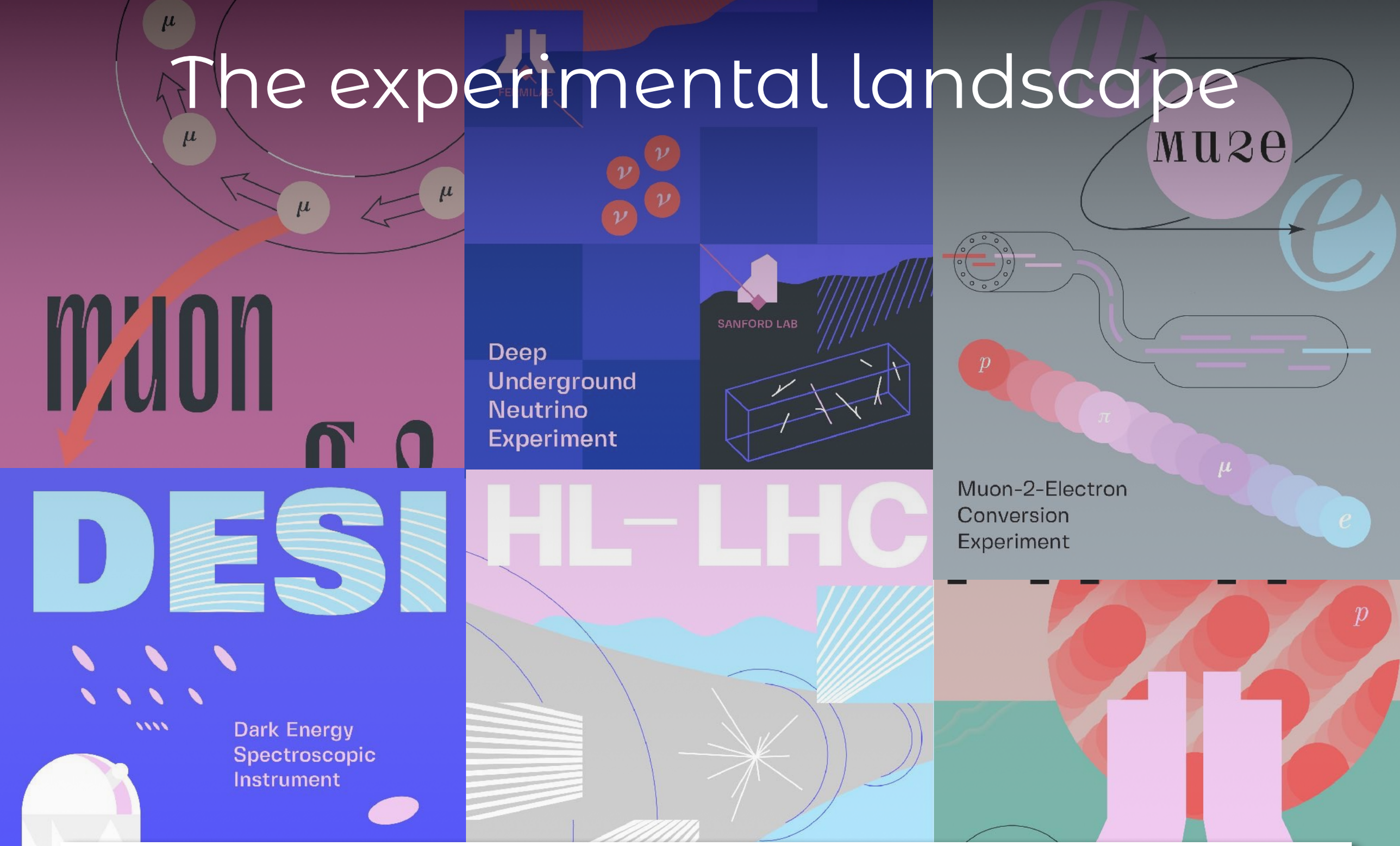
[Blum *et al.*, arXiv:1311.2198]



Measured muon g-2 **~3σ** above Standard-Model theory expectations

- ☆ Presently an *abundance of deviations from the Standard Model in the flavor sector* with significances greater than 3 standard deviations
- In the coming years, flavor-physics community will sharpen these (and other) tests of the Standard Model and increase their sensitivity to new physics through improved measurements and theory calculations

The experimental landscape



- Diverse and compelling flavor-physics program planned for the next decade

▶ *Maximizing scientific impact will require new theoretical calculations, and improved precision on existing ones*

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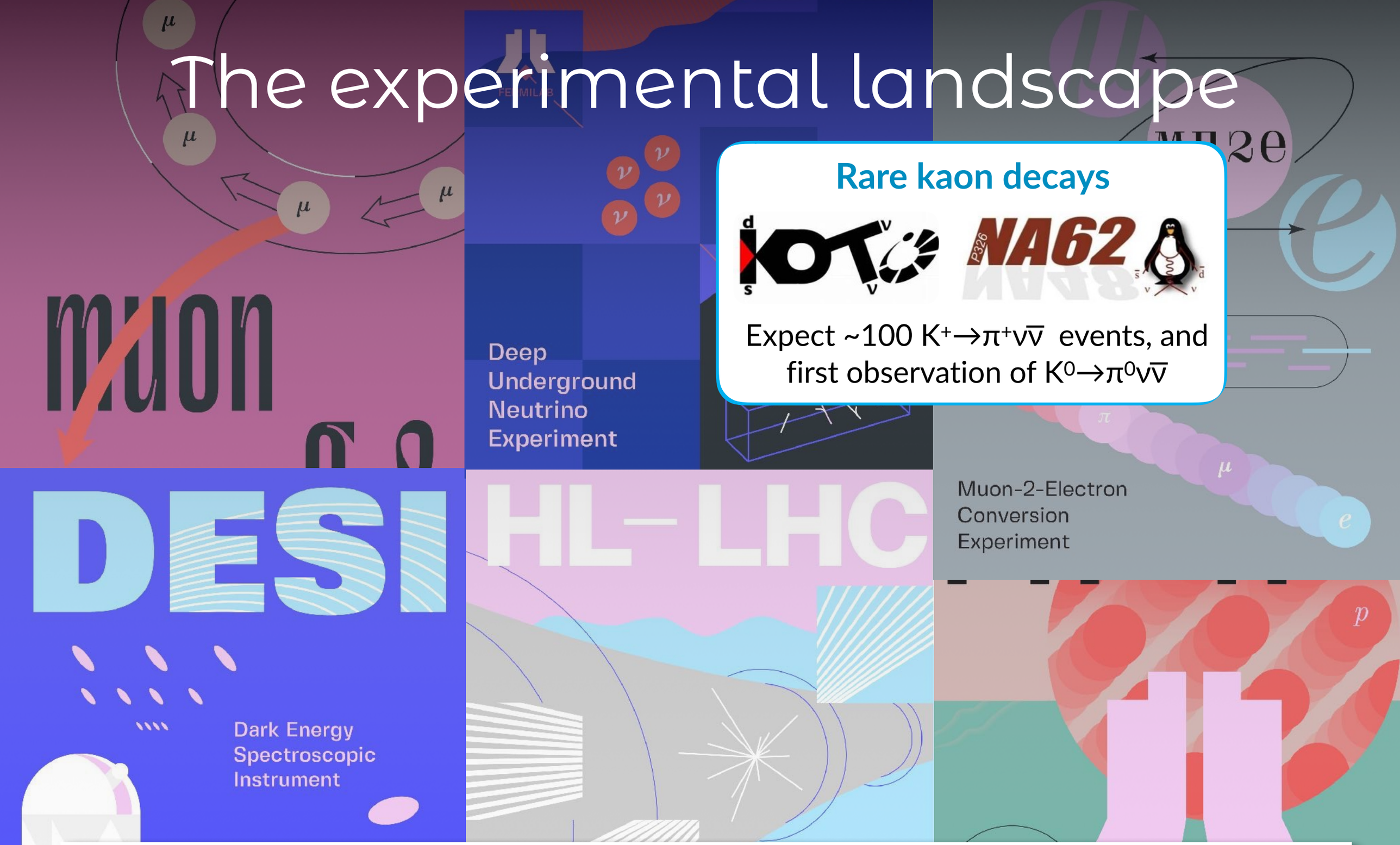

Rare kaon decays

Expect ~100 $K^+ \to \pi^+ \nu\bar{\nu}$ events, and first observation of $K^0 \to \pi^0 \nu\bar{\nu}$

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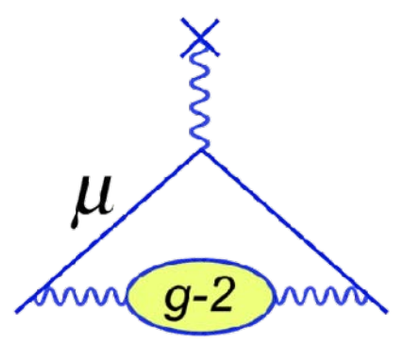

Will reduce error by factor of 4 within few years

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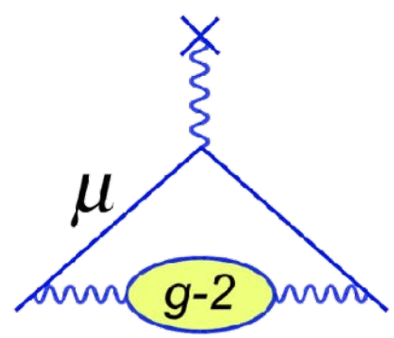

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Charm physics

Will continue collecting data at various beam energies for several years

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The experimental landscape

B physics

Belle II

Will collect **50×** the data from earlier *B-factories* by end of the run

LHCb

Will collect almost **10×** current data set before shutdown for HL-LHC

Rare kaon decays

KOTO NA62

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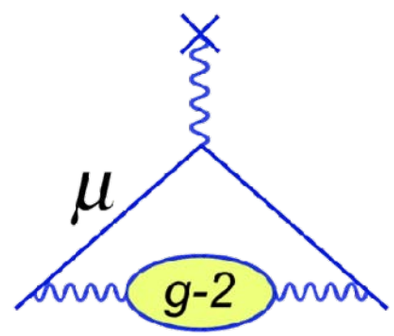

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BESIII

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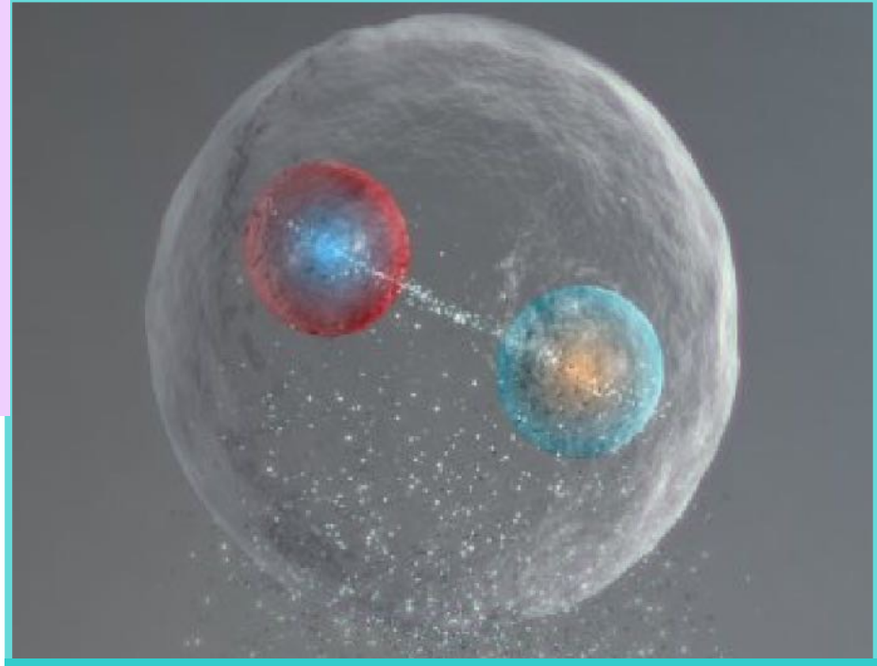
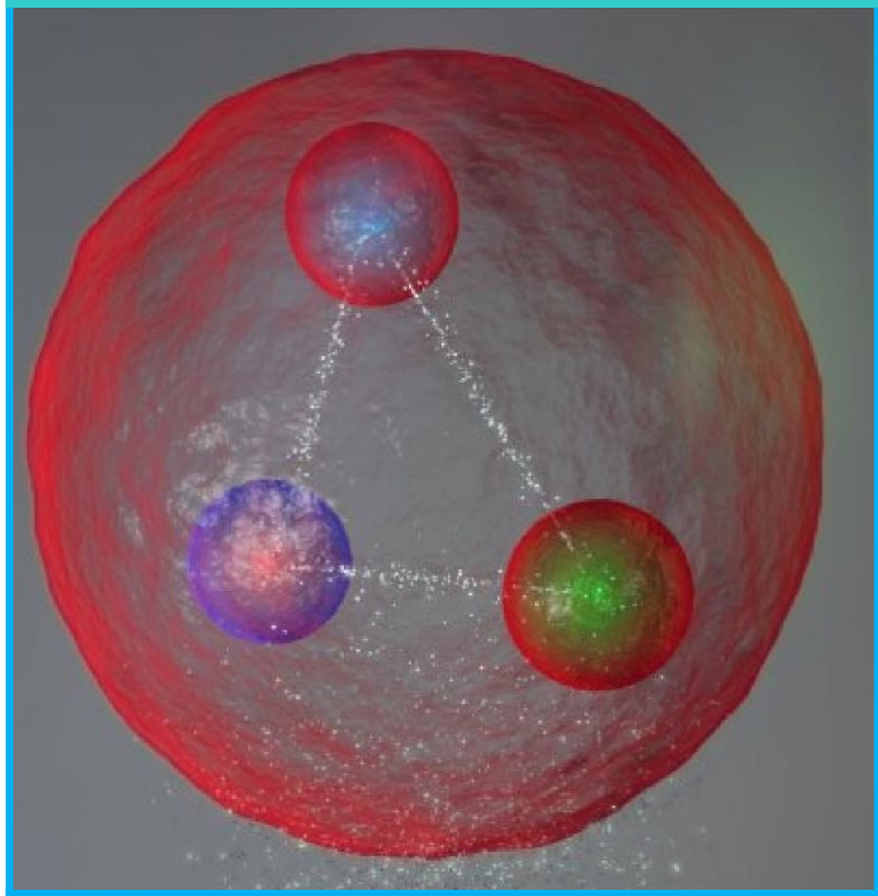
QCD is *everywhere*

- *Quantum Chromodynamics (QCD) is ubiquitous throughout particle (and nuclear) physics experiments:*
  - Detected strongly-interacting particles are always hadrons because of color confinement
  - Numerous experiments employ hadron targets to identify and characterize particles (e.g. deuterium, LAr, Si, Xe, …)
  - LHC collides proton beams at world's highest energies
- *Need nonperturbative hadronic parameters and matrix elements to relate hadronic observables measured in experiments to underlying processes involving quarks*
- Numerical lattice QCD is the only quantitative tool for studying nonperturbative QCD from first principles…



Mesons are bound states of a quark and anti-quark



Baryons are bound states of three quarks (or anti-quarks)

The USQCD flavor program

- *Access to leadership-class computing + dedicated USQCD hardware has enabled the U.S. lattice-QCD community to mount a world-leading effort in flavor physics*
  - Strong track record in producing high-impact calculations with controlled uncertainties and complete error budgets
- *Lattice QCD is now a precision tool in the flavor sector:*
  - Sub-percent uncertainties on some quantities relevant for quark-flavor physics
  - In a few cases, theoretical lattice-QCD uncertainties are below what is needed by foreseeable experiments
- *Usually, the most precise determinations are by USQCD members*

Aim to calculate QCD parameters and matrix elements with sufficient precision that they do not limit what can be learned from past, current, & future experiments

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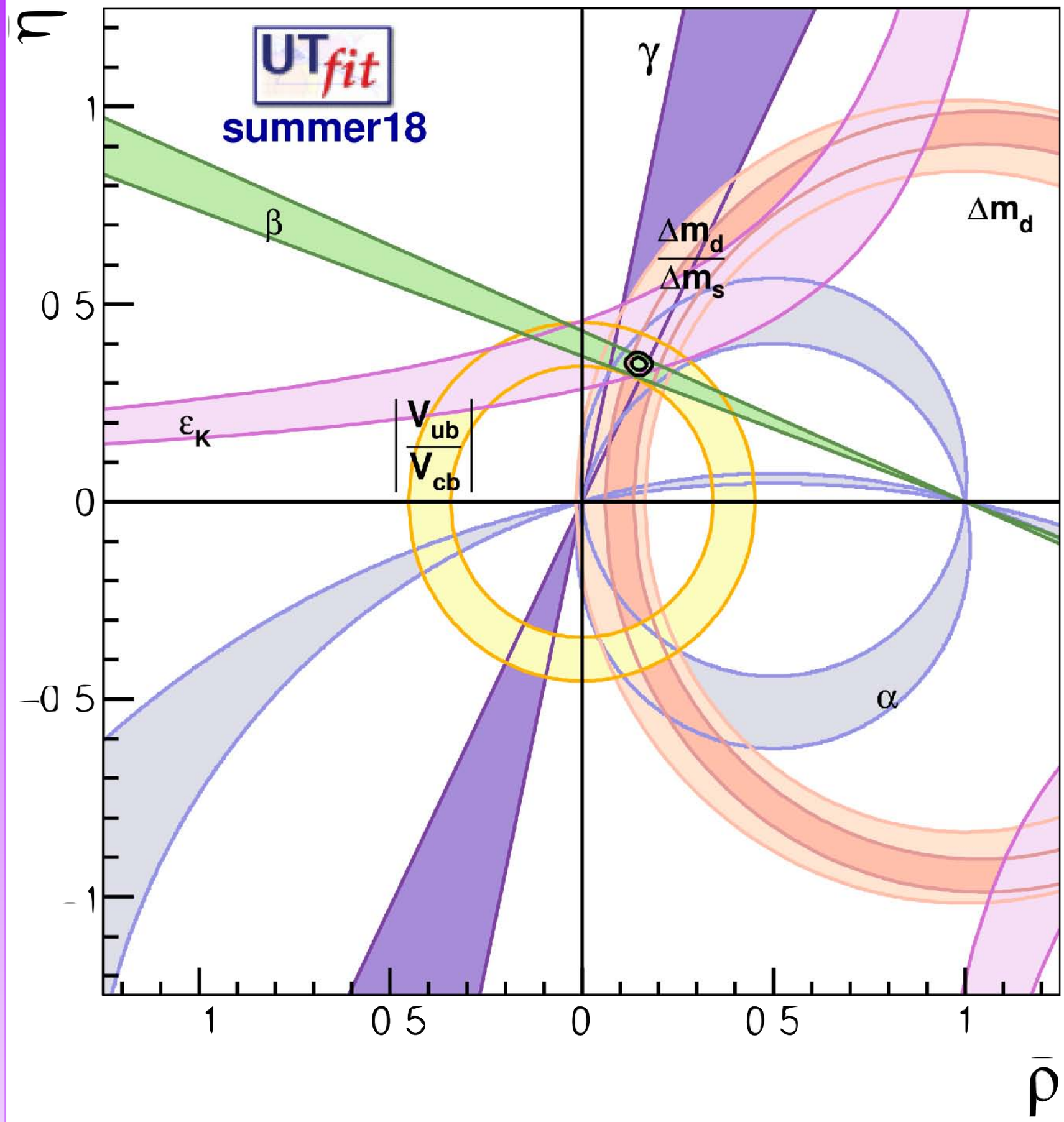
Impact of LQCD-Ext II



Higher-order hadronic-vacuum-polarization contribution to $g-2$ from lattice QCD

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PHYSICAL REVIEW LETTERS **121,** 022003 (

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Connected and Leading Disconnected Hadronic Light-by-Light Contribution to the Muon Anomalous Magnetic Moment with a Physical Pion Mass

Thomas Blum, Norman Christ, Masashi Hayakawa, Taku Izubuchi, Luchang Jin, Chulwoo Jung, and Christoph Lehner
Phys. Rev. Lett. **118**, 022005 – Published 11 January 2017

$\Lambda_c \to \Lambda l^+ \nu_l$ Form Factors and Decay Rates from Lattice Physical Quark Masses

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Phenomenology of $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ using lattice QCD calculations

Alakabha Datta,[a,b] Saeed Kamali,[a] Stefan Meinel[c,d] and Ahmed Rashed[a,e]

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(RBC and UKQCD Collaborations)

PHYSICAL REVIEW D **98,** 074509 (2018)

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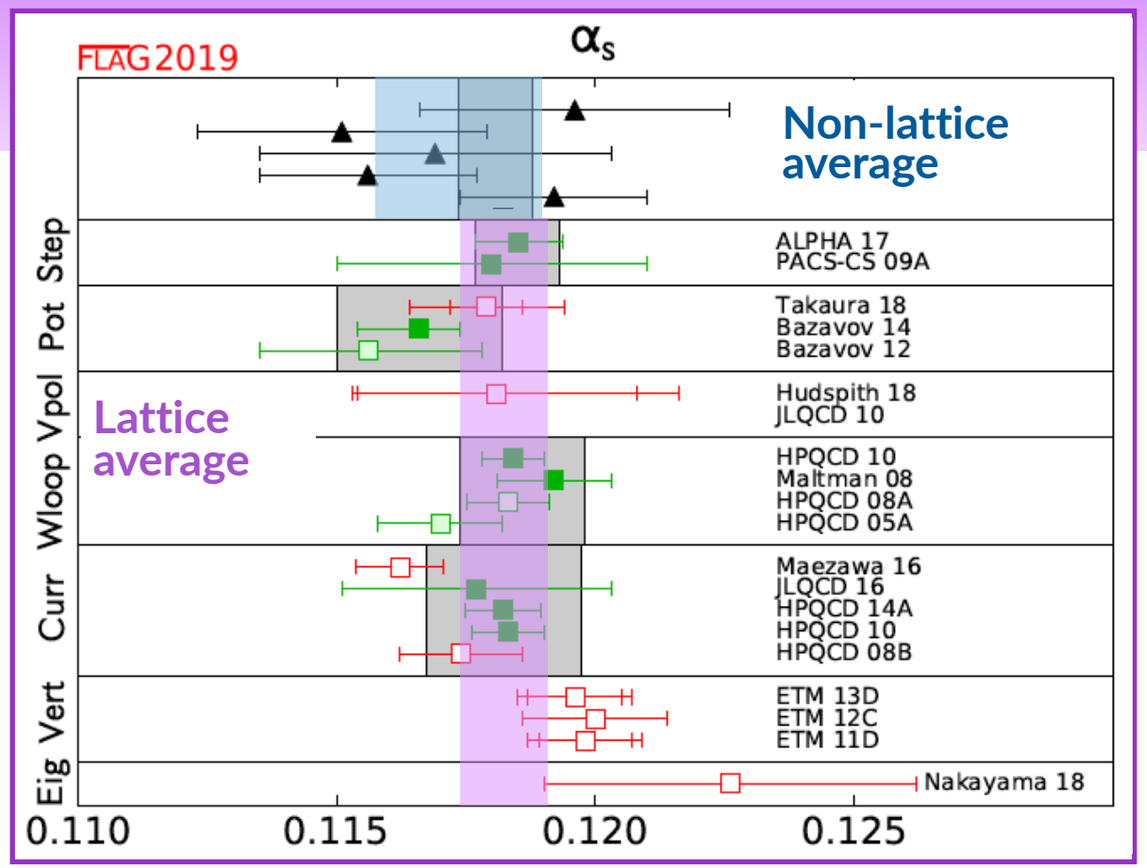
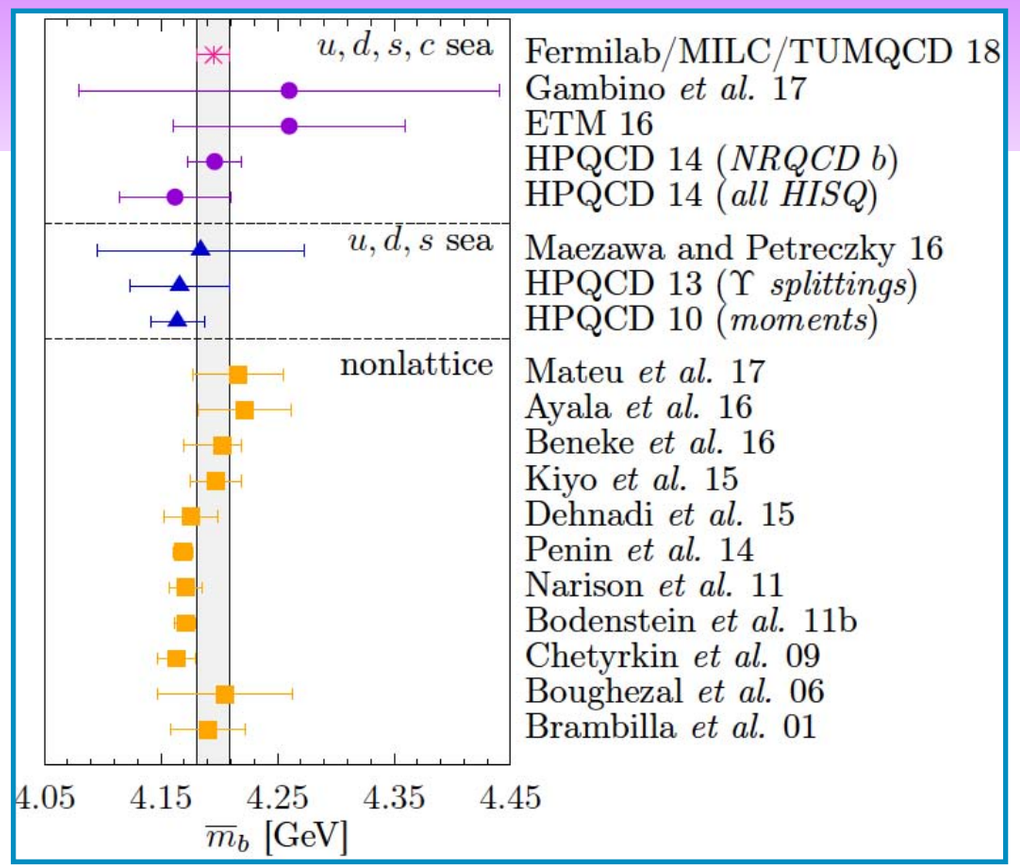


Strong coupling constant

[Flavor Lattice Averaging Group, arXiv:1902.08191]



bottom-quark mass

[Fermilab/MILC/TUMQCD, PRD98, 054517 (2018)]

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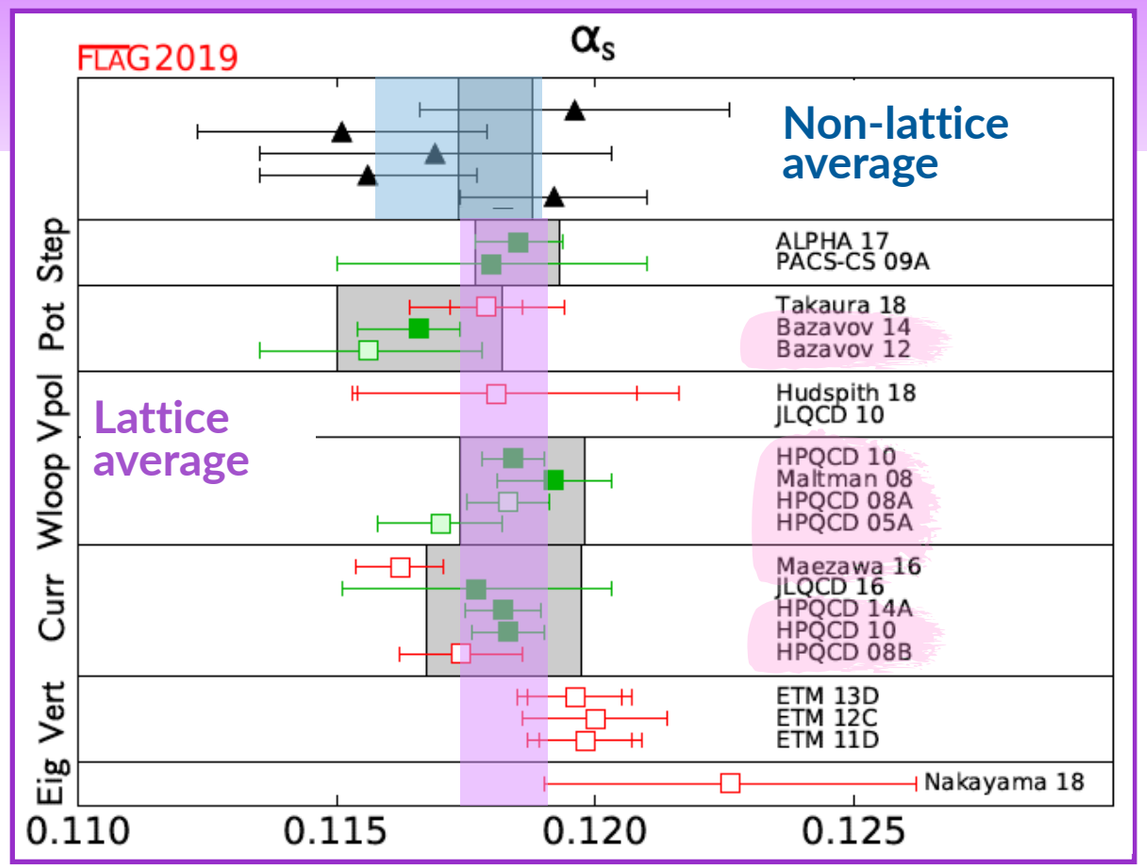

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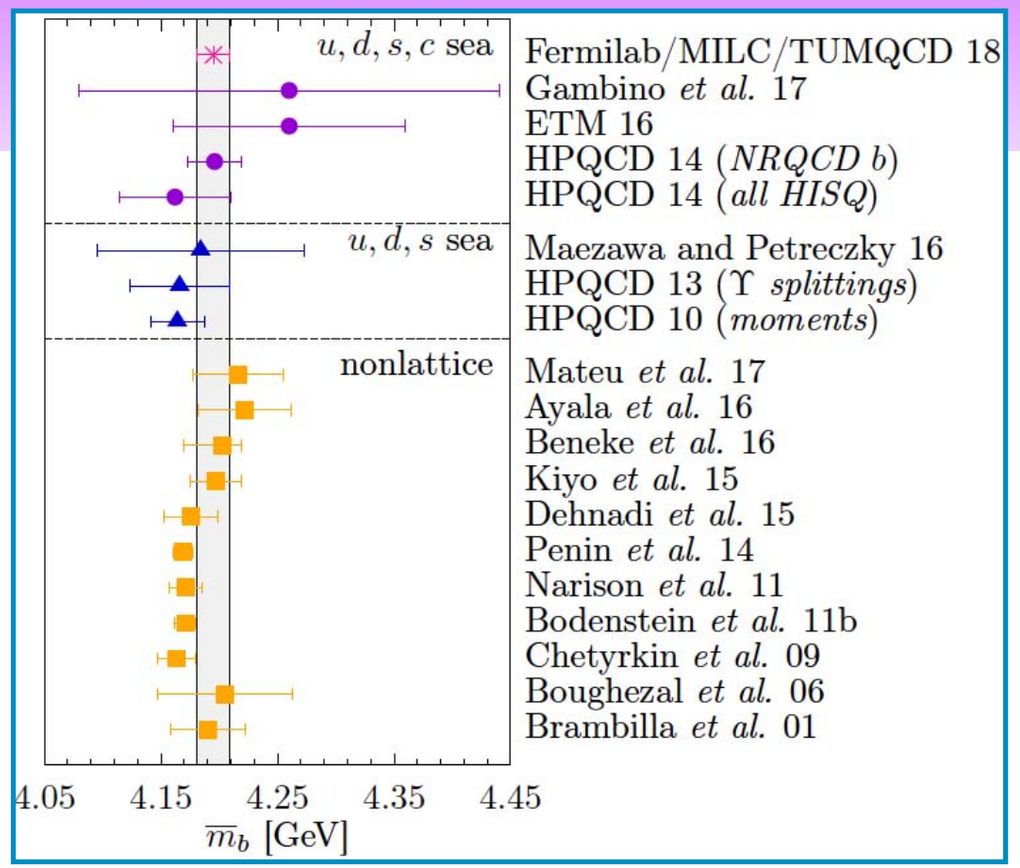

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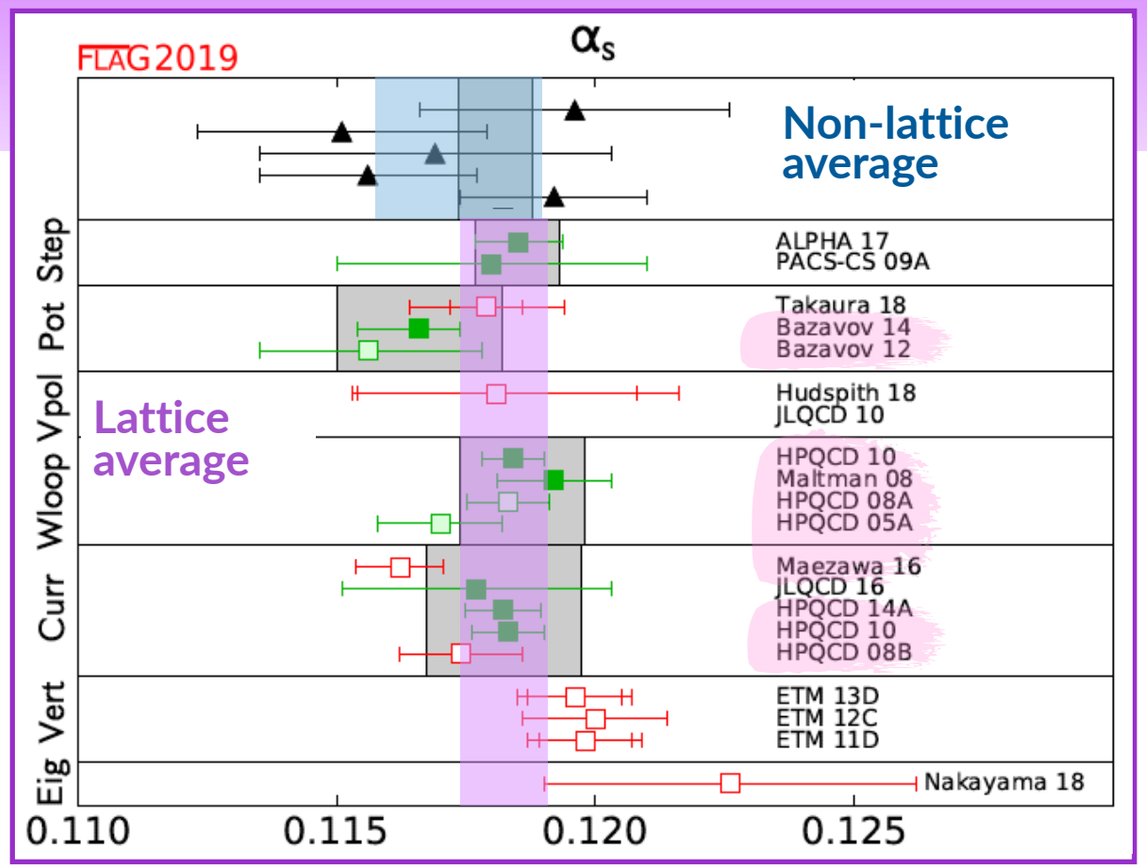

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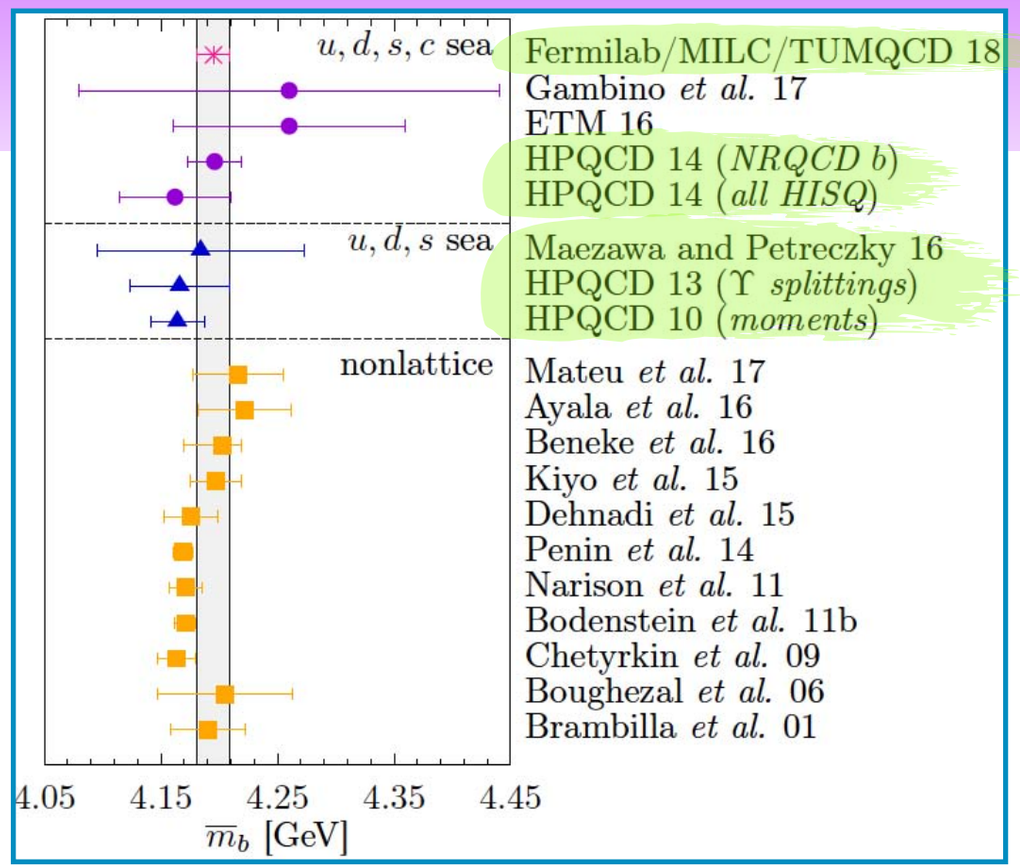

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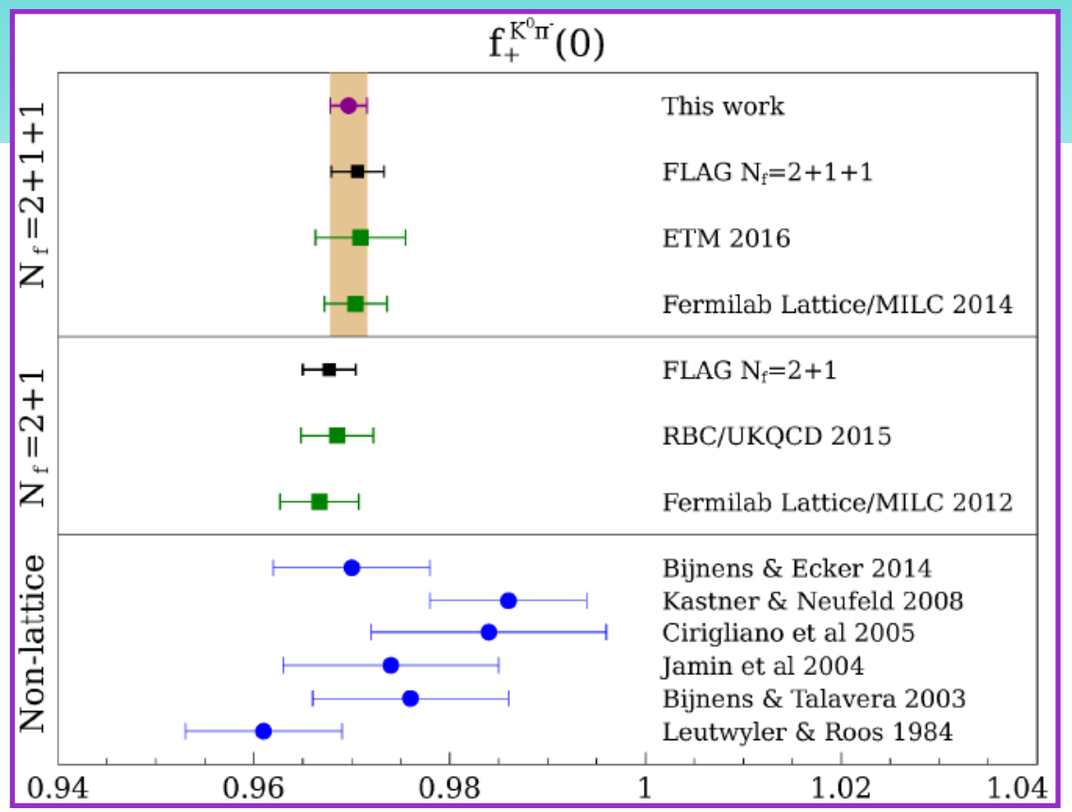
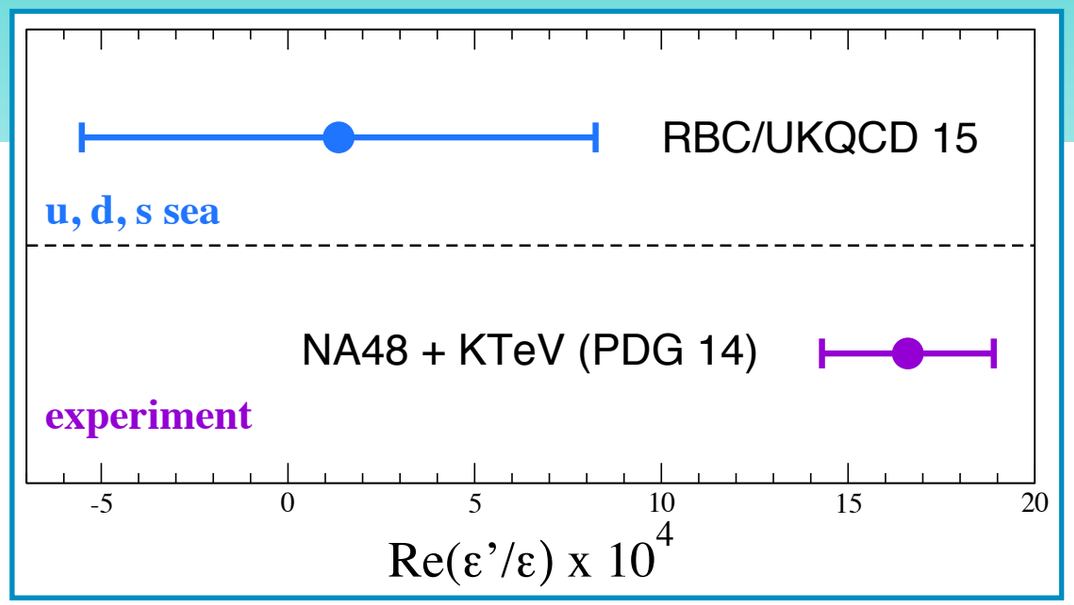


K→πlν semileptonic form factor

[Fermilab/MILC, PRD99, 114509 (2019)]

- When combined with experimental branching ratio, determines CKM matrix element $|V_{us}|$
- Key input to test of first-row CKM unitarity
- *Theoretical uncertainty now commensurate with experiment*

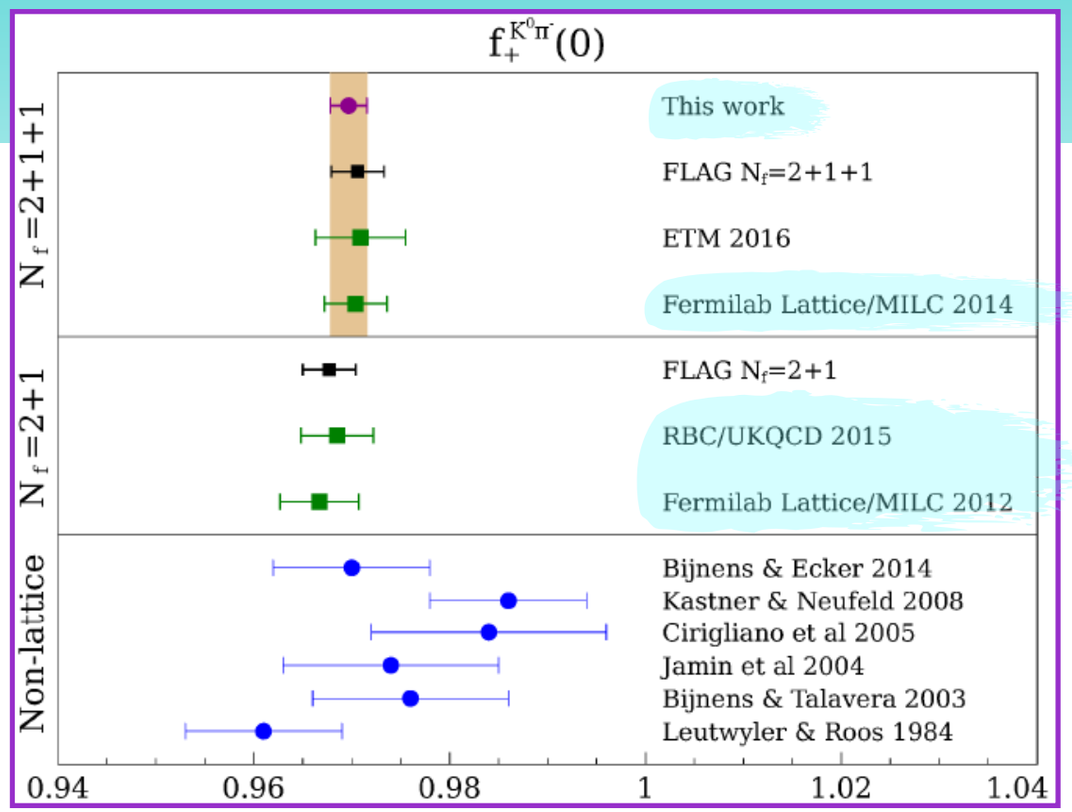


Re(ϵ'/ϵ)

[RBC/UKQCD, PRL115, 212001 (2015)]

- K→ππ decay sensitive to new particles & interactions
- Interpretation of measurements as tests of Standard Model waiting on theoretical calculation with controlled uncertainties
- Only complete calculation by RBC/UKQCD *relied upon dedicated USQCD hardware for developing and testing new methods*

Kaon decays



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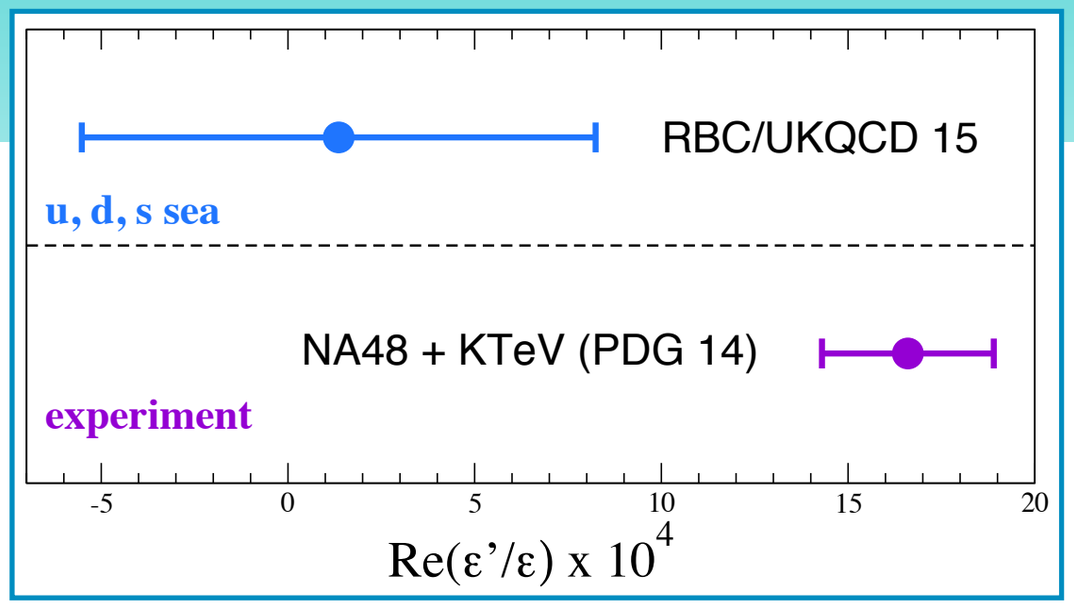

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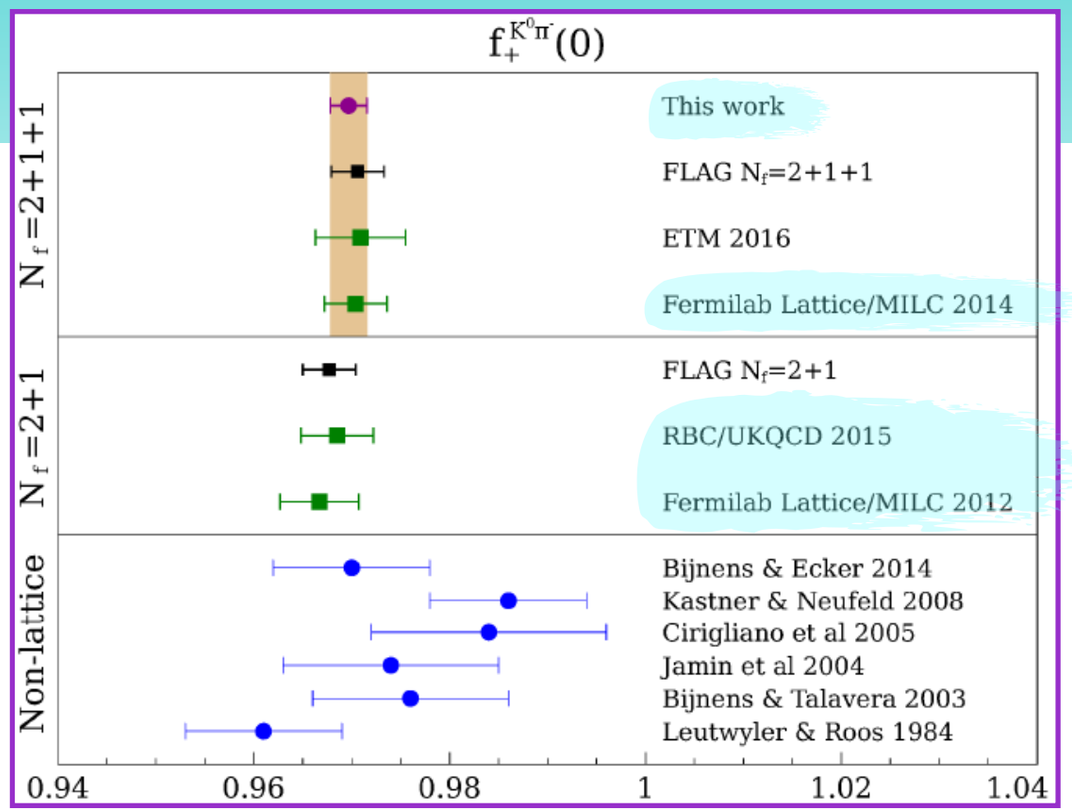

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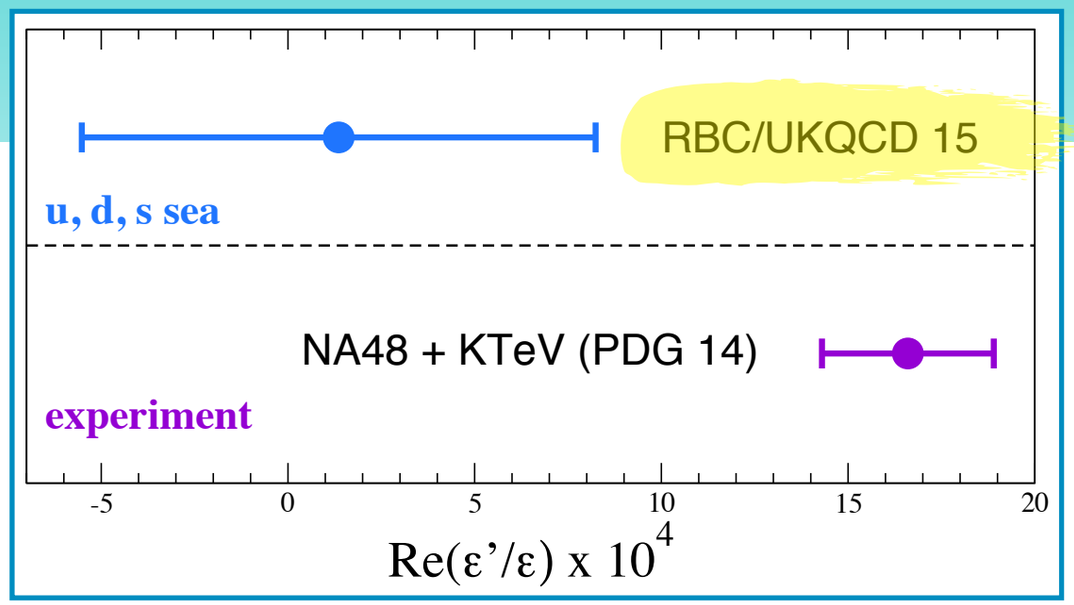

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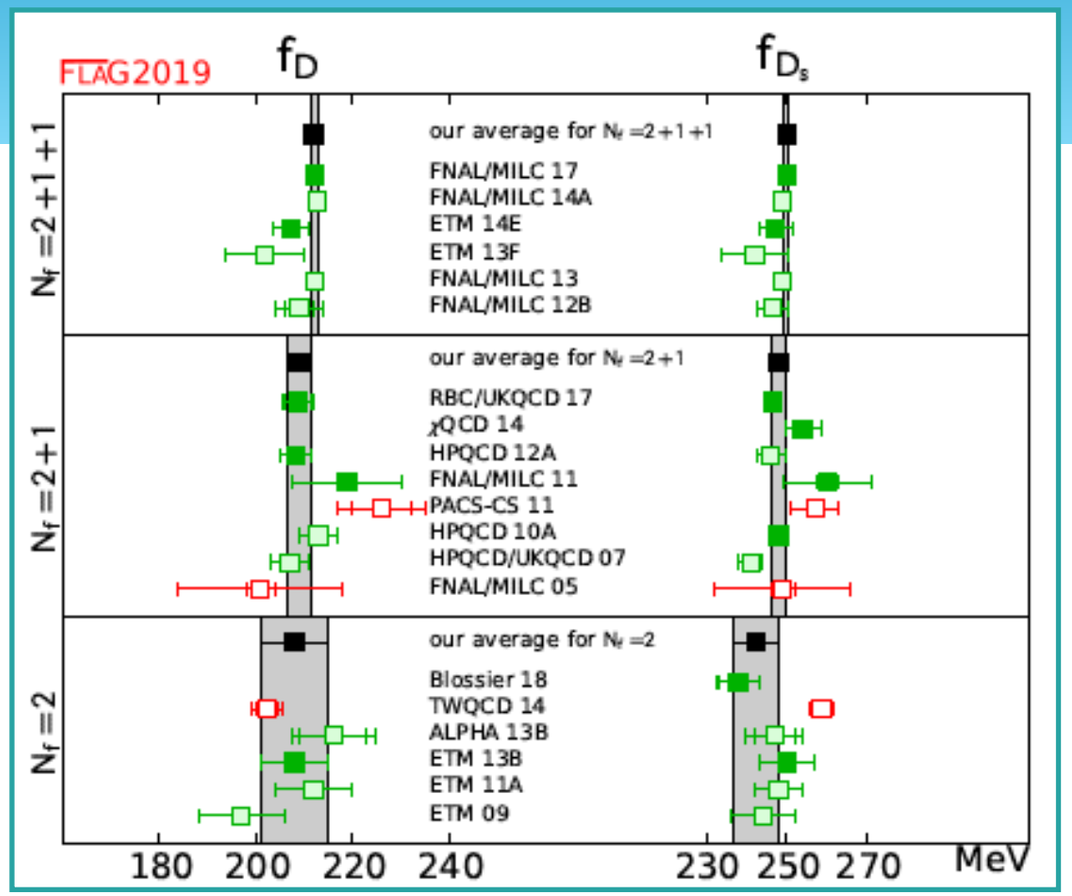
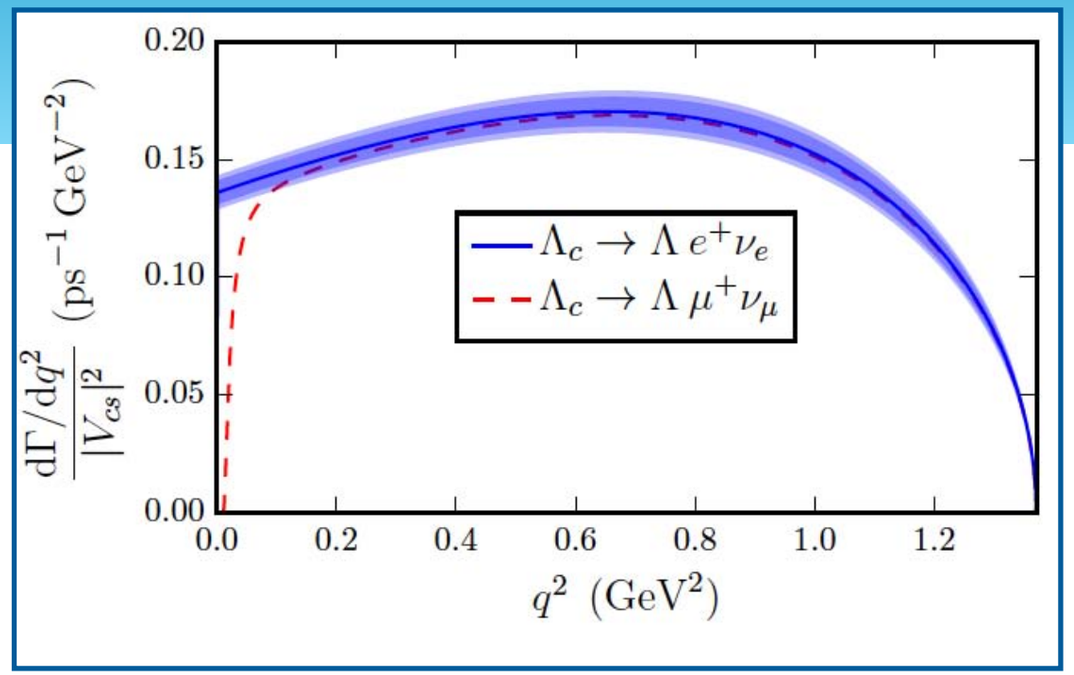


$D_{(s)}$-meson leptonic decay constants

[Flavor Lattice Averaging Group, 1902.08191]

- When combined with experimental branching ratios, determine CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$
- *Sub-percent precision beyond needs of BES III, Belle II, and LHCb for foreseeable future*

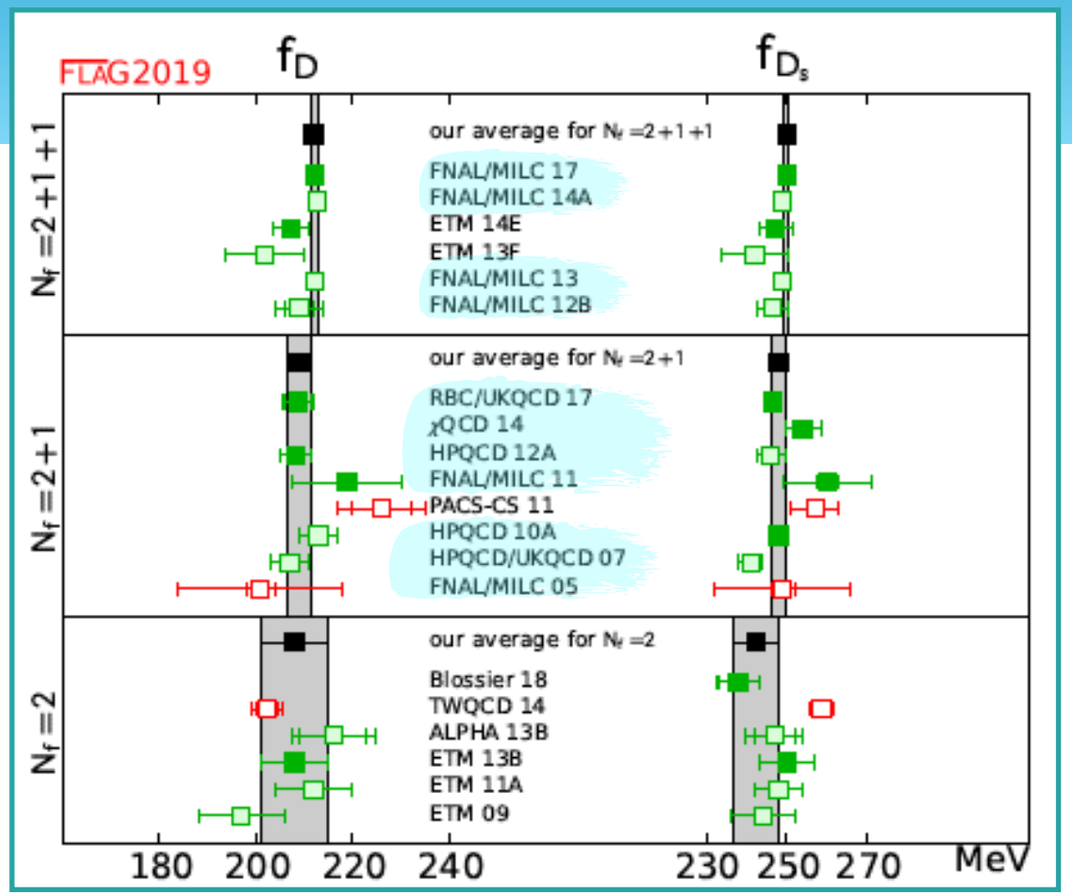


$\Lambda_c \to \Lambda l \nu$ semileptonic form factor

[Meinel, PRL118, 082001 (2017)]

- Provides complementary determination of $|V_{cs}|$ from baryon decay
- First calculation of this quantity by Meinel, a junior lattice theorist
- *Employs domain-wall fermion ensembles generated with USQCD resources*

Charmed hadron decays



$D_{(s)}$-meson leptonic decay constants

[Flavor Lattice Averaging Group, 1902.08191]

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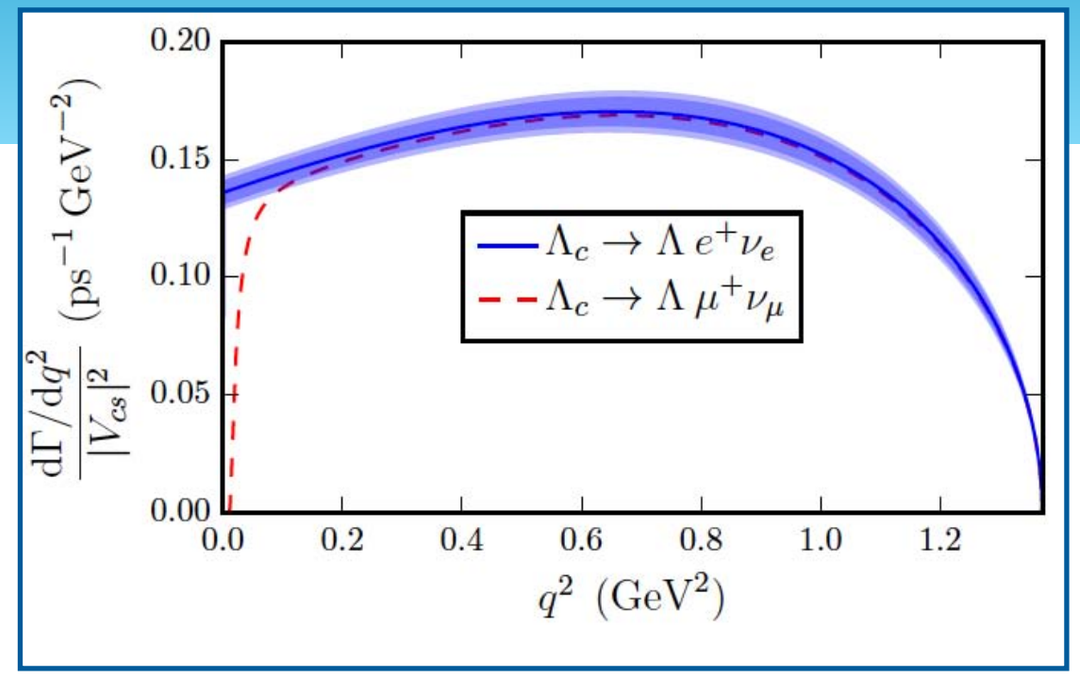

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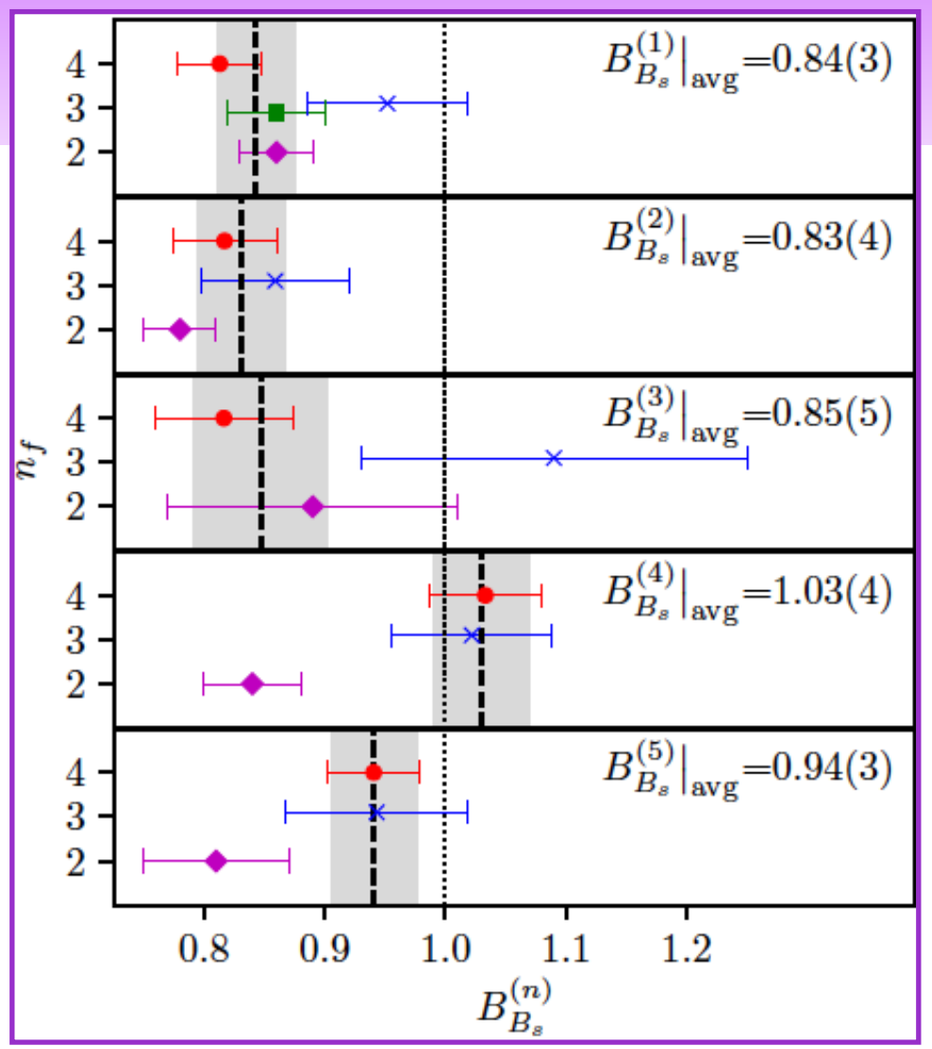
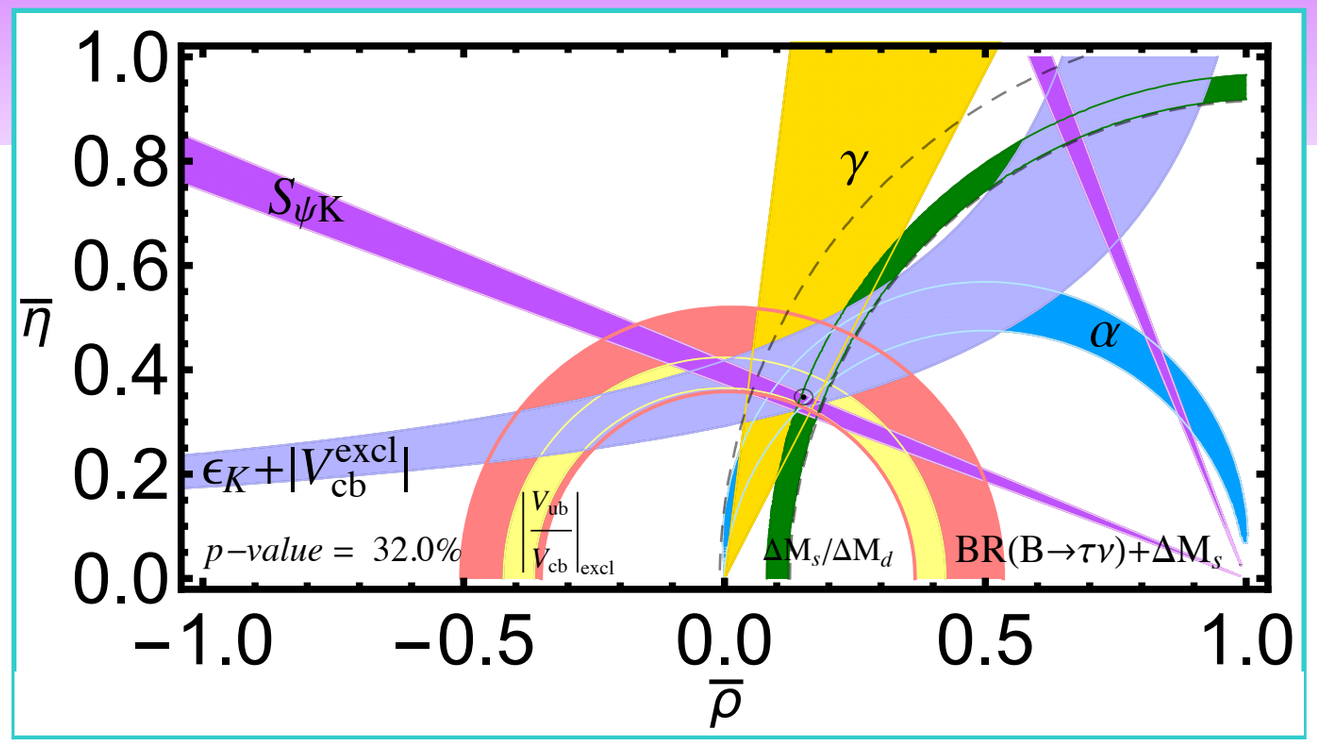
b-hadron physics



$B_{(s)}$-mixing matrix elements
[HPQCD, arXiv:1907.01025]

- First calculations of complete set of $\Delta B = 2$ matrix elements that contribute to neutral B-mixing in Standard Model and beyond



Impact on CKM unitarity triangle
[Fermilab/MILC, PRD 93, 113016 (2016)]

- When combined with experimental oscillation frequencies, matrix elements impose key constraint on apex of CKM unitarity triangle (green band)
- *New lattice-QCD calculations shrink allowed region by factor of three*
- Increases scientific impact of ***existing*** measurements

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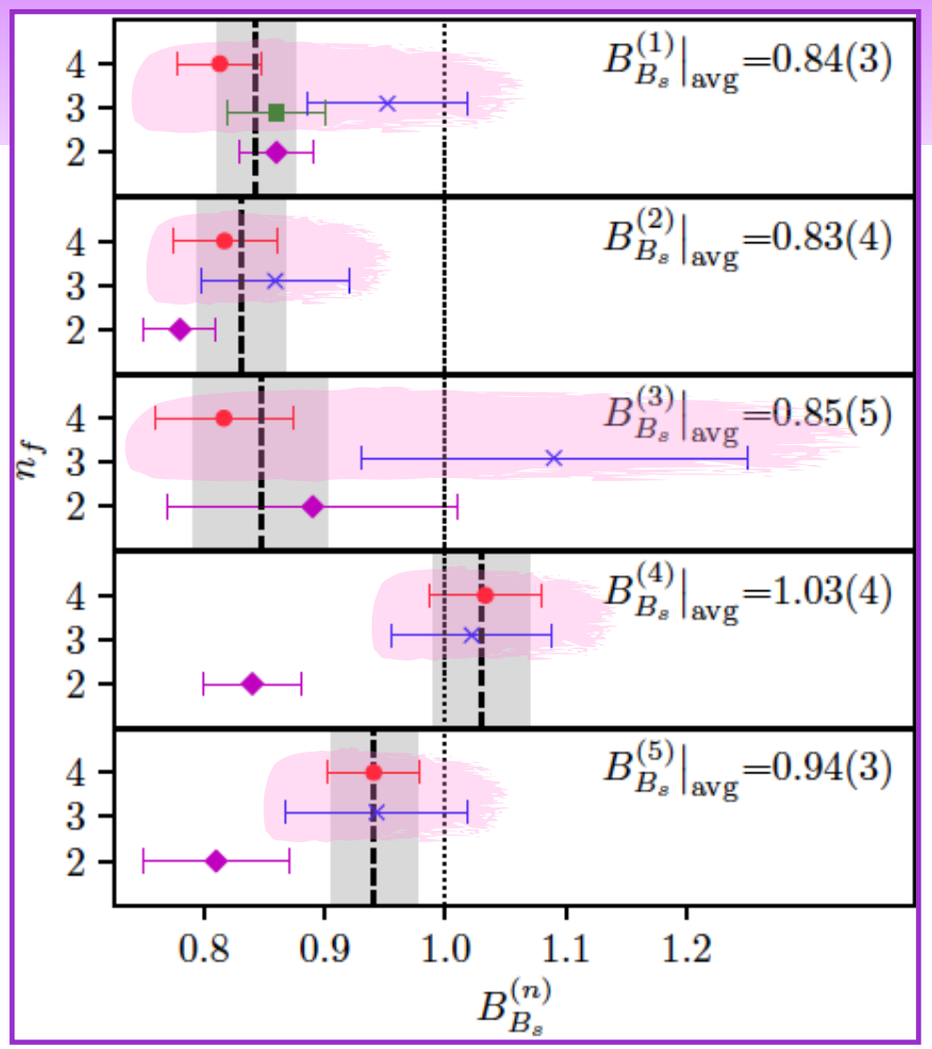

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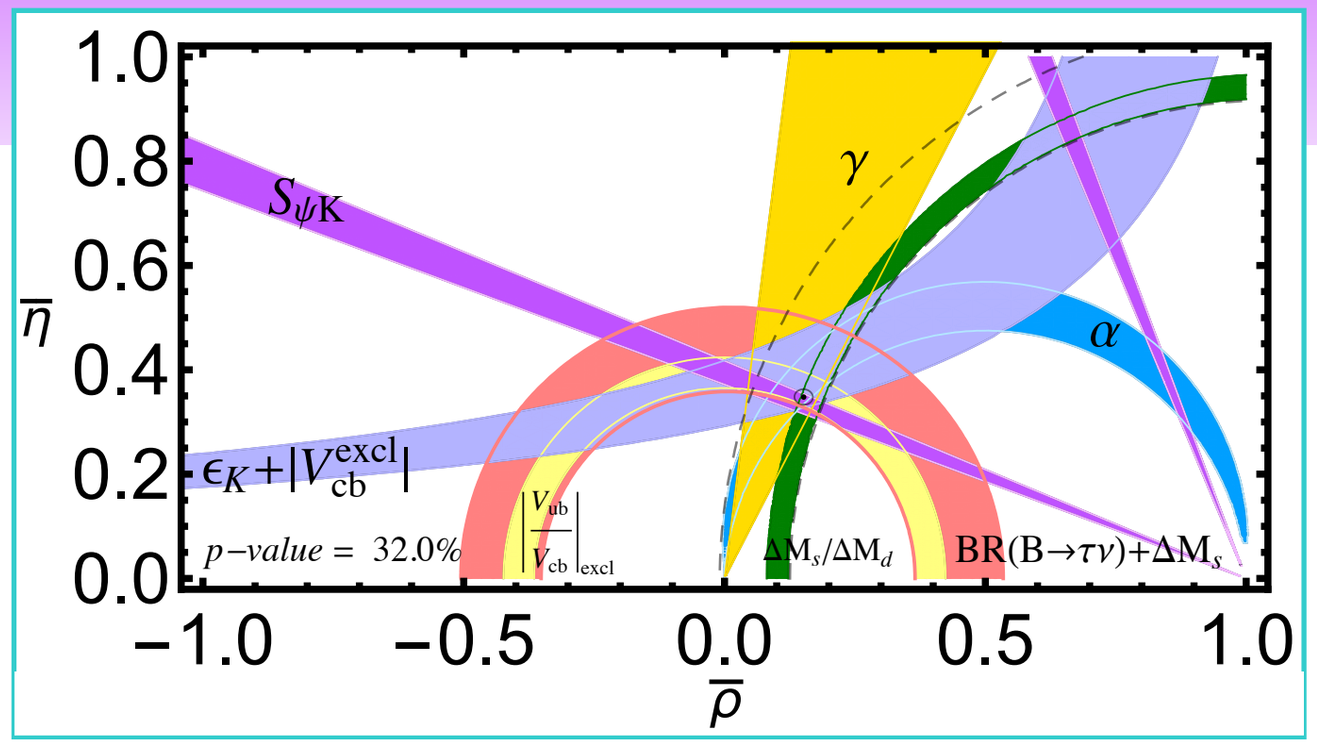

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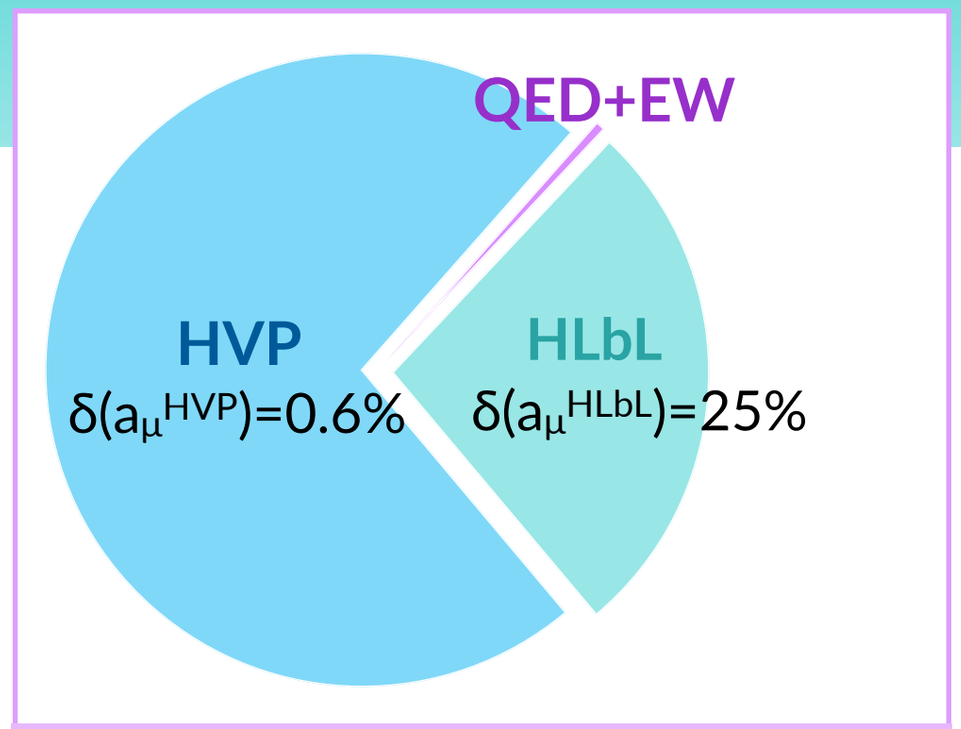
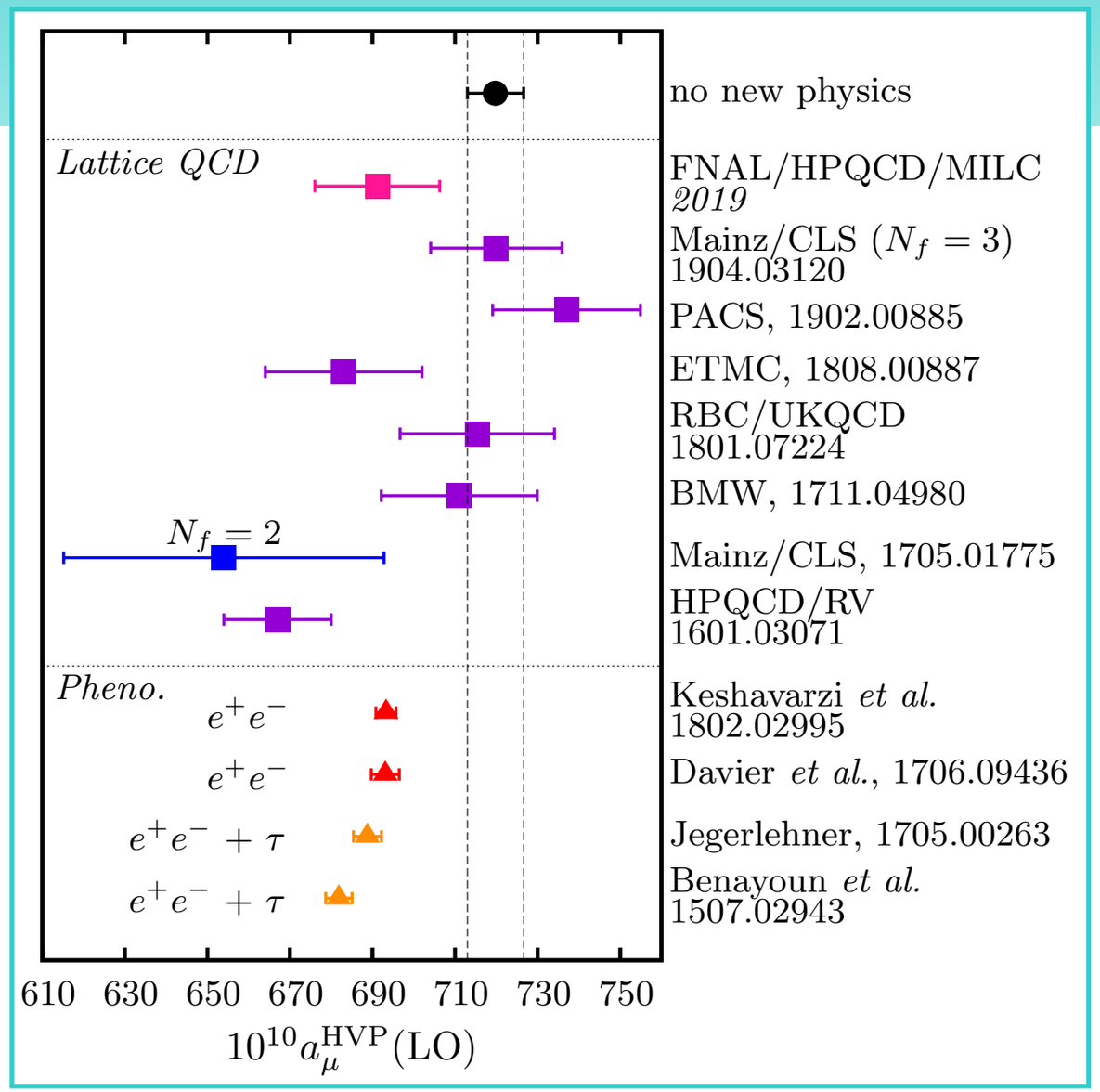
Muon anomalous magnetic moment



Error budget for muon g-2 in Standard Model



- Dominant uncertainties from hadronic vacuum polarization (HVP) and hadronic light-by-light (HLbL) contributions
- To match anticipated experimental precision, must reduce uncertainties to $\delta(a_\mu^{HVP}) \lesssim 0.2\%$ & $\delta(a_\mu^{HLbL}) \lesssim 10\%$

- Strong U.S. research program developing methods and algorithms needed to reduce uncertainties, and performing numerical calculations with controlled errors and high precision

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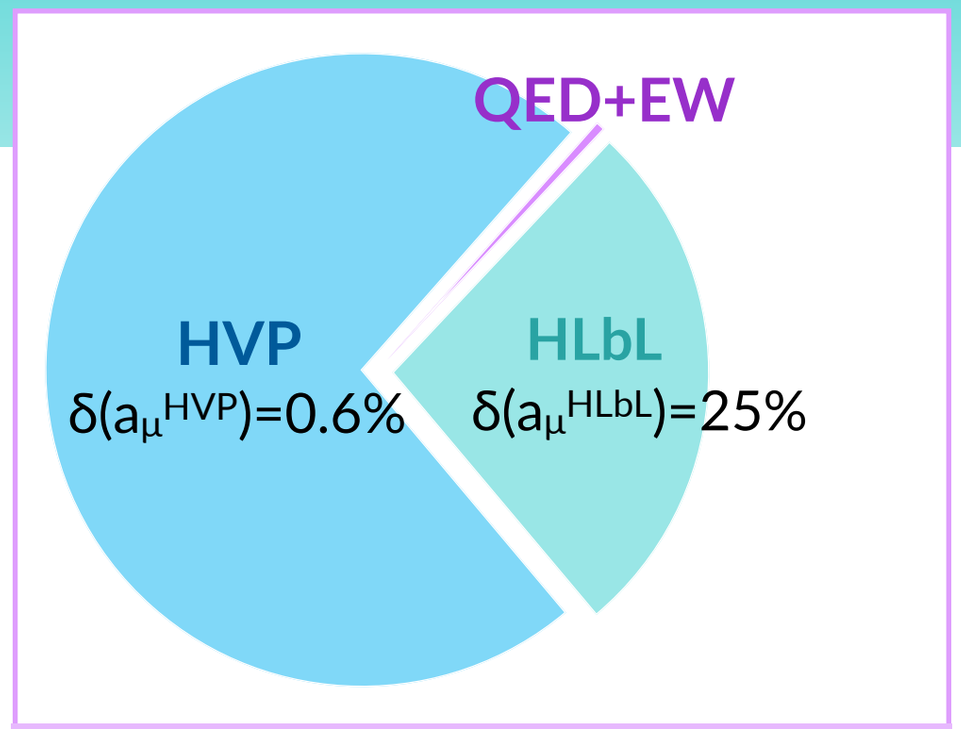

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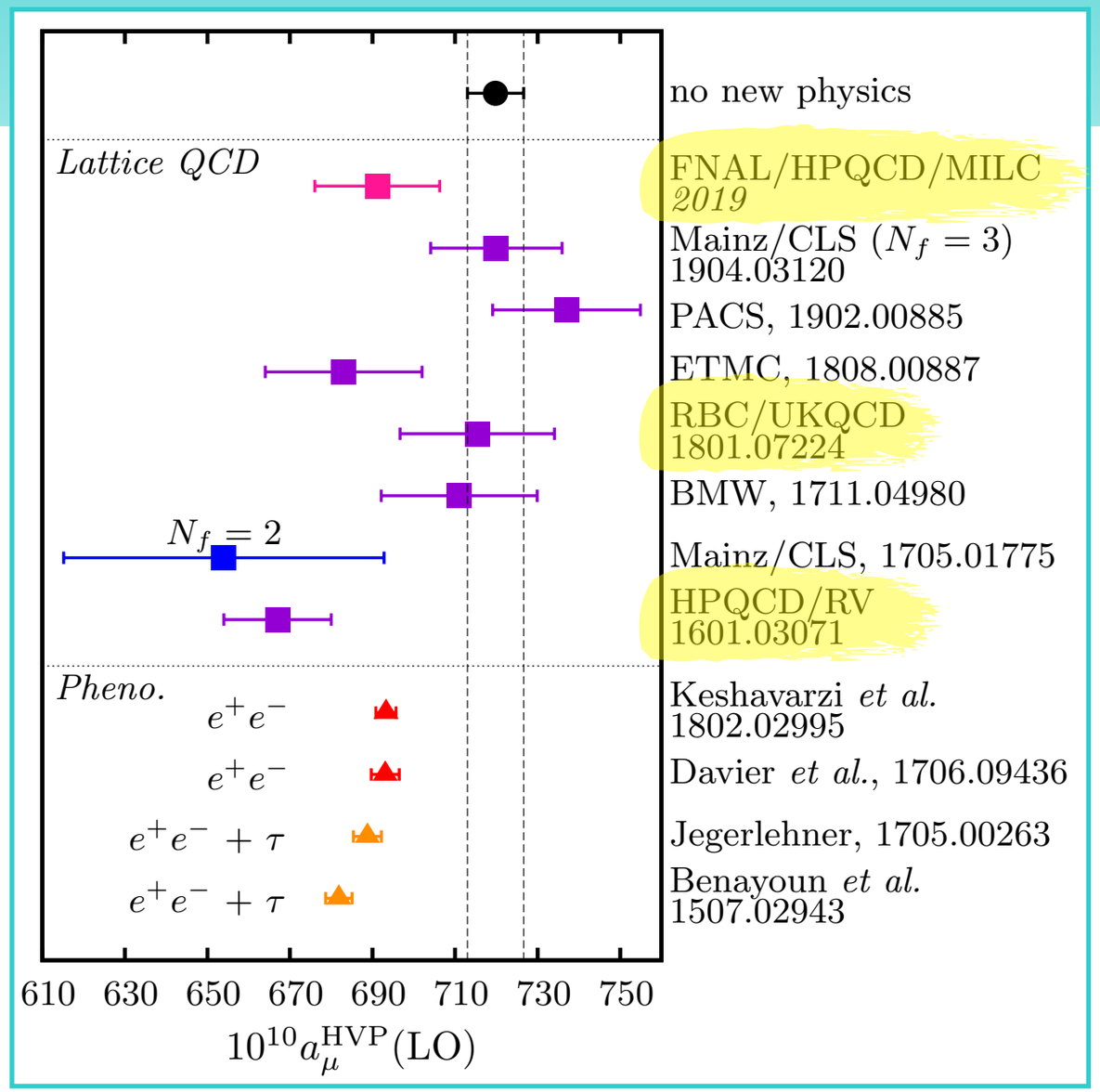

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U.S. lattice collaborations are producing cutting-edge results on muon g-2

Hadronic vacuum polarization

- First calculation of quark-disconnected contribution [RBC/UKQCD, PRL116, 232002 (2016)] ⟵ *employed USQCD resources to develop and test methods*
- First calculation of total LO contribution with physical up and down-quark masses [HPQCD+RV, PRD6, 034516 (2017)]
- First calculation of strong-isospin breaking correction [Fermilab/HPQCD/MILC, PRL120, 152001 (2018)] ⟵ *employed USQCD resources to generate and analyze gauge-field configurations*

Hadronic light-by-light

- First calculation at physical up and down-quark masses with 10% statistical precision [RBC/UKQCD, PRL118, 022005 (2017)]
- Indicates that model estimates of LbL contribution are not so inaccurate as to be the source of the discrepancy with the Standard Model
- Challenging calculation entailed a lot of trial-and-error over several years

▶ *Would not have been possible without dedicated lattice-QCD hardware for testing methods on small jobs with quick turnaround*

Priorities for LQCD-Ext III

Strategic goals

- LQCD-Ext III proposal identifies two milestones associated with flavor physics:
  - *"Complete calculations of the HVP and HLbL contributions to muon g-2 with the required precision on the timescale of Fermilab E989"*
  - *"Continue to sharpen the search for new physics in the flavor sector"*
- These are spelled out in greater detail in our community whitepaper

Opportunities for lattice QCD in quark and lepton flavor physics

Christoph Lehner,[1,*] Stefan Meinel,[2,3,†] Tom Blum,[4] Norman H. Christ,[5]
Aida X. El-Khadra,[6] Maxwell T. Hansen,[7] Andreas S. Kronfeld,[8] Jack Laiho,[9]
Ethan T. Neil,[10,3] Stephen R. Sharpe,[11] and Ruth S. Van de Water[8]

(USQCD Collaboration)

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[2] *Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[3] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[4] *Physics Department, University of Connecticut, Storrs, CT 06269-3046, USA*
[5] *Physics Department, Columbia University, New York, NY 10027, USA*
[6] *Department of Physics, University of Illinois Urbana-Champaign, Urbana, IL 61801-3003, USA*
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[8] *Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-5011, USA*
[9] *Department of Physics, Syracuse University, Syracuse, NY 13244, USA*
[10] *Department of Physics, University of Colorado, Boulder, CO 80309, USA*
[11] *Physics Department, University of Washington, Seattle WA 98195-1560, USA*

(Dated: April 20, 2019)

Abstract

This document is one of a series of whitepapers from the USQCD collaboration. Here, we discuss opportunities for lattice QCD in quark and lepton flavor physics. New data generated at Belle II, LHCb, BES III, NA62, KOTO, and Fermilab E989, combined with precise calculations of the relevant hadronic physics, may reveal what lies beyond the Standard Model. We outline a path toward improvements of the precision of existing lattice-QCD calculations and discuss groundbreaking new methods that allow lattice QCD to access new observables.

arXiv:1904.09479v1 [hep-lat] 20 Apr 2019

Target quantities

(select) Target quantities

Semileptonic b-hadron decays

- Better precision on tree-level processes, *e.g.* $B \to \pi l \nu$ and $\Lambda_b \to \Lambda_c(p)\mu^+\mu^-$, needed to fully leverage anticipated high-statistics data
- Better precision on rare decays, *e.g.* $B \to K(\pi)\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$, needed to probe present tensions with Standard Model and increase sensitivity to new physics

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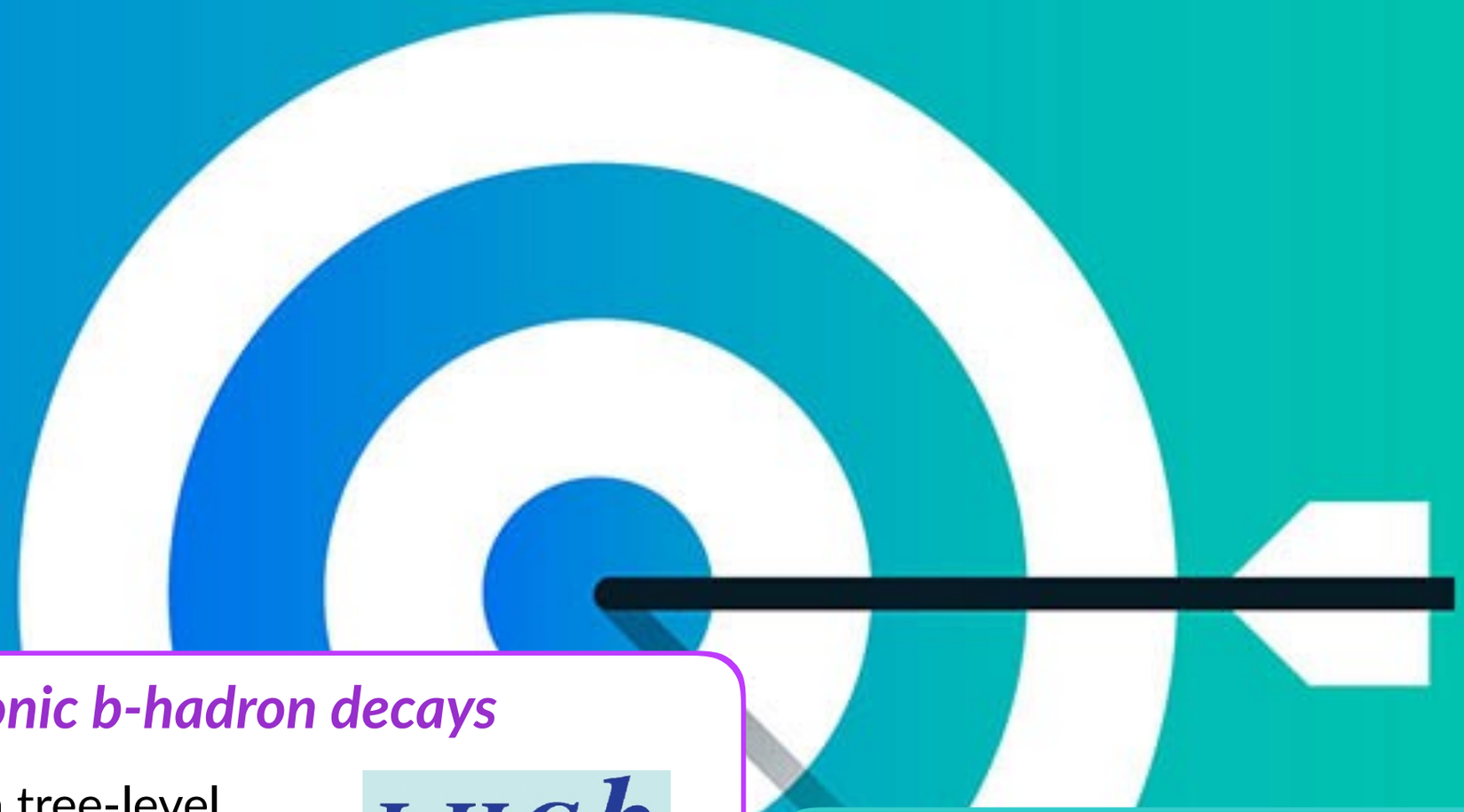

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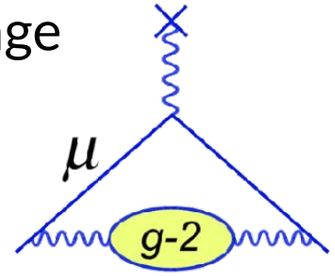
Muon g-2

- Prospects for HVP hinge mostly on increased computing power
- Current methods for HLbL sufficient, but may still profit from new ideas



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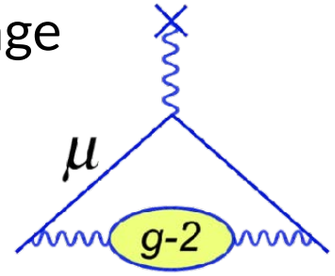

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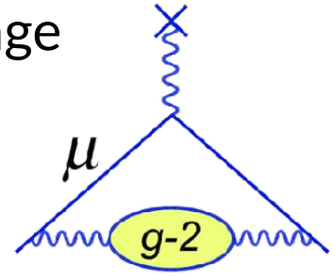

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New processes including…

- Weak decays to QCD resonances (*e.g.* K^*, ρ)
- Higher-dimension matrix elements for *B*-meson mixing
- Long-distance ΔC=1 matrix elements for *D*-meson mixing
- Long-distance contributions to rare kaon decays
- …

Semileptonic b-hadron decays

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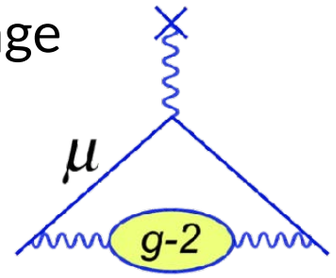
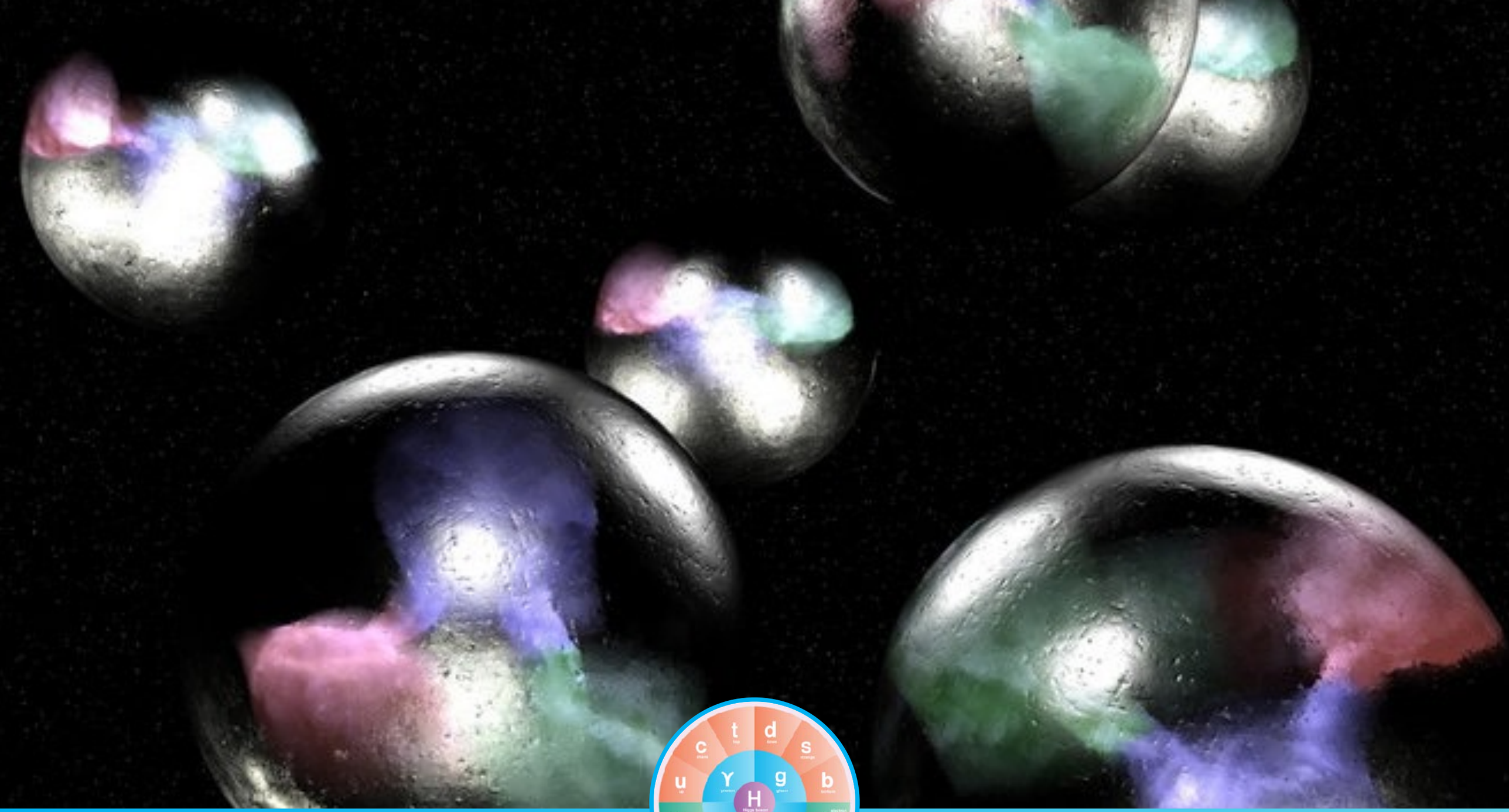
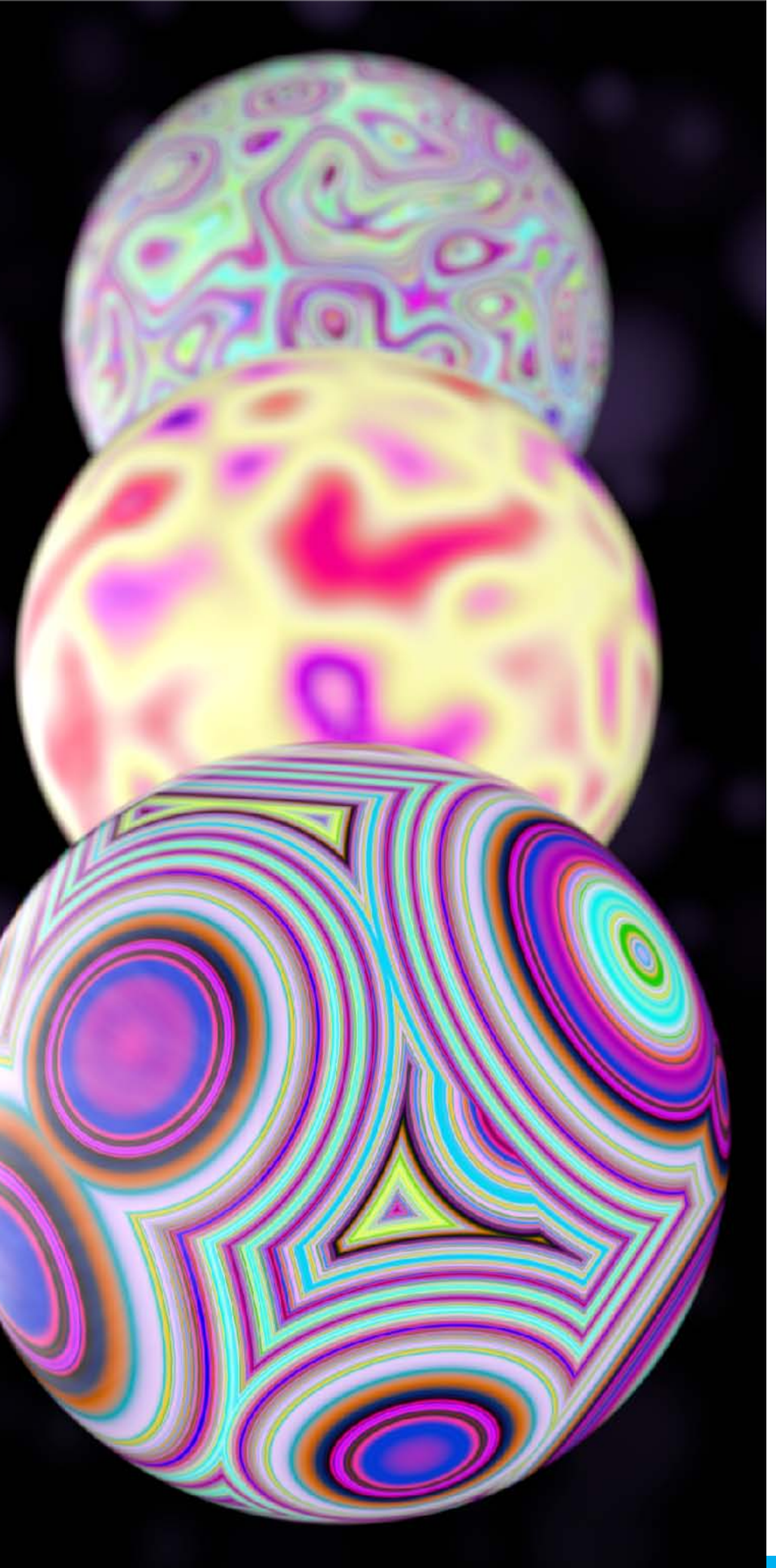




Summary and outlook



- *Quark and lepton flavor sectors are abundant with new-physics discovery potential*
  - Broad and exciting experimental program planned for the next decade
  - Reliable theoretical predictions are needed on same time scale as measurements, with commensurate uncertainties
- *USQCD has established, world-leading quark and lepton flavor-physics program*
  - Focused on QCD parameters and matrix elements are needed to interpret experimental results as tests of the Standard Model and new-physics searches
  - Whitepaper identifies strategic opportunities for lattice QCD to aid current and future experimental program and, when possible, articulates plan for achieving scientific goals
- *Without adequate funding for lattice-QCD research, the interpretation of many current and future measurements — and possible discovery of new physics — is at risk*