Lattice QCD for the Intensity Frontier

Ruth Van de Water

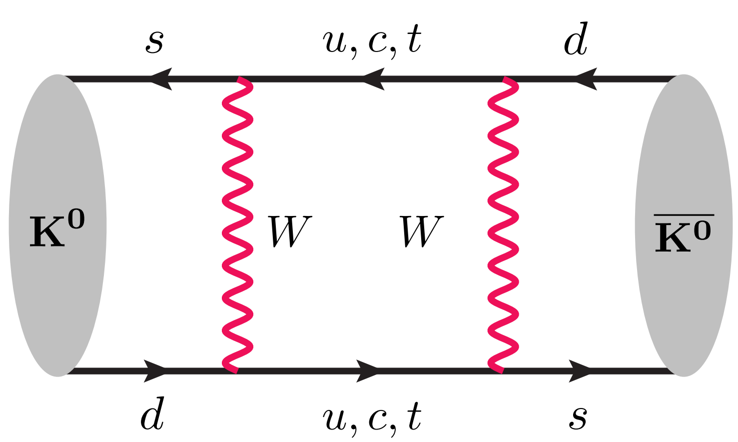
2015 USQCD All-Hands Meeting

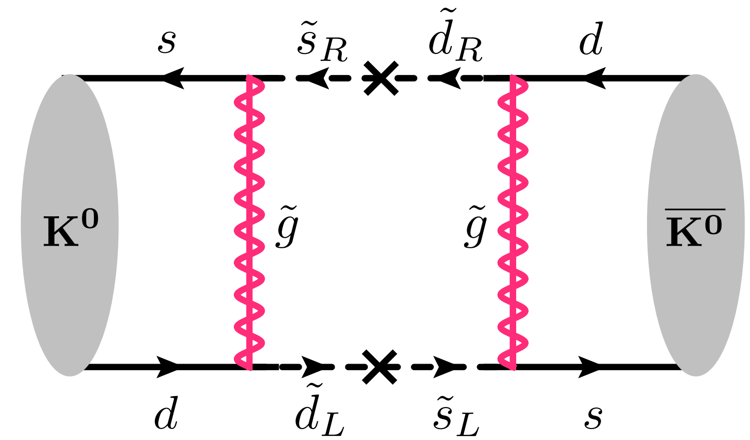
B_K

Motivation

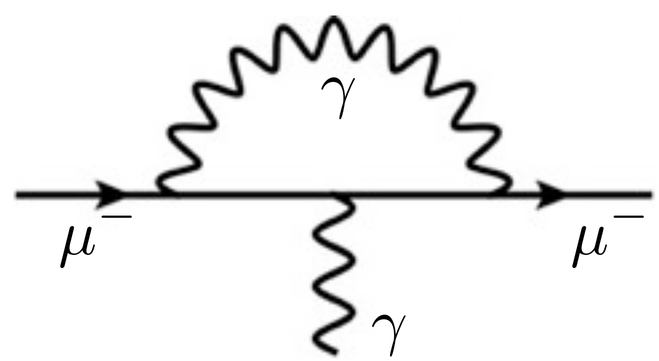
- **QM loops sensitive to new heavy particles above the TeV scale, e.g.:**

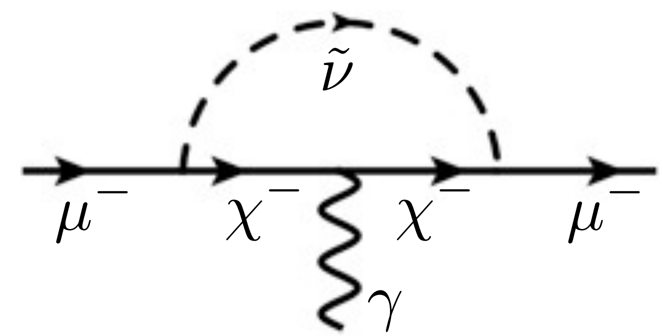
neutral kaon mixing





muon g-2





- Study fundamental physics with intense sources and sensitive detectors

- Target processes where new-physics contributions may be observable:
  - **(1)** Extremely rare (or even forbidden) in the Standard Model
  - **(2)** Predicted to high precision in the Standard Model

✦ **QM loops sensitive to new heavy particles above the TeV scale, e.g.:**

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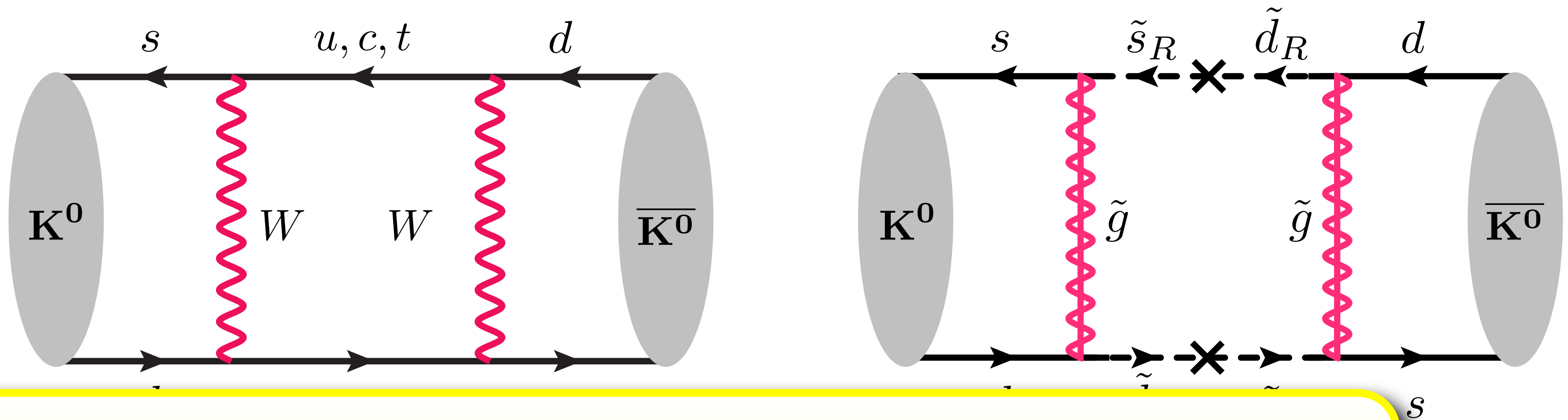

mu

- ✤ Observation of deviations from Standard-Model expectations requires equally precise theory predictions.
- ✤ Maximizing the output of the experimental program requires them on the same time scale!

✦ Study fundamental physics with intense sources and sensitive detectors

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Scope

- Current and planned experiments cover a broad range of topics in HEP/NP
- Here **focus on experiments (traditionally) supported by DOE Office of High-Energy Physics**

neutrino physics

lepton flavor violation

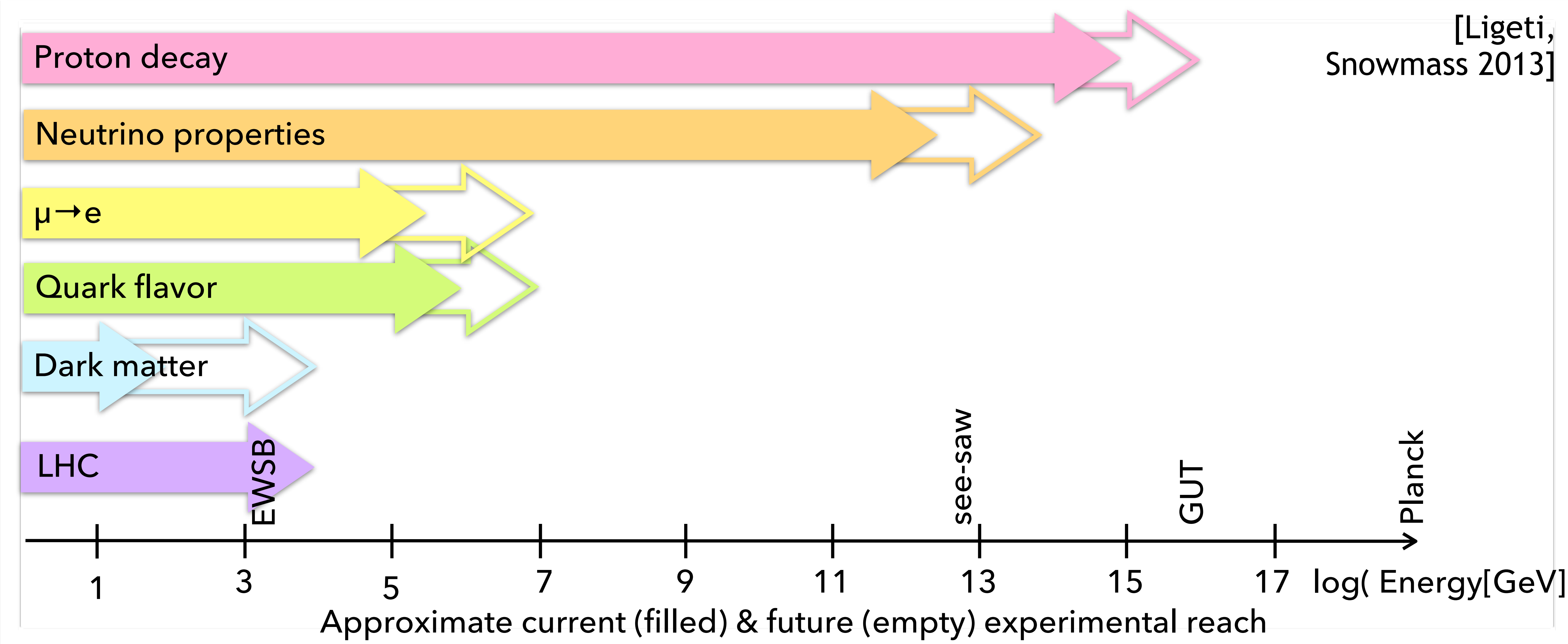
Higgs physics

B & D physics

muon g-2

kaon physics

New-physics reach



➡ **Precision measurements essential ingredient of experimental program**:

- If LHC discovers new particles, flavor & CP-violating couplings needed to determine underlying theory
- *If new physics lies above the TeV scale, indirect searches will be only probe!*

Complementarity

	LHT	RSc	4G	2HDM	RHMFV
$D^0 - \bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}$	[illegible]	[illegible]	★★		
$A_{\text{CP}}(B \to X_s\gamma)$	[illegible]	[illegible]	★		
$A_{7,8}(K^*\mu^+\mu^-)$	[illegible]	[illegible]	★★		
$B_s \to \mu^+\mu^-$	★	★	★★★	★★★	★★
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	★★★	★★★		★★
$K_L \to \pi^0\nu\bar{\nu}$	★★★	★★★	★★★		★★
$\mu \to e\gamma$	[illegible]	[illegible]	★★★		
$\tau \to \mu\gamma$	[illegible]	[illegible]	★★★		
$\mu + N \to e + N$	[illegible]	[illegible]	★★★		
d_n	[illegible]	[illegible]	★	★★★	
d_e	[illegible]	[illegible]	★	★★★	
$(g-2)_\mu$	★	★★	★		

QUARK FLAVOR

LEPTON FLAVOR

EDMs

★★★ = sizeable NP effects
★★ = moderate to small NP effects
★ = no visable NP effects

[Buras, Acta Phys.Polon.B41:2487-2561,2010]

- Different processes & observables sensitive to different new-physics scenarios
  - Pattern of measurements can distinguish between models & constrain model parameters

We do not know where the new physics lies ➜ *cast a wide net!*

USQCD scientific goals and 5-year plan

- **USQCD aims to support the US HEP experimental intensity-physics program** by "improv[ing] the accuracy of QCD calculations to the point where they no longer limit what can be learned from high precision experiments that seek to test the Standard Model" — *USQCD HEP SciDAC-3 proposal*

- 2013 White Paper *"Lattice QCD at the Intensity Frontier"* outlines a program of calculations matched to experimental priorities

  (1) "Improve the calculation of the matrix elements needed for the CKM unitarity fit"

  (2) "Calculate ... new, more computationally demanding, matrix elements that are needed for the interpretation of planned (and in some cases old) experiments"

- Target quantities and precision goals **developed with input from experimentalists and phenomenologists**

P5 science drivers

- P5 identified science drivers: **intertwined & not prioritized**

Enabling the Next Discovery

Science drivers identify the scientific motivation while the Research Frontiers provide a useful categorization of experimental techniques

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

3

Jim Siegrist, HEPAP meeting April 2015

Experimental landscape after P5

✦ HEP program narrowly focused on **smaller portfolio of prioritized experiments**

The FY 2016 HEP Budget Request

- HEP is implementing the strategy detailed in the May 2014 report of the Particle Physics Project Prioritization Panel (P5), formulated in the context of a global vision for the field
  - HEP Addresses the five compelling science drivers with research in three frontiers and related efforts in theory, computing and advanced technology R&D
  - Increasing emphasis on international partnerships (such as LHC) to achieve critical physics goals
- Energy Frontier: Continue LHC program with higher collision energy (13+ TeV)
  - The U.S. will continue to play a leadership role in LHC discoveries by remaining actively engaged in LHC data analysis and the initial upgrades to the ATLAS and CMS detectors
- Intensity Frontier: Develop a world-class U.S.-hosted Long Baseline Neutrino Facility
  - Continue the design process for an internationalized LBNF and development of a short baseline neutrino program that will support the science and R&D required to ensure LBNF success
  - Fermilab will continue to send world's highest intensity neutrino beam to NOvA, 500 miles away to Ash River, MN
- Cosmic Frontier: Advance our understanding of dark matter and dark energy
  - Immediate development of new capabilities continue in dark matter detection with baselining of 2nd-generation experiments; and in dark energy exploration with baselining of DESI and fabrication of LSST camera.

U.S. DEPARTMENT OF ENERGY | Office of Science

DOE HEP Program Status - 4/6/2015 20

Jim Siegrist, HEPAP meeting April 2015

P5 impact on LQCD program

- In budget scenarios A & B, US HEP program involves the following (*and not much else*):
  - Continued US involvement in LHC (upgrade identified as highest priority) and cosmic frontier
  - **g-2, Mu2e , and neutrinos at Fermilab**
- No room for ORKA ($K^+ \to \pi^+ \nu\nu$) or *Project X* ($K^0 \to \pi^0 \nu\nu$, EDMs, neutron-antineutron oscillations, ...)
- Participation in Japanese ILC only if "external" funds can be obtained
- Domestic experimental program primarily charged leptons and neutrinos
  - Goal for Fermilab to be global leader in neutrinos with LBNE as the flagship project
  - No domestic quark-flavor physics, although US will participate in Belle II and LHCb

What can USQCD do for HEP?

- Incomplete list of quantities aligned with science drivers that we can and should attack immediately
- Higgs boson as tool for discovery
  - b-, c-quark masses and strong coupling for precision Higgs predictions
- Physics of neutrino mass
  - Nucleon axial-vector form factor for CCQE scattering (+ other neutrino-nucleon scattering matrix elements)
- Explore the unknown
  - Quark flavor-changing matrix elements for CKM tests, rare decays, ...
  - Hadronic contributions to muon g-2
  - Light- and strange-quark content of nucleon for $\mu \to e$ conversion

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- Must keep DOE HEP priorities in mind (charged leptons & neutrinos) when formulating projects and allocating resources
- To maintain support in the near term, lattice-QCD community must meet goals for both precision and timeliness!
- To maintain support long term, must expand scope of problems that can be addressed reliably

2014-2015 USQCD science highlights

PRL **113,** 112003 (2014) PHYSICAL REVIEW LETTERS week ending 12 SEPTEMBER 2014

$K_L - K_S$ Mass Difference from Lattice QCD

Z. Bai,[1] N. H. Christ,[1] T. Izubuchi,[2,3] C. T. Sachrajda,[4] A. Soni,[2] and J. Yu[1]
[1]Physics Department, Columbia University, New York, New York 10027, USA

Kaon physics

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PRL **114,** 012001 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

Hadronic Light-by-Light Scattering Contribution to the Muon Anomalous Magnetic Moment from Lattice QCD

Thomas Blum,[1,2] Saumitra Chowdhury,[1] Masashi Hayakawa,[3,4] and Taku Izubuchi[5,2]

Muon g-2

PHYSICAL REVIEW D **89,** 114501 (2014)

Strange and charm quark contributions to the anomalous magnetic moment of the muon

Bipasha Chakraborty,[1] C. T. H. Davies,[1,*] G. C. Donald,[2] R. J. Dowdall,[3]
J. Koponen,[1] and G. P. Lepage[4,3]
(HPQCD Collaboration)[†]

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B physics

PHYSICAL REVIEW D **91,** 074510 (2015)

$B \to \pi \ell \nu$ and $B_s \to K \ell \nu$ form factors and $|V_{ub}|$ from 2 + 1-flavor lattice QCD with domain-wall light quarks and relativistic heavy quarks

J. M. Flynn,[1] T. Izubuchi,[2,3] T. Kawanai,[2,3,*] C. Lehner,[3] A. Soni,[3] R. S. Van de Water,[4] and O. Witzel[5,†]
(RBC and UKQCD Collaborations)

$\Lambda_b \to p\,\ell^- \bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c\,\ell^- \bar{\nu}_\ell$ form factors from lattice QCD with relativistic heavy quarks

William Detmold,[1] Christoph Lehner,[2] and Stefan Meinel[3,4,*]
[1] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[3] Department of Physics, University of Arizona, Tucson, AZ 85721, USA
[4] RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

$|V_{ub}|$ from $B \to \pi \ell \nu$ decays and (2+1)-flavor lattice QCD

Jon. A. Bailey,[1] A. Bazavov,[2,*] C. Bernard,[3] C.M. Bouchard,[4,5] C. DeTar,[6] D. Du,[7,8,†] A.X. El-Khadra,[7] J. Foley,[6] E.D. Freeland,[9] E. Gámiz,[10] Steven Gottlieb,[11] U.M. Heller,[12] J. Komijani,[3] A.S. Kronfeld,[13,14] J. Laiho,[8] L. Levkova,[6] Yuzhi Liu,[15] P.B. Mackenzie,[13] Y. Meurice,[16] E. Neil,[15,17] Si-Wei Qiu,[6,‡] J.N. Simone,[13] R. Sugar,[18] D. Toussaint,[19] R.S. Van de Water,[13] and R. Zhou[13]
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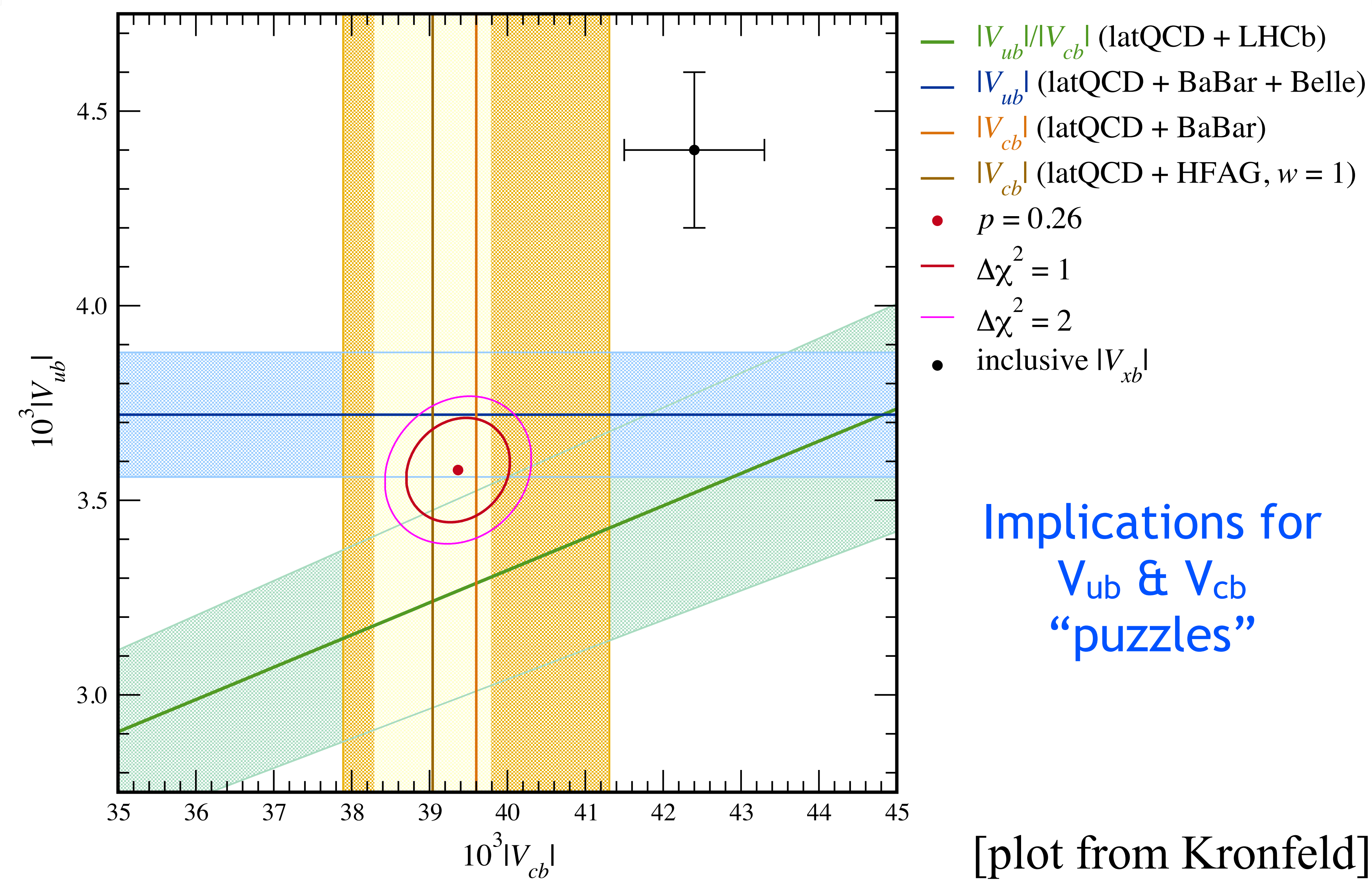

Implications for V_{ub} & V_{cb} "puzzles"

[plot from Kronfeld]

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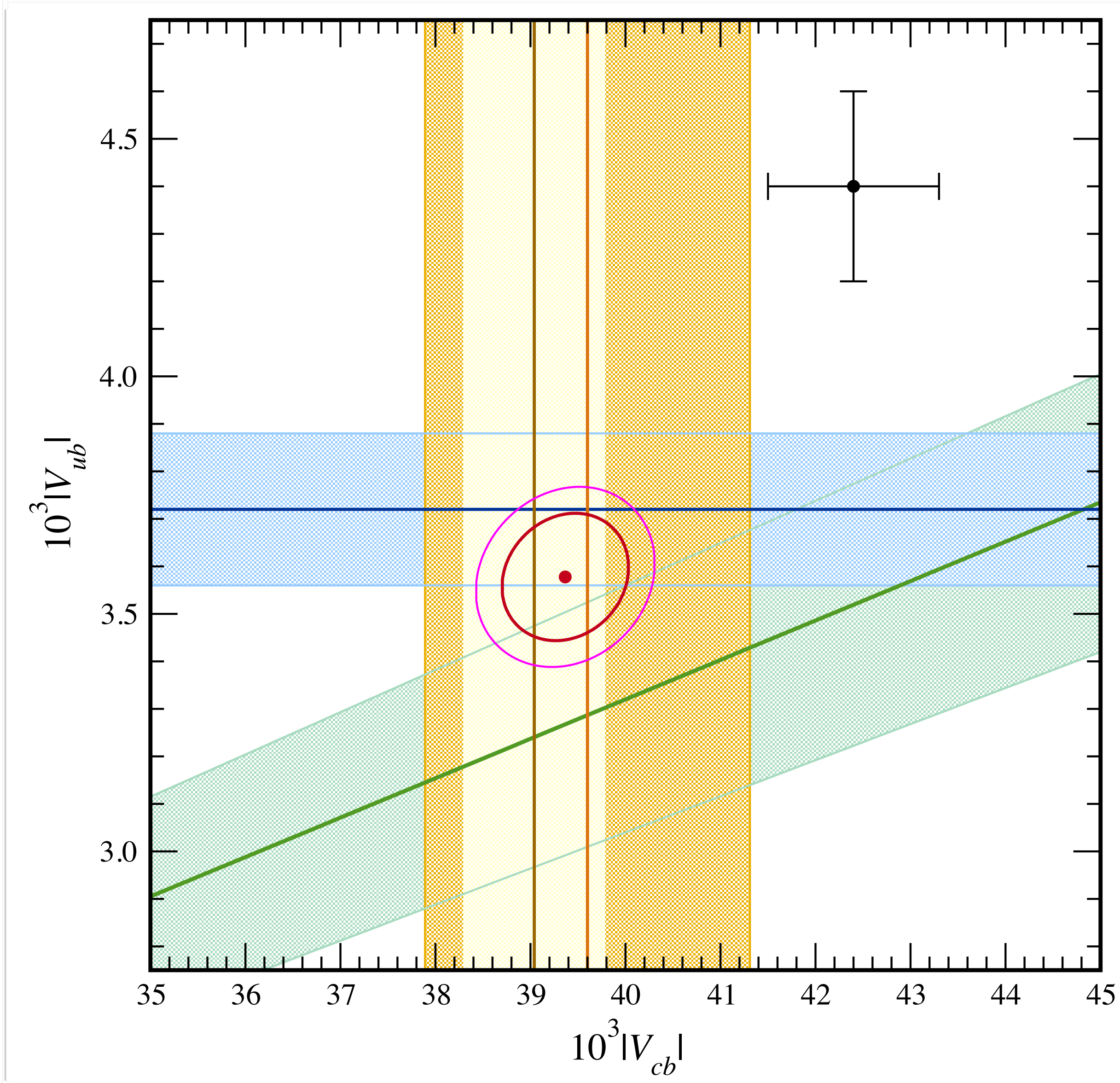

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- USQCD leading world both in new ideas and precision calculations!

SPC summary & perspective

BK

2015 project requests

(EDM & f_A IF or NP?)

- Aubin: Hadronic contributions to the muon g-2 using staggered fermions
- Blum (*RBC*): Calculation of nucleon EDMs induced by quark chromo-electric dipole moments
- Feng (*RBC/UKQCD*): Exploratory lattice calculation of the rare kaon decays
- Ishikawa (*RBC*): Neutral B meson mixing with static heavy and domain-wall light quarks at the physical point
- Izubuchi (*RBC/UKQCD*): Hadronic vacuum polarization contributions to g-2 on physical point Mobius-DWF ensemble using zMobius, AMA, MADWF, and GPU
- Kronfeld (*Fermilab/MILC*): The nucleon axial-vector form factor at the physical point with the HISQ ensembles
- Laiho (*HPQCD,Fermilab/MILC*): Muon g-2 hadronic vacuum polarization from 2+1+1 flavors
- Lehner (*RBC*): QCD + QED studies using twist-averaging
- Mackenzie (*Fermilab/MILC*): Standard-model parameters and the search for physics beyond the Standard Model with HISQ
- Mawhinney (*RBC/UKQCD*): Production of 2+1+1 flavor MDWF lattices
- Shigemitsu (*HPQCD*): High-Precision Heavy-Quark Physics
- Soni (*RBC*): Improved precision for B physics with physical-mass DW light quarks and relavistic b quarks
- Sugar (*MILC*): QCD with Four Flavors of Highly Improved Staggered Quarks fermions

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Total Requests

- 397 M Jpsi core-hours core-hours ANL BG/Q (134% full-priority time)
- 128% ANL BG/Q zero-priority time
- 125M Jpsi core-hours core-hours BNL BG/Q (108% available BNL time)
- 460M Jpsi core-hours clusters (102% available cluster time)
- 111M Jpsi core-hours GPUs (17% total GPU time)

= 67% available USQCD resources (excludes zero-priority)

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Physics addressed

(Also showing relevant USQCD efforts using outside resources)

- **Pion and Kaon physics**
  - Decay constants & light-quark masses (Mawhinney, Sugar)
  - B_K, $K\to\pi l\nu$, $K\to\pi\pi$ (Mawhinney)
  - $K\to\pi\nu\nu$ long-distance matrix elements (Feng)
- **B and D meson physics**
  - $D_{(s)}$-meson decay constants & form factors (HPQCD,Mackenzie)
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- **Muon g-2**
  - HVP (Aubin, Izubuchi, Laiho)
  - HLbL (Lehner)
- **Neutrino physics** (Kronfeld)
- **Nucleon EDMs** (Blum)

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➡ **DWF & HISQ configuration-generation + modest exploratory study**

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➡ Both nucleon projects modest

Strong points of 2015 IF proposals

- USQCD work on muon g-2 exciting!
  - Theoretical methods for HVP contribution in place → now have first proposals for large-scale calculations with physical pions and fine lattice spacings
  - USQCD leading world in strategies for HLbL
- New USQCD effort on heavy-quark masses & strong coupling
- Entire program benefitting greatly from DWF & HISQ ensembles with physical pion masses
  - Enabling (sub)-percent precision for quark-flavor calculations needed to obtain CKM matrix elements and constrain the CKM unitarity triangle
  - Essential for g-2, nucleon matrix elements, for which chiral perturbation theory is unreliable / unavailable
- Planned DWF & HISQ ensembles over next 5 years will include **dynamical QED and isospin-breaking** (*HISQ*)
  - Isospin-breaking needed to go below ~1% level for HVP
  - QED essential for complete calculation of HLbL contribution to muon g-2

Considerations & provocations

- **SPC recommends to EC allocations to deliver science objectives outlined in white papers**
  - Proposal-driven process
  - ➡ *Highly constrained by submitted proposals & available resources*

1. How to balance configuration generation & analysis? Are configuration-generation projects sufficiently far ahead that they can be temporarily slowed-down to make room for analysis?
2. How to balance supporting mature "high-priority" projects and exploratory work that will drive our future program?
3. How equally should we "spread the pain"? May be better for USQCD long term to prioritize some projects (i.e. close to fully fund) and de-prioritize others. How to do this without alienating USQCD members and undermining sense of community?
4. How much duplication is needed? (Independent checks needed, but can't afford "too much" redundancy.)

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Questions? Comments

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