Lattice QCD and Particle Physics

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Elementary Particle Physics

aka High Energy Physics

- The central theme is to explore the smallest distance scales for evidence of new particles, new interactions, new symmetries, and new structures:
  - direct production of new particles and measurements of their couplings—
    - the “BSM” lattice gauge theories of new particles;
  - observations of the cosmos, e.g., dark matter—
    - BSM to explain their nature; QCD to understand the signals;
  - precise measurements need precise calculations—
    - QCD calculations of relevant hadronic matrix element.

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Ethan

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Ethan

Andreas

QCD is Everywhere

parton distribution functions

hadronic muon g–2

decay & mixing amplitudes

esoteric hadrons:

dark-matter-nucleus cross sections

muon-nucleus cross sections

neutrino-nucleus cross sections

USQCD Community Engagement

- 2013 HEP Community Planning (aka Snowmass):
  - participation in satellite meetings as well as Minneapolis;
  - reports: Lattice, Quark Flavor, QCD, Charged Leptons, Higgs, Computing.
- Particle Physics Project Prioritization Panel (P5):
  - (invited) presentations to P5 meetings;
  - USQCD focus evolved as P5 plan developed.
- Project X Physics Study: leadership role + lattice-QCD working group.

- Long-term interactions with B-factory community; recent examples:
  - B factories legacy book (co-authors): arXiv:1406.6311 [hep-ex];
  - Belle 2 Theory-interface Platform (talks, WG conveners, Lattice Board, Advisory Board).
- Lattice Meets Experiment workshops (QCD): 2014, 2010, 2007, 2006.
- Programs/workshops at INT, KITP, MITP, Siegen, TUM, ...
- Invited talks at collaboration meetings, e.g., DUNE, g–2, BES 3, ...
- Conference IAC memberships (partial list): CKM series, Charm series, Beauty series, Lepton-Photon 2015, ...

Particle Physics Priorities

P5 Report's Science Drivers

- PB Use the Higgs boson as a new tool for discovery.
- PN Pursue physics associated with neutrino mass.
- PNBT Identify the new physics of dark matter.
- B Understand cosmic acceleration: dark energy and inflation.
- PB Explore the unknown: new particles, interactions, and physical principles.

These topics are covered in the talks: P = particle physics QCD; B = BSM LGT; N = cold nuclear QCD; T = thermodynamics.

Higgs Boson

- The recently discovered Higgs boson is a form of matter never before observed, and it is mysterious.
  - What principles determine its effects on other particles?
  - How does it interact with neutrinos or with dark matter?
  - Is there one Higgs particle or many?
  - Is the new particle really fundamental, or is it composed of others?
- The Higgs boson offers a unique portal into the laws of nature.

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Quark masses and α_s are essential ingredients.

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Neutrino Physics

- Future experiments will address the questions:
  - What is the origin of neutrino mass?
  - How are the masses ordered (referred to as mass hierarchy)?
  - What are the masses?
  - Do neutrinos and antineutrinos oscillate differently?
  - Are there additional neutrino types or interactions?
  - Are neutrinos their own antiparticles?

Neutrino Physics

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  - What is the origin of neutrino mass?
  - How are the masses ordered (referred to as mass hierarchy)?

All hinge on sufficient understanding of neutrino-nucleus cross sections and, hence, neutrino-nucleon amplitudes.

  - Do neutrinos and antineutrinos oscillate differently?
  - Are there additional neutrino types or interactions?
  - Are neutrinos their own antiparticles?

Dark Matter

- Dark matter is presumed to consist of one or more kinds of new particles.
- The properties of these particles, which are all around us, are unknown. Dark matter represents a bizarre shadow world of fundamental particles that are both omnipresent and largely imperceptible.
- Experiments are poised to reveal the identity of dark matter, a discovery that would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe.

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Measurements (limits for now) rely on scattering off nucleons and, hence, nucleon matrix elements.

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Explore the Unknown

- There are clear indicators of new phenomena awaiting discovery beyond those motivating the other four drivers.
- Particle physics is a discovery science defined by the search for new particles and new interactions, and by tests of physical principles.
- The tools for this search are varied and include very high-energy beams of protons and electrons, intense beams of protons, and cosmic sources of ultra high-energy particles.
- The searches take two basic forms: directly producing and indirectly detecting evidence for new particles.

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Variety of lattice-QCD calculations needed.

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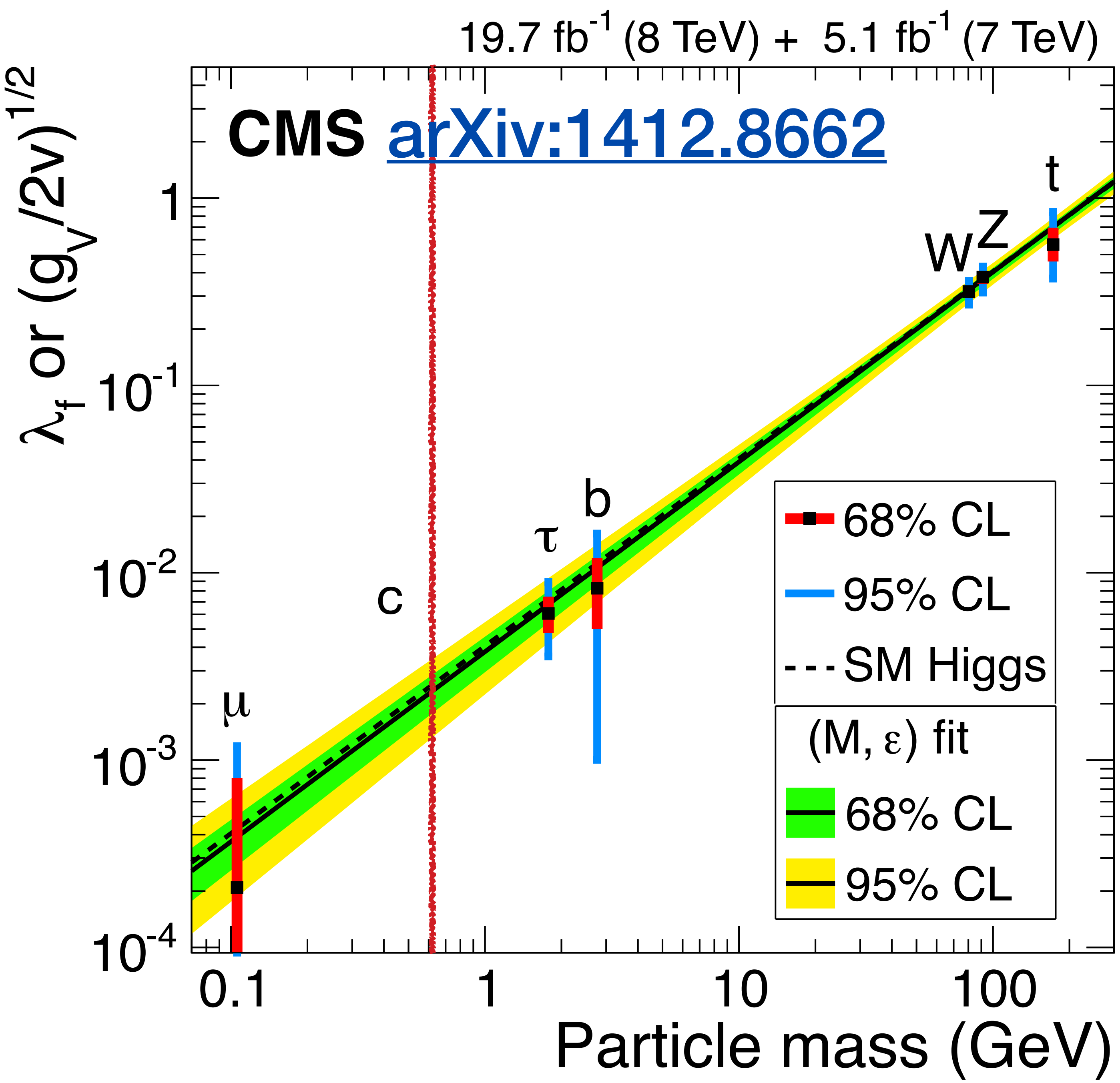
Higgs Boson

The Role of Quark Masses

- In the Standard Model, the Higgs field generates mass for quarks, charged leptons, and gauge bosons.
- To test this principle and *a fortiori* test the (posited) elementary nature of the Higgs boson, it is necessary to compare the masses to the Higgs-particle couplings.
- Couplings (typically) from Higgs boson decay.
- Quark masses from lattice QCD.

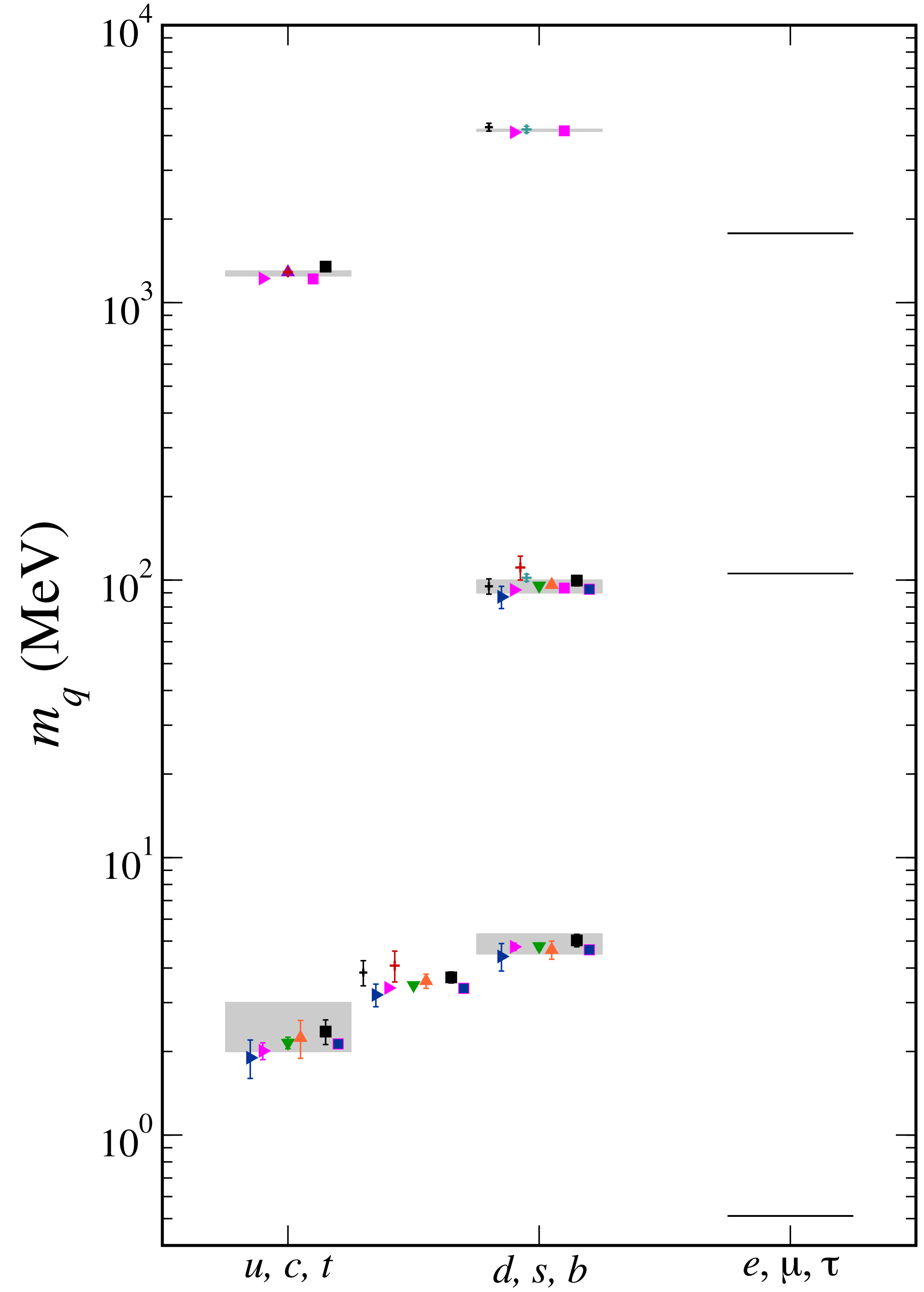
Test Higgs Couplings vs SM

- Needed to predict Higgs decays BRs.
- Future running at the LHC will reduce BR uncertainty.
- Future (circular or linear) colliders even further.
- Recent USQCD-based $m_b/m_c = 4.528(54)$ [HPQCD, arXiv:1408.4169]



Further Results

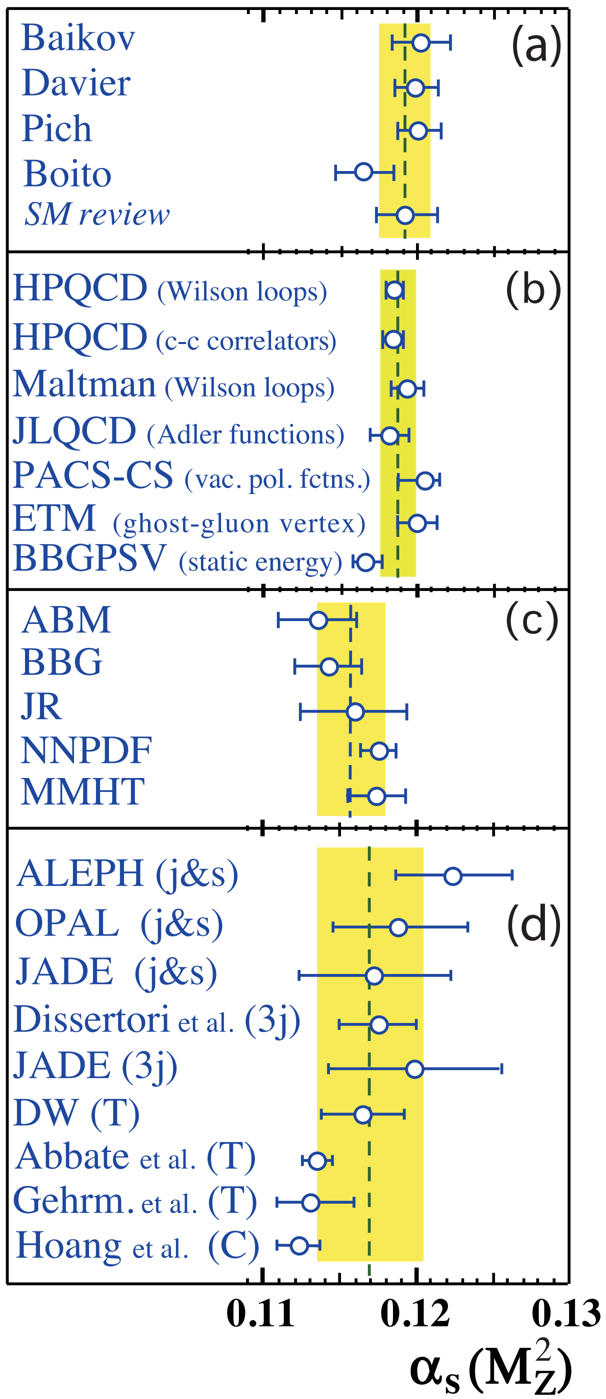
- Summary of quark masses from lattice QCD.
- Blue, magenta, and orange results from USQCD resources:
  - HPQCD most precise m_b, m_c;
  - HPQCD m_c with Fermilab/MILC mass ratios $\Longrightarrow$ most precise m_s, m_d, m_u.



Strong Coupling α_s

- Higgs BRs are also sensitive to the strong coupling α_s.
- Summary from PDG (2016, in press) at right.
- Improvements needed for both α_s and quark masses to match e^+e^- Higgs studies [arXiv:1404.0319].

- (a) τ decay
- (b) lattice
- (c) DIS
- (d) e^+e^- jets, event shapes



Neutrino Physics

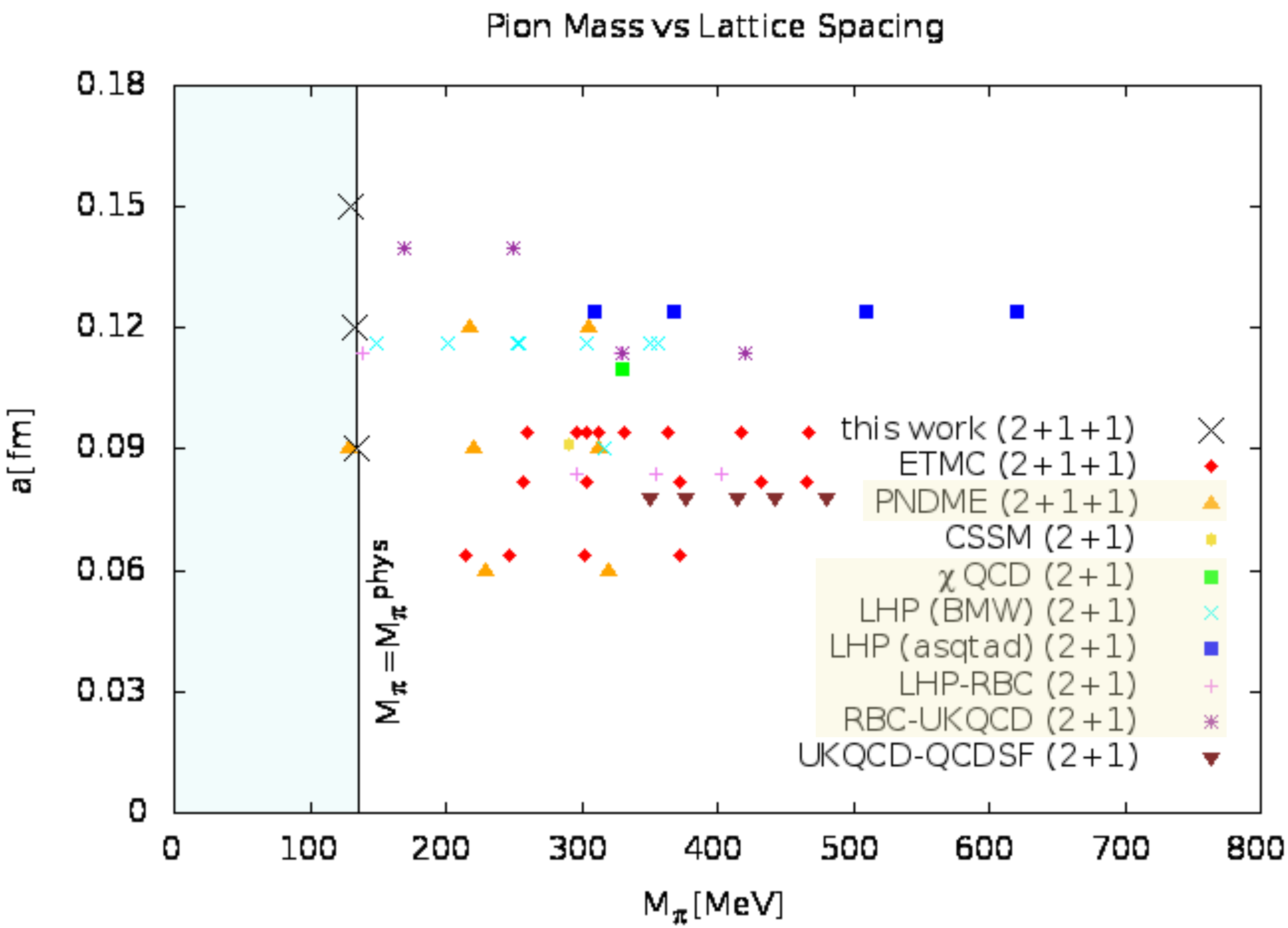
Neutrino Experiments

- … all detect neutrinos via scattering off detector materials such as carbon (in scintillator), oxygen (in water) or liquid Argon.
- Key process is neutrino-nucleon scattering, as modified by the nucleus:
  - nucleons weakly bound in nucleus, allowing for a systematic approach;
  - requires nucleon-level amplitudes, which can be computed with lattice QCD.

Useful Calculations

- Axial vector form factor $F_A(q^2)$ from $\langle N|\bar{q}\gamma^\mu\gamma^5 q|N\rangle$.
- Resonant and non-resonant excitation form factors: $\langle\Delta|\bar{q}\gamma^\mu\gamma^5 q|N\rangle$, $\langle N\pi|\bar{q}\gamma^\mu\gamma^5 q|N\rangle$.
- Two-body currents: $\langle NN|\bar{q}\gamma^\mu\gamma^5 q|NN\rangle$.
- Both charged-current and neutral-current (harder).
- Build on long history of nucleon structure calculations, aiming for dialog similar to that in quark-flavor physics.

Survey of $g_A = -F_A(0)$ Calculations



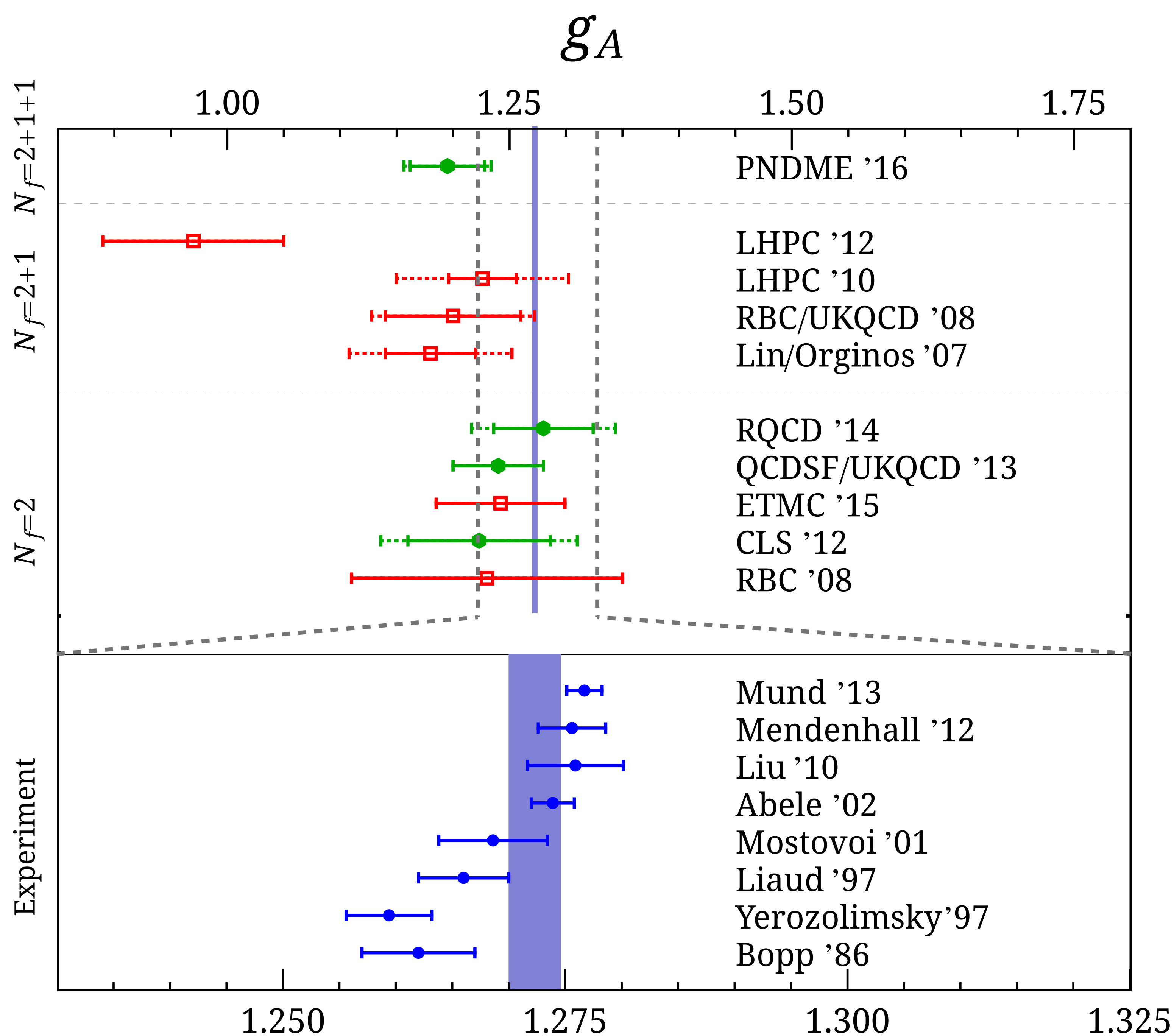
2+1 or
2+1+1

USQCD

plot by
A. Meyer

g_A Status

- Recent result clover-on-HISQ from PNDME.
- Their summary plot—
  - note different scales.
- Still a challenge.
- USQCD-supported project underway with 3 physical-mass ensembles; $F_A(q^2)$.



Dark Matter

Direct Detection

- Dark matter particles scatter off nucleons in detector, by exchanging another (unknown) particle.
- Models positing DM candidates say something about the mediator and its coupling to DM & to quarks.
- Need matrix elements of quark currents in the nucleon.
- If the mediator is a scalar, e.g., the Higgs boson, the needed matrix element cannot be measured:
  - compute it in lattice QCD.

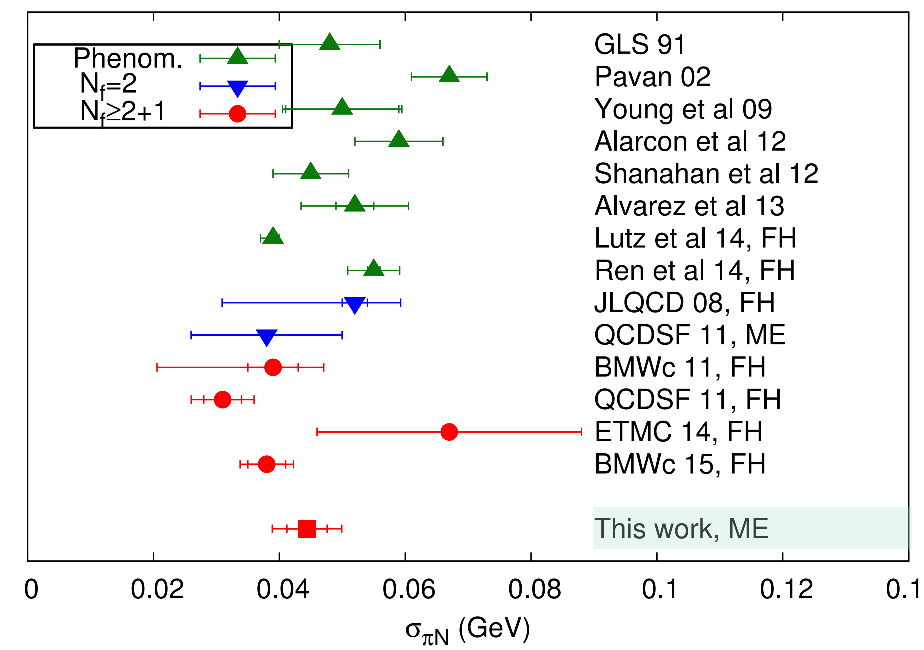
Quark Content of the Nucleon

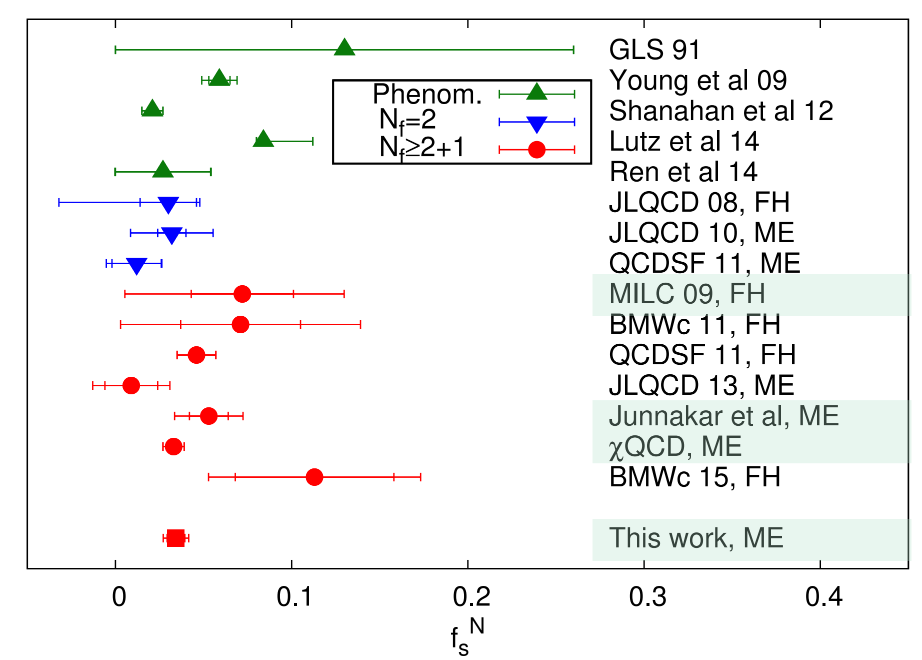
- Jargon/notation from low-energy physics:

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle$$

$$f_s = m_s\langle N|\bar{s}s|N\rangle / M_N$$

- Latest results (and plots) from χQCD [arXiv:1511.09089].
- USQCD results highlighted.
- Same matrix elements needed for muon-to-electron conversion.





Other Nucleon Matrix Elements

- Further examples of matrix elements of interest to HEP and NP:
  - Scalar and tensor charges (similar to gA in lattice QCD), probed by precise neutron decay experiments: (ultra)cold neutrons at LANL, SNS.
  - Baryon-number violation, probed in proton decay or neutron-antineutron oscillations: DUNE and proposed n-ñ experiments.
  - Electric dipole moments: a clear sign of CP violation: proton, neutron, and other systems, to disentangle strong CPV from BSM CPV: many expts, including ideas suited for FRIB.
- USQCD efforts on all these fronts.

Explore the Unknown

Two Key Avenues

- Quark flavor physics:
  - processes yielding the CKM matrix;
  - processes sensitive to contributions beyond the Standard Model.
- Muon’s anomalous magnetic moment:
  - hadronic vacuum polarization (HVP);
  - hadronic light-by-light loop (HLbL).

CKM Status

- Most of the world-leading calculations pertaining to the Cabibbo-Kobayashi-Maskawa (CKM) matrix use USQCD resources—many of them rely on these resources.

- Partial list (from years past) of tree-level processes:

  - $|V_{us}|$: f_K/f_π, $f_+(0)$ from $K \to \pi l\nu$;

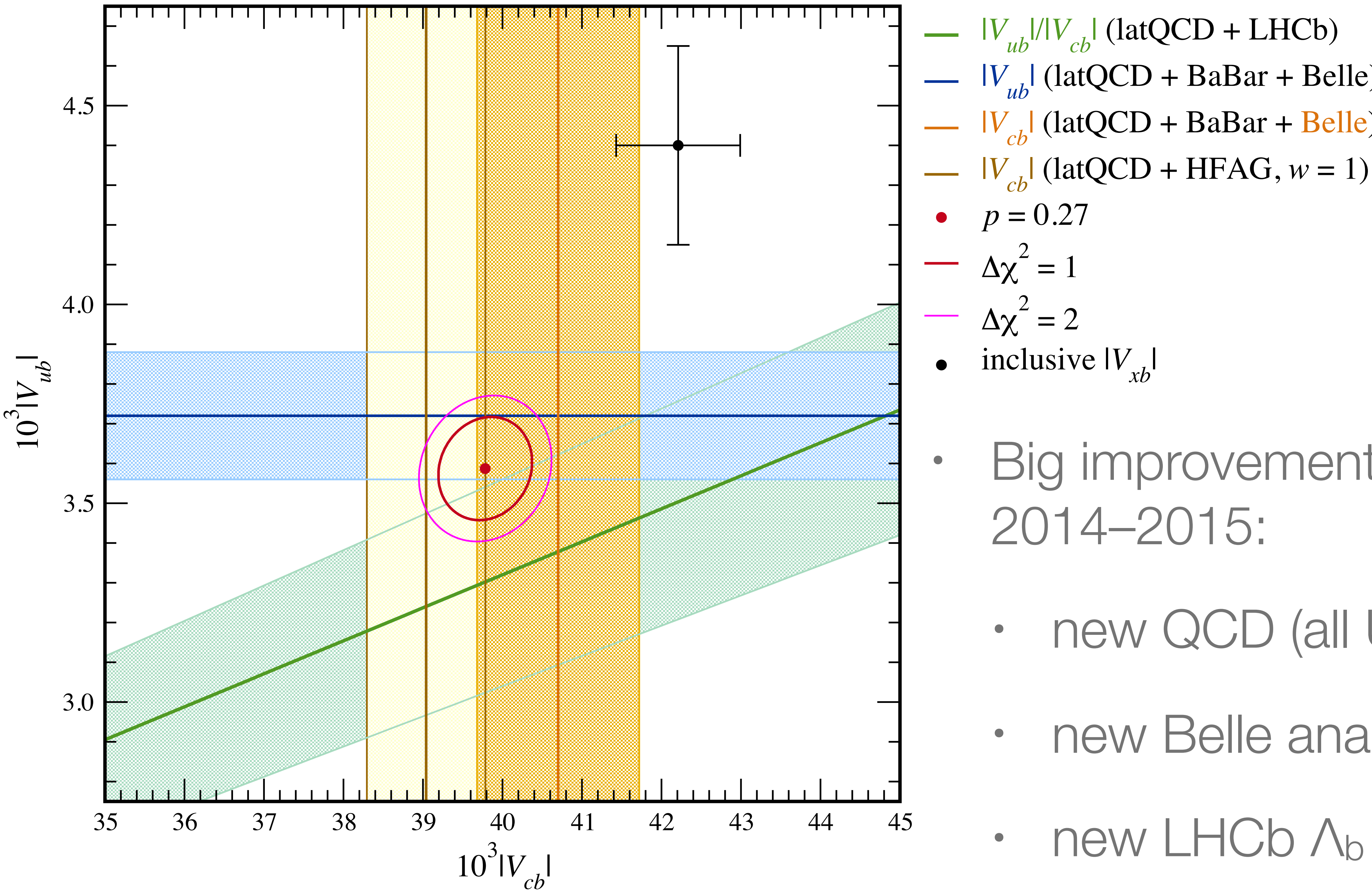
  - $|V_{cd}|$ & $|V_{cs}|$: f_D, $f_+(q^2)$ from $D \to \pi l\nu$ & f_{Ds}, $f_+(q^2)$ from $D_s \to Kl\nu$;

  - $|V_{ub}|$: f_B, $f_+(q^2)$ from $B \to \pi l\nu$;

  - $|V_{cb}|$: $f_+(q^2)$ from $B \to Dl\nu$, $A_i(q^2)$ from $B \to D^* l\nu$.

- Many results from Fermilab/MILC and some from other groups.

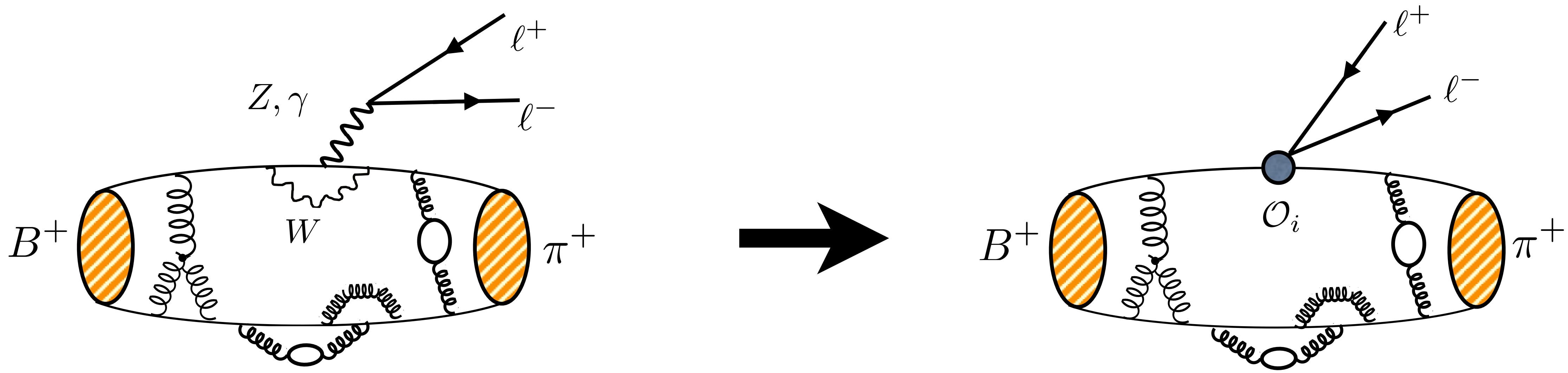
Synthesis of $|V_{ub}|$ & $|V_{cb}|$ Calculations



- Big improvements in 2014–2015:
  - new QCD (all USQCD);
  - new Belle analysis;
  - new LHCb Λ_b decay.

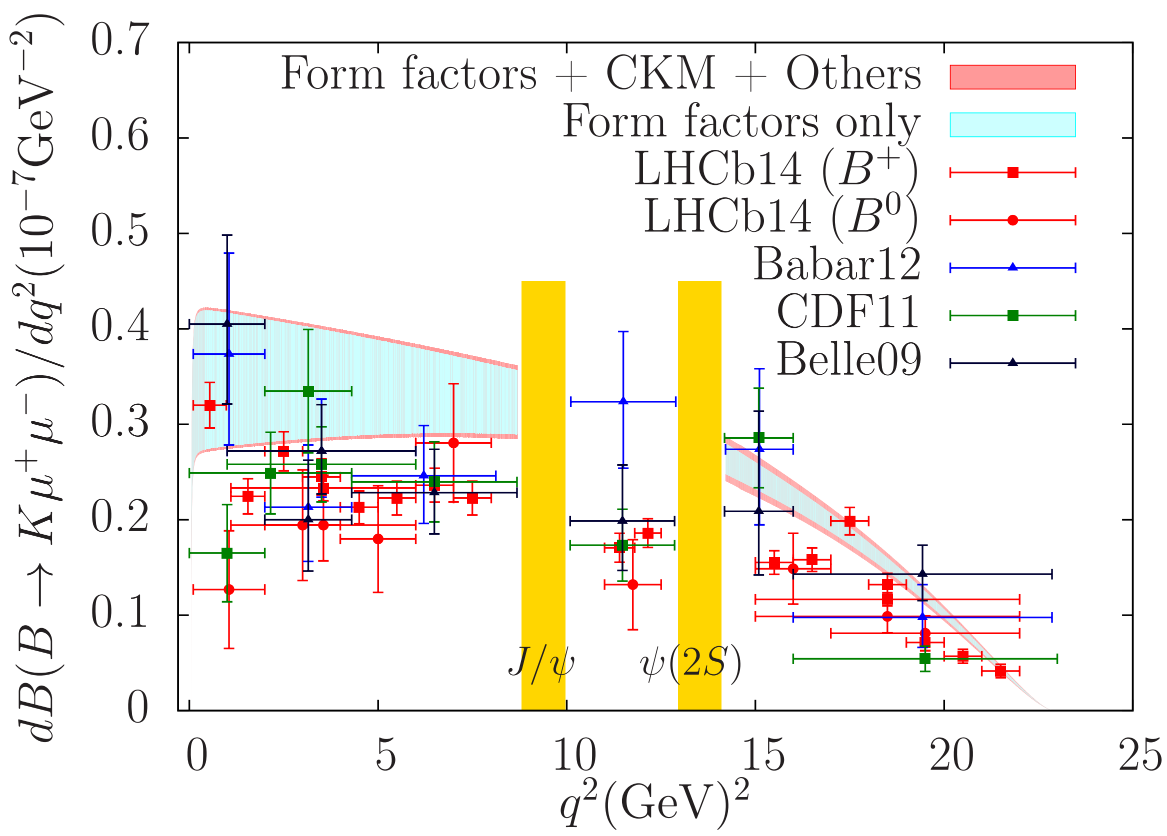
New Physics Searches

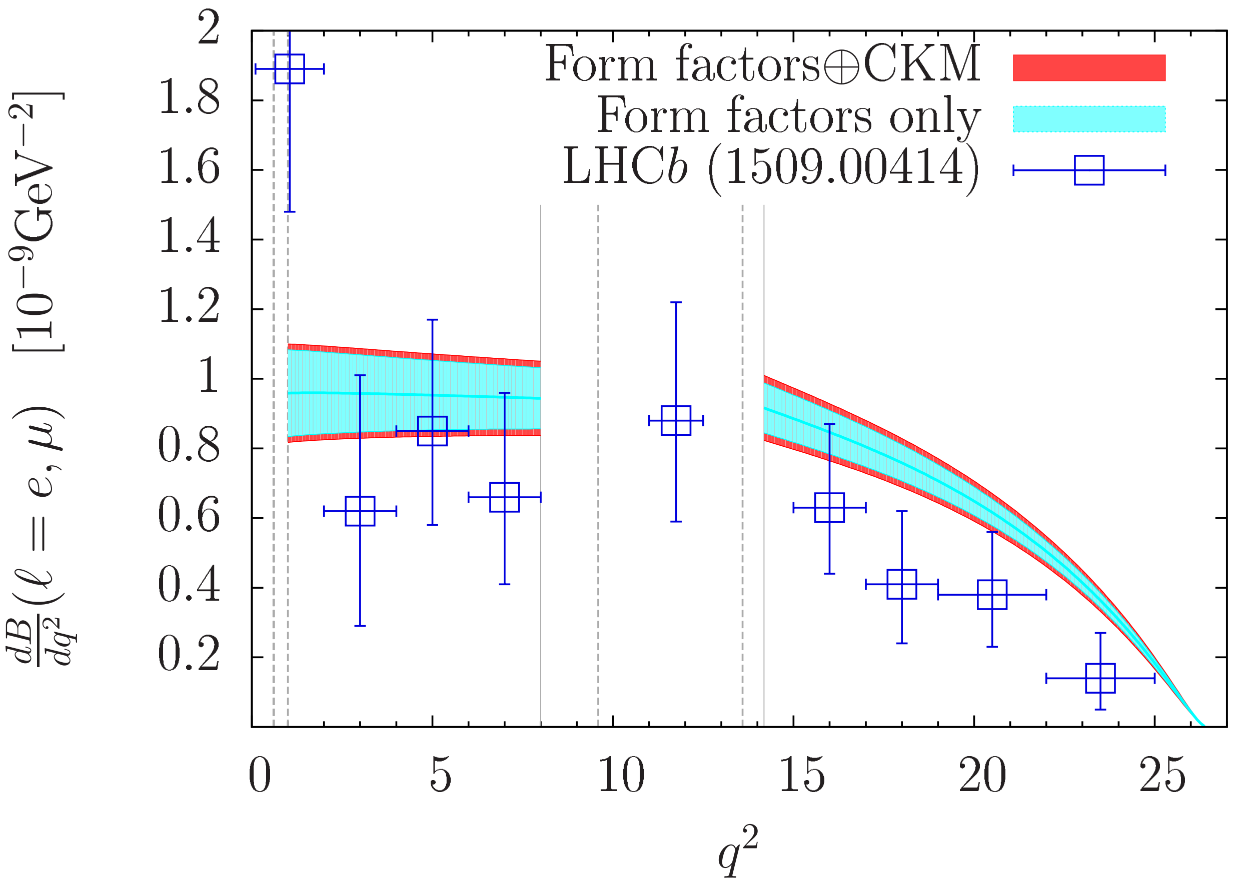
- Flavor-changing neutral currents: suppressed in SM by loop, CKM factors, and GIM mechanism:
    - could physics beyond the SM contribute?
- Examples: $B \to Kl^+l^-$, $B \to \pi l^+l^-$, $B \to K\nu\nu$, $B \to \pi\nu\nu$, all modes of interest to LHCb and Belle (II).



Kinematic Distributions

- Experimental data from LHCb [arXiv:1403.8044, arXiv:1509.00414] and earlier experiments; right plot's theory **preceded** measurement:





- LHCb wide bins: $q^2 \in [1\ \mathrm{GeV}^2, 6\ \mathrm{GeV}^2]$, and $q^2 \in [15\ \mathrm{GeV}^2, 22\ \mathrm{GeV}^2]$.

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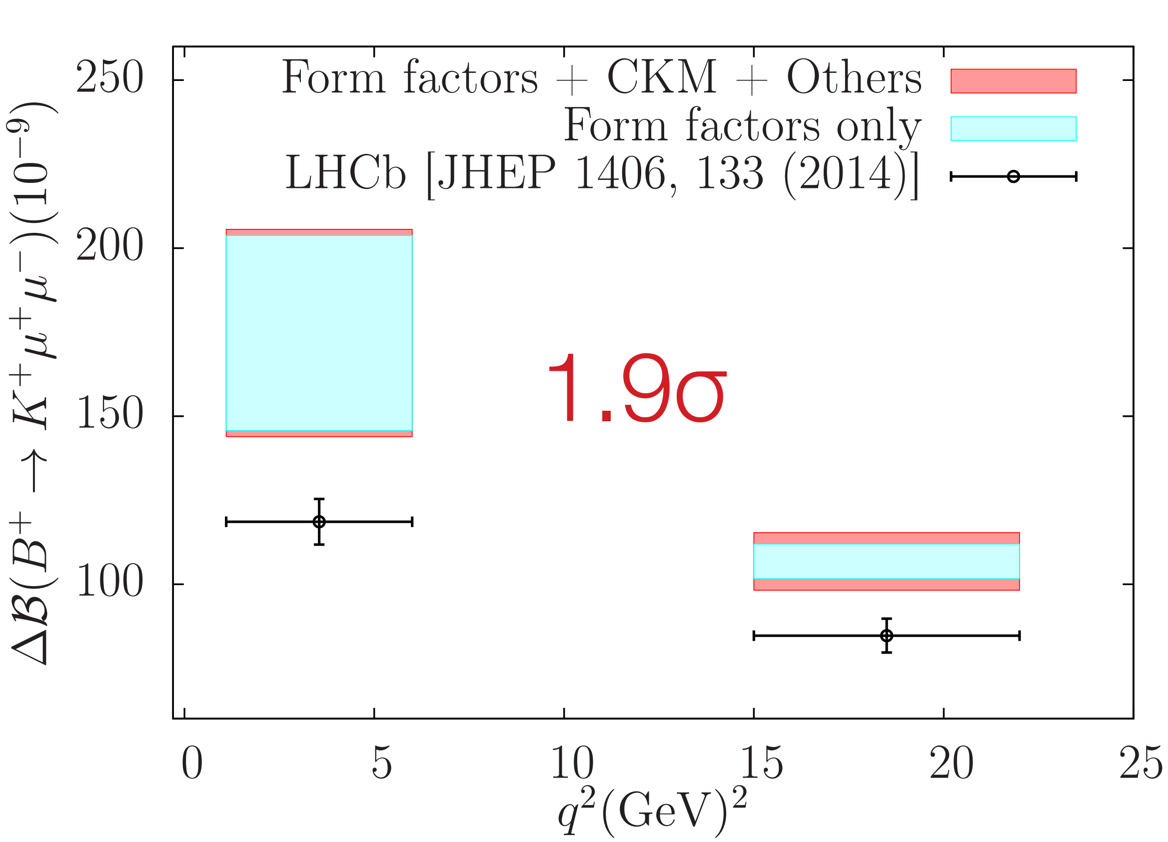

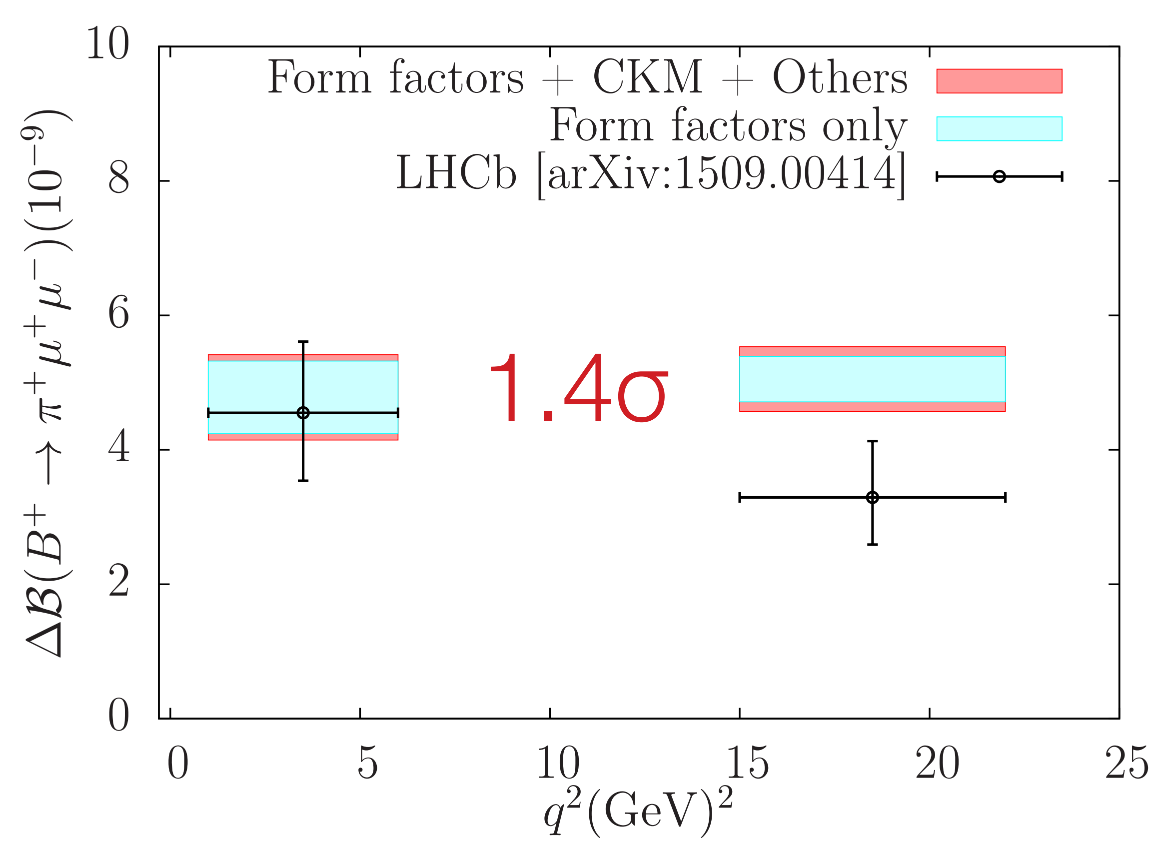

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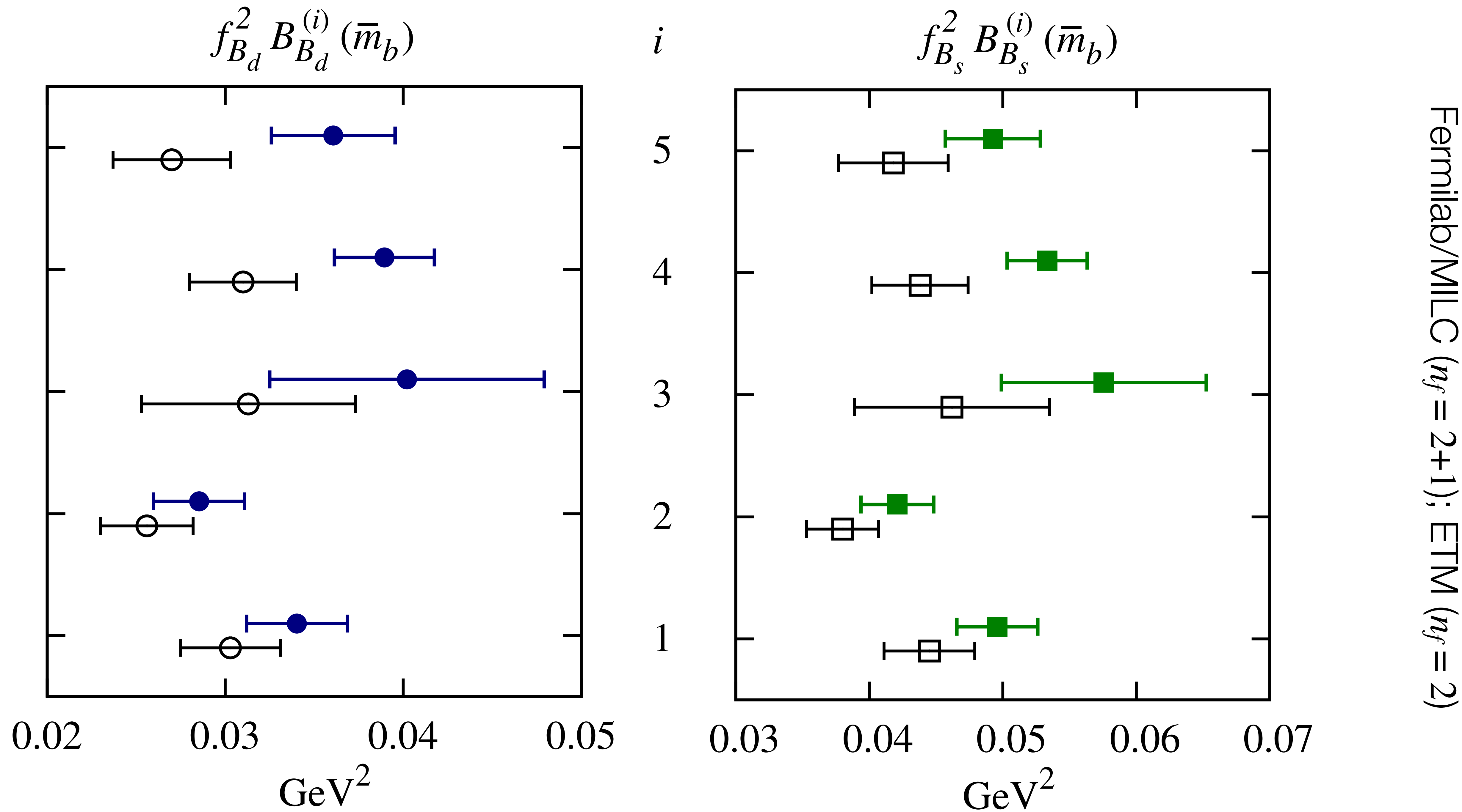
B Mixing (Fermilab/MILC), arXiv:1602.03560



Oscillation Frequencies

- Taking CKM from tree-only inputs (from CKMfitter):

$$\Delta M_d^{\rm SM} = 0.639(50)(36)(5)(13)\ {\rm ps}^{-1}$$
$$\Delta M_s^{\rm SM} = 19.8(1.1)(1.0)(0.2)(0.4)\ {\rm ps}^{-1}$$
$$\frac{\Delta M_d^{\rm SM}}{\Delta M_s^{\rm SM}} = 0.0323(9)(9)(0)(3)$$

- Contrast with the measured frequencies:

$$\Delta M_d^{\rm expt} = (0.5055 \pm 0.0020)\ {\rm ps}^{-1}$$
$$\Delta M_s^{\rm expt} = (17.757 \pm 0.021)\ {\rm ps}^{-1}$$

- These amount to discrepancies of 2.1σ, 1.3σ, and 2.9σ, respectively.

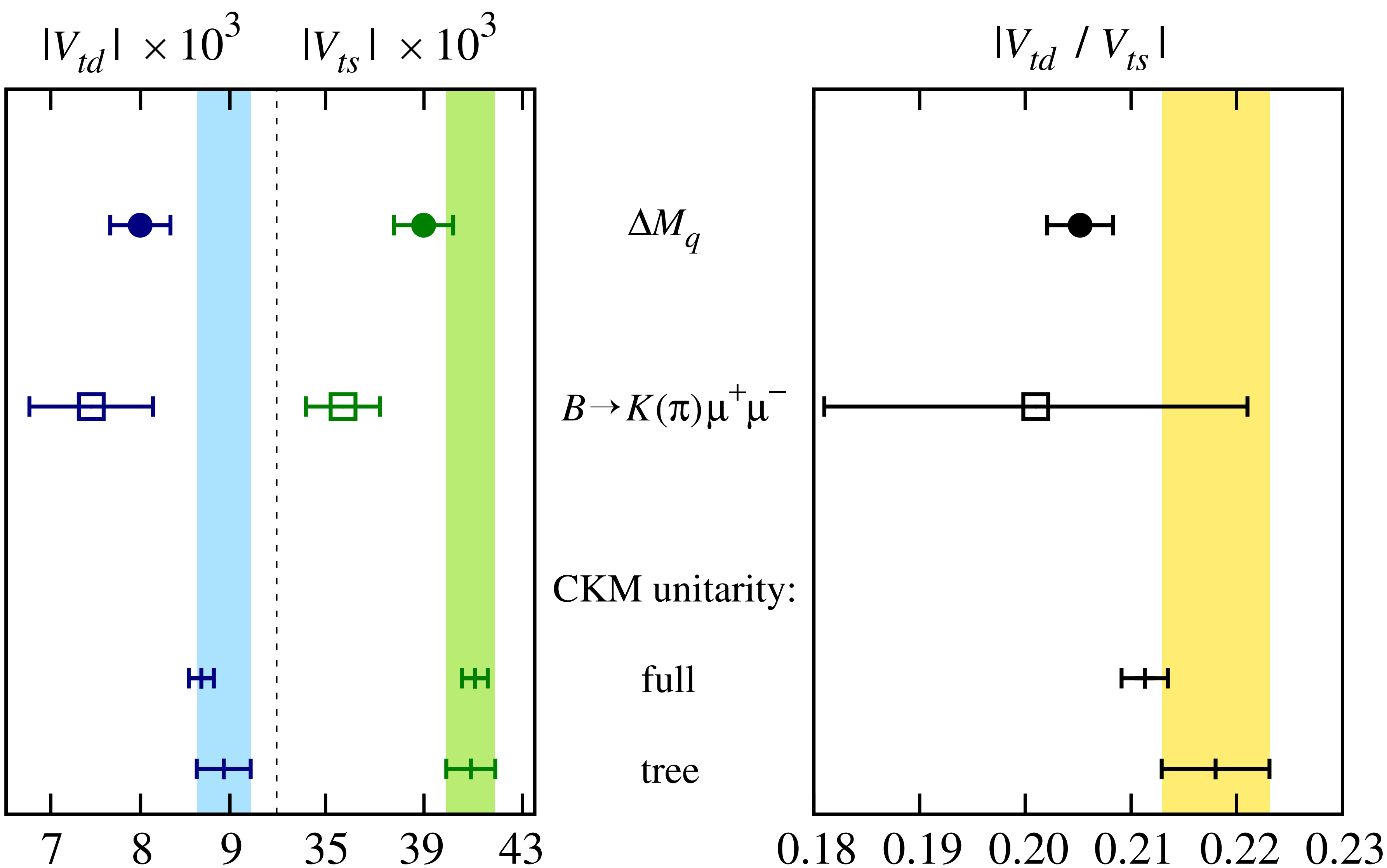
- Examine these tensions with those in other FCNC processes, casting each one as a “CKM determination”.

CKM Comparison

- CKM implied by FCNC deviate from trees + unitarity.

2.0σ, 1.2σ

2.0σ, 2.9σ



2.1σ

expt

plots by C. Bouchard

Direct CP Violation in $K \to \pi\pi$

- A long-standing goal of lattice QCD is to calculate the amplitudes for $K \to \pi\pi$ decay (e.g., Bernard et al. 1985).

- A recent milestone (RBC), leading to first full calculation of direct CP violation:

$$10^4 \,\mathrm{Re}\, \frac{\varepsilon'}{\varepsilon} = \begin{cases} 1.4(5.2)(4.6) & \text{SM} \\ 16.6(2.3) & \text{expt} \end{cases} \qquad 2.1\sigma$$

- Suggestion of new physics echoed in, e.g., Buras, arXiv:1601.00005.

Muon Anomalous Magnetic Moment

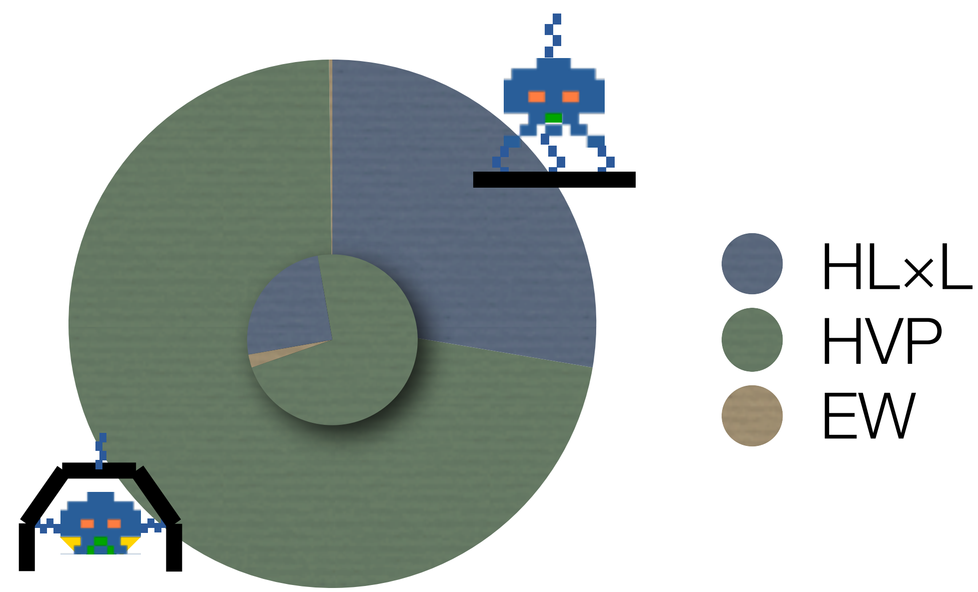
- Fermilab E989 is being mounted to explore a well-known tension between BNL E821 & SM.

$$10^{11} a_\mu = \begin{array}{ll} 116\,592\,089(63) & \text{expt} \\ 116\,591\,802(49) & \text{SM with HVP from } e^+e^- \end{array}$$

$$a = \mu \frac{2m}{e\hbar} - 1 = \frac{1}{2}(g-2)$$

285(63)(49) is a huge difference

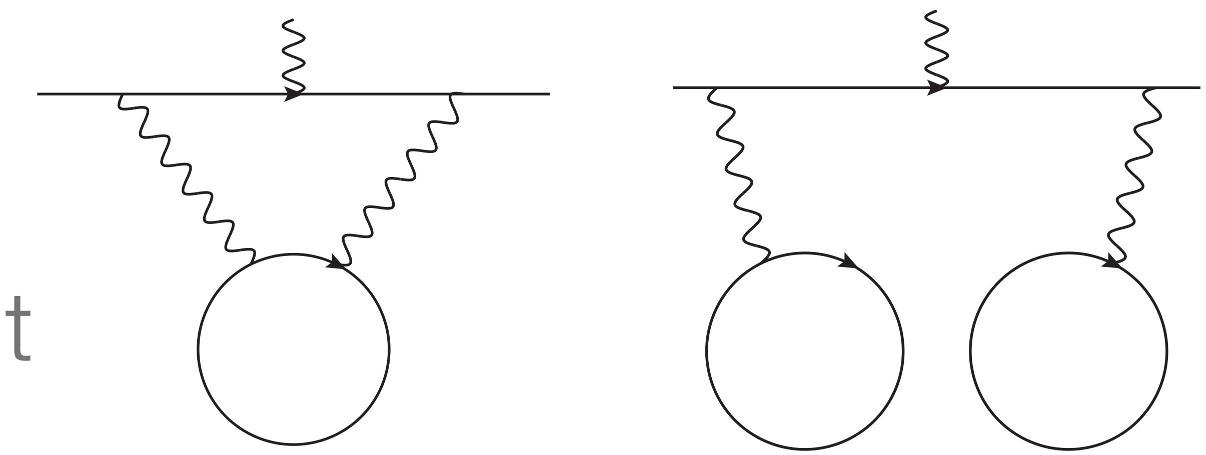
BNL E821 → FNAL E989



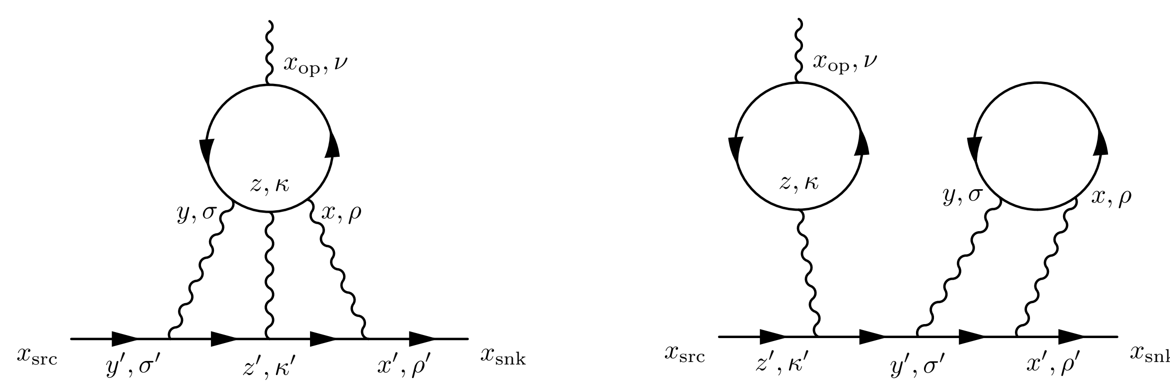
Standard Model Calculation

Hadronic Contributions

- Two kinds of hadronic contributions:
  - vacuum polarization:



    - all gluons implied but quarks & photons are connected, or disconnected
  - “light by light scattering”

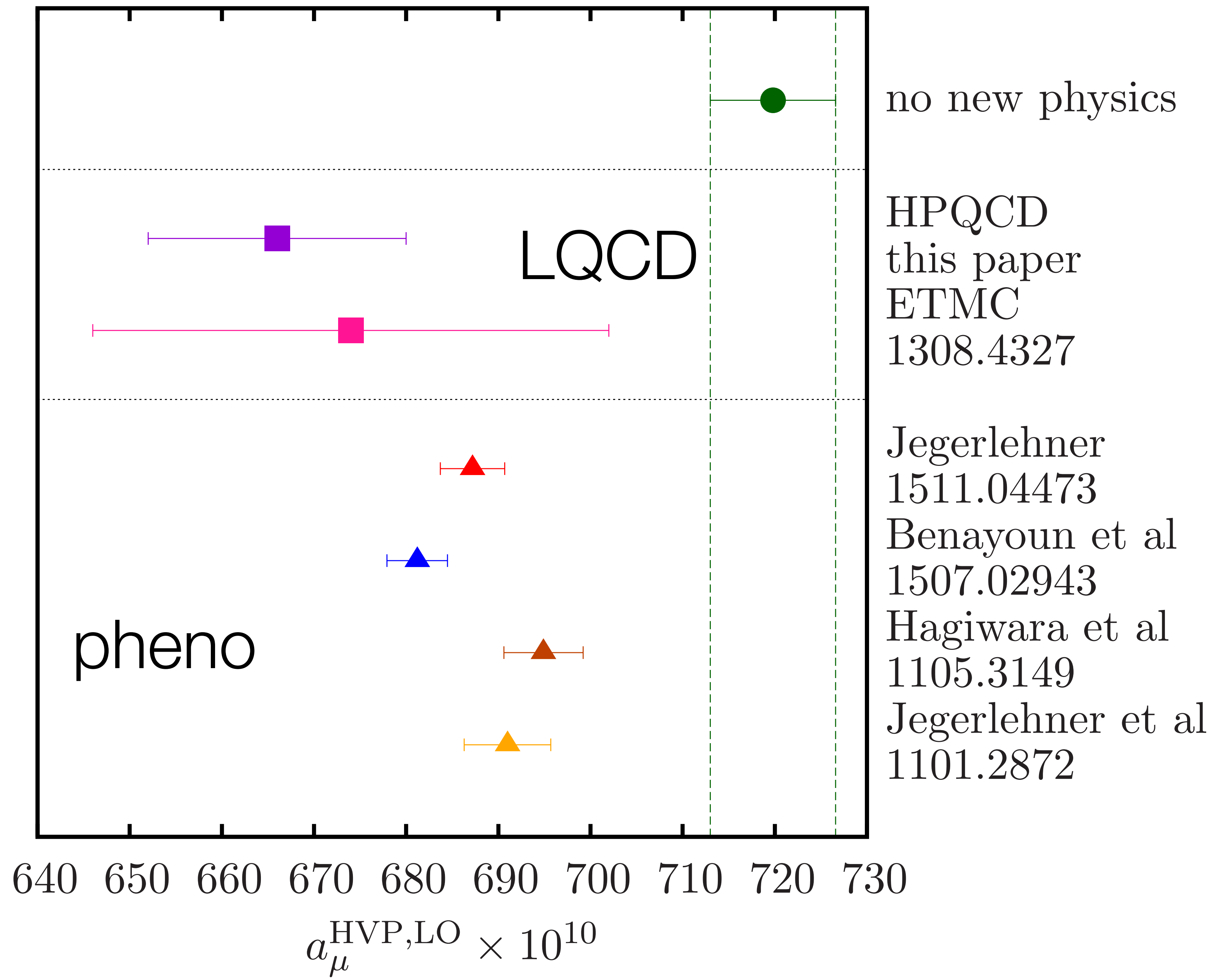


Major Progress in HVP

- New variance-reduction algorithms.
- New methods for tackling the heart of the problem.
- New estimate (HPQCD) and first calculation (RBC/UKQCD) of disconnected contribution.
- Strange contribution to HVP (HPQCD, RBC/UKQCD).
- Second full calculation of total HVP from lattice QCD, and first "significant" deviation from experiment (HPQCD).

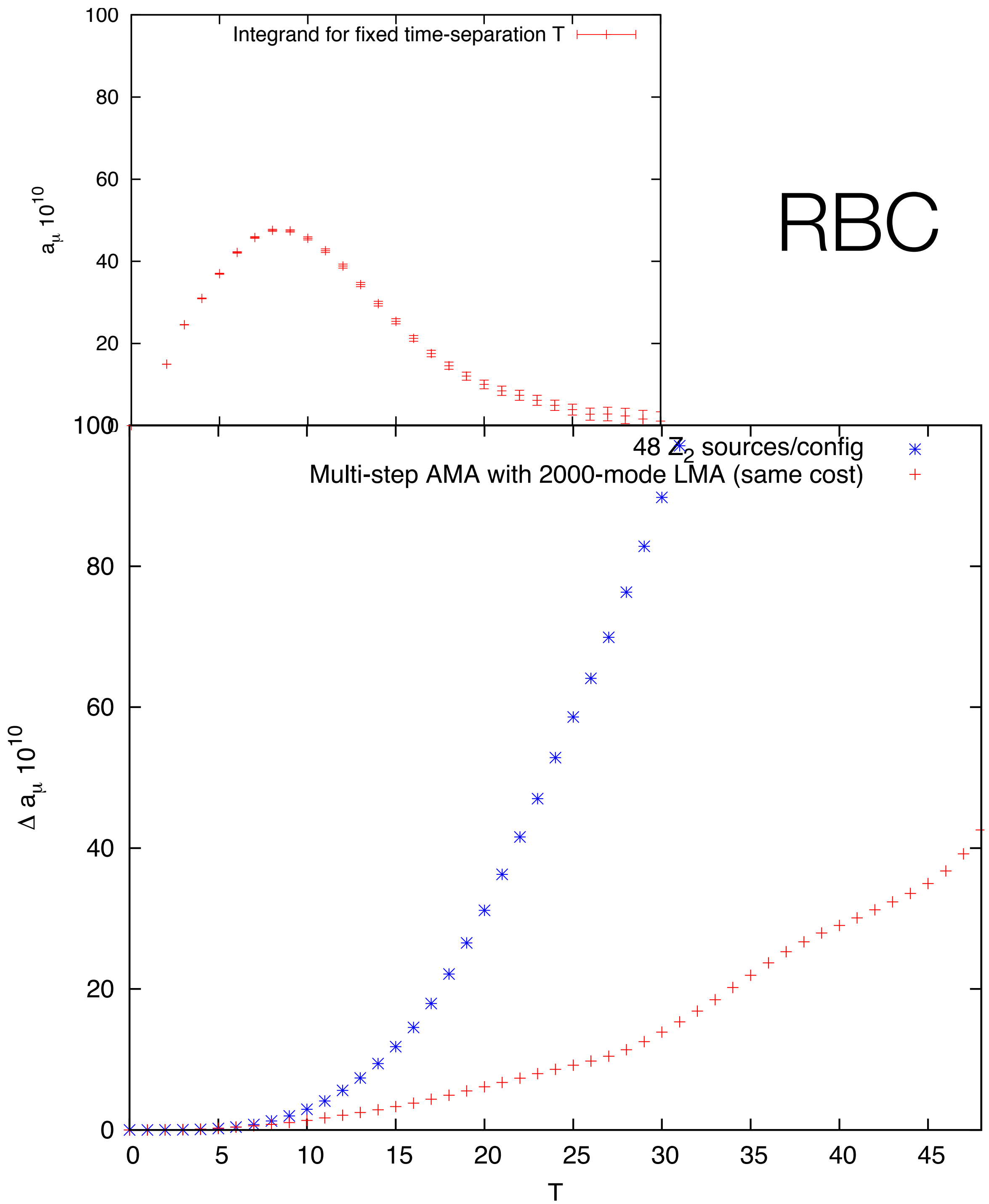
HPQCD, arXiv:1601.03071

- Second full result from lattice QCD.
- Uses MILC's 2+1+1 ensembles.
  - 3 lattice spacings;
  - 3 volumes;
  - 3 quark masses, including physical.
- 3σ from exp't.



Additional Technical Progress in HVP

- HPQCD replaced data with fit for large time separation.
- RBC is developing variance reduction techniques to avoid this blemish.



RBC

HLbL Calculation (RBC)

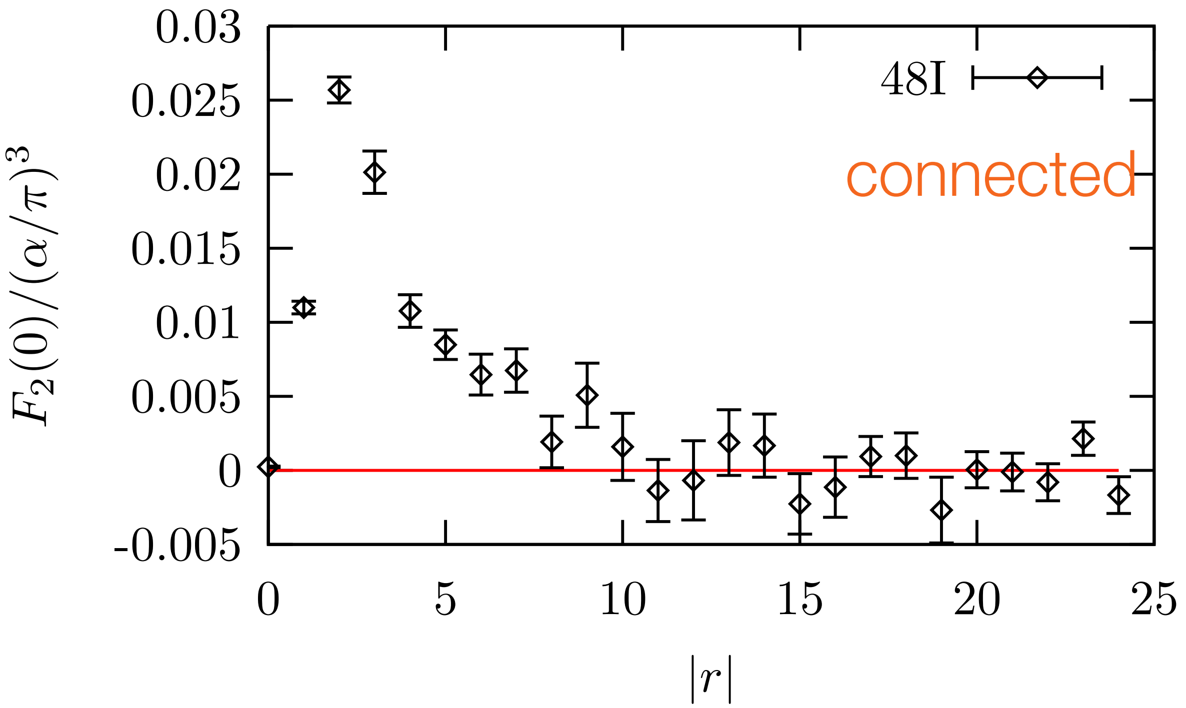
update of arXiv:1510.07100

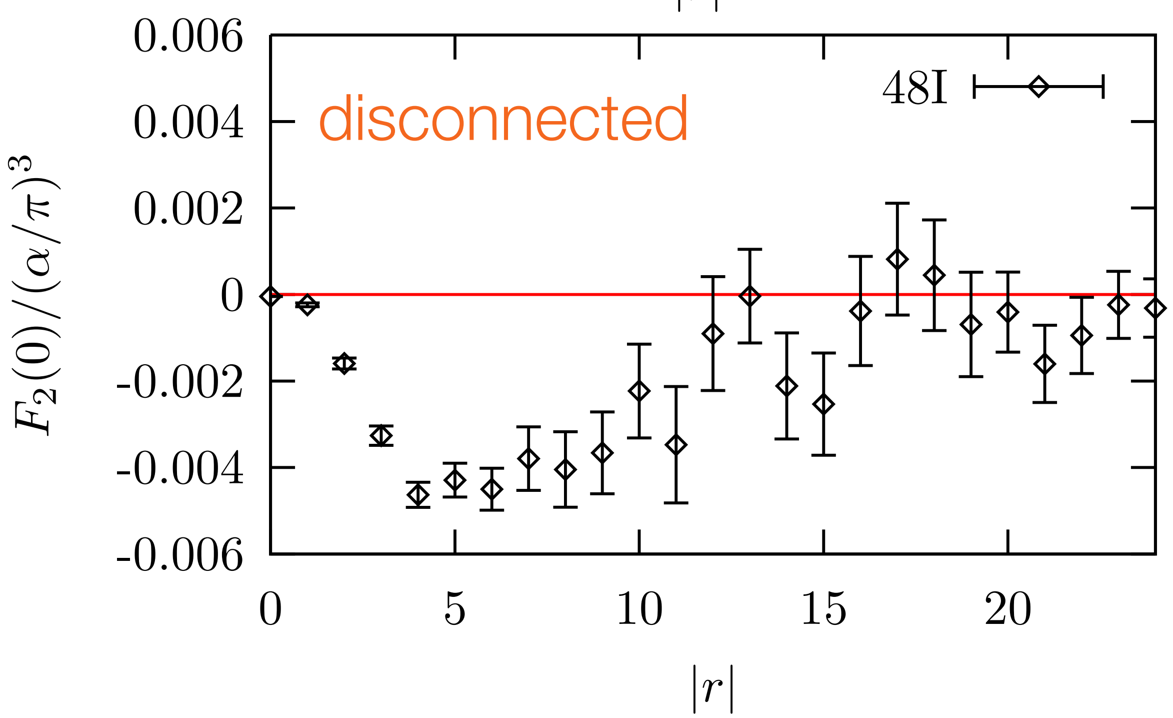
- Coordinate-space methods with “stochastic” photons.
- Desired result is integral over inter-photon distance.
- Preliminary results (stat. error):

$$10^{10} a_\mu = \begin{cases} 11.69 \pm 0.91 & \text{connected} \\ -5.60 \pm 1.26 & \text{disconnected} \end{cases}$$

cf. Glasgow consensus 10.5±2.6.

- Full error analysis yet to be done, but very encouraging.





Summary

Achievements

- Broad range of results in quark-flavor physics:
  - decay and mixing amplitudes of b-hadrons;
  - first complete calculation of kaon direct CP violation ε'.
- Striking progress in other topics:
  - first calculation of disconnected muon g–2 HVP;
  - first full calculation to “verify” the SM discrepancy.

Prospects

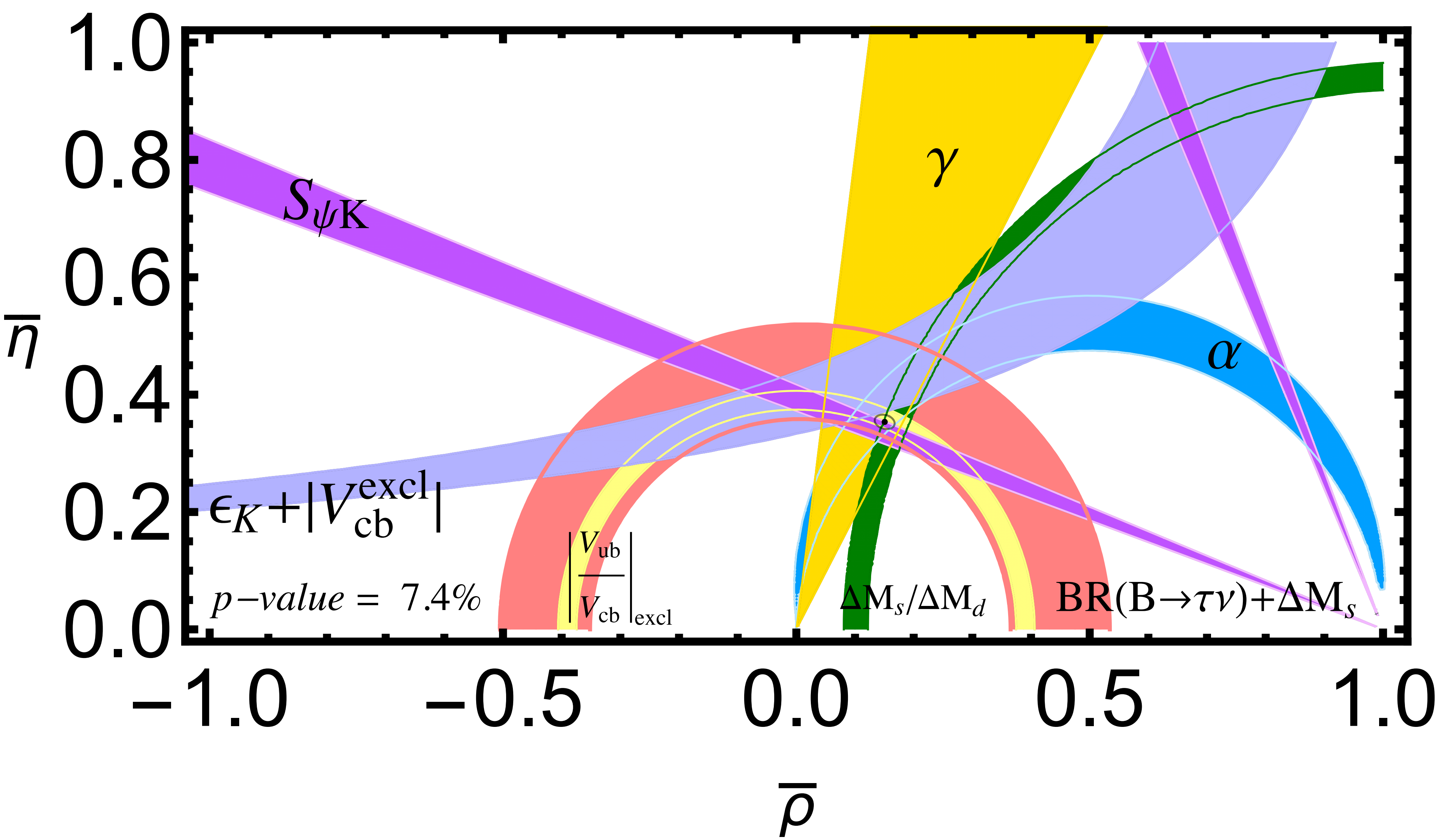
- Beginning to use light-quark methods for b quarks (on finer lattices):
  - step improvement in b-hadron properties forthcoming.
- Nucleon matrix elements pertaining to fundamental physics now an HEP (as well as NP) research topic.
- Ideas and computers conquering hadronic muon g–2:
  - HVP looks on track to meet needs of E989;
  - HLbL possibly also (with some assumptions on cleverness).

Outlook

- HEP program in USQCD is well aligned with P5's science drivers.
- As in the past, lattice QCD calculations are crucial to the success of HEP experiments.
- Broadening the scope of the program in times of shrinking resources is very difficult.

Unitarity Triangle 2016

- With recent results from Fermilab/MILC, HPQCD, RBC, and Detmold/Lehner/Meinel:



plot by
E. Lunghi

Backup

Lattice References for V_{ub} vs. V_{cb} Plot

- V_{cb} from $B \to D^* l\nu$, zero recoil: Fermilab/MILC.
- Vcv from $B \to Dl\nu$, all recoil: Fermilab/MILC, HPQCD.
- V_{ub} from $B \to \pi l\nu$, all recoil: RBC, Fermilab/MILC.
- V_{ub}/V_{cb} from $\Lambda_b \to (p/\Lambda_c)l\nu$: Detmold, Lehner, Meinel.
- Plot prepared for C. DeTar, arXiv:1511.06884