Lattice QCD at Fermilab, or
"What can lattice QCD do for you?"

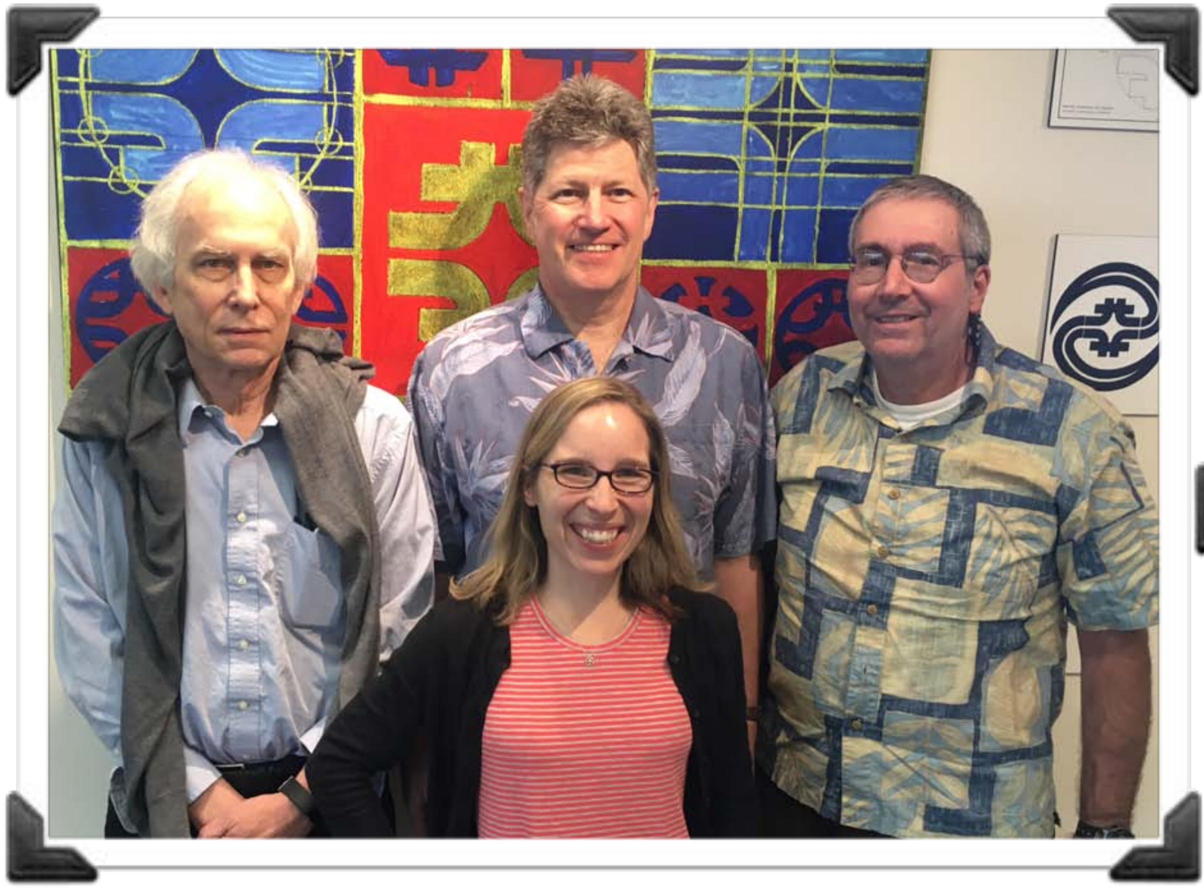
Ruth Van de Water
Fermilab

Fermilab 50th Anniversary Symposium and Users' Meeting
June 8, 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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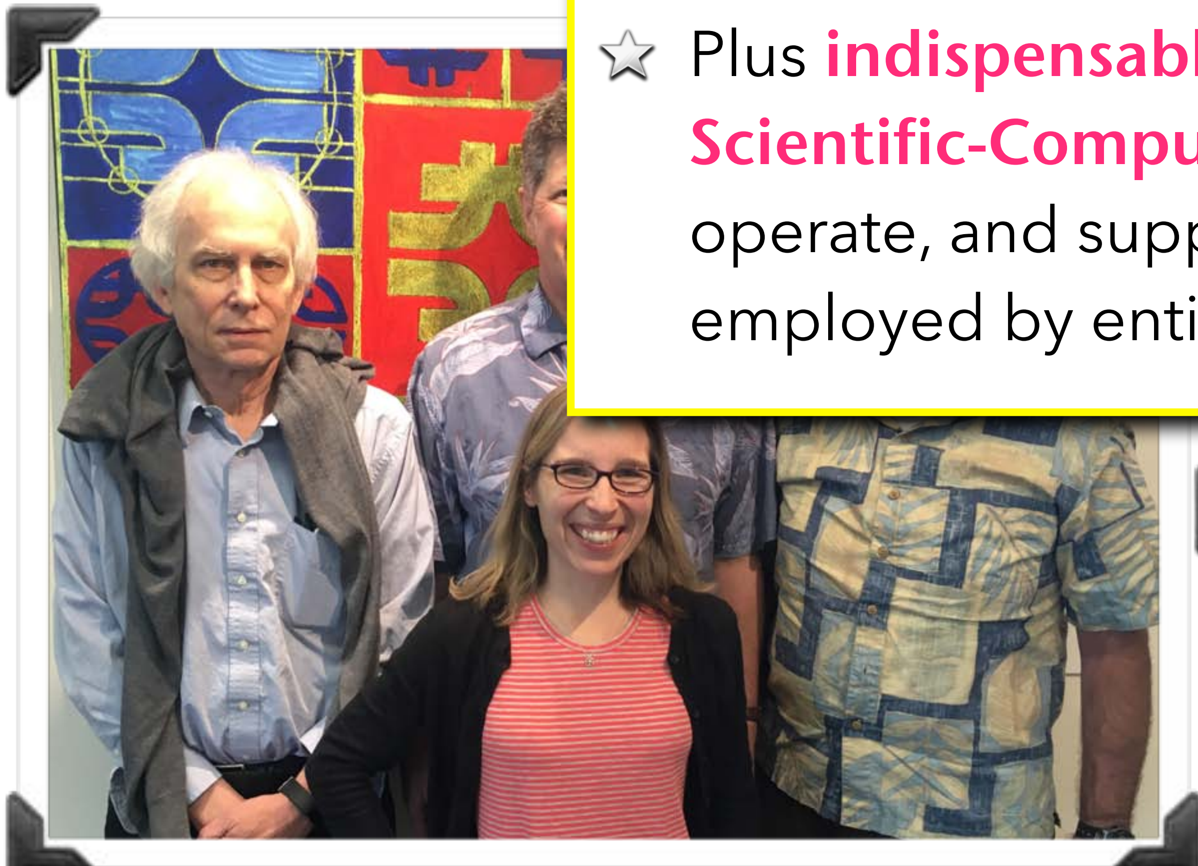
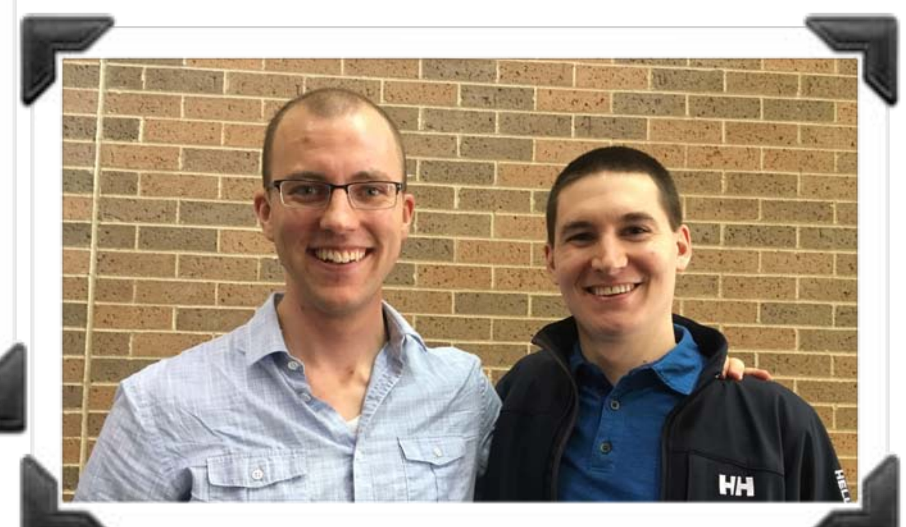
Scientists



> ☆ Plus **indispensable support from members of Scientific-Computing Division**, who deploy, operate, and support clusters @ Fermilab employed by entire U.S. LQCD community

Research Associates



Graduate students

Fermilab Distinguished Scholar

Lattice-QCD research program

- Experimental high-energy physics community searching for evidence of new particles & forces over wide range of energies and areas within particle physics
  - Revealing new physics requires reliable & precise theory!
- Fermilab lattice effort **targeting key hadronic parameters needed to interpret current & future experiments**
  - Program aligned with Fermilab and HEP-community (P5) priorities

quark flavor

- decay constants
- form factors
- mixing matrix elements

LHCb BESIII Belle II

neutrinos

- nucleon axial-vector form factor

NOvA DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Higgs physics

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

ilc FCC TLEP

muon g-2

- hadronic vacuum polarization contribution

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

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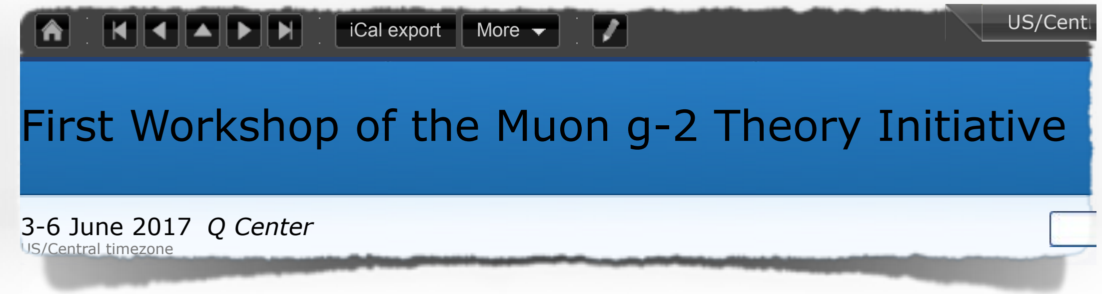
Aim to **reduce QCD uncertainties to at-or-below measurement errors** to maximize discovery potential of high-precision experiments!

muon g-2

- hadronic vacuum polarization contribution

μ $g-2$

Lattice-community leadership



- **Leaders in setting agenda of U.S. lattice-QCD program in high-energy physics**
  - Authors of USQCD-Collaboration white paper "Lattice QCD at the intensity frontier"; coordinator for Belle II Theory Interface Platform; co-convener of Lattice Field Theory Snowmass working group; co-leader of Project X Physics Study; …
- Leaders in USQCD national lattice gauge theory computing project
  - Mackenzie chair of USQCD Executive Committee
  - Fermilab hosts large share of USQCD's computing hardware
  - Simone head of High-Performance Parallel Facilities Computing Department responsible for construction & maintenance of lattice computing facility
- **Engaged with experimental community**
  - Organize and host workshops such as *"Lattice QCD meets Experiment"* series …
  - Speak at experimental collaboration meetings

Precision lattice QCD

"[An] area of striking progress has been lattice gauge theory. ... It is now possible to compute the spectrum of hadrons with high accuracy, and lattice computations have been crucial in the measurement of the properties of heavy quarks. *Continuing improvements in calculational methods are anticipated in coming years."*

– **Snowmass 2013 Executive Summary (1401.6075)**

Quantum ChromoDynamics

$$\mathcal{L}_{\rm QCD} = \frac{1}{2g^2}\mathrm{tr}\left[F_{\mu\nu}F^{\mu\nu}\right] - \sum_{f=1}^{n_f}\bar{\psi}_f\left(\not{D} + m_f\right)\psi_f + \underbrace{\frac{i\bar{\theta}}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left[F_{\mu\nu}F_{\rho\sigma}\right]}_{\text{violates } CP}$$

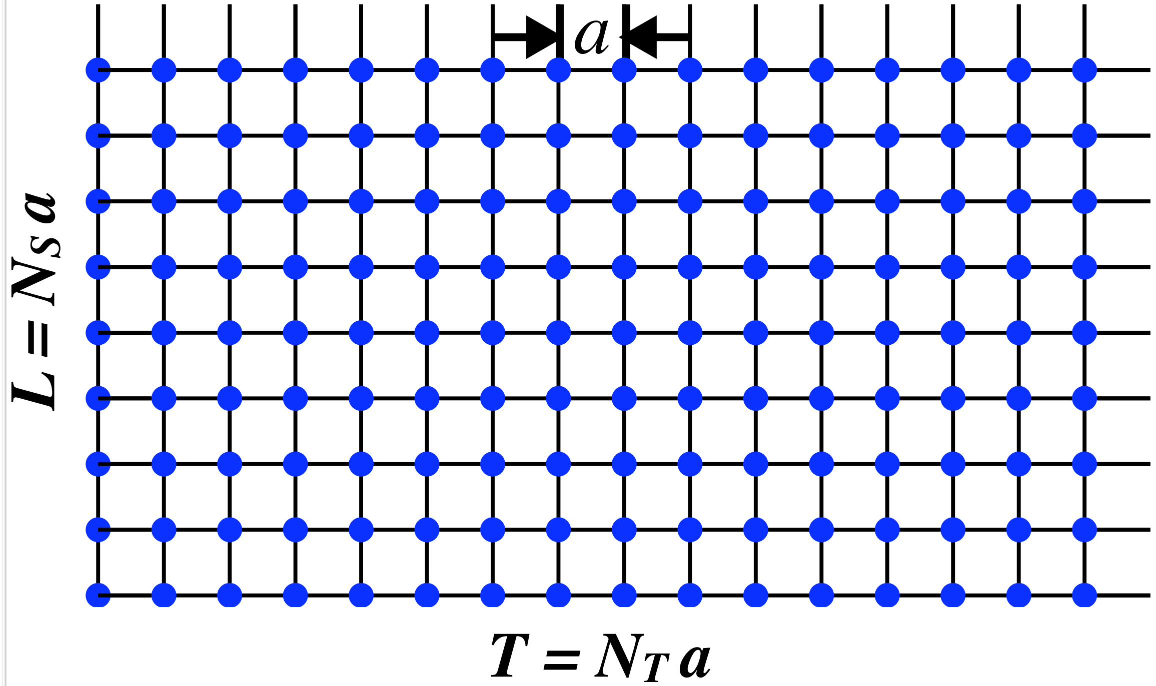
- QCD Lagrangian contains 1 + n_f + 1 parameters that can be fixed from equal number of experimental inputs

Fundamental parameter	**Experimental input**
❖ Gauge coupling g^2	r_1, m_Ω, Υ(2S-1S), or f_π
❖ n_f quark masses m_f	m_π, m_K, $m_{J/\psi}$, m_Υ, ...
❖ $\theta = 0$	neutron EDM ($|\theta| < 10^{-11}$)

- Once the parameters are fixed, everything else is a prediction of the theory
- Calculations of hadronic parameters challenging in practice because low-energy QCD is nonperturbative

Numerical lattice QCD

- Systematic method for calculating hadronic parameters from QCD first principles
- Define QCD on (Euclidean) spacetime lattice and solve path integral numerically
  - Recover QCD when lattice spacing $a \to 0$ and box size $L \to \infty$

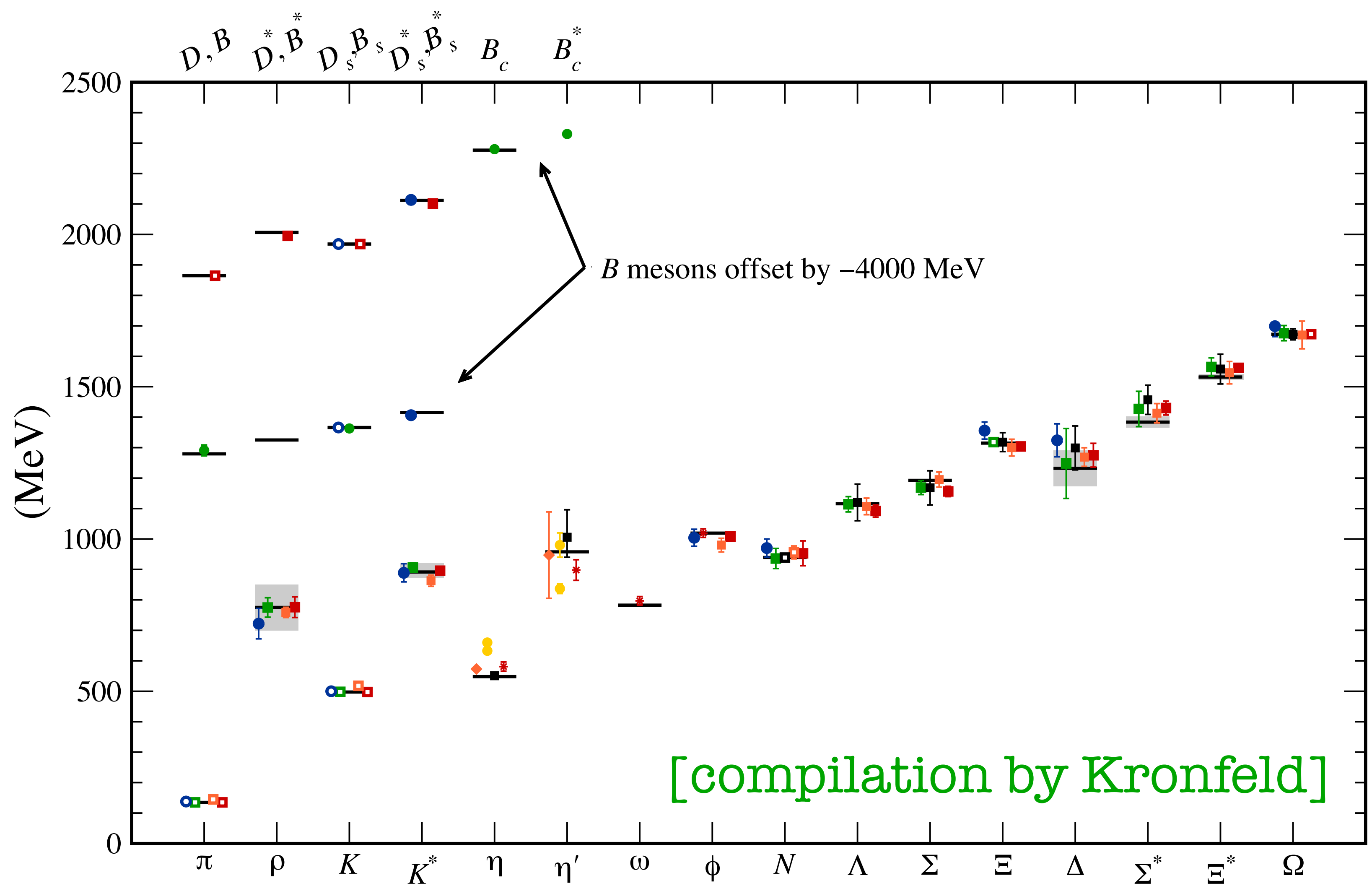


- Simulate using **Monte-Carlo methods and importance sampling**
  - Sample from all possible field configurations using a distribution given by $\exp(-S_{QCD})$
- Run codes upon **supercomputers** and dedicated clusters

- Control systematic errors using QCD gauge-field ensembles with different parameters (*quark masses, lattice spacings, spatial volumes, …*)
- **Lattice-QCD agrees with experiment for wide variety of hadron properties** including hadron masses & proton-neutron mass difference
- **Independent calculations using different methods provide corroboration** for matrix elements inaccessible by experiment

☆ Demonstrate that calculations are reliable with controlled errors!

Hadron spectrum from lattice QCD



Recent Fermilab lattice-QCD 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.*"

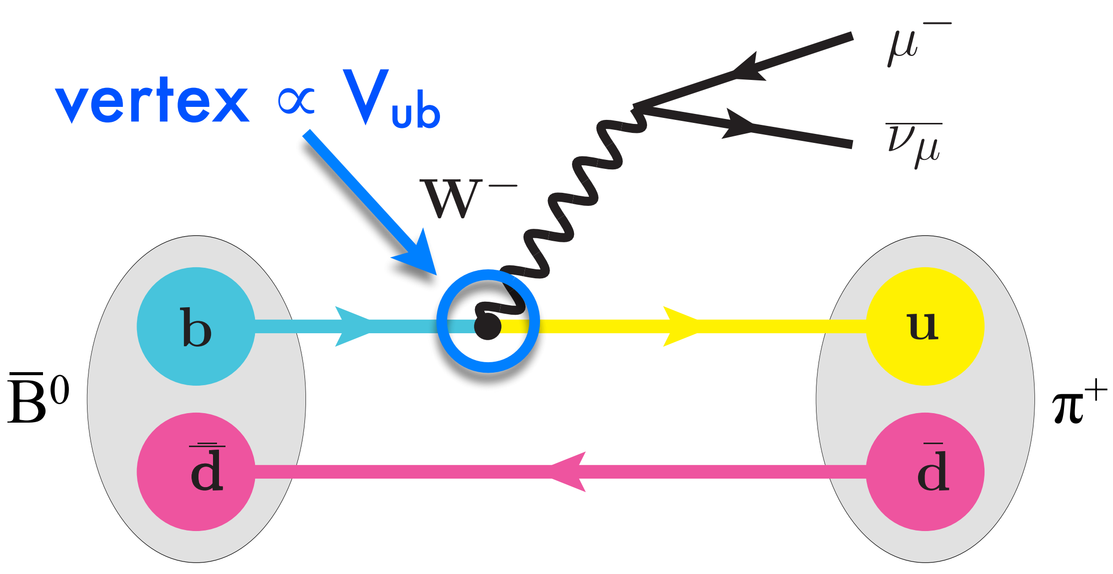
– **Snowmass 2013 Quark-flavor WG report (1311.1076)**

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:

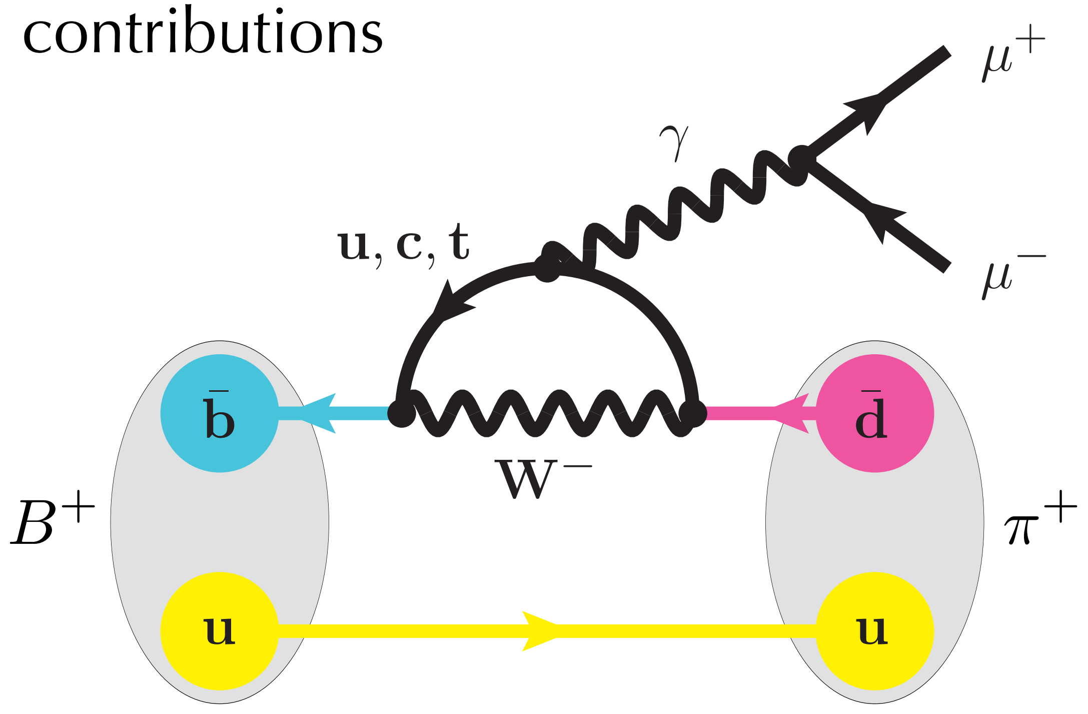
(1) Determination of CKM quark-mixing matrix elements

- 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 quark-flavor *highlights*

Cabibbo-Kobayashi-Maskawa quark-mixing matrix

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

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

Since 2015:

(1) New calculation of **$B \to \pi l \nu$ form factors** [Fermilab/MILC [PRDD92 (2015) 1, 014024] reduced error on $|V_{ub}|$ by factor of two

(2) First three-flavor **$B \to D l \nu$ form factors over full kinematic range** [Fermilab/ MILC, PRD92, 034506 (2015)] reduced error on $|V_{cb}|$ using all experimental bins

(3) First complete 3-flavor calculation of **neutral $B_{d,s}$-mixing matrix elements** [Fermilab/MILC, PRD93, 113016]

(4) First lattice-QCD result for **$B \to \pi$ tensor form factor** and prediction for $B \to \pi\mu^+\mu^-$ [Fermilab/MILC PRL115, 152002 (2015)]

Recent quark-flavor *highlights*

Cabibbo-Kobayashi-Maskawa quark-mixing matrix

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

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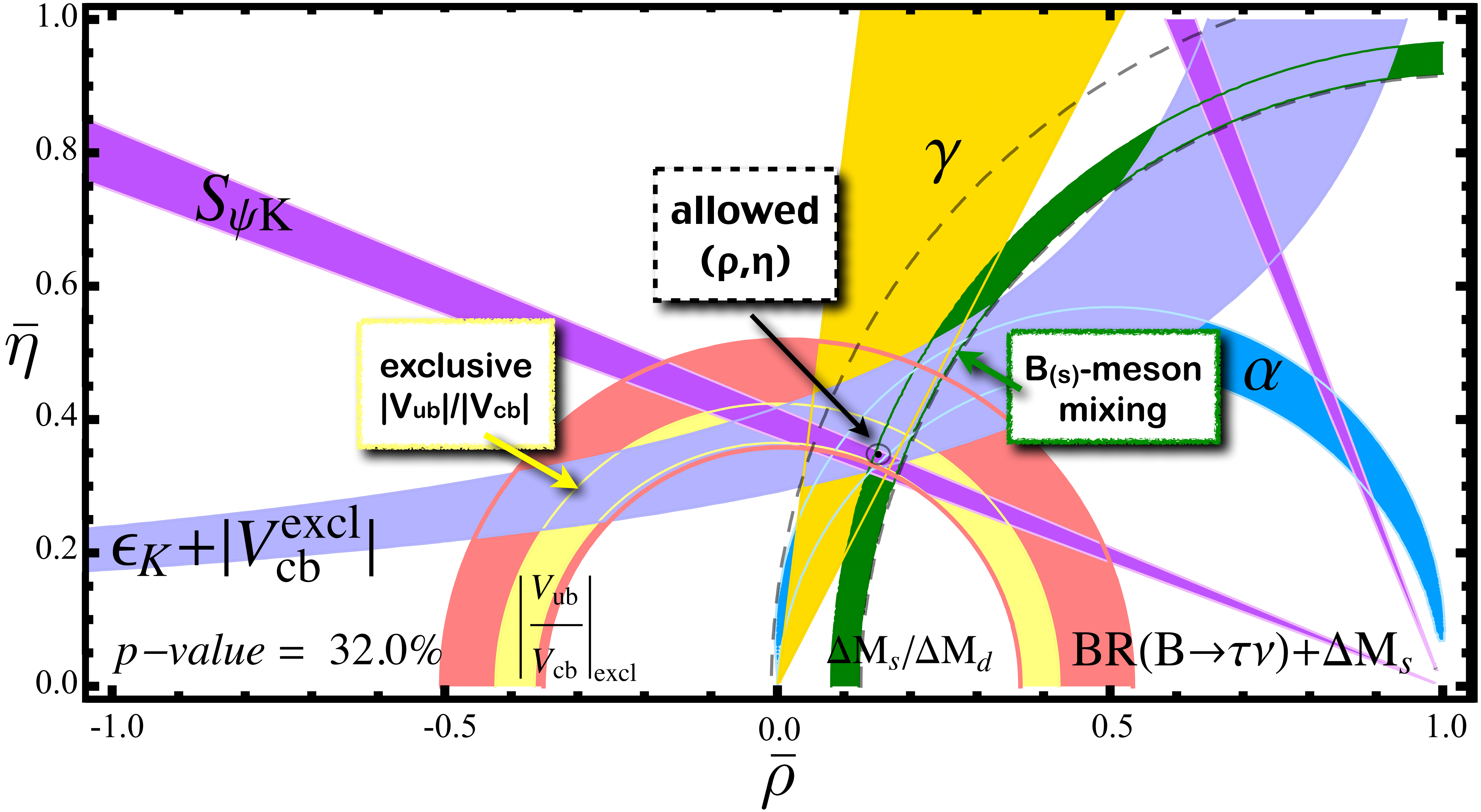
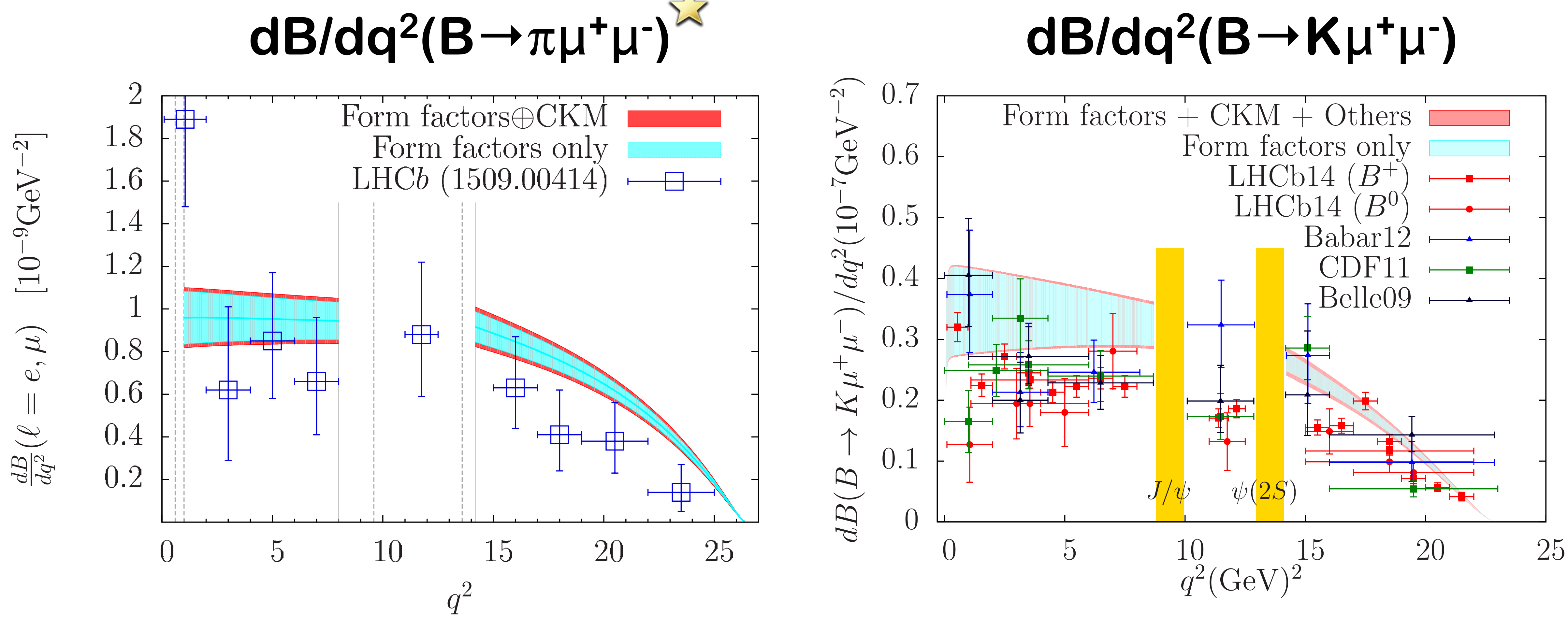
Impact on CKM unitarity-triangle fit

[Fermilab/MILC, PRD93, 113016]

[plot from E. Lunghi]



Comparison with B→π(K)μ⁺μ⁻ decay rates

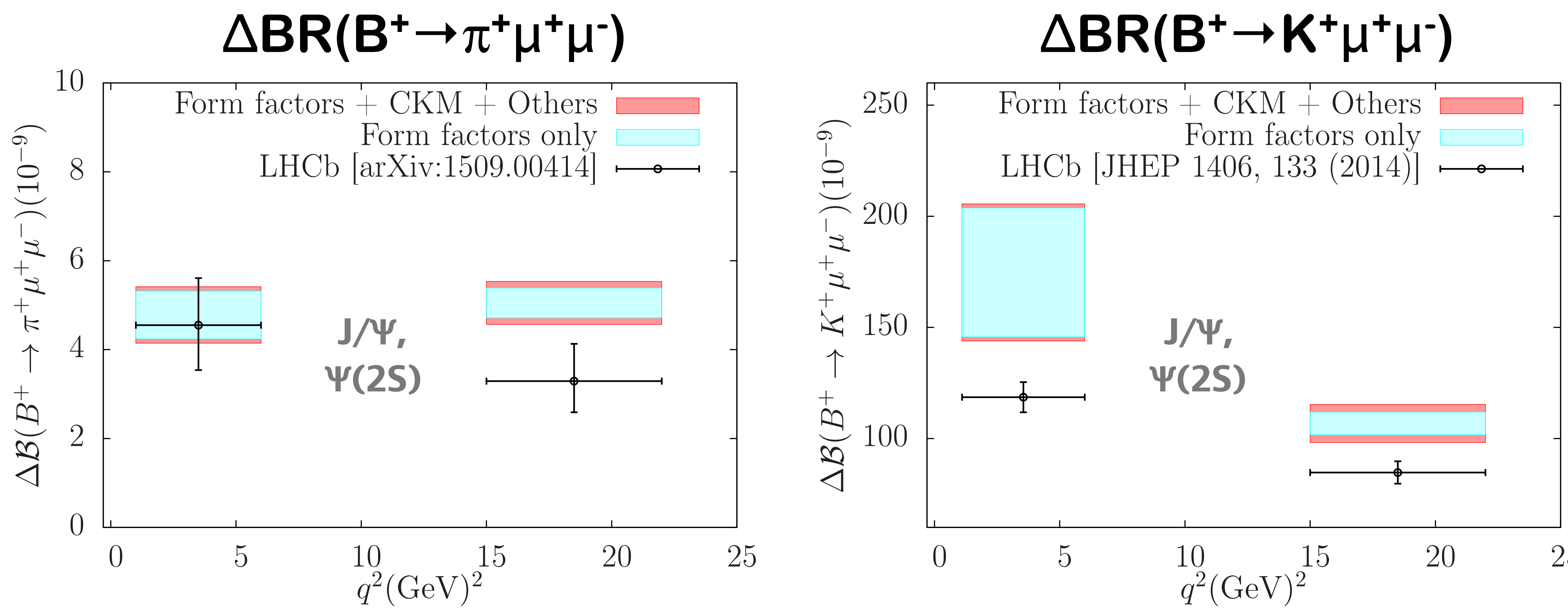


[Fermilab/MILC PRL115, 152002 (2015); PRD93 (2016) no.2, 025026]

- Theoretical & experimental q^2 shapes for B→π(K)μ⁺μ⁻ differential branching fractions consistent, but measurements lie slightly below Standard-Model expectations

Lattice-QCD prediction for dB(B→πμ⁺μ⁻)/dq² appeared before LHCb measurement!

Comparison with $B \to \pi(K)\mu^+\mu^-$ decay rates

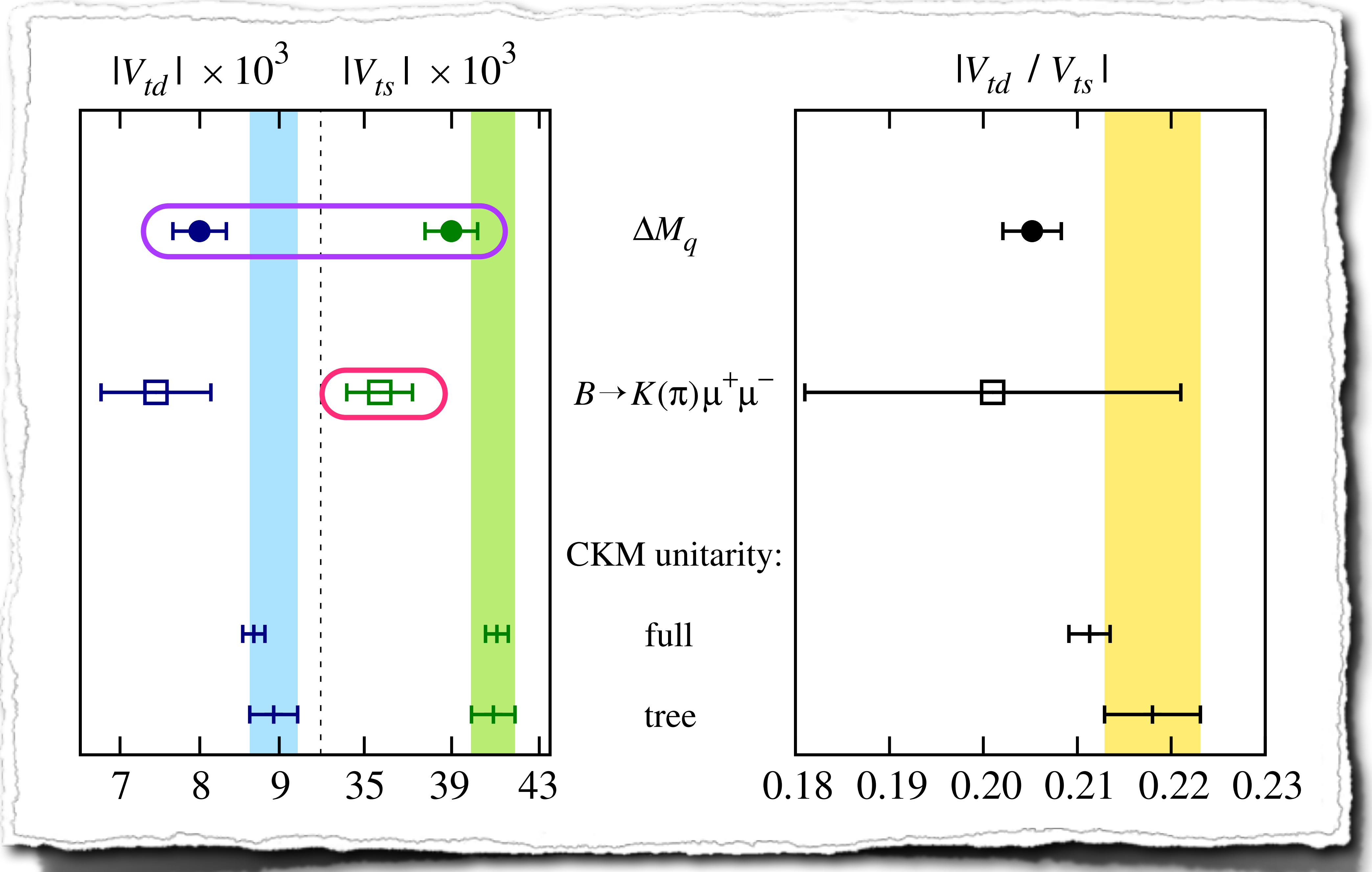


[El Khadra, Kronfeld, Van de Water et al. Phys.Rev. D93 (2016) no.3, 034005]

Measurements in four wide q^2 bins in **1.7σ combined tension** with Standard Model

Implications for $|V_{td}|$ & $|V_{ts}|$

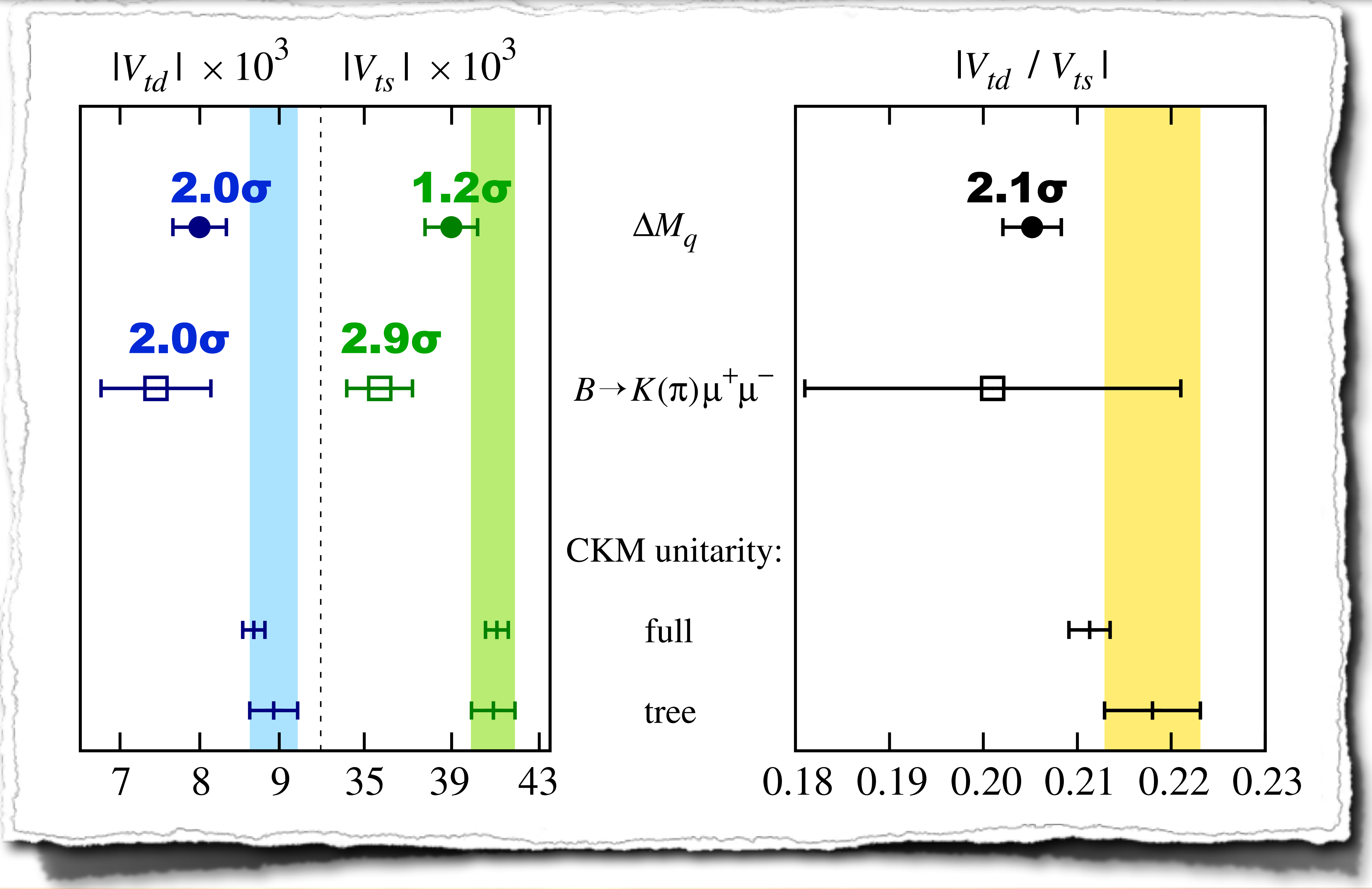
- $|V_{tq}|$ **from $B_{d,s}$-mixing ~2-3× more precise**, but still limited by hadronic matrix elements
- $|V_{ts}|$ **from B→Kμμ >2× more precise**, with commensurate theory & experimental errors



[plot C.Bouchard]

Implications for $|V_{td}|$ & $|V_{ts}|$

Determinations from flavor-changing-neutral current processes differ by ~2σ from values implied by tree-level processes + CKM unitarity



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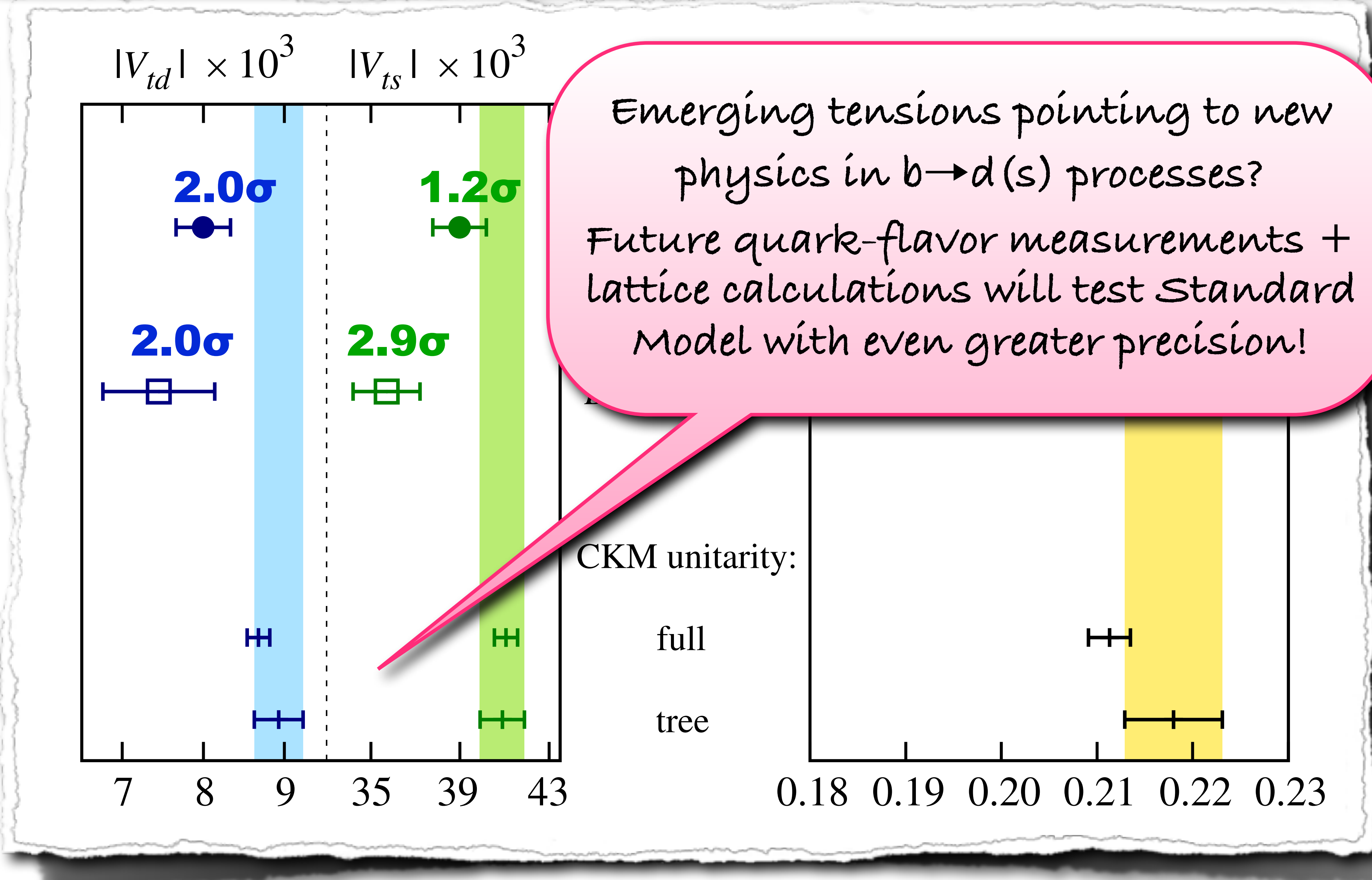


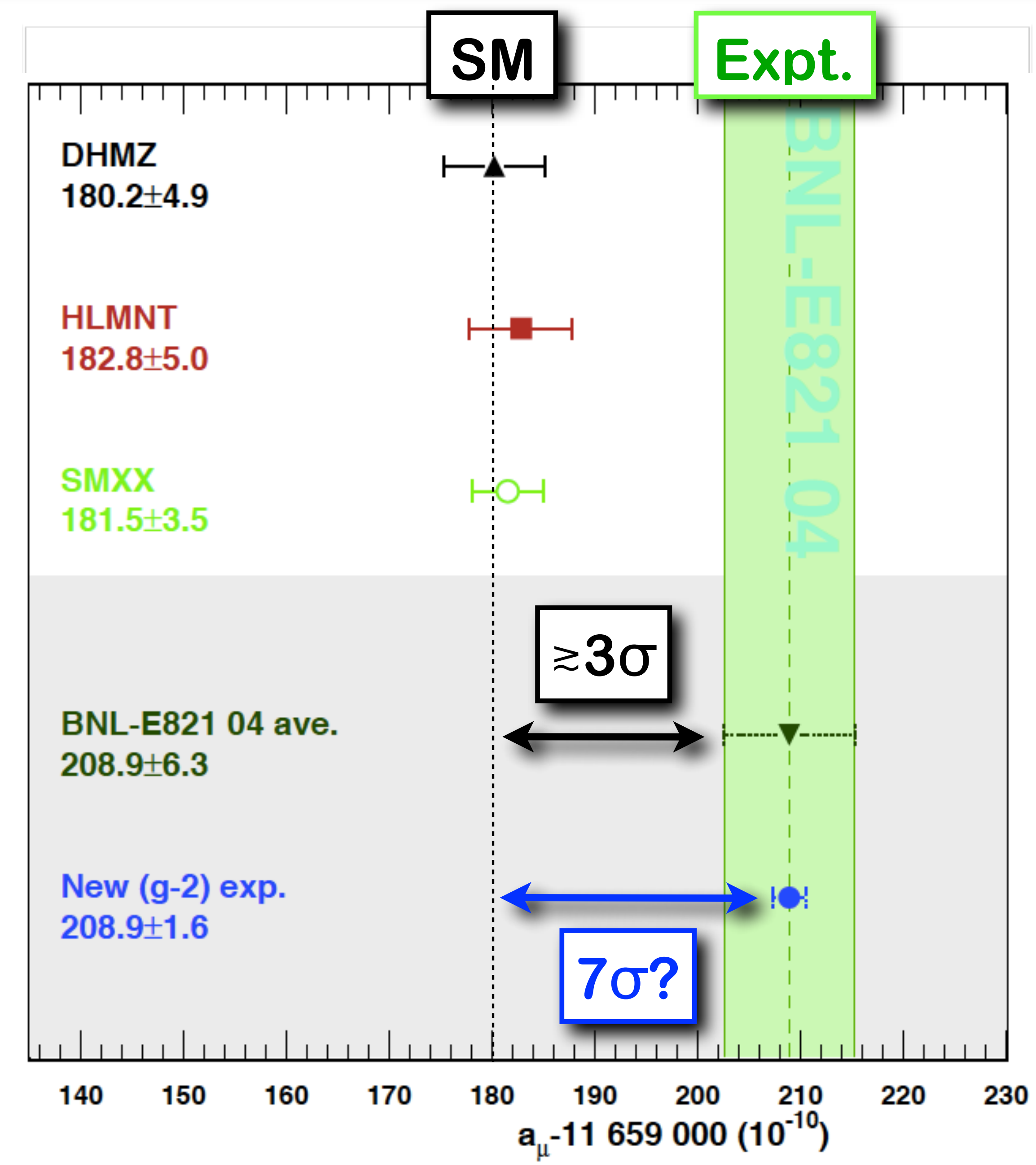
Emerging tensions pointing to new physics in b→d(s) processes?

Future quark-flavor measurements + lattice calculations will test Standard Model with even greater precision!

[*plot* C.Bouchard]

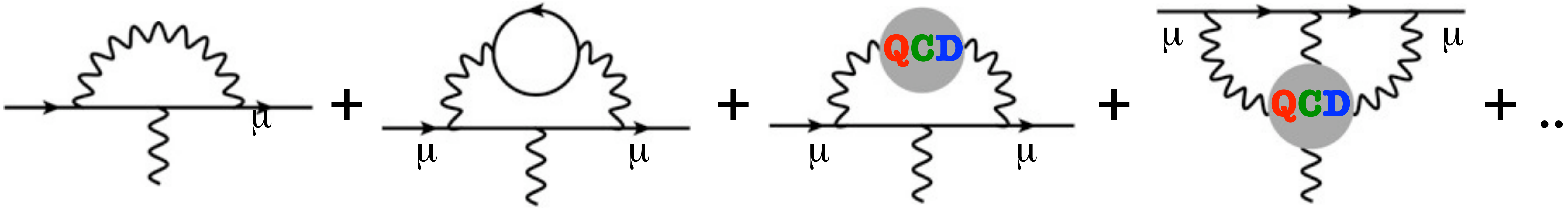
Muon anomalous magnetic moment (g-2)

- Muon anomalous magnetic moment provides sensitive probe of physics beyond the Standard Model:
  - Mediated by quantum-mechanical loops
  - Known to extremely high precision (0.54ppm)
- BNL measurement disagrees with Standard-Model theory expectations by >3σ
- Fermilab Muon g-2 Experiment aims to reduce BNL measurement error by four
  - Started running this week, and expects first results in Spring 2018!
  - ➡ **Must reduce theory error to commensurate level to identify definitively whether any deviation observed between theory and experiment is due to new physics**



[Blum et al.,arXiv:1311.2198]

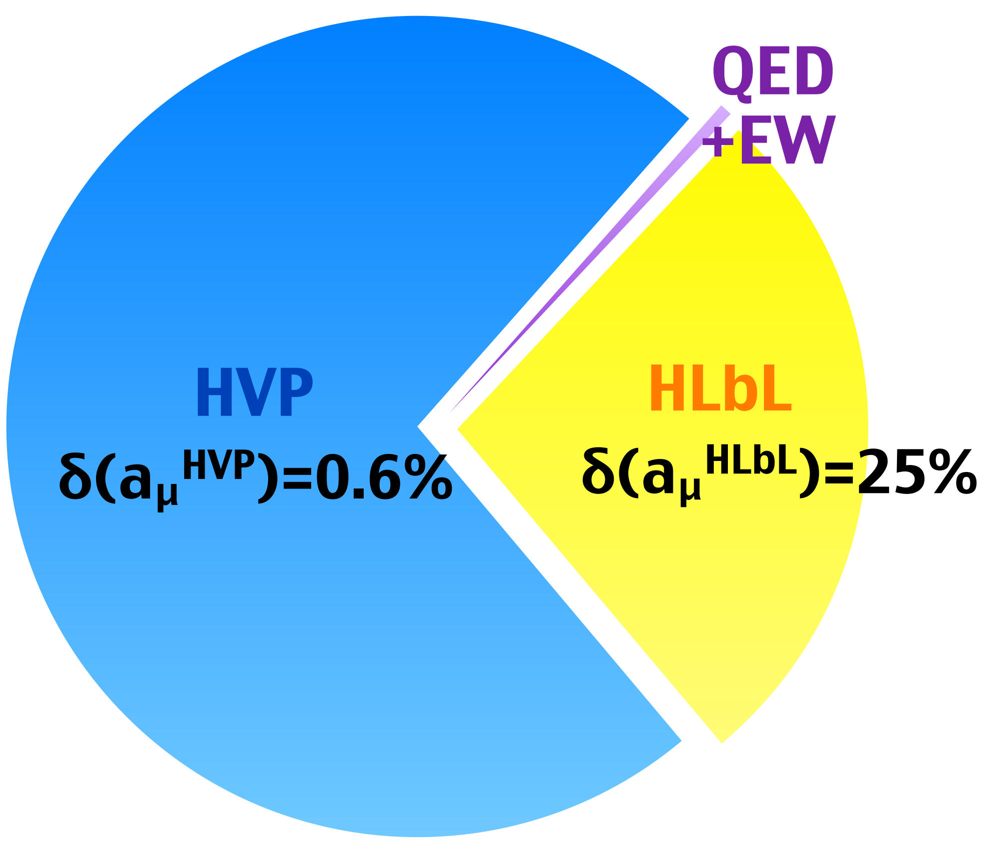
Muon g-2 in the Standard Model



QED (5 loops!) & EW (2 loops)

Hadronic vacuum polarization (HVP)

Hadronic "light-by-light" (HLbL)



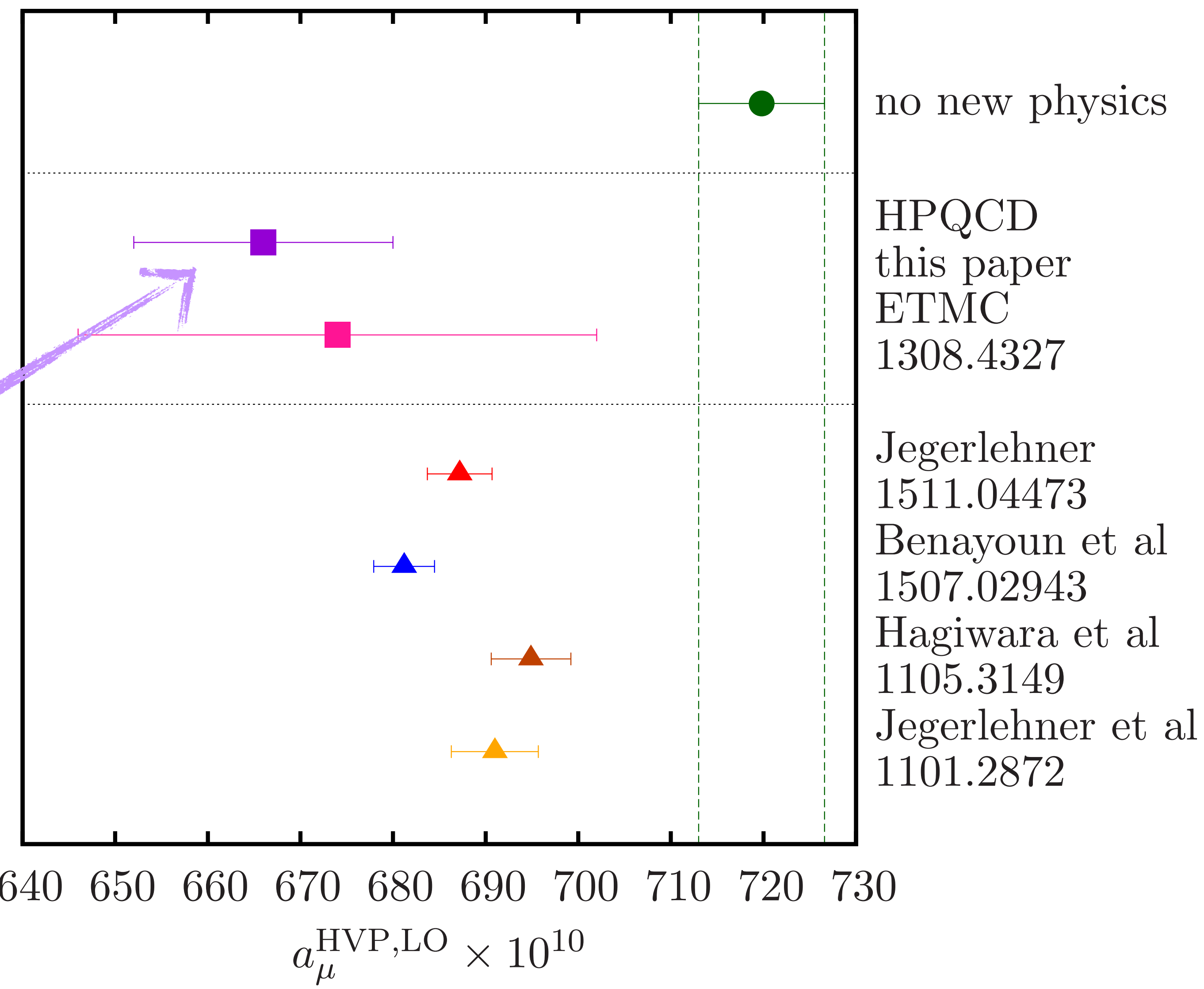
- Dominant uncertainty in Standard-Model theory value from hadronic contributions, which are calculable with lattice QCD
- To match anticipated experimental precision, **must reduce hadronic uncertainties to $\delta(a_\mu^{HVP})\lesssim 0.2\%$ & $\delta(a_\mu^{HLbL})\lesssim 10\%$**

> Fermilab Lattice Collaboration calculating the hadronic vacuum-polarization contribution, which is the largest source of theory error

2016 result for HVP contribution (a_μ^{HVP})

- Employ new method introduced by HPQCD Collaboration that sidesteps $q^2 \to 0$ extrapolation by calculating vacuum polarization function $\Pi(q^2)$ from derivatives at $q^2=0$ obtained from simple time-moments of current-current correlation functions [PRD89, 114501 (2014)]
- **First complete lattice-QCD calculation of a_μ^{HVP} to reach precision needed to observe significant deviation from experiment**
- Dominant uncertainties from the omission of electromagnetic and isospin-breaking effects, and from quark-disconnected contributions

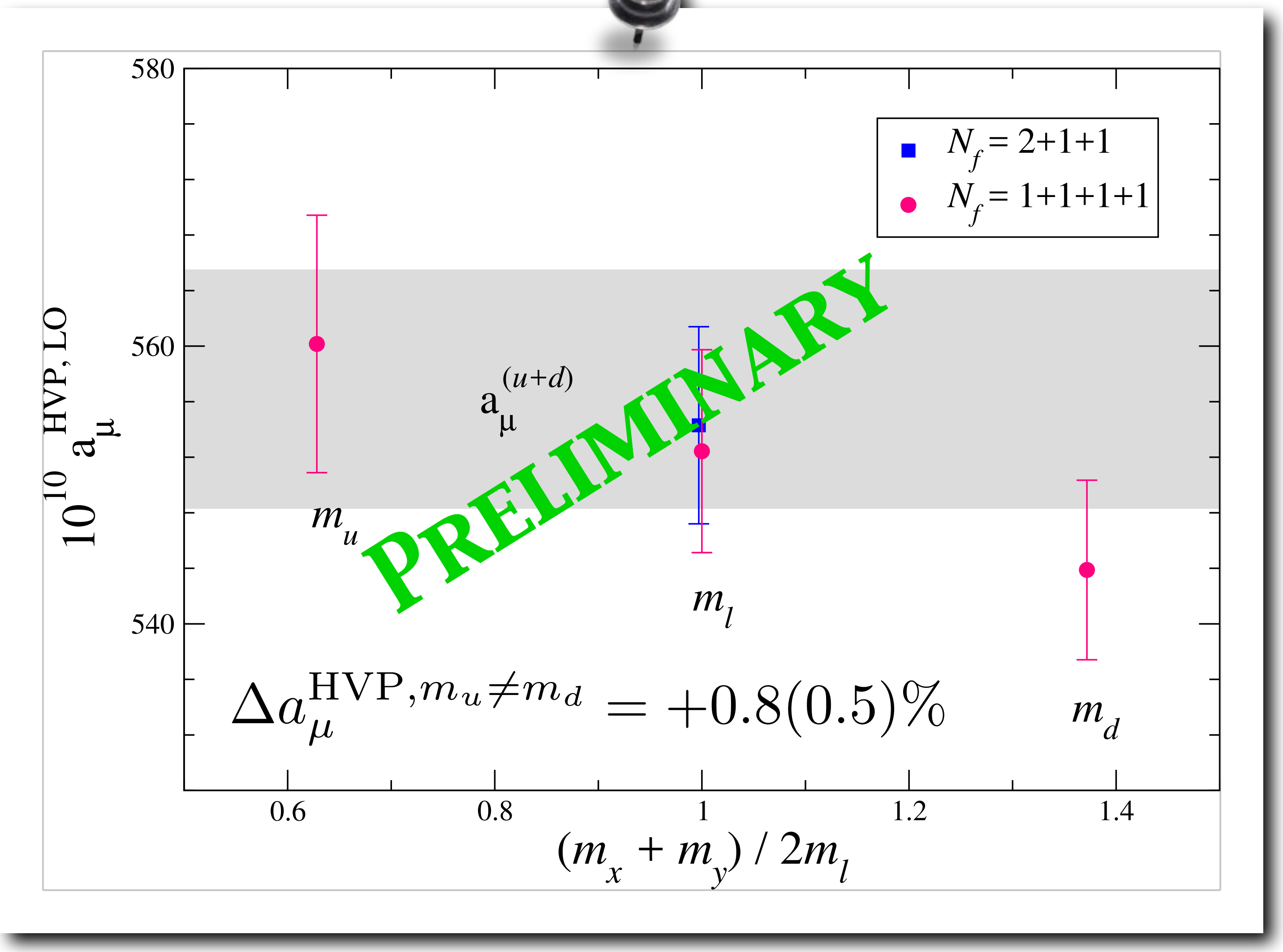
[HPQCD + RV, arXiv:1601.03071]



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

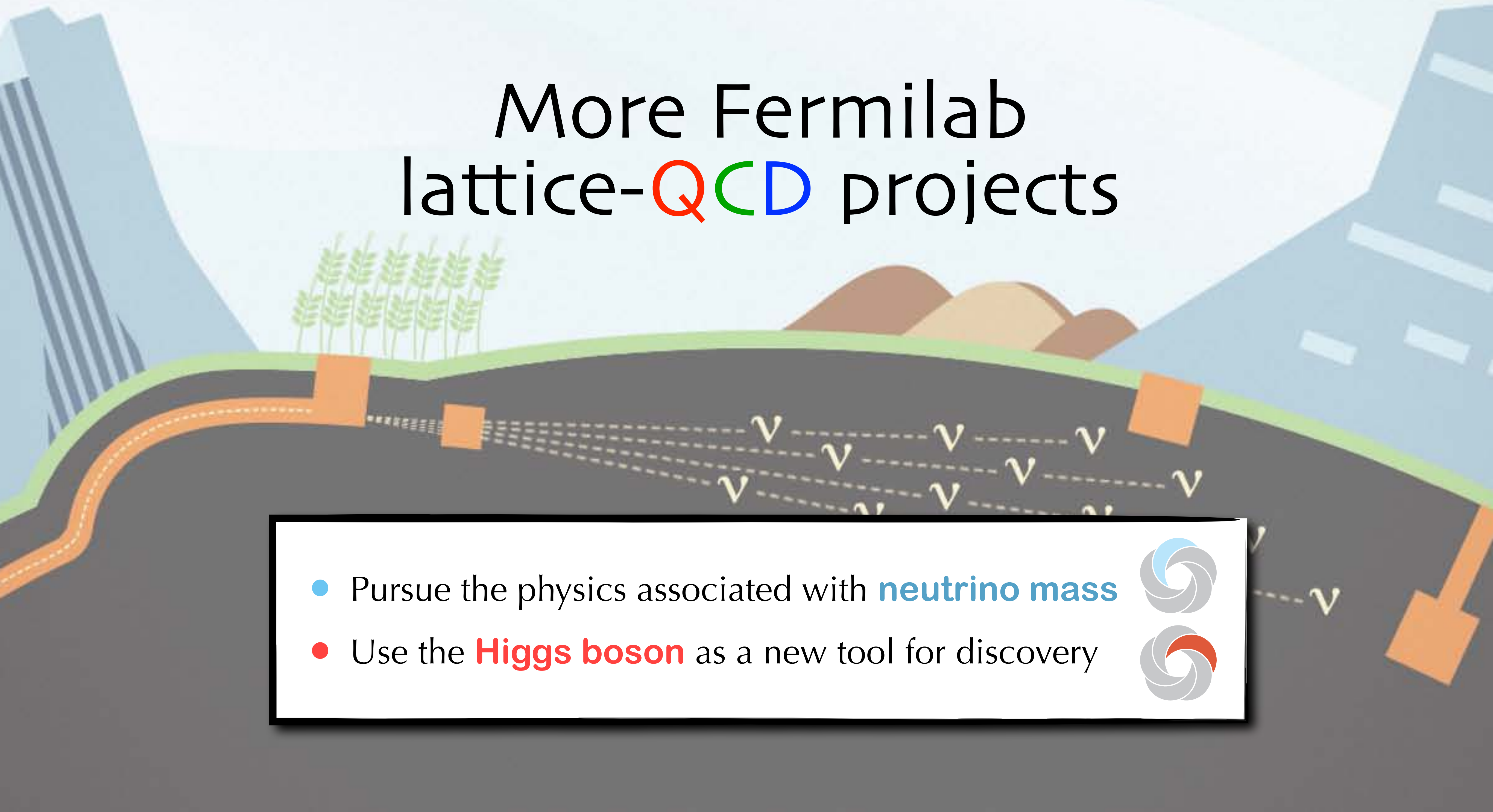
Work in progress

- Fermilab Lattice, HPQCD, & MILC Collaborations joining efforts on follow-up calculation targeting leading sources of error in earlier result
  - Analysis of recently generated data in progress, and RV will present first preliminary result from joint effort at Lattice 2017
  - Aim to reach ~1% uncertainty before first result from Muon g-2 Experiment next Spring



> Given sufficient computing resources to complete planned running, expect to obtain sub-per cent precision in the coming one or two years

More Fermilab lattice-QCD projects



- Pursue the physics associated with **neutrino mass**
- Use the **Higgs boson** as a new tool for discovery

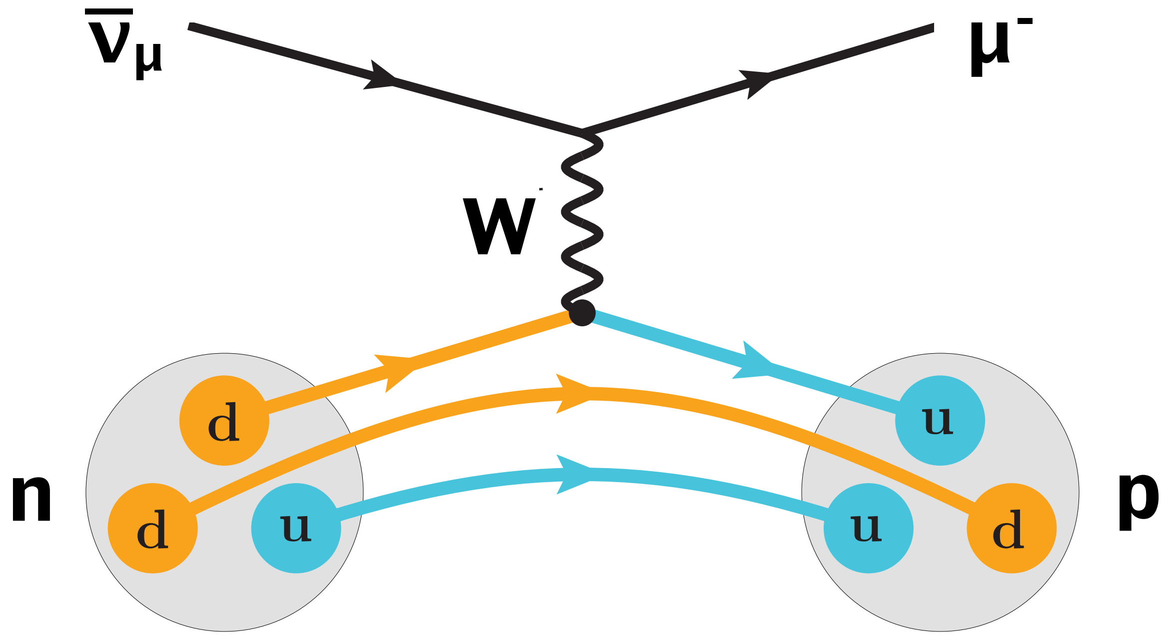
Long-baseline neutrino experiments

- ... **all detect neutrinos via scattering off detector materials** such as carbon (in scintillator), oxygen (in water), or liquid Argon
  - ➡ Reaching DUNE sensitivity goals for mass hierarchy and δ_{CP} requires reduced $\nu(\overline{\nu})$-Ar cross-section uncertainties [LBNF/DUNE Conceptual Design Report, arXiv:1512.06148]

- Underlying processes are ν-proton & ν-neutron scattering, as modified by the presence of nucleon inside atomic nucleus
  - Nucleon-level matrix elements can be calculated with controlled uncertainties in lattice QCD
  - (Nuclear model calculation still needed to relate nucleon form factor to ν-Ar cross-section)
  - Results will enable clean separation of nucleon & nuclear effects and uncertainties

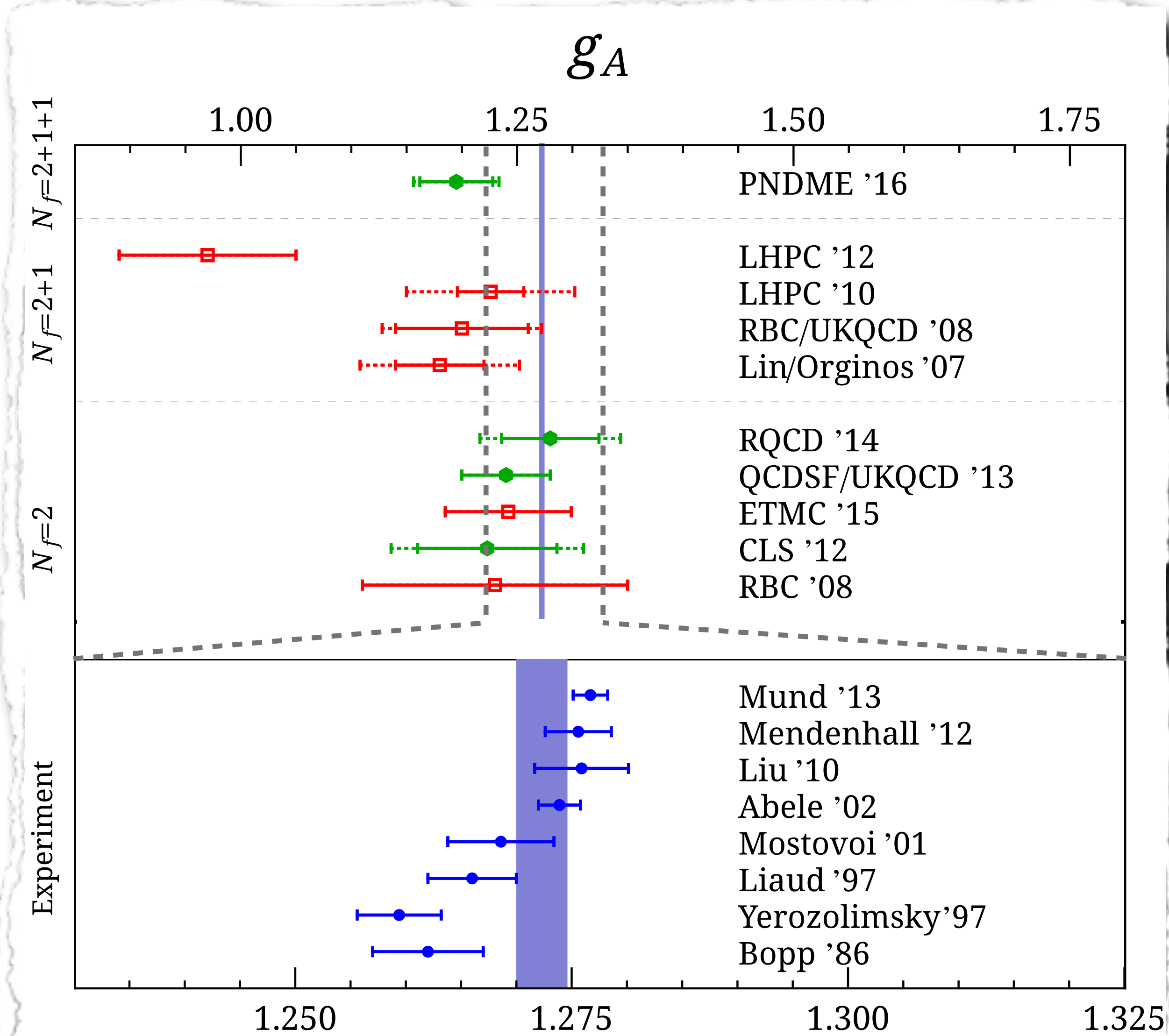
Nucleon axial-vector form factor

- Gives dominant contribution to charged-current quasielastic ν-nucleus scattering



Nucleon axial-vector coupling from lattice QCD

- Nucleon axial charge $g_A = -F_A(q^2{=}0)$ key milestone on path to form factors over full kinematic range
- Present lattice-QCD uncertainties more than 10x larger than experimental errors
- Graduate student Aaron Meyer (Chicago) leading Fermilab lattice effort to compute nucleon axial-vector form factor under Kronfeld & Richard Hill supervision
    - First blind lattice-QCD analysis of g_A
    - Method yields other useful $N \to \Delta$, $N \to N^*$, $N \to N\pi$ transition form factors from same calculation
    - Working with experimentalists, e.g. to implement model-independent form-factor parameterization into GENIE Monte Carlo



[PNDME Collaboration, PRD94 (2016) no.5, 054508]

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> Aiming to strengthen dialog between lattice theorists and neutrino / nuclear theorists and experimentalists

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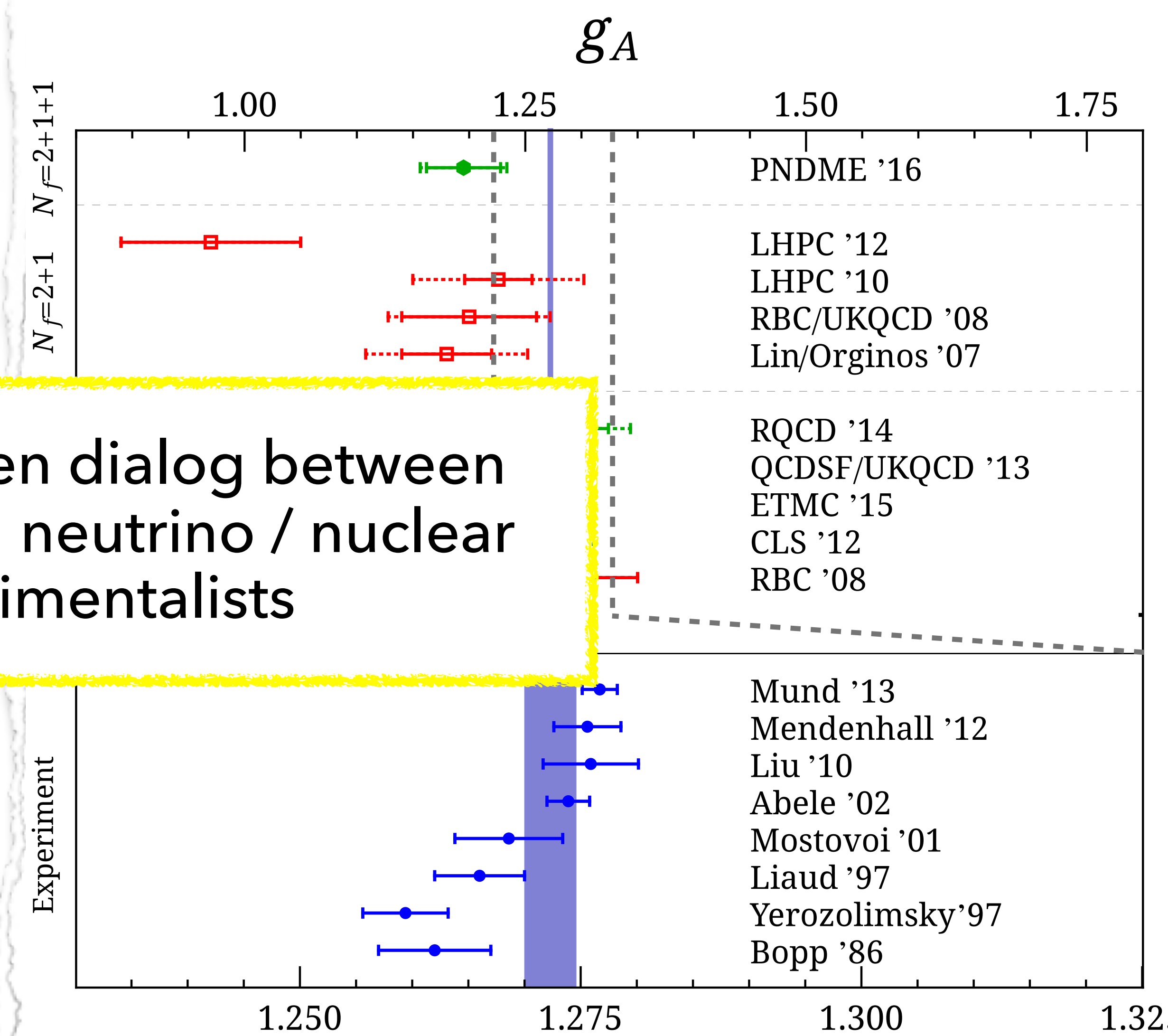
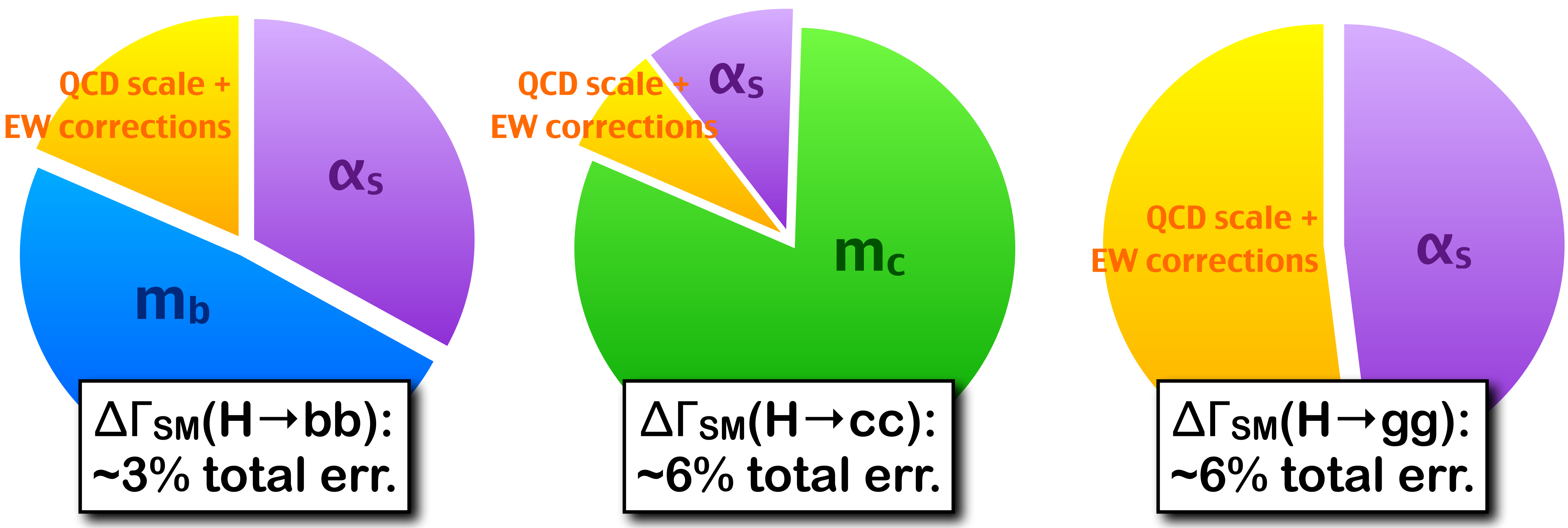


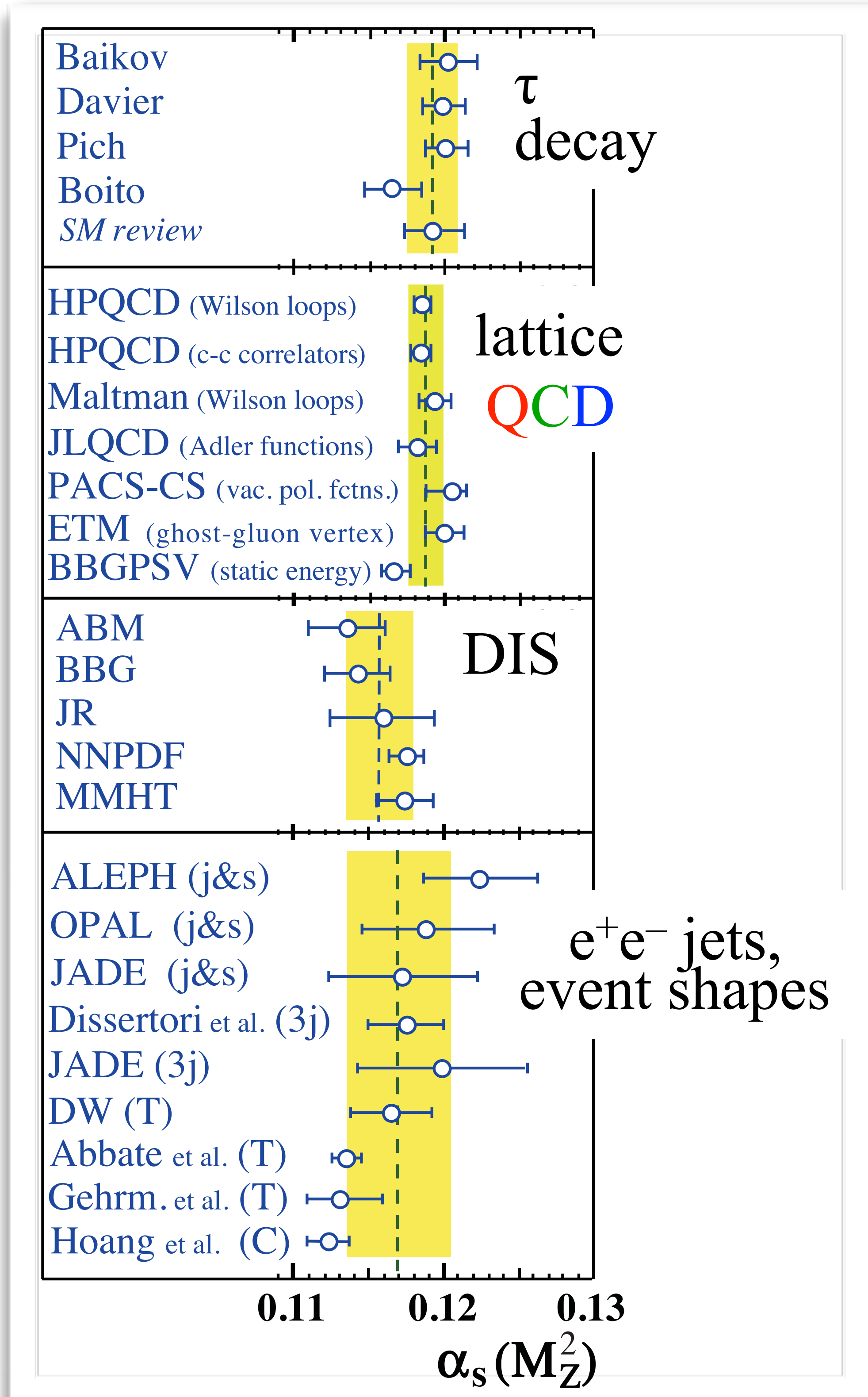
[PNDME Collaboration, PRD94 (2016) no.5, 054508]

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



Quark masses & strong coupling from lattice QCD



- Independent lattice-QCD calculations of strong coupling constant yield consistent results with greater precision than non-lattice methods
- Heavy-quark masses m_b & m_c from lattice QCD agree with non-lattice results, but with larger uncertainties
- Postdoc Aarti Veernala spearheading Fermilab lattice effort to compute these quantities on state-of-the-art four-flavor QCD lattices with finer lattice spacings than ever before
  - **Presenting first preliminary results this month** at Lattice 2017
  - m_b error dominated by discretization effects ➡ *anticipate significant improvement with new data*

Conclusions

"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**

Summary & outlook

- Lattice QCD is important throughout the experimental high-energy-physics program
  - Reliable theoretical predictions are needed on same time scale as measurements with commensurate uncertainties
- **Fermilab lattice-QCD theorists have strong record of calculations of hadronic parameters needed to interpret experimental measurements as Standard-Model tests & new-physics searches**
  - In past three 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 newer calculations to address needs of planned **ν-oscillation experiments, precision Higgs measurements**, …
- Continued support for lattice QCD at Fermilab, and also for U.S. lattice-QCD hardware & software projects, essential to achieve scientific goals and fully capitalize on enormous investments in high-energy (and nuclear) physics experimental programs!

Summary & outlook

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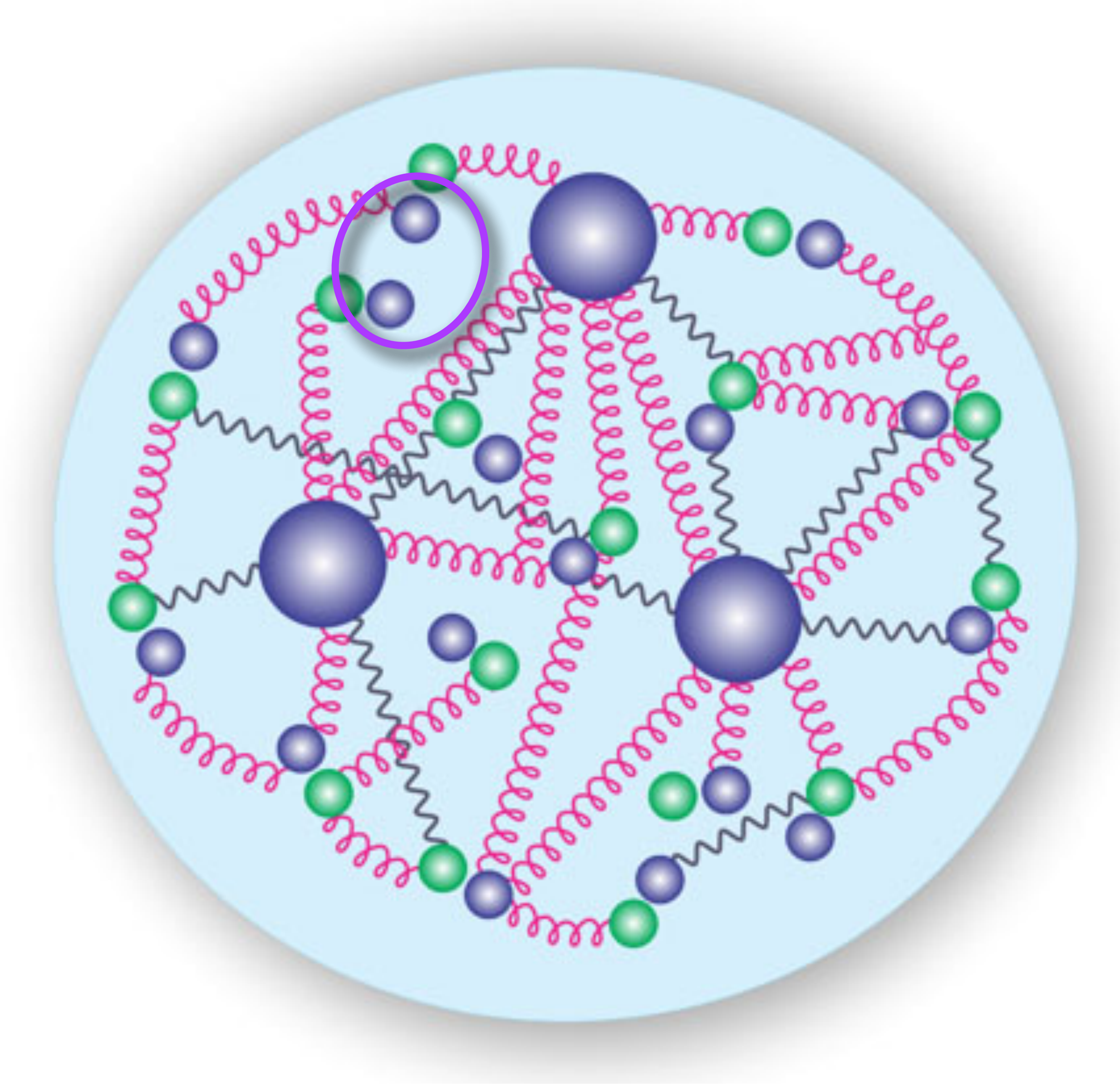
Want to provide needed theoretical support to enable Fermilab's experimental program to be successful. Please come talk to us!

Extras

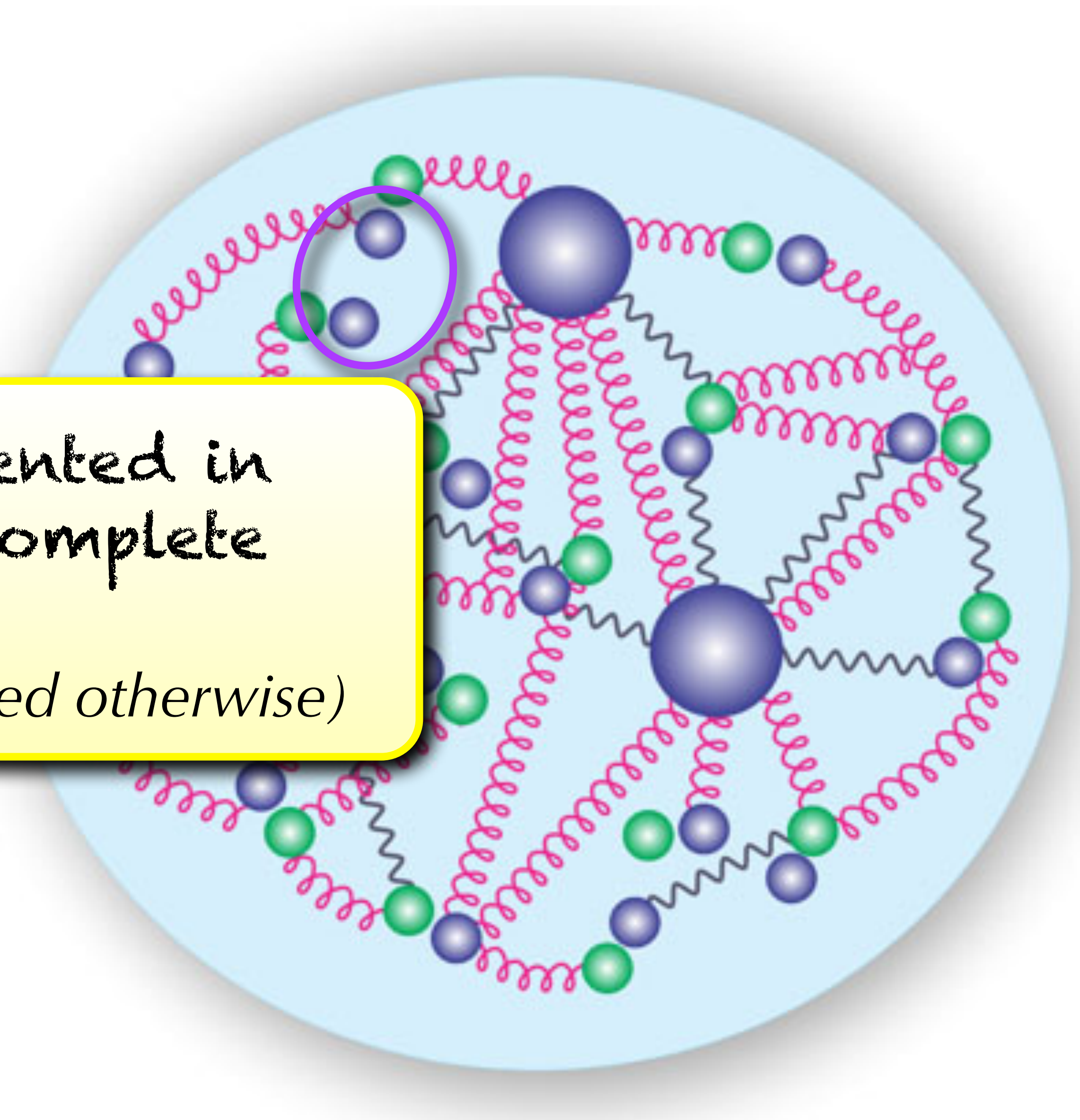
Modern lattice-QCD simulations

- Standard simulations include dynamical u, d, s (& c) quarks in the vacuum
  - (Typically sea $m_u=m_d$)
- Control systematic errors using gauge-field ensembles with different parameters:
  - Multiple lattice spacings to extrapolate to continuum limit ($a \to 0$)
  - Multiple up/down-quark masses to interpolate or extrapolate to physical $M_\pi = 135$ MeV
  - Multiple spatial volumes to estimate finite-size effects
- Most precise results for simple processes with single (stable) initial hadron & at most 1 final-state hadron



Modern lattice-QCD simulations

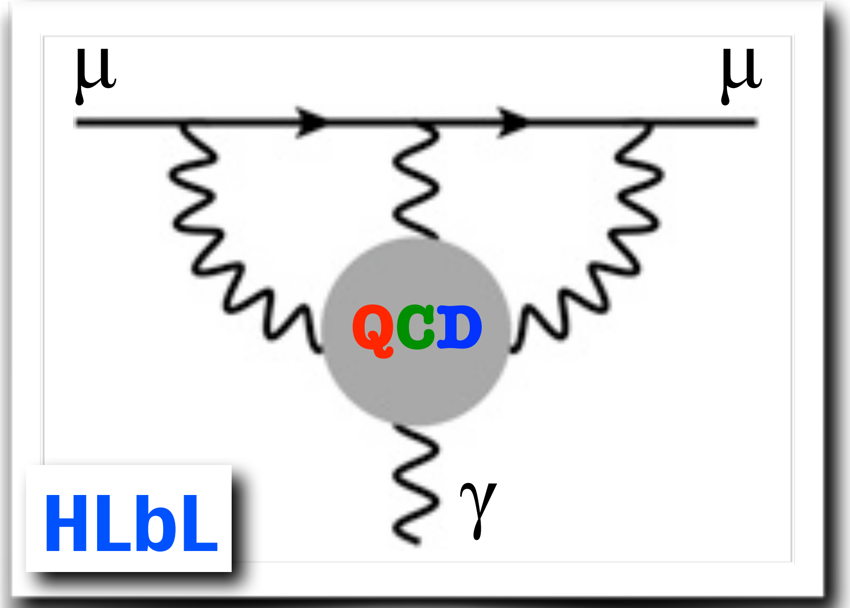
- Standard simulations include dynamical u, d, s (& c) quarks in the vacuum
  - (Typically sea m_u=m_d)
- Control systematic errors using gauge-field ensembles with different parameters:
  - Multiple lattice spa continuum limit (a
  - Multiple up/down- interpolate or extr M_π =135 MeV
  - Multiple spatial volumes to estimate finite-size effects
- Most precise results for simple processes with single (stable) initial hadron & at most 1 final-state hadron



☆ All results presented in this talk have complete error budgets
(unless explicitly stated otherwise)

Lattice-QCD progress on a_μ^{HLbL}

(Not a Fermilab result, but important for reaching target precision for g-2!)



- Lowest-order contribution of $O(\alpha_{EM}^2)$
- Current estimate from QCD models subjective and somewhat controversial

  [Glasgow consensus, Prades, de Rafael, Vainshtein, 0901.0306]

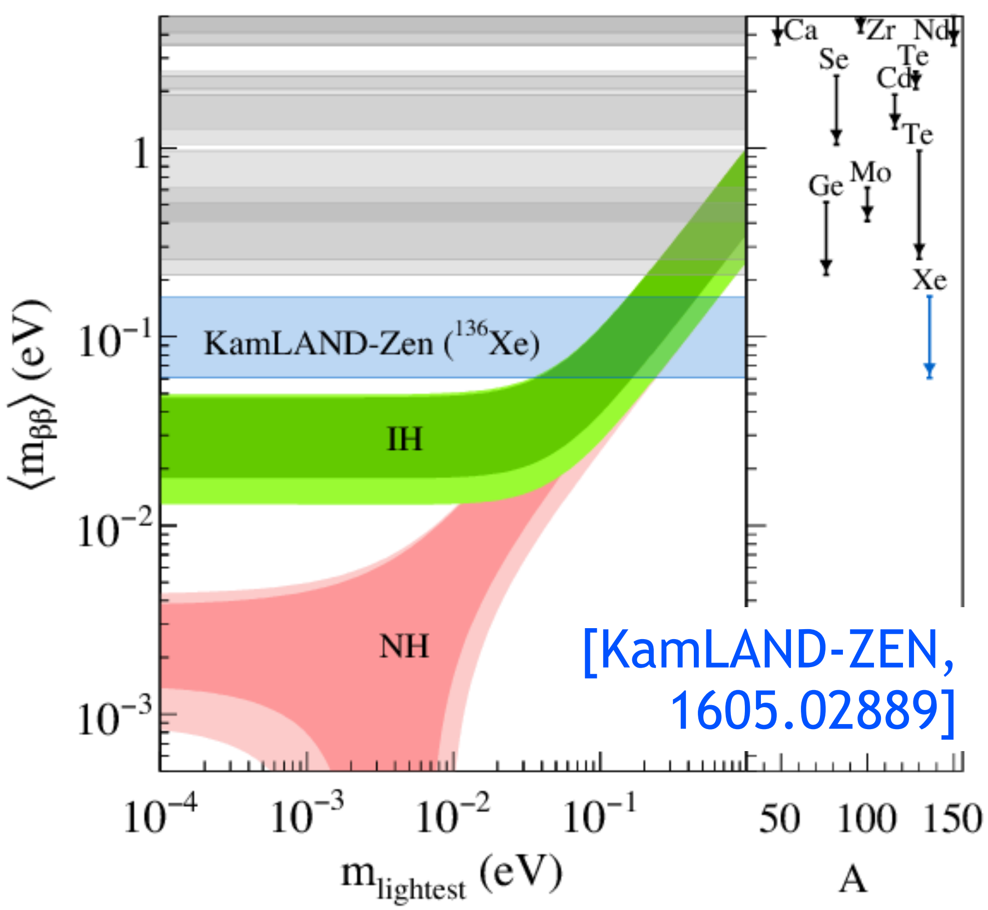
- New method from **RBC Collaboration** combines dynamical QCD gauge-field configurations with exact analytic formulae for photon propagators [Blum et al., PRD93, 014503 (2016), Jin et al., PoS LATTICE2016 (2016) 181]
  - Obtain **≲10% statistical errors at the physical pion mass** in ballpark of Glasgow consensus value $a_\mu^{HLbL,GC} \times 10^{10} = 10.5(2.6)$

$$a_\mu^{\mathrm{HLbL}} \times 10^{10} = \begin{cases} 11.60(0.96)_{\mathrm{stat.}} & \text{connected} \\ -6.25(0.80)_{\mathrm{stat.}} & \text{disconnected} \end{cases}$$

- Full study of systematic errors still needed, but **initial results encouraging!**

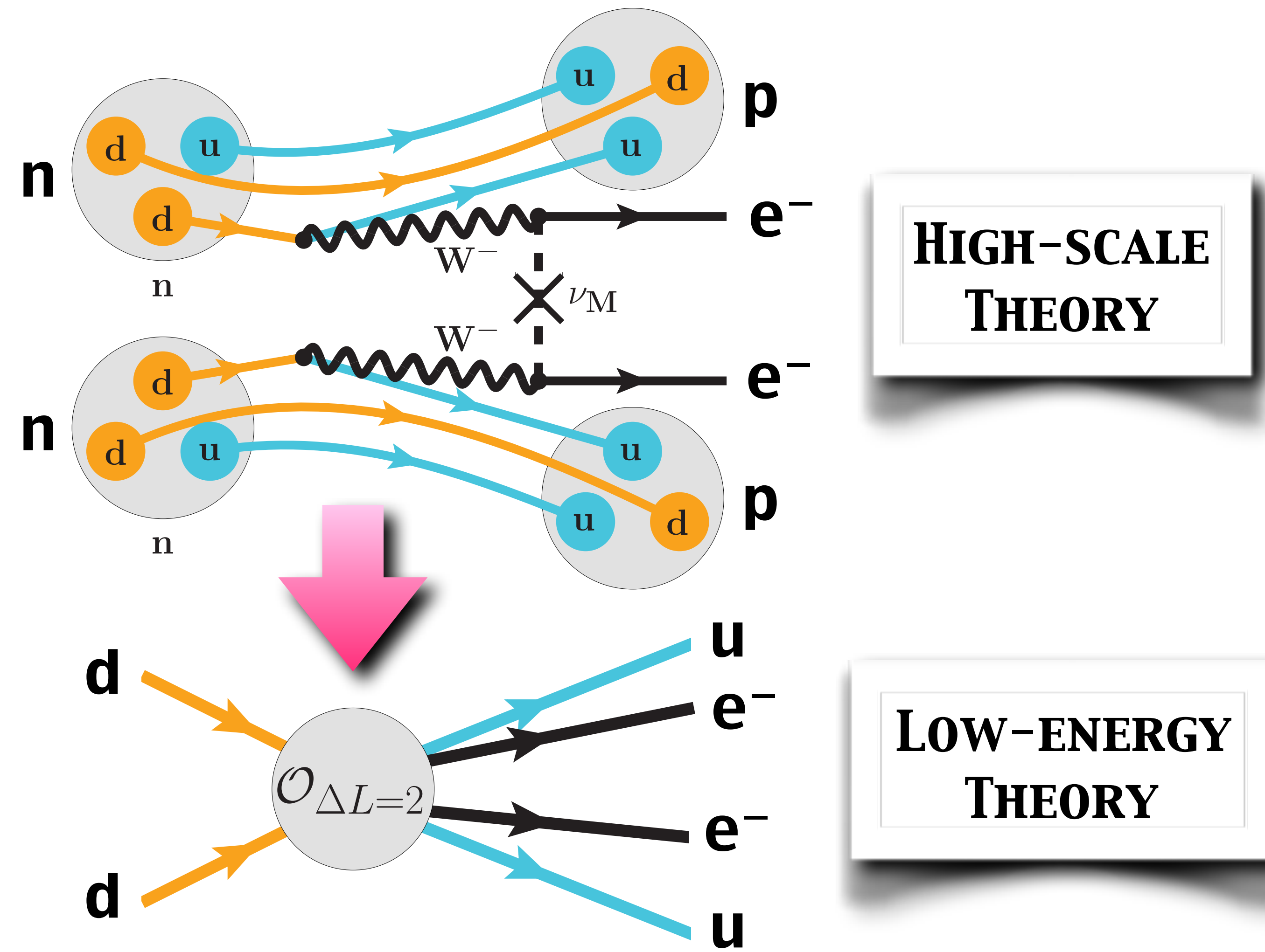
Neutrinoless double β-decay experiments

- Searching for Majorana neutrinos via **nuclear emissions of two electrons without neutrinos**



Bounds on Majorana mass limited by nuclear matrix-element uncertainties

- If Majorana ν's heavy, 0νββ decay rate parameterized by matrix elements of six-fermion effective operators $O_{\Delta L=2}$



- First LQCD calculation of hadronic matrix elements begun this year [Nicholson @ Lattice 2016]