Lattice QCD for precision particle physics, or

"What can lattice QCD do for you?"

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Fermilab

U.S. ATLAS Workshop

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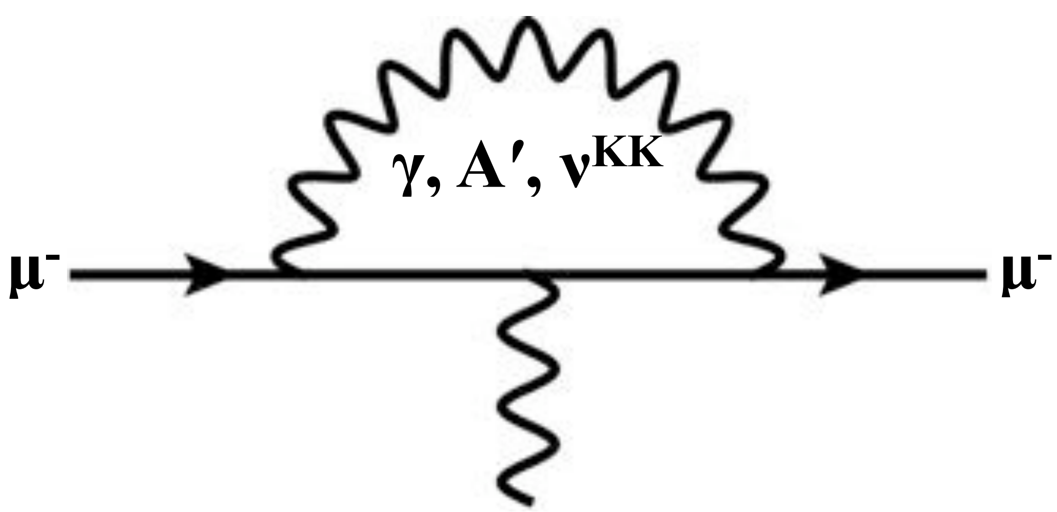
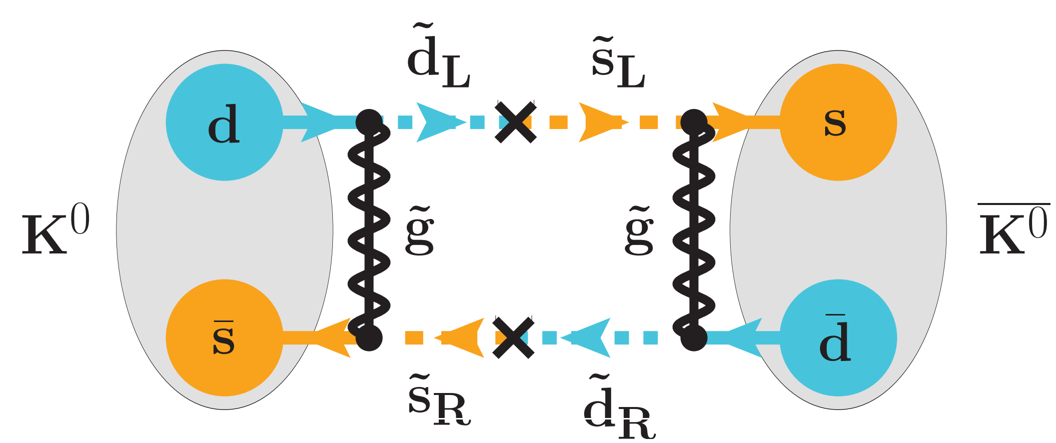
Where is the new physics?

- **Experimental high-energy physics community searching broadly for direct and indirect signs of new particles and forces** over wide range of energy scales and areas within particle physics
- High-precision measurements sensitive to **quantum-mechanical effects of new particles that would give rise to tiny deviations from Standard-Model expectations**

muon anomalous magnetic moment sensitive to SUSY, X-dimensions, dark photons, ...



s→d & b→d,s flavor-changing neutral currents sensitive to SUSY, flavor-changing Z′, leptoquarks, 4th generation, composite Higgs, ...



☆ Revealing new physics requires reliable and equally precise theory!

Lattice-QCD research program

- U.S. and worldwide lattice-QCD effort **targeting key hadronic parameters needed to interpret current & future experiments**
- Aligned with HEP community priorities and addressing the P5 "science drivers"
  - **New particles & interactions, Higgs boson, neutrino mass, dark matter, cosmic acceleration**
- Aim to reduce QCD uncertainties to at-or-below measurement errors to maximize discovery potential of high-precision experiments!

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

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

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

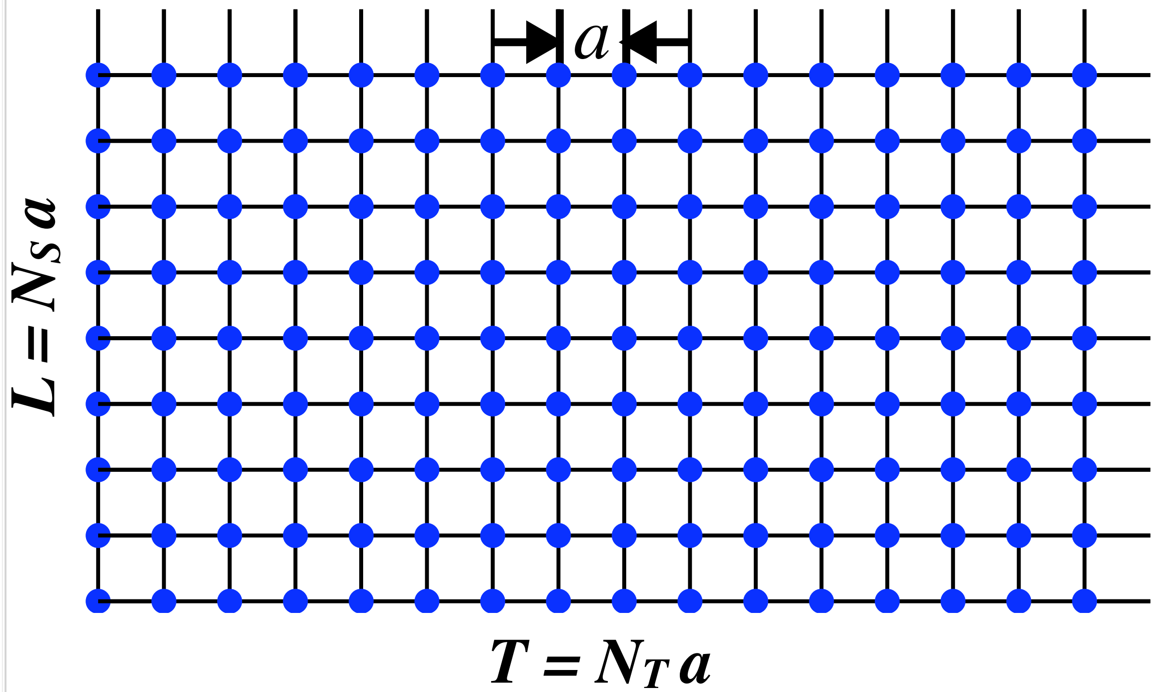
- QCD Lagrangian contains 1 + n_f + 1 parameters that can be fixed from equal number of experimental inputs

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 ($\lvert\theta\rvert < 10^{-11}$)

- 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

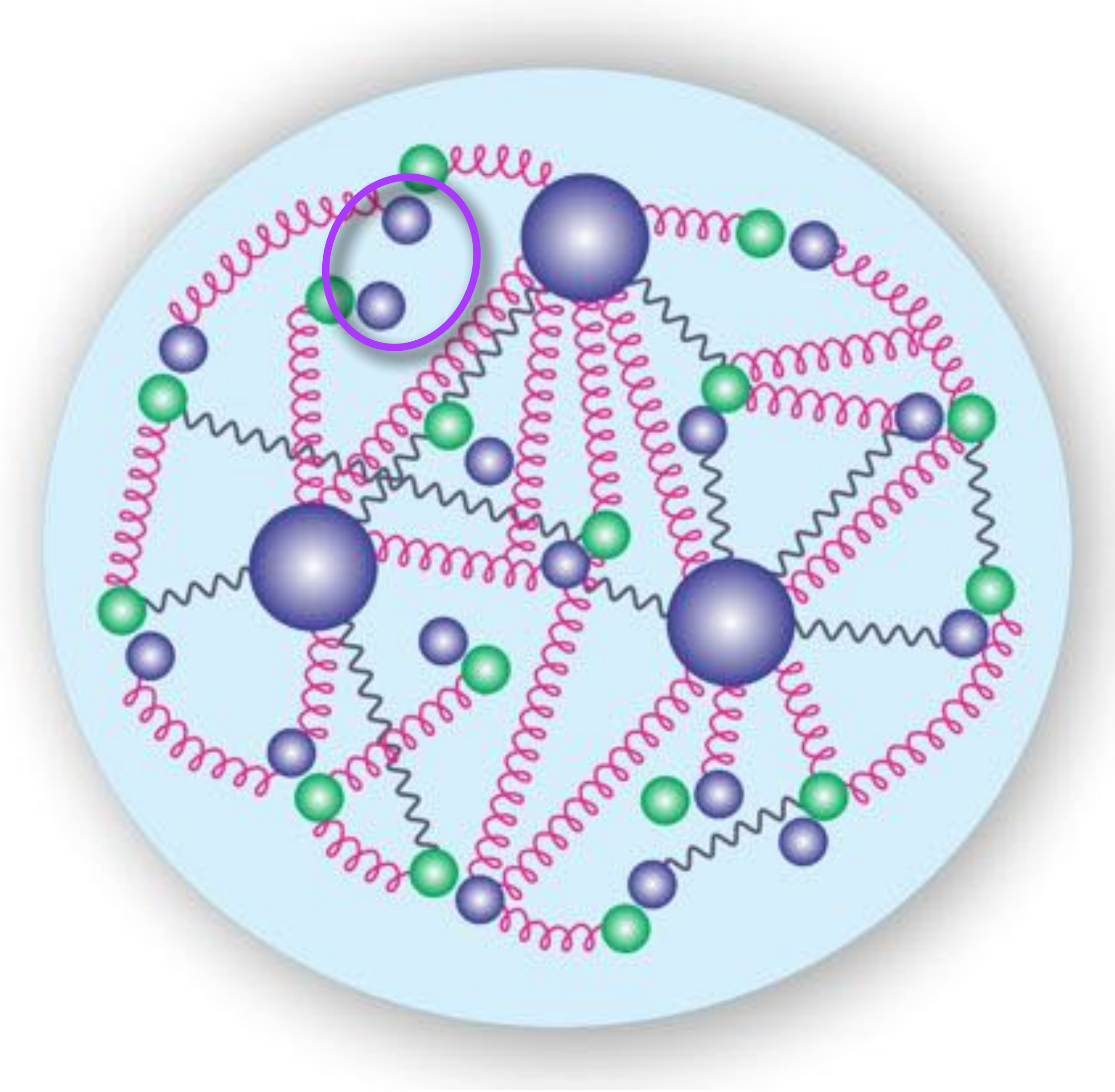
- Systematic method for calculating hadronic parameters from QCD first principles
- Define QCD on (Euclidean) spacetime lattice and solve path integral numerically
  - Recover QCD when lattice spacing $a \to 0$ and box size $L \to \infty$



- 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

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→0)
  - Multiple up/down-quark masses to interpolate or extrapolate to physical 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



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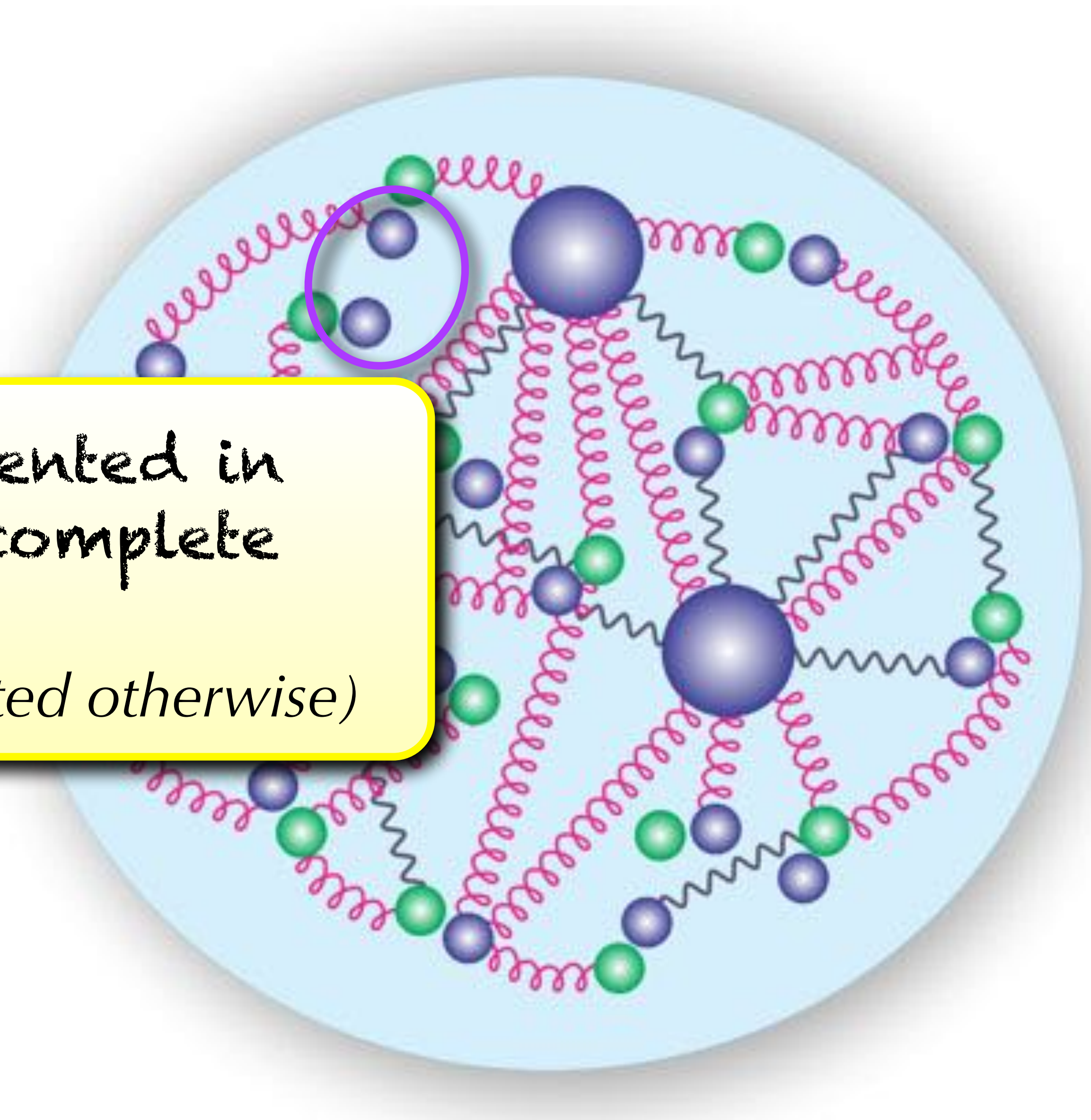
☆ All results presented in this talk have complete error budgets
(unless explicitly stated otherwise)

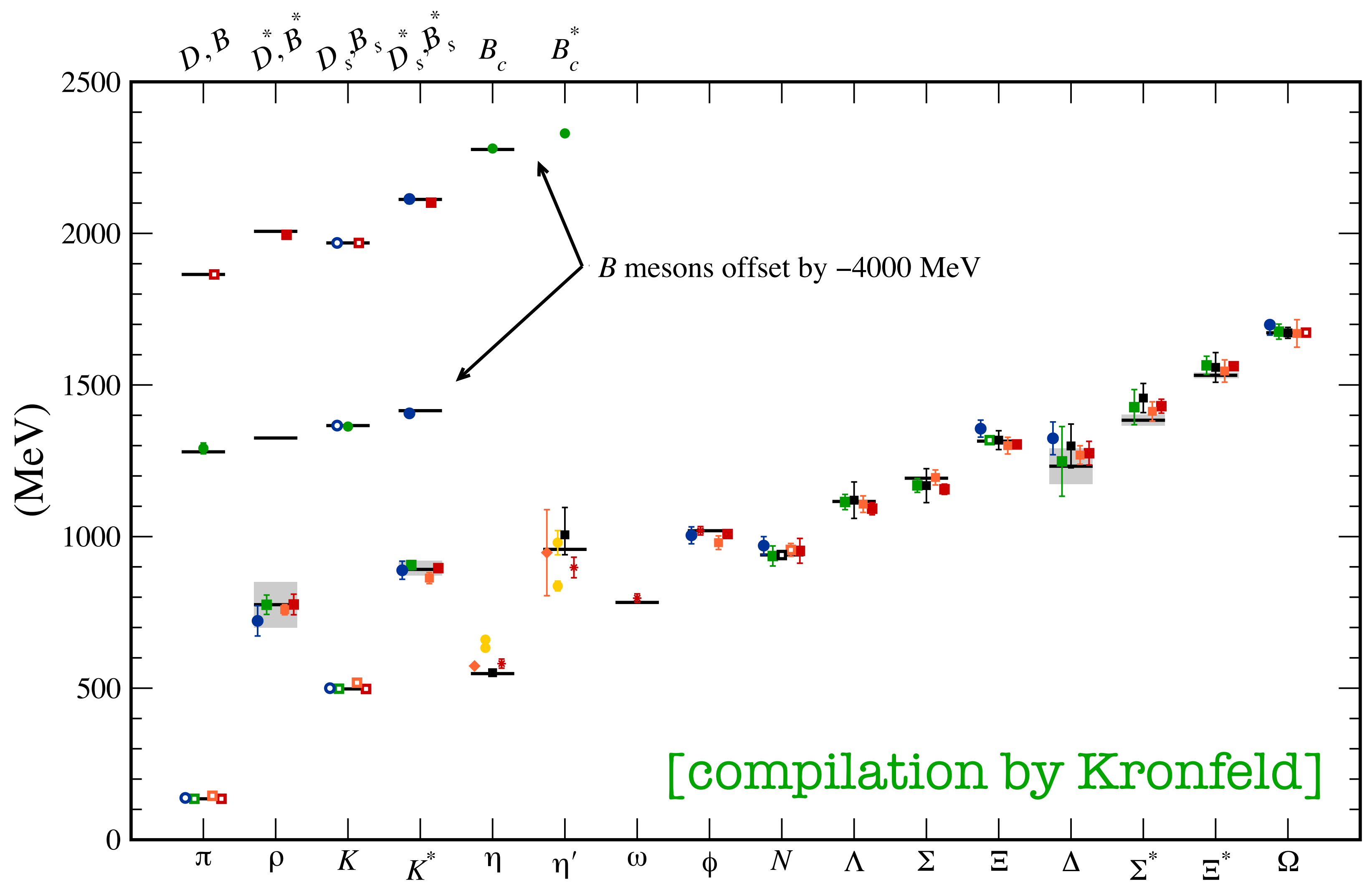


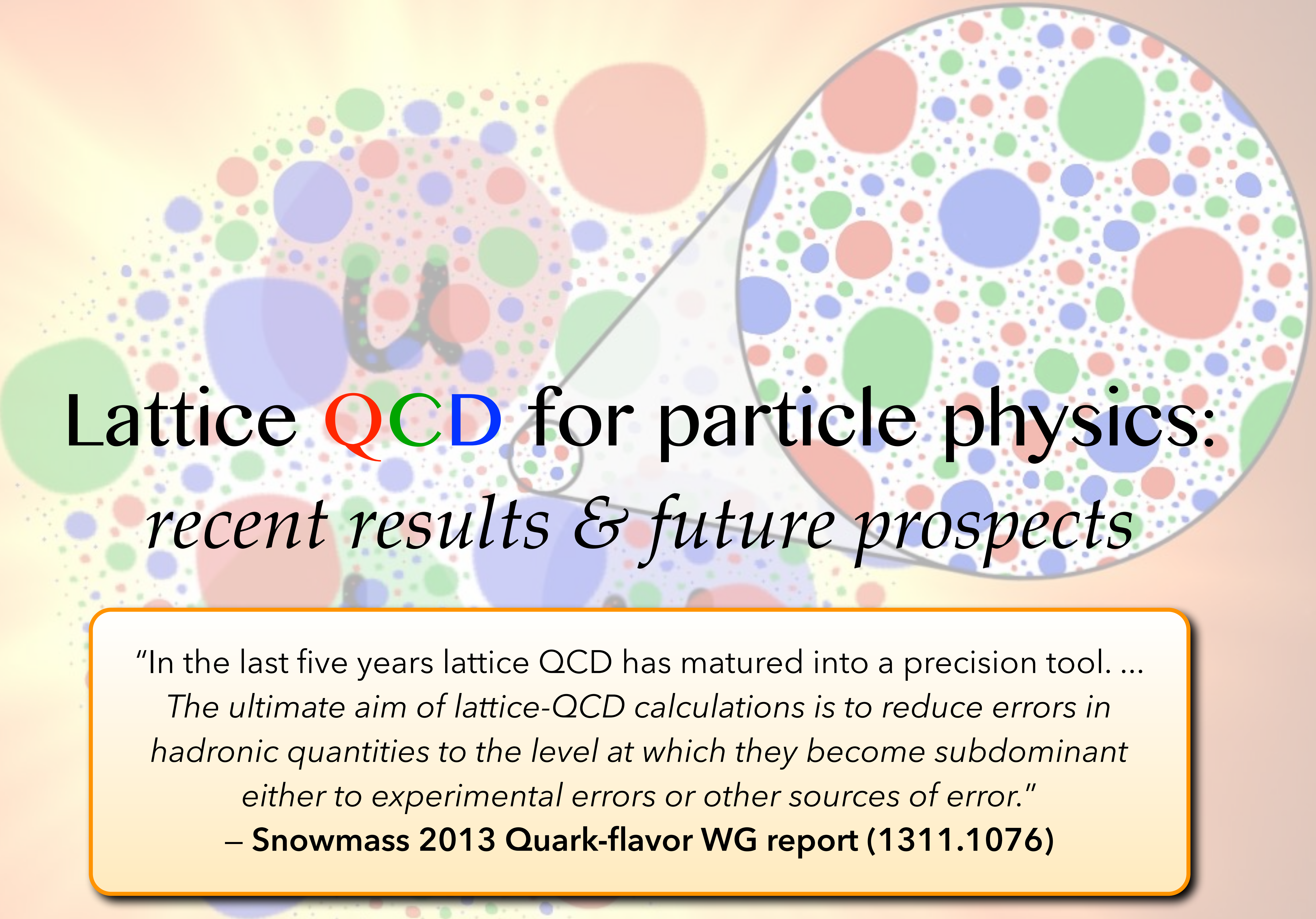
Lattice-QCD validation

- 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





Lattice QCD for particle physics:

recent results & future prospects

"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."

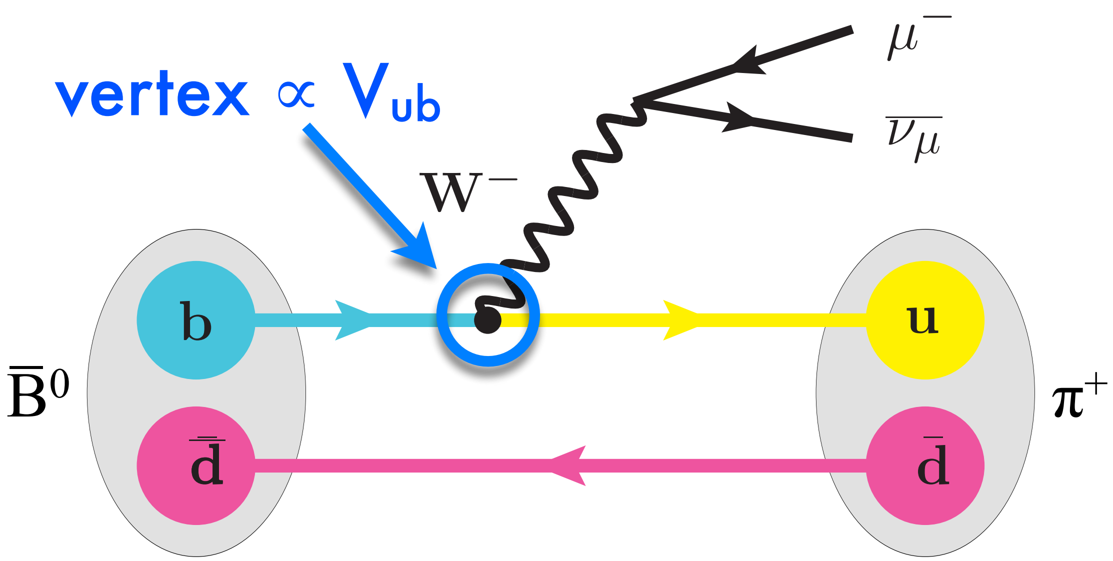
– Snowmass 2013 Quark-flavor WG report (1311.1076)

Quark-flavor physics

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

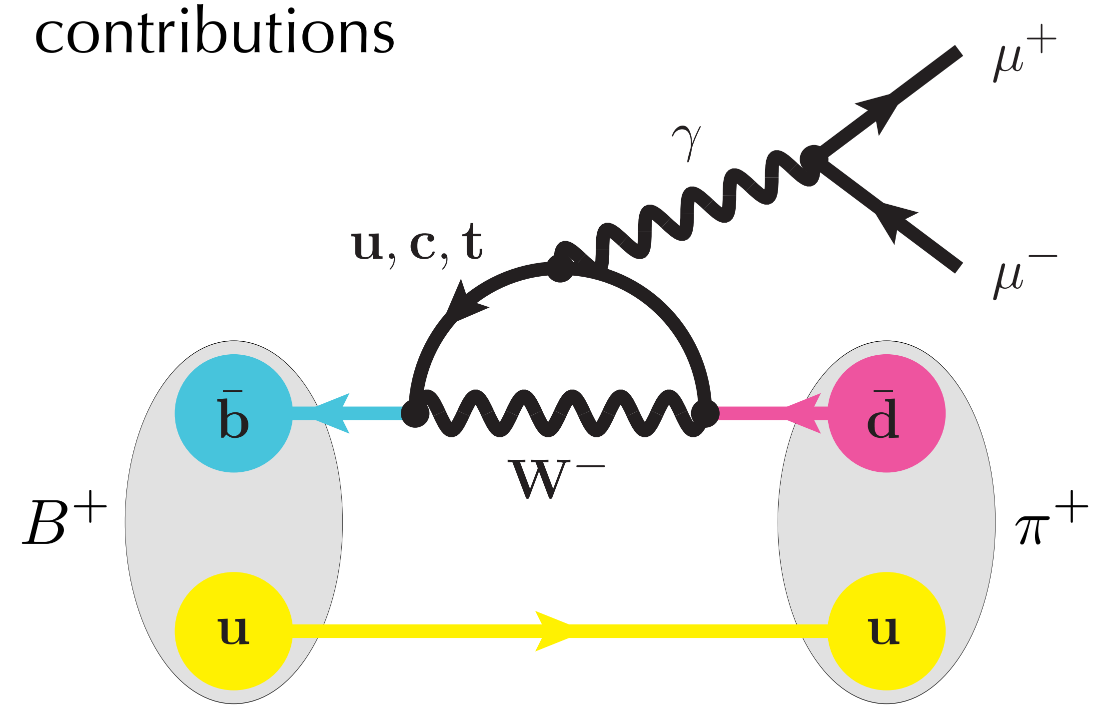
(1) Determination of CKM quark-mixing matrix elements

- 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

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

☆ Simple processes in lattice-QCD enable determinations of all CKM elements & phase except $|V_{tb}|$ (*see* recent lattice flavor-physics reviews)

New results for CKM elements include:

(1) Improved B→πlν form factors [RBC/UKQCD,PRD91 (2015) 7, 074510; Fermilab/MILC [PRDD92 (2015) 1, 014024]

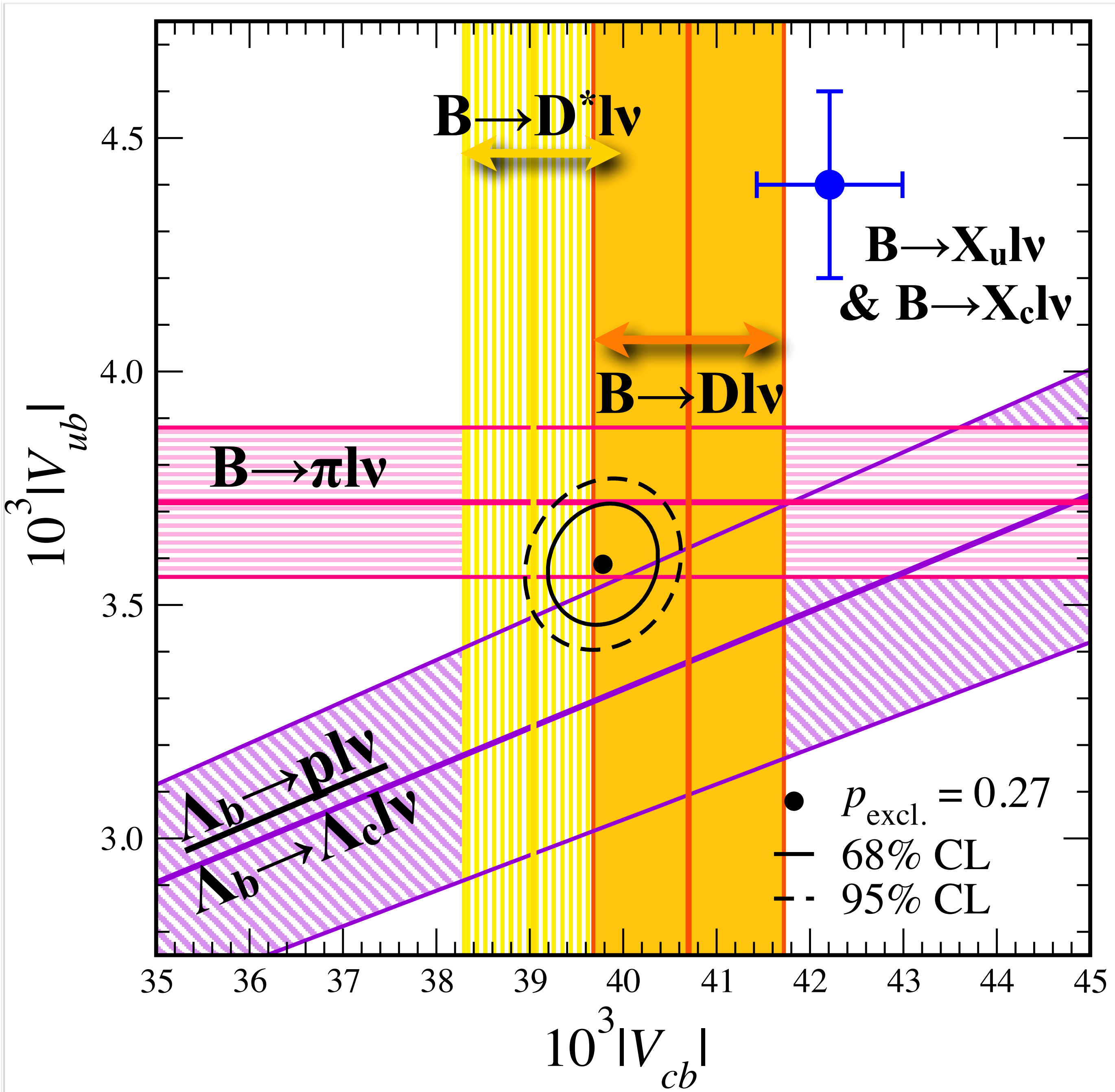
(2) First three-flavor B→Dlν form factors over full kinematic range [Fermilab/MILC, PRD92, 034506 (2015); HPQCD, PRD92, 054510 (2015)]; enabled use of experimental bins

New results for new-physics searches include:

(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→π tensor form factor and prediction for $B \to \pi\mu^+\mu^-$ [Fermilab/MILC PRL115, 152002 (2015)]

Implications for $|V_{ub}|$ & $|V_{cb}|$



[fit from Kronfeld]

- Long-standing ≈3σ tensions between $|V_{ub}|$ & $|V_{cb}|$ obtained from inclusive and exclusive tree-level semileptonic B decays

$|V_{ub}|$:

- 2× smaller error from B→πlν
- Inclusive & exclusive results continue to differ by >2σ …

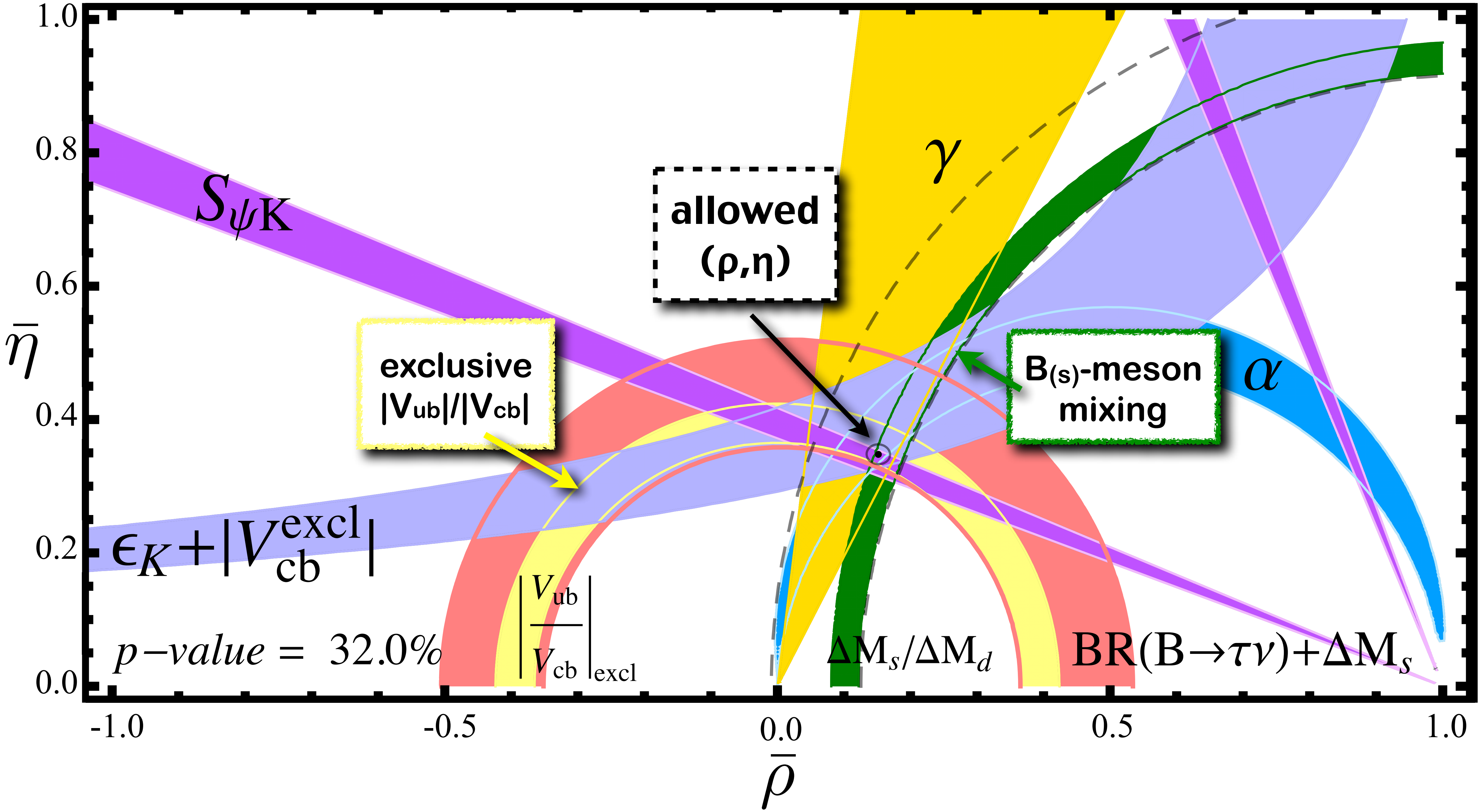
$|V_{cb}|$:

- Higher $|V_{cb}|$ from B→Dlν using full kinematic range *agrees* with inclusive value
- Lattice-QCD calculation of B→D*lν at nonzero recoil in progress … *perhaps "puzzle" will resolve itself?*

Impact on CKM unitarity-triangle fit

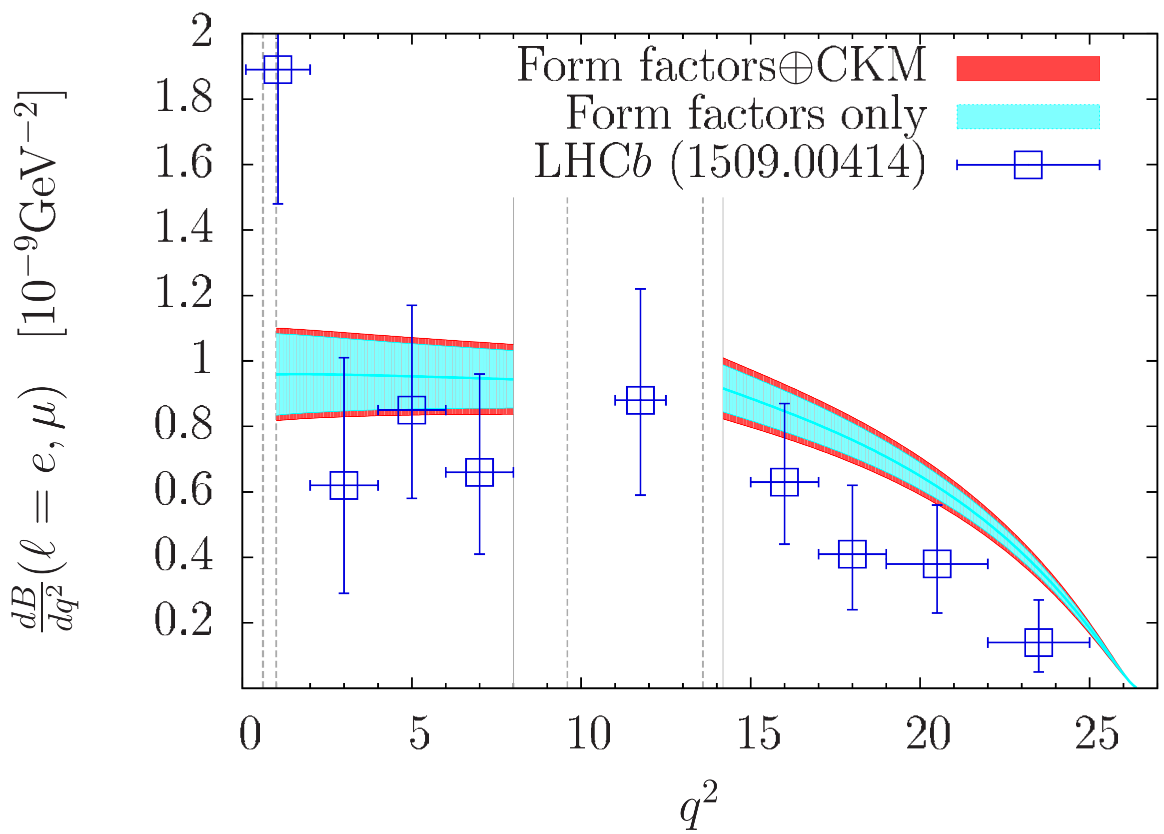
[Fermilab/MILC, PRD93, 113016]

[plot from E. Lunghi]

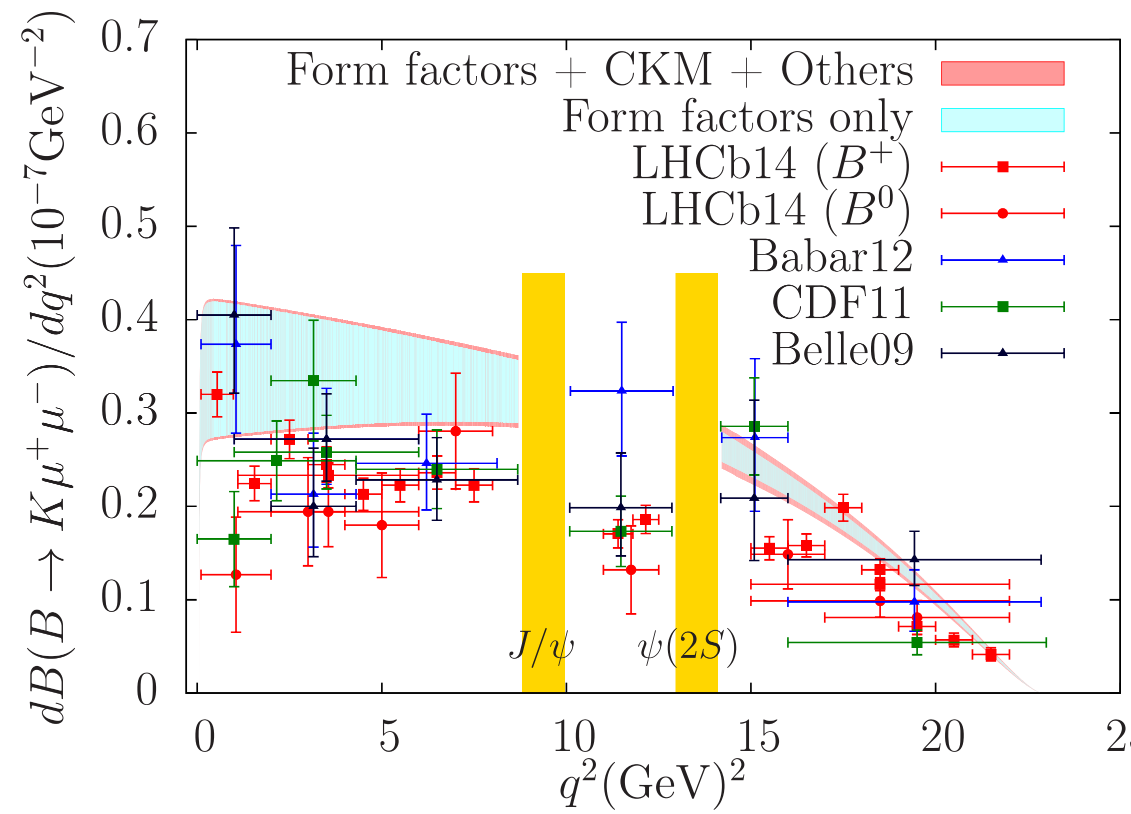


Comparison with B→π(K)$\mu^+\mu^-$ decay rates

dB/dq^2(B→π$\mu^+\mu^-$) ⭐



dB/dq^2(B→K$\mu^+\mu^-$)

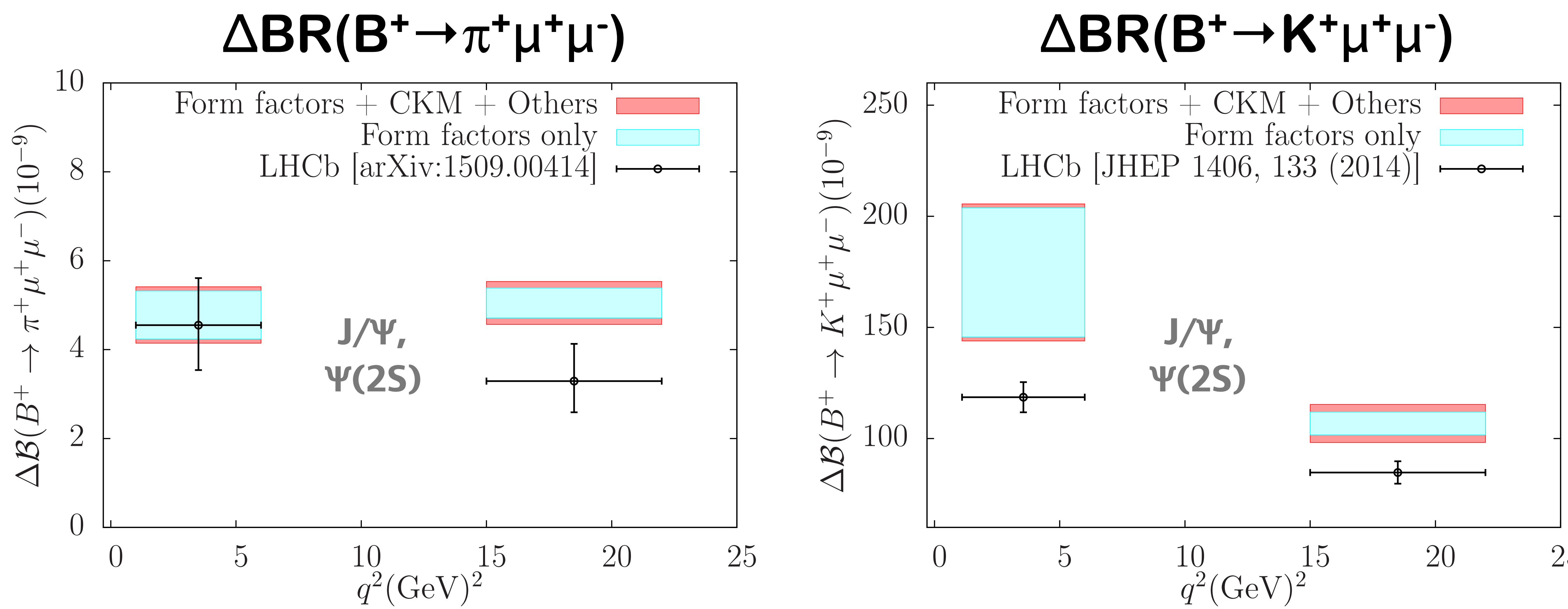


[Fermilab/MILC PRL115, 152002 (2015); PRD93 (2016) no.2, 025026]

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

⭐ Lattice-QCD prediction for dB(B→π$\mu^+\mu^-$)/dq^2 appeared before LHCb measurement!

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

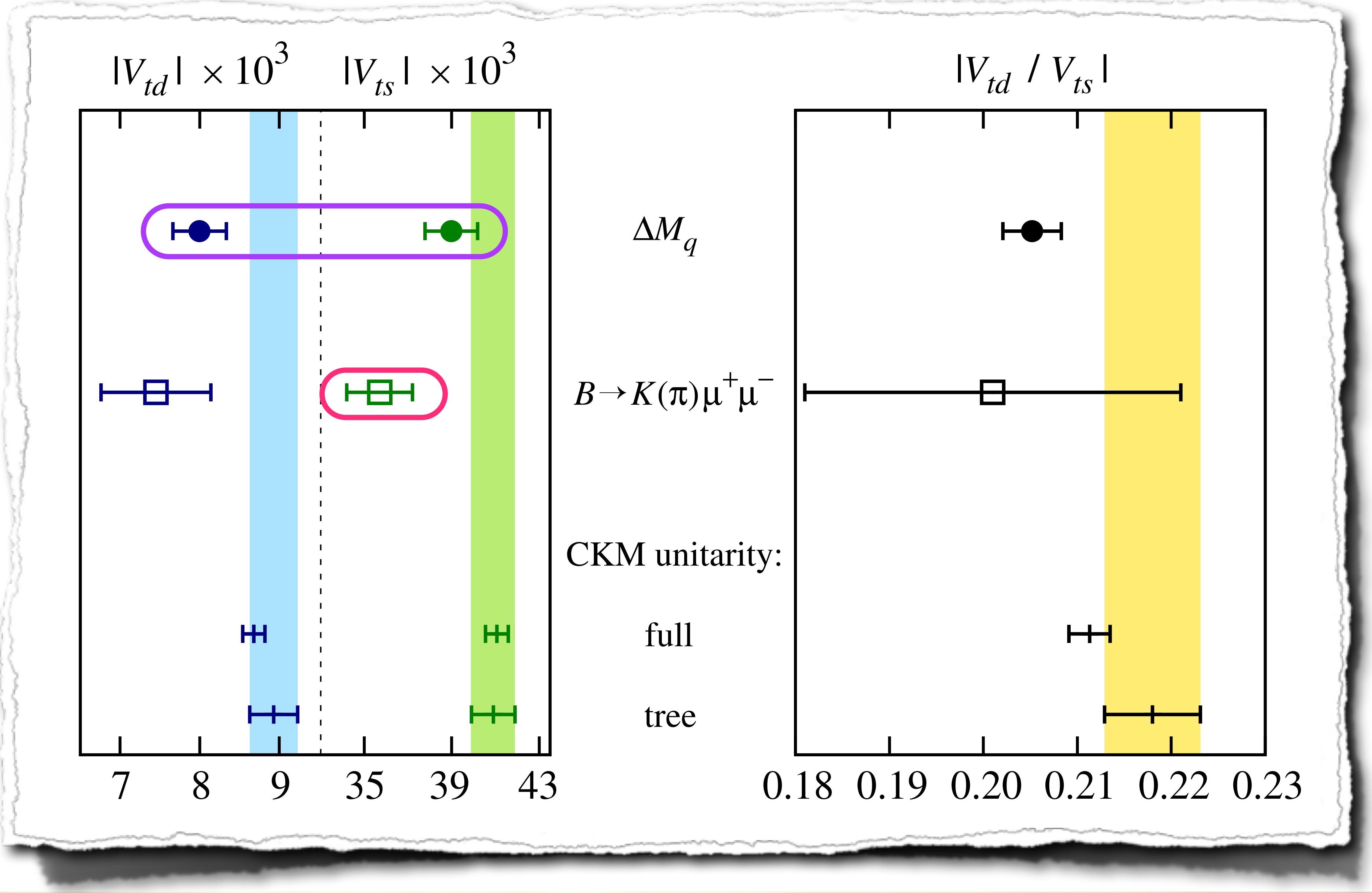


[El Khadra, Kronfeld, Van de Water et al. Phys.Rev. D93 (2016) no.3, 034005]

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

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

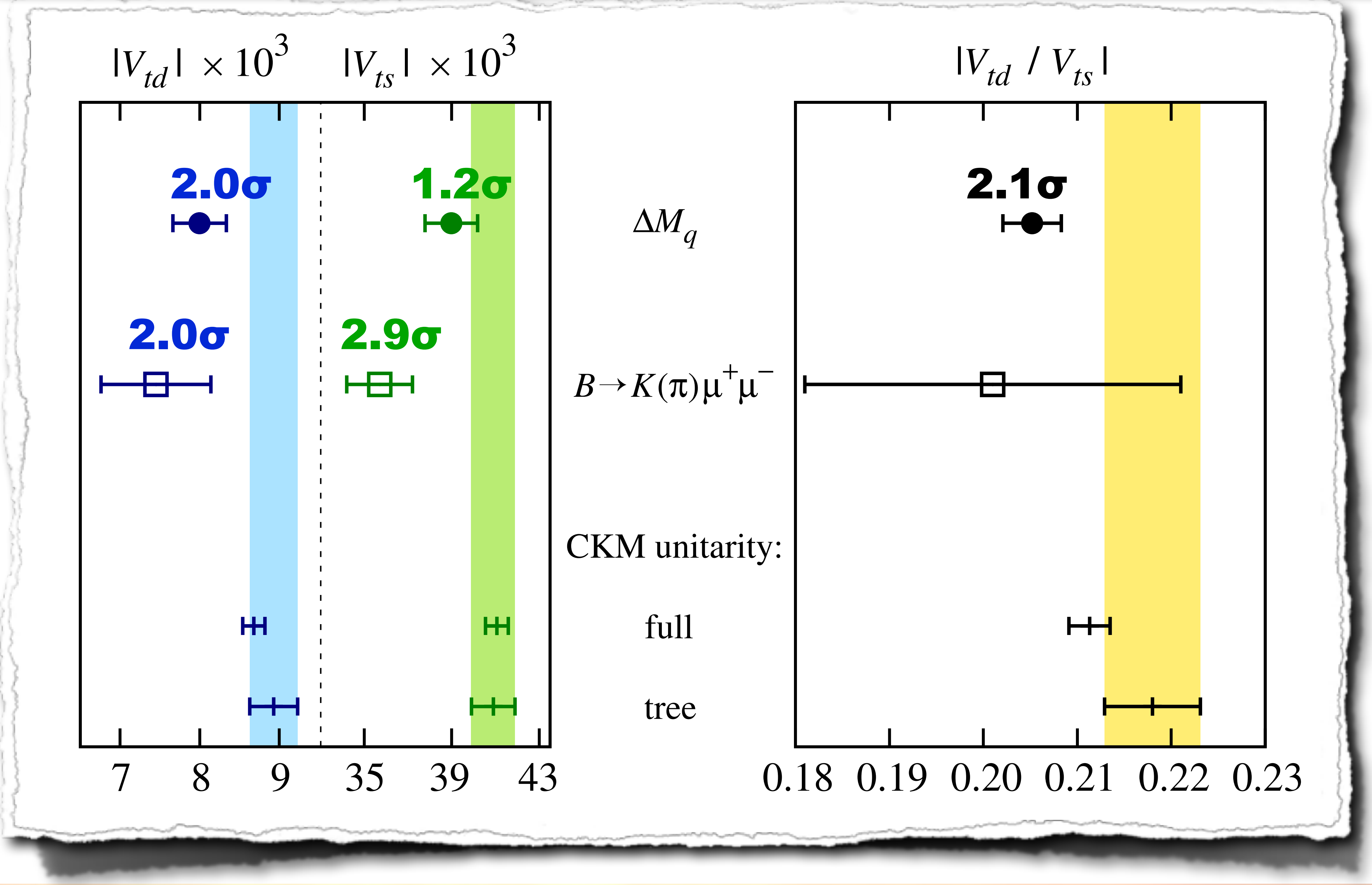
- $|V_{tq}|$ **from $B_{d,s}$-mixing ~2-3× more precise**, but still limited by hadronic matrix elements
- $|V_{ts}|$ **from B→Kμμ >2× more precise**, with commensurate theory & experimental errors



[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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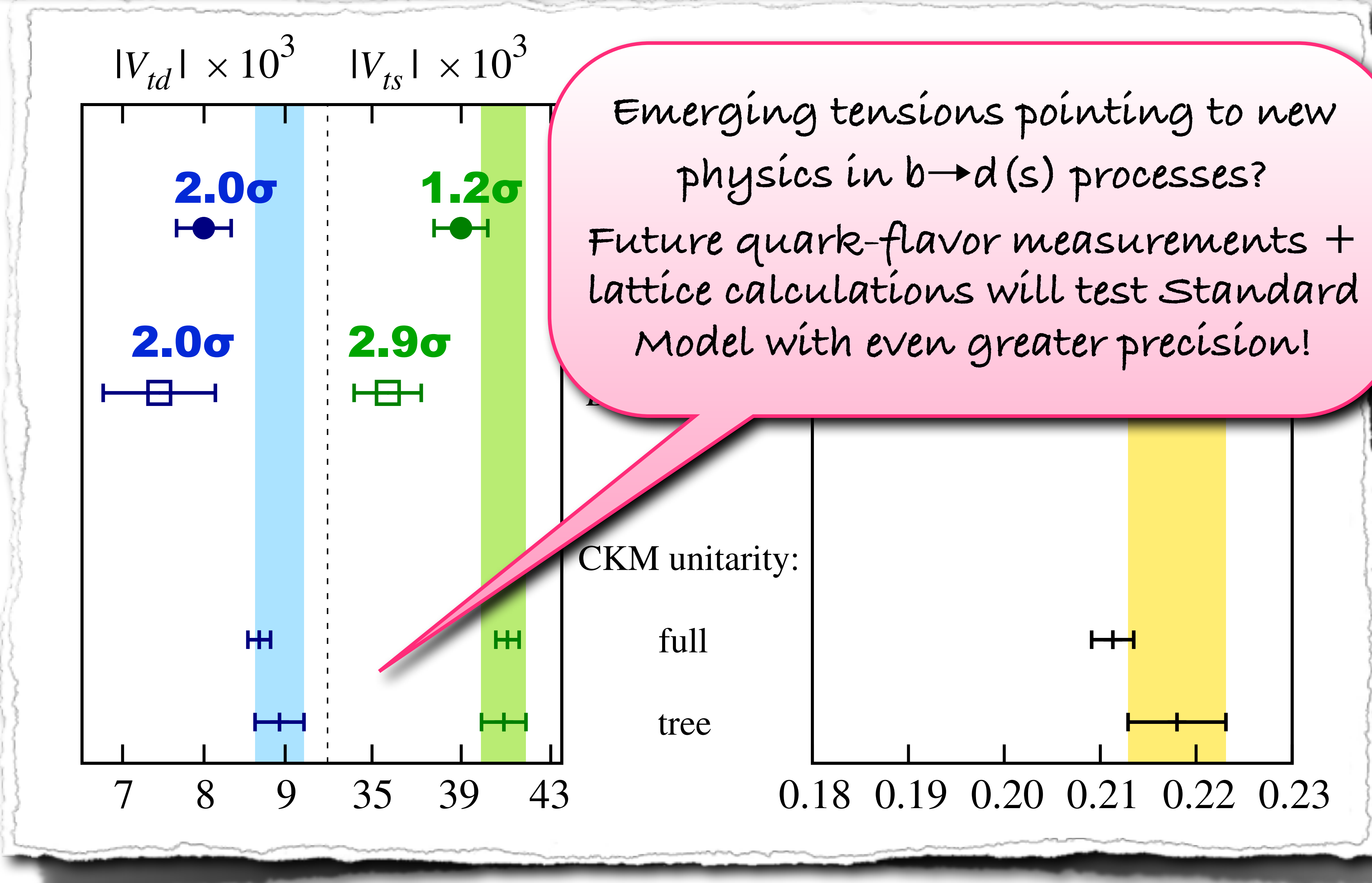


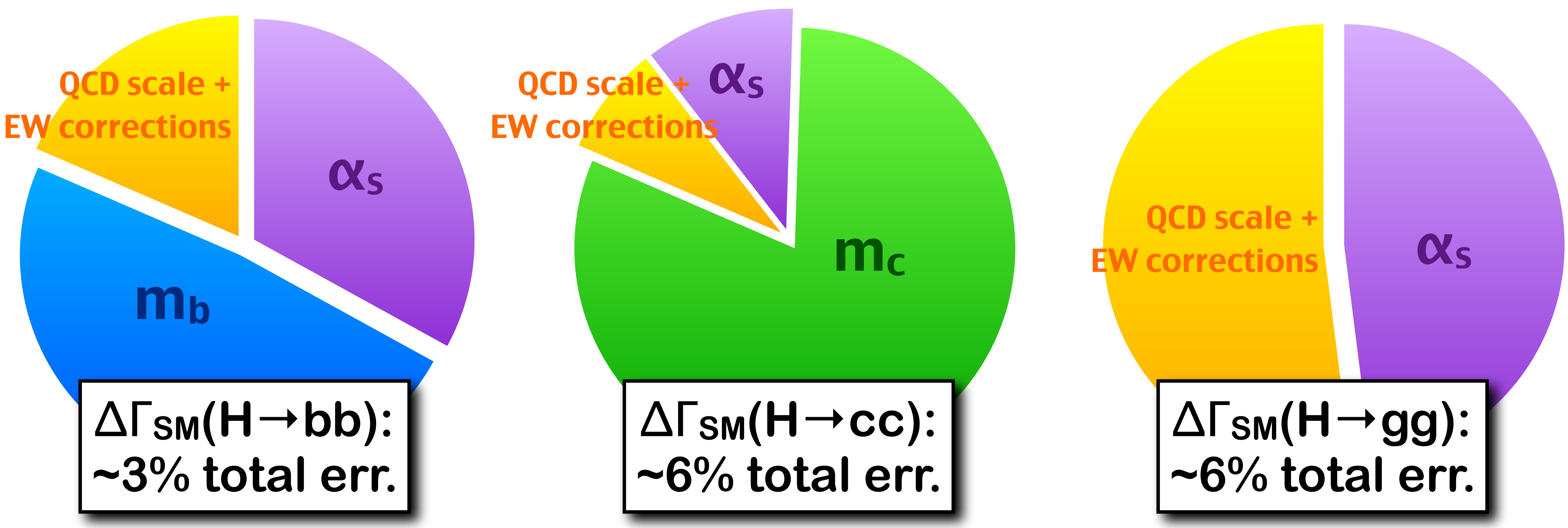
Emerging tensions pointing to new physics in b→d(s) processes?

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

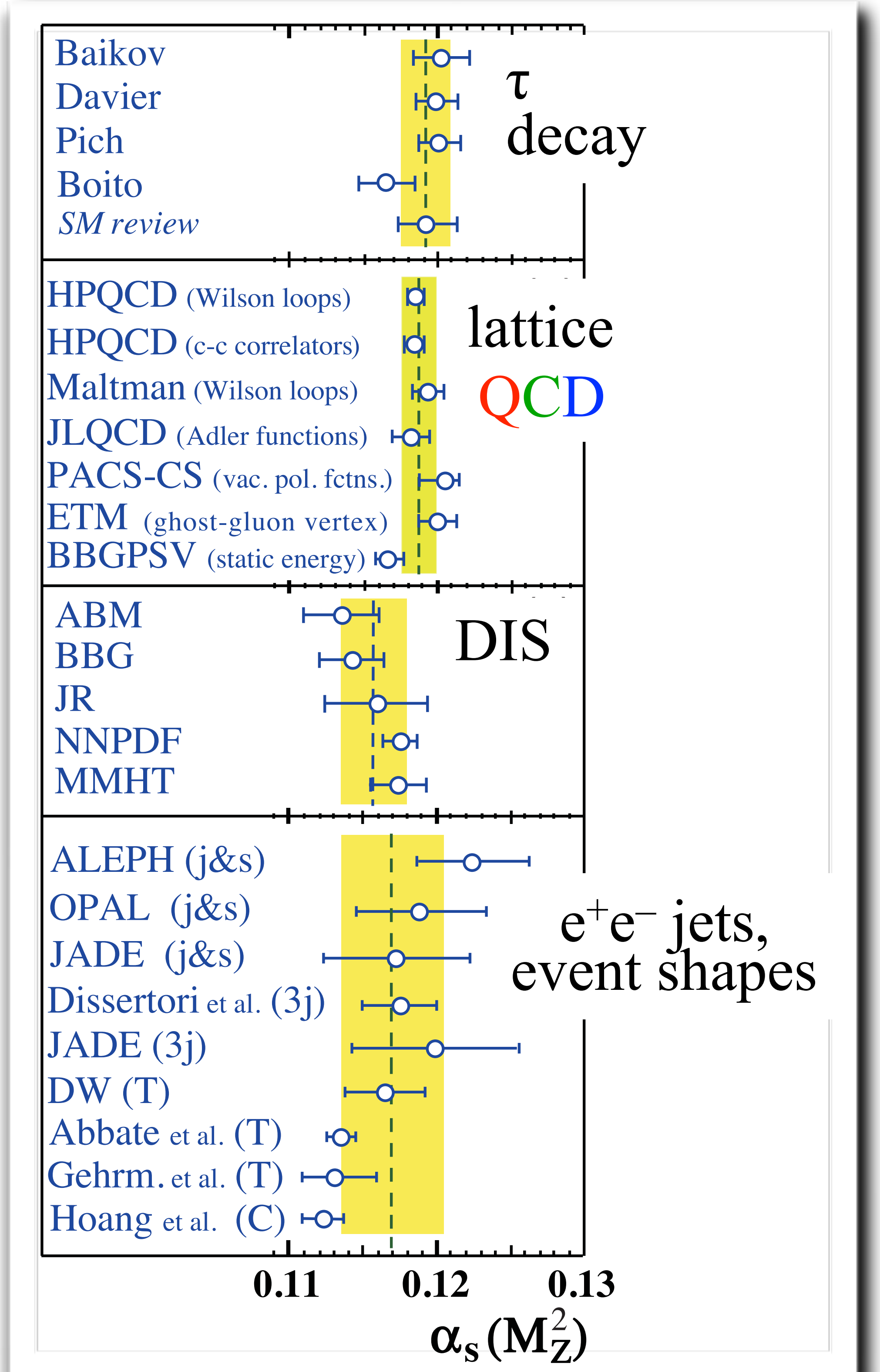
[plot C.Bouchard]

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]



α_s, m_c, & m_b from lattice QCD



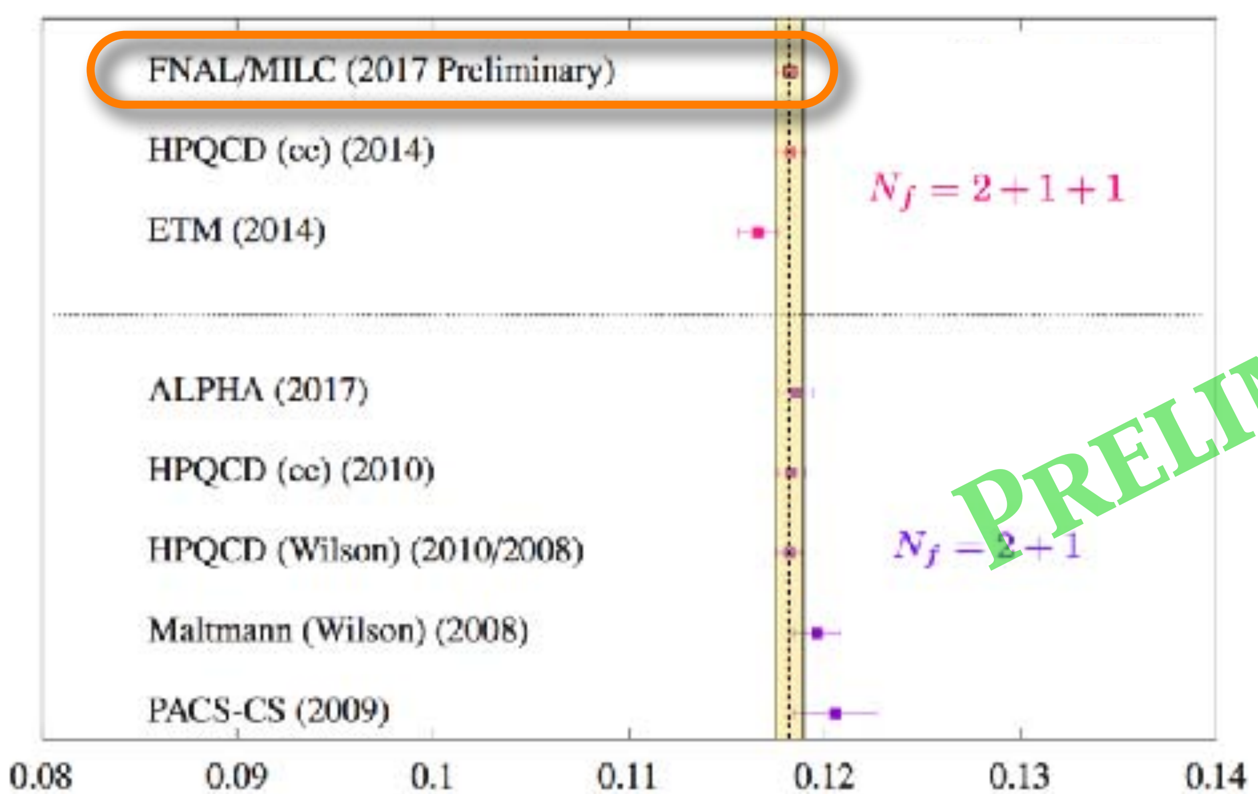
- Heavy-quark masses m_b & m_c from lattice QCD agree with non-lattice results, but with larger uncertainties
- **Independent lattice-QCD calculations of strong coupling constant α_s yield consistent results with greater precision than non-lattice methods**
  - m_b error dominated by discretization effects
  - α_s & m_c limited by perturbative truncation errors

➡ Analysis of lattice-QCD ensembles with finer lattice spacings and higher statistics will reduce uncertainties to precisions needed by future high-luminosity colliders [Lepage, Mackenzie, & Peskin, 1404.0319]

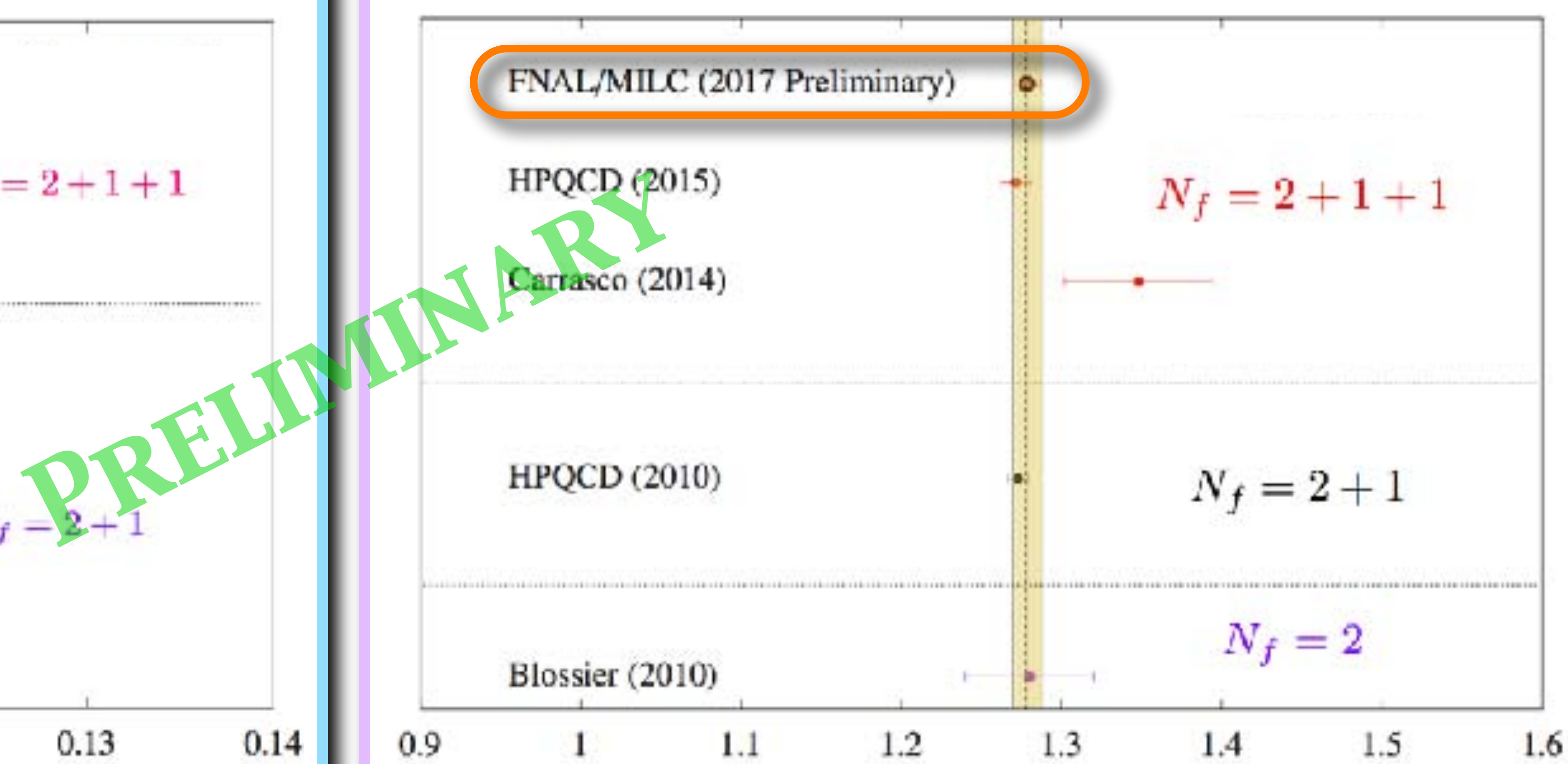
Fermilab/MILC *work in progress*

- Aarti Veernala spearheading FNAL/MILC effort to compute these quantities on state-of-the-art four-flavor QCD lattices with finer lattice spacings than ever before
  - **Presented preliminary results for α_s & m_c at Lattice 2017** ➡ *higher statistics reduce errors by better constraining possible size of unknown higher-order terms*
  - Anticipate significant reduction in m_b error with analysis of new ensembles with very fine (a~0.045 & 0.03 fm) lattice spacings!

$\alpha_s(M_Z)$

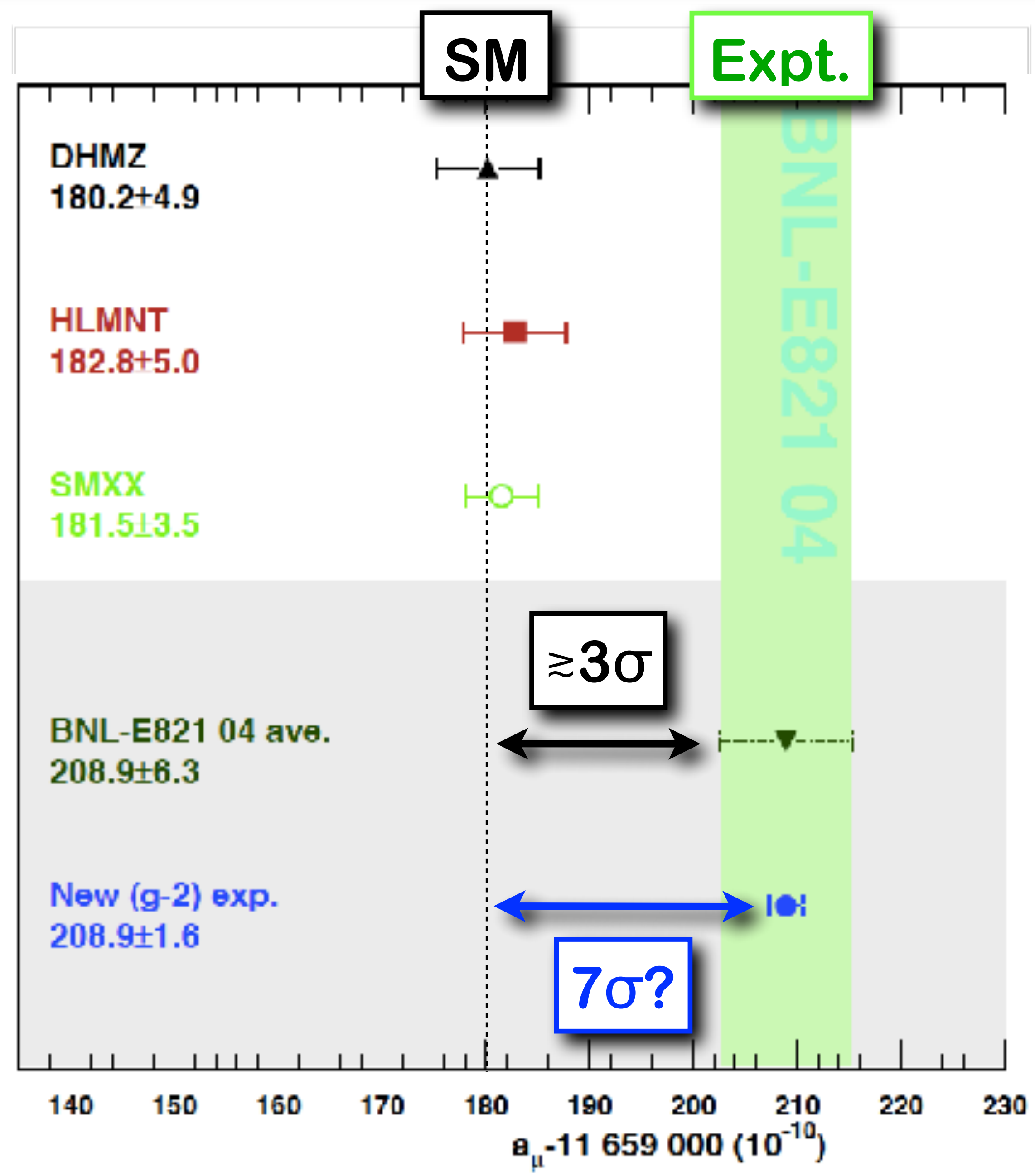


$m_c(m_c)$



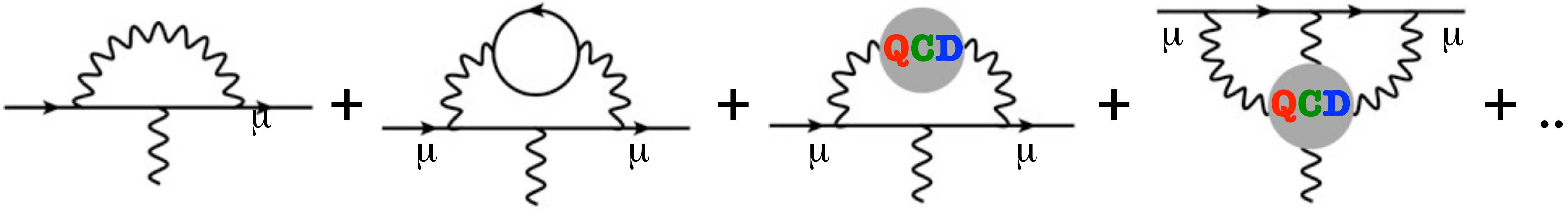
Muon anomalous magnetic moment (g-2)

- 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 in June, 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]

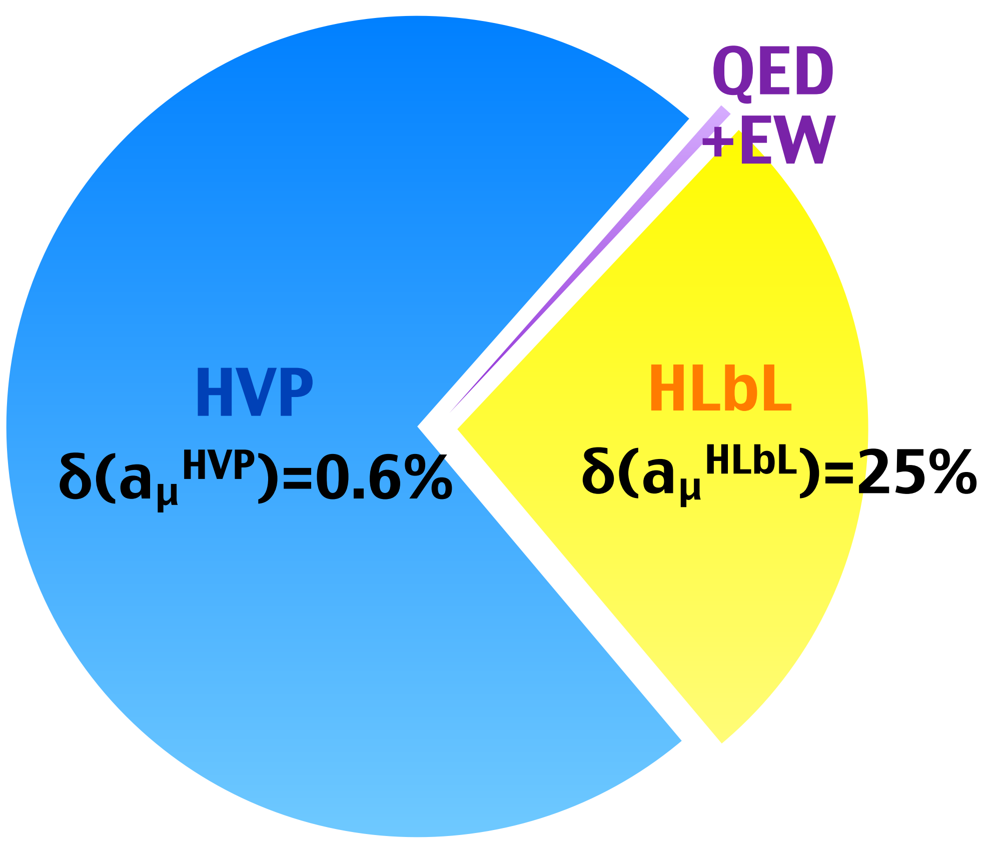
Muon g-2 in the Standard Model



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 from first principles with lattice QCD**
- To match anticipated experimental precision, **must reduce hadronic uncertainties to $\delta(a_\mu^{HVP}) \lesssim 0.2\%$ & $\delta(a_\mu^{HLbL}) \lesssim 10\%$**

> See First Workshop of Muon g-2 Theory Initiative for overview of lattice-QCD and non-lattice approaches and latest results

Results for hadronic vacuum polarization

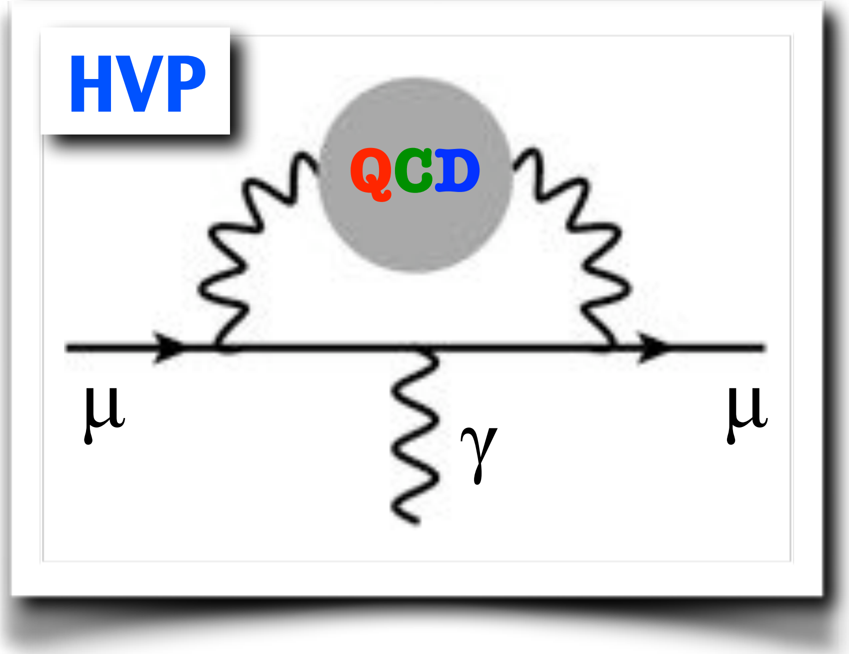
- Calculate nonperturbative vacuum polarization function in lattice QCD from correlation function of quarks' EM current [Blum, PRL 91 (2003) 052001]

- Rapid progress in past few years:

(1) First complete calculation of leading-order a_μ^{HVP} to reach precision needed to observe significant deviation from experiment [HPQCD + RV, 1601.03071 (to be published in PRD)]

(2) First calculations of quark-disconnected contribution [RBC/UKQCD, PRL116, 232002 (2016); BMW, 1612.02364]

- ~1% total lattice-QCD uncertainty in 2018 possible!



- Lowest-order contribution of $O(\alpha_{EM})$
- Current determination of $\Pi(Q^2)$ and a_μ^{HVP} from $e^+e^- \to$ hadrons limited by experimental uncertainties

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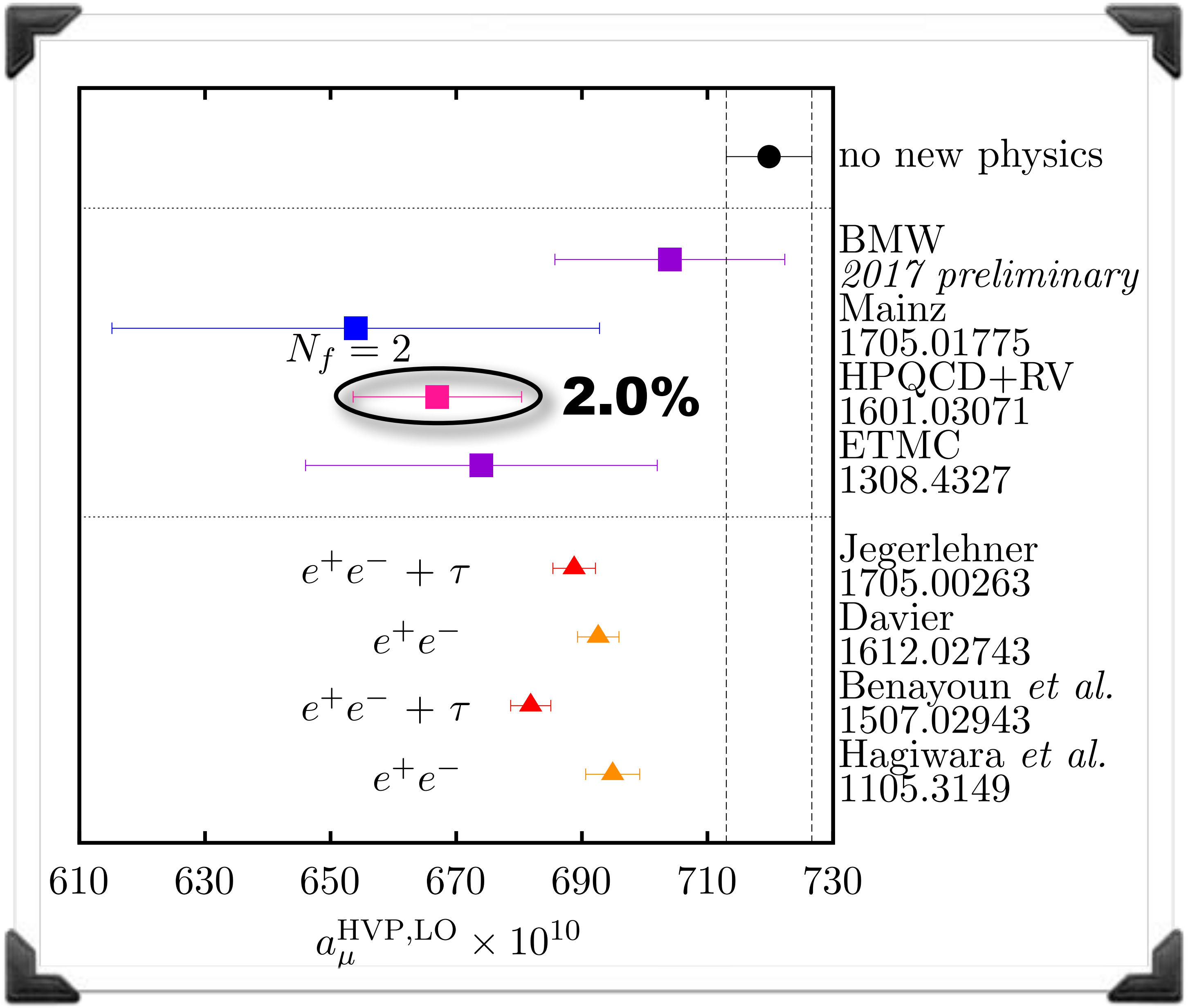
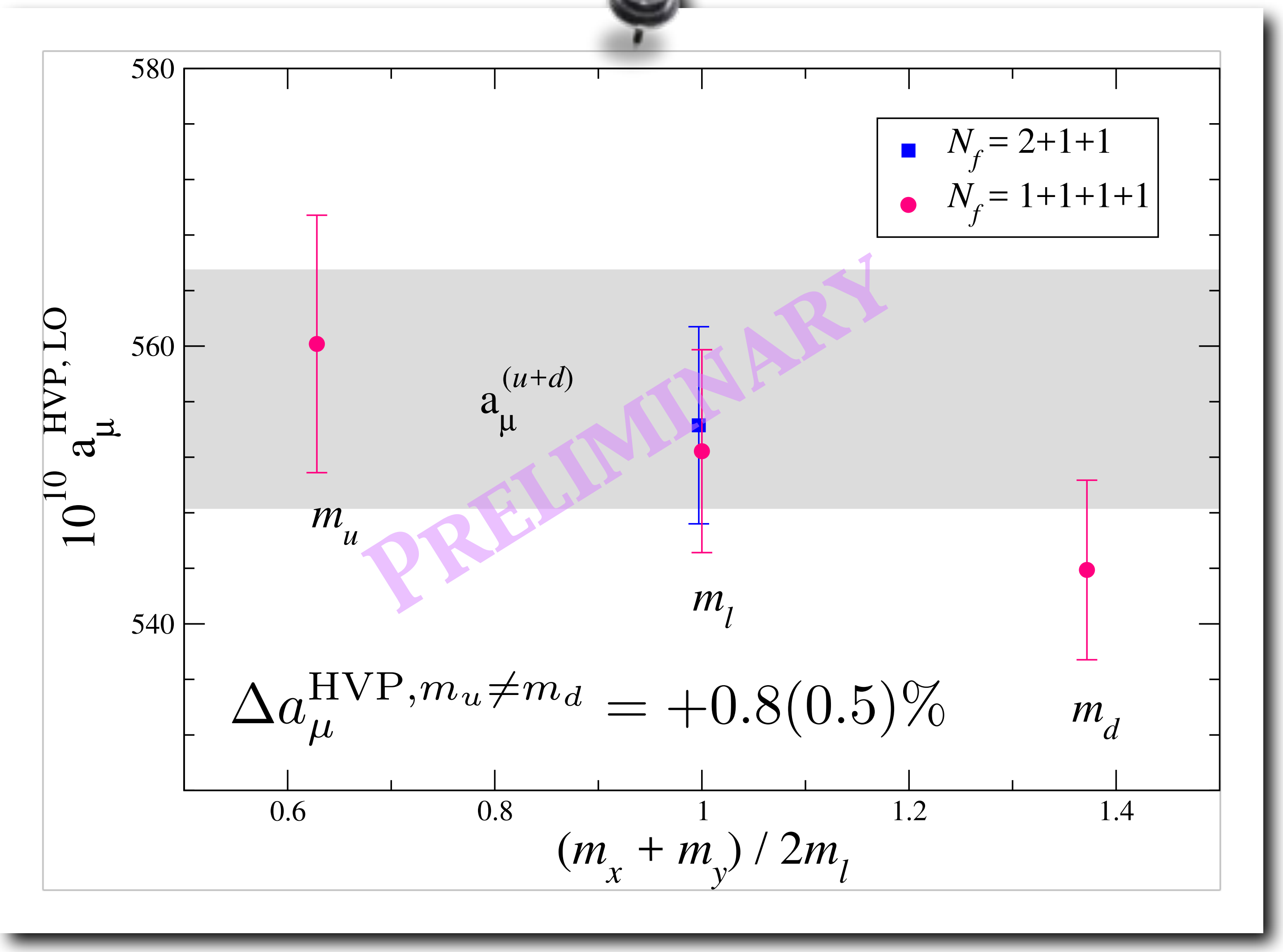


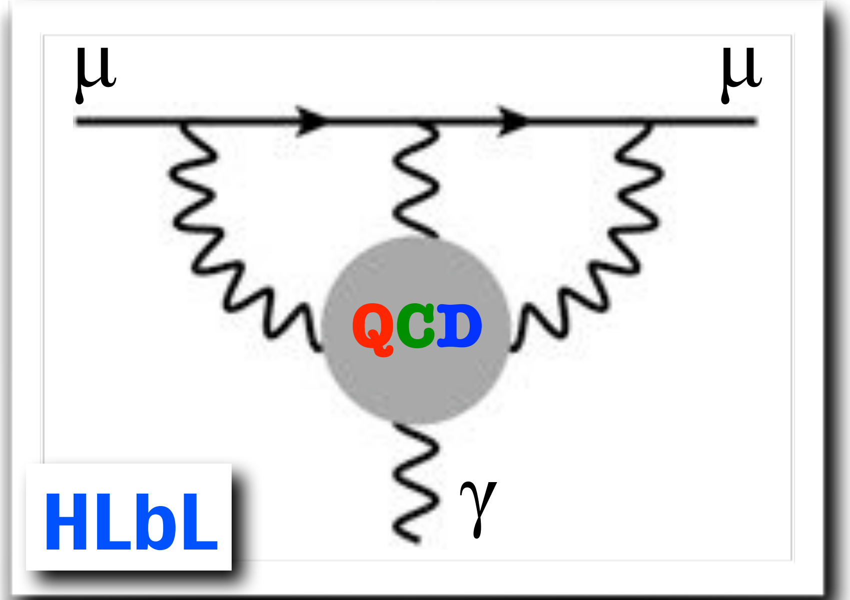
Fermilab/HPQCD/MILC *work in progress*

- Joint follow-up calculation targeting leading sources of error in most precise HPQCD+RV result from
  - (1) Omission of quarks' EM charges
  - (2) u/d-quark mass difference
  - (3) Quark-disconnected contributions
  - (4) Finite spatial volume & nonzero lattice spacing
- Key achievement is first direct lattice-QCD calculation of strong-isospin-breaking correction at the physical pion mass using new ensemble with $m_u \neq m_d$
- Also presently analyzing ensembles with finer lattice spacings, and developing dynamical QED code



▶ Aim to reach ~1% uncertainty before first result from Muon g-2 Experiment next Spring

Progress on hadronic light-by-light

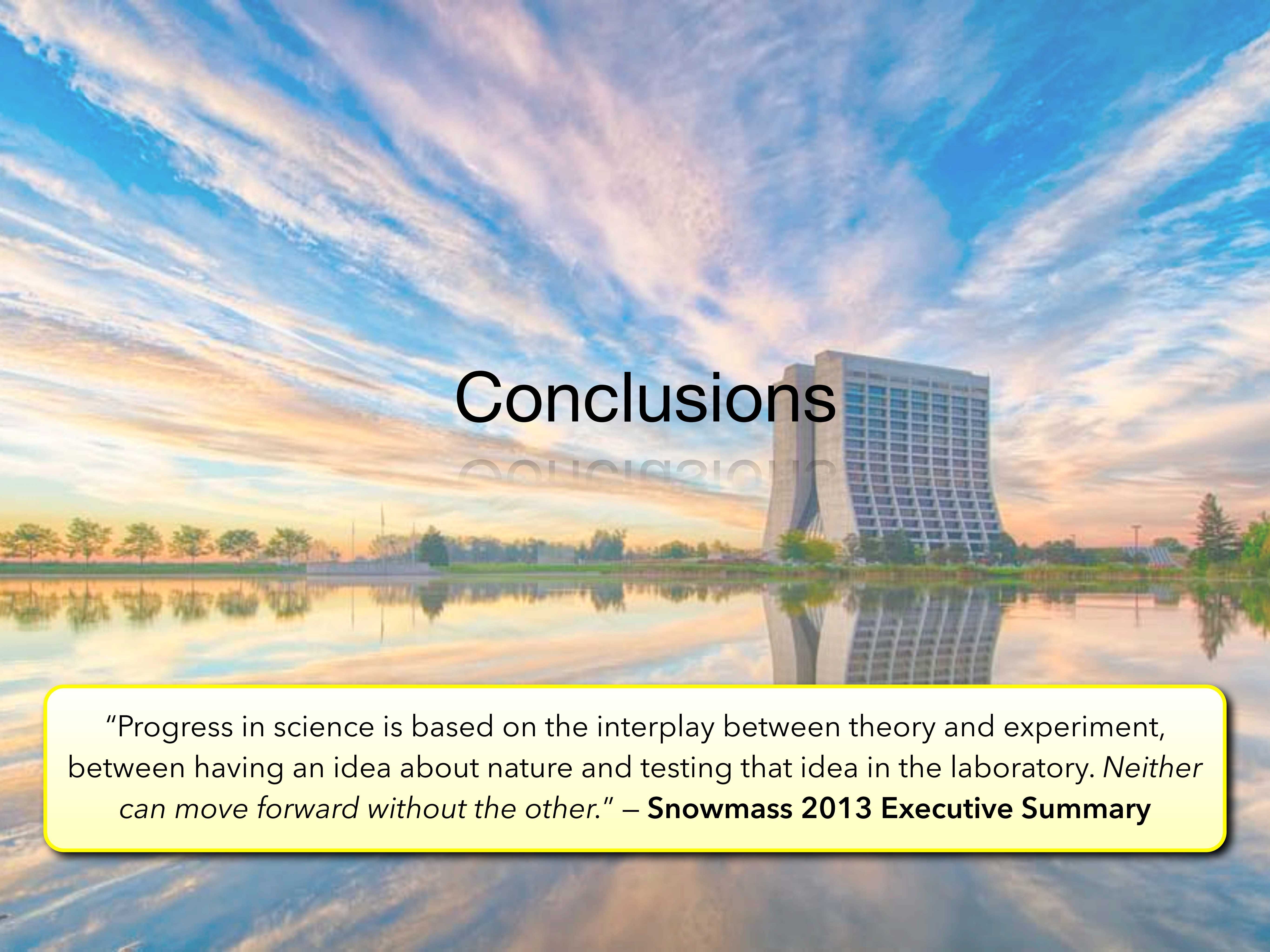


- Lowest-order contribution of $O(\alpha_{EM}^2)$
- Current estimate from QCD models subjective and somewhat controversial [Glasgow consensus, Prades, de Rafael, Vainshtein, 0901.0306]

- 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 $\lesssim$10% statistical errors at the physical pion mass in ballpark of Glasgow consensus value $a_\mu^{\mathrm{HLbL,GC}} \times 10^{10} = 10.5(2.6)$

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

- Full study of systematic errors including lattice-spacing and finite-volume effects still needed ... but initial results encouraging!



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**

Summary & outlook

- Lattice-QCD calculations needed throughout high-energy (& nuclear) physics
  - Reliable theoretical predictions are needed on same time scale as measurements with commensurate uncertainties
- In the quark-flavor sector, recent lattice-QCD results + experimental measurements imply several interesting 2σ "tensions" with Standard-Model CKM framework
- Ambitious lattice-QCD program in place to meet theory needs of current & future experiments by

  (1) Increasing precision of present calculations (*e.g.* quark flavor-changing matrix elements, quark masses & strong coupling, …)

  (2) Providing first reliable QCD calculations of more challenging quantities (*e.g.* hadronic contributions to muon g-2, ν-nucleon scattering form factors & matrix elements, …)

  ☆ *Success contingent on continued support for lattice-QCD hardware & software!*

> Future measurements combined with anticipated lattice-QCD improvements will sharpen precision tests of the Standard Model and hopefully reveal the presence of new physics!

Further Reading

See also hot-off-the-press results from [Lattice 2017](#)!

Particle Data Group reviews:

- "Lattice Quantum Chromodynamics" (Laiho, Sharpe, Hashimoto)
- "Leptonic Decays of Charged Pseudoscalar Mesons: 2015" (Rosner, Stone, RV)

Flavor Lattice Averaging Group report:

- 2016 "Review of lattice results concerning low-energy particle physics"

Snowmass working-group reports:

- "Charged Leptons"
- "Higgs Working Group Report …"
- "Lattice field theory … Scientific goals and computing needs"
- "Report of … QCD Working Group"
- "Report of … Quark Flavor Physics Working Group"

Extras...

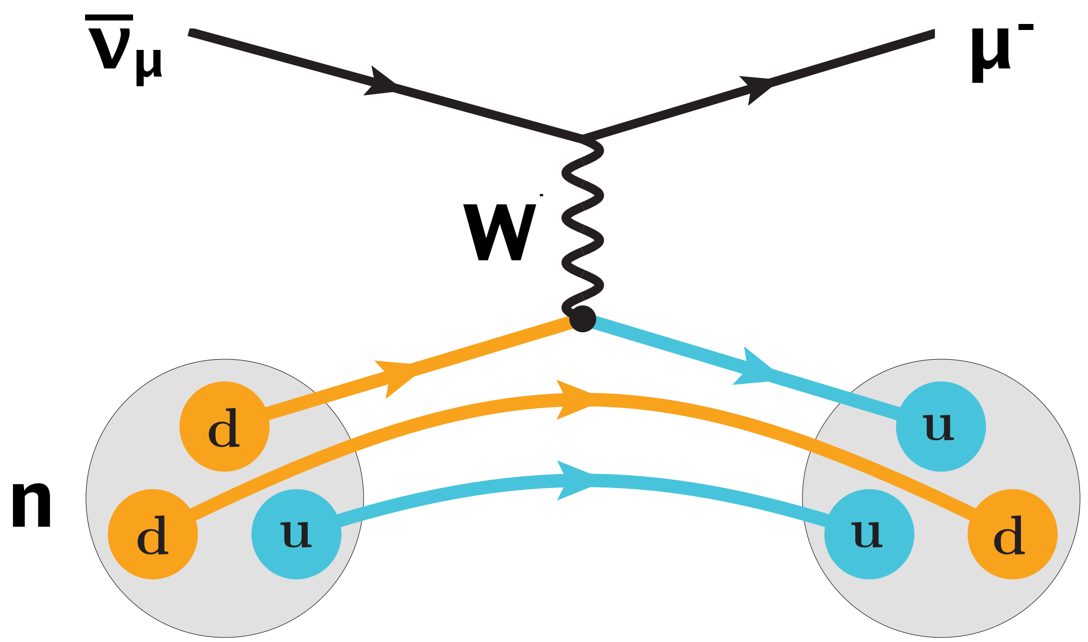
Long-baseline neutrino experiments

- ... **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 $\nu(\bar{\nu})$-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

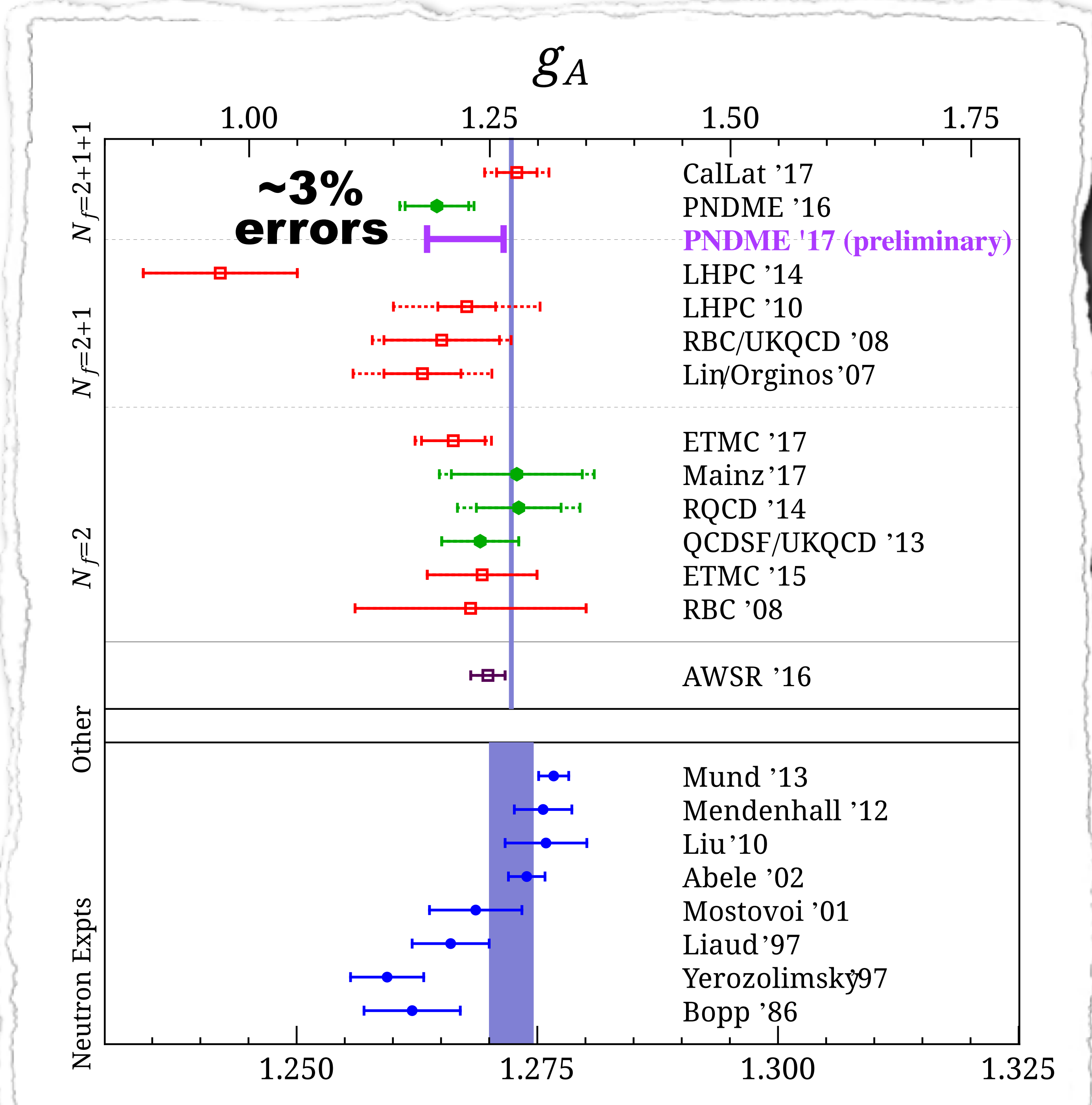
Nucleon axial-vector form factor

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



Recent lattice-QCD results for g_A

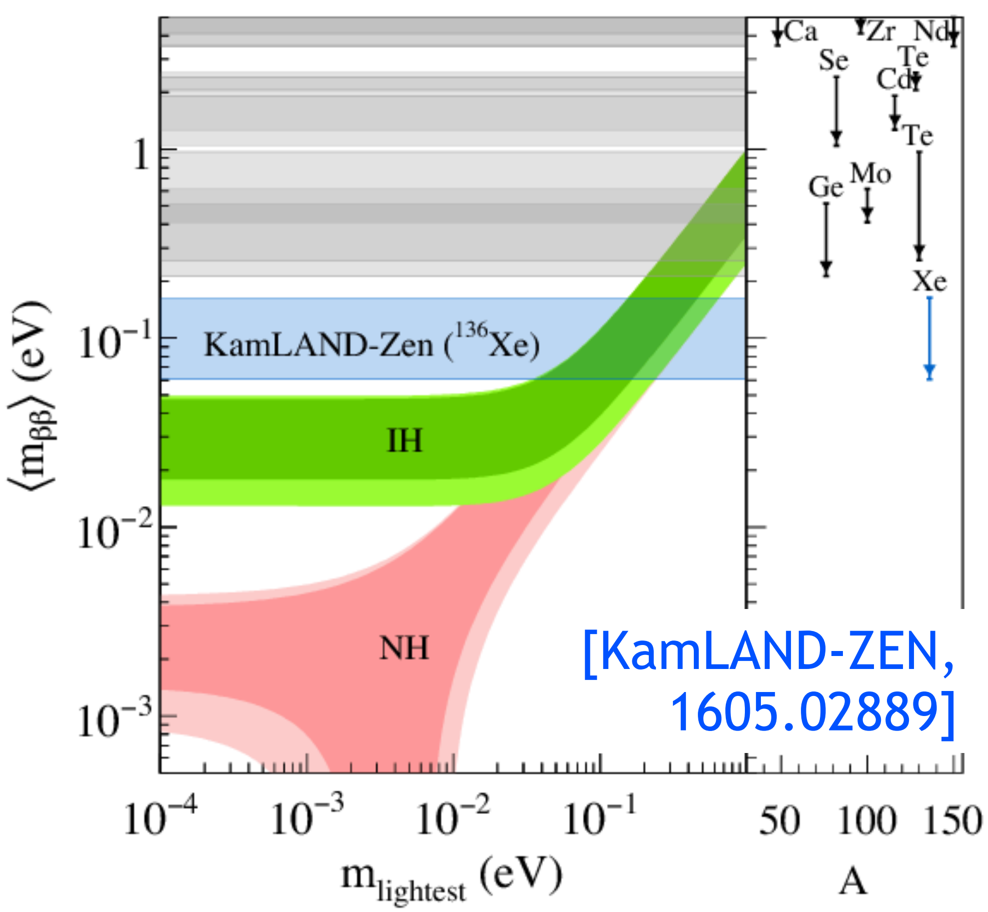
- **Nucleon axial charge $g_A = -F_A(q^2=0)$** key milestone on path to form factors over full kinematic range
- First lattice-QCD calculation with physical-mass pions & all systematics controlled by PNDME, PRD94 (2016) no.5, 054508], with independent confirmation by CallLat, 1704.01114
    - *New results agree with experimental determinations!*
    - Present lattice-QCD errors still > 10× larger
- **In few years, expect ~1% g_A & few-percent vector and axial-vector form factors**, with independent calculations providing checks



[plot courtesy of H.-W. Lin]

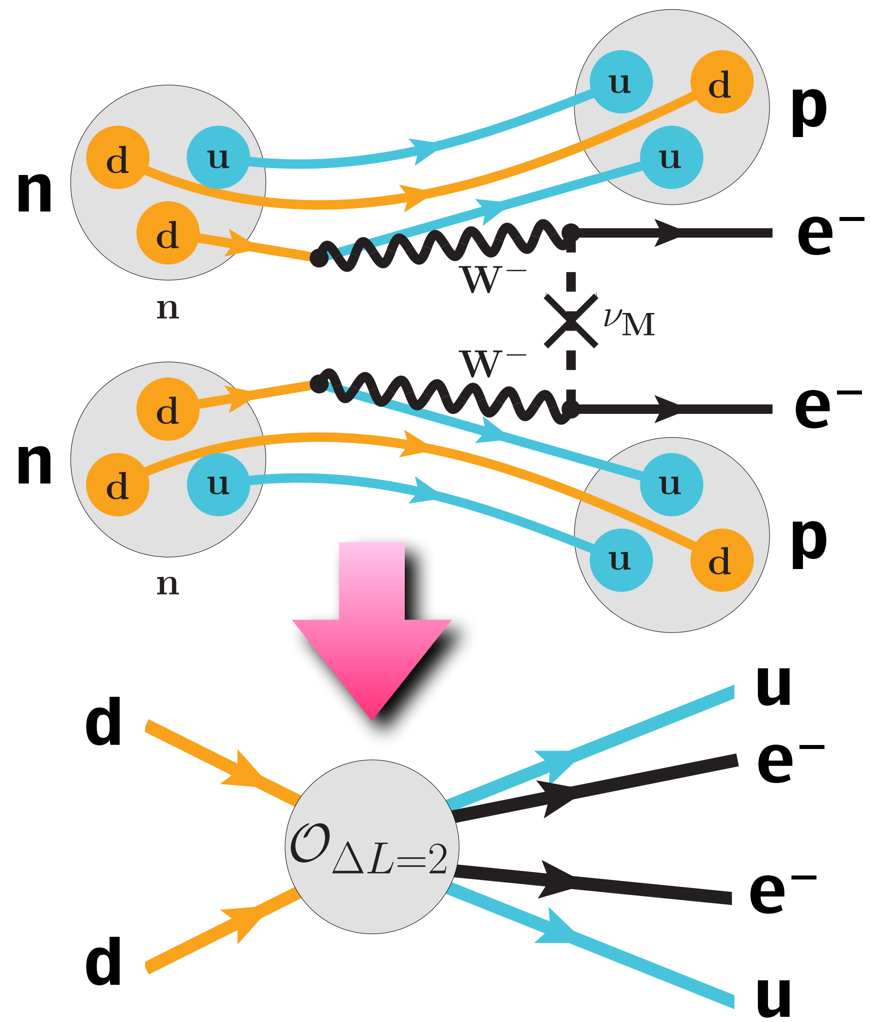
Neutrinoless double β-decay experiments

- 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 $O_{\Delta L=2}$



HIGH-SCALE THEORY

LOW-ENERGY THEORY

- First LQCD calculation of hadronic matrix elements underway [Nicholson et al., arXiv:1608.04793]

Quark-flavor-physics references

- "Lattice Quantum Chromodynamics" (Laiho, Sharpe, Hashimoto, PDG 2015)
- 2016 "Review of lattice results concerning low-energy particle physics" (Flavor Lattice Averaging Group)
- "Leptonic Decays of Charged Pseudoscalar Mesons: 2015" (Rosner, Stone, RV for PDG)
- "Light flavour physics" (Jüttner, Lattice 2015)
- "CP violation & Kaon weak matrix elements from LQCD" (Garron, Chiral Dynamics 2015)
- "Progress and prospects for heavy flavour physics on the lattice" (Pena, Lattice 2015)
- "Testing the Standard Model under the weight of heavy flavors" (Bouchard, Lattice 2015)