Recent Developments in Lattice QCD: Flavor Physics Highlights

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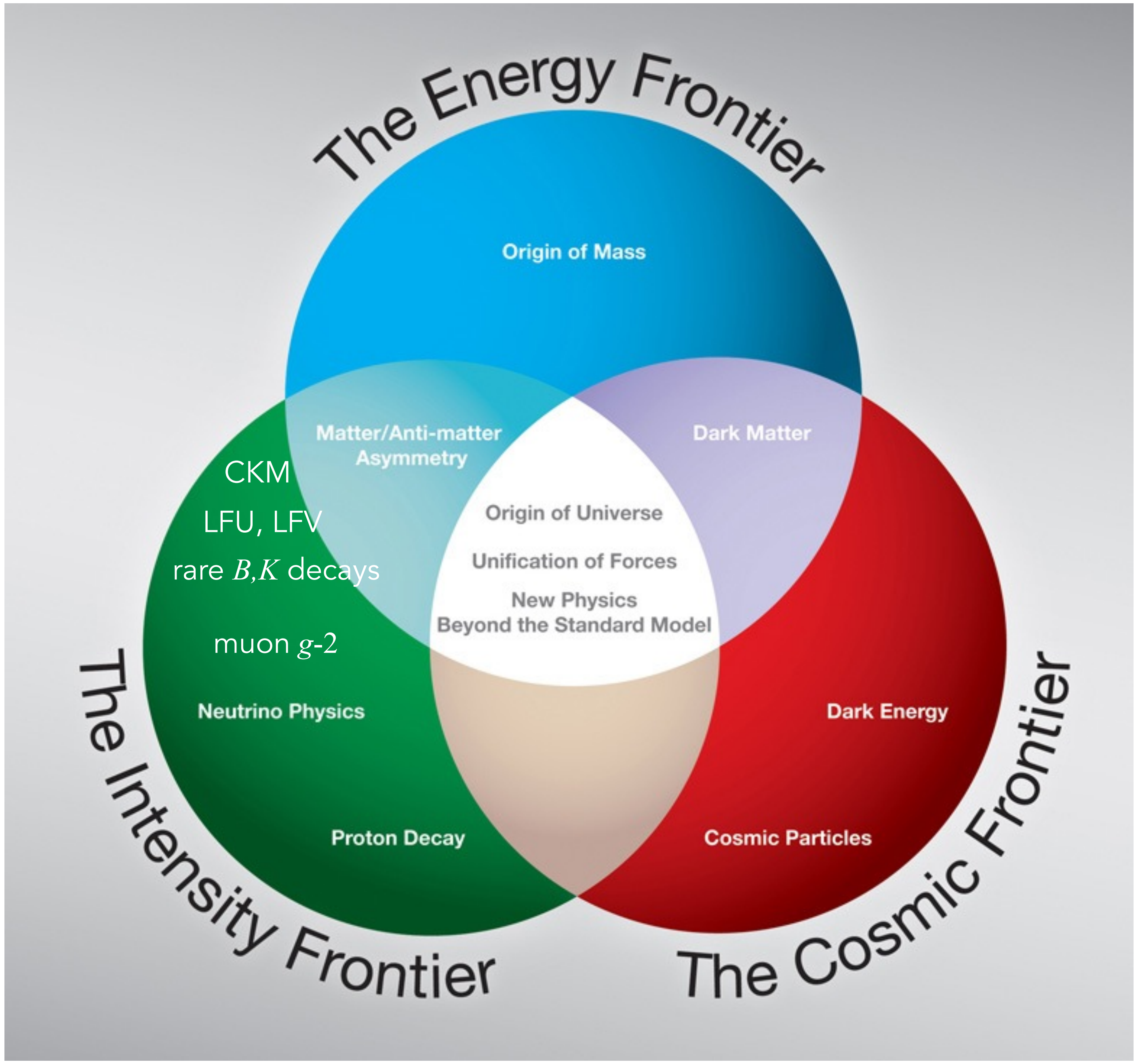
Outline

- Motivation and Introduction
- Quark Flavor Physics
- hadronic corrections to the muon g-2
- Nucleon matrix elements
- Summary and Outlook

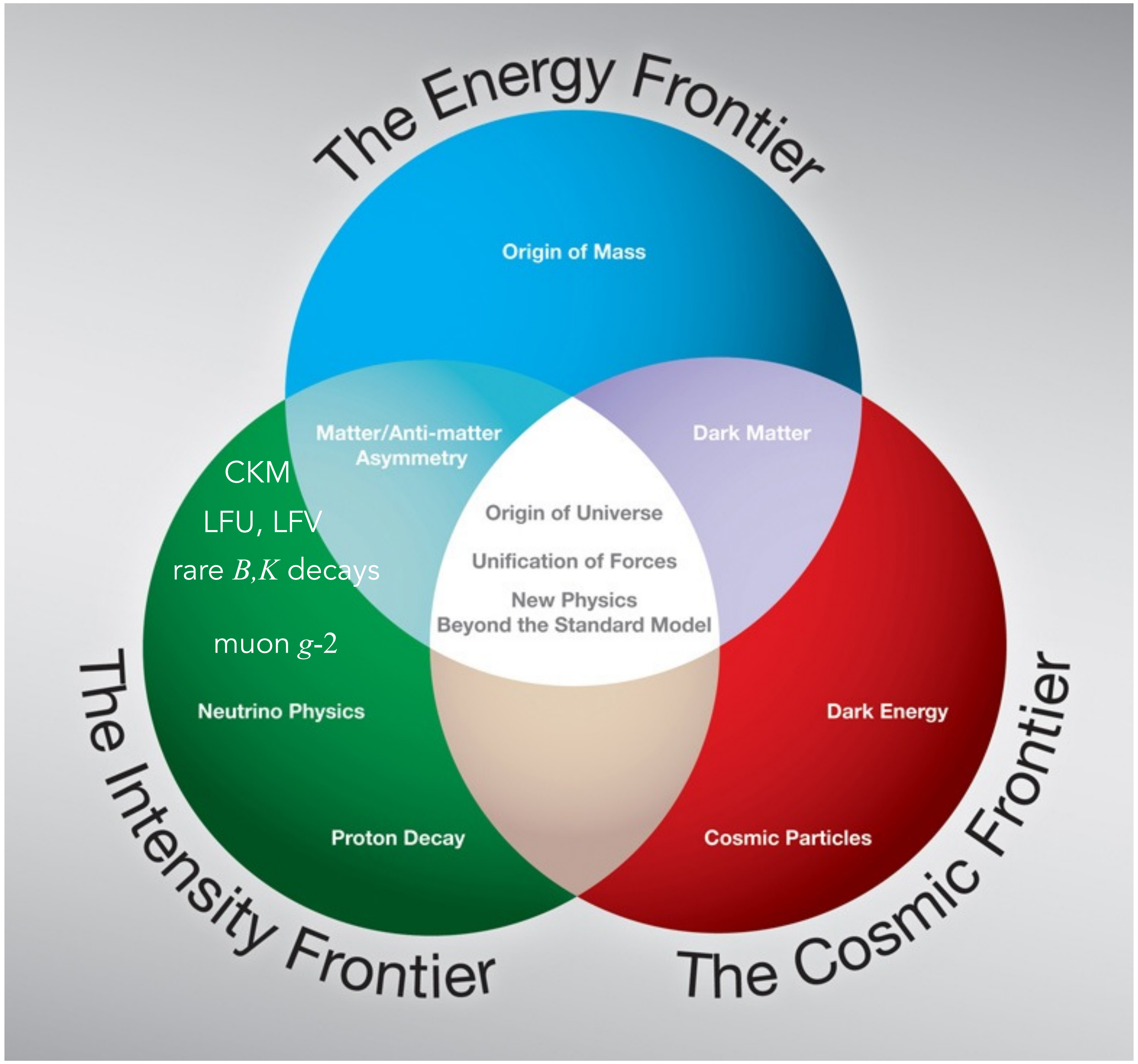
Introduction

HEP research efforts at the three frontiers are connected by the common goal to discover and understand NP …



Introduction

… and by QCD effects:



Introduction

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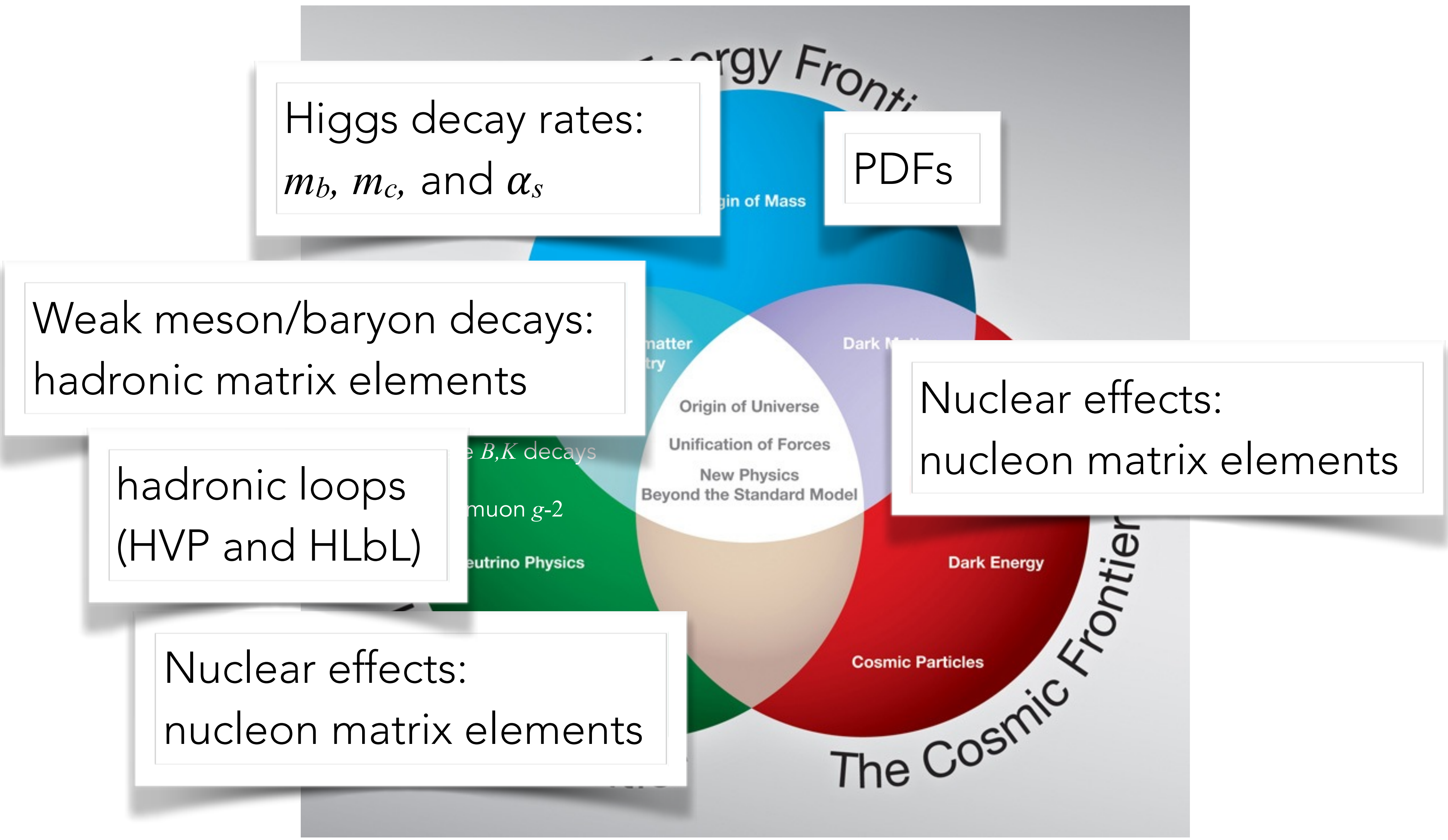


Introduction

… and by QCD effects:

Desired information on

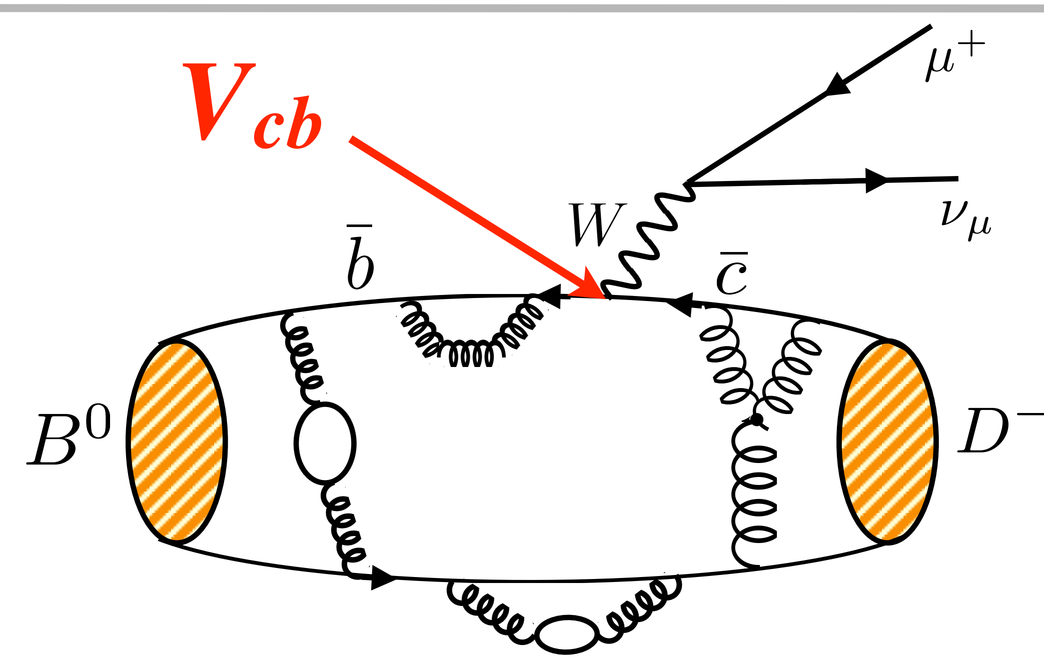
short-distance physics (BSM particles, DM, …) or fundamental parameters (CKM, m_q, α_s, θ_{23},…)

is hidden by hadronic/nuclear effects (nonperturbative QCD).

➠ need precise QCD calculations to complement experimental measurements: Lattice QCD

Introduction: quark flavor physics

example: $B^0 \to D^- \mu^+ \nu_\mu$



Experiment vs. SM theory:

(experiment) = (known) x (**CKM factors**) x (had. matrix element)

$$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2}, \frac{d\Gamma(B \to K\ell^+\ell^-)}{dq^2}, \ldots$$

$$\frac{d\Gamma(B \to D\ell\nu)}{d\omega}, \frac{d\Gamma(B \to D\tau\nu)}{d\omega}, \ldots$$

$$\Delta m_{d(s)}$$

⋮

Lattice QCD

parameterize the MEs in terms of form factors, decay constants, bag parameters, ...

Introduction: quark flavor physics

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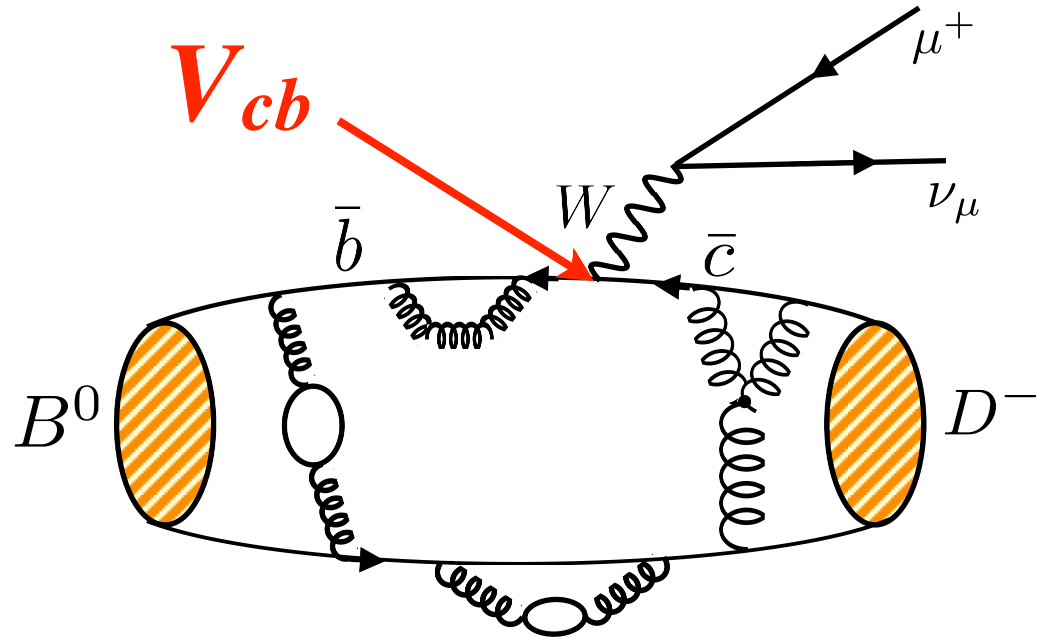


Experiment vs. SM theory:

(experiment) = (known) x (**CKM factors**) x (had. matrix element)

Two main purposes:

- ✦ combine experimental measurements with LQCD results to determine CKM parameters.
- ✦ confront experimental measurements of rare processes or lepton flavor (universality) violating observables with SM theory using LQCD inputs.

Lattice QCD

parameterize the MEs in terms of form factors, decay constants, bag parameters, ...

Introduction

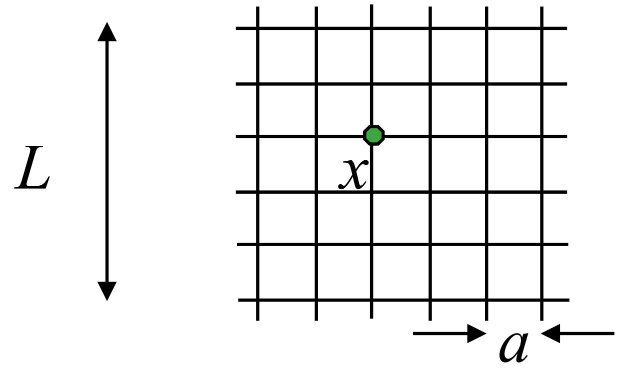
Rich program of ongoing/planned Lattice QCD calculations in support of experiments at all three frontiers…

- Quark flavor physics (LHCb, Belle-2, BaBar, BES III, NA 62,…):
  decay constants, form factors, mixing matrix elements, amplitudes…
- Muon g-2 (Fermilab and J-PARC experiments):
  hadronic corrections (HVP and HLbL)
- Neutrino, DM experiments (DUNE, NOνa, μBooNE, T2K, Mu2e, LZ, SuperCDMS,…):
  Nucleon matrix elements
- Higgs properties (LHC, ILC, …):
  quark masses and strong coupling
- LHC physics:
  PDFs
- …

…aligned with the P5 physics drivers

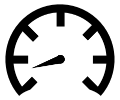
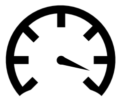
Lattice QCD Introduction

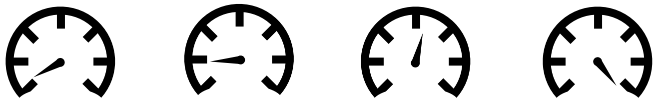
$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}\mathrm{tr} F_{\mu\nu}F^{\mu\nu}$$



- ✦ discrete Euclidean space-time (spacing a)
  derivatives ➙ difference operators, etc…
- ✦ finite spatial volume (L)
- ✦ finite time extent (T)

adjustable parameters

- ❖ lattice spacing: $a \to 0$ 
- ❖ finite volume, time: $L \to \infty,\ T > L$ 
- ❖ quark masses (m_f): $M_{H,\mathrm{lat}} = M_{H,\mathrm{exp}}$
  tune using hadron masses $m_f \to m_{f,\mathrm{phys}}$
  extrapolations/interpolations



m_{ud} m_s m_c m_b

Lattice QCD Introduction

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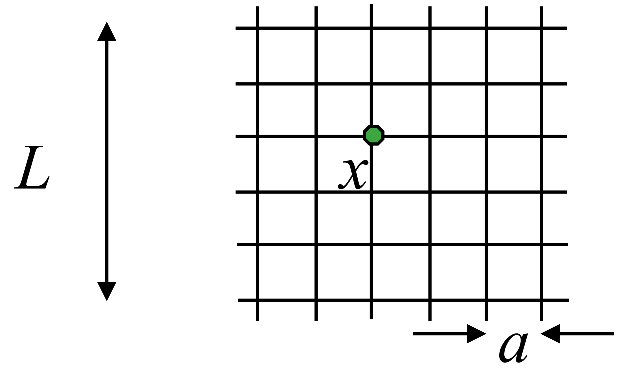

- ✦ discrete Euclidean space-time (spacing a)
  derivatives → difference operators, etc…
- ✦ finite spatial volume (L)
- ✦ finite time extent (T)

Integrals are evaluated numerically using monte carlo methods.

adjustable parameters

- ❖ lattice spacing: $a \to 0$
- ❖ finite volume, time: $L \to \infty,\ T > L$
- ❖ quark masses (m_f): $M_{H,\rm lat} = M_{H,\rm exp}$, $m_f \to m_{f,\rm phys}$

  tune using hadron masses
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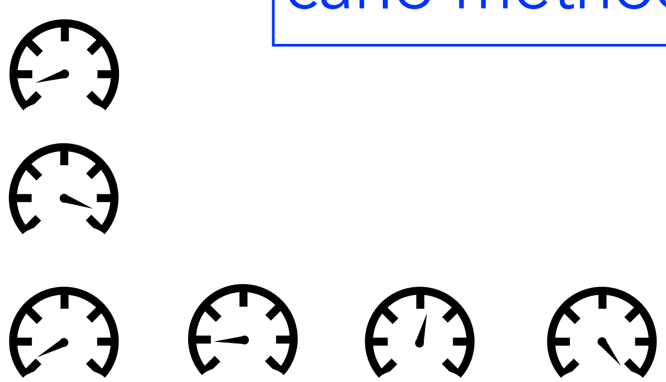
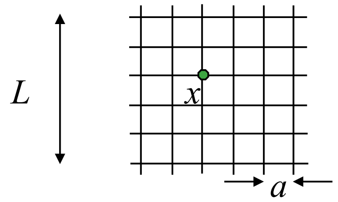


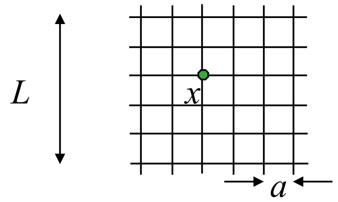
m_{ud} m_s m_c m_b



Lattice QCD Introduction

The State of the Art

- ☆ Lattice QCD calculations of simple quantities (with at most one stable meson in initial/final state) that **quantitatively account for all systematic effects** (discretization, finite volume, renormalization,…) , in some cases with
    - sub percent precision.
    - total errors that are commensurate (or smaller) than corresponding experimental uncertainties.
- ☆ Scope of LQCD calculations is increasing due to continual development of new methods:
    - baryons
    - nonleptonic decays ($K \to \pi\pi$, …)
    - resonances, scattering, long-distance effects,
    - QED effects
    - …



Lattice QCD Introduction

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☆ Lattice QCD calculations of simple quantities (with at most one stable meson in initial/final state) that **quantitatively account for all systematic effects** (discretization, finite volume, renormalization,…) , in some cases with

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☆ Scope of LQC … development of new methods:

- baryons
- nonleptonic decays ($K \to \pi\pi$, …)
- resonances, scattering, long-distance effects,
- QED effects
- …

See appendix for:

- more detailed introduction to LQCD
- LQCD success examples

Quark Flavor: CKM determinations

V_{ud} $\pi \to \mu\nu$	V_{us} $K \to \pi \ell\nu$ $K \to \mu\nu$	V_{ub} $B \to \pi \ell\nu,\ B_s \to K \ell\nu$ $\Lambda_b \to p \ell\nu$
V_{cd} $D \to \pi \ell\nu$ $D \to \ell\nu$	V_{cs} $D \to K \ell\nu$ $D_s \to \ell\nu$	V_{cb} $B_{(s)} \to D_{(s)}, D^*_{(s)} \ell\nu$
V_{td} $B^0 - \overline{B^0}$ $B \to \pi \ell\ell$	V_{ts} $B_s^0 - \overline{B_s^0}$ $B \to K \ell\ell$	V_{tb}

(ρ, η) $K^0 - \overline{K^0}$

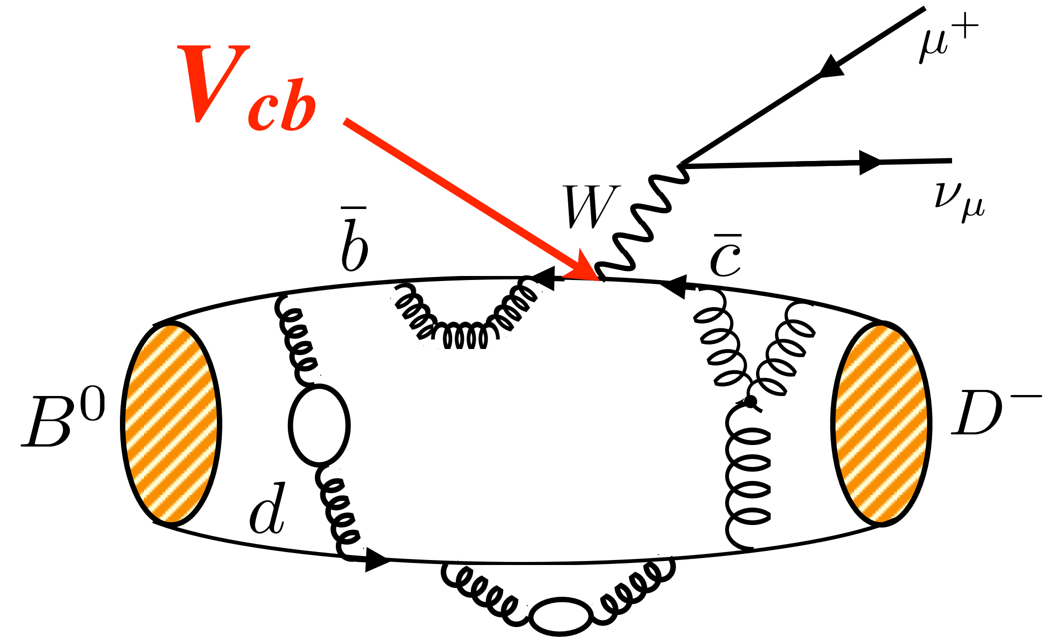
Quark Flavor: CKM determinations

Precise Lattice QCD results **with complete systematic error budgets** now exist for all these processes ➠ improved determinations of the corresponding CKM elements

V_{ud} $\pi \to \mu\nu$	V_{us} $K \to \pi \ell\nu$ $K \to \mu\nu$	V_{ub} $B \to \pi \ell\nu$, $B_s \to K \ell\nu$ $\Lambda_b \to p \ell\nu$
V_{cd} $D \to \pi \ell\nu$ $D \to \ell\nu$	V_{cs} $D \to K \ell\nu$ $D_s \to \ell\nu$	V_{cb} $B_{(s)} \to D_{(s)}, D^*_{(s)} \ell\nu$
V_{td} $B^0 - \overline{B^0}$ $B \to \pi \ell\ell$	V_{ts} $B^0_s - \overline{B^0_s}$ $B \to K \ell\ell$	V_{tb}

(ρ, η) $K^0 - \overline{K^0}$

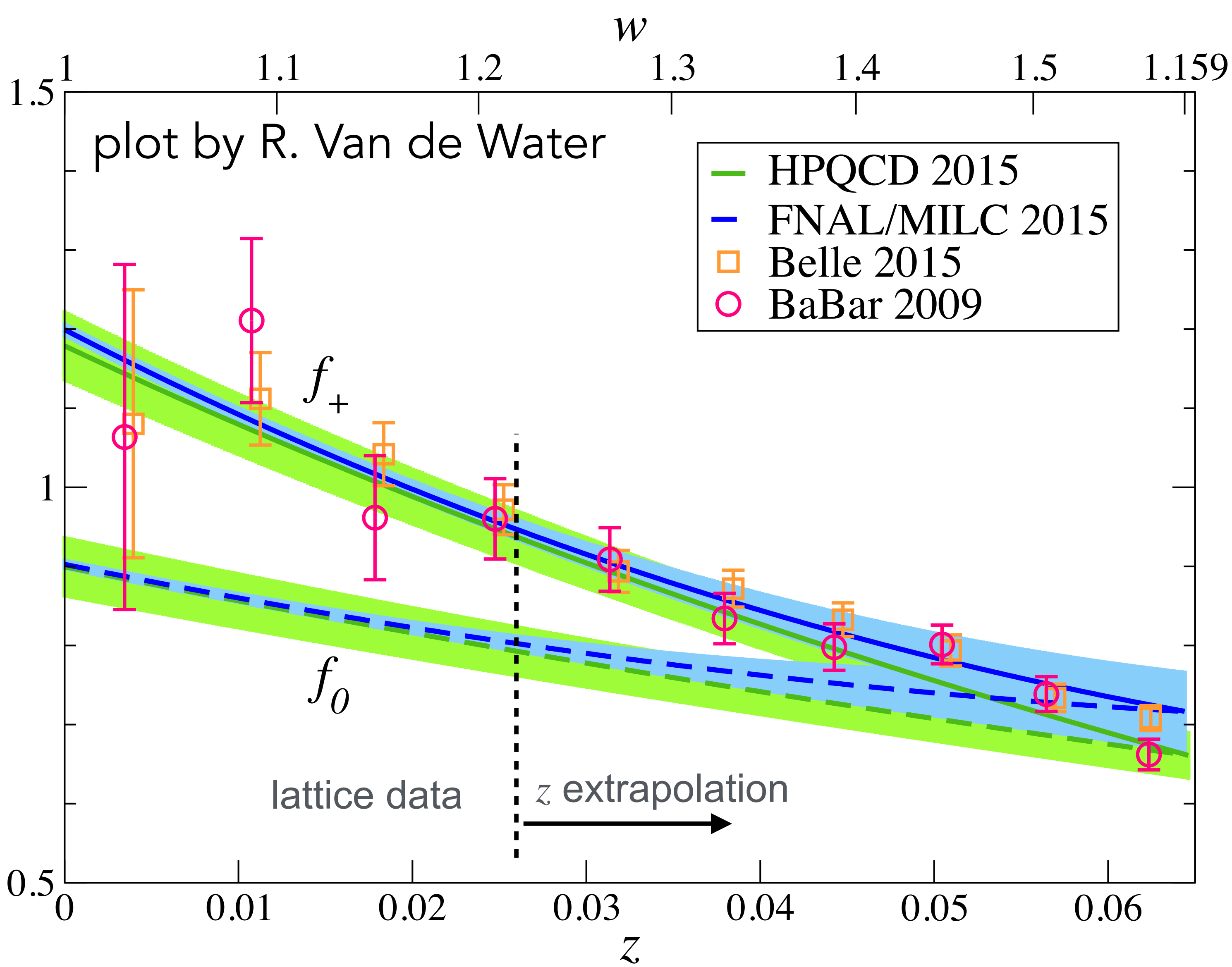
Form factors for $B \to D\,\ell\nu, \quad (\ell = e, \mu, \tau)$



$$\frac{d\Gamma(B \to D\,\mu\nu)}{dq^2} = (\text{known}) \times |V_{cb}|^2 \times f_+^2(q^2)$$

- ⋆ calculate the form factors in the low recoil energy (high q^2) range.
- ⋆ use z-expansion for model-independent parameterization of q^2 dependence.
- ⋆ calculate both form factors, $f_+(q^2), f_0(q^2)$.
- ⋆ for $f_+(q^2)$ compare shape between experiment and lattice.
- ⋆ Tensor form factor(s) are calculable in LQCD using the same methods.

Form factors for $B \to D\,\ell\nu, \quad (\ell = e, \mu, \tau)$



HPQCD (arXiv:1505.03925, PRD 2015)
FNAL/MILC (arXiv:1503.07237, PRD 2015)

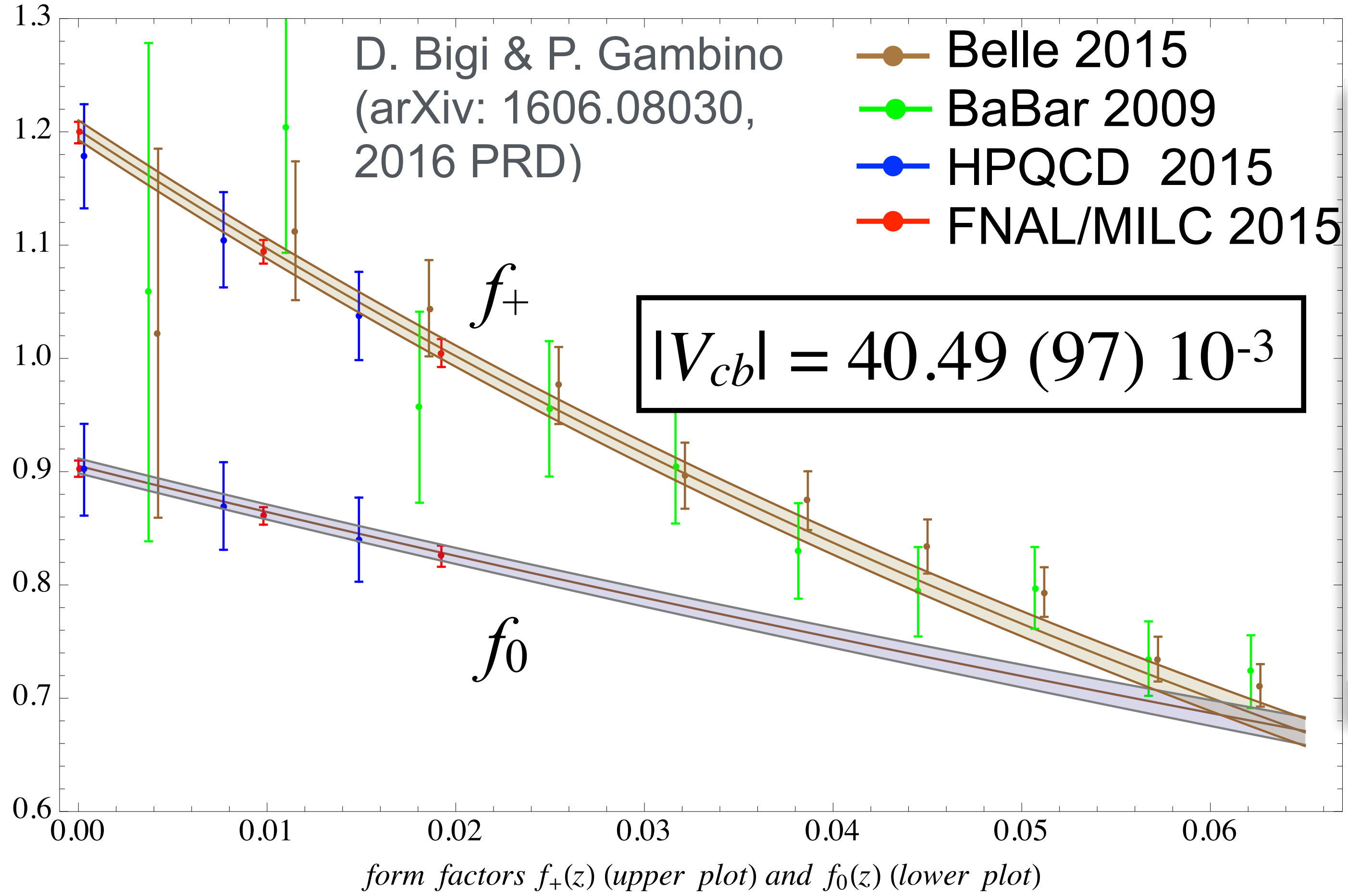
- Two LQCD calculations (FNAL/MILC, HPQCD)
- LQCD form factor uncertainties (~1.2%) smaller than experiment.

- LQCD form factors can be used to calculate the CKM free ratio:

$$R(D) \equiv \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu)}$$

$B \to D\,\ell\nu$ & $|V_{cb}|$

- combine LQCD form factors with experiment, using the BGL (Boyd, Grinstein, Lebed, hep-ph/9508211, 1996 NPB) parameterization:



★ The form factors obtained from the combined exp/lattice fit are well determined over entire recoil range.

★ Can be used for an improved SM prediction of $R(D)$.

- FLAG-3 (S. Aoki et al, arXiv:1607.00299, EPJC 2017) performs a similar combined fit using the BCL (Bourrely, Caprini, Lellouch, arXiv:0807.2722, PRD 09) parameterization.

form factor for $B \to D^* \ell \nu$ at zero recoil and V_{cb}

$$\frac{d\Gamma(B\to D^*\ell\nu)}{d\omega} = (\text{known}) \times |V_{cb}|^2 \times (\omega^2 - 1)^{1/2} |\mathcal{F}(\omega)|^2$$

HFLAV 2016: Use CLN* expression to extrapolate exp. data to ω=1:

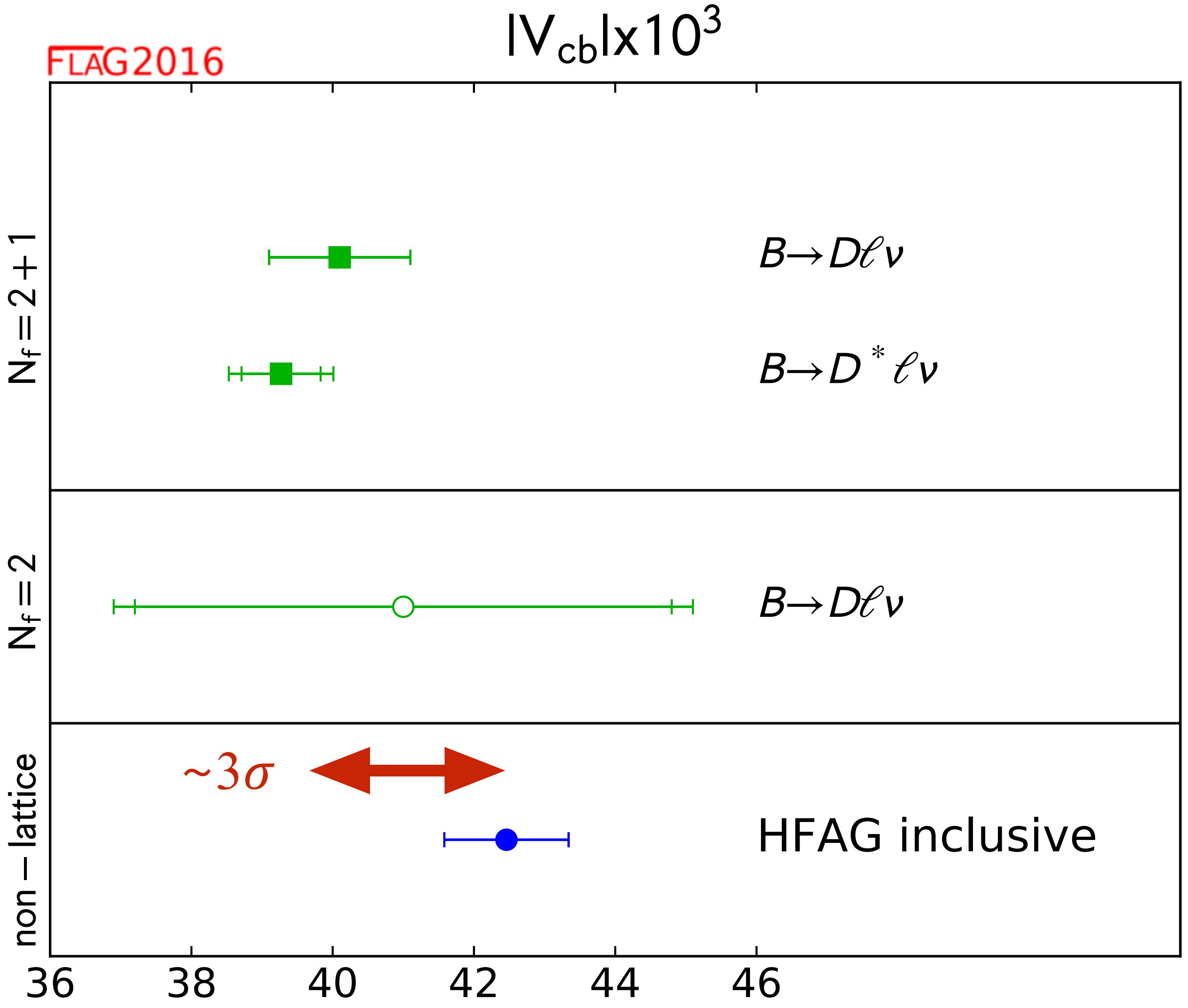
$$B \to D^*\ell\nu: \ \eta_{\mathrm{EW}}|V_{cb}|\mathcal{F}(1) = (35.61 \pm 0.11 \pm 0.41) \times 10^{-3}$$

combine with LQCD calculation of $\mathcal{F}$(1):

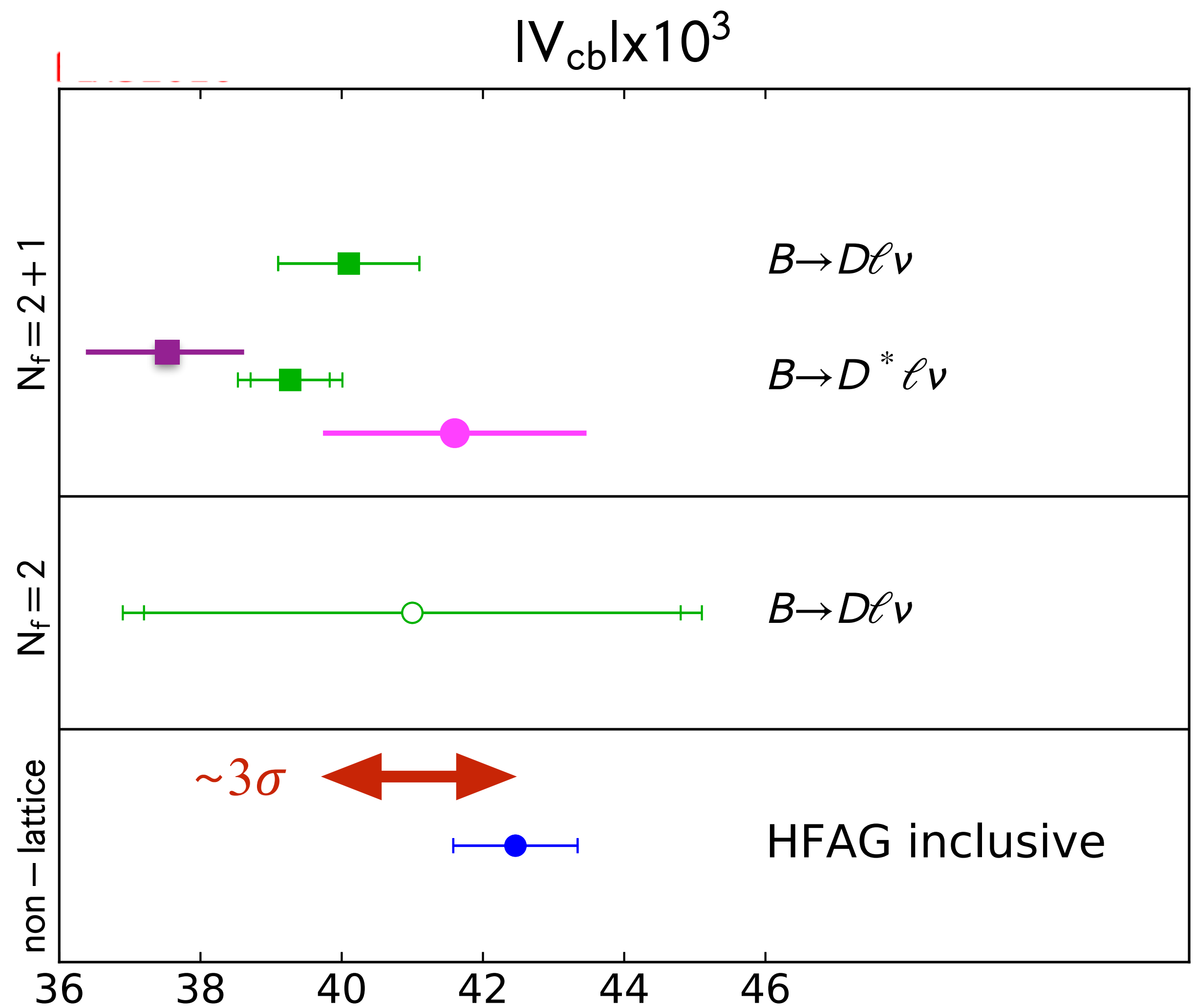
❖ FNAL/MILC 2014 (J. Bailey et al, arXiv:1403.0635, 2014 PRD): $\mathcal{F}(1) = 0.906(4)(12)$

- *CLN (Caprini, Lellouch, Neubert, hep-ph/9712417, NPB 98) is based on the model-independent z-expansion (just like BGL, BCL), but then add model-dependent assumptions about the parameters
  ➟ reduces the error from the extrapolation
- LQCD form factor data for $B \to D^*$ at nonzero recoil are not yet available.

Exclusive $|V_{cb}|$



Exclusive $|V_{cb}|$



New BELLE measurement of $B \to D^*$ decay with CLN extrapolation to w=1 and lattice $\mathcal{F}(1)$ (arXiv:1702.01521)

Two new theory analyses:

- Bigi, Gambino, Schacht (arXiv:1703.06124)
- Grinstein, Kobach (arXiv:1703.08170)

Both use new Belle data and BGL together with lattice $\mathcal{F}(1)$.

- Difference between the new CLN and BGL results hints at possible bias.
- **Need lattice form factor data for $B \to D^*$ at nonzero recoil:**

  combine with experimental data using BGL (same as for $B \to D$)

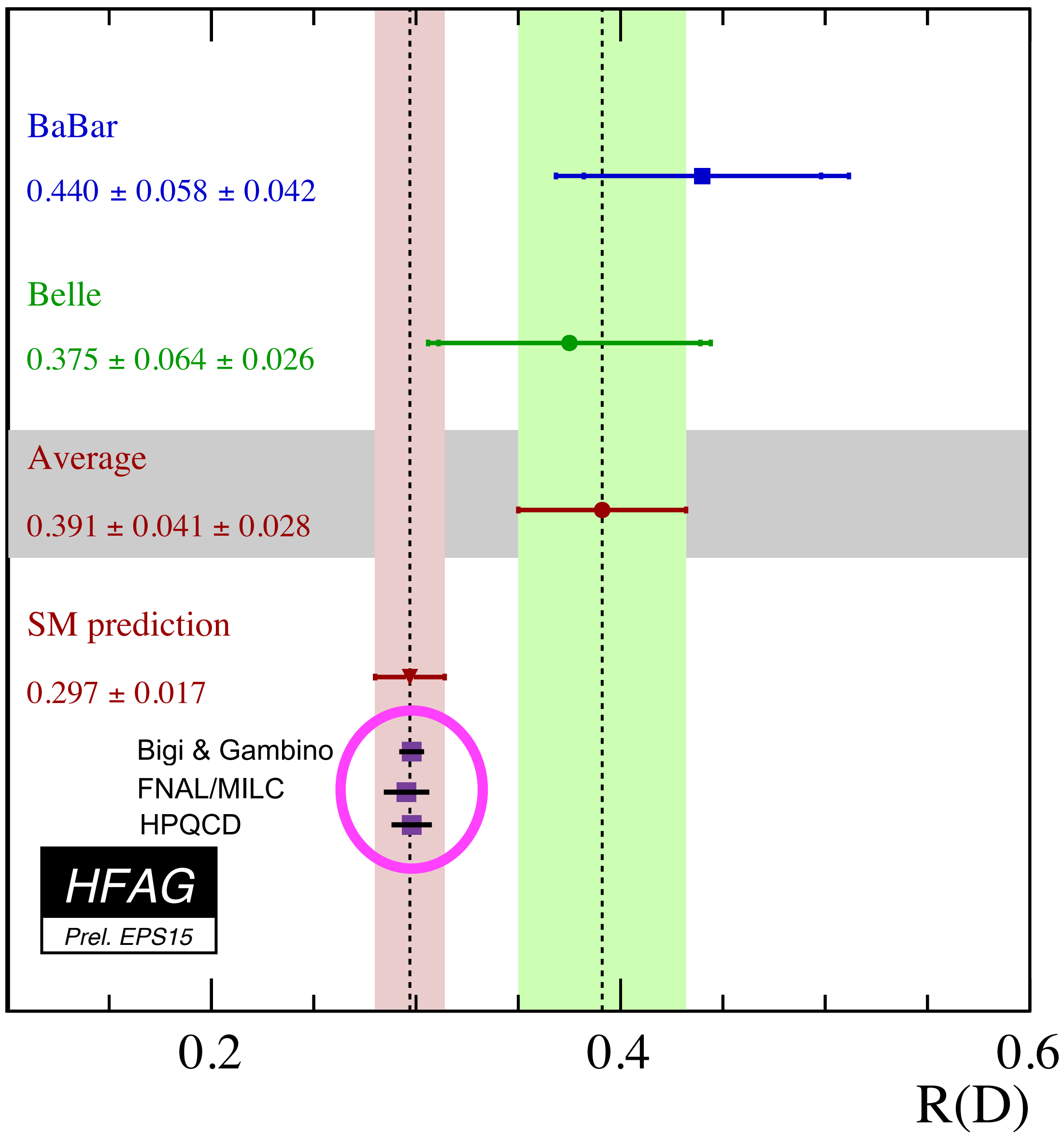
  ➟ improve precision and perhaps resolve exclusive/inclusive tension

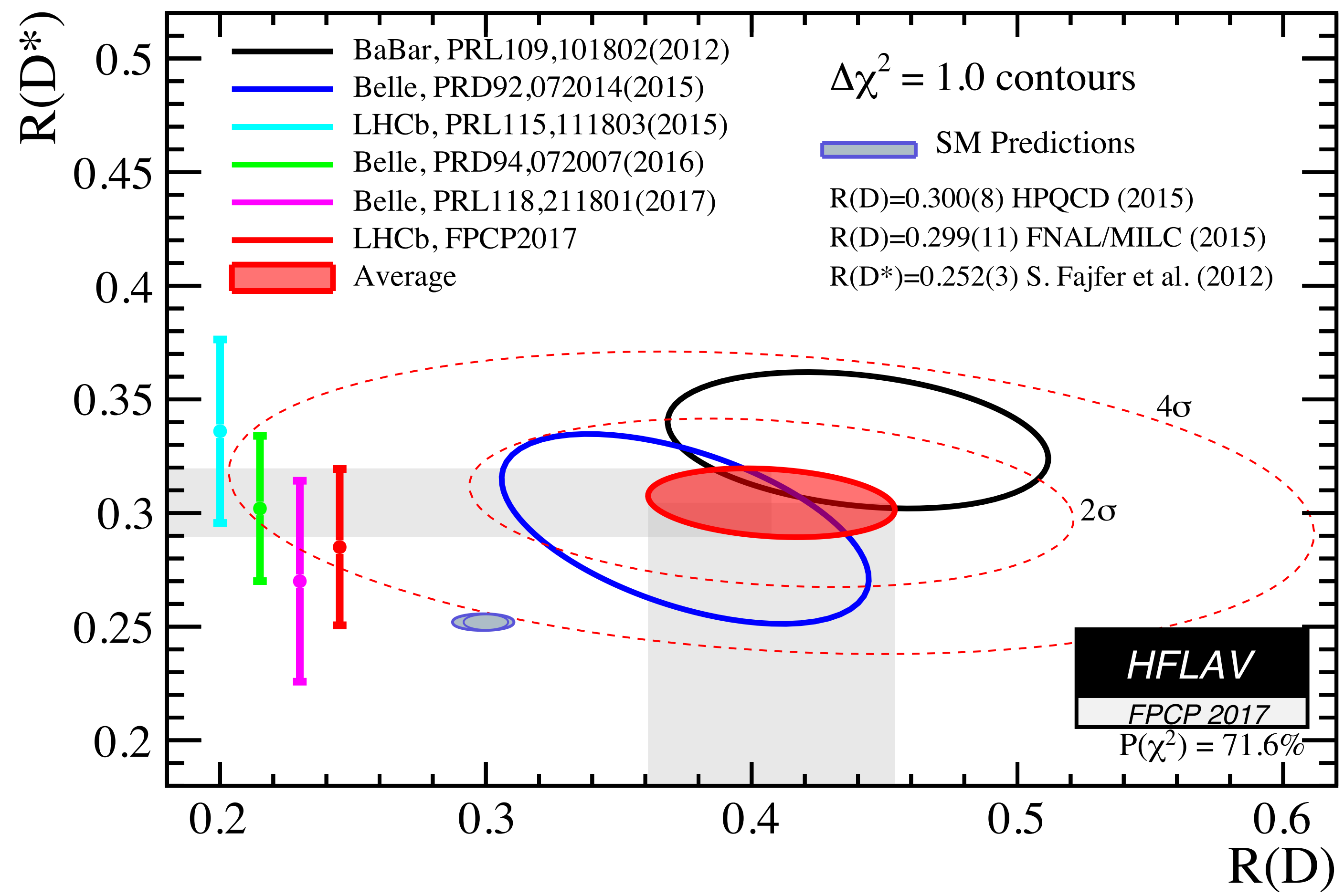
  …. in progress (FNAL/MILC, HPQCD, RBC, LANL/SNU)

BSM phenomenology: LFU τ/ℓ

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

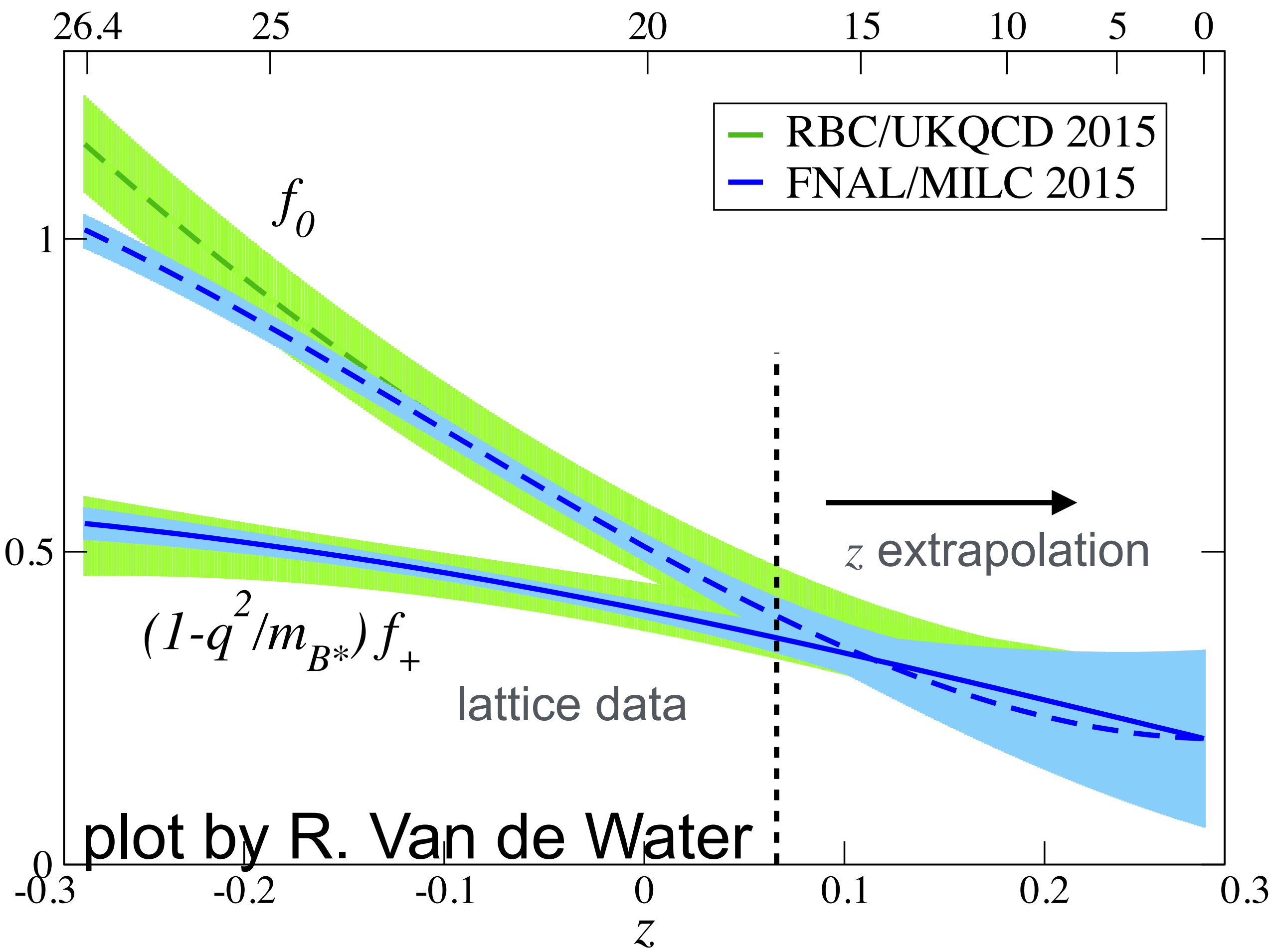
HFLAV (EPS 2015)





HFLAV 2017 average: combined 3.9σ excess

form factors for $B \to \pi \ell \nu$ & V_{ub}



RBC/UKQCD (arXiv:1501.05373, PRD 2015)

FNAL/MILC (arXiv:1503.07839, PRD 2015)

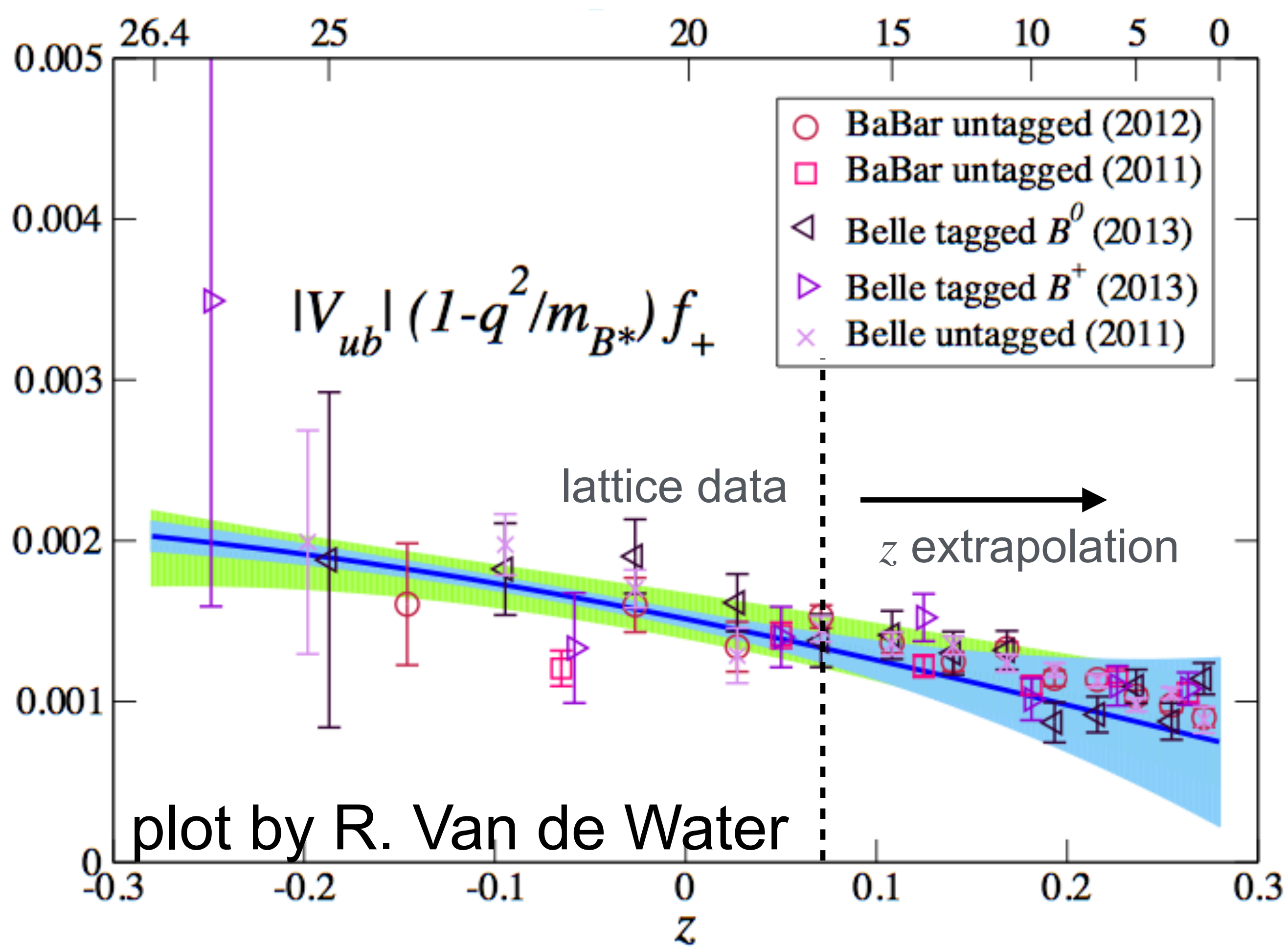
- FNAL/MILC & RBC/UKQCD form factors are in good agreement.

- Two independent LQCD **predictions** for $B_s \to K \ell \nu$ form factors (HPQCD, arXiv:1406.2279, PRD 2014; RBC, arXiv:1501.05373, PRD 2015)
  + ongoing work by FNAL/MILC (see Z. Gelzer talk @11:21 in Curia II)
  and others (see Lattice 2017 talks by …)
- also: LQCD results for form factors for rare ($B \to K, \pi$) decays:

  FNAL/MILC (arXiv:1507.01618, PRL 2015,arXiv:1509.06235, PRD 2016)

  HPQCD (arXiv:1306.0434, 1306.2384, PRL 2013)

form factors for $B \to \pi \ell \nu$ & V_{ub}



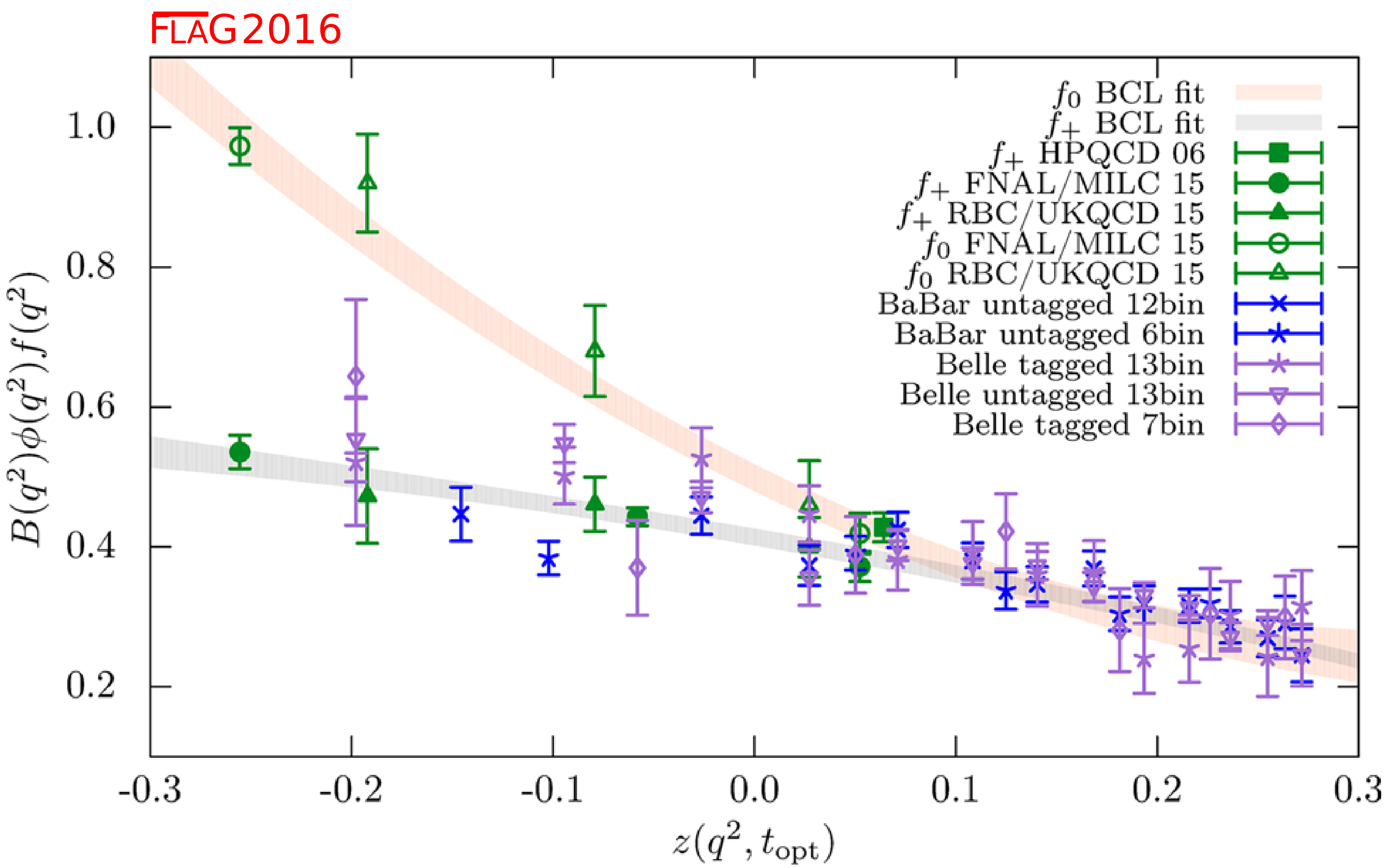
RBC (arXiv:1501.05373, PRD 2015)

FNAL/MILC (arXiv:1503.07839, PRD 2015)

$|V_{ub}| = 3.72\ (16)\ 10^{-3}$

- shape of f_+ agrees with experiment and uncertainties are commensurate
- fit lattice form factors together with experimental data to determine $|V_{ub}|$ **and** obtain form factors (f_+, f_0) with improved precision…
- similar analysis for $|V_{ub}/V_{cb}|$ from Λ_b decay with LHCb (arXiv:1503.01421, PRD 2015; arXiv:1504.01568, Nature 2015).

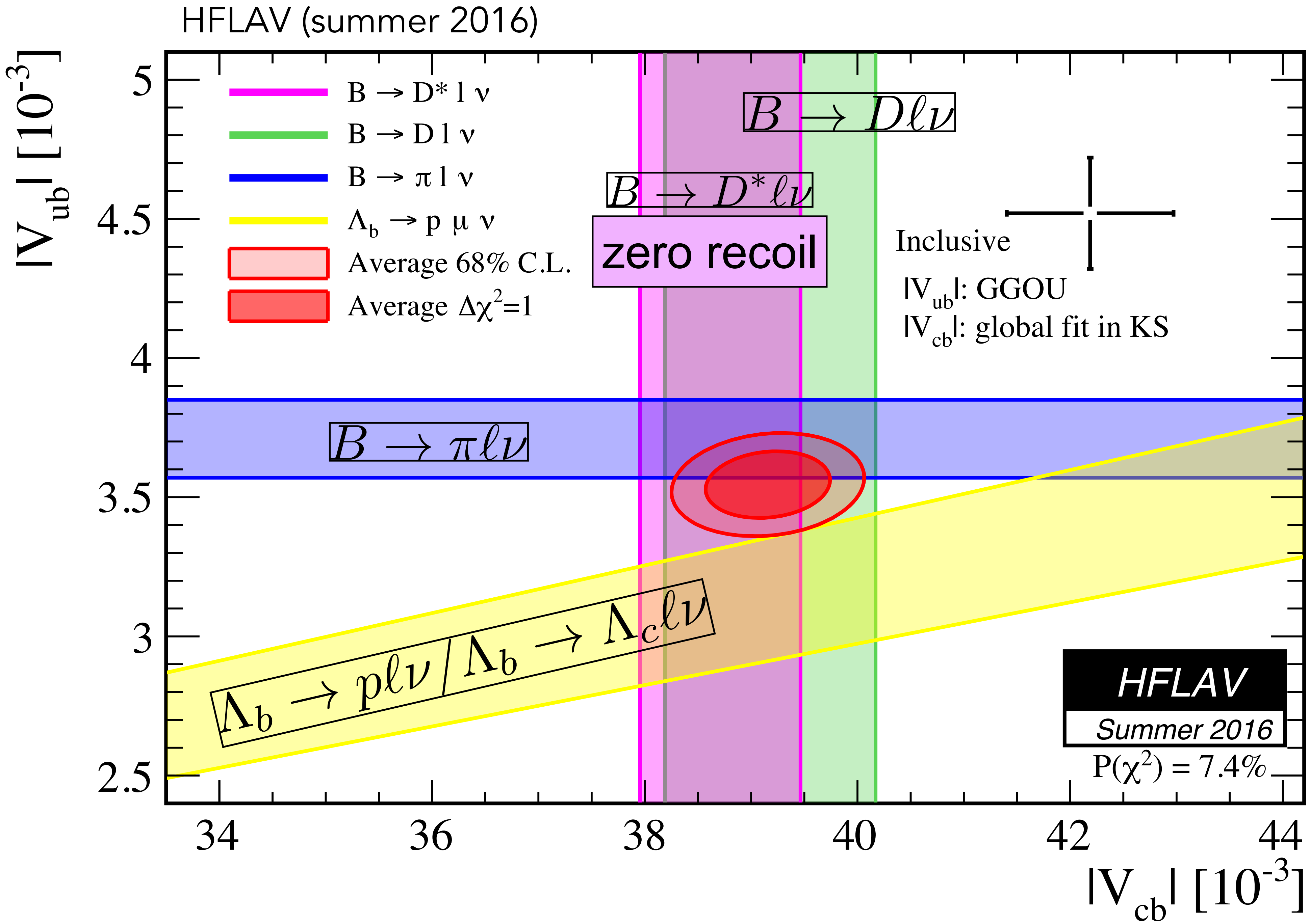
form factors for $B \to \pi \ell \nu$ & V_{ub}



S. Aoki et al (FLAG-3 review, arXiv:1607.00299, 2017 EJPC)

- shape of f_+ agrees with experiment and uncertainties are commensurate
- fit lattice form factors together with experimental data to determine $|V_{ub}|$ **and** obtain form factors (f_+, f_0) with improved precision…
- similar analysis for $|V_{ub}/V_{cb}|$ from Λ_b decay with LHCb (arXiv:1503.01421, PRD 2015; arXiv:1504.01568, Nature 2015).

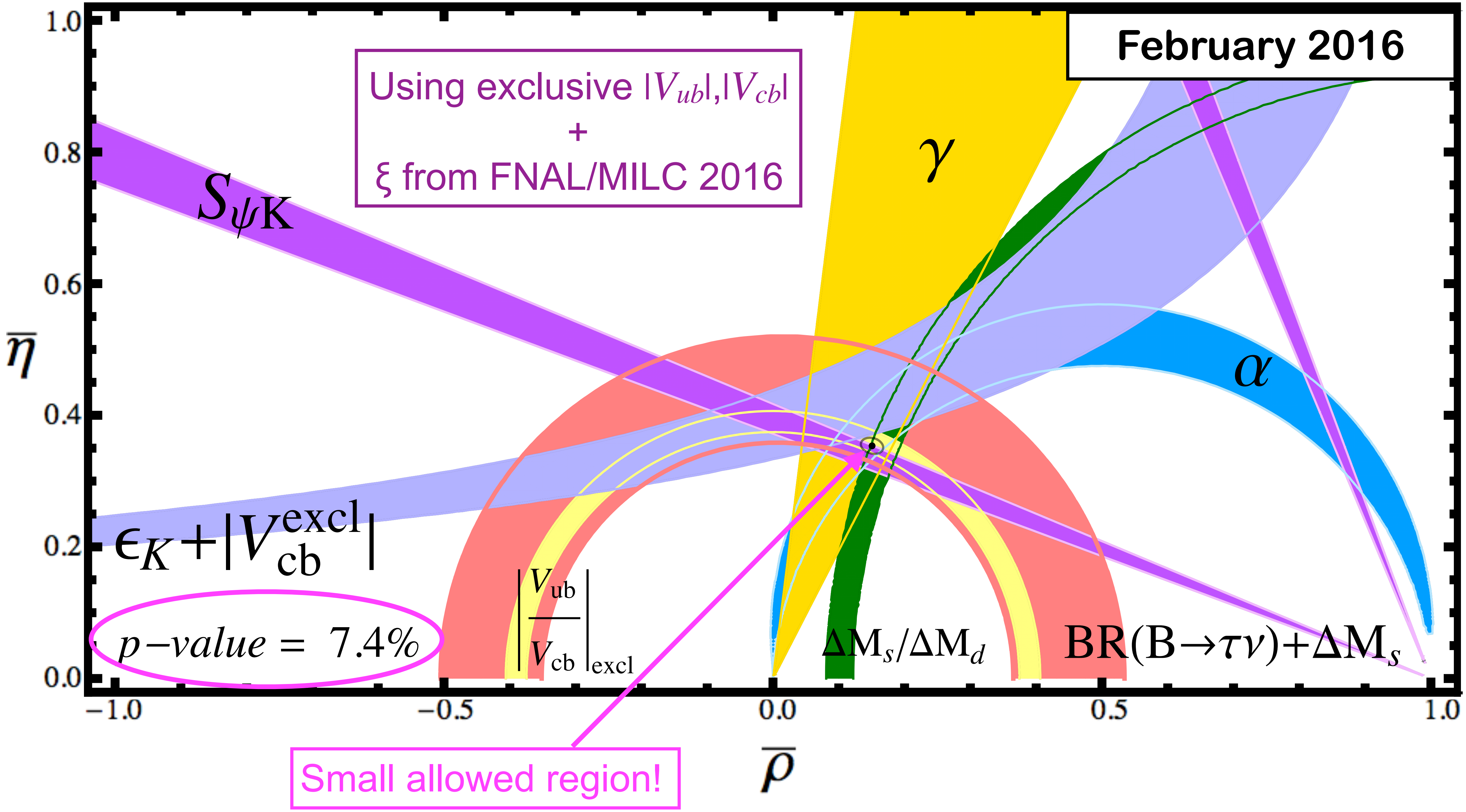
Exclusive vs. inclusive $|V_{cb}|$ and $|V_{ub}|$



~3σ tension between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$

UT analysis

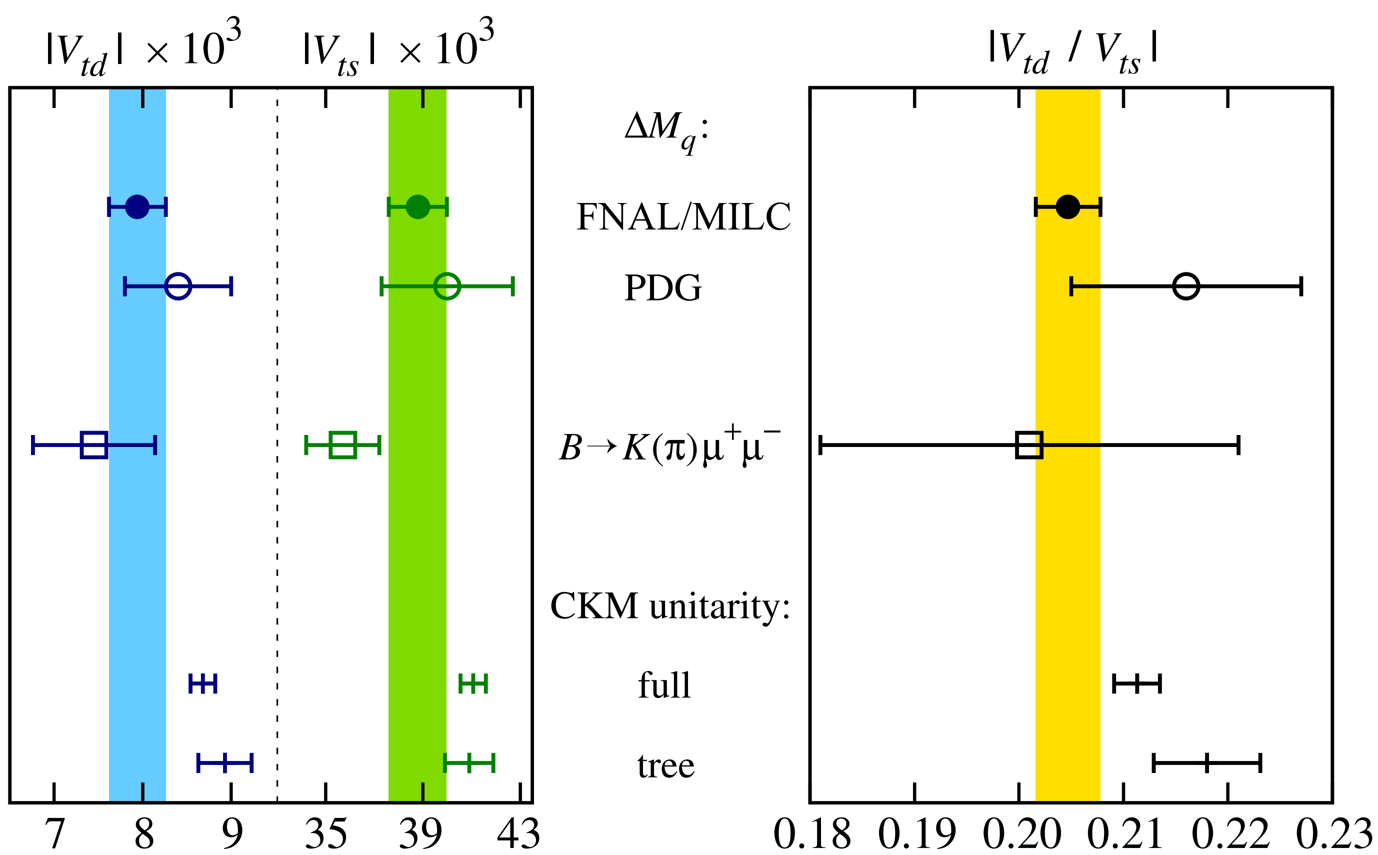
Laiho, Lunghi & Van de Water (Phys.Rev.D81:034503,2010), E. Lunghi, private comm.



Quark flavor: tensions

$B_{(s)}$-meson mixing, $B \to K, \pi\, \ell^+ \ell^-$ and $B_s \to \mu^+ \mu^-$

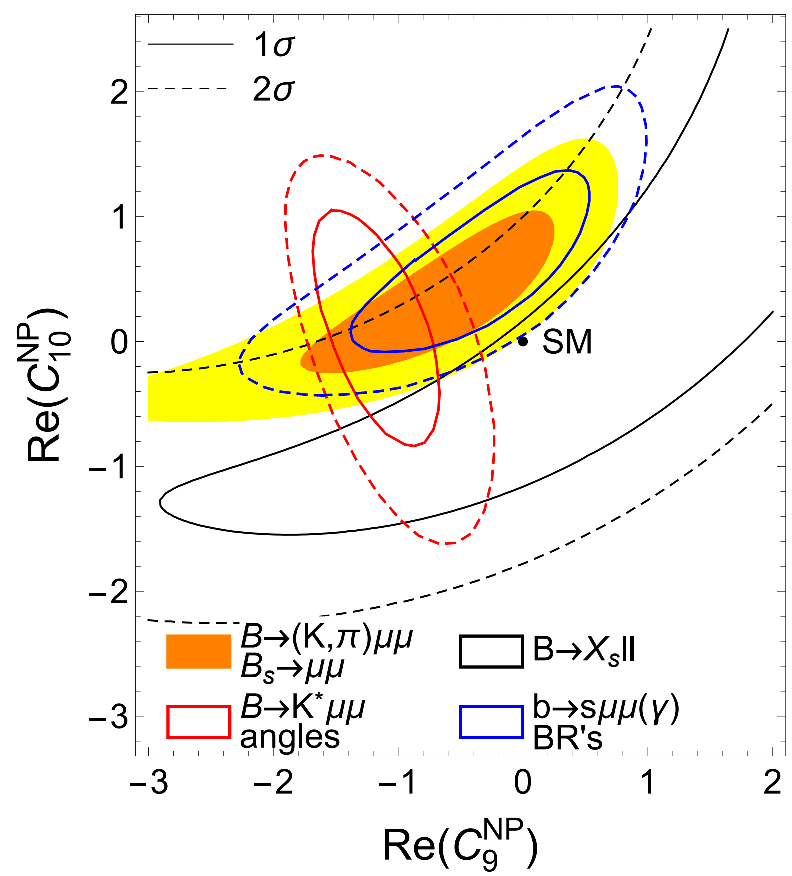
FNAL/MILC (arXiv:1602.03560, PRD 2016)



~2σ tensions between loop processes and CKM unitarity.

D. Du et al (arXiv:1510.02349, PRD 2016)

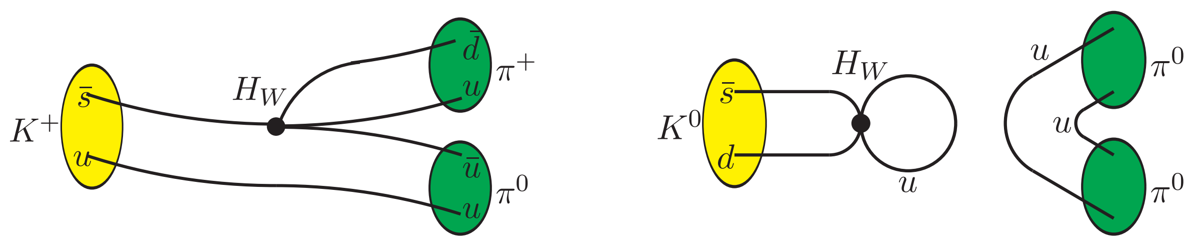
Constraints on Wilson coefficients (C_9, C_{10})



Quark flavor: Kaons - long distance effects

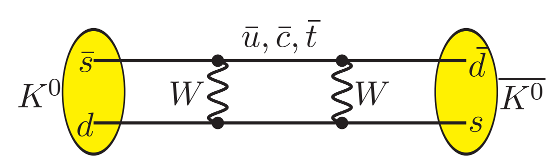
X. Feng (review @ Lattice 2017)

- $K \to \pi\pi$ decays and direct CP violation

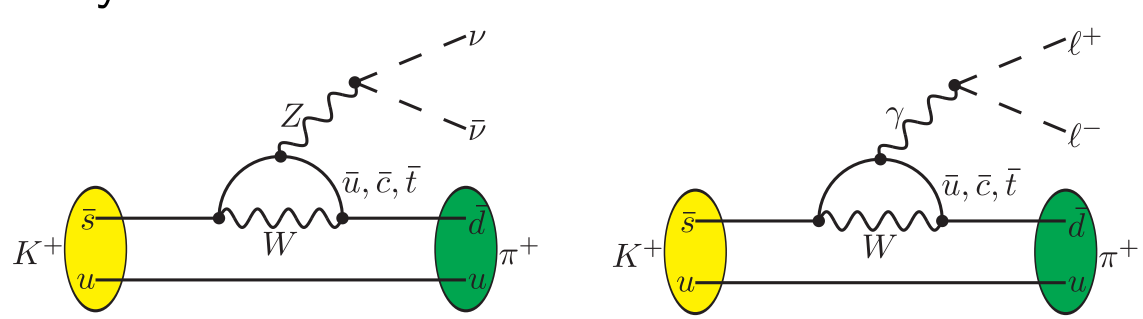


Final state involves $\pi\pi$ (multi-hadron system)

- Long-distance contributions to flavor changing processes
  - ΔM_K and ϵ_K



  - Rare kaon decays: $K \to \pi\nu\bar{\nu}$ and $K \to \pi\ell^+\ell^-$



Hadronic matrix element for bilocal operators

$$\int d^4x \langle f|T[Q_1(x)Q_2(0)]|i\rangle$$

RBC/UKQCD (2015 PRL):

$$\mathrm{Re}[\epsilon'/\epsilon] = 0.14(52)_{\mathrm{stat}}(46)_{\mathrm{syst}} \times 10^{-3}$$

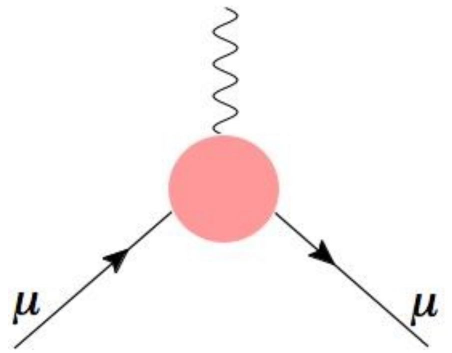
cf. experiment:

$$\mathrm{Re}[\epsilon'/\epsilon] = 1.66(23) \times 10^{-3}$$

~2σ tension

Ongoing work by RBC/UKQCD.

Charged Lepton Flavor: muon g-2



$$= (-i\,e)\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u(p)$$

- muon anomalous magnetic moment: $a_\mu = F_2(0)$
  - is generated by quantum effects (loops).
  - receives contributions from QED, EW, and QCD effects in the SM.
  - is a sensitive probe of new physics.
- QED + EW correction are known precisely:

$$\delta a_\mu^{\text{QED}} \times 10^{11} = 0.08 \qquad \delta a_\mu^{\text{EW}} \times 10^{11} = 1$$

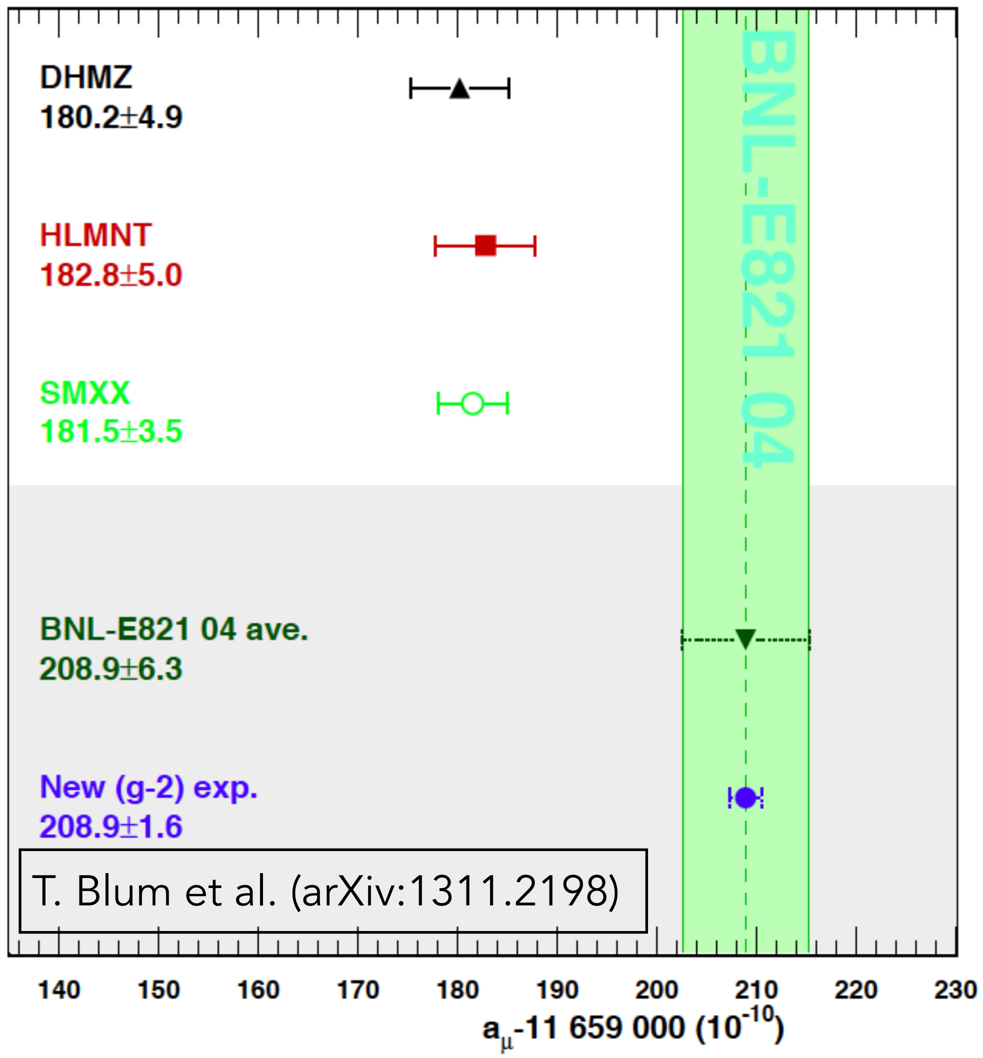
- QCD corrections are the dominant source of error in the SM prediction:

$$\delta a_\mu^{\text{had}} \times 10^{11} \sim 50$$

(Davier et al. 2011, Hagiwara et al 2011, Kurz et al 2014, Prades et al 2009, Colangelo et al 2014, Jegerlehner 2015, Benayoun et al 2015,…)

Charged Lepton Flavor: muon g-2

Experiment vs SM theory



Fermilab g-2 experiment:

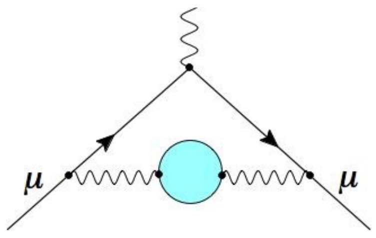
- reduce exp. error by a factor of 4
- first result with "Brookhaven level" statistics expected in 2018.
- Commissioning of beam, ``wiggle party".

J-PARC experiment:

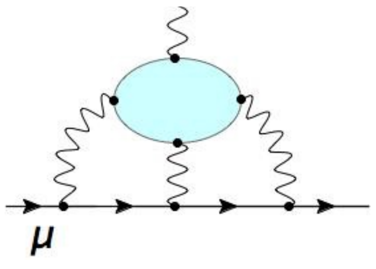
- complementary, different exp. method
- expect measurement at 0.3-0.4 ppm level

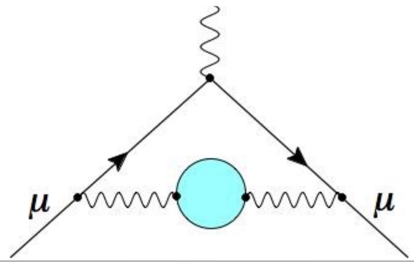
Need to reduce and better control theory errors of the hadronic corrections:

Hadronic Vacuum Polarization



Hadronic Light-by-Light



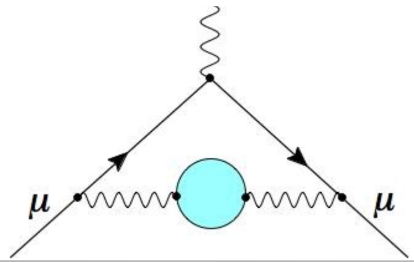


Hadronic vacuum polarization

- ✦ Target: ~0.2% total error
- ✦ Dispersion relation + experimental data for $e^+e^- \to \text{hadrons}$ (and τ data)
  - current uncertainty ~0.4-0.5%
  - can be improved with more precise experimental data
  - new experimental measurements expected/ongoing at BaBar, BES-III, Belle/Belle-II, CMD-3, SND, KLOE,….
- ✦ **Complete lattice QCD results by several groups. First with ~1.8% total error by HPQCD.** LQCD calculations need to
  - be based on physical mass ensembles
  - include disconnected contributions
  - include QED and strong isospin breaking corrections ($m_u \neq m_d$)
  - include finite volume corrections

see R. Van de Water talk (Wednesday, 2:42pm, Curia II)

- ✦ Compare intermediate quantities (moments, Taylor coefficients) with R-ratio data.
- ✦ Hybrid method: combine LQCD with R-ratio data (Lehner @ Lattice 2017)



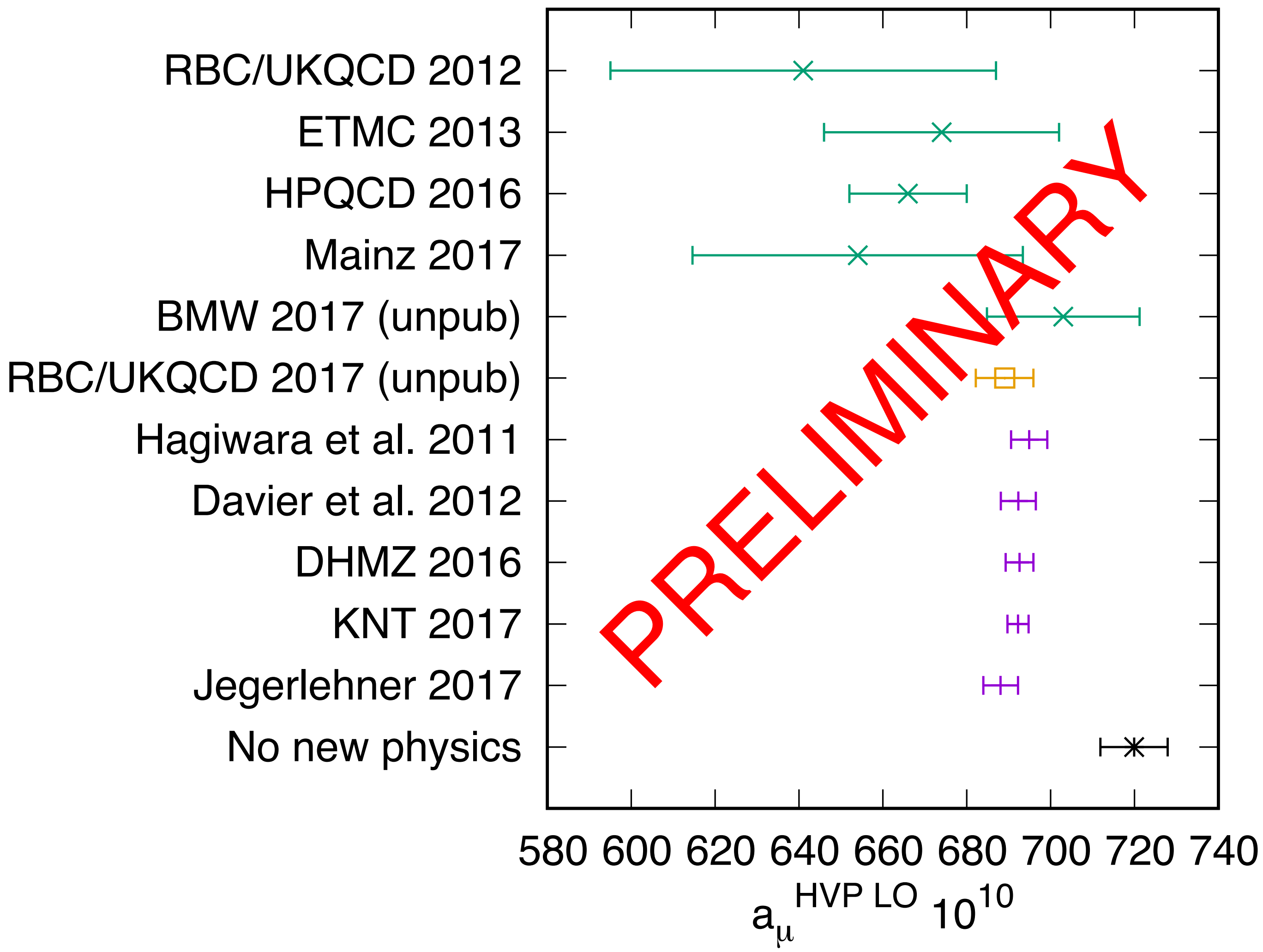
Hadronic vacuum polarization

Hybrid method: combine LQCD with R-ratio data

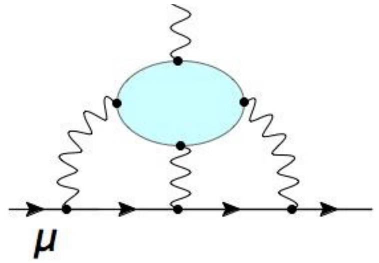
(C. Lehner @ Lattice 2017)

LQCD calculations of HVP are still much less precise than dispersive method.
But comparisons between R-ratio and lattice data are already useful.

(C. Lehner @ Lattice 2017)



- Convert R-ratio data to Euclidean correlation function (via the dispersive integral).
- Compare lattice/R-ratio data (after adding all the corrections and extrapolating to continuum, infinite volume).
- Use R-ratio data where LQCD errors are large and vice versa.
- Potential for obtaining HVP with reduced error.



Hadronic Light-by-light

Hadronic light-by-light:

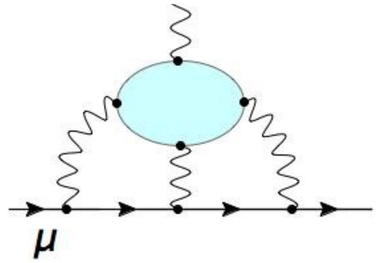
- ✦ Target: ≲ 10% total error
- ✦ current estimate "Glasgow consensus" based on different QCD models
- ✦ theory error not well determined and not improvable

Dispersive approach:

- ✦ more complicated than for HVP
  (Colangelo et al, arXiv:1702.07347; Kubis et al, 2012, 2014; Hoferichter et al, 2012, 2014; Hanhardt et al, 2013; Pascalutsa et al, Pauk et al, Danilkin et al,…)
- ✦ combine with exp. data and/or LQCD calculations

Direct lattice QCD calculations:

- ✦ QCD + stochastic QED
  (Jin et al, arXiv:1610.04603, 2016 PRL; arXiv:1705.01067)
- ✦ QCD + exact QED kernel
  (Asmussen @Lattice 2017; Green et al, arXiv:PRL 2015)
- ✦ dominant contribution from pion pole (transition form factors)
  (Gerardin et al, arXiv:1607.08174, 2016 PRD; Lattice 2017)



Hadronic Light-by-light

Breakthrough (RBC/UKQCD):

First LQCD calculation of connected and leading disconnected contribution with good statistical significance (T. Blum et al, arXiv:1610.04603, 2017 PRL).

$$a_\mu^{\mathrm{HLbL}} = (5.35 \pm 1.35) \times 10^{-10}$$

- ✦ a = 0.11 fm, L = 5.5 fm, physical pion mass, statistical error only.
- ✦ systematic error analysis (finite volume, continuum limit, …) in progress.
- ✦ also: recent work (arXiv:1705.01067) yields exponentially suppressed FV errors.

Mainz group: progress @ Lattice 2017

- ✦ First numerical tests of formulation for direct calculation (Asmussen)
- ✦ New results for the pion transition form factor (Gerardin)

Muon g-2 Theory Initiative

- Steering Committee:
  Gilberto Colangelo, Michel Davier, Simon Eidelman, AXK, Christoph Lehner, Tsutomu Mibe (E34), Andreas Nyffeler, Lee Roberts (E989), Thomas Teubner.

- The goal of the initiative is to bring the different communities are engaged in hadronic muon g-2 theory together to facilitate interactions, compare and assess the status of the various efforts and map out a strategy for obtaining the best theoretical predictions ahead of major experimental announcements.
- First Workshop took place at Fermilab (3-6 June 2017). The second workshop will be in Mainz (18-22 June 2018).
- see the appendix for more information.

First Workshop of the Muon g-2 Theory Initiative

3-6 June 2017 *Q Center*
US/Central timezone

Search

66 registered participants, 40 talks, 15 discussion sessions (525 minutes)

Nucleon matrix elements

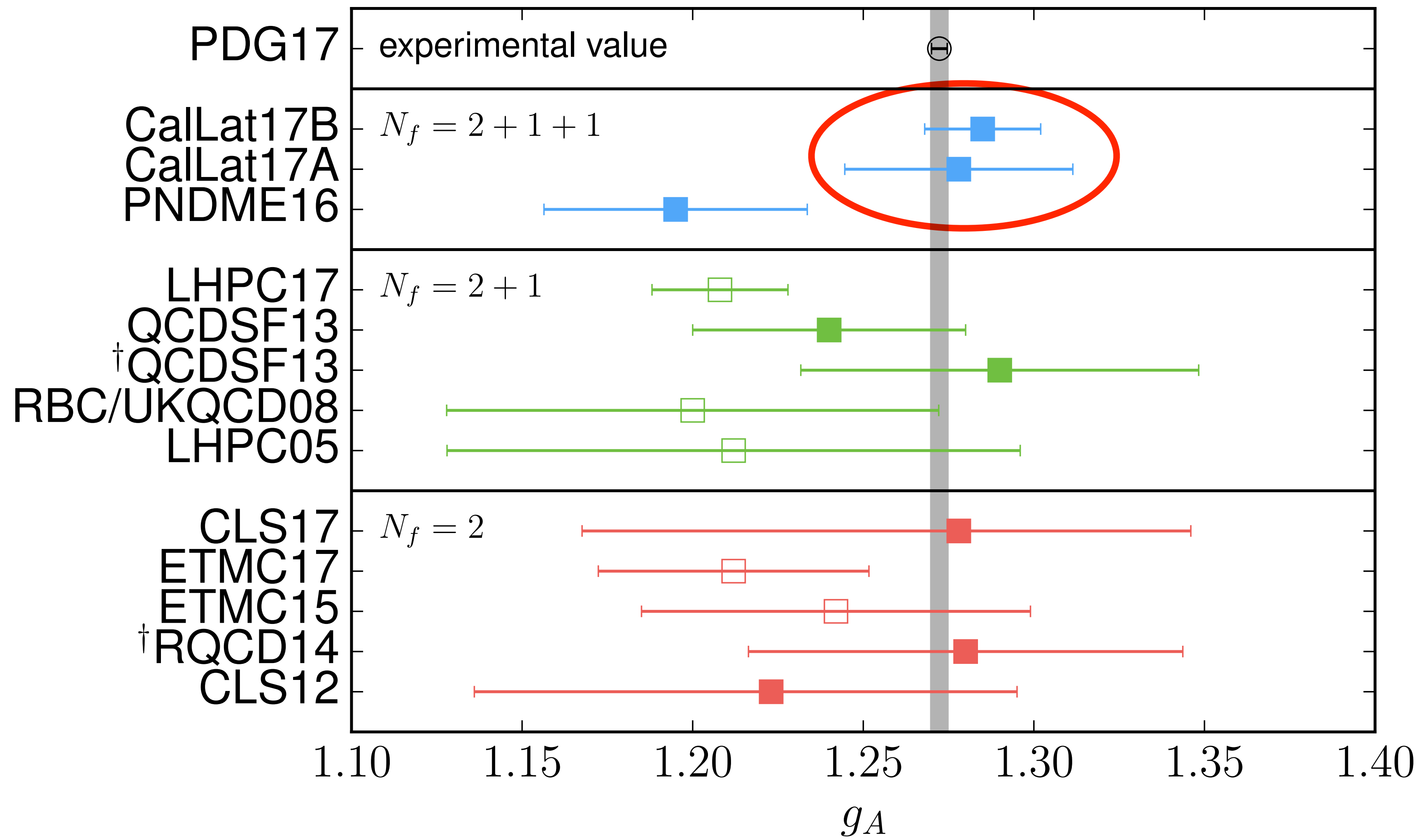
- Needed for neutrino and dark matter experiments:
  Neutrinos and DM particles (in direct detection experiments) scatter off nucleons in nuclear targets.

- Needed matrix elements depend on the underlying quark-level interactions:
    - axial current (charged and neutral) for ν's
    - scalar,… currents for DM

Nucleon matrix elements: g_A

axial charge:
$g_A = F_A(0)$

Jason Chang (priv. comm), Lattice 2017



- Several "complete" LQCD calculations.
- Recent CalLat result (arXiv:1704.01114) with small errors in good agreement with exp.

Nucleon matrix elements

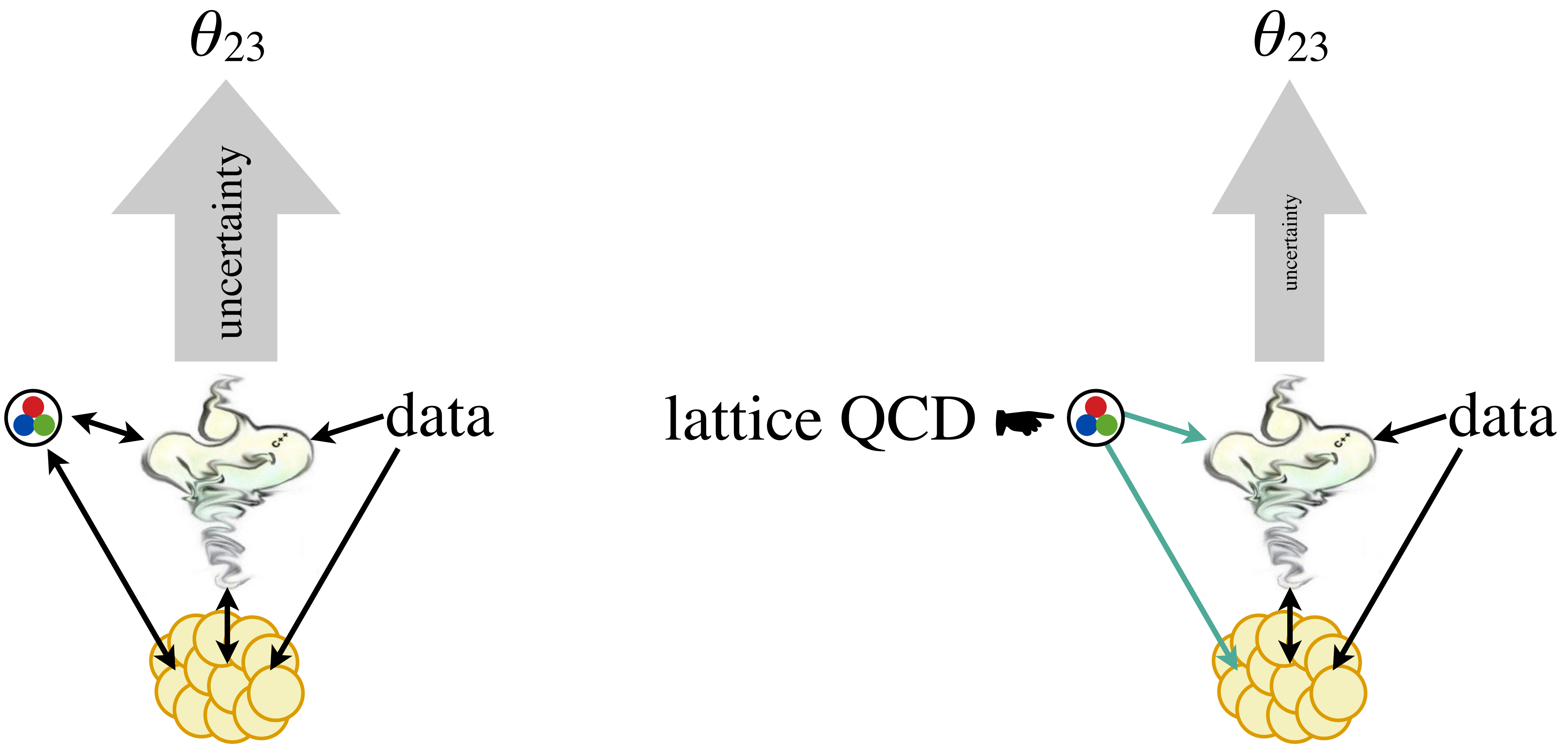
- Needed for neutrino and dark matter experiments: Neutrinos and DM particles (in direct detection experiments) scatter off nucleons in nuclear targets.

- Needed matrix elements depend on the underlying quark-level interactions:
    - axial current (charged and neutral) for ν's
    - scalar,… currents for DM

- Nucleon matrix elements then are used as inputs to
    - event generators (for example, GENIE)
    - Nuclear effective field theory
    - …

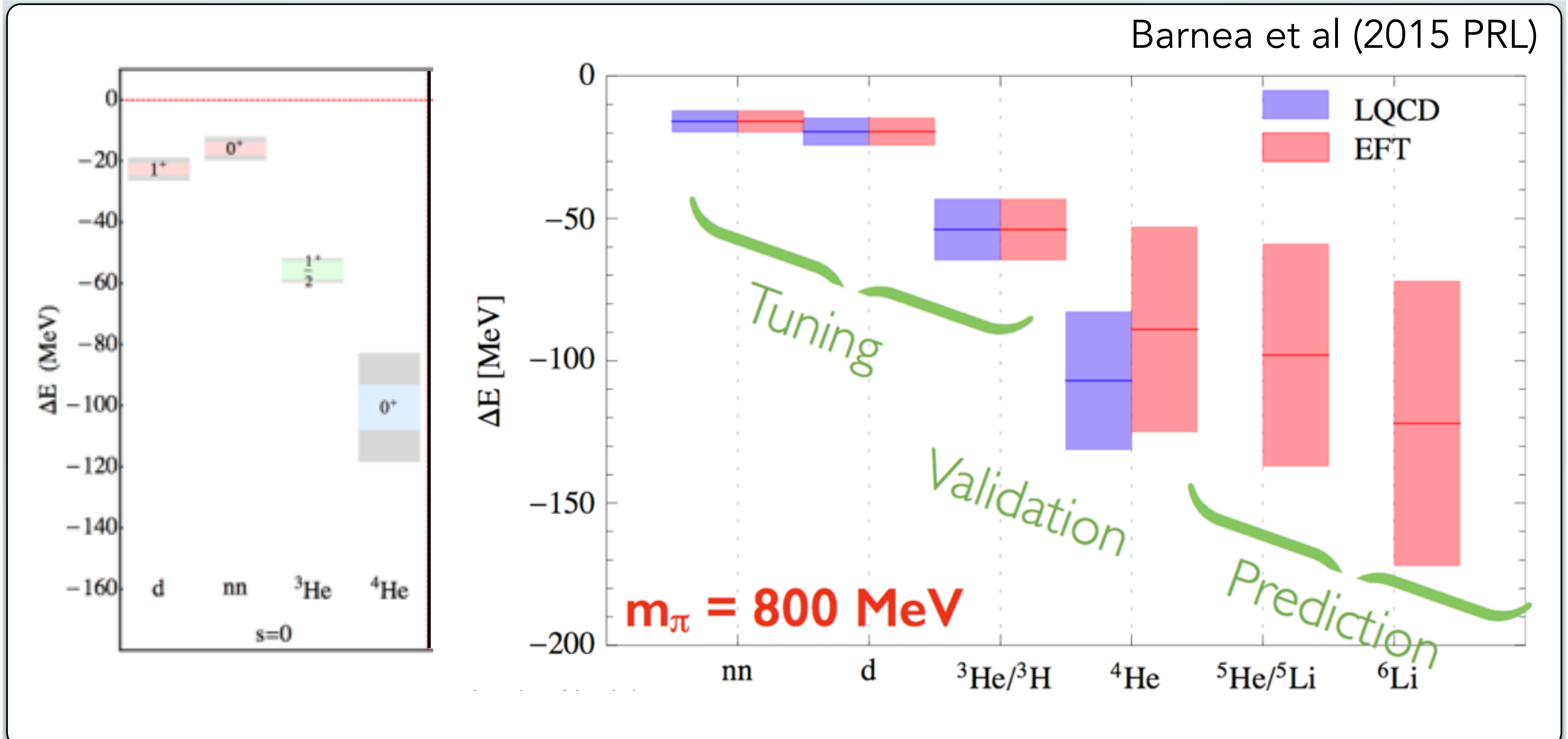
Nucleons to Nuclei

A. Kronfeld (priv. comm)



Nucleons to Nuclei

Z. Davoudi @ Lattice 2017



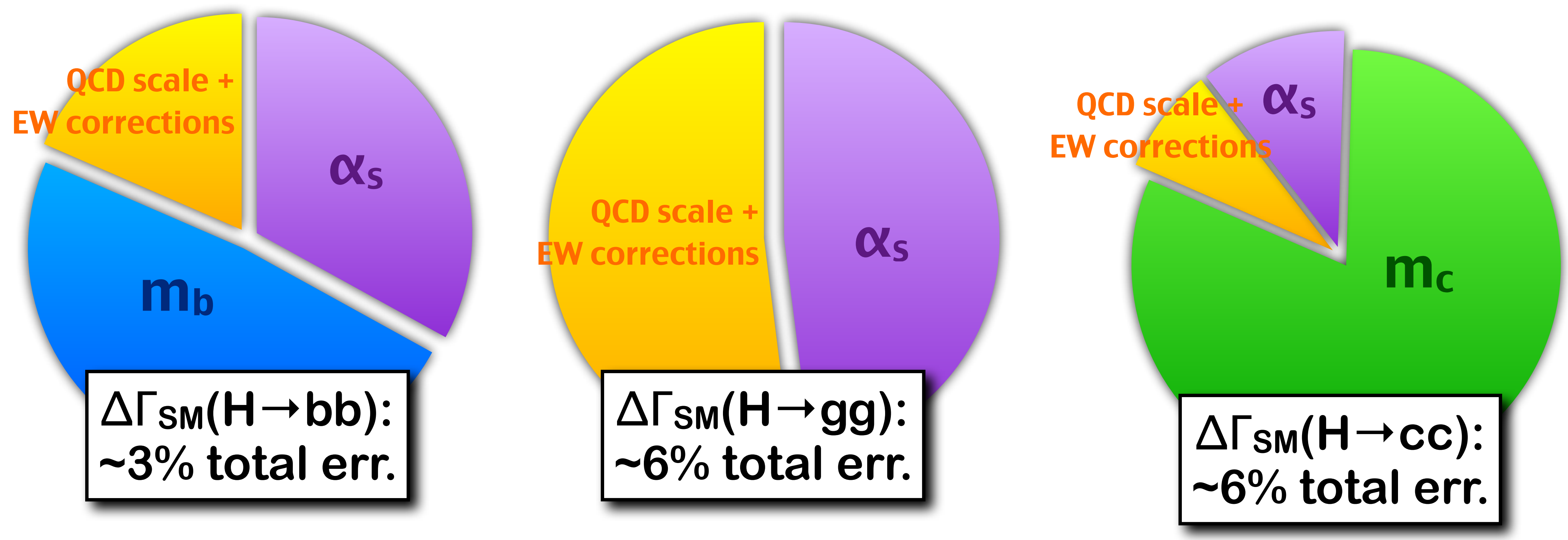
QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

(Contessi et al, arXiv:1701.06516)

Higgs decays

Aarti Veernala (FNAL/MILC) @ Lattice 2017

Uncertainties in Higgs Branching Ratios and total widths are dominated by parametric uncertainties from α_s, m_c and m_b

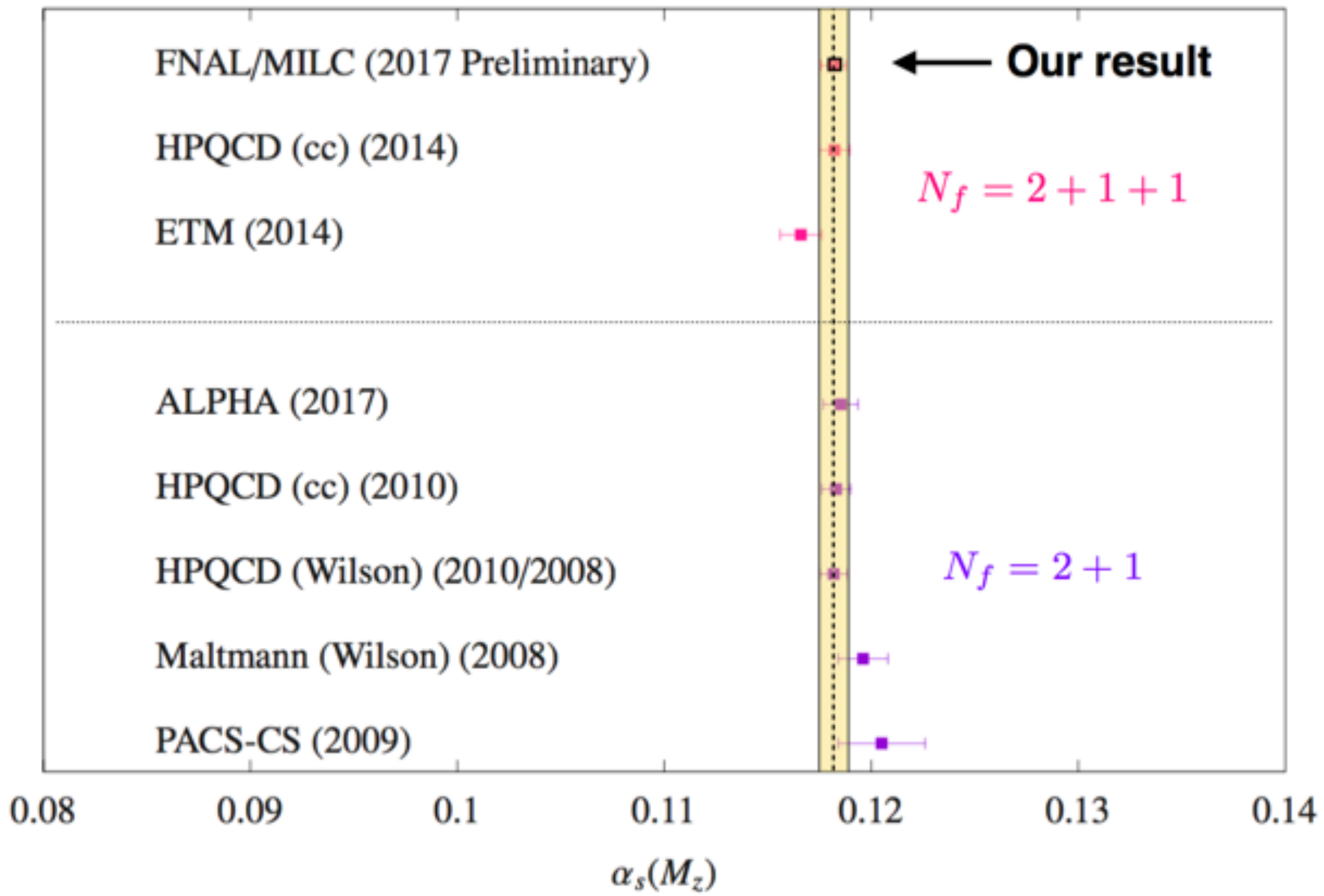


Need to improve parametric uncertainties in order to make use of measurements at future colliders (HL-LHC, ILC,…)

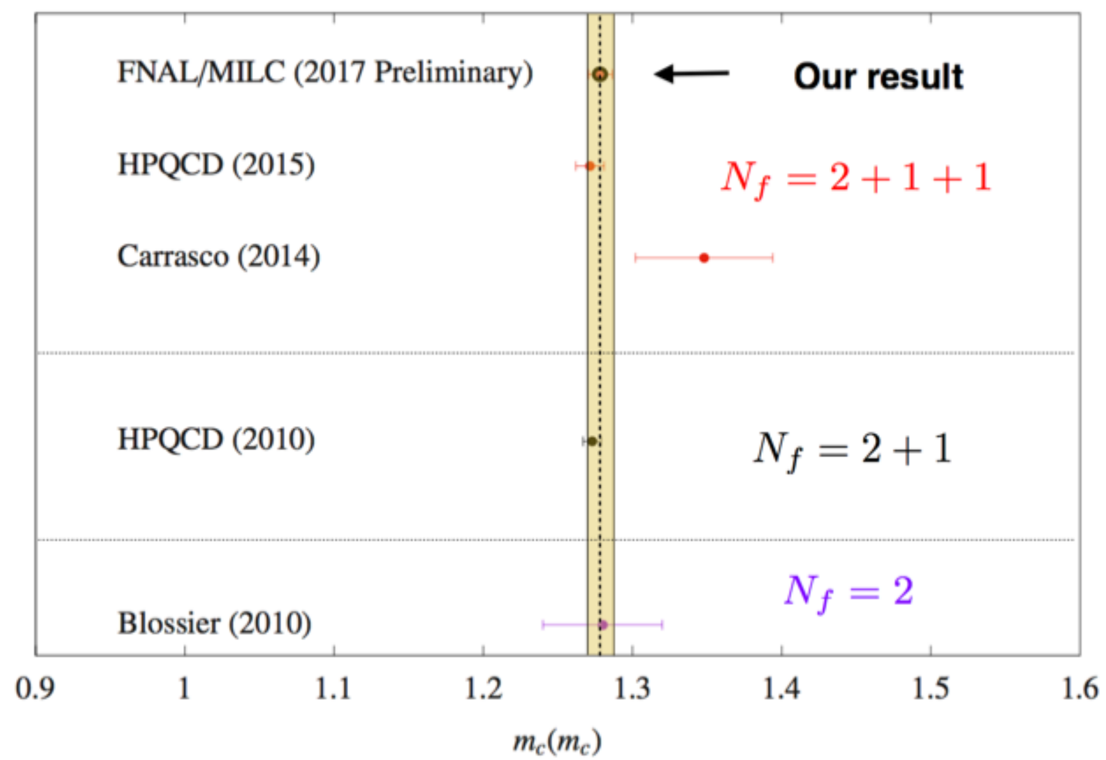
Higgs decays

Aarti Veernala (FNAL/MILC) @ Lattice 2017

$\alpha_s\,(M_Z)$



m_c



New precise results for α_s and m_c, which will improve with inclusion of more ensembles at finer lattice spacings.

Summary: quark flavor physics

(inspired by A. Kronfeld)

$\langle \bar{B}_q^0 | \mathcal{O}_i^{\Delta B=2} | B_q^0 \rangle$

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$

$\hat{B}_K \quad \ldots$

$f_{+,0}^{B \to D^{(*)}}$

$f_+^{K \to \pi} \quad f_{+,0,T}^{B \to \pi} \quad \ldots$

$f_{K^\pm} \quad f_{B_{(s)}} \quad \ldots$

→ Complexity

✓

LQCD flagship results

Summary: quark flavor physics

$\langle \bar{B}_q^0 | \mathcal{O}_i^{\Delta B=2} | B_q^0 \rangle$

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$

$\hat{B}_K \quad \ldots$

$f_{+,0}^{B \to D^{(*)}}$

$f_+^{K \to \pi} \quad f_{+,0,T}^{B \to \pi} \quad \ldots$

$f_{K^\pm} \quad f_{B_{(s)}} \ldots$

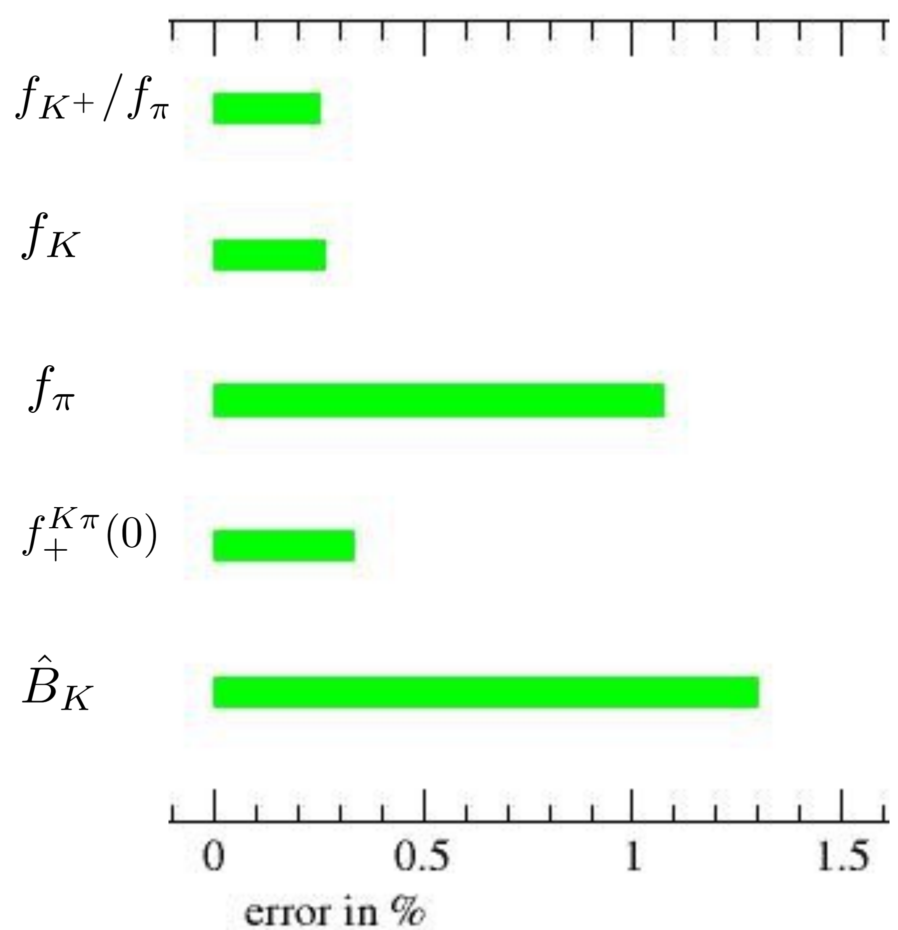
✓

LQCD flagship results

Kaon summary

For all quantities there are results that use **physical mass** ensembles

errors (in %) **FLAG-3 averages**



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Summary: quark flavor physics

$\langle \bar{B}_q^0 | \mathcal{O}_i^{\Delta B=2} | B_q^0 \rangle$

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$

$\hat{B}_K \quad \ldots$

$f_{+,0}^{B \to D^{(*)}}$

$f_+^{K \to \pi} \quad f_{+,0,T}^{B \to \pi} \quad \ldots$

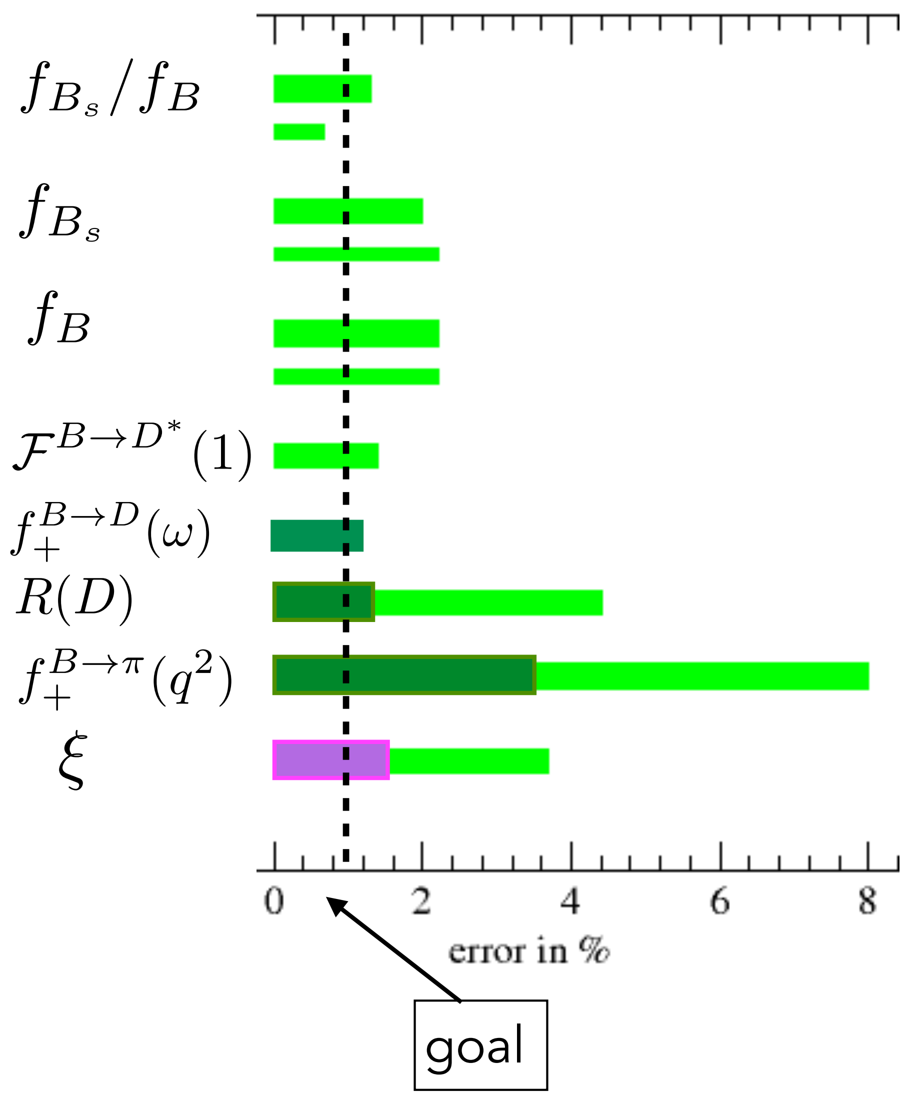
$f_{K^\pm} \quad f_{B_{(s)}} \quad \ldots$

✓

LQCD flagship results

B-meson summary

errors (in %) FLAG-2/3 averages + new results



Several quantities where lattice errors are commensurate with experimental uncertainties

Summary: quark flavor physics

(inspired by A. Kronfeld)

$\langle \bar{B}^0_q | \mathcal{O}_i^{\Delta B=2} | B^0_q \rangle$

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$

$\hat{B}_K \quad \ldots$

$f_{+,0}^{B\to D^{(*)}}$

$f_+^{K\to\pi} \quad f_{+,0,T}^{B\to\pi} \quad \ldots$

$f_{K^\pm} \quad f_{B_{(s)}} \quad \ldots$

$\langle \pi\pi_{(I=2)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$

$\Delta M_K, \, \epsilon_K$

$\langle \pi\pi_{(I=0)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$

$B \to K^* \ell\nu \to K\pi\, \ell\nu \ \ldots$

$K^+ \to \ell^+ \nu\, (\gamma) \ \ldots$

$K^+ \to \pi^+ \ell^+ \ell^-$

$K^+ \to \pi^+ \nu\bar{\nu} \ \ldots$

Complexity →

LQCD flagship results	First complete LQCD results, large(ish) errors	First results, physical params, incomplete systematics	new methods, pilot projects, unphysical kinematics

Summary: lepton flavor physics

(inspired by A. Kronfeld)

g_T, g_S

EDMs

MEs of light nuclei…

$\langle N|\bar{s}s|N\rangle$ $\sigma_{\pi N}$

g_A $F_A^{CC}(q^2)$

$F_A^{NC}(q^2)$

$\nu N \to N', \Delta, N\pi$ …

$a_\mu^{\rm HVP\ LO}$

$a_\mu^{\rm HLbL}$

$\langle N\, N|\mathcal{O}|N\, N\rangle$ …

Complexity

First complete LQCD results, large(ish) errors

First results, physical params, incomplete systematics

new methods, pilot projects, unphysical kinematics

Summary

- Lattice QCD calculations are driven by the needs of the (high energy) experiments and provide essential support to them.

- Access to adequate computational resources is essential to the continued success of the LQCD efforts!

- Recent progress is due to access to Petascale computing resources **and** many creative solutions to the varying challenges of these complex computations.

- For the many topics I didn't cover: See the talks at the Lattice 2017 conference: http://wpd.ugr.es/~lattice2017/

Outlook

Amala Willenbrock

Outlook

- ☆ Gauge field ensembles with light sea quarks at their **physical masses** are being used in a growing number of LQCD calculations.
- ☆ will need to include
  - ✦ structure-dependent QED effects
  - ➢ program being developed for kaon quantities, muon g-2

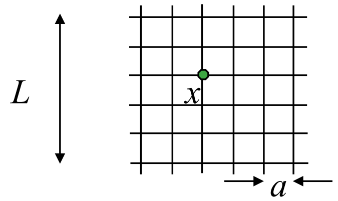
    extend to B-meson quantities
- ☆ Calculations of an increasing number of quantities (muon g-2, nucleon matrix elements, resonances,…) will become "LQCD flagship" results.
- ☆ While new quantities are added (inclusive decays, multi-hadron states, …)

Amala Willenbrock

Thank you!

Farah Willenbrock

Appendix



Lattice QCD Introduction

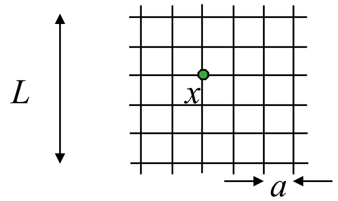
$$\langle \mathcal{O} \rangle \sim \int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}A \, \mathcal{O}(\psi, \bar{\psi}, A) \, e^{-S} \qquad S = \int d^4x \left[\bar{\psi}(\not{D} + m)\psi + \frac{1}{4}(F^a_{\mu\nu})^2 \right]$$

use monte carlo methods (importance sampling) to evaluate the integral.

Note: Integrating over the fermion fields leaves $\det(\not{D} + m)$ in the integrand. The correlation functions, $\mathcal{O}$, are then written in terms of $(\not{D}+m)^{-1}$ and gluon fields.

steps of a lattice QCD calculation:

1. generate gluon field configurations according to $\det(\not{D}+m)\, e^{-S}$
2. calculate quark propagators, $(\not{D}+m_q)^{-1}$, for each valence quark flavor and source point
3. tie together quark propagators into hadronic correlation functions (usually 2 or 3-pt functions)
4. statistical analysis to extract hadron masses, energies, hadronic matrix elements, …. from correlation functions
5. systematic error analysis



Lattice QCD Introduction

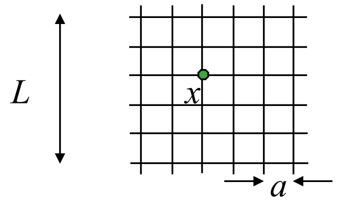
systematic error analysis

...of lattice spacing, chiral, heavy quark, and finite volume effects is based on EFT (Effective Field Theory) descriptions of QCD

➙ ab initio

- finite a: Symanzik EFT
- light quark masses: Chiral Perturbation Theory
- heavy quarks: HQET
- finite L: finite volume EFT

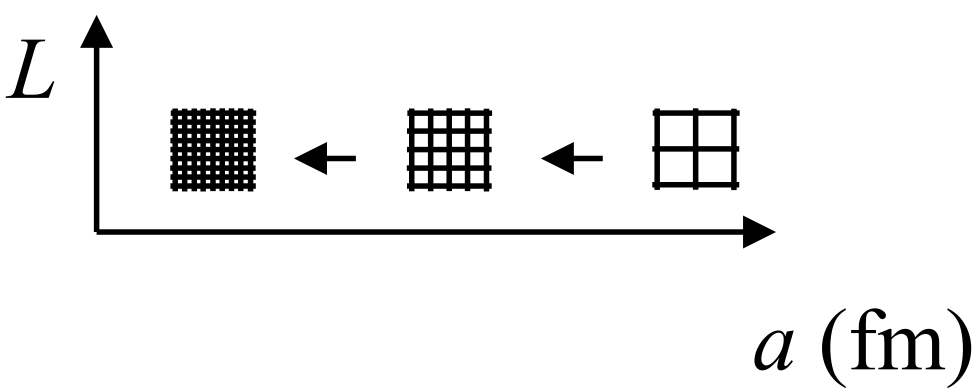
- need large enough L and small enough a and simulations with several a, L, ...

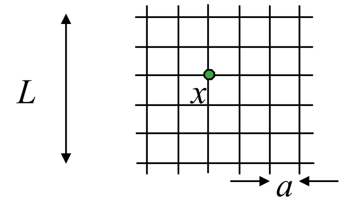


Lattice QCD Introduction

discretization effects — continuum extrapolation

- typical momentum scale of quarks gluons inside hadrons: $\sim\Lambda_{\mathrm{QCD}}$
- make a small to separate the scales: $\Lambda_{\mathrm{QCD}} \ll 1/a$
- Symanzik EFT: $\langle \mathcal{O} \rangle^{\mathrm{lat}} = \langle \mathcal{O} \rangle^{\mathrm{cont}} + O(a\Lambda)^n$, $n \geq 2$
  - provides functional form for extrapolation (depends on the details of the lattice action)
  - can be used to build improved lattice actions
  - can be used to anticipate the size of discretization effects
- to control and reliably estimate the error, repeat …





Lattice QCD Introduction

light quark mass effects

Simulations with $m_{\text{light}} = 1/2\,(m_u + m_d)$ **at the physical u/d quark masses are now available**, but they are computationally expensive and many still have

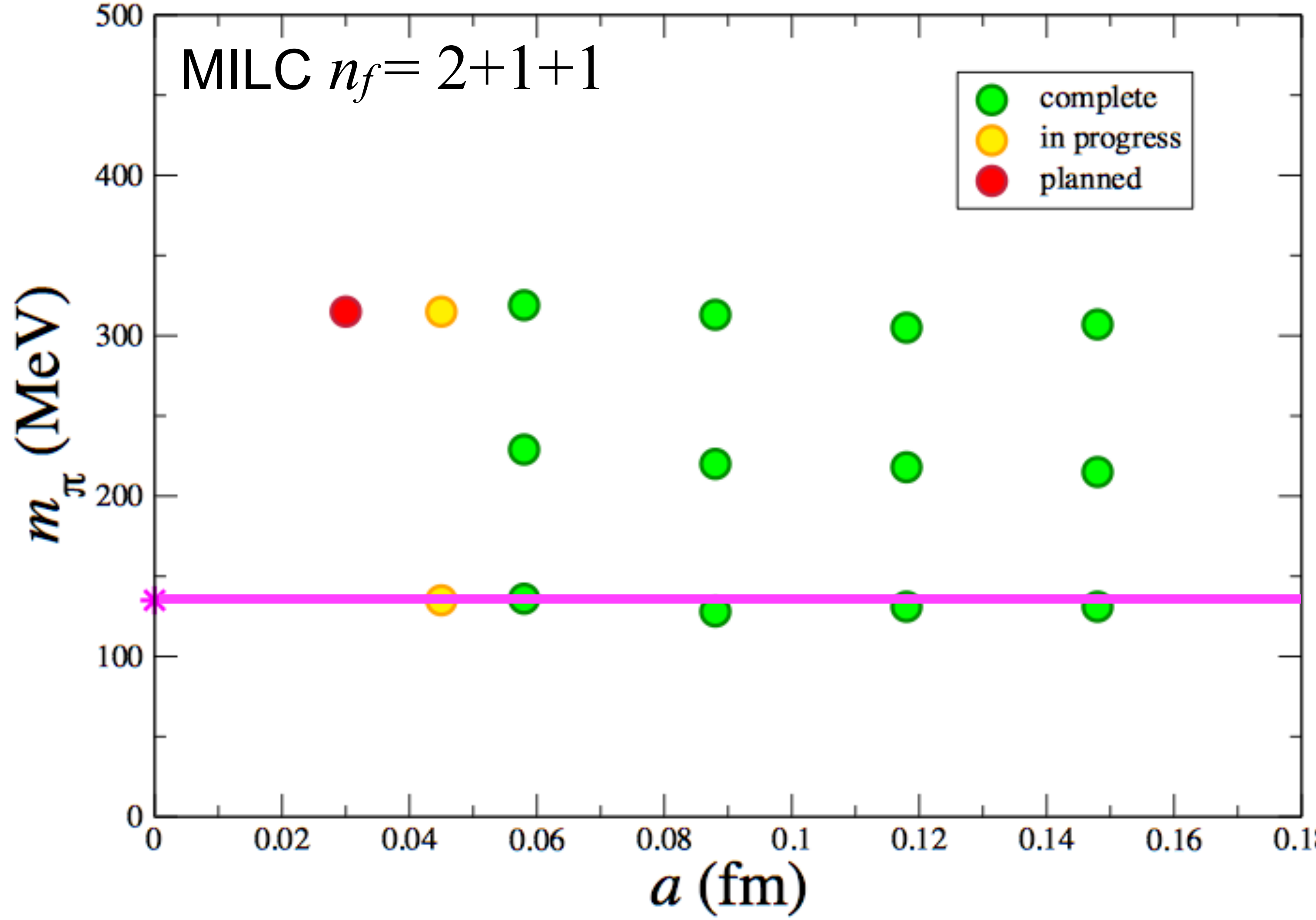
$$m_{\text{light}} > 1/2\,(m_u + m_d)_{\text{phys}}$$

Chiral Perturbation Theory (χPT) can be used to extrapolate/interpolate to the physical point.

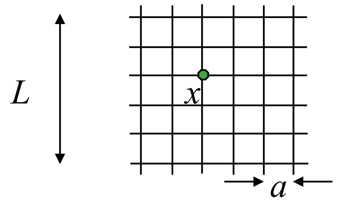
- Can include discretization effects
- It is now common practice to perform a combined continuum-chiral extrapolation/interpolation

chiral-continuum extrapolation

Example: Set of ensembles by MILC collaboration

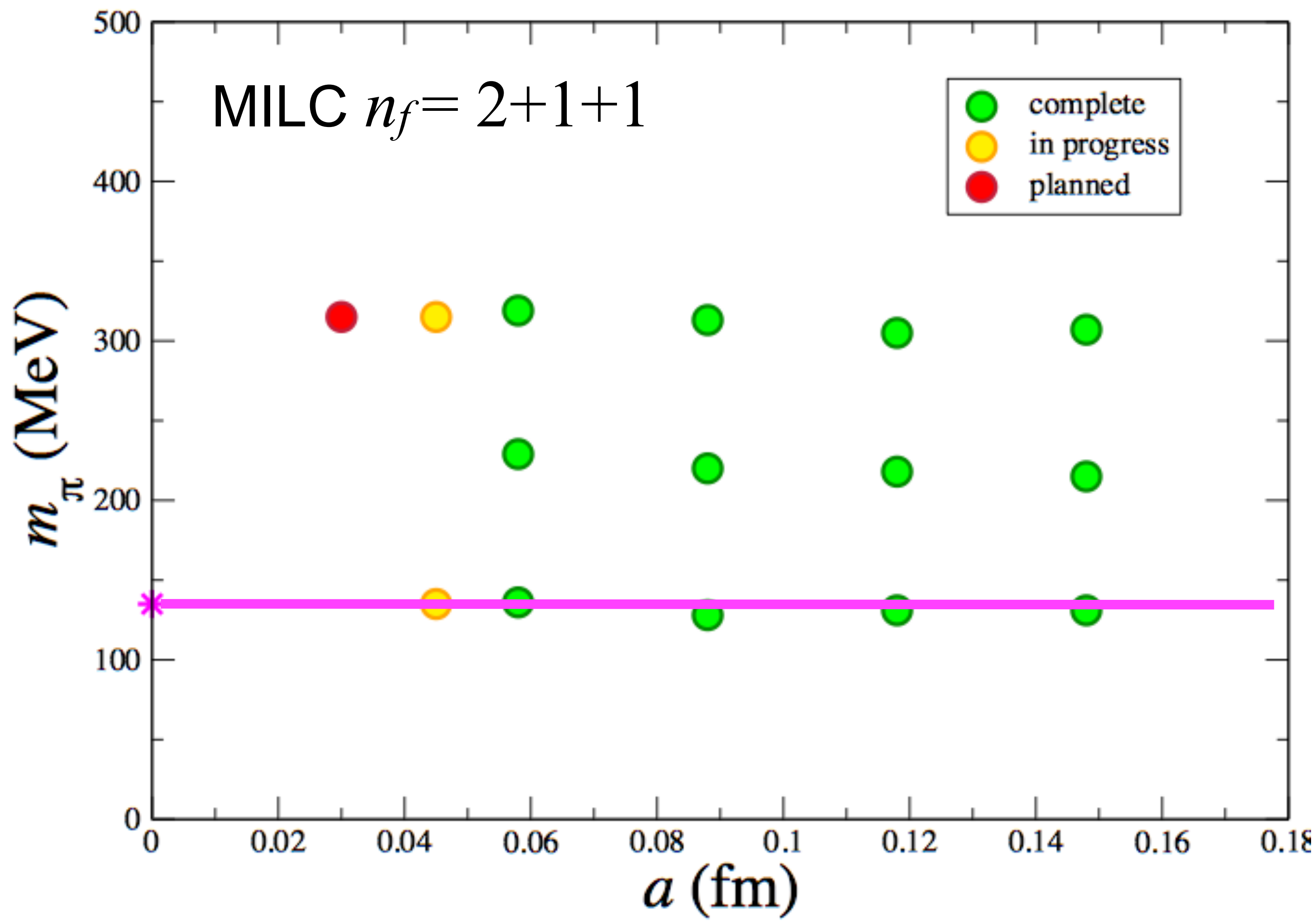


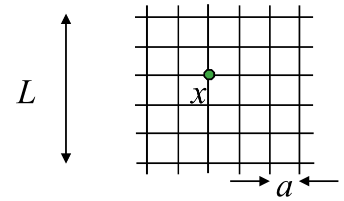
Five collaborations have now generated sets of ensembles that include sea quarks with physical light-quark masses: PACS-CS, BMW, MILC, RBC/UKQCD, ETM



Lattice QCD Introduction

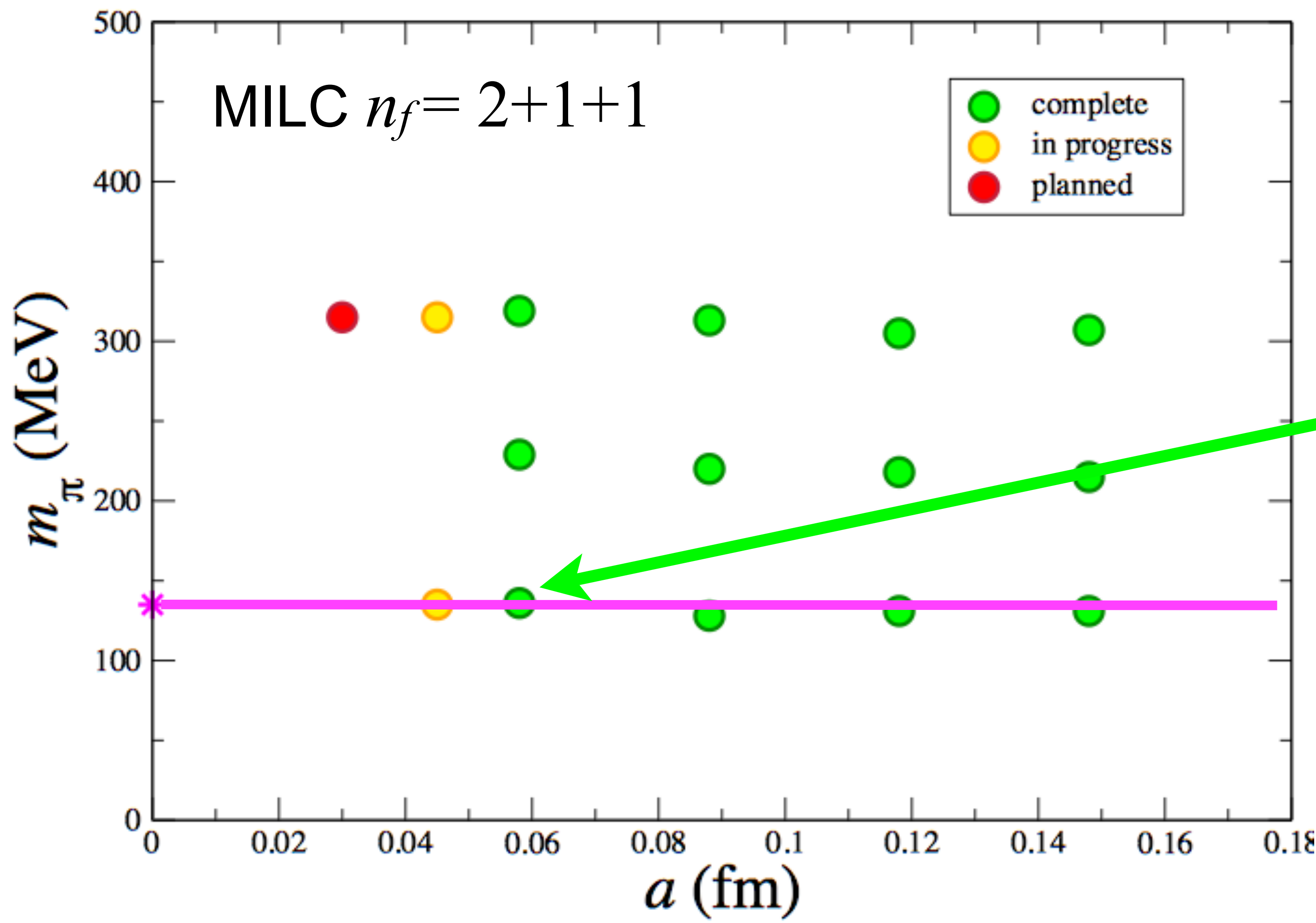
combined chiral-continuum extrapolation



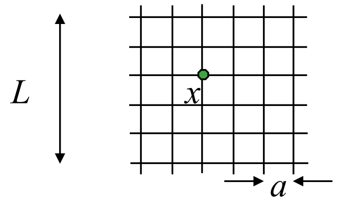


Lattice QCD Introduction

combined chiral-continuum extrapolation



$96^3 \times 192$
$a = 0.06$ fm
$L = 5.8$ fm
~660 confs



Lattice QCD Introduction

finite volume effects

One stable hadron (meson) in initial/final state:

If L is large enough, FV error $\sim e^{-m_\pi L}$

- keep $m_\pi L \gtrsim 4$

To quantify residual error:

- include FV effects in χPT
- compare results at several Ls (with other parameters fixed)

The story changes completely with two or more hadrons in initial/final state or if there are two or more intermediate state hadrons.

➠ "simple quantities":
no more than one stable hadron in initial/final state

If QED is included, FV effects also become more complicated…

Heavy Quark Treatment

- For light quarks ($m_\ell < \Lambda_{\rm QCD}$), leading discretization errors ~ $\alpha_s^k (a\Lambda_{\rm QCD})^n$
- For heavy quarks, leading discretization errors ~ $\alpha_s^k (am_h)^n$ with currently available lattice spacings

  for b quarks $am_b > 1$

  for charm $am_c \sim 0.15\text{-}0.6$

⇨ need effective field theory methods for *b* quarks
for charm can use light quark methods, if action is sufficiently improved

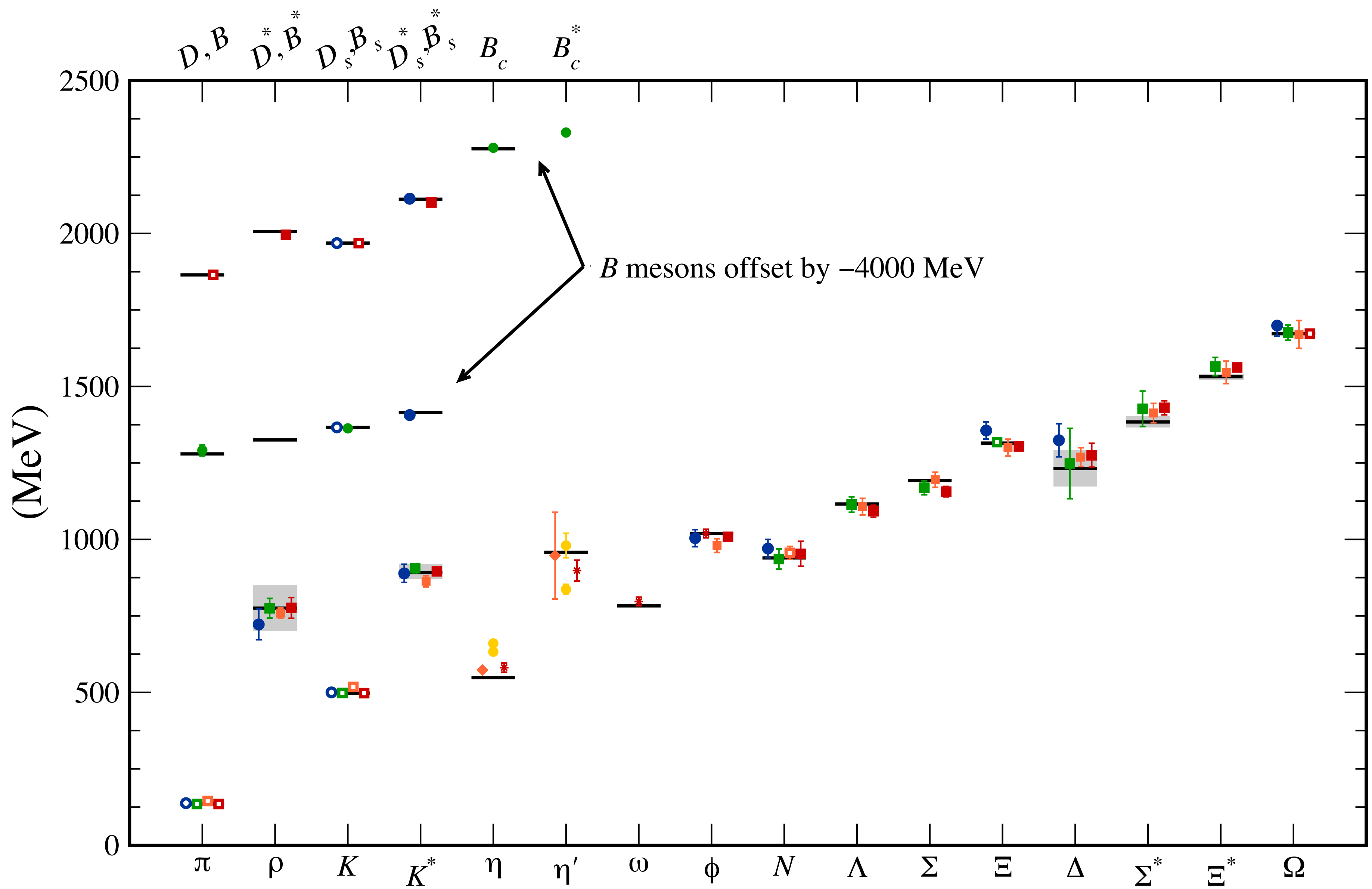
- avoid errors of $(am_b)^n$ in the action by using EFT:
  - ✦ relativistic HQ actions (Fermilab, Columbia [aka RHQ], Tsukuba)
  - ✦ HQET
  - ✦ NRQCD

or

- use improved light quark actions for charm (HISQ, tmWilson, NP imp. Wilson,...) and for *b*:
  - ✦ use same LQ action as for charm but keep $am_h < 1$,
  - ✦ use HQET and/or static limit to extrapolate/interpolate to *b* quark mass

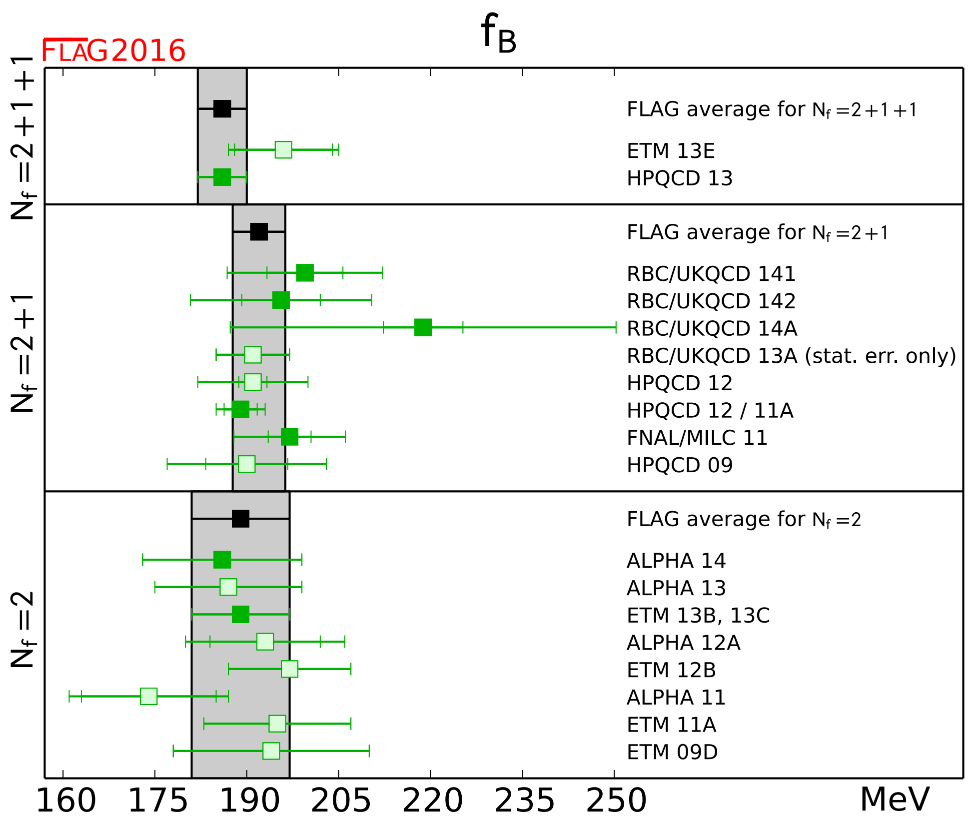
LQCD success: spectrum

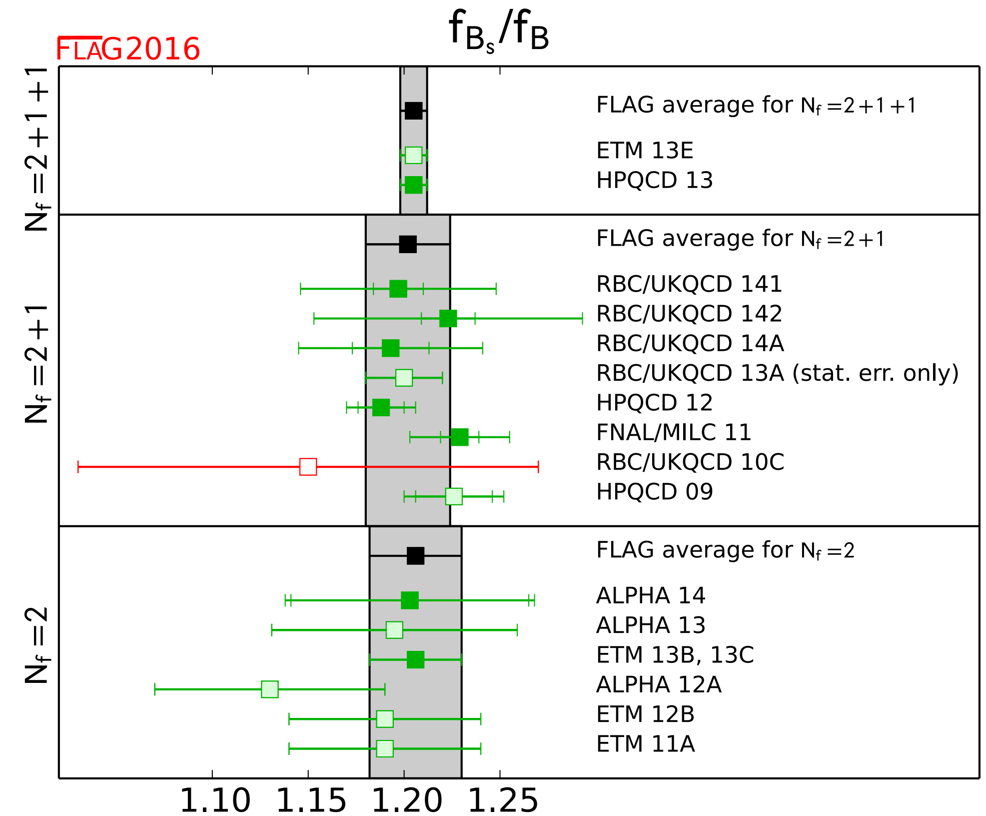
A. Kronfeld (Annu. Rev. Part. & Nucl. Sci, arXiv:1203.1204, updated)

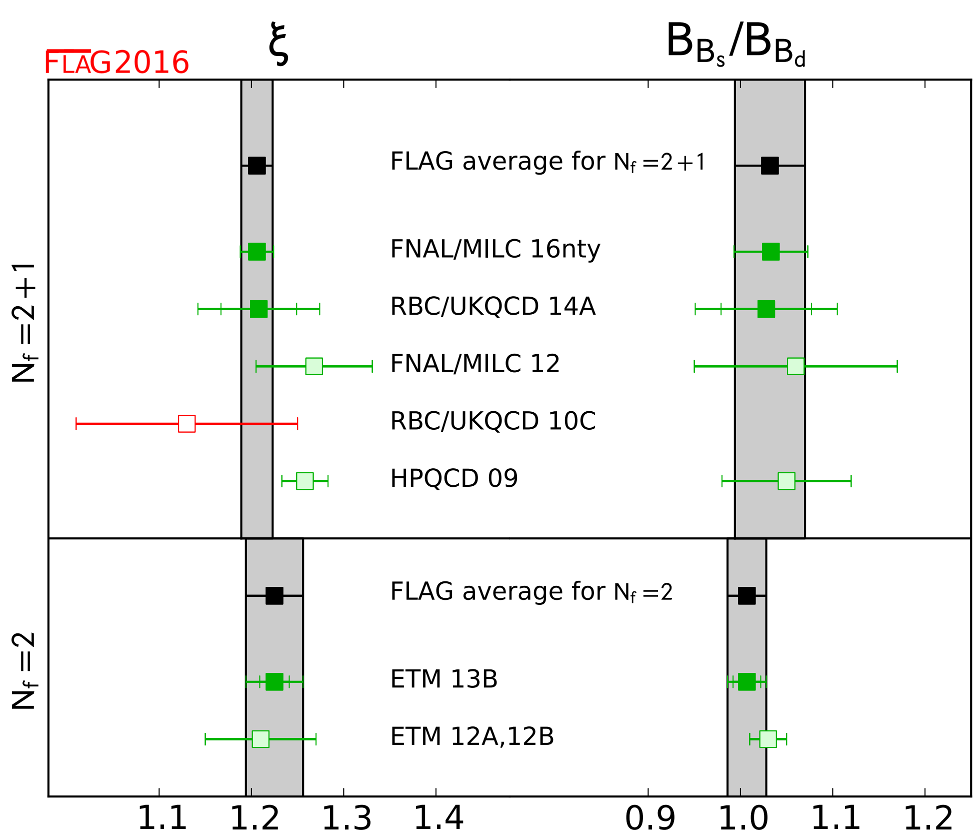


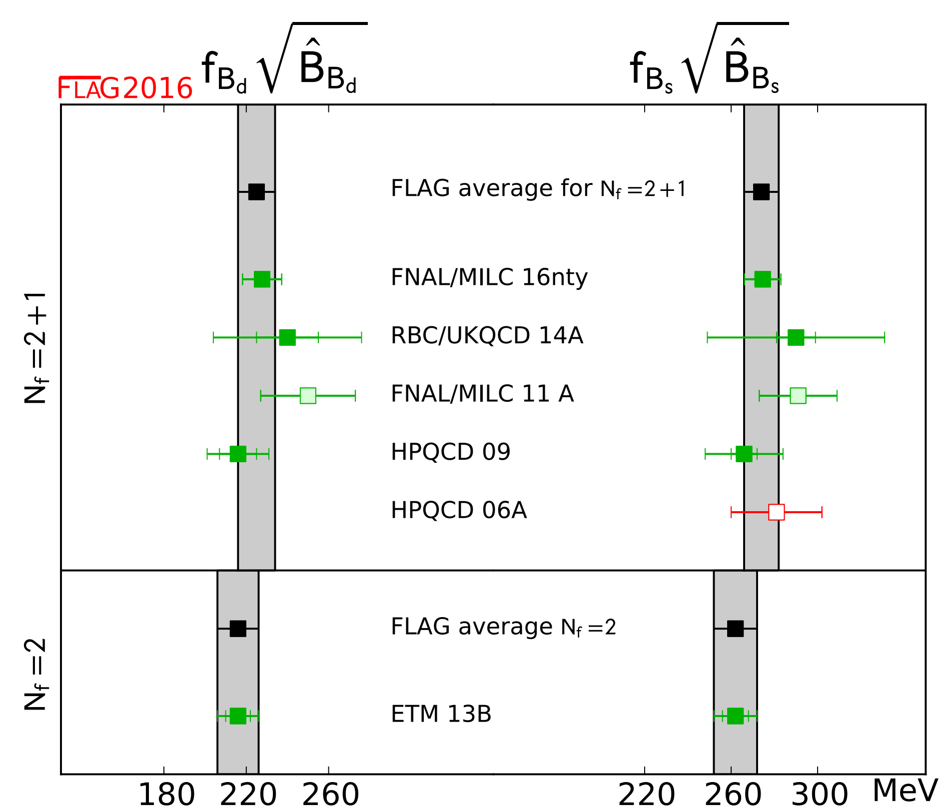
π…Ω: BMW, MILC, PACS-CS, QCDSF; η-η′: RBC, UKQCD, Hadron Spectrum (ω);
D, *B*: Fermilab, HPQCD, Mohler-Woloshyn

FLAG review of *B*-meson quantities



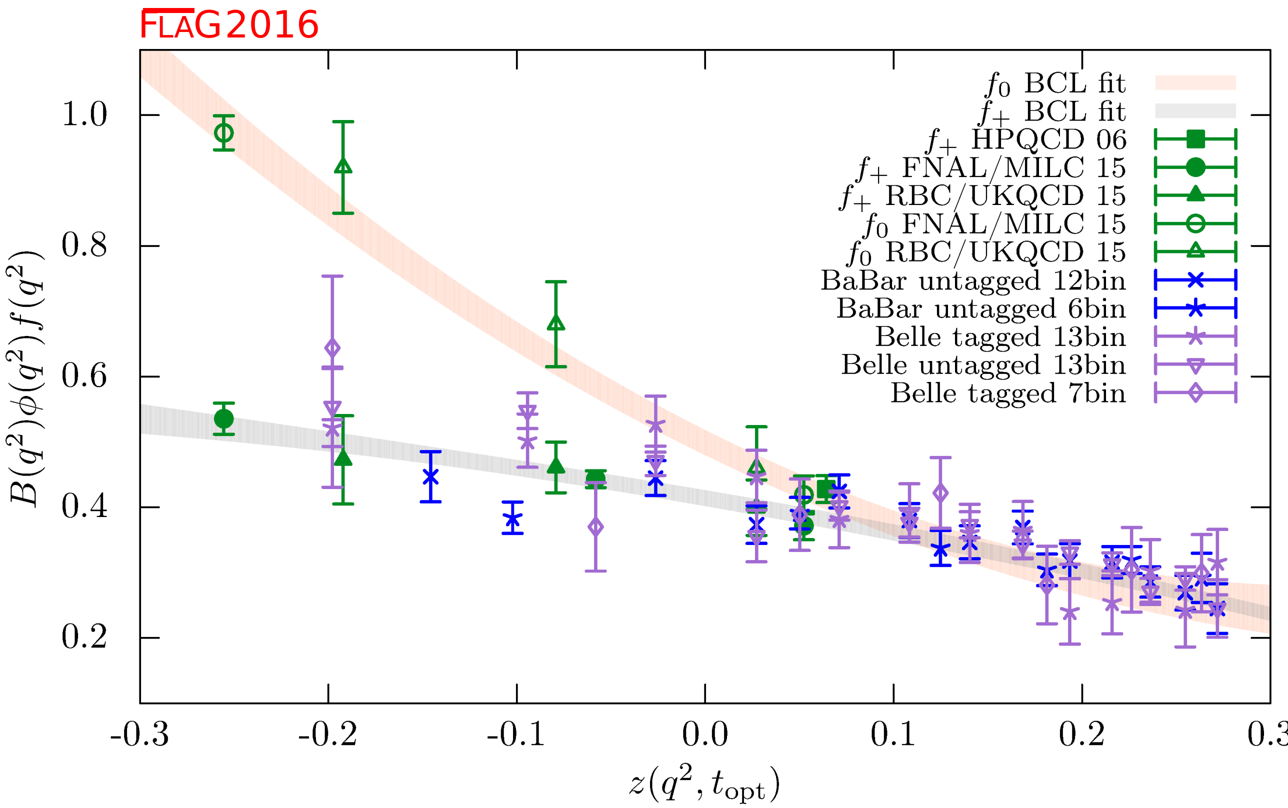




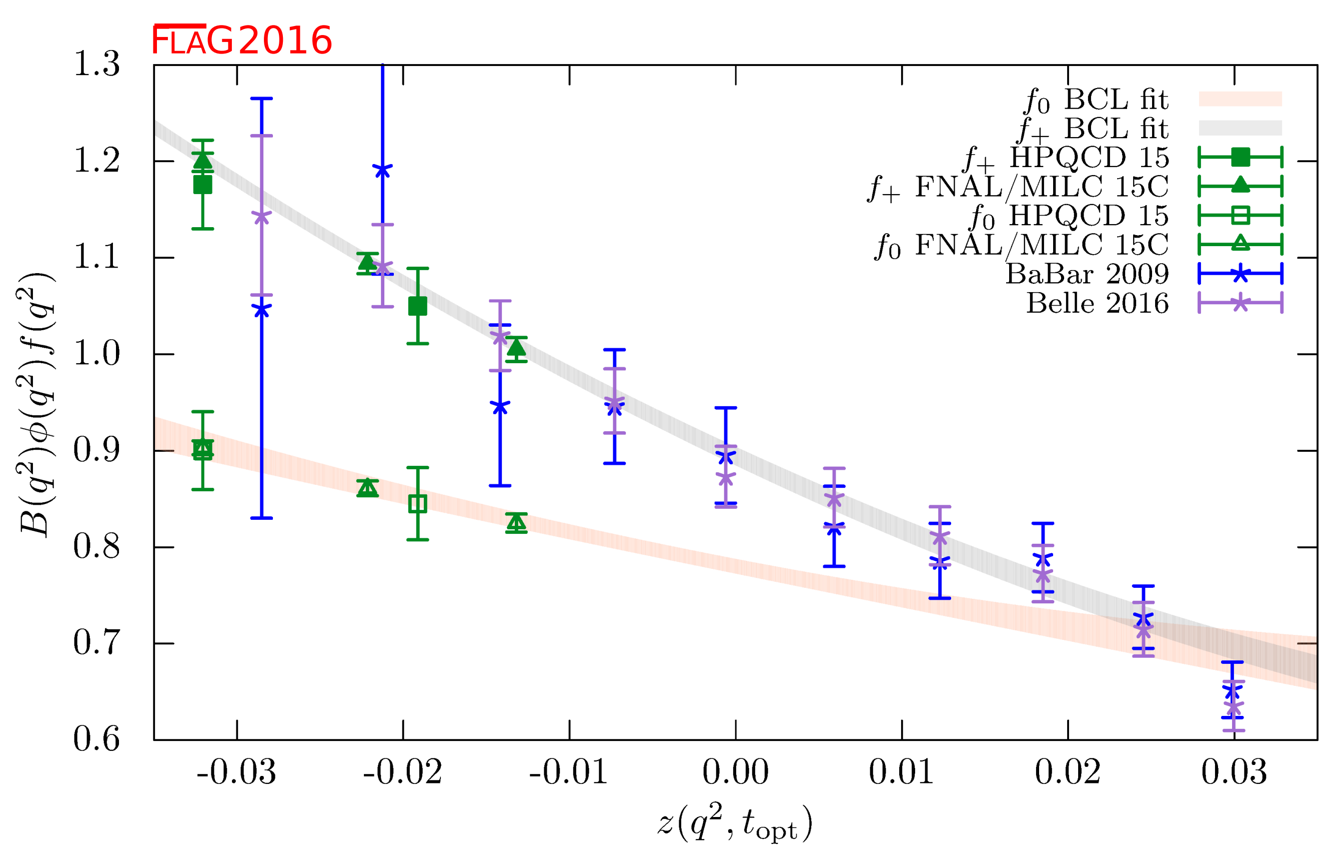


S. Aoki et al (FLAG-3 review, arXiv: 1607.00299, EPJC 17, web update)

FLAG review of *B*-meson quantities

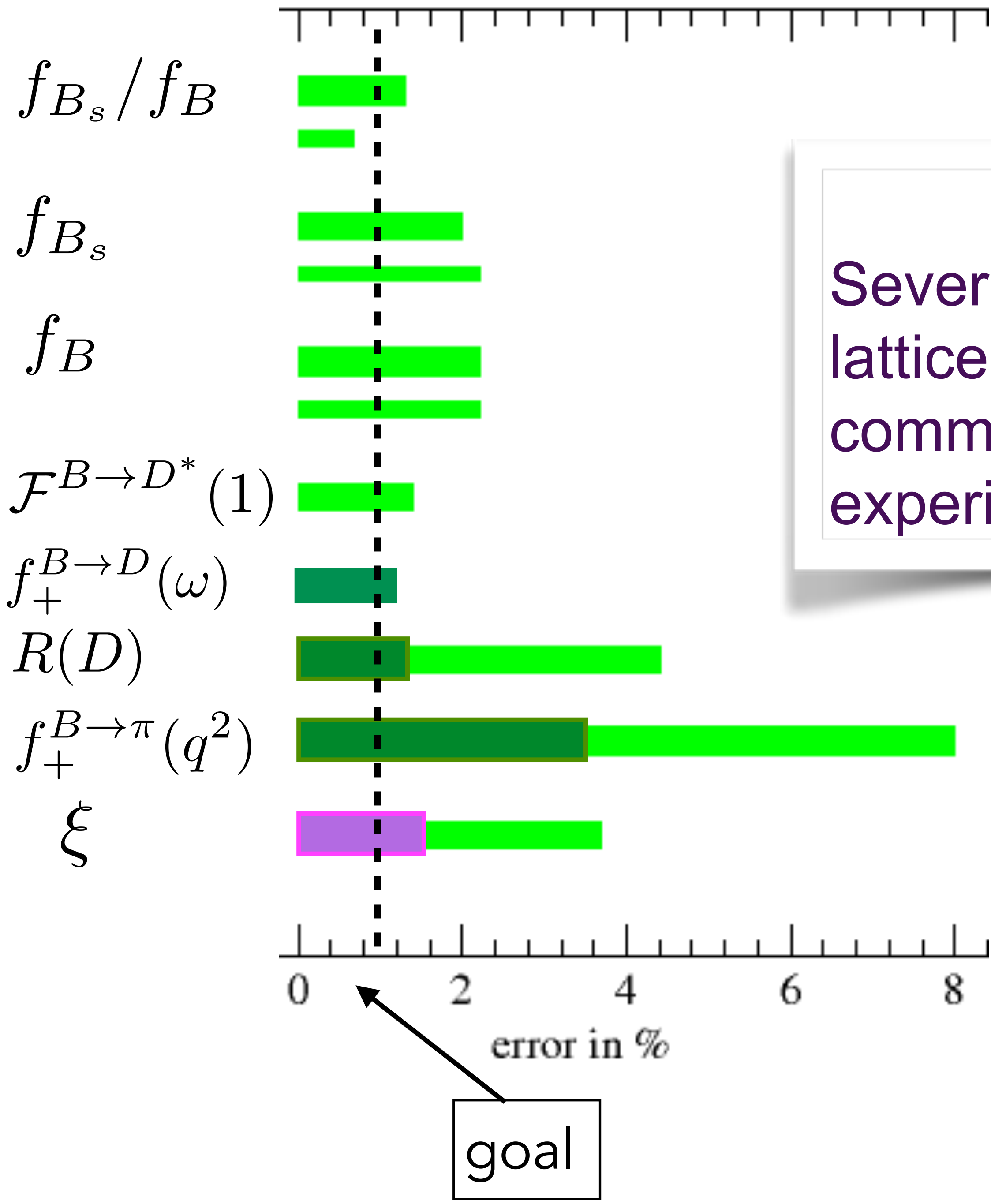


S. Aoki et al (FLAG-3 review, arXiv:1607.00299, EPJC 17, web update)



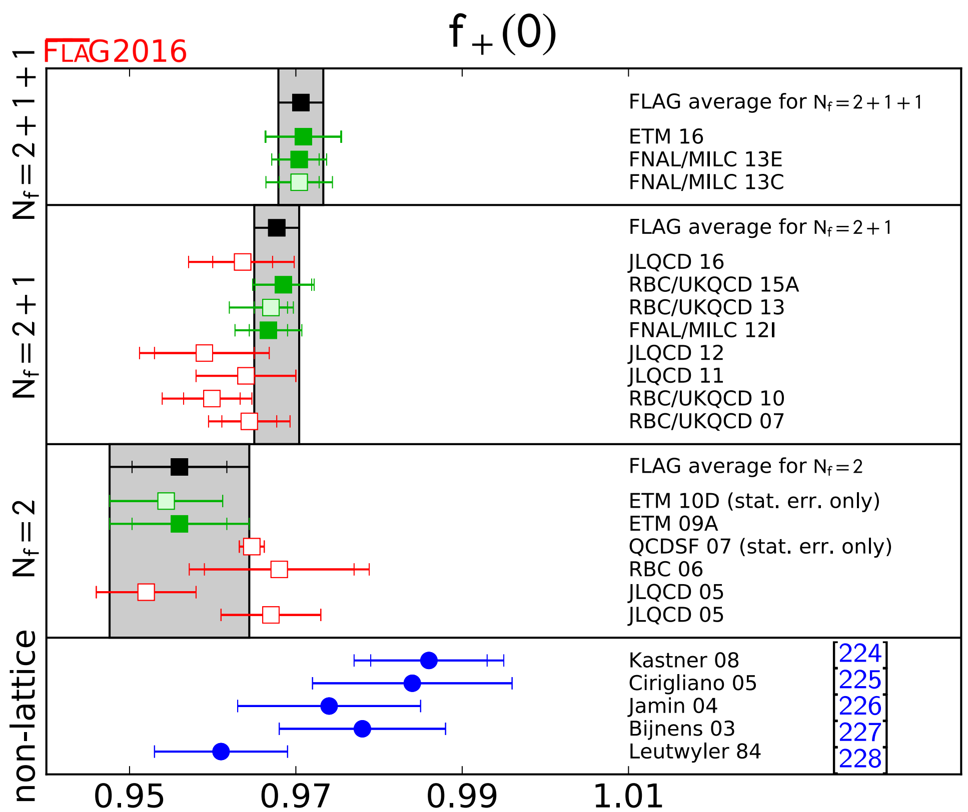
B-meson summary

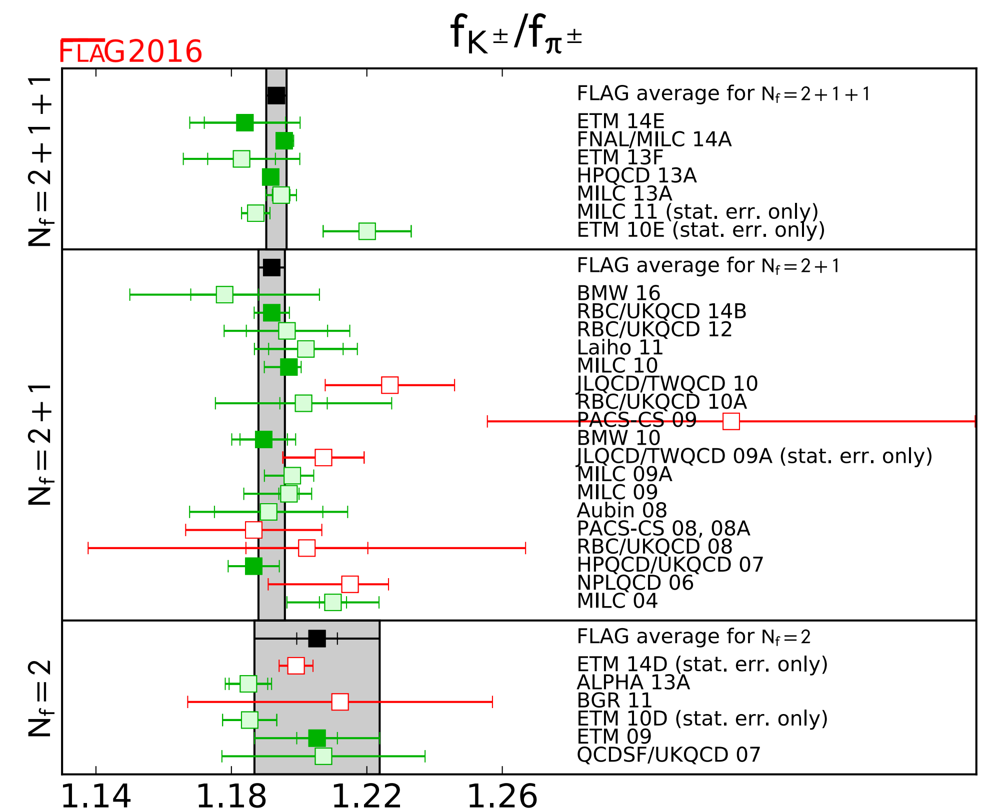
errors (in %) FLAG-2/3 averages + new results

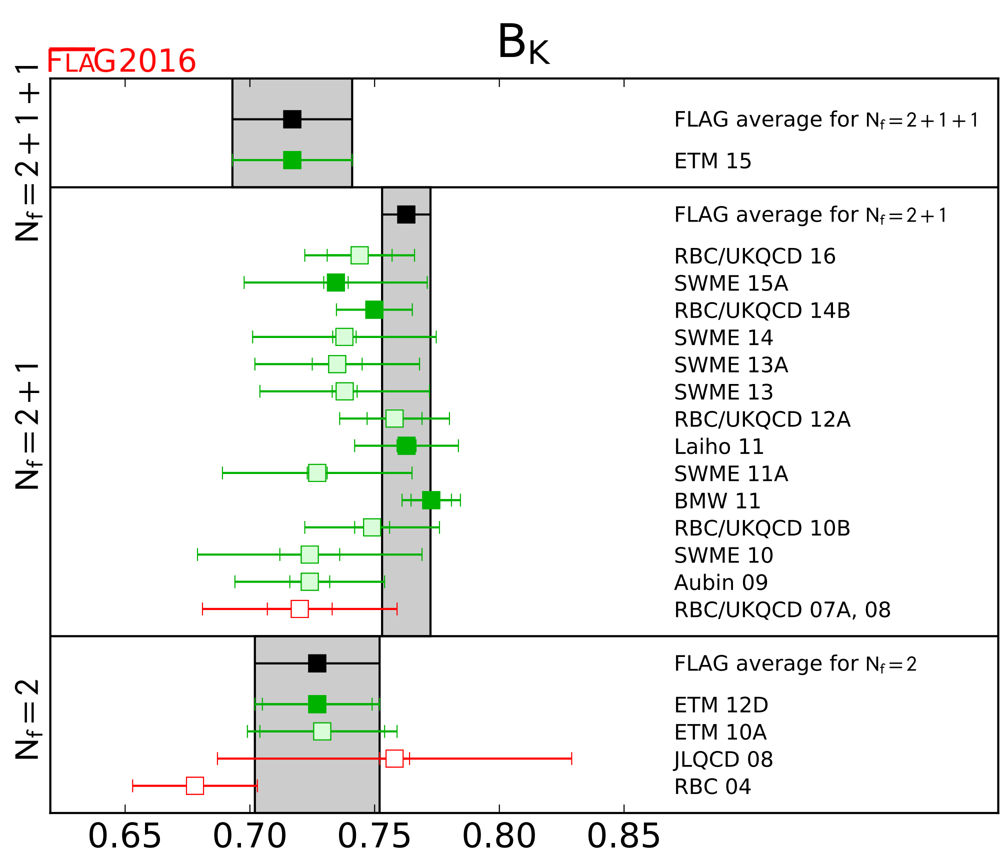


Several quantities where lattice errors are commensurate with experimental uncertainties

FLAG review of Kaon quantities





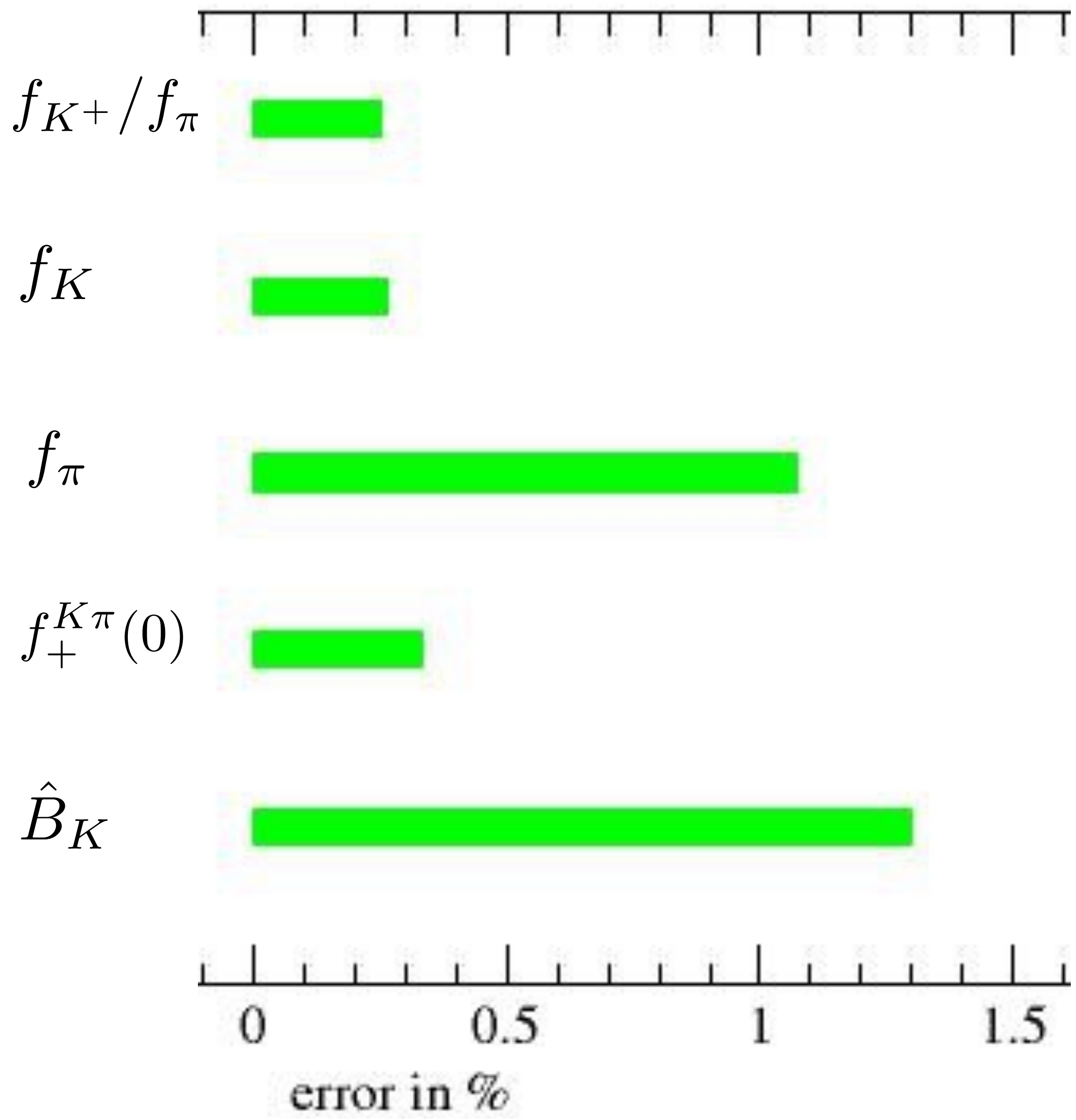


S. Aoki et al (FLAG-3 review, arXiv:1607.00299, EPJC 17, web update)

Kaon summary

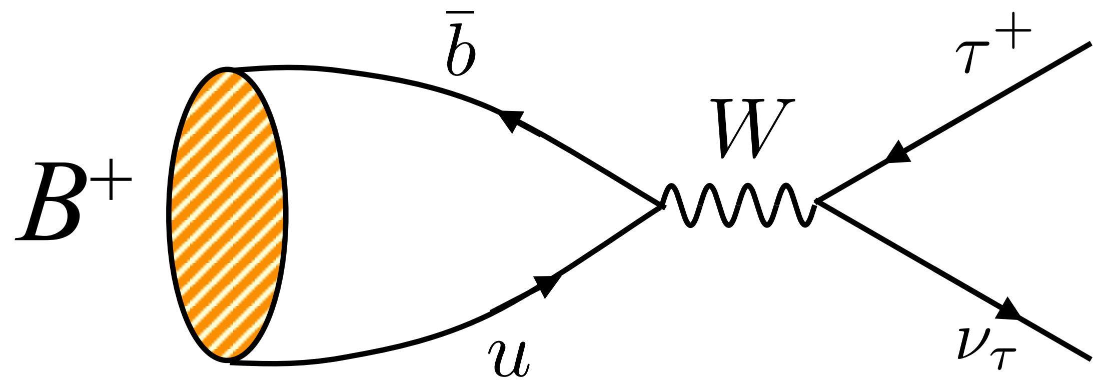
For all quantities there are results that use **physical mass** ensembles

errors (in %) **FLAG-3 averages**



Leptonic B-meson decay

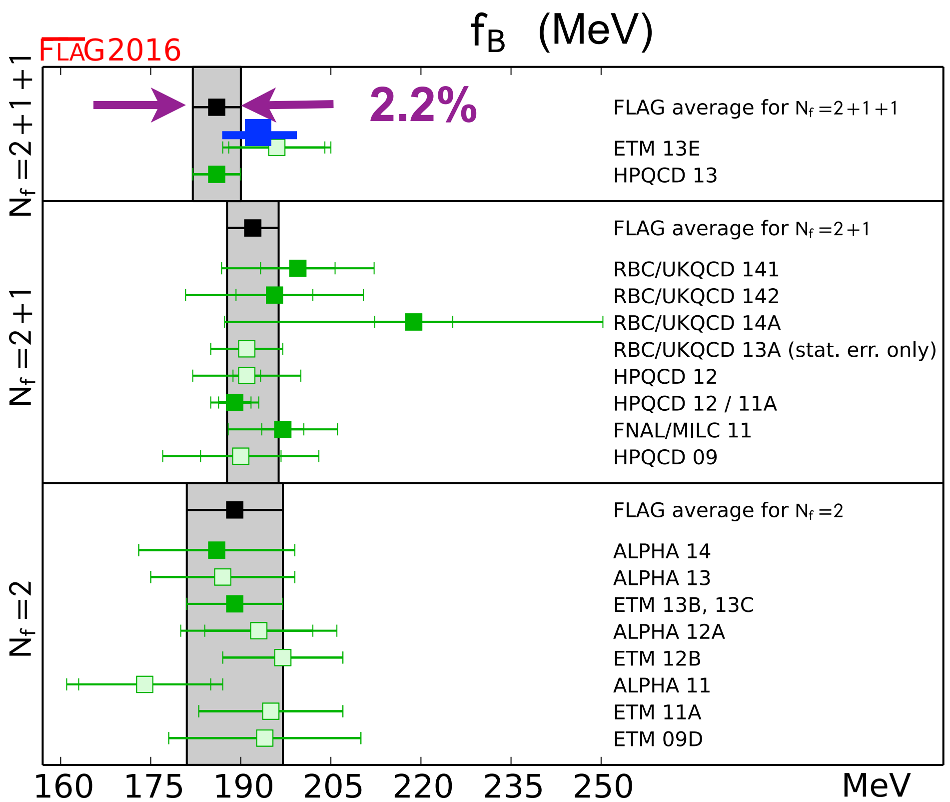
Example: $B^+ \to \tau^+ \nu_\tau$

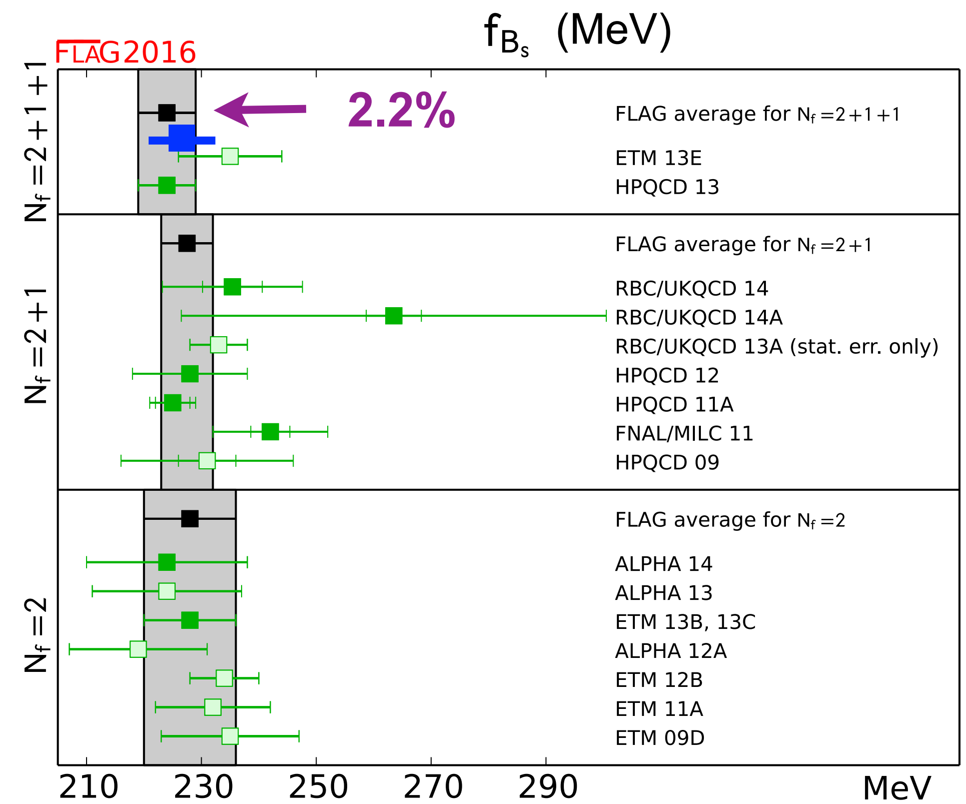


$$\Gamma(B^+ \to \tau^+ \nu_\tau) = (\text{known}) \times |V_{ub}|^2 f_B^2$$

- use experiment + LQCD input for determination of CKM element or to search for new physics.
- SU(3) **ratio** f_{B_s}/f_{B_d}: statistical and systematic errors tend to cancel.
- Decay constants are also needed for rare leptonic decay, $B_{s(d)} \to \mu\mu$.

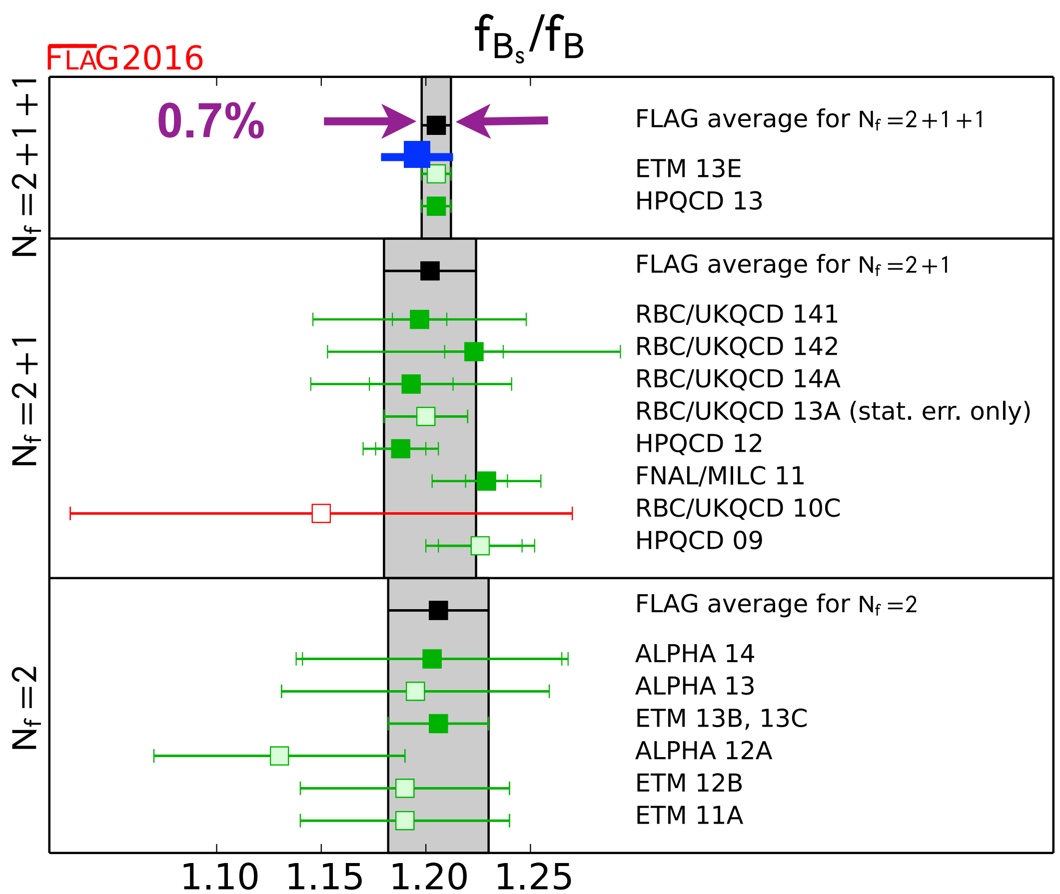
B decay constant summary





S. Aoki et al
(FLAG-3 review, arXiv:
1607.00299, EPJC 2017)

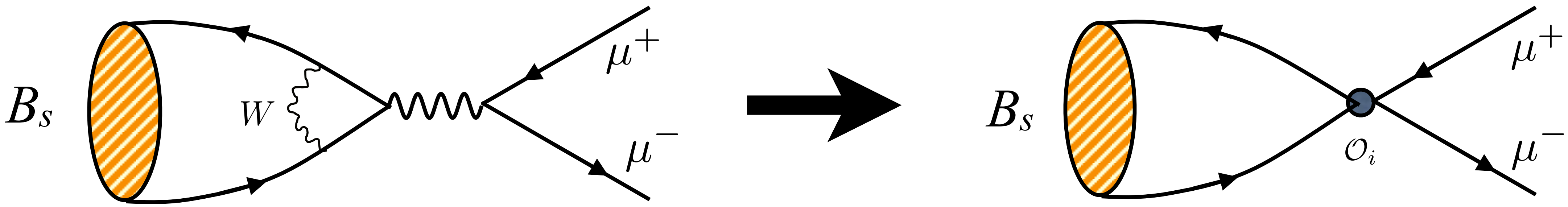
status
end 2015



- ✦ new results by ETM (arXiv:1603.04306, 2016 PRD)
- ✦ ongoing work by FNAL/MILC (Komijani @ Lattice 2016), RBC/UKQCD, …

➠ expect to reduce errors on f_B, f_{B_s} to ≲ 1%

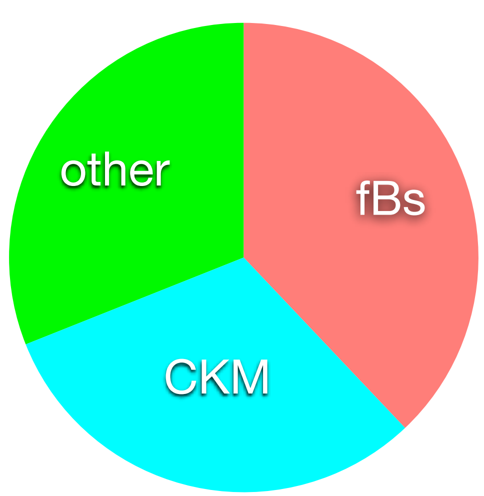
Rare leptonic decay $B_s \to \mu^+\mu^-$



Standard Model prediction: Buras, et al (arXiv:1303.3820, JHEP 2013), Bobeth, et al (arXiv:1311.0903, PRL 2014).

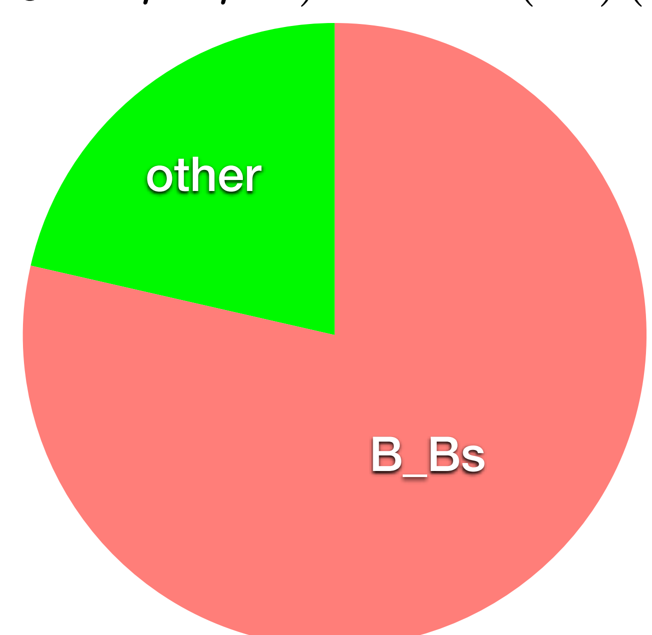
LQCD decay constant

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = 3.53(11)(9)(9) \times 10^{-9}$$



B_s mixing measurement + LQCD bag parameter

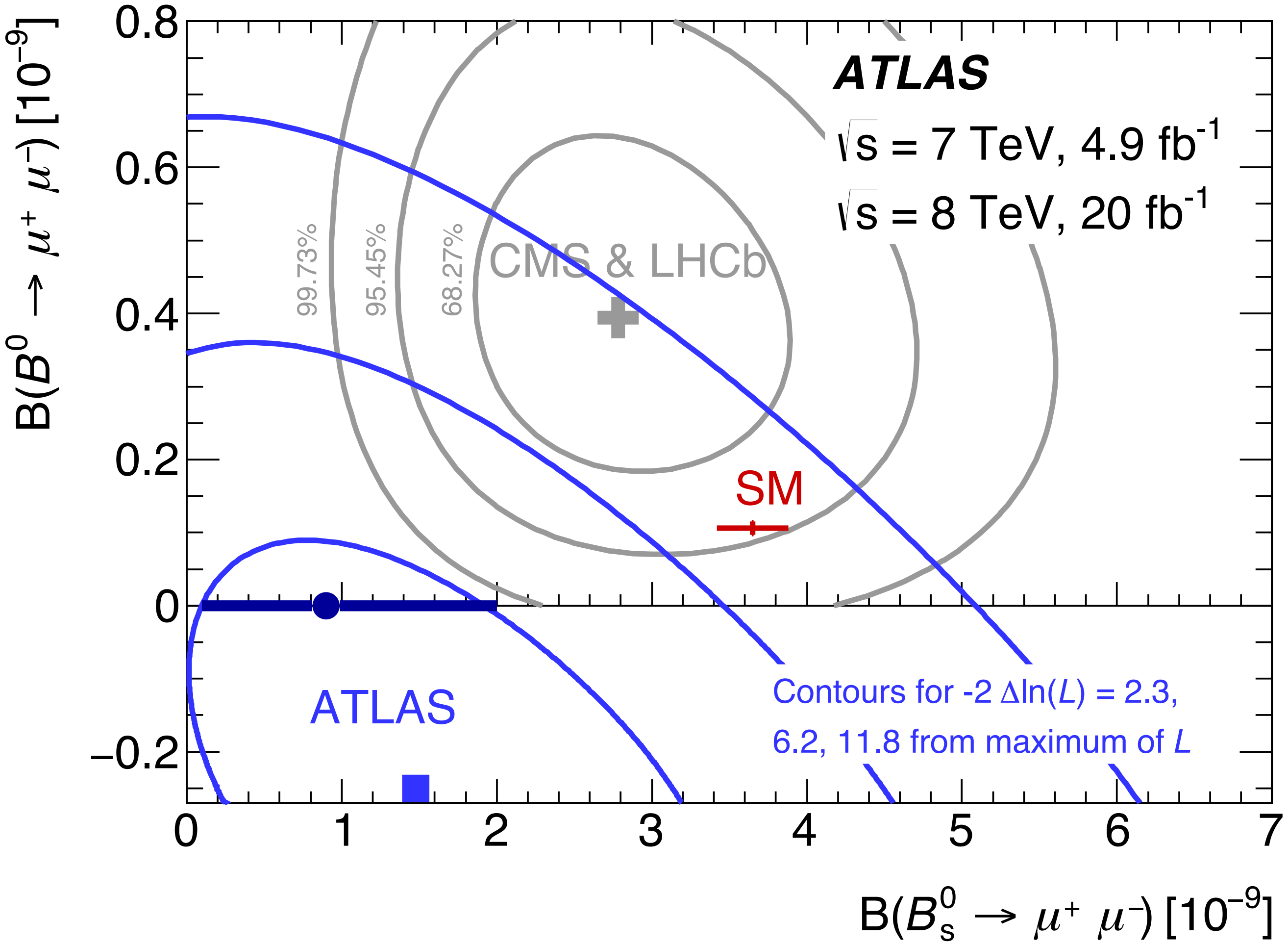
$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = 3.22(22)(6) \times 10^{-9}$$



FNAL/MILC (arXiv:1602.03560)

BSM phenomenology $B_{s(d)} \to \mu^+\mu^-$

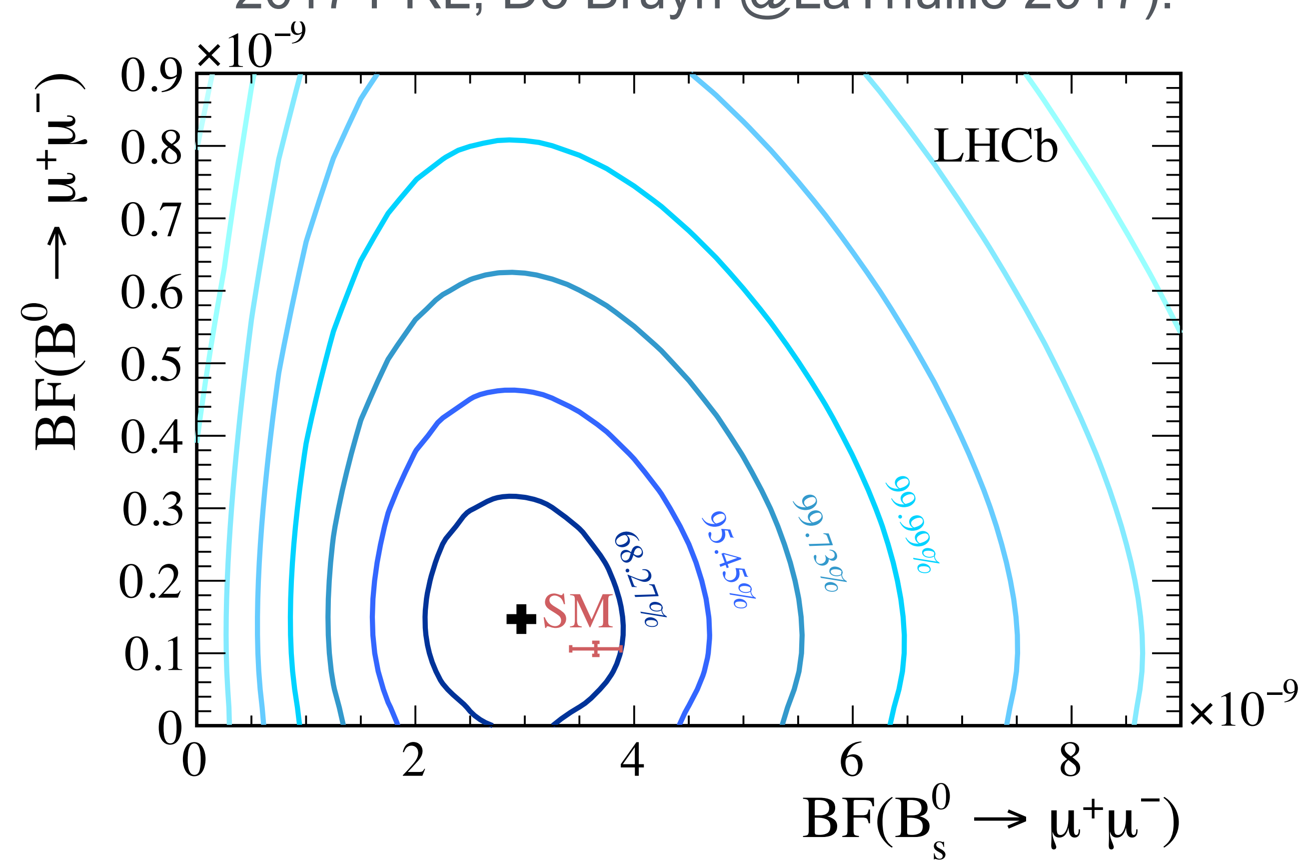
CMS+LHCb combined (arXiv:1411.4413, Nature 2015) and ATLAS (arXiv:1604.04263)



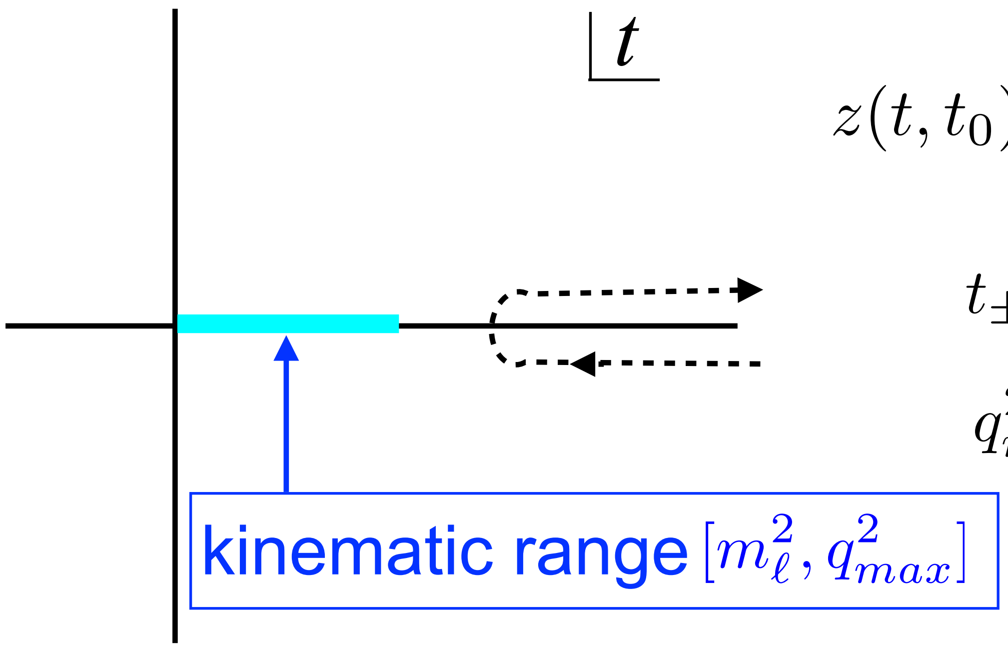
exp. measurements consistent with SM expectations, but with ample room for NP.

SM predictions depend on $f_{B(s)}$ or $\hat{B}_{B_s}$

new LHCb (arXiv:1703.05747, 2017 PRL; De Bruyn @LaThuille 2017):



The z-expansion

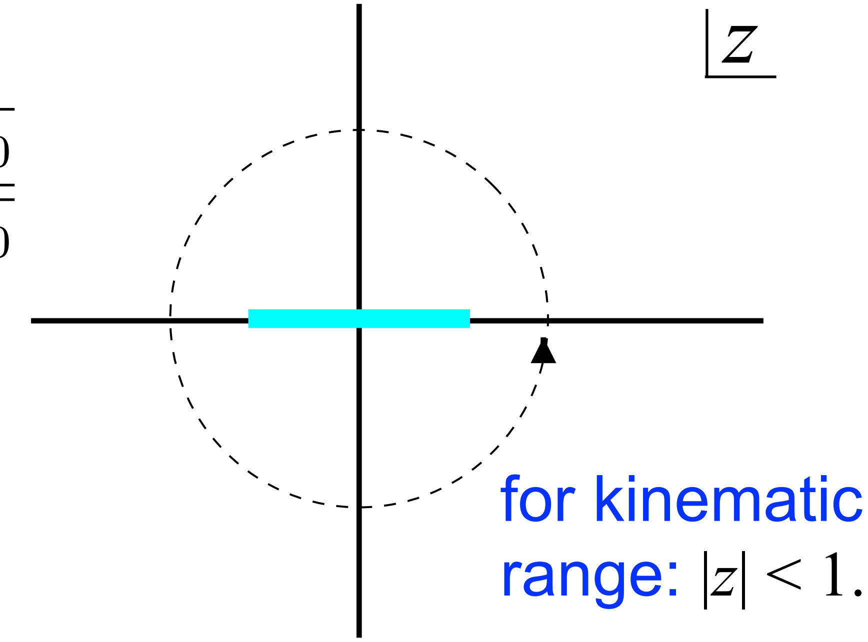


$$t = q^2$$

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$$t_\pm = (m_B \pm m_\pi)^2$$

$$q^2_{max} = t_-$$



Bourrely at al (Nucl.Phys. B189 (1981) 157)
Boyd, Grinstein, Lebed (hep-ph/9412324, PRL 95; hep-ph/9504235, PLB 95; hep-ph/9508211, NPB 96; hep-ph/9705252, PRD 97)
Lellouch (arXiv:hep- ph/9509358, NPB 96)
Boyd & Savage (hep-ph/9702300, PRD 97)
Bourrely at al (arXiv:0807.2722, PRD 09)

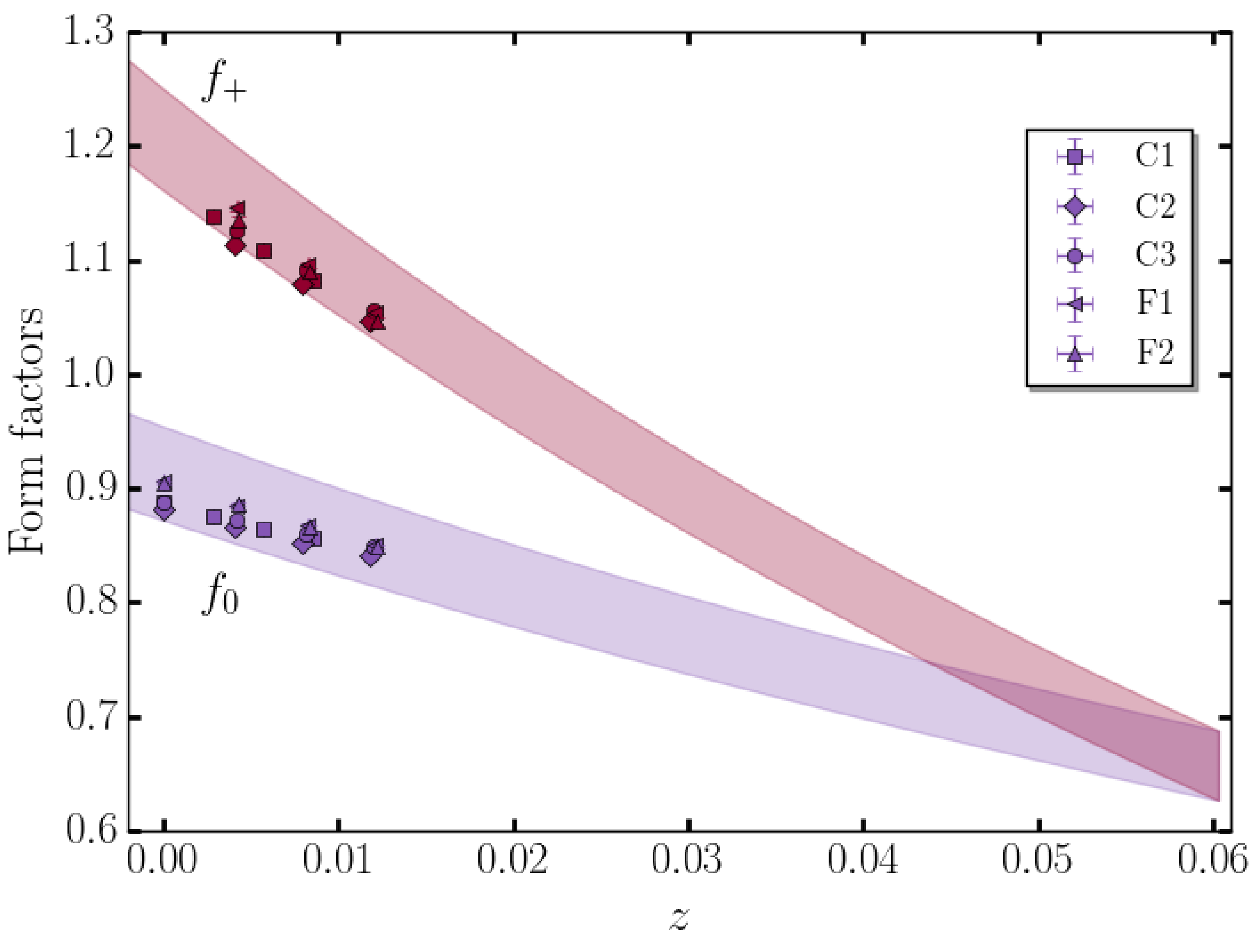
The form factor can be expanded as:

$$f(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0} a_k(t_0) z(t,t_0)^k$$

- $P(t)$ removes poles in $[t_-, t_+]$
- The choice of outer function ϕ affects the unitarity bound on the a_k.
- In practice, only first few terms in expansion are needed.

$B_s \to D_s$

☆ **new** LQCD form factors from HPQCD (Monahan et al, arXiv:1703.09728)

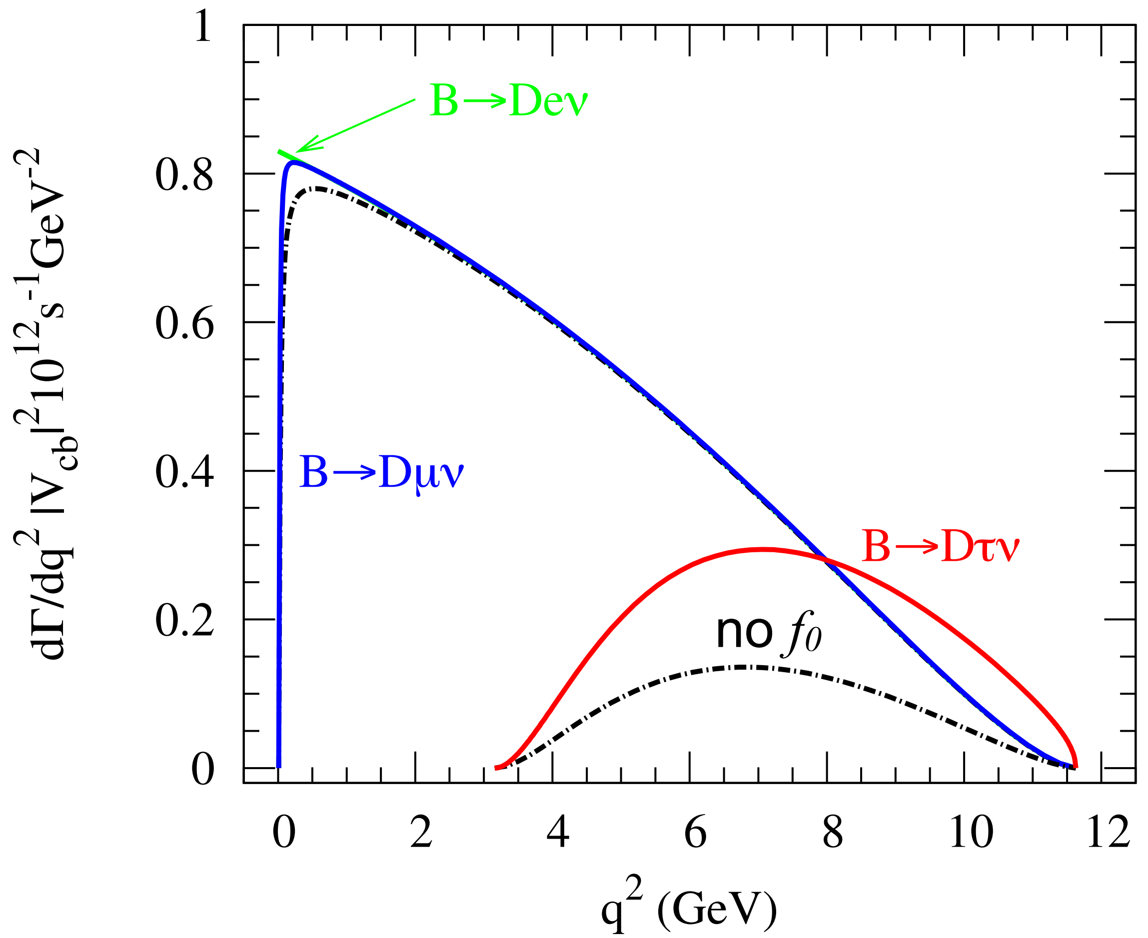


- ★ 5 MILC asqtad (2+1) ensembles two lattice spacings
- ★ NRQCD b and HISQ charm quarks
- ★ $O(a)$ improved current matched through $O(\alpha_s, \Lambda/m_b, \alpha_s a/m_b)$
- ★ $R(D_s) = 0.301\ (6)$
- ★ combine results with previous HPQCD calculation of $B \to D$ form factors to obtain ratios used for f_s/f_d.

Consistent with previous results by FNAL/MILC (Bailey et al, arXiv:1202.6346, 2012 PRD) and ETMC (M. Atoui et al, arXiv:1310.5238, 2014 EPJC).

BSM phenomenology: LFU τ/ℓ

D. Du et al (arXiv:1510.02349, PRD 2016)

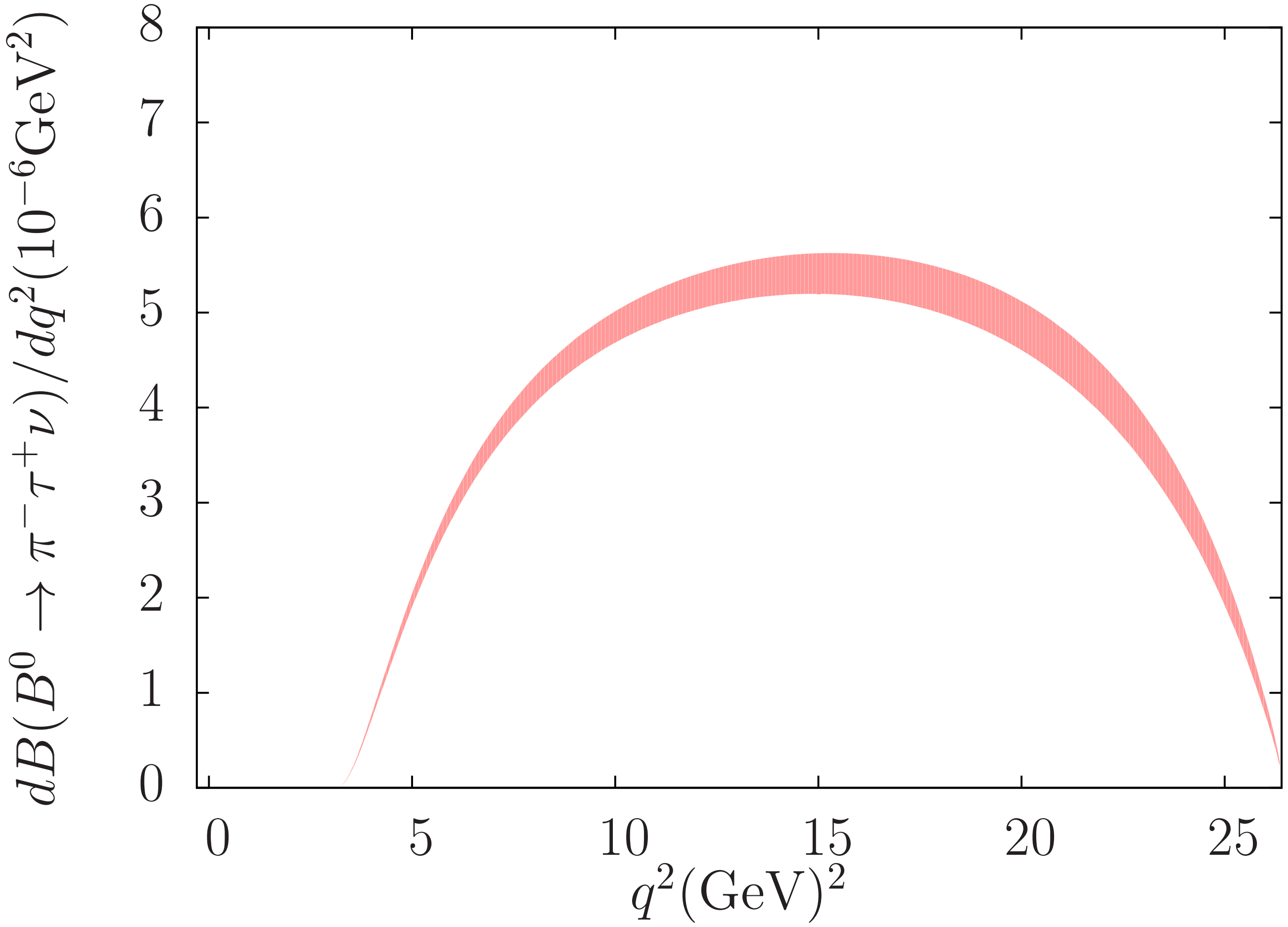


- A shape comparison using (ratios of) differential or binned decay rates to compare theory and experiment would provide useful insights.

BSM phenomenology: LFU τ/ℓ

D. Du et al (arXiv:1510.02349, PRD 2016)

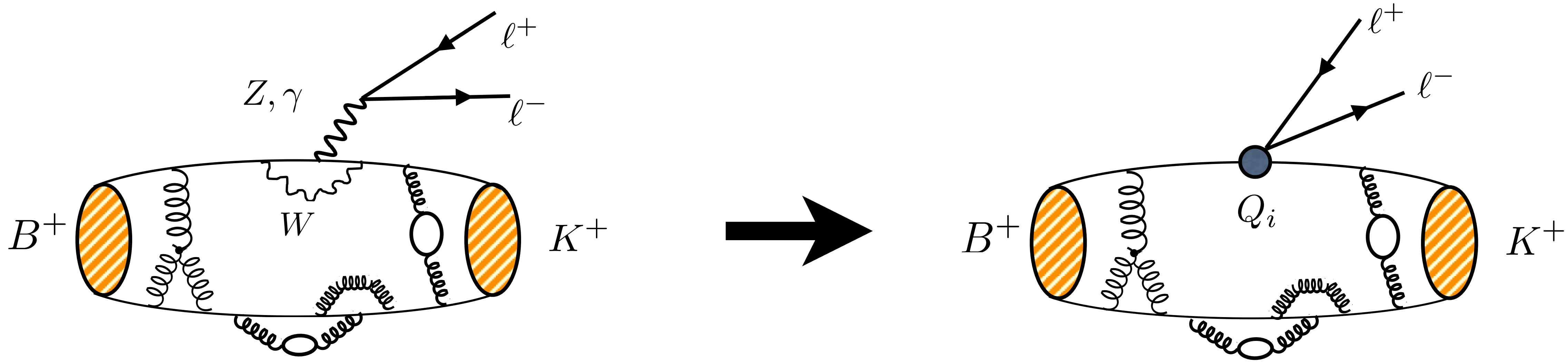
SM prediction for $R(\pi) = \frac{\mathcal{B}(B \to \pi\,\tau\nu_\tau)}{\mathcal{B}(B \to \pi\,\ell\nu)} = 0.641(17)$



Uses the form factors from the combined LQCD + exp. fit to $d\mathcal{B}(B \to \pi\ell\nu)/dq^2$

Hopefully to be measured by Belle II.

Rare semileptonic B decay



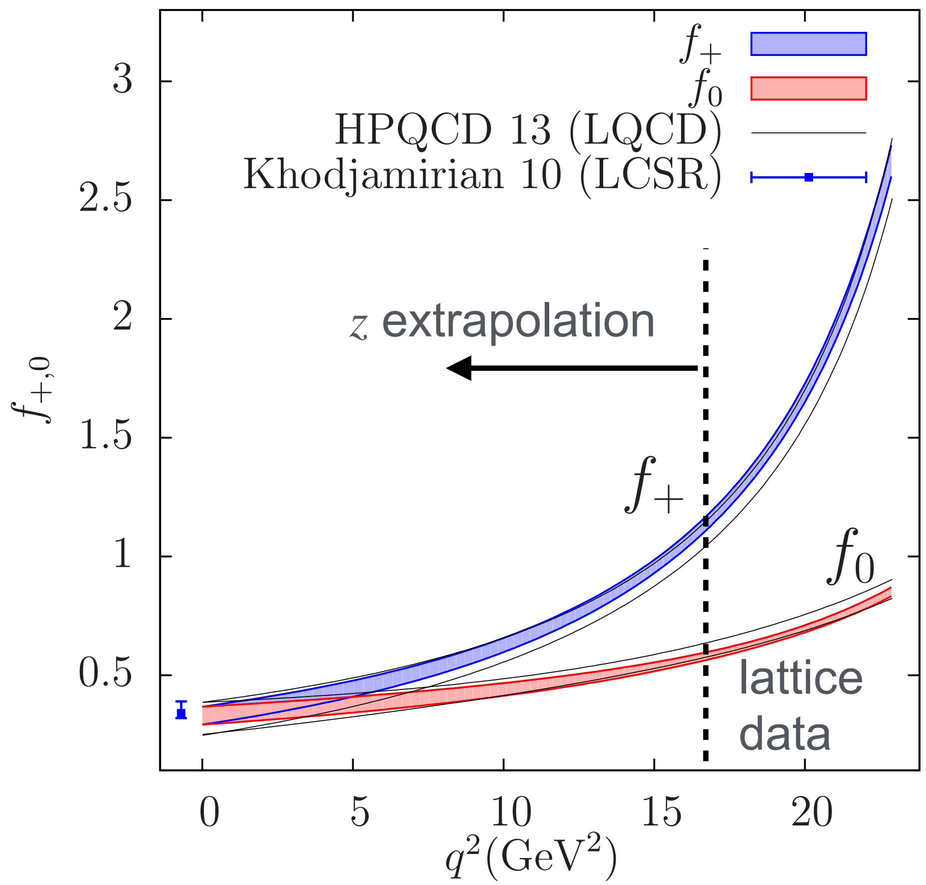
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_i C_i(\mu) Q_i + \ldots$$

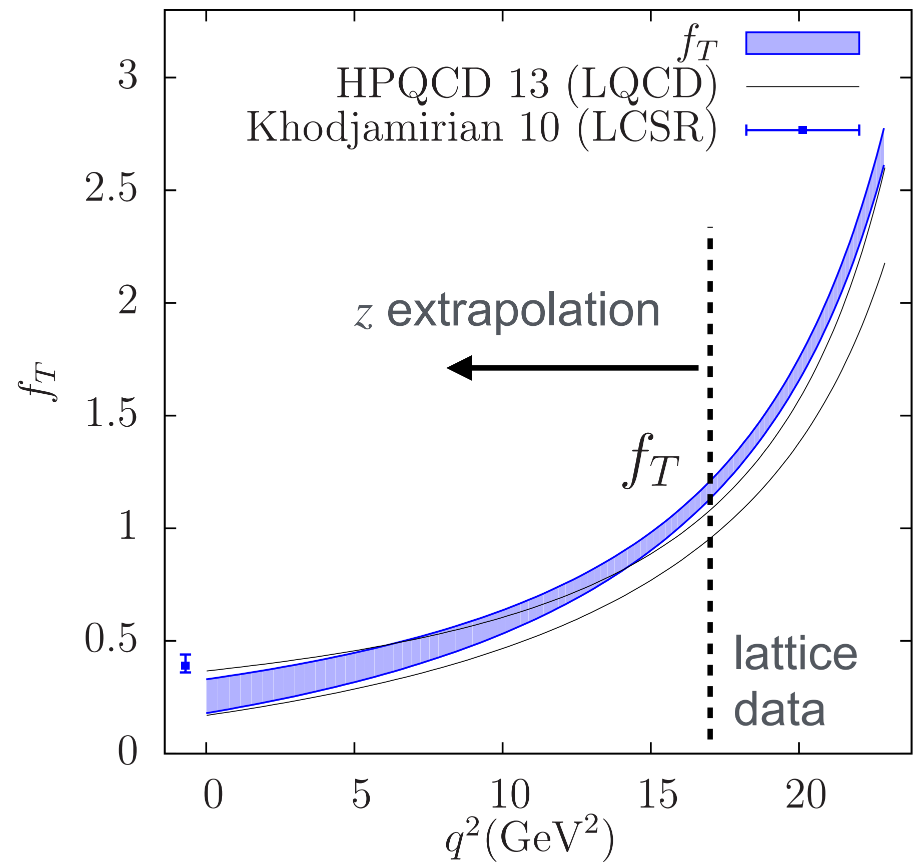
Parameterize the amplitude in terms of the three form factors $f_{+,0,T}(q^2)$:

$$A(B \to P\,\ell\ell) \sim C_7^{\text{eff}} f_T + (C_9^{\text{eff}} + C_{10}) f_+ + \text{nonfactorizable terms}$$

see Hurth talk

form factors for $B \to K\,\ell\ell$





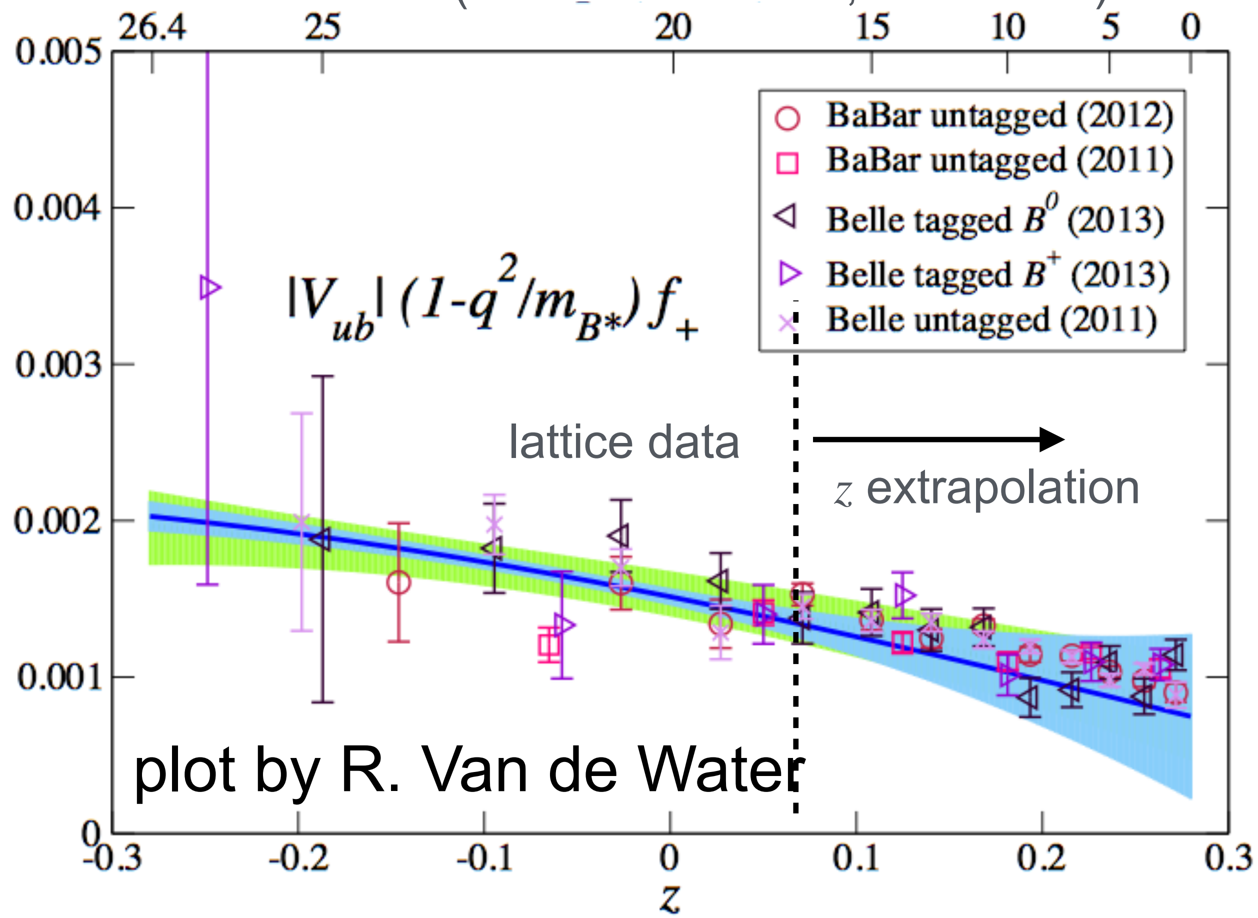
HPQCD (arXiv:1306.0434, 1306.2384, PRL 2013)

FNAL/MILC (arXiv:1509.06235, PRD 2016)

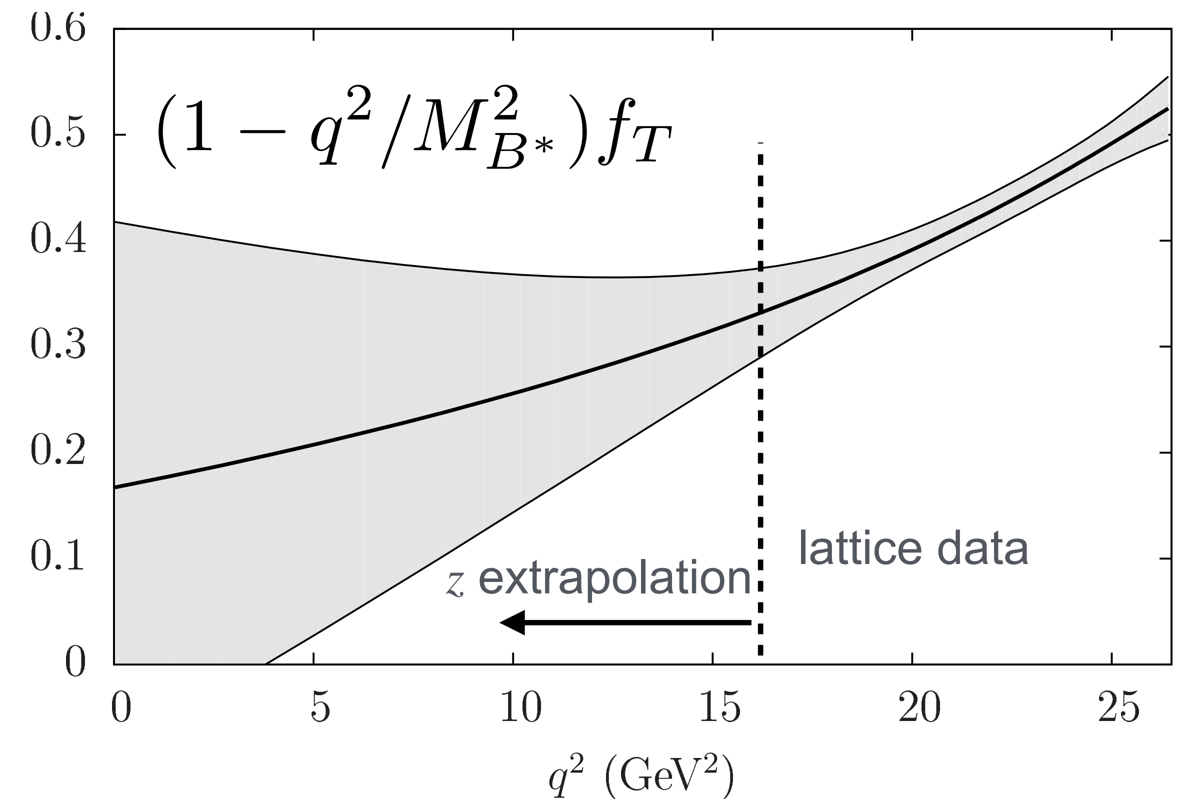
- Two LQCD calculations (on overlapping ensemble sets, different valence actions): HPQCD (NRQCD b + HISQ), FNAL/MILC (Fermilab b + asqtad)
- consistent results for all three form factors
- also consistent with LCSR (Khodjamarian et al, arXiv:1006.4945, JHEP 2010)
- Note: First LQCD calculation of $\Lambda_b \to \Lambda\,\ell^+\ell^-$ form factors (10 total) (see Meinel talk)

form factors for $B \to \pi \ell\ell$

RBC (arXiv:1501.05373, PRD 2015)
FNAL/MILC (arXiv:1503.07839, PRD 2015)



FNAL/MILC (arXiv:1507.01618, PRL 2015)

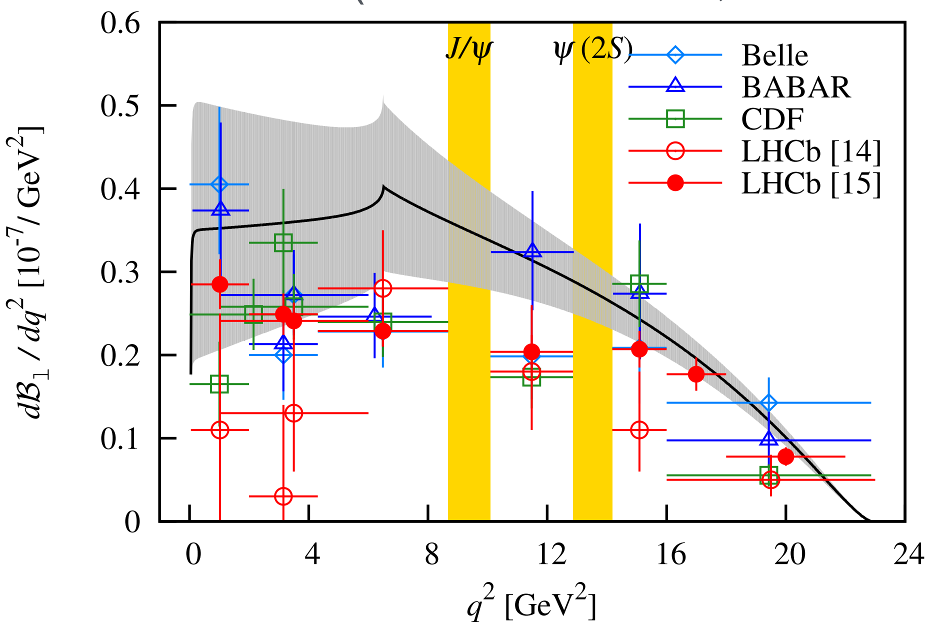


- **First** LQCD calculation of f_T by FNAL/MILC
- Take f_+, f_0 from combined fit of lattice form factors + experimental data for $d\mathcal{B}(B \to \pi \ell \nu)/dq^2$

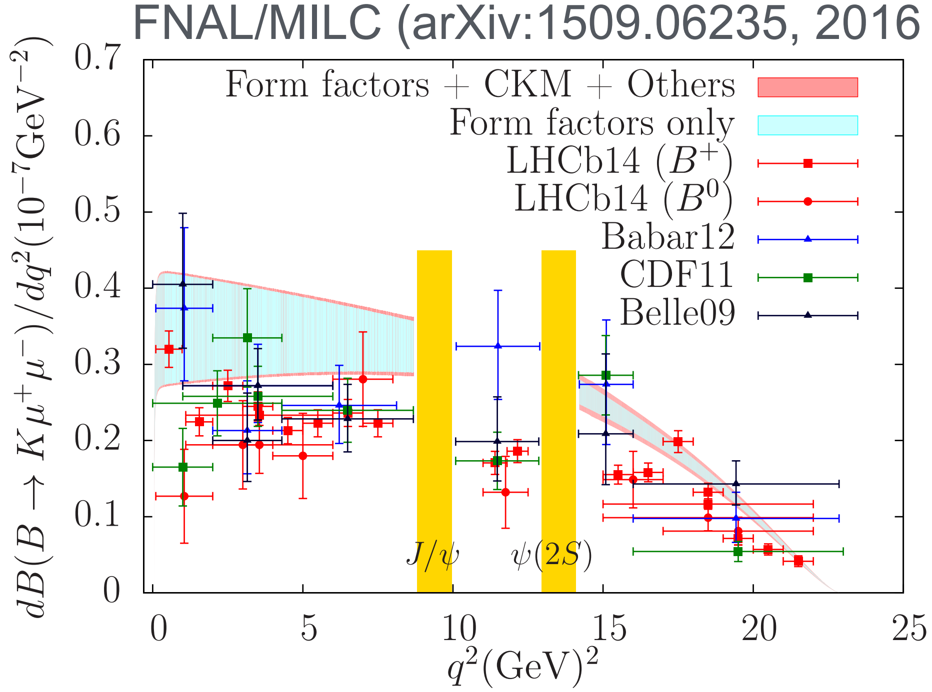
Phenomenology for $B \to K, \pi\, \ell^+ \ell^-$

Experiment vs. Theory

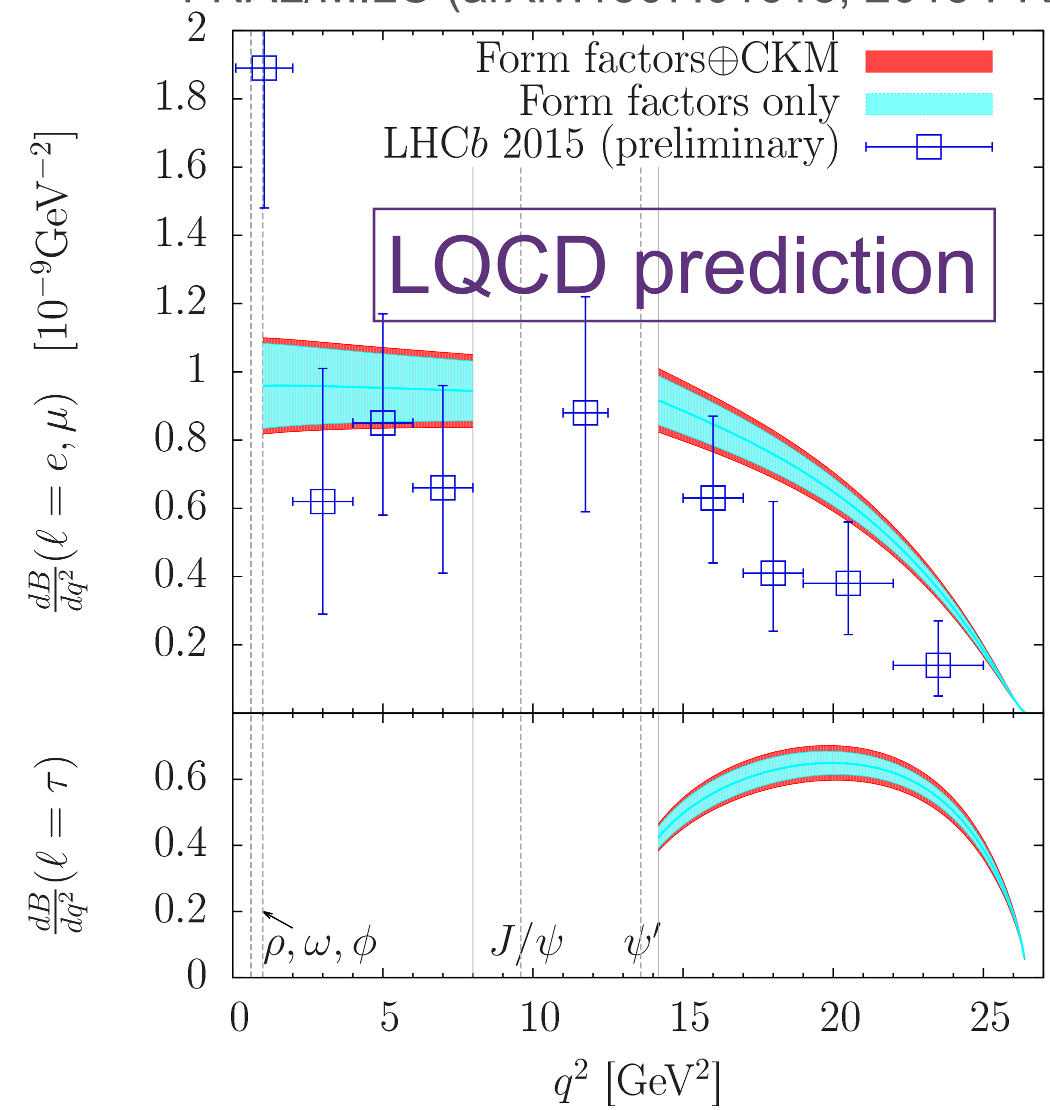
HPQCD (arXiv:1306.0434, 2013 PRL)



FNAL/MILC (arXiv:1509.06235, 2016 PRD)



FNAL/MILC (arXiv:1507.01618, 2015 PRL)



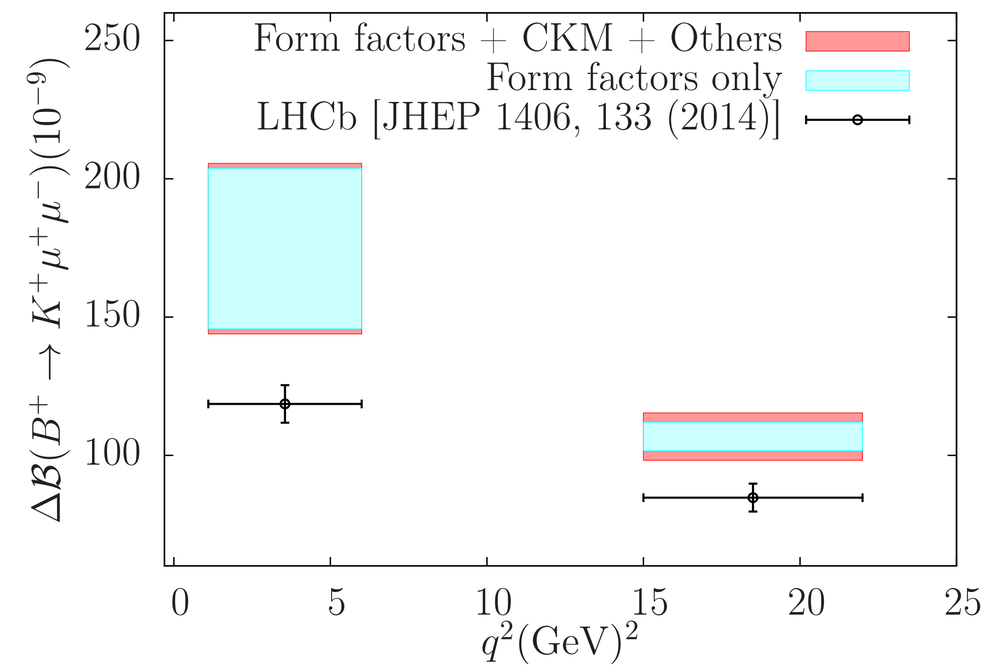
Phenomenology for $B \to K, \pi\, \ell^+ \ell^-$

Experiment vs. theory

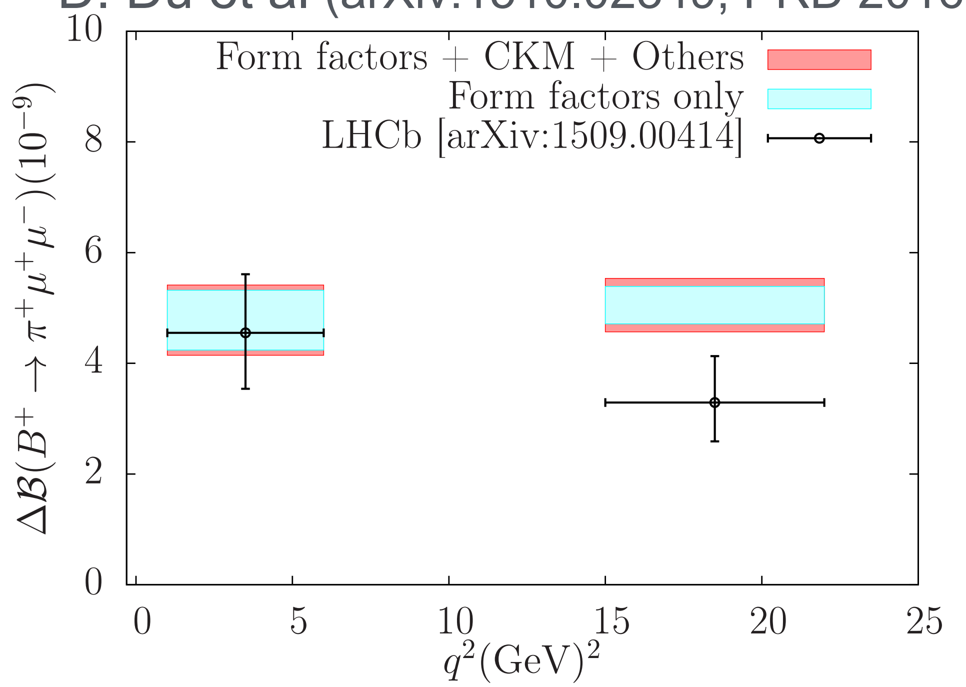
- LHCb data + FNAL/MILC form factors (arXiv:1509.00414, JHEP 2015;1403.8044, JHEP 2014)
- focus on large bins above and below charmonium resonances
- theory errors commensurate with experiment
- yields $\sim$1-2σ tensions
- $\Rightarrow$ determine $|V_{td}/V_{ts}|, |V_{td}|, |V_{ts}|$

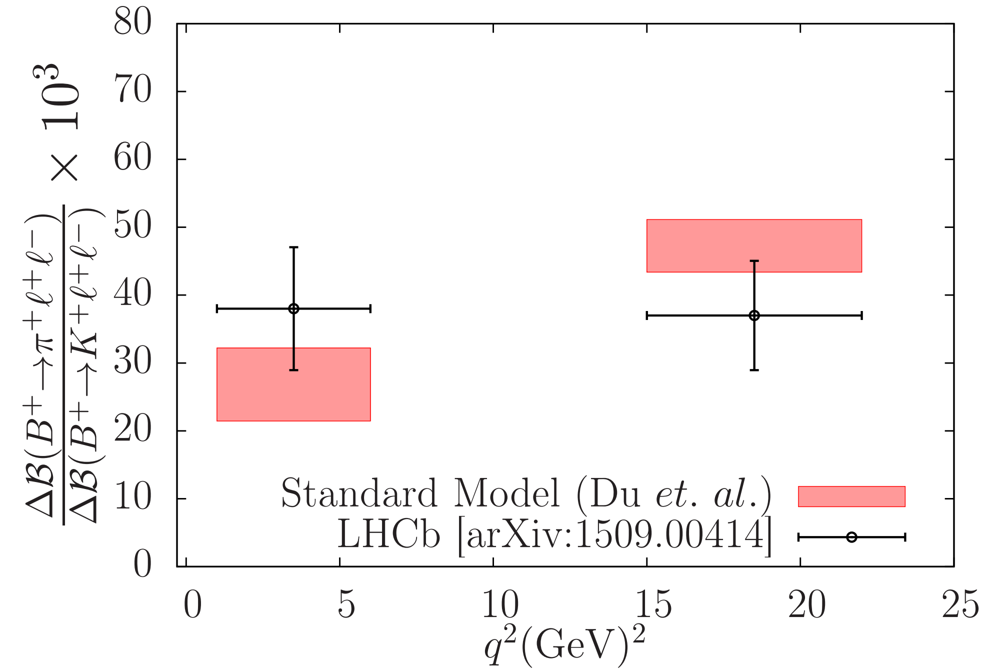
  or constrain Wilson coefficients

D. Du et al (arXiv:1510.02349, PRD 2016)



D. Du et al (arXiv:1510.02349, PRD 2016)

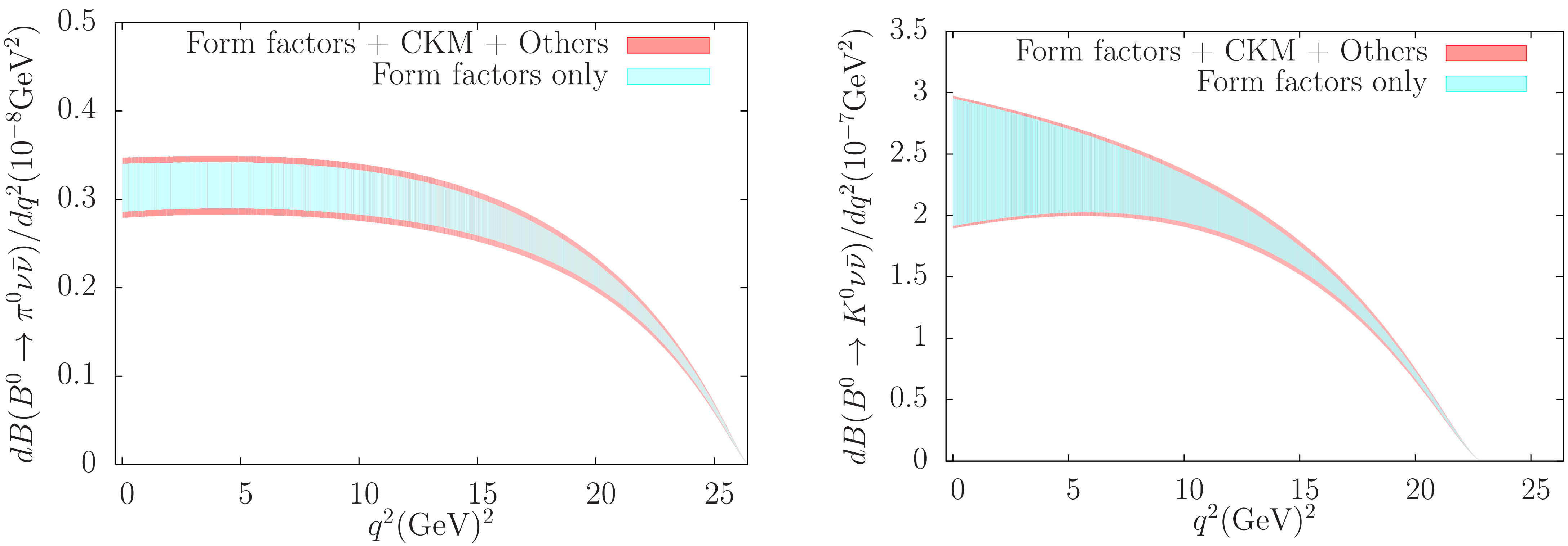




Rare semileptonic B decays to $\nu\bar{\nu}$ states

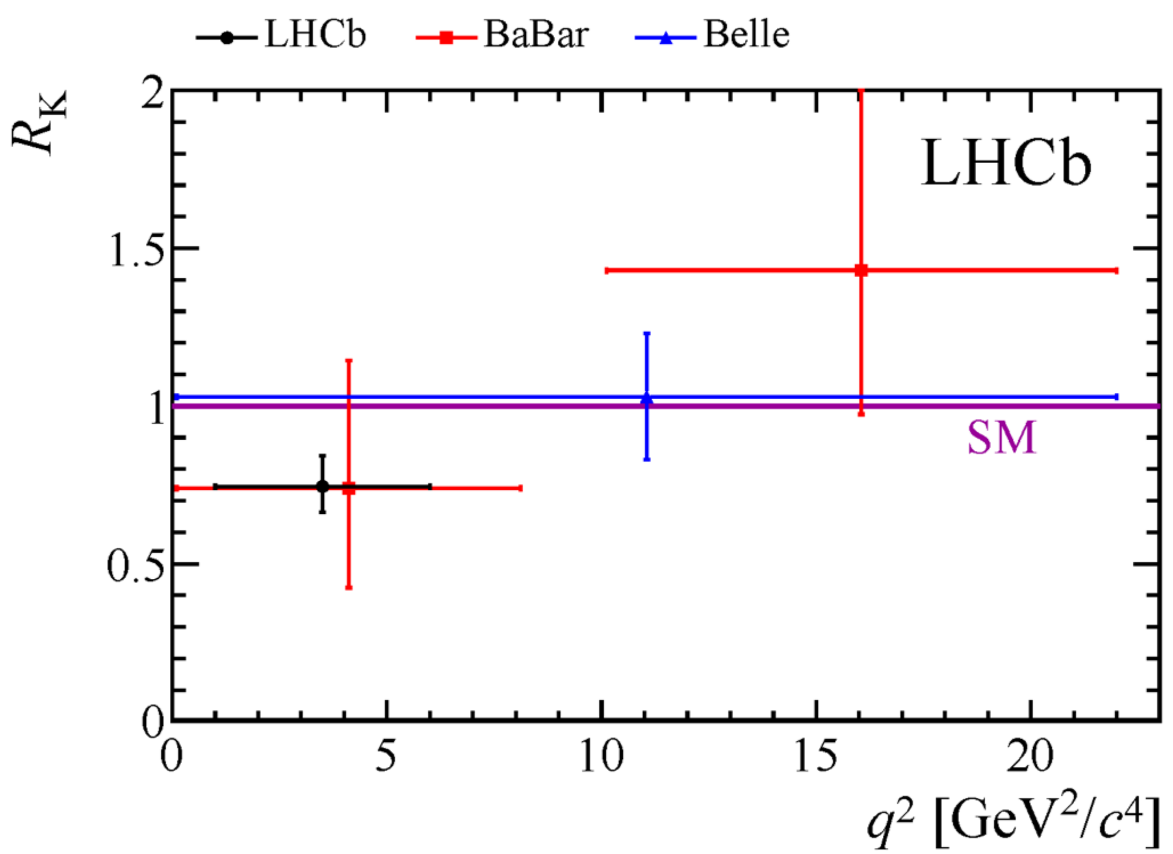
theoretically clean

D. Du et al (arXiv:1510.02349, PRD 2016)



BSM phenomenology: LFU μ/e

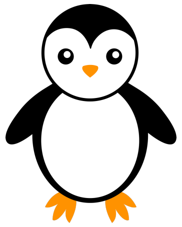
Lepton universality test: $B \to K\mu^+\mu^- / B \to K e^+ e^-$



LHCb (arXiv:1406.6482, PRL 2014):

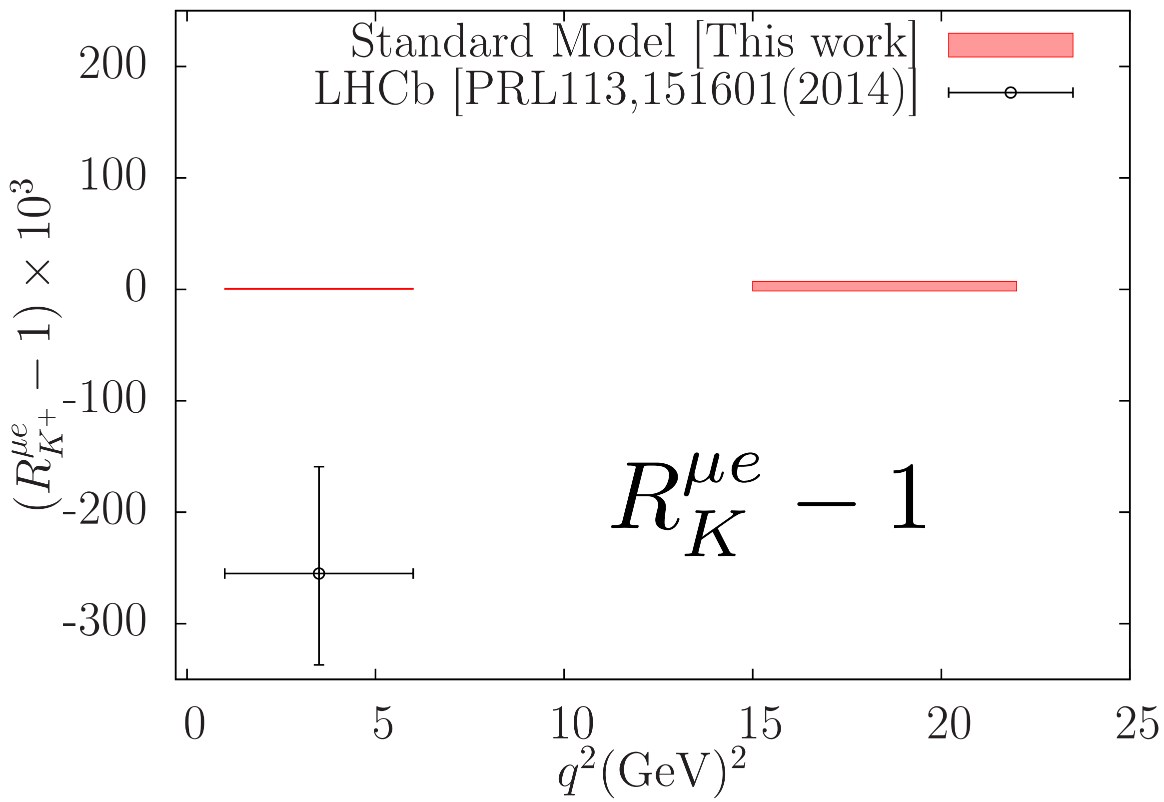
$$R_K = 0.745\,\binom{90}{74}(36)$$

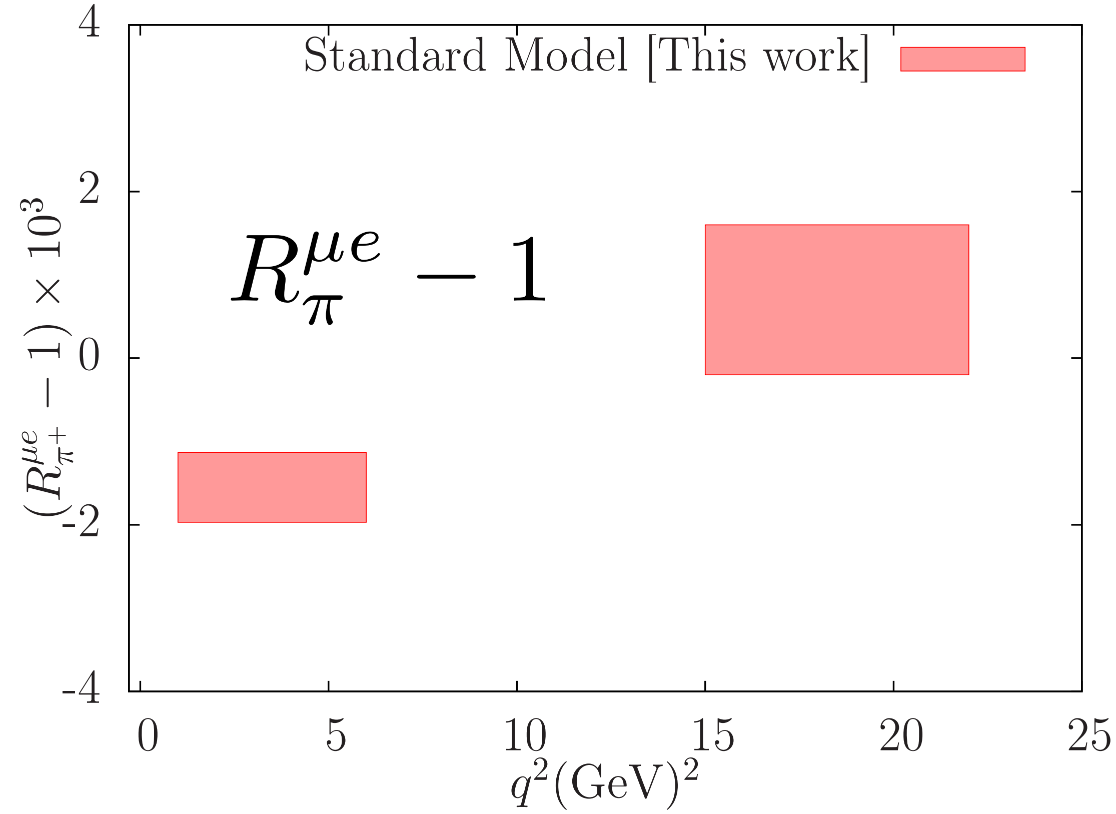
$\sim 2.6\,\sigma$ tension between LHCb measurement and SM theory



BSM phenomenology: LFU μ/e

D. Du et al (arXiv:1510.02349, PRD 2016)





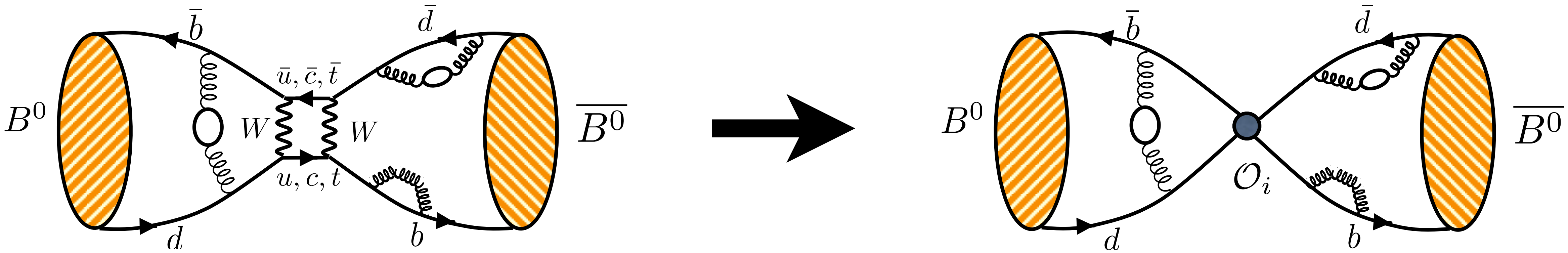
~2.6 σ tension between LHCb measurement and SM theory

In the SM these ratios are insensitive to the form factors

(see also C. Bouchard et al, arXiv:1303.0434, PRL 2013)

Neutral B meson mixing

Standard Model



SM: $\Delta M_q = (\text{known}) \times |V_{tq}^* V_{tb}|^2 \times \langle \bar{B}_q^0 | \mathcal{O}_1 | B_q^0 \rangle$

also:

$$\frac{\Delta M_s}{\Delta M_d} = \frac{m_{B_s}}{m_{B\,d}} \times \left| \frac{V_{ts}}{V_{td}} \right|^2 \times \xi^2 \quad \text{with} \quad \xi \equiv \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

$$\Delta\Gamma_q = \left[G_1 \, \langle \bar{B}_q^0 | \mathcal{O}_1 | B_q^0 \rangle + G_3 \, \langle \bar{B}_q^0 | \mathcal{O}_3 | B_q^0 \rangle \right] \cos\phi_q + O(1/m_b)$$

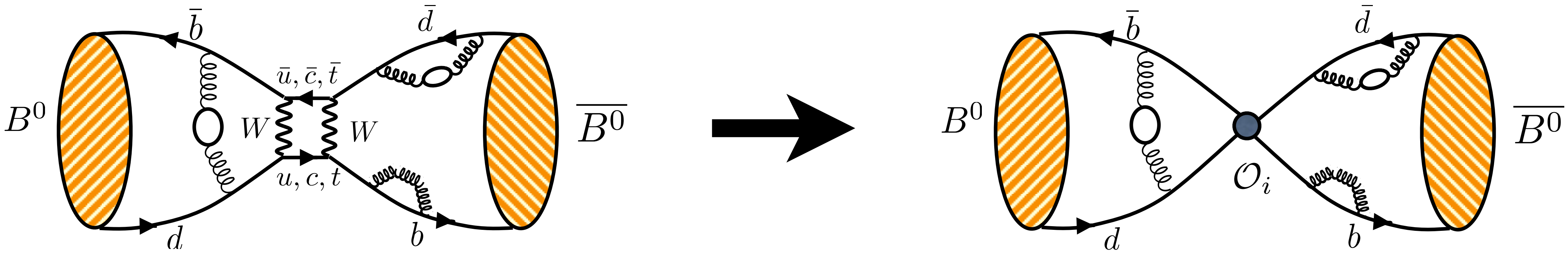
HFAG, PDG 2016 averages:

$$\Delta M_d = (0.5055 \pm 0.0020)\ \text{ps}^{-1}\ (0.4\%)$$
$$\Delta M_s = (17.575 \pm 0.021)\ \text{ps}^{-1}\ (0.1\%)$$

$$\Delta\Gamma_d/\Gamma_d = 0.001 \pm 0.010$$
$$\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.009\ \ (7.3\%)$$

Neutral B meson mixing

Standard Model



In general :

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} c_i(\mu)\mathcal{O}_i(\mu)$$

SM:

$$\mathcal{O}_1 = (\bar{b}^\alpha \gamma_\mu L q^\alpha)\ (\bar{b}^\beta \gamma_\mu L q^\beta)$$

$$\mathcal{O}_2 = (\bar{b}^\alpha L q^\alpha)\ (\bar{b}^\beta L q^\beta)$$

$$\mathcal{O}_3 = (\bar{b}^\alpha L q^\beta)\ (\bar{b}^\beta L q^\alpha)$$

BSM:

$$\mathcal{O}_4 = (\bar{b}^\alpha L q^\alpha)\ (\bar{b}^\beta R q^\beta)$$

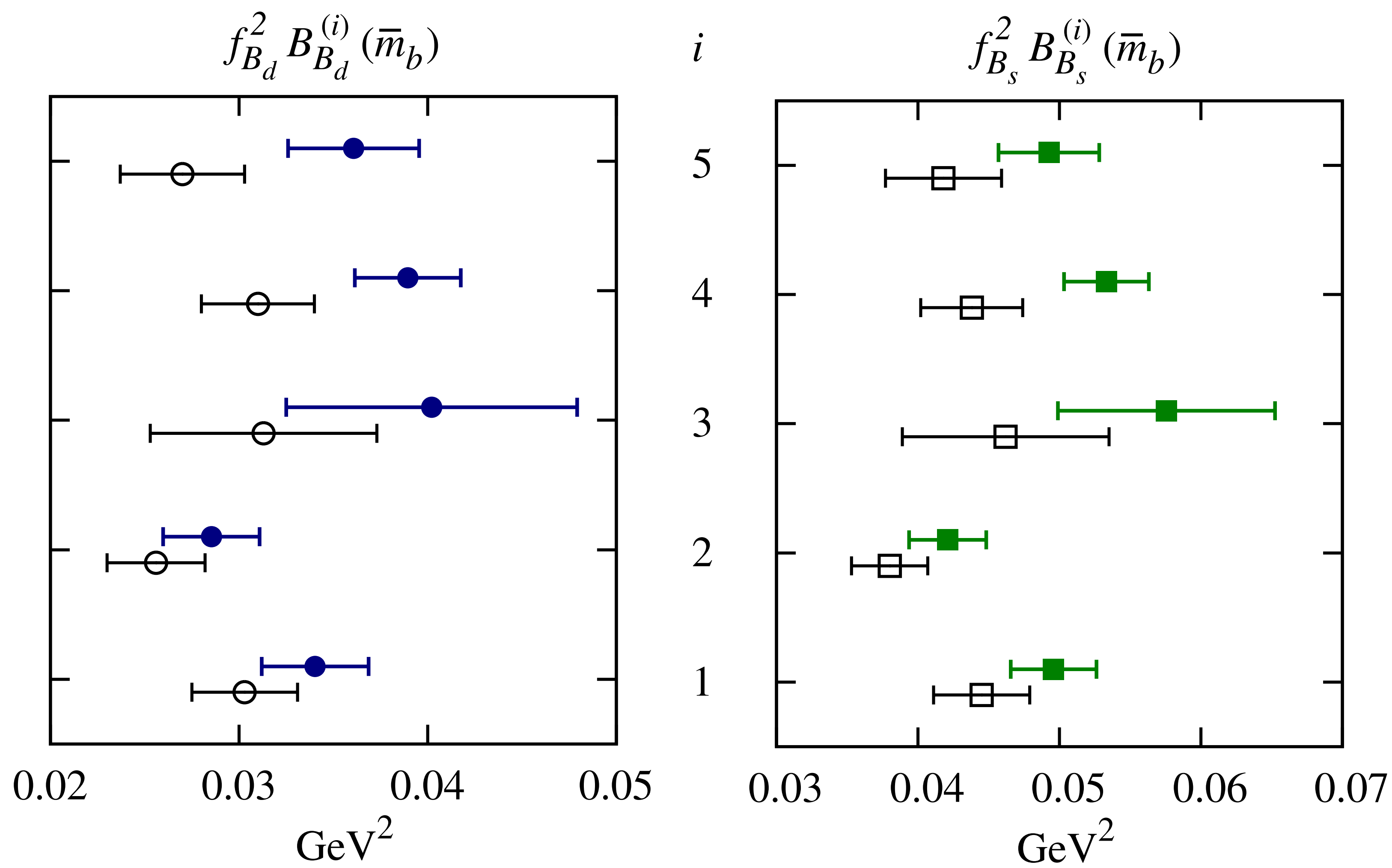
$$\mathcal{O}_5 = (\bar{b}^\alpha L q^\beta)\ (\bar{b}^\beta R q^\alpha)$$

$$\langle \mathcal{O}_i \rangle \equiv \langle \bar{B}_q^0 | \mathcal{O}_i | B_q^0 \rangle(\mu) = e_i\ m_{B_q}^2\ f_{B_q}^2\ B_{B_q}^{(i)}(\mu)$$

The matrix elements of all five operators can be calculated in LQCD.

B mixing results in comparison

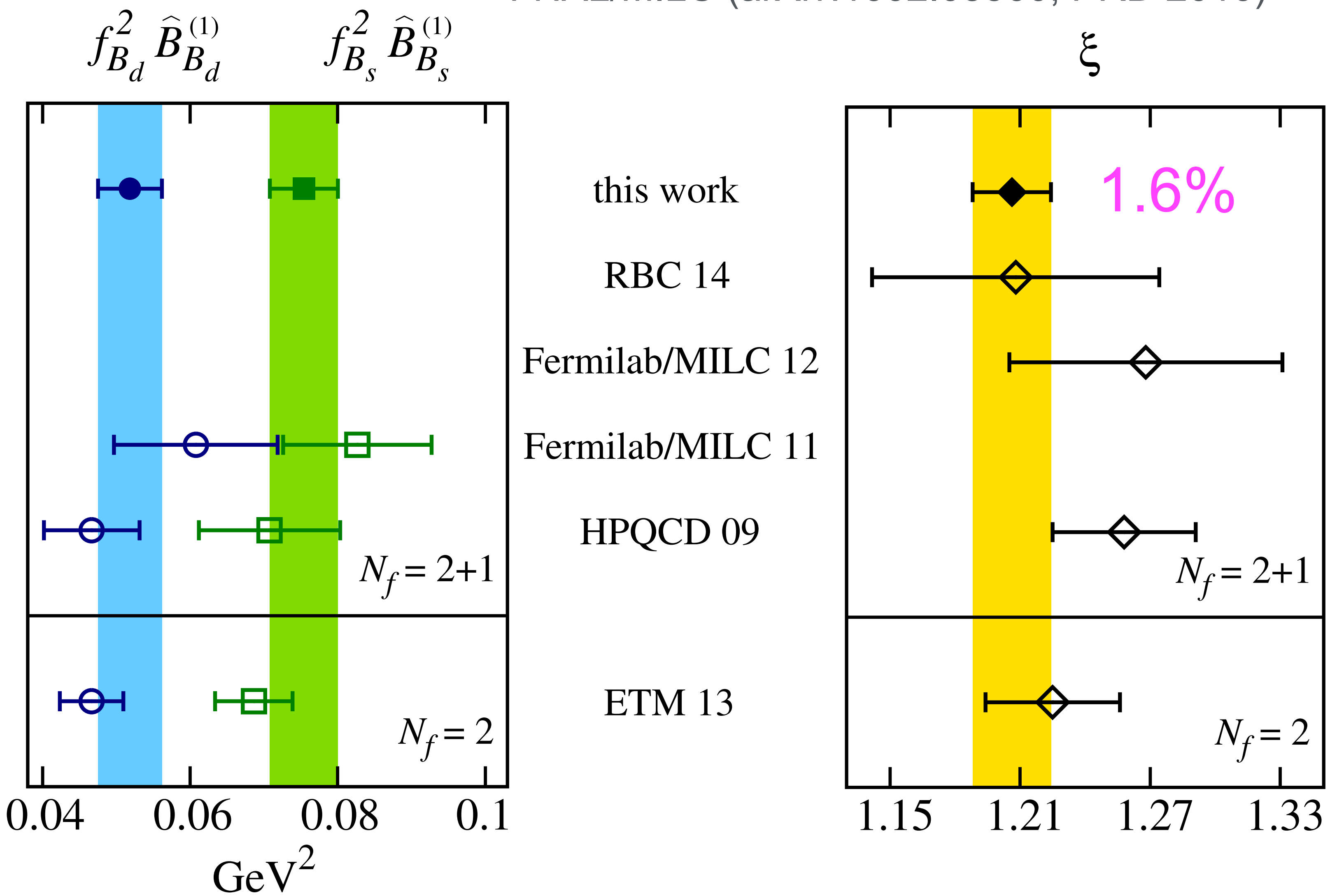
ETM (n_f=2, arXiv:1308.1851, JHEP 2014) vs. FNAL/MILC (n_f=3, arXiv:1602.03560, PRD 2016)



☆ **First** three flavor LQCD results for all five matrix elements including the correlations between all 10 MEs.

B mixing results in comparison

FNAL/MILC (arXiv:1602.03560, PRD 2016)

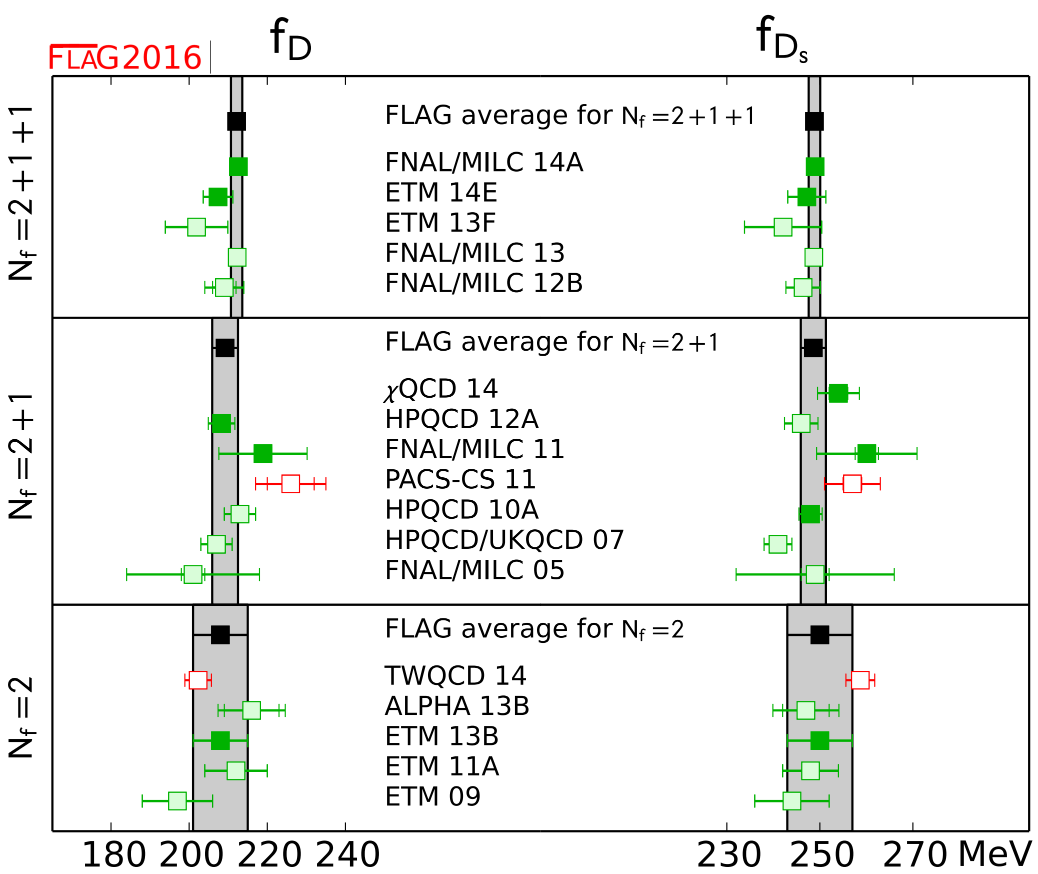


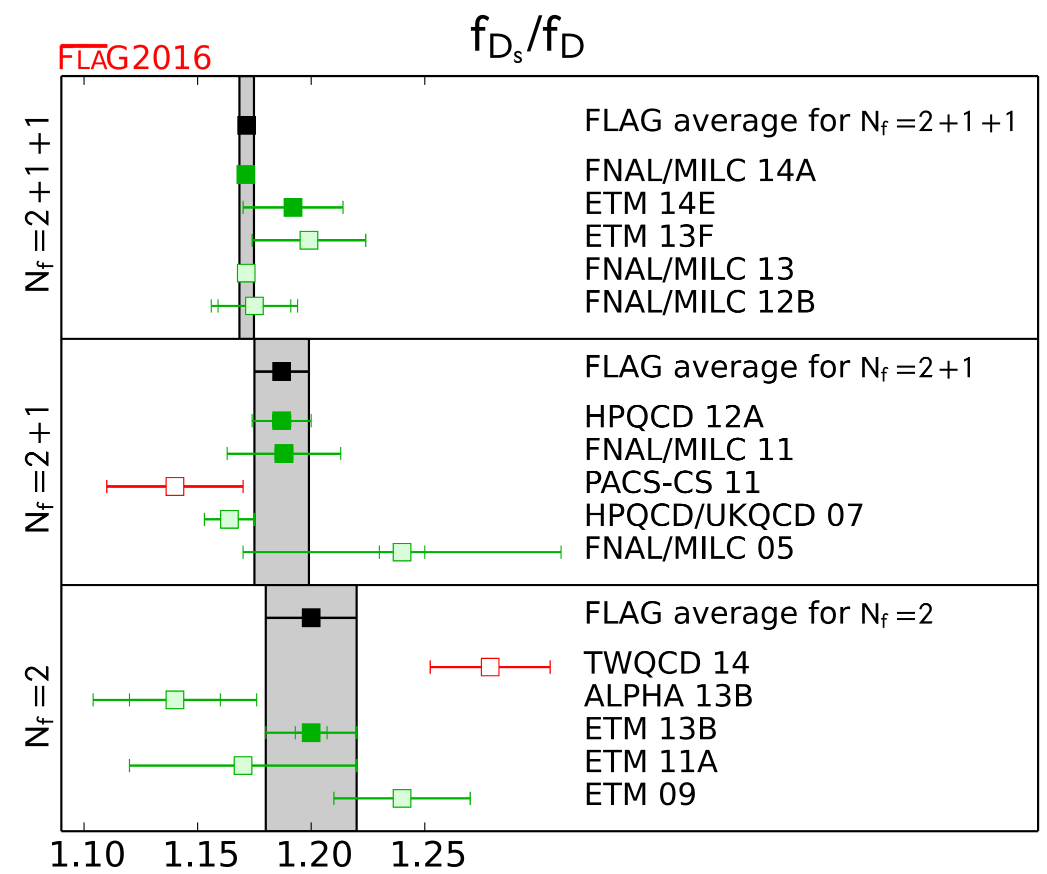
Significant reduction of errors compared to previous three flavor results, especially for ξ

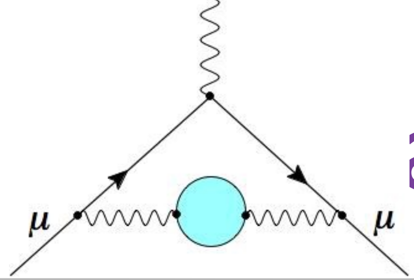
- Note: FLAG-3 is currently updating their averages for B mixing quantities to include the new FNAL/MILC results.
- ongoing LQCD calculations by HPQCD, ETM, RBC/UKQCD, …

FLAG review of *D*-meson quantities

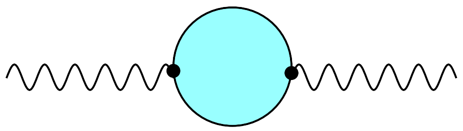
S. Aoki et al (FLAG-3 review, arXiv:1607.00299, EPJC 17, web update)







adronic vacuum polarization

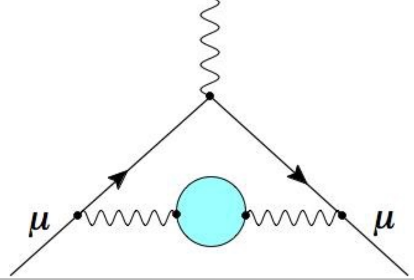


$$\hat{\Pi}(q^2) = \Pi(q^2) - \Pi(0)$$

$$\Pi_{\mu\nu} = \int d^4x e^{iqx} \langle j_\mu(x) j_\nu(0) \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi(q^2)$$

Leading order HVP correction: $$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dq^2\, w(q^2)\, \hat{\Pi}(q^2)$$

- Use optical theorem and dispersion relation to rewrite the integral in terms of the hadronic cross section
  ➟ talks by Teubner, Jegerlehner, Zhang



Hadronic vacuum polarization

Leading order HVP correction: $$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dq^2\, w(q^2)\, \hat{\Pi}(q^2)$$

- Calculate a_μ^{HVP} in Lattice QCD:
  - ✦ Calculate $\hat{\Pi}(q^2)$ and evaluate the integral (Blum,PRL 03, Lautrup et al, 71)
  - ✦ Time-momentum representation: reorder the integrations and compute $C(t) = \frac{1}{3}\sum_{i,x}\langle j_i(x,t) j_i(0,0)\rangle$

$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, \tilde{w}(t)\, C(t)$$

(Bernecker & Meyer, EPJ 12)

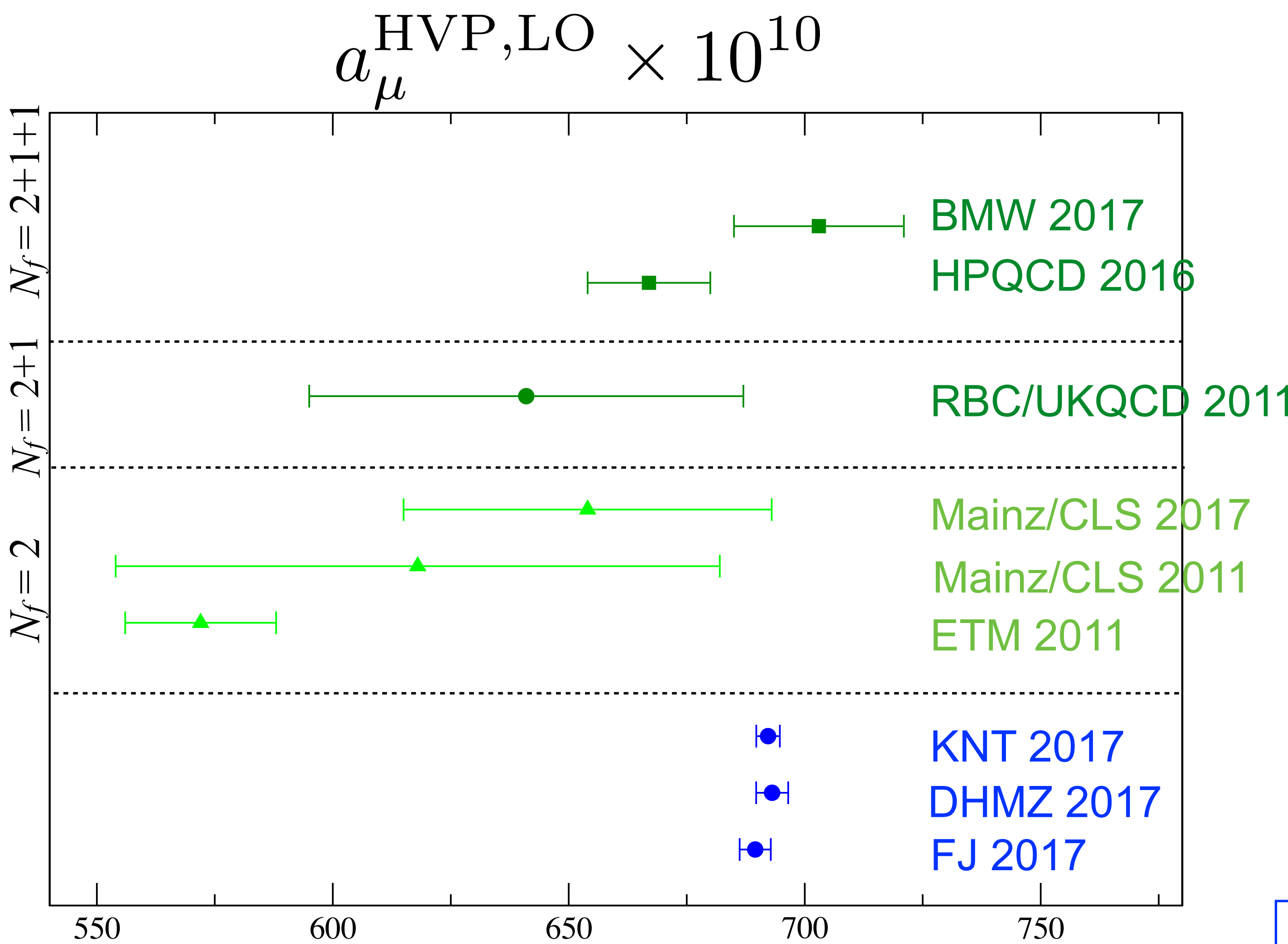
  - ✦ Time-moments: (Chakraborty et al, PRD 14)

Taylor expand $\hat{\Pi}(q^2) = \sum_k q^{2k}\Pi_k$

and compute Taylor coefficients from time moments:

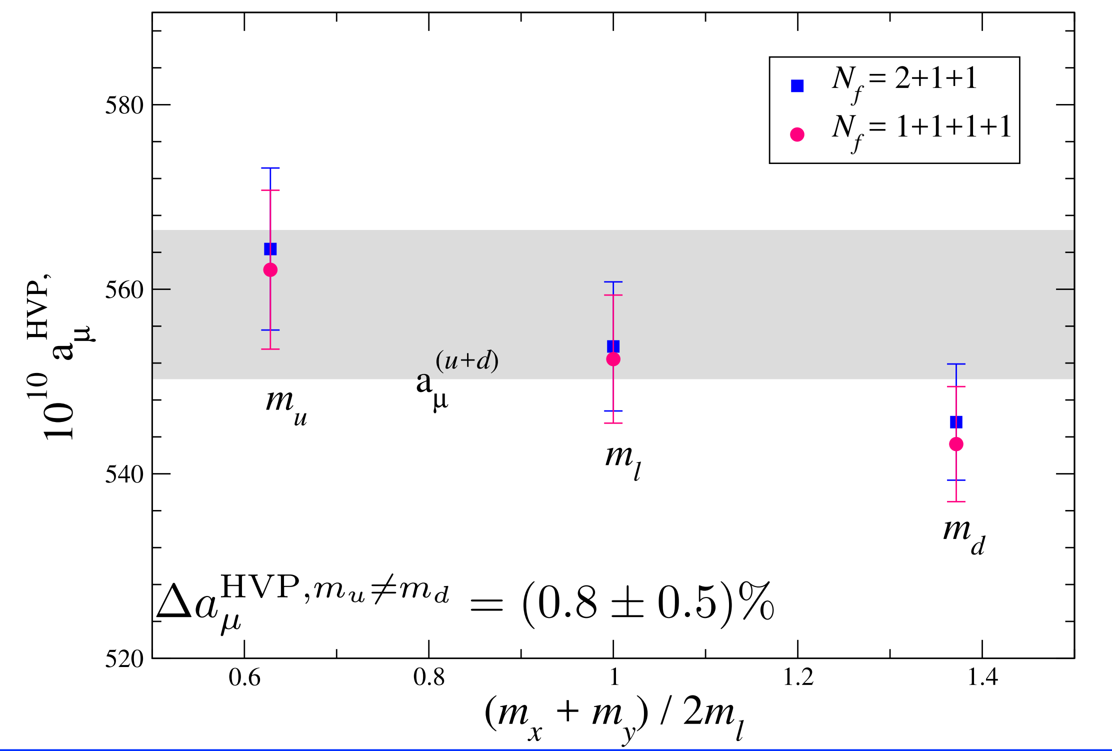
$$C_{2n} = a\sum_t t^{2n} C(t)$$

Highlights of recent LQCD HVP results



Isospin correction

R. Van de Water @ Lattice 2017 (FNAL/HPQCD/MILC)



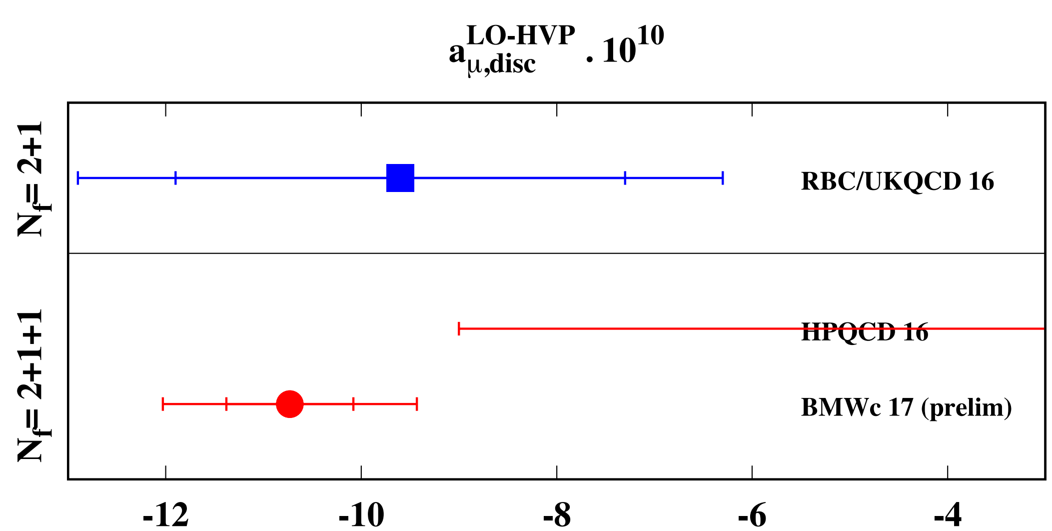
First LQCD calculation at physical pion mass.

Disconnected contribution

BMWc '17 $\delta a_{\mu,\,\rm disc}^{\rm LO\text{-}HVP} = 1.5 \times 10^{-10}$

$\rightarrow$ contributes only 0.2% to error on $a_\mu^{\rm LO\text{-}HVP}$

(Lellouch, Miura @ Fermilab muon g-2 theory workshop and Lattice 2017)



Muon g-2 Theory Initiative

Steering Committee:

- Gilberto Colangelo (Bern) gilberto@itp.unibe.ch
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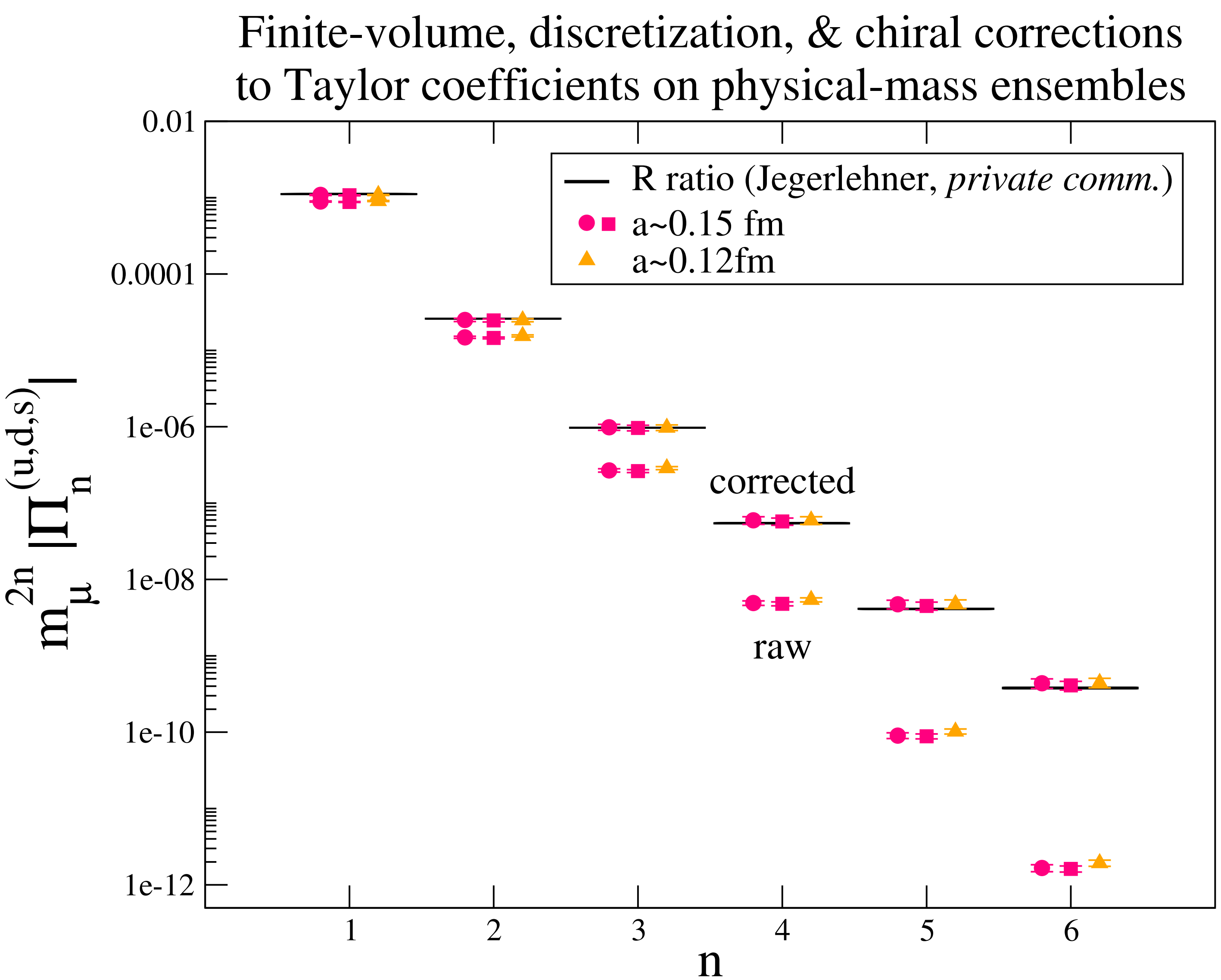
Muon g-2 Theory Initiative: Goals

- theory support to the Fermilab and J-PARC experiments to maximize their impact
  ➠ need theoretical predictions of the hadronic corrections with reduced and reliably estimated uncertainties
- summarize the theoretical calculations of the hadronic corrections to the muon g-2
  ➠ comparisons of intermediate quantities between the different approaches. For example, lattice vs experiment
  ➠ assess reliability of uncertainty estimates

Compare HPQCD results to R-ratio data

R. Van de Water @ Lattice 2017



A good test of the corrections, because the comparison was performed after the first version of the HPQCD paper (1601.03071) was posted.

Lowest moments make the largest contributions to a_μ.

Muon g-2 Theory Initiative: Goals

- theory support to the Fermilab and J-PARC experiments to maximize their impact
  ➠ need theoretical predictions of the hadronic corrections with reduced and reliably estimated uncertainties
- summarize the theoretical calculations of the hadronic corrections to the muon g-2
  ➠ comparisons of intermediate quantities between the different approaches. For example, lattice vs experiment
  ➠ assess reliability of uncertainty estimates
- combine to provide theory predictions for $a_\mu^{\rm HVP}$ and $a_\mu^{\rm HLbL}$ and write a report **before** the Fermilab and J-PARC experiments announce their first results.

Muon g-2 Theory Initiative: Plan

- Organize ``plenary" workshops to bring the different communities together
  - First workshop: held near Fermilab, June 2017: kick-off
  - Second workshop: Mainz, 18-22 June 2018: organize first report
  - 2019 & 2020 workshops: Japan? Seattle?
- Form two working groups, one for HVP and one for HLbL:
  - invite community participation
  - organize focused workshops to advance the work: winter/spring 2018
- Finalize the first report before the Fermilab experiment announces its first result with ``Brookhaven level" statistics

  target date for first report: September 2018

First Workshop of the Muon g-2 Theory Initiative

3-6 June 2017 *Q Center*
US/Central timezone

Search

- Sponsors
- Committees
- Timetable
- Registration
  - Registration Form
- List of registrants
- List of confirmed speakers
- workshop photos
- Accommodations
- Wilson Hall
- Visa Information

In the coming years, experiments at Fermilab and at J-PARC plan to reduce the uncertainties on the already very precisely measured anomalous magnetic moment of the muon by a factor of four. The goal is to resolve the current tantalizing tension between theory and experiment of three to four standard deviations. On the theory side the hadronic corrections to the anomalous magnetic moment are the dominant sources of uncertainty. They must be determined with better precision in order to unambiguously discover whether or not new physics effects contribute to this quantity.

There are a number of complementary theoretical efforts underway to better understand and quantify the hadronic corrections, including dispersive methods, lattice QCD, effective field theories, and QCD models. We have formed a new theory initiative to facilitate interactions between the different groups through organizing a series of workshops. The goal of this first workshop is to bring together theorists from the different communities to discuss, assess, and compare the status of the various efforts, and to map out strategies for obtaining the best theoretical predictions for these hadronic corrections in advance of the experimental results.

All sessions in this workshop will be plenary, featuring a mix of talks and discussions.

Muon g-2 Theory Initiative: WGs

- to sign-up for the HVP or HLbL WG
  send email to one of the WG coordinators
- HVP WG coordinators:
  - Michel Davier davier@lal.in2p3.fr
  - Simon Eidelman eidelman@cern.ch
  - Aida El-Khadra axk@illinois.edu
  - Thomas Teubner thomas.teubner@liverpool.ac.uk
- HLbL WG coordinators:
  - Gilberto Colangelo gilberto@itp.unibe.ch
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