Prospects for Precision Lattice QCD

Andreas S. Kronfeld*
Fermilab & IAS TU München

Towards the Ultimate Precision in Flavor Physics
IPPP, Durham University | April 2, 2019

DIVA = Durham International Visiting Academic

Prospects for Precision Lattice QCD⊕QED

Andreas S. Kronfeld*
Fermilab & IAS TU München

Towards the Ultimate Precision in Flavor Physics
IPPP, Durham University | April 2, 2019

DIVA = Durham International Visiting Academic

Introduction

- Where are we? Where do we need to be? What's cool and interesting?
    - Quark masses = vev × eigenvalues of the Yukawa matrices.
    - CKM matrix elements = mismatch of up-down Yukawa eigenvectors:
        - Decay constants for leptonic decays;
        - Form factors for semileptonic decays.
    - Flavor-changing neutral currents—∃ BSM contributions?

CKM and Lattice QCD

$$V = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ \pi^+ \to l^+ \nu & K^+ \to l^+ \nu & B^+ \to \tau^+ \nu \\ \pi^+ \to \pi^0 e^+ \nu & K \to \pi l^+ \nu & B \to \pi l^+ \nu \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ D^+ \to l^+ \nu & D_s^+ \to l^+ \nu & B_c^+ \to \tau^+ \nu \\ D \to \pi l^+ \nu & D \to K l^+ \nu & B \to \pi l^+ \nu \\ |V_{td}| & |V_{ts}| & |V_{tb}| \\ B^0 \to \pi^0 l^+ l^- & B^0 \to K^0 l^+ l^- & \\ B^0 \leftrightarrow \bar{B}^0 & B_s^0 \leftrightarrow \bar{B}_s^0 & \end{pmatrix}$$

$$e^{-i\delta_{\mathrm{KM}}}$$

$K^0 \leftrightarrow \bar{K}^0 \quad [\varepsilon]$

$K \to \pi\pi \quad [\varepsilon']$

B2TiP Forecasts

T. Kaneko, ASK, S. Simula

N_f	forecast	f_B[MeV]	f_{B_s}[MeV]	f_{B_s}/f_B
	current (2017)	188(3)	227(4)	1.203(7)
	5 yr w/o EM	188(1.5)	227(2.0)	1.203(0.0035)
2+1+1	5 yr w/ EM	188(2.4)	227(3.0)	1.203(0.0125)
	10 yr w/o EM	188(0.60)	227(0.80)	1.203(0.0014)
	10 yr w/ EM	188(2.0)	227(2.4)	1.203(0.012)

N_f	forecast	$f_B\sqrt{B_B^{(1)}}$	$f_B\sqrt{B_B^{(2)}}$	$f_B\sqrt{B_B^{(3)}}$	$f_B\sqrt{B_B^{(4)}}$	$f_B\sqrt{B_B^{(5)}}$
	current (2017)	169(8)	169(8)	200(19)	197(7)	190(9)
	5 yr w/o EM	169(4.0)	169(4.0)	200(9.5)	197(3.5)	190(4.5)
2+1	5 yr w/ EM	169(4.3)	169(4.3)	200(9.7)	197(4.0)	190(4.9)
	10 yr w/o EM	169(1.6)	169(1.6)	200(3.8)	197(1.4)	190(1.8)
	10 yr w/ EM	169(2.3)	169(2.3)	200(4.3)	197(2.4)	190(2.6)

Outline

- Introduction
- Quark masses
- Decay constants for leptonic decays
- Form factors for semileptonic decays
- Neutral-meson mixing
- Outlook

Other talks on lattice QCD

- Prospects for D decays [in a box] on the lattice: Max Hansen, Tu, 15:30
- News on kaon physics from the lattice: Chris Sachrajda, Wed, 16:45
- Theory developments in B mixing: Tobias Tsang, Th, 8:30

Quark masses

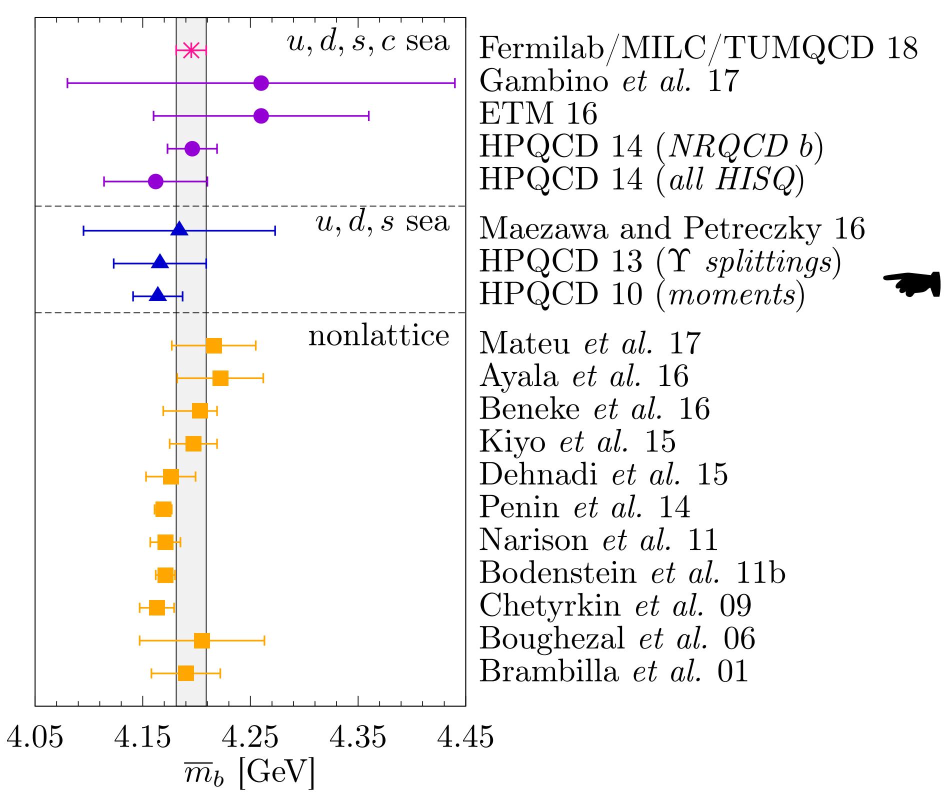
Charm and bottom masses

for averages, see
HPQCD or FLAG

- For charm, precise results with three different methods:

$$m_{c,\overline{\rm MS}}(3\,{\rm GeV}) = \begin{cases} 989.6(3.2)_{\rm corr}(5.2)_{\rm uncorr}\ {\rm MeV} & m_{0c} & \text{RI-SMOM} & \text{HPQCD} \\ 983.7(4.3)_{\rm stat}\,(3.6)_{\alpha_s+{\rm syst}}\ {\rm MeV} & M_{D_q}, M_{B_q} & \text{MRS} & \text{F/M/T} \\ 985.1(2.2)_{\rm corr}(5.9)_{\rm uncorr}\ {\rm MeV} & \langle J^5_{\bar{c}c}(t) J^5_{\bar{c}c}(0)\rangle & \text{pQCD} & \text{HPQCD} \end{cases}$$

$$m_{b,\overline{\rm MS}}(\overline{m}_b) = 4201(12)_{\rm stat}(8)_{\alpha_s+{\rm syst}}\ {\rm MeV} \quad M_{D_q}, M_{B_q} \quad \text{MRS} \quad \text{F/M/T}$$

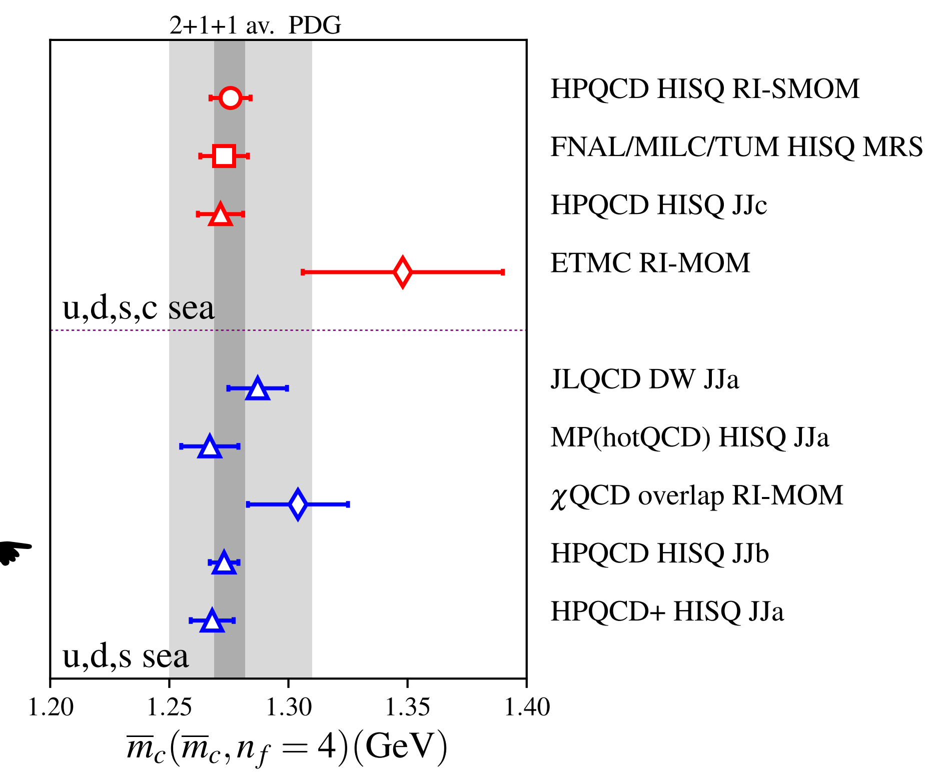


☚ 0.34%

arXiv:1802.04248

arXiv:1805.06225

{0.62, 0.57, 0.64}% ☛



Up, down, strange quarks

for averages, see
HPQCD or FLAG

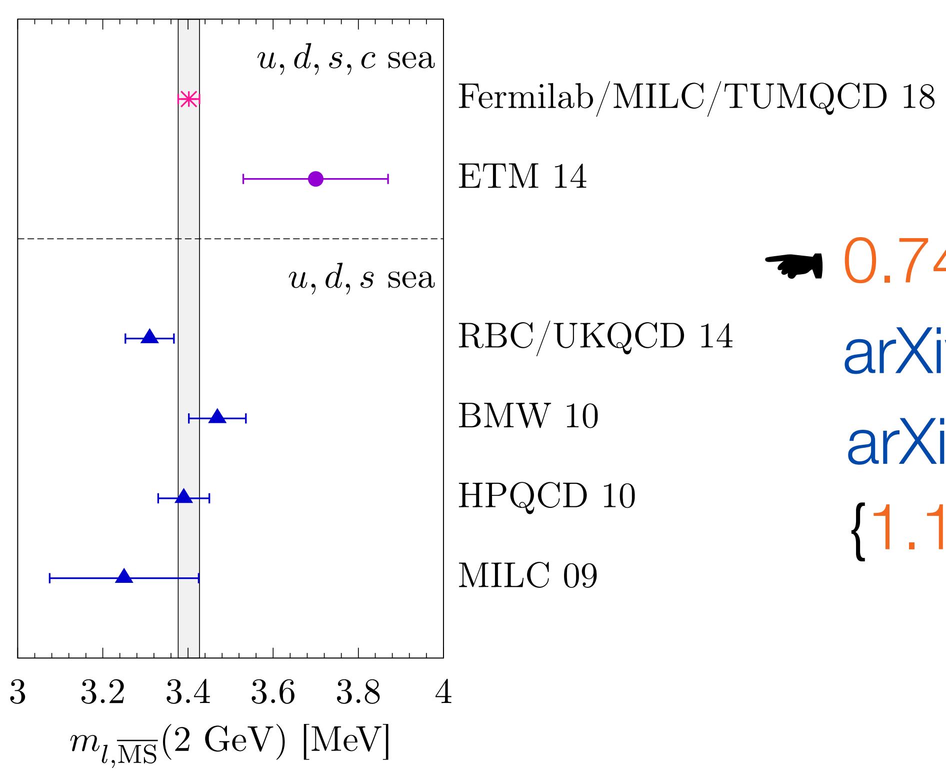
- For strange, precise results with three different methods:

$$m_{s,\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = \begin{cases} 94.49(79)_{\mathrm{corr}}(63)_{\mathrm{uncorr}}\ \mathrm{MeV} & m_{0s} \\ 92.47(39)_{\mathrm{stat}}\ (56)_{\alpha_s+\mathrm{syst}}\ \mathrm{MeV} & m_c m_{0s}/m_{0c} \\ 93.54(44)_{\mathrm{corr}}(69)_{\mathrm{uncorr}}\ \mathrm{MeV} & m_c m_{0s}/m_{0c} \end{cases}$$

RI-SMOM HPQCD
MRS F/M/T
pQCD HPQCD

$$m_{u,\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = 2.130(41)\ \mathrm{MeV} \quad m_c m_{0u}/m_{0c}$$

MRS F/M/T

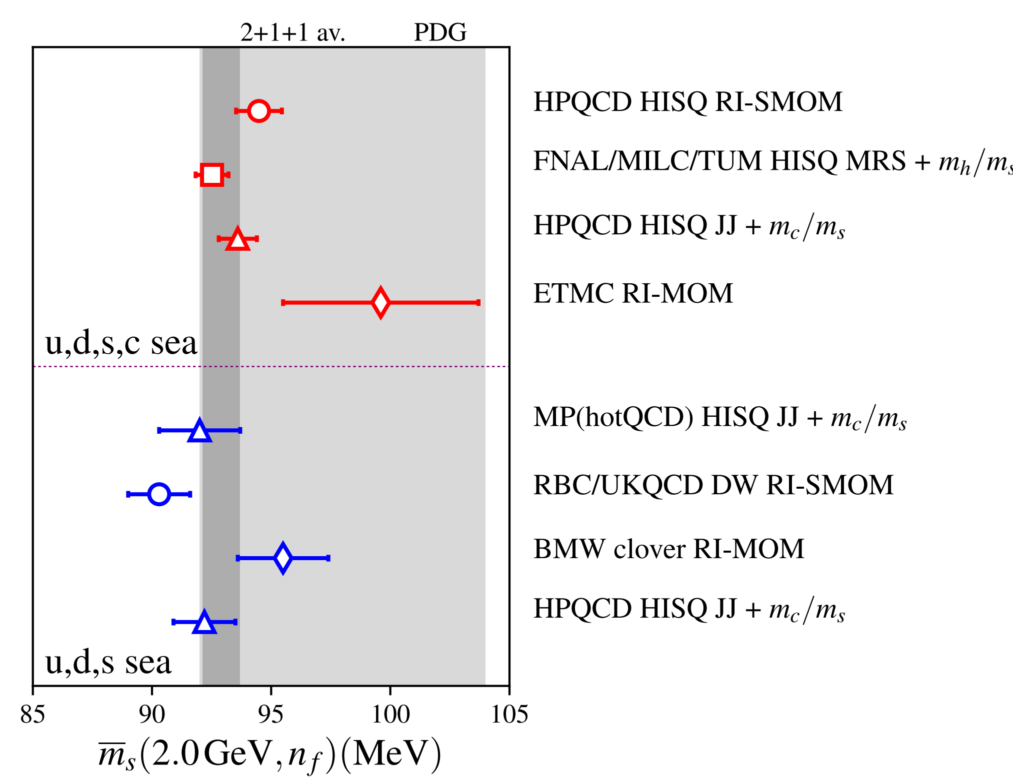


0.74% 1.9% ↑

arXiv:1802.04248

arXiv:1805.06225

{1.1, 0.74, 0.87}%



Remarks

- Up-quark mass settles the strong CP problem, modulo sharpening the controversy around instanton-induced additive mass renormalization.
- The precision for m_b, m_c is more than good enough for testing the Higgs boson's effect on quark masses at LHC and almost what ILC needs;
  - probably also for flavor physics.
- The treatment of QED is not yet rigorous and though not a dominant systematic uncertainty, it's a squishy one.
- Precision from analyses of MILC's 2+1+1 HISQ ensembles:
  - need comparable precision from different 2+1(+1) ensembles.

Leptonic decay constants

Heavy-light mesons

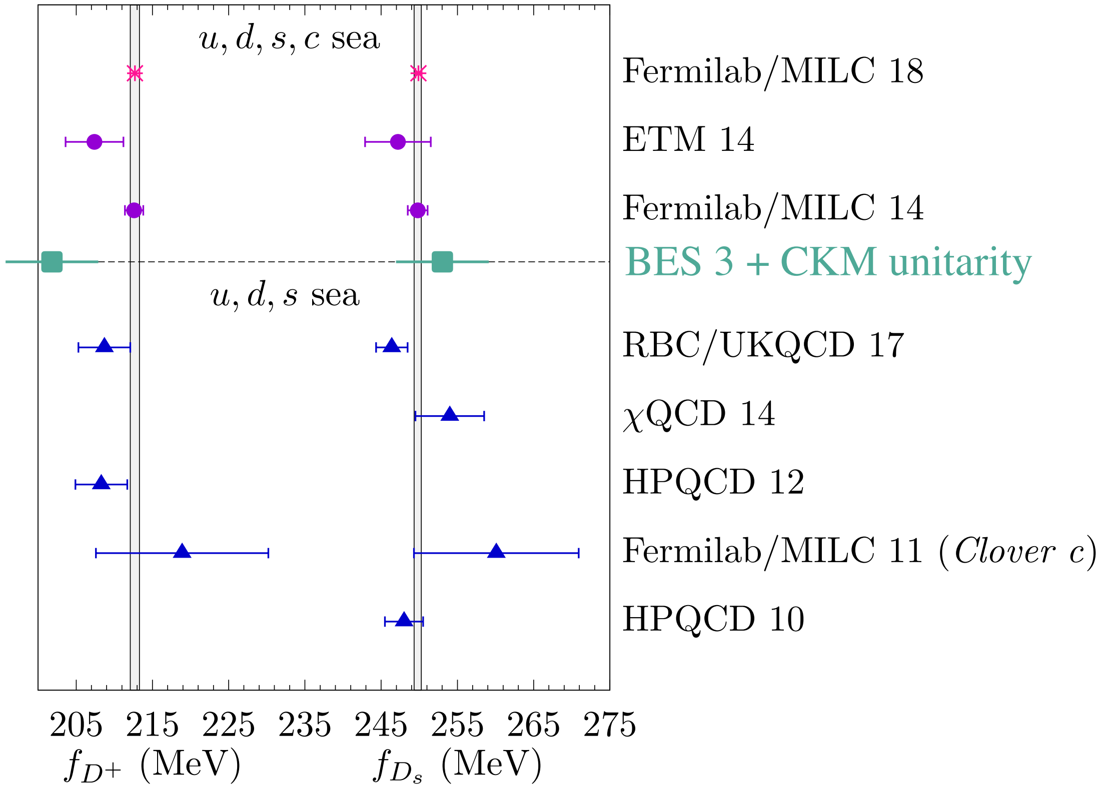
- Most precise results from Fermilab/MILC (∴ dominate FLAG averages).

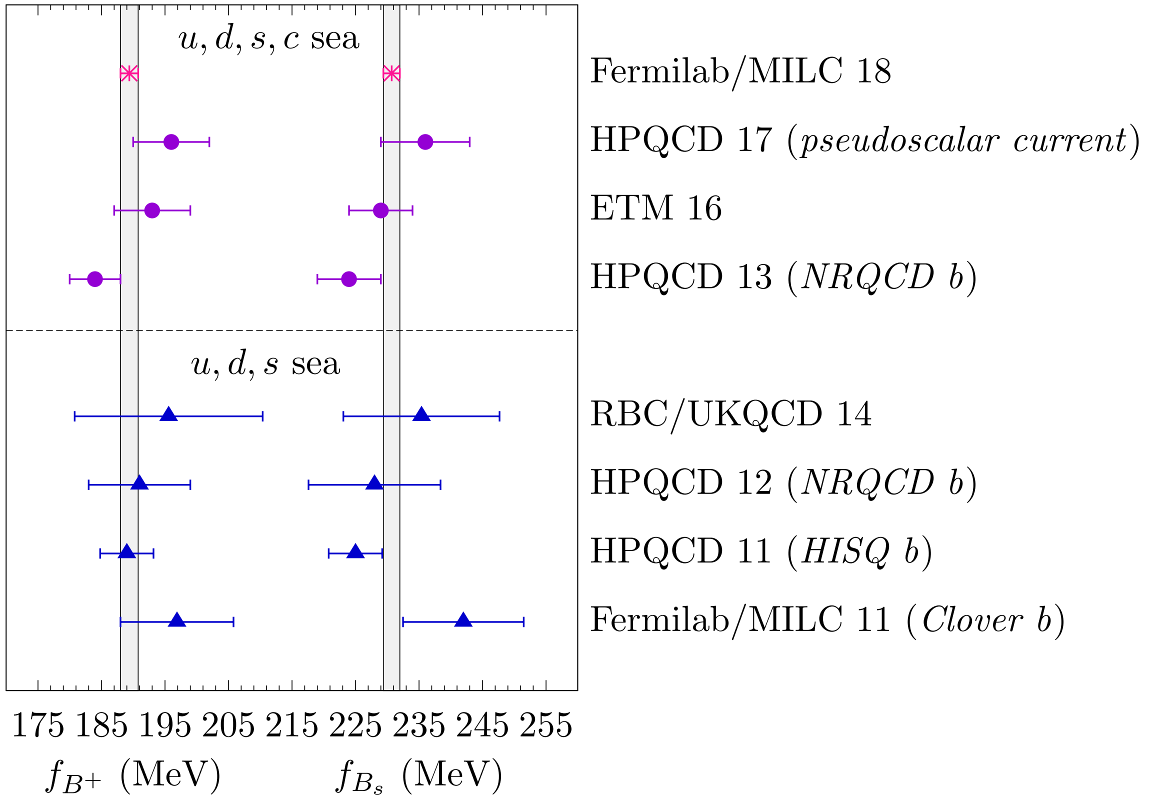
$$f_{D^+} = 212.7(0.3)_{\text{stat}}(0.4)_{\text{syst}}(0.2)_{f_{\pi,\text{PDG}}}[0.2]_{\text{EM scheme}}\ \text{MeV}$$ 0.3%

$$f_{D_s} = 249.9(0.3)_{\text{stat}}(0.2)_{\text{syst}}(0.2)_{f_{\pi,\text{PDG}}}[0.2]_{\text{EM scheme}}\ \text{MeV}$$ 0.2%

$$f_{B^+} = 189.4(0.8)_{\text{stat}}(1.1)_{\text{syst}}(0.3)_{f_{\pi,\text{PDG}}}[0.1]_{\text{EM scheme}}\ \text{MeV}$$ 0.7%

$$f_{B_s} = 230.7(0.8)_{\text{stat}}(1.0)_{\text{syst}}(0.2)_{f_{\pi,\text{PDG}}}[0.2]_{\text{EM scheme}}\ \text{MeV}$$ 0.6%





Pion and kaon

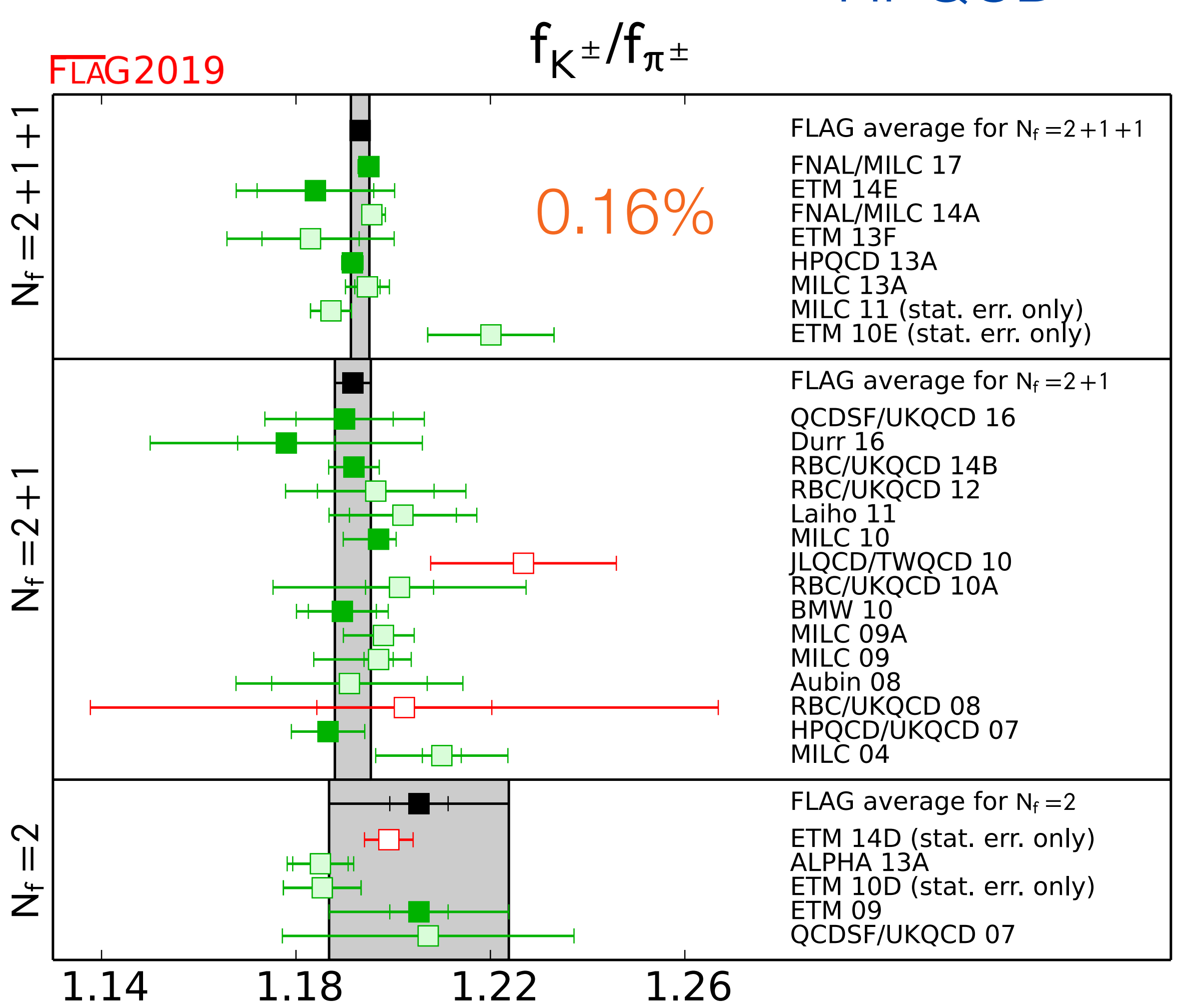
- Numerous precise results; averages from FLAG:

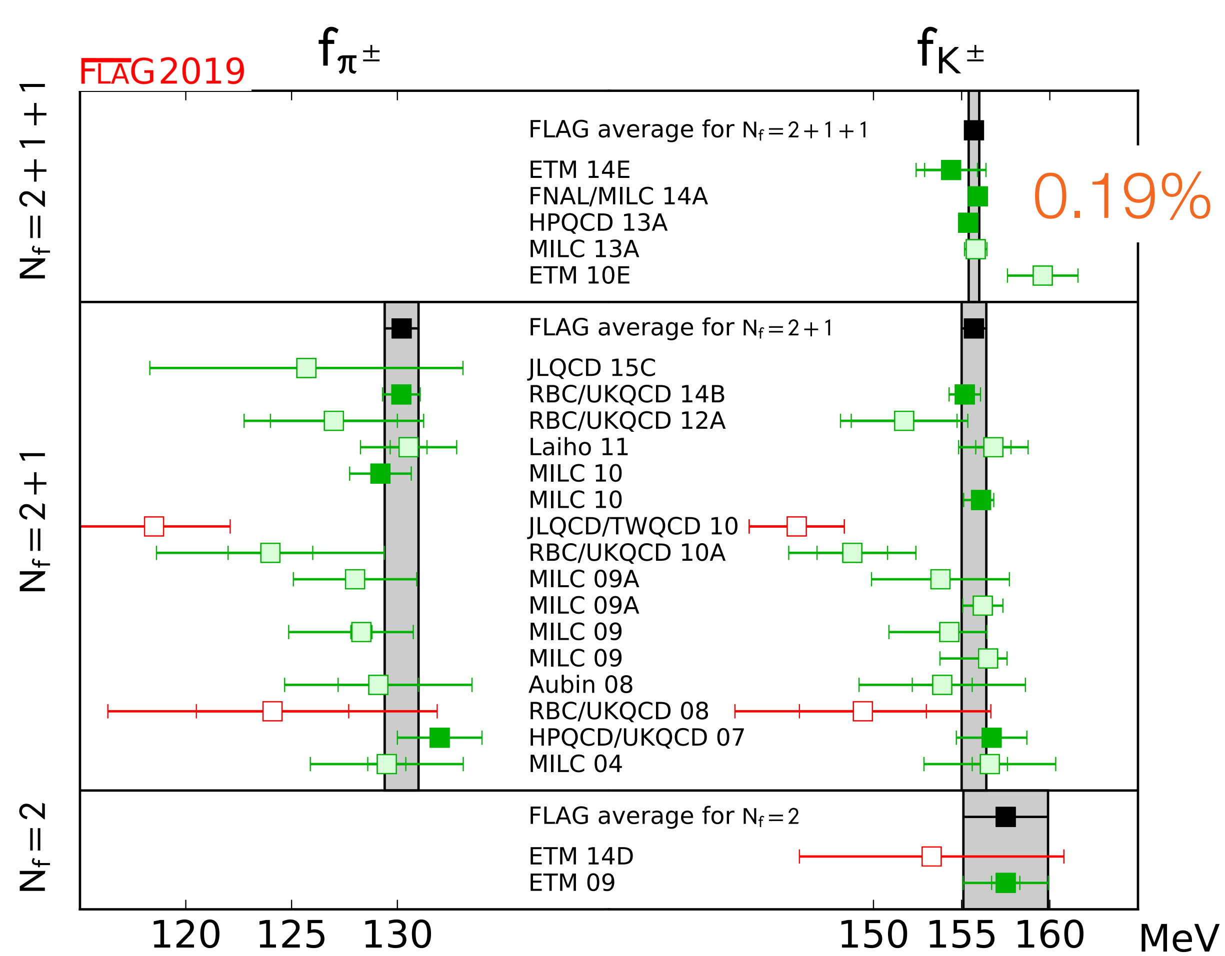
$f_{K^\pm}/f_{\pi^\pm} = 1.1932(19)$ Fermilab/MILC ETM HPQCD

$n_f = 2+1+1$

$f_{K^\pm} = 155.7(0.3)$ MeV Fermilab/MILC ETM HPQCD

$n_f = 2+1+1$





Remarks

- The precision for $f_{D(s)}$, $f_{B(s)}$ is more than good enough for BES 3, Belle II.
- The treatment of QED is not yet rigorous and though not a dominant systematic uncertainty, it's a squishy one.
- The observed rates have soft photons:
    - for pions and kaons, see Sachrajda's talk;
    - for $B_{(s)}$, $D_{(s)}$ the soft scale $\Lambda^2/M_{B,D}$ (HFS) requires more thinking.
- Precision from analyses of MILC's 2+1+1 HISQ ensembles:
    - need comparable precision from different 2+1(+1) ensembles.

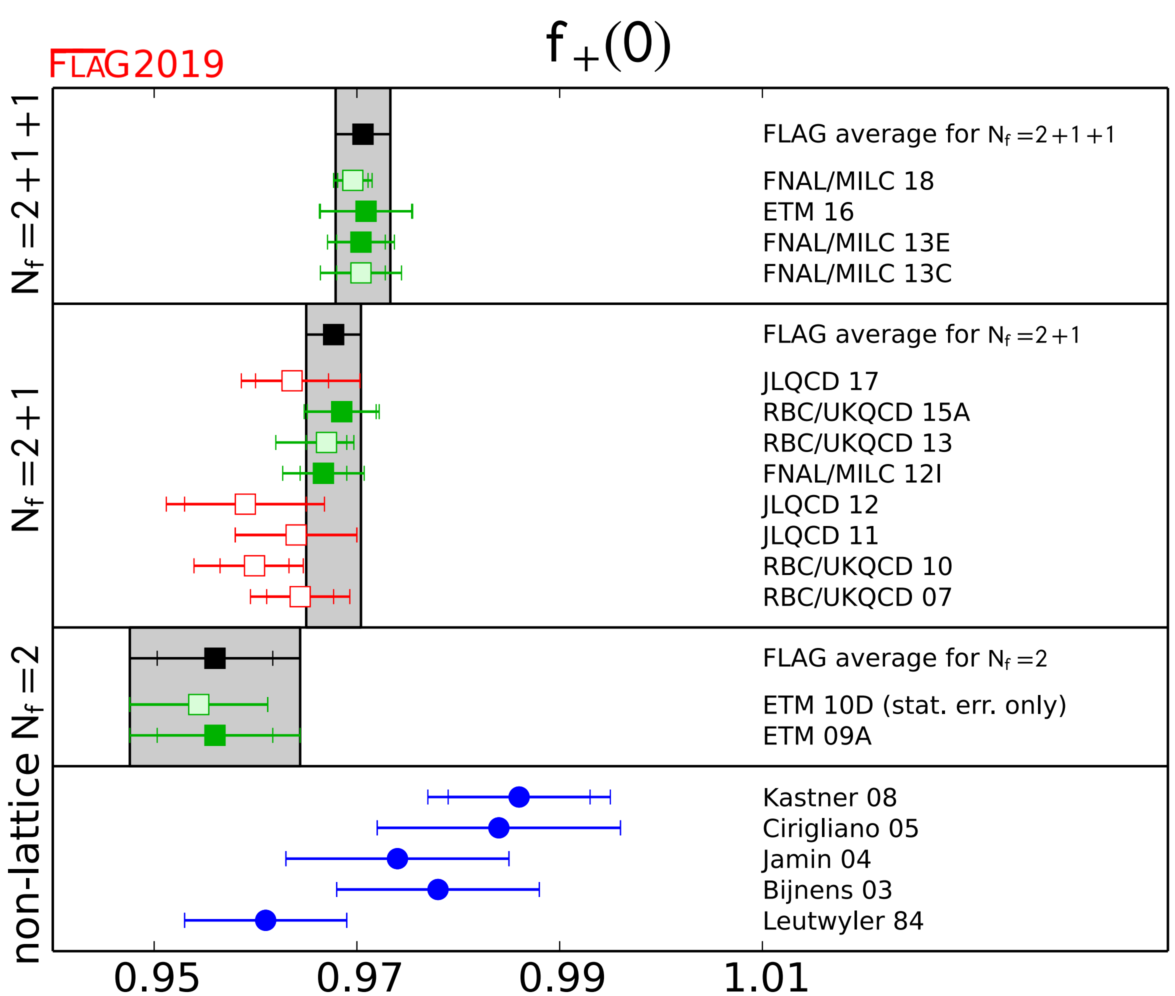
QED in a box

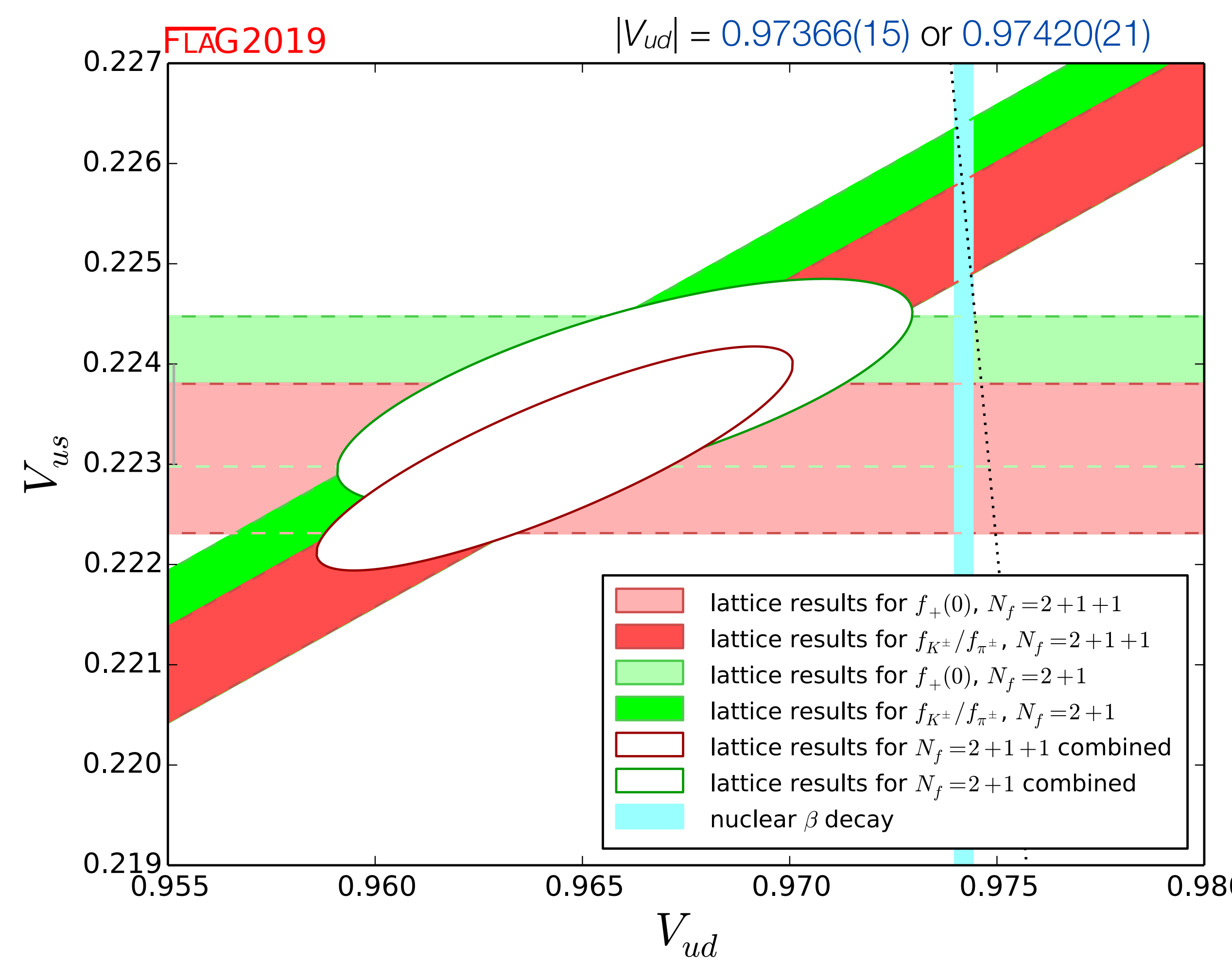
Semileptonic form factors

Kaon: unitarity crisis?

- QED and isospin-breaking contributions with chiral PT.

$$f_+^{K^0\pi^-}(0) = \begin{cases} 0.9706(27) & \text{2019 FLAG average} \qquad \text{expt: 0.2\%} \\ 0.9696(19) & \text{Fermilab/MILC 2018 (preprint)} \qquad \text{0.2\%} \end{cases}$$



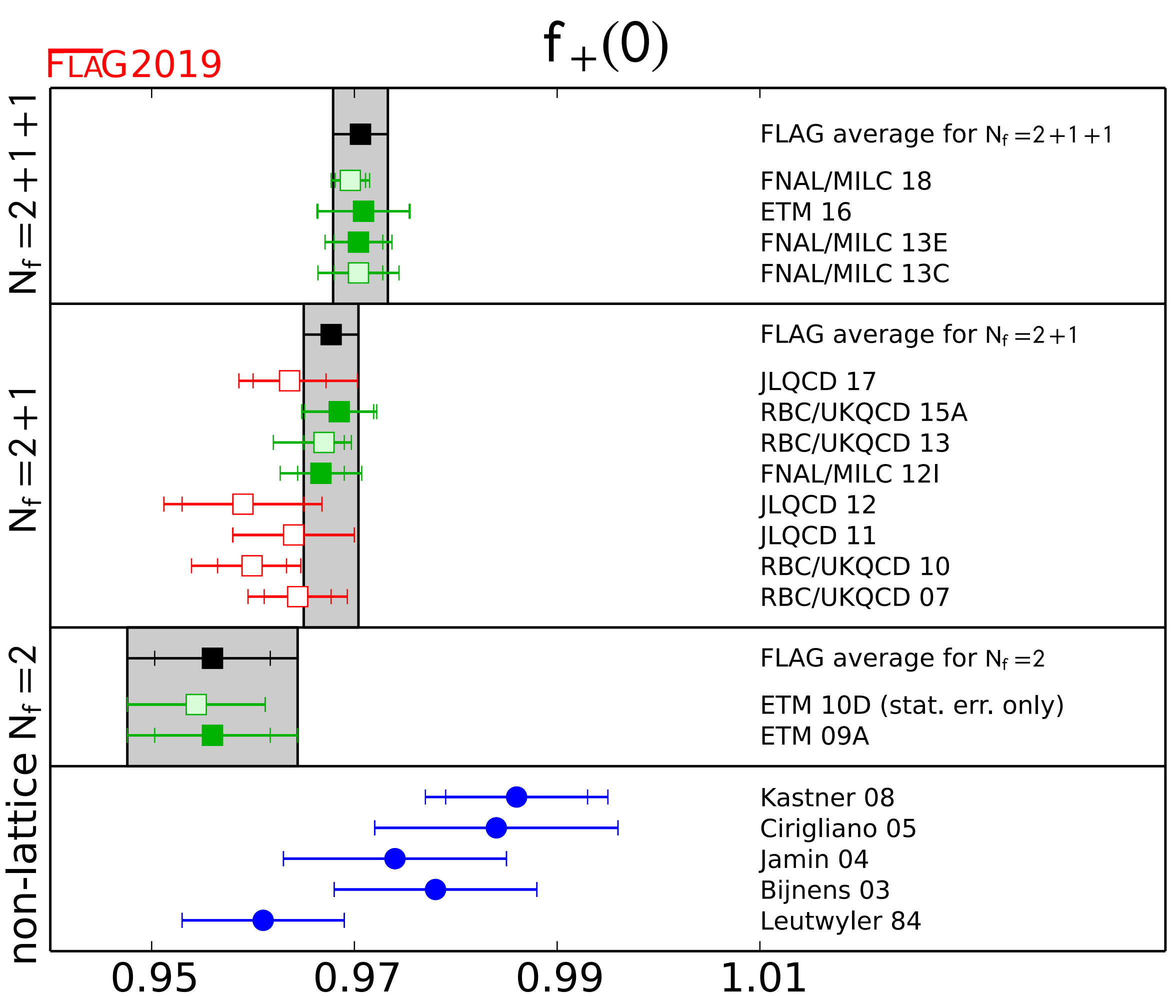


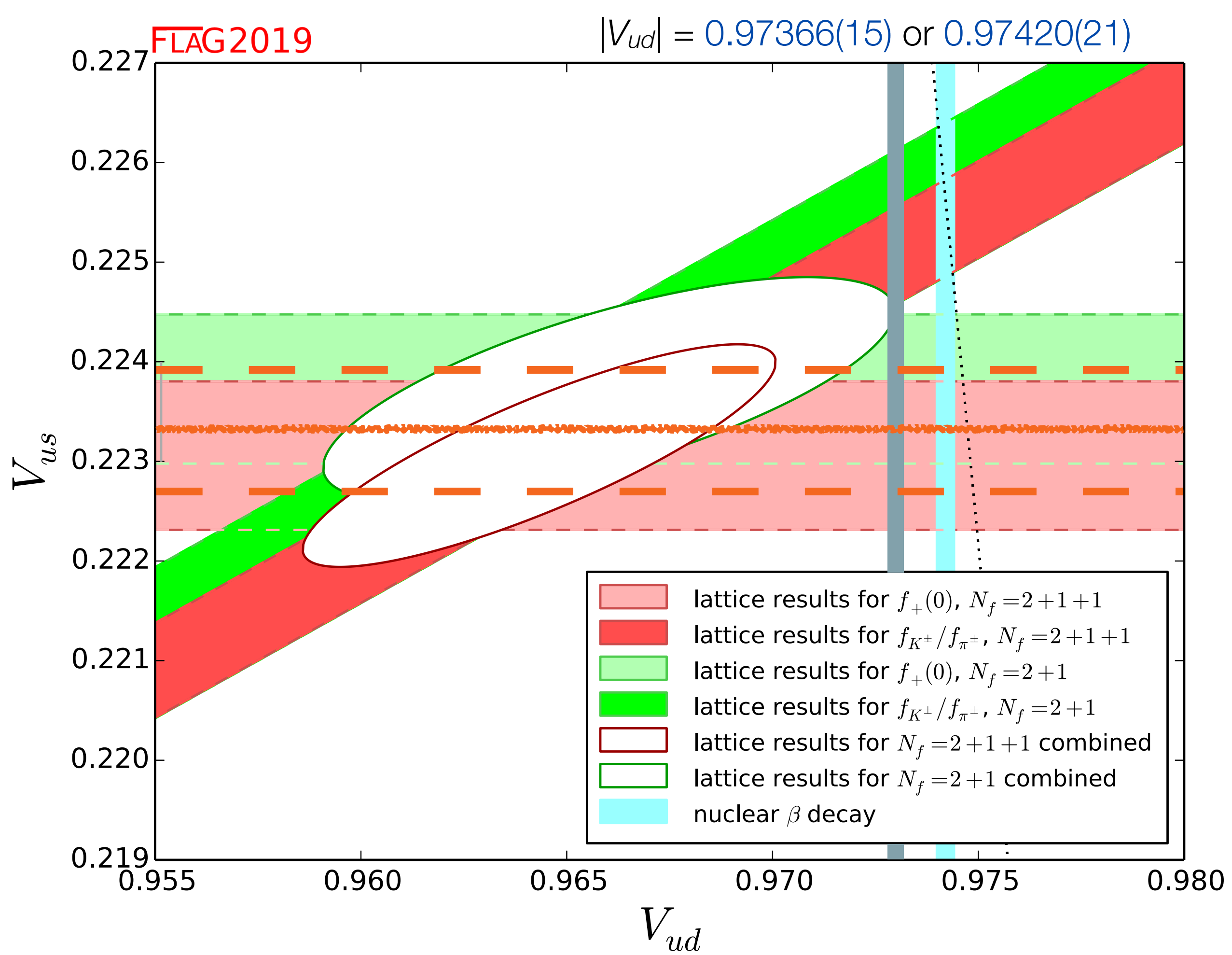
Kaon: unitarity crisis?

- QED and isospin-breaking contributions with chiral PT.

$$f_+^{K^0\pi^-}(0) = \begin{cases} 0.9706(27) & \text{2019 FLAG average} \\ 0.9696(19) & \text{Fermilab/MILC 2018 (preprint)} \end{cases}$$

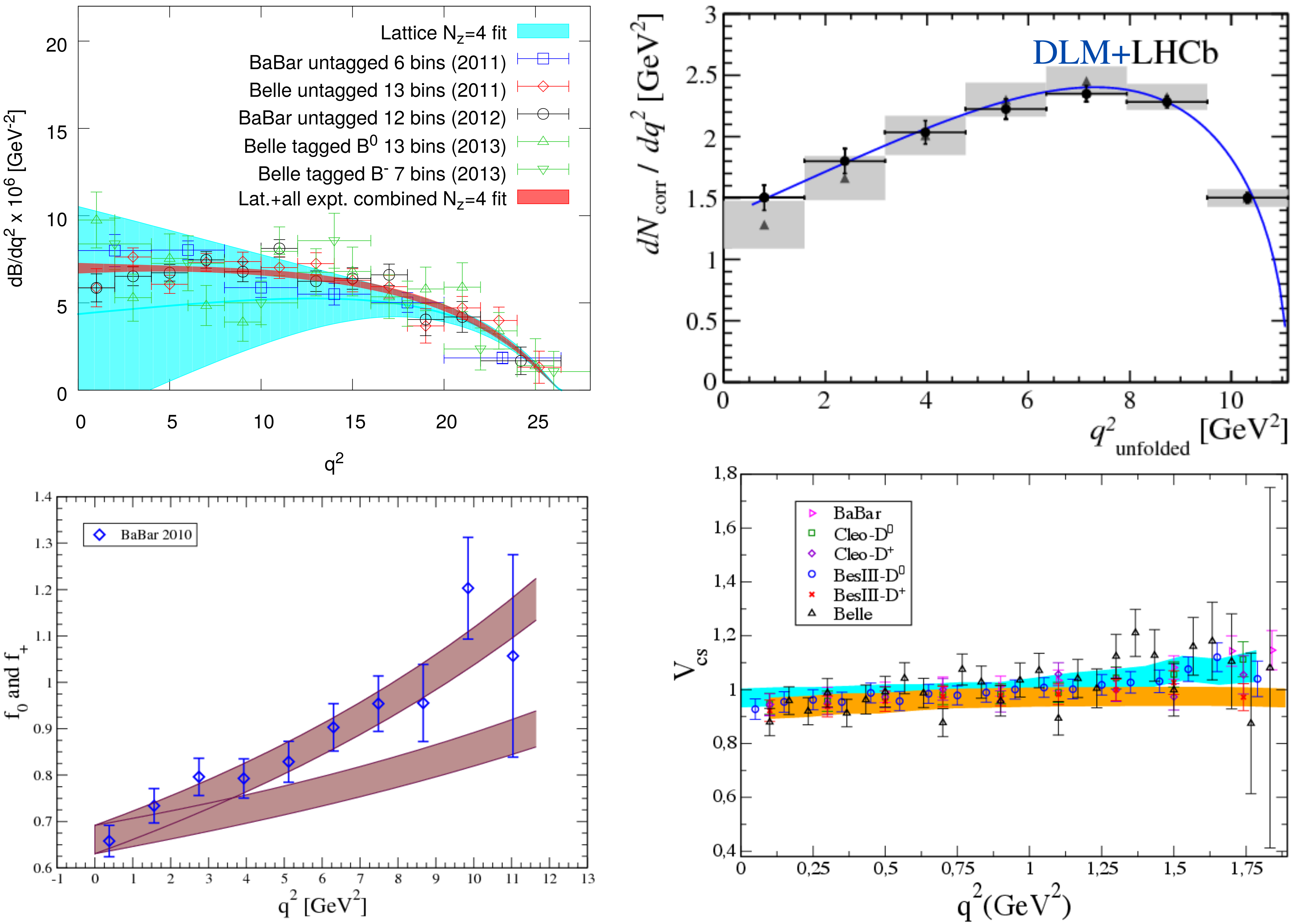
expt: 0.2%
0.2%



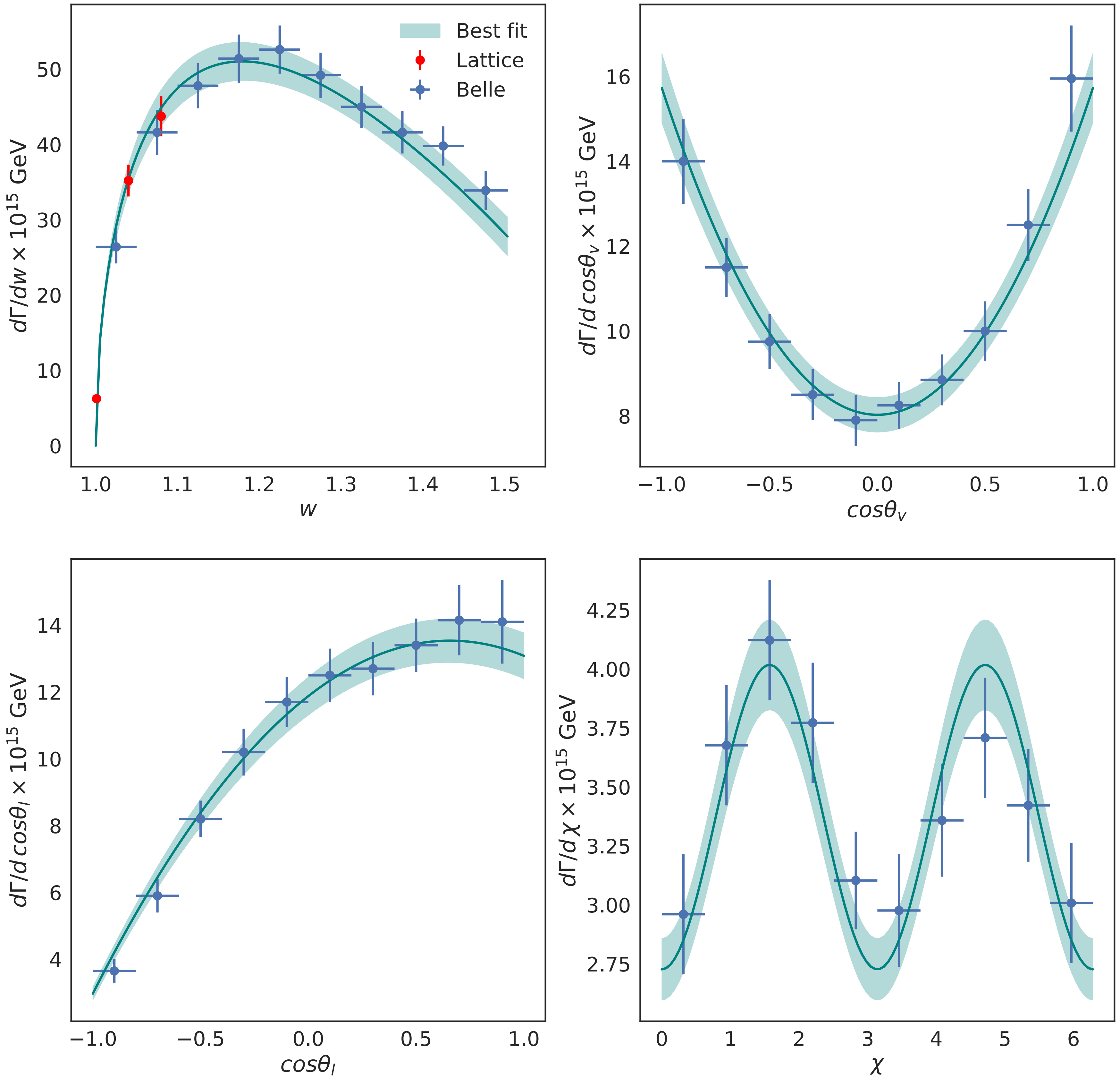


$B_{(s)}$ Mesons

- In general BSM, 3 (many) [many] form factors for $B \to P\ (V)\ [\Lambda_b \to \Lambda, p]$.
- Functions of q^2.
- Use z expansion to extend lattice QCD to full kinematic range
- Report coefficients of z expansion plus correlations between them, between various form factors.
- Joint fit to lattice QCD and experimental data yields $|V_{xb}|$ $[|V_{ub}|/|V_{cb}|]$.
- Similar approach for D semileptonic decays.


Lattice N_z=4 fit
BaBar untagged 6 bins (2011)
Belle untagged 13 bins (2011)
BaBar untagged 12 bins (2012)
Belle tagged B^0 13 bins (2013)
Belle tagged B^- 7 bins (2013)
Lat.+all expt. combined N_z=4 fit
dB/dq^2 x 10^6 [GeV^-2]
q^2
DLM+LHCb
dN_corr / dq^2 [GeV^2]
q^2_unfolded [GeV^2]
BaBar 2010
f_0 and f_+
q^2 [GeV^2]
BaBar
Cleo-D^0
Cleo-D^+
BesIII-D^0
BesIII-D^+
Belle
V_cs
q^2(GeV^2)

Progress on $B \to D^*$ SM form factors (A. Vaquero, Fermilab/MILC):



Remarks I

- Better precision needed for **BES 3**, LHCb, and Belle II:
    - await D form factors on 2+1+1 HISQ ensembles (*cf*. decay constants);
    - kaon $f_+(0)$ precision now commensurate with (legacy) experiments.
- Averages of functions are tricky:
    - in collider phenomenology, people choose a default set of PDFs and compare with different choices;
    - same could apply to form factors in flavor phenomenology;
    - phenomenological ff shape could come from joint fit (for $f_+(q^2)$).

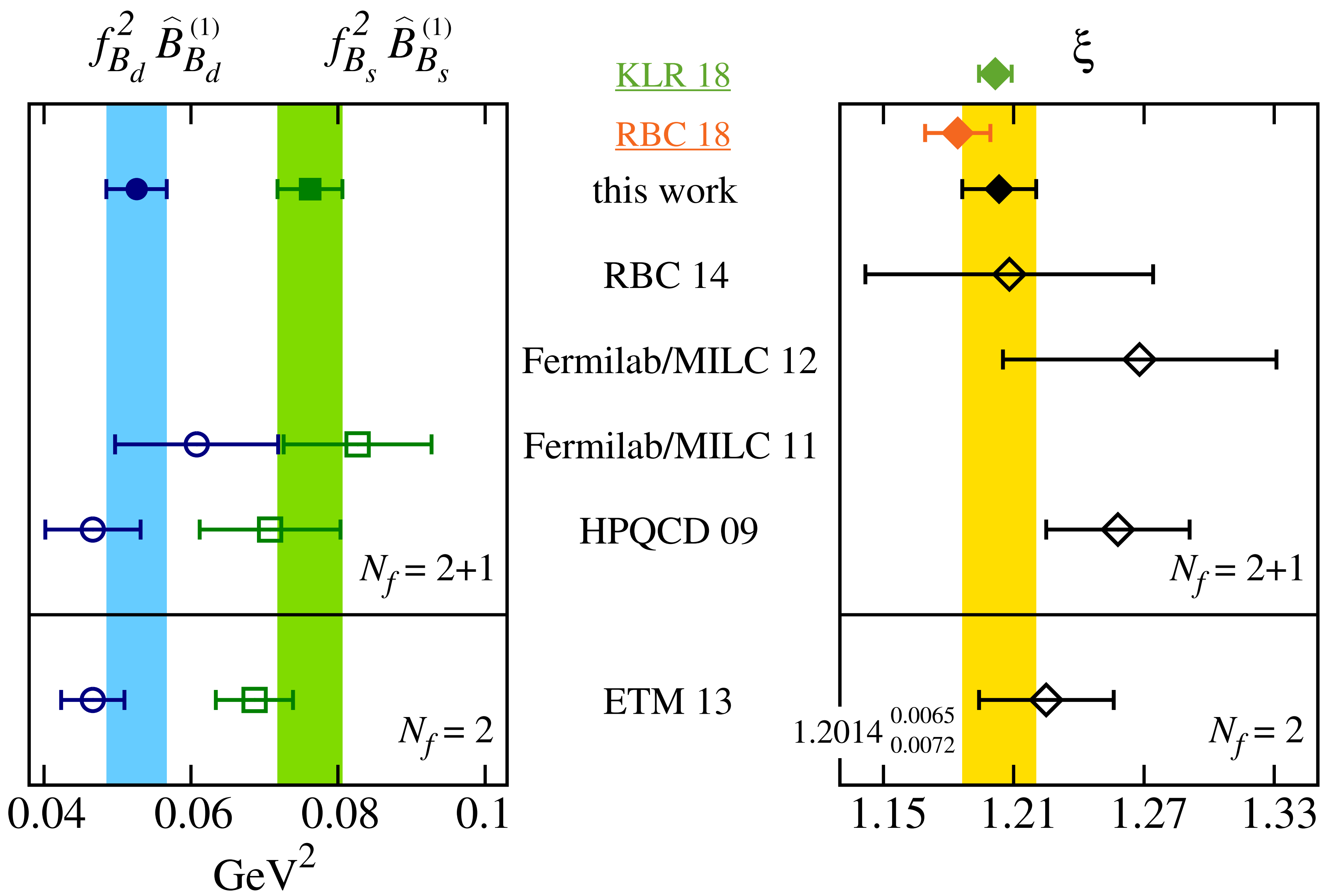
Remarks II

- Rigorous calculations with unstable hadrons ($B \to K^*$) are starting.
- QED uncertainties are relevant & the observed rates have soft photons:
  - solve the soft-scale "$\Lambda^2/M_{B,D}$" problem for leptonic decays first;
  - Coulomb photons in final state of neutral-hadron semileptonic decays should be understood better.
- Form factors for FCNC semileptonic decays are the same as those for CKM, up to isospin corrections:
  - non-factorizable QCD contributions will be more uncertain.

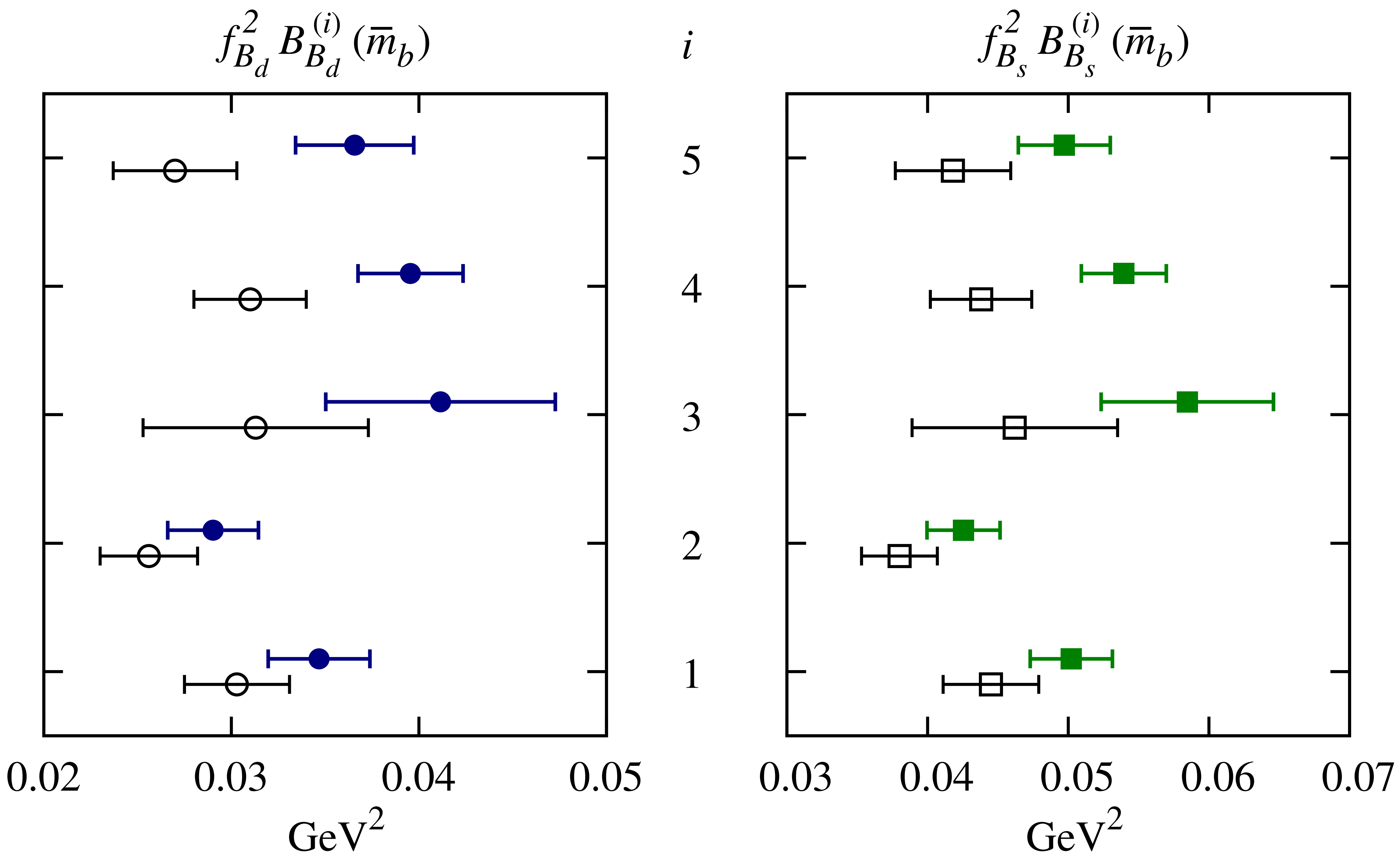
Neutral-meson mixing & Semileptonic FCNC

Neutral Meson Mixing

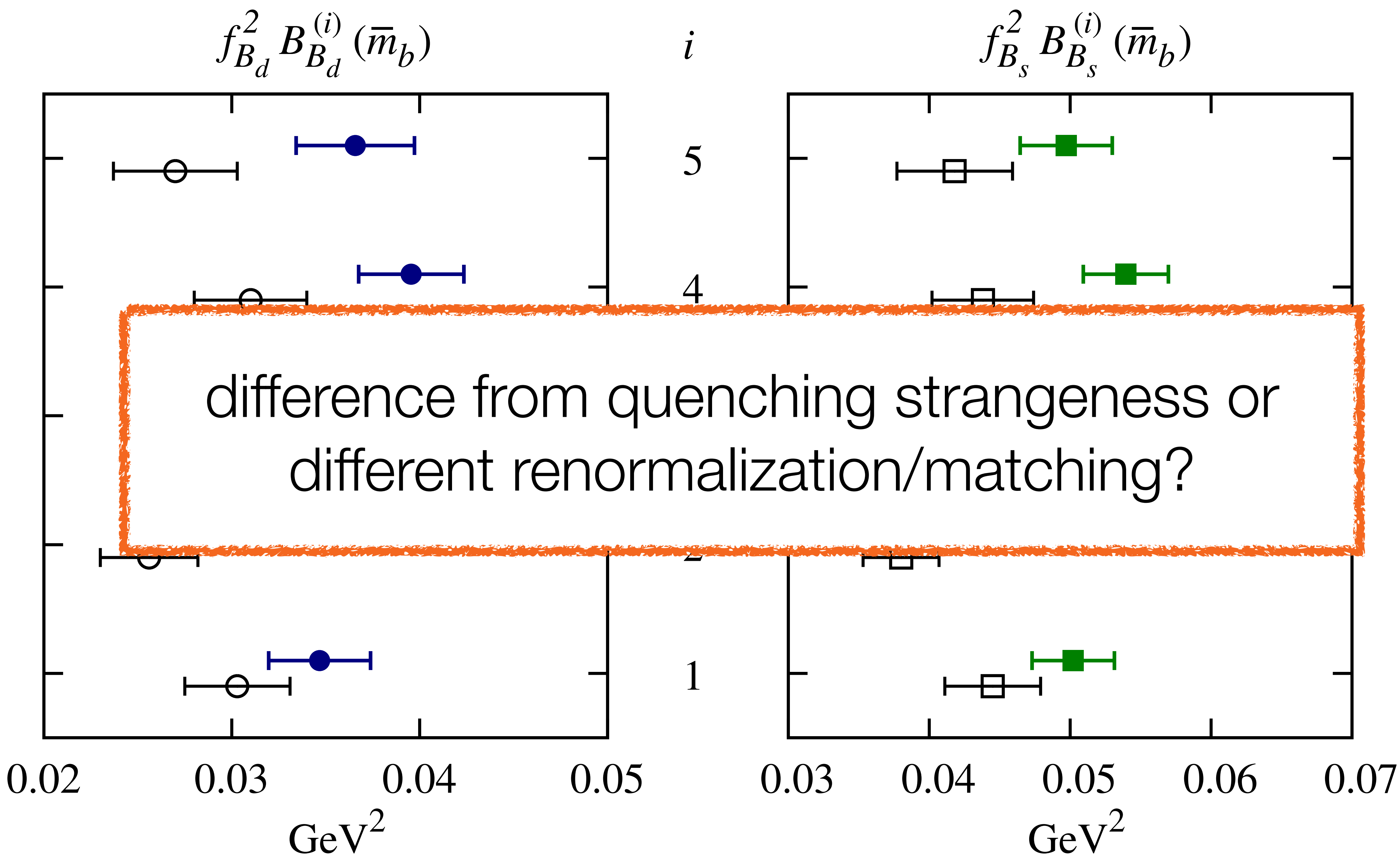
- Fermilab/MILC [arXiv:1602.03560] not in 2016 FLAG but in on-line update.



Comparison with ETM Calculation ($n_f = 2$)



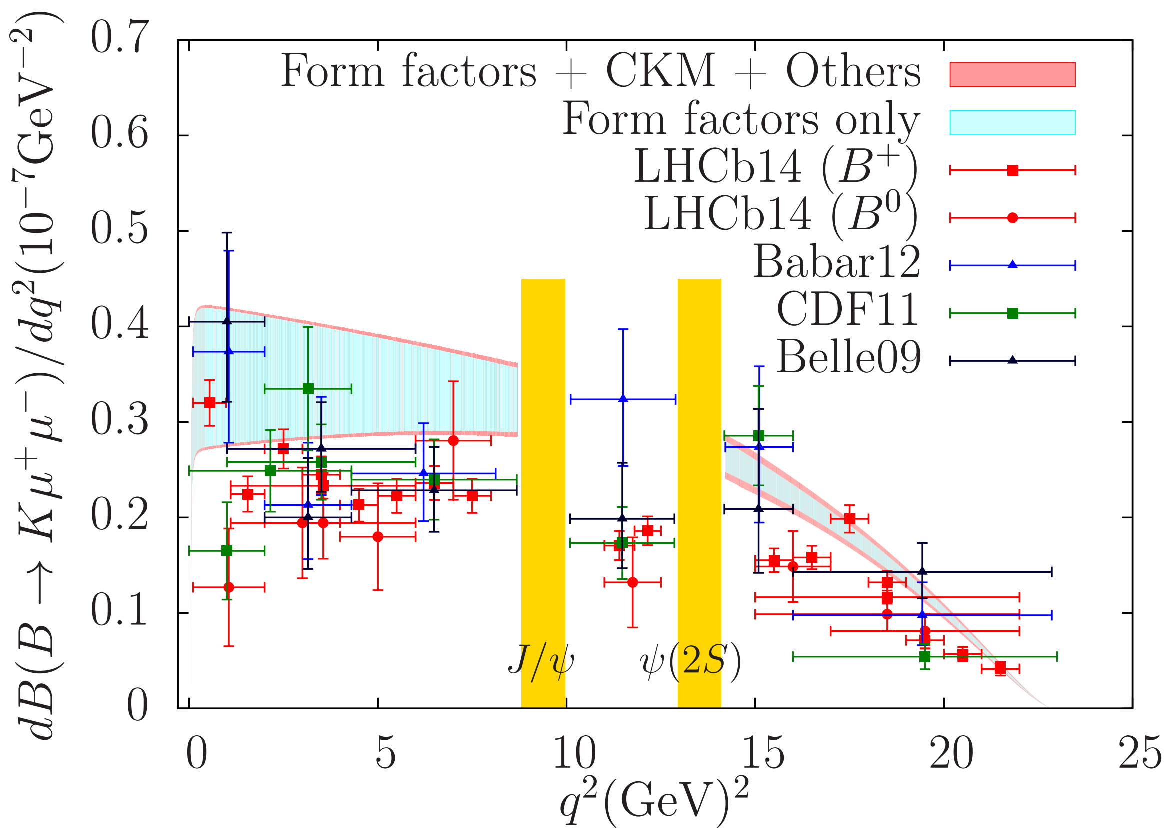
Comparison with ETM Calculation ($n_f = 2$)



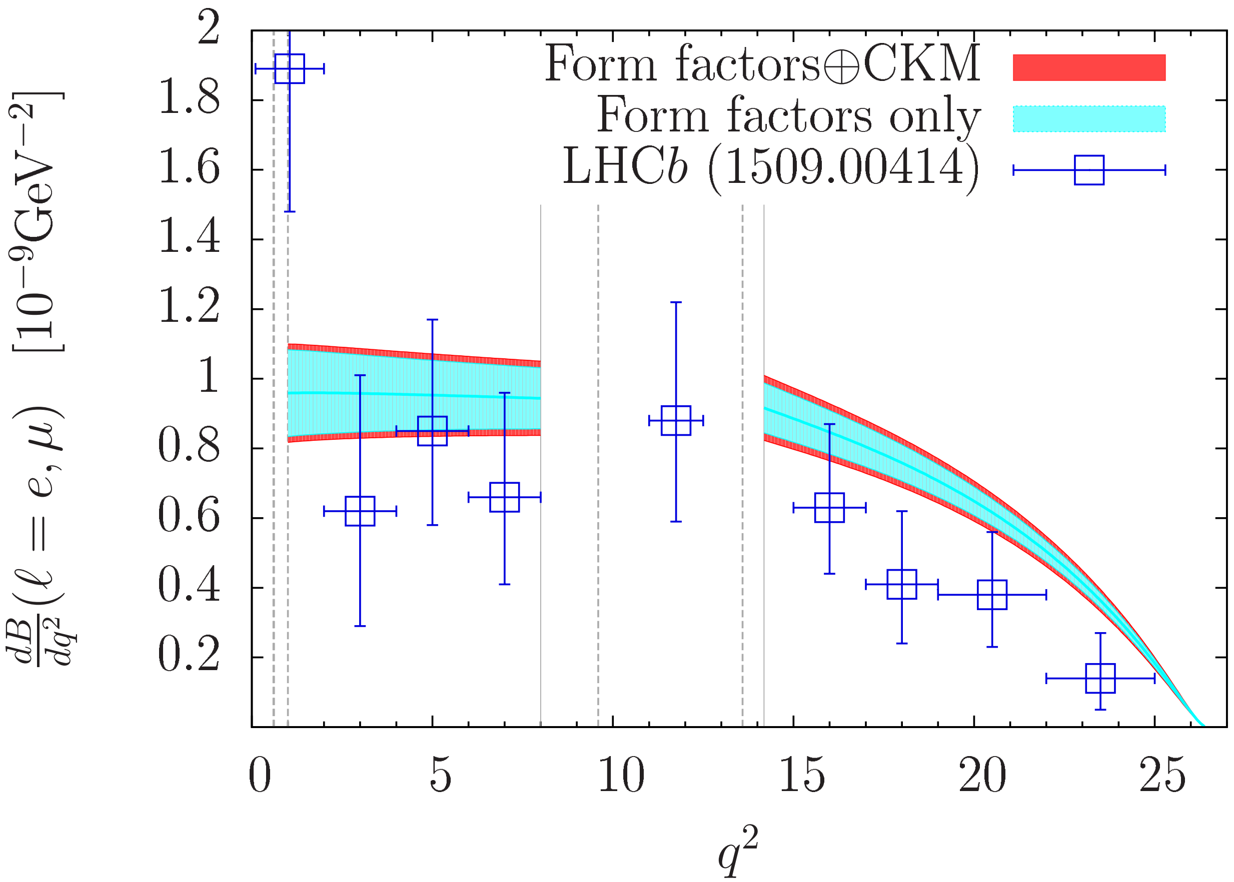
difference from quenching strangeness or different renormalization/matching?

Kinematic Distributions for $B \to Kll$ and $B \to \pi ll$

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



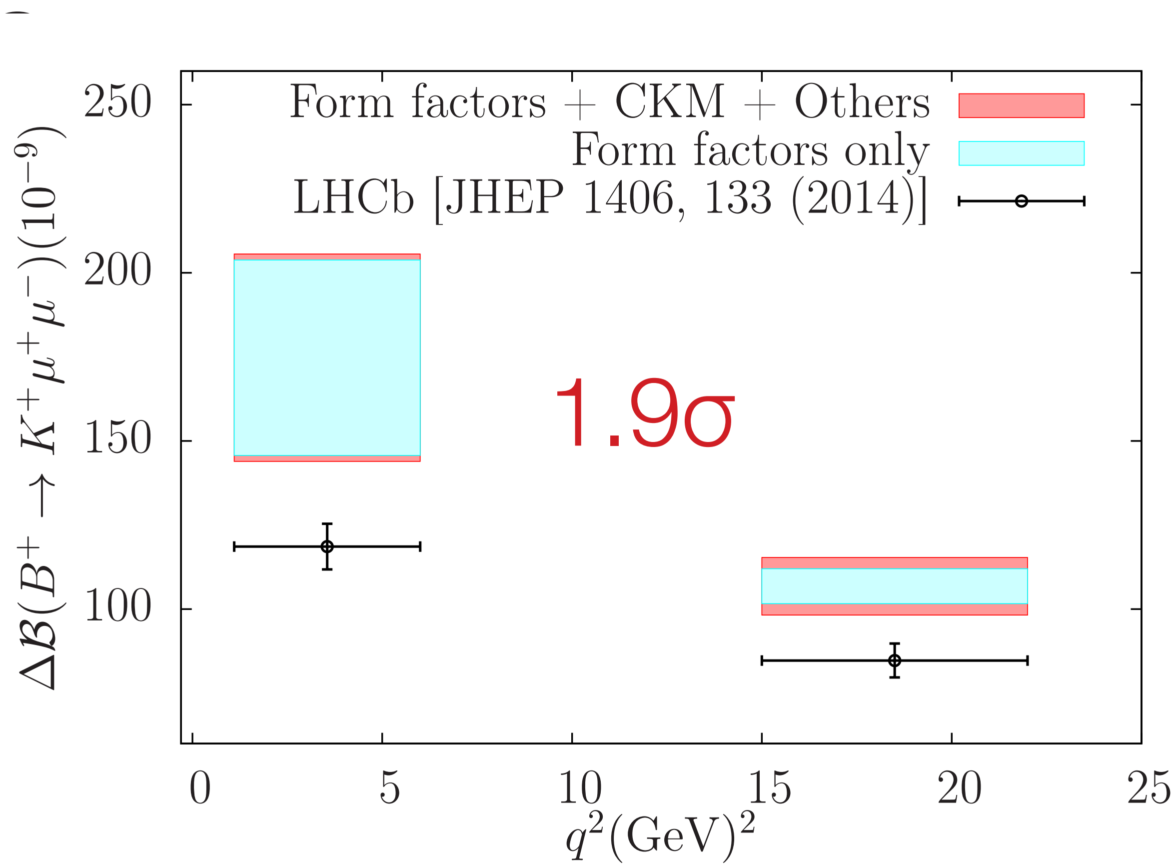
arXiv:1510.02349

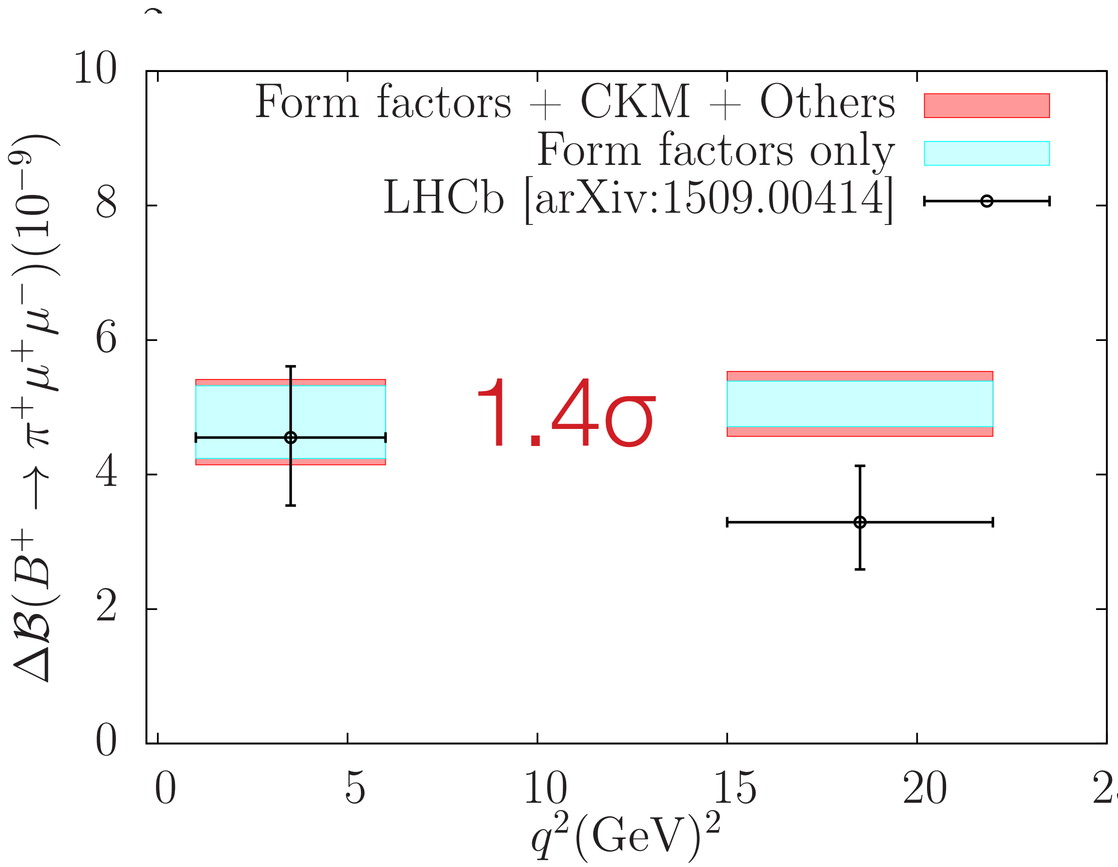


arXiv:1507.01618

Kinematic Distributions for $B \to Kll$ and $B \to \pi ll$

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



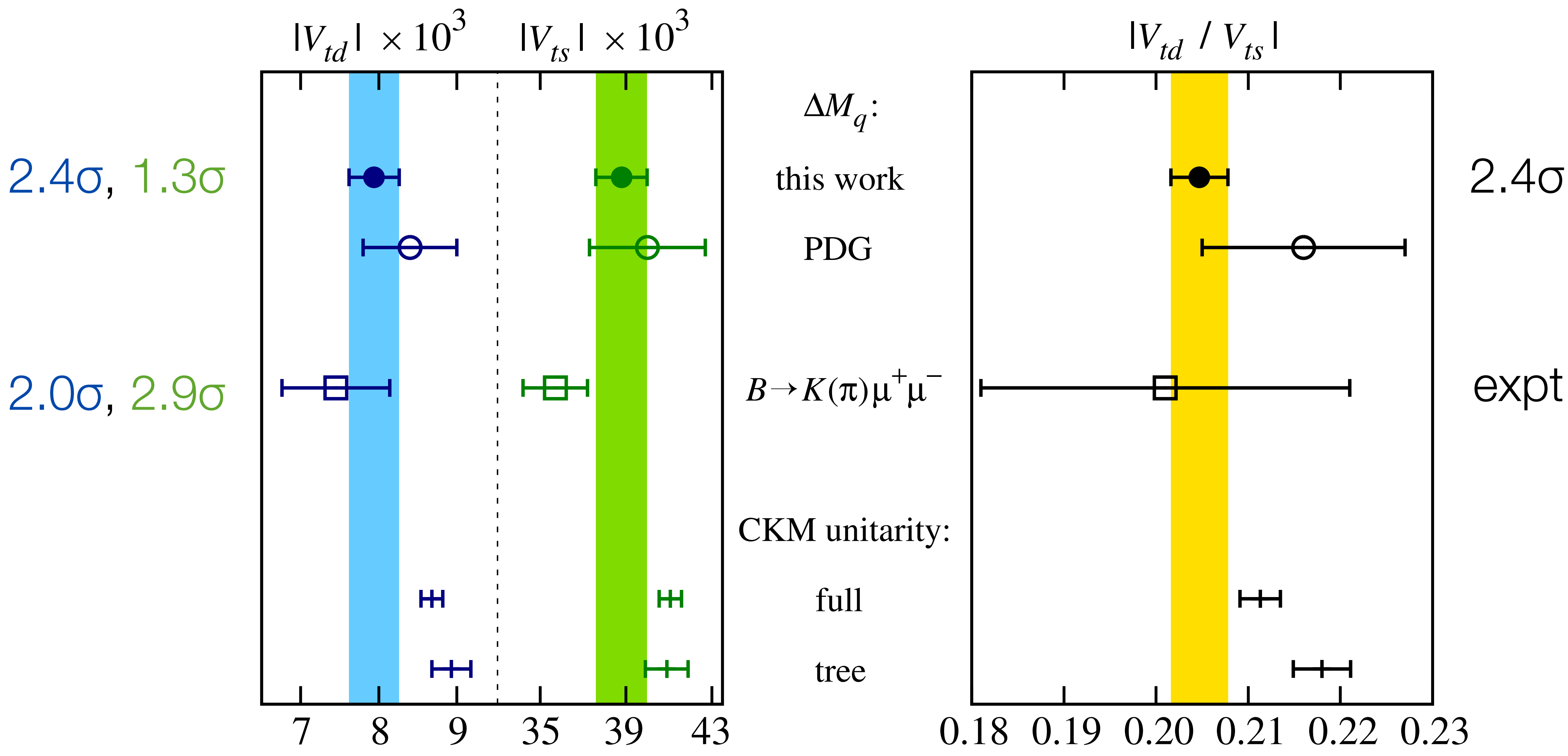


arXiv:1510.02349

arXiv:1507.01618

CKM Comparison

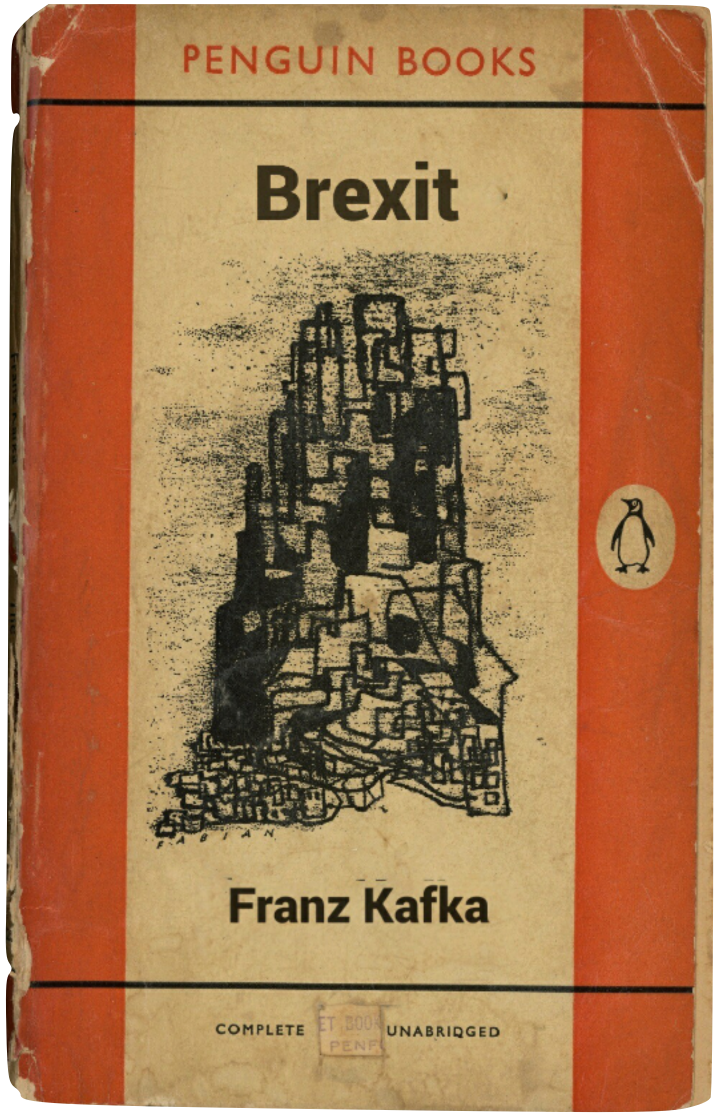
- CKM from FCNC are lower than determinations from trees and unitarity.



Remarks

- Once measured, frequencies are very precise. Thus,
  - mixing matrix elements are not precise enough for legacy experiments, let alone LHC: 3–4% vs 0.06–0.20%.
- A "heavier-than-charm" analysis of these four-quark operators will be
  - very difficult (in chiral perturbation theory) with all-staggered;
  - far off with all-domain-wall, because of the computing needed to generate a suitable range of ensembles and hadron correlators.
- Mixed-action approach: domain-wall valence on 2+1+1 HISQ sea?

Outlook



B2TiP Forecasts

T. Kaneko, ASK, S. Simula

N_f	forecast	f_B[MeV]	f_{B_s}[MeV]	f_{B_s}/f_B
	current (2017)	188(3)	227(4)	1.203(7)
	5 yr w/o EM	188(1.5)	227(2.0)	1.203(0.0035)
2+1+1	5 yr w/ EM	188(2.4)	227(3.0)	1.203(0.0125)
	10 yr w/o EM	188(0.60)	227(0.80)	1.203(0.0014)
	10 yr w/ EM	188(2.0)	227(2.4)	1.203(0.012)

N_f	forecast	$f_B\sqrt{B_B^{(1)}}$	$f_B\sqrt{B_B^{(2)}}$	$f_B\sqrt{B_B^{(3)}}$	$f_B\sqrt{B_B^{(4)}}$	$f_B\sqrt{B_B^{(5)}}$
	current (2017)	169(8)	169(8)	200(19)	197(7)	190(9)
	5 yr w/o EM	169(4.0)	169(4.0)	200(9.5)	197(3.5)	190(4.5)
2+1	5 yr w/ EM	169(4.3)	169(4.3)	200(9.7)	197(4.0)	190(4.9)
	10 yr w/o EM	169(1.6)	169(1.6)	200(3.8)	197(1.4)	190(1.8)
	10 yr w/ EM	169(2.3)	169(2.3)	200(4.3)	197(2.4)	190(2.6)

B2TiP Forecasts

T. Kaneko, ASK, S. Simula

N_f	forecast	f_B[MeV]	f_{B_s}[MeV]	f_{B_s}/f_B
	current (2017)	188(3)	227(4)	1.203(7)
	5 yr w/o EM	188(1.5)	227(2.0)	1.203(0.0035)
2+1+1	5 yr w/ EM	188(2.4)	227(3.0)	1.203(0.0125)
	10 yr w/o EM	188(0.60)	227(0.80)	1.203(0.0014)
	10 yr w/ EM	188(2.0)	227(2.4)	1.203(0.012)

N_f	forecast	$f_B\sqrt{B_B^{(1)}}$	$f_B\sqrt{B_B^{(2)}}$	$f_B\sqrt{B_B^{(3)}}$	$f_B\sqrt{B_B^{(4)}}$	$f_B\sqrt{B_B^{(5)}}$
	current (2017)	169(8)	169(8)	200(19)	197(7)	190(9)
	5 yr w/o EM	169(4.0)	169(4.0)	200(9.5)	197(3.5)	190(4.5)
2+1	5 yr w/ EM	169(4.3)	169(4.3)	200(9.7)	197(4.0)	190(4.9)
	10 yr w/o EM	169(1.6)	169(1.6)	200(3.8)	197(1.4)	190(1.8)
	10 yr w/ EM	169(2.3)	169(2.3)	200(4.3)	197(2.4)	190(2.6)

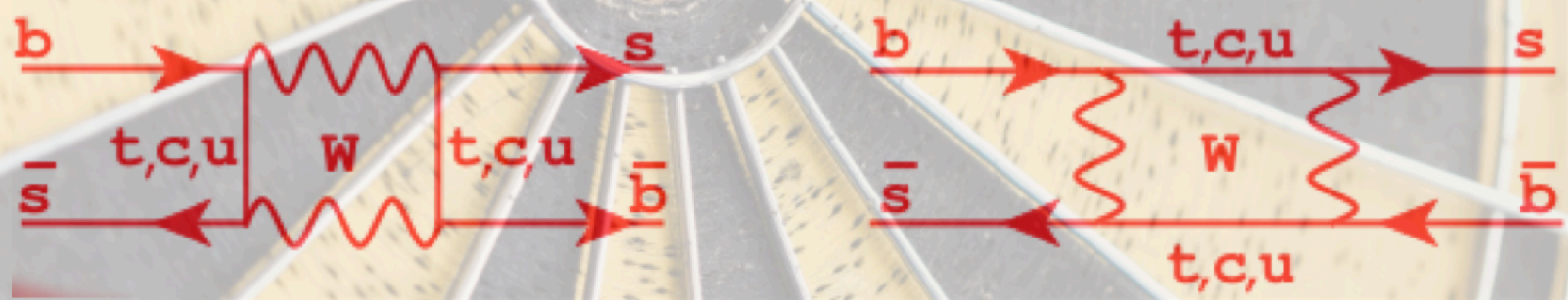
Remarks

- Precision of various quantities (compared with experiment) is either "done for now (modulo confirmation)", "proceeding apace", or "way behind":
  - leptonic decays are simple but the rate is helicity suppressed;
  - semileptonic decays are easier experimentally, but harder with lattice QCD: *e.g.*, new discretization effects for $\boldsymbol{p} > \mathbf{0}$;
  - frequencies are super precise but four-quark operators are hard.
- If you want lattice flavor physics to continue, don't just cite FLAG.
- Theoretical physics (QFT in a box) needed: QED and multi-body!

Thank you!

Towards the Ultimate Precision in Flavour Physics

2.- 4.4.2019 @Durham University



- Precision measurements of tree-level observables
- B decays to rare leptonic and semileptonic final states
- CP violation in the charm sector

Organising Committee

- Simone Bifani (Birmingham)
- Tim Gershon (Warwick)
- Alexander Lenz (Durham)
- Sneha Malde (Oxford)
- Mark Williams (Manchester)