B decays with lattice QCD: status and prospects

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Mini workshop on $D^{(*)}\tau\nu$ and related decays
KMI, 27-28 March 2017

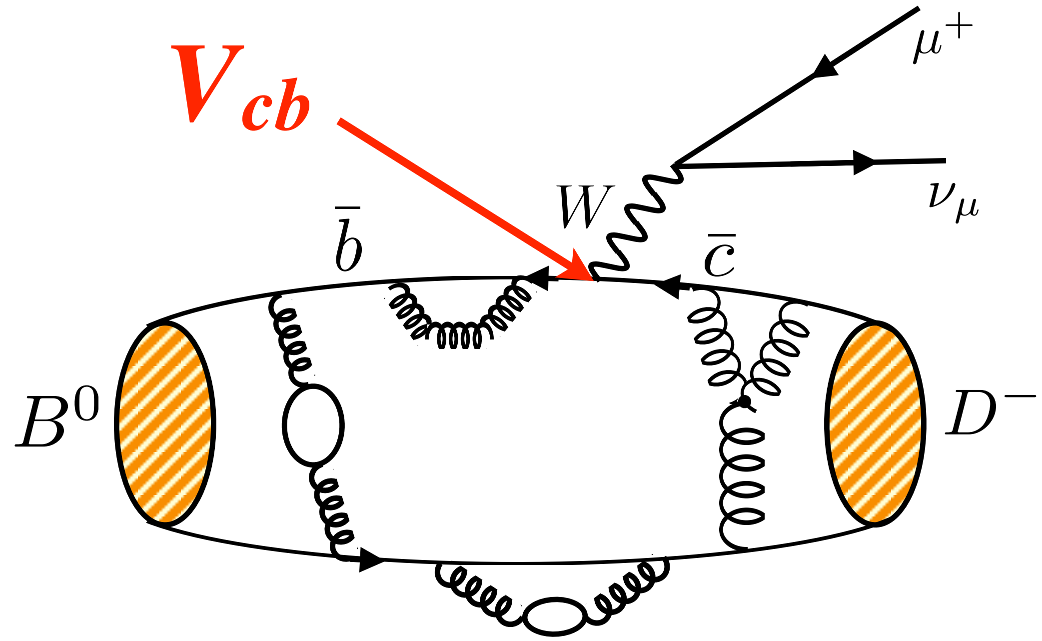
NAGOYA UNIVERSITY

Outline

- Motivation and Introduction
- lattice QCD
- $B \to D^*$ at zero recoil
- $B \to D$ at all recoil
  - combined exp-lattice fit
- $|V_{cb}|$ determinations
- LFU τ/ℓ
- Summary and Outlook

Introduction

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



Experiment vs. SM theory:

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

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

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

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

$$\vdots$$

Lattice QCD

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

Introduction

- For $|V_{cb}|$ determinations use
  - $B_{(s)} \to D_{(s)}\,\ell\nu, \quad (\ell = e, \mu)$
  - $B_{(s)} \to D^*_{(s)}\,\ell\nu, \quad (\ell = e, \mu)$
- For tests of lepton flavor universality use
  - $B_{(s)} \to D_{(s)}\,\tau\nu_\tau \;/\; B_{(s)} \to D_{(s)}\,\ell\nu_\ell$
  - $B_{(s)} \to D^*_{(s)}\,\tau\nu_\tau \;/\; B_{(s)} \to D^*_{(s)}\,\ell\nu_\ell$
- We need form factors at nonzero recoil for both.

Introduction

$$B_{(s)} \to D_{(s)}\, \ell\nu$$

$$\frac{\langle D|V^\mu|B\rangle}{\sqrt{M_B M_B}} = h_+(\omega)(v_B + v_D)^\mu + h_-(\omega)(v_B - v_D)^\mu$$

$$\mathcal{G}(\omega) = h_+(\omega) + \frac{M_B - M_D}{M_B + M_D} h_-(\omega) \sim f_+(q^2)$$

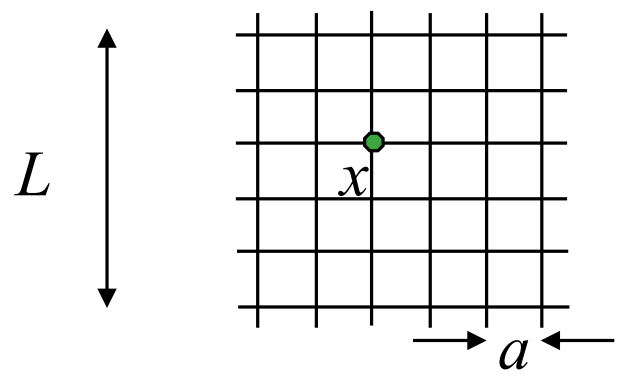
$$B_{(s)} \to D^*_{(s)}\, \ell\nu$$

$$\frac{\langle D^*(p_{D^*}, \epsilon^{(\alpha)})|A^\mu|B(p_B)\rangle}{\sqrt{M_B M_{D^*}}} = \frac{i}{2}\epsilon_\nu^{(\alpha)*}\left[g^{\mu\nu}(1+\omega)h_{A_1}(\omega) - v_B^\nu\left(v_B^\mu h_{A_2}(\omega) + v_{D^*}^\mu h_{A_3}(\omega)\right)\right]$$

$$\frac{\langle D^*(p_{D^*}, \epsilon^{(\alpha)})|V^\mu|B(p_B)\rangle}{\sqrt{M_B M_{D^*}}} = \frac{1}{2}\epsilon^{\mu\nu}{}_{\rho\sigma}\,\epsilon_\nu^{(\alpha)*}\, v_B^\rho v_{D^*}^\sigma\, h_V(\omega)$$

Lattice QCD Introduction

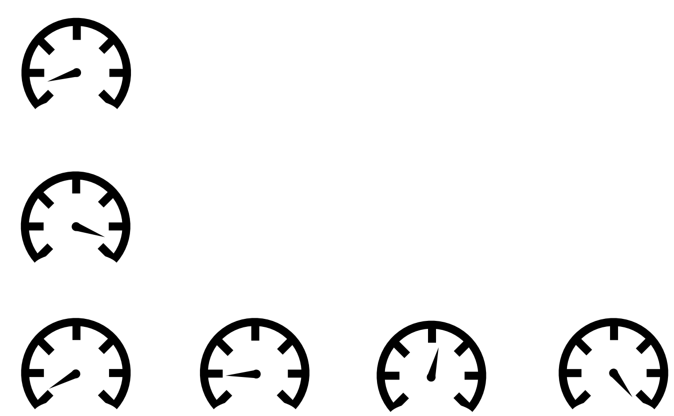
$$\mathcal{L}_{\rm QCD} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}{\rm tr} F_{\mu\nu}F^{\mu\nu}$$



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

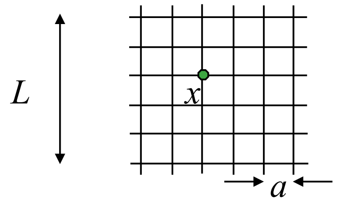
adjustable parameters

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



m_{ud} m_s m_c m_b

- ❖ also: n_f = number of sea quarks: 3 (2+1), 4 (2+1+1)



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

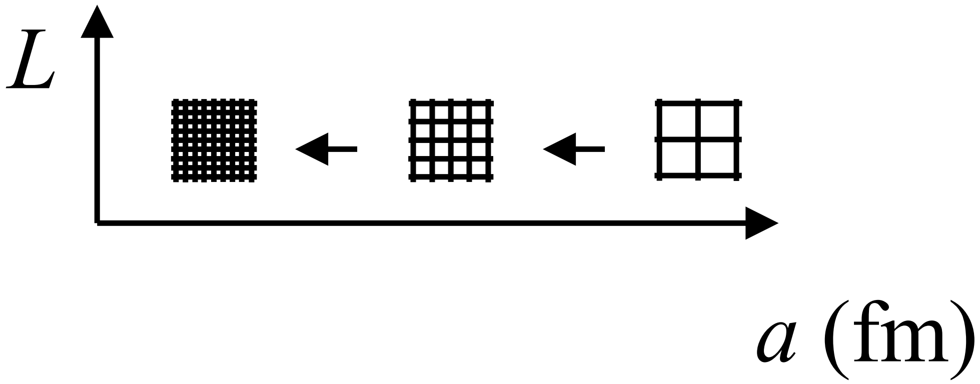
→ ab initio

The EFT description:

- provides functional form for extrapolation (or interpolation)
- can be used to build improved lattice actions/methods
- can be used to anticipate the size of systematic effects

To control and reliably estimate the systematic errors

- repeat the calculation on several lattice spacings, light quark masses, spatial volumes, ...



Lattice guide

- Need to have several (≧2) lattice spacings.
  Comparing lattice results with different actions provides good cross checks of methods used.
- "physical mass ensemble" means pion mass is at (or near) its physical value.
  If larger than in Nature, there must be a range of light quark masses, where the pions shouldn't be too heavy at low end of the range.
- box size should have $m_\pi L$ ≧4.
- sea quark flavors: 2+1, 2+1+1, 1+1+1+1
- complete systematic error analysis and budget
- FLAG: compare/combine results from different lattice groups for specific quantities.

form factor for $B \to D^{(*)} \ell\nu$ & V_{cb}

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

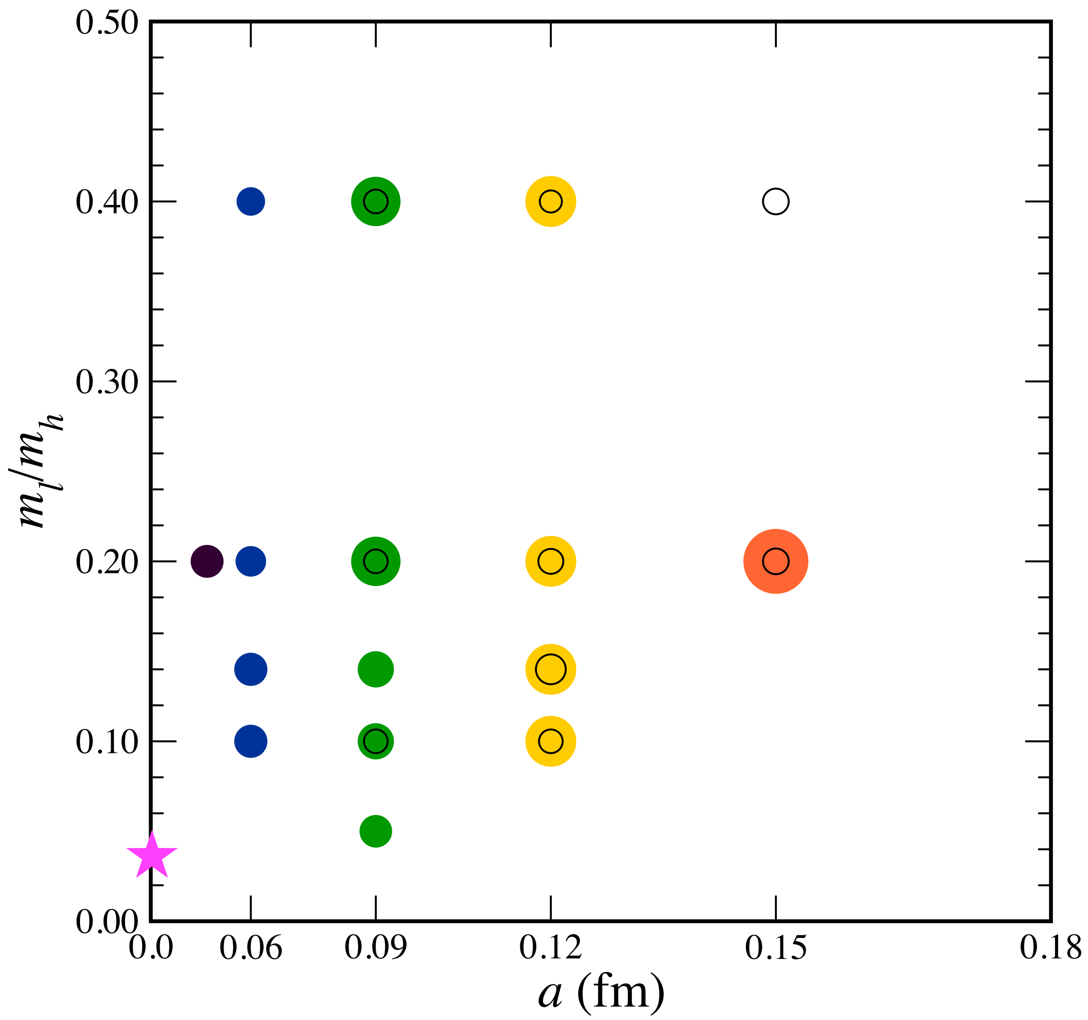
Using CLN to extrapolate to ω=1 (HFAG 2016):

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

- FNAL/MILC 2014 (J. Bailey et al, arXiv:1403.0635, 2014 PRD): $\mathcal{F}(1) = 0.906(4)(12)$
- new: HPQCD (J. Harrison @ Lattice 2016, preliminary)

Form factor for $B \to D^*$ at zero recoil

❖ FNAL/MILC 2014 (J. Bailey et al, arXiv:1403.0635, 2014 PRD):



- 15 MILC asqtad ensembles
  5 lattice spacings
  ~ 4 sea quark masses per lattice spacing
  ~ 600 - 2000 configurations
  × 4 time-sources per ensemble
- asqtad light valence quarks
- Fermilab b quarks
- $O(a)$ improved current
- mostly nonperturbative renormalization (mNPR)

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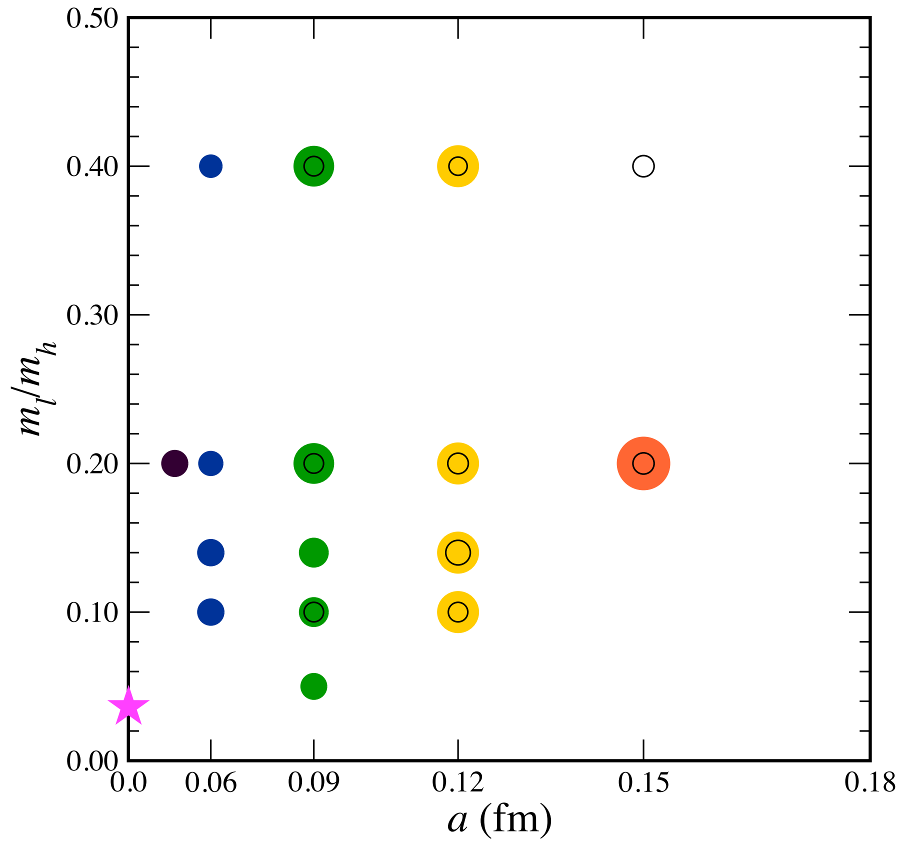

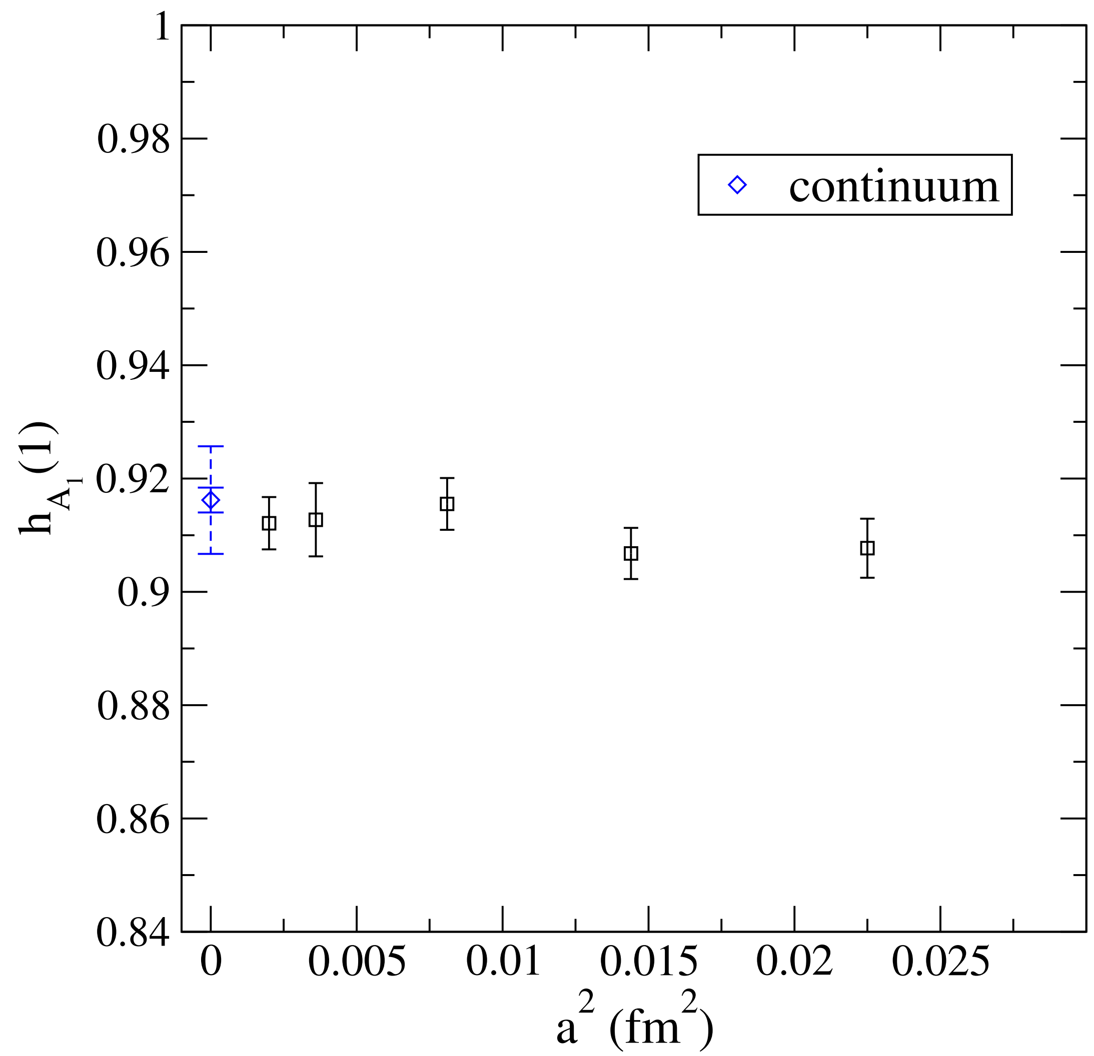

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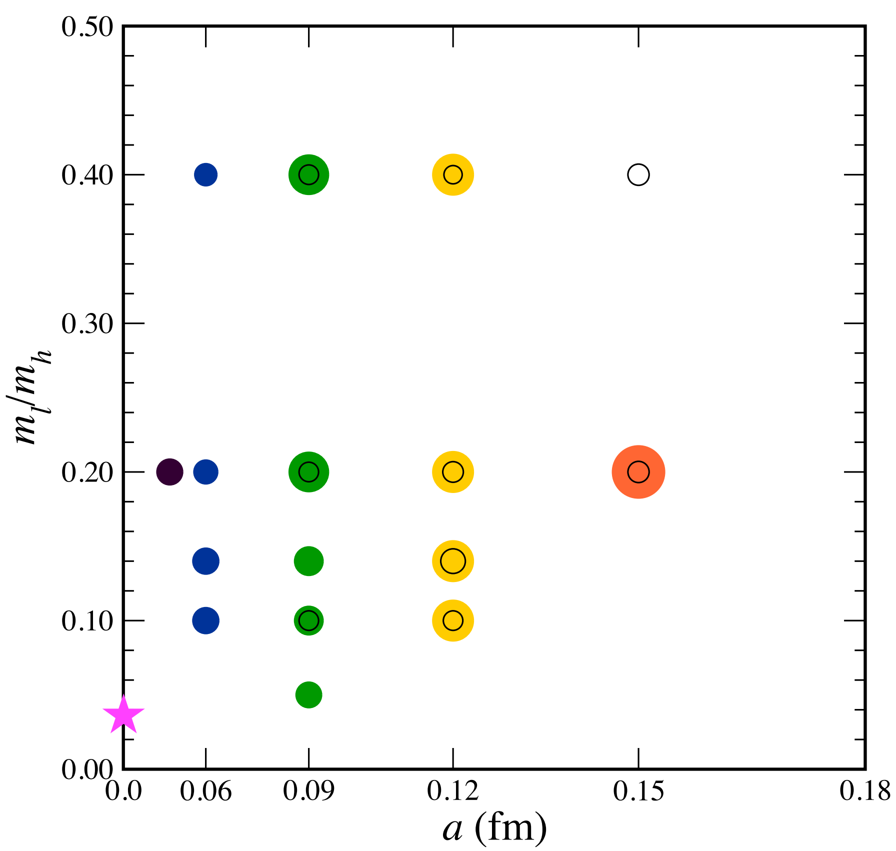
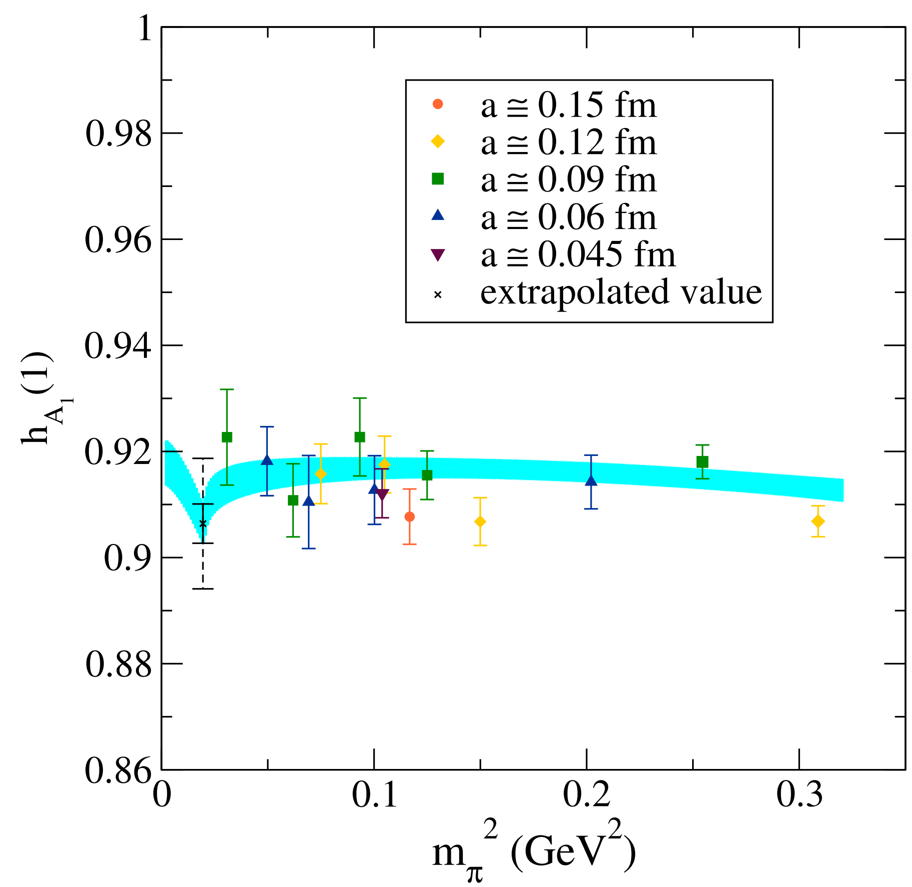




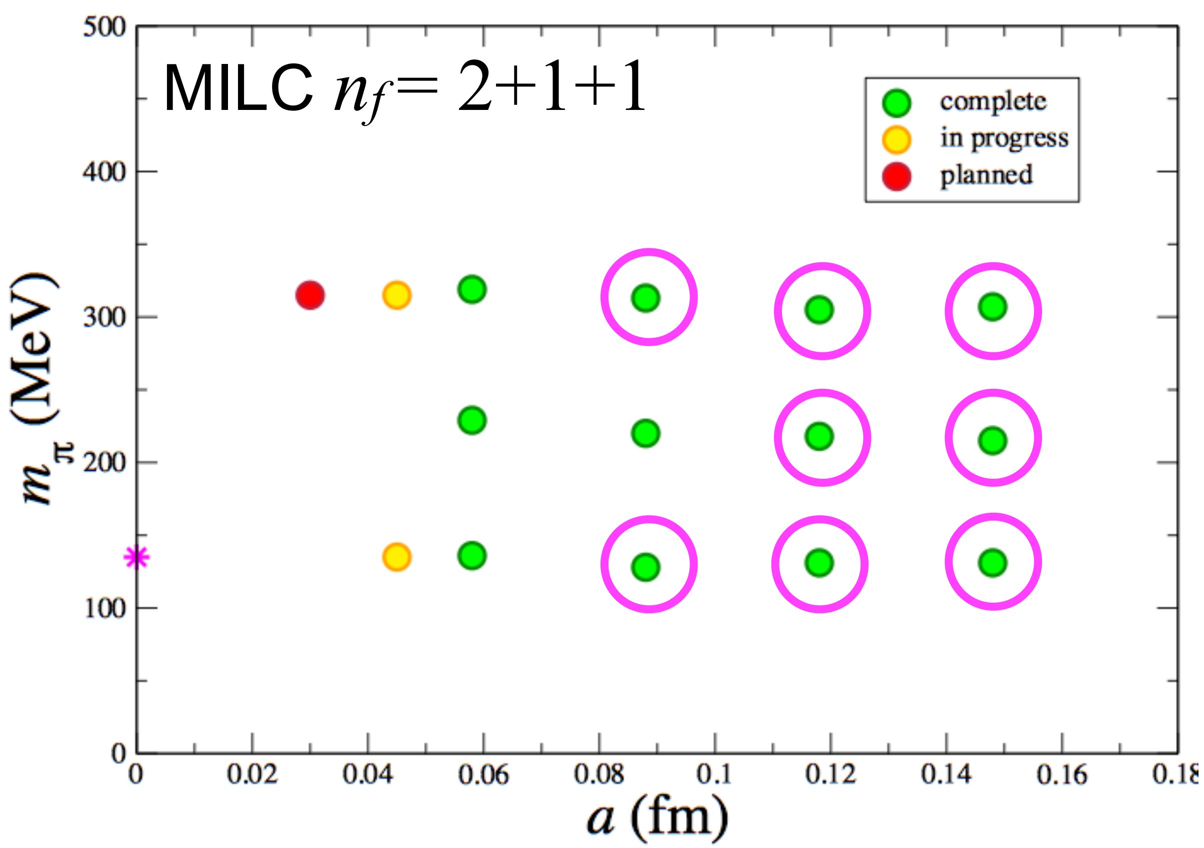
❖ combined chiral-continuum extrapolation

❖ cusp due to $D^* \to D\pi$ and $m_{D^*} - m_D \sim m_\pi$

❖ included using ChPT with $D^* D\pi$ coupling as input.

Form factor for $B \to D^*$ at zero recoil

❖ HPQCD (J. Harrison @ Lattice 2016, **preliminary**):



- 8 MILC HISQ ensembles
  3 lattice spacings
  ~ 3 sea quark masses per lattice spacing including one each at physical mass
- HISQ light valence quarks
- NRQCD b quarks
- $O(a)$ improved current
- 1-loop perturbative renormalization is the dominant source of error
- systematic error analysis in progress

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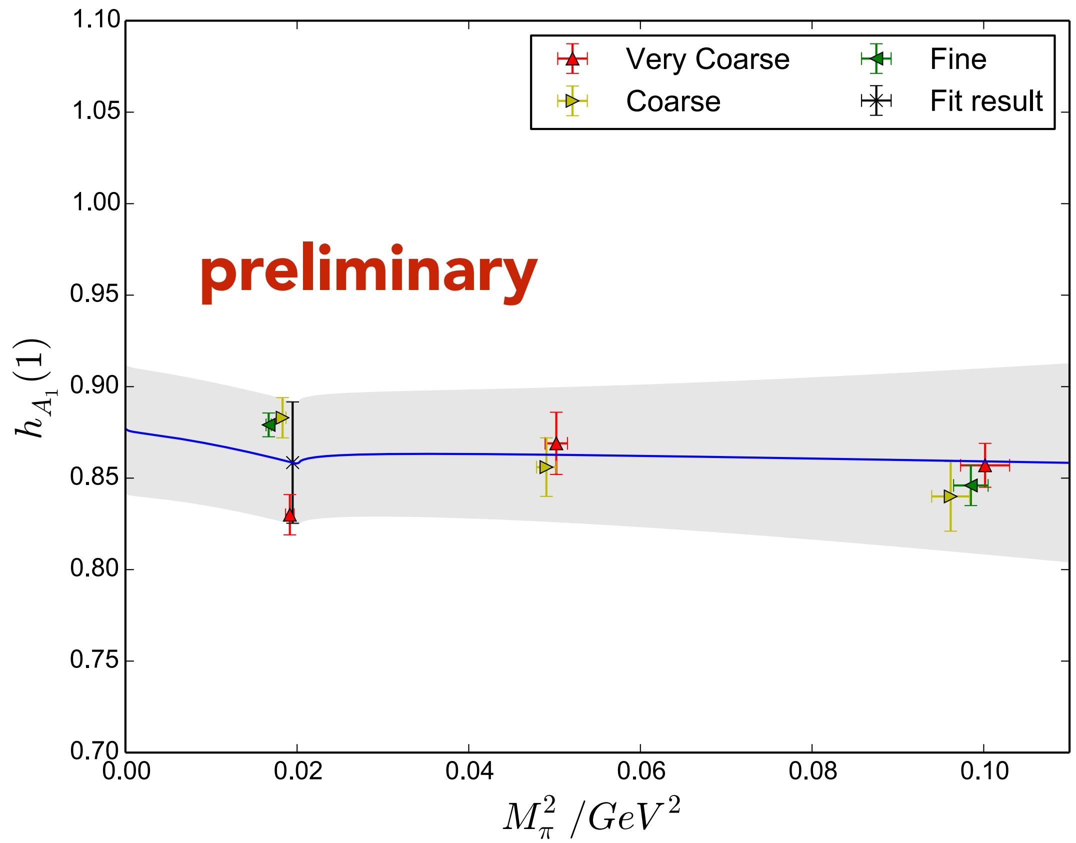

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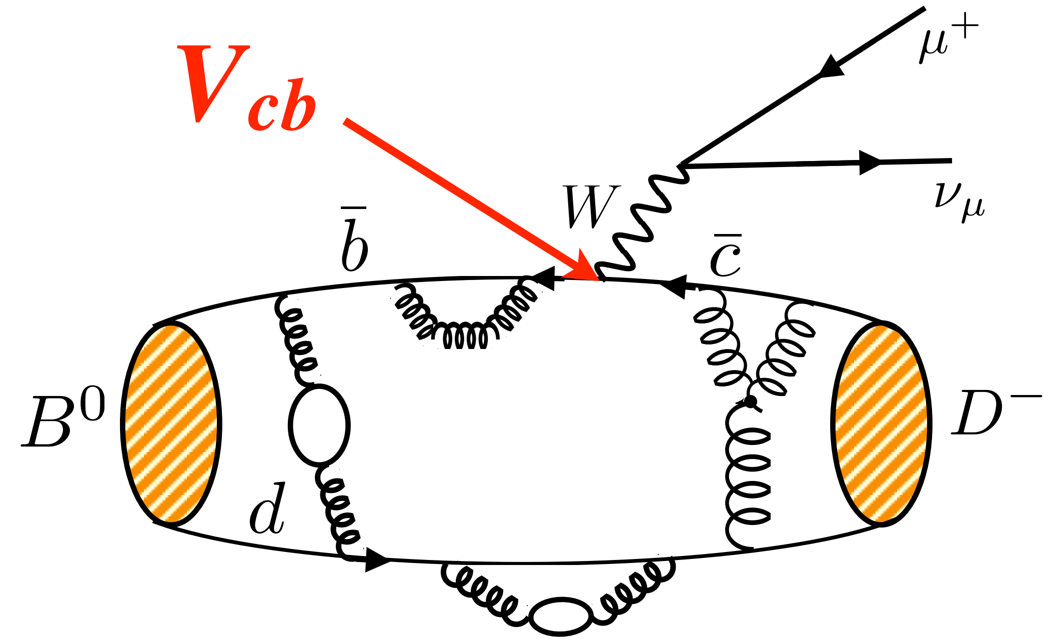
Form factors for $B \to D\,\ell\nu, \quad (\ell = e, \mu, \tau)$

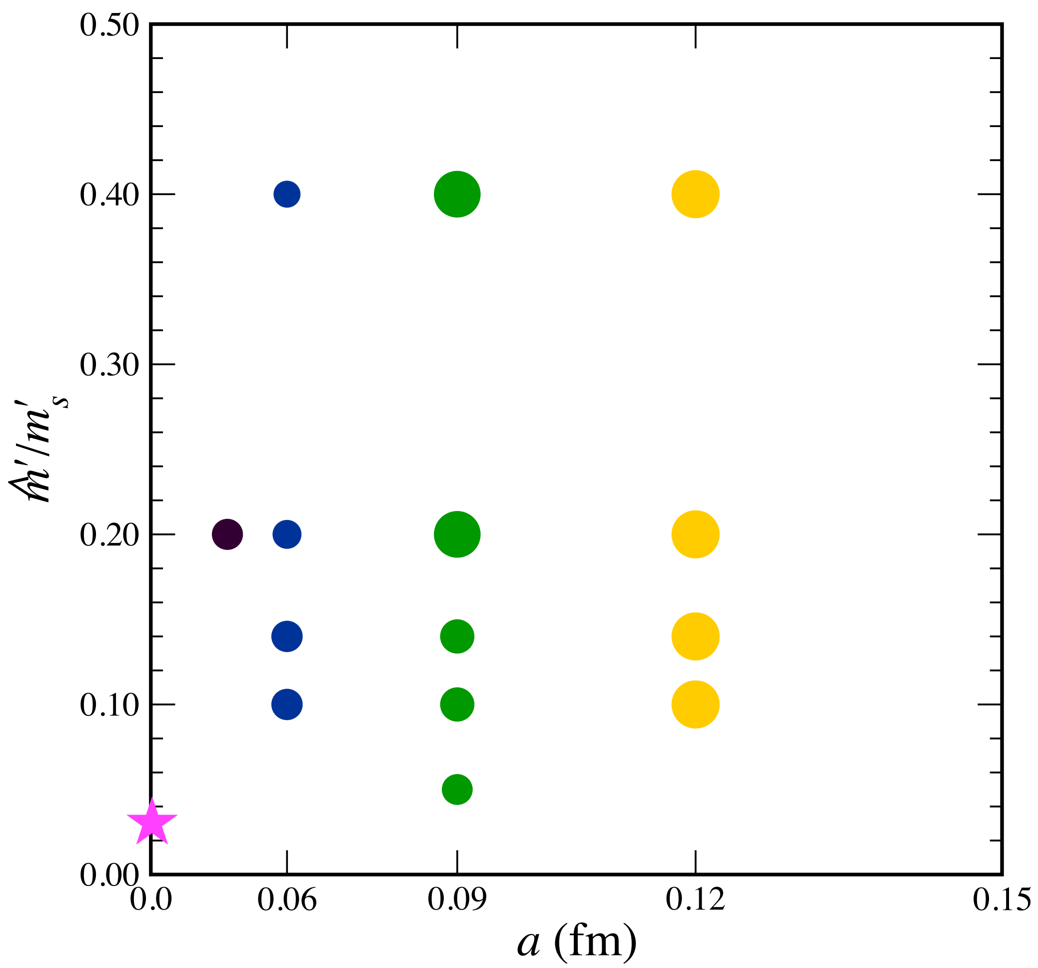


$$\frac{d\Gamma(B \to D\,\mu\nu)}{dq^2} = (\text{known}) \times |V_{cb}|^2 \times f_+^2(q^2)$$

- ⋆ 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 the complete set of form factors, $f_+(q^2), f_0(q^2)$.
- ⋆ for $f_+(q^2)$ compare shape between experiment and lattice.

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

FNAL/MILC (arXiv:1503.07237, PRD 2015)



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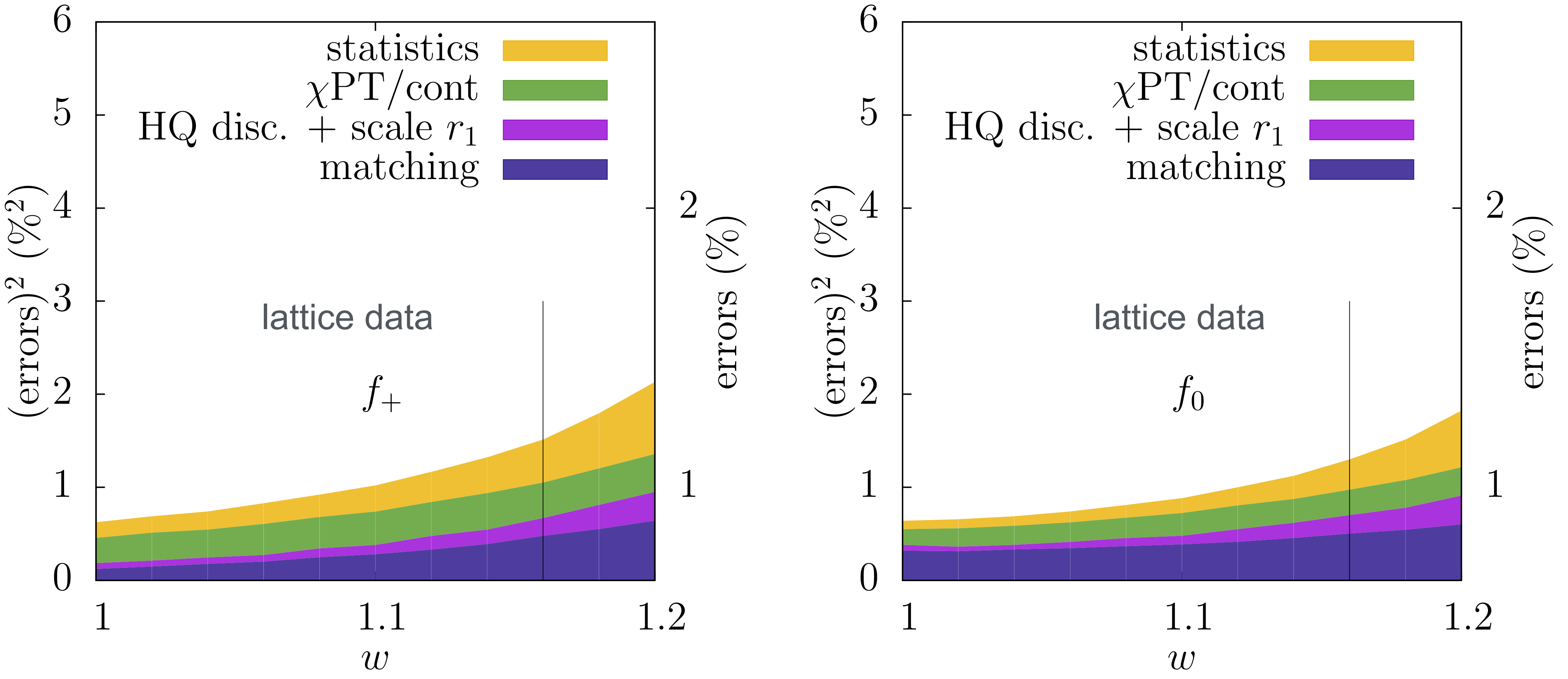
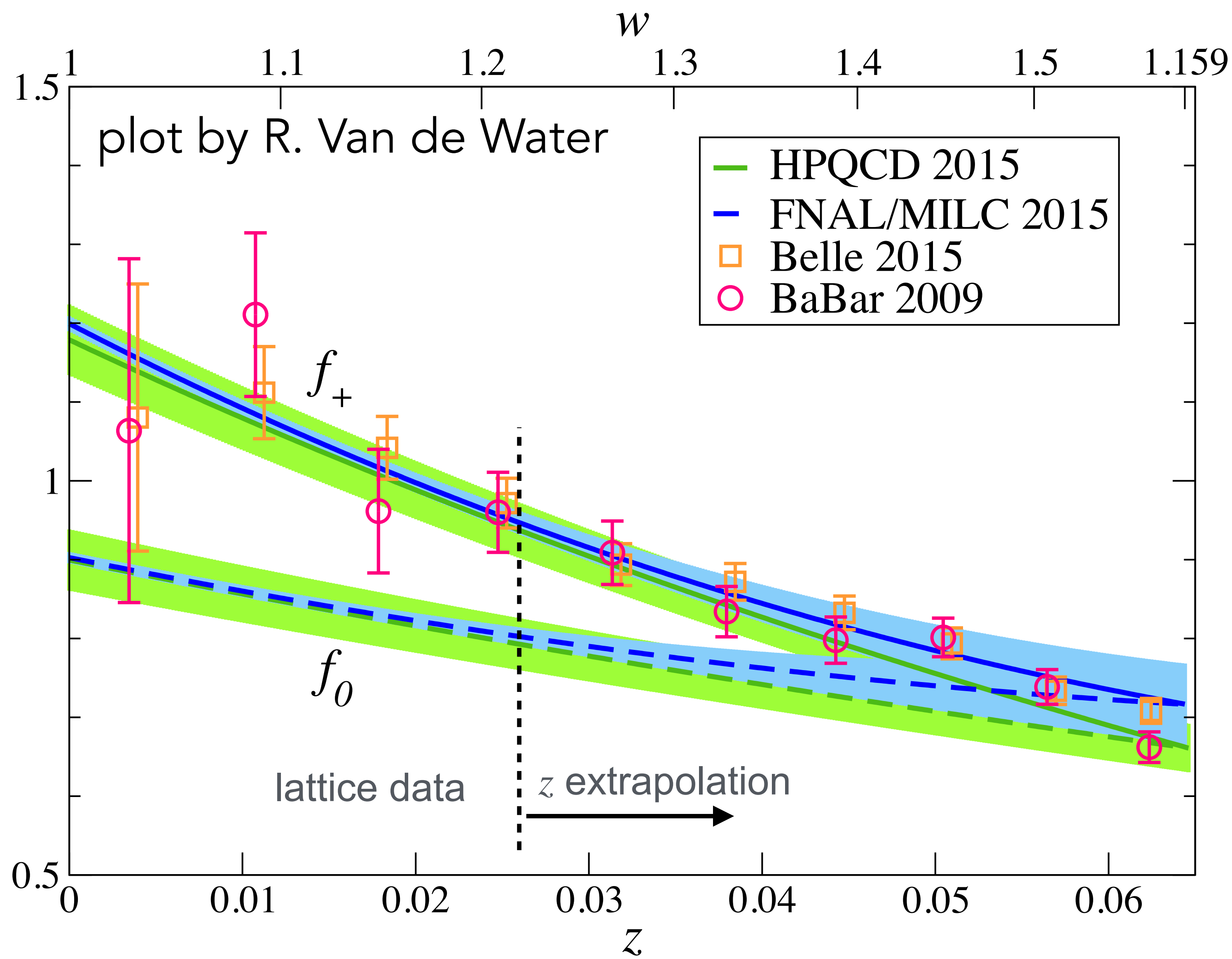


Form factors for $B \to D\,\ell\nu, \quad (\ell = e, \mu, \tau)$



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

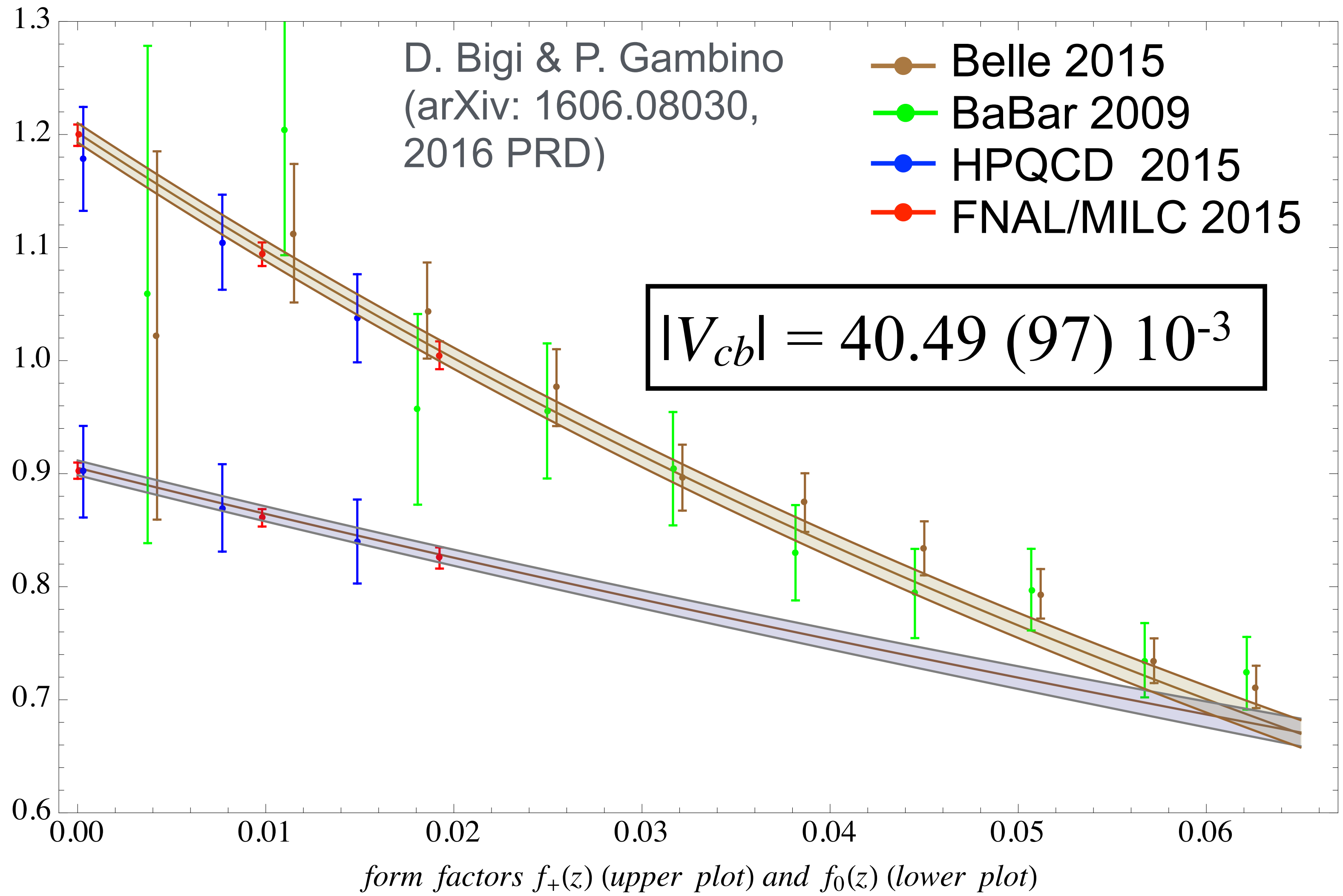
- Two LQCD calculations (FNAL/MILC, HPQCD)
- HPQCD uses 5 MILC ensembles and different valence quark actions
- LQCD form factor uncertainties (~1.2%) smaller than experiment.

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

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

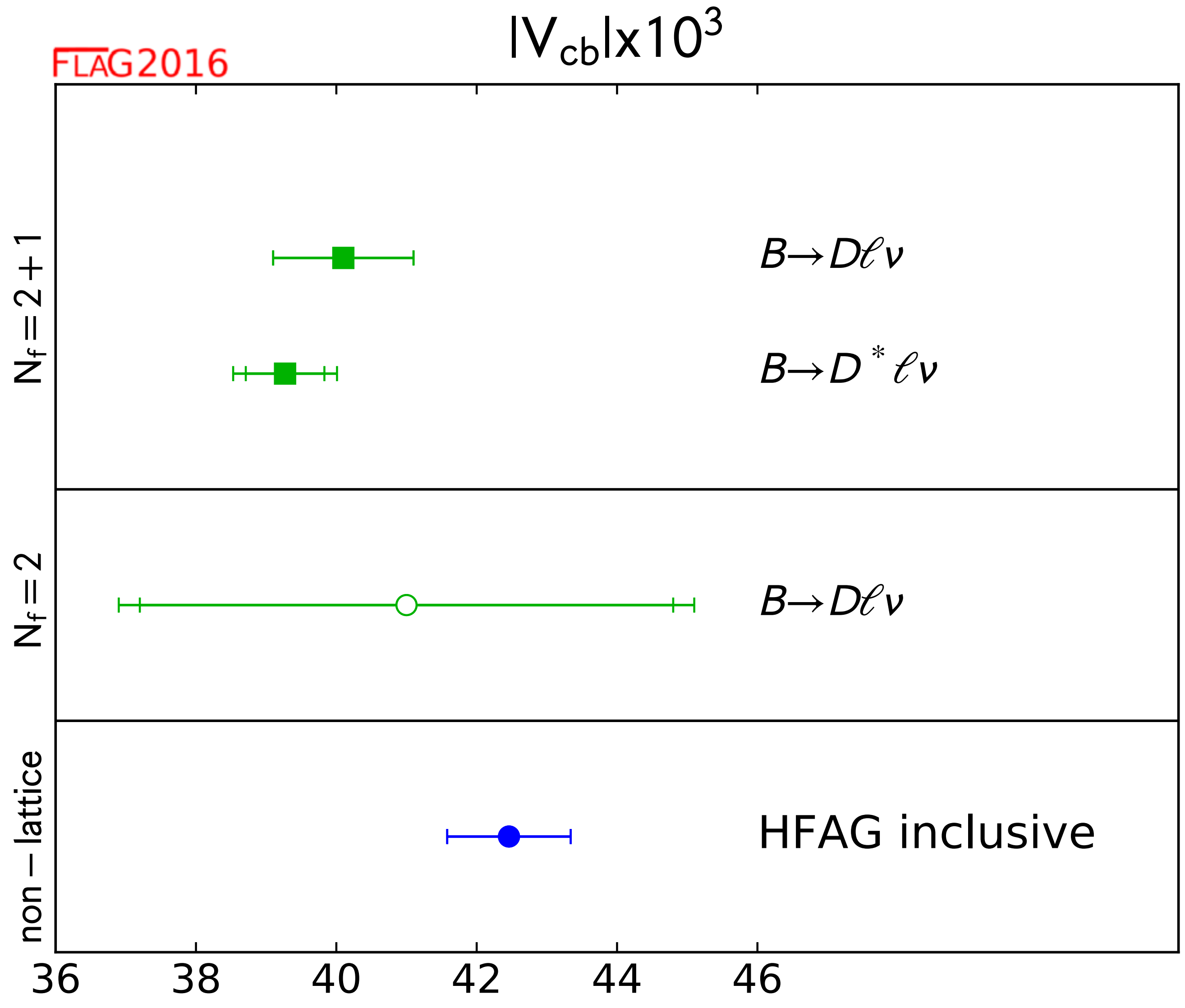
$B \to D \ell \nu$ & $|V_{cb}|$

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

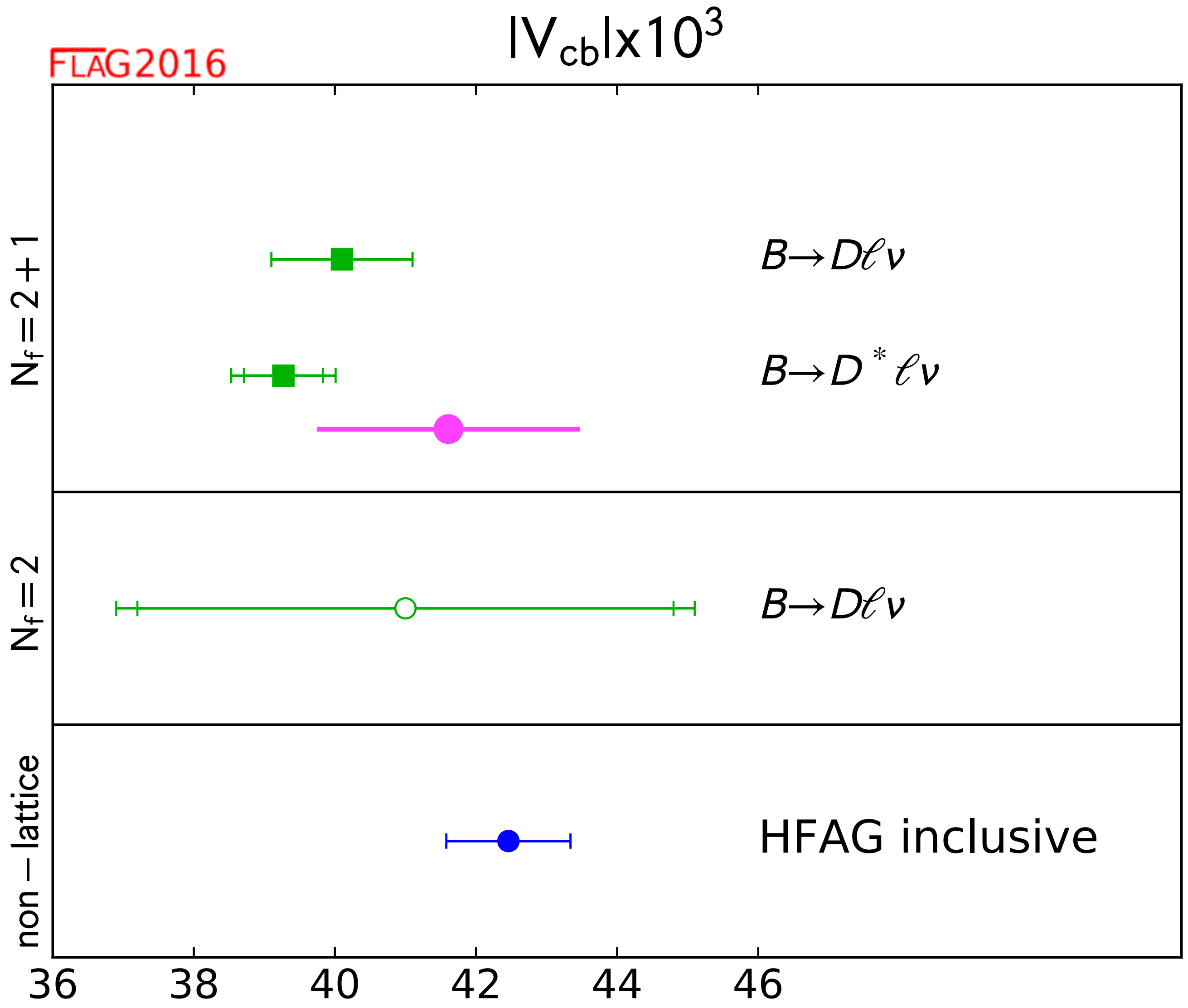


- FLAG-3 (S. Aoki et al, arXiv:1607.00299, EPJC 2017) performs a similar combined fit using the BCL parameterization.

Implications for $|V_{cb}|$



Implications for $|V_{cb}|$



Two new analyses:

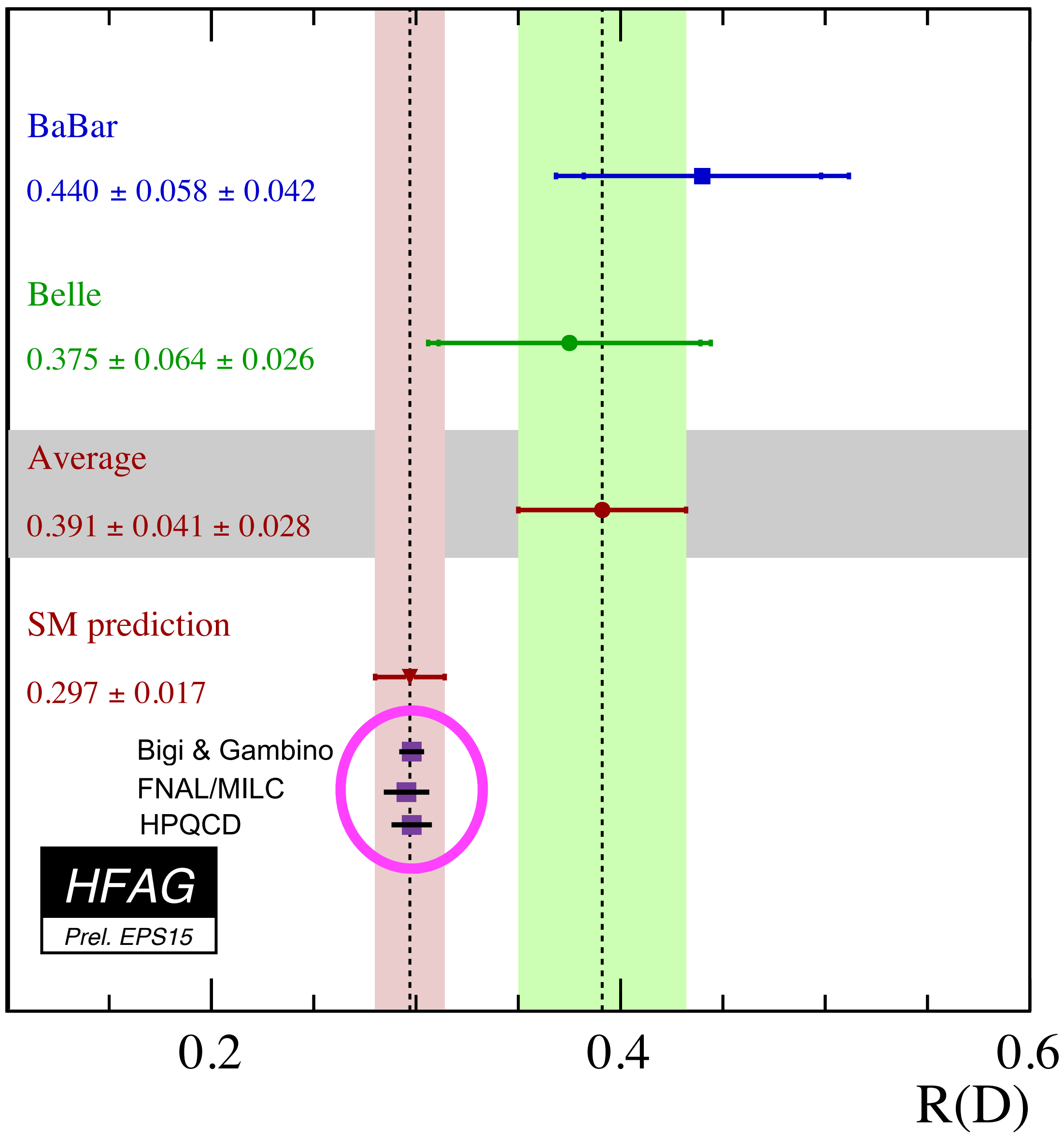
- Bigi, Gambino, Schacht (arXiv:1703.06124)
- Grinstein, Kobach (arXiv:1703.08170)

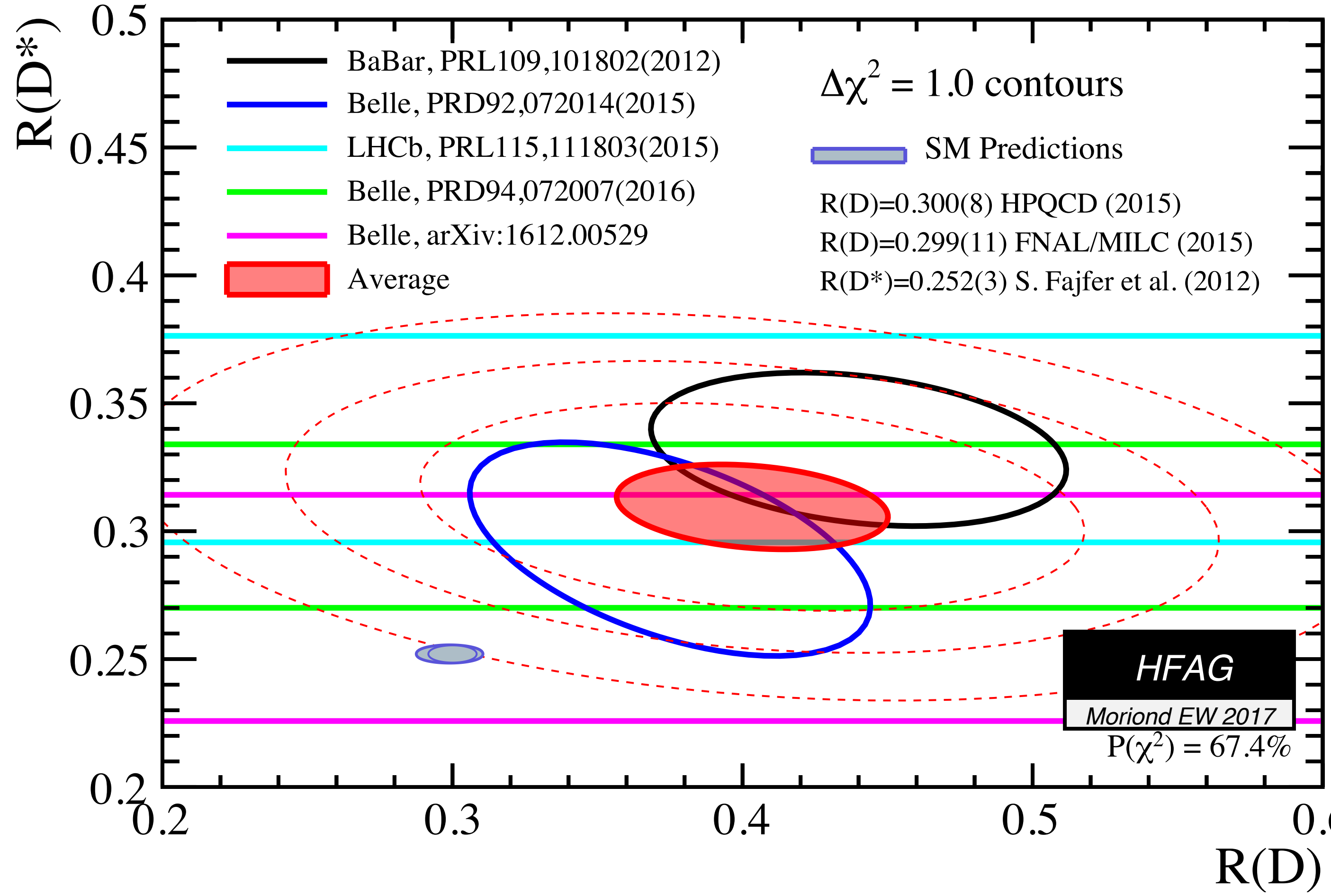
Both use new Belle data (arXiv:1702.01521) and BGL together with lattice $\mathcal{F}(1)$.

BSM phenomenology: LFU τ/ℓ

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

HFAG average for EPS 2015

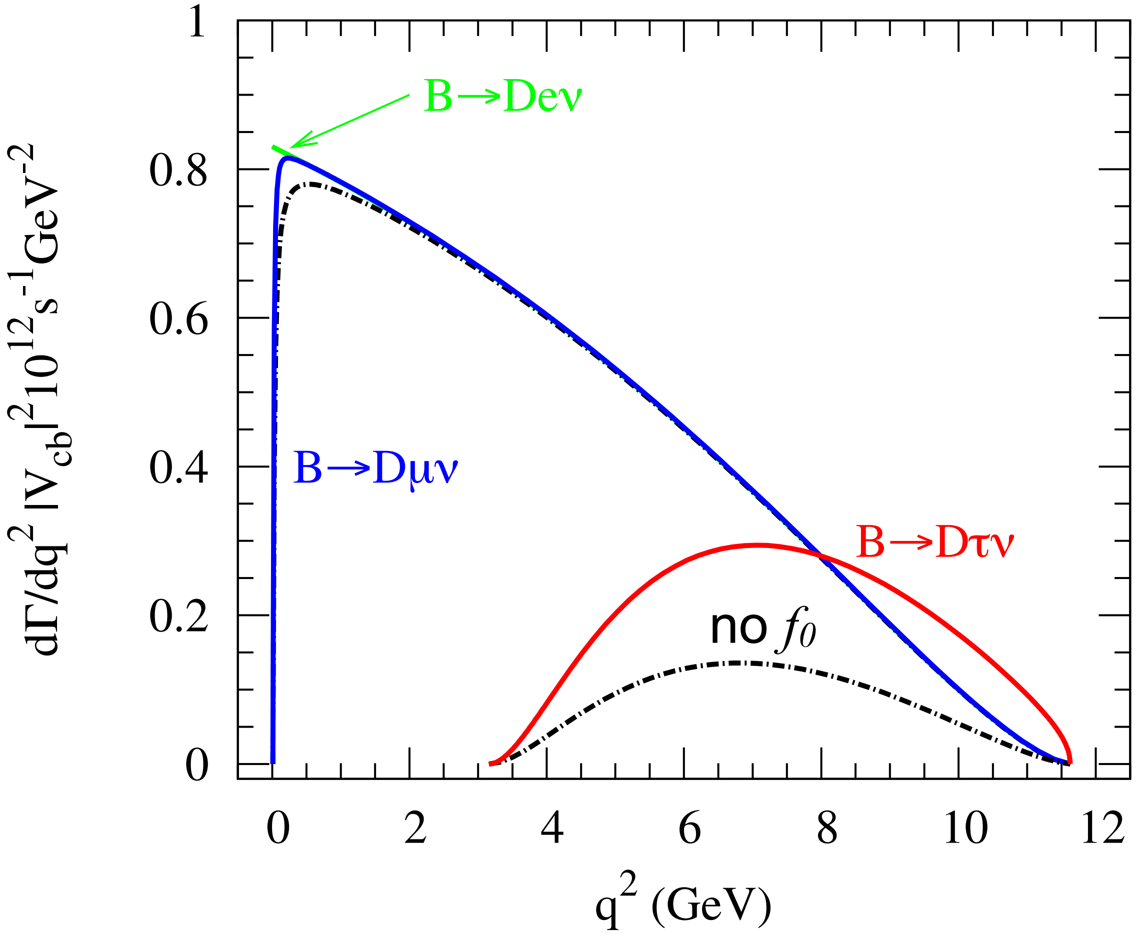




HFAG 2017 average: combined 3.9σ excess

BSM phenomenology: LFU τ/ℓ

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

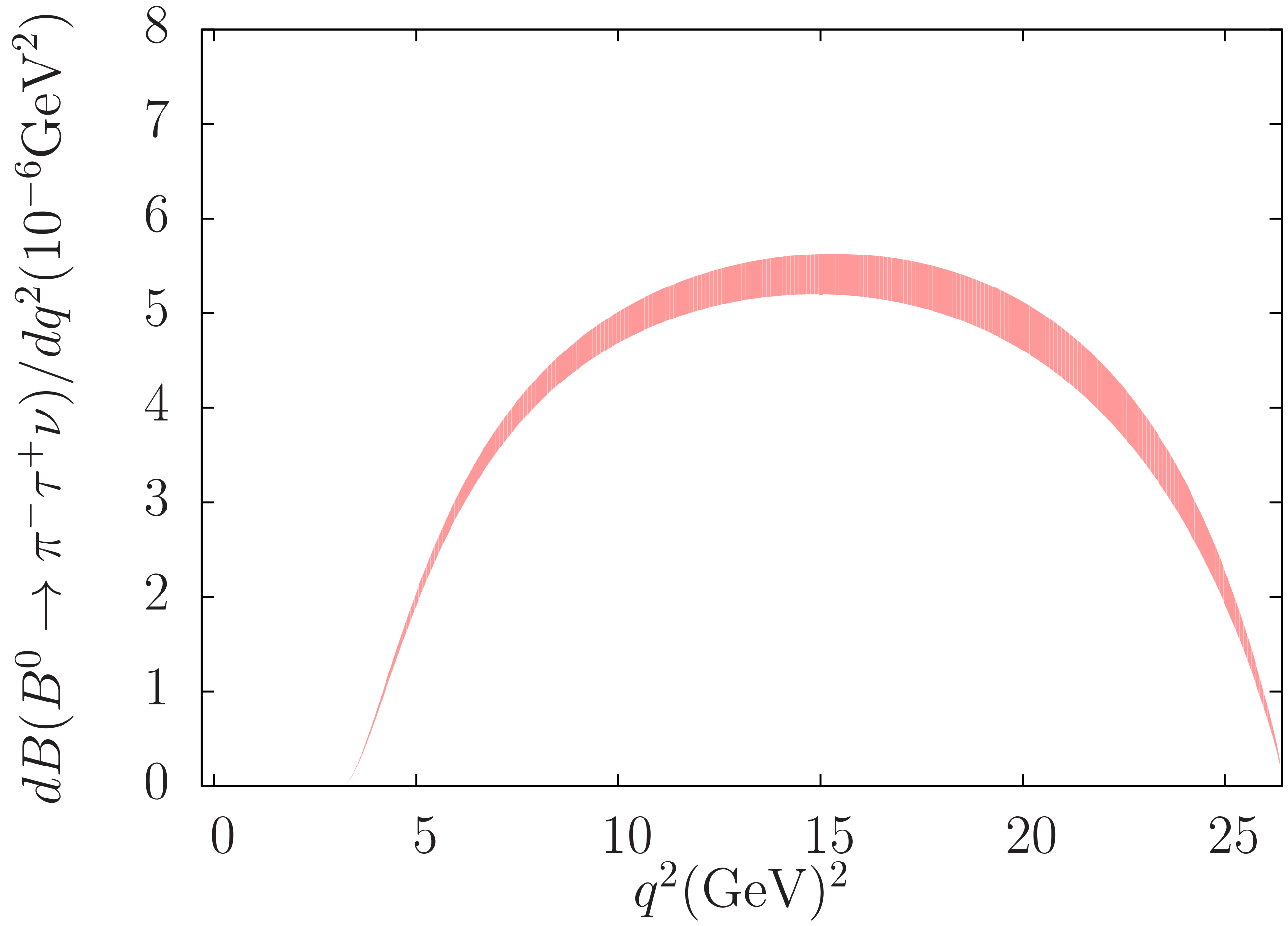


- The shape of the $B \to D^{(*)} \tau\nu$ rate is sensitive to f_0 contribution.
- Shape comparison: use (ratios of) differential or binned decay rates to compare theory and experiment.

BSM phenomenology: LFU τ/ℓ

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

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



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

Prospects for $B_{(s)} \to D_{(s)}$ form factors at all recoil

ongoing/planned LQCD calculations:

- RBC/UKQCD:
  $B \to D$ and $B_s \to D_s$ form factors
  RHQ action for b quark, DWF charm on DWF (2+1) ensembles
  preliminary results presented at Lattice 2016 (Witzel)
- HPQCD:
  $B_s \to D_s$ form factors
  NRQCD b quarks, HISQ charm on MILC asqtad (2+1) ensembles
  preliminary results presented at Lattice 2016 (Monahan)
- FNAL/MILC:
  $B \to D$ and $B_s \to D_s$ form factors
  Fermilab b,c quarks on MILC HISQ (2+1+1) ensembles (full set)
- LANL/SNU:
  $B \to D$ form factors
  Oktay-Kronfeld b,c quarks on MILC HISQ (2+1+1) ensembles
  First tests of discretization errors with OK action at Lattice 2016

Prospects for $B_{(s)} \to D^*_{(s)}$ form factors at all recoil

ongoing/planned LQCD calculations:

- HPQCD:
  NRQCD b quarks, HISQ charm on MILC HISQ (2+1+1) ensembles
- FNAL/MILC:
  1) Fermilab b,c quarks on MILC asqtad (2+1) ensembles (full set)
  2) Fermilab b,c quarks on MILC HISQ (2+1+1) ensembles (full set)
- LANL/SNU:
  Oktay-Kronfeld b,c quarks on MILC HISQ (2+1+1) ensembles
- RBC/UKQCD:
  RHQ action for b quark, DWF charm on DWF (2+1) ensembles

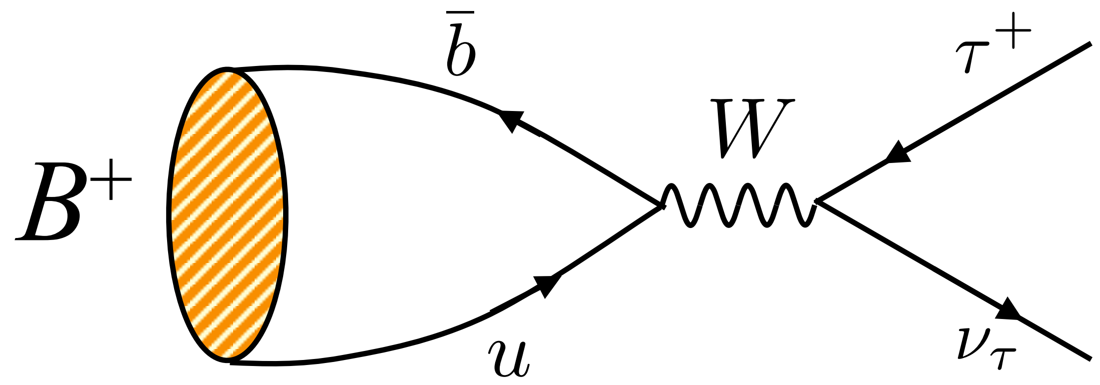
Combine binned experimental decay distributions (Belle, arXiv:1702.01521) with LQCD form factors to extract $|V_{cb}|$ and obtain improved form factors to be used for SM predictions of $R(D^{(*)})$.

Electroweak corrections, η_{EW}

- It includes a log from $W/Z/\gamma$ boxes (Sirlin, 1982): $\eta_{\mathrm{EW}} = 1 + \frac{\alpha}{\pi} \ln \frac{m_Z}{\mu}$
- In B^0 decay, there is a long-distance (universal) radiative correction due to Coulomb attraction between the final states: $\pi\alpha/2$
- Structure-dependent radiative corrections have not yet been calculated.

Leptonic B-meson decay

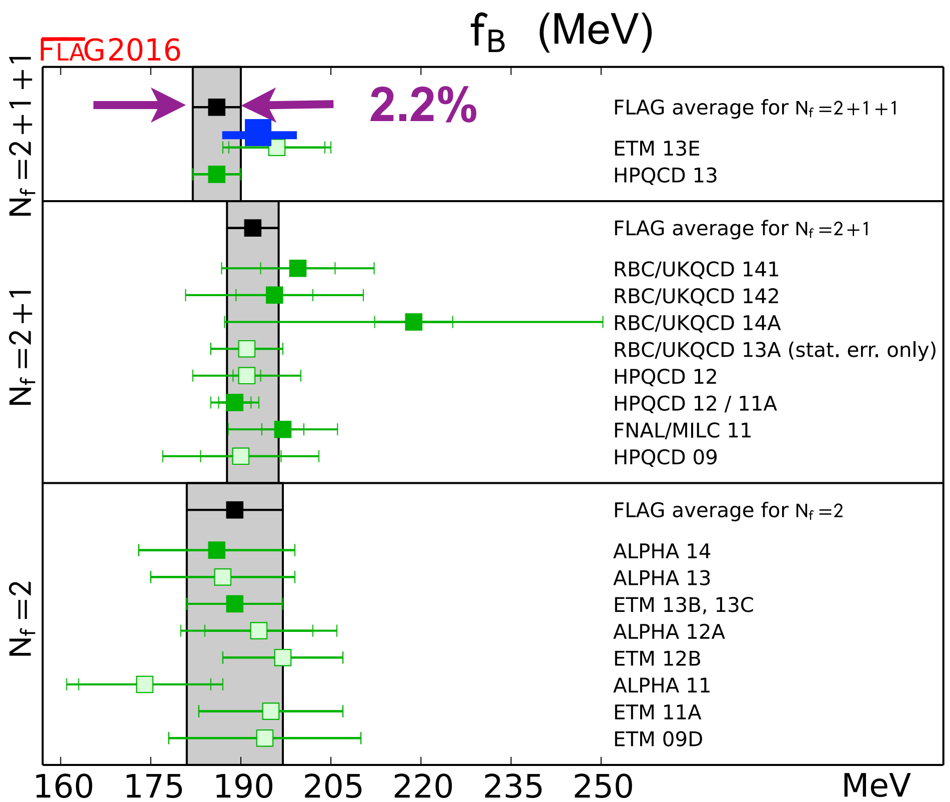
Example: $B^+ \to \tau^+ \nu_\tau$

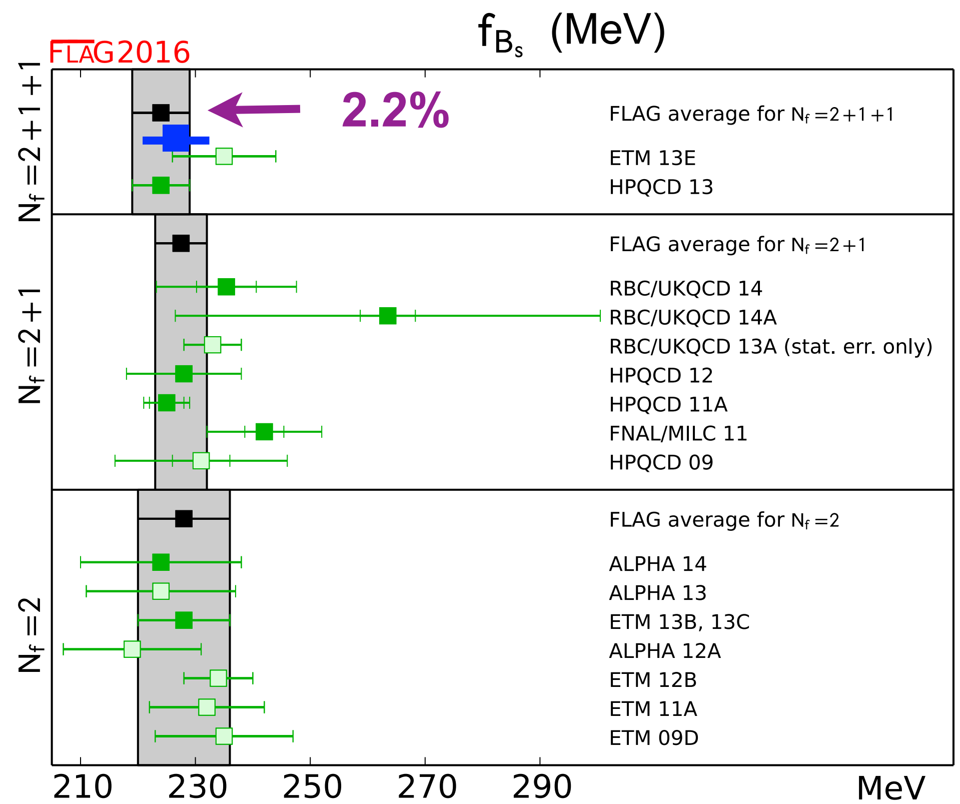


$$\Gamma(B^+ \to \tau^+ \nu_\tau) = (\text{known}) \times |V_{ub}|^2 f_B^2$$

- 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, $B_{s(d)} \to \mu\mu$.

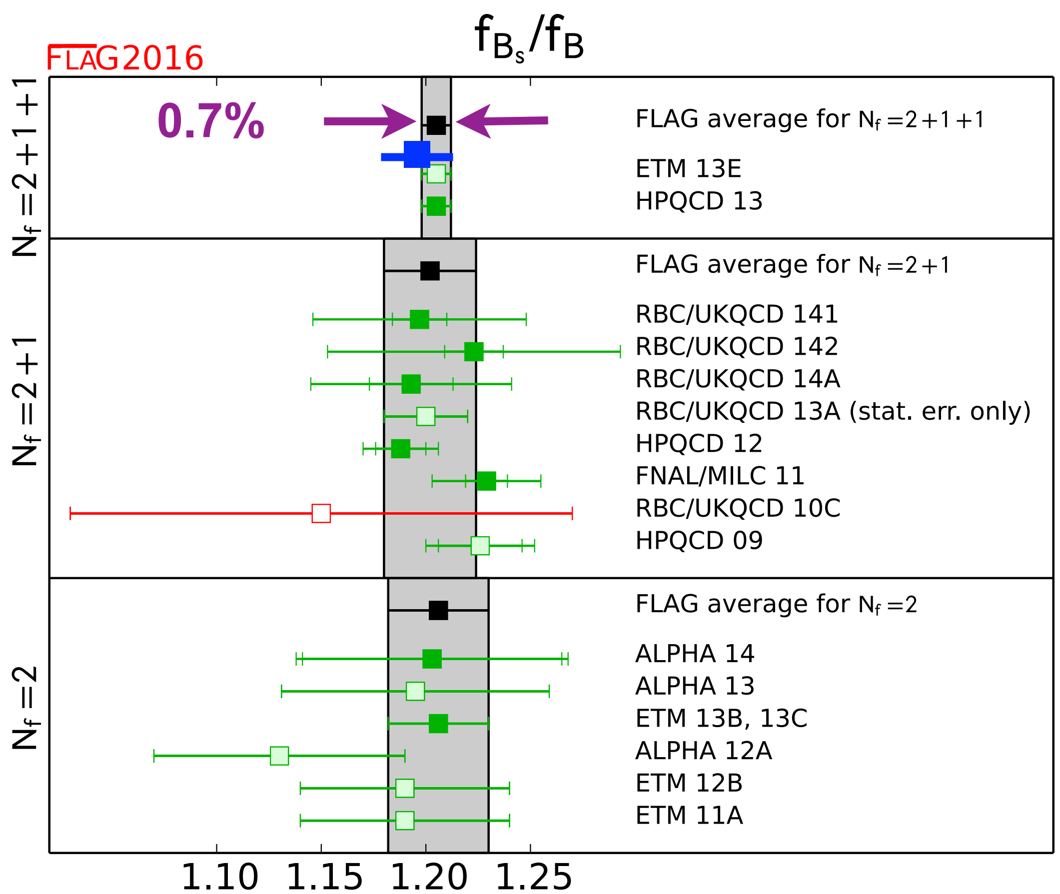
B decay constant summary





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

status
end 2015

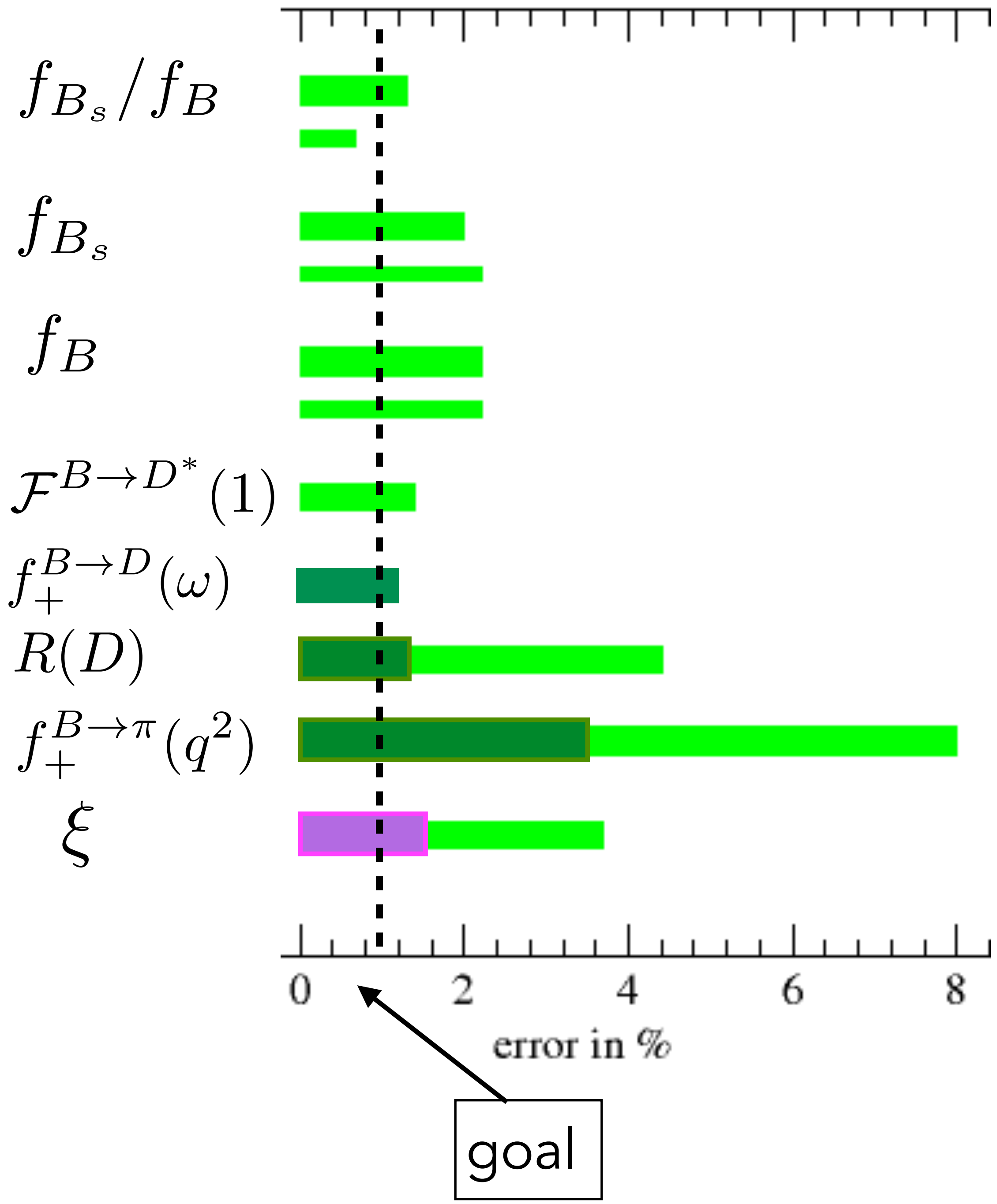


- ✦ new results by ETM (arXiv:1603.04306, 2016 PRD)
- ✦ ongoing work by FNAL/MILC (Komijani @ Lattice 2016), RBC/UKQCD, …

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

B-meson summary

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



Summary

- ☆ LQCD results exist for $B \to D$ form factors at all recoil and $B \to D^*$ form factor at zero recoil with errors that are commensurate with experimental uncertainties.
- ☆ Expect to see new LQCD results for $B_{(s)} \to D_{(s)}$ and $B_{(s)} \to D_{(s)}{}^*$ form factors at all recoil at Lattice 2017.
  - ➢ may affect the tension between exclusive and inclusive determinations of $|V_{cb}|$.
  - ➢ will enable an improved SM estimate of $R(D^*)$.
- ☆ For B decays to $D^{(*)}\tau\nu$ final states, shape comparison between theory and experiment would be useful.
- ☆ LQCD (or combined lattice +exp) form factors can also be used to obtain the predictions for $R(D^{(*)})$ and other observables from BSM theories.
- ☆ expect LQCD results for B-*meson* decay constants at 1% level soon.

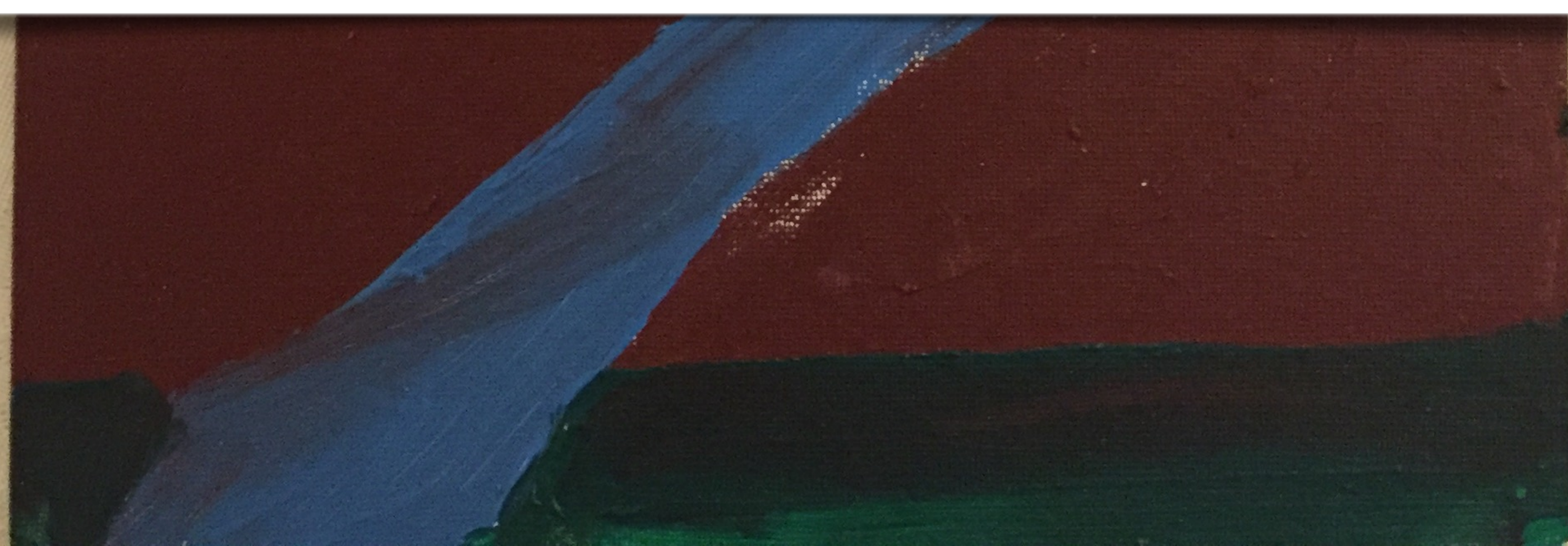
Outlook

Amala Willenbrock

Outlook

Further improvements

- 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
- Include effects of $D^* \to D\pi$ directly in the LQCD calculation. Theoretical framework for semileptonic B decays to vector meson final states under development (Briceño et al, arXiv:1406.5965, 2015 PRD; Agadjanov et al, arXiv:1605.03386).
  - ➢ LQCD pilot studies are underway for $B_s \to K^* \ell\nu,\ B \to K^* \ell\ell, \ldots$



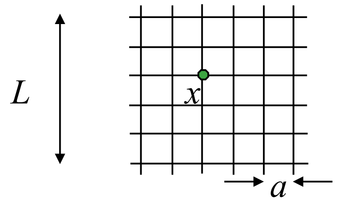
Amala Willenbrock

Thank you!

ありがとうございます

Farah Willenbrock

Backup slides



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

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

chiral-continuum extrapolation

Some ensembles still have

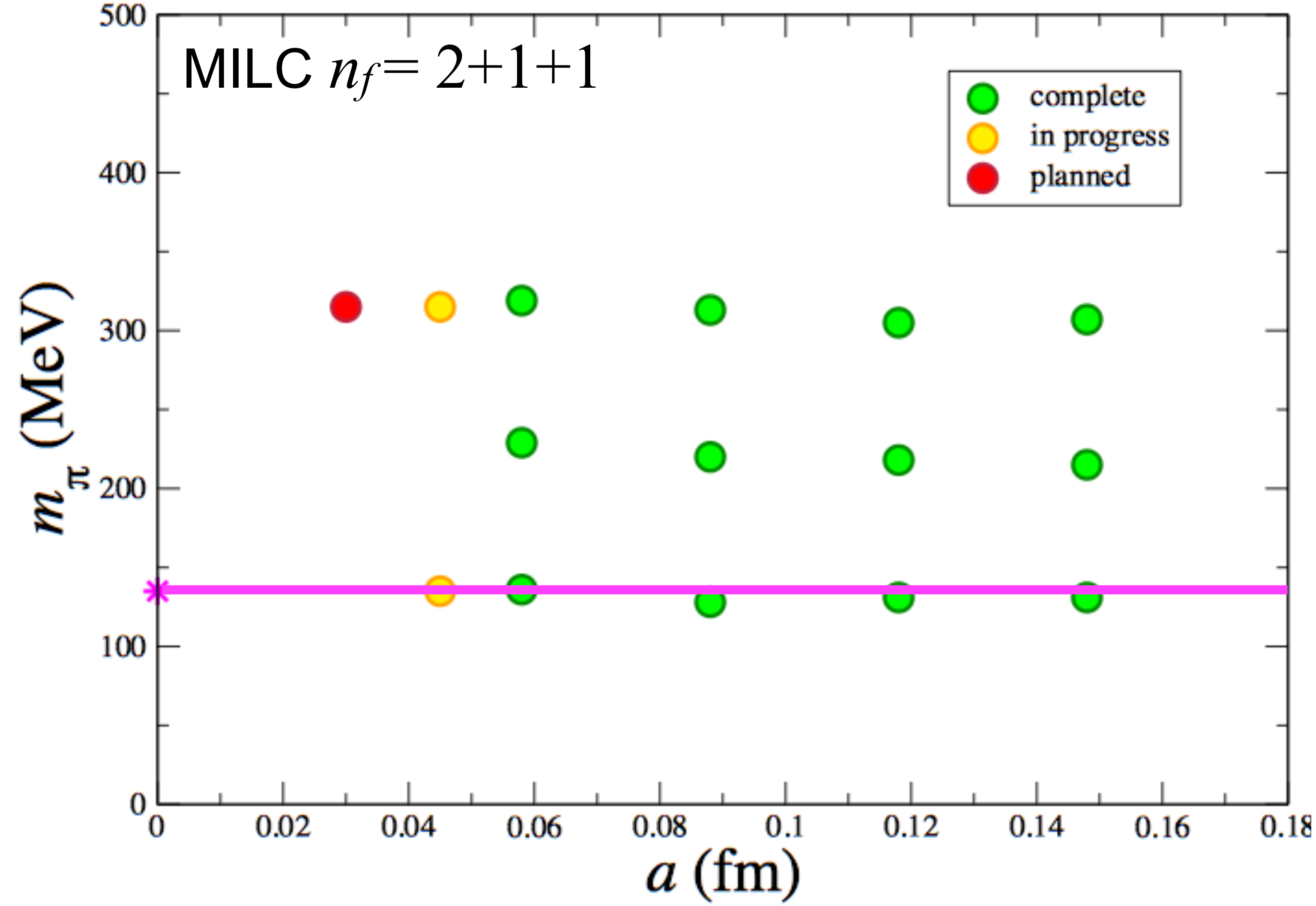
$$m_{\rm light} > 1/2\ (m_u + m_d)_{\rm phys}$$

χPT guides the extrapolation/interpolation to the physical point.

- include (light quark) discretization effects (for example, staggered χPT)
- can also add HQ discretization terms to chiral-continuum fits
- combined chiral-continuum extrapolation/interpolation
- for B,D meson processes use Heavy Meson χPT: χPT + $1/M$ expansion

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

finite volume effects

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

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

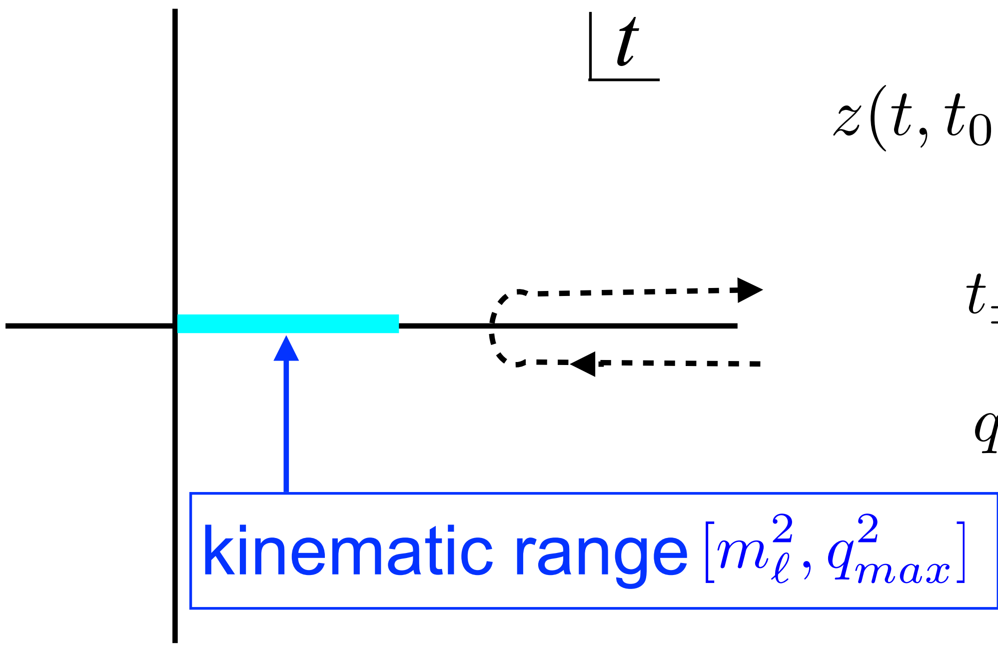
- keep $m_\pi L \gtrsim 4$

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)

The z-expansion

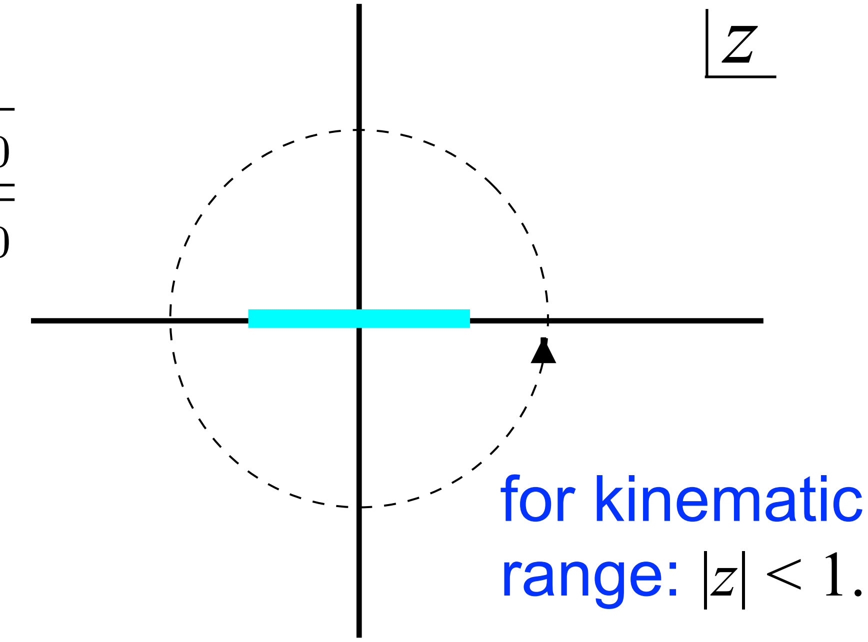


$$t = q^2$$

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

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

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



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)

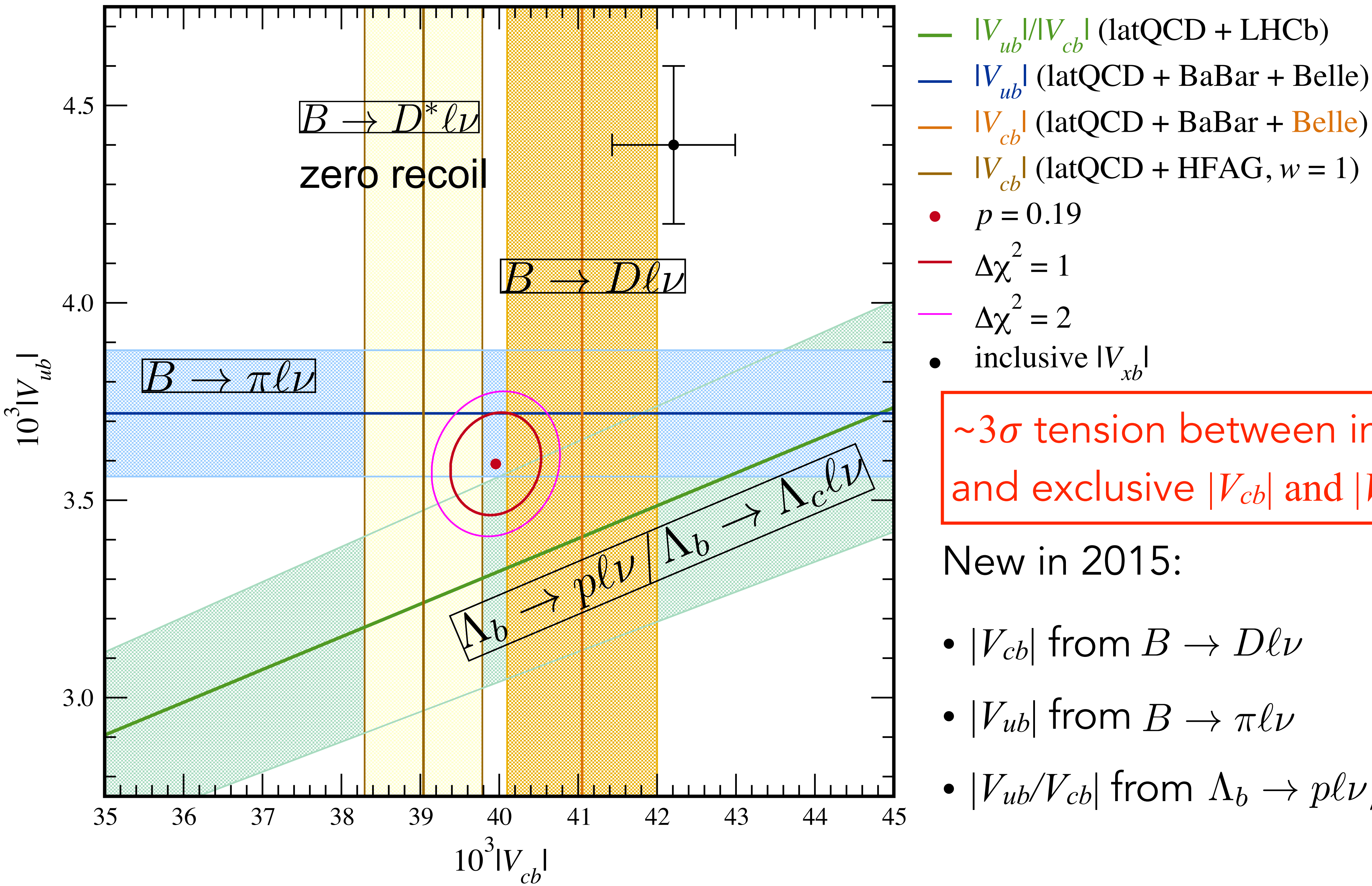
The form factor can be expanded as:

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

- $P(t)$ 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.

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

A. Kronfeld (priv. communication)

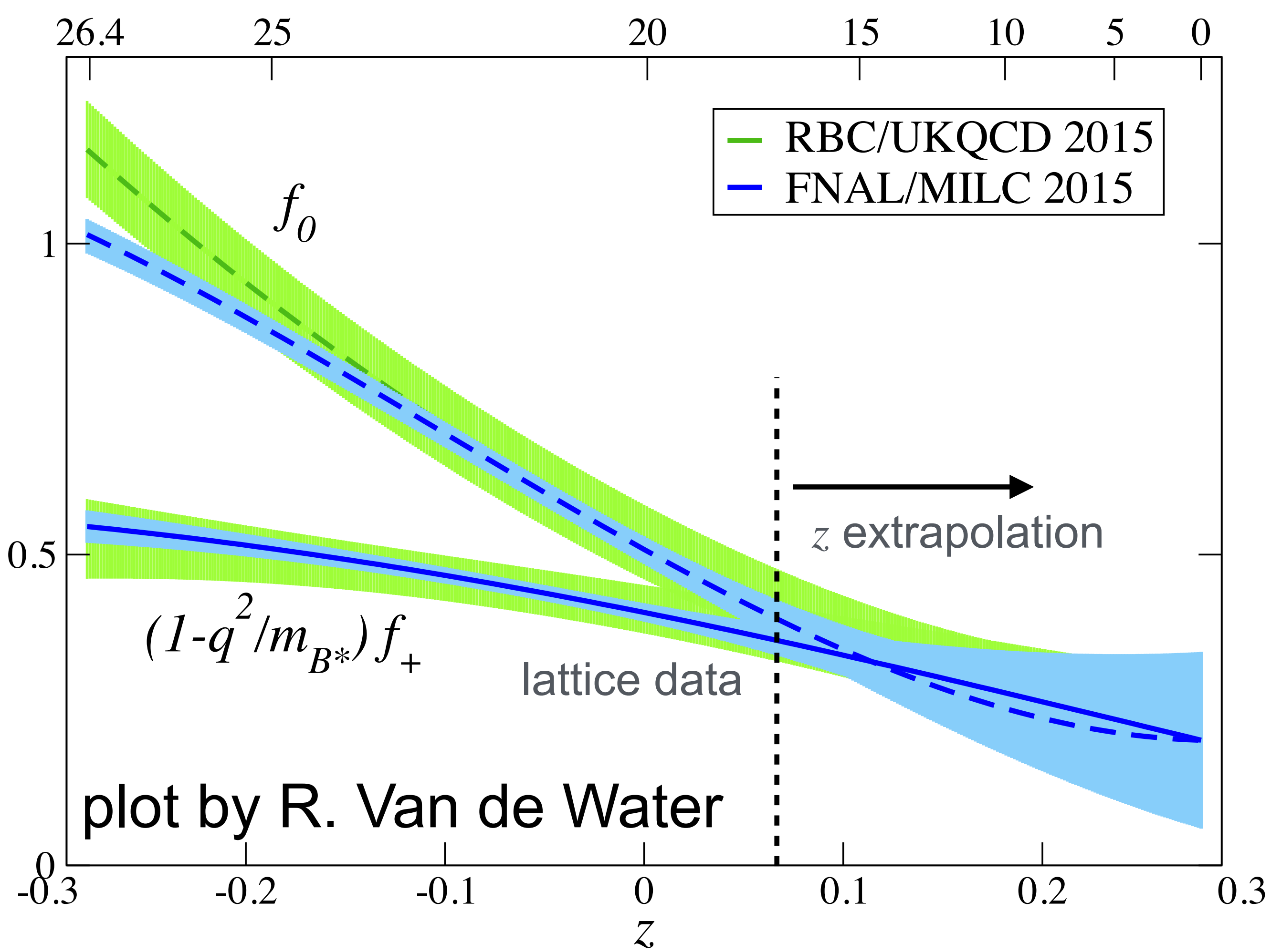


~3σ tension between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$

New in 2015:

- $|V_{cb}|$ from $B \to D\ell\nu$
- $|V_{ub}|$ from $B \to \pi\ell\nu$
- $|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\ell\nu / \Lambda_b \to \Lambda_c\ell\nu$

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

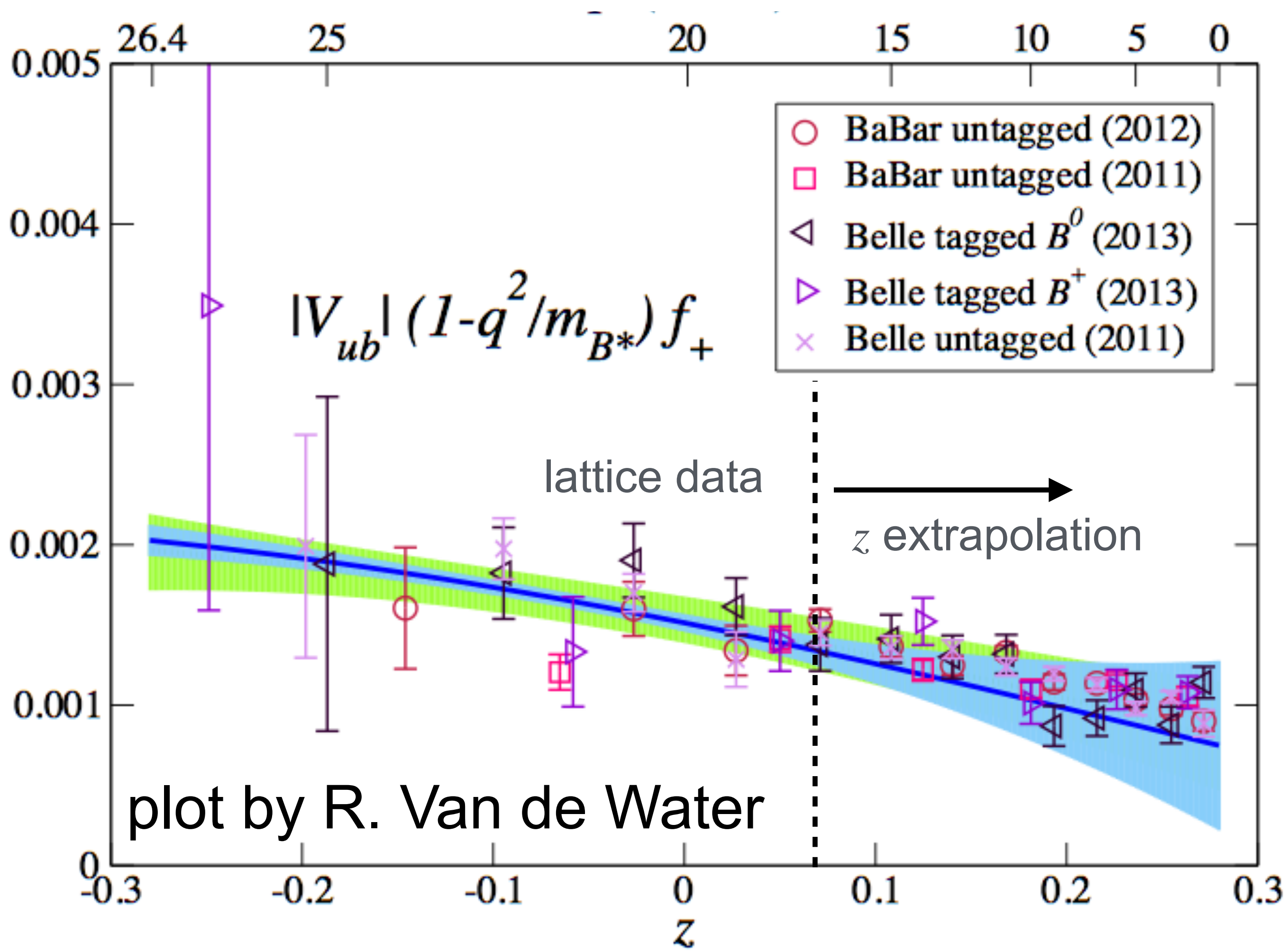


RBC (arXiv:1501.05373, PRD 2015)

FNAL/MILC (arXiv:1503.07839, PRD 2015)

- FNAL/MILC & RBC form factors are in good agreement
- HPQCD (arXiv:1510.07446, PRD 2016): f_0 with physical light quarks at zero recoil satisfies soft-pion theorem
- Note: 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 ALPHA (Banerjee, Koren @ Lattice 2016), FNAL/MILC, …

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



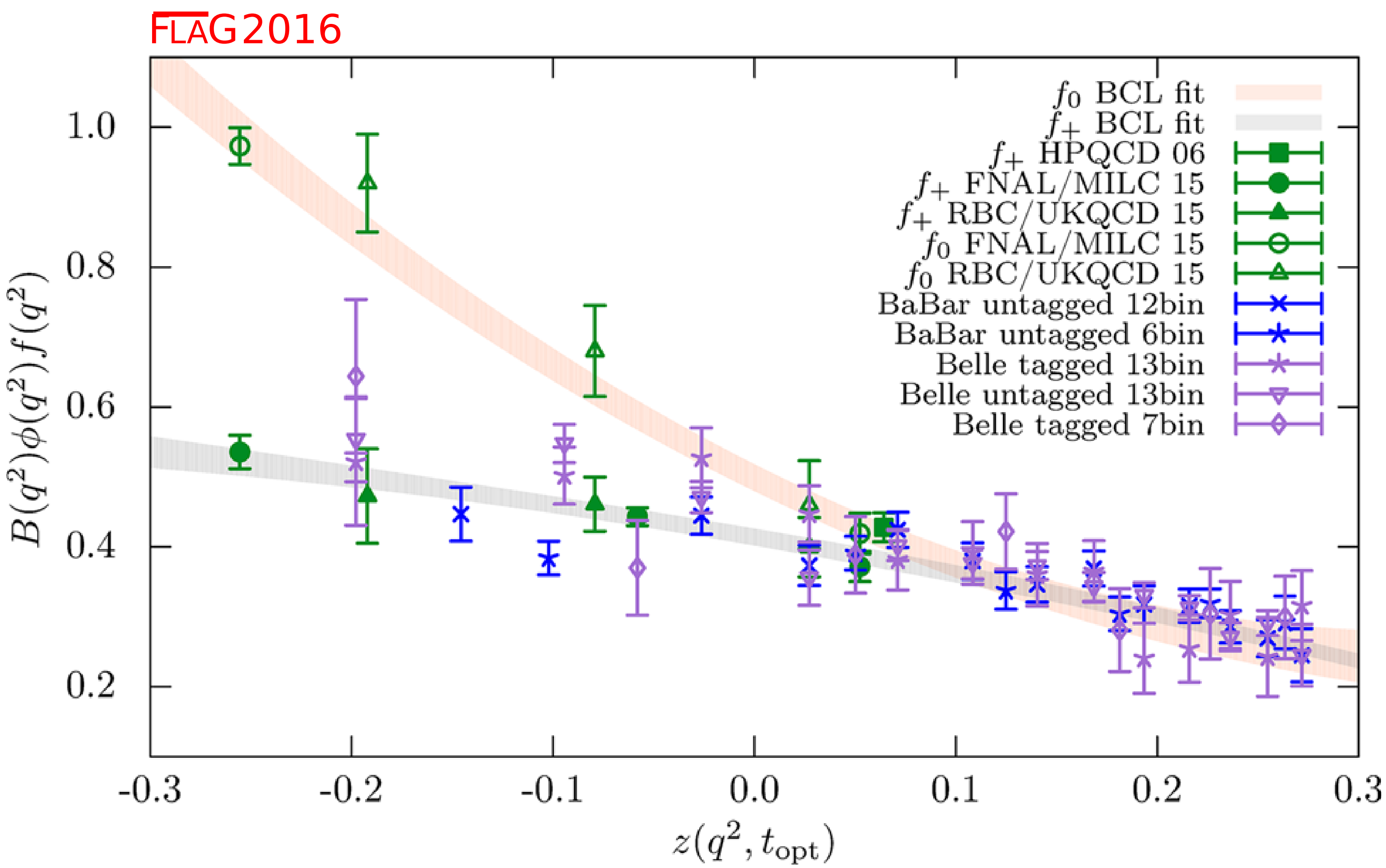
RBC (arXiv:1501.05373, PRD 2015)

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…

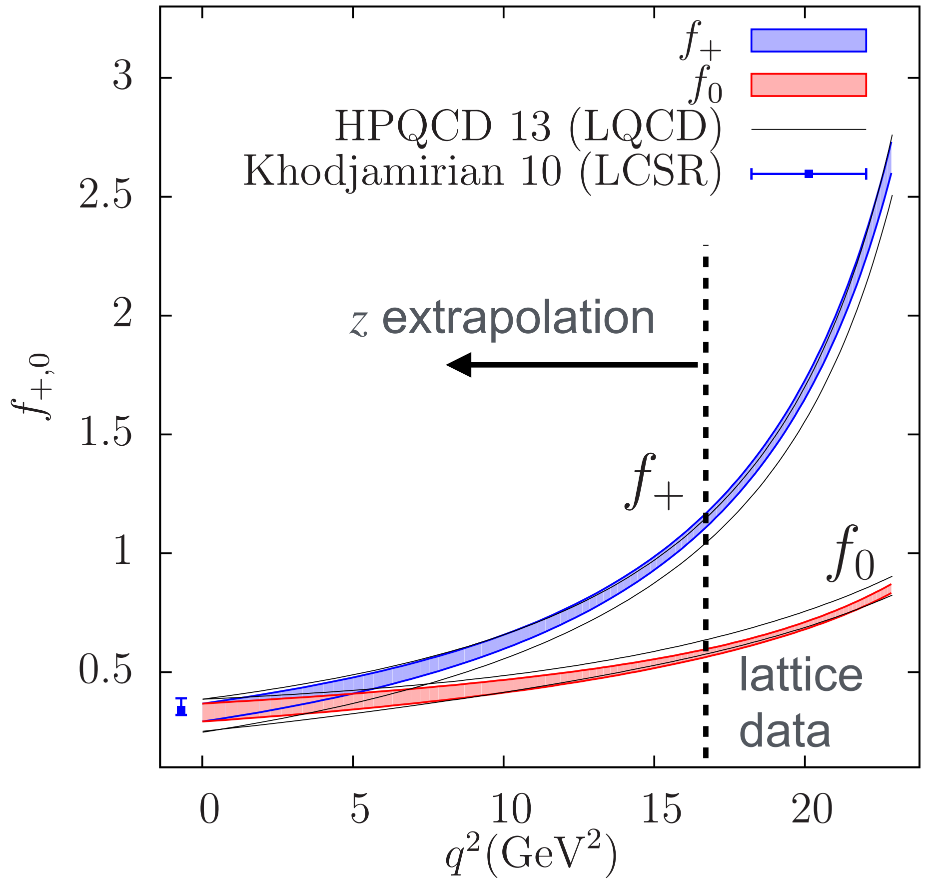
form factors for $B \to \pi \ell \nu$ & V_{ub}

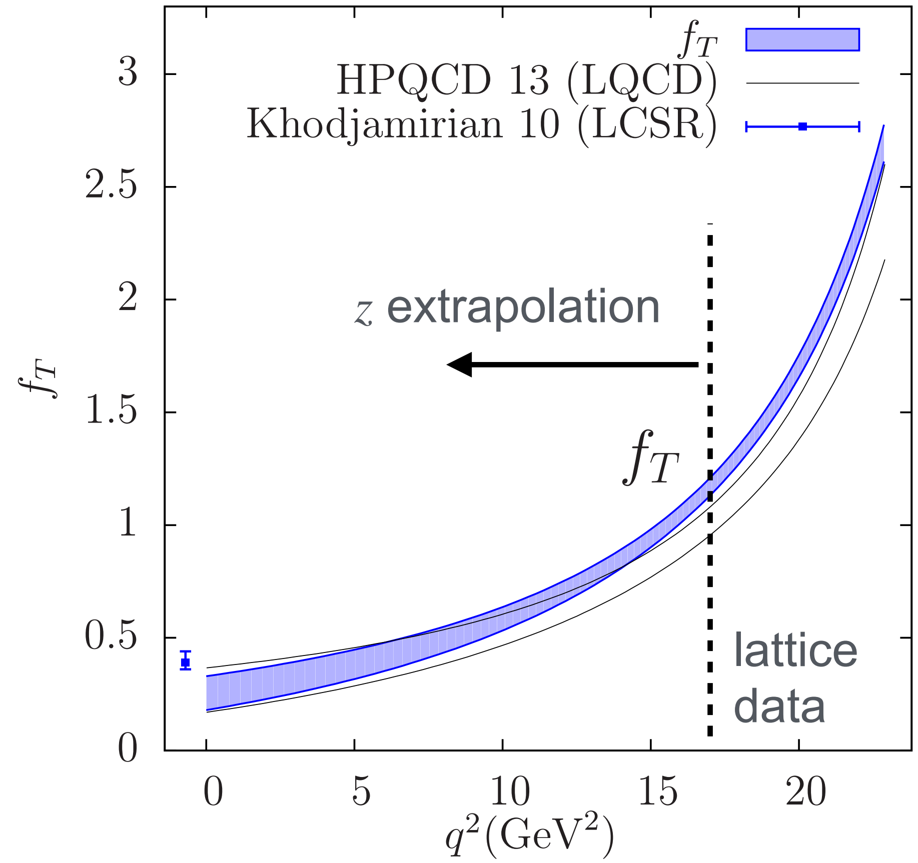


S. Aoki et al (FLAG-3 review, arXiv:1607.00299, 2017 EJPC)

- ☆ 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…

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





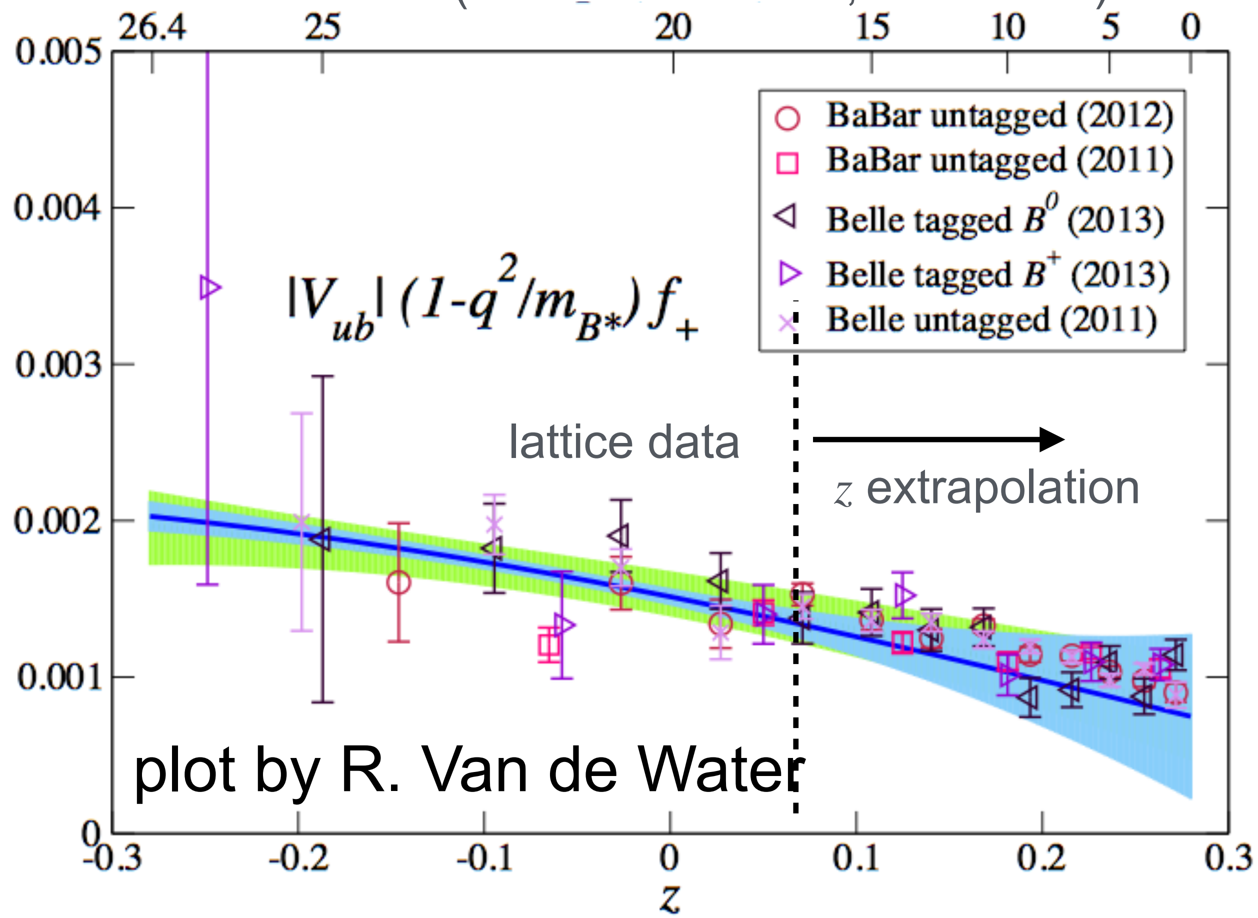
HPQCD (arXiv:1306.0434, 1306.2384, PRL 2013)

FNAL/MILC (arXiv:1509.06235, PRD 2016)

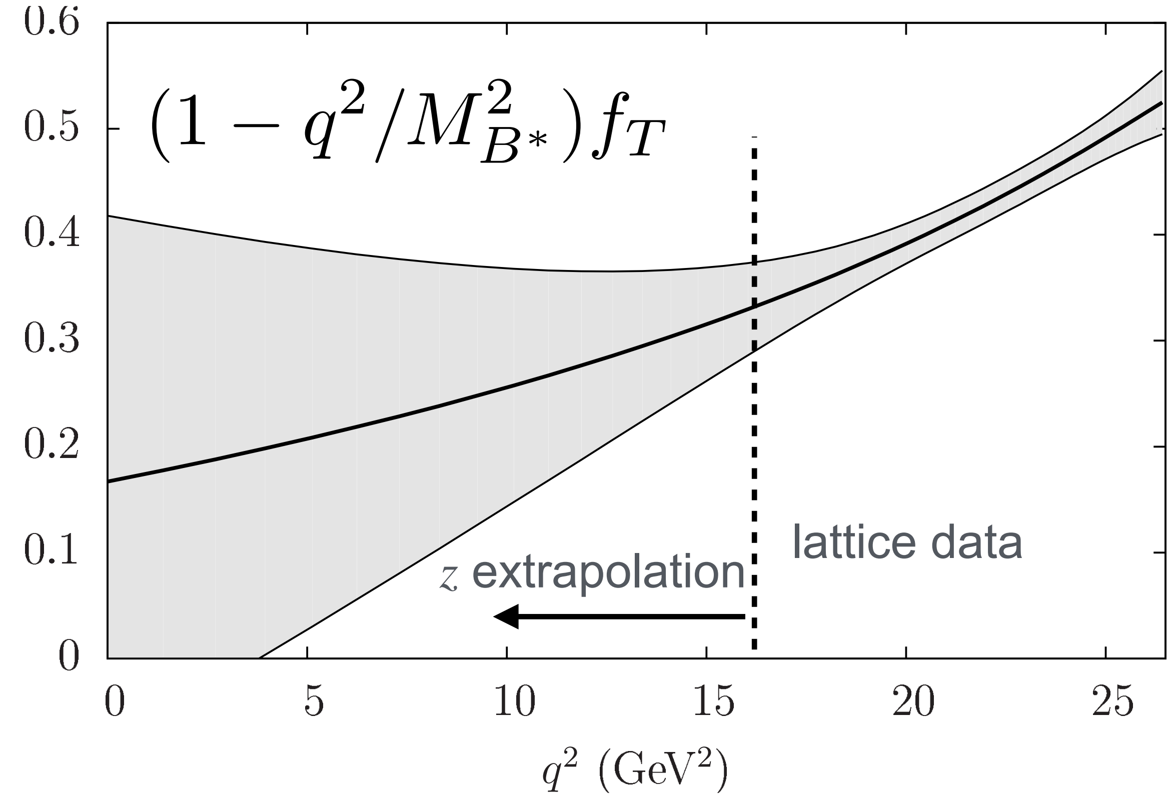
- Two LQCD calculations (on overlapping ensemble sets, different valence actions): HPQCD (NRQCD b + HISQ), FNAL/MILC (Fermilab b + asqtad)
- consistent results for all three form factors
- also consistent with LCSR (Khodjamarian et al, arXiv:1006.4945, JHEP 2010)
- Note: First LQCD calculation of $\Lambda_b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



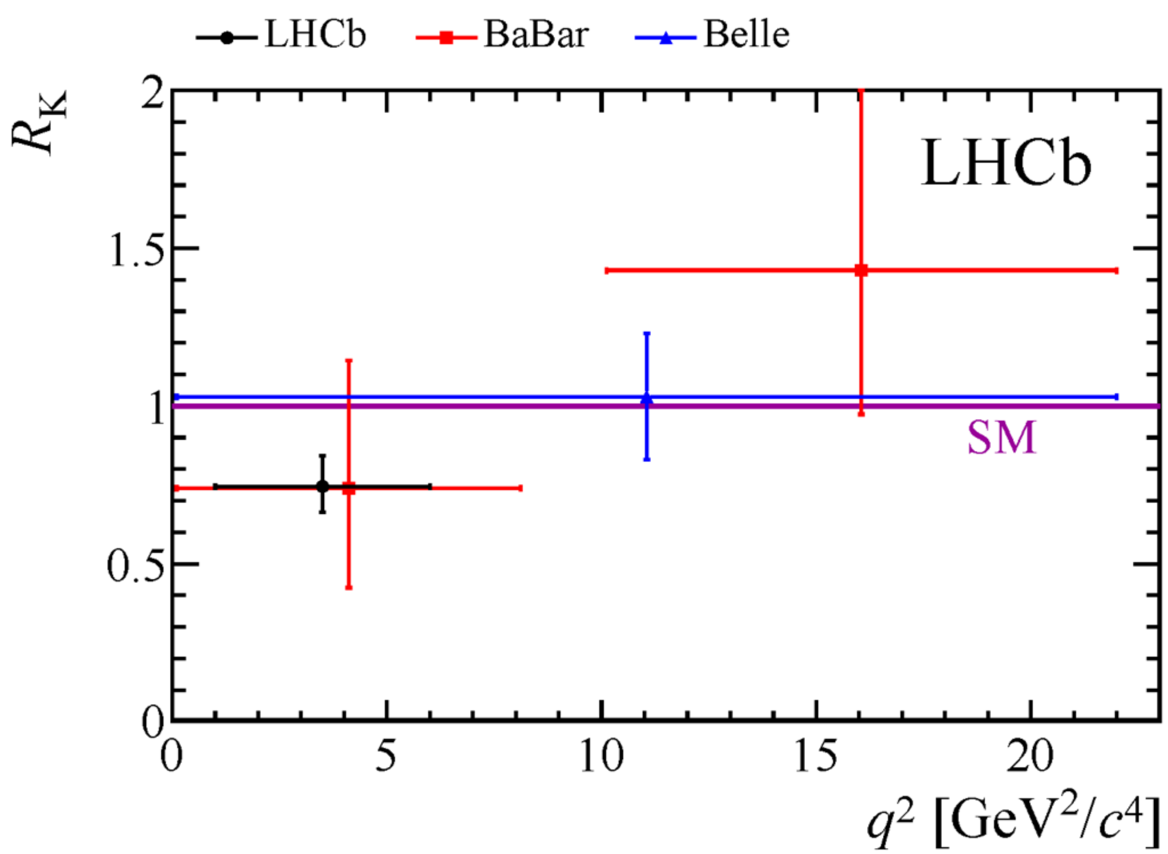
FNAL/MILC (arXiv:1507.01618, PRL 2015)



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

BSM phenomenology: LFU μ/e

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



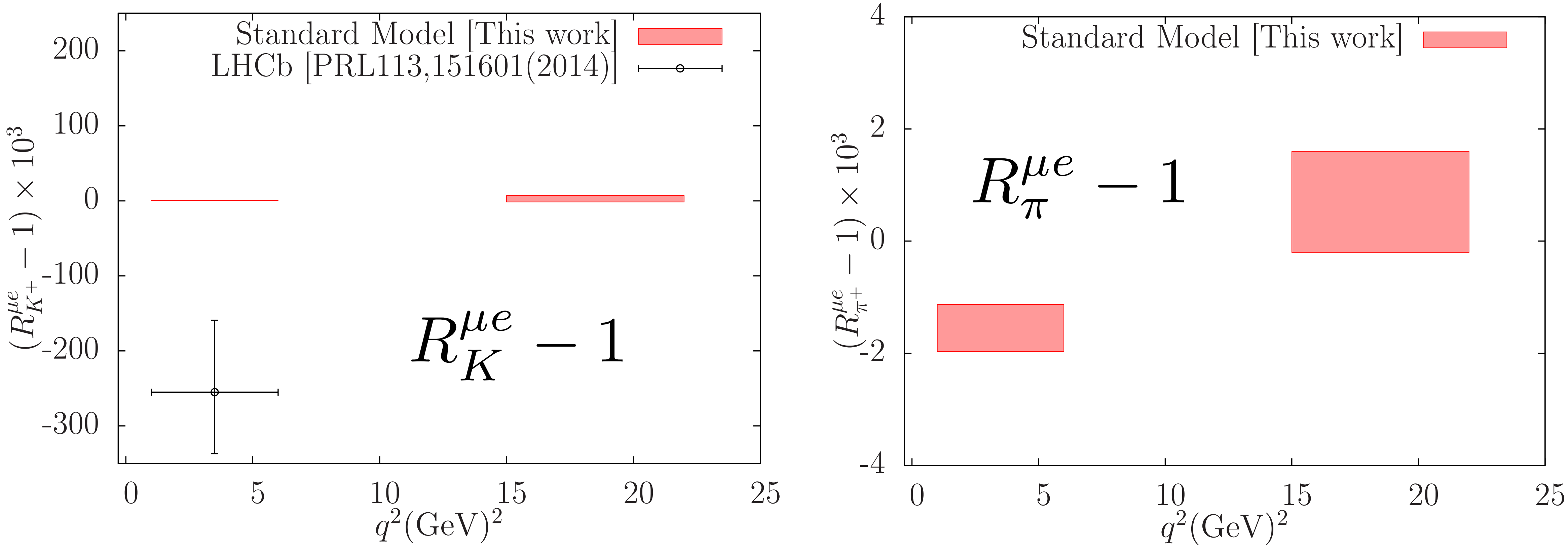
LHCb (arXiv:1406.6482, PRL 2014):

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

~2.6 σ 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)