SPC Flavor Summary

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USQCD All Hands Meeting
Jefferson Laboratory
Newport News, VA
April 28, 2017

Introduction

- Caveat: This has not been reviewed by the SPC, so please don't blame the rest of the SPC for anything you do not like.
- Goals:
  - Brief summary of 2017 B physics proposals
  - Discussion of some of the physics opportunities to pin down the CKM matrix, test the Standard Model, search for evidence of new physics

Proposals

- Determination of $|V_{cb}|$ from Semi-leptonic Decays $B \to D^{(*)} l \nu$ using the Oktay-Kronfeld Action; PI: Gupta, 26 M J-Psi core-hr
- Investigation of $B \to K \pi l^+ l^-$ Decays with Lattice QCD; PI: Leskovec, 18.9 M J-Psi core-hr
- Standard Model Parameters and the Search for Physics Beyond the Standard Model with HISQ; PI: Mackenzie, 87.4 M J-Psi core-hr + 5.7 M BG/Q core-hr
- Semi-leptonic B and B_s-decays with charming hadronic final state; PI: Soni, 17.6 M J-Psi core-hr
- The following slides will summarize the goals of each proposal.

Gupta

- ✦ Uses Oktay-Kronfeld heavy quark action for *b* and *c* quarks
- ✦ MILC HISQ ensembles: three lattice spacings and three values of pion mass at each lattice spacing.
- ✦ a=0.15, 0.12 fm done on local clusters. Time is for 250 configurations of a=0.09 fm m_l/m_s=0.1 and physical mass ensembles.
  - 2016 allocation used for m_l/m_s=0.2 ensemble
- ✦ Use truncated solver method
- ✦ Aim for 1.0% (1.1%) error for $B \to D^* l\nu$ ($B \to D l\nu$) form factors. Currently, 1.4% (1.2)%.
- ✦ More about $|V_{cb}|$ later…

Leskovec

- Studying rare flavor changing neutral current decay $B \to K \pi l^+ l^-$ in region of $K^*(892)$
- Uses 2+1 flavor dynamical clover ensemble with a=0.114 fm and m_π=317 MeV
- LHCb found anomalous angular dependence at low q^2.
- Sensitive probe of beyond standard model physics.
- Previously K^* treated as a stable particle
- Use one large volume ($32^3 \times 96$) and several moving frames
- Continuation: about 285 configurations will be analyzed this year. Would like to get to 800 with new allocation.

Mackenzie

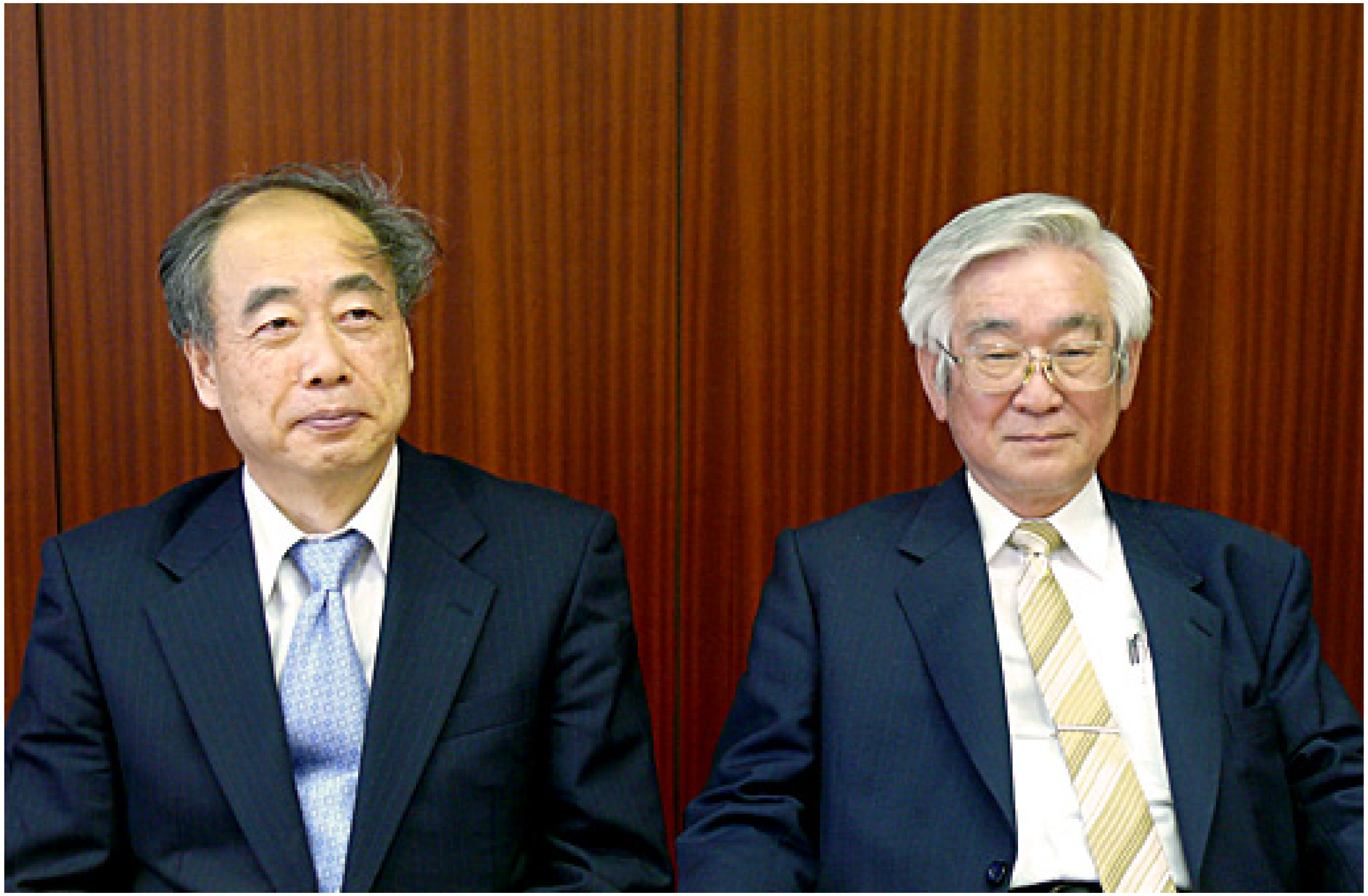
- Use 2+1+1 flavor HISQ ensembles; HISQ light valence quarks, Wilson/clover (w. FNAL interp.) *b,c* quarks; *c* quarks treated with HISQ as well for some projects
- Six lattice spacings: a≈0.15, **0.12, 0.09**, 0.06,0.042, 0.03 fm
- Physical light quark mass except for 0.03 fm ensemble
- Test CKM unitarity with broad range of decays:
  - $B\to\pi\, l\, \nu$, $B\to D^{(*)}\, l\, \nu$, $B_s\to D_s^{(*)}\, l\, \nu$, $K\to\pi\, l\, \nu$, $D\to\pi(K)\, l\, \nu$
  - neutral B meson mixing
  - $B\to\tau\, \nu$, $B\to D^{(*)}\, \tau\, \nu$, $B\to K^{(*)}\, l^+ l^-$
  - Decay constants for pseudoscalar and vector mesons
  - charm and bottom quark masses, α_s
- Aim for better precision than asqtad results

Soni

- Using Mobius domain-wall 2+1 flavor ensembles
- Seven ensembles with 0.114 fm > a > 0.711 fm, one with physical mass pion
- Relativistic heavy quark (RHQ) action
- $B \to D^{(*)}$ l ν, $B_s \to D_s^{(*)}$ l ν to determine $|V_{cb}|$
- Light and strange quark propagators are already archived.
- Will run on two $48^3 \times 96$ ensembles with a=0.11 and 0.07 fm, with pion mass 138 and 234, respectively.
  - Three other ensembles already analyzed.
- Will later compute B meson mixing, & decay constants

Kobayashi & Maskawa

- Won 2008 Nobel prize for realization that with three (or more) generations can have CP violation, which might explain baryon asymmetry of Universe.



KEK photo from nobelprize.org

CKM Matrix

✦ Some relevant processes listed under each element

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

CKM Matrix II

- CKM matrix is unitary.
  - Each row and column is a (complex) unit vector.
  - Each row (column) is orthogonal to the other rows (columns).
- Violations of unitarity are evidence of non-standard model physics.
- If two different processes are used to determine an element of the matrix and they do not agree, that is evidence for new physics.
- LQCD input for decay constants and form factors is needed to determine elements of CKM matrix

$$\mathcal{B}(D_{(s)} \to \ell\nu_\ell) = \frac{G_F^2 |V_{cq}|^2 \tau_{D_{(s)}}}{8\pi} f_{D_{(s)}}^2 m_\ell^2 m_{D_{(s)}} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2$$

First Row: Light Quarks

- ✦ Processes involving only light quarks test first row unitarity

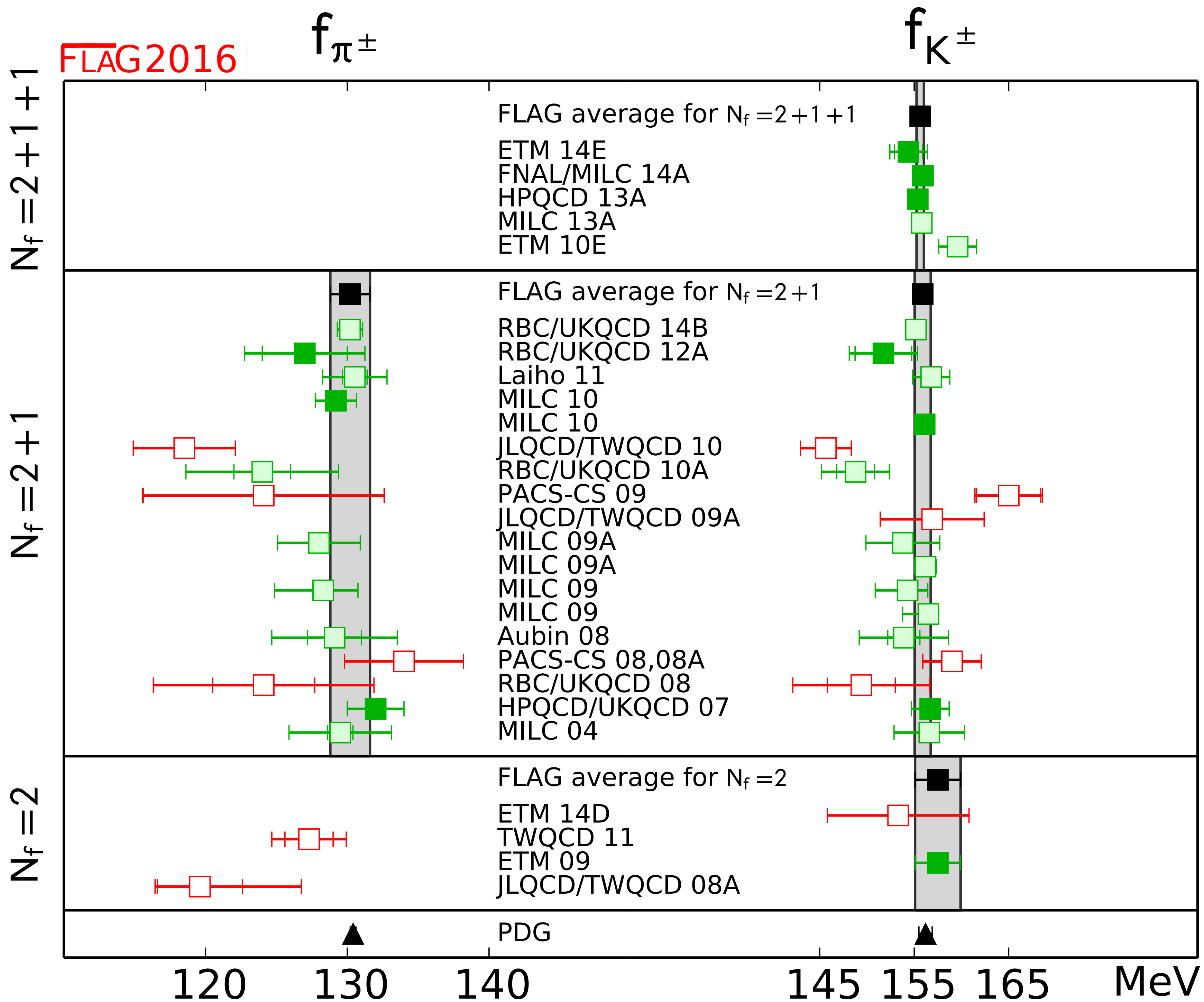
$$
\begin{pmatrix}
\mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\
\pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\
 & K \to l\nu & \\
\mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\
D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\
D \to l\nu & D_s \to l\nu & \\
\mathbf{V_{td}} &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

leptonic ($\pi \to l\nu$, $K \to l\nu$)

semileptonic ($K \to \pi l\nu$)

f_π and f_K

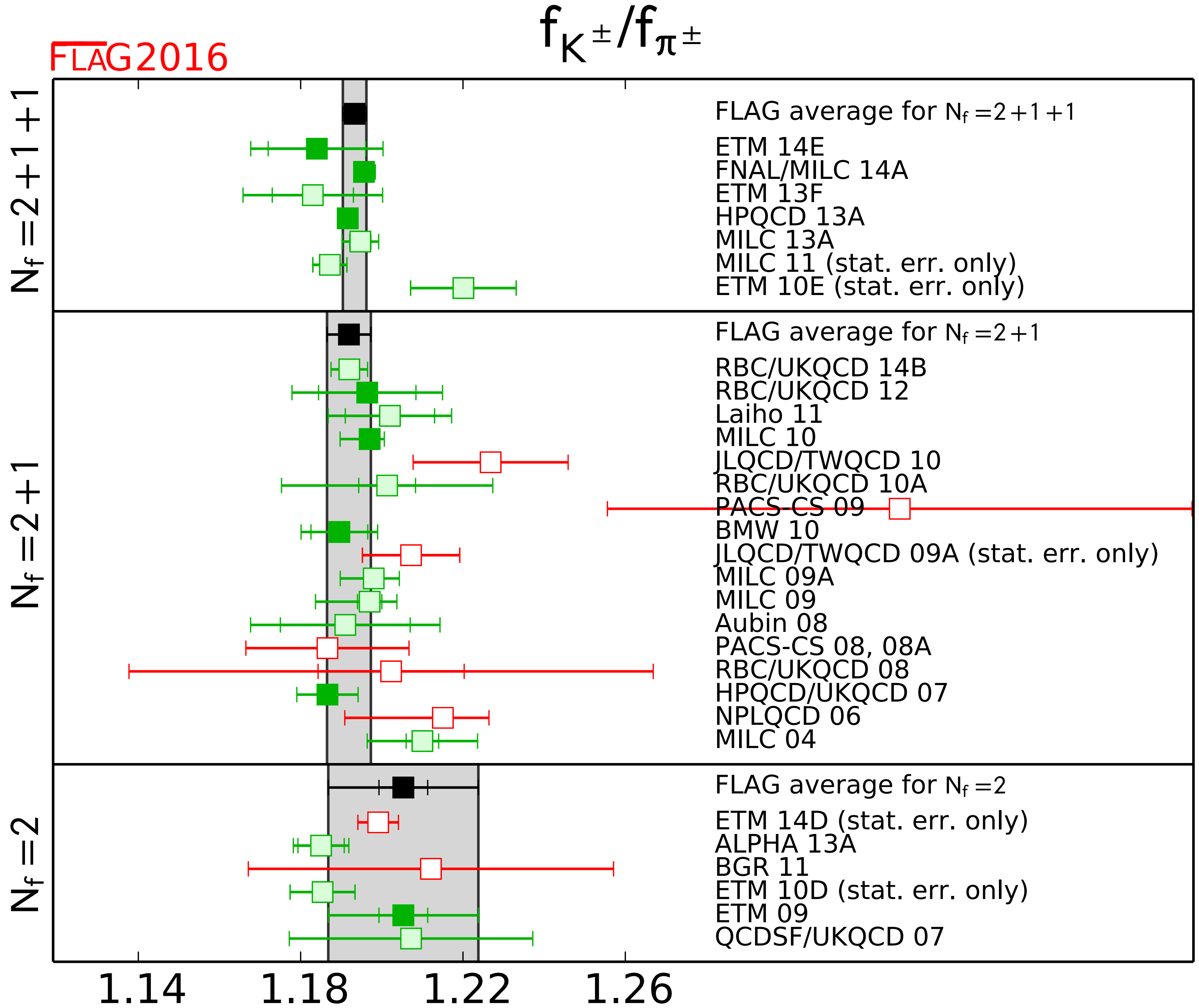
- Light decay constants as summarized by FLAG
- Some calcs. use f_π to set the scale so fewer results on left
- Ratio of decay constants is easy to calculate and used to test unitarity



f_π/f_K

- Light decay constant ratio summarized by FLAG
- From experimental measurement:

$$\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_{K^\pm}}{f_{\pi^\pm}} = 0.2758(5)$$



K semileptonic decay

- Semileptonic decays have three-body final states, so there is one kinematic variable, usually denoted q^2 , which is momentum transfer to the leptons.

$$p_K = p_\pi + q_\ell + q_\nu$$

$$q = q_\ell + q_\nu$$

- To extract $|V_{us}|$ we just need $f_+(0)$ as experiment tells us

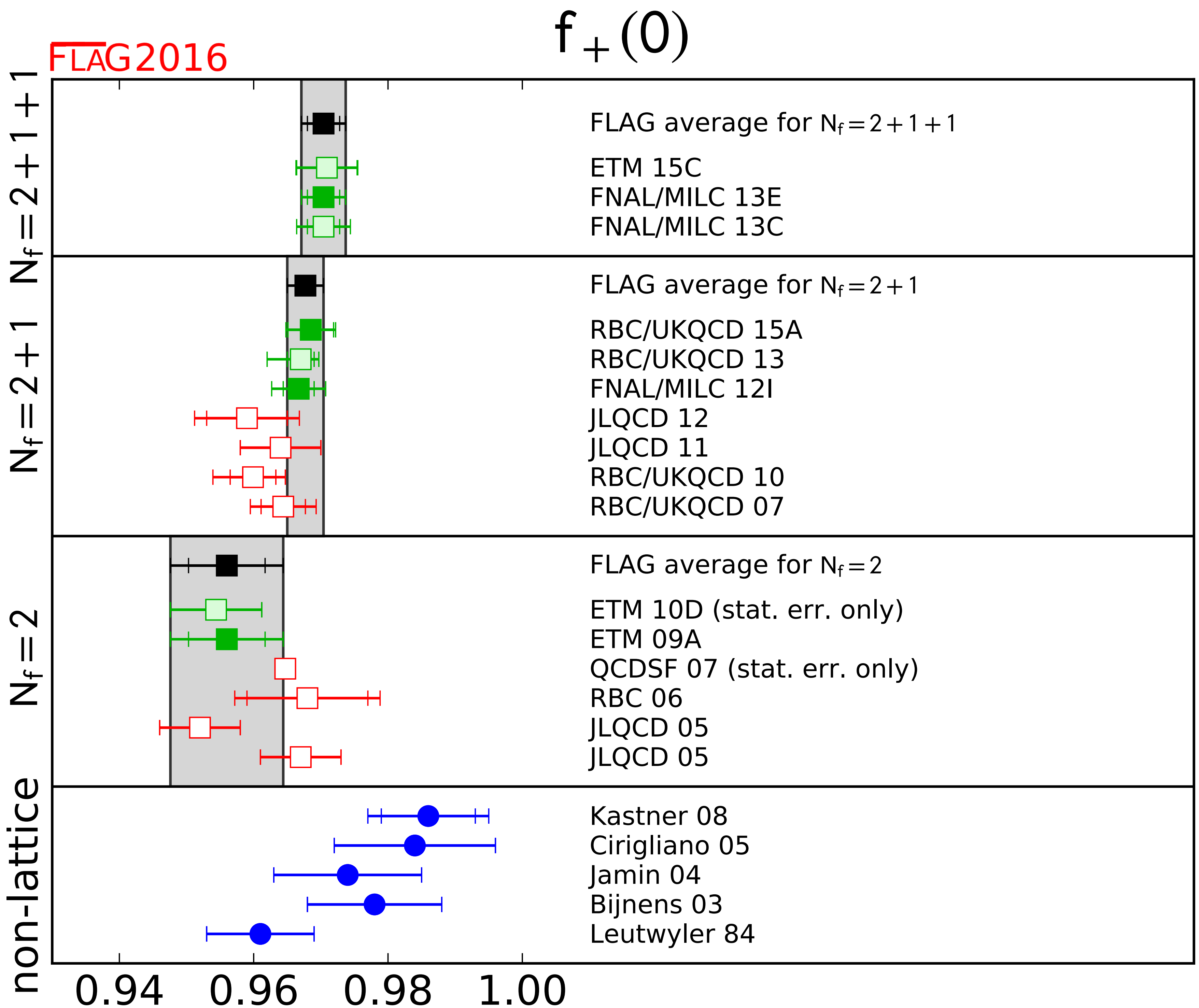
$$|V_{us}|f_+(0) = 0.2163(5)$$

- From FNAL/MILC with 2+1+1 flavors PRL 112, 112001 (2014), arXiv:1312.1228 (0.34 % error)

$$f_+(0) = 0.9704(24)(22)$$

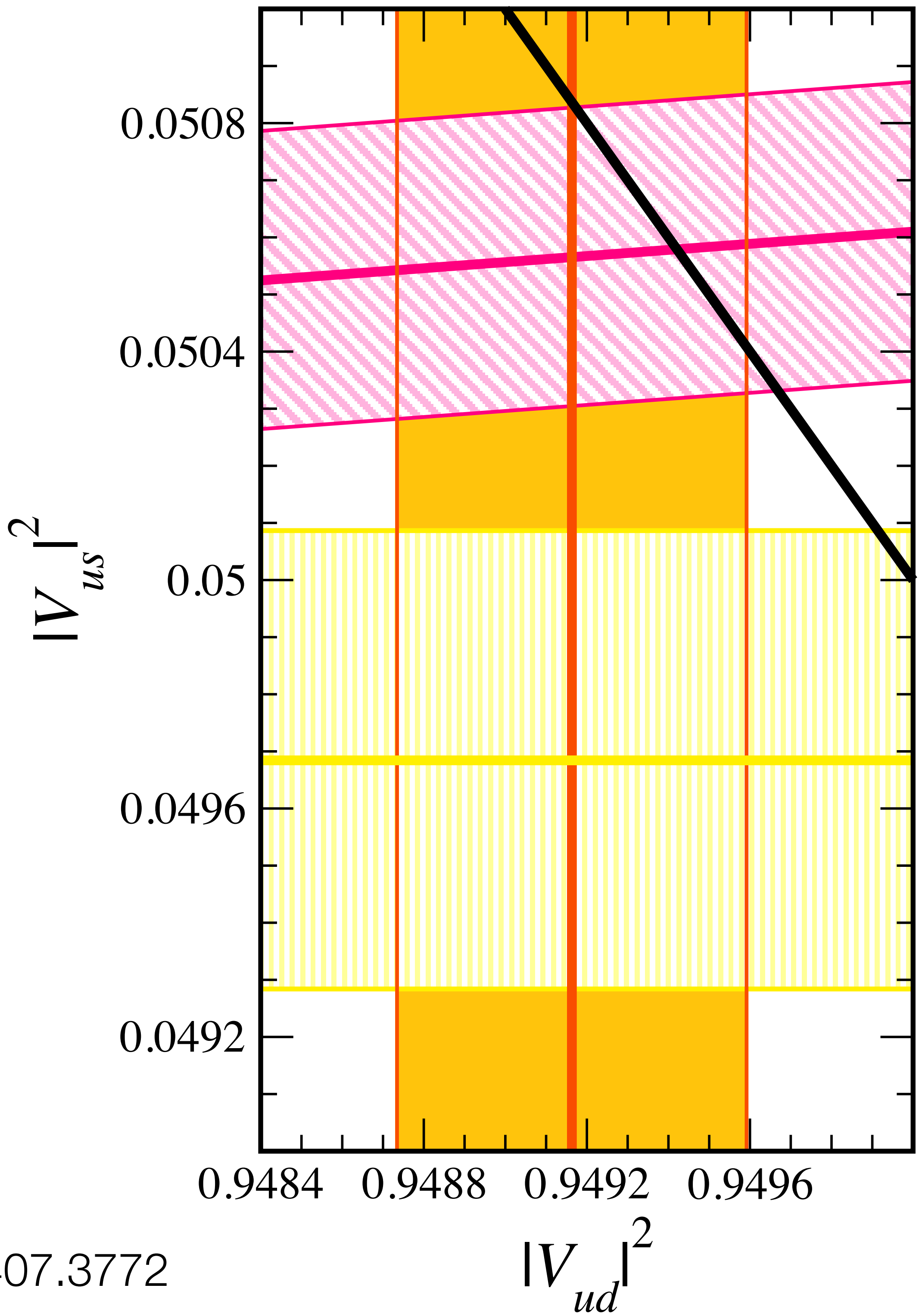
$f_+(0)$ for Kaon Decay

- FLAG averages for Kaon decay constant at q^2=0
- Only one value for N_f=2,2+1+1
- Two values for N_f=2
- Next, we look at unitarity test



First Row Unitarity Test

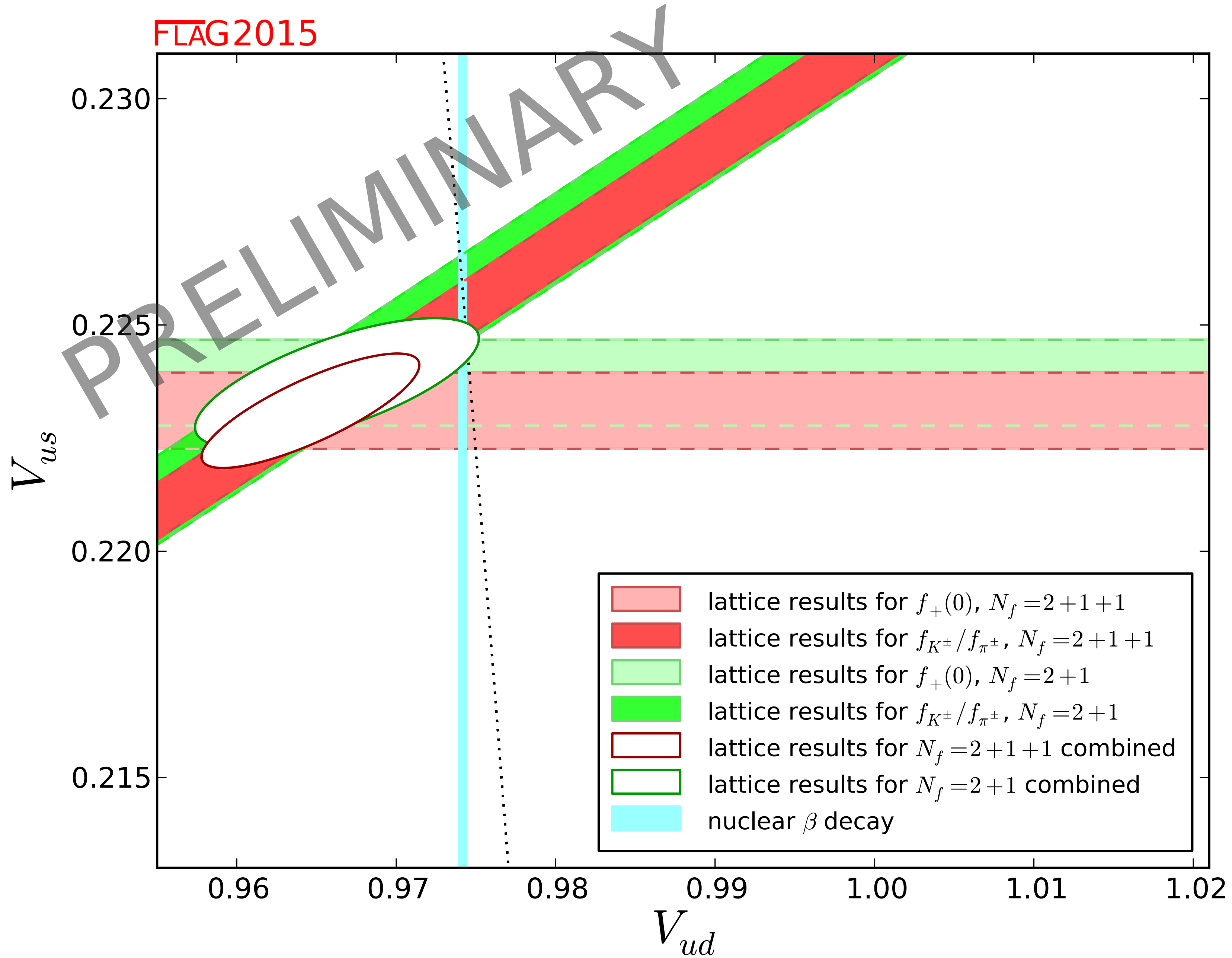
- Black line is unitarity
- Vertical band is from nuclear β decay (LQCD independent)
- Angled band is from leptonic decays
- Horizontal band is from semileptonic K decay
- Some tension between the two types of decay for 2+1+1.
- Can we reduce semileptonic error? 1611.04188



FNAL/MILC, Phys.Rev. D90 (2014) 7, 074509 arXiv:1407.3772

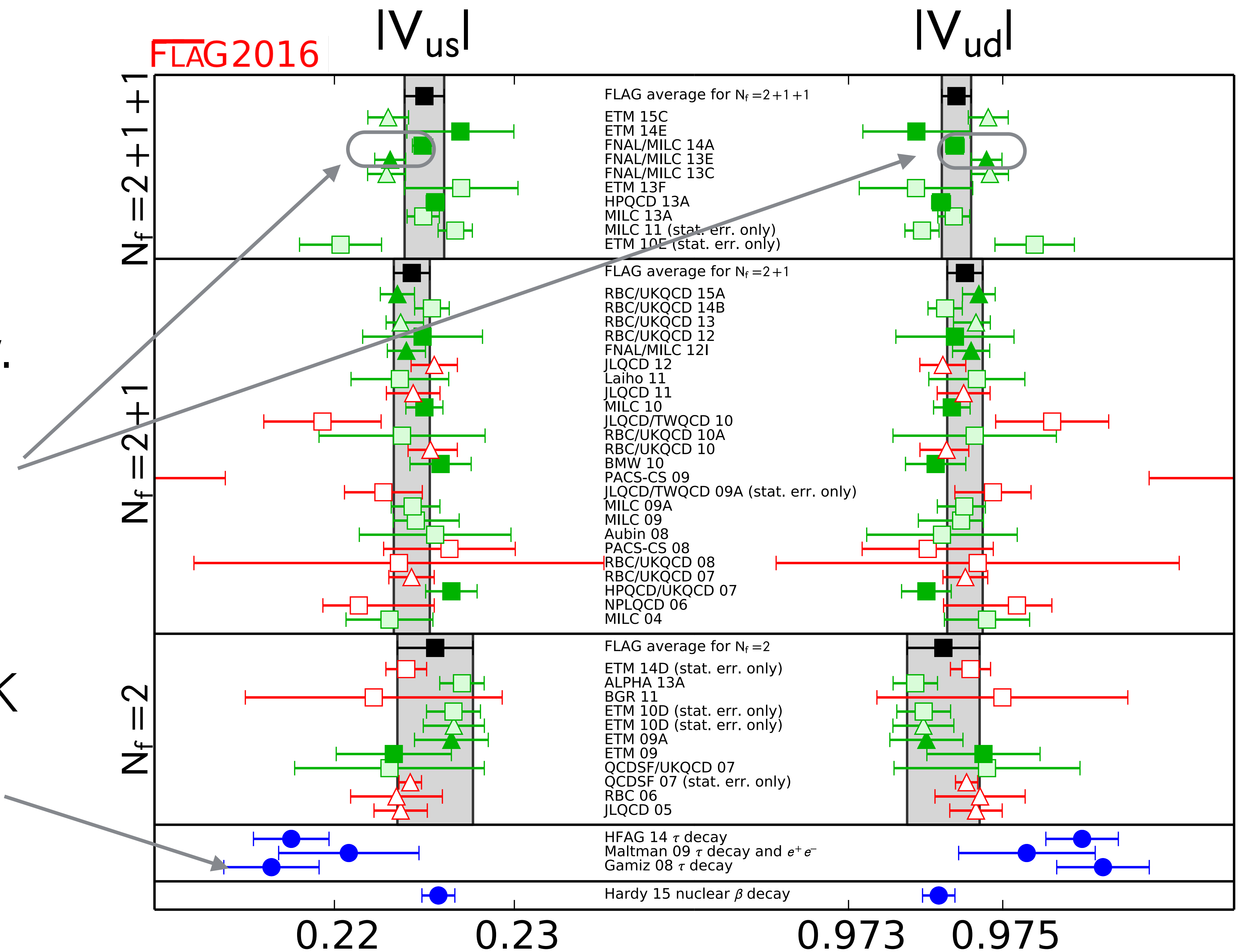
First Row Unitarity (FLAG)

- Preliminary FLAG3 results for 2+1 and 2+1+1 flavors
- Matrix elements not squared here
- Dotted line is unitarity
- 2+1 flavors has larger error and consistent with unitarity



$|V_{us}|$ & $|V_{ud}|$ Summary

- plot from FLAG
- squares leptonic
- triangles semileptonic
- good agreement w. 2+1 flavors, some tension for 2+1+1
- note tension between τ decay results and π and K decays



Second Row: Charm Quark

- ✦ Processes involving charm quark test second row unitarity

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

leptonic (→ $D \to l\nu$, $D_s \to l\nu$)

semileptonic (→ $D \to \pi l\nu$, $D \to K l\nu$, $B \to D^{(*)} l\nu$)

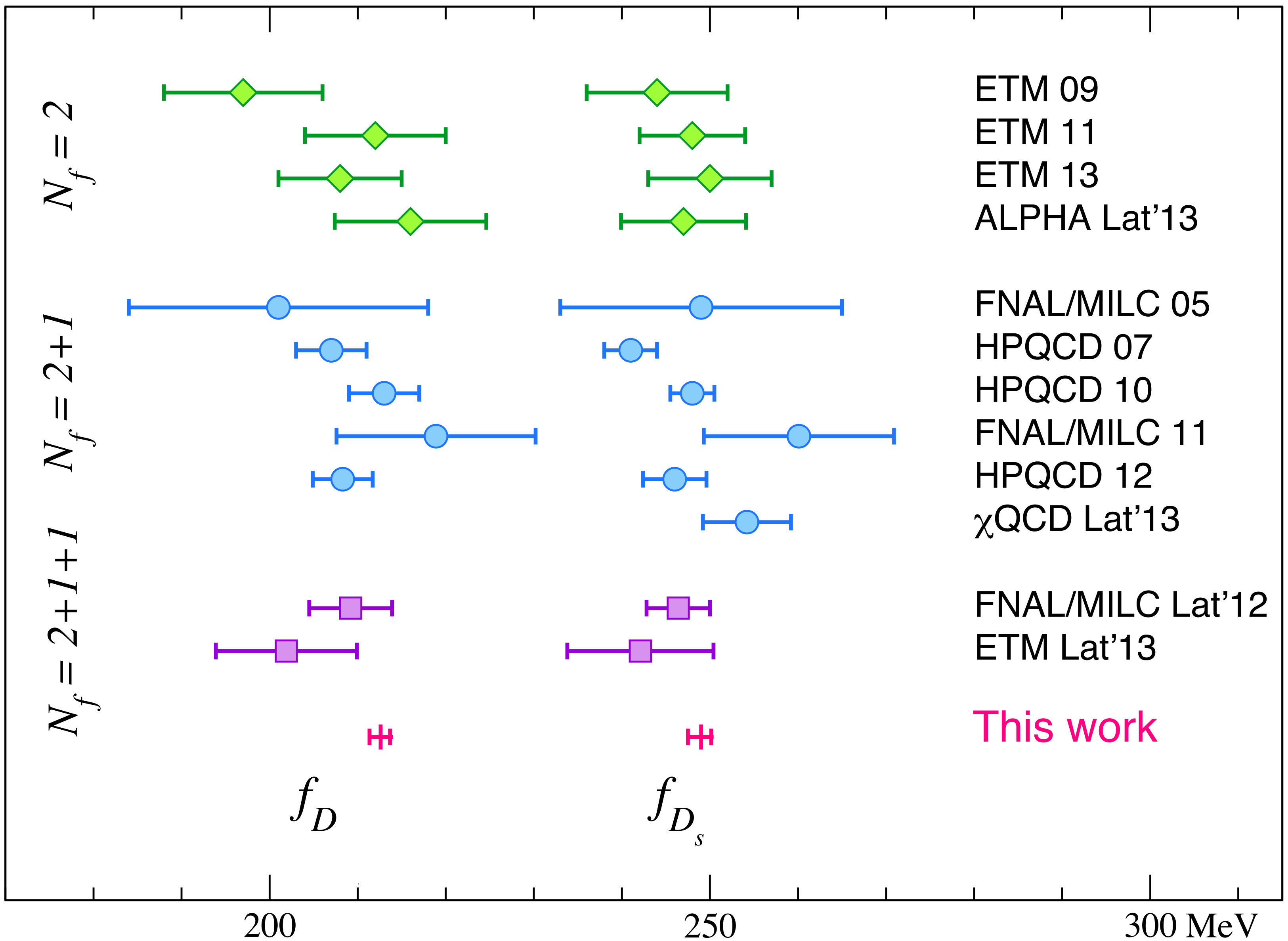
Charm Decay Constants

- Note improvement of precision from initial 2005 2+1 flavor results to current 2+1+1 flavor results.

$$f_{D^+} = 212.6(0.4)(^{+1.0}_{-1.2})\ \mathrm{MeV}$$

$$f_{D_s} = 249.0(0.3)(^{+1.1}_{-1.5})\ \mathrm{MeV}$$

- FLAG3 averages should be quite similar with slightly smaller errors

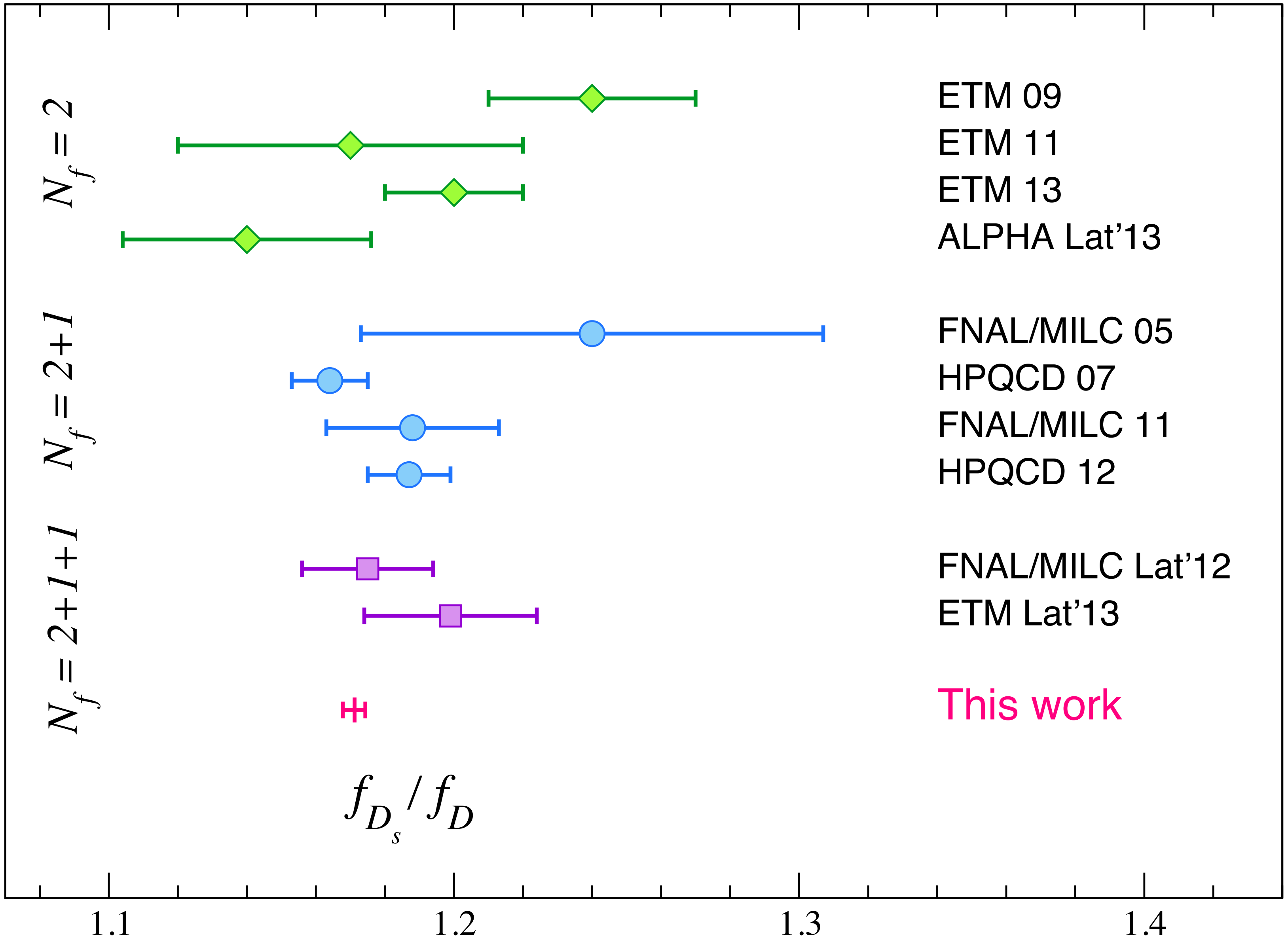


FNAL/MILC, Phys.Rev. D90 (2014) 7, 074509 arXiv:1407.3772

Charm Decay Constant Ratio

- Once again, note remarkable improvement over the past decade

$$f_{D_s}/f_{D^+} = 1.1712(10)(^{+29}_{-32})$$



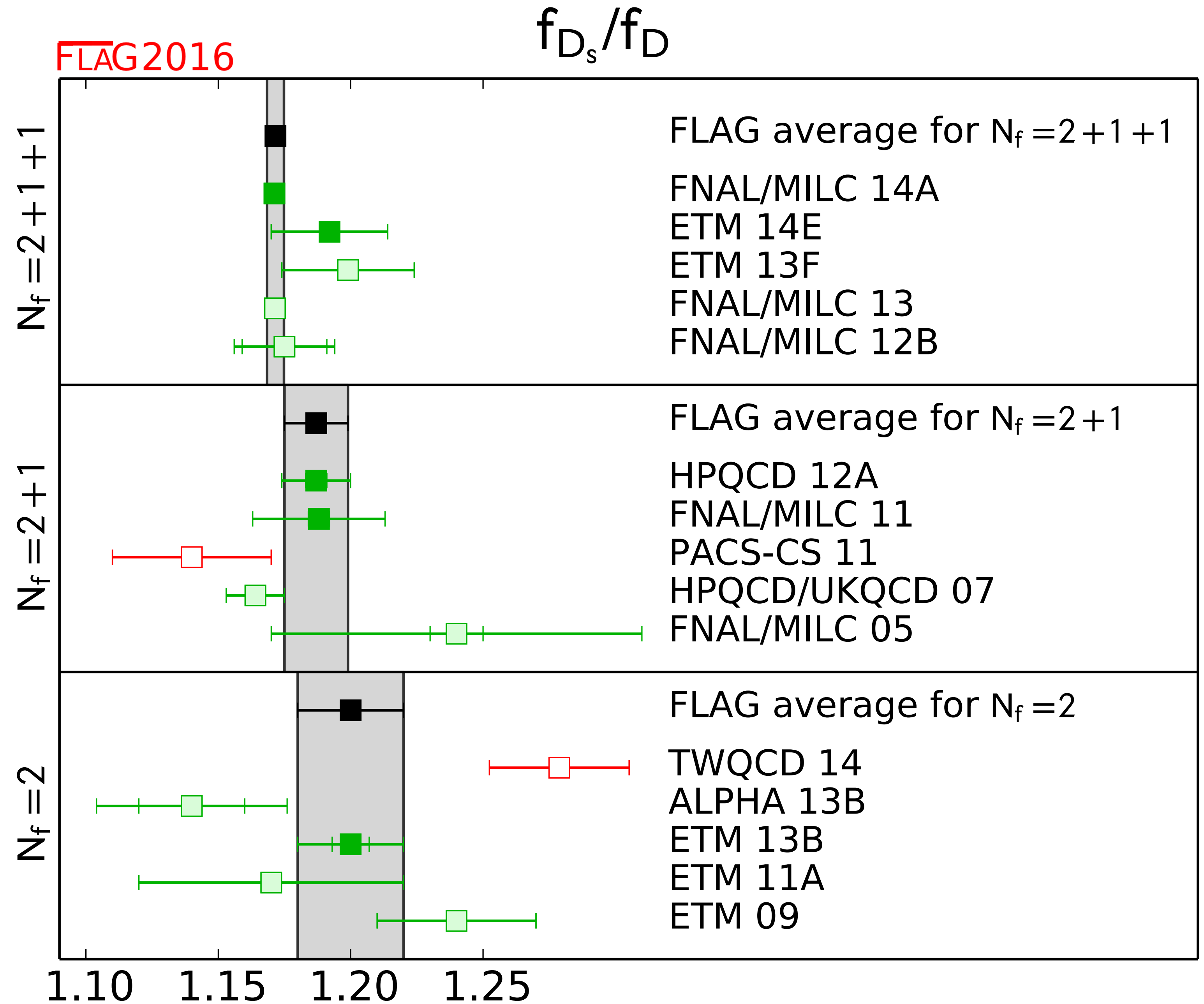
FNAL/MILC, Phys.Rev. D90 (2014) 7, 074509 arXiv:1407.3772

FLAG Charm Decay Constant Ratio

- Once again, note remarkable improvement over the past decade

$$f_{D_s}/f_{D^+} = 1.1712(10)(^{+29}_{-32})$$

- FLAG 1.1716(32) for 2+1+1 flavors



Extraction of V_{cd} & V_{cs}

- The experimental results for charm meson leptonic decays are summarized by the Heavy Flavor Averaging Group (HFAG):

$$f_D|V_{cd}| = 46.40(1.98)\mathrm{MeV}, \qquad f_{D_s}|V_{cs}| = 253.1(5.3)\mathrm{MeV}$$

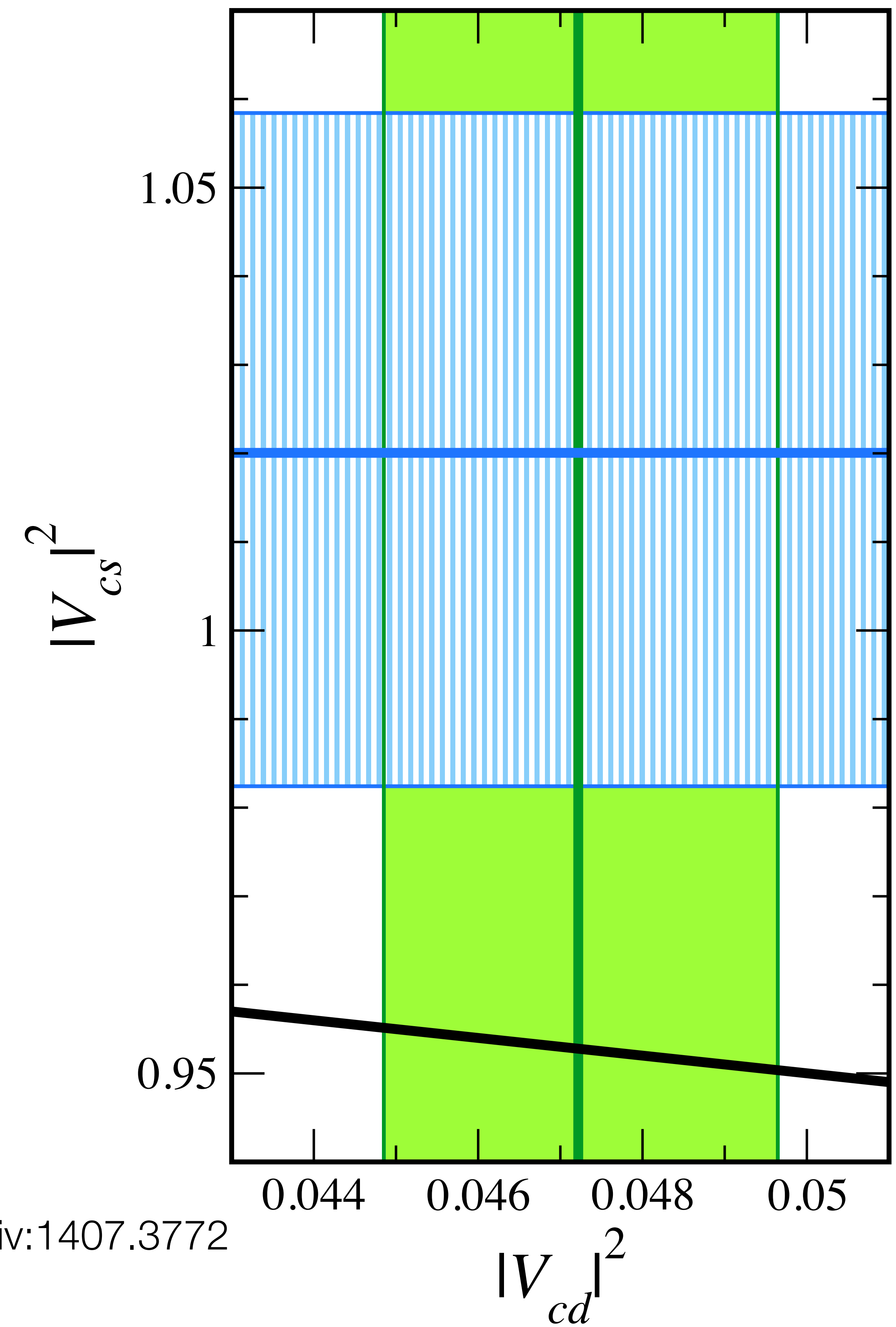
- Experimental error is 2.1-4.3%.
- Using decay constants from LQCD, we get CKM matrix elements:

$$|V_{cd}| = 0.217(1)(5)(1), \quad |V_{cs}| = 1.010(5)(18)(6)$$

- Errors are lattice, experiment, and structure dependent electromagnetic, respectively.

Second Row Unitarity

- Black line is unitarity
- Horizontal blue band is D_s leptonic decay
- Vertical green band is D^+ leptonic decay
- Note the ≈1.8 σ tension with unitarity
- Fajfer et al,. PRD91, (2015) 094009 bound new physics
- Fewer results for semileptonic D meson decays
- Expt. error dominant now.



FNAL/MILC, Phys.Rev. D90 (2014) 7, 074509 arXiv:1407.3772

D semileptonic result

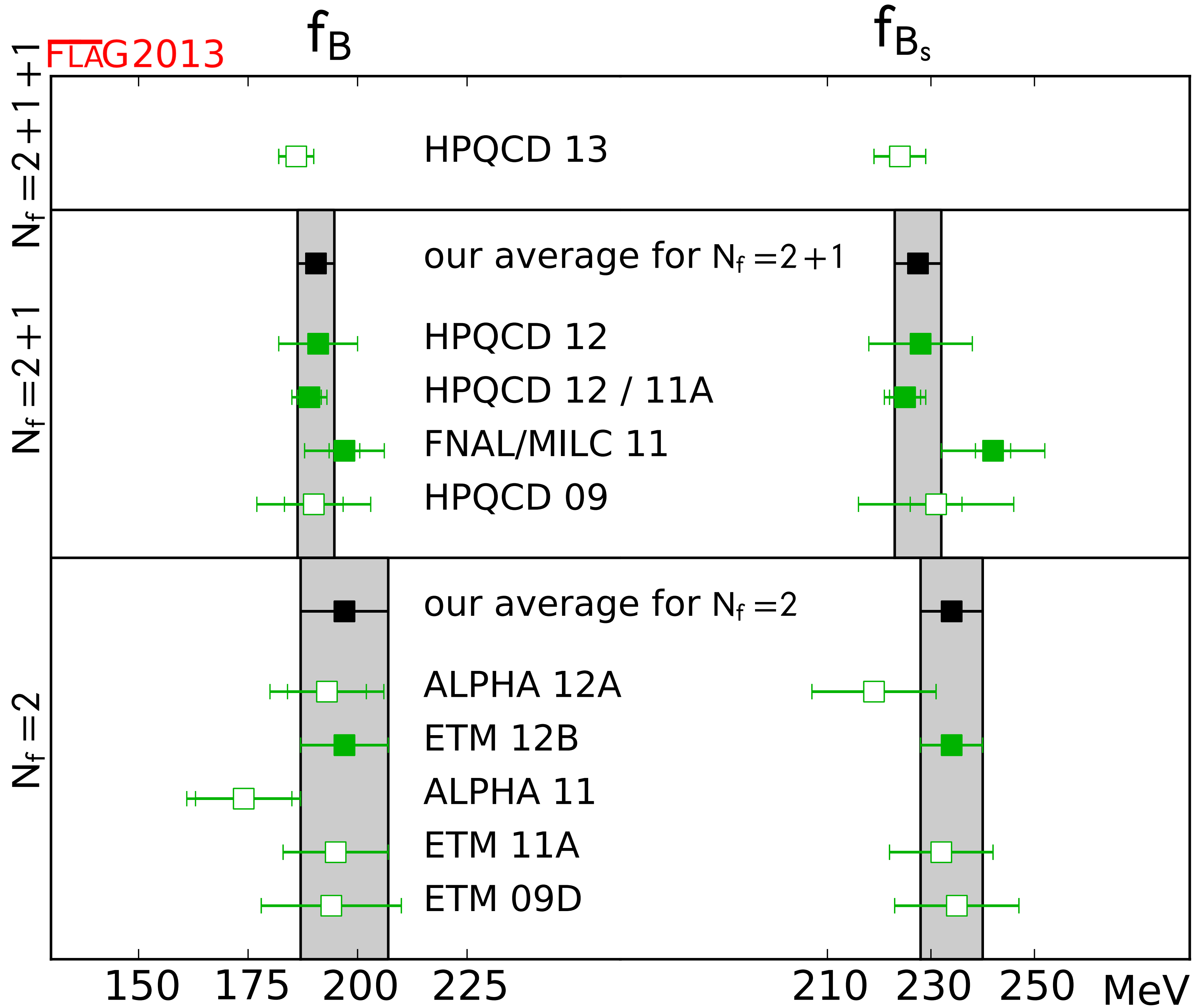
- Interestingly, there is a new BaBar paper, PRD91, 052022(2015), on semileptonic D decay that uses HPQCD result.
- It yields $|V_{cd}| = 0.206 \pm 0.007_{\rm exp} \pm 0.009_{\rm LQCD}$.
- Adding errors in quadrature 0.206 (11) compared with our leptonic decay result of 0.217(5).
- Their central value is two of our sigma below our result, but our result is only one of their sigmas high.

B Meson Decays

- ✦ Leptonic and semileptonic decays studied in LQCD
- ✦ Rare decays involving flavor changing neutral currents (FCNC) also studied
  - FCNC vanish at tree level in Standard Model, so a good place to look for new physics
  - Some tension between recent SM prediction from LQCD and LHCb measurements
  - Alternative to B meson mixing for determining $|V_{td}|$ and $|V_{ts}|$

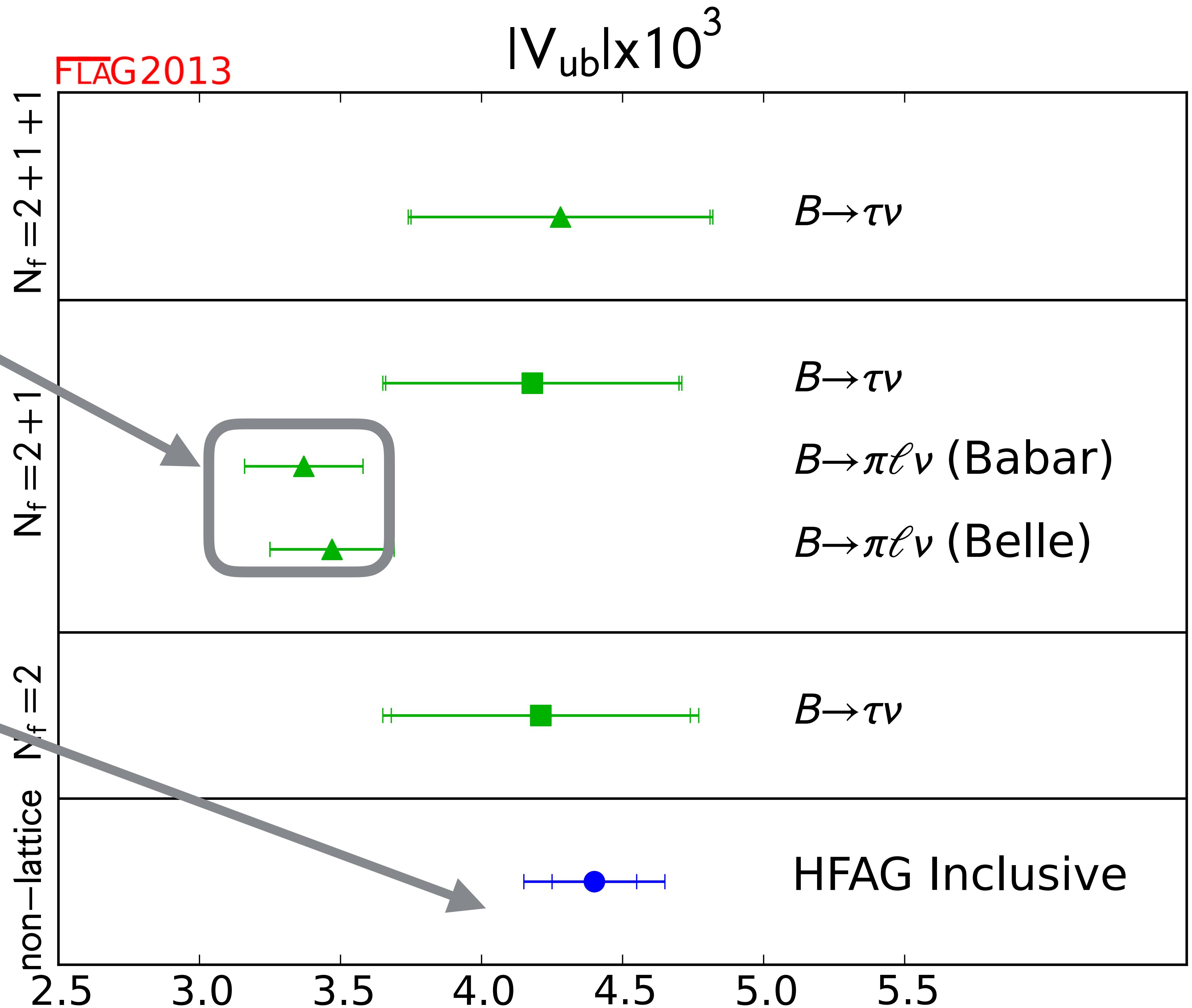
B Meson Leptonic Decays

- FLAG3 will have only minor updates to these results
  - RBC/UKQCD 2+1
  - ETM 2+1+1 (plotted)
  - both have large errors
- For 2+1 and 2+1+1 flavors errors about 2%
- f_B=190.5(4.2) MeV, f_{Bs}=227.7(4.5) MeV for 2+1 flavors (2013)



|Vub| from FLAG2

- Large errors for leptonic decays from experiment (25%)
- Semileptonic decays give smaller value
- Tension between exclusive and inclusive results
- Plot from T. Vladikas arXiv:1509.01155
- Belle II will improve B→τν measurement (5% error expected)



Exclusive B Decay Update

- FNAL/MILC updated form factors for semileptonic decays PRD 92, 014024 (2015),arXiv:1503.07839
- FLAG:

$$|V_{ub}| = 3.37(21) \times 10^{-3}, \quad N_f = 2+1; \mathrm{BaBar}$$

$$|V_{ub}| = 3.47(22) \times 10^{-3}, \quad N_f = 2+1; \mathrm{Belle}$$

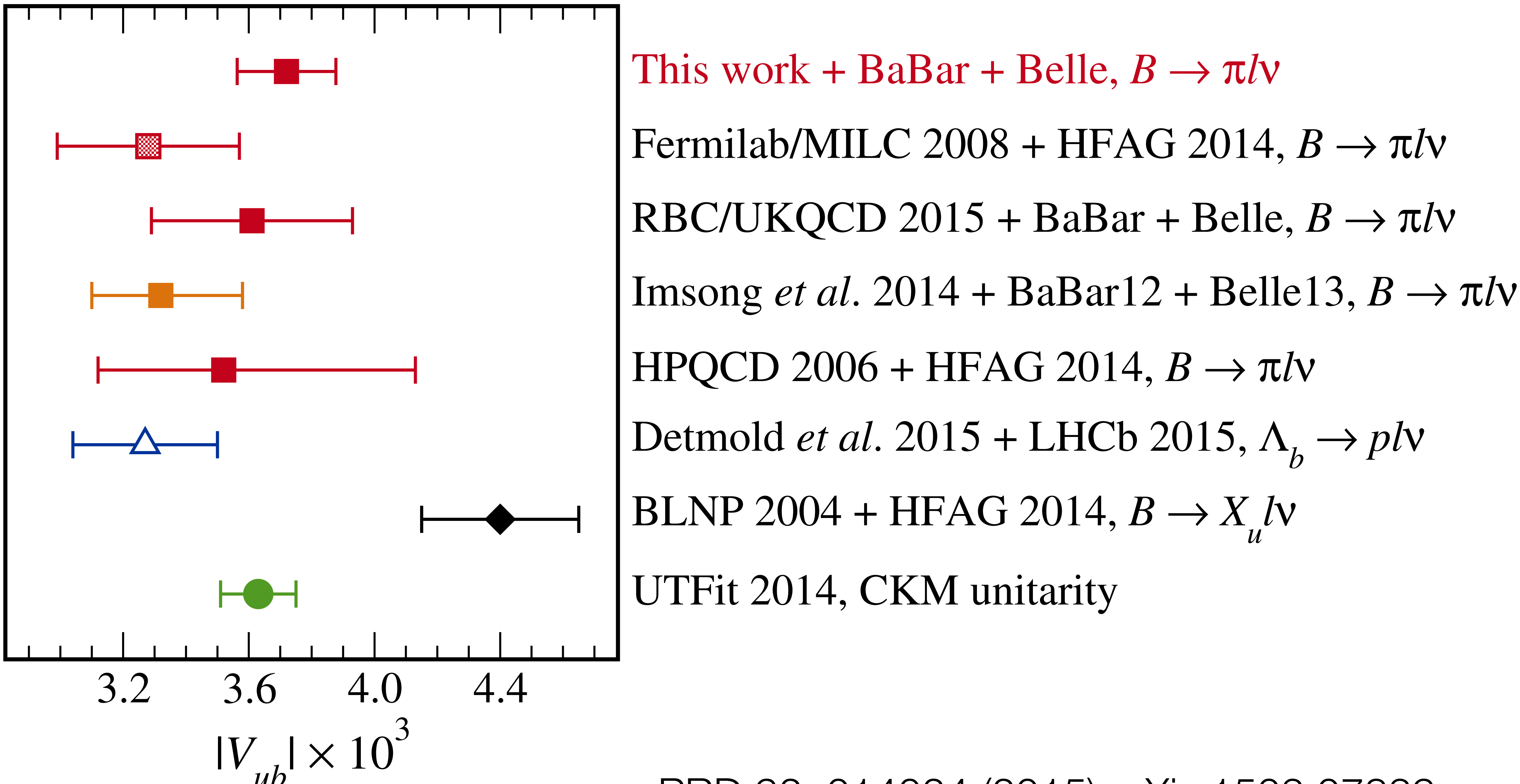
- New FNAL/MILC result

$$|V_{ub}| = 3.72(16) \times 10^{-3}, \quad N_f = 2+1; \mathrm{BaBar\&Belle}$$

- This result decreases, but does not eliminate tension between exclusive and inclusive results.
- Next slide also includes Lambda baryon decay result

Updated Semileptonic $|V_{ub}|$

Lattice error now comparable to experimental error.



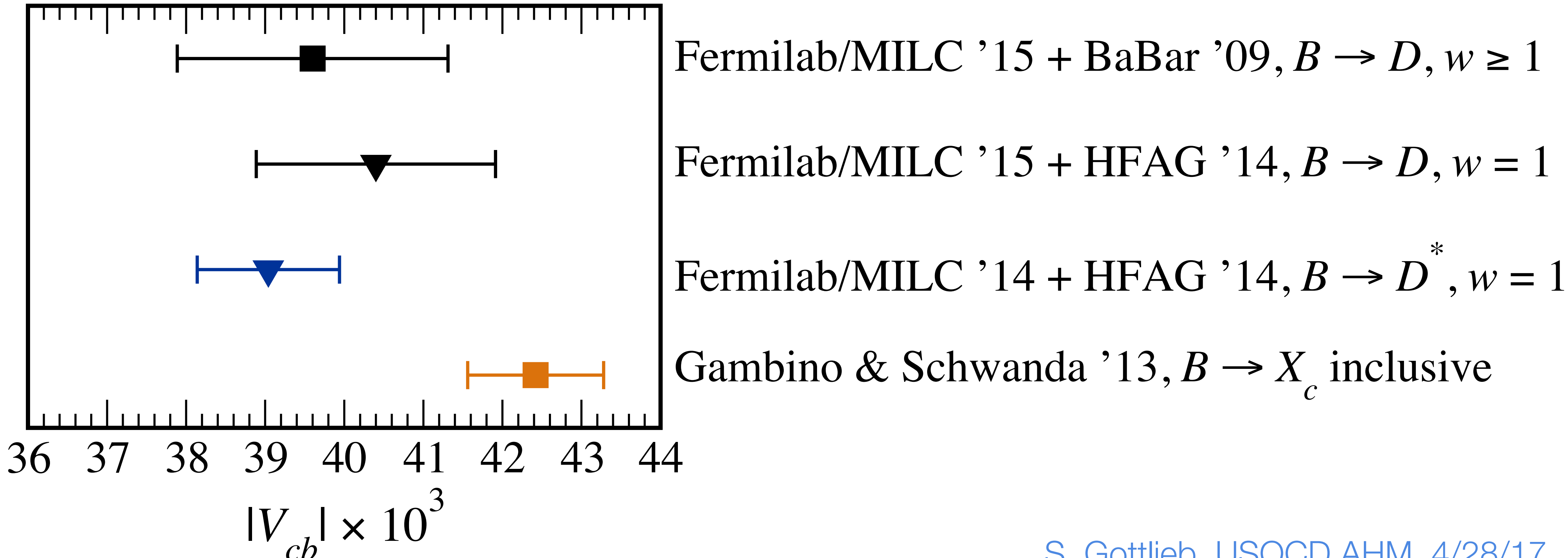
PRD 92, 014024 (2015),arXiv:1503.07839

$|V_{cb}|$

- Exclusive calculations of $B \to D^* l \nu$ and $B \to D l \nu$ yield V_{cb}
- Experimental error dominant for $B \to D l \nu$ (3.9% vs 1.4%)
- Again, tension between exclusive and inclusive results

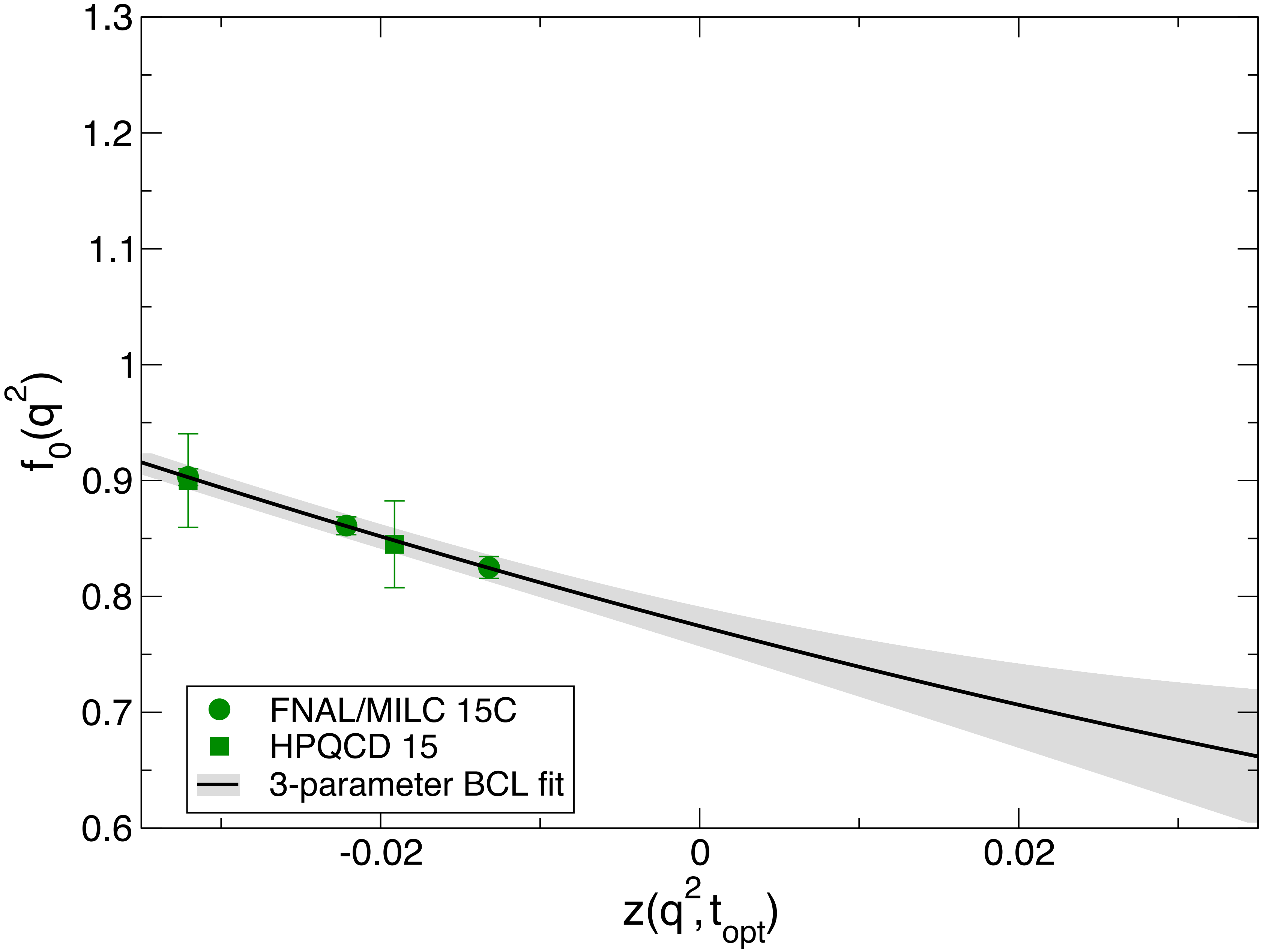
PRD 92, 034506 (2015), arXiv:1503.07237 [hep-lat]

- But two exclusive decay modes consistent



B→D l ν form factor

- Two results with 2+1 flavors both on MILC asqtad ensembles.



V_{ub} and V_{cb}: exclusive vs inclusive

uses CLN parametrization

[Caprini, Lellouch, Neubert 9712417]

- **Exclusive:**

  $|V_{ub}|_{B\to\pi\ell\nu} = 3.73(14)\times 10^{-3}$ [FLAG]

  $|V_{ub}|_{B\to\tau\nu} = 4.33(72)\times 10^{-3}$ [PDG+FLAG]

  $|V_{cb}|_{B\to D\ell\nu} = 40.1(1.0)\times 10^{-3}$ [FLAG]

  ← $|V_{cb}|_{B\to D^*\ell\nu} = 39.27(56)(49)\times 10^{-3}$ [FLAG]

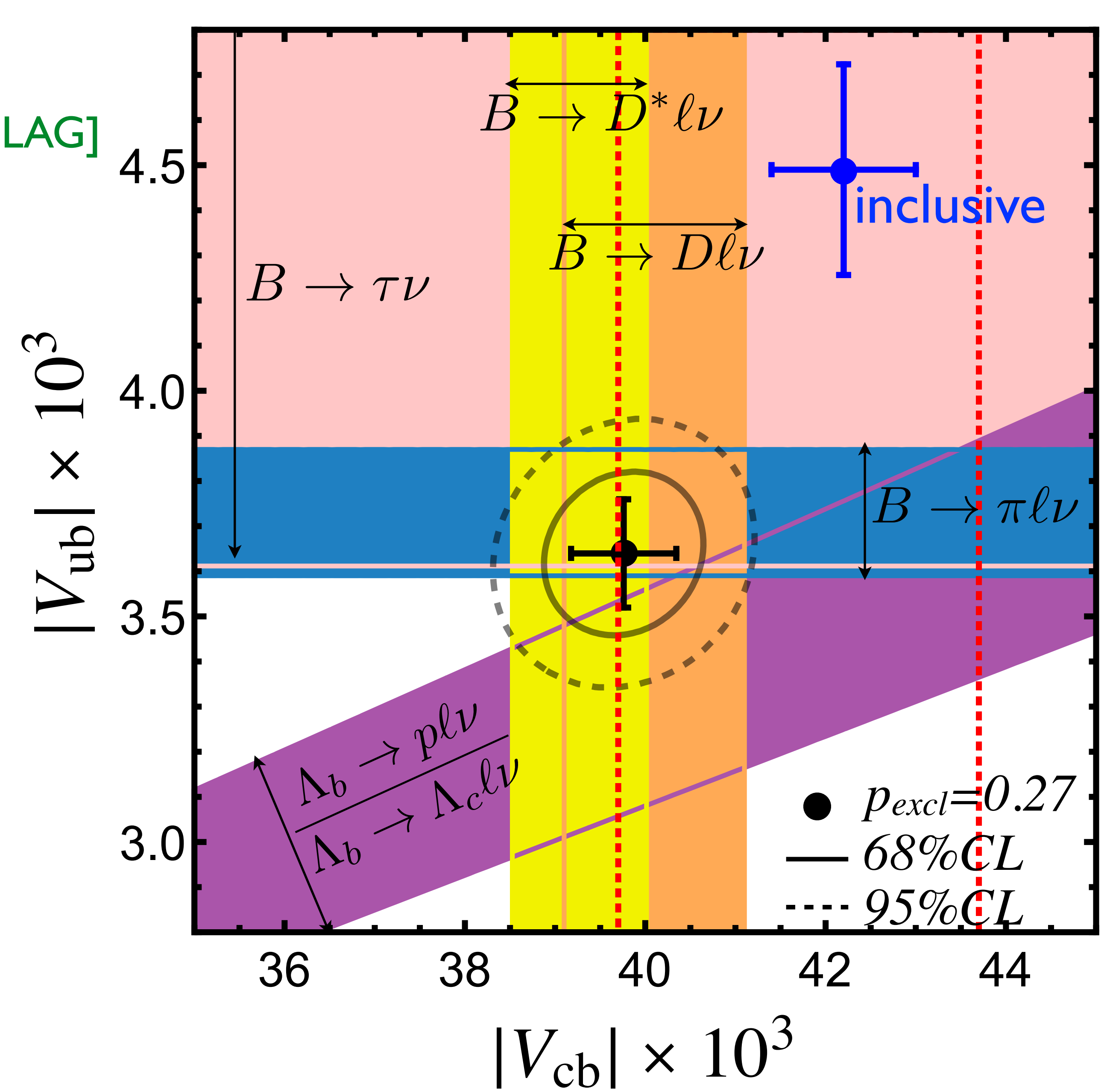
  $|V_{ub}/V_{cb}|_{\Lambda_b\to(p,\Lambda_c)\ell\nu} = 0.083(6)$ [PDG]

  [Detmold, Lehner, Meinel]

- **Inclusive [PDG]:**

  $|V_{ub}|_{B\to X_u\ell\nu} = 4.49(16)(^{+16}_{-18})\times 10^{-3}$

  $|V_{cb}|_{B\to X_c\ell\nu} = 42.2(0.7)\times 10^{-3}$



- The overall tension between all these determinations is *3.2 σ*

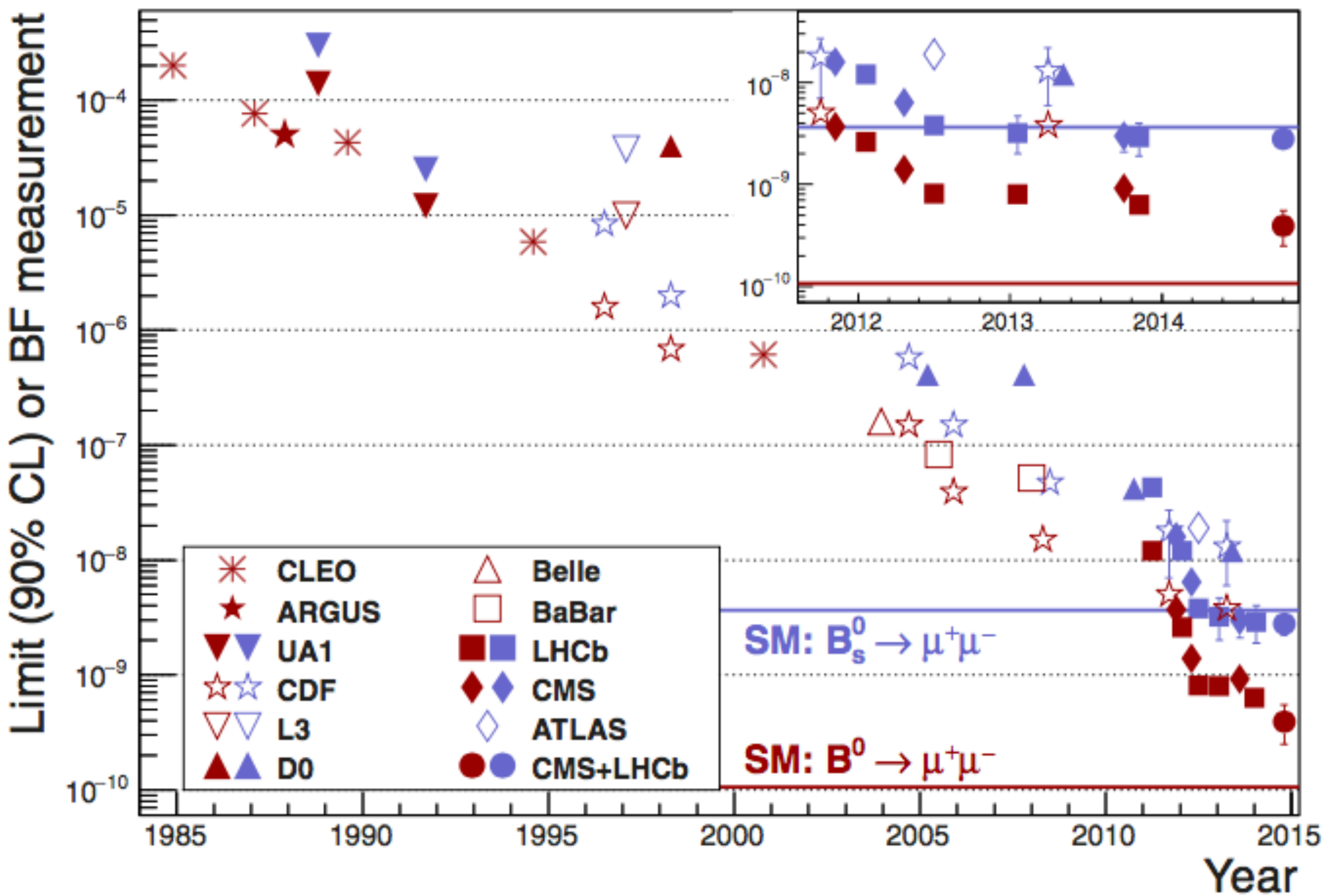
- Future progress
  - *B→D** form factor: q^2 dependence and use of BCL/BGL parametrization [Berlochner et al. 1703.05330] [Bigi, Gambino, Schacht 1703.06124] [Grinstein, Kobach 1703.08170] → $B\to D^*\ell\nu$ using the new Belle result 1702.01521
  - $B_s\to Kl\nu$

Ken Lane's List from LHCb

- ✦ $B^+ \to K^+\mu^+\mu^-/B^+ \to K^+e^+e^-$ 25%< SM (2.6σ)
- ✦ Independently, $B^+ \to K^+\mu^+\mu^-$ branching ratio 30% <SM (2σ)
- ✦ Earlier results for electron mode consistent with SM
  - Lepton nonuniversality may not demand much more from LQCD, i.e., BSM physics will change Wilson coefficients. (pheno ms.)
- ✦ $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution differs from SM by 2.9σ in two bins. Theoretical error questioned.
  - We have not done this decay. (Not gold plated…)
- ✦ $B_{(s)} \to \mu^+\mu^-$ branching ratios jointly measured by CMS and LHCb …

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

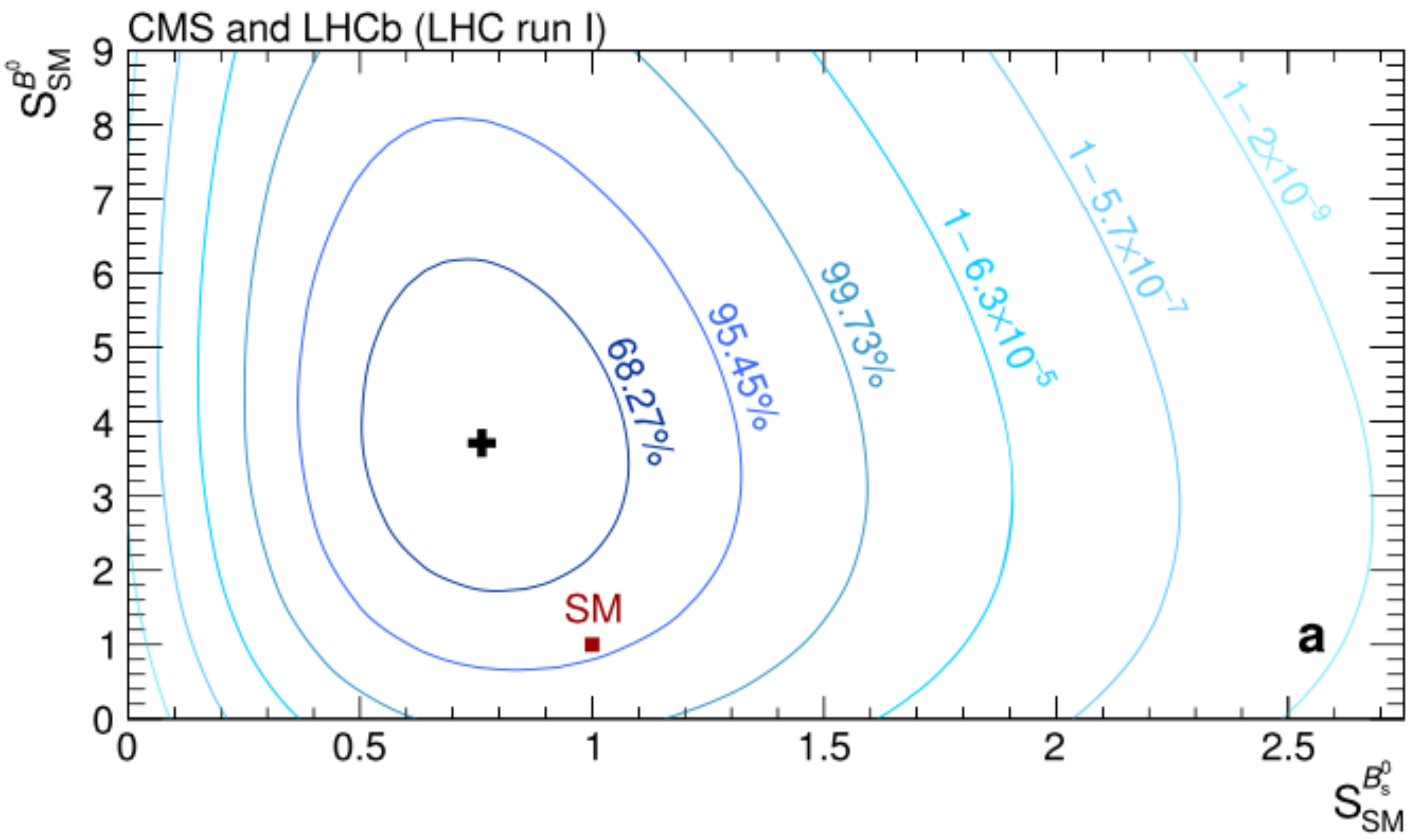
- Nature: doi:10.1038/nature14474 (we're cited)



CMS+LHCb II

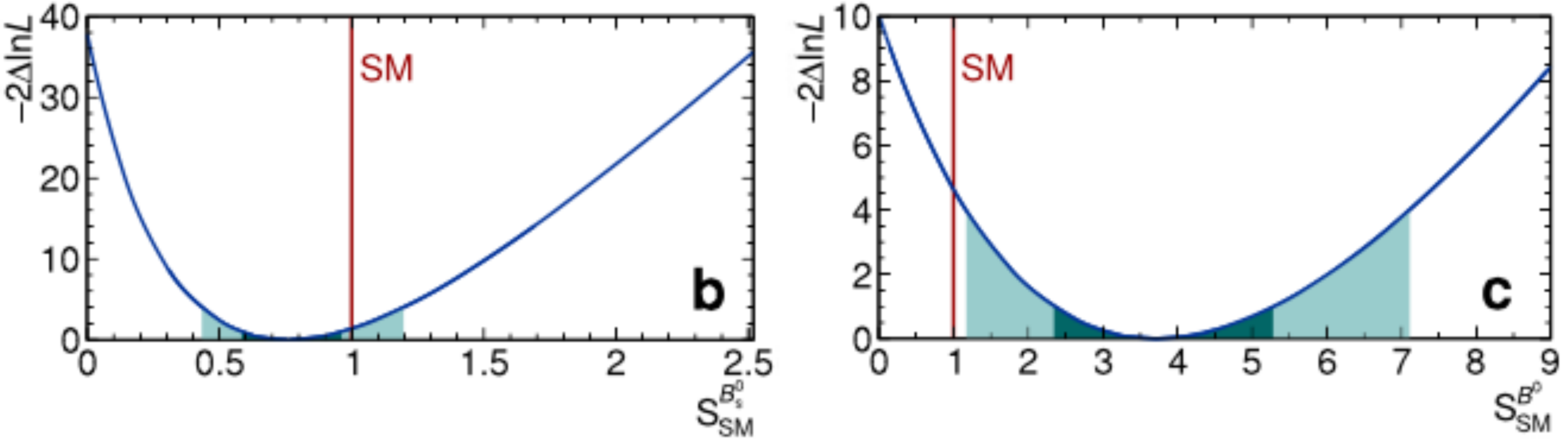
✦ 2D contour plot of branching ratios

- Bs too small by 1σ
- B too big by ≈2σ



CMS+LHCb II

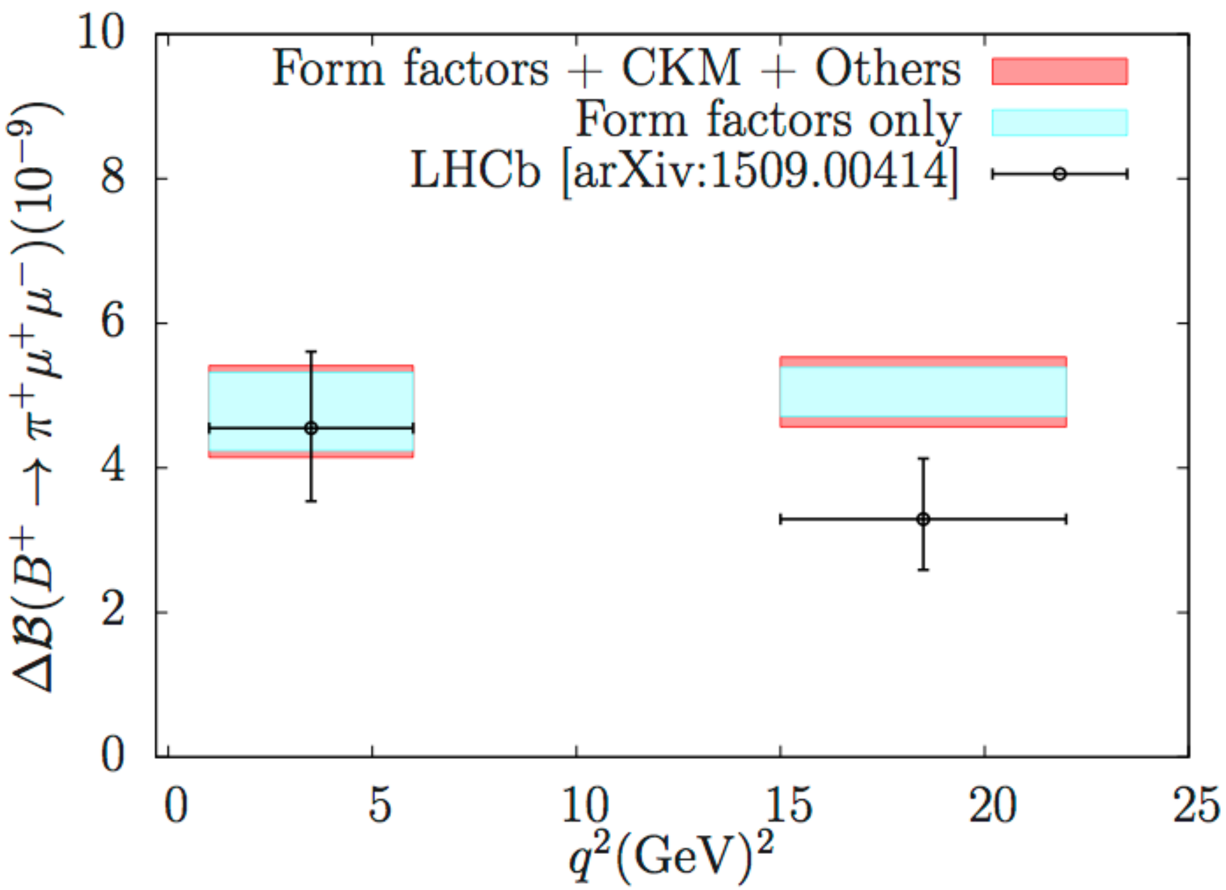
✦ Individual contour plots

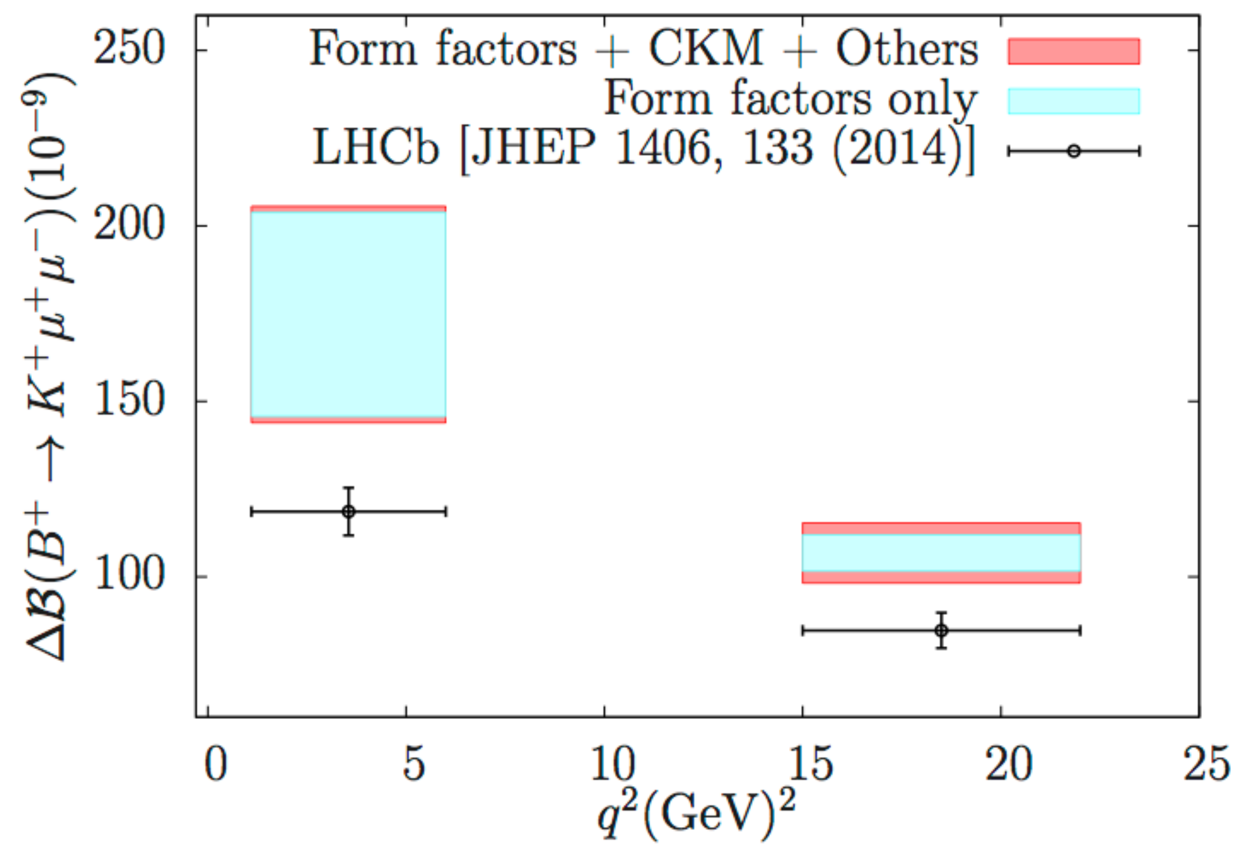


Rare B Decays

- FNAL/MILC has recently calculated form factors needed for several rare decays that require flavor changing neutral current.
- Good place to look for new physics
- Some tension between SM prediction and recent LHCb measurement

Rare B Decays II





- LHCb measurement is smaller than SM prediction in 3 of 4 bins. 1.7 σ tension.
- arXiv:1510.02349

Rare B Decays III

- Rare decays depend on $|V_{tq}|$ with q=d or s

$$|V_{td}| = 7.45(69) \times 10^{-3}, \quad |V_{ts}| = 35.7(1.5) \times 10^{-3}$$

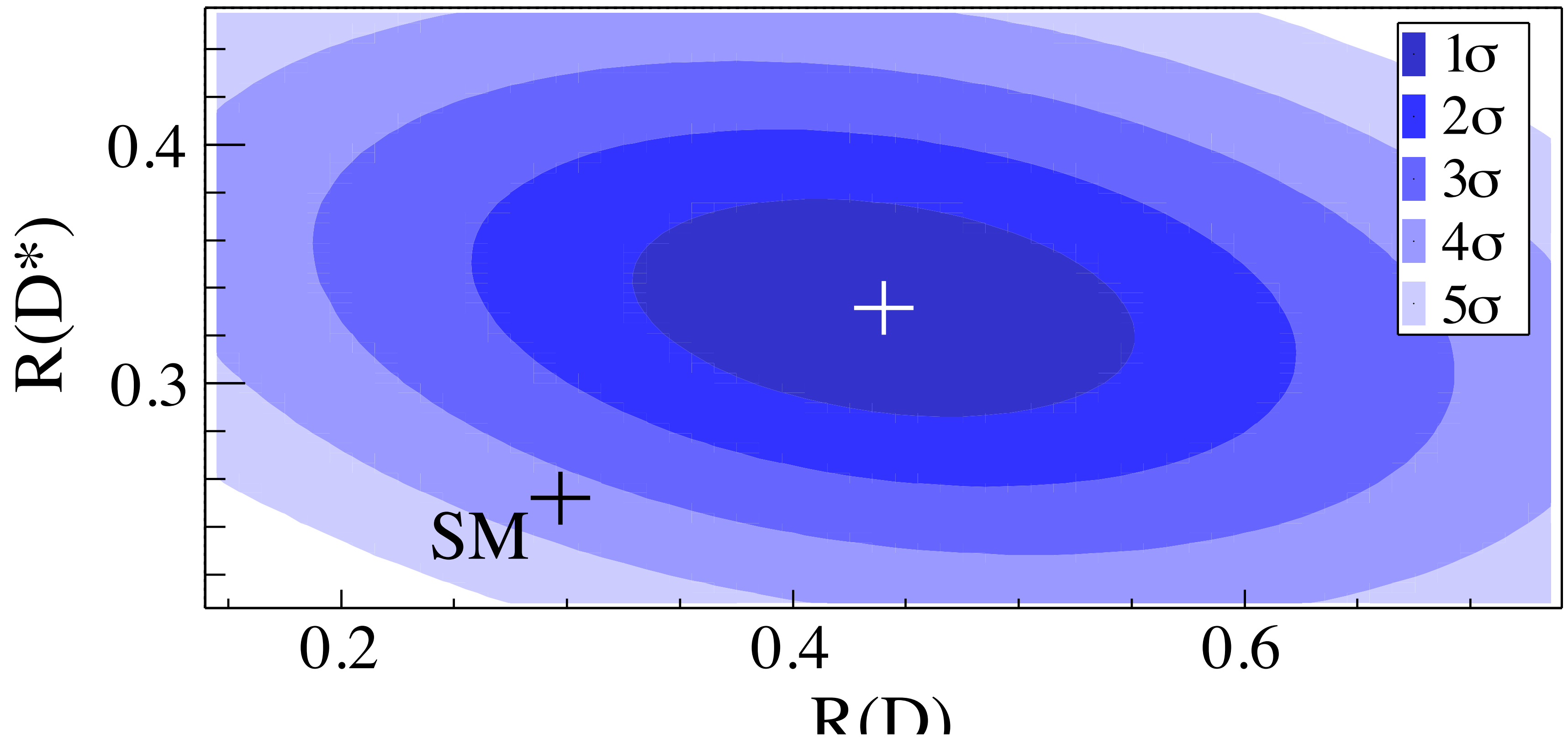
- The same elements of CKM matrix can be determined from B-meson mixing

$$|V_{td}| = 8.4(6) \times 10^{-3}, \quad |V_{ts}| = 40.0(2.7) \times 10^{-3}$$

- New $|V_{ts}|$ is 1.4 σ below that from mixing with smaller error
- Values of $|V_{td}|$ are comparable
- LQCD will help improve both determinations

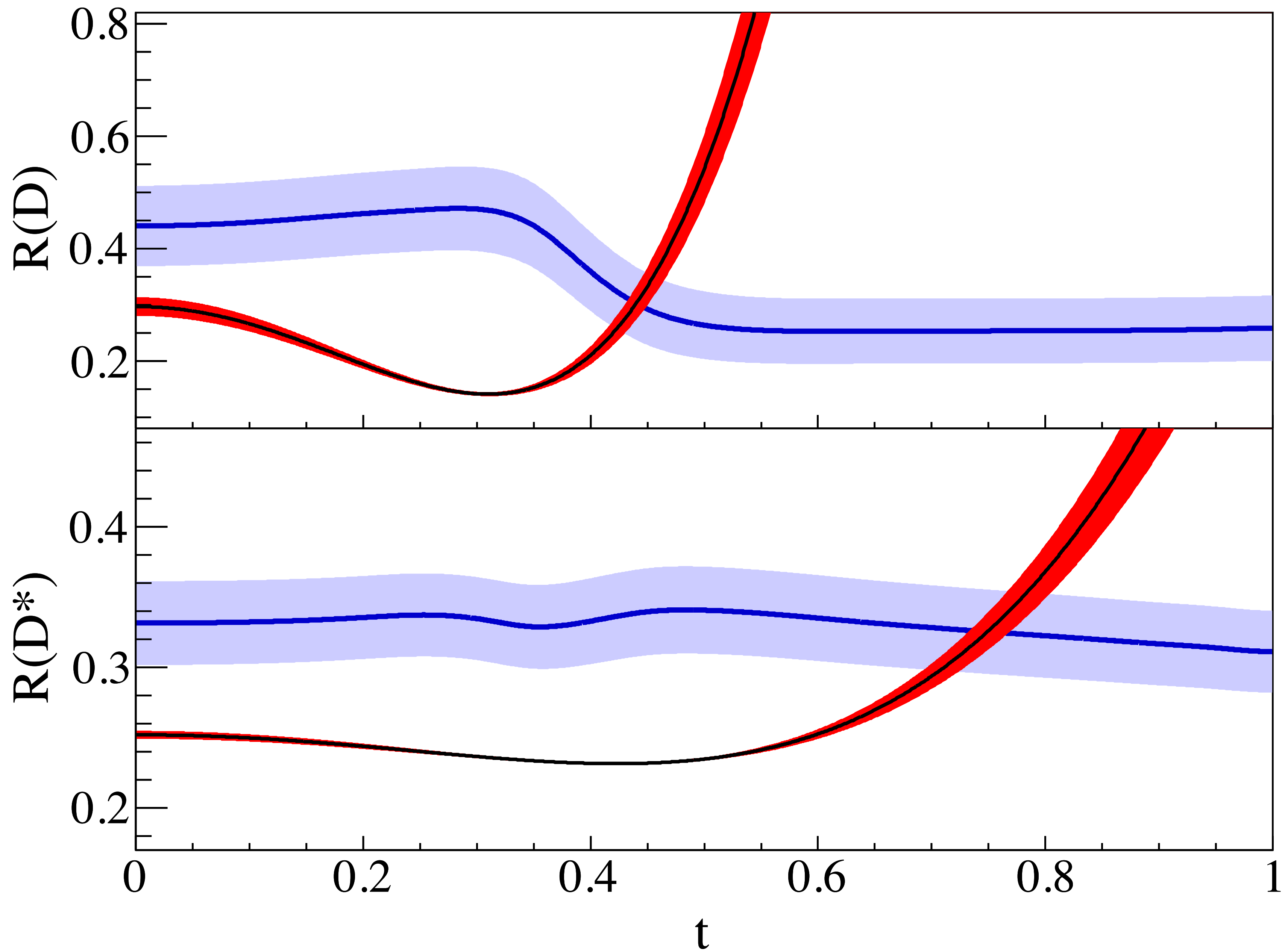
R(D) and R(D*)

- BaBar: PRD88, 072012 (2013)
- FNAL/MILC: PRL109, 071802, (2012)
- R(D): 2.0σ
- R(D*): 2.7σ
- Together: 3.4σ
- all BaBar's values
- However, no agreement is 2H model

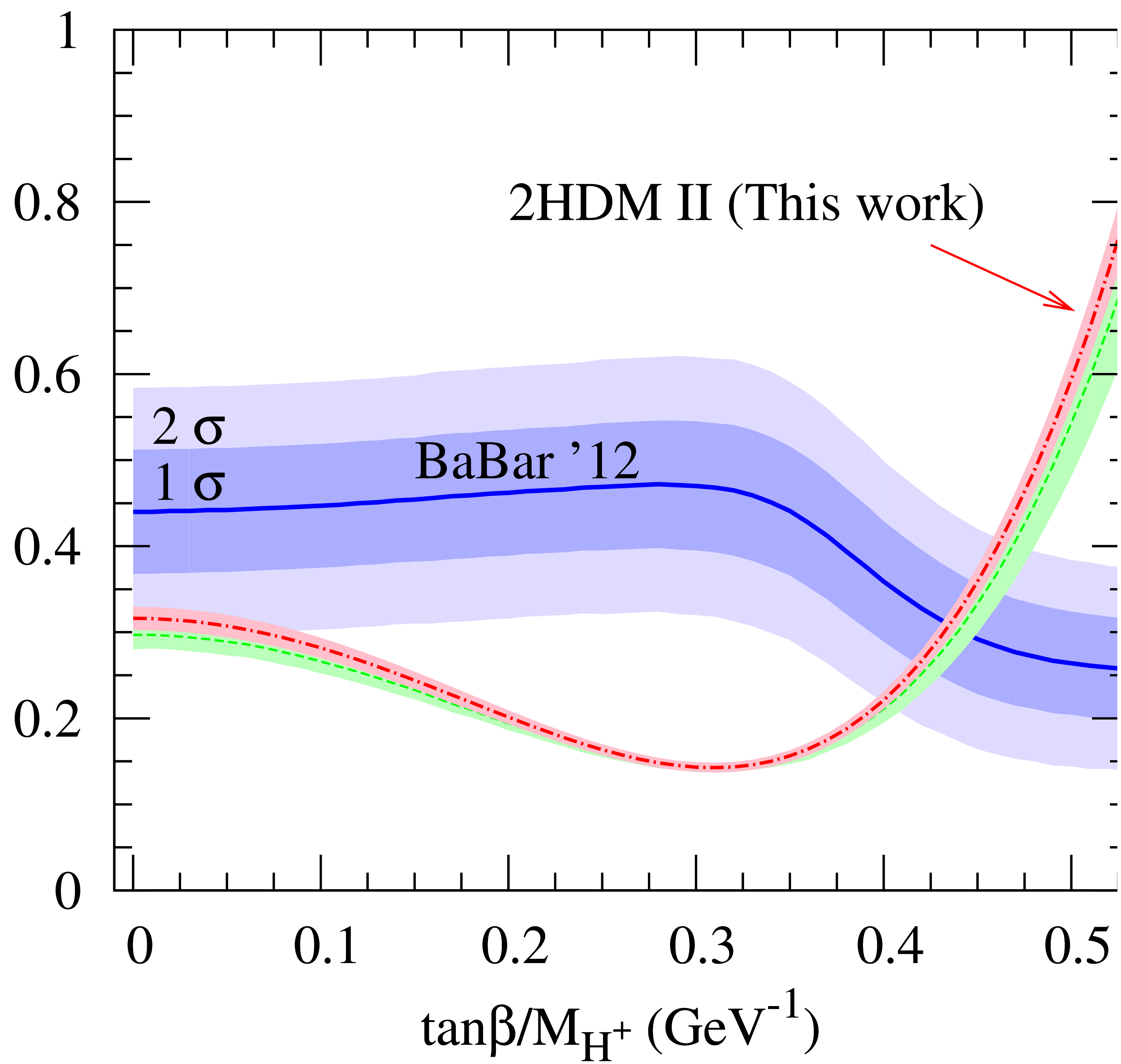


R(D) and R(D*) II

- BaBar's comparision with two Higgs doublet model predictions
- x-axis should be $\tan(\beta)/M_H$



- We slightly improve agreement between BaBar result and standard model.



Introduction

- Goal is quick summary of some of the places where there is a hint of beyond the standard model physics.
  - Emphasis on where lattice QCD might have an impact.
  - Many graphs from our recent papers.
- Obvious non-lattice:
  - neutrino masses and mixing
  - dark matter
  - dark energy
- Muon g-2
  - Many talks on this subject, so just point out it is one of the most significant anomalies.