$|V_{ub}|$ and $|V_{cb}|$ from unquenched Lattice QCD

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(Fermilab/MILC Collaborations)

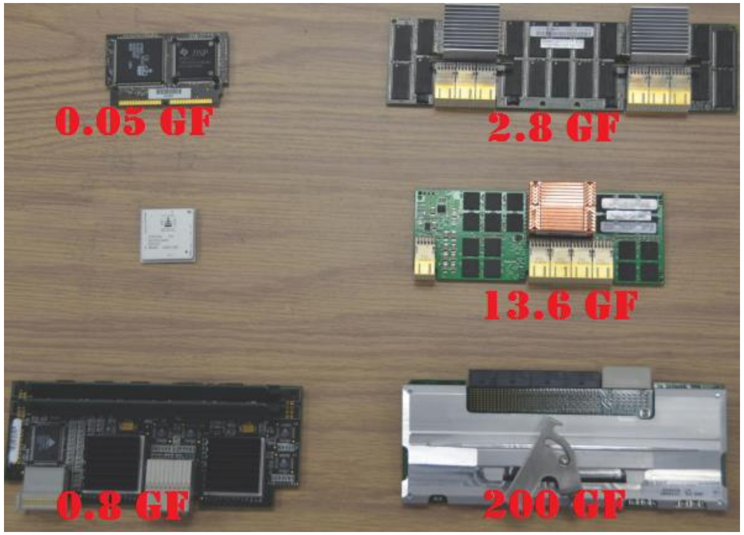
ICHEP 2016, Chicago

Why lattice QCD?

- Quantitative understanding of **non-perturbative** effects is becoming crucial for SM calculations and beyond. **Lepage, Mackenzie & Peskin, 1404.0319**

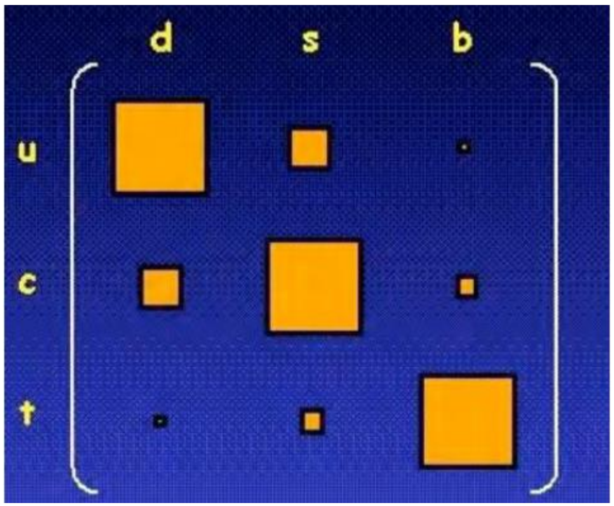
- Theoretical **precision** is a key to indirect searches for the TeV+ scale NP

- These can be/are being provided by Lattice QCD:
  - Same free parameters as in SM, but with a lattice regulator
  - A well-tested and mature method for "**simple quantities**": **A. El-Khadra CKM2014**
    mass spectra, decay constants,
    weak matrix elements (form factors)…
  - Calculations are **systematically improvable**:
    - Harness the power of hardware/software
    - Calculations can be well planned!
  - Active in many fronts:
    - Multiple hadrons (non-leptonic decays)
    - Finite temperature and density
    - QED+QCD
    - g-2



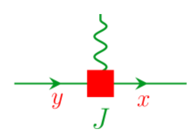
Why lattice QCD?

- LQCD provides the needed hadronic matrix elements with few-percent level precision, for the **exclusive** determinations of CKM parameters



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

(**Experiment**) = (known factor) × **(CKM element)** × **(Hadronic matrix element)**

$$\frac{d\Gamma(P \to P'\ell\nu)/dq^2}{\text{known factor}} = |V_{xy}|^2 \; | \langle P'|$$ 

$$|P\rangle \, |^2$$

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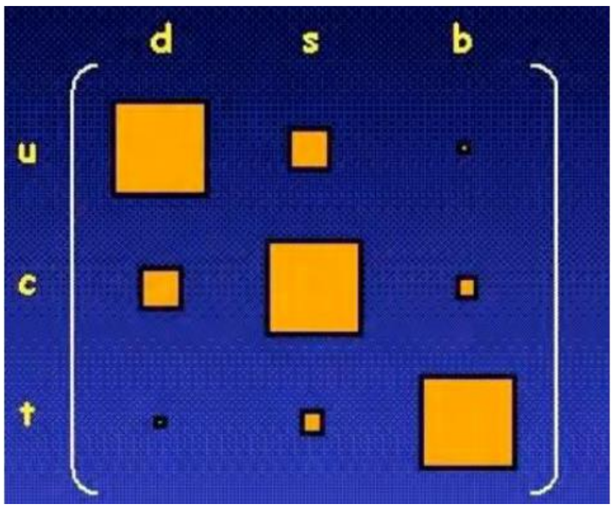


$$\begin{pmatrix} \underset{\pi \to \ell\nu}{V_{ud}} & \underset{K\to \ell\nu,\; K\to \pi\ell\nu}{V_{us}} & \underset{B\to \ell\nu,\; B\to \pi\ell\nu}{V_{ub}} \\ \underset{D\to \ell\nu,\; D\to \pi\ell\nu}{V_{cd}} & \underset{D_s\to \ell\nu,\; D\to K\ell\nu}{V_{cs}} & \underset{B\to D\ell\nu,\; B\to D^*\ell\nu}{V_{cb}} \\ \underset{\langle B_d|\bar{B}_d\rangle}{V_{td}} & \underset{\langle B_s|\bar{B}_s\rangle}{V_{ts}} & V_{tb} \end{pmatrix}$$

$\leq 1\%$ (green): $K \to \ell\nu$, $K \to \pi\ell\nu$, $D \to \ell\nu$, $D_s \to \ell\nu$

$\leq 3\%$ (blue): $B \to \ell\nu$, $D \to K\ell\nu$, $B \to D^*\ell\nu$

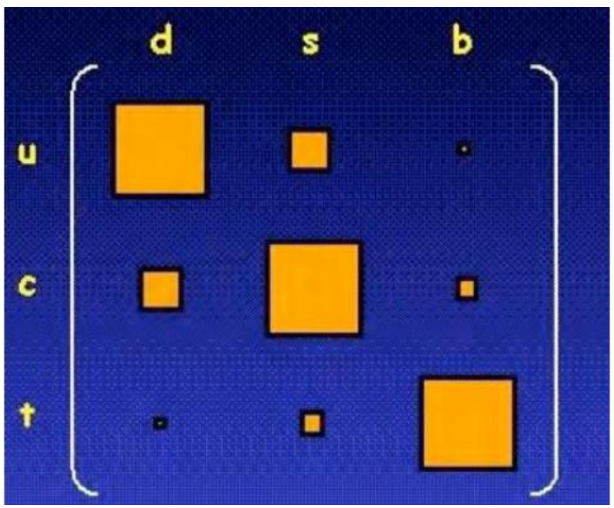
$\leq 5\%$ (yellow): $B \to \pi\ell\nu$, $D \to \pi\ell\nu$, $B \to D\ell\nu$

(Experiment) = (known factor) × **(CKM element)** × **(Hadronic matrix element)**

$$\frac{d\Gamma(P \to P'\ell\nu)/dq^2}{\text{known factor}} = |V_{xy}|^2 \; |\langle P'| \underset{y}{\rightarrow} \underset{J}{\blacksquare} \underset{x}{\rightarrow} |P\rangle|^2$$

Why lattice QCD?

- LQCD provides the needed hadronic matrix elements with few-percent level precision, for the **exclusive** determinations of CKM parameters



$$\left(\begin{array}{ccc}
\underset{\substack{\pi \to \ell\nu}}{\mathbf{V_{ud}}} & \underset{\substack{K \to \ell\nu \\ K \to \pi\ell\nu}}{\mathbf{V_{us}}} & \underset{\substack{B \to \ell\nu \\ B \to \pi\ell\nu}}{\mathbf{V_{ub}}} \\
\underset{\substack{D \to \ell\nu \\ D \to \pi\ell\nu}}{\mathbf{V_{cd}}} & \underset{\substack{D_s \to \ell\nu \\ D \to K\ell\nu}}{\mathbf{V_{cs}}} & \underset{\substack{B \to D\ell\nu \\ B \to D^*\ell\nu}}{\mathbf{V_{cb}}} \\
\underset{\substack{\langle B_d|\bar{B}_d\rangle}}{\mathbf{V_{td}}} & \underset{\substack{\langle B_s|\bar{B}_s\rangle}}{\mathbf{V_{ts}}} & \mathbf{V_{tb}}
\end{array}\right)$$

$\boxed{\Lambda_b \to p\ell\nu}$

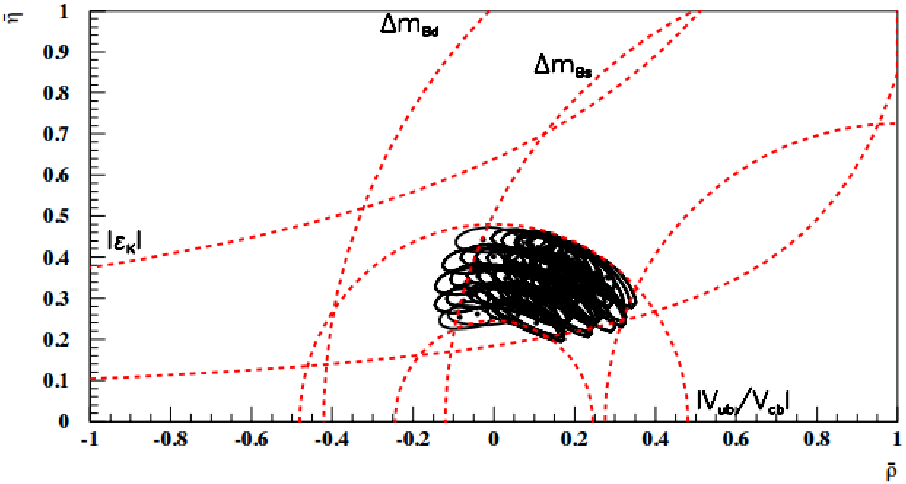
ratio

$\boxed{\Lambda_b \to \Lambda_c\ell\nu}$

(Experiment) = (known factor) × **(CKM element)** × **(Hadronic matrix element)**

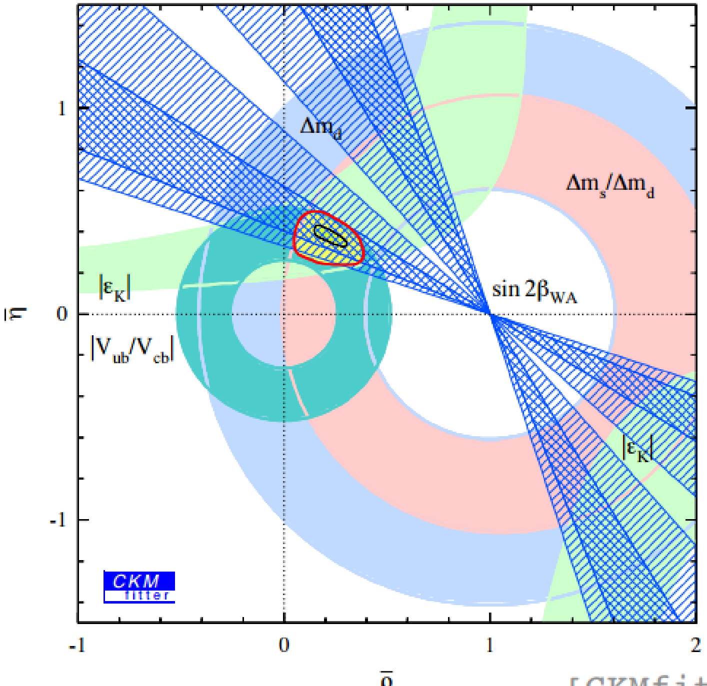
$$\frac{d\Gamma(P \to P'\ell\nu)/dq^2}{\text{known factor}} = |V_{xy}|^2 \; |\, \langle P'| \xrightarrow[y]{} \blacksquare_J \xrightarrow[x]{} |P\rangle \,|^2$$

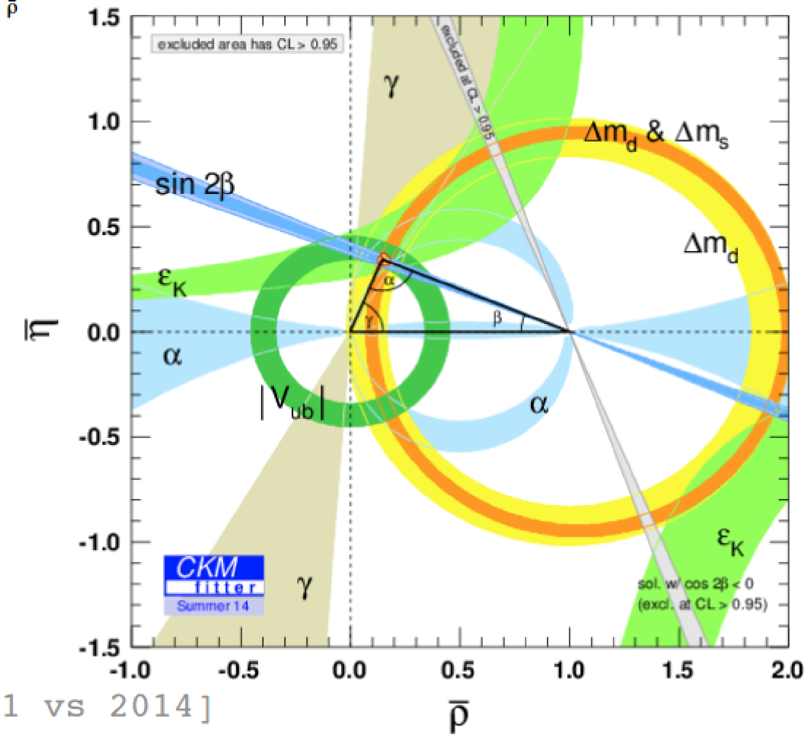
Why lattice QCD?



[BaBar Physics Book, 1999]

Pena, LAT 2015

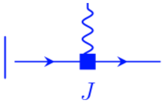


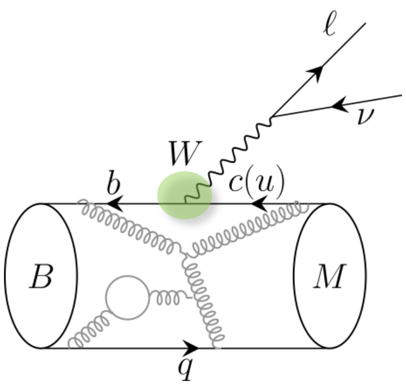


[CKMfitter 2001 vs 2014]

$B \to (P, V)$ form factors

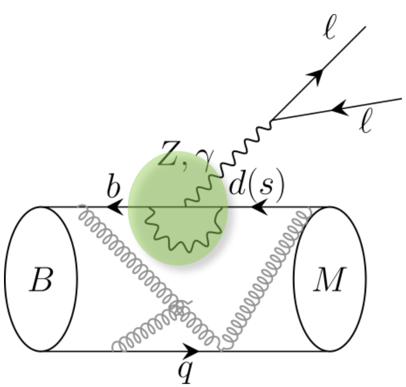
- $B \to (P, V)$ matrix elements: q^2-dependence is encoded by form factors

$| \langle P(V)|$  $|B\rangle | \longrightarrow$ form factors $f_i(q^2)$



$$\langle P|\bar{q}\gamma^\mu b|B\rangle \quad = \quad f_+(q^2)\left(p_B^\mu + p_P^\mu - \frac{M_B^2 - M_P^2}{q^2}q^\mu\right) + f_0(q^2)\frac{M_B^2 - M_P^2}{q^2}q^\mu$$

$$\langle V|\bar{q}\gamma^\mu b|B\rangle, \langle V|\bar{q}\gamma^5\gamma^\mu b|B\rangle \quad : \quad V(q^2), A_0(q^2), A_1(q^2), A_2(q^2)$$



$$\langle P(p_P)|i\bar{q}\sigma^{\mu\nu}b|B(p_B)\rangle = \frac{2}{M_B + M_P}(p_B^\mu p_P^\nu - p_B^\nu p_P^\mu)f_T(q^2),$$

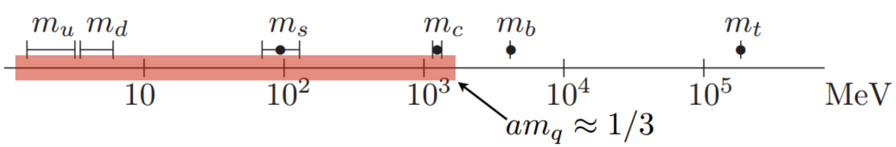
$$\langle V|\bar{q}\sigma^{\mu\nu}b|B\rangle, \langle V|\bar{q}\gamma^5\sigma^{\mu\nu}b|B\rangle \quad : \quad T_1(q^2), T_2(q^2), T_3(q^2)$$

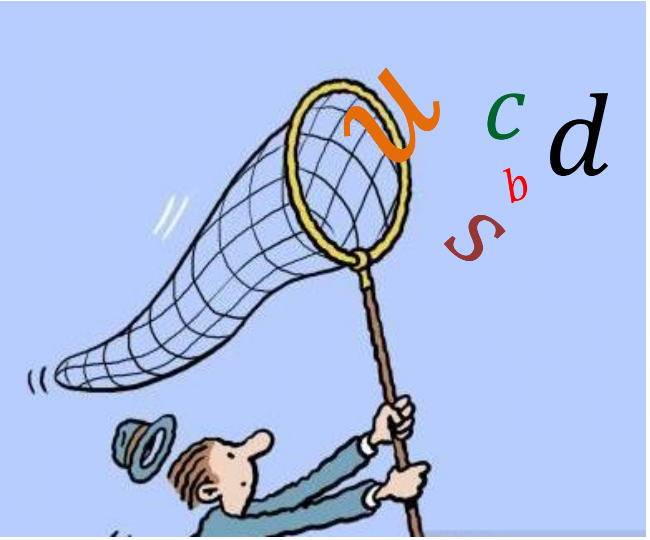
Heavy (valence) quarks on the lattice

- Heavy quark discretization error

  $$(\alpha_s)^k (am_h)^n$$

  b-quark is too heavy to satisfy $am_h < 1$





- Match to EFT to suppress HQ discretization error

- Different approaches:

  - NRQCD (HPQCD)
  - Relativistic HQ (Fermilab/MILC, RBC/UKQCD, Tsukuba)
  - HQET (Alpha)
  - Extrapolation from charm quark: (HPQCD, Fermilab/MILC, twWilson…)

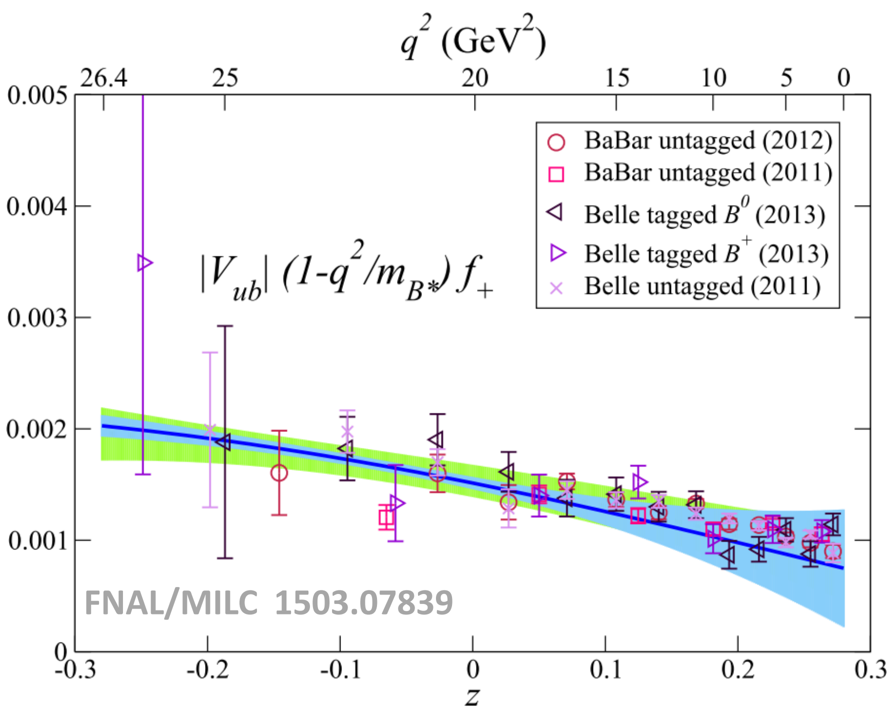
Lattice form factors for B decays

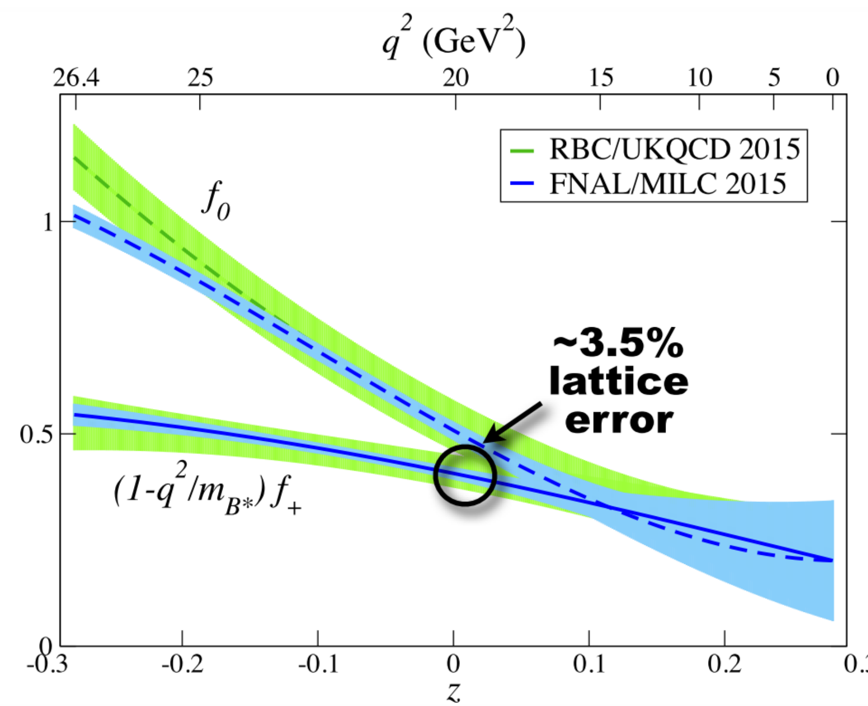
- For flavor-changing charged currents

form factor	simulated q^2	ensemble/HQ	uncertainty	Ref.
$f_{+,0}^{B\to\pi\ell\nu}$	$[17\mathrm{GeV}^2, \sim q^2_{\mathrm{max}}]$	MILC/Fermilab	$\sim$4%	FNAL/MILC 1503.07839
$f_{+,0}^{B\to\pi\ell\nu}$	q^2_{max}	MILC/NRQCD	$\sim$3%	HPQCD 1510.07446
$f_{+,0}^{B\to\pi\ell\nu}$	$q^2 = 21.22\mathrm{GeV}^2$	ALPHA/Wilson		ALPHA PLB.2016.03.088
$f_{+,0}^{B_{(s)}\to\pi(K)\ell\nu}$	$[19\mathrm{GeV}^2, \sim q^2_{\mathrm{max}}]$	DW/RHQ	8-14%(5-7%)	RBC/UKQCD 1501.05373
$f_{+,0}^{B_s\to K\ell\nu}$	$[17\mathrm{GeV}^2, \sim q^2_{\mathrm{max}}]$	MILC/NRQCD	3.5%	HPQCD 1406.2279
$f_{+,0}^{B\to D\ell\nu}$	$[9.5\mathrm{GeV}^2, q^2_{\mathrm{max}}]$	MILC/NRQCD	$\sim$5%	HPQCD 1505.03925
$f_{+,0}^{B\to D\ell\nu}$	$[8.5\mathrm{GeV}^2, q^2_{\mathrm{max}}]$	MILC/Fermilab	<1.5%	FNAL/MILC 1503.07237
$\mathcal{F}(1)^{B\to D^*\ell\nu}$	q^2_{max}	MILC/Fermilab	1.4%	FNAL/MILC 1403.0635
$f_{+,0}^{B_s\to D_s\ell\nu}$	near-q^2_{max}	ETMC/Wilson	$\sim$ 4.4%	Atoui et al. 1310.5238
$\{f_i, g_i\}^{\Lambda_b\to p\ell\nu}$	$[13\mathrm{GeV}^2, \sim q^2_{\mathrm{max}}]$	DW/RHQ	$\sim$ 5%	Detmold et al. 1503.01421
$\{f_i, g_i\}^{\Lambda_b\to\Lambda_c\ell\nu}$	$[6\mathrm{GeV}^2, \sim q^2_{\mathrm{max}}]$		$\sim$3%	

$|V_{ub}|$ from $B \to \pi \ell \nu$ decay

- *New* lattice results: RBC/UKQCD (1501.05373), FNAL/MILC (1503.07839)
- Very different gauge actions (but similar b-quark action), consistent form factors
- Form factor shape is consistent with experiment
- Largely improved uncertainty on $|V_{ub}|$ (8% → 4.3%)
- Lattice and experimental errors are commensurate





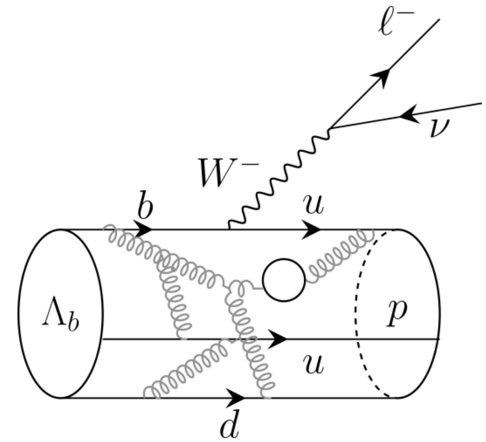
$|V_{ub}|$ from $\Lambda_b \to p\ell\nu$ decay

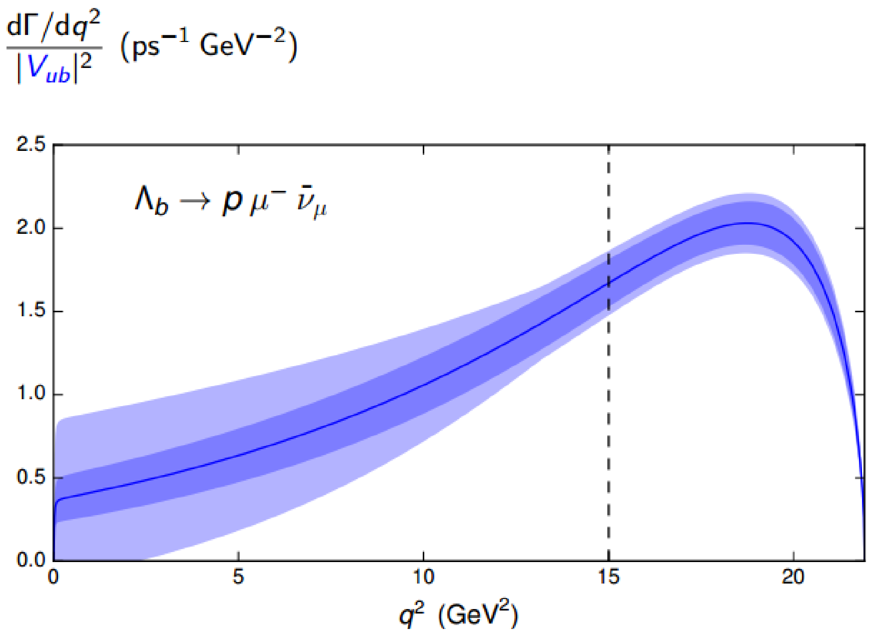
Detmold et al 1503.01421
1306.0446

- *New* alternative method to determine $|V_{ub}|$
- Sensitive to the right-handed current contributions
- Determine $|V_{ub}|/|V_{cb}|$, require $|V_{cb}|$ as input

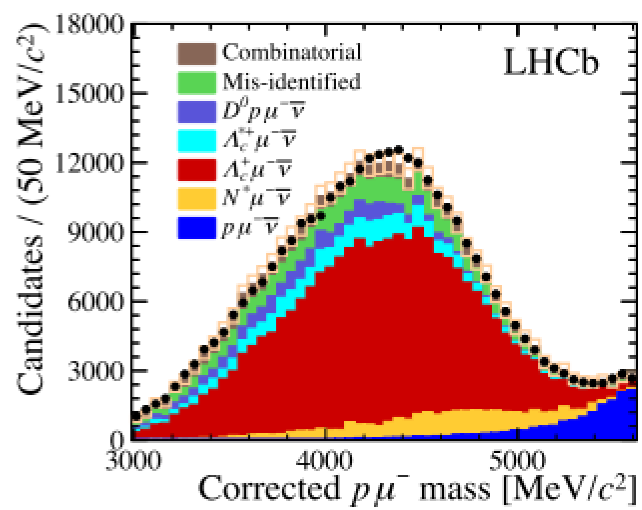
$$\frac{|V_{cb}|^2}{|V_{ub}|^2}\frac{\int_{15\,\mathrm{GeV}^2}^{q^2_{\max}}\frac{\mathrm{d}\Gamma(\Lambda_b\to p\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{7\,\mathrm{GeV}^2}^{q^2_{\max}}\frac{\mathrm{d}\Gamma(\Lambda_b\to \Lambda_c\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2} = 1.470 \pm 0.115 \pm 0.104$$

- Competitive uncertainty (5%)





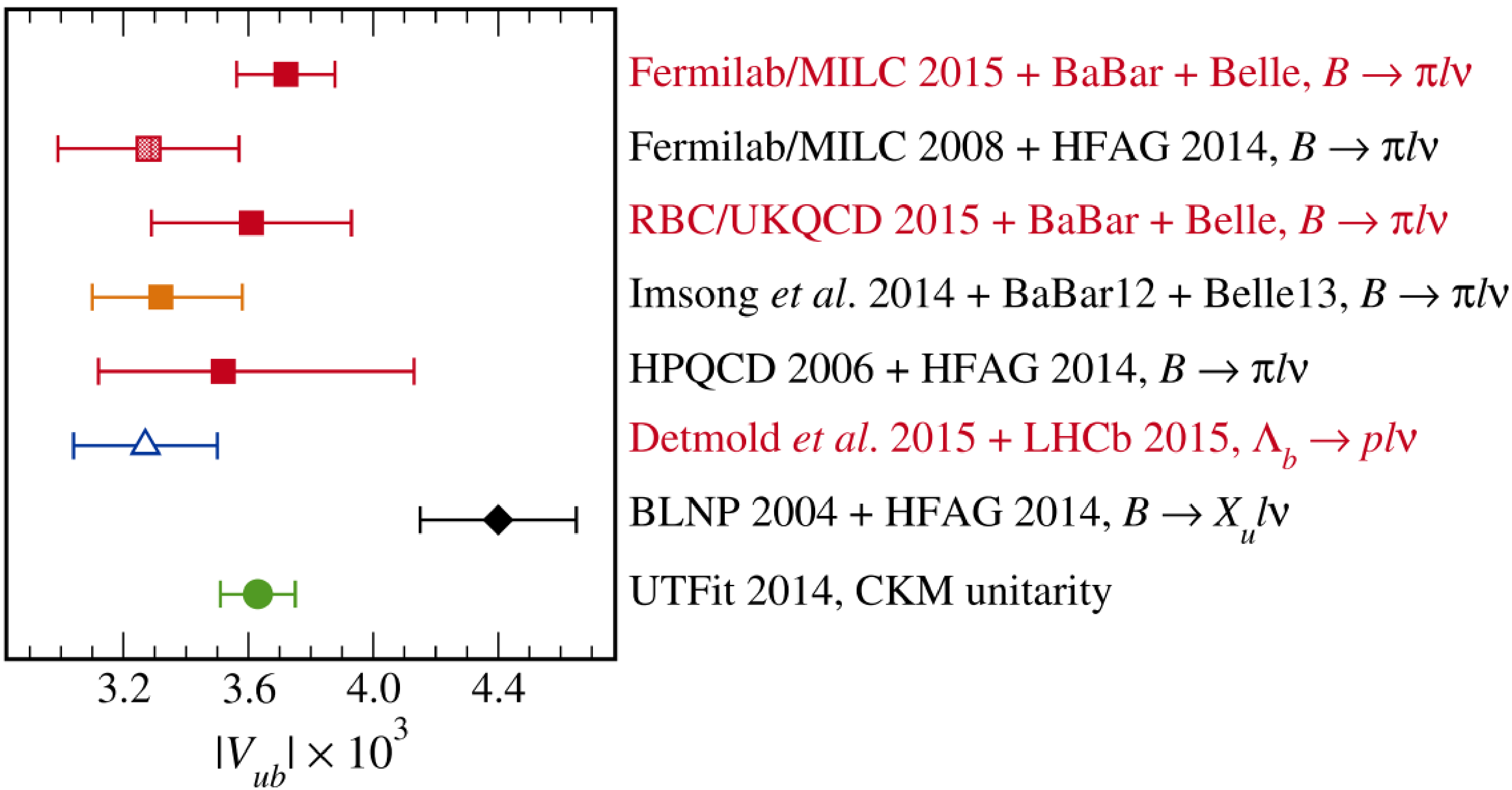
Meinel's Talk, Friday



LHCb, Nature Physics 10 (2015) 1038

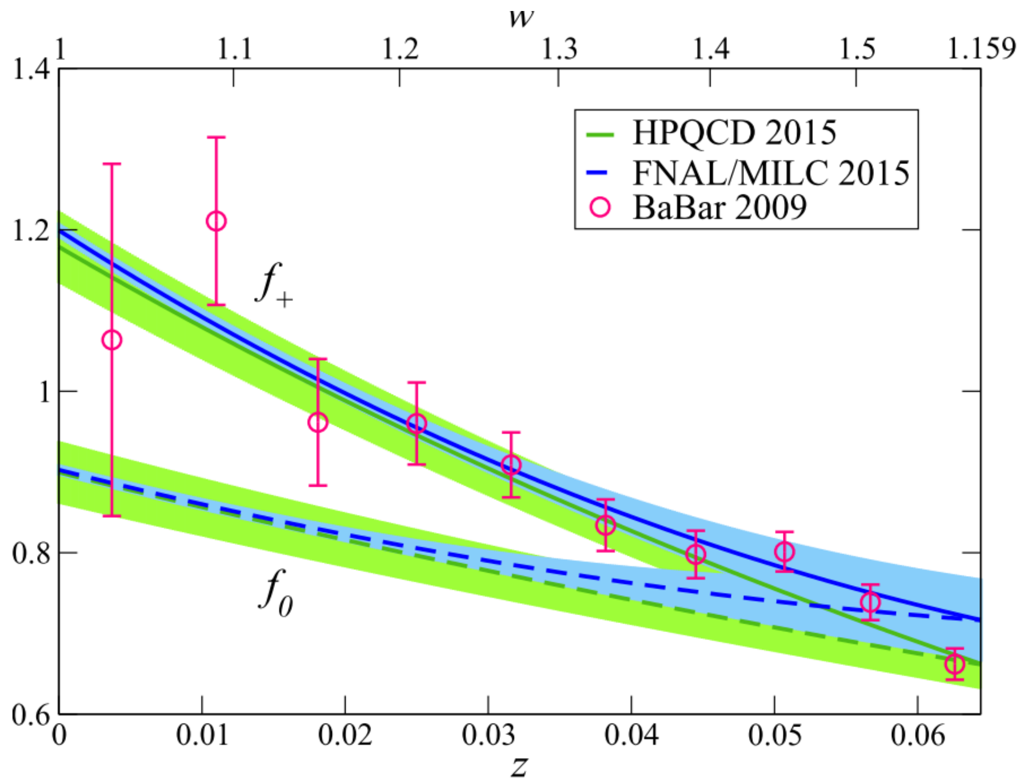
$|V_{ub}|$ summary

FNAL/MILC 1503.07839

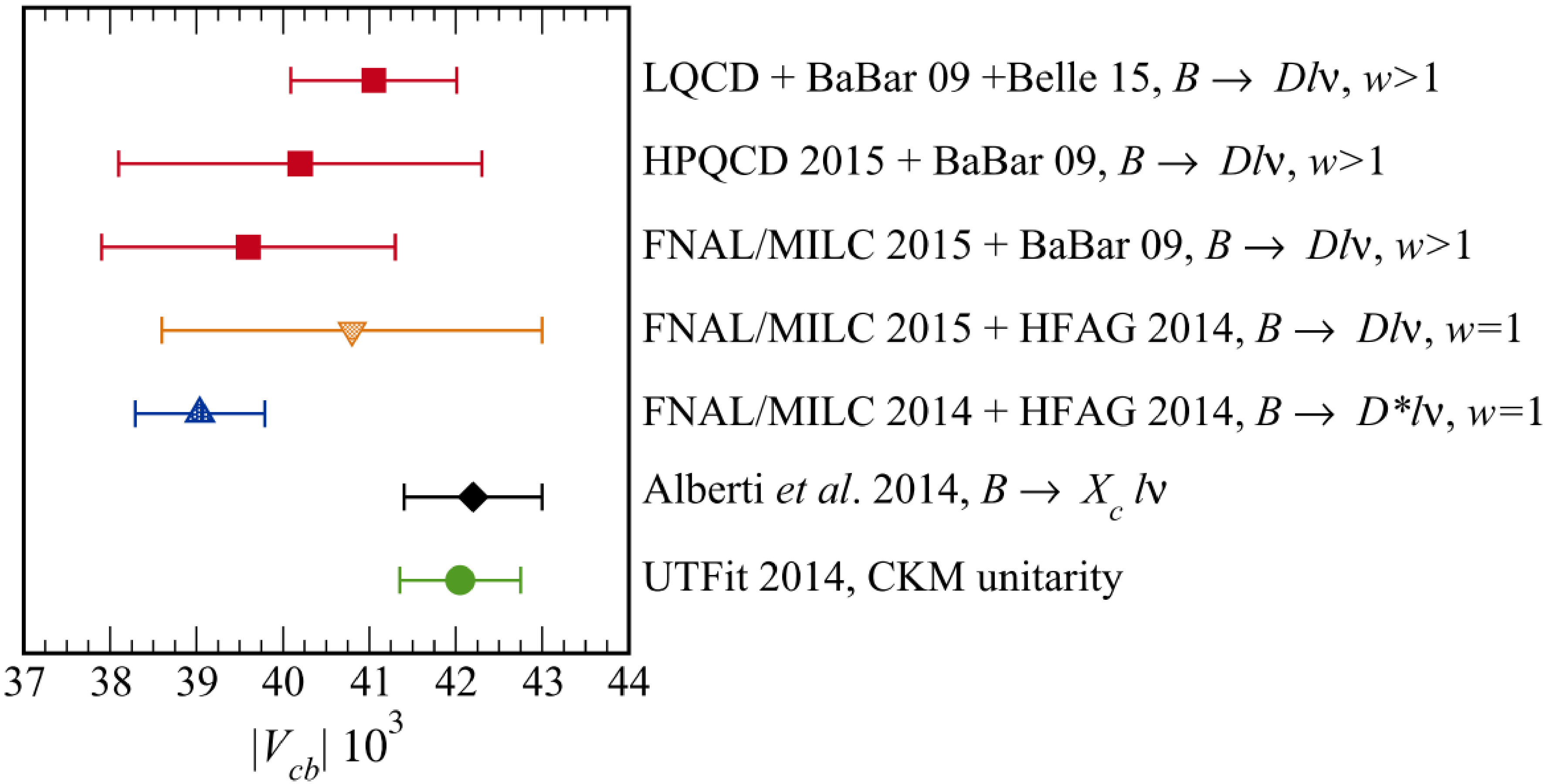


$|V_{cb}|$ from $B \to D\ell\nu$ decay (nonzero recoil)

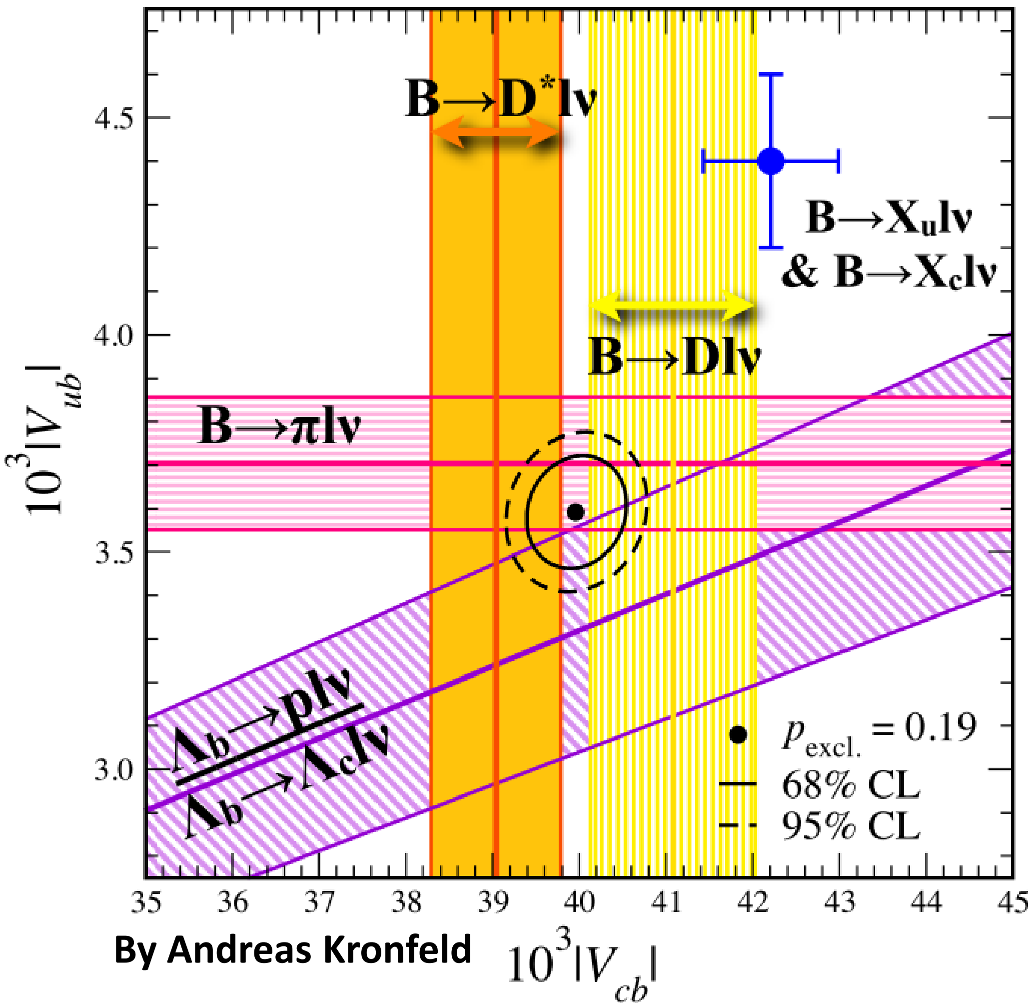
- *First* unquenched lattice results on $B \to D\ell\nu$ away from zero recoil
  FNAL/MILC 1503.07237, HPQCD 1505.03925
- Same gauge configurations but different b-quark implementation
- Consistent lattice results, good crosscheck
- Form factor shape consistent with experiment
- Experimental error dominates total error



$|V_{cb}|$ summary


LQCD + BaBar 09 +Belle 15, $B \to D l\nu$, $w>1$
HPQCD 2015 + BaBar 09, $B \to D l\nu$, $w>1$
FNAL/MILC 2015 + BaBar 09, $B \to D l\nu$, $w>1$
FNAL/MILC 2015 + HFAG 2014, $B \to D l\nu$, $w=1$
FNAL/MILC 2014 + HFAG 2014, $B \to D^* l\nu$, $w=1$
Alberti *et al*. 2014, $B \to X_c l\nu$
UTFit 2014, CKM unitarity
37 38 39 40 41 42 43 44
$|V_{cb}|\ 10^3$

$|V_{ub}|$, $|V_{cb}|$ puzzles: revisit with new results



By Andreas Kronfeld

- Very hard to explain by NP.
  Unlikely right-handed current
  Detmold et al 1503.01421
  Crivellin et al, 1407.1320

- How lattice can help:

  * Different channels: $B_s \to K\ell\nu$
  HPQCD 2014, RBC/UKQCD 2015

  * More indep. determinations:
  Lattice averaging (FLAG)
  FLAG 1310.8555

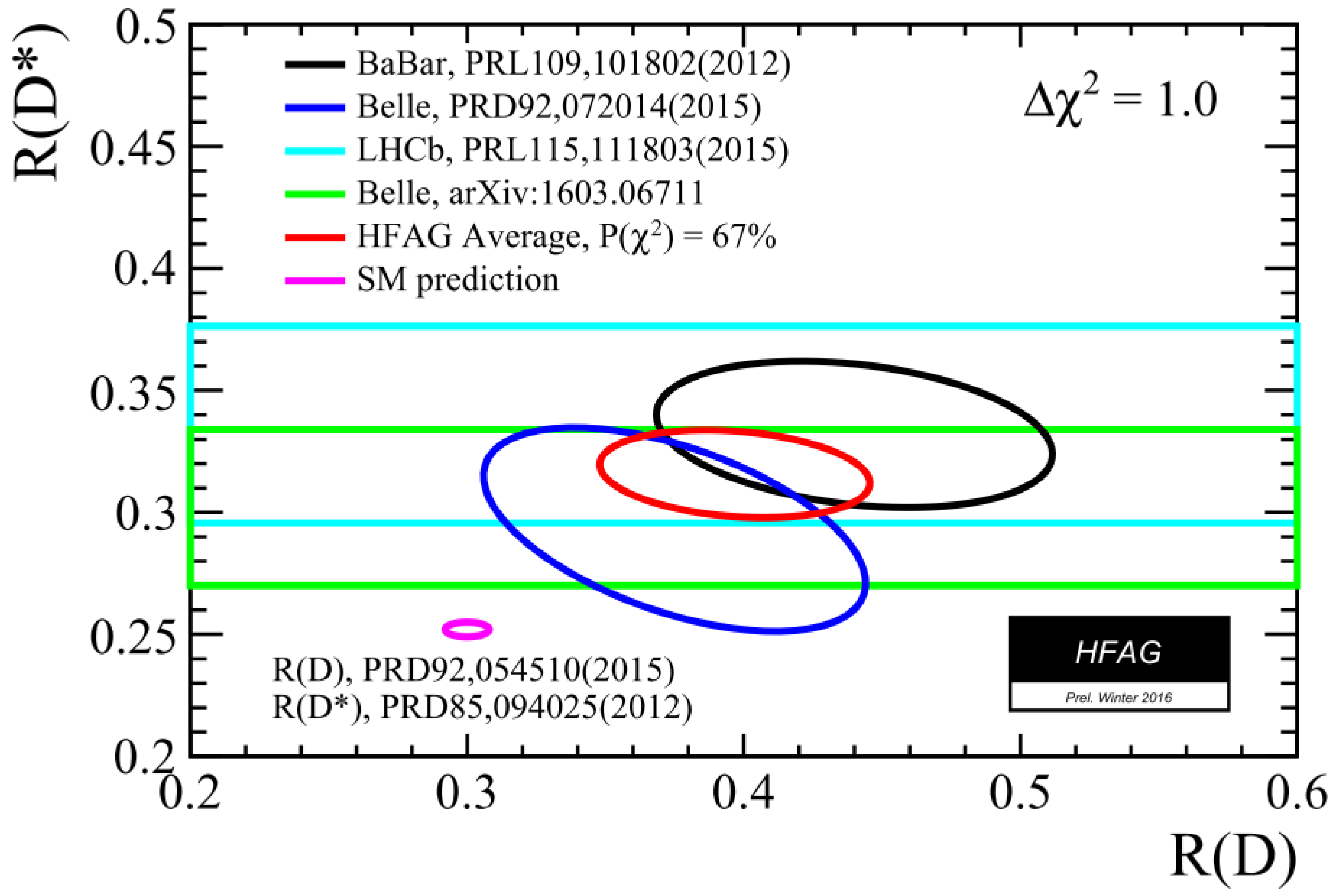
  * $B \to D^*\ell\nu$ with $w > 1$

  * Continue to improve :
  precision for the Belle II era

$R(D^{(*)})$

- Tree-level, semileptonic decays with systematic cancellations with the ratio

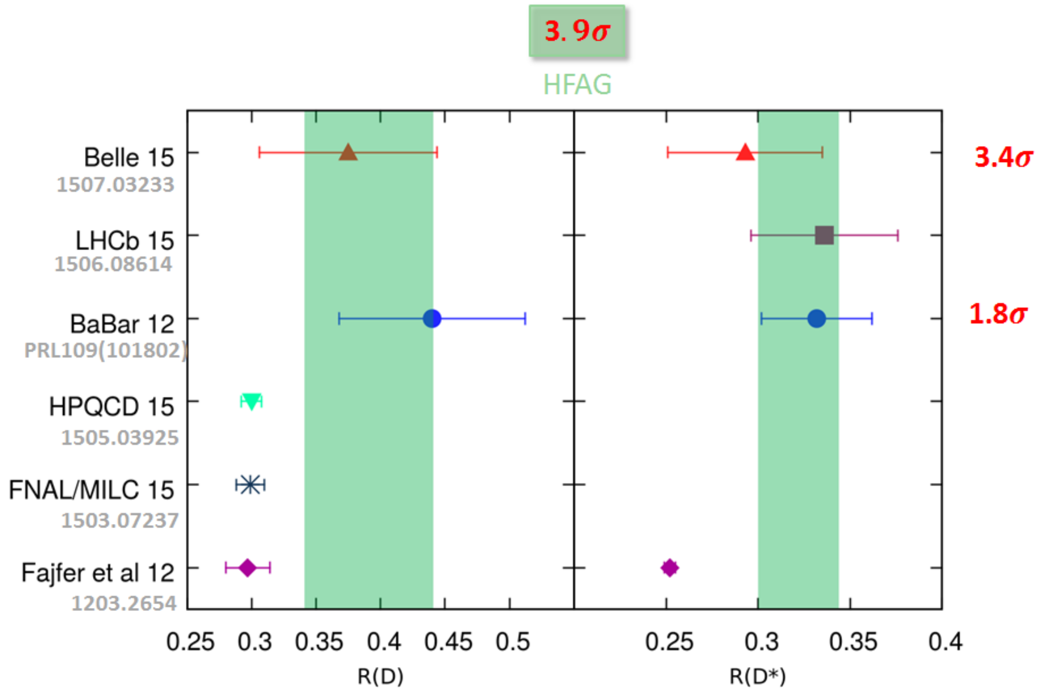
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$



$R(D^{(*)})$ from lattice

- $B \to D\ell\nu$

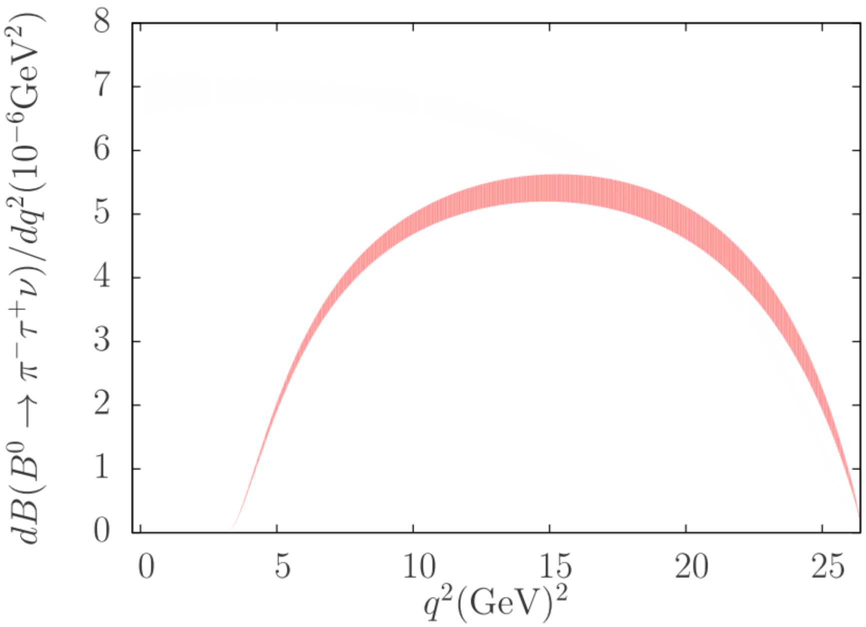
$$R(D)_{\mathrm{FNAL/MILC15}} = 0.299(11) \quad \textbf{1503.07237}$$
$$R(D)_{\mathrm{HPQCD15}} = 0.300(8) \quad \textbf{1505.03925}$$



- $B \to D^{*}\ell\nu$, on-going effort from FNAL/MILC,

$R(\pi)$

- If NP is responsible for the excess in $R(D^{(*)})$, it might also enhance $R(\pi)$
- Use the precise determination of $f_{0,+}^{B\to\pi\ell\nu}$ from lattice+experiment combined fit to compute $R(\pi)$
- Belle is searching for the $B \to \pi\tau\nu$ decay **Hamer, EPS 2015**



Du et al, 1510.02349

$$\mathrm{BR}(B^0 \to \pi^-\tau^+\nu_\tau) = 9.35(38) \times 10^{-5}$$

$$R(\pi) \equiv \frac{\mathrm{BR}(B \to \pi\tau\nu_\tau)}{\mathrm{BR}(B \to \pi\ell\nu_\ell)} = 0.641(17)$$

Dutta et al 1307.6653

Summary

- There have been major updates from Lattice QCD on the calculations of B semileptonic decays. The CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ have been updated.

- Lattice QCD calculations play an important role in the determination of $R(D^{(*)})$, which provides the precision needed to resolve the puzzle of multiple-sigma descrepancy.