SM Predictions for $R(D^*)$

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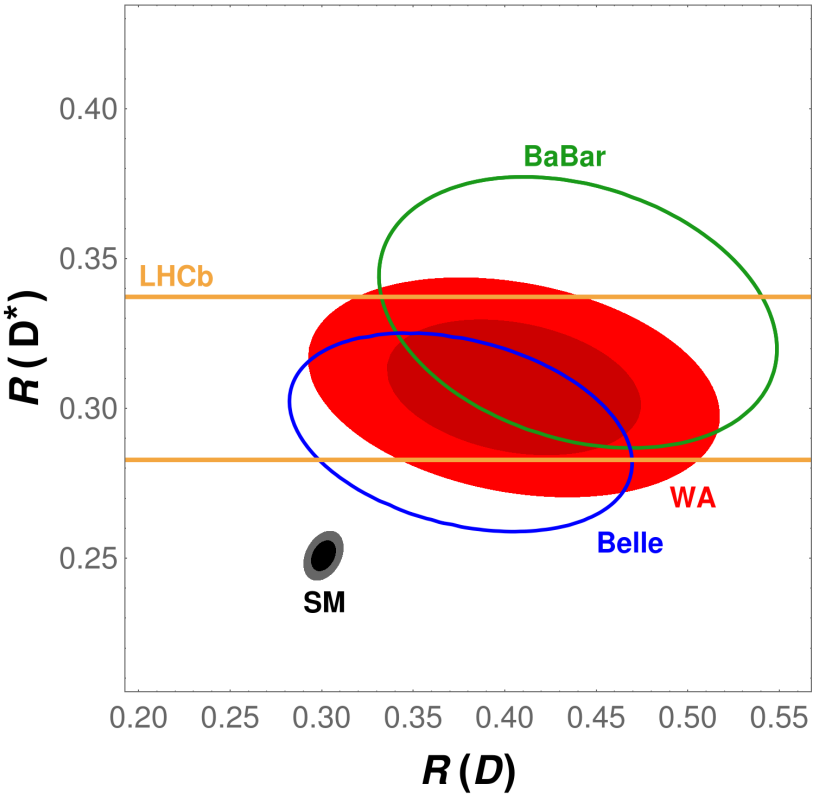
Lepton-non-Universality in $b \to c\tau\nu$ 2019

$$R(X) \equiv \frac{\mathrm{Br}(B \to X\tau\nu)}{\mathrm{Br}(B \to X\ell\nu)}, \quad \hat{R}(X) \equiv \frac{R(X)}{R(X)|_{\mathrm{SM}}}$$



contours: 68% CL
filled: 95(68)% CL

- $R(D^{(*)})$: BaBar, Belle, LHCb
  - ➥ average $\sim 4\sigma$ from SM
- τ-polarization ($\tau \to$ had) [1608.06391]
- $B_c \to J/\psi\tau\nu$ [1711.05623] : huge
- Differential rates from Belle, BaBar
- Total width of B_c
- $b \to X_c\tau\nu$ by LEP
- D^* polarization (Belle)
- New@Moriond: Belle update
  - ➥ Tension 3.4σ from the SM
  - ➥ 3.1σ with new $BR(B \to D^*\ell\nu)$

Note: only 1 result $\geq 3\sigma$ from SM

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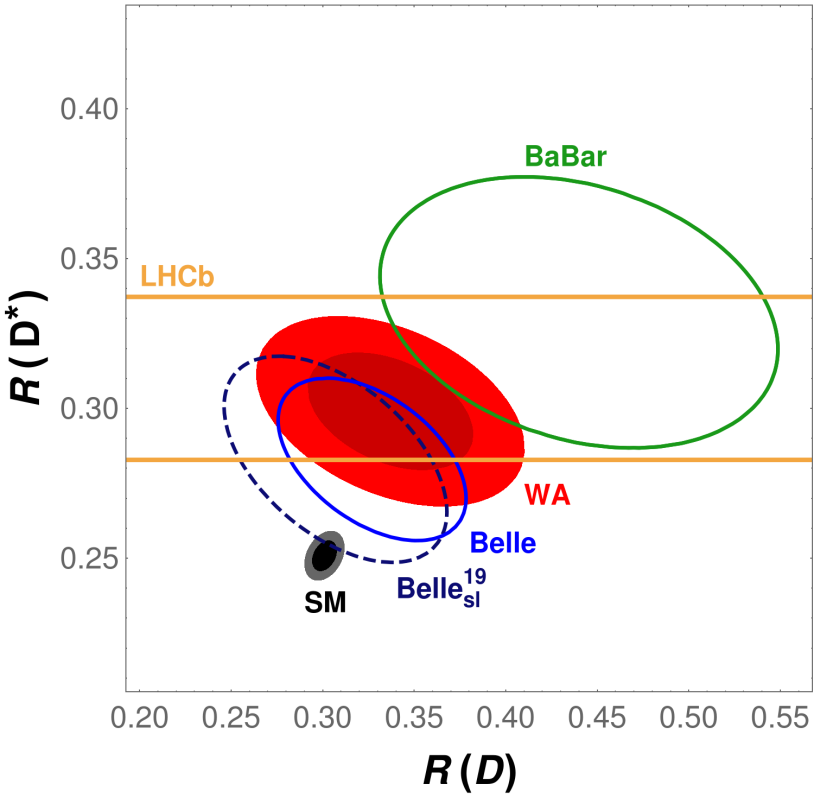

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Generalities regarding this anomaly

$\sim 15\%$ of a SM tree decay $\sim V_{cb}$: This is a huge effect!
➥ Need contribution of $\sim 5 - 10\%$ (w/ interference) or $\gtrsim 40\%$ (w/o interference) of SM

What do we do about this?

- Check the SM prediction!
  [Bigi+,Grinstein+,Bernlochner+]
- Improve understanding of backgrounds
  [Florian's talk]
- Combined analysis of all $b \to c\tau\nu$ observables [100+ papers]
  ➥ First model discrimination
- Related indirect bounds (partly model-dependent)
  ➥ High p_T searches, lepton decays, LFV, EDMs, ...
- Analyze flavour structure of potential NP contributions
  ➥ quark flavour structure, e.g. $b \to u$
  ➥ lepton flavour structure, e.g. $b \to c\ell(= e, \mu)\nu$

Comments regarding systematics and fitting [MJ/Straub'18]

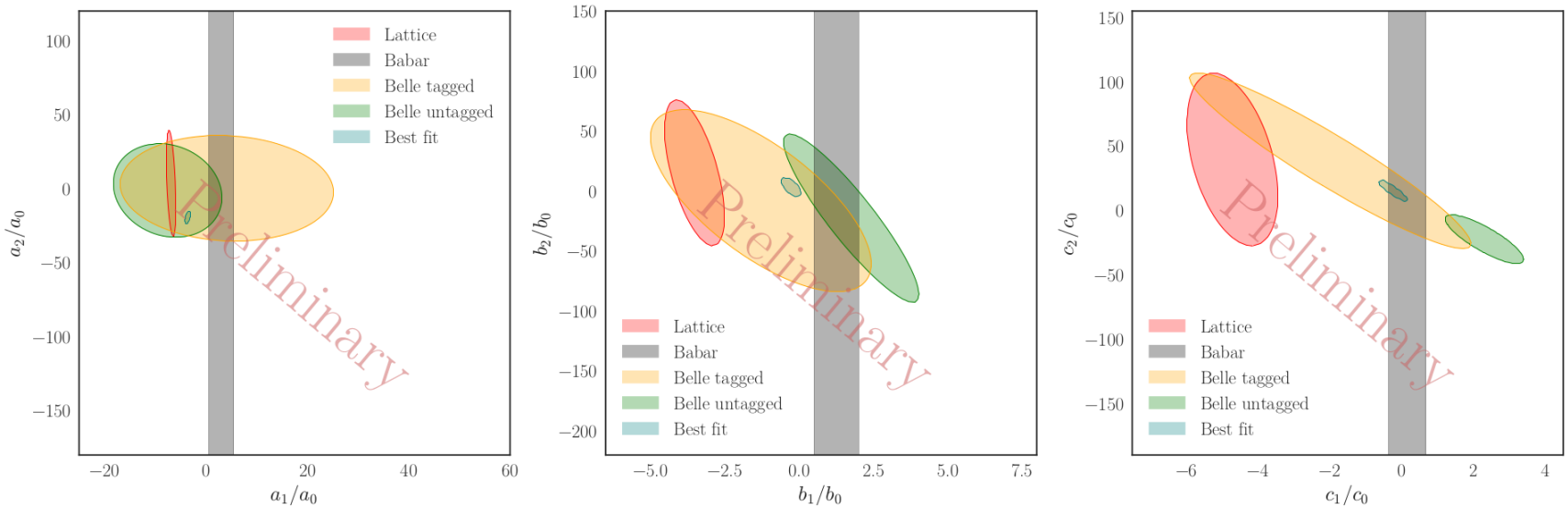
Present (and future!) precision renders small effects important:

- Form factor parametrization ($\rightarrow 1/m_c^2$ contributions!?)
- d'Agostini effect:
  assuming systematic uncertainties $\sim$ (exp. cv) introduces bias
  ➥ e.g. 1-2σ shift in $|V_{cb}|$ in Belle 2010 binned data
- Rounding in a fit with strong correlations and many bins:
  ➥ 1σ between fit to Belle 2017 data from paper vs. HEPdata
- BR measurements and isospin violation [MJ 1510.03423] :
  Normalization depends on $\Upsilon \rightarrow B^+B^-$ vs. $B^0\bar{B}^0$
  Taken into account, but simple HFLAV average problematic:
  - Potential large isospin violation in $\Upsilon \rightarrow BB$ [Atwood/Marciano'90]
  - Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
    ➥ This is one thing we want to test!
  - ➥ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
    (potentially subject to change, in contact with Belle members)
  - ➥ Relevant for **all** BR measurements at the %-level

$b \to c$ Form Factors – Lattice

Significant progress over the last years (only SM FFs):

- $B \to D$: q^2-dependent f_+, f_0 [FNAL/MILC, HPQCD'15]
  - ➥ Agreement on $R(D)$ predictions across the board
- $B \to D^*$: only at zero recoil so far [FNAL/MILC, HPQCD]
  - ➥ Stronger dependence on additional inputs, larger variations
- "Soon": $B \to D^*$ @ finite recoil [FNAL/MILC,HPQCD,JLQCD,LANL]
  - ➥ Preliminary results [A.Vaquero@Lattice'18] :



  - ➥ important step forward; tension with experiment?

$R(D^*)$ from data + lattice + unitarity [Gambino/MJ/Schacht'19]

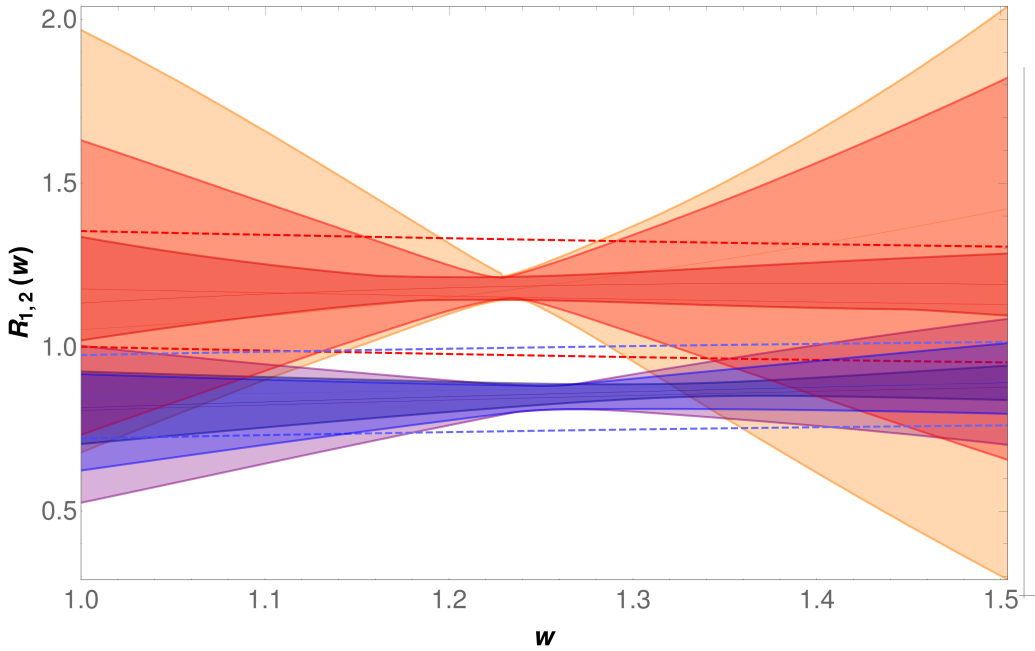
(see also [Fajfer+,Nierste+,Bernlochner+,Bigi+,Grinstein+,Nandi+...])
Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

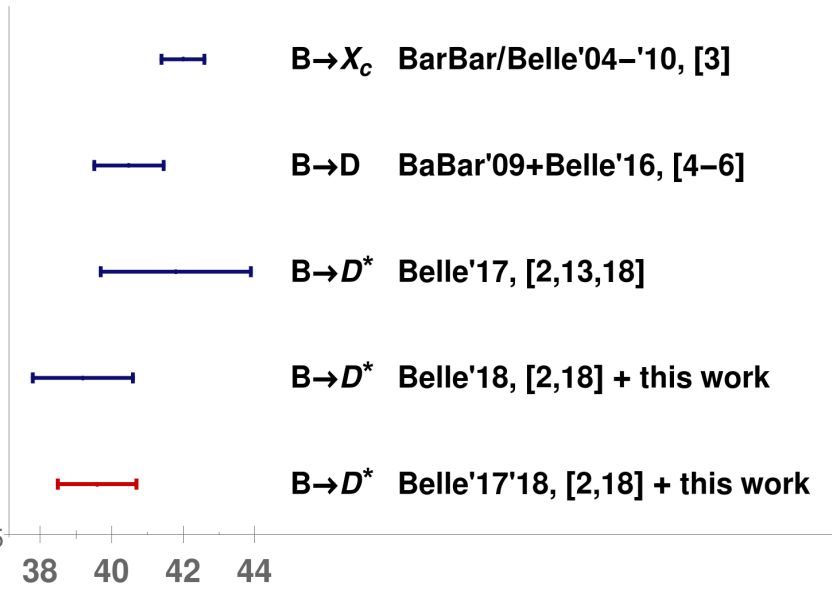
➥ *"Tension with the (V_{cb}) value from the inclusive approach remains"*

Analysis of 2017+2018 Belle data with BGL form factors:

- Datasets roughly compatible
- d'Agostini bias important
- All FFs to z^2 to include uncertainties
- 2018: no parametrization dependence

$$R(D^*) = 0.254^{+0.007}_{-0.006}$$





Theory determination of $b \to c$ Form Factors

SM: BGL fit to data + FF normalization $\to |V_{cb}|$

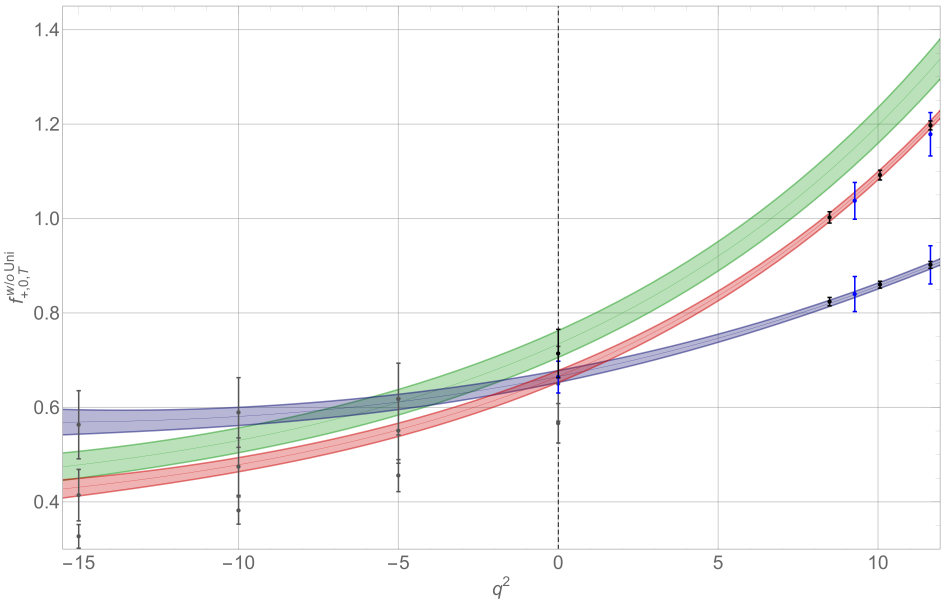
NP: can affect the q^2-dependence, introduces additional FFs

➥ To determine general NP, FF shapes needed from theory

In [MJ/Straub'18,Bordone/MJ/vDyk('19)] , we use all available theory input:

- Unitarity bounds (using results from [BGL,Bigi/Gambino(/Schacht)'16'17])
- LQCD for $f_{+,0}(q^2)$ $(B \to D)$, $h_{A_1}(q^2_{\max})$ $(B \to D^*)$ [HPQCD'15,'17,Fermilab/MILC'14,'15]
- LCSR for all FFs [Gubernari/Kokulu/vDyk'18]
- Consistent HQET expansion [Bernlocher+] to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$
  ➥ improved description

FFs under control;
$R(D^*) = 0.252(4)$
[Bordone/MJ/vDyk('19), **preliminary**]



$B \to D\pi$ vs. $B \to D^*$ I [MJ/vDyk('19)]

Claim in 2018 [Chavez-Saab/Toledo] : $R(D\pi) \sim 0.275$, "*Closing the gap*" . . .

➥ This was wrong, erratum: 0.253 (in line w/ others)

Erratum due to numerical issue; here: conceptual issue

The amplitudes for the decay chain are written as

$$\langle D^*(k,\eta)|\, \bar{c}\gamma^\mu(1-\gamma_5)b\, |\bar{B}(k+q)\rangle \equiv \eta^*_\alpha(k)\mathcal{M}^{\mu\alpha}$$
$$\langle D\pi|\, \mathcal{L}_{\rm QCD}\, |D^*(k,\eta)\rangle = \eta_{\alpha'}(k)\mathcal{M}^{\alpha'}$$

- $\mathcal{M}^{\mu\alpha}$ is then parametrized in a standard way by FFs
- The polarization sum in narrow width approximation yields

$$\sum_{\lambda=\pm1,0} \eta(\lambda)_\alpha \eta^*(\lambda)_{\alpha'} = -\left(g_{\alpha\alpha'} - \frac{k_\alpha k_{\alpha'}}{M^2_{D^*}}\right)$$

➥ For $k_\alpha k^\alpha = M^2_{D^*}$, a contribution $\sim k^\alpha$ in $\mathcal{M}^{\alpha\mu}$ vanishes!

$B \to D\pi$ vs. $B \to D^*$ II [MJ/vDyk('19)]

Allowing for a propagating off-shell D^*:
Additional terms have to be suppressed by $\Gamma_{D^*}/|k_{D^*}|$!

Why does that not happen in [Chavez-Saab/Toledo'18] ?

- $\mathcal{M}^{\alpha\mu}$ has to fulfill on-shell-condition $k_\alpha \mathcal{M}^{\alpha\mu} = 0$ for on-shell D^*!
- The standard FF parametrization does not fulfill this
  - ➥ Usually irrelevant due to the narrow-width approximation
  - ➥ Off-shell D^*: $k_\alpha \mathcal{M}^{\alpha\mu} = 0$ must be ensured modifiying FFs

$$q^\mu \mapsto q^\mu - \frac{(q \cdot k)}{k^2} k^\mu \,,$$

$$g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \mapsto g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} - \frac{k^\mu k^\nu}{k^2} + \frac{(q \cdot k)\, k^\mu q^\nu}{k^2\, q^2} \,.$$

Result: expected suppression of off-shell contributions
➥ Tiny, can be safely neglected

Conclusions

Indications of LFNU in $b \to c\tau\nu$ transitions remain exciting!

- Precision analyses require careful treatment of small effects
  - ➥ e.g. d'Agostini bias
- Form factors:
  - significant recent + coming progress in LQCD
  - new Belle data allows for improved $R(D^*)$ determination
  - theory determinations for NP required
  - combining theory information: FFs controlled @ $1/m_c^2$
- $B \to D\pi$ vs. $B \to D^*$: onshell-condition has to be included
  - ➥ Effects negligible

Exciting times ahead in semileptonic decays!

BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

➥ Relevant for $\sigma_{\mathrm{BR}}/\mathrm{BR} \sim \mathcal{O}(\%)$

Branching ratio measurements require normalization...

- B factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from B factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

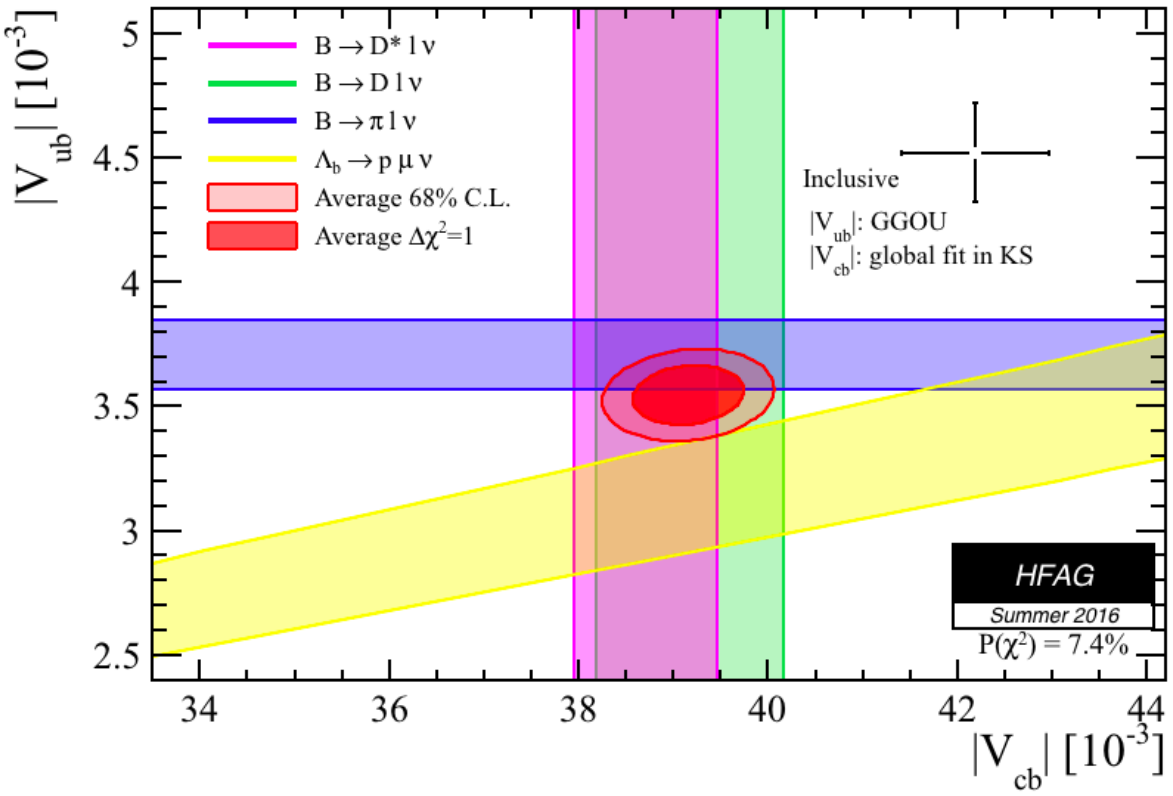
Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
  - ➥ This is one thing we want to test!

➥ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
(potentially subject to change, in contact with Belle members)

$|V_{xb}|$: inclusive versus exclusive

Long-standing problem, motivation for NP [e.g. Voloshin'97] :



- Very hard to explain by NP [Crivellin/Pokorski'15] (but see [Colangelo/de Fazio'15])

➥ Suspicion: experimental/theoretical systematics?

$|V_{cb}|$: Recent developments

Recent Belle $B \to D, D^* \ell\nu$ analyses

Recent lattice results for $B \to D$

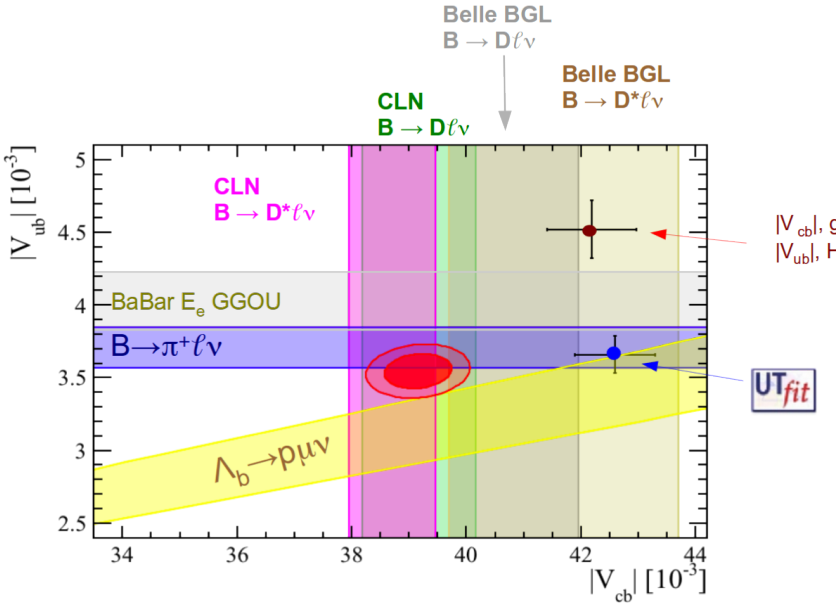
[FNAL/MILC, HPQCD, RBC/UKQCD (ongoing)]

➥ $B \to D$ between incl. + $B \to D^*$

New lattice result for $B \to D^*$ [HPQCD]

➥ $V_{cb}^{\rm incl}$ cv, compatible with old result

$B \to D^* \ell\nu$ re-analyses with CLN, $|V_{cb}| = 39.3(1.0)10^{-2}$ [Bernlochner+'17] + BGL [Bigi+,Grinstein+'17] (Belle only), $|V_{cb}| = 40.4(1.7)10^{-2}$



[Plot modification by M. Rotondo]

Theoretical uncertainties previously underestimated, in two ways:

- $1/m_c^2$ contributions likely underestimated in CLN
- Uncertainty given in CLN ignored in experimental analyses

➥ Inclusive-exclusive tension softened