Non-lattice perspective on V_{ub} and NP Searches

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Implications of LHCb measurements and future prospects
November 4th, 2015

The Tension between V_{ub} Determinations

However, the determinations of $|V_{ub}|$ from the individual decay channels do not agree well: [HFAG 2014, 1412.7515]

$$V_{ub}^{B\to\pi\mu\nu} = (3.28 \pm 0.29) \times 10^{-3} \qquad V_{ub}^{B\to X_u\mu\nu} = (4.41 \pm 0.21) \times 10^{-3}$$

What can cause the observed tension? (Focussing only on theory problems)

1. we do not understand the inclusive rate well enough
2. we do not understand the exclusive hadronic matrix elements well enough
3. new physics contributions affect the inclusive and exclusive rates differently

This talk: focus on options 2 and 3!

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Updates of QCD Sum Rules

QCD Sum Rules in a Nutshell

f_B from a 2-point QCD Sum Rule

$$F(p^2) = \int \frac{d^4x}{(2\pi)^4} e^{-ip\cdot x} \langle 0 | \mathcal{T}\left\{ j_5(x), j_5(0) \right\} | 0 \rangle$$

$$F^{\mathrm{OPE}}(p^2) = \int_{m_b^2}^{\infty} \frac{\rho^{\mathrm{OPE}}(s)\mathrm{d}s}{s - p^2}$$

$$F^{\mathrm{had}}(p^2) = \frac{f_B^2 M_B^2}{M_B^2 - p^2} + \int_{(M_B + 2M_\pi)^2}^{\infty} \frac{\rho(s)\mathrm{d}s}{s - p^2}$$

Apply Borel transform $p^2 \to M^2$, and introduce some threshold $s_0 > m_b^2$ so that

$$f_B^2 = \frac{1}{M_B^2} \int_{m_b^2}^{s_0} e^{-\frac{s - M_B^2}{M^2}} \rho^{\mathrm{OPE}}(s)\mathrm{d}s$$

Then determine s_0 from M^2 independence of f_B^2.

Decay Constants

[Gelhausen,Khodjamirian,Pivovarov,Rosenthal 1404.5891]

- updates all heavy-meson decay constants ($B_{(s)}$ and $D_{(s)}$ systems)
- first study to take impact of radially-excited states into account

$$\rho(s) \supset \frac{M_{B'}\Gamma_{B'}}{(s - M_{B'}^2)^2 + M_{B'}^2\Gamma_{B'}^2} M_{B'}^2 f_{B'}^2$$

for radially-excited B' meson with $J^P = 0^-$

- excerpt: results for f_B

$$f_B = 207^{+17}_{-9}\ \text{MeV} \qquad \text{w/o radially-excitated state}$$

$$f_B = 200^{+18}_{-10}\ \text{MeV} \qquad \text{w/ radially-excitated state}$$

compatible with FLAG average ($N_f = 2 + 1$) at less than 1σ

Extracting V_{ub} from $B \to \tau\nu$

Branching ratio measurements

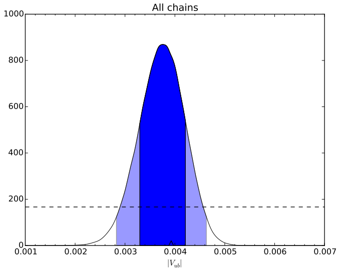
(sys+stat error combined)

$$\mathcal{B}(B^+ \to \tau^+\overline{\nu}) = (1.70 \pm 0.82) \cdot 10^{-4}$$ [BaBar 0912.2453 (semileptonic tag)]

$$\mathcal{B}(B^+ \to \tau^+\overline{\nu}) = (1.83^{+0.58}_{-0.55}) \cdot 10^{-4}$$ [BaBar 1207.0698 (hadronic tag)]

$$\mathcal{B}(B^+ \to \tau^+\overline{\nu}) = (0.72^{+0.29}_{-0.27}) \cdot 10^{-4}$$ [Belle 1208.4678 (hadronic tag)]

$$\mathcal{B}(B^+ \to \tau^+\overline{\nu}) = (1.25 \pm 0.39) \cdot 10^{-4}$$ [Belle 1503.05613 (semileptonic tag)]



Result for $|V_{ub}|$ [my own fit using 1404.5891]

- result
  $|V_{ub}^{B\to\tau\nu}| = (3.75^{+0.45}_{-0.45}) \cdot 10^{-3}$
- goodness of fit
  $\chi^2/\text{d.o.f.} = 4.16/3$
  good fit, with p value of 0.24

QCD Sum Rules in a Nutshell

$f_+^{B\pi}(q^2)$ from a Light-Cone QCD Sum Rule

$$F(q^2,(p+q)^2) = \int \frac{d^4x}{(2\pi)^4} e^{-iq\cdot x} \langle \pi(p) | \mathcal{T}\{J_\mu(x), j_5(0)\} |0\rangle \Big|_{p_\mu \text{ coeff. only}}$$

$$F^{\text{OPE}}(q^2,(p+q)^2) = \int_{m_b^2}^{\infty} \frac{\rho^{\text{OPE}}(q^2,s)\mathrm{d}s}{s-(p+q)^2}$$

$$F^{\text{had}}(q^2,(p+q)^2) = \frac{f_B f_+^{B\pi}(q^2) M_B^2}{M_B^2-(p+q)^2} + \int^{\infty} \frac{\rho(q^2,s)\mathrm{d}s}{s-(p+q)^2}$$

Final sum rule after Borel transformation

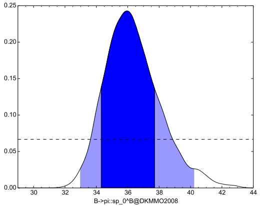
$$f_+^{B\pi} = \frac{1}{f_B M_B^2} \int_{m_b^2}^{s_0} e^{-\frac{s-M_B^2}{M^2}} \rho^{\text{OPE}}(s)\mathrm{d}s$$

$B \to \pi$ Form Factor from LCSR

[Imsong,Khodjamirian,Mannel,DvD 1409.7816]

LCSR Results

- Bayesian framework with gaussian prior for Borel parameters
  - constrain thresholds from first moment of sum rule
  - peaking posterior for thresholds
- posterior-predictive distributions for the form factor yield
  - $f_+(q^2)$, 1st and 2nd derivatives w.r.t. q^2
  - evaluated at two q^2 points:
    $q^2 = 0$ and $q^2 = 10\,\text{GeV}^2$
  - 6-by-6 correlation matrix
    largest corr.: $\rho\left[f_+(0), f_+(10\,\text{GeV}^2)\right] = 0.925$
  - parametric uncertainties reduced to $\sim 8\%$



$B \to \pi$ Form Factor from LCSR

[Imsong,Khodjamirian,Mannel,DvD 1409.7816]

Fit to z Series

$$f_+^{B\pi}(q^2) = \frac{f_+^{B\pi}(0)}{1 - q^2/M_{B^*}^2}$$
$$\times \left[1 + b_1^+(z(q^2) - z(0)) + b_2^+ O\left(z^2\right) + b_3^+ O\left(z^3\right)\right]$$

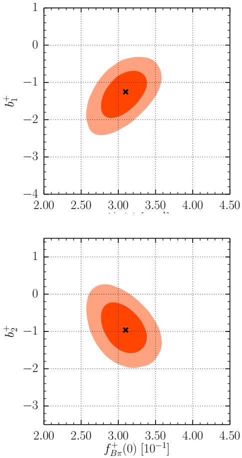
$z \equiv z(q^2)$:

- conformal map from q^2 to complex z plane
- automatically fulfills analyticity constraints

fitting 3 parameters:

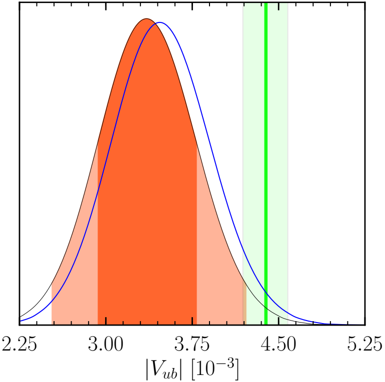
- normalization $f_+^{B\pi}(0)$
- two shape parameters b_1^+, b_2^+
- b_3^+ fixed from threshold behaviour

parametrization follows [Bourrely,Caprini,Lellouch 0807.2722]



Extracting V_{ub} from $B \to \pi^+ \mu \overline{\nu}$

[Imsong,Khodjamirian,Mannel,DvD 1409.7816]



- 2010 data: Belle+BaBar, 6 bins $q^2 \leq 12\,\text{GeV}^2$
- 2010 data vs inclusive: barely compatible @ 99% prob.
- 2013 data: Belle+BaBar, 6 bins $q^2 \leq 12\,\text{GeV}^2$
- 2013 data increases tension
- 1D marginals:
  - $|V_{ub}|^{2010} = (3.43^{+0.27}_{-0.23}) \cdot 10^{-3}$
  - $|V_{ub}|^{2013} = (3.32^{+0.26}_{-0.22}) \cdot 10^{-3}$

68%, 95%, 99% prob. contours for 2010 data
68%, 95%, 99% prob. contours for 2013 data
central value and 68% CL interval for GGOU [HFAG 2014, 1412.7215]

$\overline{B} \to \{\rho, \omega\}$ Form Factors from LCSR [Bharucha,Straub,Zwicky 1503.05534]

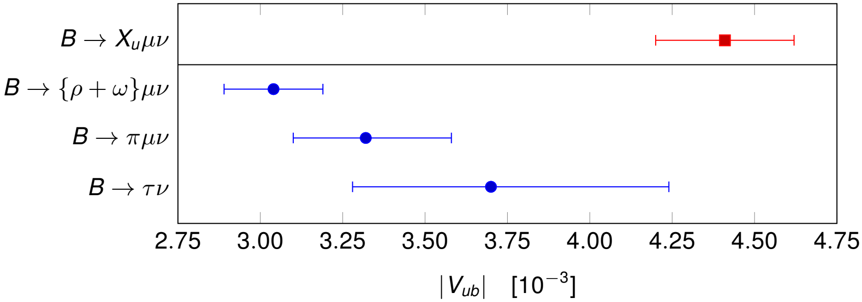
- update $B_{(s)} \to V$ form factor results, $V = \rho, \omega, K^*, \phi$
- changes to previous analyses reduce parametric uncertainties
  - extensive use of equations of motion to reduce number of threshold parameters
  - correlate threshold and Borel parameters for f_B and form factor sum rules
- z-series fit to LCSR (and LCSR+Lattice) result
  - form factors at $q^2 = 0$ and shape parameters
  - find sizeable correlations among fit parameters
  - numeric results available as ancillary files

Extracting V_{ub} from $B \to \{\rho, \omega\}\mu\bar{\nu}$

[Bharucha,Straub,Zwicky 1503.05534]

- use of various bins, $|V_{ub}|$ available for each bin
- from $B \to \rho\ell\nu$:
  - BaBar, $q^2 < 7\,\text{GeV}^2$, $|V_{ub}| = (2.54 \pm 0.33) \times 10^{-3}$
  - Belle, $q^2 < 8\,\text{GeV}^2$, $|V_{ub}| = (3.45 \pm 0.27) \times 10^{-3}$
  - Belle, $q^2 < 12\,\text{GeV}^2$, $|V_{ub}| = (3.29 \pm 0.22) \times 10^{-3}$
- from $B \to \omega\ell\nu$:
  - BaBar, $q^2 < 8\,\text{GeV}^2$, $|V_{ub}| = (3.33 \pm 0.41) \times 10^{-3}$
  - BaBar, $q^2 < 12\,\text{GeV}^2$, $|V_{ub}| = (3.31 \pm 0.36) \times 10^{-3}$
  - Belle, $q^2 < 7\,\text{GeV}^2$, $|V_{ub}| = (2.54 \pm 0.42) \times 10^{-3}$
- my naive weighted average: $|V_{ub}| = (3.04 \pm 0.15) \times 10^{-3}$

Comparison of Non-Lattice $|V_{ub}|$



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New Physics Searches

Search for NP in Semileptonic $b \to u$ Transitions

Effective Field Theory

Modify the effective $b \to u\ell\nu$ vertex by adding a different chirality in the hadronic current:

$$\mathcal{L}^{\text{eff}}_{b\to u} = \frac{G_F V^{\text{eff}}_{ub}}{\sqrt{2}} \left[\mathcal{C}_{V,L}\mathcal{O}_{V,L} + \mathcal{C}_{V,R}\mathcal{O}_{V,R}\right]$$

where

$$\mathcal{O}_{V,R} = [\bar{u}(x)\gamma^{\mu}(1+\gamma_5)b(x)]\,[\bar{\ell}(x)\gamma_{\mu}(1-\gamma_5)\nu(x)]$$

Consequently:

- $|V_{ub}^{B\to\tau\nu}|^2 \to |V_{ub}^{\text{eff}}|^2 \left|\mathcal{C}_{V,L} - \mathcal{C}_{V,R}\right|^2$
- $|V_{ub}^{B\to\pi\ell\nu}|^2 \to |V_{ub}^{\text{eff}}|^2 \left|\mathcal{C}_{V,L} + \mathcal{C}_{V,R}\right|^2$
- $|V_{ub}^{\text{incl.}}|^2 \to |V_{ub}^{\text{eff}}|^2 \left(|\mathcal{C}_{V,L}|^2 + |\mathcal{C}_{V,R}|^2\right)$

Strategy

[Feldmann, Müller, DvD 1503.09063]

- fit $\mathcal{C}_{V,L}$ and $\mathcal{C}_{V,R}$ from data ($B \to \tau\overline{\nu}$, $B \to \pi\mu\nu$, $B \to X_u\mu\nu$)
  - choose global phase as phase of $V_{ub}^{\text{eff}} \cdot \mathcal{C}_{V,L}$
  - $\mathcal{C}_{V,L}$ is real-valued in the fit
- introduce nuisance parameters for exclusive decays, using informative priors
  - $B^- \to \tau^-\overline{\nu}$: B decay constant f_B from 2ptSRs
    [Gelhausen,Khodjamirian,Pivovarov,Rosenthal 1404.0891]
  - $\overline{B}^0 \to \pi^+\mu^-\overline{\nu}$: form factor $f_+(q^2)$ from LCSRs
    [Imsong,Khodjamirian,Mannel,DvD 1409.7816]
- use several fit scenarios and perform statistical comparison
  1. no right-handed currents: $\mathcal{C}_{V,R} = 0$, fit $\mathcal{C}_{V,L}$
     - equivalent to determination of $|V_{ub}| = |V_{ub}^{\text{eff}}\mathcal{C}_{V,L}|$
  2. real-valued right-handed currents
  3. complex-valued right-handed currents

Results

[Feldmann, Müller, DvD 1503.09063]

Scenario 1

- find $|\mathcal{C}_{V,L}| = 1.02 \pm 0.05$ at 68% probability
  - corresponds to $|V_{ub}| = (4.07 \pm 0.20) \cdot 10^{-3}$ at 68% prob.
- $\chi^2 = 18.54$ for 28 degrees of freedom
  - excellent fit with p value of 91%
- however: form factor pull does not enter χ^2
  - 3 form factor parameters with pull of $\sim 3\sigma$

Scenario 2 and 3

- best fit point: $C_{V,L} = 1.025$, $\mathrm{Re}\,(C_{V,R}) = -0.079 + i\,0$
- χ^2 increases to 20.47 for 27 (26) degrees of freedom
  - still very good fit with p value of 81% (77%)
- $\mathcal{C}_{V,R}$ compensates need to adjust form factor (FF pull down to $\sim 2\sigma$)
- looses against scenario 1 in posterior odds with 1 : 27.8 (1 : 100)

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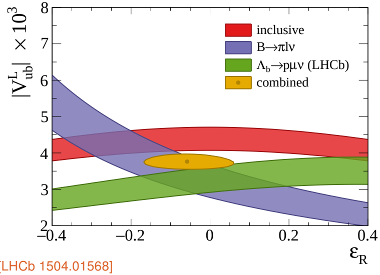
Comments on V_{ub} from $\Lambda_b \to p\ell\overline{\nu}$



[LHCb 1504.01568]

The LHCb measurement of V_{ub} in $\Lambda_b \to p\ell\overline{\nu}$ is the first measurement of V_{ub} in a baryon decay.

The different spin structure between meson and baryon decays gives rise to complementary information on the Wilson coefficients $\mathcal{C}_{V,L(R)}$.

But: The V_{ub} extraction relies heavily on the normalization to $\Lambda_b \to \Lambda_c\mu\overline{\nu}$. In fact, LHCb extracts the ratio V_{ub}/V_{cb}. Needs accurate and precise predictions of the ratio of (binned) hadronic matrix elements, currently only available from lattice QCD

[Detmold,Lehner,Meinel 1503.01421]

However: We can test the lattice results by applying continuum QCD methods.

Testing the $\Lambda_b \to \Lambda_c$ Form Factors

[T. Mannel, DvD 1506.08780]

Inclusive bound from 2pt correlation function

$$T_\Gamma(\varepsilon) \sim \int \mathrm{d}^4x\, e^{i(v\cdot x)\varepsilon} \langle \Lambda_b | \mathcal{T}\left\{ \bar{b}_v(x)\Gamma c_v(x), \bar{c}_v(0)\Gamma b_v(0) \right\} |\Lambda_b\rangle$$

- v: velocity of the b and c quark in the Λ_b rest frame
- ε: excitation energy of the intermediate state above M_{Λ_c}

Contour integral of $T(\varepsilon)$ encompasses *all* contributions to the imaginary part of the forward matrix element:

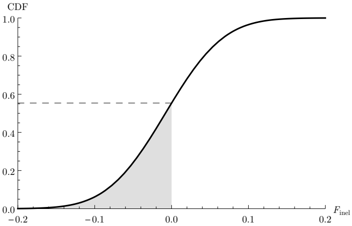
- elastic
- all inelastic

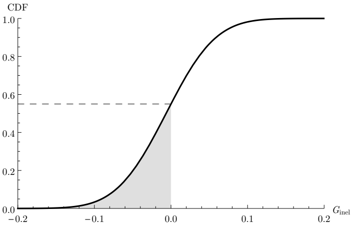
upper bound on the sum of exclusive form factors at the zero recoil point.

Inelastic Contributions at Zero-Recoil

- $X_{\text{inel}} \equiv$ difference between inclusive bound and lattice values at zero recoil
  - draw samples from predictive distributions
  - expect $X > 0$
- $X = F, G$, for vector and axialvector currents, respectively

For both currents we find that the lattice results for the $\Lambda_b \to \Lambda_c$ transitions exceed the inclusive bounds at 55% probability.





But: $\langle X_{\text{inel}} \rangle$ of the same size as leading OPE uncertainty $O\left(\alpha_s/m^2\right)$.

Conclusion

Conclusion

- tension between $|V_{ub}|^{\text{incl}}$ and $|V_{ub}|^{\text{excl}}$ persists
  - progress in QCD sum rules progress cannot alleviate the tension
- the tension could be due to New Physics
  - global analysis suggests that right-handed currents alone cannot explain the tension
- LHCb's measurement of $\Lambda_b \to p\mu^-\overline{\nu}$ important for V_{ub}/V_{cb} determination; complementary probe of NP
  - however: zero-recoil sum rules suggest that $\Lambda_b \to \Lambda_c$ lattice form factors are slightly too large

In Memoriam

Imkong Sentitemsu Imsong

† October 30th 2015