Angular analysis of $\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ with hadronic tagging at *BABAR*

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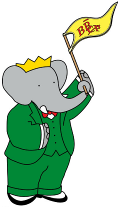
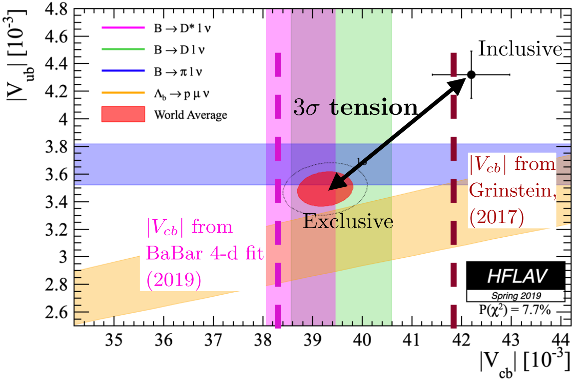
(on behalf of the BaBar Collaboration)

ICHEP, Bologna, 2022



$|V_{ub}|$-$|V_{cb}|$: TENSIONS IN TWO CRITICAL PARAMETERS

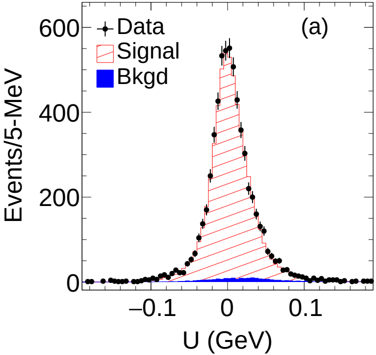


- Circa 2017, Grinstein/ Gambino: $|V_{cb}|$ "resolved" by zero-recoil extrapolation issue?
- 2019: back to the drawing board.
- 2021/22: lattice $w > 1$ FF's.

- Note: some tension in $|V_{cb}|$ between $B \to D^*$ and $B \to D$.
- Stress-testing HQET and flavor-SU(3) ($B \to D^{(*)}$ vs $B_s \to D_s^{(*)}$).
- Implications of the form-factors on SL LFUV.

Recap of *BABAR*-19 $B \to D^*$ paper [PRL123, 091801 (2019)]

- First full 4-d $\overline{B} \to D^* \ell^- \overline{\nu}_\ell$ angular analysis with hadronic tagging.
- Single missing neutrino fully reconstructed ($U = E_\nu - p_\nu$).



- Extremely clean. Percent level resolutions in angular variables.
- ~ 6000 signal events. $N = 2$ (linear) BGL (hep-ph/9508211) fit adequate.
- Negligible effect on extracted $|V_{cb}|$ between BGL and CLN FF parameterisations.

HQET FF's and the ratio observables

- H_λ amplitudes are written in terms of four form-factors.
- HQET: FF's only depend on w, the gamma-factor between B and recoiling D^*.

$$\frac{\langle D^*(v',\varepsilon)|V^\mu|\overline{B}(v)\rangle}{\sqrt{m_B m_{D^*}}} = i h_V(w)\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu v'_\alpha v_\beta$$

$$\frac{\langle D^*(v',\varepsilon)|A^\mu|\overline{B}(v)\rangle}{\sqrt{m_B m_{D^*}}} = h_{A_1}(w)(w+1)\varepsilon^{*\mu} - h_{A_2}(w)(\varepsilon^*\cdot v)v^\mu - h_{A_3}(w)(\varepsilon^*\cdot v)v'^\mu$$

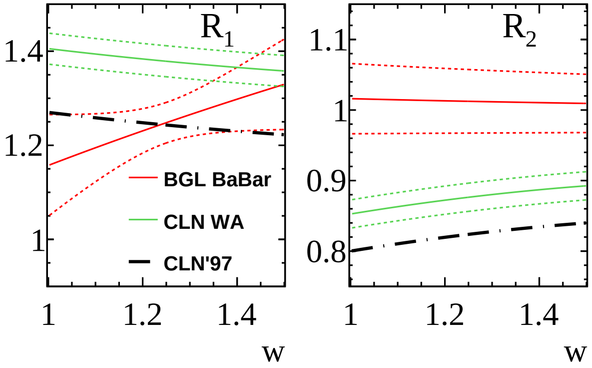
$$A_1 = \frac{w+1}{2} r' h_{A_1}$$

$$A_2 = \frac{r h_{A_2} + h_{A_3}}{r'} \equiv \frac{R_2 h_{A_1}}{r'}$$

$$V = \frac{h_V}{r'} \equiv \frac{R_1 h_{A_1}}{r'}$$

- HQS limit: $\{h_V, h_{A_1}, h_{A_3}\} \to \zeta(w)$ and $h_{A_2} \to 0$.
- The two ratio observables $R_{1,2}$ have reduced hadronic uncertainties.
- BGL basis $\{f_0, F_1, g, F_2\}$: rewrites h_{V,A_1,A_2,A_3}.

BABAR-19: DEVIATIONS IN $R_{1,2}$



- Figure as is, from the *BABAR*-19 paper using BGL fits.
- "CLN-WA" used HFLAV16 numbers.
- CLN'97: original paper w/o uncertainties.

$R_{1,2}$ CONUNDRUM (CONTD.)

- $R_1(1)$ moved from 1.404 ± 0.032 (HFLAV16) to 1.269 ± 0.026 (HFLAV21, *BABAR*-19 not included). Almost 3.3σ change! Latest number is close to *BABAR*-19.

- Experimentally, needs to be resolved: $R_2(1) \sim [h_{A_2}, h_{A_3}]/h_{A_1}$. HFLAV21 (excluding *BABAR*-19) quotes $R_2(1) \sim 0.85$.

Further developments: lattice $w > 1$ data

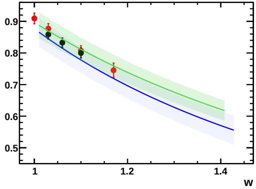
- Significant inputs from lattice now in $w > 1$ for $B \to D^*$. Independent validations of FFs.
- FNAL/MILC and JLQCD ($B \to D^*$) and HPQCD ($B_s^0 \to D_s^*$, full q^2). Lots of checks possible.
- Checks for flavor SU(3) in $B_{(s)} \to D_{(s)}^*$. Include BABAR $B \to D$ data.
- Goal: joint $B \to D^{(*)}$ HQET fits including all information, to interpret the FFs.
- Caveat: *everything shown today is preliminary*.

$B \to D^*$ BABAR + LATTICE FITS: SETUP

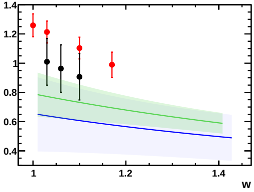
- Dataset remains the same as in BABAR-19 paper ($N_{\text{sig}} \sim 6000$).
- Main change is access to $N = 3$ BGL expansion due to including the new lattice $w > 1$ data w/o breaking unitarity conditions.
- $\{3, 3, 3, 2\}$ z expansion configuration for BGL basis $\{f_0, F_1, g, F_2\}$.
- F_2 is least constrained. Lattice-only.
- Try various combinations of BABAR + lattice:
  - **BaBar+lattice fit result** is in green.
  - HPQCD data is blue
  - FNAL/MILC data is red.
  - JLQCD data is black.
- HPQCD $B_s \to D_s^*$ FF converted to $B \to D^*$ using flavor SU3.

BaBar + HPQCD [FNAL/MILC, JLQCD]

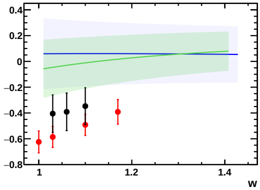
h_{A_1}:



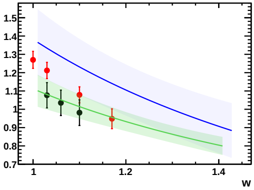
h_{A_3}:



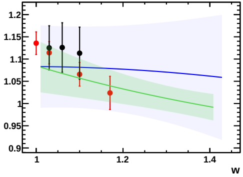
h_{A_2}:



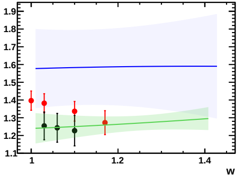
h_V:



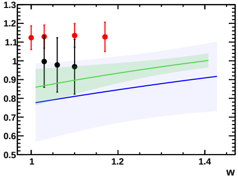
R_0:



R_1:

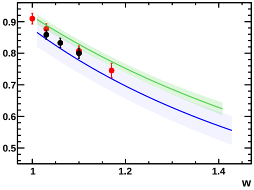


R_2:

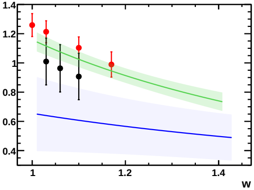


BaBar + FNAL/MILC [HPQCD, JLQCD]

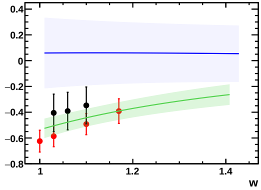
h_{A_1}:



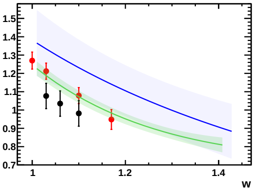
h_{A_3}:



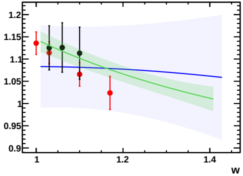
h_{A_2}:



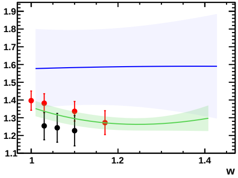
h_V:



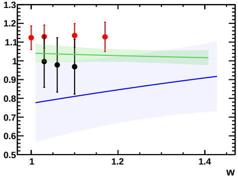
R_0:



R_1:

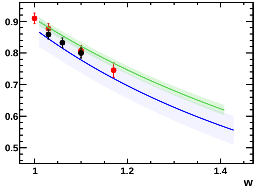


R_2:

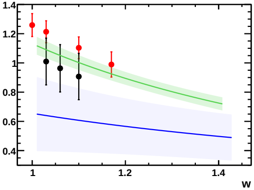


BaBar + FNAL/MILC + HPQCD [JLQCD]

h_{A_1}:



h_{A_3}:



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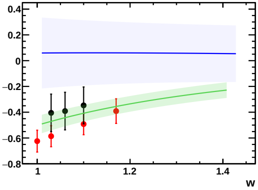
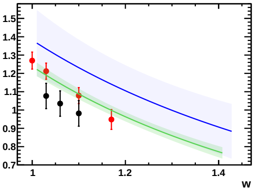
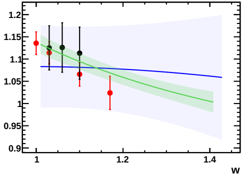


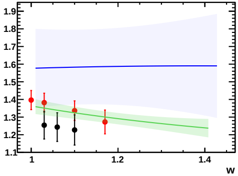
h_V:



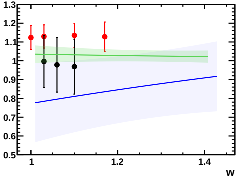
R_0:



R_1:

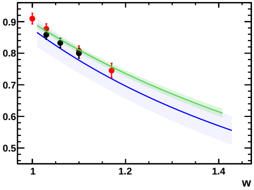


R_2:

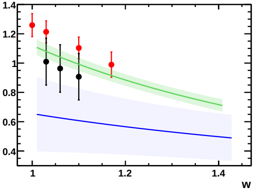


BaBar + FNAL/MILC + HPQCD + JLQCD

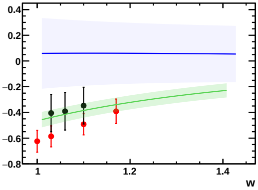
h_{A_1}:



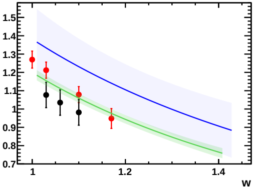
h_{A_3}:



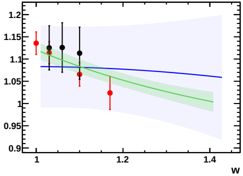
h_{A_2}:



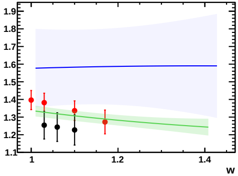
h_V:



R_0:



R_1:



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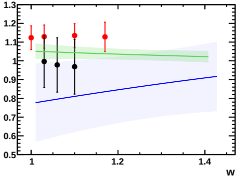

TAKEAWAYS: FORM-FACTORS

- Adding three new independent lattice data over the past two years did not change the overall conclusions in *BABAR*-2019 paper.
- Especially true in the "clean" ratio observables $R_{1,2}$.
- Some movement among different lattice calculations.
- HPQCD errors are largest and trends show some deviations from *BABAR* +FNAL/MILC+JLQCD. Flavor SU3 violation for $B \to D^*$?
- These combined fits are most precise, and also robust (no funny instabilities).

Fit qualities

Type	BABAR NLL	MILC χ^2	HPQCD χ^2	JLQCD χ^2
HPQCD	103441	69.7	3.6	25.1
MILC+JLQCD	103441	14.2	20.2	5.7
ALL	103443	13.1	8.0	5.9

- Also FNAL/MILC uncertainties as provided are smallest.
- Overall, BABAR can accommodate the new lattice data (χ^2/ndf<1) quite well.

Effect of lattice on $|V_{cb}|$

- Use HFLAV-16 $B \to D^*$ BFs, but include all lattice data now.
- $|V_{cb}| \times 10^3$ moves from 38.36 ± 0.90 to 38.93 ± 0.68. *Not* sensitive to zero-recoil extrapolation.

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- $|V_{cb}| \times 10^3$ moves from 38.36 ± 0.90 to 38.93 ± 0.68. *Not* sensitive to zero-recoil extrapolation.
- Using the updated HFLAV-21 BFs, the number is 39.83 ± 0.71.
- Uncertainties on the BGL coefficients certainly improves the lattice data. No issue with unitarity as well.

Charged RH current search

- Heavy RH W^- boson: deviation from pure $(V - A)$ structure.
- Parameterization: $h_V \to h_{V,SM}(1 + \varepsilon_R)$. Axial FF's unchanged.
- Smoking gun: strong discrepancy between lattice (pure SM) and data (SM+NP) in $R_1(1)$, along with good agreement in $R_2(1)$.
- Lattice fixing the SM FF's allows ε_R searches from just the shape (independent of $|V_{cb}|$).
- *BABAR* +lattice fits converged, blinded.

Summary and next steps

- *BaBar*-19 FF + $|V_{cb}|$ conclusions very robust. Survives checks from new lattice data and combined *BaBar*-lattice results most precise FFs.
- *BaBar* $B \to D$ data getting ready to be incorporated in joint $B \to D^{(*)}$ HQET fits.
- Stringent test for HQET: can adding higher order corrections allow fitting the data.

The generic 4-d PDF [PRD 92, 033013 (2015)]

- Differential rate (4-d fit pdf):

$$\frac{d\Gamma}{dq^2 d\Omega} \propto \sum_{i=1}^{14} f_i(\Omega)\Gamma_i(q^2)$$

- Transversity q^2 amplitudes:

$$H_0(q^2) \equiv h_0$$
$$H_{\{\parallel,\perp\}}(q^2) \equiv h_{\{\parallel,\perp\}} \underbrace{e^{i\delta_{\{\parallel,\perp\}}}}_{\text{NP phase}}$$

- Orthonormal angular basis:
  - $Y_l^m \equiv Y_l^m(\theta_l, \chi)$
  - $P_l^m \equiv \sqrt{2\pi} Y_l^m(\theta_V, 0)$

i	$f_i(\Omega)$	$\Gamma_i^{\text{tr}}(q^2)/(\mathbf{k}q^2)$
1	$P_0^0 Y_0^0$	$h_0^2 + h_\parallel^2 + h_\perp^2$
2	$P_2^0 Y_0^0$	$-\frac{1}{\sqrt{5}}(h_\parallel^2 + h_\perp^2) + \frac{2}{\sqrt{5}} h_0^2$
3	$P_0^0 Y_2^0$	$\frac{1}{2\sqrt{5}}\left[(h_\parallel^2 + h_\perp^2) - 2h_0^2\right]$
4	$P_2^0 Y_2^0$	$-\frac{1}{10}(h_\parallel^2 + h_\perp^2) - \frac{2}{5} h_0^2$
5	$P_2^1 \sqrt{2}\, Re(Y_2^1)$	$-\frac{3}{5} h_\parallel h_0 \cos\delta_\parallel$
6	$P_2^1 \sqrt{2}\, Im(Y_2^1)$	$\frac{3}{5} h_\perp h_0 \sin\delta_\perp$
7	$P_0^0 \sqrt{2}\, Re(Y_2^2)$	$-\frac{3}{2\sqrt{15}}(h_\parallel^2 - h_\perp^2)$
8	$P_2^0 \sqrt{2}\, Re(Y_2^2)$	$\frac{\sqrt{3}}{10}(h_\parallel^2 - h_\perp^2)$
9	$P_0^0 \sqrt{2}\, Im(Y_2^2)$	$\sqrt{\frac{3}{5}} h_\perp h_\parallel \sin(\delta_\perp - \delta_\parallel)$
10	$P_2^0 \sqrt{2}\, Im(Y_2^2)$	$-\frac{\sqrt{3}}{5} h_\perp h_\parallel \sin(\delta_\perp - \delta_\parallel)$
11	$P_0^0 Y_1^0$	$-\sqrt{3} h_\perp h_\parallel \cos(\delta_\perp - \delta_\parallel)$
12	$P_2^0 Y_1^0$	$\frac{3}{\sqrt{15}} h_\perp h_\parallel \cos(\delta_\perp - \delta_\parallel)$
13	$P_2^1 \sqrt{2}\, Re(Y_1^1)$	$\frac{3}{\sqrt{5}} h_\perp h_0 \cos\delta_\perp$
14	$P_2^1 \sqrt{2}\, Im(Y_1^1)$	$-\frac{3}{\sqrt{5}} h_\parallel h_0 \sin\delta_\parallel$