# $\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ analysis with *BABAR* data and comparison with new lattice predictions

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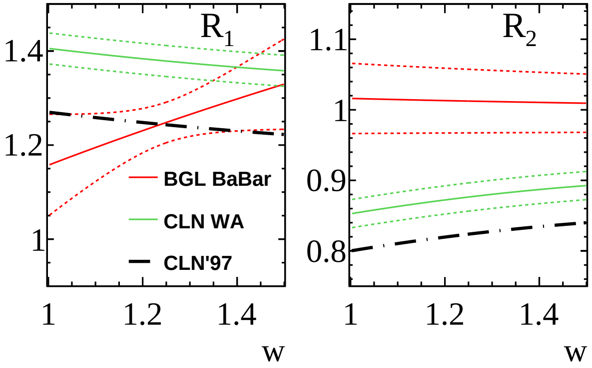
# Highlights from the *BABAR*-19 $B \to D^*$ paper

- First full 4-d $\overline{B} \to D^* \ell^- \overline{\nu}_\ell$ angular analysis with hadronic tagging: 1903.10002.
- Exclusive $|V_{cb}|$ showed little dependence on BGL/CLN and remained in tension with inclusive.
- Strong deviation with CLN-WA in $R_{1,2}(1)$ FF ratios:




- Figure as is, from the *BABAR*-19 paper.
- "CLN-WA" used HFLAV16 numbers.

# SUMMARY OF *BABAR*-19 RESULTS (CONTD.)

- $R_1(1)$ moved from $1.404 \pm 0.032$ (HFLAV16) to $1.269 \pm 0.026$ (HFLAV21, *BABAR*-19 not included). Almost $3.3\sigma$ 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 (new today!)

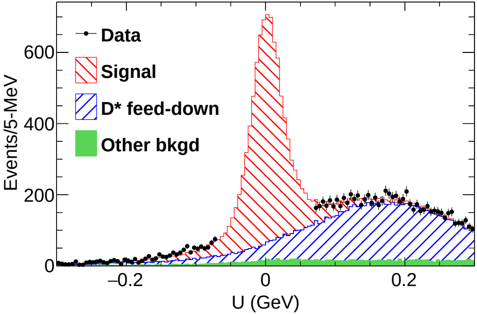
- Significant inputs from lattice now in $w > 1$ for $B \to D^*$. Independent validations of FFs.
- MILC and JLQCD ($B \to D^*$) and HPQCD ($B_s^0 \to D_s^*$, full $q^2$). Lots of checks possible.
- Checks for flavor SU(3) in $B_{(s)} \to D_{(s)}^*$.
- Include *BaBar* $B \to D$ data. Flavor SU3 checks.
- Goal: joint $B \to D^{(*)}$ HQET fits including all information, to interpret the FFs.
- Caveat: *everything shown today is preliminary*.

# $B \to D$: INTRODUCTION

- Rate $\propto \sin^2\theta_\ell \mathbf{k}^3|f_+|^2$. $\lambda = 0$ projection of spin-1 $W^{*+}$.
- Scalar/tensor current searches for $\cos\theta_\ell$ terms interesting, but we need new MC flat in $\cos\theta_\ell$ (not available).
- Lattice has access to $f_0$ FF with the $q^2 = 0$ relation $f_+(0) = f_0(0)$. HISQ uses this relation at $w = w_{\rm max}$.
- Data analysis has two challenges:
  - Acceptance and background subtraction do *not* factorize. Really a 2d problem.
  - Large $D^*$ feeddown has strong PHSP dependence.
- We perform a full 2-d unbinned ML angular analysis, with special care for a data-driven background subtraction.

# Stacked histograms for $B \to D\ell^- \overline{\nu}_\ell$

- After all selections (all modes merged):



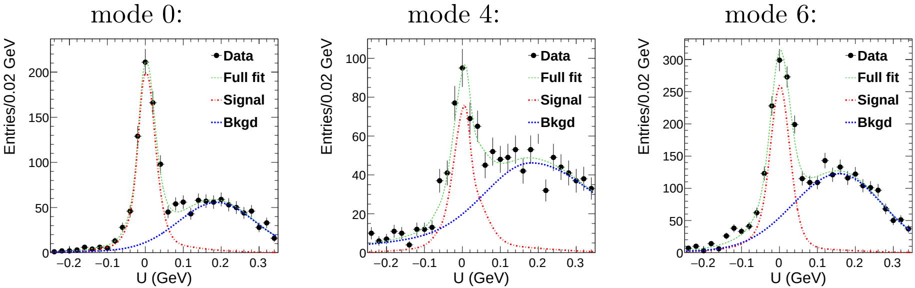

- $U = E_{\text{miss}} - p_{\text{miss}}$ in the $B$ RF. Better variable than $mm^2$.
- Main take-aways: no peaking component and the (out of the box generic $B\bar{B}$) MC follows the data well in the sidebands.
- Assume background template from MC under the signal. Signal part is handled in a data-driven fashion.

# Breakdown into individual modes

- Main motivation is that each mode has different acceptance and background characteristics.
- Handled independently and the NLL's summed in the end.

| $\ell^-$ | $D$ | decay mode | mode |
|---|---|---|---|
| $e^-$ | $D^0$ | $K^-\pi^+$ | 0 |
| | | $K^-\pi^+\pi^0$ | 1 |
| | | $K^-\pi^+\pi^-\pi^+$ | 2 |
| $e^-$ | $D^+$ | $K^-\pi^+\pi^+$ | 3 |
| | | $K^-\pi^+\pi^+\pi^0$ | 4 |
| $\mu^-$ | $D^0$ | $K^-\pi^+$ | 5 |
| | | $K^-\pi^+\pi^0$ | 6 |
| | | $K^-\pi^+\pi^-\pi^+$ | 7 |
| $\mu^-$ | $D^+$ | $K^-\pi^+\pi^+$ | 8 |
| | | $K^-\pi^+\pi^+\pi^0$ | 9 |

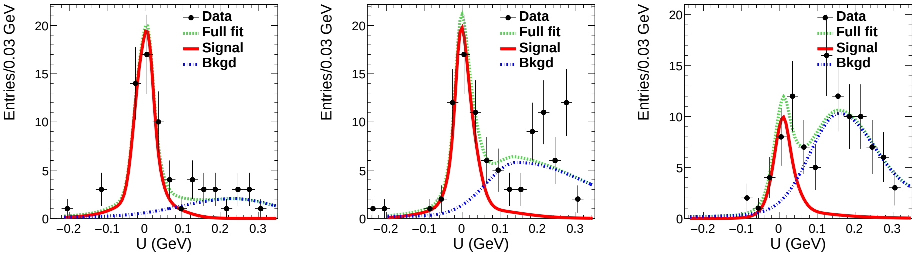
# Sample data fits, integrated over $q^2$ and $\cos\theta_\ell$




- The central widths of the signal are allowed to be floated slightly for Data/MC differences. The normalizations are always floated.

# Sample data fits in different $\cos\theta_\ell$ bins

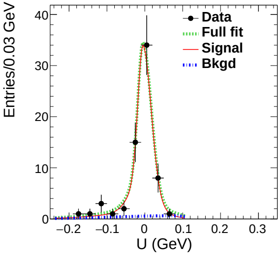
$\cos\theta_\ell = -0.55$: $\cos\theta_\ell = 0.45$: $\cos\theta_\ell = 0.75$:




- Background *shape* varies in phase-space and modewise. Shown for mode 2.
- Signal-background separation method tracks this correlation smoothly in $q^2$-$\cos\theta_\ell$. Assigns an event-wise signal probability/weight, $Q_i$. Unlike sWeights, always $> 0$.

# The $q^2 \to 0$ region issue

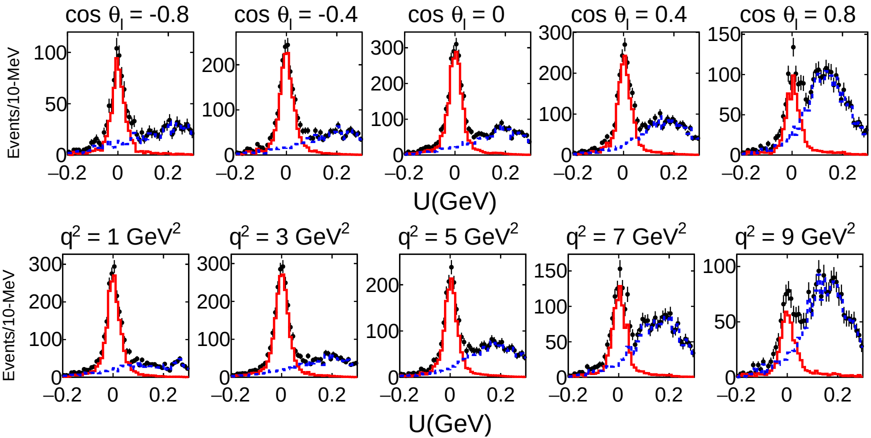
- $q^2 < 0.5$ GeV$^2$ region: clean and significant signal.
- However, background peaks, so very difficult to estimate the background in a data-driven fashion.




- Same issue in *BABAR*-10 and Belle-16 $B \to D\ell^-\overline{\nu}_\ell$.
- Phase-space "edges" trimmed. Fiducial region is $|\cos\theta_\ell| < 0.97$ and $q^2 \in [0.5, 10]$ GeV$^2$

# Final signal-background separation results

- signal and background integrated over all modes and phase-space.



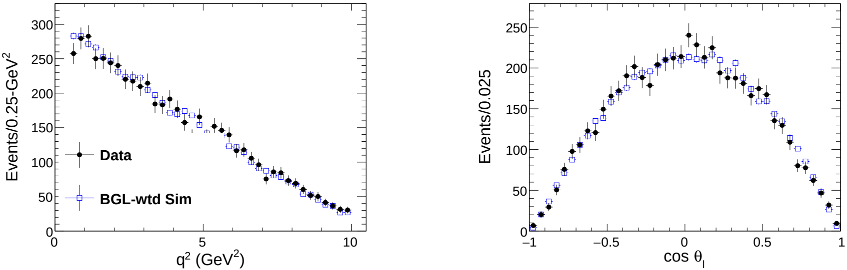

- Tails removed subsequently with $|U| < 50$ MeV cut.

# "Non-extended" UML angular fits

- Unbinned maximum likelihood fits without absolute normalization (tagging efficiency).
- BGL: $N = 2$ (nominal) and $N = 3$ tested. CLN as well.
- Lattice MILC (1503.07237) constrains the $w \to 1$ region.
- To extract $|V_{cb}|$, include Belle (1510.03657) $d\Gamma/dw$ points.
- External data added as Gaussian constraints to the fit NLL.

# 1-D PROJECTIONS

- "Accepted" MC weighted by the fit results should match the background-subtracted data.




- Expected $\sin^2\theta_\ell$ shown for $B \to D\ell^-\overline{\nu}_\ell$ for the first time. Demonstrates quality of neutrino reconstruction.
- NP via deviations from this behavior has been searched in $B \to K\mu^+\mu^-$ at LHCb.

# $B \to D$ NUMERICAL RESULTS (NOT SHOWN)

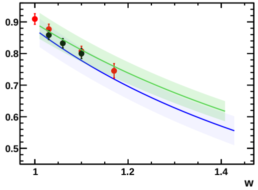
- Dominant systematic is the background subtraction.
- PRD being prepared: $|V_{cb}|$ from $B \to D$, form-factors and flavor SU3 checks with $B_s \to D_s$ (HPQCD)
- Update to previous *BABAR* 2010 paper (0904.4063). Main goal is to prepare data for joint $B \to D^{(*)}$ fits.

# $B \to D^*$ BaBar + lattice fits: setup

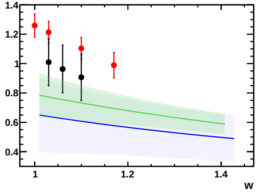
- Dataset remains the same as in BaBar-19 paper.
- Main change is access to $N = 3$ BGL expansion due to including the new lattice $w > 1$ data w/o breaking unitarity conditions.
- $\{3, 3, 3, 2\}$ $z$ expansion configuration for BGL basis $\{f_0, F_1, g, F_2\}$.
- $F_2$ is least constrained. Lattice-only.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

BaBar + HPQCD [MILC, JLQCD]

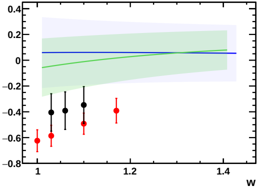
$h_{A_1}$:



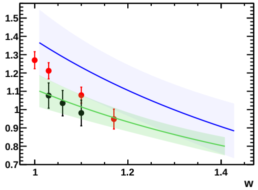

$h_{A_3}$:



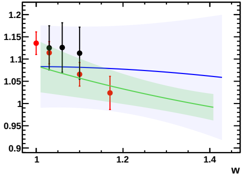

$h_{A_2}$:



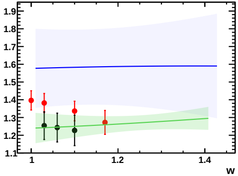

$h_V$:



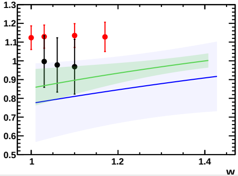

$R_0$:




$R_1$:

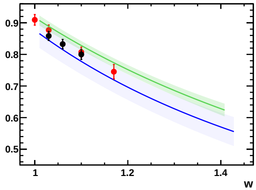



$R_2$:

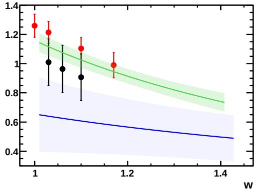


## BaBar + MILC [HPQCD, JLQCD]

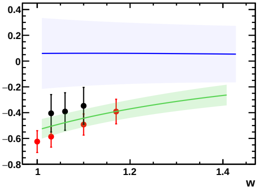
$h_{A_1}$:



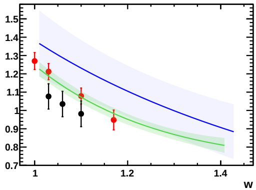

$h_{A_3}$:



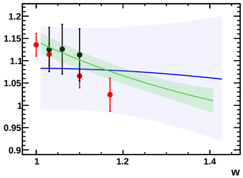

$h_{A_2}$:



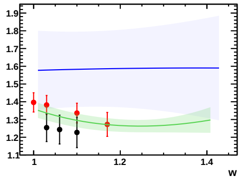

$h_V$:



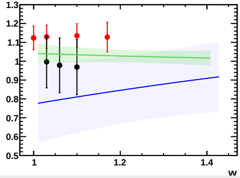

$R_0$:




$R_1$:

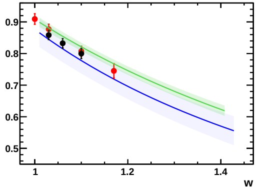



$R_2$:

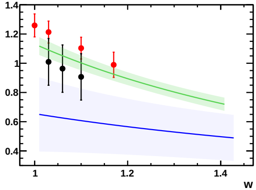


## BaBar + MILC + HPQCD [JLQCD]

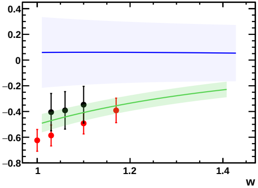
$h_{A_1}$:



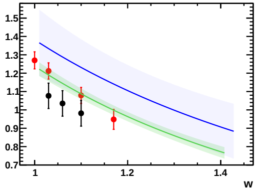

$h_{A_3}$:



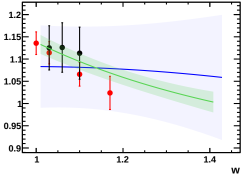

$h_{A_2}$:



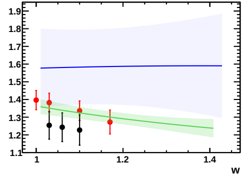

$h_V$:



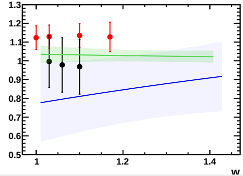

$R_0$:




$R_1$:

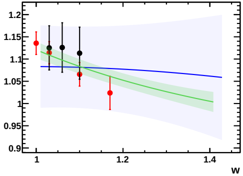



$R_2$:

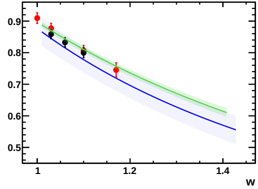


# BaBar + MILC + HPQCD + JLQCD

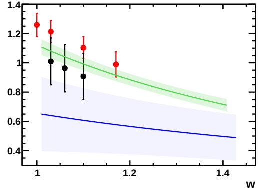
$R_0$:



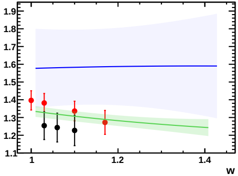

$h_{A_1}$:



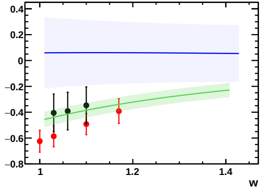

$h_{A_3}$:



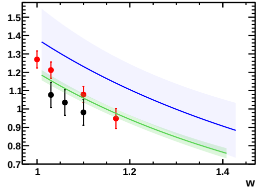

$R_1$:



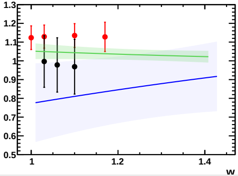

$h_{A_2}$:




$h_V$:




$R_2$:



# Takeaways

- 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* +MILC+JLQCD. Flavor SU3 violation for $B \to D^*$?
- These combined fits are most precise, and also robust (no funny instabilities).

# Summary of fit results

| Type | *BABAR* NLL | MILC $\chi^2$ | HPQCD $\chi^2$ | JLQCD $\chi^2$ |
|---|---|---|---|---|
| HPQCD | 103441 | 69.7047 | 3.58412 | 25.0954 |
| MILC+JLQCD | 103441 | 14.1659 | 20.1721 | 5.63138 |
| ALL | 103443 | 13.1148 | 7.97299 | 5.91532 |

- Number of data points: 14 (MILC), 12 (HPQCD, JLQCD).
- Also MILC uncertainties as provided are smallest.
- Overall, *BABAR* can accommodate the new lattice data 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 $38.36 \pm 0.90$ to $38.93 \pm 0.68$,
- Using the updated HFLAV-21 BFs, the number is $39.83 \pm 0.71$.
- Uncertainties on the BGL coefficients certainly improves the lattice data. No issue with unitarity as well.

# RH current searches

- Parameterization: $h_V \to h_V(1 + \varepsilon_R)$. Axial FF's unchanged.
- Fits converged, blinded.
- Smoking gun: strong discrepancy between lattice (pure SM) and data (SM+NP) in $R_1(1)$, along with good agreement in $R_2(1)$.

# Summary and next steps

- *BABAR* $B \to D$ data getting ready to be incorporated in joint $B \to D^{(*)}$ HQET fits.
- *BABAR*-19 FF + $|V_{cb}|$ conclusions very robust. Survives checks from new lattice data and combined *BABAR*-lattice results most precise FFs.
- We're waiting for the updated BLPR paper for the joint $B \to D^{(*)}$ HQET fits.

# $Q$-VALUE TECHNIQUE

- Signal/background lineshapes varying strongly in PHSP: Near PHSP edges or specific backgrounds.
- Metric $d_{ij} = \sum_k (\phi_{k,i} - \phi_{k,j})^2$ to define closest-neighbor points.
- Event-wise fits on $N_c = 50, 100, ...$ closest-neighbor points.
- Extract $Q_i = S_i/(S_i + B_i)$ as $> 0$ probability/weights for each data event.
- CPU-heavy (GPUs?), but gets around the problem of correlations.