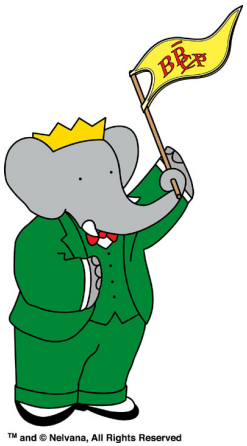
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ with hadronic tagging at *BABAR*

[PRL123,091801(2019) + PRD110,032018(2024)]

Biplab Dey

(on behalf of the BaBar Collaboration)

Challenges in SL decays, Vienna 2024



$|V_{ub}|$ AND $|V_{cb}|$: FLAGSHIP SM VARIABLES

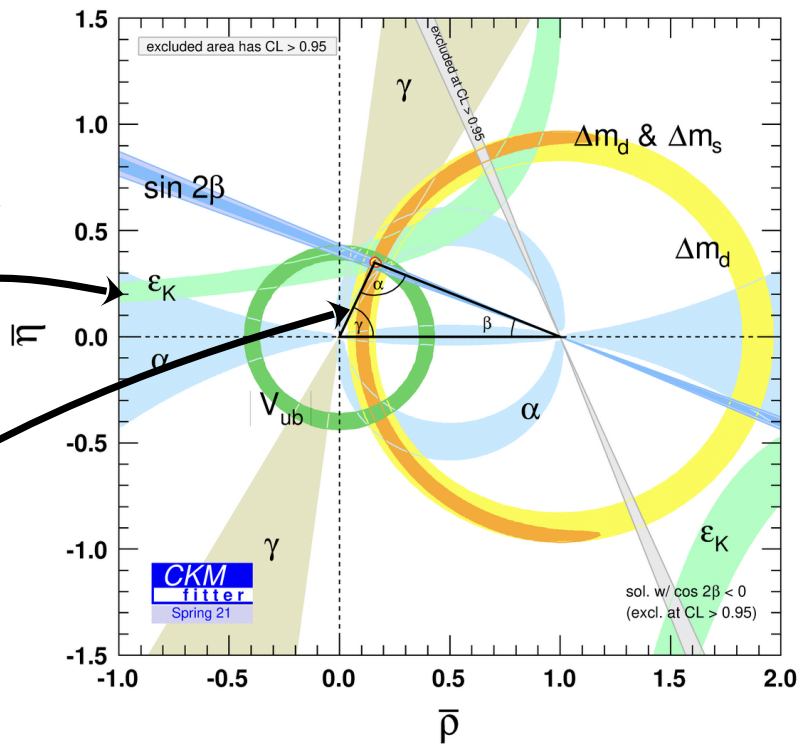
- V_{xb} play critical roles in the unitarity test of $V_{\rm CKM}$.

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \overset{V_{ub}}{A\lambda^3(\rho-i\eta)} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} V_{cb} \sim 0.04$$

Unitarity Triangle

$$\varepsilon_K \propto |V_{cb}|^4$$

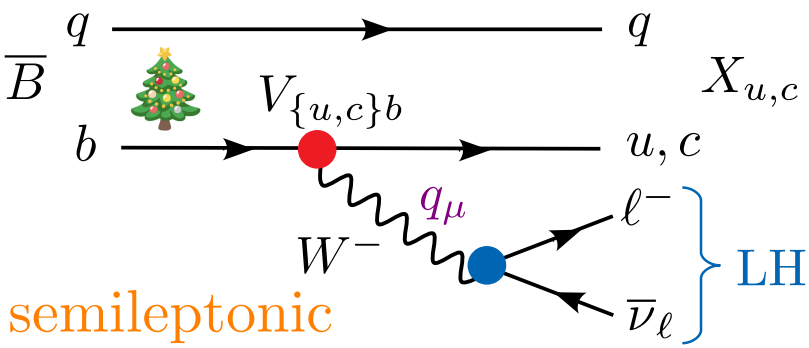
$$\frac{|V_{ub}|}{|V_{cb}|} \sim (10 \pm 0.4)\%$$



- $\sin 2\beta$ (loop) known to better than 2%. Side opposite is $|V_{ub}|/|V_{cb}|$.
- Rare FCNC processes $\propto |V_{cb}|^2 \left[\frac{|V_{tb}^* V_{ts}|^2}{|V_{cb}|^2}\right] \Rightarrow$ theory uncertainty.

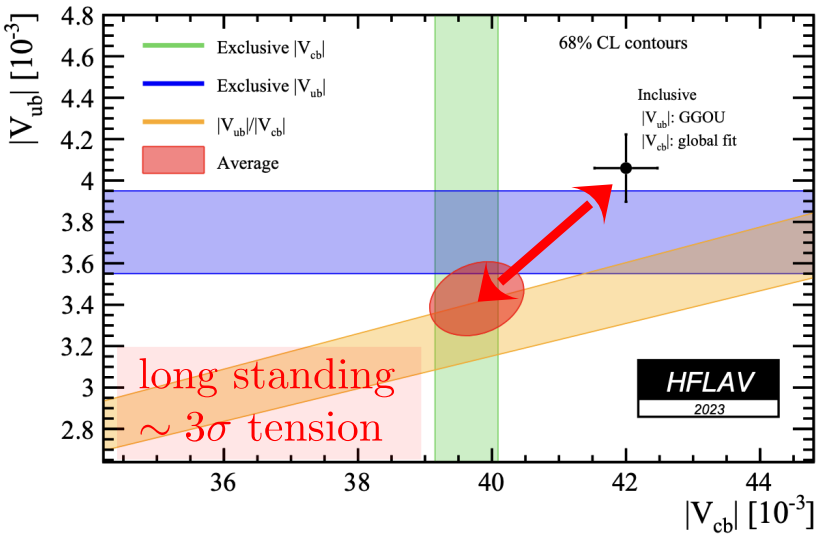
$|V_{ub}|$ AND $|V_{cb}|$: PROCEDURES AND TENSIONS

- Leptonic $B^+_{u,c} \to \tau^+ \nu_\tau$: theoretically clean, experimentally hard.



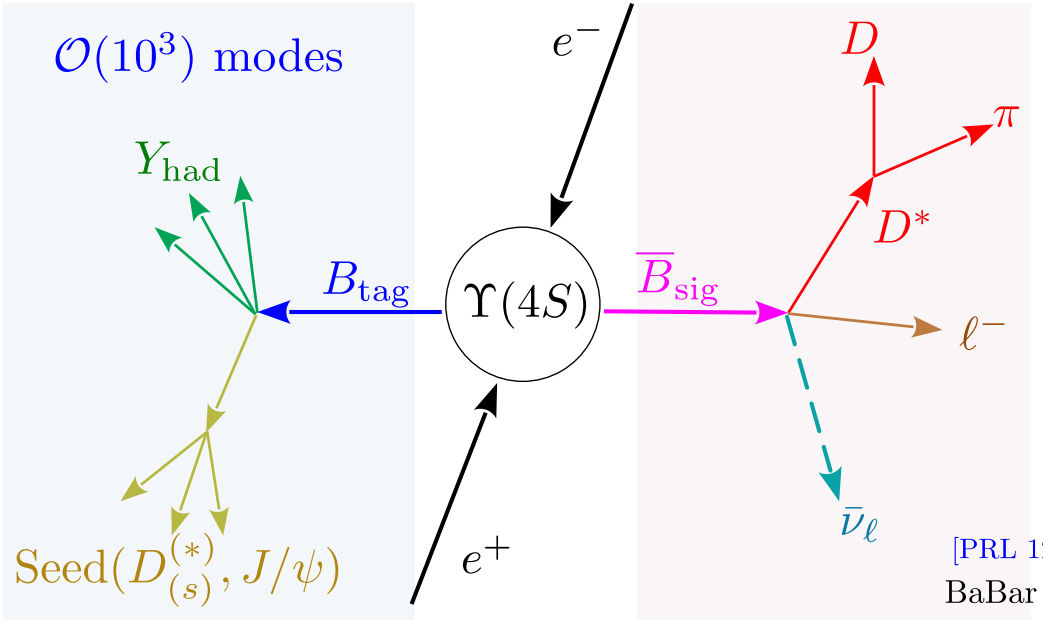
- $X_{u,c}$ is exclusive $\{\pi, \rho, \omega, D^{(*)}...\}$. Or inclusive sum of states.
- Different theory inputs: OPE (inclusive) and FFs (exclusive)

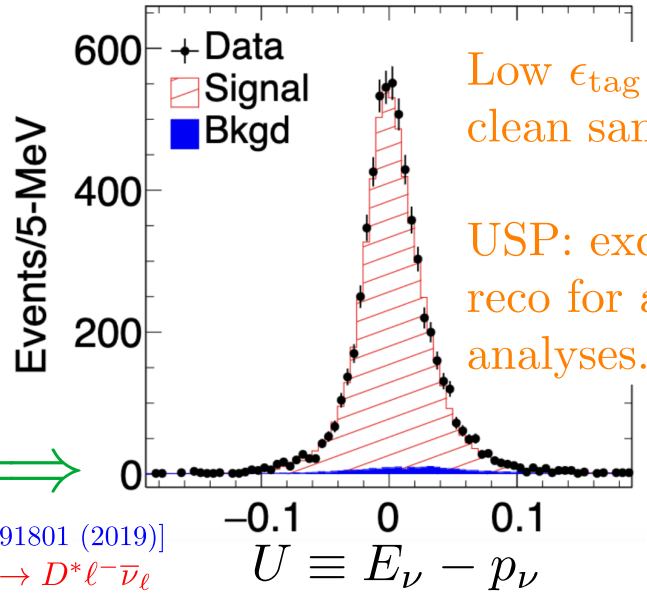
- Exclusive systematically lower than inclusive for both $|V_{ub}|$ and $|V_{cb}|$ by $\sim$ 5-10%.
- QCD effects, experimental issues with the normalizations, or NP?



To tag or not to tag

- $\mathcal{B}(B \to X_c \ell^- \overline{\nu}_\ell) \sim 10\%$. Dominant statistics, but at least one missing neutrino $\Rightarrow$ hadronic tagging at e^+e^- machines.





Low $\epsilon_{\rm tag}$ but clean sample.

USP: excellent $\vec{p}_\nu$ reco for angular analyses.

[PRL 123, 091801 (2019)]
BaBar $B \to D^* \ell^- \overline{\nu}_\ell$

- BF measurements: calibration for ensuring $\dfrac{\epsilon^{\rm MC}_{\rm tag}\big|_{\rm signal}}{\epsilon^{\rm MC}_{\rm tag}\big|_{\rm control}} \to 1$ is hard.

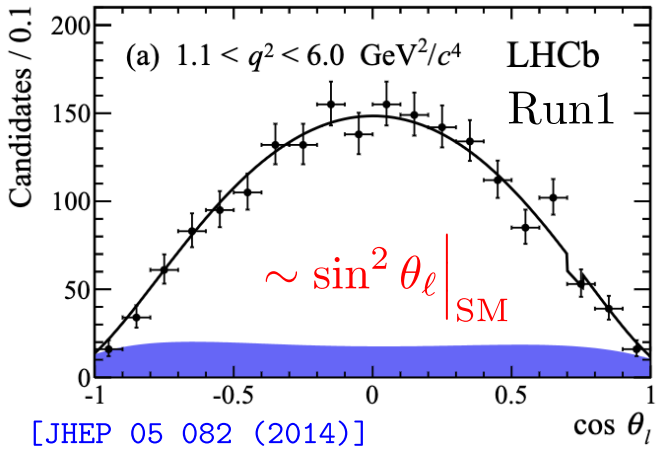
$B \to D\ell^-\overline{\nu}_\ell$

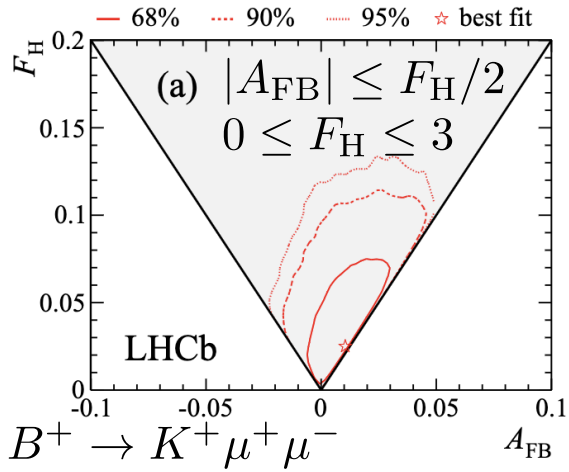
[PRD110,032018 (2024)]

$\overline{B} \to D\ell^-\overline{\nu}_\ell$: ORIGINAL MOTIVATION

- θ_ℓ: lepton helicity angle in W^* rest frame.
- In SM, (almost) pure $\sin^2\theta_\ell$. Look for non-zero $F_{\rm H}$ and $A_{\rm FB}$ in rate $\propto \frac{3}{4}(1-F_{\rm H})\sin^2\theta_\ell + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_\ell \Rightarrow$ SM null test.

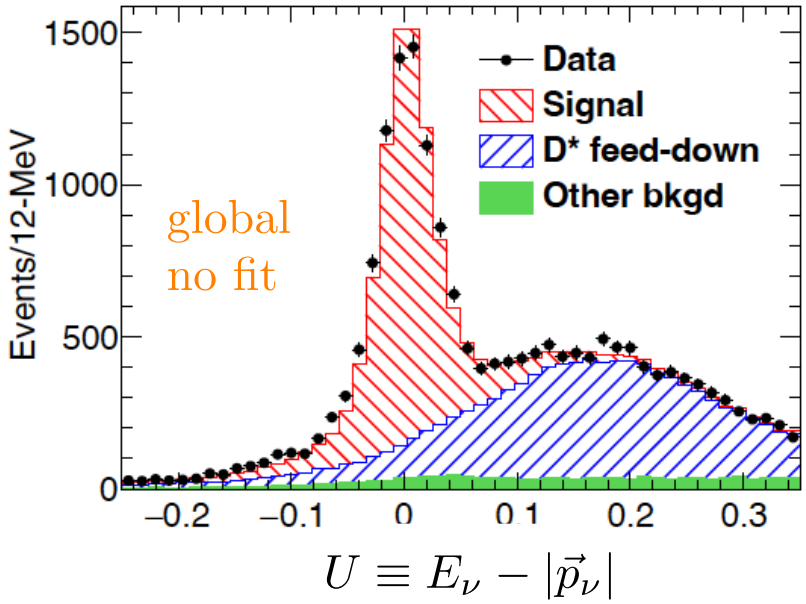
- Done at LHCb for $B^+ \to K^+\mu^+\mu^-$.
- Unfortunately, *BABAR* MC generated as $\sin^2\theta_\ell$. Needed flat.

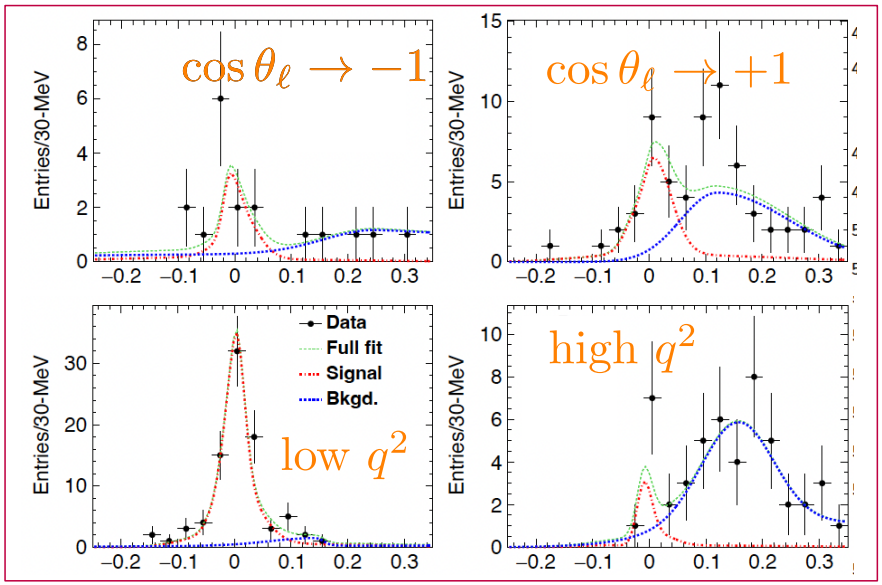




- $\overline{B} \to D\ell^-\overline{\nu}_\ell$ at *BABAR* complicated by the fact it's a sum of 10 different modes with independent backgrounds, angular efficiencies.

$B \to D\ell^-\overline{\nu}_\ell$: ANALYSIS SETUP





- Full *BABAR* dataset w/ hadronic tagging. 2d problem in $\{q^2, \cos\theta_\ell\}$.

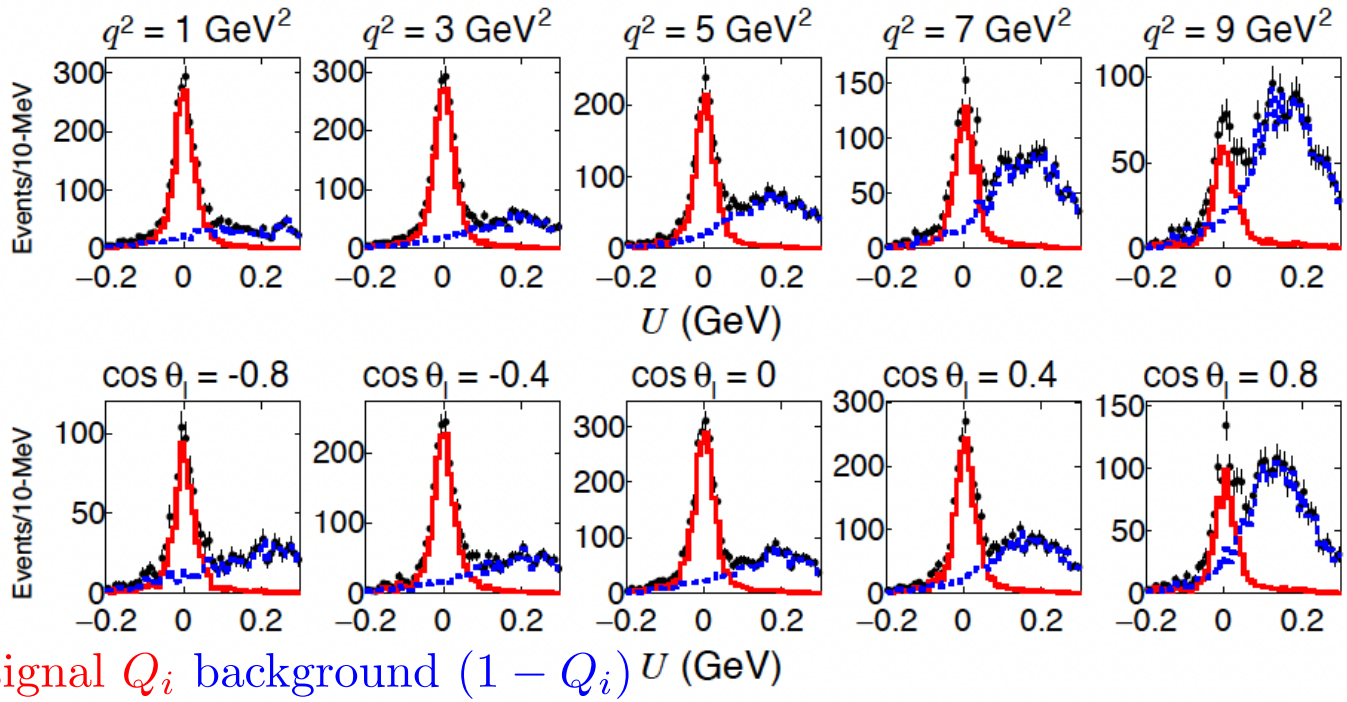
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell} = \frac{G_F^2|V_{cb}|^2\eta_{\mathrm{EW}}^2}{32\pi^3}k^3|f_+(q^2)|^2\sin^2\theta_\ell$$

- Rate factorizes but efficiency and background correlated.
- U-fit in "local" phase-space for given event. Signal/background *shapes* from sim. $\Rightarrow$ data-driven.
- Event-wise weight for unbinned angular fits: $Q_i = \dfrac{\mathcal{S}(U_i)}{\mathcal{S}(U_i) + \mathcal{B}(U_i)}$

Bkgd subtraction validations

ℓ^-	D	decay mode	mode	$N_{\rm sig}$	$N_{\rm bkgd}$
e^-	D^0	$K^-\pi^+$	0	539	63
		$K^-\pi^+\pi^0$	1	813	196
		$K^-\pi^+\pi^-\pi^+$	2	550	82
e^-	D^+	$K^-\pi^+\pi^+$	3	721	41
		$K^-\pi^+\pi^+\pi^0$	4	204	120
μ^-	D^0	$K^-\pi^+$	5	433	64
		$K^-\pi^+\pi^0$	6	798	221
		$K^-\pi^+\pi^-\pi^+$	7	608	84
μ^-	D^+	$K^-\pi^+\pi^+$	8	665	55
		$K^-\pi^+\pi^+\pi^0$	9	233	134
			Total	5563	1061

- Lineshapes also depend on the reconstruction mode. 10 modes are treated independently.
- Unlike sWeights, tracks correlations between sig/bkgd lineshapes and phase-space.

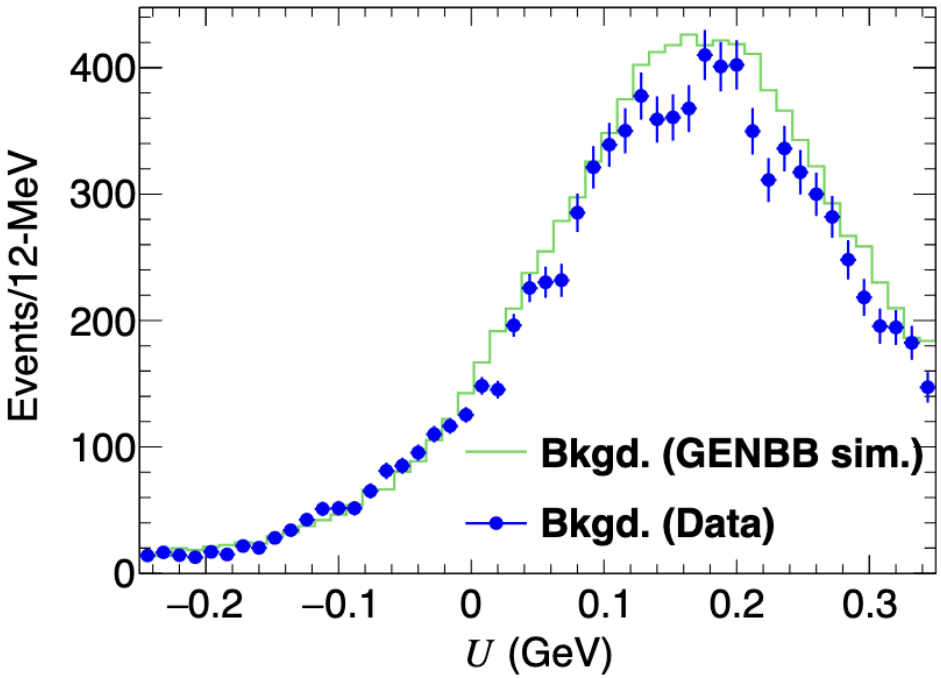


signal Q_i background $(1 - Q_i)$

- 1d projections, integrated over all 10 modes.

Bkgd subtraction validations (contd.)

- Final Q-value fits done with signal/bkgd. shapes fixed from MC. Within statistics, seen to work quite well. Variations as systematic uncertainties.
- Comparison between final data and generic $B\overline{B}$ MC bkgd.:



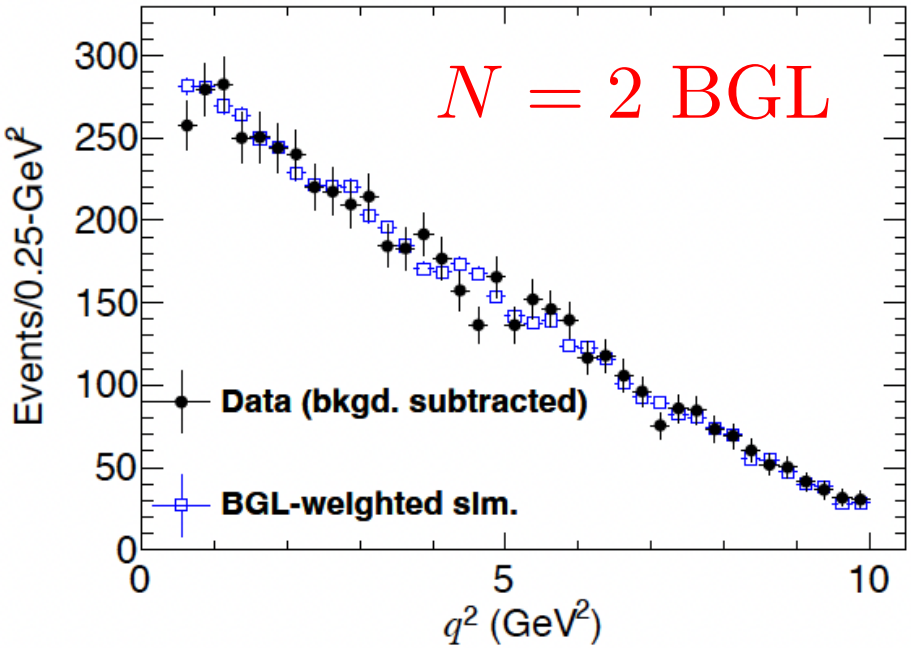
- Fortunately the MC does a pretty good job in getting the shapes right.
- Detailed mode-by-mode fit validations in fine 1-d bins in $\{q^2, \cos\theta_\ell\}$ performed.

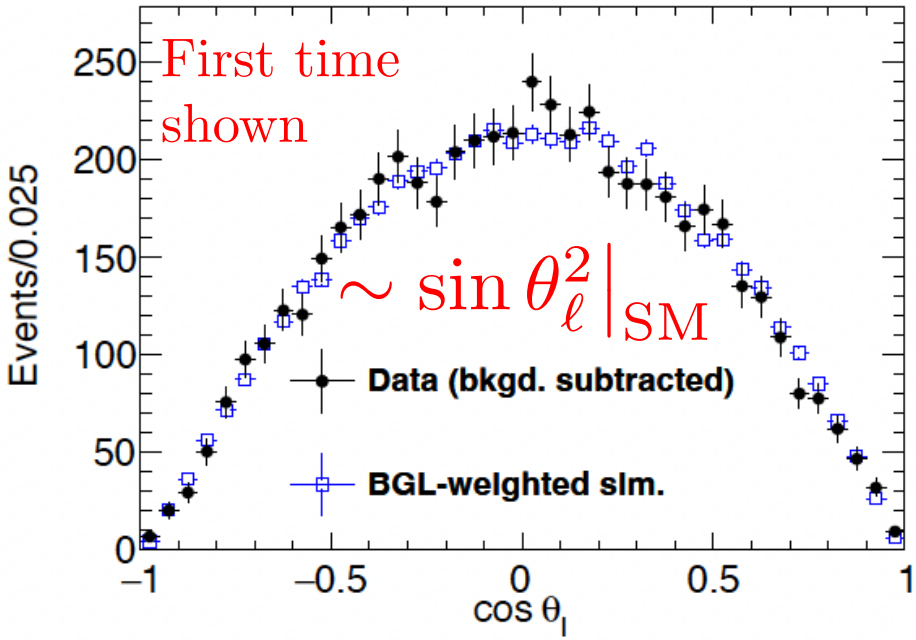
BGL FIT RESULTS

- BGL z-expansion fit to form-factors f_+ and f_0 ($\to$ lattice, time-like)

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_n^i z^n$$

- Unbinned non-extended ML 2d fits to *BABAR* + FNAL/MILC (Gaussian constraints). $d\Gamma/dq^2$ from Belle-16 optionally included.
- Independent $[-2\ln\mathcal{L}]_k$ from 10 modes summed at the end.



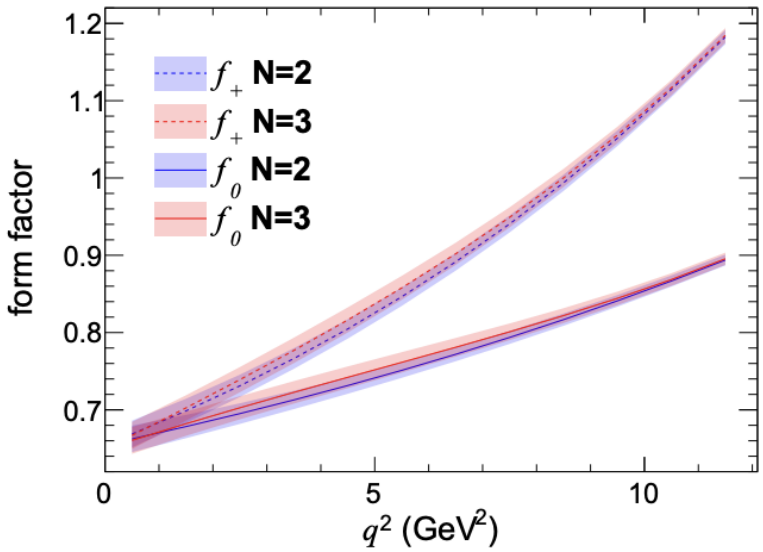


Effect of $N = 3$ BGL expansion

- From FF fits, $\Gamma' = \dfrac{\Gamma^{\rm FF}_{\rm tot}}{|V_{cb}|^2}$. $|V_{cb}| = \sqrt{\dfrac{\mathcal{B}}{\Gamma'\tau_B}}$ from updated HFLAV $\mathcal{B}$.

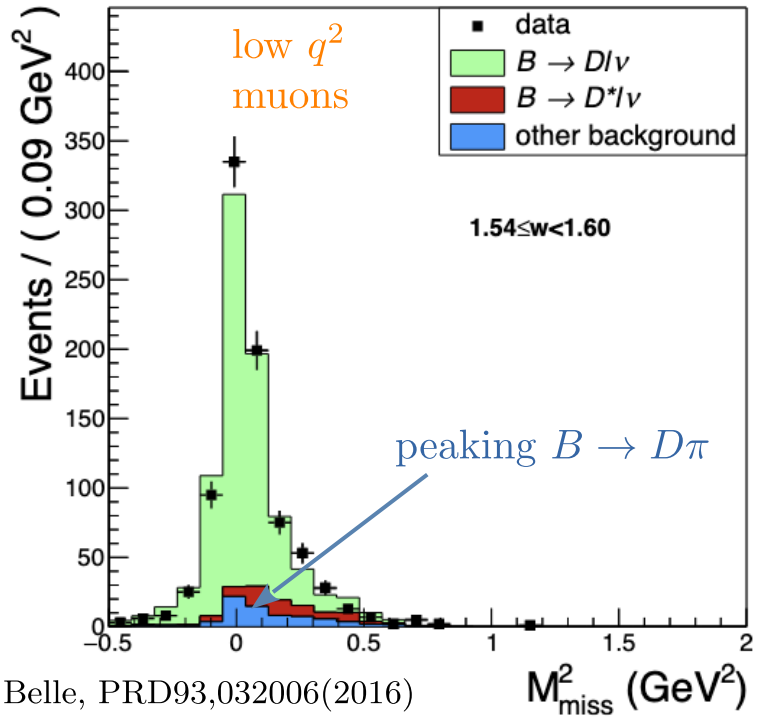
- BGL fits using *BABAR*, FNAL/MILC, Belle-16 ($d\Gamma/dq^2$ shape):

$\mathcal{B}$ measurement (had-tagged)	$N = 2$	$N = 3$
	$\lvert V_{cb}\rvert \times 10^3$	
BaBar-10, B^0	40.02 ± 1.76	39.60 ± 1.76
BaBar-10, B^+	38.67 ± 1.41	38.25 ± 1.42
Belle-16, B^0	41.66 ± 1.21	41.22 ± 1.24
Belle-16, B^+	41.27 ± 1.22	40.82 ± 1.25
	$R(D)$ SM prediction	
	0.2983 ± 0.0047	0.2995 ± 0.0038



- For $B \to D$, mild effect of going from $N = 2$ to $N = 3$ BGL.
- Summer-23 tension in $R(D) \sim 2\sigma$.

Comment: low q^2 difficulty

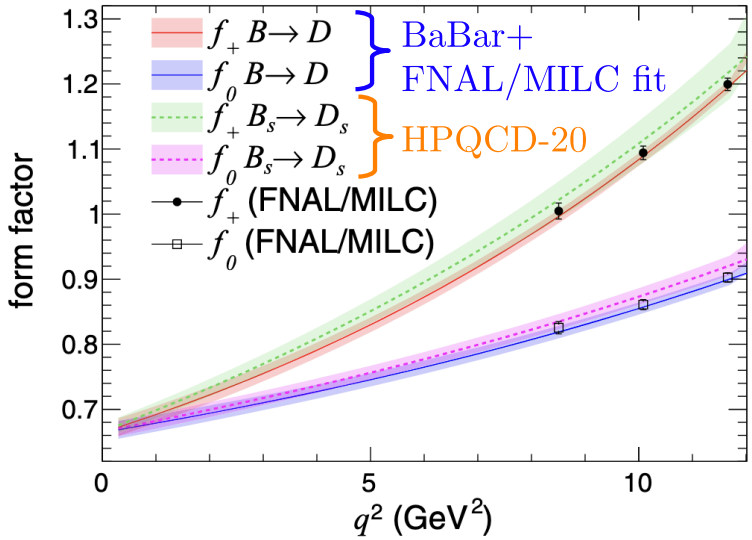


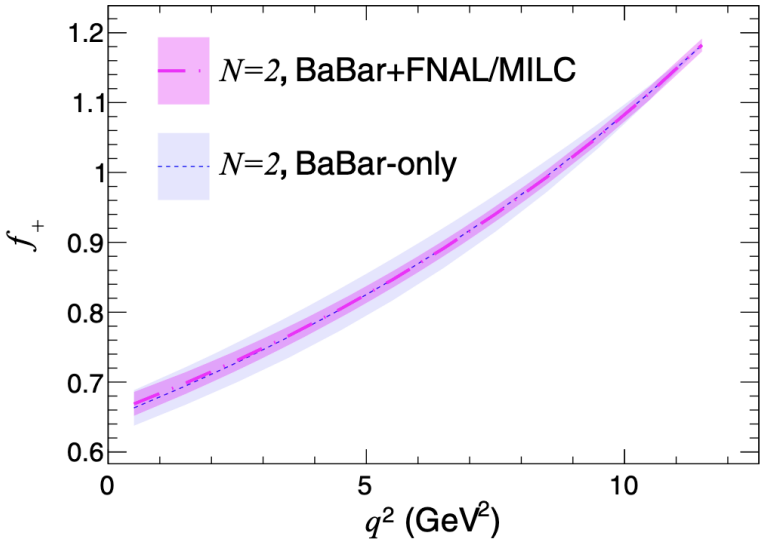
Belle, PRD93,032006(2016)

- Clean, but very hard to get rid of the small remnant background in a data-driven fashion (no sidebands).
- In particular, for muon mode, $B \to D\pi$ shows up as peaking.
- Possible (Belle II) to PID-substitute $\mu \to \pi$ and kin. fit to nothing missing.

- Current *BABAR* analysis, we trim at $q^2 > 0.5$ GeV^2 to avoid this peaking component.

Comment: comparisons w/ lattice





- (Qualitatively) good agreement with flavor SU(3) in comparison with HPQCD.
- Also good agreement in the FF shape for f_+, between *BABAR*-only and *BABAR* +FNAL/MILC fit.
- Full covariance matrices of BGL fits included in the PRD as supplementary material.

Comment: exclusive $|V_{cb}|$ from $B \to D$

Measurement	$\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell) \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
BABAR-10 [14]	$\mathcal{B}_{B^0} = (2.15 \pm 0.11 \pm 0.14)$	40.02 ± 1.76
BABAR-10 [14]	$\mathcal{B}_{B^+} = (2.16 \pm 0.08 \pm 0.13)$	38.67 ± 1.41
Belle-16 [15]	$\mathcal{B}_{B^0} = (2.33 \pm 0.04 \pm 0.11)$	41.66 ± 1.22
Belle-16 [15]	$\mathcal{B}_{B^+} = (2.46 \pm 0.04 \pm 0.12)$	41.27 ± 1.23

- This analysis relies on external BF input for the overall $|V_{cb}|$ normalization.
- Belle-16 systematically higher than *BABAR*-10

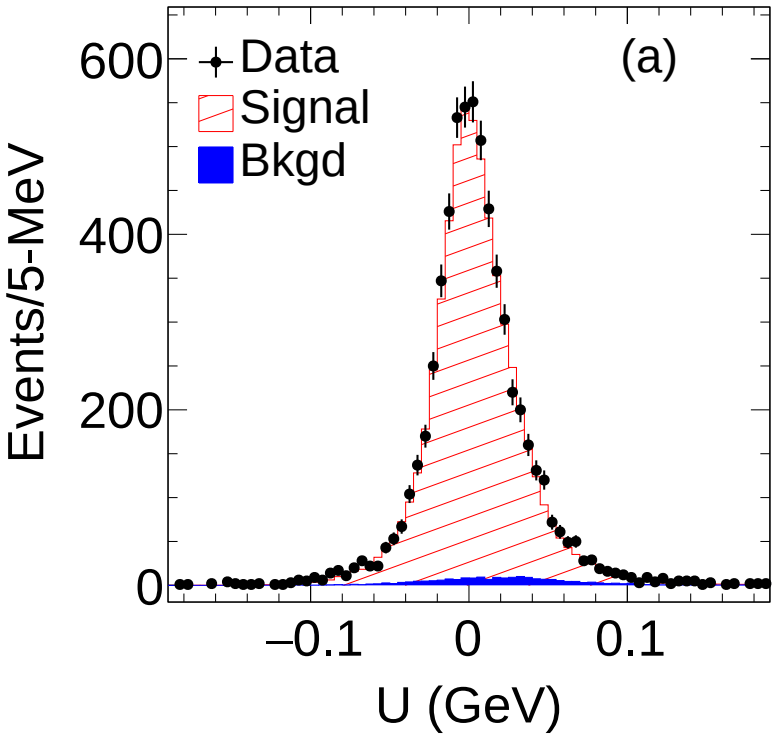
- Naively, $B \to D$ $|V_{cb}|$ is closer to inclusive+in tension with $B \to D^*$, but this being driven by the Belle-16 input.
- Note: prelim. Belle II untagged $B \to D$ $|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$ (FPCP'23).

$B \to D^* \ell^- \overline{\nu}_\ell$

[PRL123,091801(2019) + 24XX.XXXX]

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.
- As for $B \to D$, overall normalization from external BF.



- Extremely clean. Background subtraction from generic $B\overline{B}$ MC + systematic.
- ~ 6000 signal events. $N = 2$ (linear) BGL fit adequate.
  $|V_{cb}| = (38.36 \pm 0.90) \times 10^{-3}$.
- 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^*.

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

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

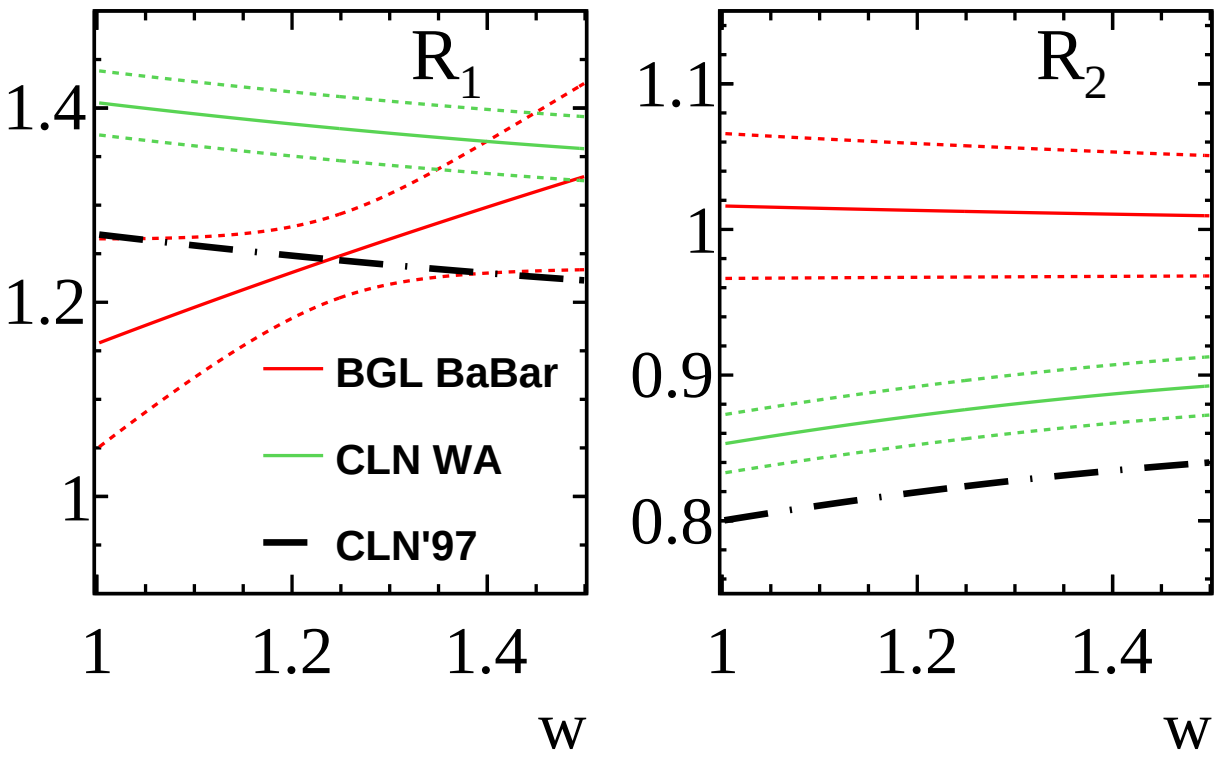
$$A_1 = \frac{w+1}{2}r' h_{A_1}$$

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

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

- 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}.
- Small RH admixture ϵ_R: add $(1 \pm \epsilon_R)$ factor for the vector (g) and axial-vector (f, F_1) FFs, respectively.

BABAR-19: CONUNDRUMS 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.

- $R_1(1)$ 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.
- HFLAV21 (excluding *BABAR*-19) quotes $R_2(1) \sim 0.85$.
- These are *BABAR*-only BGL. *BABAR* +lattice fits important.

Ongoing development at *BABAR*

- New $w > 1$ lattice data: FNAL/MILC and JLQCD ($B \to D^*$) and HPQCD ($B_{(s)} \to D^*_{(s)}$).
- Preliminary joint *BABAR* +lattice $B \to D^*$ fits were shown at ICHEP'22. Being finalized.
- Available unbinned $B \to D$ data being added to joint $B \to D^{(*)}$ *BABAR* +lattice HQET fits.
- Angular moments analysis of $\overline{B} \to \{D^*, \rho^0\}\ell^-\overline{\nu}_\ell$ in q^2 bins.

Summary

- Hadronic tagged *BABAR* SL still a unique dataset. Excellent for unbinned full angular analyses.
- For $B \to D$: FF's seem quite stable and getting more precise. Normalization remains a concern.
- For $B \to D^*$: still much to understand about the FFs. Apparent $|V_{cb}|$ exclusive discrepancies among $B_{(s)} \to D_{(s)}^{(*)}$ concerning.