BaBar $\overline{B} \to D^{*}\ell^{-}\overline{\nu}_{\ell}$ amplitude analysis confronting latest lattice data

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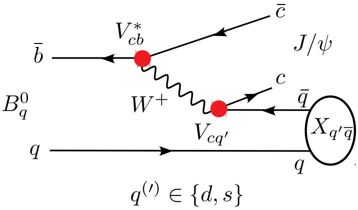
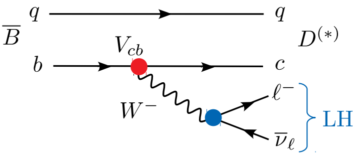
RH quark-mixing vertex

- SM: weak interaction is purely left-handed (LH), both for leptonic and hadronic transitions.
- Leptonic side strongly constrained by a purely LH neutrino, but still room on the hadronic side for a RH component



- Affects operators for such diagrams, but two hadronic vertices difficult to probe (gluonic penguins, FSI effects, ...)



- Point-like and pure LH leptonic vertex allows clean probe of hadronic vertex.

$\overline{B} \to D^*\ell^-\overline{\nu}_\ell$: GOLDEN MODE FOR RH PROBES

$D \longleftarrow \overline{B} \xrightarrow{\lambda=0} W^{*-}_{L,R}$

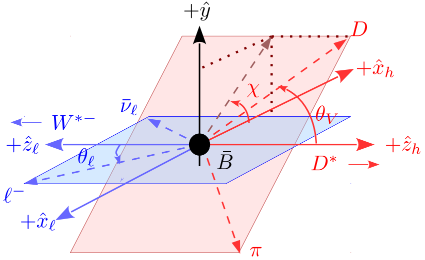
spin-0 spin-0 spin-1

- $\overline{B} \to D\ell^-\overline{\nu}_\ell$: spin-info of recoiling W^* lost. Only vector FFs, $f_{0,+}$.

$D^* \longleftarrow \overline{B} \xrightarrow{\lambda=0,\pm1} W^{*-}_{L,R}$

spin-1 spin-0 spin-1

- $\overline{B} \to D^*\ell^-\overline{\nu}_\ell$: spin-1 D^* retains spin-info. Both vector (V) and axial-vector ($A_{1,2,3}$) FFs.



- $\sqrt{q^2}$: di-lepton mass. 3 angles: $\Omega \in \{\theta_l, \theta_V, \chi\}$
- Full angular analysis allows to probe the relative ratio of the V and A components.

Global RH constraints

- We refer to the global RH analysis in 1703.04751.
- Weak collider constraints.
- Tree-level data is more constraining than $\Delta F = 2$ (mixing, etc.).
- 10% effect in $Re(\epsilon_R)$ allowed. Constraints on $Im(\epsilon_R)$ even weaker.
- Older SL papers (eg. 0907.2461) mostly looked at the normalisation.
- But ϵ_R can be cleanly probed by the angular analysis, independent of the $|V_{cb}|$ normalisation issue (see 2106.13855).

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:

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

- 0rthonormal 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	$f_i(\Omega)$	$\Gamma_i^{\mathrm{tr}}(q^2)/(\mathbf{k}q^2)$
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	$P_2^1 \sqrt{2}\, Im(Y_1^1)$	$-\frac{3}{\sqrt{5}} h_\parallel h_0 \sin\delta_\parallel$

HQET FF's and the ratio observables

- H_λ amplitudes are written in terms of the FFs.
- 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.

ϵ_R AND THE $\sin\chi$ TERMS [1505.02873]

- Define H_λ for $b \to c\ell^-\overline{\nu}_\ell$ $(\overline{B}^0,\ B^-)$.
- Ignoring overall normalisation, RH component as $V \to (1+\epsilon_R)V$.
- In SM, the amplitudes are relatively real. $\sin\chi$ terms are zero.
- Non-zero $\Gamma_{\{6,9,10,14\}}$ would be clear sign of NP!

i	$f_i(\Omega)$	$\Gamma_i^{\rm tr}(q^2)/(\mathbf{k}q^2)$
1	$P_0^0 Y_0^0$	$h_0^2 + h_\parallel^2 + h_\perp^2$
2	$P_2^0 Y_0^0$	- $\frac{1}{\sqrt{5}}(h_\parallel^2 + h_\perp^2) + \frac{2}{\sqrt{5}} h_0^2$
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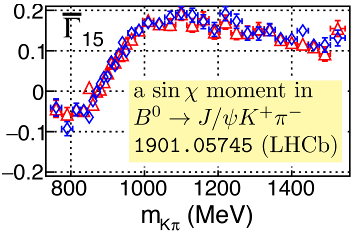
CP conjugation (delicate!)

- Under CP conjugation, $\overline{\chi} = -\chi$, $\overline{H}_\lambda(\delta_S, \delta_W) = H_{-\lambda}(\delta_S, -\delta_W)$.
- The strong phase δ_S can also lead to a $\sin\chi$ term, but lead to same signed moments for B and $\overline{B}$ then.

B^0, $\overline{B}^0$:

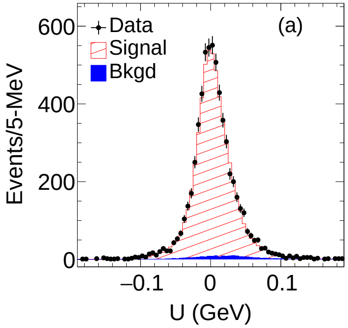


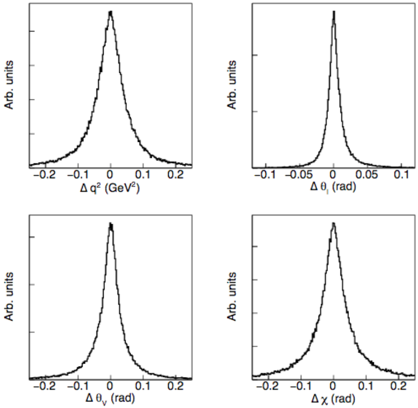
- See also 1903.02567.

- Checked explicitly in $B^0 \to J/\psi\, K^+\pi^-$.
- True CPV: $\sin\chi$ terms must be *different* between $\overline{B}$ and B.
- $\epsilon_R \to \epsilon_R^*$, between $\overline{B}$ and B, assuming no strong phase for the SL case.

BaBar data analysis [PRL123, 091801 (2019)]

- Pros: hadronic tagging allows very clean sample and extremely good resolutions (%-level) in the angular variables.
- Con: low efficiency. $N_{\rm sig} \sim 6000$ for a 4-d analysis.

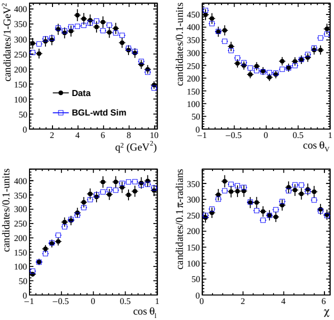




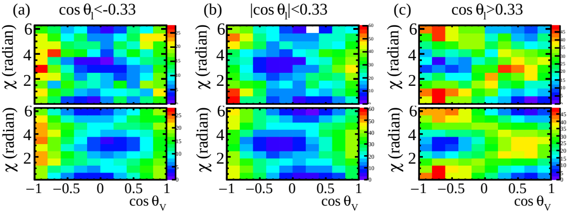
Data/MC comparisons [PRL123, 091801 (2019)]

- Acceptance in full 4-d using norm. integrals included in the fit
- Accepted MC (incl. eff. effects) weighted by the BGL results should match the data in all multi-dim. distributions.

1-d distributions:



3-d in angles, q^2-integrated:



Top row: Data

Bottom row: Acc. MC wtd by BGL

BGL "truncation" issue

- BaBar-19 BGL fit was a linear expansion ($N = 2$). Seen to be adequate, given the maximum value of the expansion parameter was $z_{\rm max} \sim 0.028$.
- Claim by other papers $\Rightarrow$ doesn't affect the FF, but underestimates uncertainties (?).
- Same papers never seem to explain, how *exactly* they include the unitarity constraints in the BGL parameters (higher terms break unitarity).
- We will publish one version of the fit with $N = 3$, irrespective of unitarity breaking (overfitting?).

New MILC data!

Semileptonic form factors for $B \to D^*\ell\nu$ at $\boxed{\text{nonzero recoil}}$ from $2+1$-flavor lattice QCD

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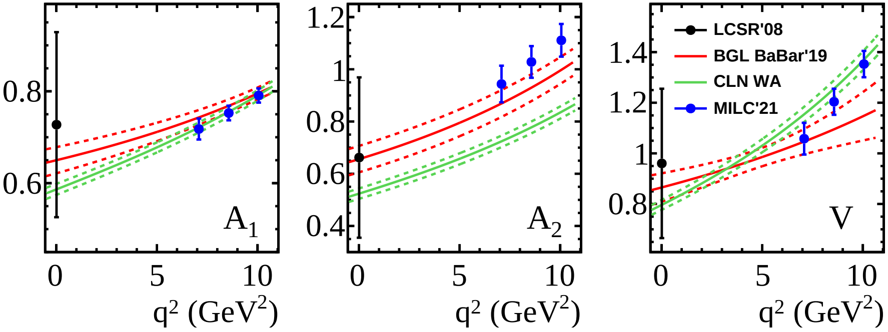
(Fermilab Lattice and MILC Collaborations)

[2105.14019 May 2021]

- Long awaited $w > 1$ data for the golden channel.
- Non-zero recoil allows direct comparisons with data for the first time.
- Lattice is pure SM. Data, might not be so.

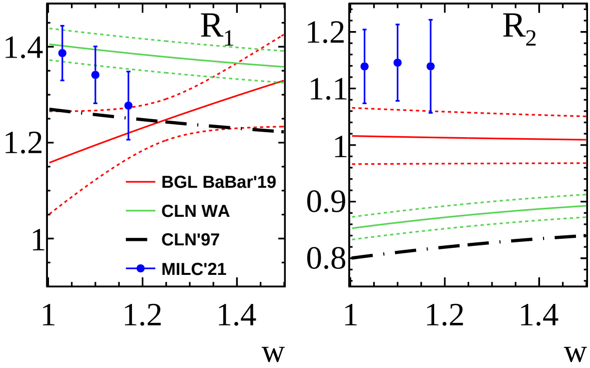
Comparisons in the $\{A_1, A_2, V\}$ FF basis

- Within BaBar, both BGL and CLN gave very comparable results.
- Clear discrepancy in A_2 with CLN-WA.
- Now including MILC data – confirms this discrepancy.



COMPARISONS IN $\{R_1, R_2\}$ RATIOS

- $R_1 \sim h_V/h_{A_1}$ and $R_2 \sim [h_{A_2}, h_{A_3}]/h_{A_1}$.



- MILC $R_1(1)$ is $\sim 15\%$ higher than BaBar (although the slopes also differ). ϵ_R can affect R_1 but not R_2.

More on $R_2(1)$ (expt.)

- BaBar-19 fit simply did not like lower $R_2(1)$, both CLN/BGL. Strong feature of the data.

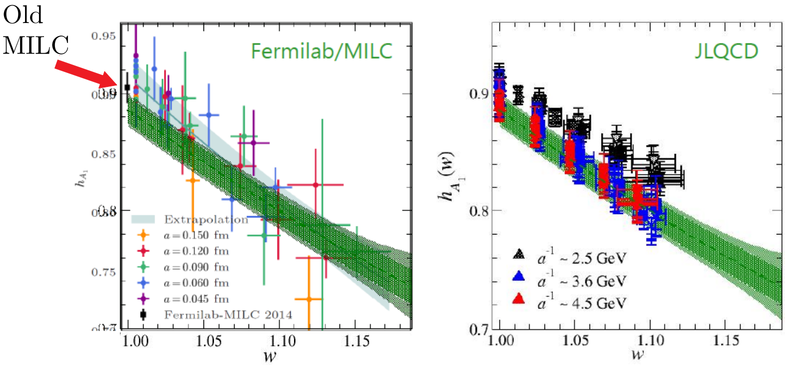
- Every single analysis other than BaBar-19 found $R_2(1) \sim 0.85$. Reflected in current HFLAV.

measurement	type	$R_2(1)$
BaBar-06	untagged 4d	0.885 ± 0.047
Belle-17	tagged 4×1d	0.87 ± 0.10
Belle-18	untagged 4×1d	0.852 ± 0.022
HFLAV-latest	–	0.852 ± 0.018

- Without tagged+4d, ambiguous/multiple solutions $\Rightarrow$ end up with incorrect solution?

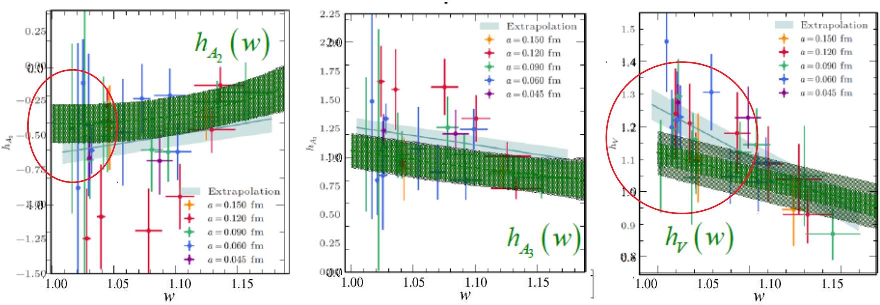
Preliminary comparisons among JLQCD/MILC

- Taken from T. Kaneko's FPCP-21 talk.
- Overall good agreement in h_{A_1}. Slight slope difference.



Preliminary comparisons among JLQCD/MILC

- $h_{A_2}(1)$ is significantly negative.
- Some slope difference in h_V between JLQCD/MILC.



My interpretation of unofficial JLQCD

- Roughly, these are what I read off from the FPCP JLQCD slides:
  - $R_1(1) \sim 1.29$: closer but still higher than BaBar-19 ("some" room for ϵ_R still)
  - $R_2(1) \sim 1.06$: excellent agreement with BaBar-19.
  - Slopes slightly less steep than MILC.

Summary and ongoing work

- Availability of the "SM data" (lattice) now allows disentangling the RH component in $b \to c$.
- Higher value of $R_2(1)$ seen by BaBar-19 confirmed by lattice.
- MILC $R_1(1)$ higher than BaBar. Raises prospect of searching for ϵ_R.
- Looking forward to JLQCD results. Preliminary data suggests in better agreement with BaBar than MILC.
- Combined MILC + BaBar fits allowing for a complex ϵ_R ongoing.