Unbinned Angular Analysis of $B \to D^*(D\pi)\ell\nu_\ell$ Decay and C_{V_R}

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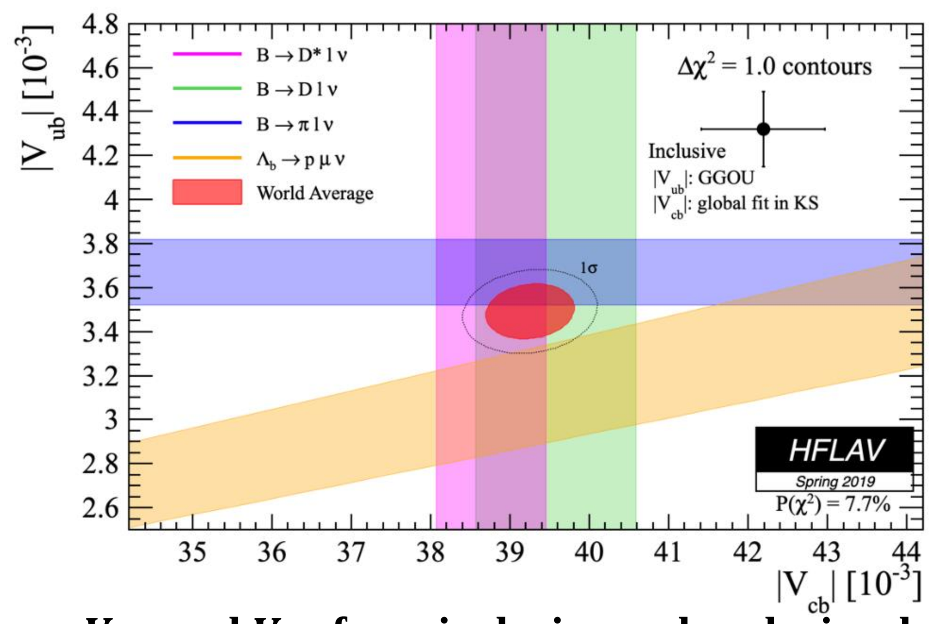
Introduction

V_{cb} puzzle:

Inclusive decay: $B \to X_c\ell\nu$ ($X_c = D, D^*, D_0^*$ ...)

Exclusive decay: $B \to D^{(*)}\ell\nu$

in. 42.16(50) vs ex. 39.70(60) $\sim 3\sigma$ tension



V_{ub} and V_{cb} from inclusive and exclusive decays

Right-handed vector current:

$$\mathcal{O}_{V_L} = (\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_L)\,,\quad \mathcal{O}_{V_R} = (\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_L)\,.$$

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}}V_{cb}\left[C_{V_L}\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R}\right] + \text{h.c.}$$

Un-binned angular analysis:

Existing binned analysis (projected χ^2 fit): Belle ’17 ’18 [1,2];

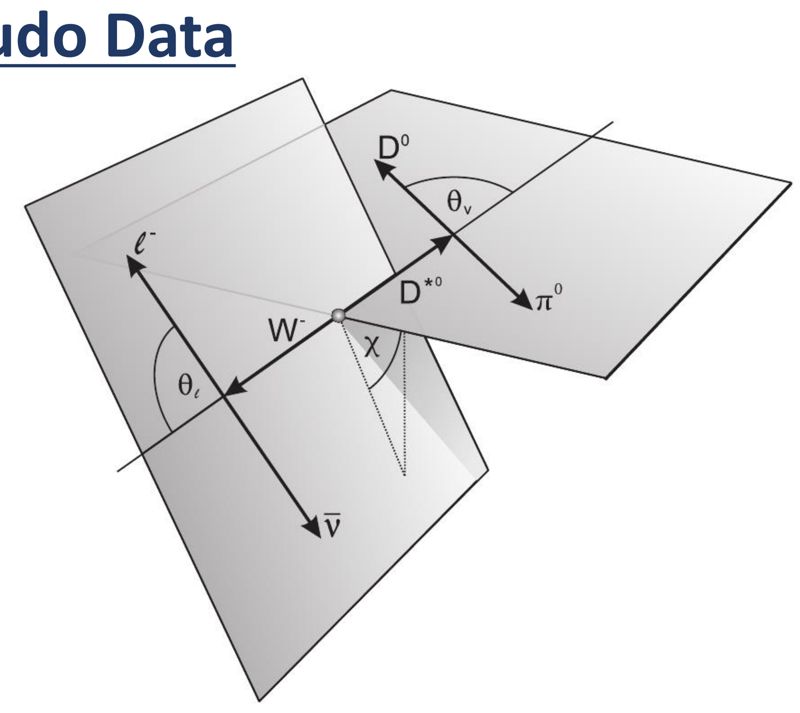
The experimental determination of $\langle g_i\rangle$ can be pursued by the maximum likelihood method:

$$\mathcal{L}(\langle\vec{g_i}\rangle) = \sum_{i=1}^{N}\ln\hat{f}_{\langle\vec{g_i}\rangle}(e_i)$$

Generation of Pseudo Data

Normalized probability density function (PDF):

$$\begin{aligned}\hat{f}_{\langle\vec{g}\rangle}(\cos\theta_V,\cos\theta_\ell,\chi) &= \frac{9}{8\pi}\\
\times\Big\{&\frac{1}{6}(1-3\langle g_{1c}\rangle+2\langle g_{2s}\rangle+\langle g_{2c}\rangle)\sin^2\theta_V+\langle g_{1c}\rangle\cos^2\theta_V\\
&+(\langle g_{2s}\rangle\sin^2\theta_V+\langle g_{2c}\rangle\cos^2\theta_V)\cos 2\theta_\ell\\
&+\langle g_3\rangle\sin^2\theta_V\sin^2\theta_\ell\cos 2\chi\\
&+\langle g_4\rangle\sin 2\theta_V\sin 2\theta_\ell\cos\chi+\langle g_5\rangle\sin 2\theta_V\sin\theta_\ell\cos\chi\\
&+(\langle g_{6s}\rangle\sin^2\theta_V+\langle g_{6c}\rangle\cos^2\theta_V)\cos\theta_\ell\\
&+\langle g_7\rangle\sin 2\theta_V\sin\theta_\ell\sin\chi+\langle g_8\rangle\sin 2\theta_V\sin 2\theta_\ell\sin\chi\\
&+\langle g_9\rangle\sin^2\theta_V\sin^2\theta_\ell\sin 2\chi\Big\}\,,\end{aligned}$$



Kinematic angles for $B \to D^*(D\pi)\ell\nu_\ell$

CLN parametrization:

$$\begin{aligned}h_{A_1}(w) &= h_{A_1}(1)(1-8\rho_{D^*}^2 z+(53\rho_{D^*}^2-15)z^2\\
&\quad-(231\rho_{D^*}^2-91)z^3)\,,\\
R_1(w) &= R_1(1)-0.12(w-1)+0.05(w-1)^2\,,\\
R_2(w) &= R_2(1)+0.11(w-1)-0.06(w-1)^2\,.\end{aligned}$$

BGL parametrization:

$$g(z) = \frac{1}{P_g(z)\phi_g(z)}\sum_{n=0}^{N}a_n^g z^n\,,\; f(z) = \frac{1}{P_f(z)\phi_f(z)}\sum_{n=0}^{N}a_n^f z^n\,,$$

$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)}\sum_{n=0}^{N}a_n^{\mathcal{F}_1}z^n\,.$$

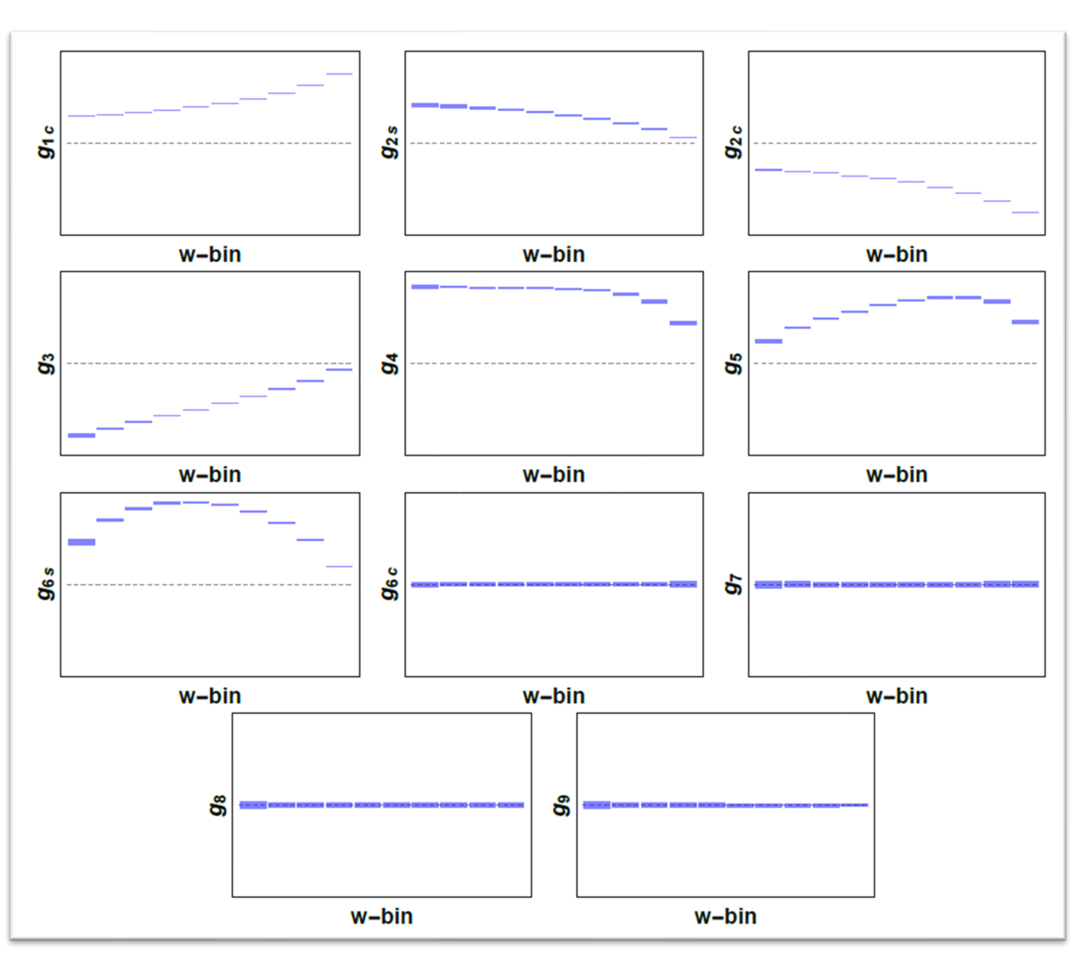
Pseudo data for $\langle g_i\rangle$ in the CLN parametrization:

N_{event} = (5306, 8934, 10525, 11241, 11392, 11132, 10555, 9726, 8693, 7497)

Pseudo data for $\langle g_i\rangle$ in the BGL parametrization:

N_{event} = (5239, 8868, 10500, 11264, 11455, 11217, 10638, 9776, 8676, 7368)

$\langle g_i\rangle$ generated in 10 w bins with covariance matrices by toy Monte-Carlo method



$\langle g_i\rangle$ generated in 10 w bins in the CLN parametrization

Results of Sensitivity Study

CLN fit:

$$R_1(1) = \frac{h_V(1)}{h_{A_1}(1)}$$

$$\begin{aligned}\vec{v} &= (\rho_{D^*}^2, R_1(1), R_2(1), C_{V_R})\\
&= (1.106, 1.229, 0.852, 0)\\
\sigma_{\vec{v}} &= (3.177, 0.049, 0.018, 0.021)\end{aligned}$$

$$\rho_{\vec{v}} = \begin{pmatrix} 1. & -0.016 & -0.763 & 0.095\\ -0.016 & 1. & 0.006 & -0.973\\ -0.763 & 0.006 & 1. & -0.117\\ 0.095 & -0.973 & -0.117 & 1.\end{pmatrix}$$

C_{V_R} can be determined to precision of ~2 (4)% in CLN (BGL) parametrization.

BGL fit:

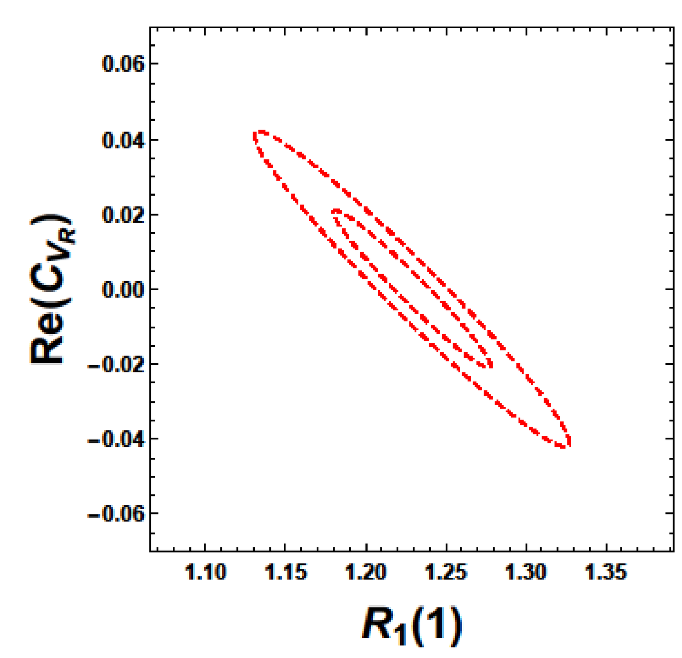
$$h_V(1) = \frac{m_B\sqrt{r}}{P_g(0)\phi_g(0)}a_0^g$$

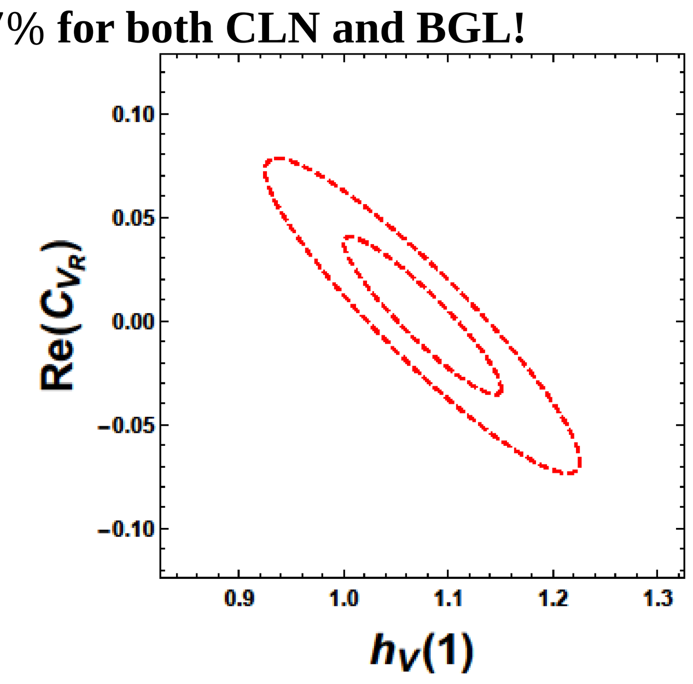
$$\begin{aligned}\vec{v} &= (a_0^f, a_1^f, a_1^{\mathcal{F}_1}, a_2^{\mathcal{F}_1}, a_0^g, C_{V_R})\\
&= (0.0132, 0.0169, 0.0070, -0.0852, 0.0241, 0.0024)\\
\sigma_{\vec{v}} &= (0.0002, 0.0109, 0.0026, 0.0352, 0.0017, 0.0379)\end{aligned}$$

$$\rho_{\vec{v}} = \begin{pmatrix} 1. & 0.022 & 0.039 & -0.035 & 0.000 & 0.189\\ 0.022 & 1. & 0.860 & -0.351 & 0.000 & 0.316\\ 0.039 & 0.860 & 1. & -0.762 & 0.000 & 0.283\\ -0.035 & -0.351 & -0.762 & 1. & 0.000 & -0.119\\ 0.000 & 0.000 & 0.000 & 0.000 & 1. & -0.923\\ 0.189 & 0.316 & 0.283 & -0.119 & -0.923 & 1.\end{pmatrix}$$

C_{V_R} and the vector form factor are highly correlated!

$Im(C_{V_R})$ can also be determined at precision of 0.7% for both CLN and BGL!





$R_1(1)$ - C_{V_R} and $h_{V_1}(1)$ - C_{V_R} contours

Fit to the forward-backward asymmetry (A_{FB}) of the charged lepton:

Advantage: one angle measurement

$$\langle\mathcal{A}_{FB}\rangle \equiv \frac{\int_0^1\frac{d\Gamma}{d\cos\theta_\ell}\mathrm{d}\cos\theta_\ell-\int_{-1}^0\frac{d\Gamma}{d\cos\theta_\ell}\mathrm{d}\cos\theta_\ell}{\int_0^1\frac{d\Gamma}{d\cos\theta_\ell}\mathrm{d}\cos\theta_\ell+\int_{-1}^0\frac{d\Gamma}{d\cos\theta_\ell}\mathrm{d}\cos\theta_\ell} = 3\langle g_{6s}\rangle$$

$$\rho_{\vec{v}} = \begin{pmatrix} 1. & 0.008 & -0.873 & 0.262\\ 0.008 & 1. & -0.040 & -0.931\\ -0.873 & -0.040 & 1. & -0.296\\ 0.262 & -0.931 & -0.296 & 1.\end{pmatrix}$$

$$\begin{aligned}\vec{v} &= (\rho_{D^*}^2, R_1(1), R_2(1), C_{V_R})\\
&= (1.106, 1.229, 0.852, 0.000)\\
\sigma_{\vec{v}} &= (2.200, 0.049, 0.031, 0.022)\end{aligned}$$

C_{V_R} can be determined at a precision of 2.2% using A_{FB} alone! Almost as good as the full set of $< g_i >$!

Summary

- **The un-binned angular analysis is useful for the precision measurement of C_{V_R} by circumventing the V_{cb} puzzle.**
- **C_{V_R} is strongly correlated to the vector form factor.**
- **The real (imaginary) part of C_{V_R} can be determined at precision of 2-4 (1) % using the full set of $\langle g_i\rangle$.**
- **A_{FB} ($\langle g_{6s}\rangle$) alone can determine C_{V_R} at almost equally good precision as the full set of $\langle g_i\rangle$.**

References

[1] E. Waheed et al. [Belle], Phys. Rev. D 100, no.5, 052007 (2019) [erratum: Phys. Rev. D 103, no.7, 079901 (2021)]

[2] A. Abdesselam et al. [Belle], [arXiv:1702.01521 [hep-ex]]

Questions and comments are welcome!

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