Measurement of $|V_{cb}|$ *in* $\overline{\mathrm{B}} \to D l^- \bar{\nu}_l$ with hadronic tagging at BaBar

Fergus Wilson, Rutherford Appleton Laboratory

On behalf of the BaBar Collaboration

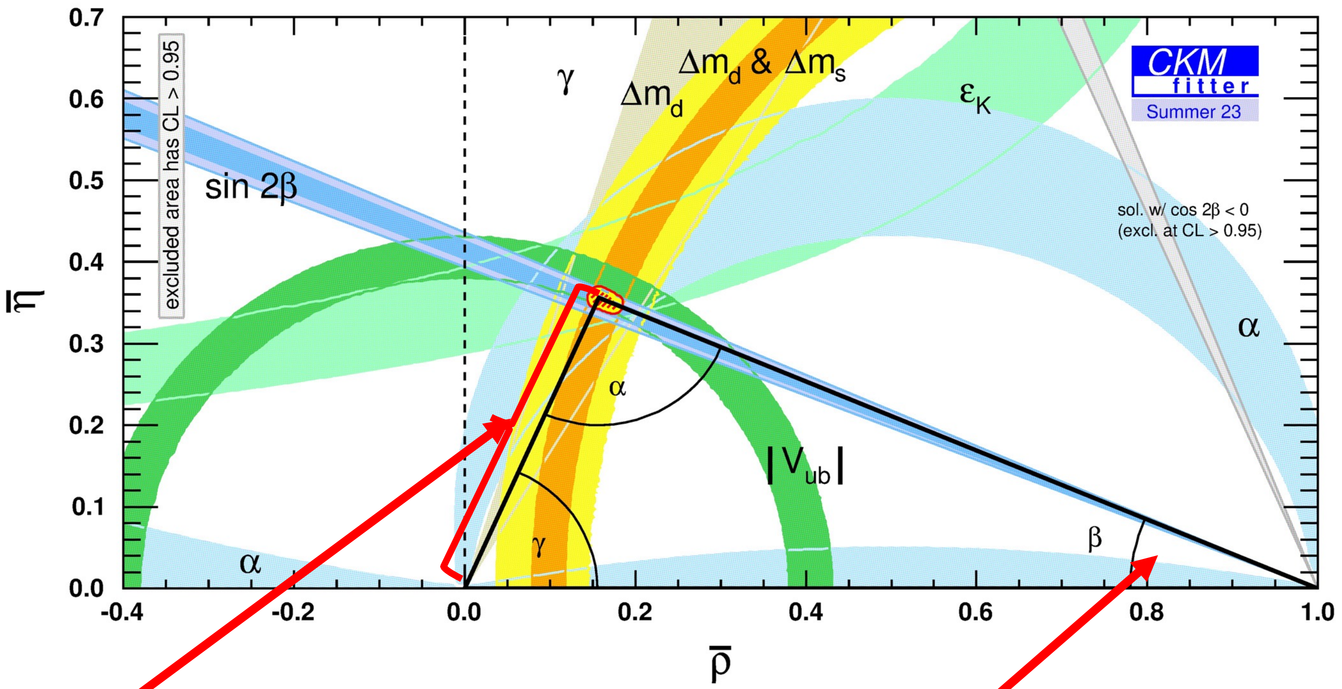
Lake Louise Winter institute, 18th – 24th February 2024

Unitarity Triangle and $|V_{cb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Angles and sides have been measured to a high precision.

Important to measure sides and angles as New Physics could appear in discrepancies in measurements

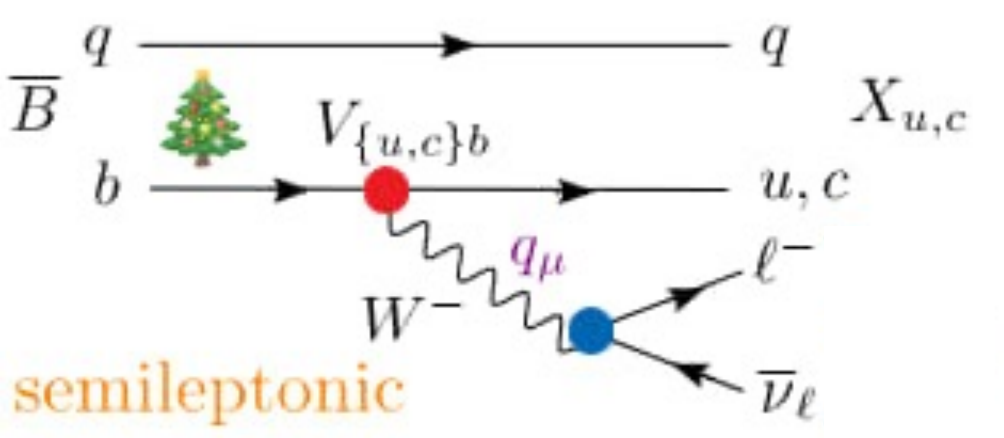


Sin2β known to within ~2%

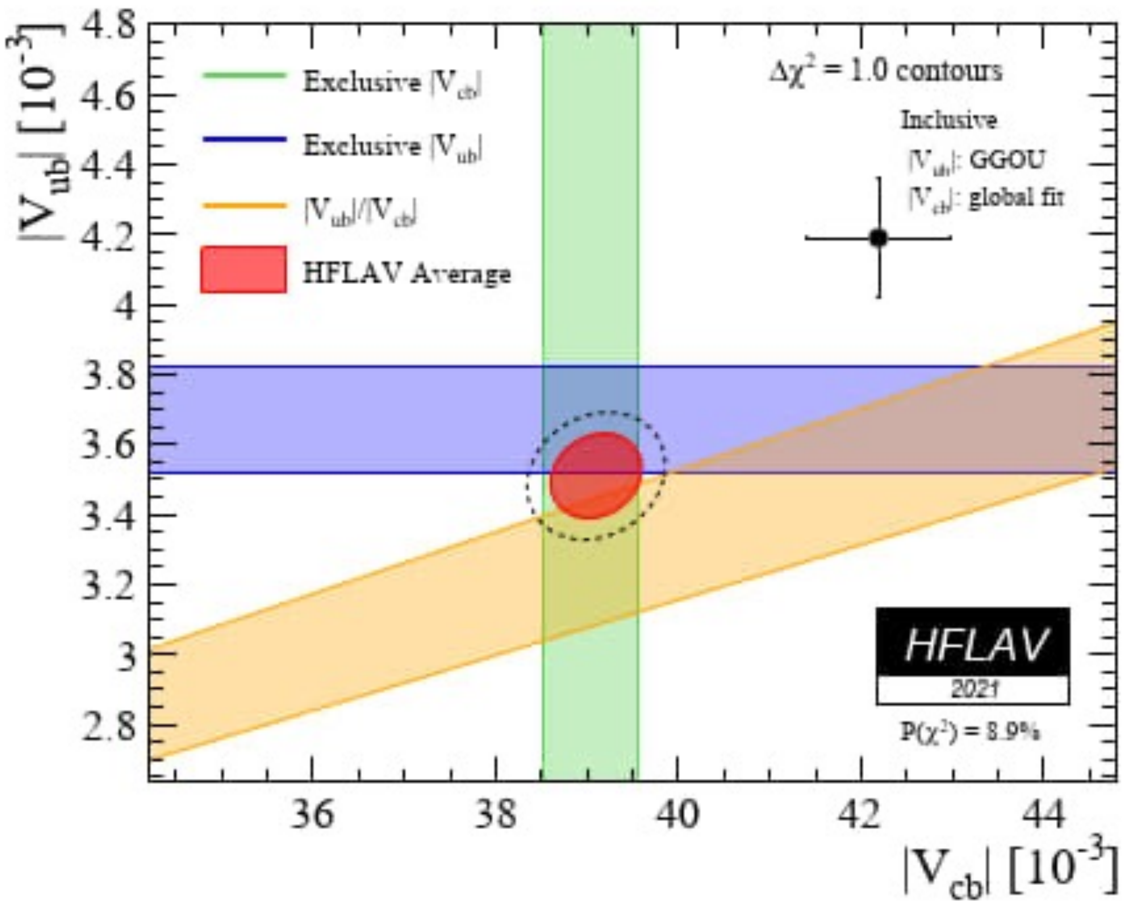
$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \left|\frac{V_{ub}}{V_{cb}}\right| \frac{1}{tan\theta_c}$$

$$\frac{\delta|V_{cb}|}{|V_{cb}|} \sim 1.5\% \qquad \frac{\delta|V_{ub}|}{|V_{ub}|} \sim 4\%$$

Measurement Methods and Current Status



Can measure through
Inclusive decays: sum over all hadronic final states
Exclusive decays: reconstruct $X_{u,c}$



Exclusive vs. Inclusive measurements: lower signal efficiency, better background rejection, measure as a function of q^2, BUT need Form Factors to describe hadronization process

Exclusive measurements systematically lower than inclusive for both $|V_{ub}|$ and $|V_{cb}|$ by 5% - 10% (~3σ)

Explanations: Experimental or theoretical? Perhaps even New Physics.

Decay Rates and Form Factors

In the massless lepton limit, $\overline{B} \rightarrow D l^- \overline{\upsilon}_l$ amplitude depends on a single vector Form Factor f_+ (scalar f_0 Form Factor becomes relevant when $m_l > 0$):

$$\frac{d\Gamma}{dq^2 dcos\theta_l} = \frac{G_F^2 |V_{cb}|^2 \eta_{EW}^2}{32\pi^3} k^3 |f_+(q^2)|^2 sin^2\theta_l \quad \text{with } k = m_D\sqrt{w^2 - 1}$$

Form Factor sometimes written as $G(w)^2 = \frac{4r}{(1+r)^2} f_+(w)^2$

There are different methods of expressing the Form Factor parameterisations:

CLN: $G(w) = G(1)(1 - 8\rho_D^2 z(w) + (51\rho_D^2\text{-}10)\, z(w)^2 - (252\rho_D^2 - 84) z(w)^3)$

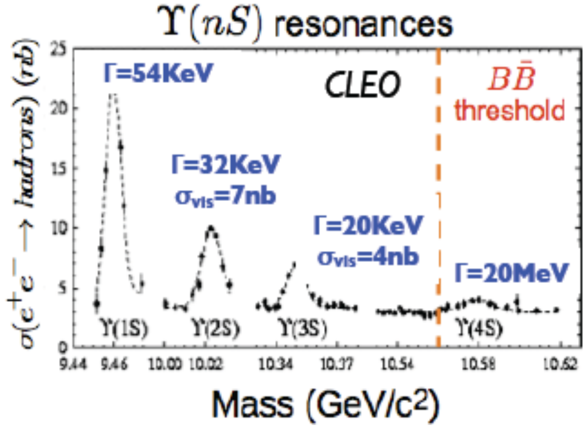
BGL: $f_i(z) = \frac{1}{P_i(z), \phi_i(z)} \sum_{n=0}^{N} a_n^i z^n \quad i \in \{+, 0\}$

Both with $z(w) = \frac{(\sqrt{w+1} - \sqrt{2})}{(\sqrt{w+1} + \sqrt{2})} \quad w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$

CLN: ρ_D^2 and G(1) free parameters
BGL: a_n^i free parameter, N = 2 or 3
$P_i(z), \phi_i(z)$ supplied by theory.

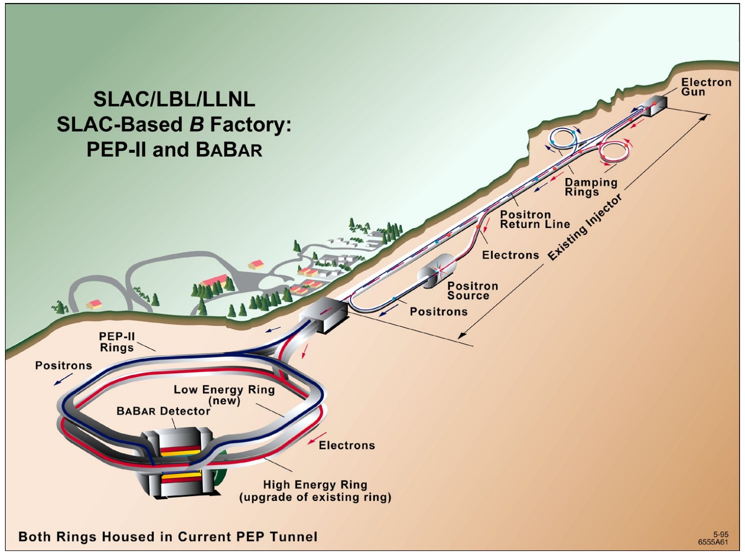
BaBar at SLAC PEP-II: 1999 - 2008

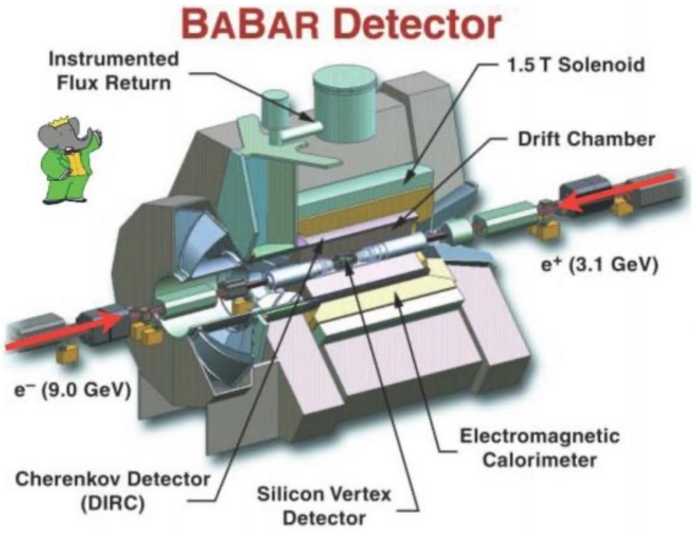
- Asymmetric beam energies nominally colliding 3.1 GeV e^+ and 9.0 GeV e^- at (mostly) the Υ(4S) resonance

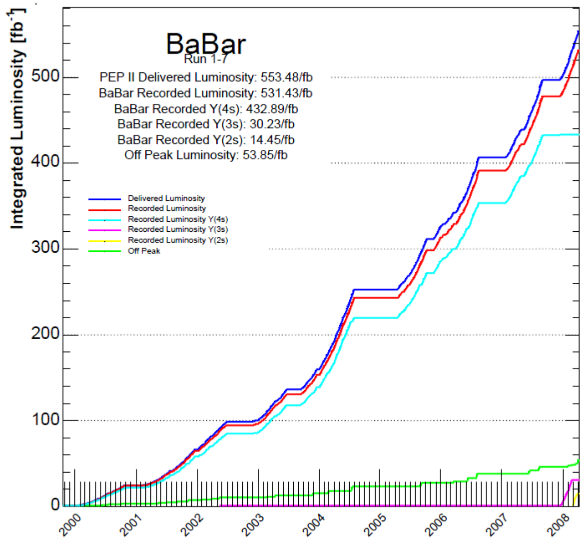


	Lumi	$B\bar{B}$ Events
$\Upsilon(4S)$	424 fb^{-1}	471×10^{6}
$\Upsilon(3S)$	28 fb^{-1}	121×10^{6}
$\Upsilon(2S)$	14 fb^{-1}	99×10^{6}
$\tau^+\tau^-$		$\sim 450\times10^{6}$

Only Υ(4S) used in this analysis

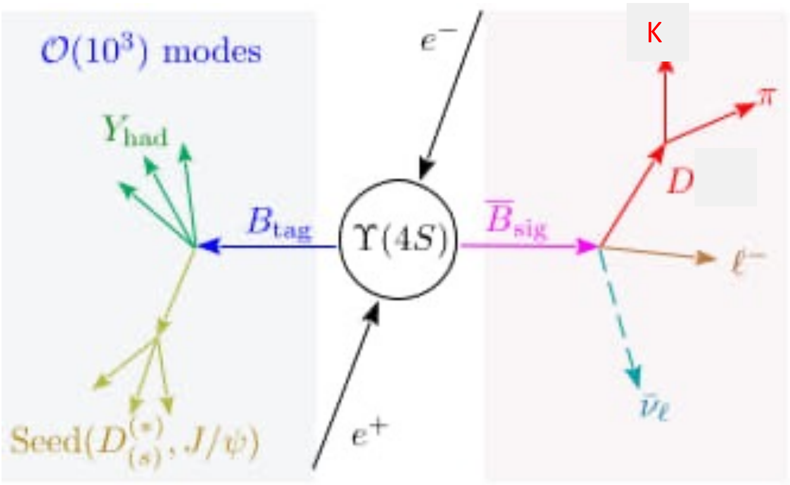


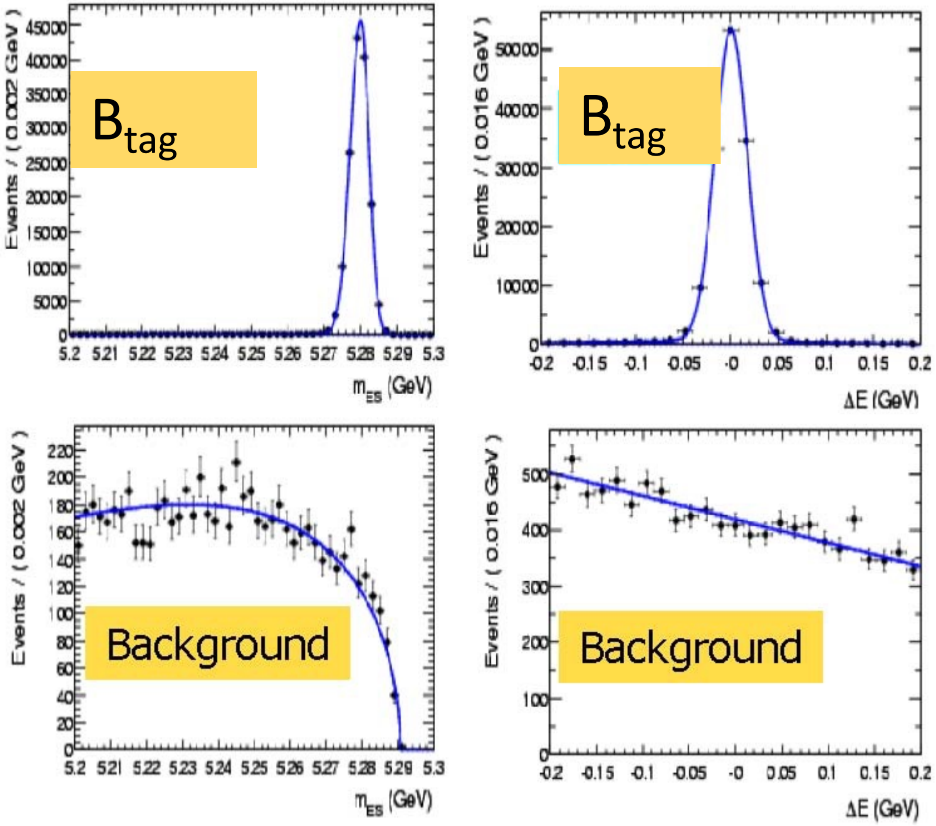




Tagging and selection

arXiv:2311.15071





Signal-side decays

ℓ^-	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
μ^-	D^0	$K^-\pi^+$	5
		$K^-\pi^+\pi^0$	6
		$K^-\pi^+\pi^-\pi^+$	7
μ^-	D^+	$K^-\pi^+\pi^+$	8
		$K^-\pi^+\pi^+\pi^0$	9

Y_{had} system: charmless light hadrons

$|\Delta E| < 72$ MeV

$m_{ES} > 5.27$ GeV

$$q = p_{B_{sig}} - p_D$$

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_{tag}^{*2}}$$

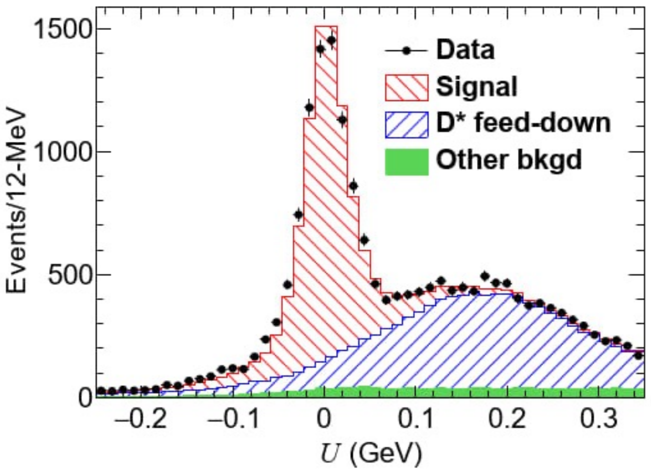
$$\Delta E = E_{tag}^* - E_{beam}^*$$

Science and Technology Facilities Council

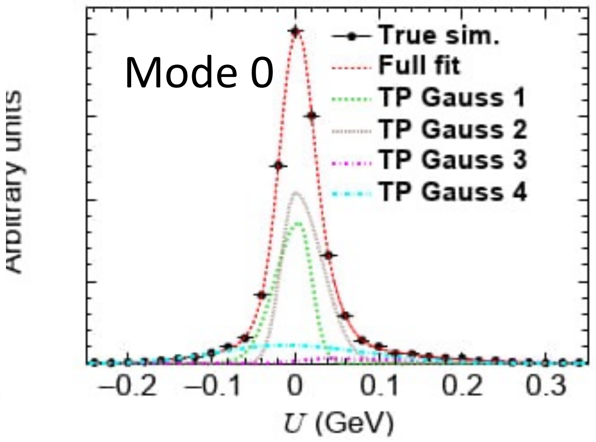
Background distribution dependent on q^2 and $\cos\theta_l$

Step 1: Perform fits to simulation to observable U in bins of q^2 and $\cos\theta_l$ for the 10 signal modes.

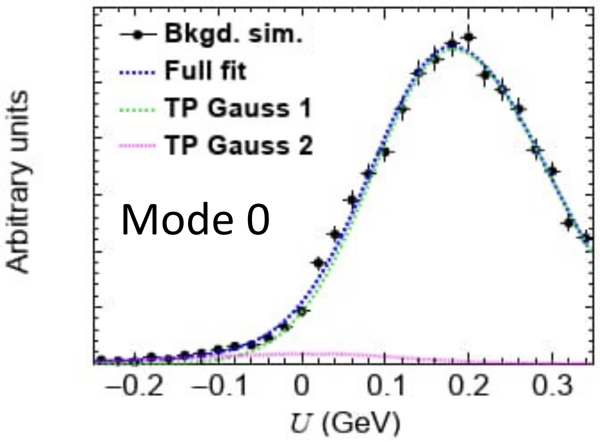
Step 2: Fit to data with fixed parameters for tails, other parameters allowed to float



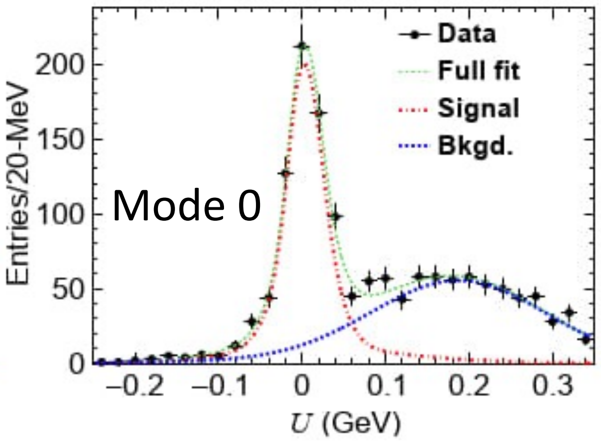
$$U = E^*_{miss} - p^*_{miss} = E^*_{\upsilon} - p^*_{\upsilon}$$



Signal



Background



Data

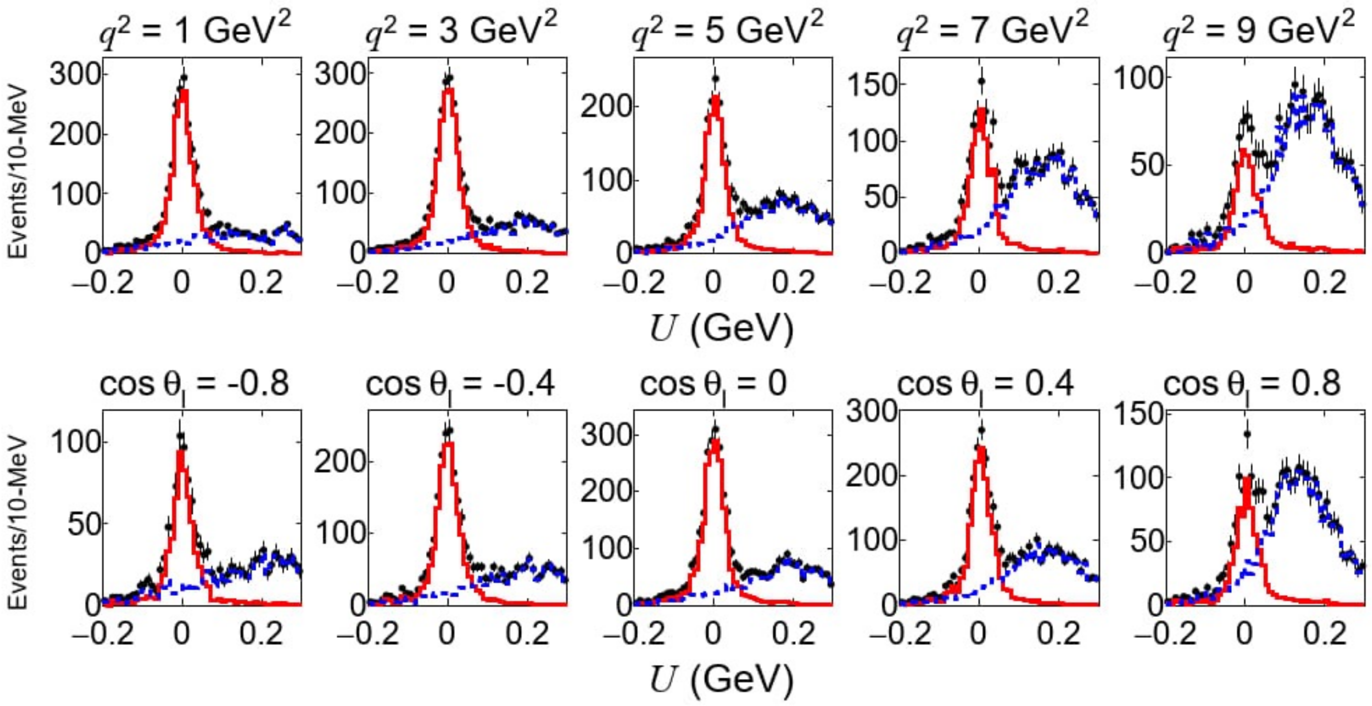
Binned and continuous fitting

Rather than use a binned distribution, the analysis uses:

$$g_{ij}^2 = \sum_{k=1}^{n} \left[\frac{\phi_k^i - \phi_k^j}{r_k}\right]^2 \qquad (\text{n=2}, r_{q^2} = 10\ GeV^2, r_{cos\theta_l} = 2)$$

Fit the N_c=50 nearest events, and extract a Q-factor:

$$Q_i = \frac{S_i(U_i)}{S_i(U_i)+B_i(U_i)} \Rightarrow \text{Total yield}, y = \sum_i Q_i$$



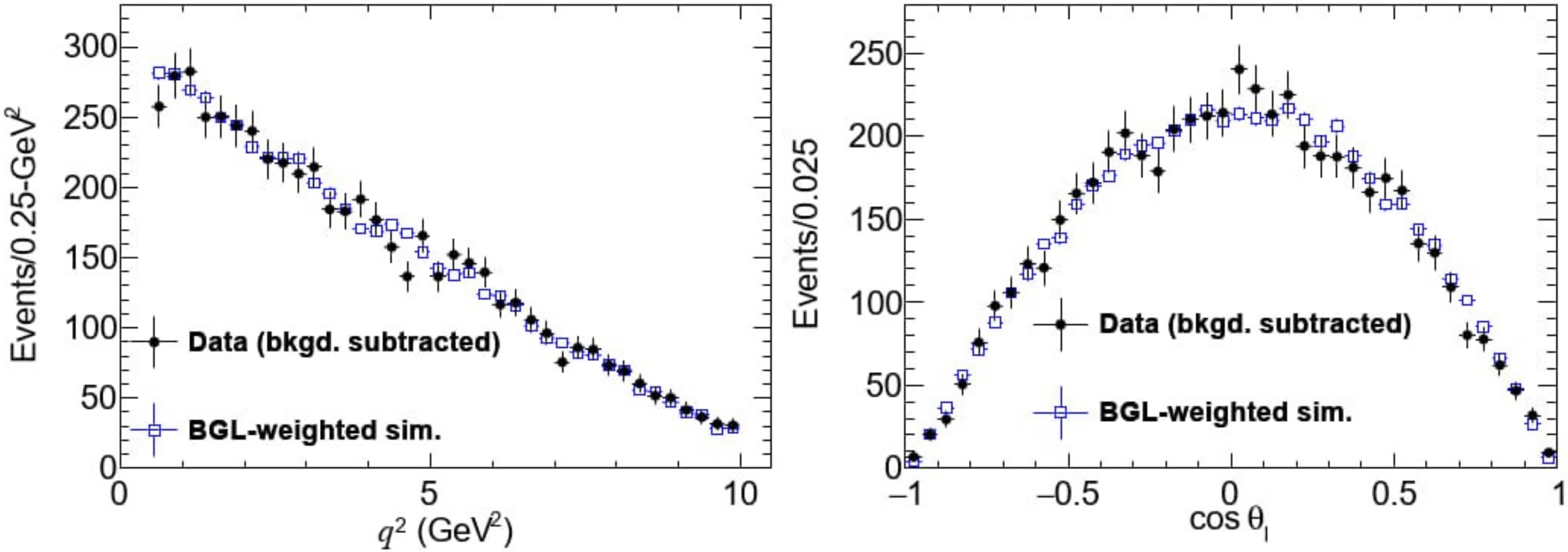
ℓ^-	D	decay mode	mode	$N_{\rm sig}$	$N_{\rm bkgd}$
e^-	D^0	$K^-\pi^+$	0	539	63
		$K^-\pi^+\pi^0$	1	813	196
		$K^-\pi^+\pi^-\pi^+$	2	550	82
e^-	D^+	$K^-\pi^+\pi^+$	3	721	41
		$K^-\pi^+\pi^+\pi^0$	4	204	120
μ^-	D^0	$K^-\pi^+$	5	433	64
		$K^-\pi^+\pi^0$	6	798	221
		$K^-\pi^+\pi^-\pi^+$	7	608	84
μ^-	D^+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

Boyd-Grinstein-Lebed BGL results

arXiv:2311.15071

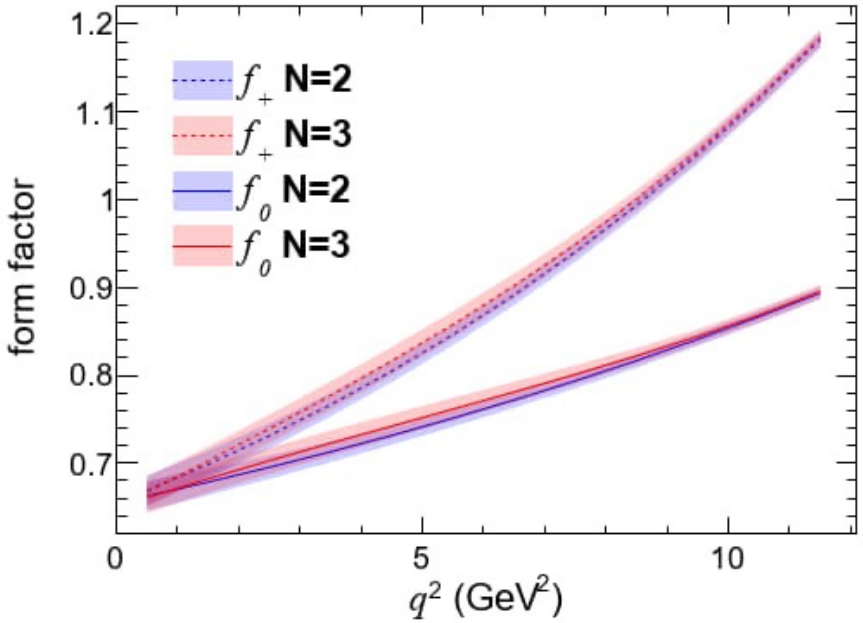
Different background approaches

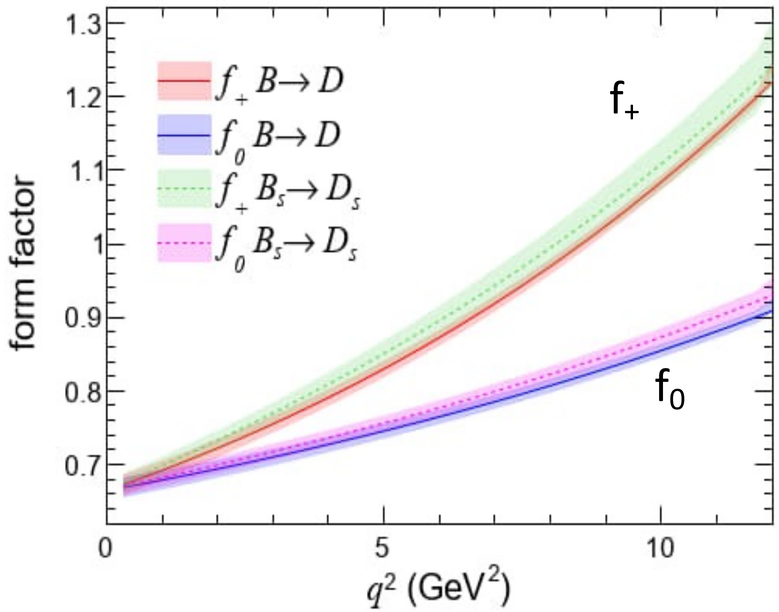
fit configuration	$a_0^{f+} \times 10$	a_1^{f+}	a_2^{f+}	$a_1^{f_0}$	$a_2^{f_0}$	$\|V_{cb}\| \times 10^3$	χ^2_{MILC}	χ^2_{Belle}
BABAR-1, Belle	0.126 ± 0.001	-0.096 ± 0.003	0.352 ± 0.052	-0.059 ± 0.003	0.155 ± 0.049	41.09 ± 1.16	1.15	24.50
BABAR-2, Belle	0.126 ± 0.001	-0.096 ± 0.003	0.352 ± 0.052	-0.059 ± 0.003	0.155 ± 0.049	41.12 ± 1.16	1.17	24.54
BABAR-3, Belle	0.126 ± 0.001	-0.096 ± 0.003	0.350 ± 0.052	-0.059 ± 0.003	0.153 ± 0.049	41.12 ± 1.16	1.18	24.55
BABAR-4, Belle	0.126 ± 0.001	-0.096 ± 0.003	0.352 ± 0.052	-0.059 ± 0.003	0.156 ± 0.049	41.05 ± 1.17	1.14	24.45
BABAR-1	0.126 ± 0.001	-0.097 ± 0.003	0.334 ± 0.063	-0.059 ± 0.003	0.133 ± 0.062	-	1.55	-

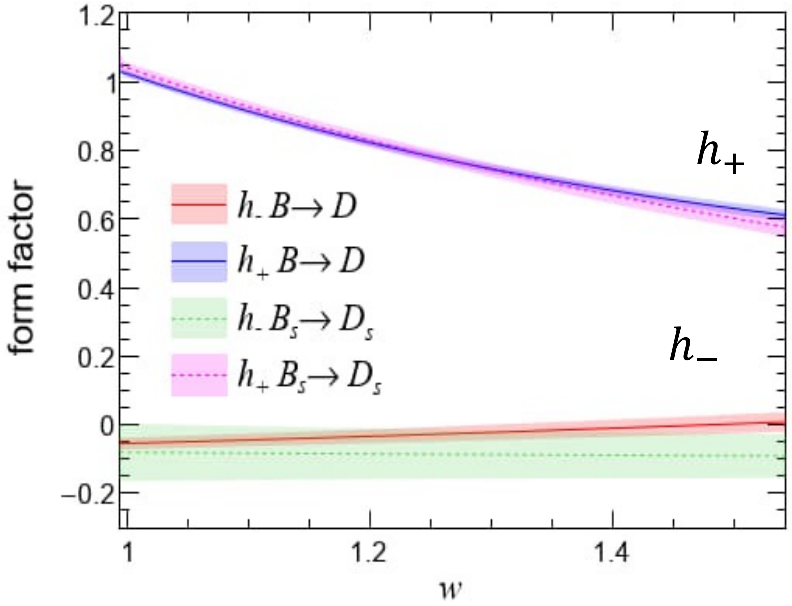


Boyd-Grinstein-Lebed BGL and HPQCD comparisons

arXiv:2311.15071





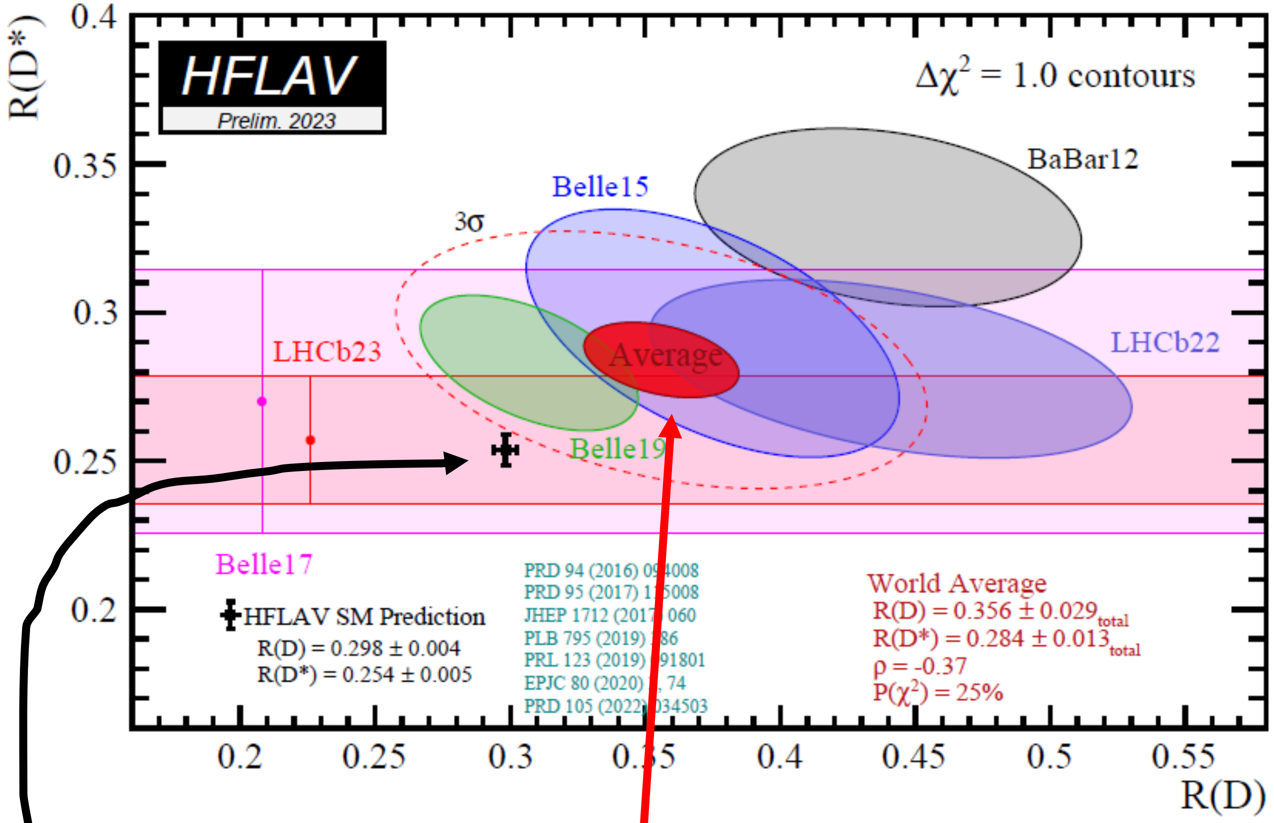


Little difference in N=2 and N=3 BGL expansion

$B_s \to D_s$ distribution: comes from HPQCD [PRD 101, 074513 (2020)]
$B \to D$ distribution: from this analysis.
If SU(3) symmetry perfect, should agree. Mostly agree.

Lepton Universality

arXiv:2311.15071



Can write differential decay rate as function of q^2, Form Factors and lepton mass

$$\frac{d\Gamma}{dq^2} = f(q^2, f^2_{+/0}, m^2_l)$$

$$\Rightarrow\ R(D) = \frac{\int_{m_\tau^2}^{(m_B-m_D)^2} \Gamma(q^2, m_\tau)\, dq^2}{\int_{m_l^2}^{(m_B-m_D)^2} \Gamma(q^2, m_l)\, dq^2}$$

HFLAV 2023 average R(D)= 0.357 ± 0.029

Standard Model prediction e.g: 0.300 ± 0.008

This result: 0.300 ± 0.004

Summary

arXiv:2311.15071

- First two-dimensional, unbinned angular analysis (q^2, $cos\vartheta_l$) for the process $\overline{\mathrm{B}} \rightarrow D l^- \bar{\upsilon}_l$ using a novel event-wise signal-background separation technique.
- Shows the lepton helicity distribution follows a $sin^2\vartheta_l$ distribution as expected by Standard Model.
- Fits to BGL and CLN Form Factor parametrisations have been performed.
- $|V_{cb}|$ = (41.09 ± 1.16) x 10^{-3}. This is closer to the inclusive value than the exclusive value from $\overline{\mathrm{B}} \rightarrow \mathrm{D}^* \, l^- \bar{\upsilon}_l$
- R(D) = 0.300 ± 0.004 agrees with SM prediction. HFLAV 2023 value = 0.357 ± 0.029.
- To be published soon.
- More results to appear this year.

Caprini-Lellouch-Neubert (CLN) results

arXiv:2311.15071

fit configuration	$\mathcal{G}(1)$	ρ_D^2	$\|V_{cb}\| \times 10^3$	$\chi^2_{\text{FNAL/MILC}}$	χ^2_{Belle}
BABAR-1, Belle	1.056 ± 0.008	1.155 ± 0.023	40.90 ± 1.14	1.04	24.65
BABAR-2, Belle	1.056 ± 0.008	1.156 ± 0.023	40.92 ± 1.14	0.99	24.72
BABAR-3, Belle	1.056 ± 0.008	1.156 ± 0.023	40.92 ± 1.14	1.00	24.71
BABAR-4, Belle	1.056 ± 0.008	1.154 ± 0.023	40.87 ± 1.14	1.09	24.57
BABAR-1	1.053 ± 0.008	1.179 ± 0.027	–	0.53	–