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Model-independent extraction of form-factors and $|V_{cb}|$ in $B \to D \ell \nu$ with hadronic tagging

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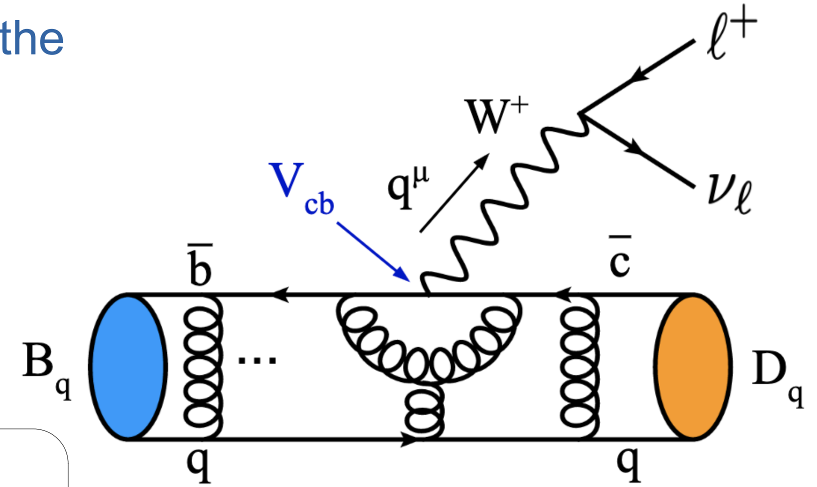
On behalf of BaBar Collaboration

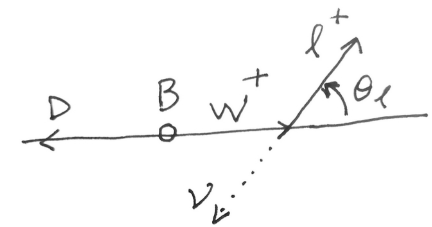
- In the SM the amplitude for B→Dℓν depends only from the Vector interaction term

$$\langle D|\bar{c}\gamma_\mu b|\overline{B}\rangle_V = f_+(q^2)\left((p_B+p_D)_\mu - \frac{(p_B+p_D)\cdot q}{q^2}q_\mu\right) + f_0(q^2)\frac{(p_B+p_D)\cdot q}{q^2}q_\mu$$



For light leptons
ℓ=e,μ

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



- |V$_{cb}$| via measurement of differential decay width shape

  + Knowledge of BF(B→Dℓν) from external inputs

  + Points or parameters for form factor normalization using Lattice QCD

P. Gambino's talk 29/5

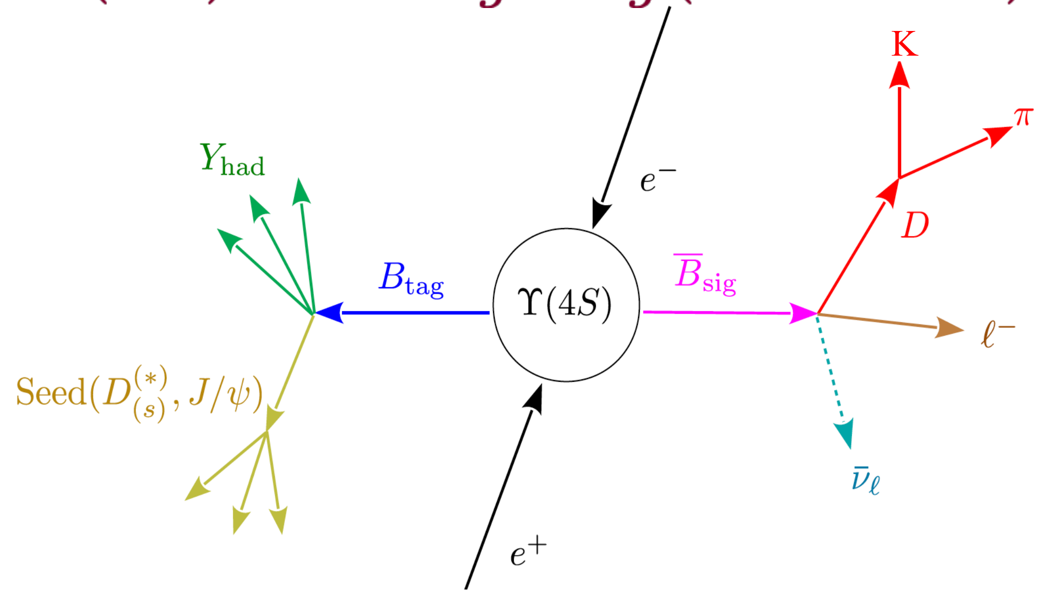
- Form factors parameterization:
  - **CLN**: model dependent, unaccounted uncertainties
  - **BGL**: less model assumptions

Caprini, Lellouch, Neubert Nucl. Phys. B530,153(1998)
Boyd, Grinstein, Lebed, Nucl.Phys.B462,493(1996)

Data sample: the hadronic tagging

- Analysis based on 426 fb^{-1} at Υ(4S)
- Hadronic tagging
  - Suppress continuum $e^+e^- \to q\bar{q}$ and combinatorial background
  - Improve the resolution on the kinematics of the signal decay
    - Boost kinematics in the B_{sig} rest frame
    - Increase the signal/background separation

$$\Upsilon(4S) \to B_{tag} B_{sig}(\to D\ \ell \nu_\ell)$$



- Improved B_{tag} algorithm used also in other BaBar semileptonic analysis
  - $B \to D^* \ell \nu$ angular analysis PRL 123 (2019) 9, 091801
  - Observation of $B \to D^{(*)}\pi\pi\ell\nu$ PRL 116 (2016) 041801
  - Measurement of R(D)-R(D*) PRL 109 (2012) 101802
- 2968 modes, different seeds considered (D^0, D^+, D_s, J/ψ) and looser cuts on intermediate states: tagging efficiency 0.2-0.3%

B→Dℓν reconstruction

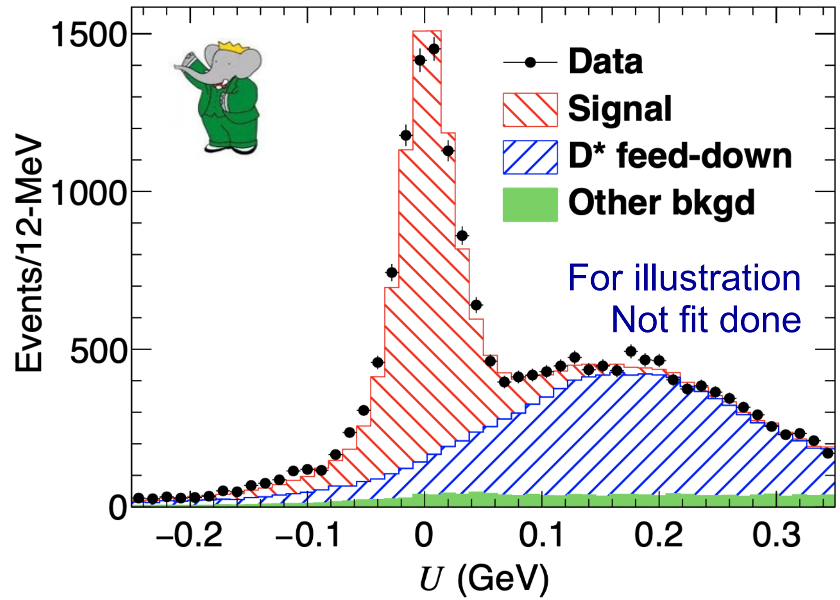
- Full exclusive event topology is reconstructed
- Tracks and photons from B_{tag} are removed from signal reconstruction:
  - B_{tag}^0 & $B^0 \to D^- \ell^+ \nu$, $\ell = e, \mu$
  - B_{tag}^- & $B^+ \to D^0 \ell^+ \nu$, $\ell = e, \mu$
    - D^0 reconstructed in the cleanest modes
  - Positive Particle identification for all particles

ℓ^-	D	decay mode	mode	N_{sig}	N_{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

- Discriminating variable

$$U = E^*_{\text{miss}} - |\vec{p}^{\,*}_{\text{miss}}| = E^*_\nu - |\vec{p}^{\,*}_\nu|$$

  - Signal: one neutrino missing U=0
  - Dominant background $B \to D^* \ell \nu$: one missing π or γ, U ~ m_{miss} ~ 140 MeV



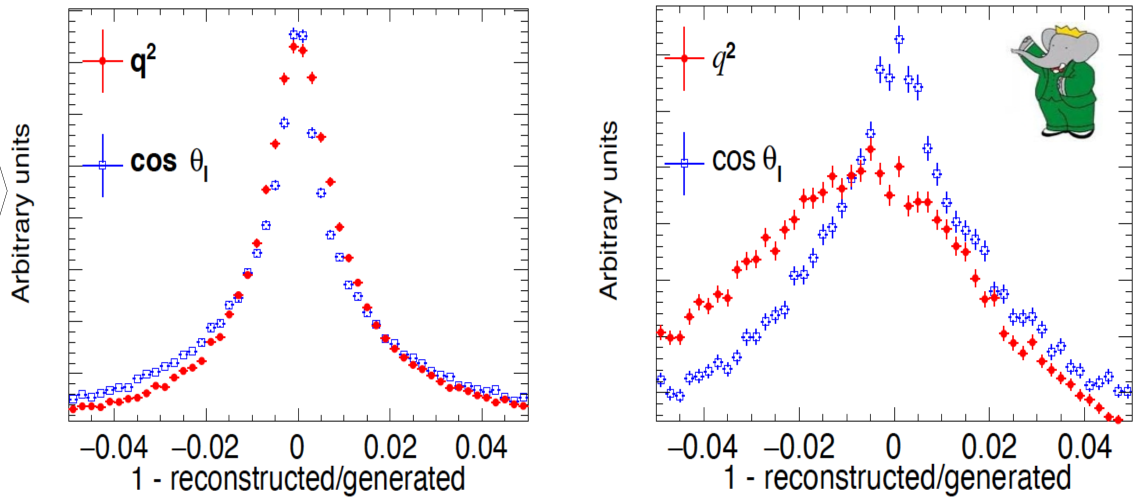
B→Dℓν reconstruction

- Minimal selection:
  - $|\mathbf{p}_{e,lab}| > 200$ MeV + brem. recovery, $|\mathbf{p}_{\mu,lab}| > 300$ MeV
  - Event further cleaned requiring $E_{extra}=\Sigma E_{\gamma} > 800$ MeV (depending on the mode)

- Kinematic fit of the full event topology: $e^+e^- \rightarrow Y(4S) \rightarrow B_{tag}$ & $B\rightarrow D\ell\nu$
  - Mass constraint: B_{tag}, B_{sig}, D
  - Vertex constraint: beam spot, secondary vertices

Probability of the χ^2 of the kinematic fit used as additional discriminating variable

- For selected candidates
  - Second kinematic fit: ν mass constrained
  - Significant improvement in resolutions



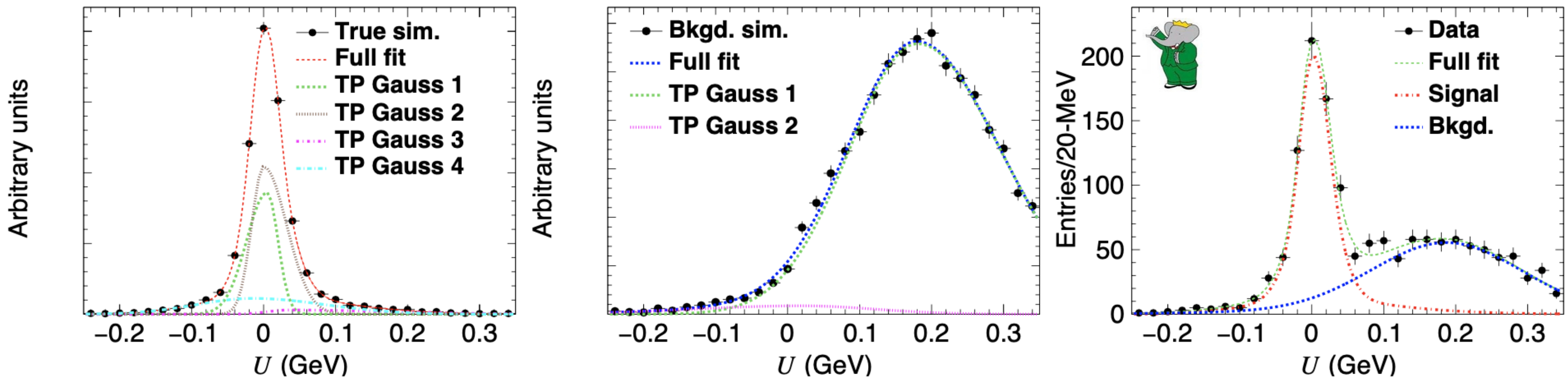
Signal and background model

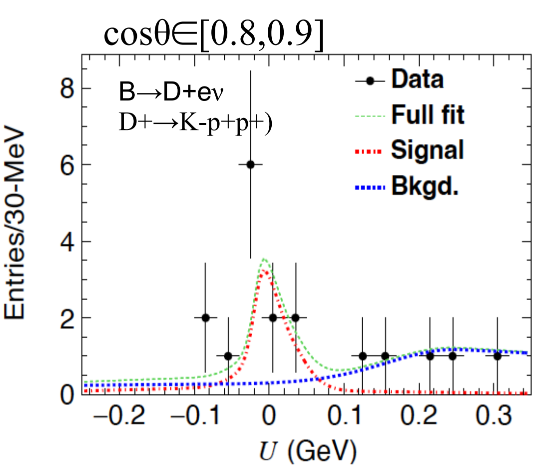
- Signal and background lineshapes derived from simulation samples
  - Signal: 4 TP Gaussians, shape of the tails kept fixed to simulation
  - Background: 2 TP Gaussians, all parameters free

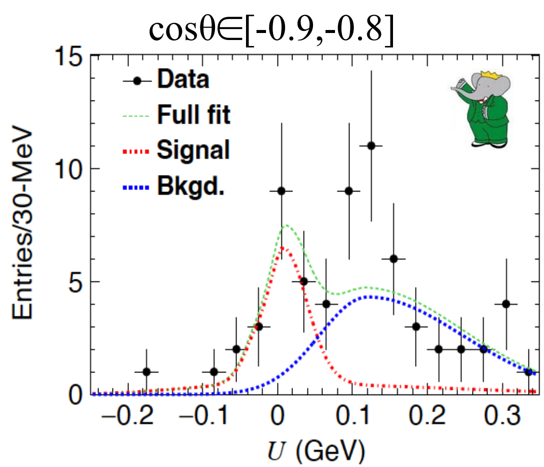
Bifurcated Gaussian

$$f_i(x;\mu_i,\sigma_{L,i},\sigma_{R,i},N_i) = N_i \times \begin{cases} e^{-(x-\mu_i)^2/2\sigma_{L,i}^2}, & \text{for } x \le \mu_i \\ e^{-(x-\mu_i)^2/2\sigma_{R,i}^2}, & \text{for } x > \mu_i. \end{cases}$$

$B \to D e \nu$ ($D^0 \to K^+\pi^-$) integrated over q^2 and $\cos\theta_\ell$





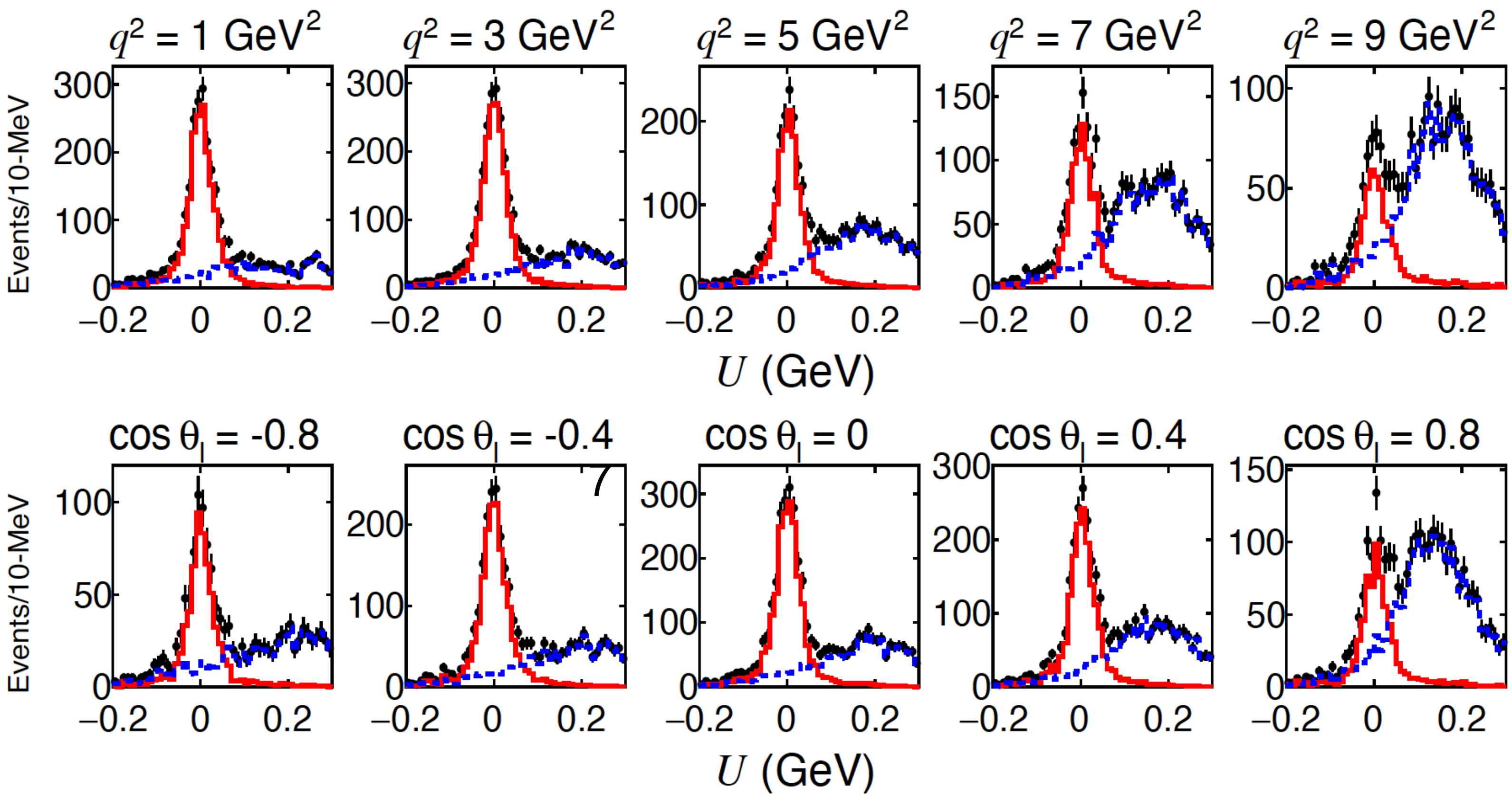


Example of "pathological" phase-space regions
Lineshapes from simulation

- Signal and background shapes vary in phase-space and modewise
- The chosen signal and background models have flexibility to fit the data

Final signal-background results

- $U = E^*_{miss} - |p^*_{miss}|$ distributions integrated over all modes and bins of phase space



Signal and **background** shapes obtained from sum of weights Q_i

$\Delta q^2 = 2\ \text{GeV}^2$

$\Delta\cos\theta_\ell = 0.2$

- Even if q^2 and $\cos\theta_\ell$ factorize in the signal $d\Gamma$, they are correlated for the background
- Efficiency depends on both (q^2-θ_ℓ) and D decay mode → better signal-background separation using both (q^2-θ_ℓ) separately for each D decay mode

Unbinned ML global fit

- In this measurement the branching ratio is not extracted
  - Analysis is only sensitive to shapes
- The shape of the form factor and $|V_{cb}|$ are determined from a combined UML fit
  - Lattice **FNAL/MILC** are used to constrain high q^2 region
  - **Belle 2016** $d\Gamma/dq^2$ points are included as gaussian constraints

J. A. Bailey et al. (**FNAL/MILC**) PRD 92, 034506 (2015)
R. Glattauer et al. (**Belle**), P RD 955 93, 032006 (2016)

$$\mathbb{L}_{\text{total}}(\vec{x}) = -2\ln\mathcal{L}(\vec{x})|_{BABAR} + \chi^2(\vec{x})|_{\text{Belle}} + \chi^2(\vec{x})|_{\text{FNAL/MILC}}$$

Systematics included

BGL $N=2$	value	CLN	value
$\|V_{cb}\| \times 10^3$	41.10 ± 1.17	$\|V_{cb}\| \times 10^3$	40.90 ± 1.14
$a_0^{f+} \times 10$	0.126 ± 0.001	$\mathcal{G}(1)$	1.056 ± 0.008
a_1^{f+}	-0.096 ± 0.003	ρ_D^2	1.155 ± 0.023
a_2^{f+}	0.352 ± 0.053		
a_1^{f0}	-0.059 ± 0.003		
a_2^{f0}	0.155 ± 0.050		

BGL N=3

variable	value
$a_0^{f+} \times 10$	0.126 ± 0.001
a_1^{f+}	-0.098 ± 0.004
a_2^{f+}	0.626 ± 0.241
a_3^{f+}	-3.939 ± 3.194
a_1^{f0}	-0.061 ± 0.003
a_2^{f0}	0.435 ± 0.205
a_3^{f0}	-3.977 ± 2.840
$\|V_{cb}\| \times 10^3$	40.74 ± 1.18
$\chi^2_{\text{FNAL/MILC}}$	0.001
χ^2_{Belle}	23.68

Fit results and systematics

Only statistical uncertainties

fit configuration	$a_0^{f+} \times 10$	a_1^{f+}	a_2^{f+}	a_1^{f0}	a_2^{f0}	$\|V_{cb}\| \times 10^3$	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	-

- Dominant systematic is due to background subtraction model

$$|V_{cb}| = \sqrt{\frac{\mathcal{B}}{\Gamma' \tau_B}}$$

Measurement	$\mathcal{B}(\overline{B} \to D\ell^- \overline{\nu}_\ell) \times 10^2$	$\|V_{cb}\| \times 10^3$
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

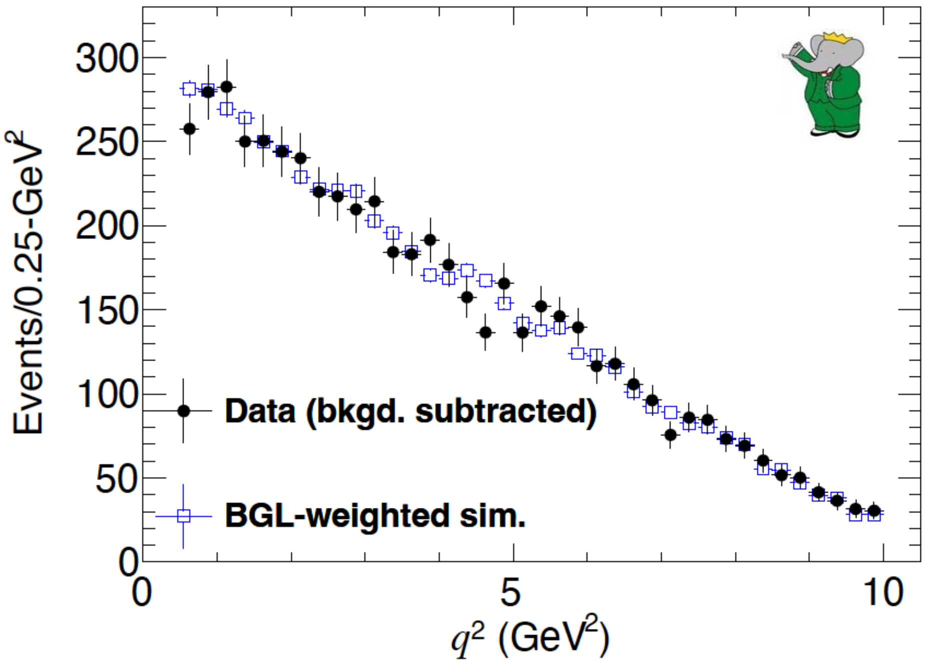
- Values of $|V_{cb}|$ are slightly higher than $B \to D^* \ell \nu$, and consistent with inclusive determination

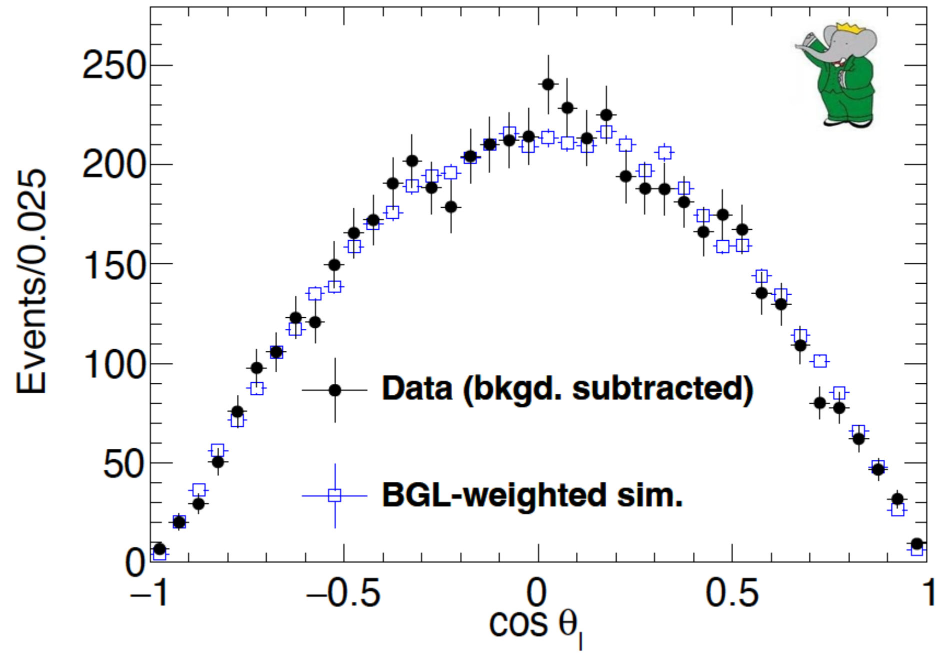
From inclusive $B \to X_c \ell \nu$

$$|V_{cb}| \times 10^3 = (42.19 \pm 0.78)$$

HFLAV, PRD 107, 052008 (2023)

1D Projections





- Good agreement between background subtracted data and simulation events re-weighted by BGL fit results
- Angular distribution follows the expected $\sin^2\theta_\ell$ distribution

- Angular distribution would allow model-independent NP search through departure from pure $\sin^2\theta_\ell$

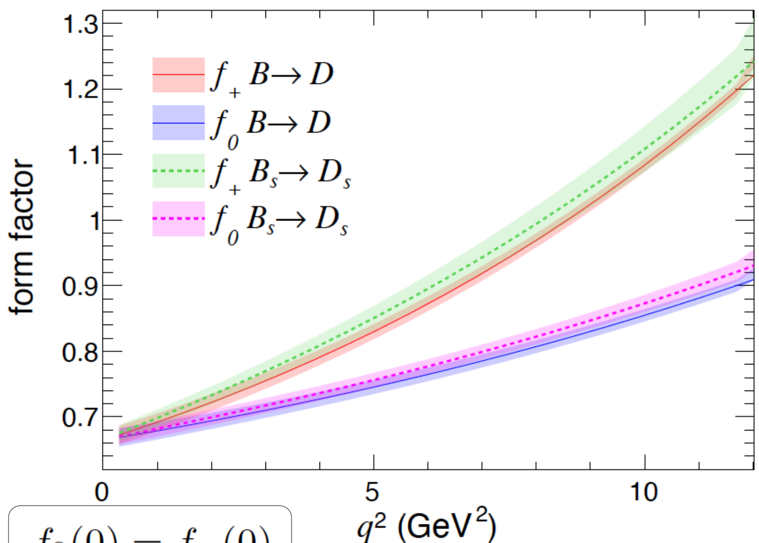
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}(1 - F_{\mathrm{H}})\sin^2\theta_\ell + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell$$

Not in this analysis!

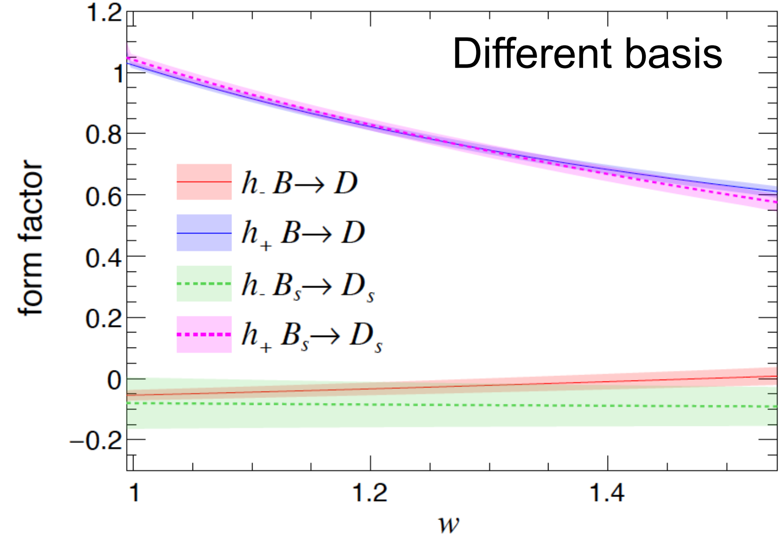
Comparison with $B_s \to D_s$ Form Factors and R(D)

- Comparison of form factors with **HPQCD** calculation for $B_s \to D_s$ over the entire q^2 range
  - Assuming $SU(3)_F$ symmetry, the form factors are expected to be equivalent

E.McLean et al., (**HPQCD**) PRD 101, 074513 (2020



$f_0(0) = f_+(0)$



Fit result (BaBar + Belle + MILC/FNAL) consistent with HPQCD ⇒ role of the spectator cannot be very large

M.Bordone et al. EPJC 80 (2020) 4, 347 for a recent HQET analysis

- Prediction on R(D)

$$\mathcal{R}(D) = \frac{\int_{m_\tau^2}^{(m_B-m_D)^2} \Gamma(q^2, m_\tau) dq^2}{\int_{m_\ell^2}^{(m_B-m_D)^2} \Gamma(q^2, m_\ell) dq^2 \big|_{\ell=e/\mu}} \Bigg|_{\text{SM theory}}^{BaBar} = 0.300 \pm 0.004$$

Summary

- **Novel tagged analysis of $B \to D \ell \nu$**
  - Signal extracted with an unbinned approach in a reduced model dependence
  - Unbinned ML fit using external inputs from FNAL/MILC at high q^2 and BF from Belle
    - $|V_{cb}|$ results are obtained with BGL (and CLN)
  - Results consistent with other measurements
    - $|V_{cb}|$ consistent with inclusive, and slightly higher than HFLAV $|V_{cb}|$ from $B \to D^* \ell \nu$
  - Form factors shape consistent with Lattice calculations

- **Paper with detailed information will be released soon**
  - Data on which the analysis is based on, will also be released in later stage
    - Because the default fit is unbinned, discussion is ongoing about the format of the data to release
  - A combined joint fit with the BaBar 2019 $B \to D^* \ell \nu$ analysis will be released in a separate paper

Backup

Data sample: the hadronic tagging

- Analysis based on 426 fb^{-1} at Y(4S)
- Hadronic tagging
  - Suppress continuum $e^+e^- \to q\bar{q}$ and combinatorial background
  - Improve the resolution on the kinematics of the signal decay
    - Boost kinematics in the B_{sig} rest frame
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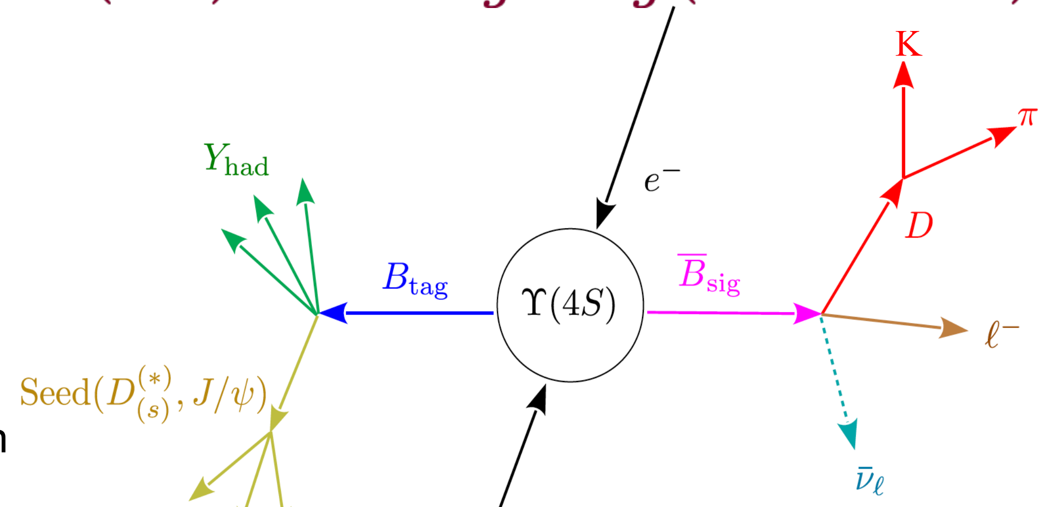
$$\Upsilon(4S) \to B_{tag} B_{sig}(\to D\ \ell \nu_\ell)$$



- Most precise previous measurements using hadronic B tagging are from BaBar and Belle

  Phys.Rev.Lett.104 011902(2010)

  Phys.Rev.D193 032006(2016)

- Untagged measurement at BaBar, Belle II and LHCb (using the B_s)

  Phys.Rev.D79 012002 (2009)

  ArXiv:2210.13143

  Phys.Rev.D101 072004 (2020)
  Combining $B_s \to D_s \mu\nu$ and $B_s \to D_s^* \mu\nu$