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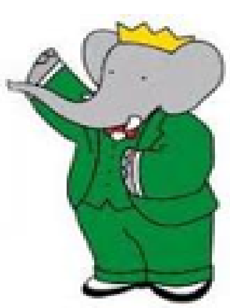
Full 4D angular analysis of $B \to D^* l \nu$ at BaBar

Phys.Rev.Lett. 123 (2019) no.9, 091801



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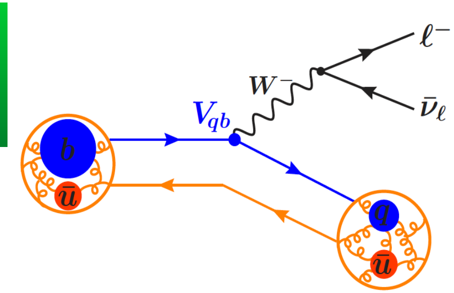
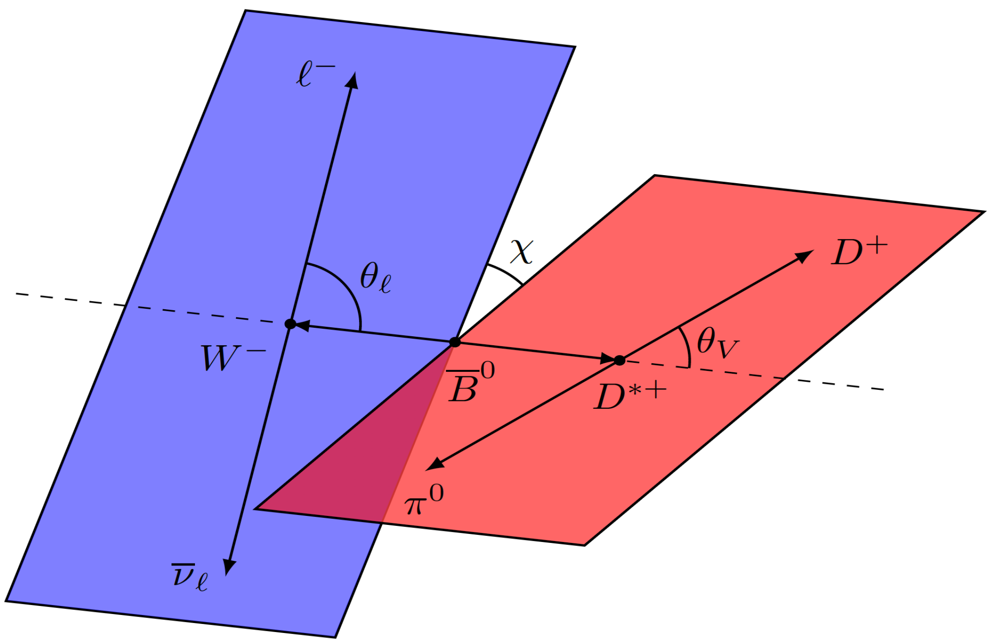
On behalf of the BaBar collaboration

$B \to D^* l\nu$ with $D^* \to D\pi$ decays



- $B \to D^* \ell \nu$ ($D^* \to D\pi$) decay has a 4-body topology
  - $q^2 = (p_B - p_{D^*})^2$
  - 3 angles: $\Omega = \{\theta_\ell, \theta_V, \chi\}$
  - The spin of D* retains information on the spin of the recoiling W*
    - Rich phenomenology
    - Sensitive to New Physics

$B \to D^* W^*$, $W^* \to \ell \nu$



- The differential decay rate is

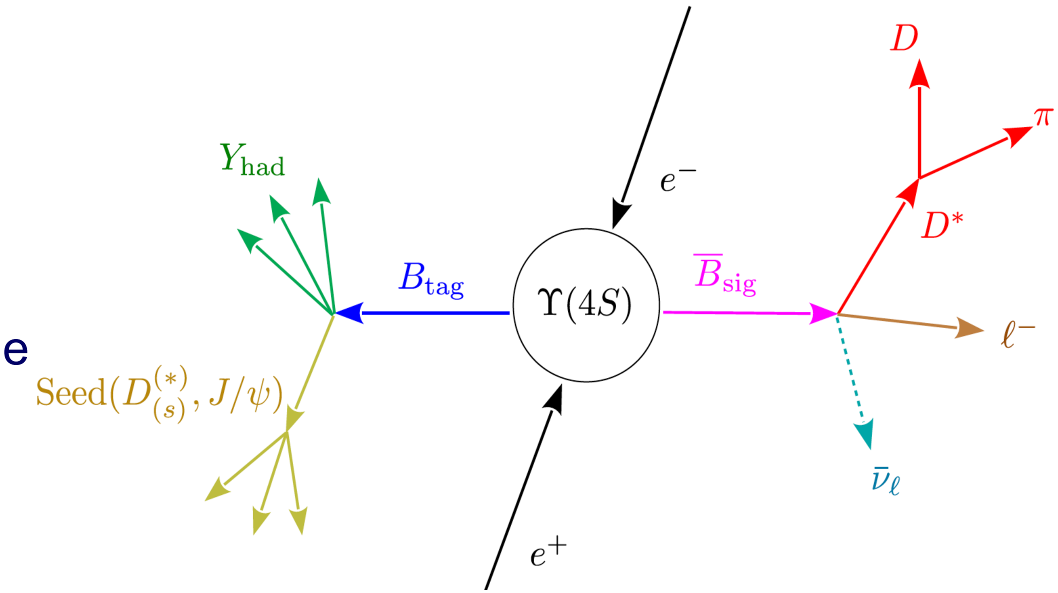
$$\frac{d\Gamma}{dq^2 d\Omega} \propto \sum_{i=1}^{14} f_i(\Omega)\Gamma_i(q^2)$$

- Functions $f_i(\Omega)$ depend only on angles $\Omega = \{\theta_\ell, \theta_V, \chi\}$
- $\Gamma_i(q^2)$ are functions of the helicity amplitudes $H_{+,-,0}$
  - Can be expressed in terms of axial and vector form factors $\{A_1, A_2, V\}$

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
- Improved B_{tag} algorithm used also in
  - $B \to D^{(*)}\pi\pi\ell\nu$ PRL 116 (2016) 041801
  - 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

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



- But no requirements on purity of the tag side: sample is very clean

Data sample: the hadronic tagging

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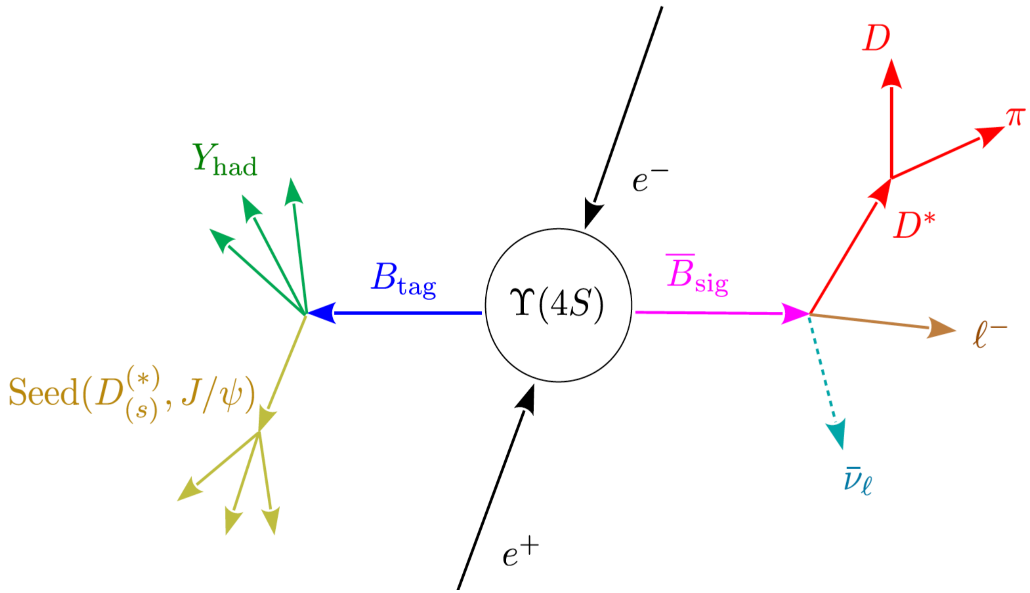


- Most precise previous measurements to the data are from BaBar and Belle

  Phys.Rev.D77:032002(2008)

  Phys.Rev.D100:052007(2019)

- Untagged samples: high efficiency but higher background and unconstrained kinematics
- Fit the projections to the 4-dimensions $q^2, \theta_\ell, \theta_V, \chi$
  - Strong statistical correlation between the bins in the various projections need to be considered
  - Reduced sensitivity to form factor shapes

Selection

- Full exclusive event topology reconstructed: no additional tracks
  - B_{tag}^0 & $B^0 \to D^{*-} \ell^+ \nu$, with $D^{*-} \to D^0 \pi^-$, $\ell = e, \mu$
  - B_{tag}^- & $B^+ \to D^{*0} \ell^+ \nu$, with $D^{*0} \to D^0 \pi^0$, $\ell = e, \mu$
    - D^0 reconstructed in the cleanest mode: $K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^+$
  - Positive Particle identification for all particles

- Minimal selection:
  - $|\mathbf{p}_{\pi,lab}| < 400$ MeV, $|\mathbf{p}_{e,lab}| > 200$ MeV + brem. recovery, $|\mathbf{p}_{e,lab}| > 300$ MeV
  - $\Delta m = m(D\pi) - m(D)$ consistent with PDG at 4σ

Selection

- Full exclusive event topology reconstructed: no additional tracks
  - B_{tag}^0 & $B^0 \rightarrow D^{*-}\ell^+\nu$, with $D^{*-} \rightarrow D^0\pi^-$, ℓ=e,μ
  - B_{tag}^- & $B^+ \rightarrow D^{*0}\ell^+\nu$, with $D^{*0} \rightarrow D^0\pi^0$, ℓ=e,μ
    - D^0 reconstructed in the cleanest mode: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$
  - Positive Particle identification for all particles
- Minimal selection:
  - $|\mathbf{p}_{\pi,lab}| < 400$ MeV, $|\mathbf{p}_{e,lab}| > 200$ MeV + brem. recovery, $|\mathbf{p}_{e,lab}| > 300$ MeV
  - $\Delta m = m(D\pi)-m(D)$ consistent with PDG at 4σ
- 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, D*,ν
  - Vertex constraint: beam spot, secondary vertexes
  - Probability of the χ^2 of the kinematic fit used as discriminating variable
  - Event further cleaned requiring $E_{extra}=\Sigma E_\gamma < 0.4$-$0.6$ GeV (depending on the mode)

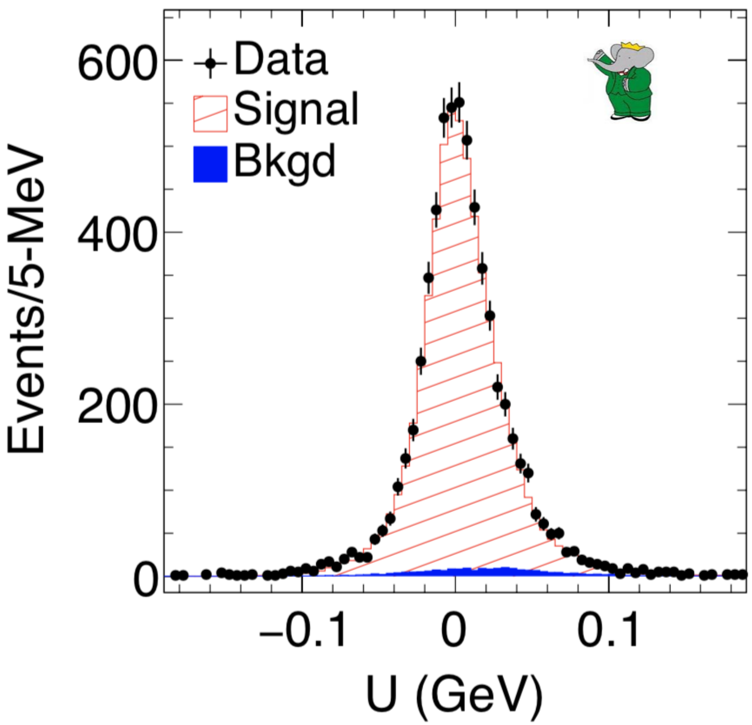
The discriminating variable U

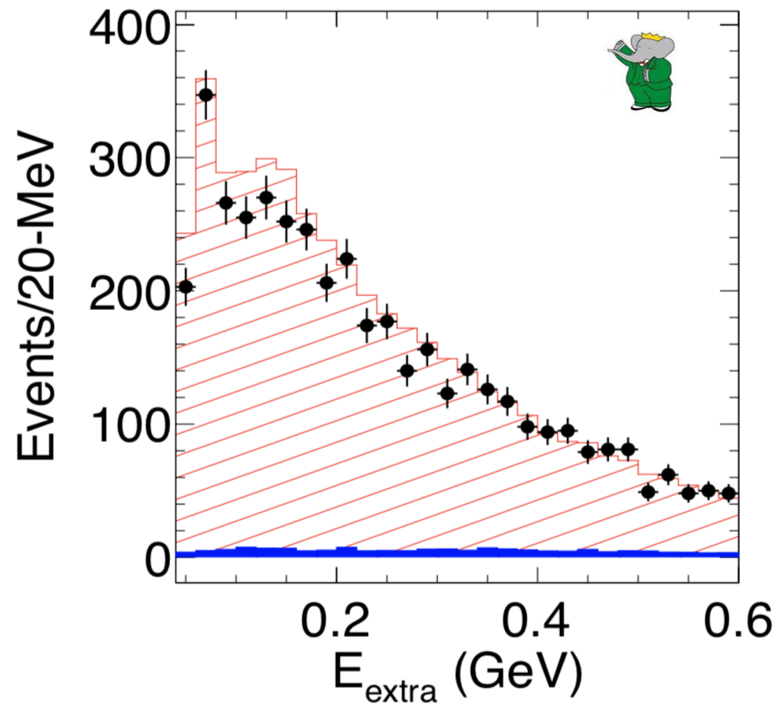
- Signal variables computed in B $_{sig}$ rest frame

$$U = E_{\text{miss}} - |\vec{p}_{\text{miss}}| = E_{\nu} - |\vec{p}_{\nu}|$$

From kinematic fit without ν-mass constraint

- Small background ~ 2%
- Good data-MC agreement in all variables





Requiring |U|<90 MeV

- 6112 total candidate

- background is 2% all due to BB events

Fit of the Form Factors

- Signal is very clean: background modeled from simulation
- Unbinned ML fit using the full 4D differential rate $$\frac{d\Gamma}{dq^2 d\Omega}$$
- All selected events enter
  - Background contribution described in the ML
- Signal acceptance in the full 4-D phase space obtained from a large sample of signal events generated flat in $dq^2 d\Omega$

- External parameters are used to obtain $|V_{cb}|$ from the FF's shape given by the angular variables, added as gaussian constraints in the likelihood
  - Rely on BF($B \rightarrow D^* \ell \nu$) and lifetimes from HFLAV
  - $h_{A1}(w=1) = 0.906 \pm 0.013$ FNAL/MILC

$$\Gamma_{tot} \equiv \int \frac{d\Gamma}{dq^2 d\Omega} dq^2 d\Omega = \frac{BF(B \rightarrow D^* \ell \nu)}{\tau_B}$$

CLN fit results: $|V_{cb}|$

- Using CLN parameterization

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84
1.122 ± 0.024	1.270 ± 0.026	0.852 ± 0.018	$38.76 \pm 0.042 \pm 0.055$

HFLAV Spring 2019 (BaBar'19 not-included)

- Result includes systematics
- Many cross checks performed
  - Analysis separated in B^0 and B^+: π^0 and π^+ slow
  - Separation in lepton mode and D decay modes
  - Effect of resolution on kinematic variables ($\sigma(q^2)$=0.072 GeV^2) negligible
  - Dominant contribution to systematics is from the residual background

BGL fit results: $|V_{cb}|$

- In the BGL fit, the z-expansion is truncated at N=1
  - With the present sensitivity, N=2 terms statistical insignificant and mostly violates unitarity
  - $|V_{cb}|$ + 5 coefficients: **a^f_0, a^f_1, a^{F1}_1, a^g_0, a^g_1**
- Two relations used to connect the coefficients

$$\begin{cases} f(q^2_{max}) = 2\sqrt{m_B m^*_D} \cdot h_{A_1}(q^2_{max}) \\ F_1(q^2_{max}) = (m_B - m_{D^*}) f(q^2_{max}) \end{cases}$$

→ a^f_0 is constrained by h_{A1}

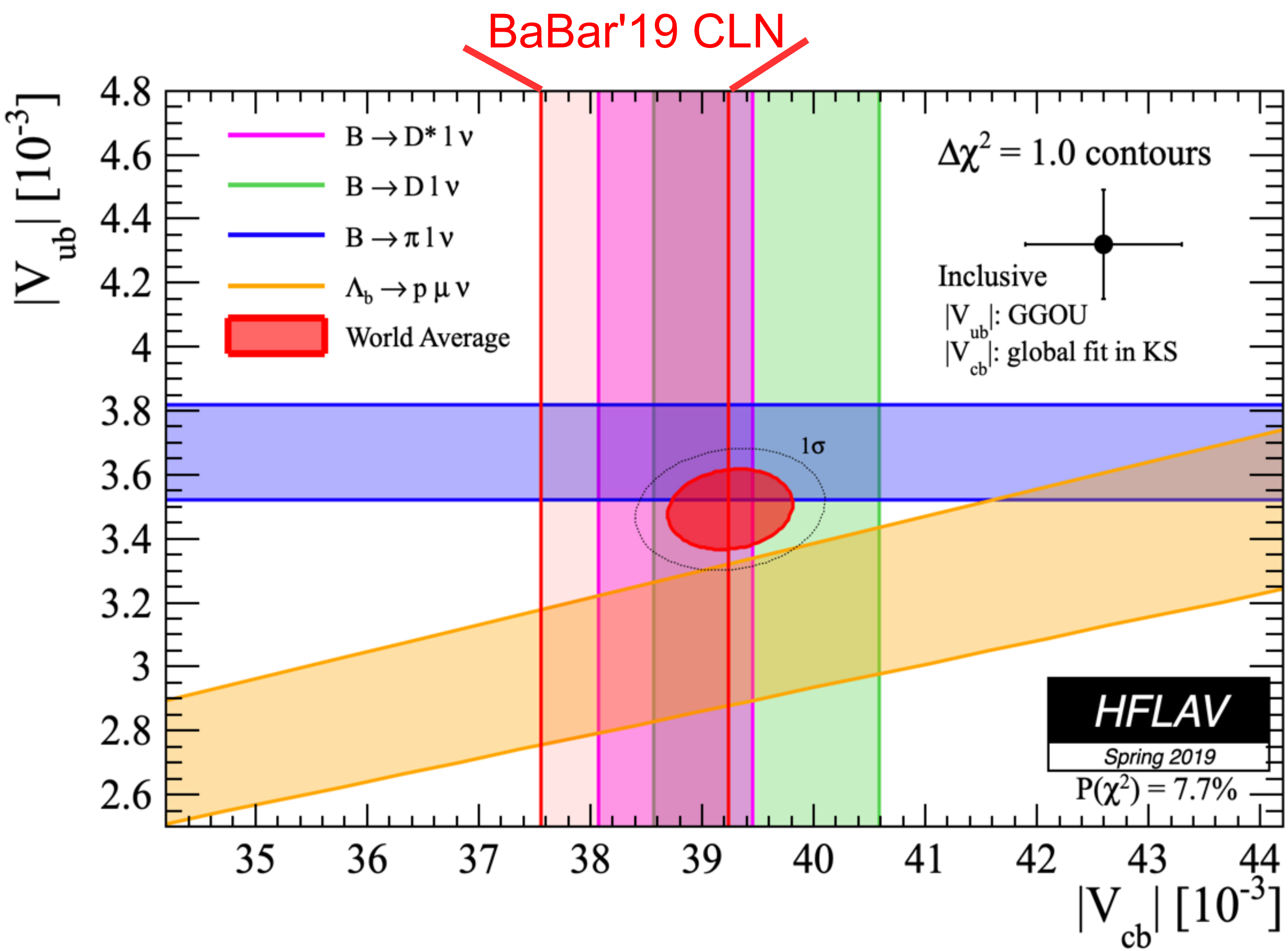
→ a^{F1}_0 is not independent

$a_0^f \times 10^2$	$a_1^f \times 10^2$	$a_1^{F_1} \times 10^2$	$a_0^g \times 10^2$	$a_1^g \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
1.29 $\pm$0.03	1.63 $\pm$1.00	0.03 $\pm$0.11	2.74 $\pm$0.11	8.33 $\pm$6.67	38.36 $\pm$0.90

- $|V_{cb}|$ consistent with BaBar-CLN fit and CLN-WA

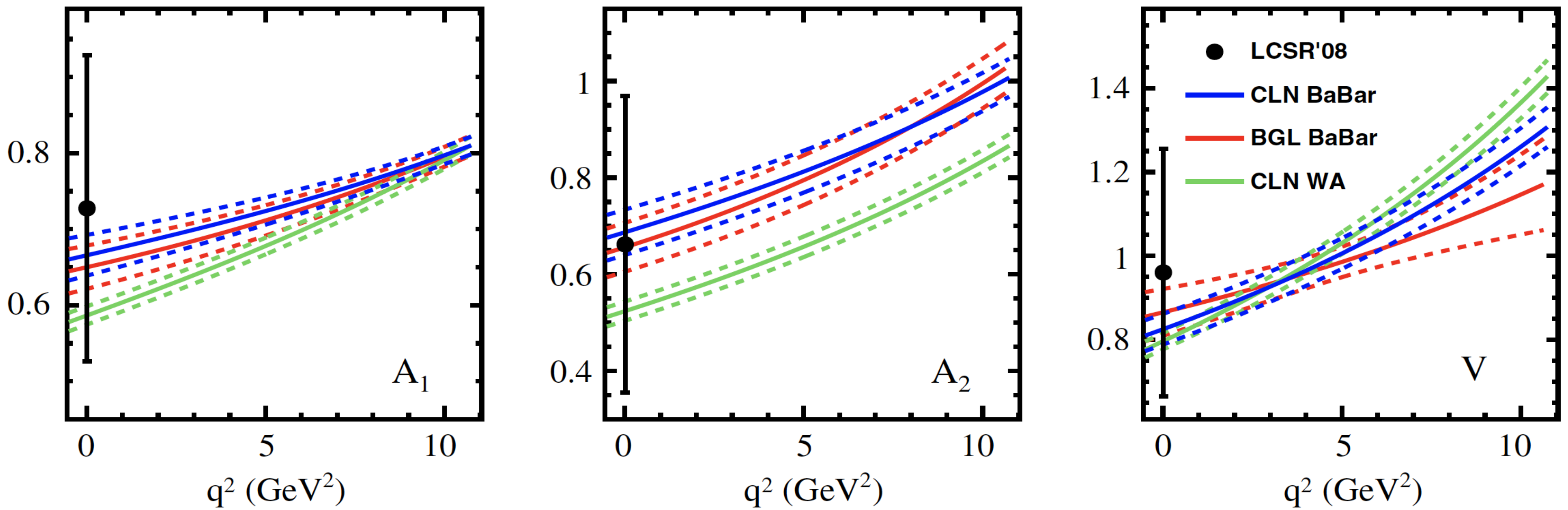
$|V_{cb}|$

- Both CLN and BGL values for $|V_{cb}|$ are consistent with the World Average
- Still in tension with inclusive $|V_{cb}|$



BGL results: form factors shapes

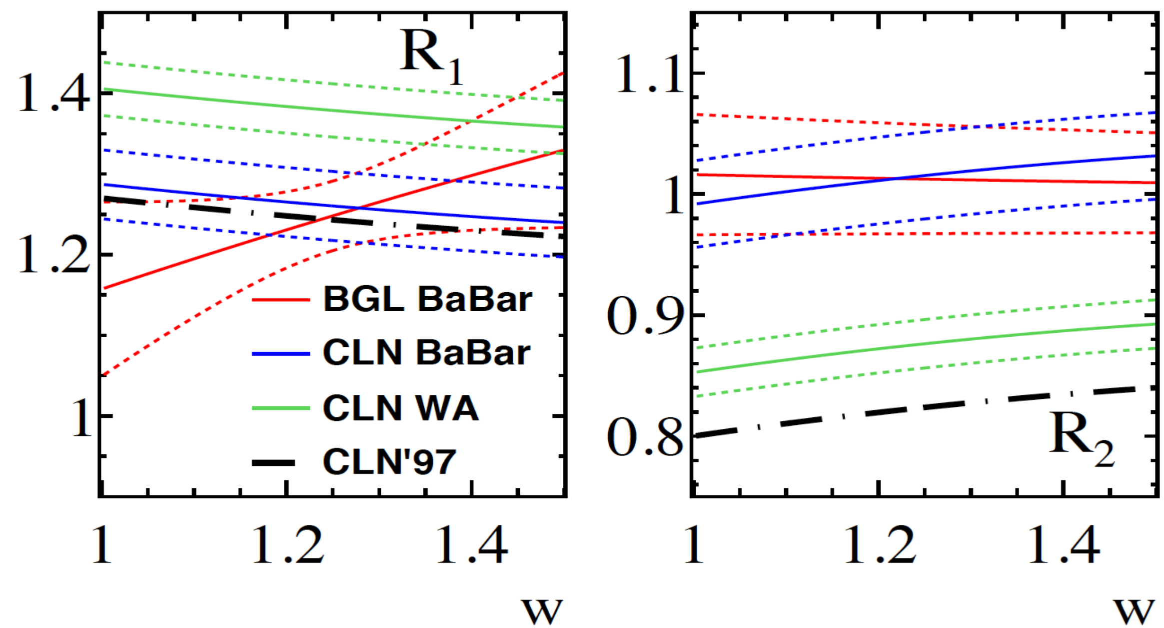
LCSR'08: Faller et al EPJC60 (2009) 603



- BGL FF's differ from CLN-WA both in scale and in shape
- In terms of ratios R_1 and R_2
  - R_1 has positive slope
  - R_2 is flat

$$R_1 = (w+1) m_B m_{D^*} \frac{g}{f}$$

$$R_2 = \frac{w-r}{w-1} - \frac{F_1}{m_B(w-1)f}$$



Impact on R(D*) prediction

- The BGL form factors lead to an updated prediction for R(D*)
  - R(D*)=0.253 ± 0.005
  - The uncertainty on the additional form factors needed for massive leptons follows the assumptions in Gambino'17 JHEP11 (2017) 061 (dominant source of uncertainty)

	R(D)	R(D*)	RD-RD* #σ from SM	RD* only #σ from SM
Bernlochner et al. PRD95(2017)115008	0.299±0.003	0.257 ± 0.003		
Bigi et al. JHEP1711(2017)061		0.260 ± 0.008		
Jaiswal el al. JHEP1712(2017)060	0.299±0.004	0.257 ± 0.005		
HFLAV	**0.299±0.004**	**0.258 ± 0.005**	**3.08**	**2.5**
BaBar PRL123(2019),091801		0.253 ± 0.005	3.43	2.8
Gambino et al. PLB795(2019)386		0.254 ± 0.007	3.16	2.6
Bordone et al. ArXiv:1908.09398 (no exp.)	0.298±0.003	0.247 ± 0.006	3.77	3.2
Bordone el al. ArXiv:1908.09398	0.297±0.003	0.250 ± 0.003	3.87	3.2

Prediction using BaBar only result is compatible with the most recent predictions
BaBar result can be included in the most recent calculations

The predictions that use the unpublished Belle result are systematically higher than the most recents

Summary

- First tagged full 4-D angular analysis of $B \to D^* \ell \nu$
  - Used both B^0 and B^+
  - $|V_{cb}|$ consistent with world average for both CLN and BGL
    - persistent difference with inclusive determination
  - Updated prediction for R(D*) consistent with most recent predictions

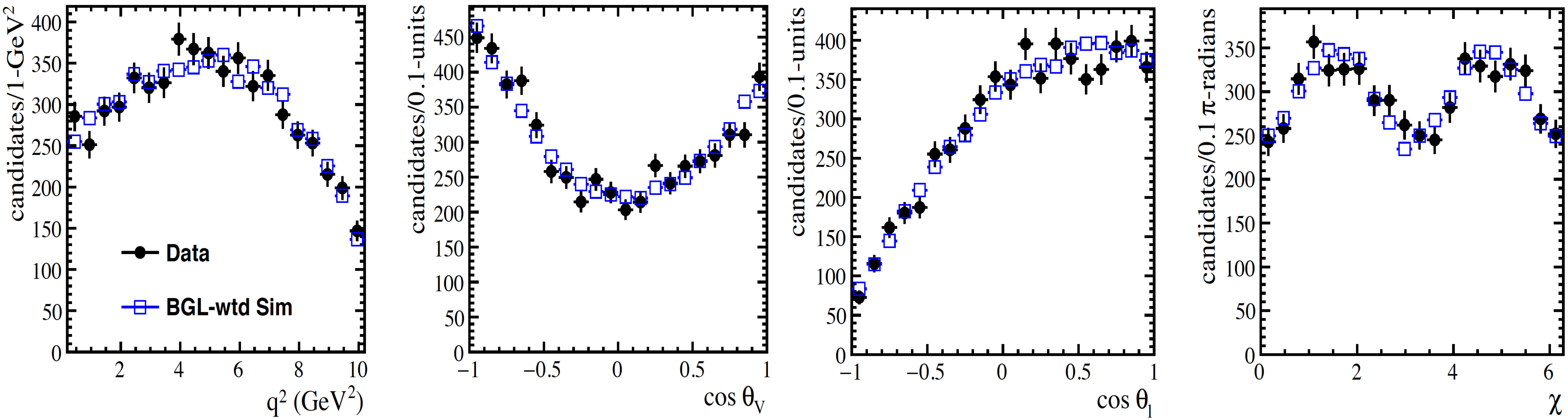
- Result published [Phys.Rev.Lett. 123 (2019) no.9, 091801]
  - Long PRD under internal review: more information + combined fit with $B \to D \ell \nu$

- Waiting for Lattice calculations at w>1
  - Many in the pipeline
- Results need confirmation from a Belle full 4-D angular analysis

BACKUP

Data/MC comparison

- 1D-projections: data and simulated data re-weighted with fit results obtained with BGL parameterization



- Distributions of the angles, integrated in q^2