$B \to D^* \ell\nu$ form factors with a full angular analysis at BaBar

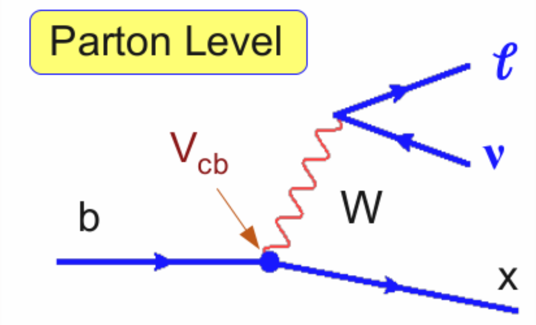
Motivations

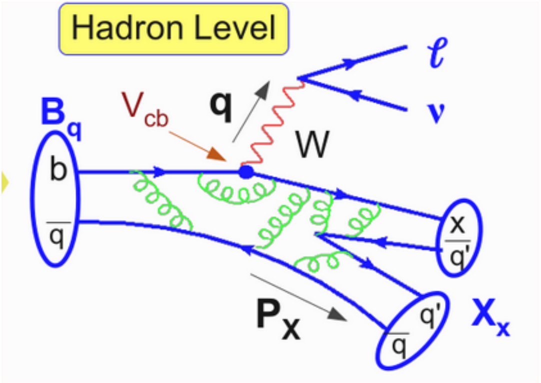
- Many long – standing issues in HF-Physics
- $|V_{cb}|$ determination:
  - from $b \to c \ell \nu$ decays : $|V_{cb}| = (42.19 \pm 0.78) \cdot 10^{-3}$
  - from $B \to D^* \ell \nu$ decays : $|V_{cb}| = (38.76 \pm 0.42_{exp} \pm 0.55_{th}) \cdot 10^{-3}$
- New Physics arising from Form Factors ?

M.Rotondo FPCP 2020 (HFLAV averages)

A Game of Roles

- Theory-experiments interplay
- Theory:
  - convert from *ideal quark world*
  - to the *observed hadron* reality
- Experiments
  - compute rates, *Br*
  - *constrain theory* prediction through measurements of spectra, differential rates, *Form Factors*





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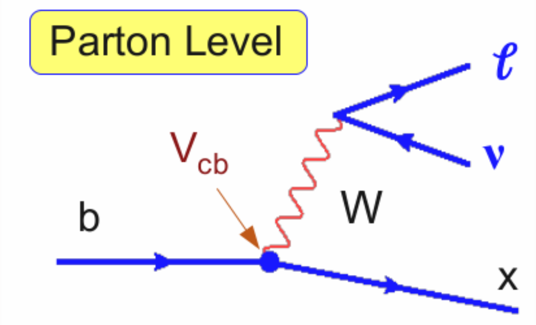
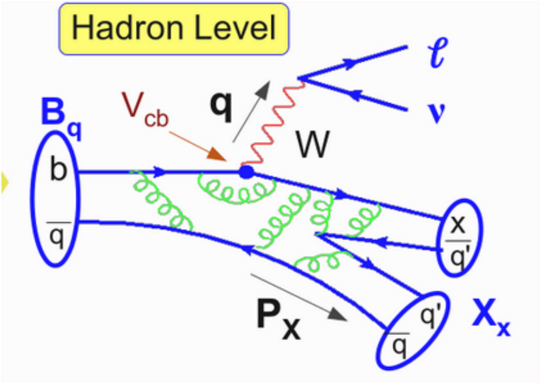




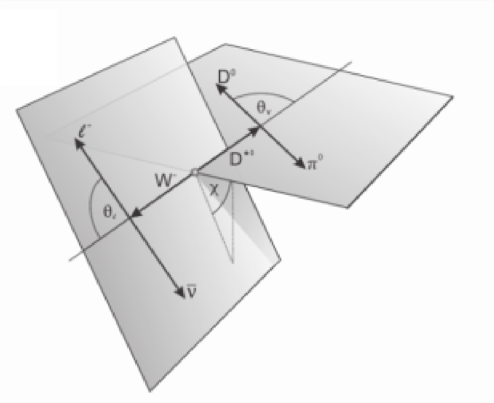
THIS TALK

$B \to D^* \ell \nu$ in a nutshell

Phase Space   Helicity Amplitudes

$$\frac{d\Gamma}{dq^2 d\Omega} = \frac{G_F^2 m_B^5}{48\pi^3} |V_{cb}|^2 \eta_{EW} P(q^2, \Omega) \times F.F.(q^2, \Omega)$$

- 3 form factors (one Vector, two Axial Vector)
  - measured through 4D fit to
    - $q^2 = (p_B - p_{D^*})^2 = (p_\nu + p_\ell)^2 = t$
    - helicity angles $\Omega = (\theta_\ell, \theta_V, \chi)$
  - limited data size, need input (shapes) from theory



Form Factors

$$q^2 \rightarrow \omega = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}} \rightarrow z = \frac{\sqrt{\omega+1} - \sqrt{2}}{\sqrt{\omega+1} + \sqrt{2}}$$

$1 < \omega < 1.53$

$0 < z < 0.23$

Form Factors a la BGL

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- Boyd Grinstein Lebed :
  - power series expansion with minimal theoretical assumptions

$$F_i(z) = \frac{1}{P_i(z)\,\phi_i(z)} \Sigma_{n=0}^{N} a_{i,n} z^n$$

$a_{i,n}$ free (fit) parameters subject to the analicity bound:

$$\sum_{n=0}^{\infty} a_i, n^2 \leq 1$$

[PRL 74,4603 (1995)]

Form Factors a la BGL

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Stop at N=1 due to statistical limitations

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Form Factors a la CLN

$$q^2 \rightarrow \omega = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}} \rightarrow z = \frac{\sqrt{\omega+1} - \sqrt{2}}{\sqrt{\omega+1} + \sqrt{2}}$$

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- Caprini Lellouch Neubert :
  - use HQET bounds to reduce the number of free parameters

$$h_{A1}(\omega) = h_{A1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15) z^2 - (231\rho^2 - 91) z^3\right]$$

"Universal IsgurWise function"

$$R_2(\omega) = R_2(1) + 0.11(\omega - 1) - 0.06(\omega - 1)^2$$

$$R_1(\omega) = R_1(1) - 0.12(\omega - 1) + 0.05(\omega - 1)^2$$

Ratios of FF wrt h(w)

Lattice QCD :
$h_{A1}(1)$ = 0.895 +- 0.026/ 0.906+-0.013

[Nucl.Phys. B530, 153(1998)]

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Fit one shape and two normalization parameters

Lattice QCD :
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The measurements

"Old" approach:

- Select "untagged" sample
  - Large data sets
  - Sizable background
  - Coarse resolution due to missing neutrino
  - Fit to 1D projections

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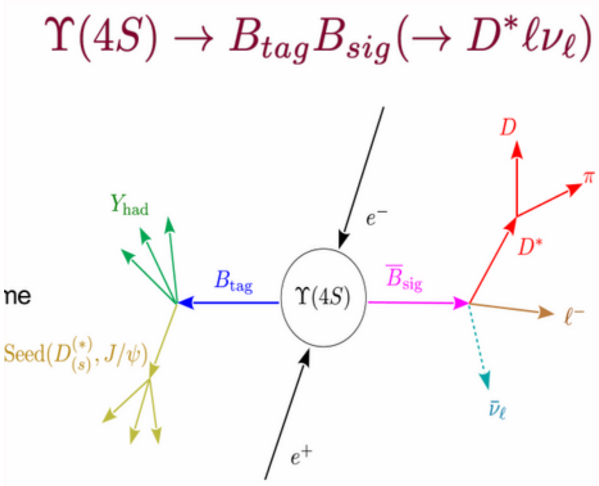
This talk:

- Exploit "tagged" events
  - Smaller data set
  - Negligible background
  - Terrific resolution due to kinematic bounds
  - Full fit to 4D space

Tagged Analysis

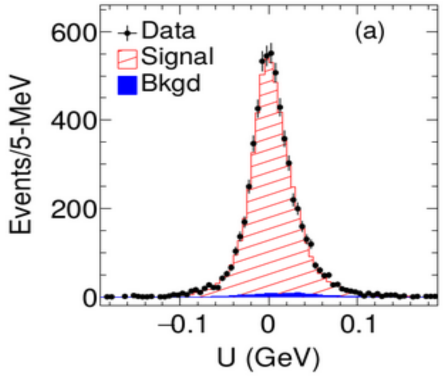
- Tag side
  - fully reconstructed hadronic B decay
  - loose selection: high efficiency / low purity
- Signal side:
  - $B^{0/+} \longrightarrow D^{*\,+/0}\, \ell \nu$
    - $D^{*+/0} \longrightarrow \pi^{+/0} D^0$,
      - $D^0 \longrightarrow K\pi$, $K\pi^+\pi^-$, $K3\pi$



Selection

- Over-constrained system:
  - $U = E_{miss} - p_{miss}$ (missing neutrino)

$FWHM = 50\ MeV$



Selection

- Over-constrained system:
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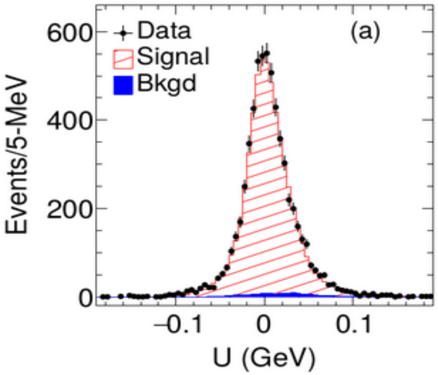
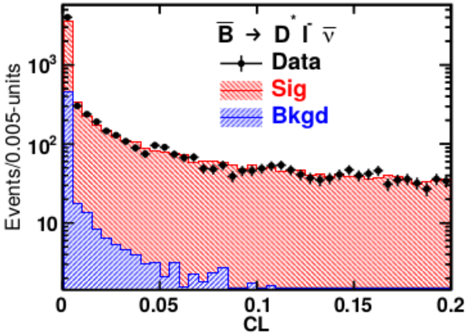
  - Confidence Level

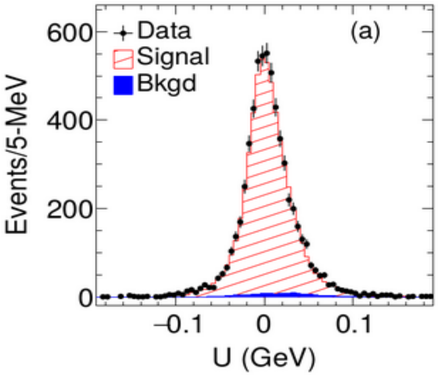


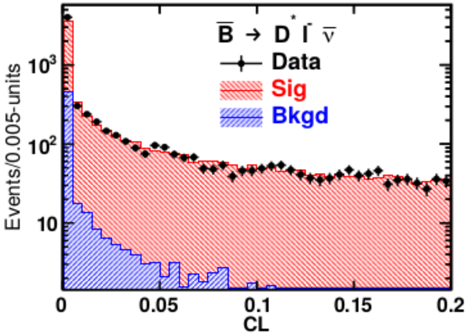


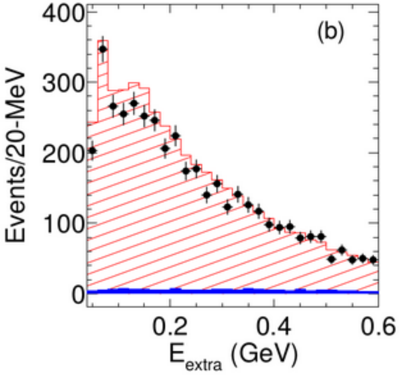
Selection

- Over-constrained system:
  - $U = E_{miss} - p_{miss}$ (missing neutrino)
  - Confidence Level
  - Extra energy carried by low energy photons

Background < 3%







Fits

1) Not-extended Unbinned Maximum Likelihood

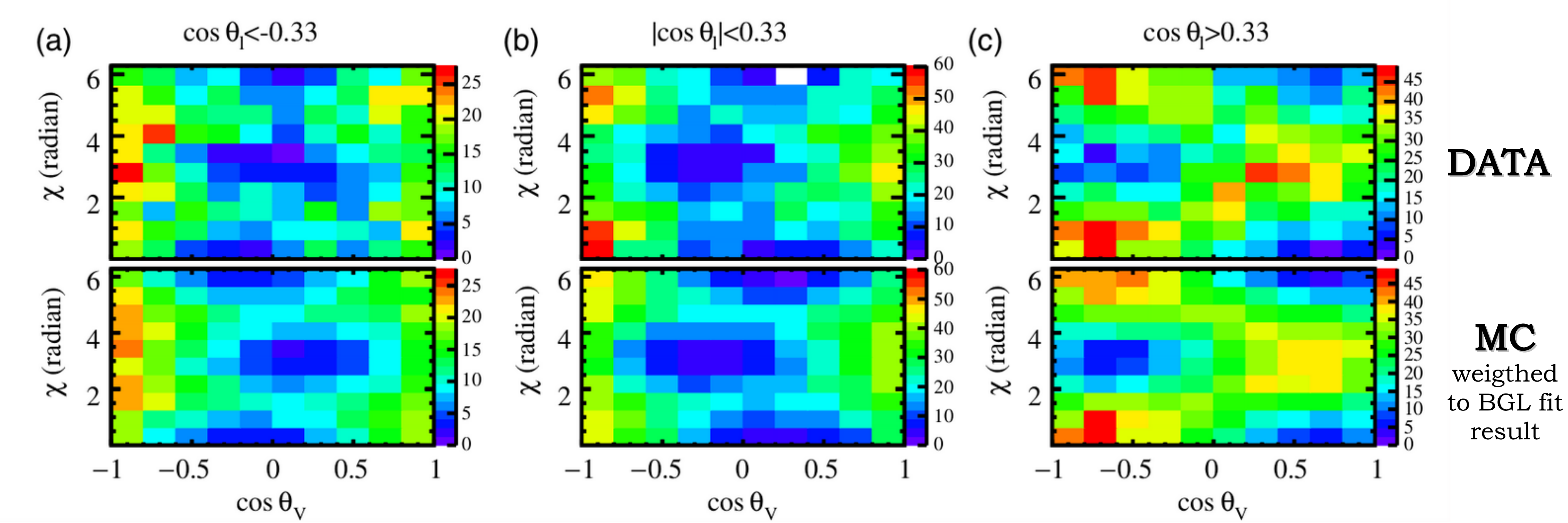
- Measure F.F. parameters only

2) Extended UML to measure in addition $|V_{cb}|$

- Integrated rate constrained to the WA values of the ratios

$$\int \frac{d\Gamma}{dq^2 d\Omega} dq^2 d\Omega = \frac{\mathrm{Br}\left(B \to D^* l \nu_l\right)}{\tau(B)}$$

Fit Quality



$$\frac{\chi^2}{nbins} = \frac{103}{100} \qquad \frac{\chi^2}{nbins} = \frac{89}{100} \qquad \frac{\chi^2}{nbins} = \frac{96}{100}$$

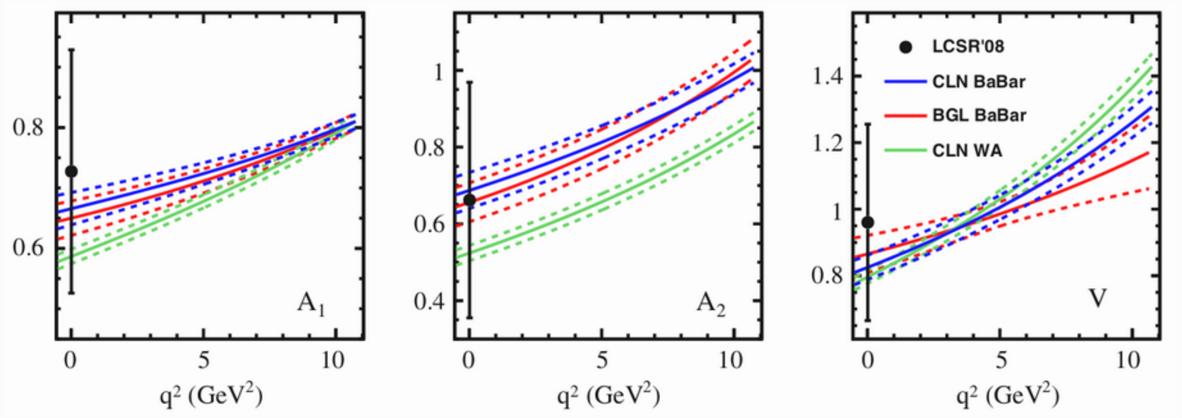
Results

BGL

$a_0^f \times 10^2$	$a_1^f \times 10^2$	$a_1^{F_1} \times 10^2$	$a_0^g \times 10^2$	$a_1^g \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
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

CLN

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84



BGL and CLN provide consistent shapes

CLN fit NOT CONSISTENT with CLNWA (HFLAV) :

p = 0.17 %

Conclusions

- New approach paves the way for future measurements of $|V_{cb}|$ and FF
  - negligible background
  - excellent resolution
- Shape of FF is at odds with previous measurements
- This does not seem to explain the inclusive/exclusive puzzle
- Huge data set from Super-B-factory Belle2 will allow to:
  - solve present contradictions (hopefully)
  - release theory constraints for a less-model-dependent determination

Backup

Partial Decay Width

$$\frac{d\Gamma}{dq^2 d\Omega} = [(H_+^2(1-\cos\theta_\ell)^2 + H_-^2(1+\cos\theta_\ell)^2)\sin^2\theta_V$$
$$+ 2H_0 \sin\theta_\ell \sin 2\theta_V \cos\chi[H_+(1-\cos\theta_\ell)$$
$$- H_-(1+\cos\theta_\ell)] + 4H_0^2\sin^2\theta_\ell\cos^2\theta_V$$
$$- 2H_+H_-\sin^2\theta_\ell\sin^2\theta_V \cos 2\chi]$$
$$\times \frac{3}{8(4\pi)^4} G_F^2 \eta_{\mathrm{EW}}^2 |V_{cb}|^2 \frac{kq^2}{m_B^2} \mathcal{B}(D^* \to D\pi),$$

$$H_0 = \frac{1}{2m_{D^*}\sqrt{q^2}}((m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2)$$
$$- \frac{4m_B^2 k^2}{m_B + m_{D^*}} A_2(q^2)),$$

$$H_\pm = (m_B + m_{D^*})A_1(q^2) \mp \frac{2m_B k}{(m_B + m_{D^*})} V(q^2),$$

CLN Parameters

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84

$1.122 \pm 0.015 \pm 0.019$ $\quad 1.27 \pm 0.026$ $\quad 0.85 \pm 0.02$ $\quad 38.76 \pm 0.42_{\mathrm{exp}} \pm 0.55_{th}$