Measurement of the Semileptonic $B \to D^{(*)} l \nu$ Decays Using a Global Fit

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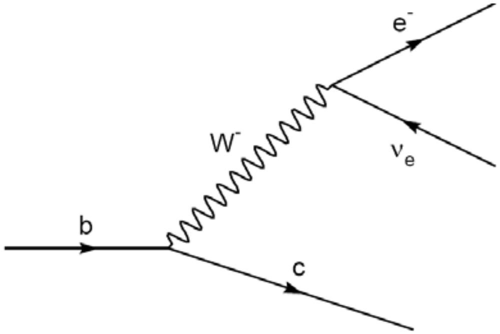
Kenji Hamano,
University of Victoria

Semileptonic B decays and $|V_{cb}|$

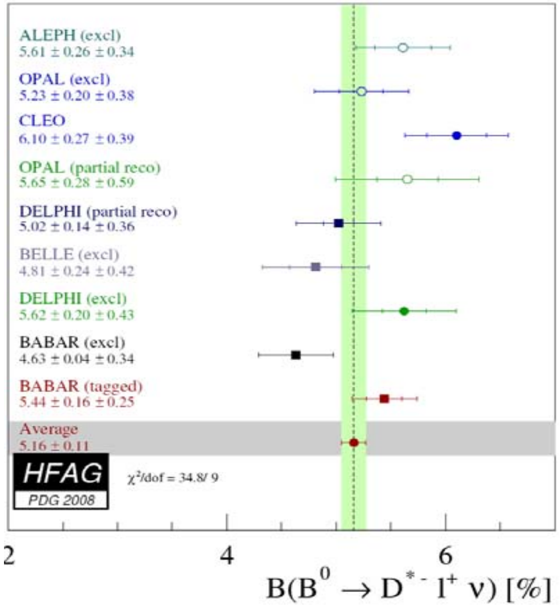


- Semileptonic B decays
  - Inclusive decay BF~10%
    - $B\text{->}X_c l\nu$

      (X_c : meson system including a charm quark)
  - Exclusive decays
    - $B\text{->}Dl\nu$ ~2.5%
    - $B\text{->}D^* l\nu$ ~5.5%
    - $B\text{->}D^{(*)}\pi l\nu$ (this include $B\text{->}D^{**}l\nu$) ~1%
    - $B\text{->}D^{(*)}\pi\pi l\nu$ ~1% ?
- Best mode to measure $|V_{cb}|$
  - Experimentally accessible : Branching fraction~10%
  - Theoretically accessible : Heavy quark symmetry can be used to access non-perturbative QCD.

Motivation

- Poorly measured $B\text{->}Dl\nu$ mode.
  - Current accuracy is ~10-15%
- Inconsistency in $B\text{->}D^*l\nu$ mode.
  - $B^0\text{->}D^{*-}l^+\nu$ branching fraction disagree between measurements.
  - $D^*\text{->}D\pi$ reconstruction issue :
    - The π is very soft (transverse momentum < 200MeV) and difficult to reconstruct.



χ^2/dof = 34.8/9 (CL = 0.)

- Inclusive – exclusive disagreement.
  - $|V_{cb}|$ from inclusive and exclusive measurements differ 2σ.
  - Sum of $B\text{->}Dl\nu$, $B\text{->}D^*l\nu$ and $B\text{->}D^{(*)}\pi l\nu$ branching fraction does not add up to inclusive branching fraction.

Overview of method

- Reconstruct only $D^0 l$ and $D^+ l$ pairs.
  - Do not explicitly reconstruct D^* or D^{**}.
  - Free from soft π reconstruction issue.
  - Can access D^* and D^{**} because they feed down to D.
- Use kinematic variables to separate exclusive modes :
  - 3-dimensional (3D) binning in
    - Lepton momentum
    - D momentum
    - cosTheta(B-Dl)

      = cosine of the angle between B and Dl pair,

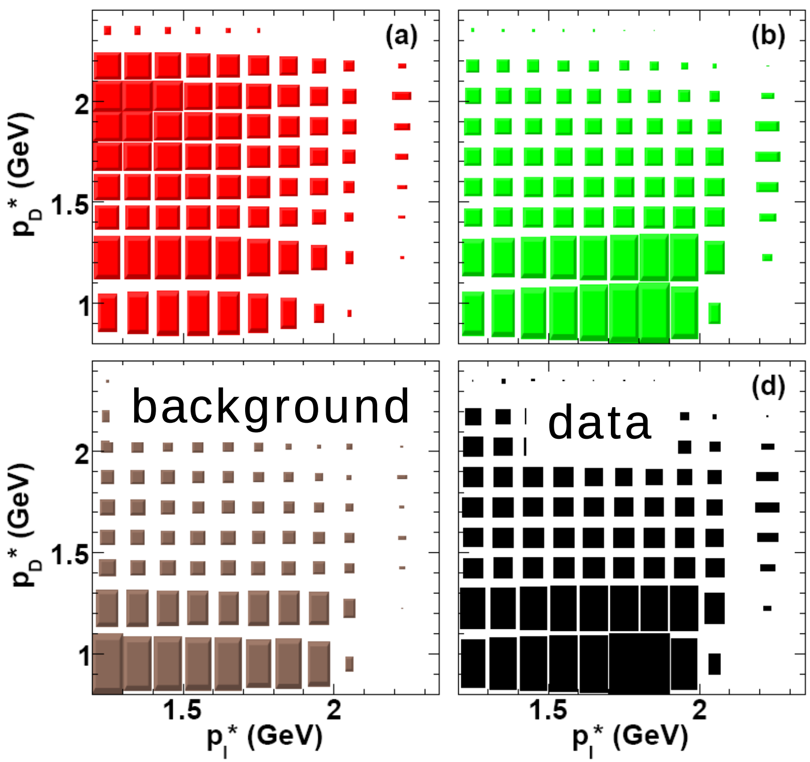
      assuming decay was $B \to Dl\nu$.
- Simultaneously fit to $D^0 l$ and $D^+ l$ distributions with the sum of 3D MC histograms.
  - Fit for $B \to Dl\nu$ and $B \to D^* l\nu$ branching fractions and form factor parameters.
  - Isospin constraints on $B \to D^{(*)}(\pi) l\nu$ decays.

2D distributions

2D distributions of candidates on (p_l^*, p_D^*) plane to show separation power.

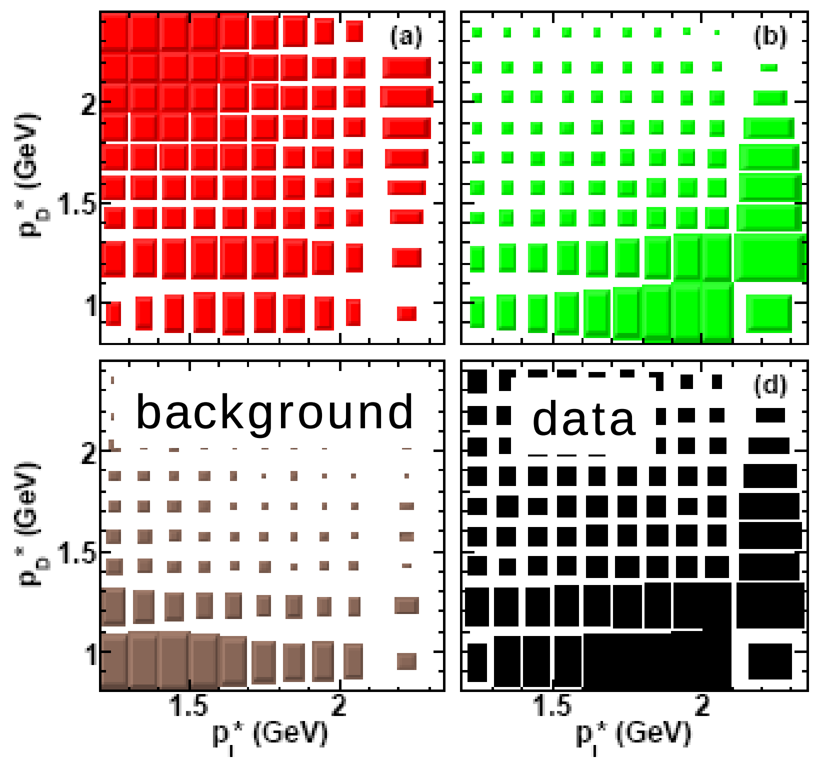
-1 < cosTheta(B-Dl) < 0

$Dl\nu$ $D^*l\nu$

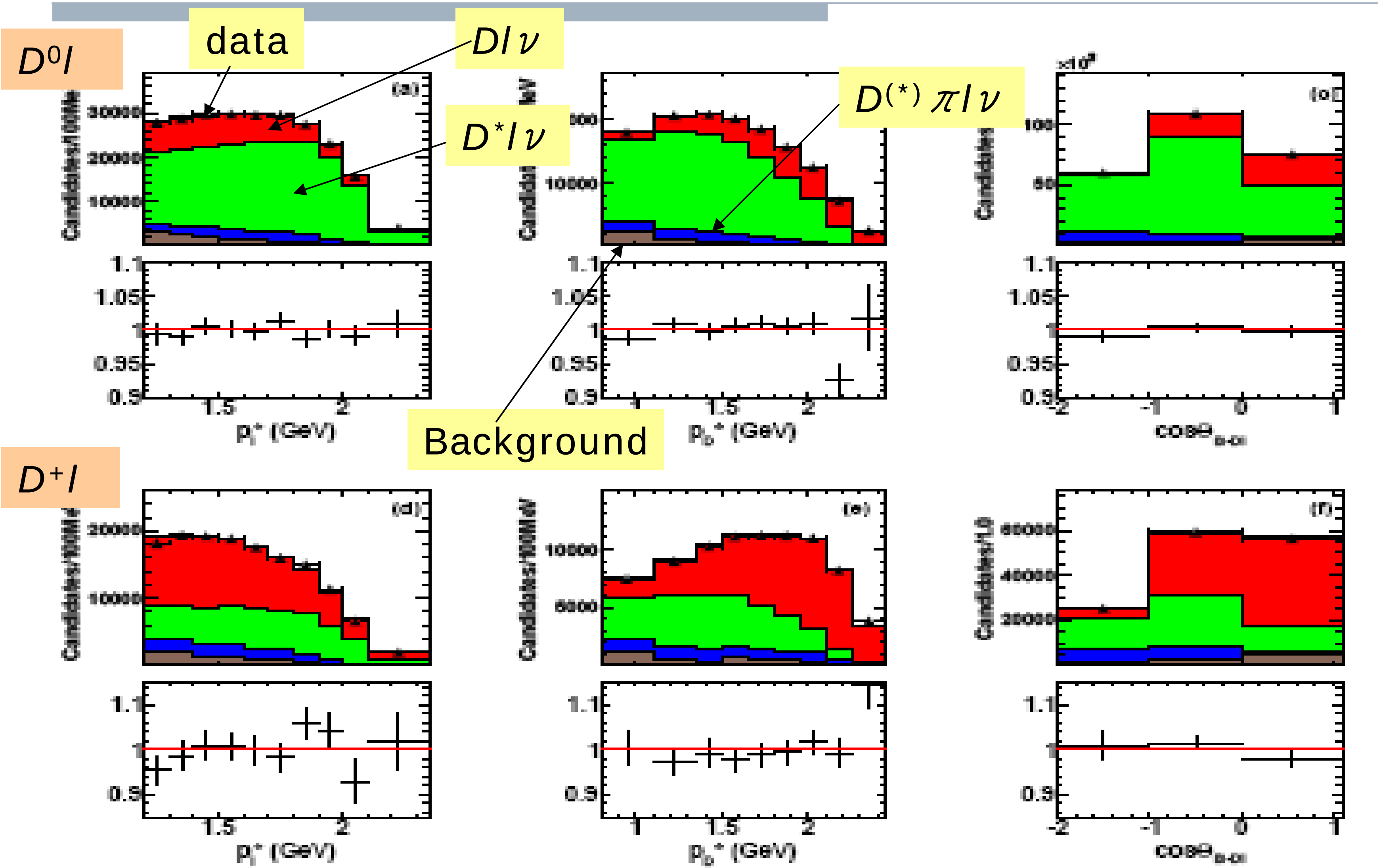


0 < cosTheta(B-Dl) < 1.1

$Dl\nu$ $D^*l\nu$

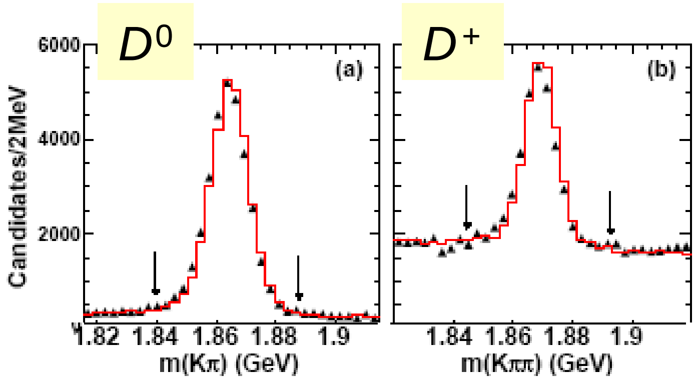


Projection plots (Electron)



Event selection

- Continuum background is subtracted using off-peak data.
- Pre-selection of events
  - Cuts are adjusted on MC to maximize statistical significance of $Dl\nu$ yields after continuum subtraction.
  - Cuts on B and D vertex probabilities to suppress combinatorial background.
  - Cuts on the angle between thrust axis of "Dl pair" and "other charged tracks and neutrals" to suppress continuum background.
- Combinatorial background is subtracted using D mass sidebands.
- To reduce $B\bar{B}$ backgrounds :
  - $p^*_l > 1.2$ GeV, $p^*_D > 0.8$ GeV
  - -2 < cosTheta(B-Dl) < 1.1
- Run1-4, 207fb^{-1} of data was used.



Exclusive decay rates and form factor

- Semileptonic decay rate is
  - $\Gamma \propto |V_{cb}|^2 \, |J(w)|^2$
  - This $J(w)$ is the form factor part
    - $J(w) \propto F(1) \, [1 - \rho^2 (w-1) + ...]$ $(0<(w-1)<0.6)$
    - ρ^2 is the form factor slope.
    - w is the velocity transfer
      - $w = v_B * v_D = p_B * p_D / (m_B * m_D)$
      - Related to momentum transfer q^2.
- Putting everything together
  - $\Gamma \propto (F(1)|V_{cb}|)^2 \, [1 - \rho^2 (w-1) + ...]^2$

Form factor slope

We can measure only this product.
Needs lattice QCD input for $F(1)$ to extract $|Vcb|$.

CLN parameterization

- We used parameterization based on Caprini-Lellouch-Neubert (Nucl.Phys.B530, 153(1998)).
  - Include higher order of (w-1).
  - Relate curvature and slope using dispersive bounds.
  - Can be expressed with one parameter : slope ρ^2
- $\Gamma \propto (F(1)|V_{cb}|)^2 \times$

$$[1-8\rho^2 z+(51\rho^2-10)z^2+(231\rho^2-91)z^3]^2$$

where

$$z=\frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}} \qquad (0<(w-1)<0.6) \quad (0<z<0.06)$$

Fitting Method

- χ^2 is given by

$$\chi^2 = \sum_i \frac{\left(N_i^{data} - \sum_j C_j M_{ij}^{MC}\right)^2}{\left(\sigma_i^{data}\right)^2 + \sum_j \left(C_j \sigma_{ij}^{MC}\right)^2}$$

  - i = bin
  - N_i = number of data candidates in i-th bin, afer off-peak subtraction.
  - M_{ij} = number of simulated candidates of mode j in i-th bin.
  - j = exclusive decay modes.
    - $j=1$: $Dl\nu$, $j=2$: $D^*l\nu$ etc.
  - σ = corresponding statistical uncertainties.
- Coefficients C_j include variables to fit for :

  $Dl\nu$ and $D^*l\nu$ branching fractions and form factor slopes.
- Fit to electron and muon separately and combine them.

$B\text{->}D^{**}l\nu$ and $B\text{->}D^{(*)}\pi\pi l\nu$

- $B\text{->}D^{**}l\nu$
  - We use HQET-inspired Leibovich-Ligeti-Stewart-Wise model (Phys.Rev.D57,308(1998)).
  - This is the first time this model was used in Babar analysis.
- $B\text{->}D^{(*)}\pi\pi l\nu$
  - This is completely unknown decay mode.

    BF($B\text{->}D^{(*)}\pi\pi l\nu$) = (1.1 ± 1.1) % is assumed to saturate inclusive BF.
  - We generate decays of the type :

    $B\text{->}X_c l\nu$ -> $D^{(*)}\pi\pi l\nu$,

    $B\text{->}Y_c l\nu$ -> $D^{(*)}\rho l\nu$ -> $D^{(*)}\pi\pi l\nu$
  - We assume 4-intermediate resonances:

name	mass (GeV)	width (GeV)	spin
X_c	2.61	0.3	0
X_c^*	2.61	0.3	1
Y_c	2.87	0.1	0
Y_c^*	2.87	0.1	1

Mass just above $D^*\pi\pi$ threshold

Mass just above $D^*\rho$ threshold

Systematic uncertainties (summary)

- Main source of systematic errors :
  - Not well measured $B \to D^{(*)}\pi l\nu$ branching fractions and form factors.
  - Unknown $B \to D^{(*)}\pi\pi l\nu$ component.
  - D^* and D decay branching fractions.
  - Electron : Radiative correction.

    Muon : Particle identification.

Systematic uncertainties (all)

item	Electron sample						Muon sample					
	ρ^2_D	$\rho^2_{D^*}$	$\bar{D}^0\ell^+\nu$	$\bar{D}^{*0}\ell^+\nu$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$	ρ^2_D	$\rho^2_{D^*}$	$\bar{D}^0\ell^+\nu$	$\bar{D}^{*0}\ell^+\nu$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$
R'_1	0.44	2.77	0.69	-0.38	0.60	0.71	0.46	2.69	0.72	-0.40	0.61	0.70
R'_2	-0.37	1.04	-0.18	0.30	-0.30	0.49	-0.42	0.97	-0.19	0.30	-0.31	0.48
D^{**} slope	-1.04	-2.64	-0.09	-0.09	-0.64	-0.90	-0.93	-2.74	-0.12	-0.10	-0.56	-0.96
D^{**} FF approximation	-1.01	0.56	-0.10	0.22	-0.63	0.29	-1.18	0.60	-0.11	0.23	-0.68	0.32
$\mathcal{B}(B^+ \to D^{(*)}\pi\ell\nu)$	0.41	-0.36	-0.09	-0.88	0.19	-0.56	0.75	-0.41	0.01	-0.95	0.41	-0.61
$f_{D_2^*/D_1}$	-0.22	0.09	-0.23	0.10	-0.24	0.08	-0.28	0.10	-0.25	0.12	-0.28	0.09
$f_{D_0^* D\pi/D_1 D_2^*}$	-2.55	1.49	-1.91	1.19	-2.46	1.08	-3.44	1.63	-1.94	1.27	-2.85	1.18
$f_{D_1^* D^*\pi/D_1 D_2^*}$	1.38	-0.88	1.03	-0.59	1.30	-0.59	1.85	-0.92	1.06	-0.65	1.51	-0.63
$f_{D\pi/D_0^*}$	-0.80	-1.25	0.33	0.16	-0.30	-0.33	-0.75	-1.20	0.29	0.18	-0.26	-0.32
$f_{D^*\pi/D_1^*}$	-0.18	-0.05	-0.12	0.19	-0.16	0.08	-0.26	-0.04	-0.14	0.21	-0.21	0.09
NR D^*/D ratio	0.69	-0.17	0.26	-0.13	0.53	-0.09	0.81	-0.16	0.26	-0.14	0.56	-0.11
$\mathcal{B}(B^+ \to D^{(*)}\pi\pi\ell\nu)$	1.14	-2.03	0.25	-1.30	0.78	-1.31	1.86	-1.77	0.40	-1.22	1.18	-1.20
X^*/X an Y^*/Y ratio	0.58	-1.18	0.09	-0.28	0.38	-0.53	0.70	-1.04	0.08	-0.25	0.41	-0.47
X/Y and X^*/Y^* ratio	0.72	-0.85	0.21	-0.66	0.52	-0.61	1.02	-0.79	0.25	-0.64	0.67	-0.58
$D_1 \to D\pi\pi$	2.09	-1.59	0.74	-1.09	1.60	-1.06	2.57	-1.53	0.75	-1.08	1.77	-1.05
$f_{D_2^*}$	-0.07	-0.01	-0.06	0.04	-0.07	0.02	-0.09	-0.00	-0.06	0.04	-0.08	0.02
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.67	-0.01	0.42	-0.34	0.60	-0.17	0.73	-0.01	0.40	-0.34	0.59	-0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.62	0.01	-0.21	-1.57	0.26	-0.78	0.82	0.10	-0.27	-1.61	0.31	-0.77
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	-1.27	-0.40	-2.03	0.30	-1.74	0.02	-1.23	-0.41	-1.96	0.27	-1.62	-0.00
τ_{B^+}/τ_{B^0}	0.22	0.17	0.61	0.27	0.43	0.19	0.19	0.17	0.57	0.28	0.39	0.20
f_{+-}/f_{00}	0.81	0.43	0.63	-0.54	0.78	-0.13	0.82	0.49	0.54	-0.53	0.70	-0.10
Number of $B\overline{B}$ events	0.00	-0.00	-1.11	-1.11	-0.55	-0.55	0.00	-0.00	-1.11	-1.11	-0.55	-0.55
Off-peak Luminosity	0.04	0.01	-0.02	-0.00	0.02	0.00	0.06	0.00	-0.02	-0.00	0.02	-0.00
B momentum distribution	-0.89	0.63	1.28	-0.55	-1.11	0.47	1.19	-0.09	1.24	-0.66	1.26	-0.36
Lepton PID eff.	0.47	0.17	1.20	0.83	0.87	0.47	3.14	0.09	5.08	5.86	1.99	2.93
Lepton mis-ID	0.03	0.01	-0.01	-0.01	0.01	-0.00	2.49	0.71	-0.57	-0.51	1.03	-0.01
Kaon PID	0.06	0.83	0.27	0.24	0.17	0.39	0.96	0.72	0.34	0.29	0.68	0.39
Tracking eff.	-0.90	-0.46	-3.29	-2.02	-2.17	-1.16	-0.51	-0.30	-3.30	-2.11	-1.93	-1.16
Radiative corrections	-2.95	-1.08	-2.89	-0.71	-2.99	-0.70	-0.71	-0.62	-0.82	-0.24	-0.78	-0.33
Bremsstrahlung	0.07	-0.00	-0.13	-0.29	-0.03	-0.14	0.00	0.00	0.00	0.00	0.00	0.00
Vertexing	0.80	-0.68	0.63	0.59	0.78	0.07	1.66	-0.78	0.95	0.54	1.37	0.01
Background	1.32	1.12	0.63	0.34	1.05	0.52	1.55	1.10	0.67	0.38	1.15	0.49
Total	**5.90**	**5.84**	**5.97**	**4.09**	**5.91**	**3.29**	**7.69**	**5.67**	**7.29**	**7.14**	**6.01**	**4.33**

Results

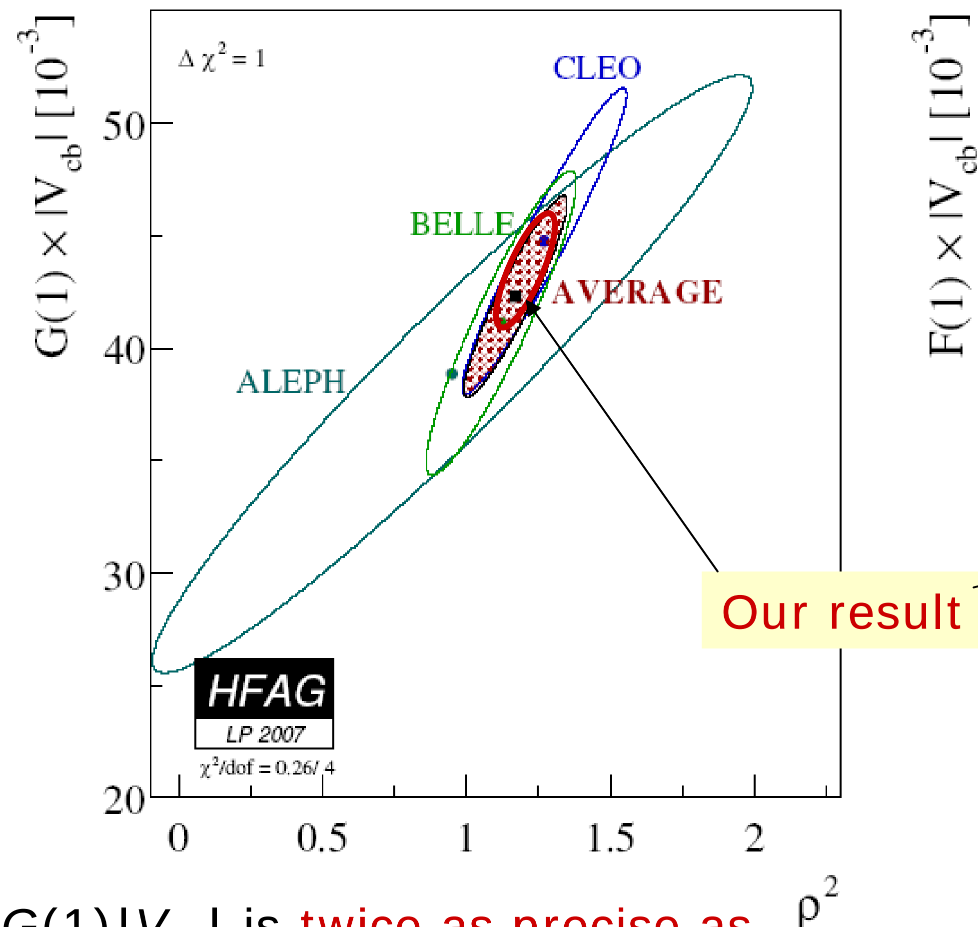
Parameters	De sample	$D\mu$ sample	combined result
ρ_D^2	$1.27 \pm 0.05 \pm 0.07$	$1.16 \pm 0.06 \pm 0.09$	$1.23 \pm 0.04 \pm 0.07$
$\rho_{D^*}^2$	$1.22 \pm 0.02 \pm 0.07$	$1.23 \pm 0.03 \pm 0.07$	$1.21 \pm 0.02 \pm 0.07$
$\mathcal{B}(\bar{D}^0\ell^+\nu)(\%)$	$2.43 \pm 0.03 \pm 0.14$	$2.30 \pm 0.04 \pm 0.17$	$2.38 \pm 0.03 \pm 0.13$
$\mathcal{B}(\bar{D}^{*0}\ell^+\nu)(\%)$	$5.38 \pm 0.03 \pm 0.22$	$5.19 \pm 0.04 \pm 0.37$	$5.32 \pm 0.02 \pm 0.21$
χ^2/n.d.f. (probability)	$425/470$ (0.93)	$498/466$ (0.15)	$2.1/4$ (0.71)

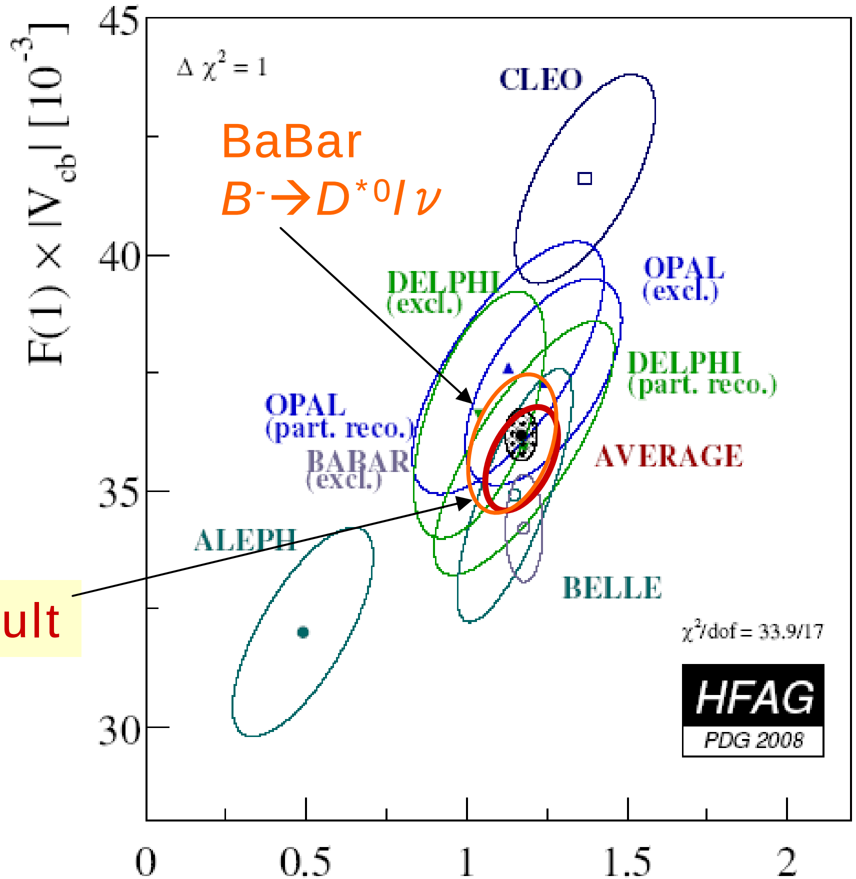
- Good χ^2.
- Electron and muon results are consistent.
- Combined results agree with world average.

$$Dl\nu \longrightarrow \mathcal{G}(1)|V_{cb}| = (44.2 \pm 0.8 \pm 2.4) \times 10^{-3}$$

$$D^*l\nu \longrightarrow \mathcal{F}(1)|V_{cb}| = (35.6 \pm 0.2 \pm 1.2) \times 10^{-3}.$$

Comparison with others





$G(1)|V_{cb}|$ is twice as precise as world average.

$F(1)|V_{cb}|$ is as good as best single measurement.

$|V_{cb}|$

$$D^*\ell\nu:\ |V_{cb}| = (38.2 \pm 0.2 \pm 1.3 \pm 0.9) \times 10^{-3}$$

$$D\ell\nu:\ |V_{cb}| = (41.1 \pm 0.8 \pm 2.2 \pm 0.9) \times 10^{-3}.$$

- These two results agree.
- We used (Okamoto *et.al*., hep-lat/0409116)

$$\mathcal{G}(1) = 1.074 \pm 0.018 \pm 0.016$$

and (Laiho, arXiv:0710.1111[hep-lat])

$$\mathcal{F}(1) = 0.924 \pm 0.012 \pm 0.019$$

Inclusive average (HFAG, Kinetic Scheme)

$|V_{cb}| = (41.91 \pm 0.19 \pm 0.28 \pm 0.59) \times 10^{-3}$

Averaging with other Babar results.

- We average over Babar measurements :

[6] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **100**, 151802 (2008).
[9] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **77**, 032002 (2008).
[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **100**, 231803 (2008).

- to get

$$\mathcal{B}(B^- \to D^{*0}\ell\overline{\nu}) = (5.49 \pm 0.20)\% \quad (\chi^2 \text{ probab.}=0.17)$$
$$\rho^2_{D^*} = 1.19 \pm 0.05 \quad (\chi^2 \text{ probab.}=0.87)$$
$$\mathcal{F}(1)|V_{cb}| = (35.0 \pm 1.0) \times 10^{-3} \quad (\chi^2 \text{ probab.}=0.67)$$

$$\mathcal{B}(B^- \to D^{0}\ell\overline{\nu}) = (2.35 \pm 0.10)\% \quad (\chi^2 \text{ probab.}=0.95)$$

- Details are in BAD1586

Summary

- We used global fit to determine

  Form factor slopes :
  $$\rho^2_D = 1.23 \pm 0.04 \pm 0.07$$
  $$\rho^2_{D*} = 1.21 \pm 0.02 \pm 0.07$$

  Branching fractions :
  $$\mathcal{B}(B^+ \to \bar{D}^0 \ell^+ \nu) = (2.38 \pm 0.03 \pm 0.13)\%$$
  $$\mathcal{B}(B^+ \to \bar{D}^{*0} \ell^+ \nu) = (5.32 \pm 0.02 \pm 0.21)\%$$

- This method is quite different from and complementary to previous measurements.
- Results agrees with world average.
- We calculated $G(1)|V_{cb}|$ and $F(1)|V_{cb}|$
  - $G(1)|V_{cb}|$ is twice as accurate as world average.
  - $F(1)|V_{cb}|$ is as precise as best single measurement.
- $|V_{cb}|$ is also extracted.
- Documents :
  - PRD draft : BAD1781
  - Support document : BAD1586

Projection plots (Muon)