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

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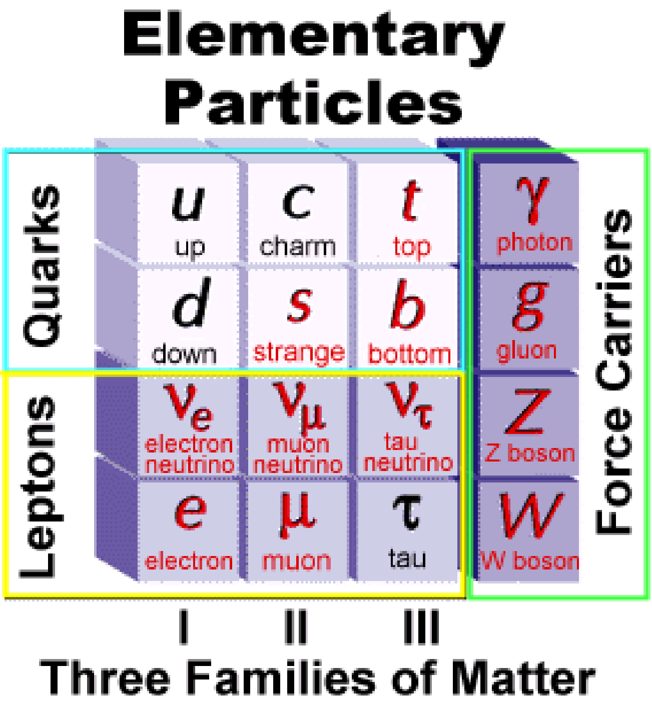
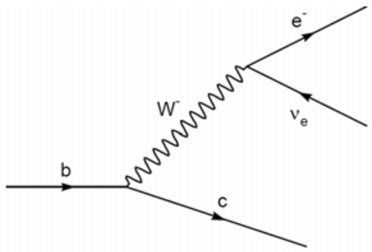
Standard Model

- Successful theory of elementary particles.
- Three families of quarks and leptons
- The CKM matrix

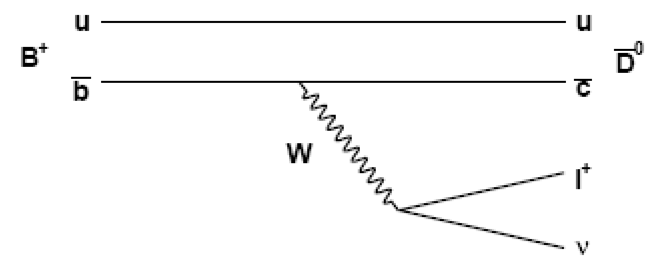
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- Mix three families of quarks
- Allow flavor changing transitions such as
  - $b \rightarrow c + W$
  - Amplitude is proportional to $|V_{cb}|$ (free parameter of the Standard Model)



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

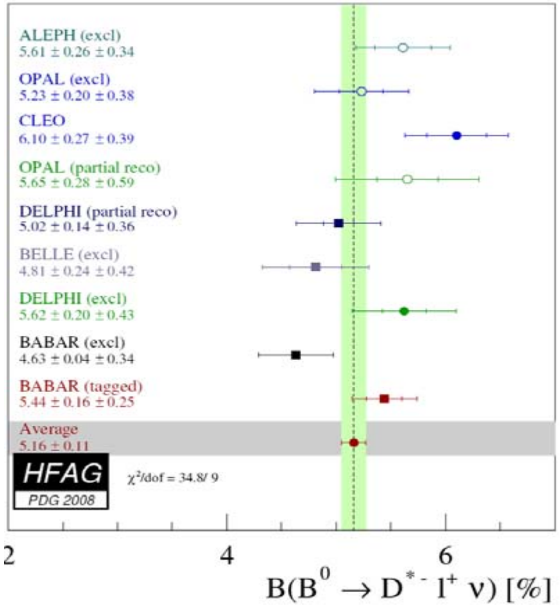


- Semileptonic $B(q\bar{b})$ decays
  - Inclusive decay BF~10%
    - $B\text{->}X_c l \nu$

      (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.

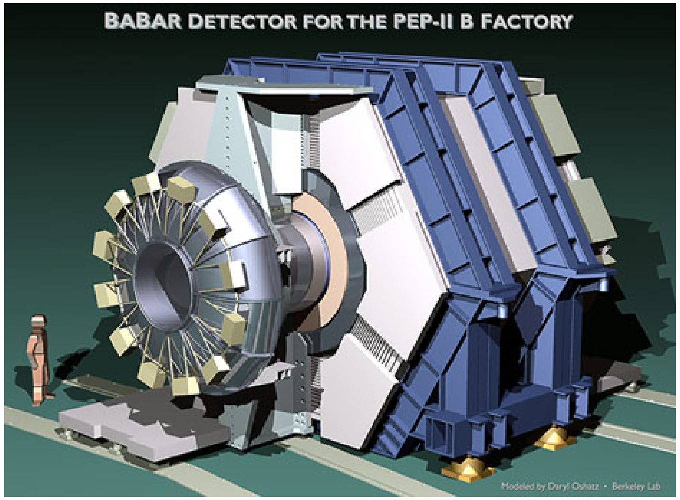


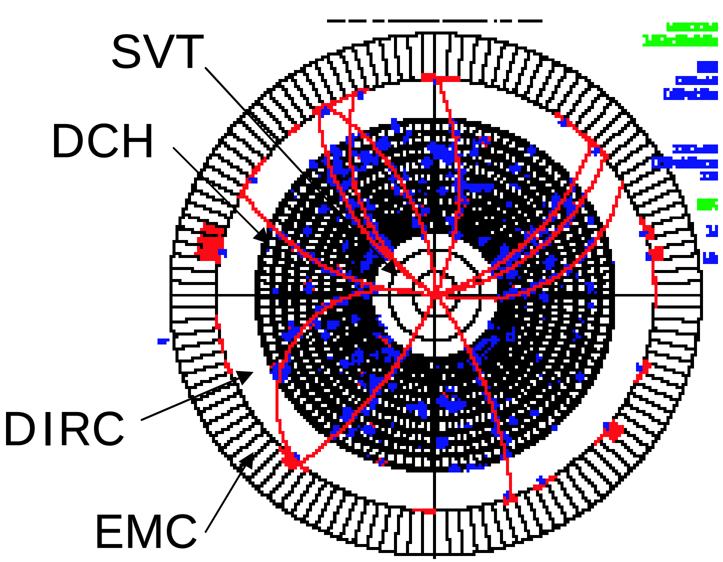
$\chi^2/\text{dof} = 34.8/9$ (CL = 0.)

- 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.

BABAR experiment

- PEP II collider produces $B\bar{B}$ pairs.
- Babar detector :
- Silicon Vertex Tracker (SVT)
- Drift Chamber (DCH)
  - Charged track reconstruction, PID
  - SVT and DCH are in 1.5 T magnetic field.
- Cerenkov Detector (DIRC)
  - PID
- Electromagnetic Calorimeter (EMC)
  - Photon and electron detection
- Instrumented Flux Return (IFR)
  - Muon and neutral hadron detection





Overview of method

- Reconstruct only D^0l and D^+l pairs. (l = e or μ)
  - 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 $B\text{->}Dl\nu$.

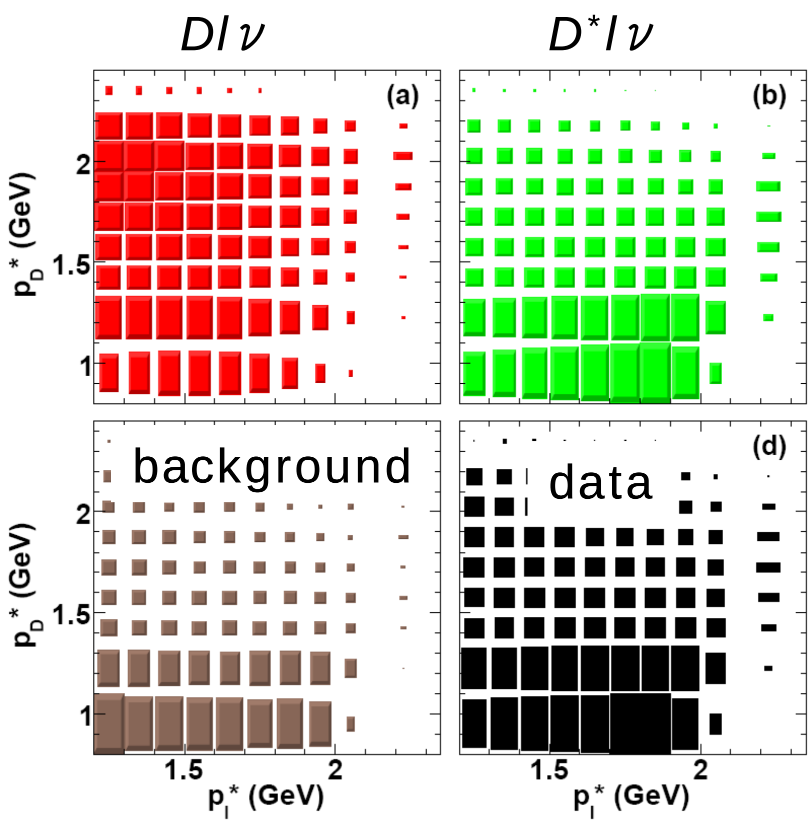
$$\cos\Theta_{B-Dl} = \frac{2E_B E_{Dl} - m_B^2 - m_{Dl}^2}{2|p_B||p_{Dl}|}$$

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

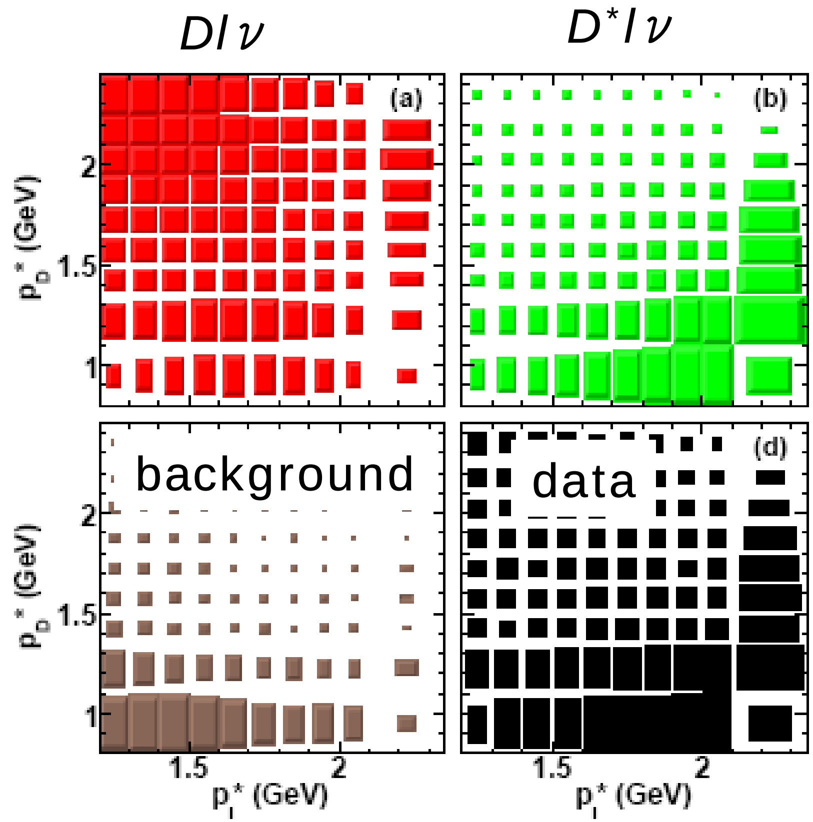
2D distributions

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

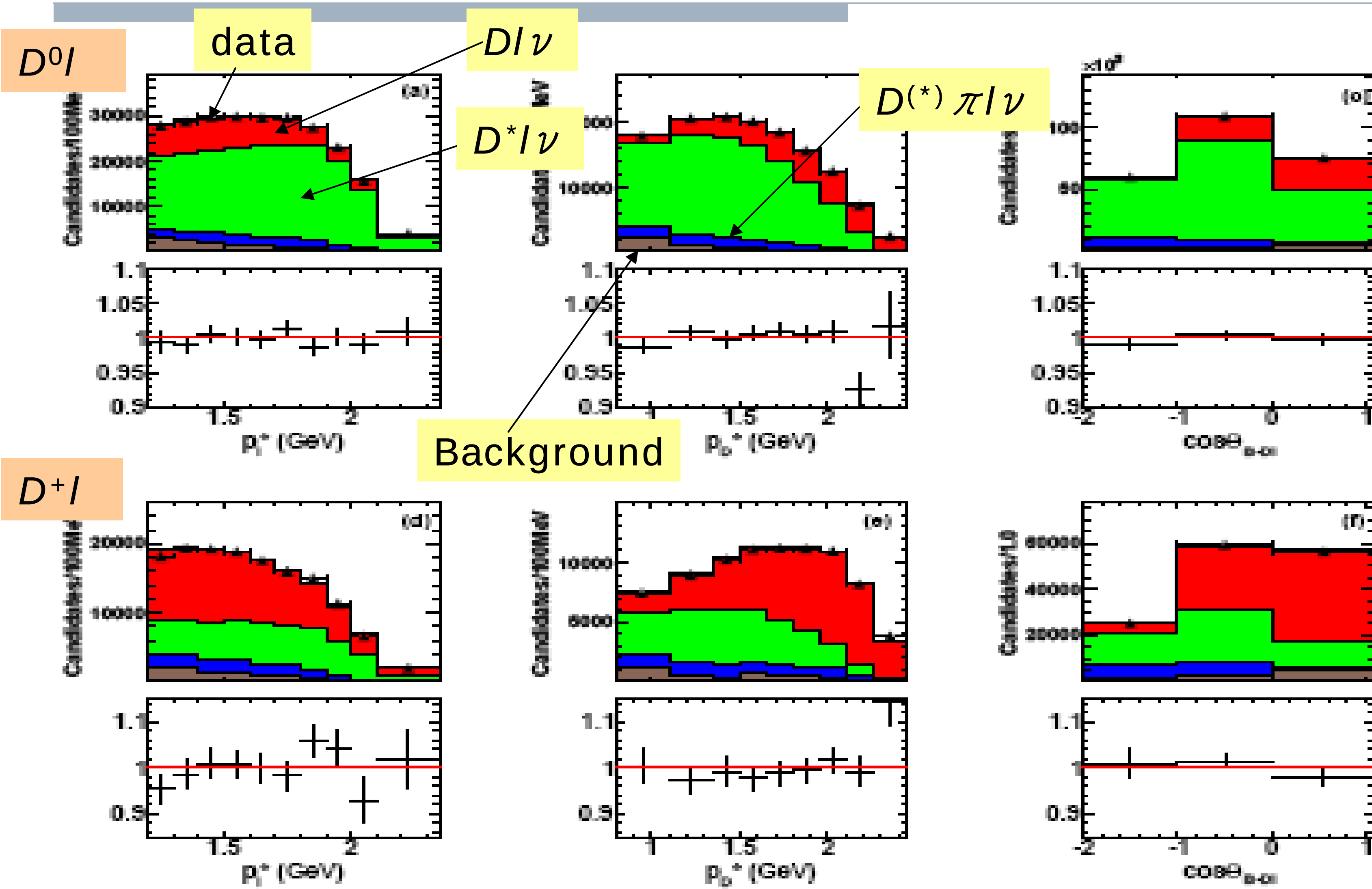
-1 < cosTheta(B-Dl) < 0



0 < cosTheta(B-Dl) < 1.1

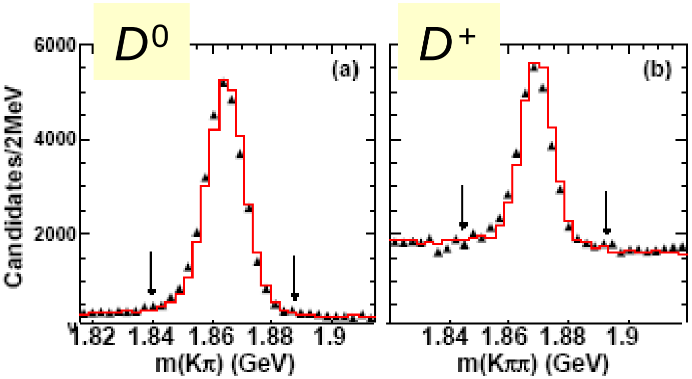


Projection plots (Electron)



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
  - $-2 < \cos\text{Theta}(B\text{-}Dl) < 1.1$
- 207fb^{-1} of data was used. 230 million $B\bar{B}$-pairs,

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

Form factor slope

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

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

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

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 after systematic study.

$B\to D^{**} l \nu$ and $B\to D^{(*)} \pi \pi l \nu$

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

    $B\to X_c l \nu \to D^{(*)} \pi \pi l \nu$,

    $B\to Y_c l \nu \to D^{(*)} \rho l \nu \to D^{(*)} \pi \pi l \nu$
  - 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 $B\text{->}D^{(*)}\pi l \nu$ branching fractions and form factors.
  - Unknown $B\text{->}D^{(*)}\pi \pi l \nu$ component.
  - D^* and D decay branching fractions.
  - Electron : Radiative correction.

    Muon : Particle identification.

Systematic uncertainties (all)

item	Electron sample						Muon sample					
	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$
R_1'	0.45	2.78	0.69	−0.38	0.60	0.71	0.47	2.70	0.73	−0.40	0.61	0.70
R_2'	−0.38	1.04	−0.18	0.30	−0.31	0.49	−0.43	0.98	−0.19	0.30	−0.32	0.48
D^{**} slope	−1.11	−2.65	−0.09	−0.10	−0.68	−0.91	−1.04	−2.73	−0.12	−0.12	−0.60	−0.97
D^{**} FF approximation	−0.84	0.58	−0.11	0.20	−0.53	0.29	−1.00	0.61	−0.12	0.22	−0.59	0.31
$\mathcal{B}(B^- \to D^{(*)}\pi\ell\overline{\nu})$	0.42	−0.37	−0.11	−0.88	0.19	−0.56	0.77	−0.43	−0.01	−0.95	0.40	−0.62
$f_{D_2^*/D_1}$	−0.32	0.14	−0.33	0.14	−0.35	0.12	−0.41	0.15	−0.36	0.16	−0.40	0.13
$f_{D_0^*D\pi/D_1D_2^*}$	−2.16	1.16	−1.52	0.97	−2.02	0.86	−2.91	1.27	−1.53	1.03	−2.34	0.94
$f_{D_1^*D^*\pi/D_1D_2^*}$	1.10	−0.70	0.82	−0.45	1.03	−0.45	1.46	−0.72	0.85	−0.50	1.19	−0.49
$f_{D\pi/D_0^*}$	−0.75	−1.14	0.31	0.15	−0.27	−0.30	−0.70	−1.10	0.27	0.16	−0.24	−0.29
$f_{D^*\pi/D_1^*}$	−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	0.70	−0.14	0.27	−0.16	0.53	−0.10	0.83	−0.13	0.27	−0.17	0.58	−0.12
$\mathcal{B}(B^- \to D^{(*)}\pi\pi\ell\overline{\nu})$	1.14	−2.03	0.25	−1.29	0.77	−1.30	1.87	−1.77	0.40	−1.21	1.18	−1.19
X^*/X and Y^*/Y ratio	0.59	−1.18	0.09	−0.28	0.38	−0.52	0.70	−1.04	0.08	−0.24	0.41	−0.47
X/Y and X^*/Y^* ratio	0.73	−0.85	0.20	−0.66	0.51	−0.61	1.03	−0.79	0.24	−0.63	0.66	−0.58
$D_1 \to D\pi\pi$	2.12	−1.59	0.74	−1.08	1.60	−1.06	2.60	−1.53	0.75	−1.07	1.77	−1.04
$f_{D_2^*}$	−0.11	−0.01	−0.09	0.06	−0.11	0.03	−0.13	−0.01	−0.09	0.06	−0.11	0.03
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.70	−0.01	0.43	−0.34	0.61	−0.17	0.76	−0.01	0.41	−0.34	0.60	−0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.67	0.01	−0.20	−1.64	0.29	−0.82	0.89	0.10	−0.26	−1.69	0.35	−0.81
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	−1.37	−0.42	−2.16	0.31	−1.85	0.02	−1.33	−0.43	−2.08	0.28	−1.73	−0.00
τ_{B^-}/τ_{B^0}	0.24	0.17	0.62	0.27	0.45	0.19	0.20	0.17	0.58	0.28	0.39	0.20
f_{+-}/f_{00}	0.84	0.44	0.66	−0.54	0.81	−0.13	0.86	0.49	0.57	−0.53	0.74	−0.10
Number of $B\overline{B}$ events	0.00	−0.00	−1.11	−1.11	−0.56	−0.55	0.00	−0.00	−1.11	−1.11	−0.56	−0.55
Off-peak Luminosity	0.05	0.01	−0.02	−0.00	0.02	0.00	0.06	0.00	−0.02	−0.00	0.02	−0.00
B momentum distrib.	−0.90	0.64	1.28	−0.55	−1.11	0.48	1.22	−0.10	1.25	−0.66	1.28	−0.36
Lepton PID eff	0.48	0.17	1.20	0.83	0.88	0.47	3.19	0.09	5.08	5.86	1.99	2.93
Lepton mis-ID	0.03	0.01	−0.01	−0.01	0.02	−0.00	2.52	0.71	−0.58	−0.50	1.03	−0.01
Kaon PID	0.06	0.83	0.27	0.24	0.17	0.39	0.97	0.73	0.35	0.29	0.69	0.39
Tracking eff	−0.93	−0.46	−3.31	−2.02	−2.19	−1.16	−0.54	−0.30	−3.33	−2.11	−1.96	−1.16
Radiative corrections	−2.98	−1.07	−2.87	−0.72	−2.98	−0.71	−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	0.81	−0.67	0.63	0.60	0.78	0.08	1.69	−0.77	0.96	0.54	1.38	0.01
Background total	1.39	1.12	0.64	0.34	1.07	0.51	1.58	1.09	0.67	0.38	1.16	0.49
Total	**5.76**	**5.72**	**5.89**	**4.04**	**5.74**	**3.21**	**7.48**	**5.53**	**7.23**	**7.10**	**5.77**	**4.25**

Results

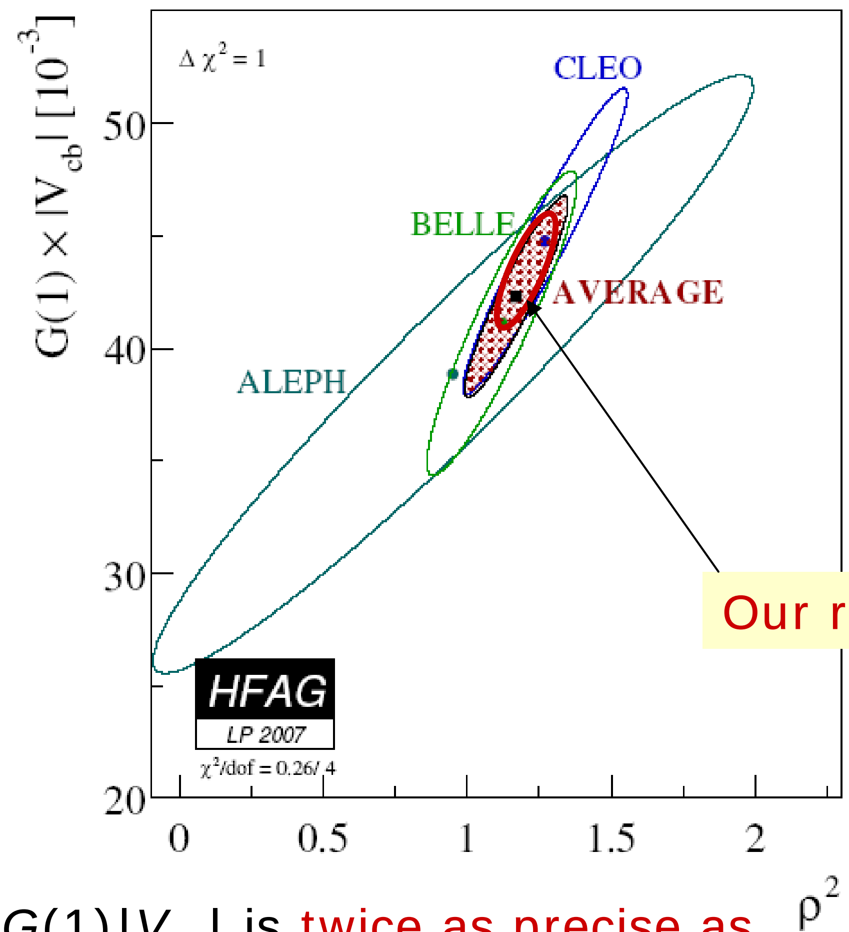
Parameters	De sample	$D\mu$ sample	combined result
ρ_D^2	$1.26 \pm 0.05 \pm 0.07$	$1.15 \pm 0.06 \pm 0.09$	$1.22 \pm 0.04 \pm 0.07$
$\rho_{D^*}^2$	$1.22 \pm 0.02 \pm 0.07$	$1.23 \pm 0.03 \pm 0.07$	$1.21 \pm 0.02 \pm 0.07$
$\mathcal{B}(D^0 \ell \overline{\nu})(\%)$	$2.41 \pm 0.03 \pm 0.14$	$2.29 \pm 0.04 \pm 0.16$	$2.36 \pm 0.03 \pm 0.12$
$\mathcal{B}(D^{*0} \ell \overline{\nu})(\%)$	$5.42 \pm 0.03 \pm 0.22$	$5.23 \pm 0.04 \pm 0.37$	$5.37 \pm 0.02 \pm 0.21$
χ^2/n.d.f. (probability)	424/470 (0.94)	496/466 (0.16)	2.1/4 (0.72)

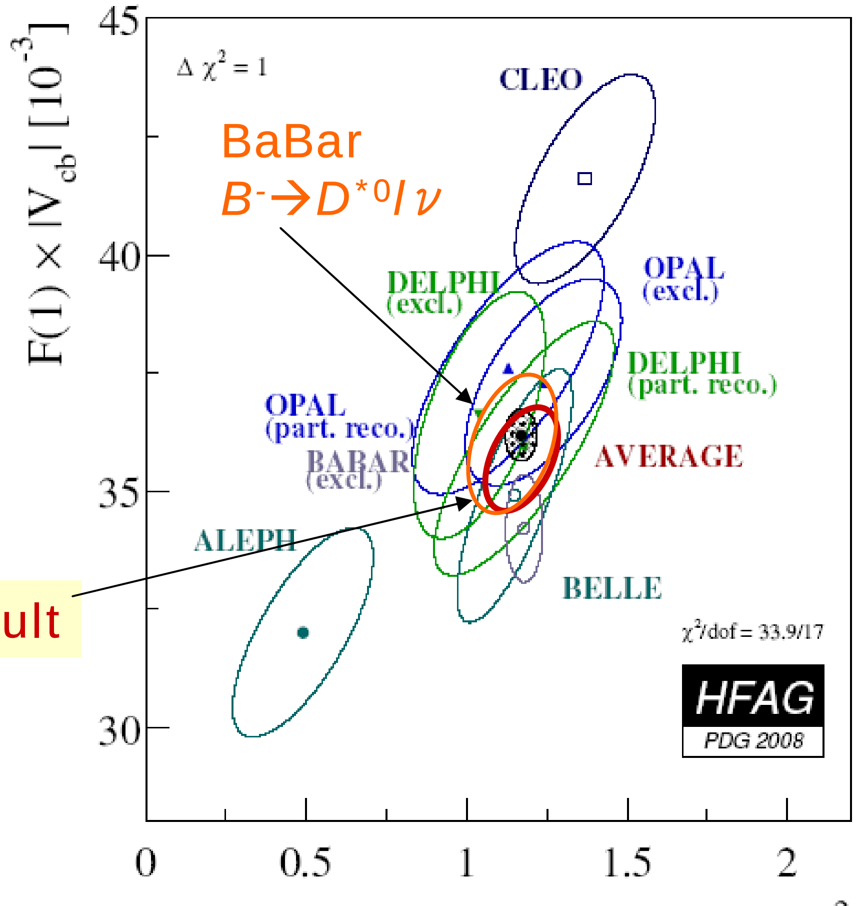
- Good χ^2.
- Electron and muon results are consistent.
- Combined results agree with world average.

$$Dl\nu \longrightarrow \mathcal{G}(1)|V_{cb}| = (43.8 \pm 0.8 \pm 2.3) \times 10^{-3}$$

$$D^*l\nu \longrightarrow \mathcal{F}(1)|V_{cb}| = (35.7 \pm 0.2 \pm 1.2) \times 10^{-3}$$

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.

$|V_{cb}|$

$$D\ell\nu : \ |V_{cb}| \ = \ (40.5 \pm 0.8 \pm 2.1 \pm 0.9) \times 10^{-3}.$$

$$D^*\ell\nu : \ |V_{cb}| \ = \ (38.5 \pm 0.2 \pm 1.3 \pm 1.0) \times 10^{-3}.$$

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

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

and (Bernard *et.al*., arXiv:0808.2519[hep-lat])

$$F(1) = 0.0921 \pm 0.013 \pm 0.020$$

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

$$\mathcal{B}(B^- \to D^{*0}\ell\overline{\nu}) = (5.47 \pm 0.19)\%$$ (χ^2 probab.=0.38)

$$\rho^2_{D^*} = 1.19 \pm 0.04$$ (χ^2 probab.=0.90)

$$\mathcal{F}(1)|V_{cb}| = (34.8 \pm 0.8) \times 10^{-3}$$ (χ^2 probab.=0.33)

$$\mathcal{B}(B^- \to D^0\ell\overline{\nu}) = (2.33 \pm 0.09)\%$$ (χ^2 probab.=0.85)

- Good agreement between Babar measurements.

Summary

- We used global fit to determine
  - Form factor slopes :
$$\rho_D^2 = 1.22 \pm 0.04 \pm 0.07$$
$$\rho_{D^*}^2 = 1.21 \pm 0.02 \pm 0.07,$$
  - Branching fractions :
$$\mathcal{B}(B^- \to D^0 \ell \overline{\nu}) = (2.36 \pm 0.03 \pm 0.12)\%$$
$$\mathcal{B}(B^- \to D^{*0} \ell \overline{\nu}) = (5.37 \pm 0.02 \pm 0.21)\%$$
- 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.
- Submitted to Physical Review D.

Projection plots (Muon)