Measurements of $|V_{cb}|$ at BaBar

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DPF/JPS, University of Hawaii
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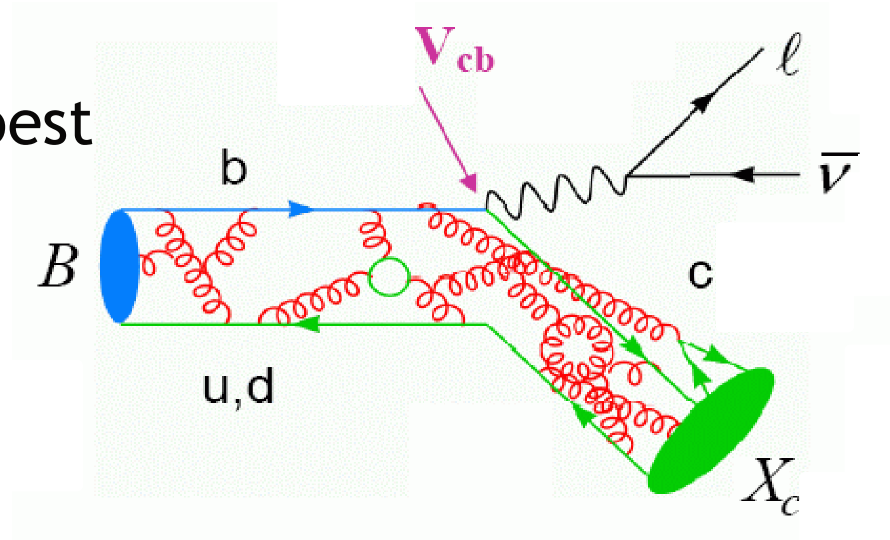
Introduction

- $|V_{cb}|$ precision measurement important to test unitarity of CKM matrix

Semileptonic B decays provide the best method to measure $|V_{cb}|$



- Simple theoretical description at parton level
- Rates depend on CKM matrix elements and quark masses

- Poor knowledge of B semileptonic decays into states other than *D,D** dominant background source of exclusive $|V_{cb}|$ (e.g. $D^{*}\pi l\nu$ background in $D^{*}l\nu$)

$B \to$ charm $l\nu$ decays

- Despite quite large BF, 30% of $B \to X_c l \nu$ affected by large uncertainties

Decay Mode	Branching Fraction
$B^0 \to l^+ \nu_l$ + anything	10.4 ± 0.4 %
$B^0 \to D^*(2010) - l^+ \nu_l$	5.35 ± 0.20 %
$B^0 \to D^- l^+ \nu_l$	2.12 ± 0.20 %
$B^0 \to \bar{D}^0 \pi^- \ell^+ \nu_\ell$	(0.32 ± 0.10) %
$B^0 \to \bar{D}^{*0} \pi^- \ell^+ \nu_\ell$	(0.65 ± 0.15) %
$B^0 \to D^{**} l^+ \nu_l$	??
$B^0 \to D^{(*)-} n\pi l^+ \nu_l$	??

$\mathcal{B}(B^0 \to D^{(*)}\pi l \nu)$ = 1.47 ± 0.20 ± 0.17% (Belle)

Decay Mode	Branching Fraction
$B^+ \to l^+ \nu_l$ + anything	10.9 ± 0.4 %
$B^+ \to \bar{D}^*(2007)^0 \ell^+ \nu_\ell$	(6.5 ± 0.5) %
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	(2.15 ± 0.22) %
$B^+ \to \bar{D}_1(2420)^0 \ell^+ \nu_\ell$	(0.56 ± 0.16) %
$B^+ \to \bar{D}_2(2460)^0 \ell^+ \nu_\ell$	< 0.8% @90CL
$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$	(0.53 ± 0.10) %
$B^+ \to D^{*+} \pi^+ \ell^+ \nu_\ell$	(0.64 ± 0.15) %
$B^+ \to \bar{D}^{(*)} n\pi \ell^+ \nu_\ell$	??

PDG 06

$\mathcal{B}(B^- \to D^{(*)}\pi l \nu)$ = 1.81 ± 0.20 ± 0.20% (Belle)

- Sum of exclusive modes does not match inclusive $B \to X_c l \nu$:

$$\mathcal{B}(B \to X_c l \nu) \neq \mathcal{B}(D l \nu) + \mathcal{B}(D^* l \nu) + \mathcal{B}(D^{**} l \nu)$$

5(10)% of $B \to X_c l \nu$ missing for B^-(B^0)

- What are we missing? $B \to D^{(*)} n\pi l \nu$? other charm final states ?

Decay Distribution for $B^0 \to D^{*-} \ell^+ \nu$

- Differential decay rate :

Form Factor — Phase space

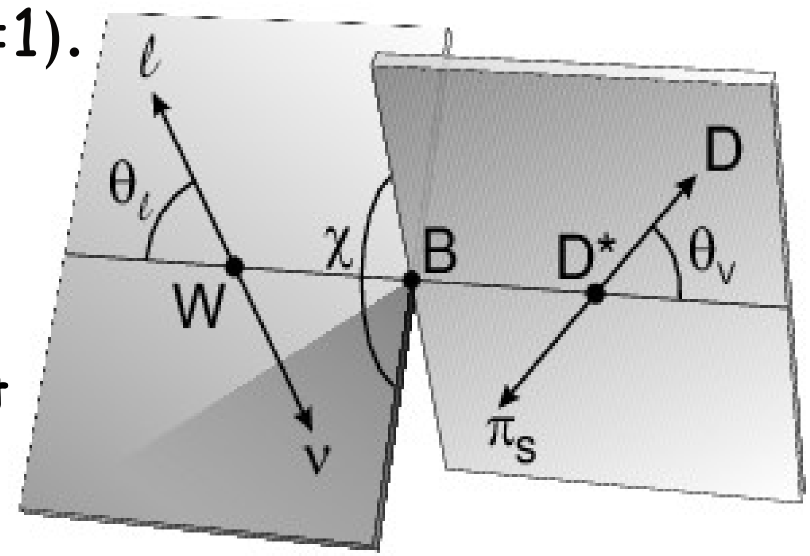
$$\frac{d\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} F(w,\theta_\ell,\theta_V,\chi) G(w)$$

$$w \equiv v_B \cdot v_{D^*} = \frac{M_B^2 + M_{D^*}^2 - q^2}{2 M_B^2 M_{D^*}^2}$$

- The shape of $F(w,\theta_l,\theta_V,\chi)$ can be parameterized with $R_1(w)$, $R_2(w)$ (form factor ratios) and ρ^2 (slope at w=1).

- Curvature constrained by analyticity: we use Caprini, Lellouch and Neubert (CLN) parameterization

Caprini, Lellouch, Neubert NPB530 (1998) 153



- Goal is to measure $R_1(w=1)$, $R_2(w=1)$, ρ^2

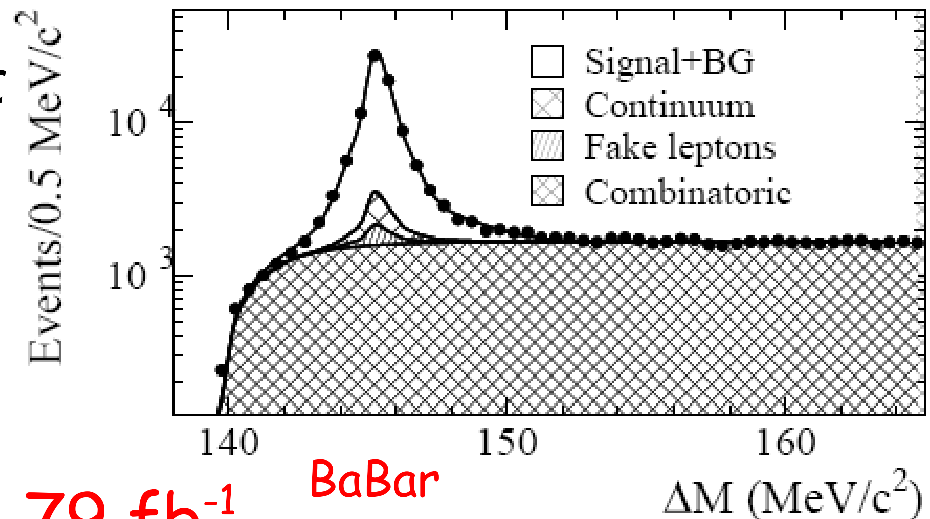
Form factor and V_{cb} measurements

- Select $D^{*-}l^{+}\nu_l$ events, $p^*_l > 1.2$ GeV/c

  $D^{*-} \to D^0\pi^-$, $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$
- Estimate combinatoric BBbar background from $\Delta m = m(D^0\pi) - m(D^0)$ fit
- Reduce D** model dependence in MC by estimating D** background fraction by fitting $\cos\theta_{BY}$ distribution on data

$$\cos\theta_{BY} = -\frac{M_B^2 + M_Y^2 - 2E_B E_Y}{2p_B p_Y}$$

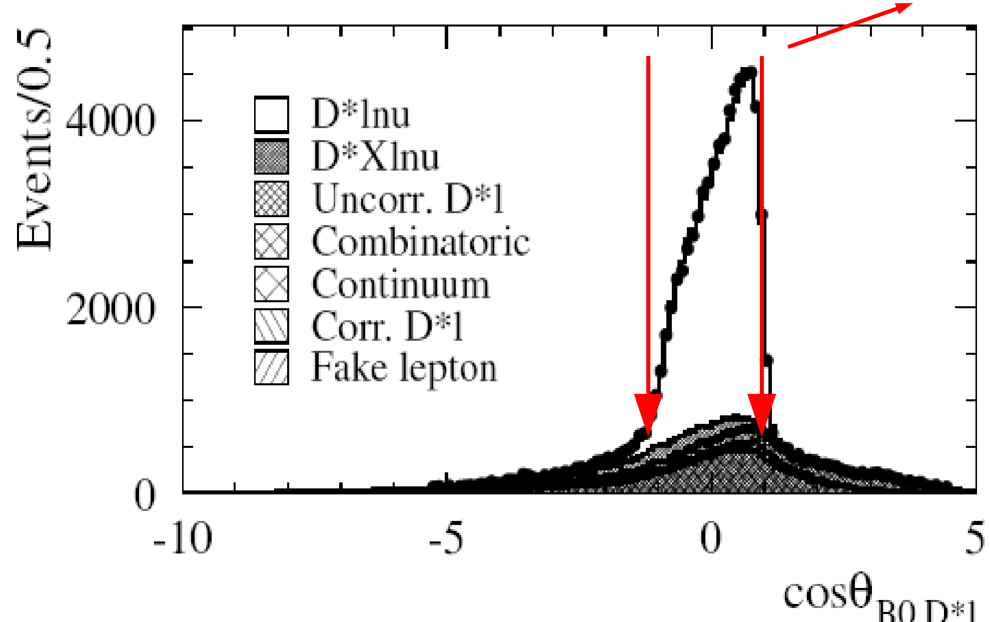
- About 69k events, purity ~76.7%



79 fb^{-1}

BaBar Preliminary

$|\cos\theta_{BY}| < 1.2$



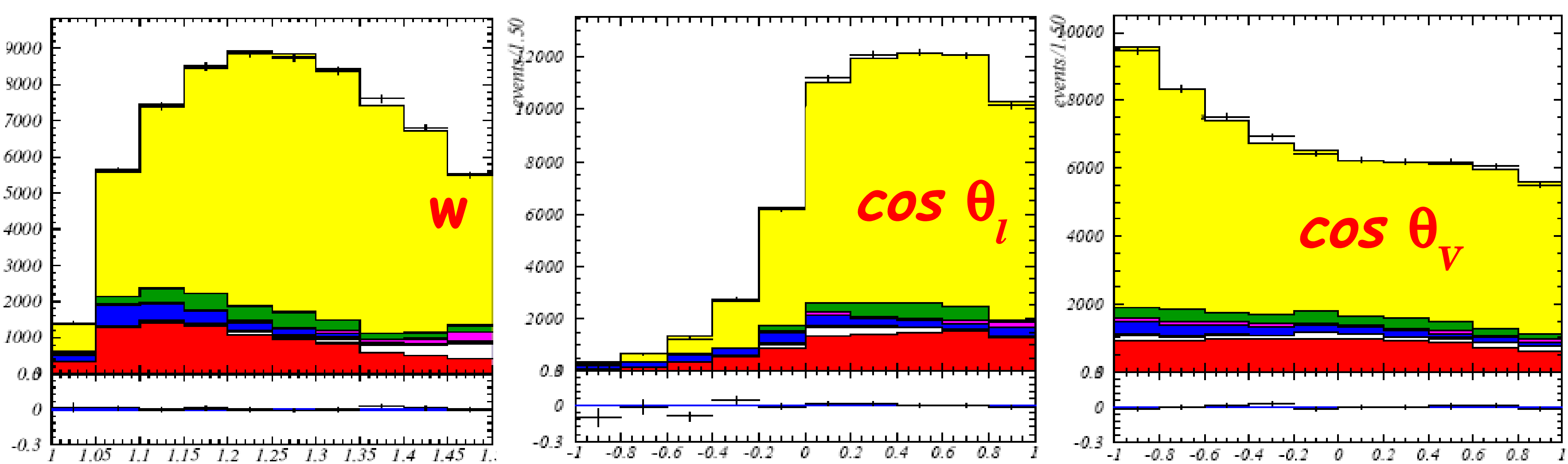
Form factor and V_{cb} measurements

- Simultaneous χ^2 fit to one-dimensional projections of *w*, $cos\,\theta_l$ and $cos\,\theta_V$, integrated over χ, by using reweighted MC predictions
- Measure $|V_{cb}|$ and the form-factor parameters correctly accounting for the mutual correlations

Data vs background estimate and fitted MC signal

$D^*l\nu$
$D^*Xl\nu$
Fake lepton
Uncorrelated D^*l
Correlated D^*l
Continuum
Combinatoric

BaBar Preliminary



χ^2/ndof= 23.99/24

Form factor and V_{cb} measurements

- We measure:

$$R_1 = 1.329 \pm 0.131(stat.) \pm 0.044(syst.)$$
$$R_2 = 0.859 \pm 0.077(stat.) \pm 0.022(syst.)$$
$$\rho^2 = 1.156 \pm 0.094(stat.) \pm 0.028(syst.)$$

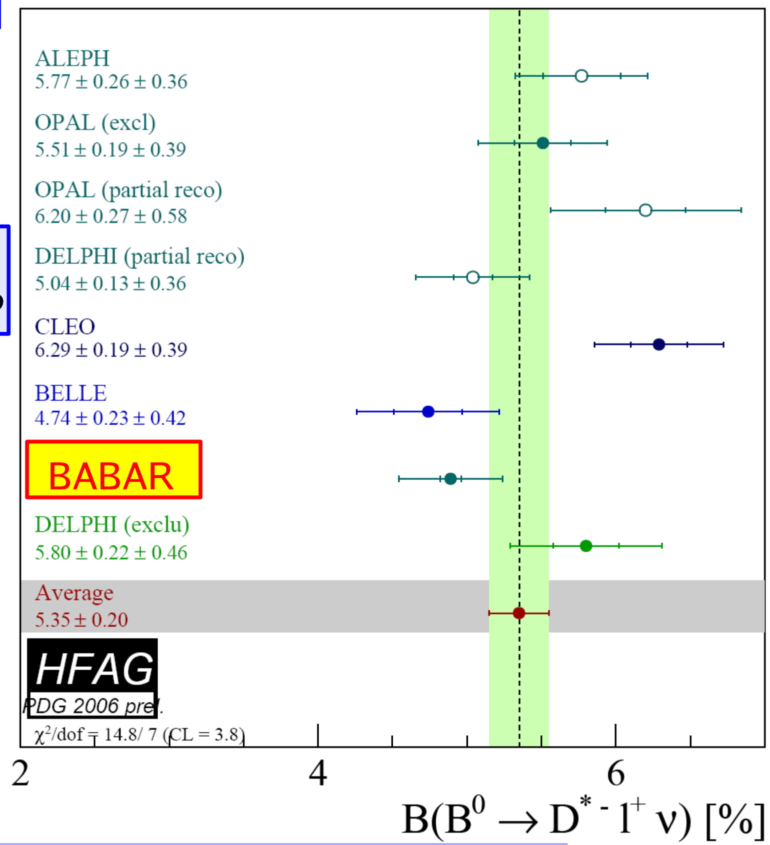
79 fb^{-1}

hep-ex/0607076

$$\mathcal{F}(1)|V_{cb}| = (35.03 \pm 0.39 \pm 1.15) \times 10^{-3}$$

$$\mathcal{B}(B^0 \rightarrow D^{*-} l^{+} \nu_l) = (4.84 \pm 0.05(stat.) \pm 0.39(syst.))\%$$

Compatible with previous BABAR result and BELLE,
CLEO and LEP results higher!



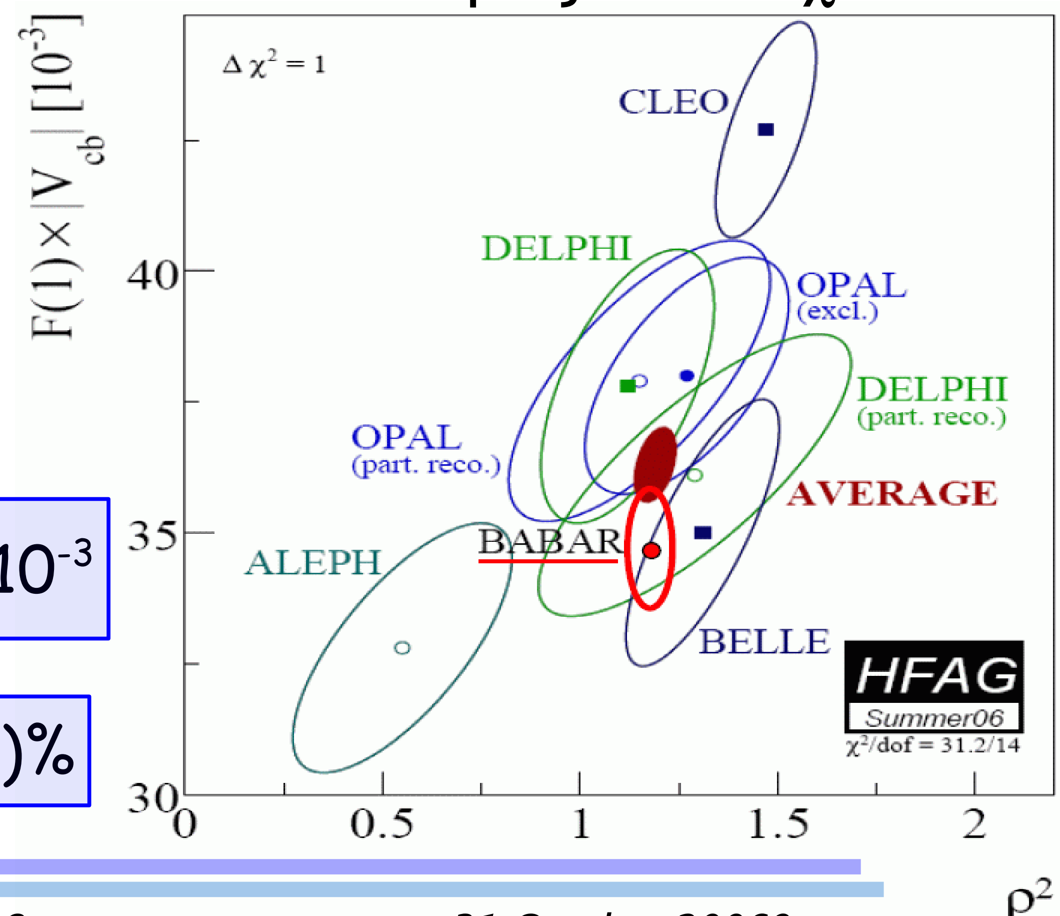
Form factor and V_{cb} average

- BaBar has also performed a different form factor measurement on the $B^0 \to D^{*-} l^+ \nu$ decay (hep-ex/0602023, accepted for publication)
  - Same data sample, statistical overlap between the two analysis is small (different D^0 decay channels, etc.)
  - Unbinned 4-dim maximum likelihood fit vs 1-d projection χ^2 fit
- Our Average:

$$R_1 = 1.417 \pm 0.061 \pm 0.044$$
$$R_2 = 0.836 \pm 0.037 \pm 0.022$$
$$\rho^2 = 1.179 \pm 0.048 \pm 0.028$$

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$$

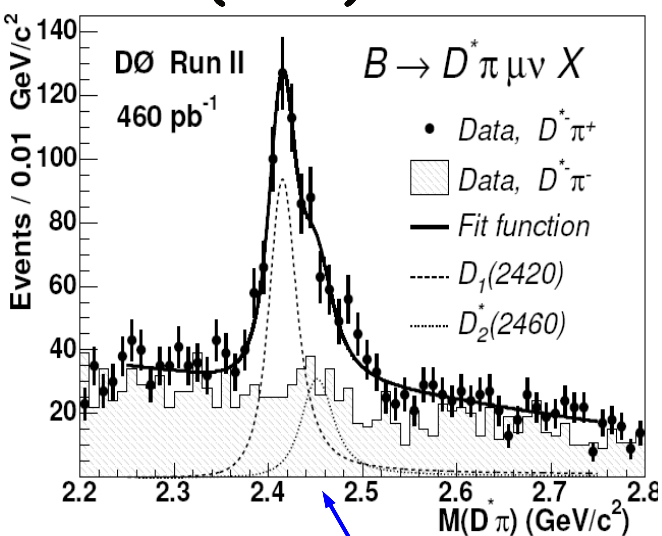
$$\mathcal{B}(B^0 \to D^{*-} l^+ \nu_l) = (4.77 \pm 0.04 \pm 0.39)\%$$



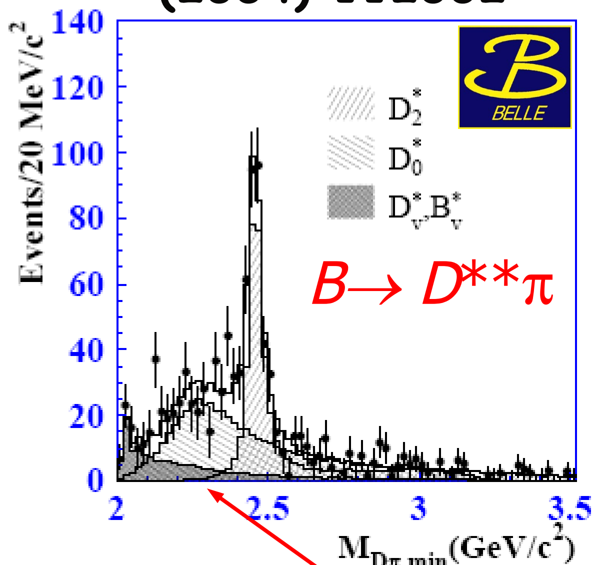
$B \to D^{**} l \nu$ decays

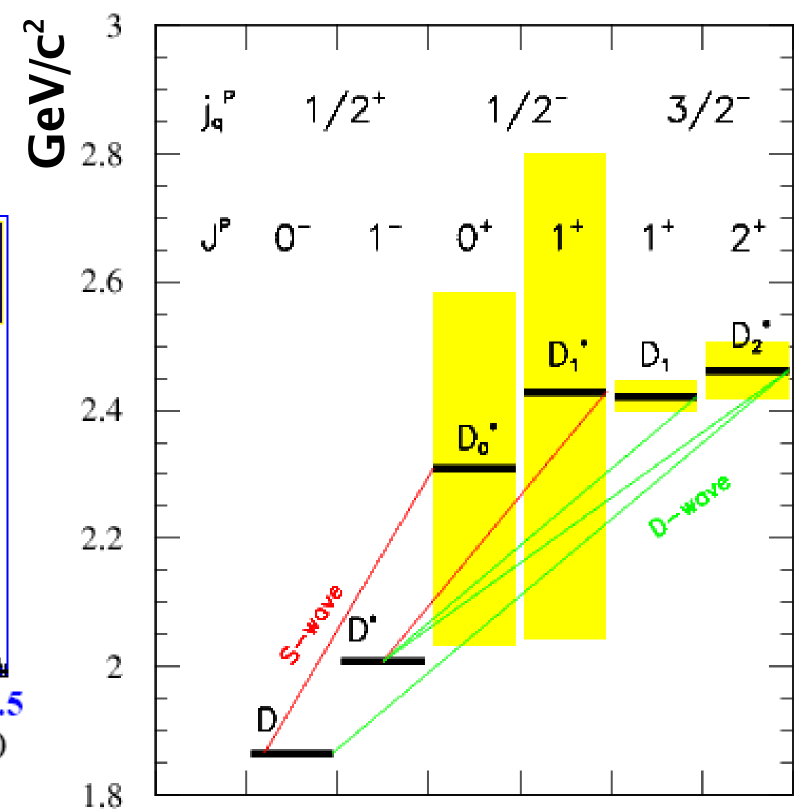
- We know very little about $D^{**} l \nu$

Abazov et al, PRL 95 (2005) 171803



Abe et al, PRD 69 (2004) 112002





Charm States

Narrow resonances ($D_1(2420)$, $D^*_2(2460)$), wide resonances, non-resonant states $D^{(*)} n\pi l \nu$?

Uncertainty on $B^- \to D_{1,2} l^- \nu$ measurements larger than 30%

A. Anastassov et al, PRL 80 (1998) 4127

$\mathcal{B}(B\to D^{**}l\nu)$ Measurement

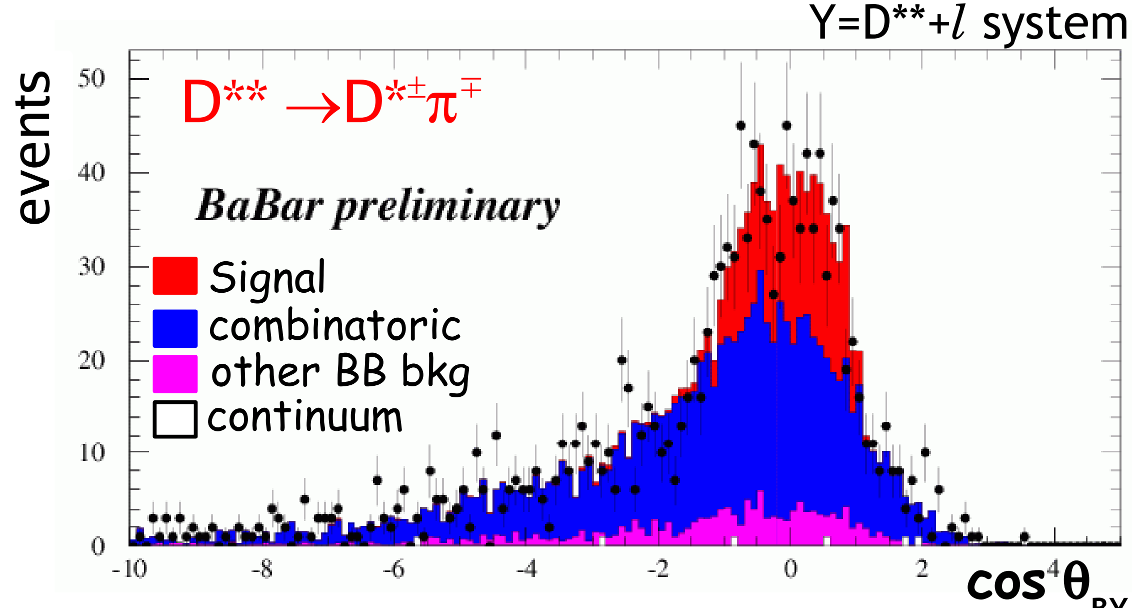
- Untagged analysis, reconstruct only $D^{**}\to D^{(*)}\pi^{\pm}$:

  $B^0\to D^{**-}(D^{*0}\pi^-)\,l^+\nu$ $\qquad$ $B^-\to D^{**0}(D^+\pi^-)\,l^-\nu$

  $B^0\to D^{**-}(D^0\pi^-)\,l^+\nu$ $\qquad$ $B^-\to D^{**0}(D^{*+}\pi^-)\,l^-\nu$

- Reconstruct B semileptonic decays by identifying a high energy lepton (p^*_l >0.8 GeV/c, l = e or μ) and requiring $|\cos\theta_{BY}|$ <1
- Focus only on narrow states$\to$ broad resonances require full event reconstruction

$\varepsilon(D^{*\pm}\pi^{\mp})=(6.54\pm0.28)\%$
$\varepsilon(D^{*0}\pi^{\pm})=(5.26\pm0.41)\%$
$\varepsilon(D^{\pm}\pi^{\mp})=(7.59\pm0.67)\%$
$\varepsilon(D^{0}\pi^{\pm})=(14.77\pm1.46)\%$



$\mathcal{B}(B\to D^{**}l\nu)$ Measurement

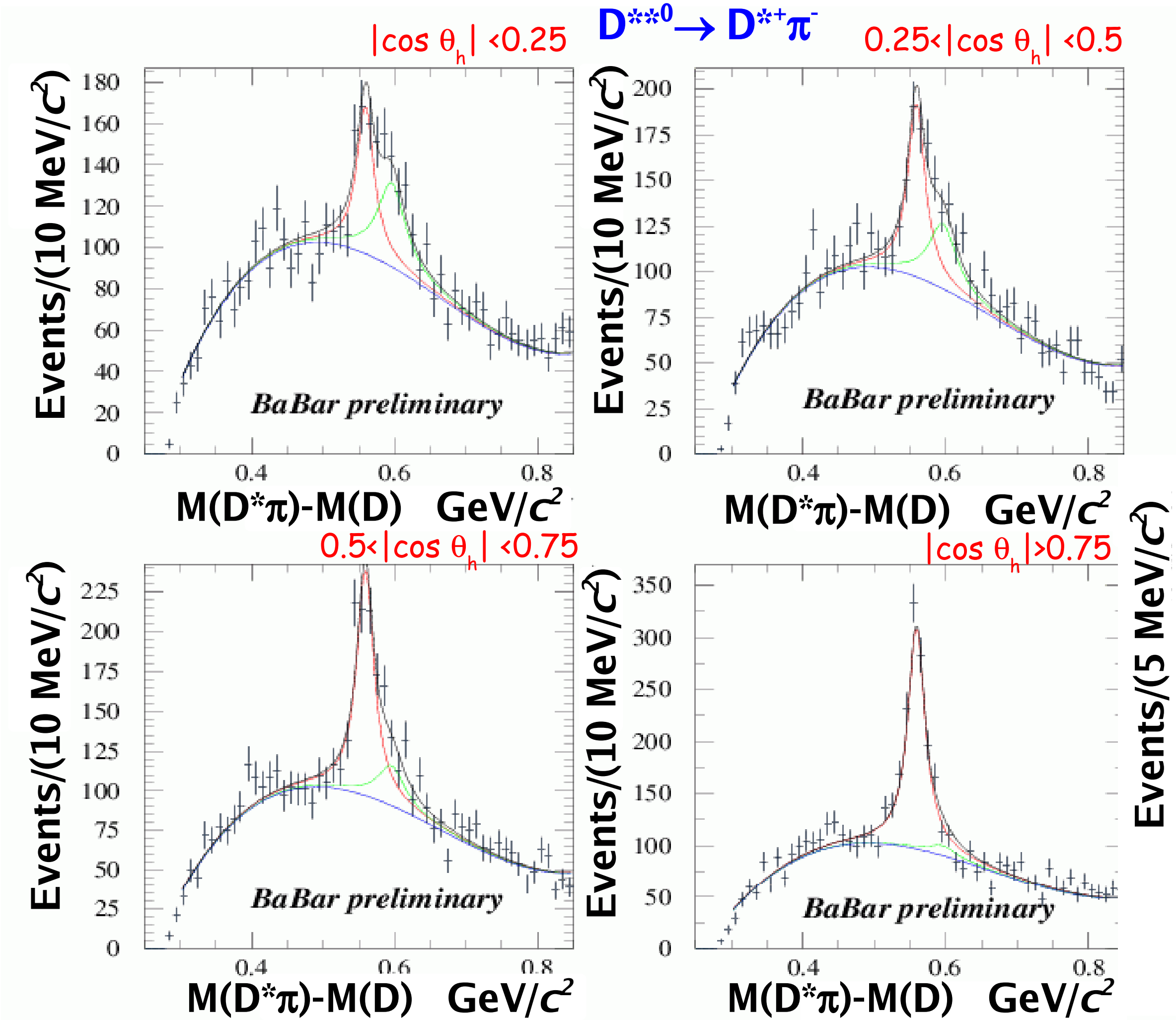
- Simultaneous fit to *M(D**)-M(D)* for the 4 modes
- Fit in different *D** helicity bins

D1 polarization

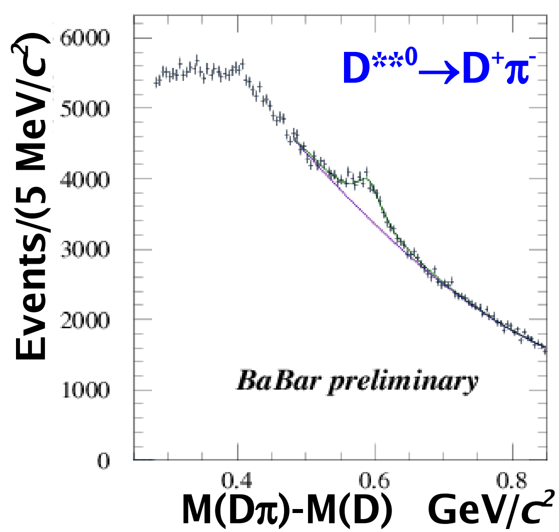
helicity (D_2) α $\sin^2\theta_h$

helicity (D_1) α $1+A\cos^2\theta_h$

θ_h angle between π from D** and D*
in D* rest frame
A=2 for unpolarized D-wave decay



$B^-\to D^{**0}(D^{(*)+}\pi^-)l^-\nu$



Global
χ^2/ndof=698.4/600

$\mathcal{B}(B\to D^{**}l\nu)$ Measurement

- Global fit results from 208 fb^{-1} for the 4 modes:

$$\mathcal{B}(B^-\to D_1^0 l^- \nu) = (4.48 \pm 0.26(stat.) \pm 0.35(syst.))\cdot 10^{-3}$$

$$\mathcal{B}(B^-\to D_2^{*0} l^- \nu) = (3.54 \pm 0.32(stat.) \pm 0.54(syst.))\cdot 10^{-3}$$

$$\mathcal{B}(B^0\to D_1^- l^+ \nu) = (3.64 \pm 0.32(stat.) \pm 0.49(syst.))\cdot 10^{-3}$$

$$\mathcal{B}(B^0\to D_2^{*-} l^+ \nu) = (2.70 \pm 0.35(stat.) \pm 0.43(syst.))\cdot 10^{-3}$$

$$\mathcal{B}(D_2^*\to D\pi) = 0.69 \pm 0.03$$

Mixing Parameter $A = 2.75 \pm 0.44$

BaBar Preliminary

$$\mathcal{B}(B\to D_1^0 l^- \nu X) = (3.3 \pm 0.6)\cdot 10^{-3}$$

$$\mathcal{B}(B\to D_2^{*0} l^- \nu X) = (4.4 \pm 1.6)\cdot 10^{-3}$$

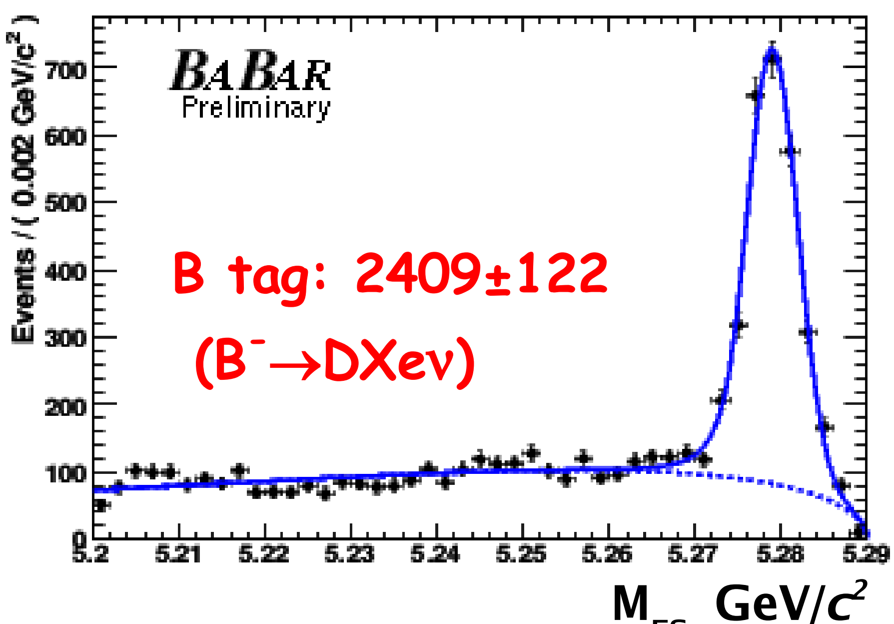
Compare e.g. with D0 , using $b\to B$ =39% and isospin

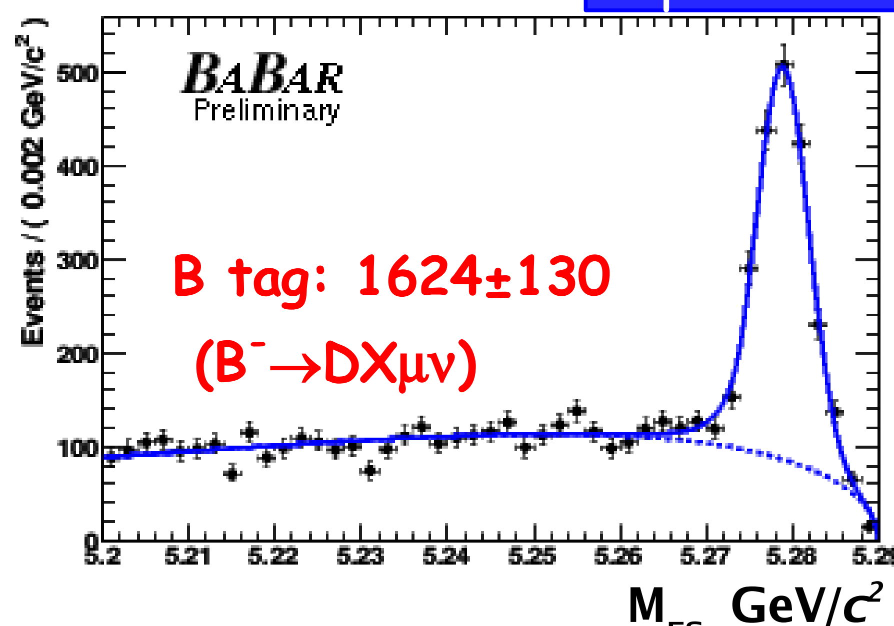
Abazov et al, PRL 95 (2005) 171803

$\Gamma(B^- \to D^{(*,**)} l\nu)/\Gamma(B^- \to DXl\nu)$ Measurement

- Measure simultaneously D, D* and D** contributions in a $B^- \to DXl\nu$ sample
- $B^- \to DXl\nu$ (l = e or μ, p^*_l >0.6 GeV/c) events selected by identifying the Dl system on the recoil of a B fully reconstructed in a hadronic mode $\to$ low efficiency, high purity
- Inclusive analysis, sensitive to all $D^{(*)}\pi$ states (D^{**}, non resonant...)

hep-ex/0607067

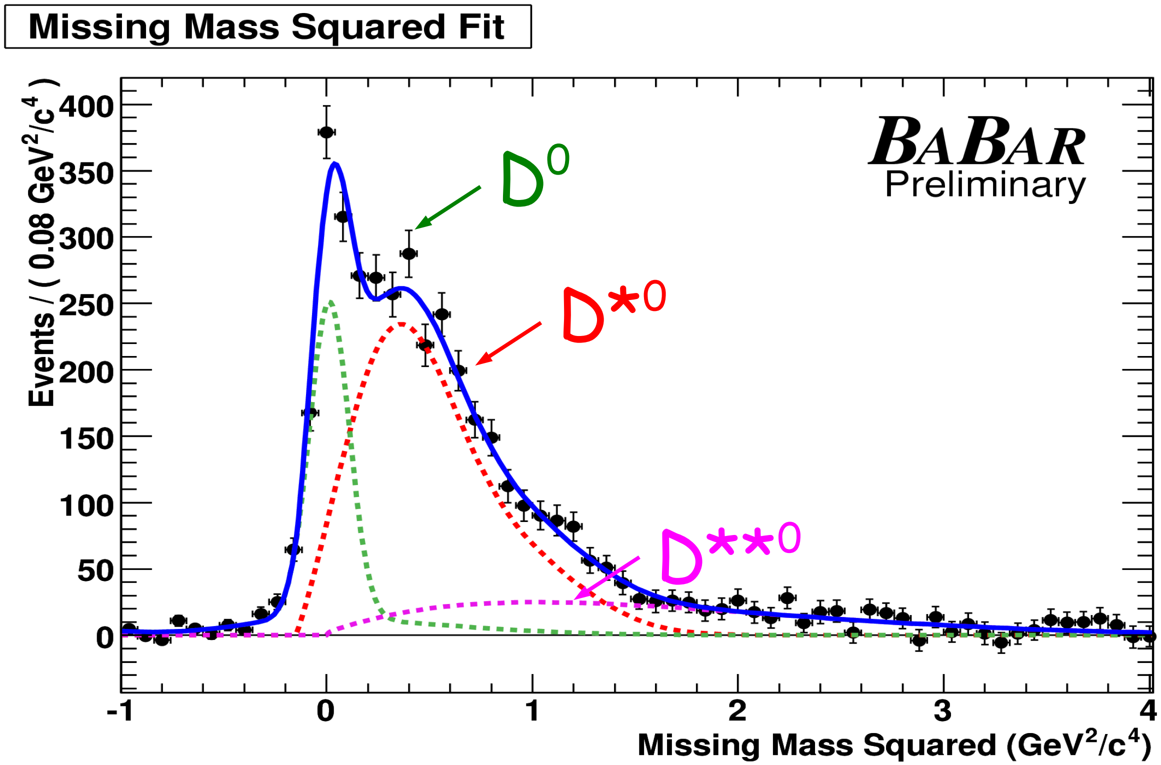




$\Gamma(B^- \to D^{(*,**)} l\nu)/\Gamma(B^- \to DXl\nu)$ Measurement

- Global χ^2 fit to : missing mass squared, lepton momentum, additional charged track multiplicity
- Use exclusively reconstructed $B^- \to Dl\nu$, $B^- \to D^* l\nu$, $B^- \to D^{**} l\nu$ data samples to build Probability Density Functions in order to minimize Monte Carlo dependence

$$B \to DXl\nu = B \to Dl\nu + B \to D^* l\nu + B \to D^{(*)}\pi l\nu$$



$\Gamma(B^- \to D^{(*,**)} l\nu)/\Gamma(B^- \to DXl\nu)$ Measurement

BaBar Preliminary

$211\ fb^{-1}$

- We measure:

$\Gamma(B^- \to D^0 l\nu)/\Gamma(B^- \to DX l\nu) = 0.210 \pm 0.017(stat.) \pm 0.021(syst.)$

$\Gamma(B^- \to D^{*0} l\nu)/\Gamma(B^- \to DX l\nu) = 0.611 \pm 0.021(stat.) \pm 0.027(syst.)$

$\Gamma(B^- \to D^{**0} l\nu)/\Gamma(B^- \to DX l\nu) = 0.173 \pm 0.017(stat.) \pm 0.021(syst.)$

- Relative branching ratio $\Gamma(B^- \to D^{**0} l\nu)/\Gamma(B^- \to DX l\nu)$ sensitive to non resonant states $B^- \to D^{(*)} n\pi l\nu$ with $n \geq 1$

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Decay Mode	Branching Fraction
$B^+ \to l^+ \nu_l$ + anything	10.9 ± 0.4 %
$B^+ \to \bar{D}^*(2007)^0 \ell^+ \nu_\ell$	(6.5 ± 0.5) %
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	(2.15 ± 0.22) %
$B^+ \to \bar{D}_1(2420)^0 \ell^+ \nu_\ell$	(0.56 ± 0.16) %
$B^+ \to \bar{D}_2(2460)^0 \ell^+ \nu_\ell$	$< 0.8\%$ @90CL
$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$	(0.53 ± 0.10) %
$B^+ \to D^{*+} \pi^+ \ell^+ \nu_\ell$	(0.64 ± 0.15) %
$B^+ \to \bar{D}^{(*)} n\pi \ell^+ \nu_\ell$	??

The $\mathcal{B}(B\to D^*l\nu)$ Puzzle

- BaBar measures:

$\mathcal{B}(B^0\to D^{*-}l^+\nu_l) = (4.77 \pm 0.39)\%$

Form-Factor and V_{cb} measurement

$\mathcal{B}(B^-\to D^{*0}l^-\nu_l) = (6.81 \pm 0.39)\%$

$\mathcal{B}(B^-\to D^{(*)}\pi l^-\nu_l) = (1.93 \pm 0.30)\%$

$\Gamma(B^-\to D^{(*,**)}l\nu)/\Gamma(B^-\to DXl\nu)$ measurement

- Disagreement between charged and neutral $B\to D^*l\nu_l$
- BaBar results compatible with BELLE:

Liventsev et al, PRD 72 (2002) 051109

$\mathcal{B}(B^0\text{->}D^{*-}l\nu_l)$= 4.70± 0.24(stat.)%

$\mathcal{B}(B^-\text{->}D^{*0}l\nu_l)$= 6.06± 0.25(stat.)%

$\mathcal{B}(B^-\text{->}D^{(*)}\pi l\nu_l)$= 1.81± 0.20 ±0.20%

$R_{D^*}=\mathcal{B}(B^-\to D^{*0}l^+\nu_l)/\mathcal{B}(B^0\to D^{*-}l^+\nu_l)$ = 1.32± 0.07

≠ $\tau(B^+)/\tau(B^0)$=1.071 :Puzzle?

Combined BaBar and Belle

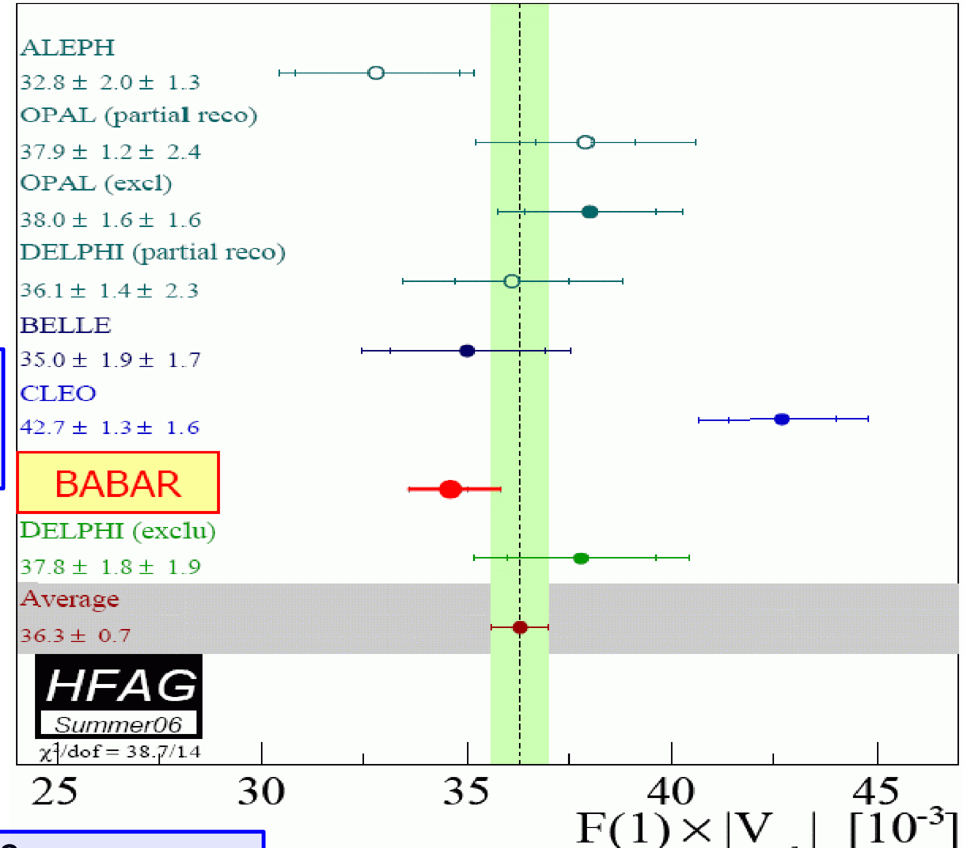
Summary

- New BaBar $|V_{cb}|$ and form-factor parameter measurements reduce total uncertainty to less than 5%

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$$

- With $h_{A1}(1)=\mathcal{F}(1)=0.919^{+0.030}_{-0.035}$

  Hashimoto et al, PRD 66 (2002) 014503



$$|V_{cb}| = (37.74 \pm 0.35(\mathit{stat.}) \pm 1.25(\mathit{syst.})^{+1.23}_{-1.44}) \times 10^{-3}$$

- Inclusive analysis: $|V_{cb}| = (41.96 \pm 0.23_{exp.} \pm 0.35_{HQE} \pm 0.59_{\Gamma SL}) \times 10^{-3}$

  PRD 73 (2006) 073008

- High accuracy measurement of $\mathcal{B}(B \to D_{1,2} l\nu)$ and $\Gamma(B^- \to D^{(*,**)} l\nu)/\Gamma(B^- \to DXl\nu)$ will help to understand disagreement between inclusive rate and sum of exclusive modes

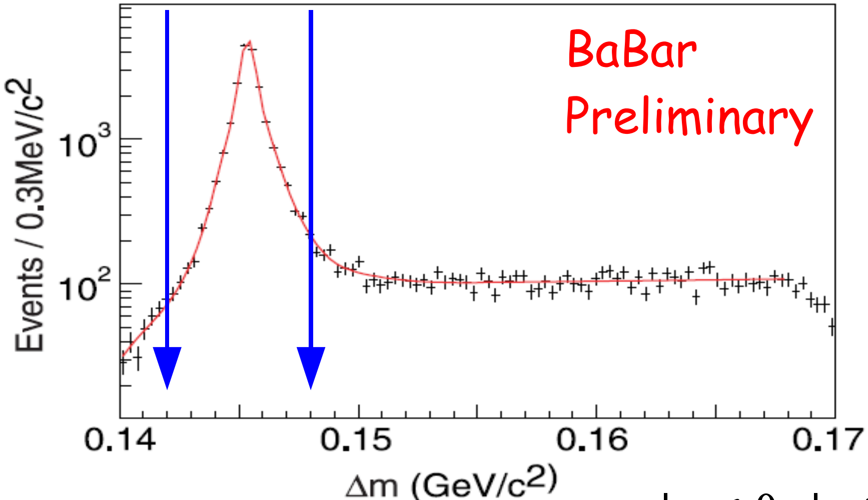
Backup Slides

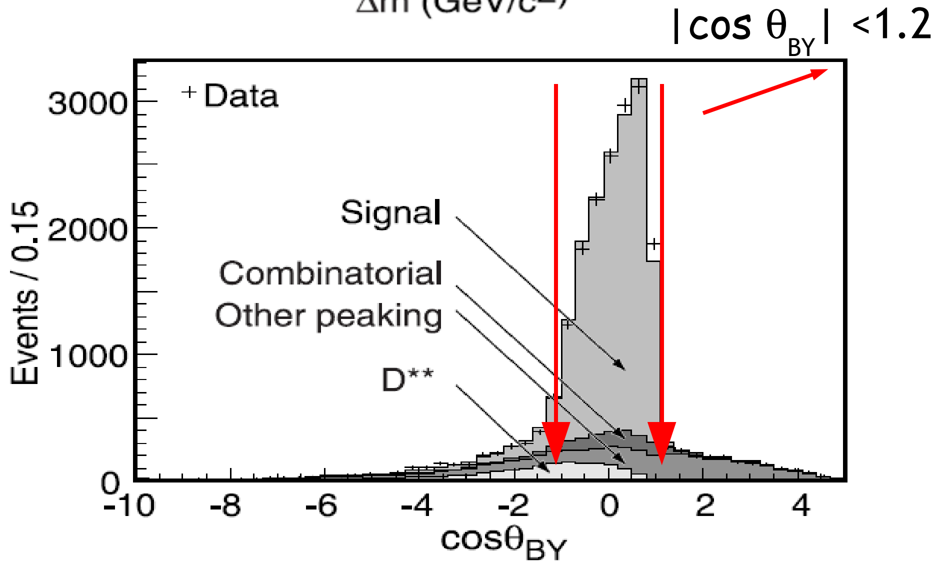
Form factor and V_{cb} measurements

- Select $D^{*-}e^+\nu_e$ events, $p^*_l > 1.2$ GeV/*c*
  $D^{*-} \to D^0\pi^-$, $D^0 \to K\pi$
- Estimate combinatoric BB background from $\Delta m = m(D^0\pi) - m(D^0)$ fit
- Reduce D** model dependence in MC by estimating D** background fraction by fitting $\cos\theta_{BY}$ distribution on data

$$\cos\theta_{BY} = -\frac{M_B^2 + M_Y^2 - 2E_BE_Y}{2p_Bp_Y}$$

➡ 16k events, purity ~85%





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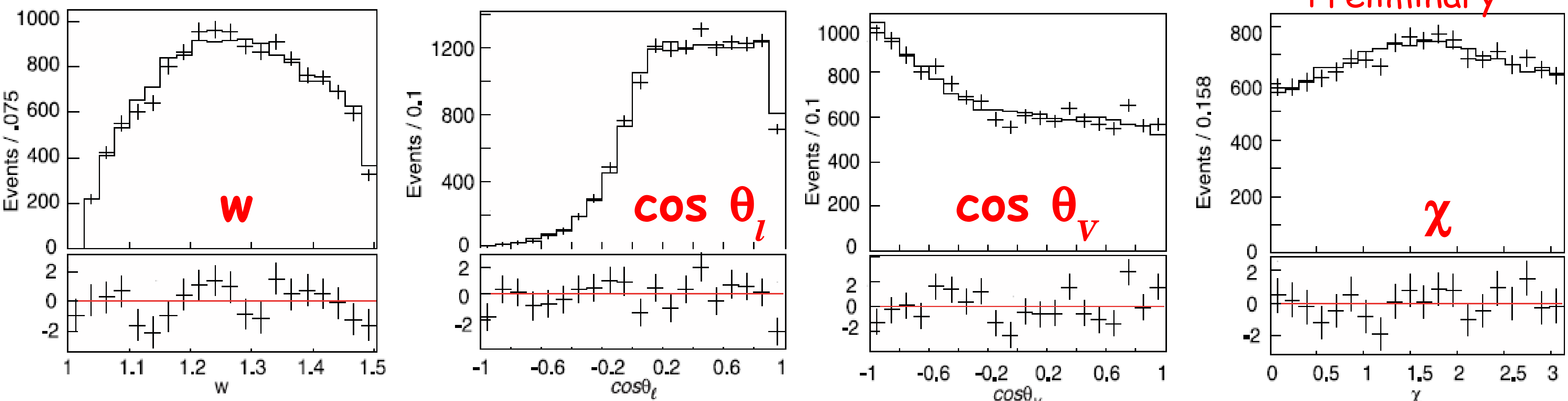
$B^0 \to D^{*-} l^+ \nu$ Form factor measurements

- Perform maximum likelihood fit to the four-dimensional cross sections
- one-dimensional projections of fitted distributions:

BaBar Preliminary



79 fb^{-1}

Signal MC vs. bkgd.-subtracted data

- We measure:

$$R_1 = 1.396 \pm 0.060(\textit{stat.}) \pm 0.035(\textit{MC stat.}) \pm 0.027(\textit{syst.})$$

$$R_2 = 0.885 \pm 0.040(\textit{stat.}) \pm 0.022(\textit{MC stat.}) \pm 0.013(\textit{syst.})$$

$$\rho^2 = 1.145 \pm 0.059(\textit{stat.}) \pm 0.030(\textit{MC stat.}) \pm 0.035(\textit{syst.})$$

$\mathcal{B}(B\to D^{**}l\nu)$ Measurement

- Systematic error dominated by limited Monte Carlo statistics and background modeling:

Source	$\Delta\mathcal{B}(B\to D^{**}\ell\nu)/\mathcal{B}(B\to D^{**}\ell\nu)[\%]$			
	D_1^0	D_2^{*0}	$D_1^{\pm}$	$D_2^{*\pm}$
Efficiency MC Statistic	5.9	5.4	8.8	8.1
Tracking	1.3	1.4	0.8	0.7
Particle identification	3.3	3.9	4.1	2.2
π^0-efficiency	0.1	0.1	4.1	0.3
Number of $B\overline{B}$	1.1	1.4	0.5	0.7
$\mathcal{B}(D^{*\pm}\to D^0\pi^{\pm})$	0.9	0.3	0.1	0.1
$\mathcal{B}(D^{*0}\to D^0\pi^0)$	0.1	0.2	6.6	0.4
$\mathcal{B}(D^0\to K\pi)$	2.7	0.6	3.3	1.9
$\mathcal{B}(D^{\pm}\to K\pi\pi)$	0.2	3.9	0.5	1.1
Modeling	3.1	12.7	3.0	13.3
Background parameterization	2.2	1.4	2.7	1.8
Total	7.8	15.2	13.5	15.9

Relativistic Breit-Wigner for signal peaks, third-order polynomials for background

$\Gamma(B^- \rightarrow D^{(*,**)} l\nu)/\Gamma(B^- \rightarrow DXl\nu)$ Measurement

- Systematic error dominated by reconstruction efficiency measurement and fit variations:

Systematic uncertainties in the measurement of $\Gamma(B^- \rightarrow D^{(*,**)0}\ell^-\bar{\nu}_\ell)/\Gamma(B^- \rightarrow DX\ell^-\bar{\nu}_\ell)$.

	Systematic uncertainty on $\Gamma(B^- \rightarrow D^{(*,**)0}\ell^-\bar{\nu}_\ell)/\Gamma(B^- \rightarrow DX\ell^-\bar{\nu}_\ell)$		
	$B^- \rightarrow D^0\ell\nu_\ell$	$B^- \rightarrow D^{*0}\ell\nu_\ell$	$B^- \rightarrow D^{**0}\ell\nu_\ell$
Tracking efficiency	0.009	0.008	0.004
Neutral reconstruction	0.001	0.003	0.0009
Electron ID	0.0008	0.002	0.0007
Muon ID	0.006	0.02	0.005
Inclusive Reconstruction			
Cascade decay background	0.01	0.01	0.01
Conversion and Dalitz decay background	0.001	0.004	0.001
MC statistics and M_{ES} fit	0.012	0.01	0.011
Cross-feed corrections	0.001	0.002	0.004
Exclusive Reconstruction			
Feed-down and feed-up corrections	0.003	0.002	0.002
MC signal shapes	0.002	0.002	0.007
D^{**0} track multiplicity	0.005	0.002	0.005
M_{ES} fit	0.0007	0.004	0.003
Cross-feed corrections	0.0003	0.0006	0.0009
Fit Technique			
Missing mass and lepton momentum PDF	0.007	0.002	0.008
Total Systematic Error	0.021	0.027	0.021

- Limited systematics from MC D** modeling due to analysis technique, which relies on data