Measurement of exclusive semileptonic B to D decays and the determination of exclusive $|V_{cb}|$

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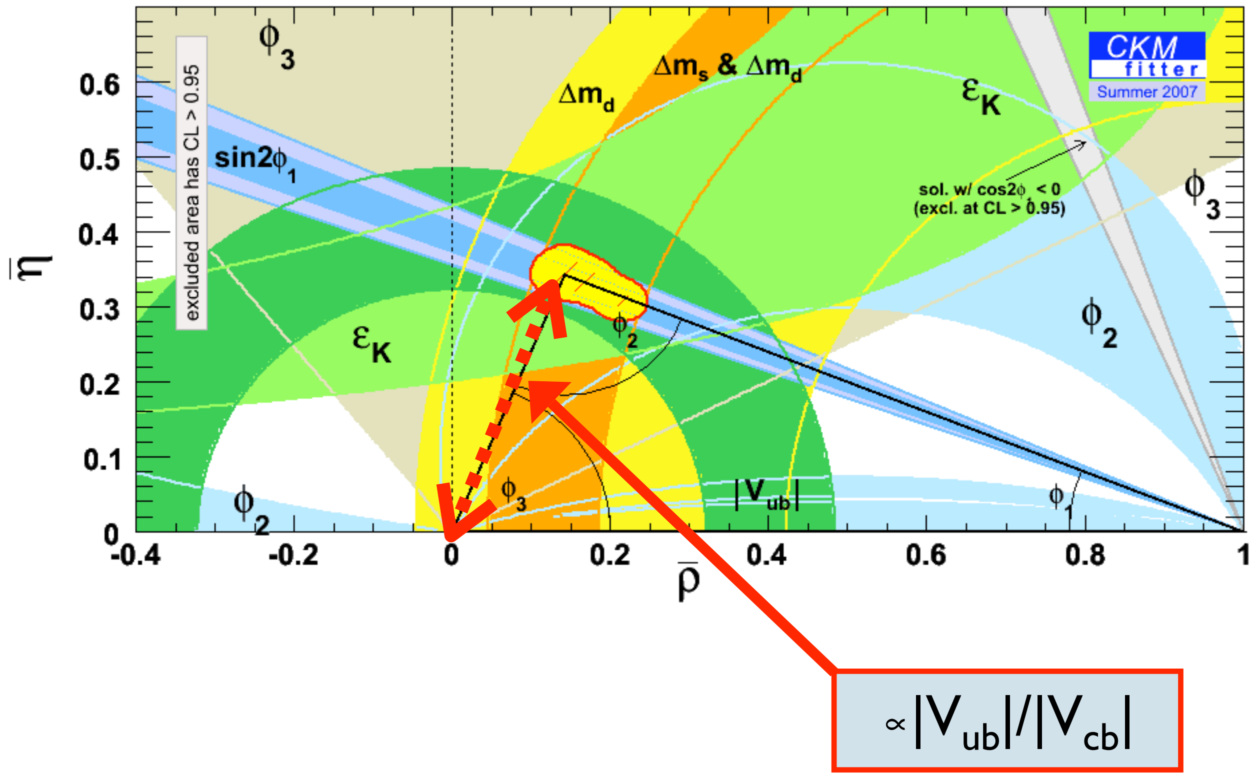
HQL Melbourne June 2008

The Significance of $|V_{cb}|$ Measurements

CKM are fundamental SM parameters, size not theoretically predicted.

Constrain one side of the Unitarity Triangle

The precise determination of $|V_{ub}|/|V_{cb}|$ provides a benchmark for testing new physics in other processes.



- Current precision
  - $\sin 2\varphi_1$ < 4%
  - $|V_{cb}|$ ~ 1-2% inclusive

    ~ 3-4% exclusive
  - $|V_{ub}|$ ~ 7% inclusive

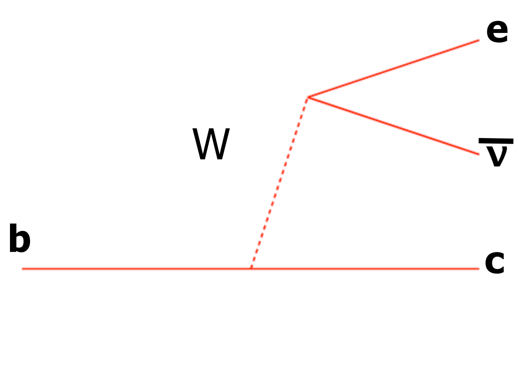
    >10% exclusive

Precise exclusive determinations used to check inclusive results, and probe our understanding of HQET

Semileptonic *B* decays

tree level, short distance:

$b \rightarrow c\, e\, \nu$



decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b

perturbative regime (α_s^n)

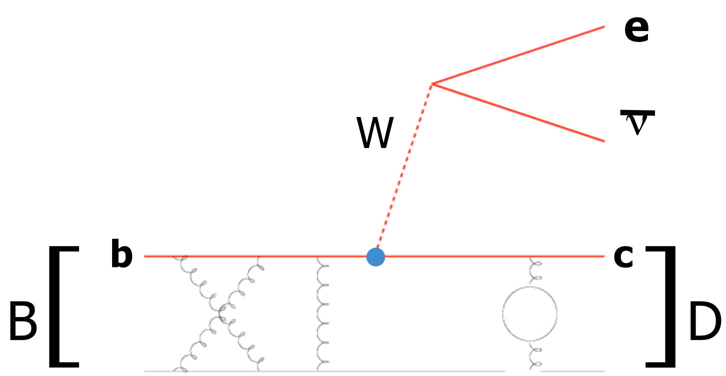
Semileptonic *B* decays

tree level, short distance:

B → D e ν

decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b

perturbative regime (α_s^n)

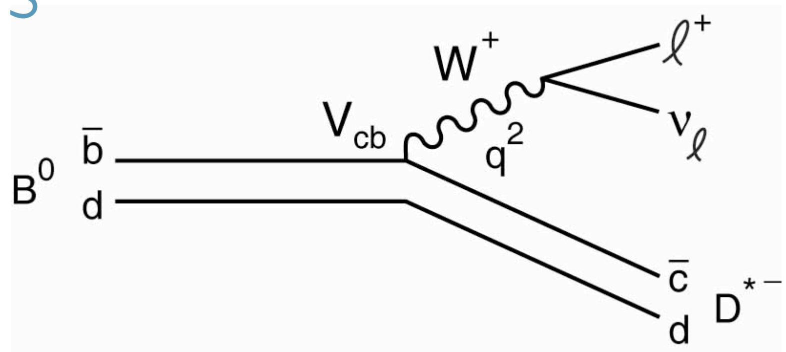


But quarks are bound by soft gluons: non-perturbative

+ long distance:

long distance interactions of b quark with light quark

Exclusive Semileptonic Decays



One hadronic current.

Matrix element for semileptonic decays:

$$(M_{Q\bar{q}} \to X_{q'\bar{q}} \to X_{q'\bar{q}}\ell^- \bar{\nu}_\ell) = -i\frac{G_F}{\sqrt{2}} V_{q'Q} L^\mu H_\mu$$

Leptonic current exactly known.

Hadronic current described by Form Factors (FF), functions of squared momentum transfer q^2.

Exclusive rates are determined by |*Vcb*| and Form Factors (FF)

FF are calculated using non-perturbative methods.

- Theoretically calculable at kinematic limits.
- Lattice QCD works if D* is at rest relative to the B.

Empirical extrapolation is necessary to extract |Vcb| from measurements.

Measure differential rates to constrain the FF shape, then use FF normalization from the theory for |Vcb|.

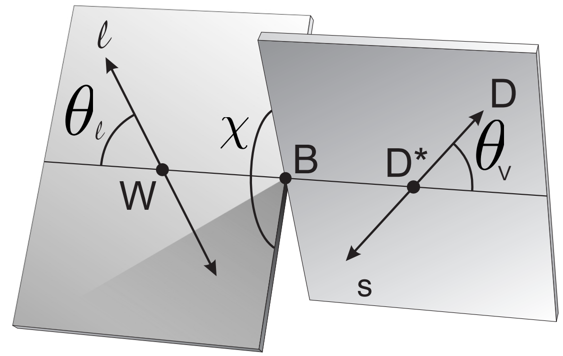
$|V_{cb}|$ and Form factors from $B \to D^* l \nu$

Differential decay rate

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

Incorporates 3 non-trivial form factors $A_1(w)$, $A_2(w)$, and $V(w)$.

Phase space



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

***D** boost in the *B* rest frame**

HQ symmetry (b and c mass infinite) predicts a single universal FF, normalised to 1 at zero recoil.

HQET relates the 3 FF's to each other through Heavy Quark Symmetry, leaving 3 free parameters that are determined experimentally.

Amplitude ratios:

$$R_1(w) = V/A_1$$
$$R_2(w) = A_2/A_1$$

Curvature:

$$\rho^2(w) = -dF/dw|_{w=1}$$

Using parameterisation to extract 3 parameters from 4 observables in the data: w, $\theta_\nu, \theta_\ell, \chi$

Caprini et al., *Nucl. Phys.* B530 153 (1998).

Experimentally clean, a check of inclusive methods.

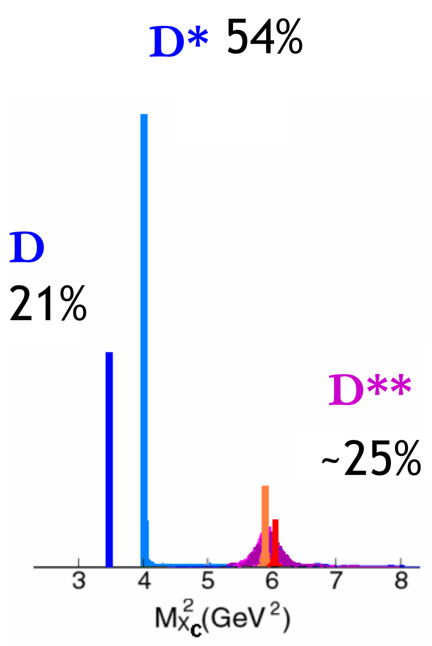
The X_c system

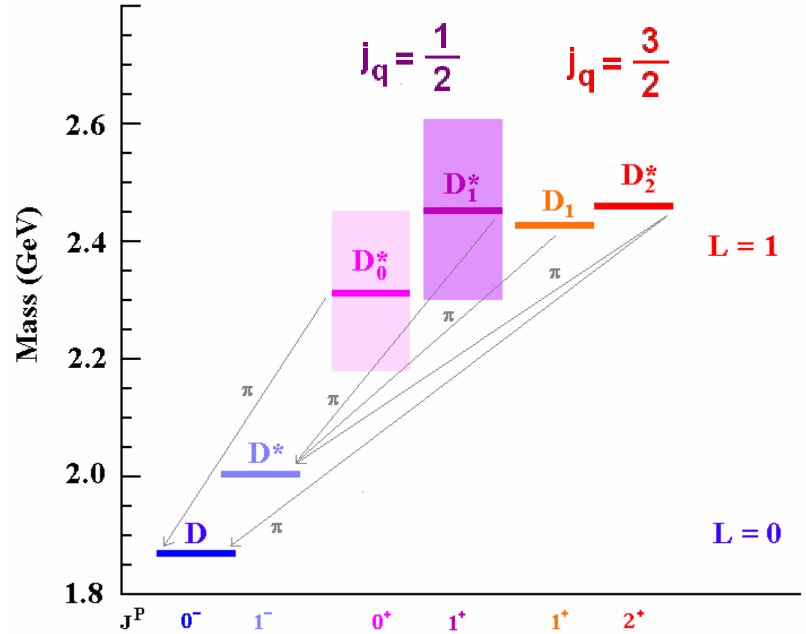
In addition to the well measured Δ-like $D^{(*)}$ components are the D** , P-wave excitations of D-mesons.

⇒HQET predicts ***four D** mesons***: ***2 narrow*** and ***2 wide***, all observed in hadronic B decays.

(hep-ex/0307021, hep-ex/0611054)

BR(B→Xcl ν)~10.5%





BUT, Heavy Quark Symmetry also predicts Γ(B→ Narrow l ν) >> Γ(B→ Broad l ν)

New BaBar and Belle measurements seem to defy this, eluding to a non-negligible contribution from non-resonant decay.

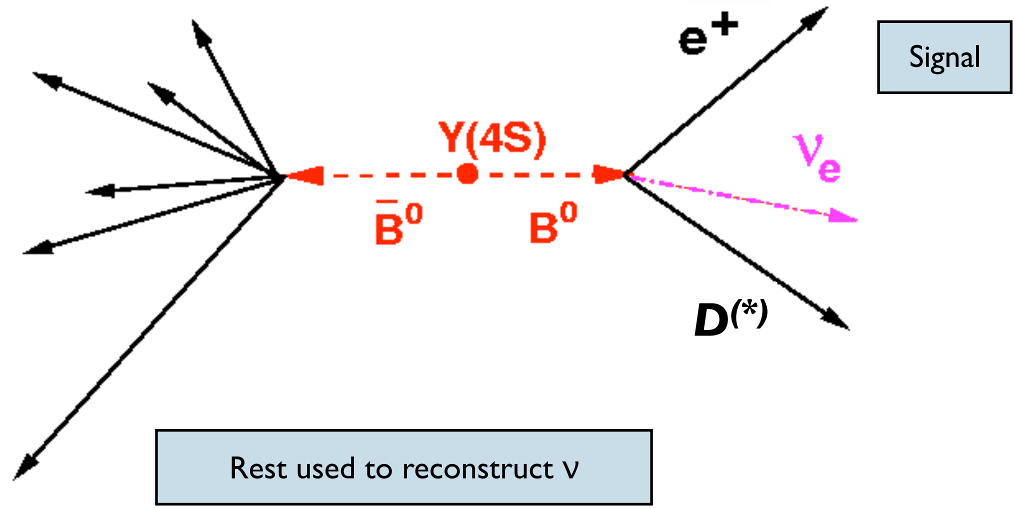
The components of the *Xc* system are not yet fully understood.

BR[%] HFAG ave.	**B^0**	**B^+**
Inclusive - Σ Exclusive	***2.08 ± 0.34***	***1.62 ± 0.42***

Measurement methods/samples

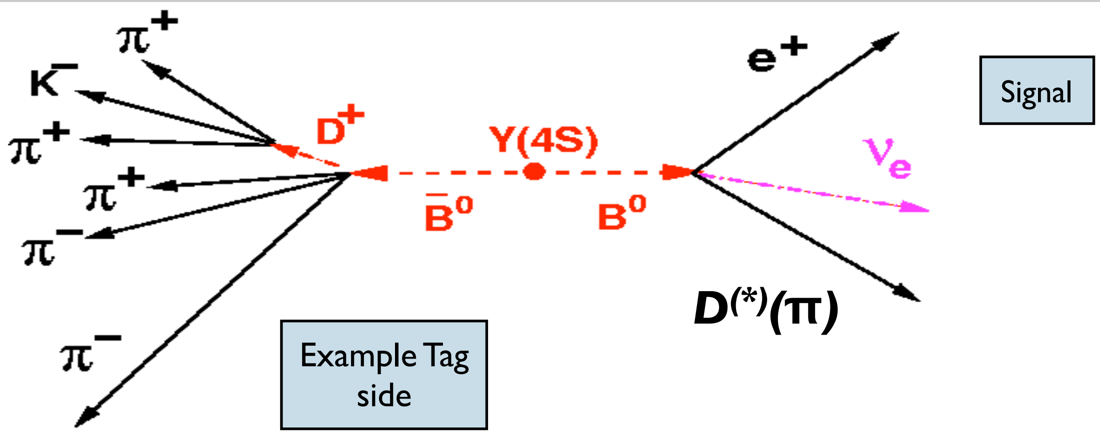
Untagged
⇒(|Vcb| and FF analyses)

- Initial 4-momentum known.
- Missing 4-momentum = ν.
- Reconstruct $B \rightarrow D^{(*)}\ l\ \nu$ using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$.



Full Reconstruction Tag ("B Beam")
⇒(BR(D(*)(π) l ν) analyses)

- One B reconstructed completely in known $b \rightarrow c$ mode.
- Many modes used.



$|V_{cb}|$ *and FF from* $D^{(*)}$

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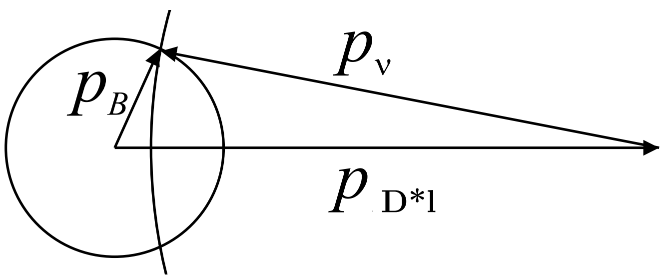
$B^0 \to D^{*+}\, l\, \nu$ selection

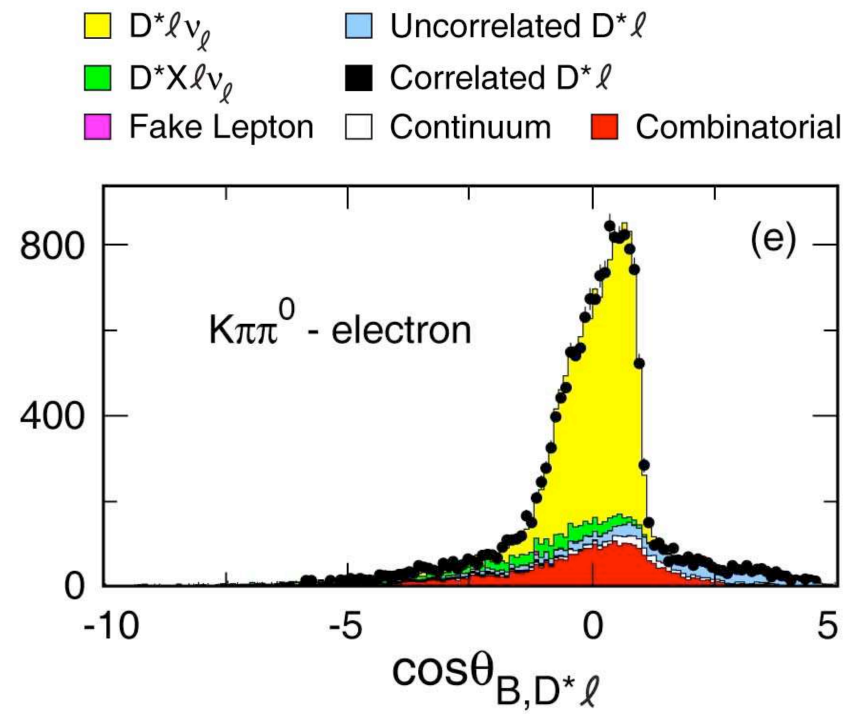
BaBar

Select $B^0 \to D^{*+}\, l\, \nu$ $(D^{*+} \to D^0 \pi)$ events with $p^*_l > 1.2$ GeV.

Estimate backgrounds (comb., D**) from $\Delta M = M(D^*) - M(D)$ and $\cos\theta_{BY}$.



$$\cos\theta_{BY} = \left. \frac{2E_B E_T - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|} \right|_{Y \equiv D^{*0} e}$$



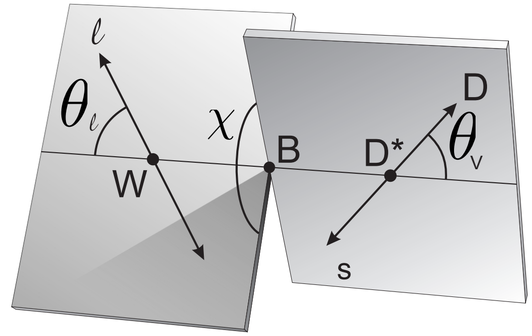
BaBar analyses:

(1) Three D modes: $D \to K\pi$, $K\pi\pi$, $K\pi\pi\pi$, $\chi 2$ fit to 1D projections.

(2) One D mode: $D \to K\pi$, 4D maximum likelihood fit

$B^0 \rightarrow D^{*+} l \nu$ Form factors

Phys.Rev. D77:032002 (2008)

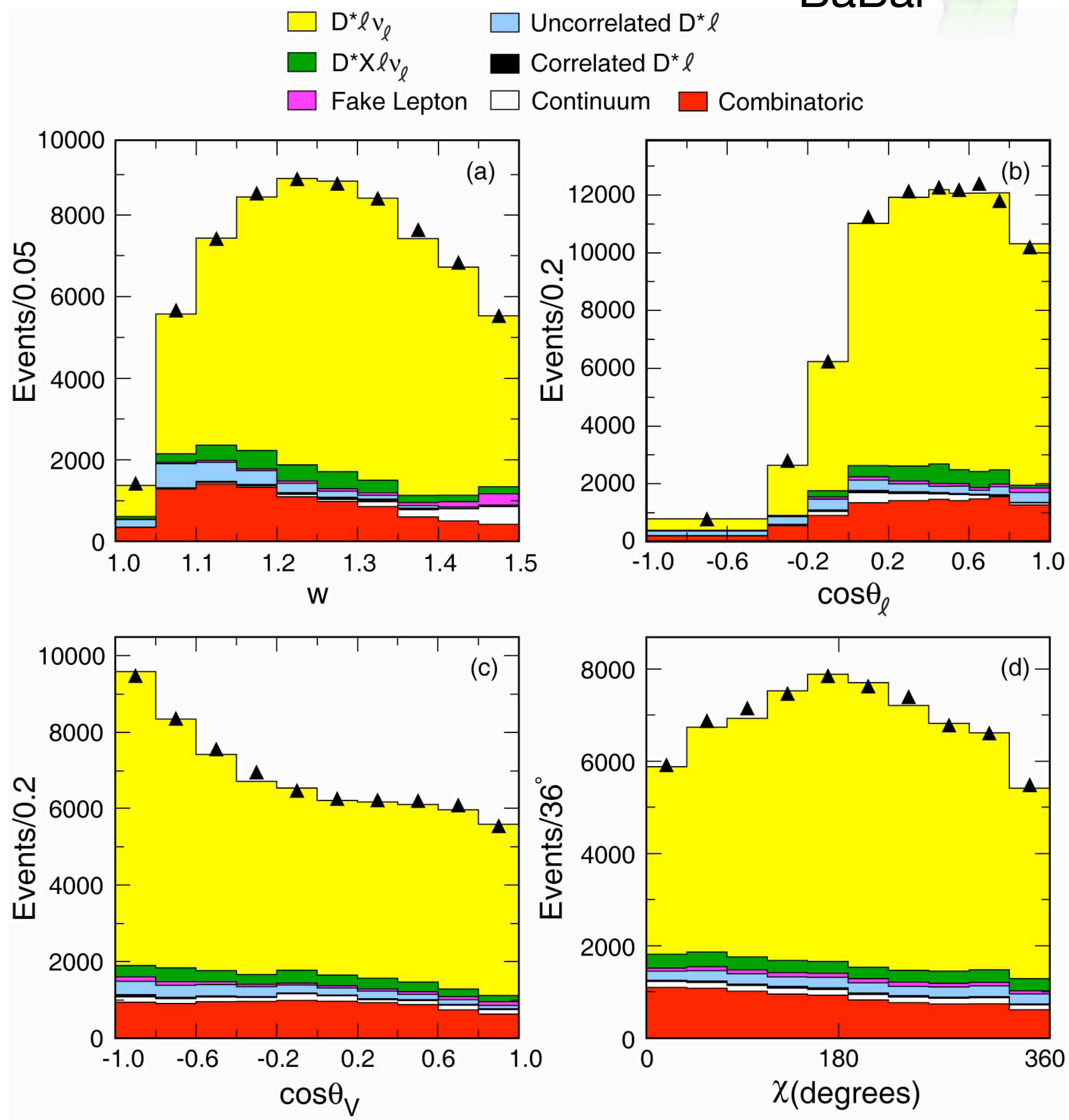


BaBar

Simultaneous χ^2 fit fit 1D projections in w, cosθ_l, cosθ_V (integrated over angle χ).

79M B/Bbar pairs

First simultaneous measurement of form factors and |Vcb|, fully accounting for all correlations.



Final results combined with Phys. Rev. D74 092004 (which uses a full 4D fit) to give:

$$\rho^2 = 1.191 \pm 0.048 \pm 0.028$$
$$R_1(1) = 1.429 \pm 0.061 \pm 0.044$$
$$R_2(1) = 0.827 \pm 0.038 \pm 0.022$$
$$F(1)|V_{cb}| = (34.4 \pm 0.3 \pm 1.1) \times 10^{-3}$$

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$|V_{cb}|$ and form factors from $B^- \to D^{0*} e \nu$

BaBar

arXiv: 0712.3493 [hep-ex]

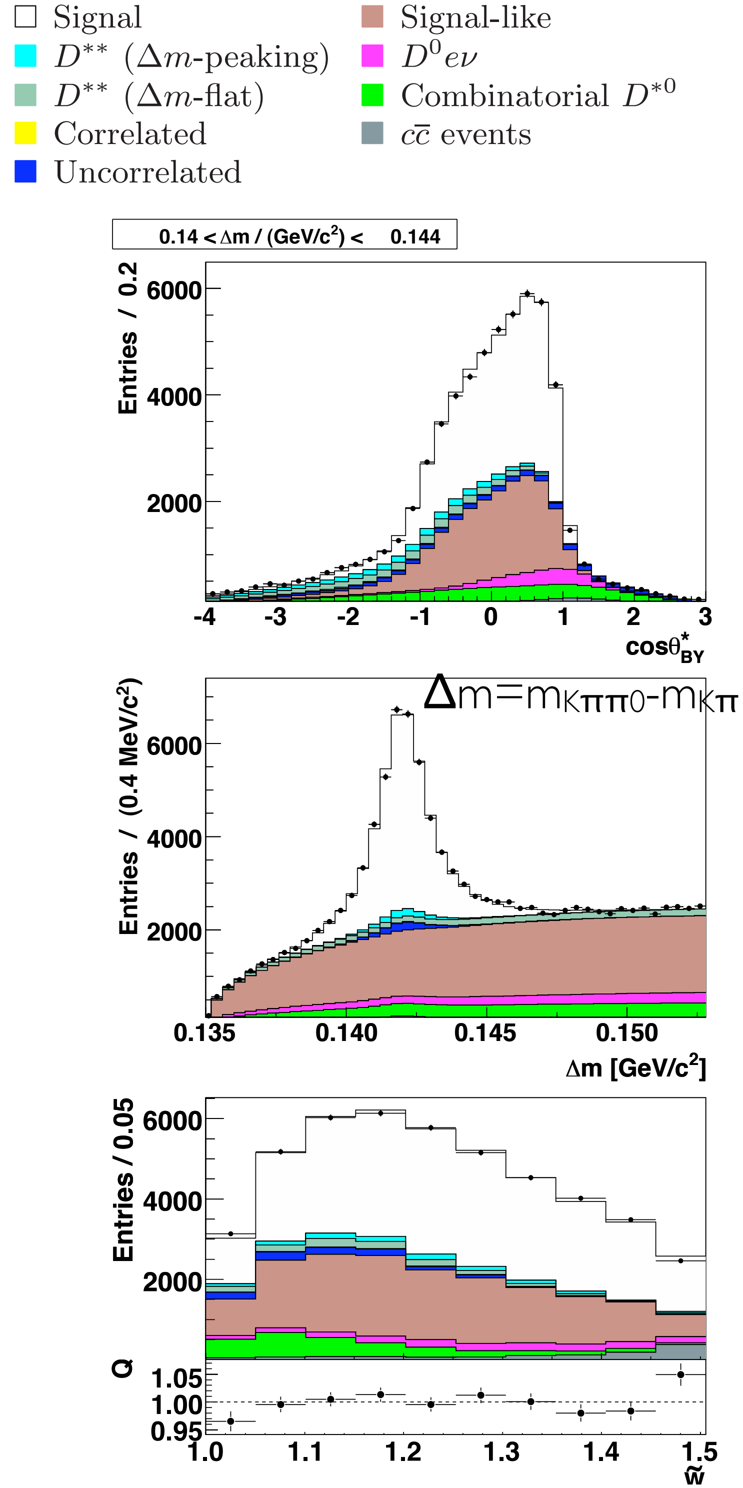
226M B/Bbar pairs

- Look at: $D^{*0} \to \pi^0 D^0$ and $D^0 \to K^- \pi^+$
- Binned maximum likelihood fit in Δm, $\cos\theta_{BY}$ and ω^2
- Main background: mis-reconstructed $B^{\pm 0} \to D^{*0\pm} e \nu$

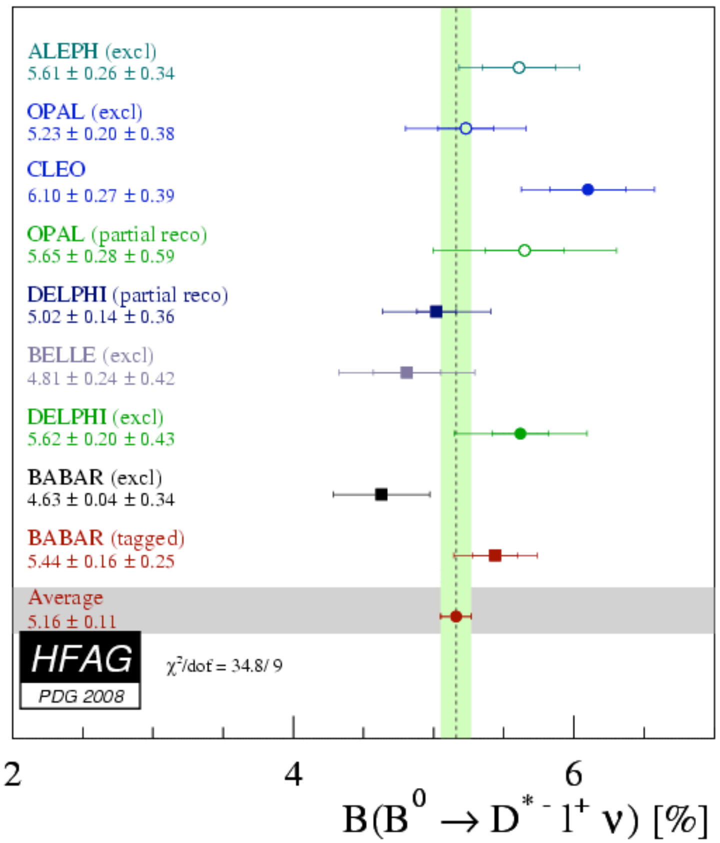
$$F(1)|V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \cdot 10^{-3}$$
$$\rho^2 = 1.16 \pm 0.06 \pm 0.08$$
$$\mathcal{B}(B \to D^{*0}) = (5.56 \pm 0.08 \pm 0.41)\%$$

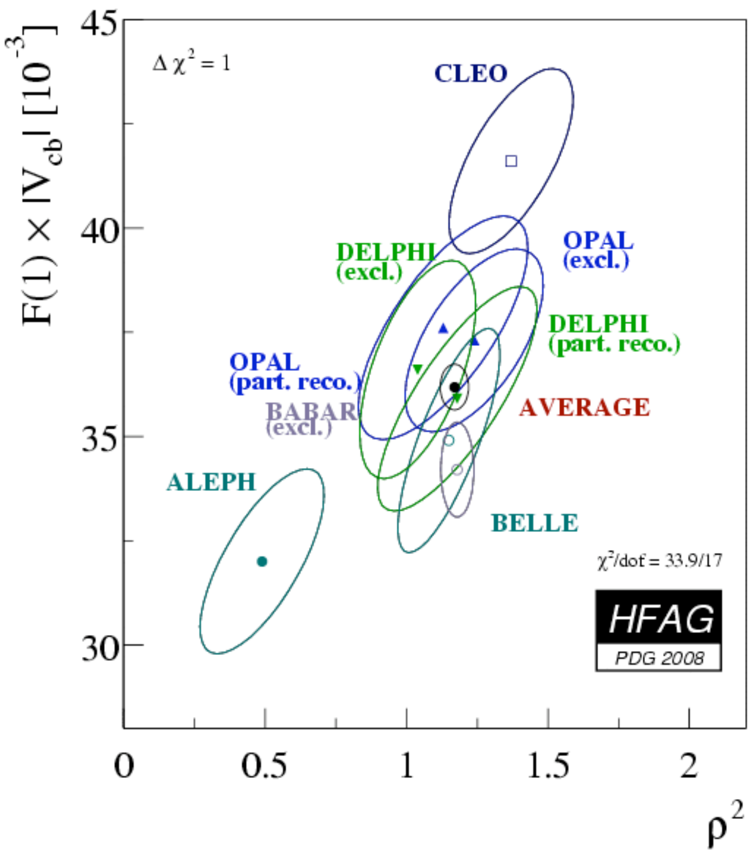
- Main systematic uncertainties:
  π^0 reconstruction efficiency, *BR*($D^{*0} \to \pi^0 D^0$)
  $R_1(1)$ and $R_2(1)$ for ρ^2

- Complementary to $D^{*+} l \nu$ analyses



$|Vcb|$ World average: from $B^0 \rightarrow D^{*+} e \nu$





HFAG average:

$F(1)|Vcb|=$**$(36.18 \pm 0.55)x10^{-3}$**

$\rho^2=$**1.17 ± 0.05**

Lattice	F(1)**	$\|V_{cb}\|$ exclusive	incl.* Vs excl.
Hashimoto *et al*. PRD66 104503, 2002	0.919 ± 0.033	**$(39.37 \pm 0.60_{exp.} \pm 1.37_{theo})x\ 10^{-3}$**	~1.6 σ
Laiho *et al*. PoS LATTICE2007:358, 2006	0.930 ± 0.022	**$(38.90 \pm 0.59_{exp.} \pm 0.90_{theo})x\ 10^{-3}$**	~2.7 σ

*Discrepancy observed w.r.t HFAG 1S scheme inclusive result $|Vcb|=(41.78 \pm 0.30_{fit} \pm 0.08_{\tau B})\ x\ 10^{-3}$.

Errors dominated by systematic errors in the lattice calculation of F(1).

$BR(B \rightarrow D^{(*)}\ (\pi)\ l\ \nu)$

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$B \to D^{**} l \nu$: A test of HQET

Although not directly used for $|V_{cb}|$, measurements of $B \to D^{**} l \nu$ are important for systematics in almost all semileptonic B analyses.

They also provide an essential test of HQET, relied upon for exclusive $|V_{cb}|$ determination.

- In the heavy quark limit (m_b and $m_c \to \infty$), only two independent form factors:

$\tau_{1/2}$ and $\tau_{3/2}$ for $j_l = 1/2, 3/2$

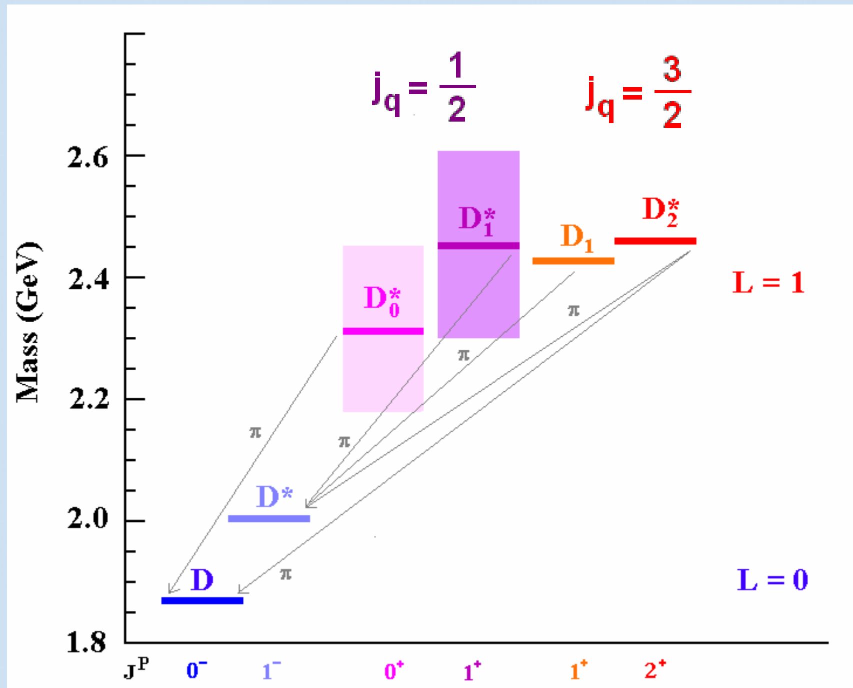
$$\Gamma(B \to D^*_2 l \nu\, ;\, D_1 l \nu) \propto |\tau_{3/2}(w)|^2$$

$$\Gamma(B \to D^*_0 l \nu\, ;\, D^*_1 l \nu) \propto |\tau_{1/2}(w)|^2$$

Theorists consistently predict the same result:

$$\Gamma(B \to D^*_2 l \nu\, ;\, D_1 l \nu) \sim 10 \times \Gamma(B \to D^*_0 l \nu\, ;\, D^*_1 l \nu)$$

Narrow Broad



N. Uraltsev, Phys. Lett. B501:86 (2001)

M. Neubert, Phys. Rev. D46 3914 (1992)

A. Le Yaouanc, hep-ph/0003087,

Branching Fractions of $B \to D^{(*)}\pi\, l\, \nu$

Belle

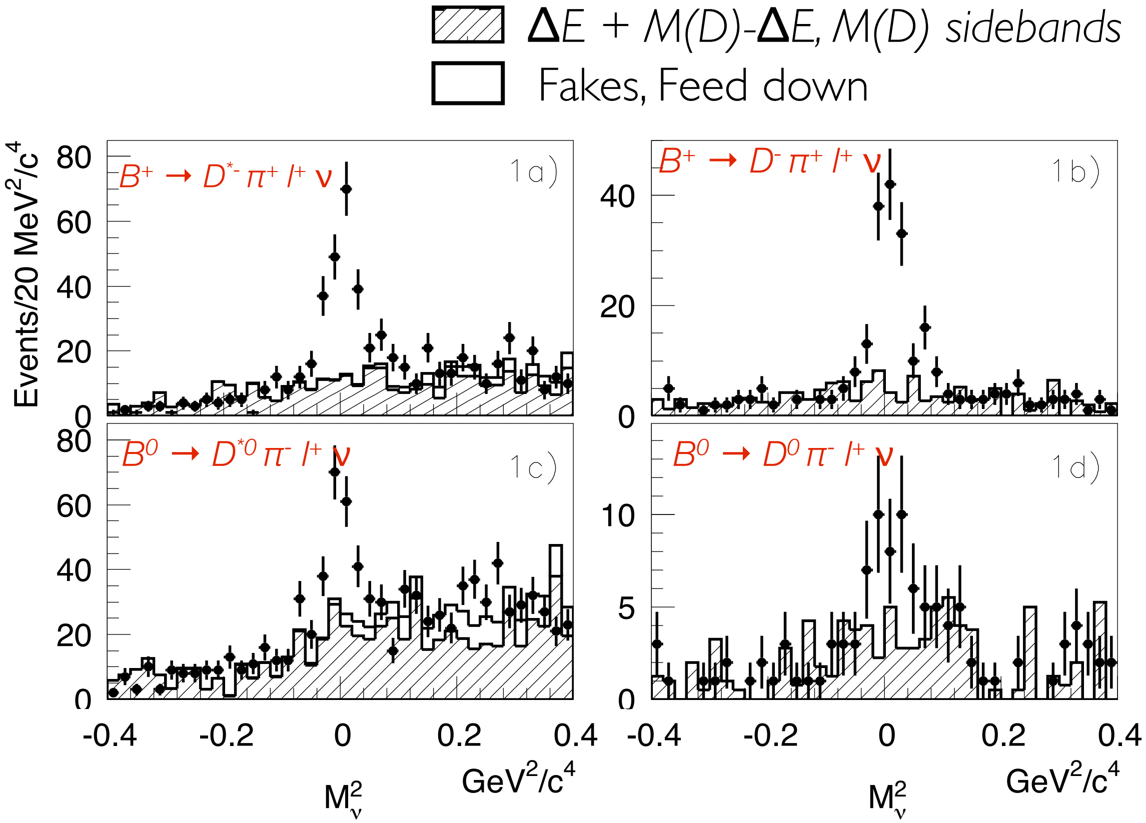
657M B/Bbar pairs

D. Liventsev et al. , PRD 77, 091503 (2008)

- Reconstruct e, μ and $D^{(*)(0)(\pm)}$ in the recoil side of a B Beam event.
  P_{lepton}> (0.6 GeV BaBar, 1.0 GeV Belle).

- Fitting missing mass squared:

$$M_\nu^2 = (P_{\rm beam} - P_{B_{\rm tag}} - P_{B_{\rm sl}})^2$$



$|M_\nu^2| < 0.1$ GeV²

- Backgrounds are subtracted using data:

$\Delta E \equiv E_{\rm tag} - E_{\rm beam}$ $M(D_{\rm sl})$ sidebands

$D^{(*)}\pi h^+$ fakes

- Feed-down subtracted using MC

- Branching ratios are calculated relative to the normalization modes to cancel out the Btag reconstruction efficiency

Branching Fractions of $B \to D^{(*)}\pi\, l\, \nu$

657M B/Bbar pairs

D. Liventsev et al. , PRD 77, 091503 (2008)

Belle

- Very clear peaks for narrow D1 and D2 states
- Large BR for D^*_0 , but no evidence for D_1'

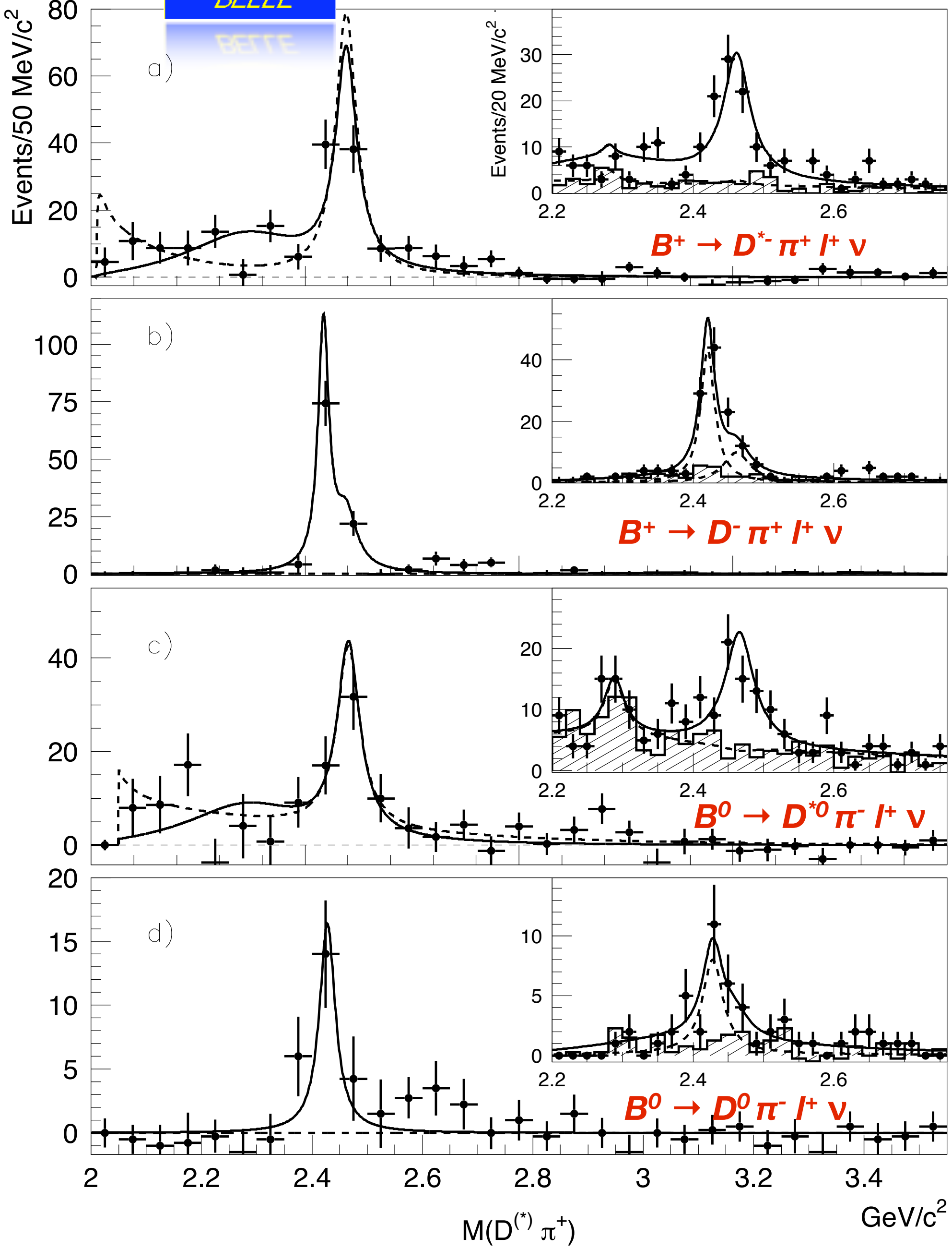
$$\mathcal{B}(\text{mode}) \equiv \mathcal{B}(B \to D^{**}\ell\nu) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^+)$$

$D\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to \bar{D}_0^{*0}\ell^+\nu$	102 ± 19	$0.24 \pm 0.04 \pm 0.06$	5.4
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	94 ± 13	$0.22 \pm 0.03 \pm 0.04$	8.0
$B^0 \to D_0^{*-}\ell^+\nu$	61 ± 22	$0.20 \pm 0.07 \pm 0.05$	2.6
$B^0 \to D_2^{*-}\ell^+\nu$	68 ± 13	$0.22 \pm 0.04 \pm 0.04$	5.5

$D^*\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to \bar{D}_1^{*0}\ell^+\nu$	-5 ± 11	< 0.07 @ 90% C.L.	
$B^+ \to \bar{D}_1^{0}\ell^+\nu$	81 ± 13	$0.42 \pm 0.07 \pm 0.07$	6.7
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	35 ± 11	$0.18 \pm 0.06 \pm 0.03$	3.2
$B^0 \to D_1^{*-}\ell^+\nu$	4 ± 8	< 0.5 @ 90% C.L.	
$B^0 \to D_1^{-}\ell^+\nu$	20 ± 7	$0.54 \pm 0.19 \pm 0.09$	2.9
$B^0 \to D_2^{*-}\ell^+\nu$	1 ± 6	< 0.3 @ 90% C.L.	



- **dominant syst due to Breco Br($D^{(*)(0)(\pm)}$) and track reconstruction.**

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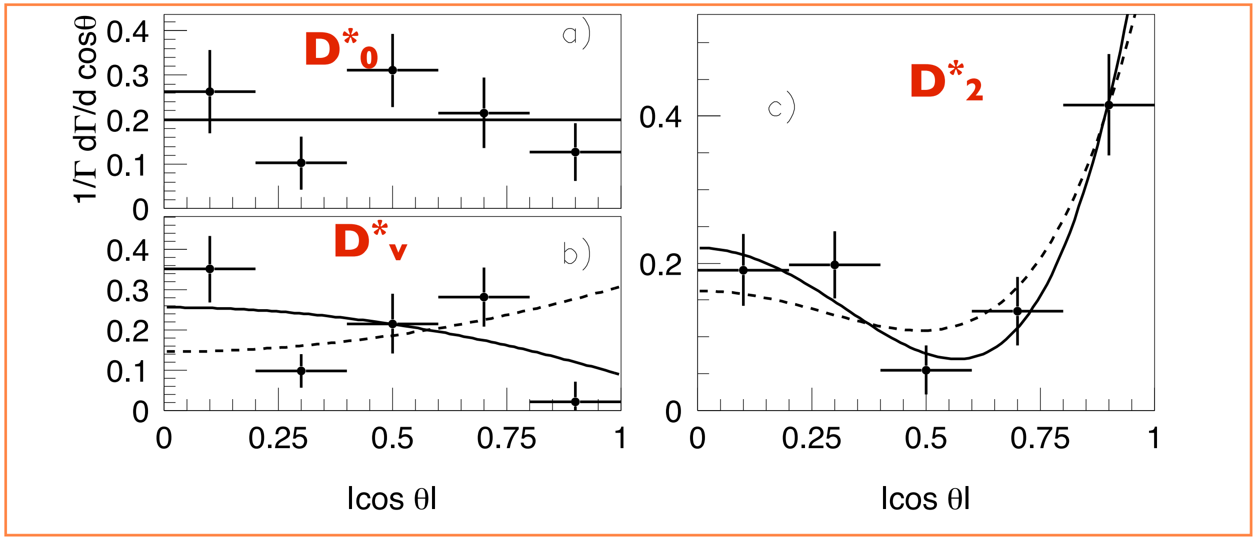
Helicity distributions of $(B \to D_0^*, D_2^* \pi\, l\, \nu)$

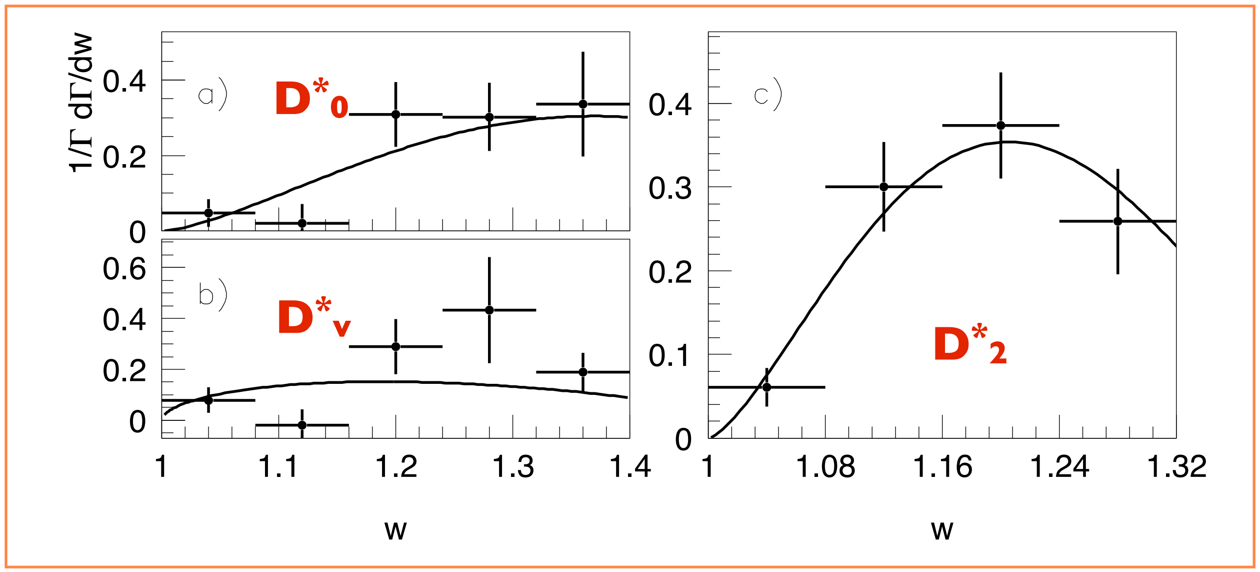
Belle

D. Liventsev et al., PRD 77, 091503 (2008)

- $D\pi$ invariant mass fit in bins of helicity.
- θ angle between
    - π in D** rest frame and D** boost vector



- Helicity distributions for D*0 and D*2 fit with
    - J= 0 (χ^2/ndf = 6.0/4)
    - J= 2 (χ^2/ndf = 2.0/3)



Branching Fractions of
B → D$^{(*)}$(π) l ν

BaBar

341M B/Bbar pairs

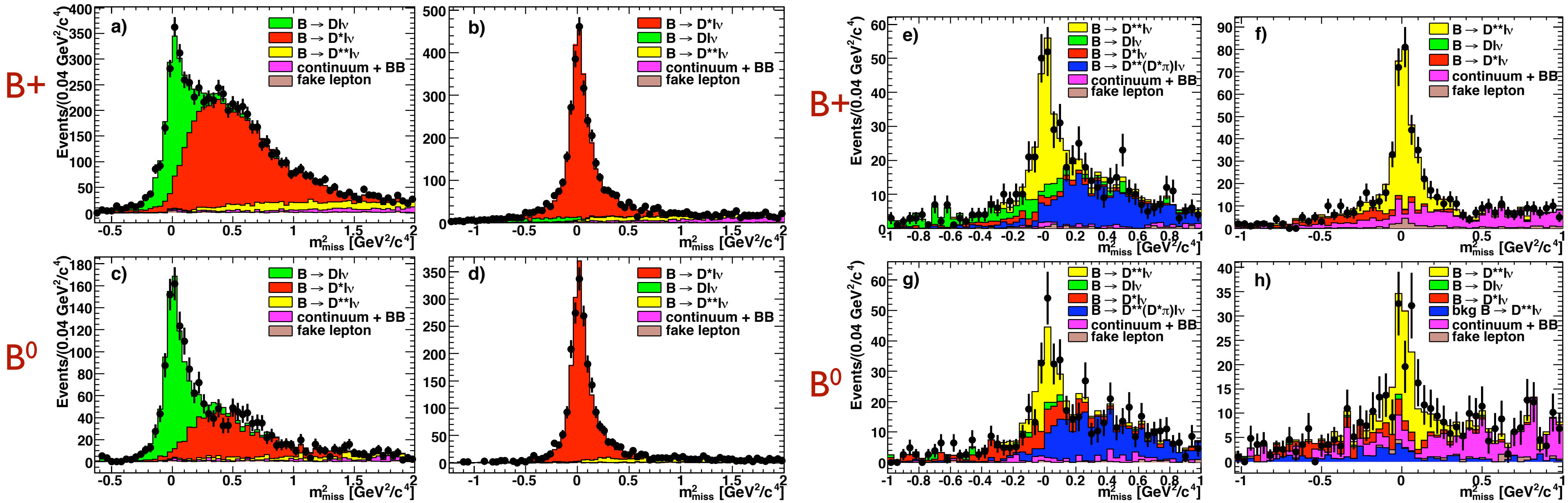
B. Aubert *et al.*, PRL 100, 151802 (2008)

Mode	$\mathcal{B}(B^-)$ [%]	$\mathcal{B}(\overline{B}^0)$ [%]
$D\ell^-\overline{\nu}_\ell$	$2.33 \pm 0.09 \pm 0.09$	$2.21 \pm 0.11 \pm 0.12$
$D^*\ell^-\overline{\nu}_\ell$	$5.83 \pm 0.15 \pm 0.30$	$5.49 \pm 0.16 \pm 0.25$
$D\pi^\pm\ell^-\overline{\nu}_\ell$	$0.42 \pm 0.06 \pm 0.03$	$0.43 \pm 0.08 \pm 0.03$
$D^*\pi^\pm\ell^-\overline{\nu}_\ell$	$0.59 \pm 0.05 \pm 0.04$	$0.48 \pm 0.08 \pm 0.04$

Results consistent with isospin symmetry

$$\mathcal{B}(B^- \to D^{(*)}\pi\ell^-\overline{\nu}_\ell) = (1.52 \pm 0.12_{stat.} \pm 0.10_{syst.})\%$$

$$\mathcal{B}(\overline{B^0} \to D^{(*)}\pi\ell^-\overline{\nu}_\ell) = (1.37 \pm 0.17_{stat.} \pm 0.10_{syst.})\%$$



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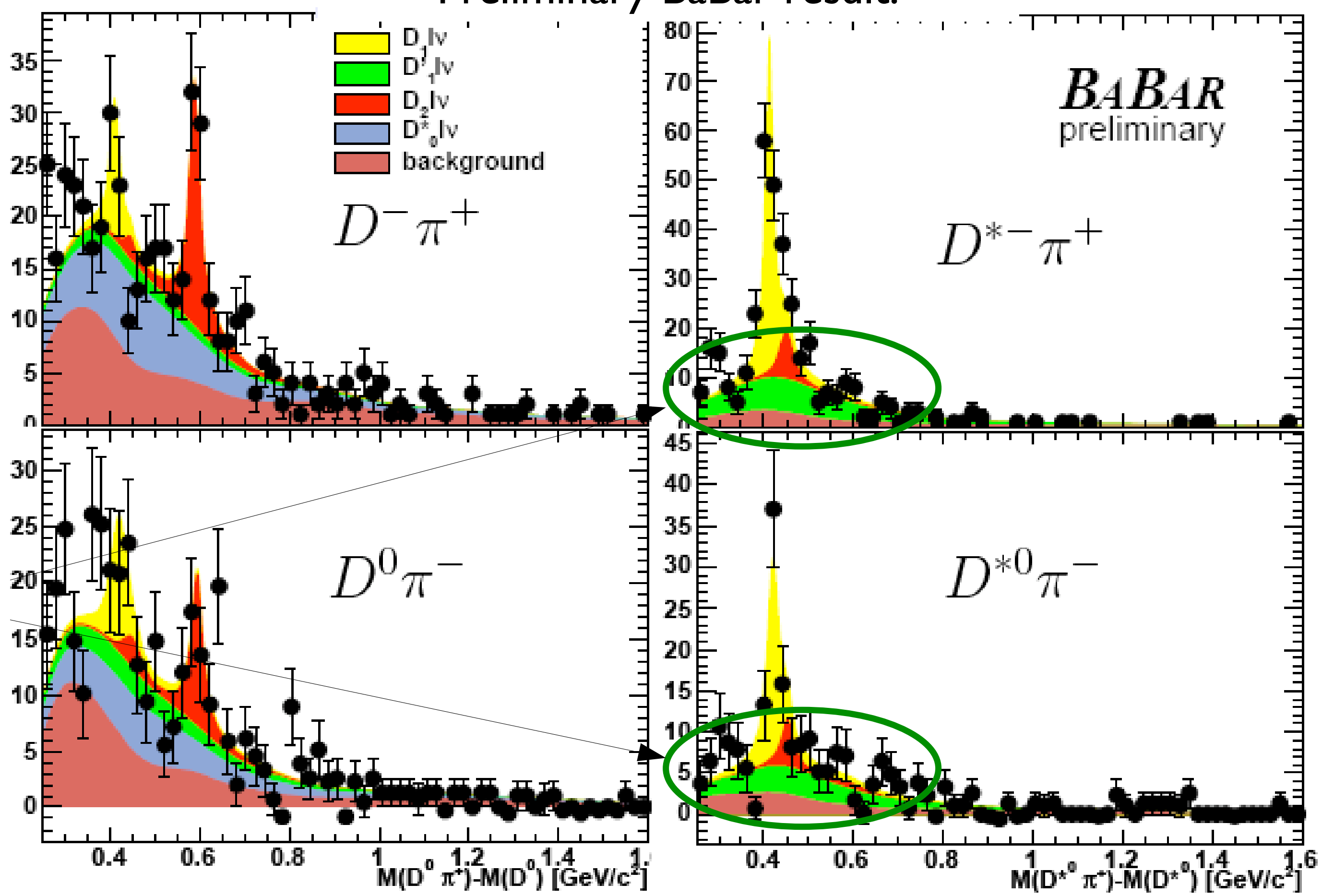
Fit to $B \to D^{**}\ l\,\nu$ components

BaBar

- Simultaneous fit to all 4 channels, including crossfeeds.
- BG normalised from fits to B_{tag} mass.
- Large BR for wide states - in disagreement with HQET.

Preliminary BaBar result.



$B \rightarrow D^{**}\ l\ \nu$ Branching fraction results

Decay Mode	$\mathcal{B}\ (\bar{B} \rightarrow D^{**}\ell^-\bar{\nu}_\ell) \times \mathrm{B}\ (D^{**} \rightarrow D^{(*)}\pi)$ %(BELLE)	BABAR Branching Fraction
	$D\pi$ invariant mass fit	
$B^- \rightarrow D_0^{*0}\ell^-\bar{\nu}_\ell$	$0.24 \pm 0.04 \pm 0.06$	$0.28 \pm 0.05 \pm 0.04$
$B^- \rightarrow D_2^{*0}\ell^-\bar{\nu}_\ell$	$0.22 \pm 0.03 \pm 0.04$	$0.16 \pm 0.03 \pm 0.01$
$\bar{B}^0 \rightarrow D_0^{*+}\ell^-\bar{\nu}_\ell$	$0.20 \pm 0.07 \pm 0.05$	$0.47 \pm 0.09 \pm 0.07$
$\bar{B}^0 \rightarrow D_2^{*+}\ell^-\bar{\nu}_\ell$	$0.22 \pm 0.04 \pm 0.04$	$0.08 \pm 0.04 \pm 0.02$
	$D^*\pi$ invariant mass fit	
$B^- \rightarrow D_1^{\prime 0}\ell^-\bar{\nu}_\ell$	< 0.07 @ 90CL	$0.27 \pm 0.05 \pm 0.05$
$B^- \rightarrow D_1^{0}\ell^-\bar{\nu}_\ell$	$0.42 \pm 0.07 \pm 0.07$	$0.29 \pm 0.03 \pm 0.03$
$B^- \rightarrow D_2^{*0}\ell^-\bar{\nu}_\ell$	$0.18 \pm 0.06 \pm 0.03$	$0.07 \pm 0.01 \pm 0.01$
$\bar{B}^0 \rightarrow D_1^{\prime +}\ell^-\bar{\nu}_\ell$	< 0.5 @ 90CL	$0.37 \pm 0.07 \pm 0.05$
$\bar{B}^0 \rightarrow D_1^{+}\ell^-\bar{\nu}_\ell$	$0.54 \pm 0.19 \pm 0.09$	$0.25 \pm 0.05 \pm 0.03$
$\bar{B}^0 \rightarrow D_2^{*+}\ell^-\bar{\nu}_\ell$	< 0.3 @ 90CL	$0.04 \pm 0.02 \pm 0.01$

Belle: non-resonant $D^{(*)}\pi l\nu$ consistent with zero.

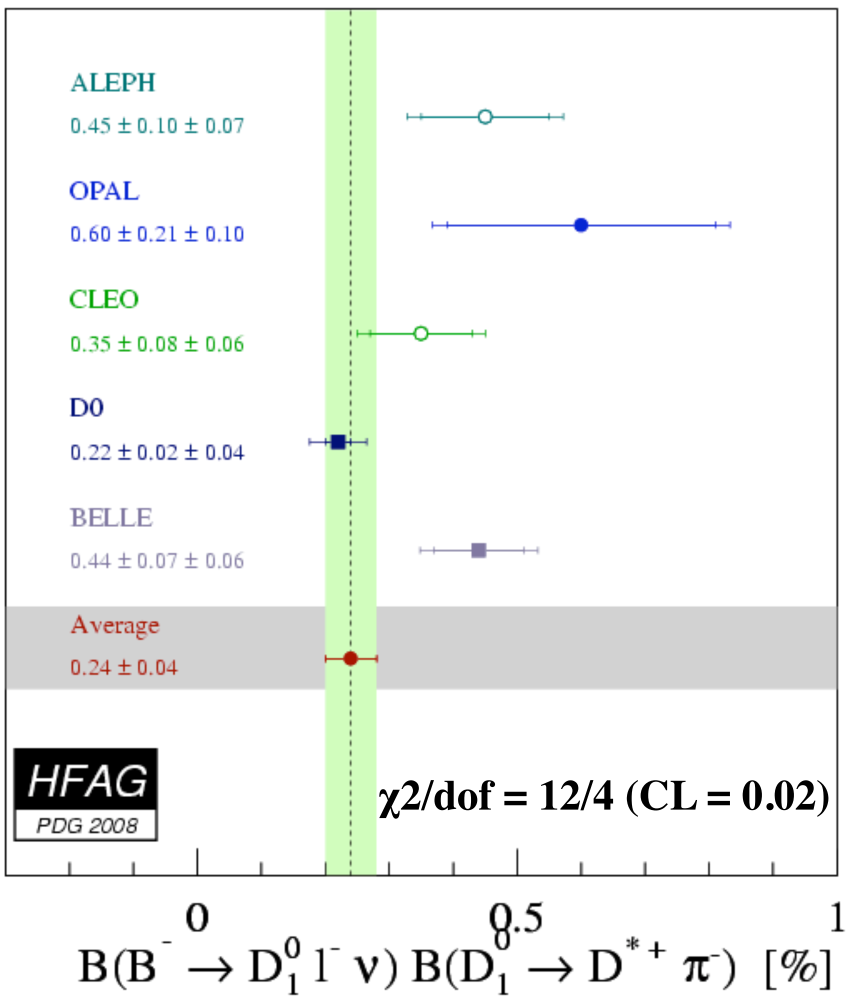
BaBar: non-resonant fixed to zero in fit.

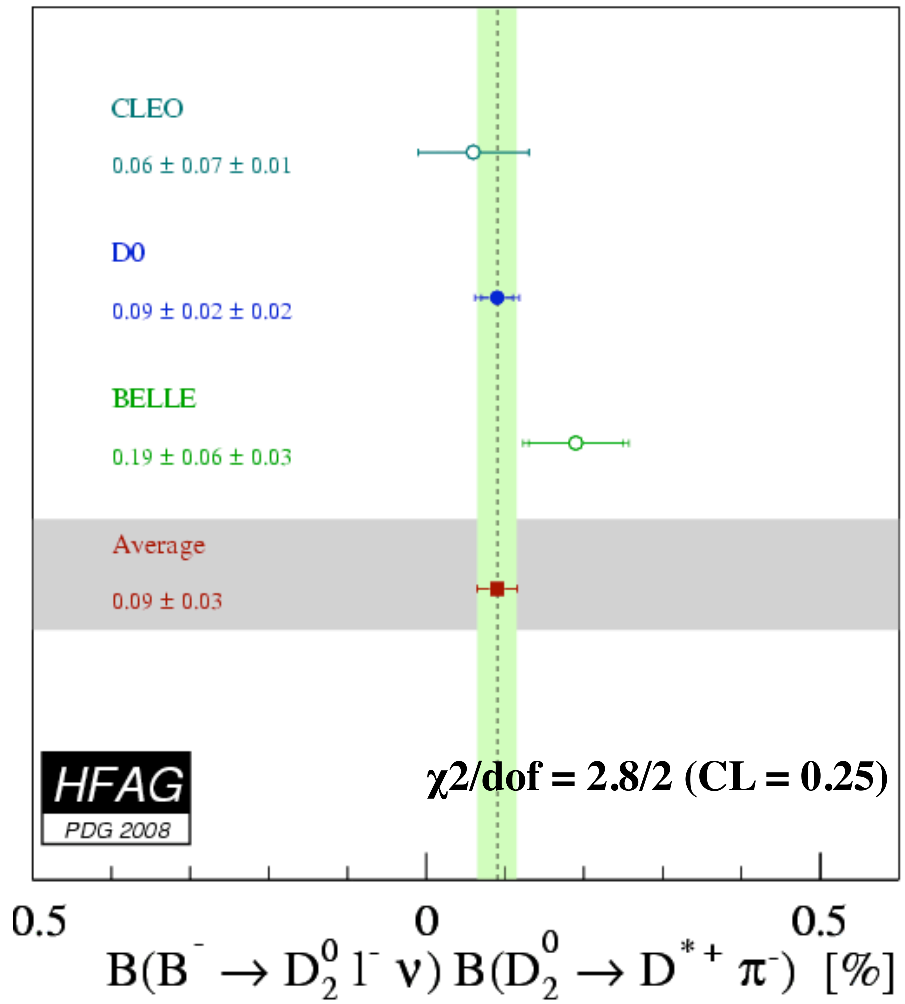
D_1' BR > 6 sigma significance in BaBar; not found in Belle.

*World averages of D** l nu measurements*

- Many measurements of narrow states, with the common assumptions:

$$\mathcal{B}(b \to B) = 37.8 - 39.7\%$$
$$\mathcal{B}(D_1 \to D^* \pi^+) = 66.7\%$$
$$\mathcal{B}(D_2^* \to D^* \pi^+) = 20\%$$





Inconsistency with HQET

BR[%] HFAG ave.	B^0	B^+
D^*	5.16 ± 0.11	6.07 ± 0.29
D	2.17 ± 0.12	2.27 ± 0.11
$D\pi$	0.43 ± 0.06	0.42 ± 0.05
$D^*\pi$	0.49 ± 0.08	0.61 ± 0.05
Σ Exclusive (measured)	8.25 ± 0.19	9.37 ± 0.32
inclusive	10.33 ± 0.28	10.99 ± 0.28
Inclusive - Σ Exclusive	***2.08*** ± ***0.34***	***1.62*** ± ***0.42***

2 big questions...

Experiment:
There's a big hole in the measurement of the exclusive X_c components. What's missing?

Theory:
Why is there such a discrepancy between HQET prediction and measurement for the narrow and wide state BR?

Phys. Lett. B609, 298 (2005)

Quenched lattice computations of using static heavy quarks (infinitely massive b and c) give:

$$\tau_{1/2}(1) = 0.41(5) \quad < \quad \tau_{3/2}(1) = 0.57(10)$$

BPS symmetry (N. Uraltsev, hep-ph/0312001)

Use an approximate non-pertrubative symmetry for heavy mesons, predicting $|\tau_{1/2}(w)|^2=0$.

Jugeau et al., hep-ph/0407176

HQET rules apply at w=1 (zero recoil) and infinite mass. Extensions have been performed to first order in $1/m_c$ and all w.

N. Isgur, hep-ph/9811377

Isgur predicted a non-negligible non-resonant contribution 10 years ago!

Conclusions

$D^{(*)}$ and exclusive |Vcb|

$B^- \to D^{0*}\, l\, \nu$

New measurement with simultaneous extraction of form factor parameters.

|Vcb| = (39.37 ± 0.60 ± 1.37)10^{-3} ~*1.5* **σ** *difference to inclusive results*.

⇒uncertainty from F(1) is dominant, requiring more input from Lattice!

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

no different to expectation from BR ($B^0 \to D^{+*}\, l\, \nu$)

D^{**}

Narrow, $B \to D_1/D_2\, l\, \nu$ decays observed and properties studied.

Large BR for *wide* $B \to D_0^*\, l\, \nu$ observed by BaBar **and** Belle, contradicting HQET predictions.

BaBar has found the D_1' state, not yet seen by Belle.

But, If j_l=1/2 states dominate there is a problem with HQET!

15-20 % of the semileptonic decay rate is not allocated.

Experiment

Heavier states or non-resonant contributions**?**
Need further analysis of broad states and what saturates the inclusive sum.

Theory

Missing $1/m_c$ corrections in theoretical predictions.
Need unquenched lattice calculations.

If we do not control $B \to D^{**}\, l\, \nu$ can we fully trust the HQET based exctraction of exclusive $|V_{cb}|$?

backup

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BaBar $B \to D^{**} \, l \, \nu$ systematics.

	Systematic uncertainty on $\Gamma(\overline{B} \to D^{**}(D^{(*)}\pi)\ell^-\bar{\nu}_\ell)/\Gamma(\overline{B} \to X\ell^-\bar{\nu}_\ell)$			
	$\bar{B} \to D_1\ell^-\bar{\nu}_\ell$	$\bar{B} \to D_1'\ell^-\bar{\nu}_\ell$	$\bar{B} \to D_2^*\ell^-\bar{\nu}_\ell$	$\bar{B} \to D_0^*\ell^-\bar{\nu}_\ell$
Tracking efficiency	1.5	1.9	1.2	1.6
Neutral reconstruction	2.6	1.8	1.2	0.9
lepton ID	1.2	1.2	1.2	1.5
Soft particle efficiency	1.2	1.2	0.4	-
Monte Carlo corrections				
$\overline{B}^0 - B^-$ cross-feed	0.3	0.3	0.2	0.2
$D^{(*)}$ Form factors	0.8	0.8	0.5	0.4
D^{**} Form factors	1.0	2.5	1.2	2.0
$D^{(*)}$ branching fractions	3.9	3.9	3.8	3.8
$\overline{B} \to X\ell^-\bar{\nu}_\ell$ branching fraction	1.7	1.7	1.7	1.7
B_{tag} selection	4.8	4.8	4.7	4.6
Fit technique				
$\overline{B} \to X\ell^-\bar{\nu}_\ell$ yield	0.7	0.7	0.7	0.7
$\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell$ yield	5.6	10.6	7.4	8.5
Total systematic error	9.3	13.0	10.0	11.0
Statistical error	9.9	12.2	15.2	13.1