Experimental Results on V_{cb} and $b \to c\ell\nu$ Transitions

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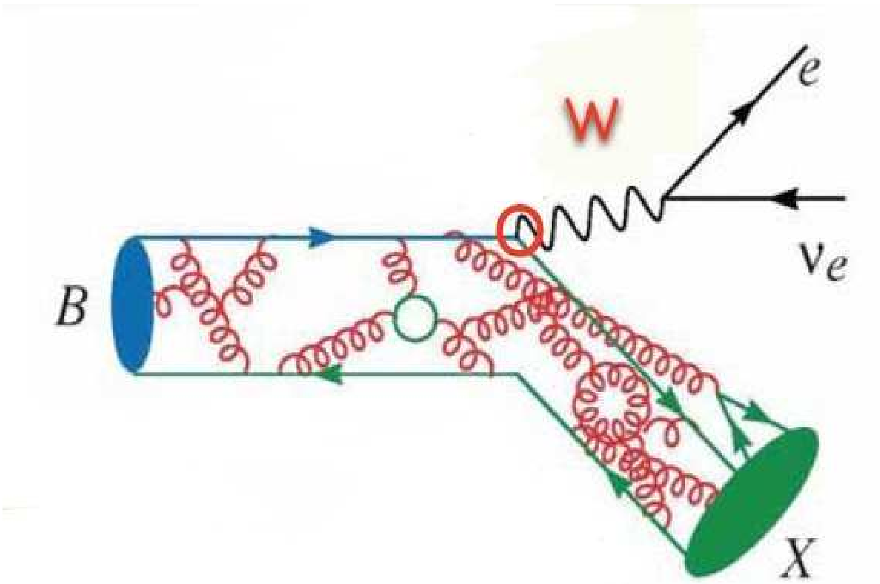
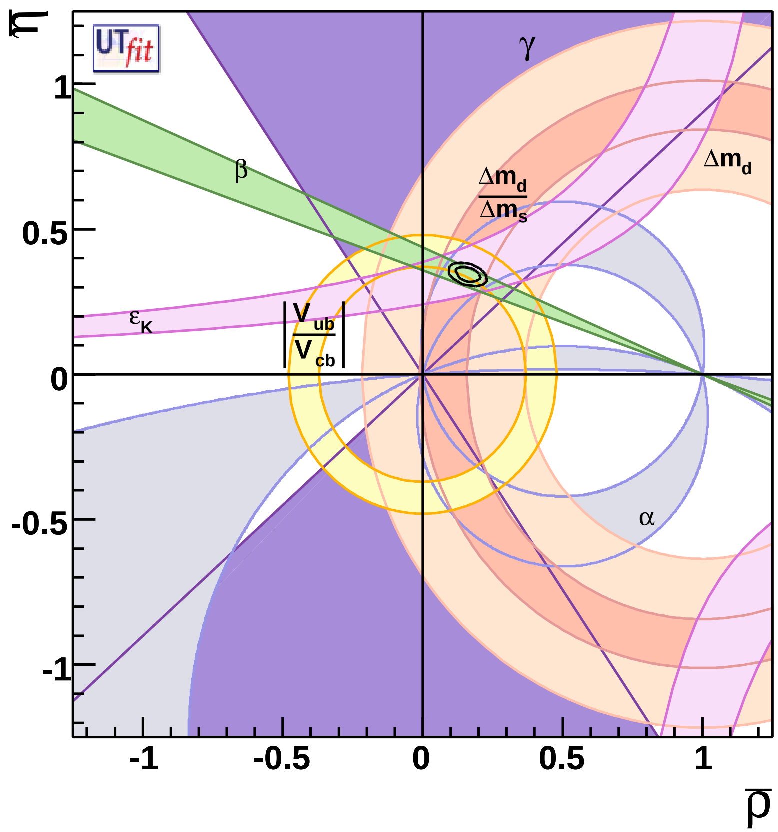
- Motivation
- V_{cb} from exclusive $B \to D^*\ell\nu$
- Results on exclusive branching ratios
- V_{cb} from Kinematic Spectra
- Conclusion

Semileptonic Decays because...

On tree level the decay is split into a leptonic and hadronic current



- sensitive to CKM element V_{cb}
- depend on QCD corrections to $b \longrightarrow c\ell\nu$
  $\Rightarrow$ probes hadronic structure of the B



Two ways to adress this:

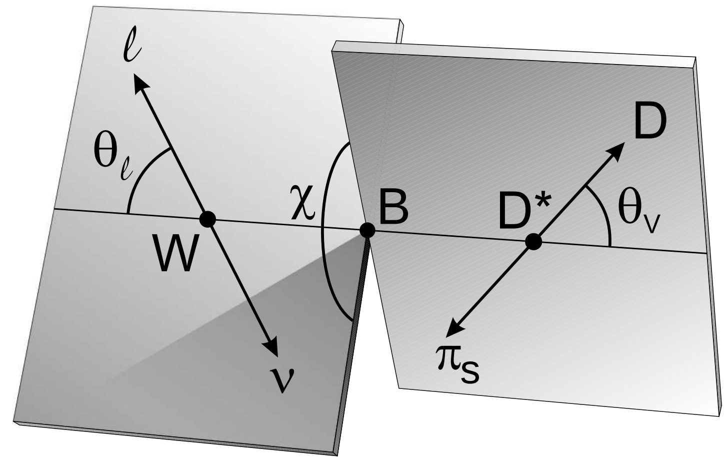
- **exclusive** : form factors modeling dynamics
  have to be extrapolated or
  measured shape needs normalisation
- **inclusive** : OPE and quark masses
  parameters are fitted from moments

V_{cb} from exclusive $B \to D^{*+}\ell\nu$

Result from BaBar (hep-ex/0607076) based on $79\,\mathrm{fb}^{-1}$

Full decay rate expressed in 3 helicity amplitudes H_i, depending on three angles:

$$\frac{d\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi}$$



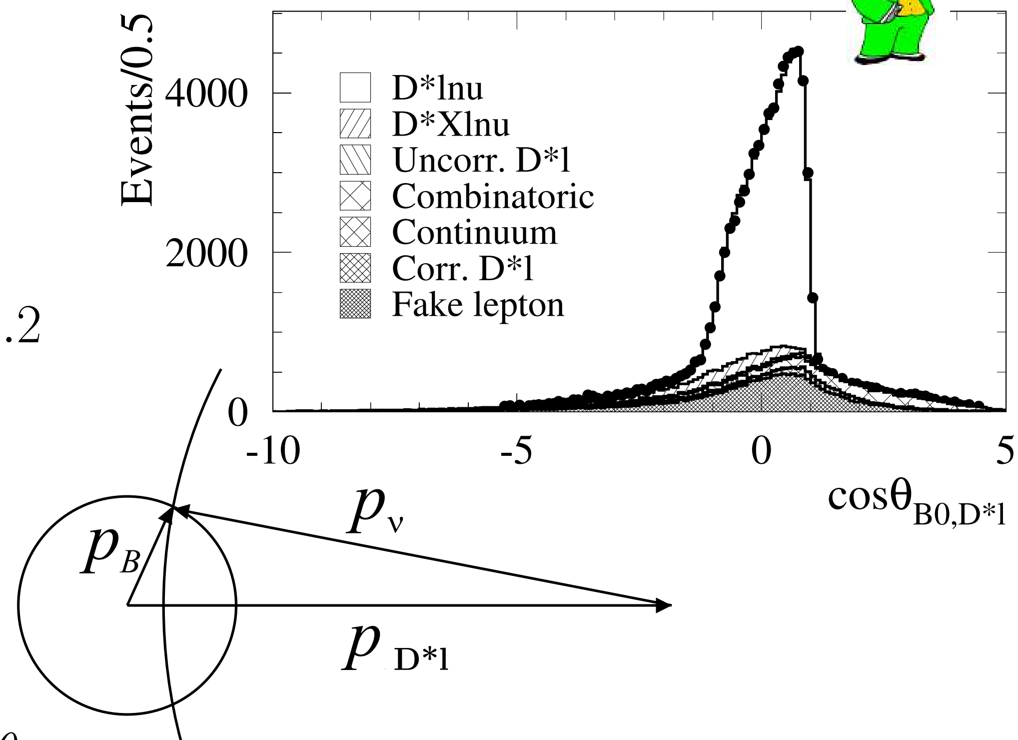
H_i theoretically described by three form factors R_1, R_2 and h_{A1} as functions of $w = v_B \cdot v_{D^*}$ by *Caprini, Lellouch* and *Neubert.* Nucl.Phys.B 530,153 (1998)

$$\begin{aligned} h_{A1}(w) &= h_{A1}(1)\left[1-\rho^2 z+(53\rho^2-15)z^2-(231\rho^2-91)z^3\right] \\ R_1(w) &= R_1(1)-0.12(w-1)+0.05(w-1)^2 \\ R_2(w) &= R_2(1)+0.11(w-1)-0.06(w-1)^2 \end{aligned}$$

$$z=\frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

V_{cb} from exclusive $B \to D^{*+}\ell\nu$ – contd.

- $p_\ell > 1.2\,\mathrm{GeV}/c$ (e and μ)
- D^* in $D^0\pi^\pm$,
  D^0 in $K\pi, K\pi\pi^0, K\pi\pi\pi$
- $|\cos\theta_{B,D^*\ell}| = |-\frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}| < 1.2$
- w averaged over allowed region in $\cos\theta_{B,D^*\ell}$.



- project data on $w, \cos\theta_\ell$ and $\cos\theta_V$
- split each projection into 10 bins and fit the form factors and $|V_{cb}|$ in common
- full correlations are taken into account

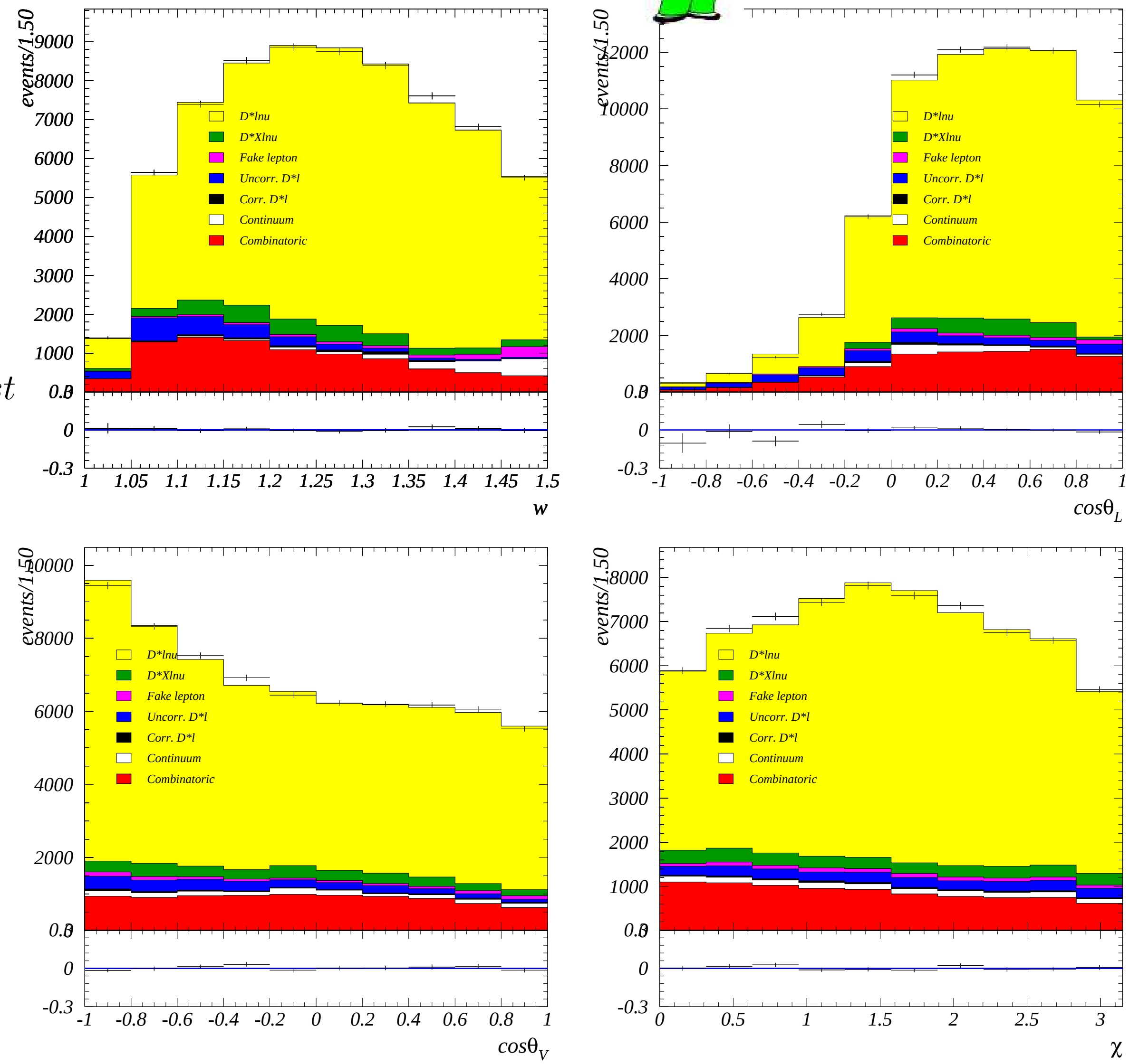
V_{cb} from exclusive $B \to D^{*+}\ell\nu$ – contd.

Combination with earlier result
(Phys.Rev.D74,092004 – e only)

$$
\begin{aligned}
R_1 &= 1.417 \pm 0.061 \pm 0.044 \\
R_2 &= 0.836 \pm 0.037 \pm 0.022 \\
\rho^2 &= 1.179 \pm 0.048 \pm 0.028 \\
|V_{cb}| &= (37.74 \pm 0.35_{stat} \pm 1.25_{syst} \\
&\quad {}^{+1.23}_{-1.44}\,{}_{theory}) \cdot 10^{-3}
\end{aligned}
$$

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

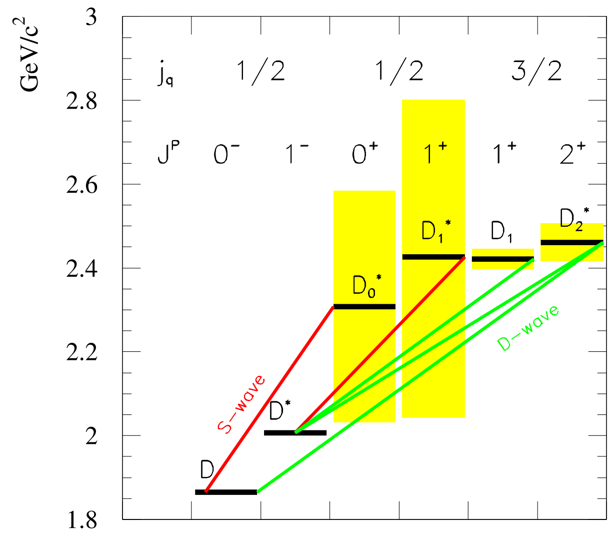
using $h_{A1}(1) = 0.919^{+0.030}_{-0.035}$
from *Hashimoto et al.* (PRD 66,014503)



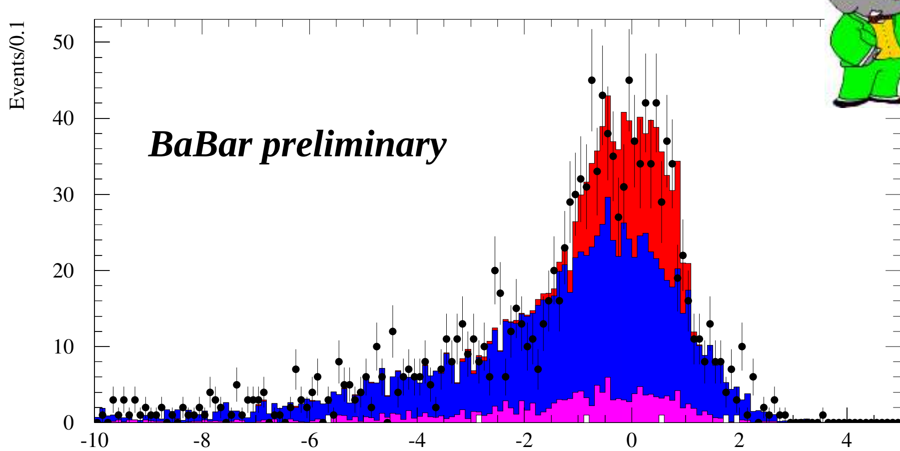
Measurement of Narrow Orbitally Excited D^{**}

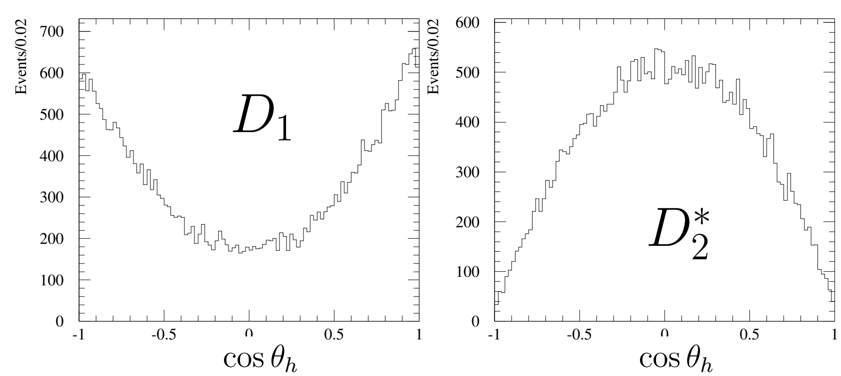
Babar measurement based on $208\,\mathrm{fb}^{-1}$

- Reconstruct D^{**} in four exclusive modes $D^{*0}\pi^+$, $D^{*-}\pi^+$, $D^0\pi^+$ and $D^-\pi^+$,
- e or μ with $p_\ell > 0.8\,\mathrm{GeV}/c$
- Selection and veto using $\cos_{B,D^{*(*)}\ell}$
- Separation between D_1 and D_2^* using D^* helicity
- Simultaneous fit to 10 different spectra in $\Delta m = m(D^{**}) - m(D^0)$

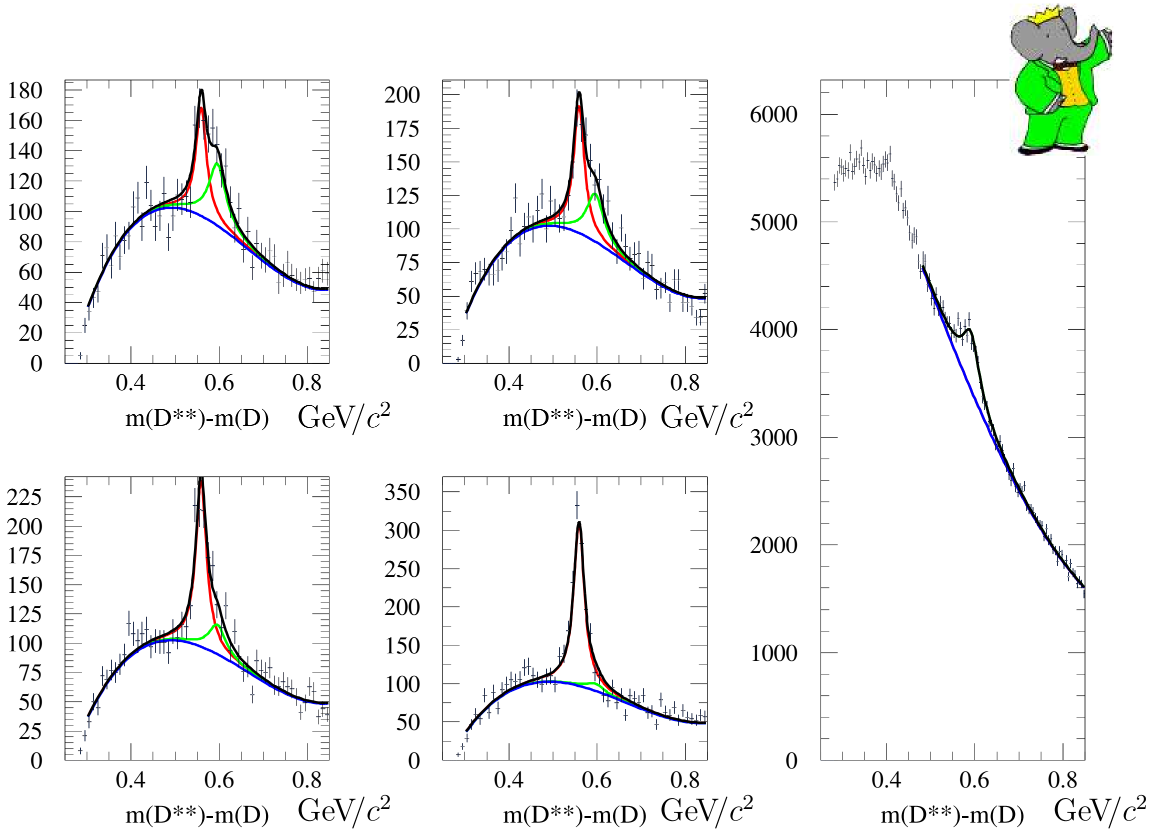


Charm States





Exclusive Narrow D^{**} – contd.



prelim. result

Fit constrains/allows

- Isospin holds for D^{**} decays
- Nothing but $D^{**} \to D^{(*)}\pi$
  Belle: $D_1 \to D\pi\pi \approx 20\%$
- Variation in
  $\Gamma(D_2^* \to D^*\pi)/\Gamma(D_2^* \to D\pi)$
- Polarisation/mixing of 1^+ state

$$\begin{aligned}
\mathcal{B}(B^+ \to D_1^0 \ell^+ \nu_\ell) &= (4.48 \pm 0.26 \pm 0.35)10^{-3} \\
\mathcal{B}(B^+ \to D_2^{*0} \ell^+ \nu_\ell) &= (3.54 \pm 0.32 \pm 0.54)10^{-3} \\
\mathcal{B}(B^0 \to D_1^- \ell^+ \nu_\ell) &= (3.64 \pm 0.32 \pm 0.49)10^{-3} \\
\mathcal{B}(B^0 \to D_2^{*-} \ell^+ \nu_\ell) &= (2.70 \pm 0.35 \pm 0.43)10^{-3}
\end{aligned}$$

Note: $\mathcal{B}_{D_2^*}/\mathcal{B}_{D_1} \approx 0.8$

Combined Measurement of Exclusive Branching Fractions

Babar measurement based on $340\,\text{fb}^{-1}$.

Idea: reconstruct D and ℓ from a semileptonic decay and the other B_{tag} in hadronic mode use what is left in the event to distinguish between $D\ell\nu$, $D^*\ell\nu$ and $D^{**}\ell\nu$.

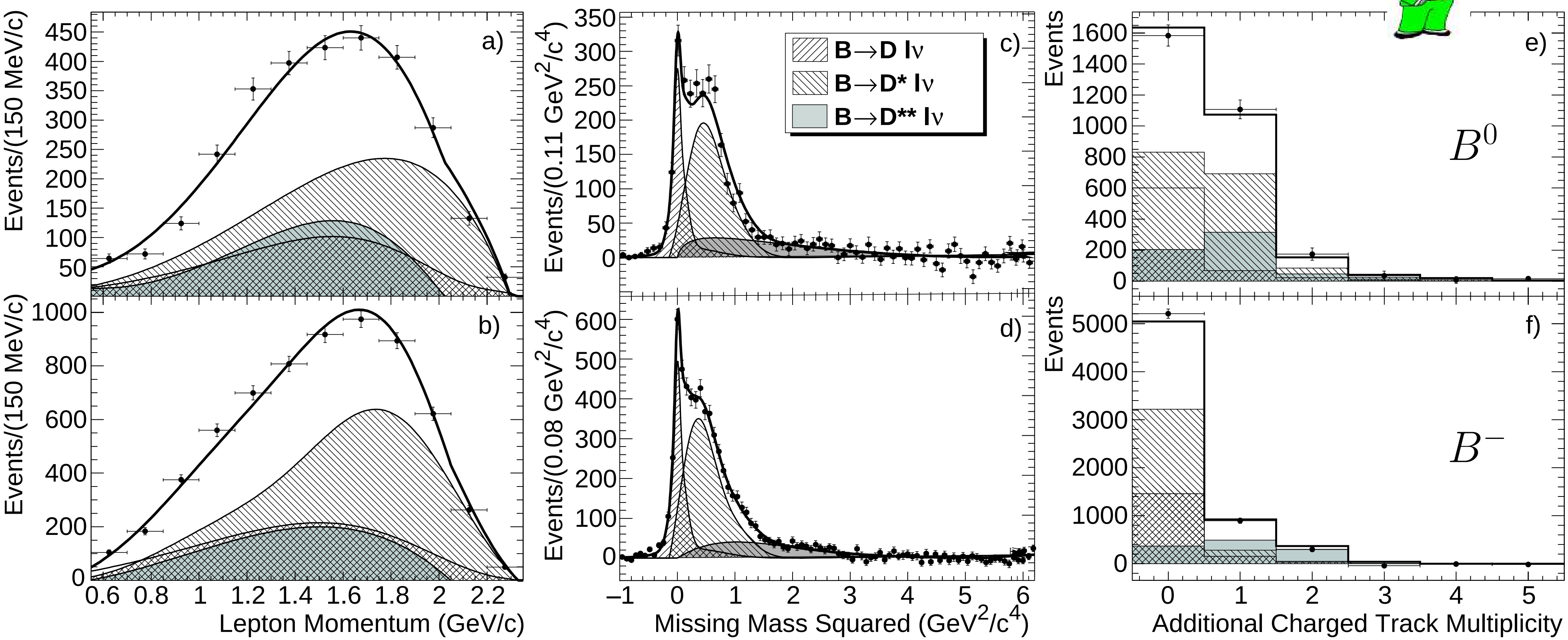
- e or μ with $p_\ell > 0.6\,\text{GeV}/c$
- D^0 in 9 channels
  K and $< 4\pi$, KK and $\pi\pi$.
  no more than one π^0
- D^+ in 7 channels
  K and $< 4\pi$, $K^-K^+\pi$ and K_S^0K
  no more than one π^0

- B_{tag} in $B \to DY$
  with Y:
  - having total charge ± 1
  - contains in total up to 5 charged K and π
  - contains up to 2 K_S^0 and π^0 each
- giving about 1000 different decay chains

Contributions fitted from three largely uncorrelated quantities:

- lepton momentum p_ℓ
- m^2_{miss} : invariant mass of all except the reconstructed B, D and ℓ
- N_{trk} : number of charged tracks not used for the reconstructed part

BRs for $B \to D/D^*/D^{**}\ell\nu$ – contd.



PDF's determined from signal enriched data (purity 75-91%)

based on selection in m^2_{miss} and $\Delta m = m(D^*) - m(D)$

Total $\chi^2/DOF = 1.21$ (B^0)

Total $\chi^2/DOF = 0.94$ (B^-)

BRs for $B \to D/D^*/D^{**}\ell\nu$ – contd.

Ratio	B^- (%)	B^0 (%)
$\frac{\Gamma(B\to D\ell\nu)}{\Gamma(B\to DX\ell\nu)}$	$22.7 \pm 1.4 \pm 1.6$	$21.5 \pm 1.6 \pm 1.3$
$\frac{\Gamma(B\to D^*\ell\nu)}{\Gamma(B\to DX\ell\nu)}$	$58.2 \pm 1.8 \pm 3.0$	$53.7 \pm 3.1 \pm 3.6$
$\frac{\Gamma(B\to D^{**}\ell\nu)}{\Gamma(B\to DX\ell\nu)}$	$19.1 \pm 1.3 \pm 1.9$	$24.8 \pm 3.2 \pm 3.0$

$$
\begin{aligned}
\mathcal{B}(B^- \to D^0\ell^-\nu) &= (2.42 \pm 0.15 \pm 0.17)\% \\
\mathcal{B}(B^- \to D^{*0}\ell^-\nu) &= (6.20 \pm 0.19 \pm 0.32)\% \\
\mathcal{B}(B^- \to D^{**0}\ell^-\nu) &= (2.04 \pm 0.14 \pm 0.20)\% \\
\mathcal{B}(B^0 \to D^{+}\ell^-\nu) &= (2.19 \pm 0.16 \pm 0.13)\% \\
\mathcal{B}(B^0 \to D^{*+}\ell^-\nu) &= (5.46 \pm 0.33 \pm 0.37)\% \\
\mathcal{B}(B^0 \to D^{**+}\ell^-\nu) &= (2.52 \pm 0.32 \pm 0.31)\%
\end{aligned}
$$

If it is assumed all X_c decaying to DX one can take PDG for total

Precision comparable to current world knowledge

hep-ex/0703027

Determination of HQE Parameters

Total semileptonic width $\Gamma_{c\ell\nu}$ can be parametrised by m_b, m_c and other theory parameters

$$\Gamma_{c\ell\nu} = \frac{G_F m_b^5}{192\pi^3}|V_{cb}|^2(1 + A_{ew})A_{pert}A_{nonpert} \cong |V_{cb}|^2 f_{OPE}(m_b, m_c, \vec{a})$$

- A_{pert} expansion in Λ_{QCD}/m_b
- $A_{nonpert}$ expansion in powers of $1/m_b$

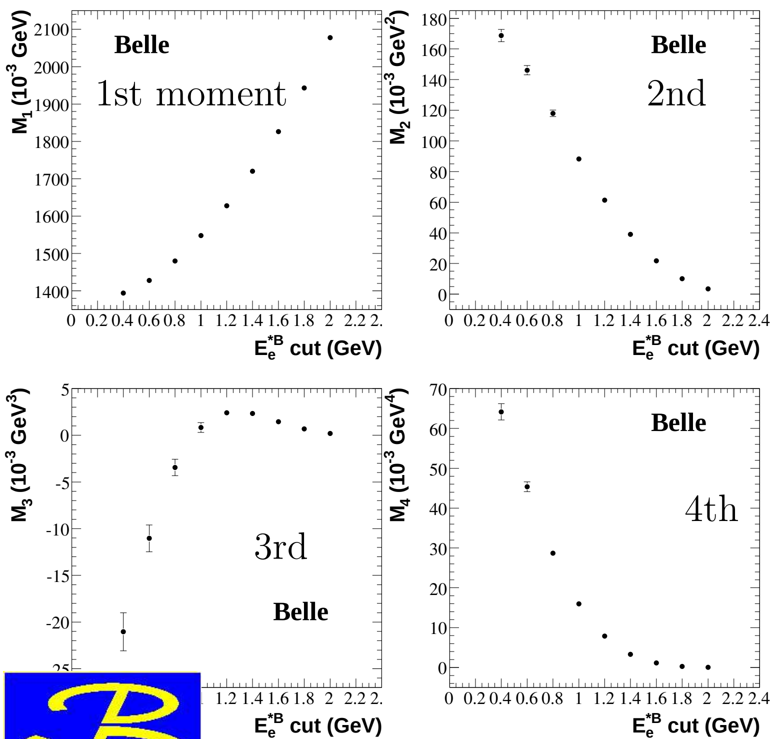
Set of theory parameters $\vec{a}$ depend on ansatz:

- **kinetic scheme**
  P. Gambino and *N. Uraltsev*, Eur.Phys.J. C34, 181 (2004)
- **1S scheme**
  C. Bauer, Z. Ligeti, M. Luke, A. Manohar, M. Trott, PRD 70 094017 (2004)

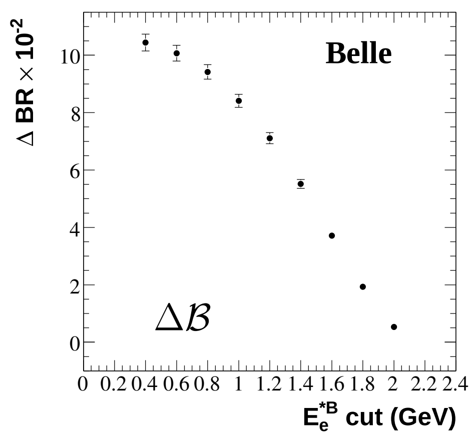
Simultaneous extraction of $|V_{cb}|$, $\Gamma_{c\ell\nu}$, m_b, m_c and $\vec{a}$ from measured moments of electron energy E_e, hadronic mass m_{had} in $B \to X_c\ell\nu$ and photon energy E_γ in $B \to X_s\gamma$.

Moments of Electron Energy Spectrum E_e

Recent results from Belle (PRD 75 032001) using $140\,\text{fb}^{-1}$



- reconstruct one B (tag) exclusively in several hadronic modes
- unfold E_e assuming $m_e = 0$
- takes all correlations into account



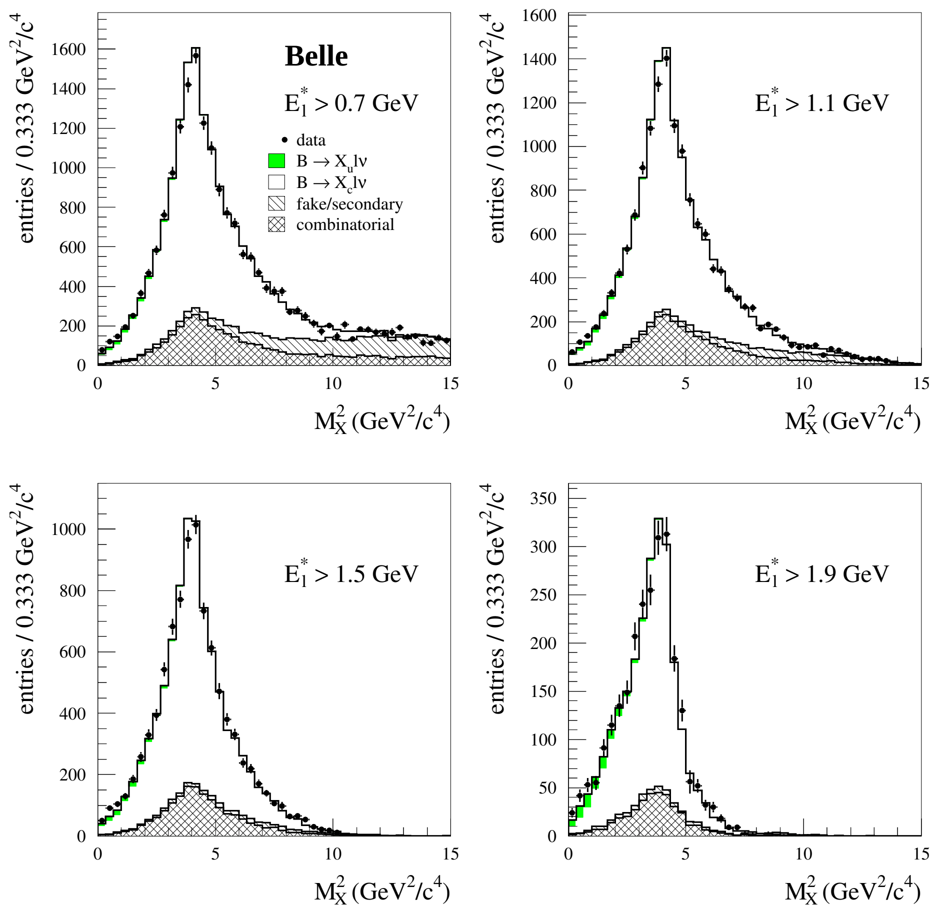
$\mathcal{B}(B^+)|_{E_\ell>0.4\text{GeV}} =$
$(10.79 \pm 0.25 \pm 0.27) \cdot 10^{-3}$

$\mathcal{B}(B^0)|_{E_\ell>0.4\text{GeV}} =$
$(10.08 \pm 0.30 \pm 0.22) \cdot 10^{-3}$

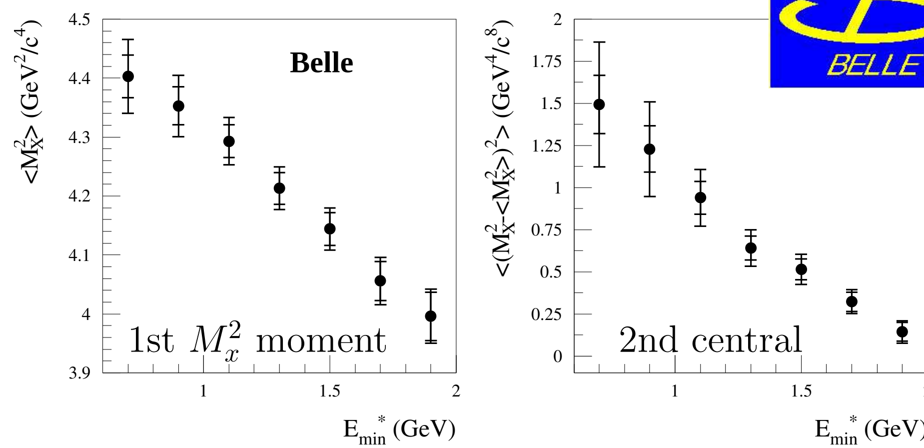
Also BaBar: Phys.Rev.D69 111104 (2004), CLEO: Phys.Rev.D70 032003 (2004), DELPHI: Eur.Phys.J.C45 35 (2006)

Moments of Hadron Mass Spectrum m_{had}

Recent results from Belle (PRD 75 032005) using $140\,\text{fb}^{-1}$



- selection as above
- threshold in E_e from 0.7 to 1.9 GeV
- takes all correlations into account



Also BaBar: Phys.Rev.D69 111103 (2004), CLEO: Phys.Rev.D70 032002 (2004),

DELPHI: Eur.Phys.J.C45 35 (2006), CDF: Phys.Rev.D71 051103 (2005)

HQE Parameters and $|V_{cb}|$ – Extraction from Moments

Taking the above and spectra for E_γ (hep-ex/0508005), Belle fits a total of 71 truncated moments, theoretically described (up to $\mathcal{O}(1/m_b^3)$) by 7 parameters.

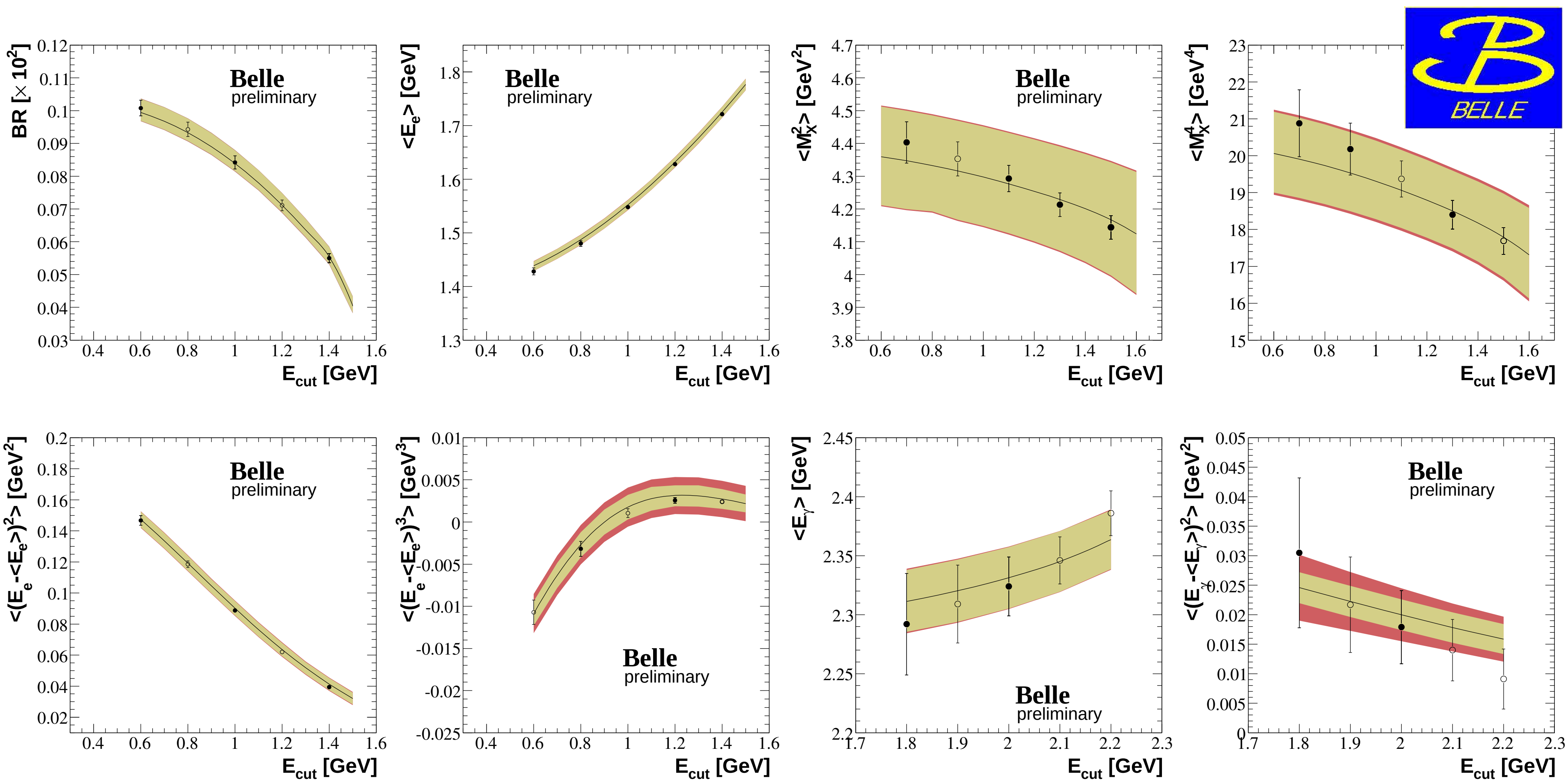
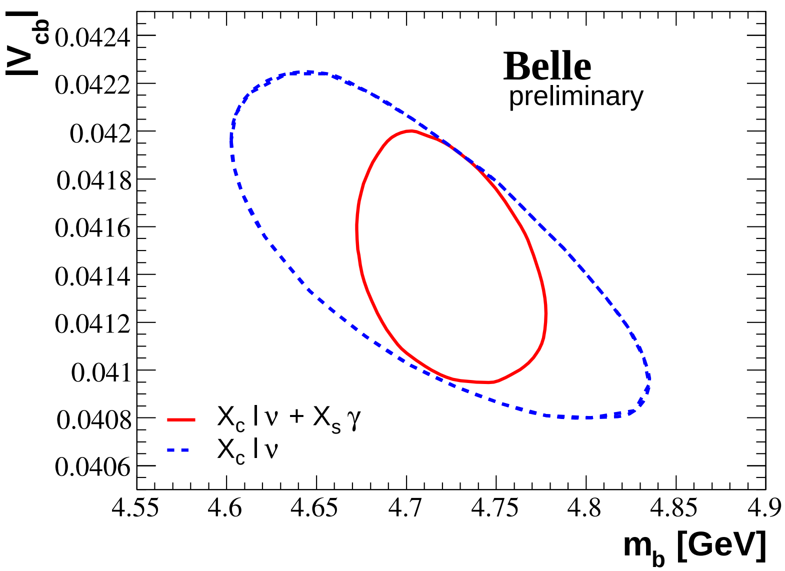


Illustration for 1S scheme hep-ex/06110747

HQE Parameters and $|V_{cb}|$ – Results

1S scheme

$$|V_{cb}| = (41.49 \pm 0.52_{fit} \pm 0.20_{\tau_B}) \cdot 10^{-3}$$
$$m_b^{1S} = (4.729 \pm 0.048)\,\mathrm{GeV}$$

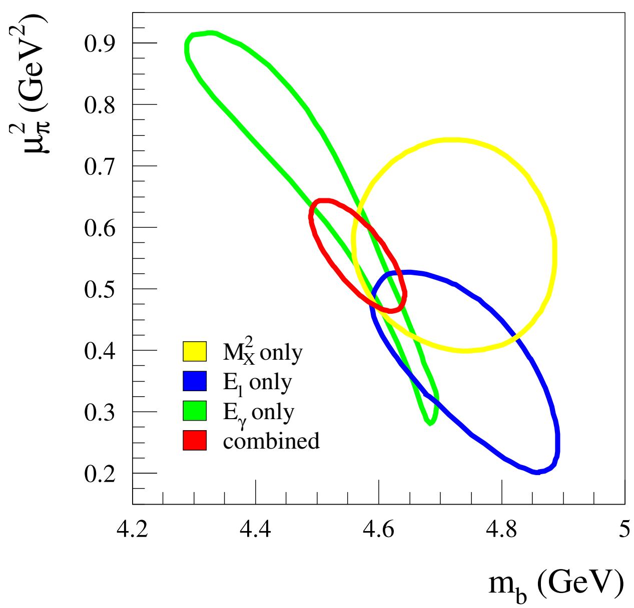


hep-ex/06110747

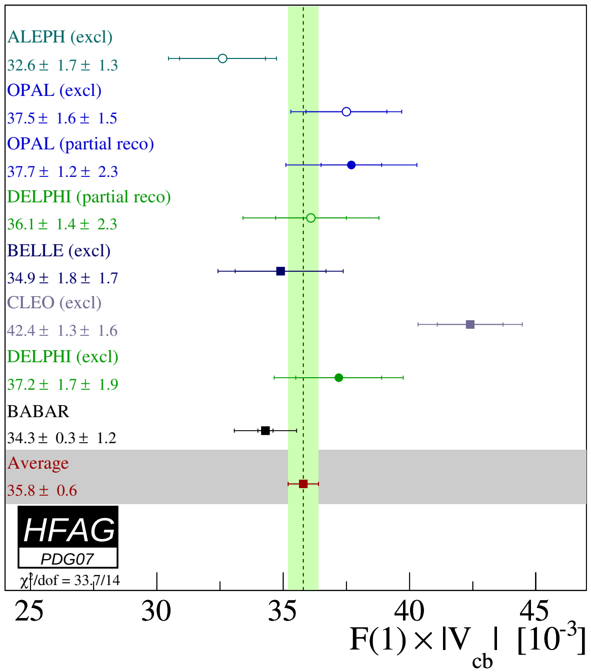
Good agreement to O.Buchmüller and H.Flächer
PRD 73, 073008 (2006)

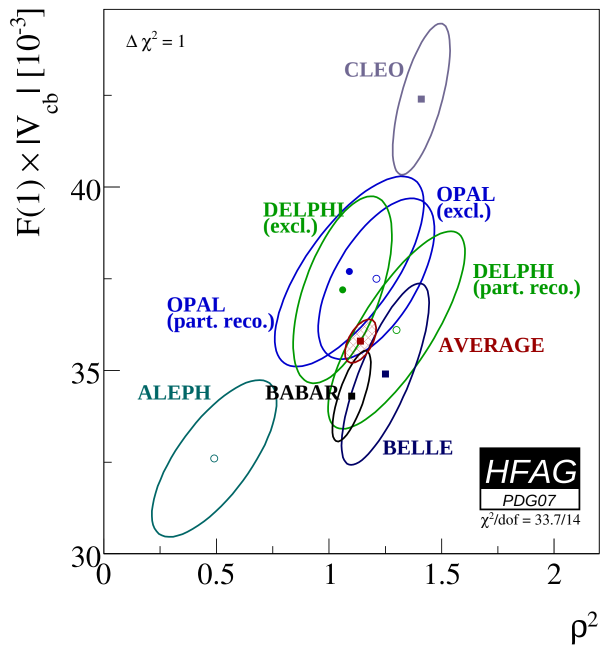
kinetic scheme

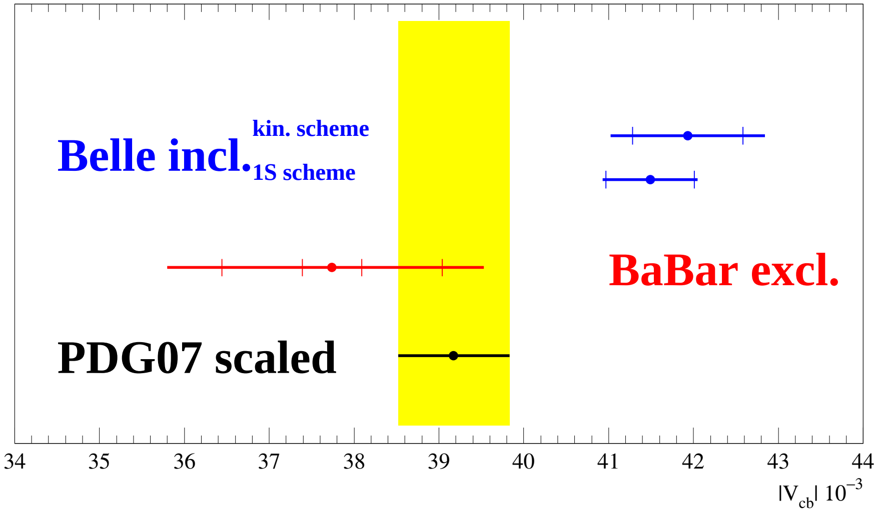
$$|V_{cb}| = (41.93 \pm 0.65_{fit} \pm 0.07_{\alpha_s} \pm 0.63_{theo}) \cdot 10^{-3}$$
$$m_b = (4.564 \pm 0.076_{fit} \pm 0.003_{\alpha_s})\,\mathrm{GeV}$$
$$m_c = (1.105 \pm 0.116_{fit} \pm 0.005_{\alpha_s})\,\mathrm{GeV}$$
$$\mathcal{B}_{c\ell\nu} = (10.590 \pm 0.164_{fit} \pm 0.006_{\alpha_s})\%$$

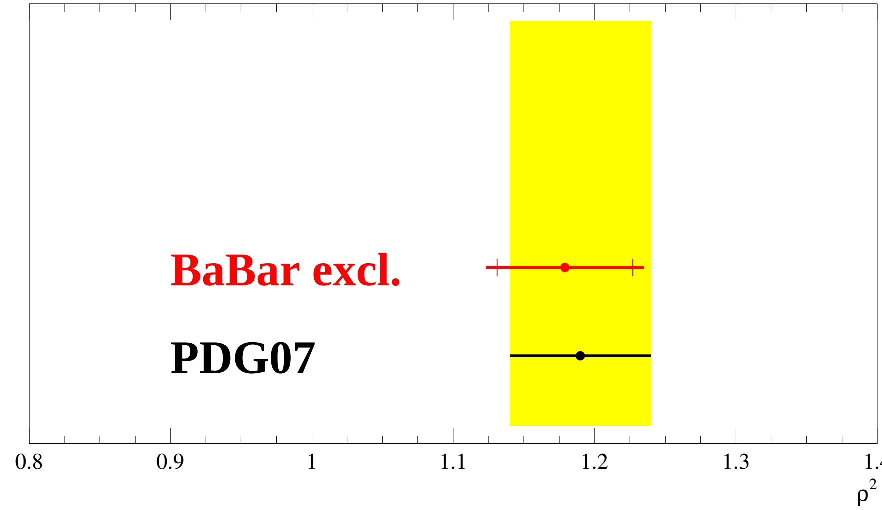


Summary on $|V_{cb}|$









Conclusion

Many improvements in understanding the inclusive semileptonic decay rate and filling it up with exclusive charm states

- Using the full availible datasets at the B Factories will further improve our knowledge, especially about exclusive decay modes
  e.g. isospin symmetry ...?
- Results from different data sets, experiments and methods converge
- $|V_{cb}|$ measured at a 2% level:
  - $|V_{cb}| = (41.49 \pm 0.52_{fit} \pm 0.20_{\tau_B}) \cdot 10^{-3}$ *incl. moments*
  - $|V_{cb}| = (37.74 \pm 0.35_{stat} \pm 1.25_{syst} \, {}^{+1.23}_{-1.44}{}_{theory}) \cdot 10^{-3}$ *excl. D^**

Backup

HQE Parameters and $|V_{cb}|$ – Fitted Parameters

1S scheme

$$
\begin{aligned}
|V_{cb}| &= (41.49 \pm 0.52_{fit} \pm 0.20_{\tau_B}) \cdot 10^{-3} \\
m_b^{1S} &= (4.729 \pm 0.048)\,\mathrm{GeV} \\
\Lambda &= m_\Upsilon(1\mathrm{S})/2 - m_b^{1S} \\
\lambda_1 &= (-0.30 \pm 0.04)\,\mathrm{GeV}^2 \\
\lambda_2 &= 0.1227 - 0.0145\lambda_1 \\
\tau_1, \tau_2, \tau_3, \rho_1 &: \text{combined to } m_\chi \text{ and } M_\chi \\
&\quad\ \text{of order } \Lambda_{QCD} \\
\rho_2 &= 0.1361 + \tau_2 \\
\tau_4 &= 0
\end{aligned}
$$

kinetic scheme

$$
\begin{aligned}
|V_{cb}| &= (41.93 \pm 0.65_{fit} \pm 0.07_{\alpha_s} \pm 0.63_{theo}) \cdot 10^{-3} \\
\mathcal{B}_{c\ell\nu} &= (10.590 \pm 0.164_{fit} \pm 0.006_{\alpha_s})\% \\
m_b &= (4.564 \pm 0.076_{fit} \pm 0.003_{\alpha_s})\,\mathrm{GeV} \\
m_c &= (1.105 \pm 0.116_{fit} \pm 0.005_{\alpha_s})\,\mathrm{GeV} \\
\mu_\pi^2 &= (0.557 \pm 0.091_{fit} \pm 0.013_{\alpha_s})\,\mathrm{GeV}^2 \\
\mu_G^2 &= (0.358 \pm 0.060_{fit} \pm 0.003_{\alpha_s})\,\mathrm{GeV}^2 \\
\tilde{\rho}_D^3 &= (0.162 \pm 0.053_{fit} \pm 0.008_{\alpha_s})\,\mathrm{GeV}^3 \\
\rho_{LS}^3 &= (-0.174 \pm 0.098_{fit} \pm 0.003_{\alpha_s})\,\mathrm{GeV}^3
\end{aligned}
$$

hep-ex/0611047

HQE Parameters and $|V_{cb}|$ – Kinetic Scheme

hep-ex/0611047

$$|V_{cb}| = (41.93 \pm 0.65_{fit} \pm 0.07_{\alpha_s} \pm 0.63_{theo}) \cdot 10^{-3}$$

$$\mathcal{B}_{c\ell\nu} = (10.590 \pm 0.164_{fit} \pm 0.006_{\alpha_s})\%$$

$$m_b = (4.564 \pm 0.076_{fit} \pm 0.003_{\alpha_s})\ \text{GeV}$$

$$m_c = (1.105 \pm 0.116_{fit} \pm 0.005_{\alpha_s})\ \text{GeV}$$

$$\mu_\pi^2 = (0.557 \pm 0.091_{fit} \pm 0.013_{\alpha_s})\ \text{GeV}^2$$

$$\mu_G^2 = (0.358 \pm 0.060_{fit} \pm 0.003_{\alpha_s})\ \text{GeV}^2$$

$$\tilde{\rho}_D^3 = (0.162 \pm 0.053_{fit} \pm 0.008_{\alpha_s})\ \text{GeV}^3$$

$$\rho_{LS}^3 = (-0.174 \pm 0.098_{fit} \pm 0.003_{\alpha_s})\ \text{GeV}^3$$

Buchmüller & Flächer

PRD73, 073008 (2006)

$$|V_{cb}| = (41.96 \pm 0.23_{fit} \pm 0.35_{HQE} \pm 0.59_{\Gamma_{SL}}) \cdot 10^{-3}$$

$$\mathcal{B}_{c\ell\nu} = (10.71 \pm 0.10_{fit} \pm 0.08_{HQE})\%$$

$$m_b = (4.590 \pm 0.025_{fit} \pm 0.030_{HQE})\ \text{GeV}$$

$$m_c = (1.142 \pm 0.037_{fit} \pm 0.045_{HQE})\ \text{GeV}$$

$$\mu_\pi^2 = (0.401 \pm 0.019_{fit} \pm 0.035_{HQE})\ \text{GeV}^2$$

$$\mu_G^2 = (0.297 \pm 0.024_{fit} \pm 0.046_{HQE})\ \text{GeV}^2$$

$$\rho_D^3 = (0.174 \pm 0.009_{fit} \pm 0.022_{HQE})\ \text{GeV}^3$$

$$\rho_{LS}^3 = (-0.183 \pm 0.054_{fit} \pm 0.071_{HQE})\ \text{GeV}^3$$