Study of the $B \to X_c l \nu$ Decays with BaBar Detector and Determination of $|V_{cb}|$

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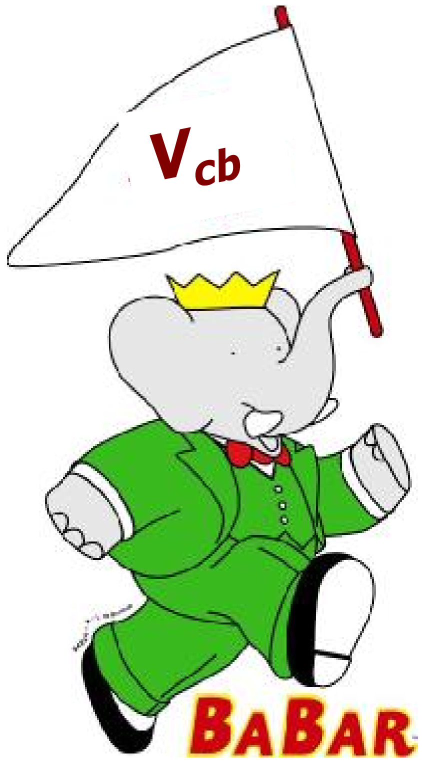


Inclusive $B \to X_c l \nu$ Decays

Moments of hadronic mass and lepton energy

PR D69,111103, PR D69,111104

HQE fits to energy dependence of moments

PRL 93, 011803

Exclusive $B \to D^{*+} l \nu$ Decays

Form Factors

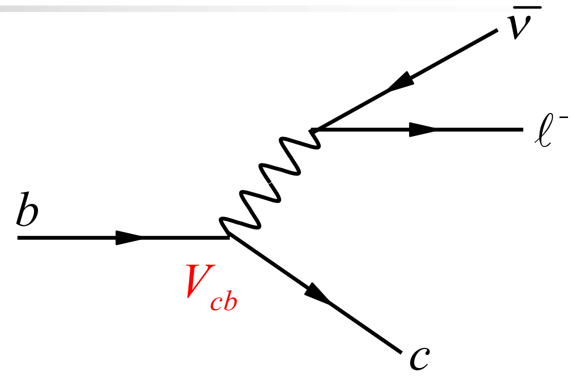
Extraction of $|V_{cb}|$ in the context of HQET

hep-ex/0408027, submitted to PRD

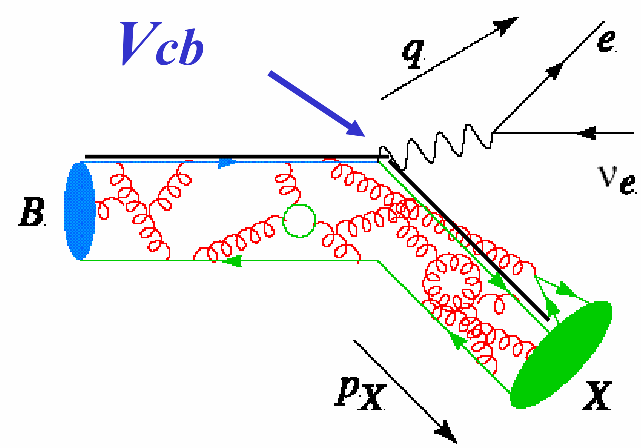
Semileptonic B Decay – Why are they Interesting

- Semileptonic decays
  - relatively simple theoretically at the parton level
  - rate depends on CKM elements $|V_{cb}|$ and the quark masses m_b and m_c

$$\Gamma(b \to c\ell\bar{\nu}) \propto |V_{cb}|^2 m_b^2 (m_b - m_c)^3$$



  - the leptonic current factors out cleanly, thus one can probe strong interactions in B mesons
  - sensitive to QCD corrections, OPE
  - accessible experimentally, the $B \to D^* l \nu$ has the largest single decay rate.



- A precise determination of |Vcb| with reliable errors important for
  - understanding B decay rates
  - testing of the unitarity of the CKM matrix and predictions of CP violation in B mesons

HQE Expansions

- Heavy Quark Expansions, tool to correct for QCD effects
  - Expansion in terms of $1/m_b$ and $\alpha_s(m_b)$
  - Separate short- and long-distance effects at $\mu \sim 1$ GeV
    - Perturbative corrections calculable from m_b m_c $\alpha_s(m_b)$
    - Non-perturbative parameters cannot be calculated

- We choose calculation by Gambino & Uraltsev **hep-ph/0401063 & 0403166**
  - Kinetic mass scheme to $O(1/m_b^3)$
  - E_ℓ moments $O(\alpha_s^2)$
  - m_X moments $O(\alpha_s)$

- 8 parameters to be fitted

$$|V_{cb}| \quad m_b \quad m_c \quad B(B \to X_c \ell \nu) \quad \mu_\pi^2 \quad \mu_G^2 \quad \rho_D^3 \quad \rho_{LS}^3$$

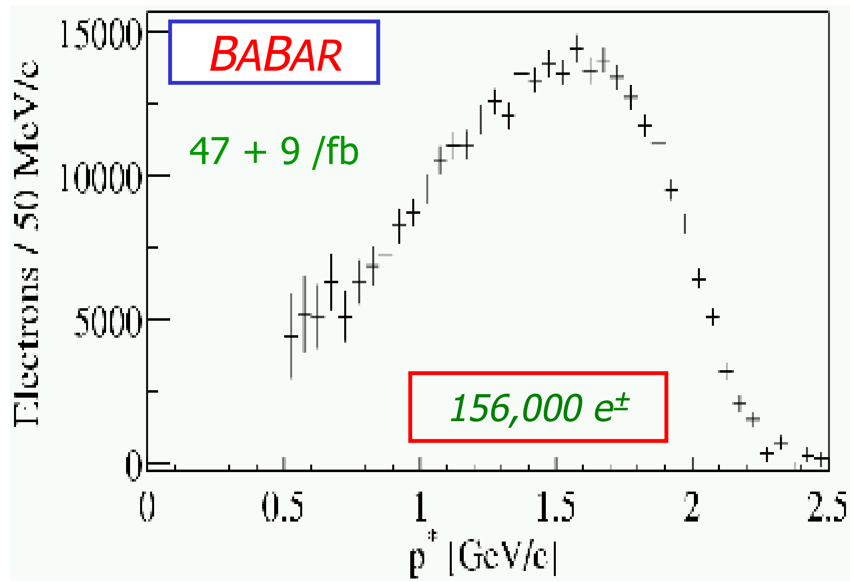
μ_π^2: kinetic; μ_G^2: chromomagnetic — $O(1/m_b^2)$

ρ_{LS}^3: spin-orbit; ρ_D^3: Darwin — $O(1/m_b^3)$

- Measure 8 moments, each as a function of minimum lepton energy E_l

Measurement of Electron Energy Moments

- Inclusive $e^{\pm}$ spectrum in 3×10^6 electron-tagged ($1.4<p^*<2.3$ GeV/c) $B\bar{B}$ events
  - *Corrected for detector effects*
  - *Corrected for non-prompt electrons*
    – lepton charge correlation and MC
  - *Corrected for $B^0 - \bar{B}^0$ mixing*



- Moments for E_{cut} = 0.6 … 1.5 GeV
  - *Corrected for the final state radiation*
  - *Translated to B rest frame*
  - *Subtracted $B \to X_u \ell \nu$ decays*

$$M_0^\ell = \frac{\int_{E_{cut}}^{\infty} d\Gamma}{\Gamma_B}$$

Partial BF

$$M_1^\ell = \frac{\int_{E_{cut}}^{\infty} E_\ell d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}$$

$$M_n^\ell = \frac{\int_{E_{cut}}^{\infty} (E_\ell - M_1^\ell)^n d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}, (n = 2, 3)$$

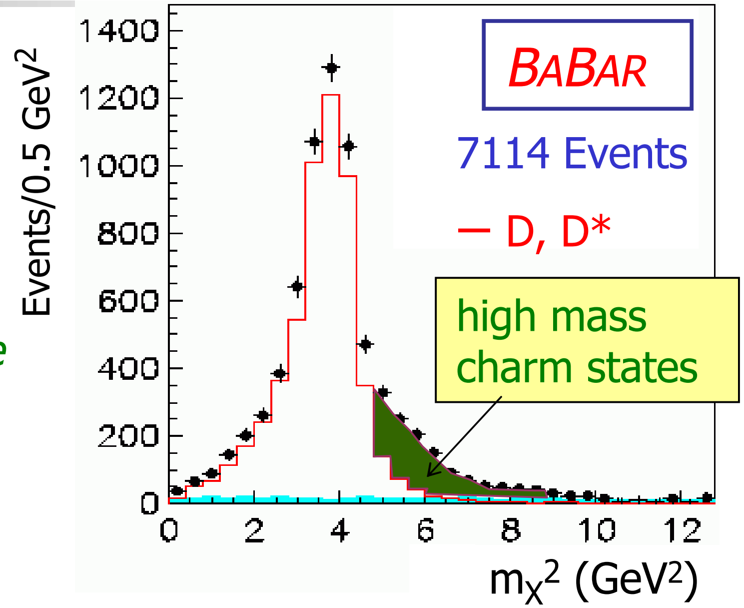
Lepton
Energy Moments

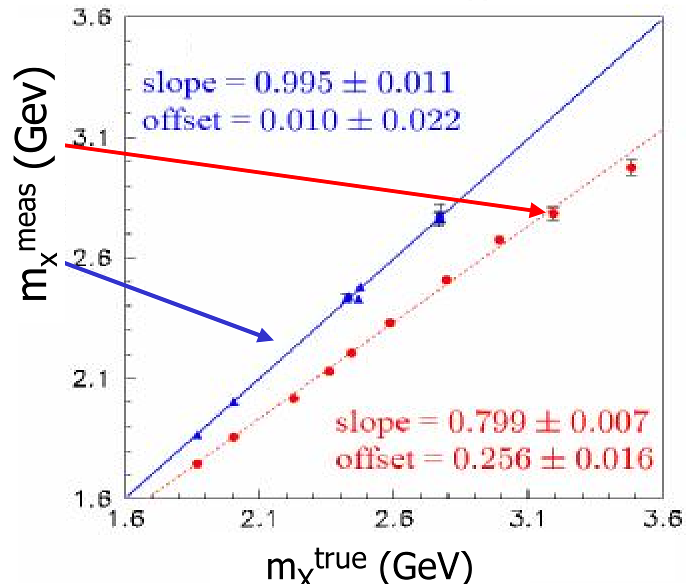
Measurement of Hadron Mass Moments

- $B\bar{B}$ events tagged by a fully reconstructed hadronic B decays
  - *$e^{\pm}$ or $\mu^{\pm}$ with $E_l > E_{cut}$ (0.9…1.6 GeV/c)*
  - *Lepton charge – B flavor correlation*
  - *Improve m_X measurement by kinematic fit to whole event, resolution ~350 MeV*
- To eliminate dependence of moments on uncertain BF and unknown masses of high mass charm mesons we calibrate m_X measurement
- Calibrate m_X based on MC simulation
  - *Linear relation between m_X^{meas} and m_X^{true}*
  - *Validate calibration with excl. $B \to D^{(*)} \ell \nu$*
- Moments corrected for detector effects and bkg

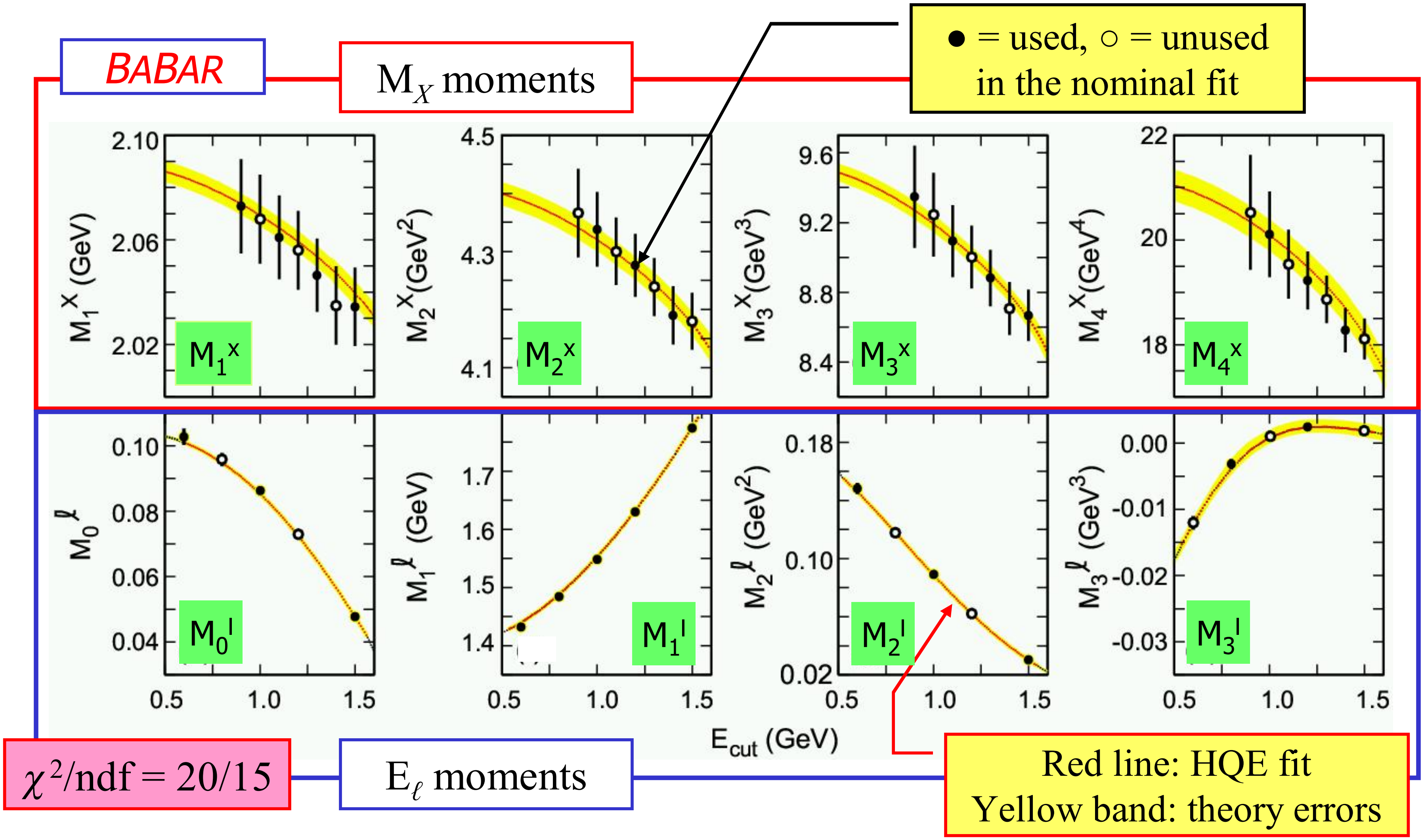
$$M_n^X = \frac{\int_{E>E_{cut}} m_X^n \, d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}, \ (n = 1, 2, 3, 4)$$

Hadron mass moments





HQE Fits to Hadron Mass and Lepton Energy Moments



HQE Fit Results (kinetic mass scheme, scale μ=1)

Uncalculated corrections to Γ

$$|V_{cb}| = (41.4 \pm 0.4_{\rm exp} \pm 0.4_{\rm HQE} \pm 0.6_{\rm th}) \times 10^{-3}$$

$$\mathcal{B}_{c\ell\nu} = (10.61 \pm 0.16_{\rm exp} \pm 0.06_{\rm HQE})\%$$

$$m_b = (4.61 \pm 0.05_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.02_{\alpha_s})\,\mathrm{GeV}$$

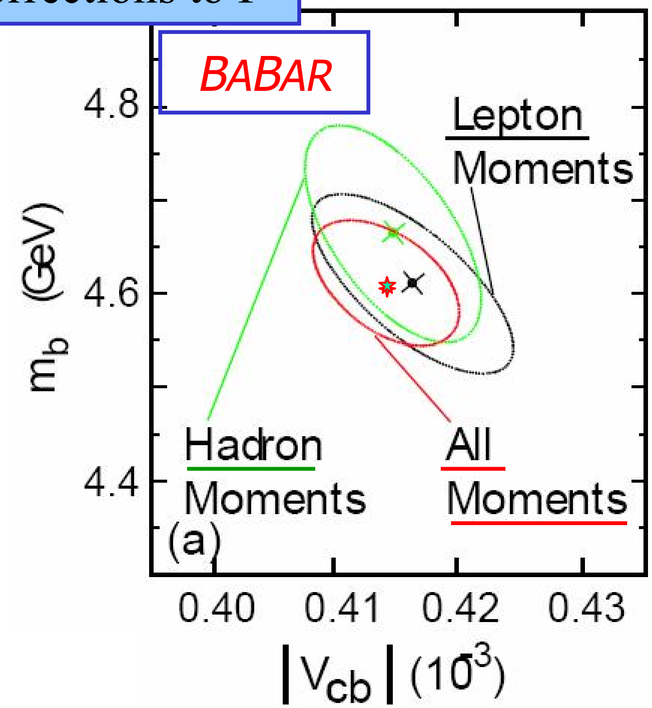
$$m_c = (1.18 \pm 0.07_{\rm exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\,\mathrm{GeV}$$

$$\mu_\pi^2 = (0.45 \pm 0.04_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.01_{\alpha_s})\,\mathrm{GeV}^2$$

$$\mu_G^2 = (0.27 \pm 0.06_{\rm exp} \pm 0.03_{\rm HQE} \pm 0.02_{\alpha_s})\,\mathrm{GeV}^2$$

$$\rho_D^3 = (0.20 \pm 0.02_{\rm exp} \pm 0.02_{\rm HQE} \pm 0.00_{\alpha_s})\,\mathrm{GeV}^3$$

$$\rho_{LS}^3 = (-0.09 \pm 0.04_{\rm exp} \pm 0.07_{\rm HQE} \pm 0.01_{\alpha_s})\,\mathrm{GeV}^3$$

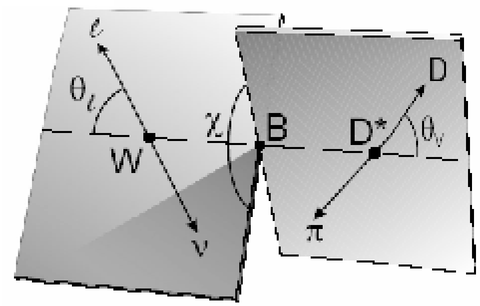


- Separate fits to hadron and lepton moments give consistent results
- μ_G^2 and ρ_{LS}^3 are consistent with B-B* mass splitting and HQ sum rules
- Considerable improvement in precision for $|V_{cb}|$ (±2%) and $B_{cl\nu}$ (1.6%) and quark masses (factor of 6), as well as HQE parameters

Decay Distributions for $B^0 \to D^{*-} l^+ \nu$

- Differential decay rate depends on 3 helicity amplitudes

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw \, d\cos\theta_\ell \, d\cos\theta_V \, d\chi} = \frac{6 G_F^2 |V_{cb}|^2 M_B M_{D^*}^2 r \sqrt{(w^2-1)}(1 - 2wr + r^2)}{8(4\pi)^4}$$



$$\Big\{ {H_+}^2 (1-\cos\theta_\ell)^2 \sin^2\theta_V + {H_-}^2 (1+\cos\theta_\ell)^2 \sin^2\theta_V$$
$$+4{H_0}^2 \sin^2\theta_\ell \cos^2\theta_V - 2H_+H_- \sin^2\theta_\ell \sin^2\theta_V \cos(2\chi)$$
$$-4H_+H_0 \sin\theta_l (1-\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi$$
$$+4H_-H_0 \sin\theta_l (1+\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi \Big\}$$

- Amplitudes H_i are expressed in terms of 3 form factors

$$A_2(w) = \frac{R_1(w)}{R^{*2}} \frac{2}{w+1} A_1(w) \qquad V(w) = \frac{R_2(w)}{R^{*2}} \frac{2}{w+1} A_1(w)$$

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

- Perfect HQ symmetry implies $R_1(w)=R_2(w)=1$, i.e. A_2 and V are identical
- $A_1(w)$ can be related to the Isgur-Wise function

$$h_{A_1}(w) = h_{A_1}(1) \left(1 - \rho^2 (w-1) + c(w-1)^2 + \ldots\right)$$

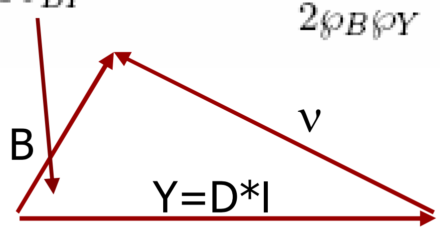
- Goal is to determine $R_1(w)$, $R_2(w)$, ρ^2, c:

  limited data: $R_1(w) = R_1(w=1)$, $R_2(w) = R_2(w=1)$, c=0

$B^0 \to D^{*-} l^+ \nu$ Background Subtraction

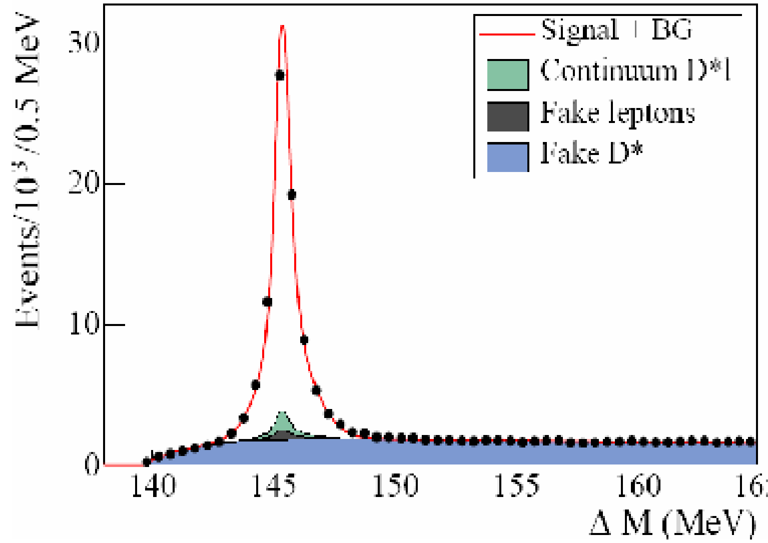
- Select: $D^{*-} l^+ \nu$: $e^\pm$, $\mu^\pm$ $1.2 < p^*_l < 2.4$ GeV/c
  $D^{*-} \to \overline{D}^0 \pi_S^-$, $\overline{D}^0 \to K^+ \pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$
- estimate bkg separately in 10 bins of w
  - Control data samples: $\Delta M = M(D^0 \pi_S) - M_D$
    - *Signal in $|\Delta M - 145.5\ \mathrm{MeV}| < 2.5$ MeV*
    - *Background contributes both to peak and sidebands*
  - MC simulated signal and bkg: $\cos\Theta_{BY}$
    - *assume missing particle in the decay is a neutrino.*

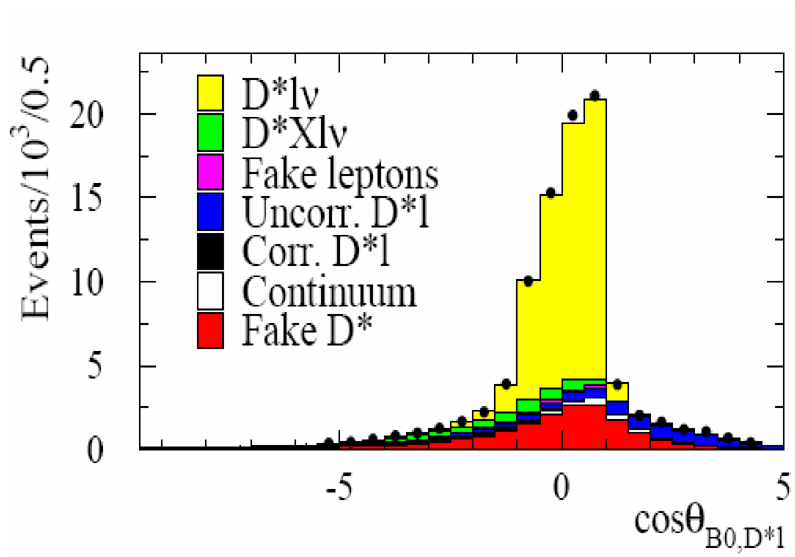
$$\cos\theta_{BY} = -\frac{M_B^2 + M_Y^2 - 2E_B E_Y}{2\wp_B \wp_Y}.$$



signal confined to $|\cos\Theta_{BY}| < 1.0$,

- *71k events, purity 76%*





Extraction of $|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$ Decays

- The decay rate integrated over angles is

$$\frac{d\Gamma}{dw} \propto \mathcal{G}(w)\mathcal{F}(w)^2|V_{cb}|^2,$$

G(w) phase space factor

F(w) form factor, predicted at w=1 or q^2_{max}

- extrapolate rate to w=1 and compare with HQET predictions.
- With the FF definition of Caprini, Lellouch, and Neubert **Nucl. Phys. B530, 153**

$$\mathcal{F}(w)^2\mathcal{G}(w) = h_{A_1}(w)^2\sqrt{w-1}(w+1)^2\left\{2\left[\frac{1-2wr+r^2}{(1-r)^2}\right]\right.$$
$$\left.\times\left(1+R_1(w)^2\frac{w-1}{w+1}\right)+\left[1+(1-R_2(w))\frac{w-1}{1-r}\right]^2\right\}$$

$$r = \frac{M_{D^{*+}}}{M_{\bar{B}^0}}$$

- and

$$R_1(w) \approx R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$

$$R_2(w) \approx R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

We use measurements by CLEO:
$R_1(1) = 1.18 \pm 0.32$
$R_2(1) = 0.71 \pm 0.23$

- with w dependence of the FF as function of single slope parameter ρ_{A1}^2

$$\frac{h_{A_1}(w)}{h_{A_1}(1)} \approx 1 - 8\rho^2_{A_1}z + (53\rho^2_{A_1} - 15)z^2 - (231\rho^2_{A_1} - 91)z^3$$

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

Extraction of $|V_{cb}|$ from w Distribution

- *Perform χ^2 fit to w distribution, with backgrou… estimated from ΔM and cos Θ_{BY} distributions*
- *Fit separately $e^{\pm}$ and $\mu^{\pm}$, and adjust efficiencies for data/MC variations*
- Results of the fit:

$$h_{A1}(1)|V_{cb}|=(35.5 \pm 0.3_{stat} \pm 1.6_{syst}) \times 10^{-3}$$
$$\rho_{A1}^2 = 1.29 \pm 0.03_{stat} \pm 0.27_{syst}$$

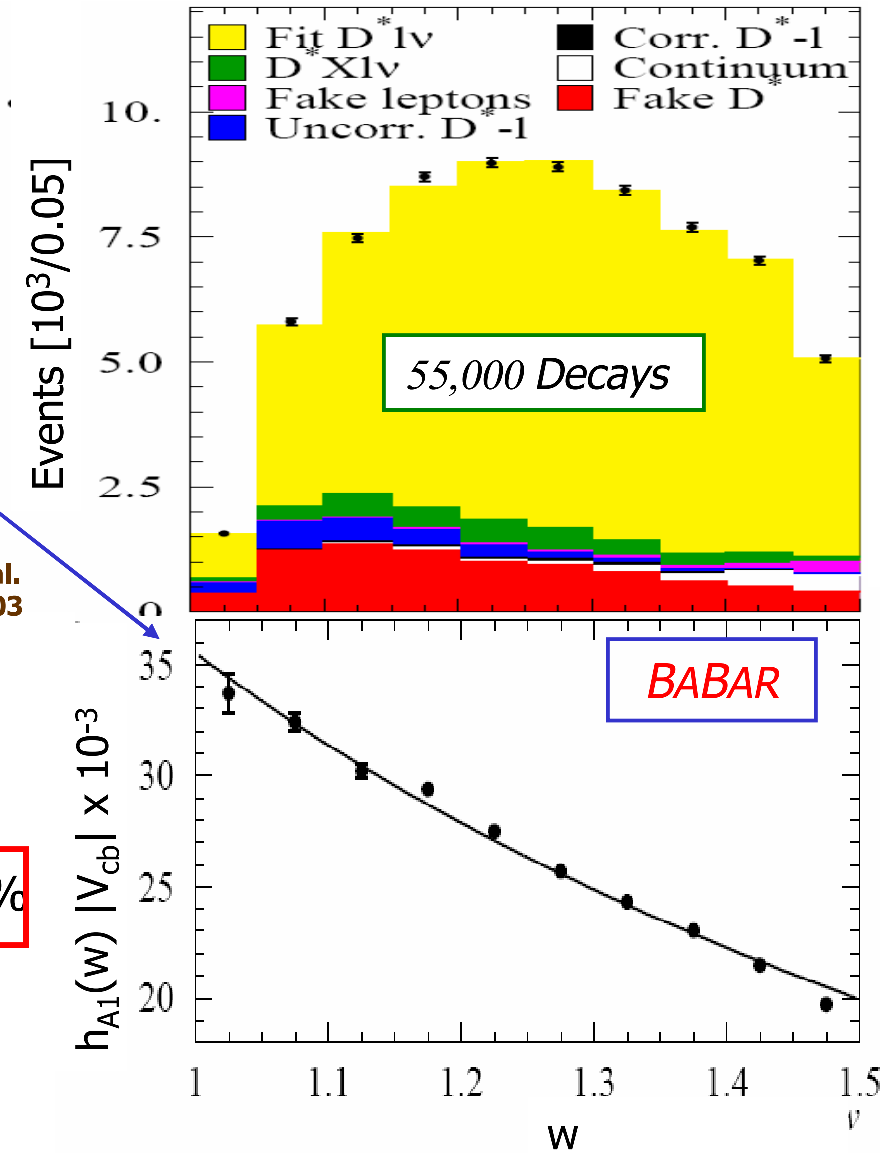
- With $h_{A1}(w=1) = 0.919^{+0.030}_{-0.035}$ **Hashimoto et al. PRD 66, 014503**

$$|V_{cb}| = (38.7 \pm 0.3_{stat} \pm 1.7_{syst} \pm^{1.5}_{1.3\,A_1}) \times 10^{-3}$$

- Branching fraction

$$\mathcal{B}(B^0 \to D^{*-} l^+ \nu) = 4.90 \pm 0.07_{stat} \pm 0.36_{syst})\%$$

- Syst. errors dominated by error on R_1, R_2



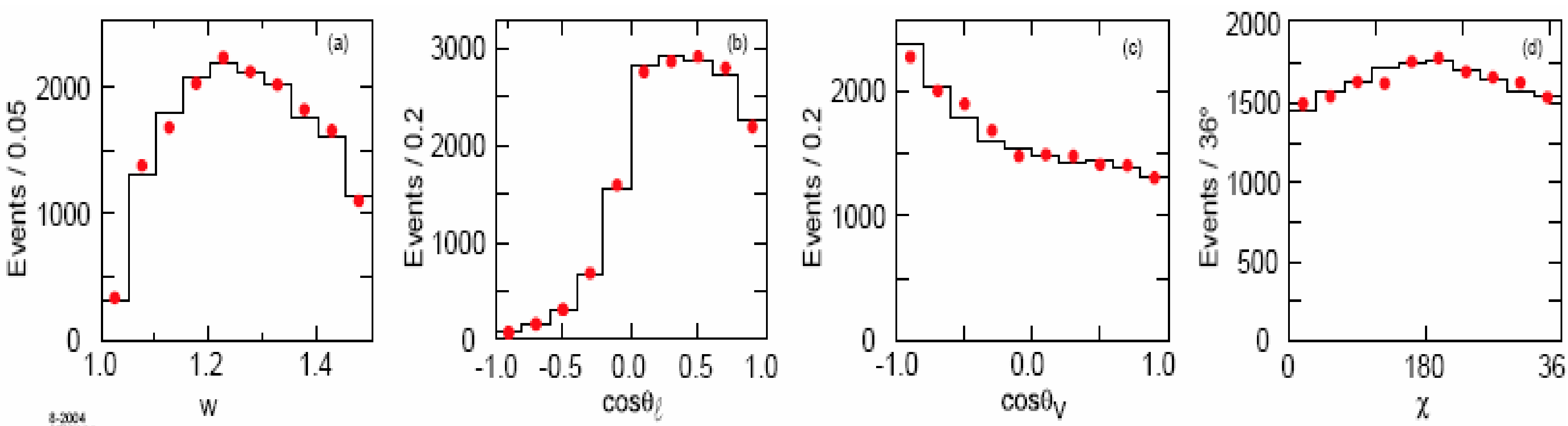
$B \to D^* l \nu$: Fit to Differential 4-dim. Cross Section

- Perform unbinned max. likelihood fit to 4-dim. cross sections
- Projections of fitted distributions

  Data restricted to: $e^{\pm}$, $D^0 \to K^- \pi^+$

***BABAR* Preliminary**

Dominant syst. uncertainties:
Background subtraction



- Preliminary Results

We assume: c=0.0; our results are also consistent with $R_1(w)$ and $R_2(w)$ parameterization by Caprini et al.

$R_1 = 1.328 \pm 0.060_{stat} \pm 0.025_{syst}$

$R_2 = 0.920 \pm 0.048_{stat} \pm 0.013_{syst}$

$\rho^2 = 0.769 \pm 0.043_{stat} \pm 0.032_{syst}$

$R_1 = 1.18 \pm 0.30 \pm 0.12$ **CLEO**

$R_2 = 0.71 \pm 0.22 \pm 0.07$ PRL 76 3898 (1996)

$\rho^2 = 0.91 \pm 0.15 \pm 0.06$

- stat. errors dominate (data &MC) – though improved by factor of 4 - 5

Conclusions

- Based on 80/fb, ~30% of the current BABAR data, we have made significant advances in the analysis of semileptonic B decays.
- HQE fits to moments hadronic mass and lepton energy moments yield

$$|V_{cb}| = (41.4 \pm 0.4_{\exp} \pm 0.4_{HQE} \pm 0.6_{theory}) \times 10^{-3}$$

$\mathcal{B}(B \rightarrow X_c l \nu) = (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\%$

Also high precision measurement of m_b and m_c, and exp. determination of HQE parameters.

- Analysis of $B \rightarrow D^{*-} l^+ \nu$ result in (still based on CLEO FF)

$$|V_{cb}| = (38.7 \pm 0.3_{stat} \pm 1.7_{syst} \pm^{1.5}_{1.3\, A_1}) \times 10^{-3}$$

$\mathcal{B}(B^0 \rightarrow D^{*-} l^+ \nu) = (4.90 \pm 0.07_{stat} \pm 0.36_{syst})\ \%$

The dominant errors remain the large uncertainties in R1 and R2.

Substituting the FF with the preliminary BABAR measurement we obtain

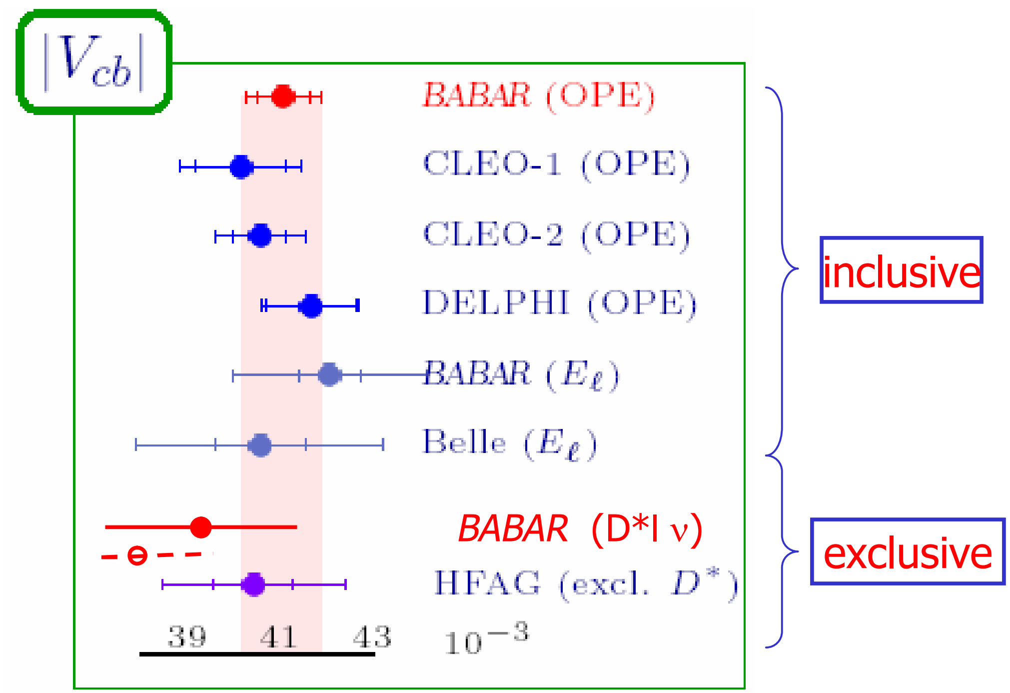
$$|V_{cb}| = (37.0 \pm 0.3_{stat} \pm 1.3_{syst} \pm^{1.5}_{1.3\ A_1}) \times 10^{-3}$$

The shift is due to change in acceptance (lepton spectrum) and w dependence, including some subtle differences in the definitions of the FF

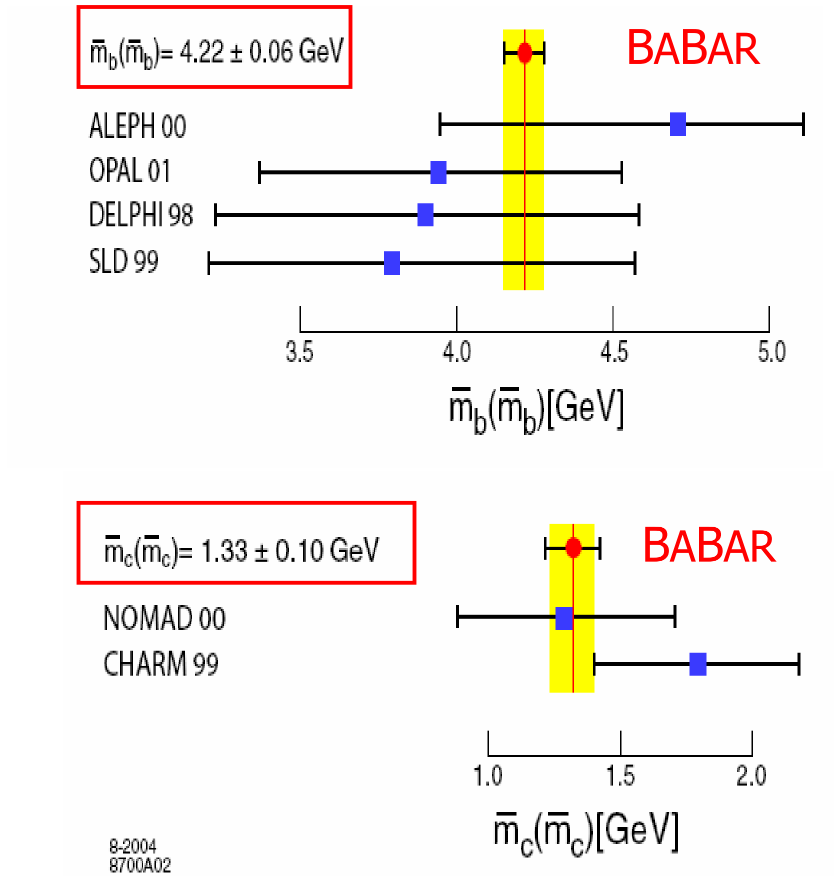
- Present experimental accuracy requires further increase of precision of theoretical calculations to realize its potential in determination of fundamental Standard Model parameters.

Summary of BABAR Results on $|V_{cb}|$

Recent Measurements of $|V_{cb}|$



Exp. Determination of Quark Masses



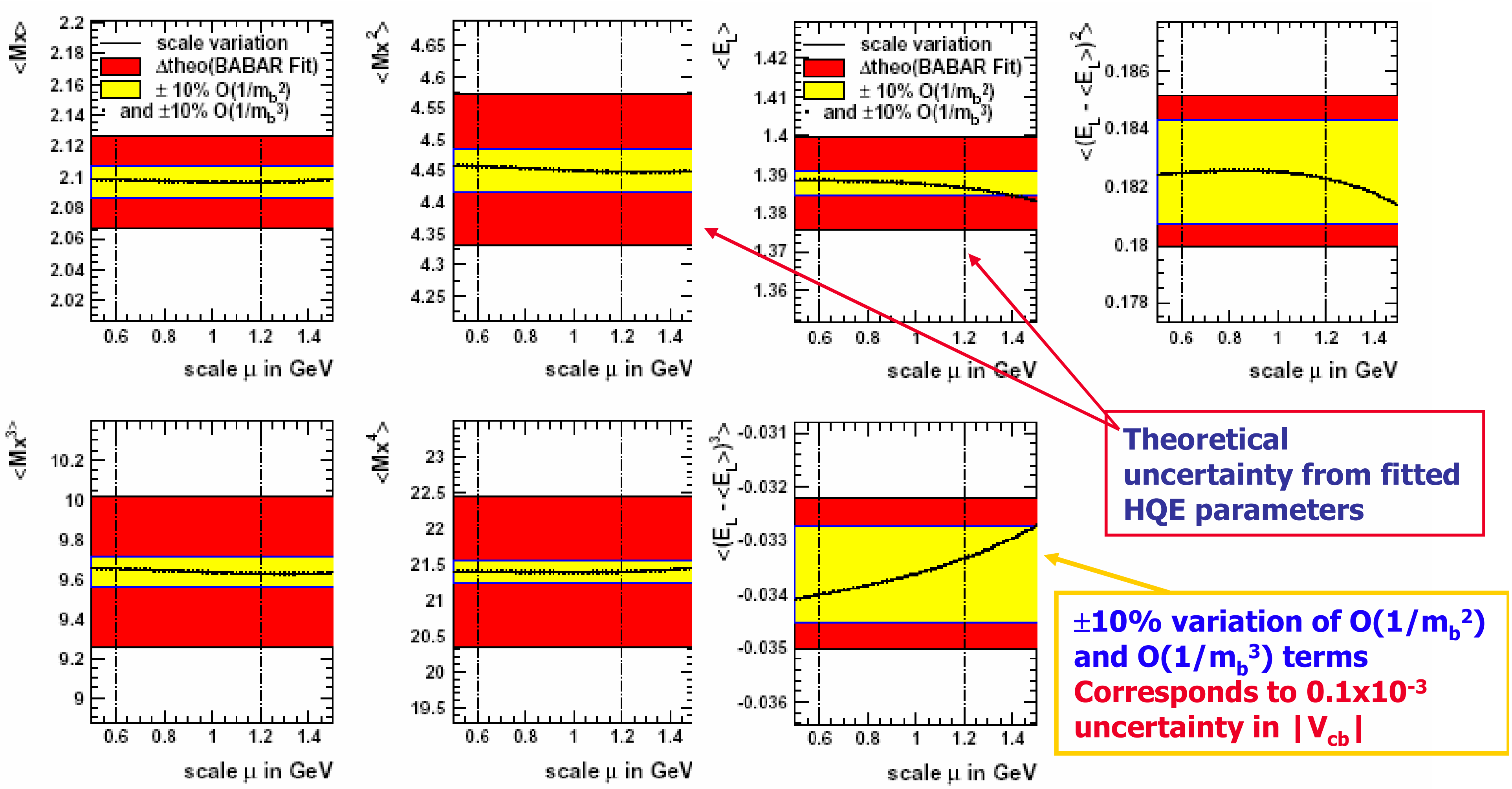
Conversion to MS scheme (N. Uraltsev)

Back-up Slides

*) Private communication: O. Buchmüller, P. Gambino, N. Uraltsev

Scale Dependence of HQE in the Kinetic Scheme

- Variation of the scale dependent HQE parameters simultaneously in the range μ=[0.5-1.5] GeV. (except c-quark mass μ=[0.6-1.2] GeV). *)

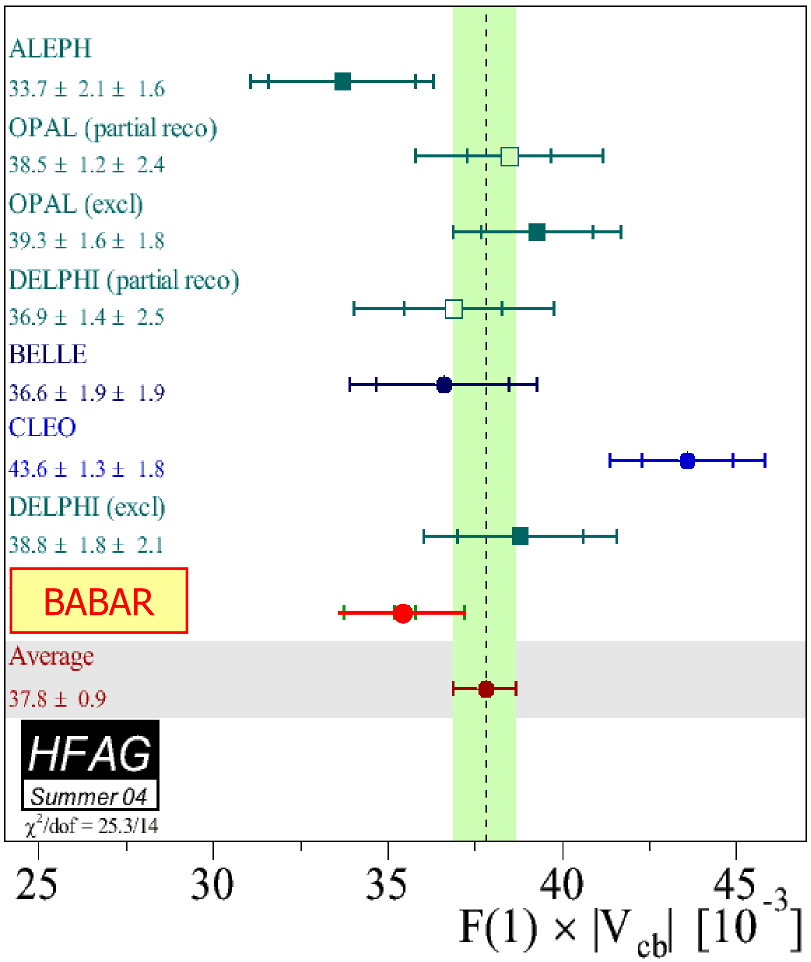


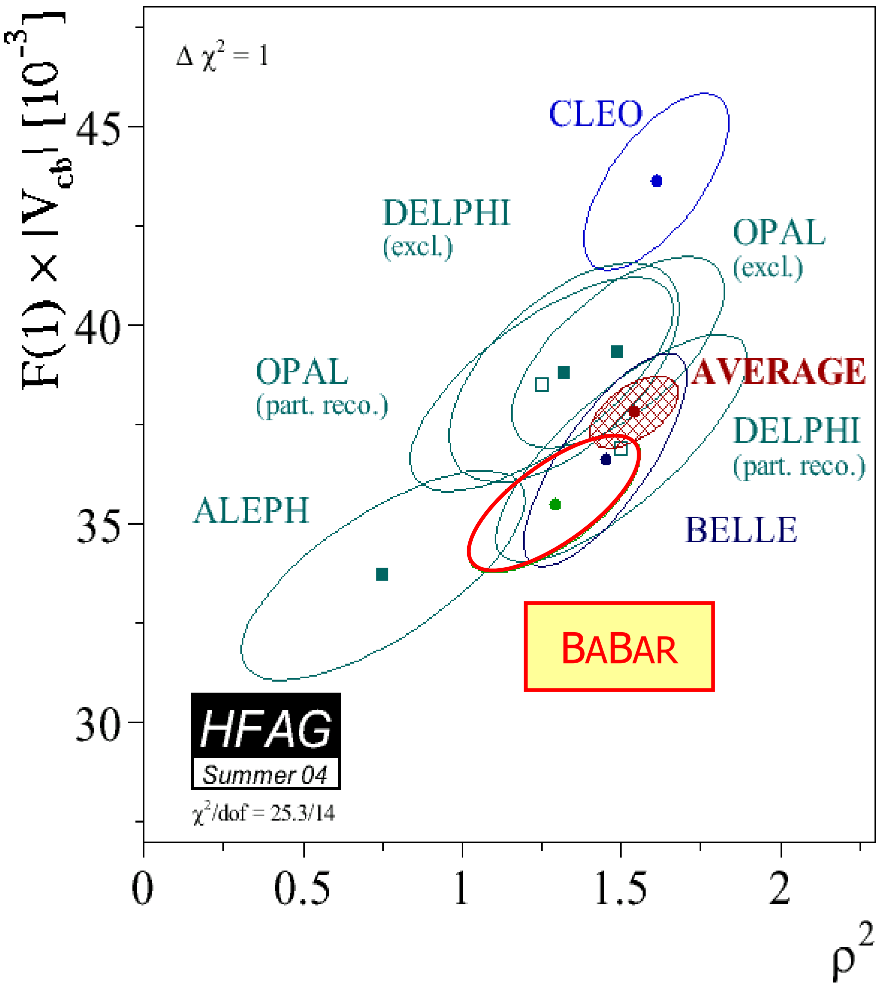
Scale Dependence of HQE in the Kinetic Scheme *

- The observed scale dependence of the predicted moments in the kinetic scheme is very small and even for scale variations in the range μ=[0.5-1.5] GeV (the default is μ=1GeV),
- the observed moment shifts are covered by an uncertainty of the $O(1/m_b^2)$ and $O(1/m_b^3)$ contributions of $\pm$10%.
- Such an uncertainty translates to an error on $|V_{cb}|$ of 0.1×10^{-3}, compared to the assigned theoretical error of $\Delta |V_{cb}|$ (theo-BABAR) $=0.7 \times 10^{-3}$.

*) private communication: O. Buchmüller, P. Gambino, N. Uraltsev

$|V_{cb}|$ Measurements based on $B \rightarrow D^* l \nu$ Decays





Back-up Slides