Determination of $|V_{cb}|$

and related results from *BABAR*

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on behalf of the BABAR Collaboration

$|V_{cb}|$ from inclusive B semileptonic decays

Lepton energy moments → HQE fit ← Hadron mass moments

$|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \to X_c \ell \nu)$, etc.

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Why $|V_{cb}|$ — and How

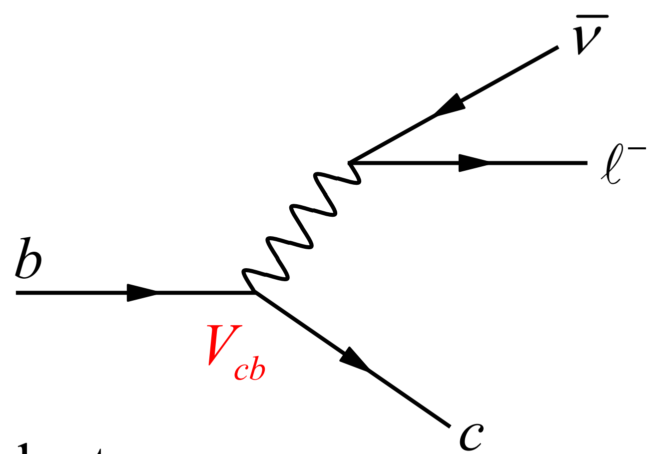
V_{cb} is the "mother of (almost) all B decays"

- Precise determination with reliable errors important for:
  - predicting B decay rates
  - testing unitarity of the CKM matrix

Semileptonic B decays offer best probe

- Leptonic current factors out cleanly
- Tree-level rate

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

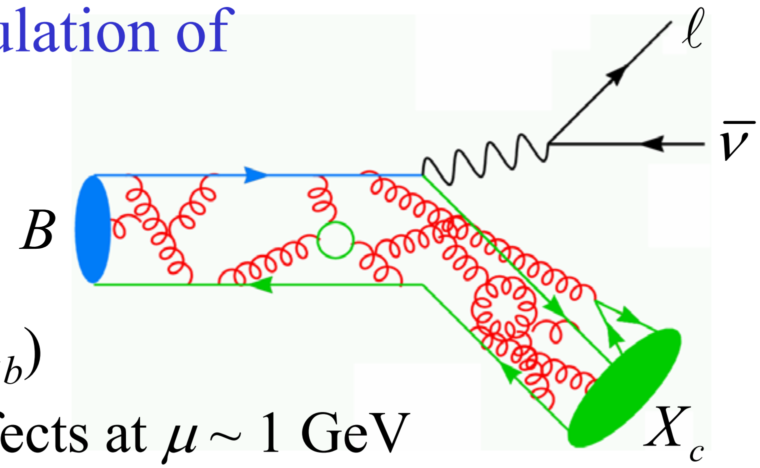


- QCD corrections relate this to the measured rates
  - Inclusive $\Gamma(B \to X_c \ell \nu)$
  - Exclusive $\Gamma(B \to D^* \ell \nu)$, $\Gamma(B \to D \ell \nu)$, etc.

Inclusive $|V_{cb}|$ Measurement

Heavy Quark Expansion allows calculation of

- Inclusive rate
- Lepton energy (E_ℓ) moments
- Hadron mass (m_X) moments



- 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 corrections cannot be calculated
    - Ex: 4 parameters up to $\mathcal{O}(1/m_b^3)$ in the kinetic scheme

Strategy: Measure rate + as many moments as possible

- Determine all parameters by a global fit
- Over-constrain to validate the method

Observables

Define 8 moments from inclusive E_ℓ and m_X spectra

$$M_0^\ell = \frac{\int d\Gamma}{\Gamma_B}$$

Partial branching fraction

$$M_1^\ell = \frac{\int E_\ell d\Gamma}{\int d\Gamma} \qquad M_i^\ell = \frac{\int \left(E_\ell - M_1^\ell\right)^i d\Gamma}{\int d\Gamma} \quad (i = 2,3)$$

Lepton energy moments

$$M_i^X = \frac{\int m_X^i d\Gamma}{\int d\Gamma} \quad (i = 1,2,3,4)$$

Hadron mass moments

- E_ℓ is measured in the B rest frame
- Integrations are done for $E_\ell > E_{cut}$, with E_{cut} varied in 0.6–1.5 GeV

hep-ex/0403030, to appear in PRD

Electron Energy Moments

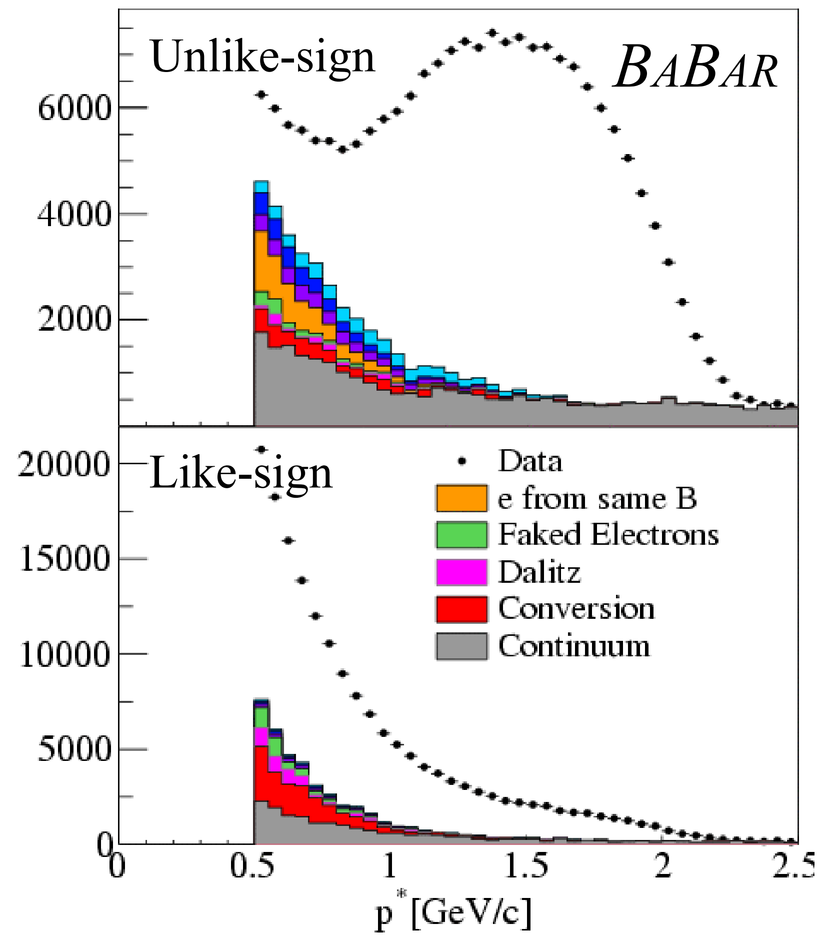
BABAR data, 47.4 fb^{-1} on $\Upsilon(4S)$ resonance + 9.1 fb^{-1} off-peak

Select events with 2 electrons

- One ($1.4 < p^* < 2.3$ GeV) to "tag" a $B\bar{B}$ event
- The other ($p^* > 0.5$ GeV) to measure the spectrum

Use charge correlation

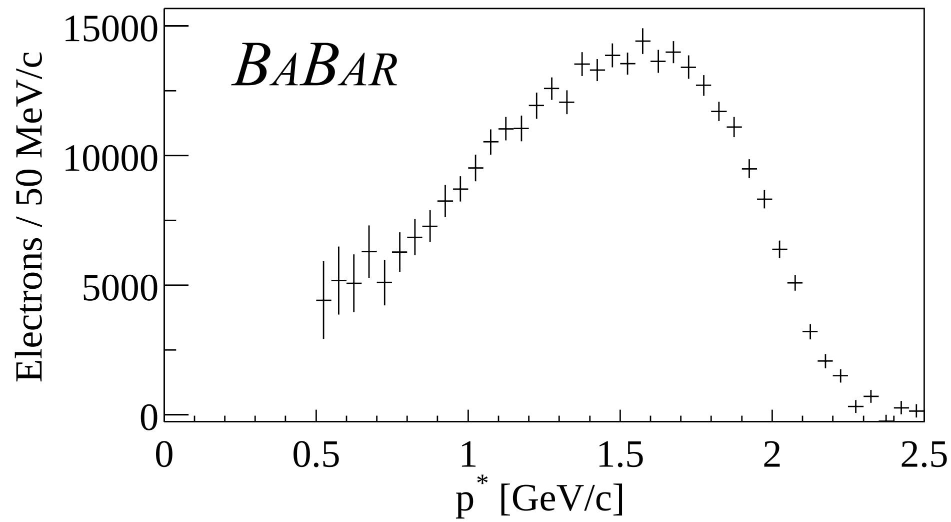
- Unlike-sign events
  - dominated by $B \to X_c e\nu$
- Like-sign events
  - $D \to Xe\nu$ decays, B^0 mixing



Electron Energy Moments

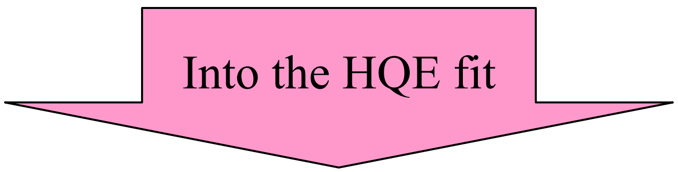
Turn the like-/unlike-sign spectra → E_ℓ spectrum

- Divide by the efficiency
- Account for B^0 mixing
- Correct for the detector material (Bremsstrahlung)



Calculate the moments for $E_{cut} = 0.6 \ldots 1.5$ GeV

- Move from Υ(4*S*) to *B* rest frame
- Correct for the final state radiation using PHOTOS
- Subtract $B \to X_u \ell \nu$



hep-ex/0403031, to appear in PRD

Hadron Mass Moments

BABAR data, 81 fb^{-1} on Υ(4*S*) resonance

Select events with a fully-reconstructed *B* meson

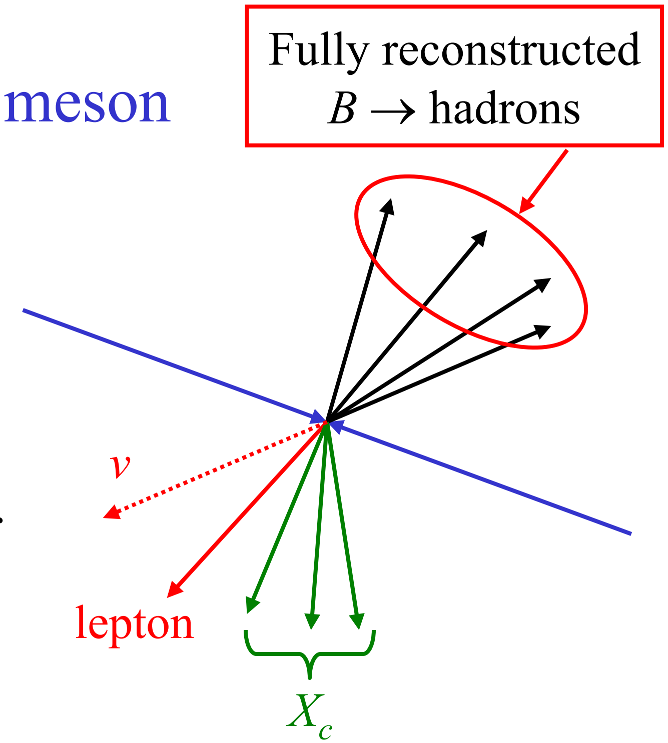
- Use ~1000 hadronic decay chains
- Rest of the event contains one "recoil" *B*
  - Flavor and momentum known

Find a lepton with $E > E_{cut}$ in the recoil-*B*

- Lepton charge consistent with the *B* flavor
- m_{miss} consistent with a neutrino

All left-over particles belong to X_c

- Improve m_X with a kinematic fit → $\sigma = 350$ MeV
  - 4-momentum conservation; equal m_B on both sides; $m_{\text{miss}} = 0$



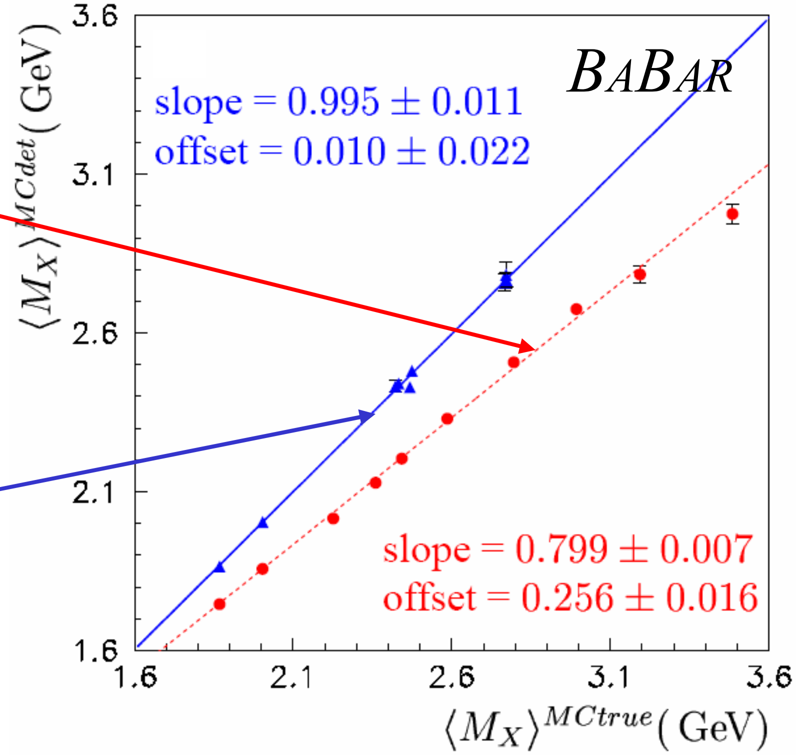
Hadron Mass Moments

Measured m_X < true m_X

- Linear relationship
  → Calibrate using simulation
  - Depends (weakly) on decay multiplicity and m^2_{miss}

Validate calibration procedure

- Simulated events in exclusive final states
- $D^{*\pm} \to D^0\pi^\pm$ in real data, tagged by the soft $\pi^\pm$



Calculate mass moments with E_{cut} = 0.9 … 1.6 GeV

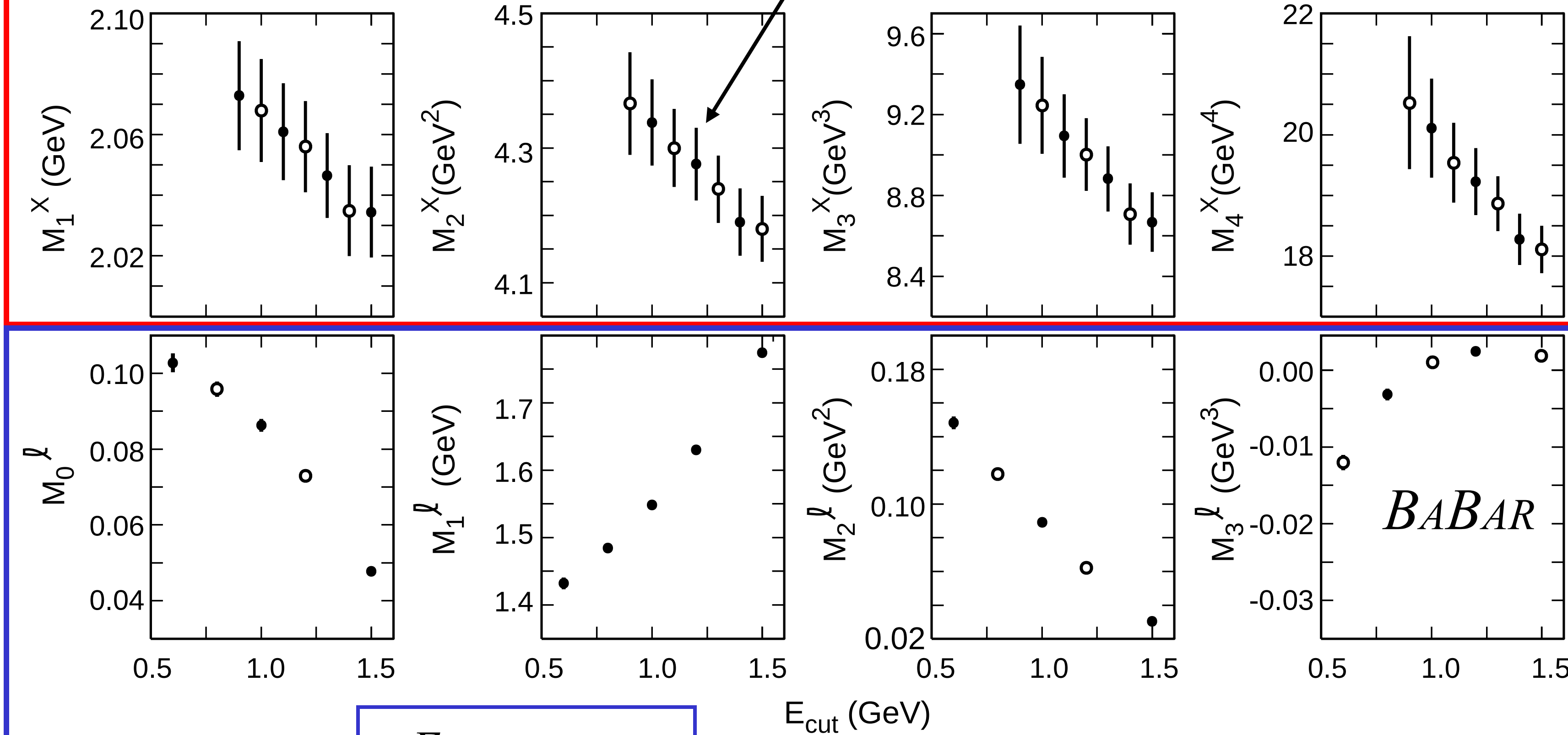
Into the HQE fit

hep-ex/0404017, to appear in PRL

Inputs to HQE Fit

Error bars are stat. & syst. with comparable sizes

m_X moments



E_ℓ moments

Systematic Errors

Dominant experimental systematic errors

- Electron energy moments
  - Tracking and electron ID efficiencies
  - Background from secondary leptons ($B \to D/D_s/\tau \to e$)
  - Bremsstrahlung correction
  - $B \to X_u \ell \nu$ subtraction
- Hadron mass moments
  - Detector efficiency and resolution
  - Background in fully-reconstructed B
  - Other background
    - Hadron mis-ID, $\tau^+\tau^-$, $B \to X_u \ell \nu$, secondary leptons

HQE Parameters

Calculation by Gambino & Uraltsev (hep-ph/0401063 & 0403166)

- Kinetic mass scheme to $\mathcal{O}(1/m_b^3)$
- E_ℓ moments $\mathcal{O}(\alpha_s^2)$
- m_X moments $\mathcal{O}(\alpha_s)$

8 parameters to determine

$|V_{cb}|$ m_b m_c $\mathcal{B}(B \to X_c \ell \nu)$ μ_π^2 μ_G^2 ρ_D^3 ρ_{LS}^3

kinetic, chromomagnetic } $\mathcal{O}(1/m_b^2)$

spin-orbit, Darwin } $\mathcal{O}(1/m_b^3)$

8 moments available with several E_{cut}

- Sufficient degrees of freedom to determine all parameters without external inputs
- Fit quality tells us how well HQE works

Fitting Method

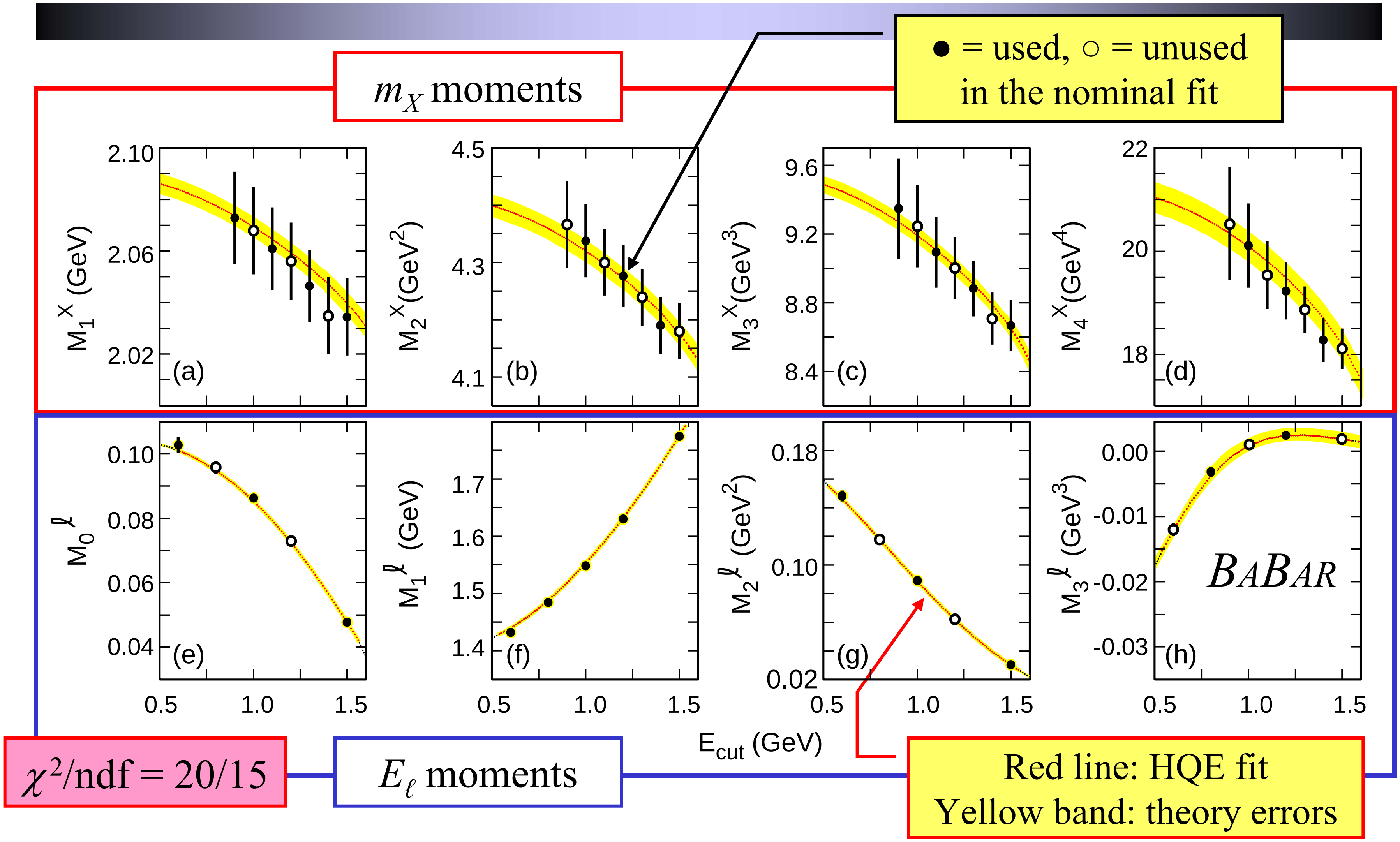
Use linearized expression for the HQE predictions

- Difference from fit using the full expression small

Data points (48 of them) are strongly correlated

- Each fit uses a subset in which all correlation coefficients are <95%
- Full error matrix for experimental errors (stat. and syst.)
- Theory errors: vary slopes of the linearized expressions
  - ±20% for the $\mathcal{O}(1/m_b^2)$ terms, ±30% for the $\mathcal{O}(1/m_b^3)$ terms
  - Fully correlated for each moment at different E_{cut}
  - Uncorrelated between different moments
- Fit results stable for different treatment of the theory errors

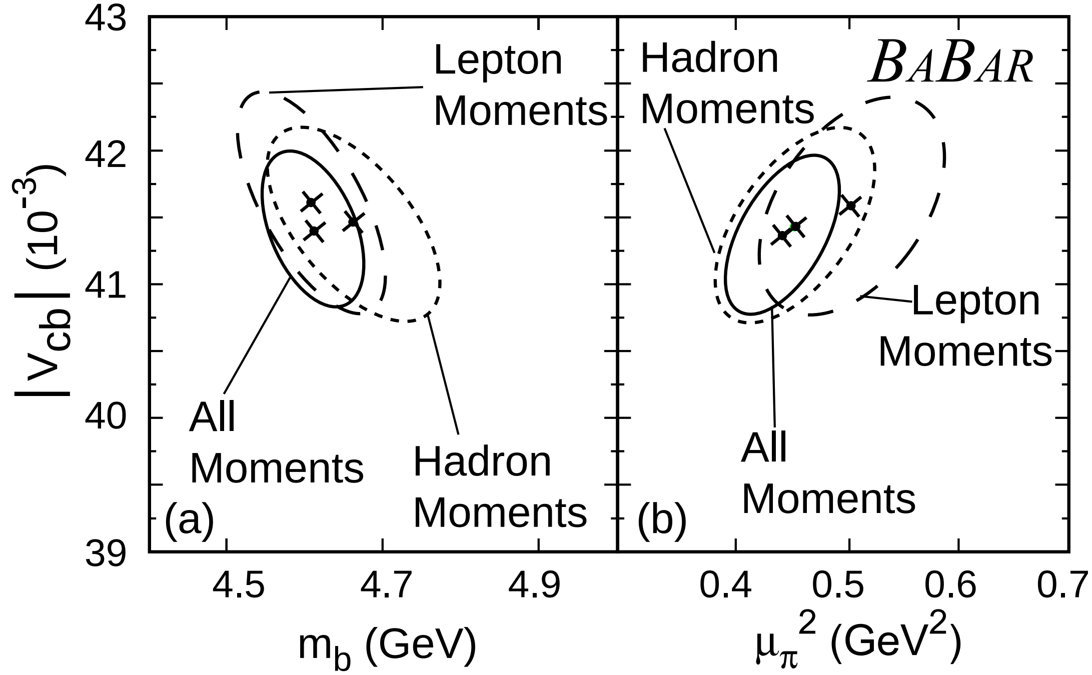
HQE Fit Results



HQE Fit Consistency

HQE describes BaBar data very well

- $\chi^2/\text{ndf} = 20/15$
- Separate fit of E_ℓ and m_X moments agree



HQE Fit Results

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

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

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

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

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

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

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

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

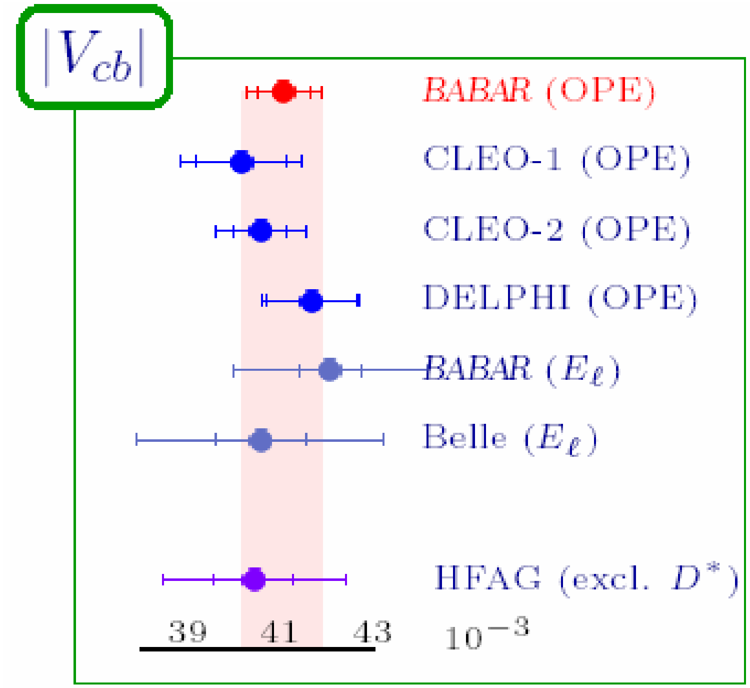
Uncalculated corrections to Γ

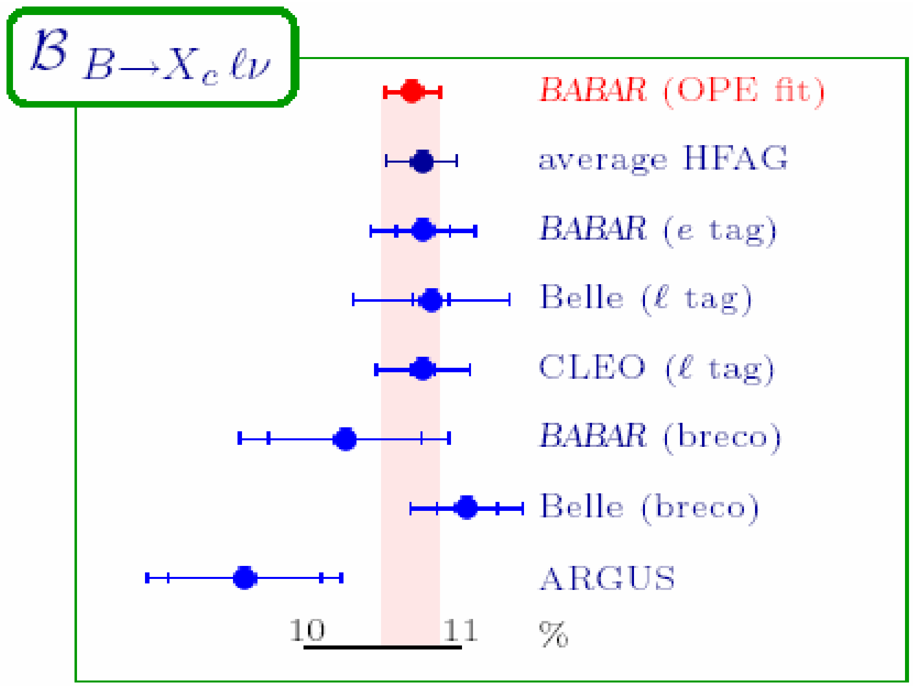
kinetic mass scheme with $\mu = 1$ GeV

- μ_π^2 and ρ_{LS}^3 consistent with B-B^* mass splitting and QCD sum rules

In Perspective

New BABAR result compares well with previous measurements





- $|V_{cb}|$ is now measured to ±2%

Heavy Quark Masses

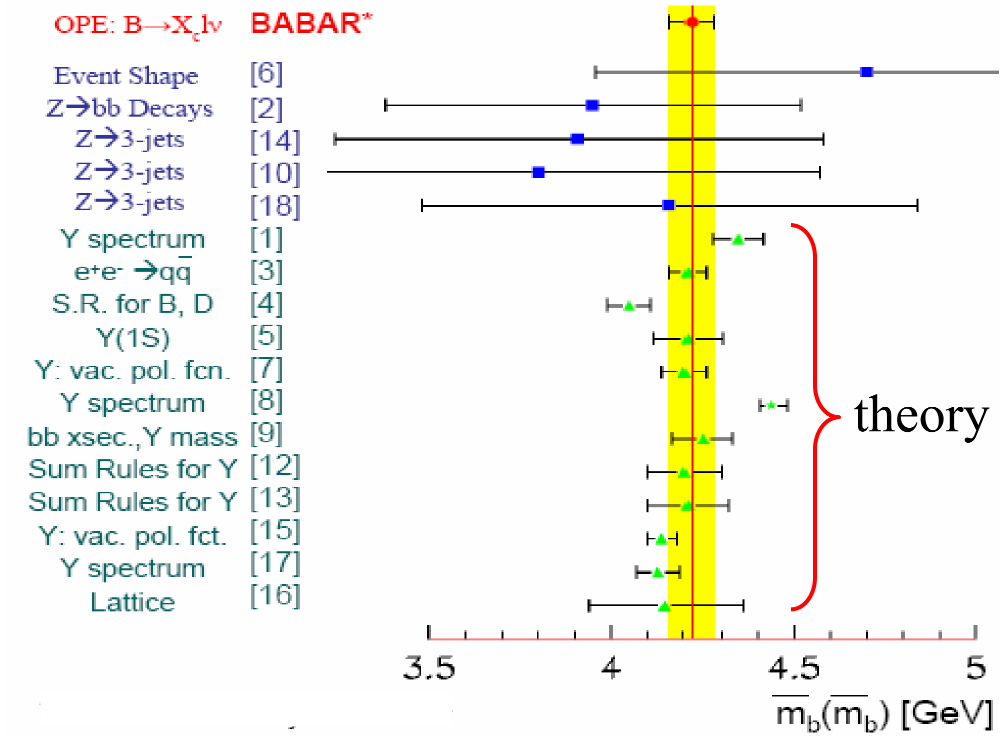
Convert m_b and m_c into $\overline{\mathrm{MS}}$ scheme (N. Uraltsev)

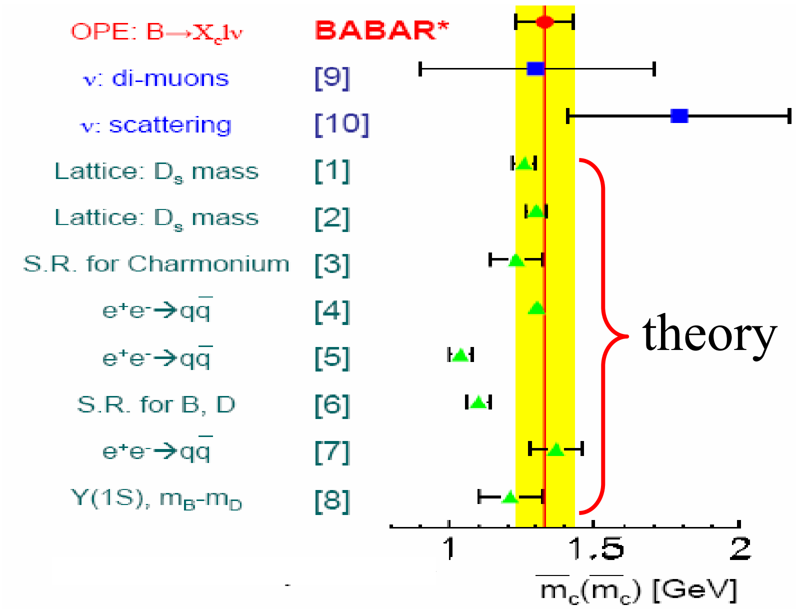
$$m_b^{\mathrm{kin}}(1\,\mathrm{GeV}) = (4.61 \pm 0.05_{\mathrm{exp}} \pm 0.04_{\mathrm{HQE}} \pm 0.02_{\mathrm{th}})\,\mathrm{GeV}$$

$$m_c^{\mathrm{kin}}(1\,\mathrm{GeV}) = (1.18 \pm 0.07_{\mathrm{exp}} \pm 0.06_{\mathrm{HQE}} \pm 0.02_{\mathrm{th}})\,\mathrm{GeV}$$

$$\bar{m}_b(\bar{m}_b) = 4.22 \pm 0.06\,\mathrm{GeV}$$

$$\bar{m}_c(\bar{m}_c) = 1.33 \pm 0.10\,\mathrm{GeV}$$





References in PDG 2002

Summary

BABAR has made significant progress in determination of $|V_{cb}|$

- HQE fit of E_ℓ and m_X moments → 2% error on $|V_{cb}|$

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

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

$$m_b^{\mathrm{kin}}(1\,\mathrm{GeV}) = (4.61 \pm 0.05_{\mathrm{exp}} \pm 0.04_{\mathrm{HQE}} \pm 0.02_{\alpha_s})\,\mathrm{GeV}$$

$$m_c^{\mathrm{kin}}(1\,\mathrm{GeV}) = (1.18 \pm 0.07_{\mathrm{exp}} \pm 0.06_{\mathrm{HQE}} \pm 0.02_{\alpha_s})\,\mathrm{GeV}$$

  - No external constraints on the non-perturbative parameters
  - Fit quality and consistency support validity of the HQE application

- It also determines m_b and m_c precisely

$$\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.06\,\mathrm{GeV}$$

$$\overline{m}_c(\overline{m}_c) = 1.33 \pm 0.10\,\mathrm{GeV}$$