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Inclusive Semileptonic B Decays at BABAR - $|V_{cb}|$ and Extraction of HQE Parameters

Henning Flächer (Royal Holloway)
on behalf of the BABAR Collaboration

Measurement of
- Hadronic Mass Moments
- Lepton Energy Moments

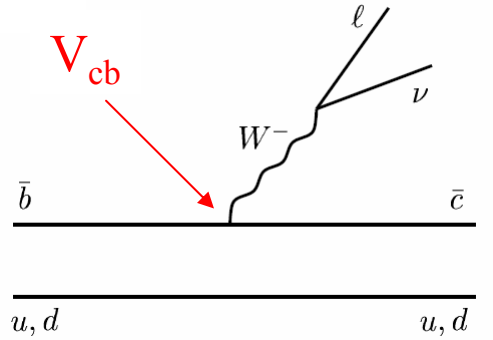
OPE Fit to Moments

**XXXIXth Rencontres de Moriond,
QCD and High Energy Hadronic Interactions**

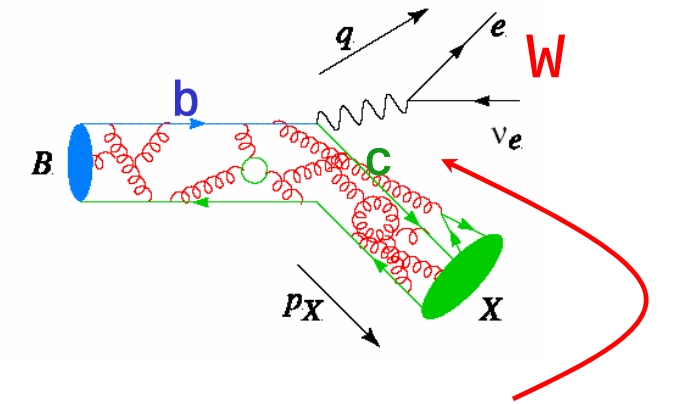
Motivation

Semileptonic B decays provide best access to $|V_{cb}|$.

Tree level:



But: b quark interacts with light degrees of freedom



No interaction between W →l ν and c-quark

- $\Gamma(B \to X_c l\nu) \alpha\ m_b^2(m_b-m_c)^3$
- Leptonic and hadronic currents factorise
- Hadronic matrix element has to be corrected for interactions with rest of B meson
- Expand in powers of $1/m_b$ in terms of local operators
- Expectation values of these operators are properties of the b quark within the B meson.

Theoretical Approach: Heavy Quark Expansion

- ***no local predictions for $d\Gamma/dE_e$ or $d\Gamma/dM_X$***
- ***but*** *transition rates* and *moments* of *inclusive* distributions can be reliably calculated with the help of Operator Product Expansions.

Inclusive Semileptonic B Decays

Heavy Quark Expansions

Heavy Quark Expansions connect the inclusive decay width to $|V_{cb}|$:

Γ_{SL} proportional to $|V_{cb}|^2$, but perturbative and non-perturbative corrections to free quark decay needed → double expansion in α_s and $1/m_b$

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

4 parameters at order α_s^2 and $1/m_b^3$

Non-perturbative parameters are not well known!

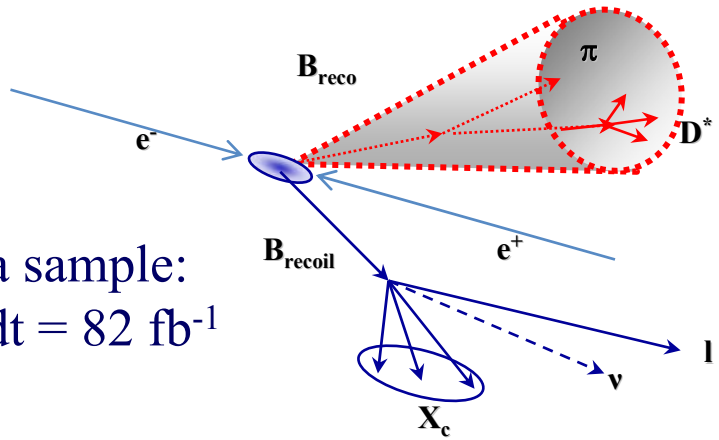
→ Use moments of inclusive distributions where same parameters appear!

$$< X^n > (E_{cut}) = \left. \frac{\int (X - X^0)^n \frac{d\Gamma}{dX} dX}{\int \frac{d\Gamma}{dX} dX} \right|_{E_l > E_{cut}} \cong f'_{OPE}(m_b, m_c, a_i)$$

- hadronic mass distribution $<M_X^n>$
- lepton energy spectrum $<E_l^n>$
  (with restrictions on the minimum lepton momentum!)
- Complimentary information from photon energy spectrum in b→sγ decays

Hadronic Mass Moments: Tagging

Analysis performed on the recoil of fully reconstructed hadronic B decays

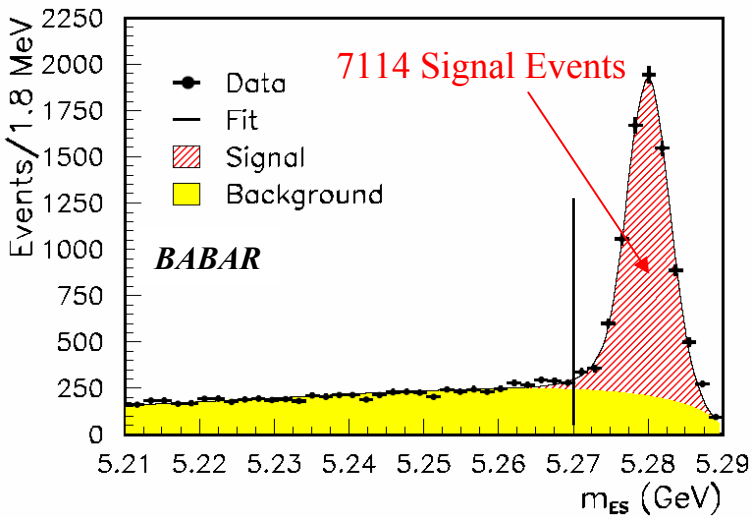


B_{reco} tag:

- **Semi-exclusive reconstruction of ≈ 1000 B decay chains**
- **Beam-energy substituted mass m_{ES} used for combinatorial background subtraction**

Data sample:
$\int L\,dt = 82\ fb^{-1}$

- B flavour known
- B four-momentum known
- reduced combinatorics
- m_{ES} sideband used for background subtraction
- limited statistics



m_{ES}

Hadronic Mass Moments: $B \to X_c l \nu$

$B \to X_c l \nu$ signal:

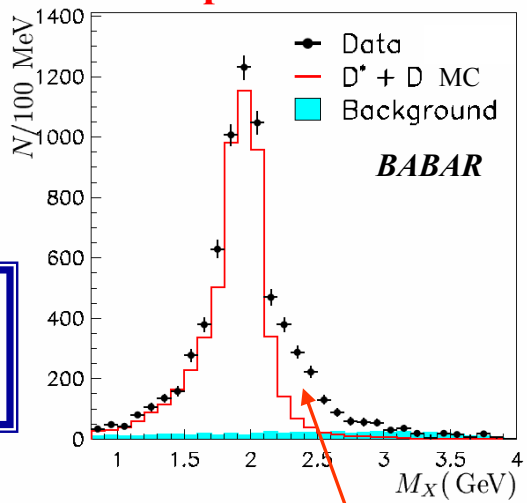
- require exactly one lepton (e or μ) with momentum p* in B rest frame > p^*_{min}
- lepton charge consistent with prompt B decay
- missing energy and missing momentum consistent with neutrino

Kinematic fit to the whole event results in improved M_X resolution

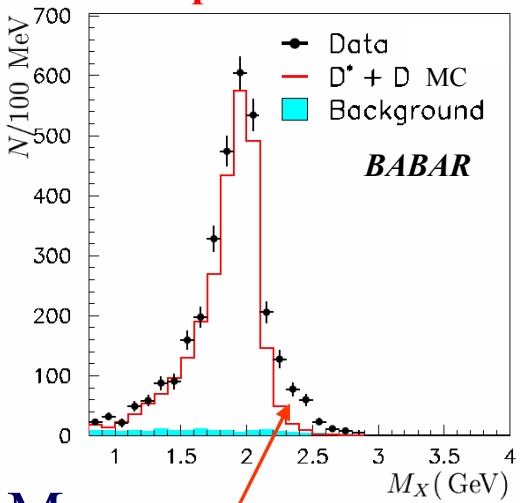
$\sigma(M_X) \approx 350$ MeV

Reconstruction of all kinematic quantities in rest frame of B meson

p* > 0.9 GeV



p* > 1.6 GeV



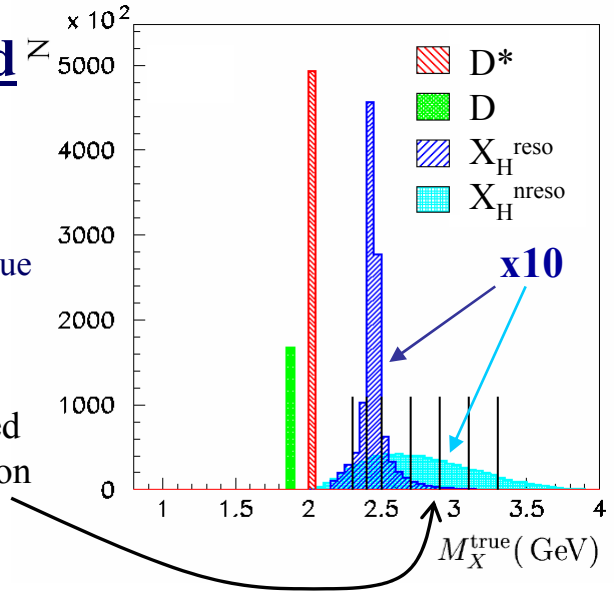
M_X

- **Measure moments of mass spectrum as function of minimum lepton momentum p***
- **Increasing contributions from high mass final states for lower lepton momenta**

Hadronic Mass Moments: Calibration via MC

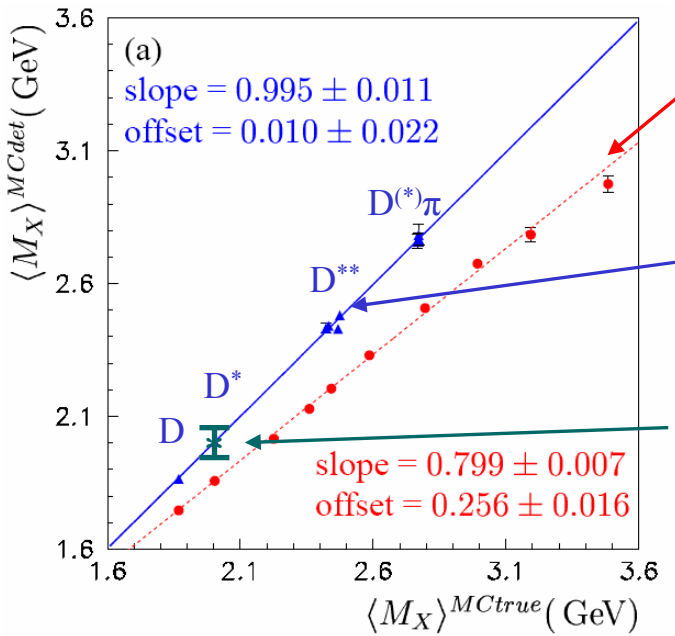
Measured mass spectrum needs to be corrected for detector resolution and efficiency losses

- Exploit observed linear relations between measured and generated masses in bins of M_X^{true}
- Calibrate on an event-by-event basis



binning used for calibration

Very little dependence on branching fractions and modelling of high mass final states!



Calibration curve derived with mix of final states

verified by mean masses of exclusive final states after calibration

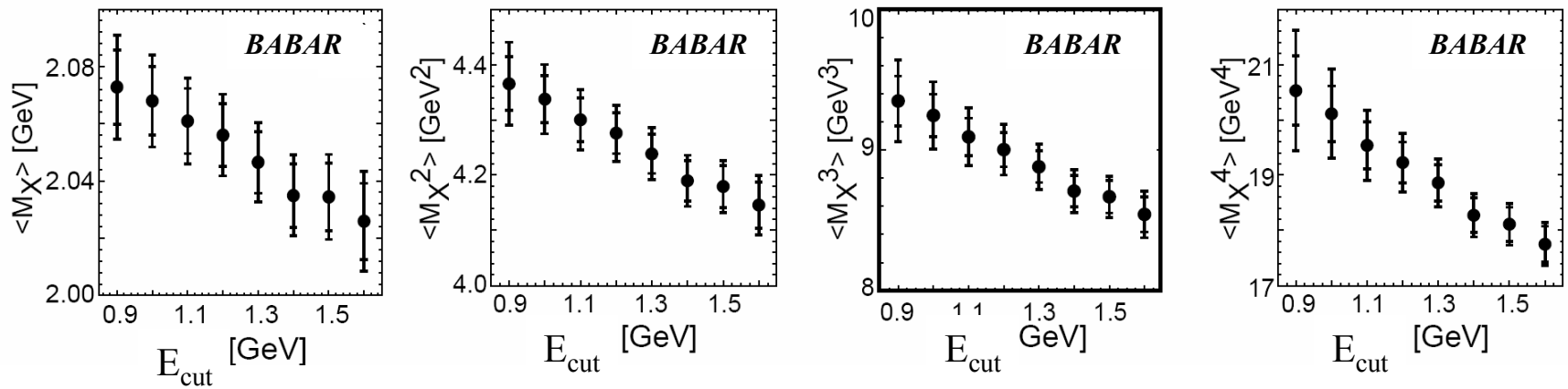
Validated on DATA sample of partially reconstructed $B \rightarrow D^{*\pm} l\nu$ ($D^{*\pm} \rightarrow D^0\pi^\pm$) decays

Main uncertainties:
- Detector Response
- Background Subtraction

Hadronic Mass Moments: Results for $\langle M_X^n \rangle$

Moments $\langle M_X^n \rangle$ (n=1,…4) of the hadronic mass spectrum in $B \to X_c l \nu$ decays for 0.9 GeV < E_{cut} < 1.6 GeV

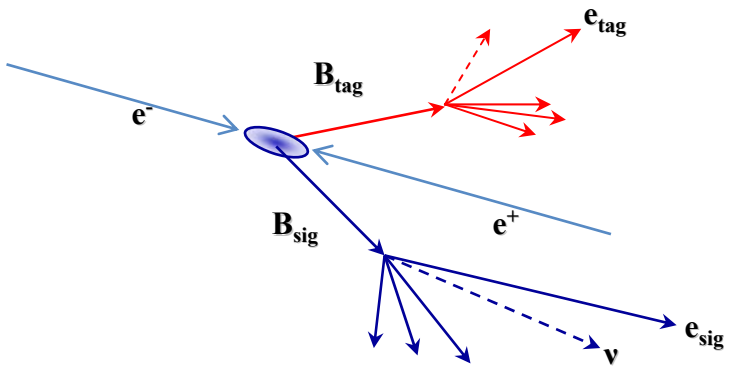
- Clear dependence on E_{cut} of lepton.
- Comparable statistical and systematic errors.
- Individual measurements are highly correlated!



To be submitted to Phys. Rev. D: hep-ex/0403031

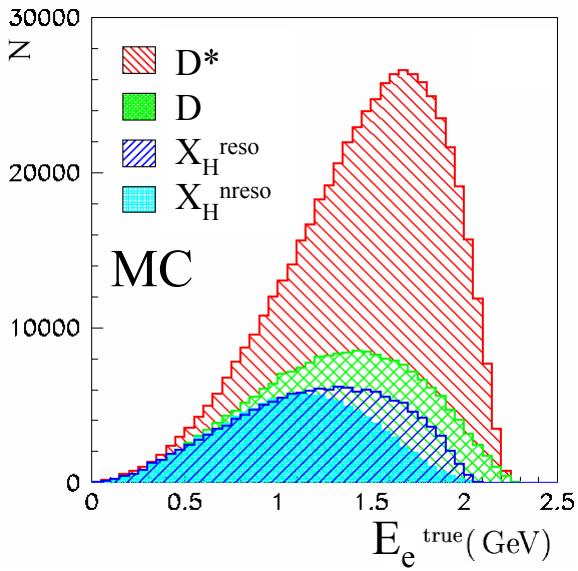
Lepton Energy Spectrum & Moments

- Tag events with high energetic electron ($p^* > 1.4$ GeV in Y(4S) frame)
- Look for second electron in the event ($p^* > 0.5$ GeV in Y(4S) frame)

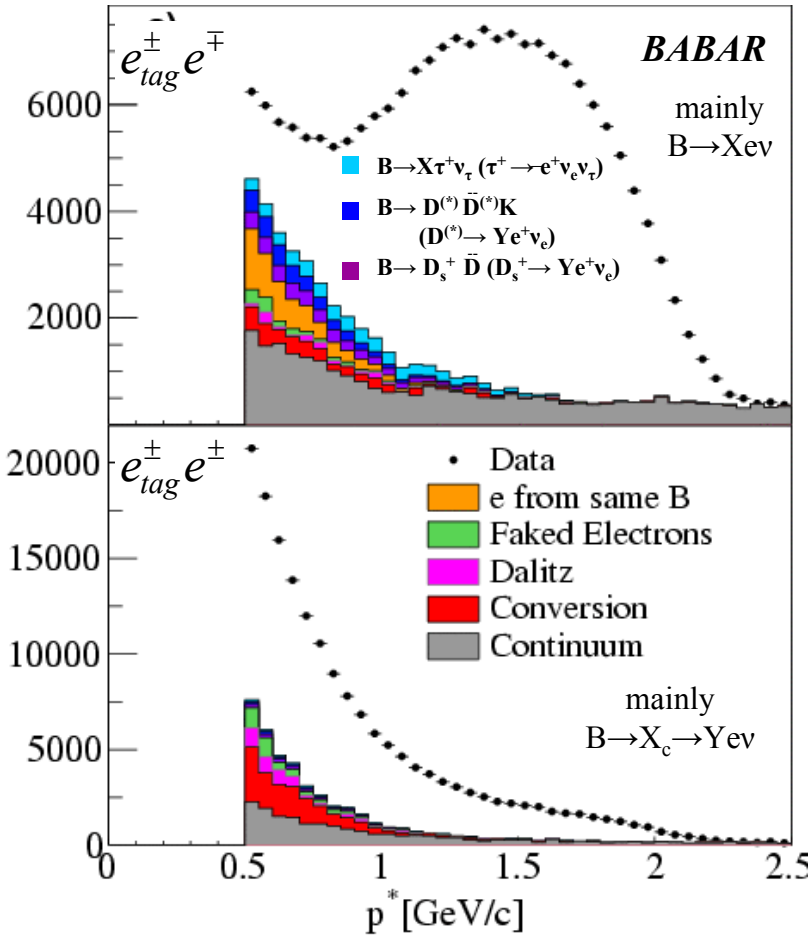


- Large statistics
- Suppress backgrounds from J/Ψ decays by cutting on invariant mass
- Backgrounds from secondary decays are reduced by cutting on opening angle
- Continuum background is subtracted by using the off-resonance data sample

Lepton momentum spectrum:

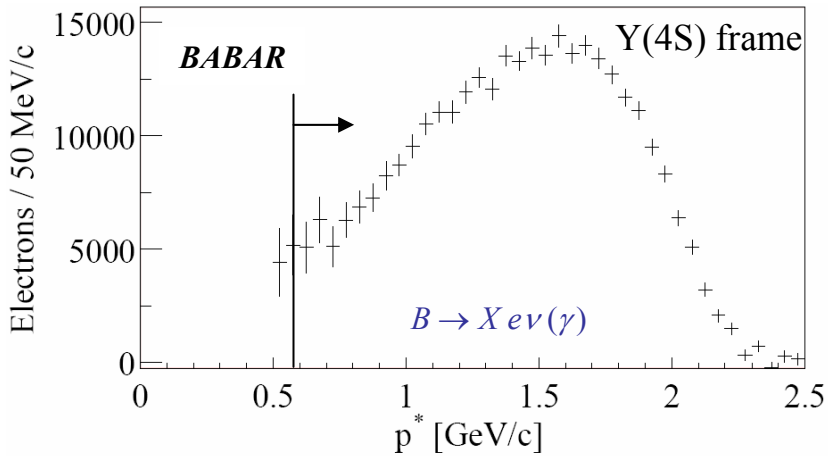


Lepton Energy Spectrum



Data sample:
$\int L\,dt = 47.4\ fb^{-1}$

- Split sample into unlike-sign $e^{\pm}_{tag}e^{\mp}$ and like-sign $e^{\pm}_{tag}e^{\pm}$ events
- Account for $B^0\overline{B}^0$ mixing
- Correct for electron efficiency
- Correct for Bremsstrahlung in detector but not for internal QED radiative effects



Partial Branching Fraction:

$$Br(B \to Xe\nu(\gamma), E_e > 0.6\ GeV) =$$

$$(10.36 \pm 0.06_{stat} \pm 0.23_{sys})\%$$

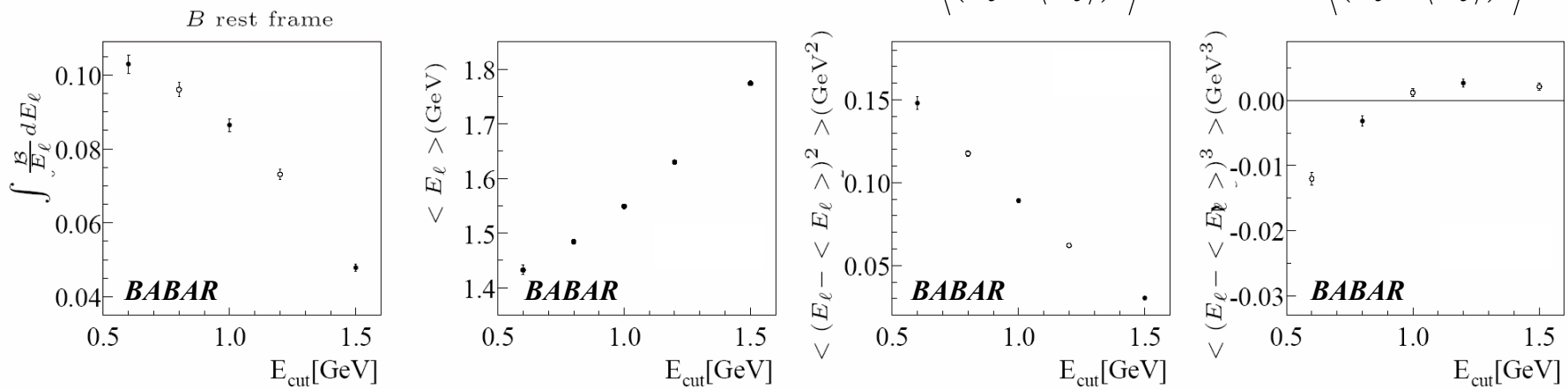
Moments of the Lepton Energy Spectrum

Moments of electron energy spectrum are corrected for:

- B momentum
- QED radiative effects
- B $\rightarrow X_u l\nu$ background

Individual measurements are highly correlated!

$Br(B \rightarrow X_c e \nu)$ $\langle E_e \rangle$ $\left\langle \left(E_e - \langle E_e \rangle\right)^2 \right\rangle$ $\left\langle \left(E_e - \langle E_e \rangle\right)^3 \right\rangle$



To be submitted to Phys. Rev. D: hep-ex/0403030

Extraction of $|V_{cb}|$ and HQE parameters from OPE fit to Data

We use calculations in kinetic mass scheme by Gambino and Uraltsev

hep-ph/0401063
hep-ph/0403166

8 Fit Parameters: total $B(B \to X_c l\nu)$, $|V_{cb}|$, m_b and m_c

$O(1/m_b^2)$ {
- μ_π^2 - expectation value of kinetic energy of b quark inside B meson
- μ_G^2 - expectation value of chromomagnetic moment operator

$O(1/m_b^3)$ {
- ρ_D^3 - expectation value of Darwin operator
- ρ_{LS}^3 - expectation value of Spin-Orbit operator

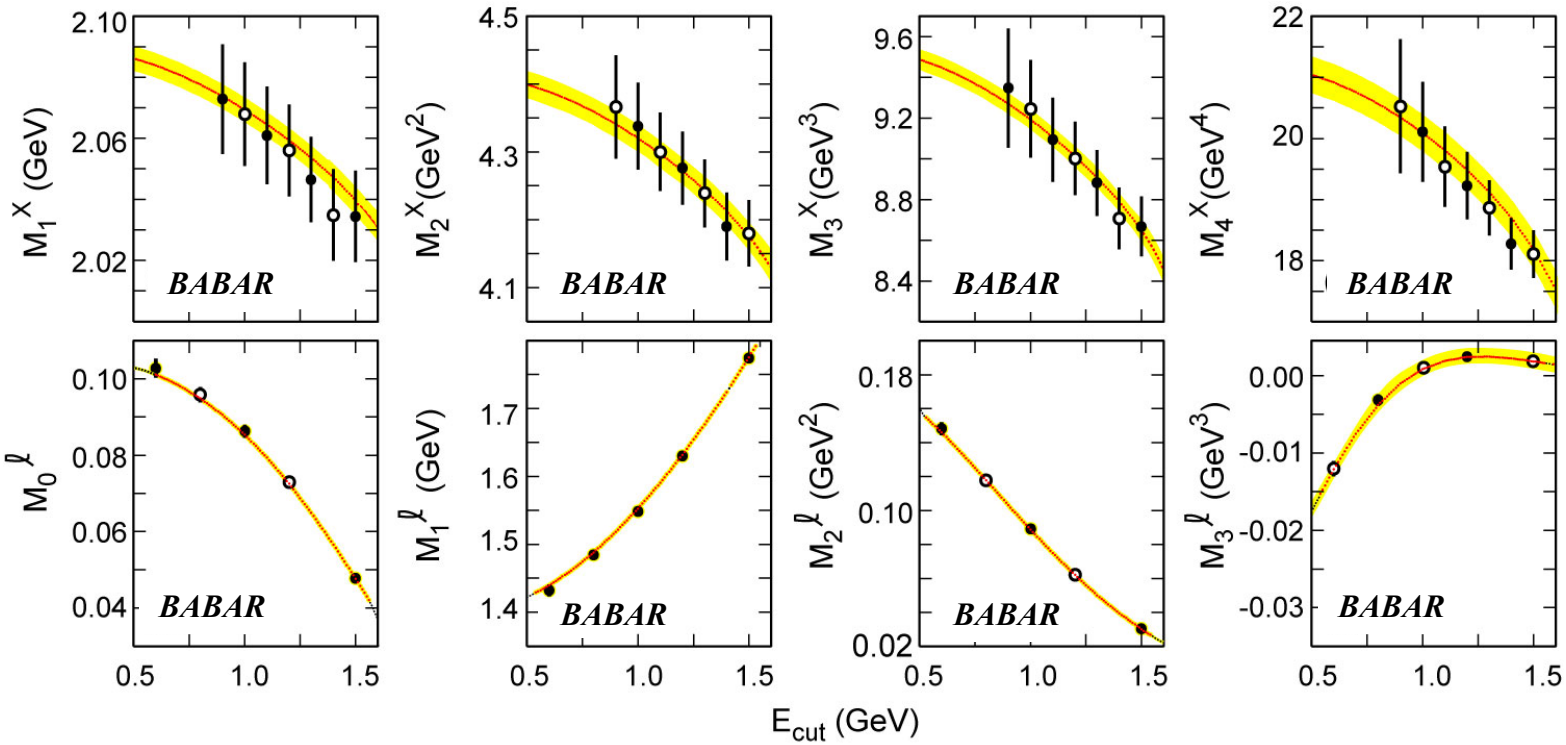
Perform 3 separate Fits:

- Electron and Hadron Moments combined (all parameters free)
  For consistency also:
  - Electron Energy Moments only
  - Hadron Mass Moments only

Hadron Mass Moments have higher sensitivity to the fit parameters, but precision of Lepton Energy Moments is higher, therefore leading to a comparable sensitivity.

Simultaneous Fit to Hadron Mass and Electron Energy Moments

- All parameters unconstrained.
- Only solid points are used in the fit.
- Correlations taken into account.
- Error bars show experimental errors (stat. & syst.)
- Bands correspond to theoretical uncertainties.



$\chi^2 = 15$
$N_{dof} = 20$

Calculations are taken from Gambino and Uraltsev hep-ph/0401063
hep-ph/0403166

Fit Results

$$
\begin{aligned}
|V_{cb}| &= (41.4 \pm 0.4_{\text{exp}} \pm 0.4_{\text{HQE}} \pm 0.2_{\alpha_s} \pm 0.6_{\Gamma_{SL}}) \times 10^{-3} \\
Br(B \to X_c e \nu) &= (10.61 \pm 0.16_{\text{exp}} \pm 0.06_{\text{HQE}})\% \\
m_b(1\ GeV) &= (4.61 \pm 0.05_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.02_{\alpha_s})\ GeV \\
m_c(1\ GeV) &= (1.18 \pm 0.07_{\text{exp}} \pm 0.06_{\text{HQE}} \pm 0.02_{\alpha_s})\ GeV
\end{aligned}
$$

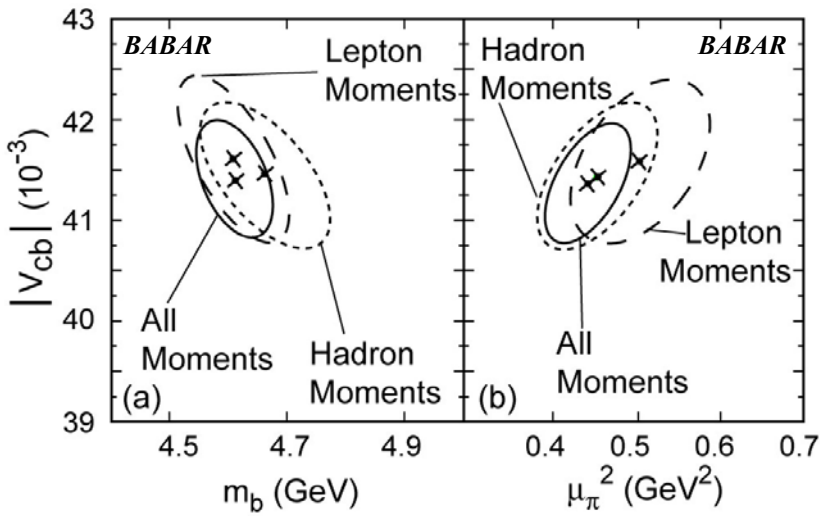
kinetic mass scheme

$$
\begin{aligned}
\mu_\pi^2 &= (0.45 \pm 0.04_{\text{exp}} \pm 0.04_{\text{HQE}} \pm 0.01_{\alpha_s})\ GeV^2 \\
\mu_G^2 &= (0.27 \pm 0.06_{\text{exp}} \pm 0.03_{\text{HQE}} \pm 0.02_{\alpha_s})\ GeV^2 \\
\rho_D^3 &= (0.20 \pm 0.02_{\text{exp}} \pm 0.02_{\text{HQE}} \pm 0.00_{\alpha_s})\ GeV^3 \\
\rho_{LS}^3 &= (-0.09 \pm 0.04_{\text{exp}} \pm 0.07_{\text{HQE}} \pm 0.01_{\alpha_s})\ GeV^3
\end{aligned}
$$

To be submitted to Phys. Rev. Lett.

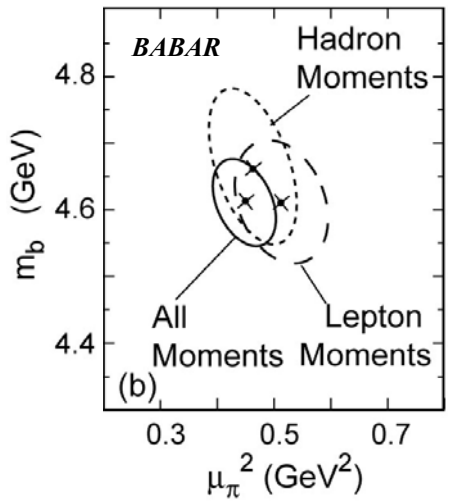
Strong correlation between m_b and m_c:

$m_b(1\ \text{GeV}) - m_c(1\ \text{GeV}) = (3.44 \pm 0.03_{\text{exp}} \pm 0.02_{\text{HQE}} \pm 0.01_{\alpha_s})\ \text{GeV}$

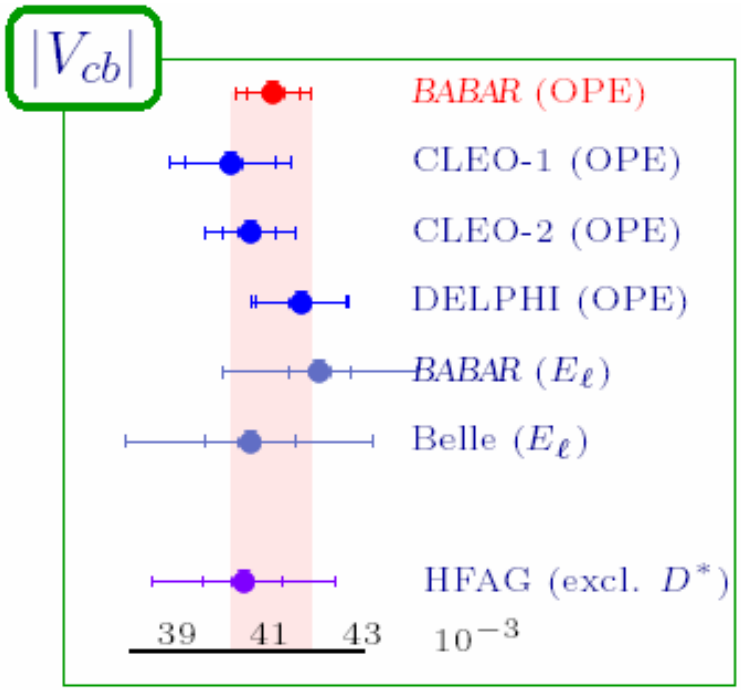


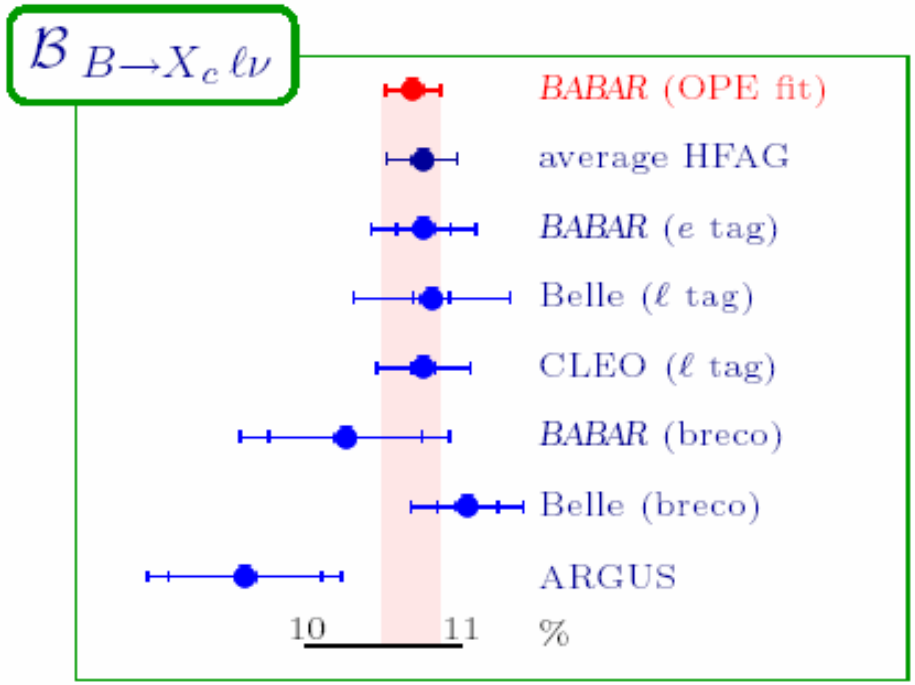
2D projections of the fit result:

$\Delta\chi^2=1$ ellipses

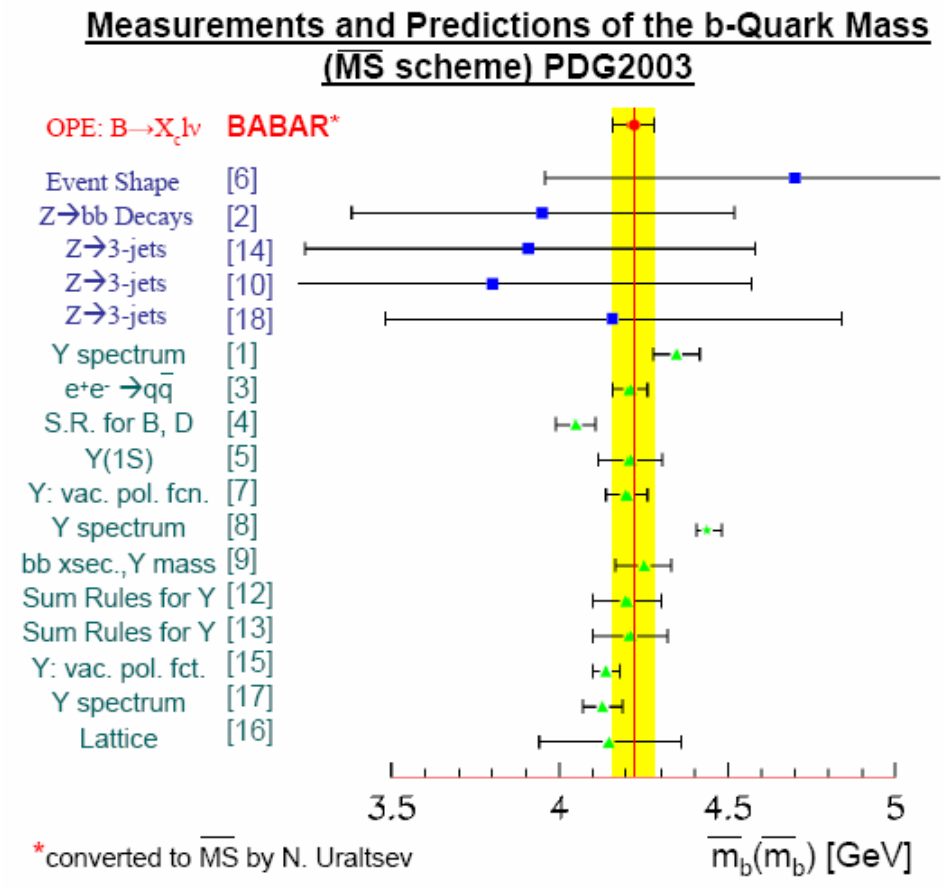


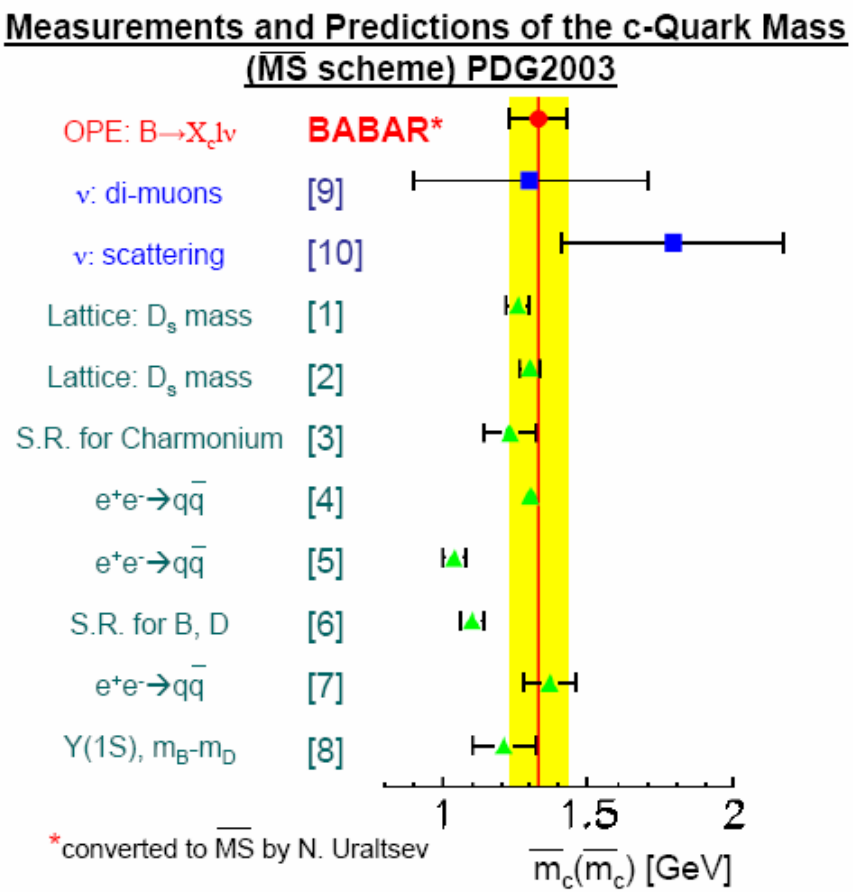
Comparison with previous Determinations





Comparison with other Determinations





$\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.06$ GeV *BABAR* $\overline{m}_c(\overline{m}_c) = 1.33 \pm 0.10$ GeV

Conversion from kinetic mass scheme to $\overline{\text{MS}}$ scheme with hep-ph/9708372, hep-ph/0302262
See also report from CKM WS hep-ph/0304132

Summary

New Measurements of

- Hadronic Mass Moments up to 4th order for 0.9 GeV < E_{cut} < 1.6 GeV hep-ex/0403031
- Lepton Energy Moments up to 3rd order for 0.6 GeV < E_{cut} < 1.5 GeV hep-ex/0403030
  inclusive electron spectrum and partial branching fraction measurement

Serve as input to **OPE fit** with no external constraints:

to be submitted to Phys. Rev. Lett.

$$
\begin{aligned}
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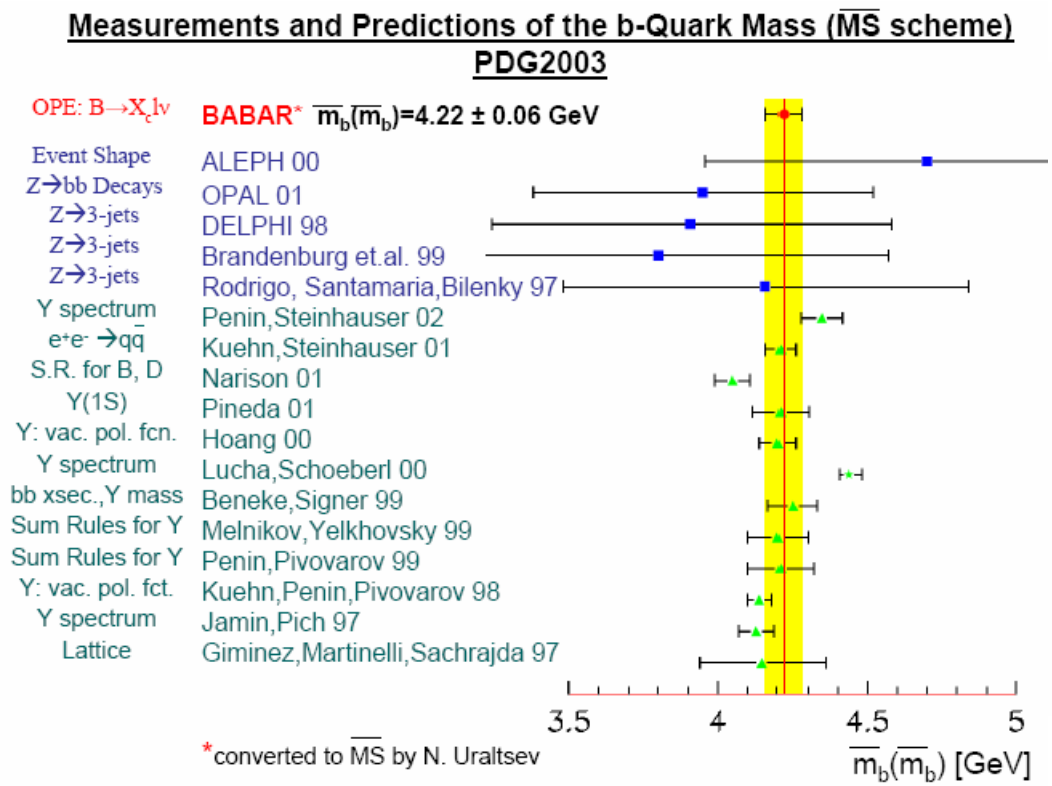
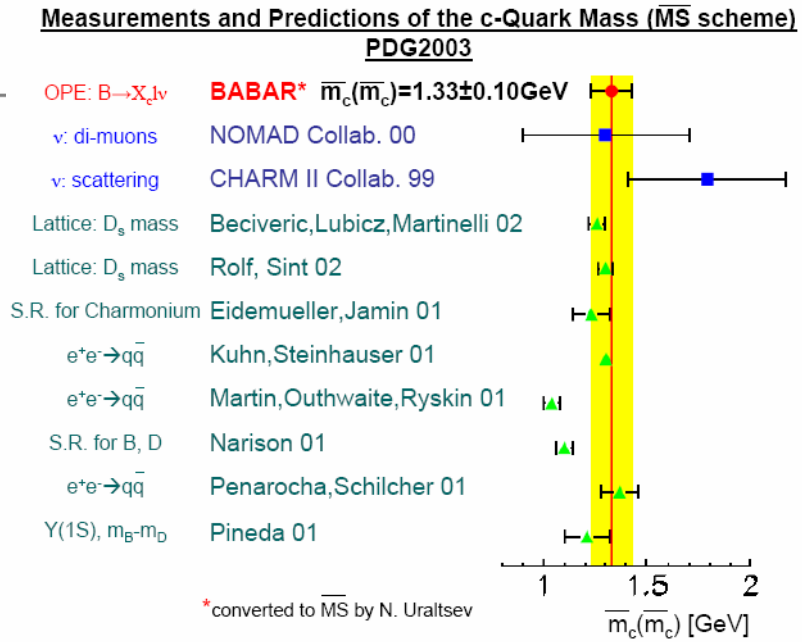
\end{aligned}
$$

resulting in much reduced experimental and theoretical uncertainties (5% → 2% on $|V_{cb}|$ from BaBar)

Consistent results from separate fits to hadron mass and lepton energy moments

Comparison with other Determinations





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