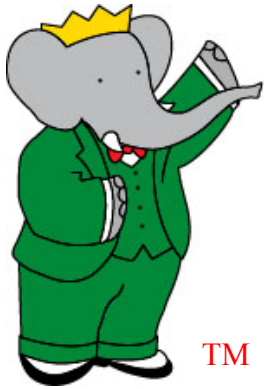
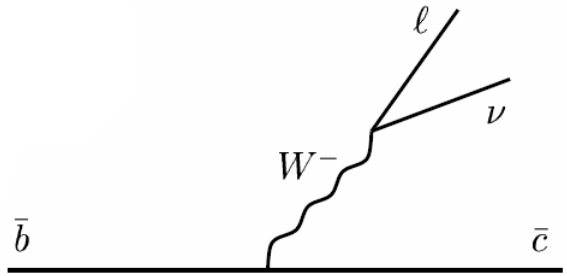



# Studies of semileptonic B decays with the BaBar experiment: Measurement of $|V_{cb}|$ and Heavy Quark Parameters

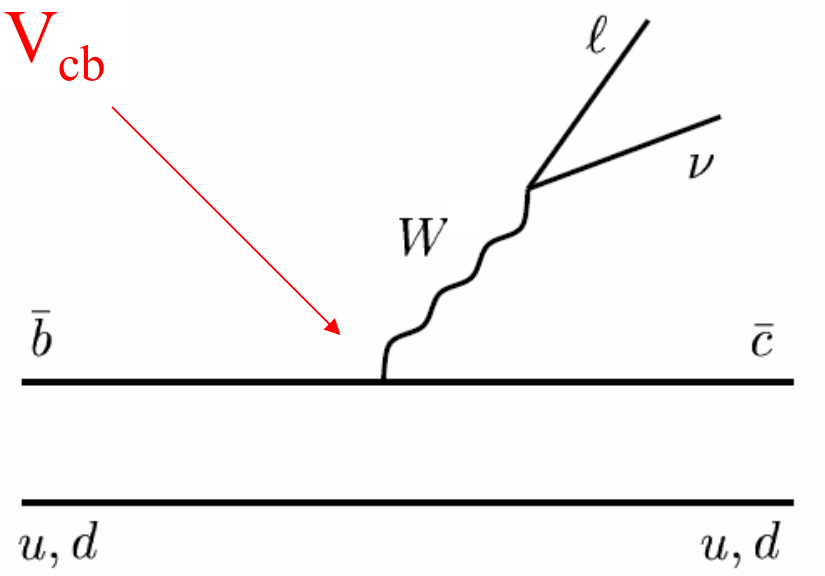
**hep-ex/0403030, 0403031, 0404017**

Jeffrey Berryhill
University of California, Santa Barbara
For the BaBar Collaboration

APS Meeting
Denver, Colorado
May 1, 2004

# Why study semileptonic B decays?

Tree level, short distance:

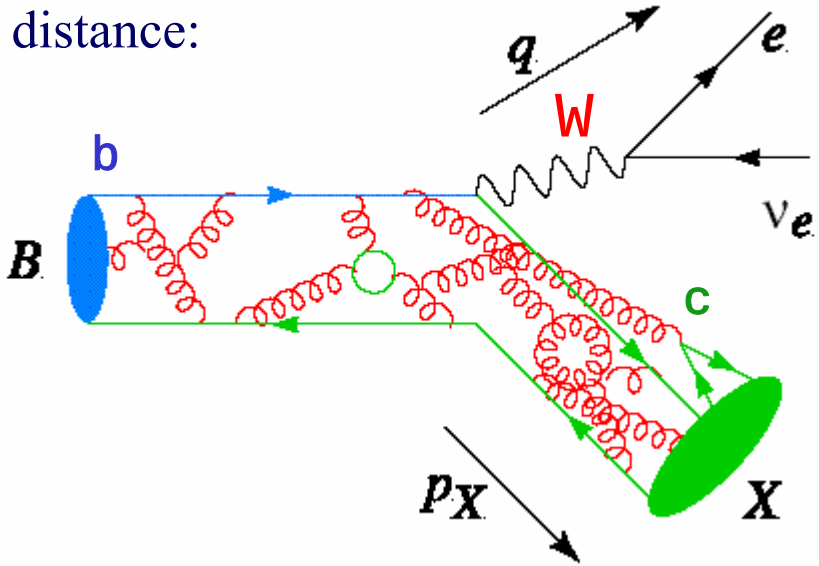



**Precision electroweak physics**

- Decay properties depend directly on fundamental Standard Model parameters: $|V_{cb}|$ , $m_b$, $m_c$
- $|V_{cb}|$ : essential ingredient in tests of CKM unitarity
- $m_b$, $m_c$: important in predictions of B decay rates, precision electroweak observables

# Why study semileptonic B decays?

+ higher order & long distance:




## QCD phenomenology of heavy quarks

- Higher order QCD ($\alpha_s^n$) corrections to short-distance interaction
- Non-perturbative, long-distance interactions of b quark with light quark
- Need theoretical technology to factorize these two effects and produce observables with precise relation to short distance parameters

# The Heavy Quark Expansion (HQE)

An operator product expansion in the heavy quark limit

- Short-distance, perturbative physics in the coefficients of operator products (to some order in $\alpha_s$). Calculable!

- Long-distance, non-perturbative physics in exp. values of products of quark operators (to some order in $1/m_b$). NOT calculable. Measure them!

$$\Gamma_{c\ell\nu} = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{ew}) A_{pert}(r, \mu) \times$$
$$\left[ z_0(r) \left( 1 - \frac{\mu_\pi^2 - \mu_G^2 + \frac{\rho_D^3 + \rho_{LS}^3}{m_b}}{2m_b^2} \right) \right.$$
$$\left. -2(1-r)^4 \frac{\mu_G^2 + \frac{\rho_D^3 + \rho_{LS}^3}{m_b}}{m_b^2} + d(r) \frac{\rho_D^3}{m_b^3} + \mathcal{O}(1/m_b^4) \right].$$
$$r = m_c^2/m_b^2$$

N.B. Several HQE schemes exist; op's and coeff's are scheme dependent

# HQE and spectral moments

•Multiple b → c *l* ν observables needed for simultaneous extraction of all HQE parameters

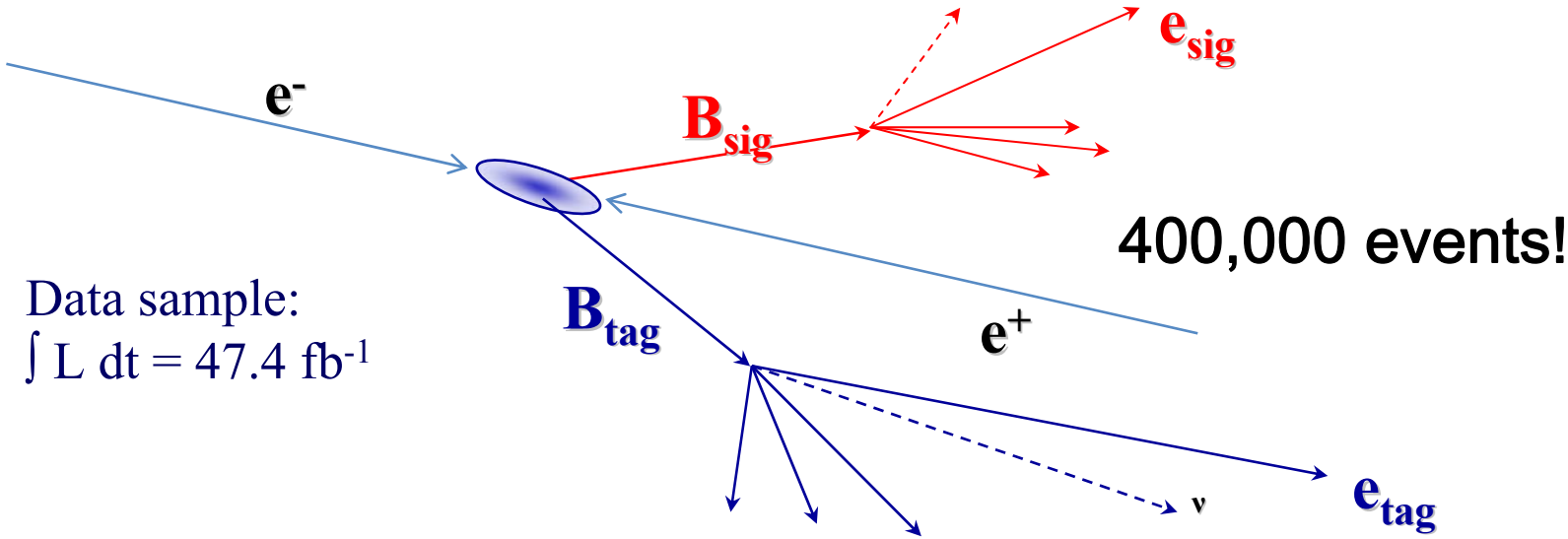
•HQE calculations now exist for several inclusive spectral moments of the semileptonic decay products, as a function of the minimum (B rest frame) lepton energy , $E_{cut}$, required:

$$< X^n > (E_{cut}) = \left. \frac{\int (X - X^0)^n \frac{d\Gamma}{dX} dX}{\int \frac{d\Gamma}{dX} dX} \right|_{E_l > E_{cut}}$$

•Partial branching fraction n = 0 moment
•Lepton-energy spectrum $<E_l^n>$ n = 1, $< E_l^n - <E_l^1> >$, n = 2,3
•Hadronic-mass distribution $<M_X^n>$ n= 1,2,3,4
•photon energy spectrum in b→sγ decays $<E_\gamma^n>$ (not discussed here)

# Lepton Energy Spectrum: Selection

- Tag Y(4S) events with high energy electron ($p^* > 1.4$ GeV in Y(4S) frame) "$e_{tag}$"
- Measure spectrum of any second electron in the event ($p^* > 0.5$ GeV in Y(4S) frame) "$e_{sig}$"
- Split into same sign (mostly from D to X $l\,\nu$) and opposite sign (mostly signal) samples



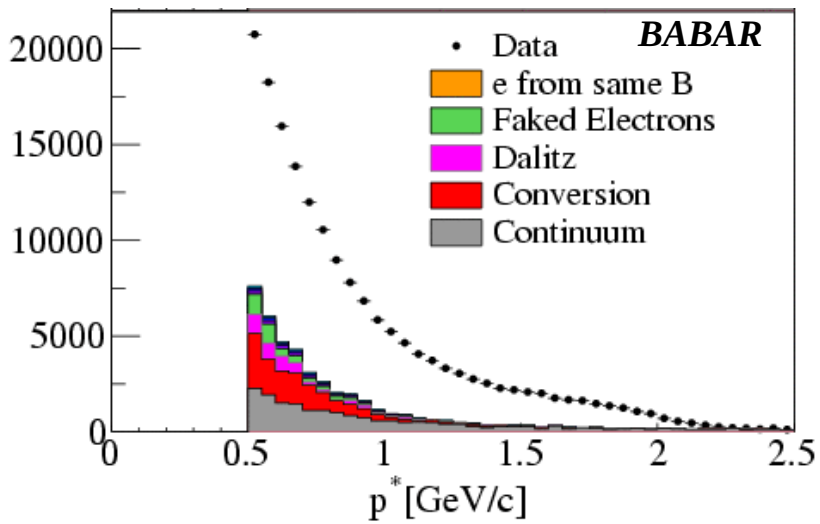
# Lepton Energy Spectrum: Background

- Suppress charm decay electrons in opp. sign sample with opening angle cut and J/psi veto

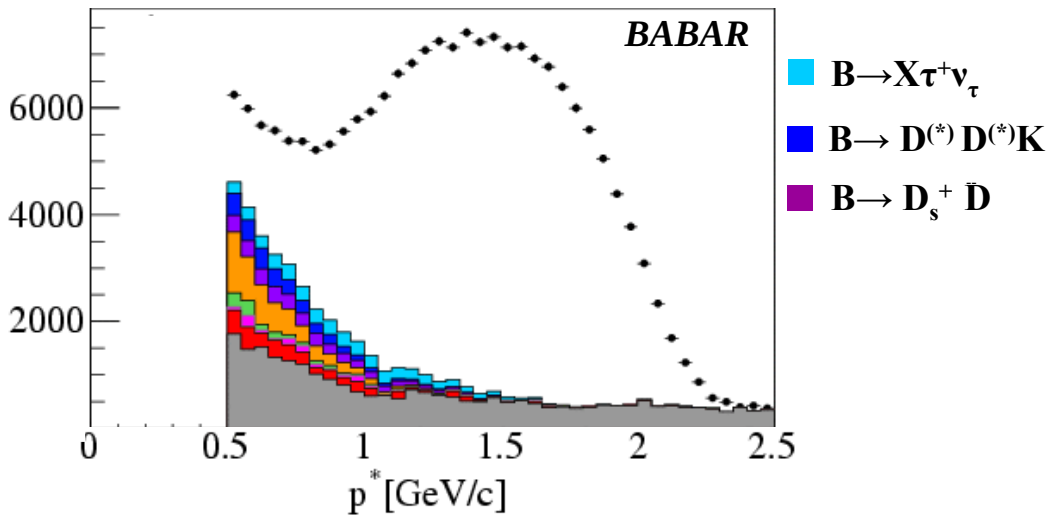
Subtract remaining background:

- continuum with off-resonance data
- charm decays with same sign dielectron data (corrected for mixing)
- fake/conversion/Dalitz electrons estimated from data
- b to ccs and b to cτν decays from MC

Same sign (mostly from D decays)




Opp. sign (mostly from B decays)



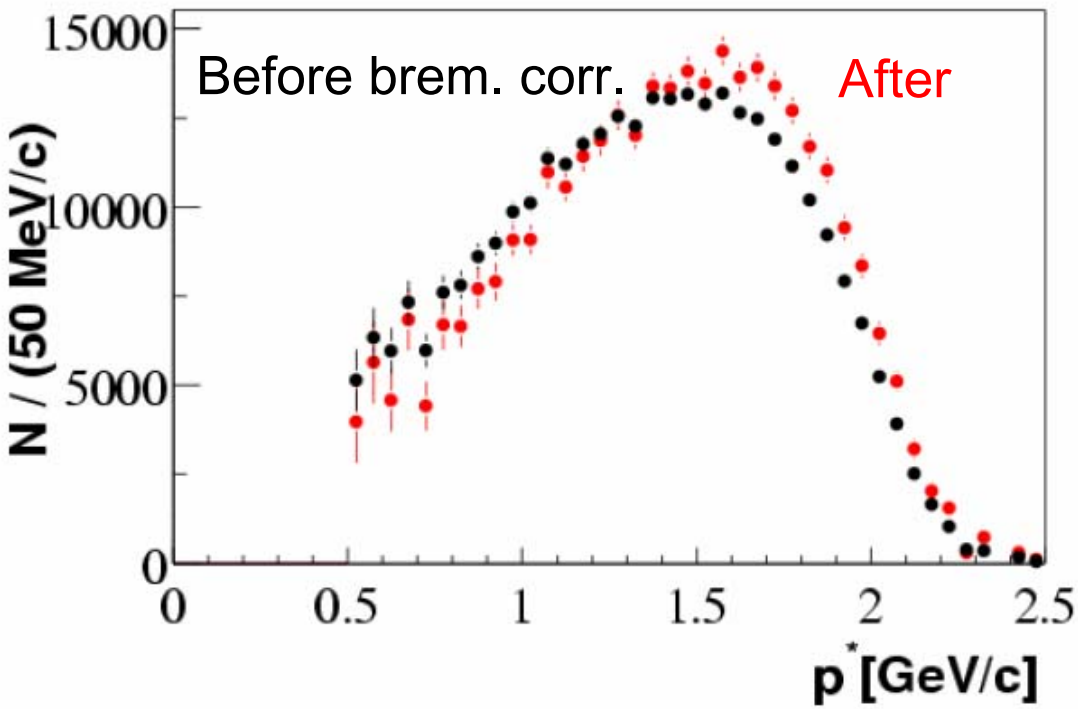
# Lepton Energy Spectrum: Corrections

•Electron ID efficiency precisely measured in radiative Bhabhas vs. (p, cos θ, +/-)

•Detector Bremsstrahlung corrected via inversion of smearing matrix (detector material model $X_0$ agrees with data to 0.14%!)

• B momentum correction from B spectrum in data

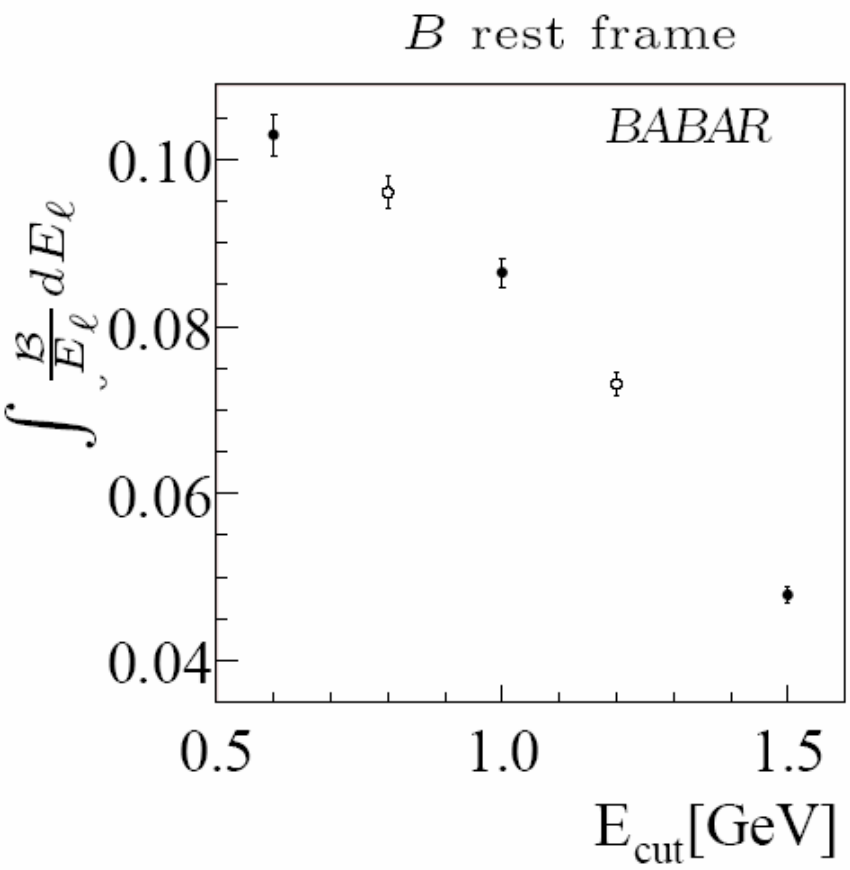
• B →$X_u l\nu$ background estimated from measured BF, MC spectral shape

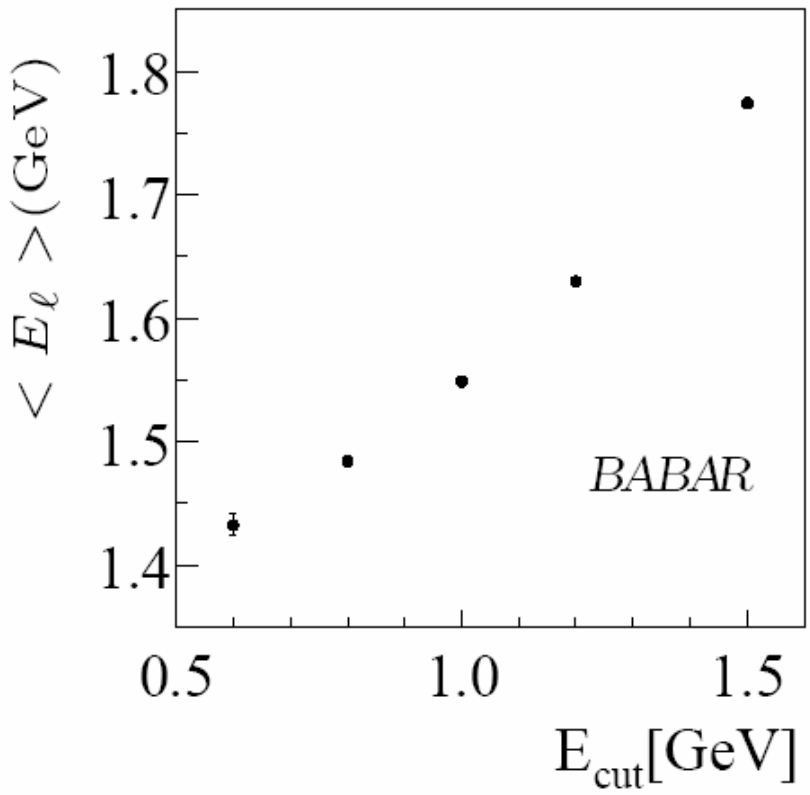


# Lepton Energy Spectrum: Moments

Individual measurements are highly correlated!

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



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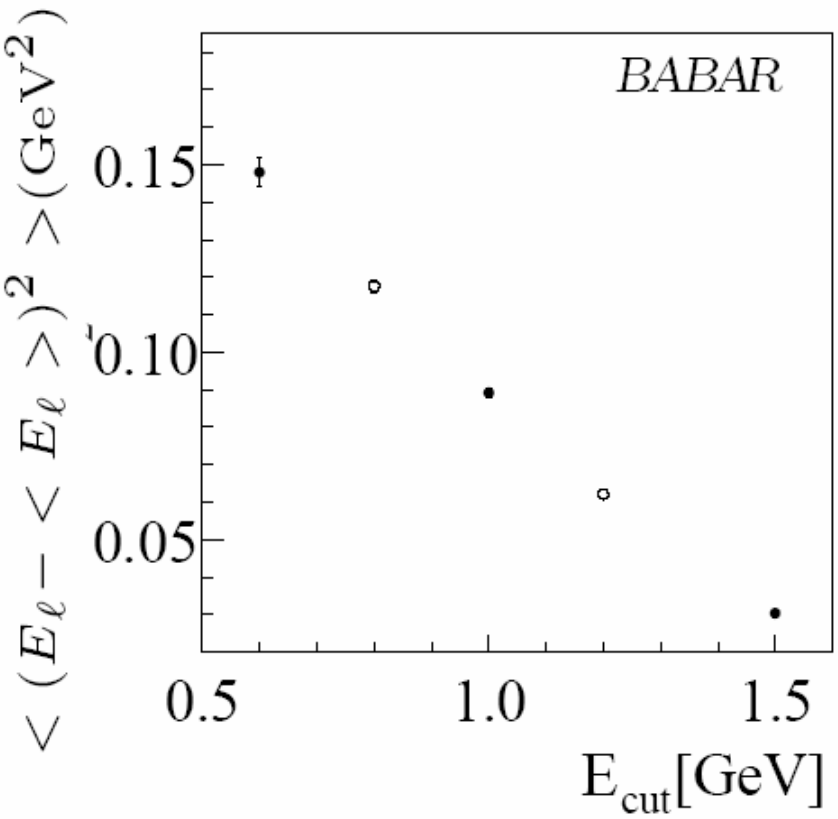
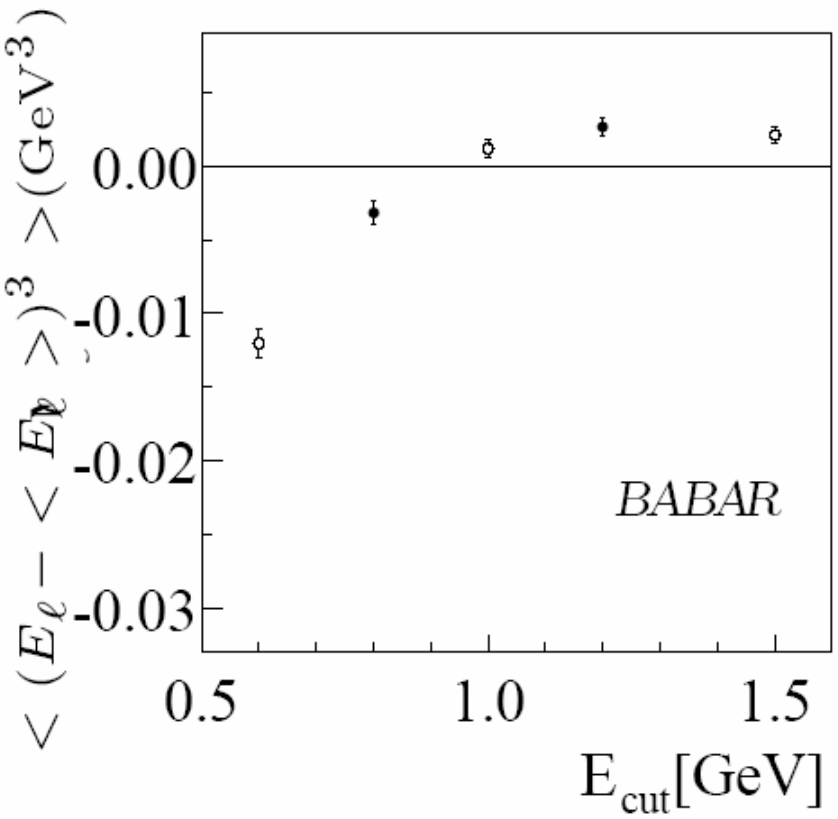
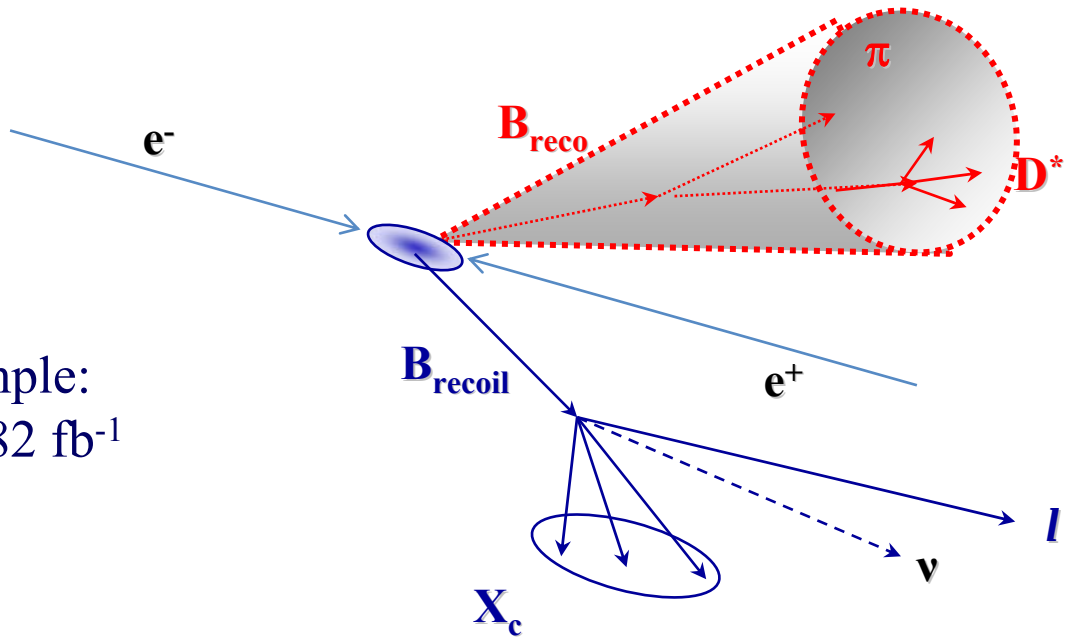


# Hadronic-Mass Spectrum: Selection

- Tag Y(4S) decays with fully reconstructed hadronic B decays "$B_{reco}$"

- Measure $X_c$ mass in "$B_{recoil}$" side of the event:
  - exactly one "right sign" lepton (*e* or μ)
  - lepton p* in B rest frame > 0.9 GeV
  - |net charge| <= 1
  - $E_{miss}$ and $P_{miss}$ consistent with neutrino

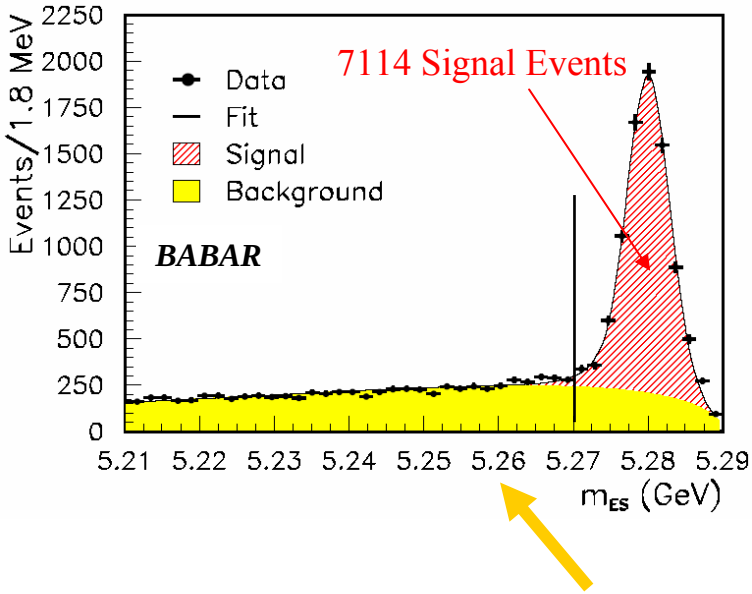



7000 events

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

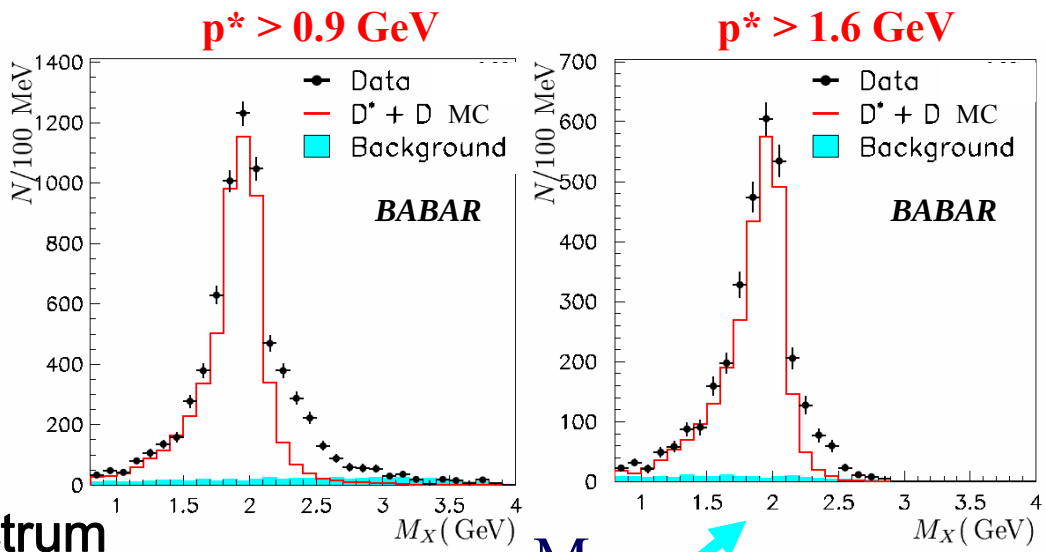
# Hadronic-Mass Spectrum: Background

$B_{reco}$ mass peak in selected events




$M_x$ extracted from kinematic fit to the entire event

$\sigma(M_X) \approx 350$ MeV



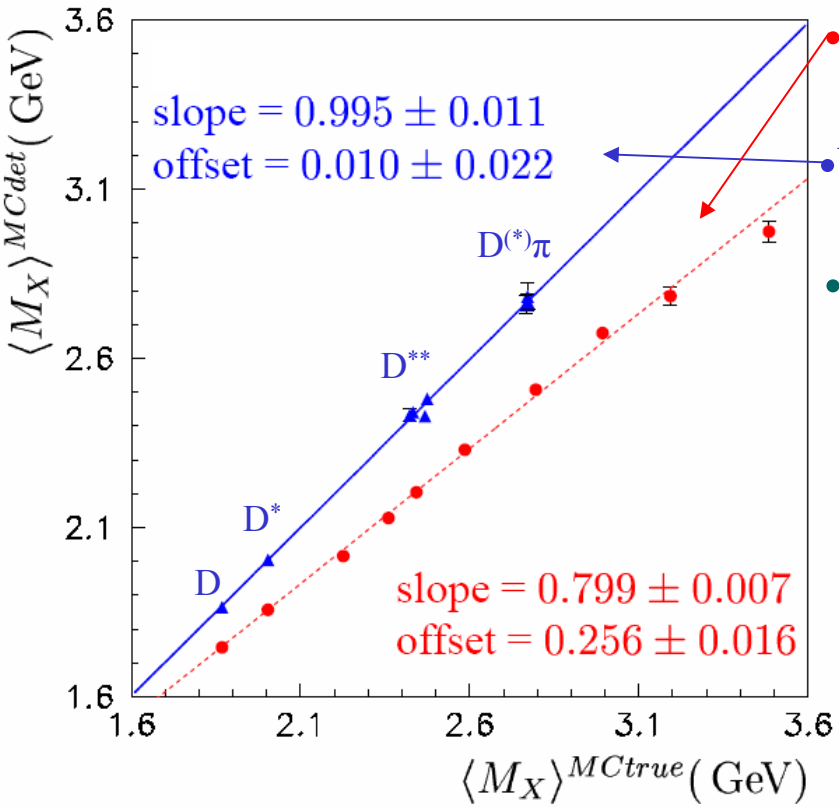

Combinatoric background $M_x$ spectrum estimated from $B_{reco}$ $m_{ES}$ sideband

$M_X$

Small remaining background spectrum estimated from MC

# Hadronic-Mass Moments: Corrections

- Exploit observed linear relations between measured and generated masses
- Calibrate on an event-by-event basis, separately for each moment
- 9 MC calib. curves for each moment: 3X3 bins of (multiplicity, Emiss – Pmiss)



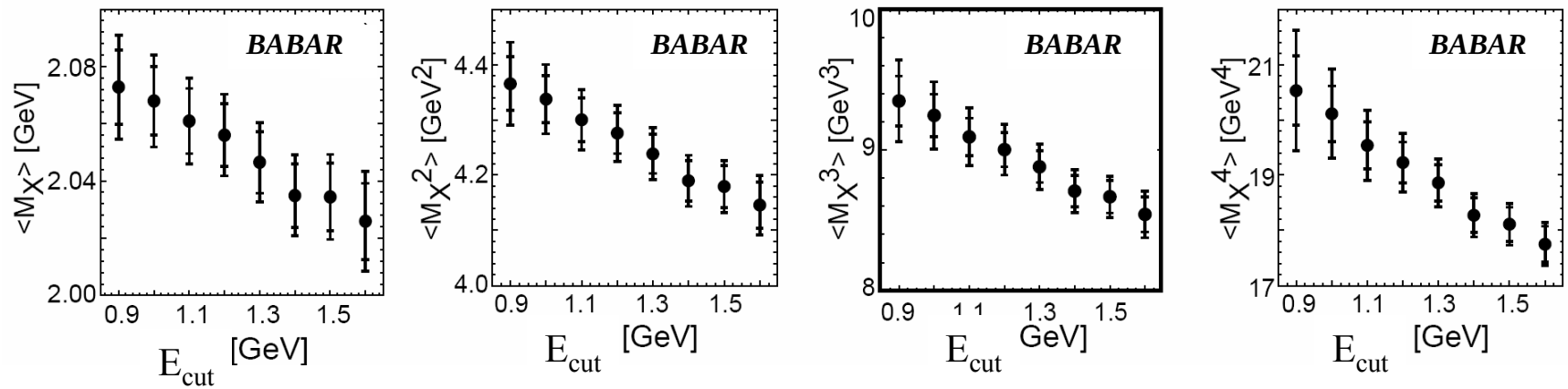

- Calibration curve from inclusive $X_c\, l\, \nu$ MC
- Validated in MC on exclusive final states
- Validated on partially reconstructed $B \rightarrow D^{*\pm} l \nu$ ($D^{*\pm} \rightarrow D^0 \pi^{\pm}$) DATA

Main uncertainties:
Detector Response
Background Subtraction
Little model dependence!!

# Hadronic-Mass Moments

**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!




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

# Fit of HQE Parameters to Moments

We use calculations in kinetic mass scheme by Gambino and Uraltsev (HQE to order $1/m_b^3$, $\alpha_s^2$ )

hep-ph/0401063
hep-ph/0403166

8 Fit Parameters:

- BF($B \to X_c l \nu$), $|V_{cb}|$, $m_b$, $m_c$ and 4 HQE parameters:

$O(1/m_b^2)$:
- $\mu_\pi^2$ - exp. value of kinetic energy of b quark inside B meson
- $\mu_G^2$ - exp. value of chromomagnetic moment operator

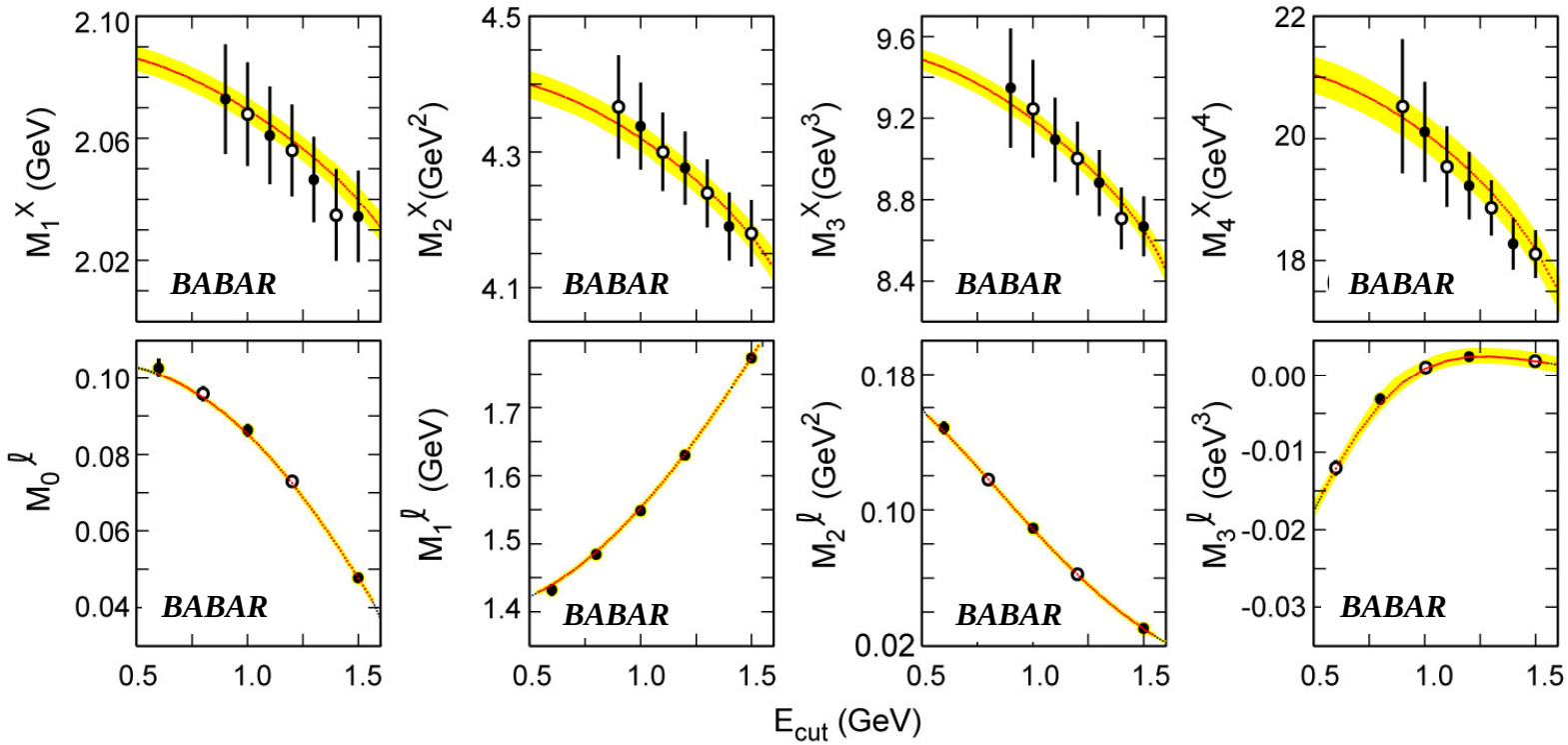
$O(1/m_b^3)$:
- $\rho_D^3$ - exp. value of Darwin operator
- $\rho_{LS}^3$ – exp. value of Spin-Orbit operator

27 lepton-energy and hadronic-mass moment measurements
27 separate HQE prediction functions in the 8 fit parameters
(higher order moments sensitive to higher order HQE parameters)

# HQE Fit Results

- 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.




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

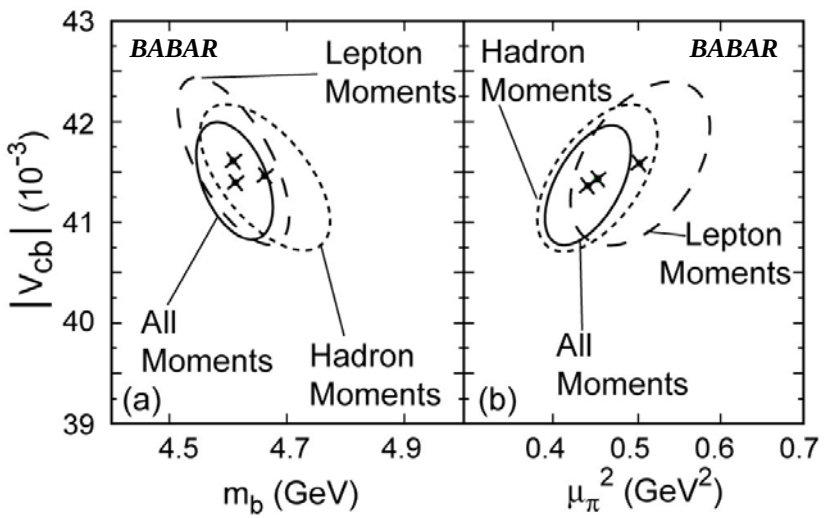
# Fit Results

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

kinetic mass scheme

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

submitted to Phys. Rev. Lett. hep-ex/0404017

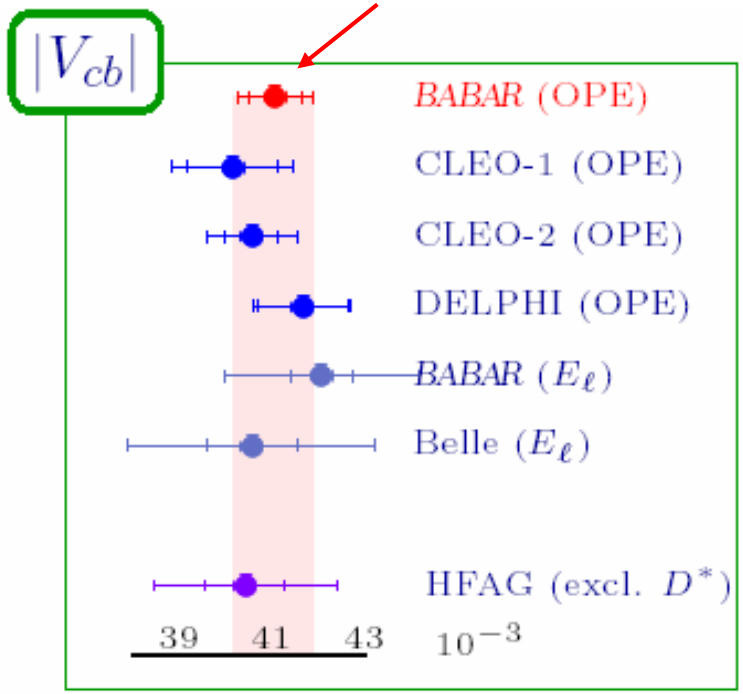


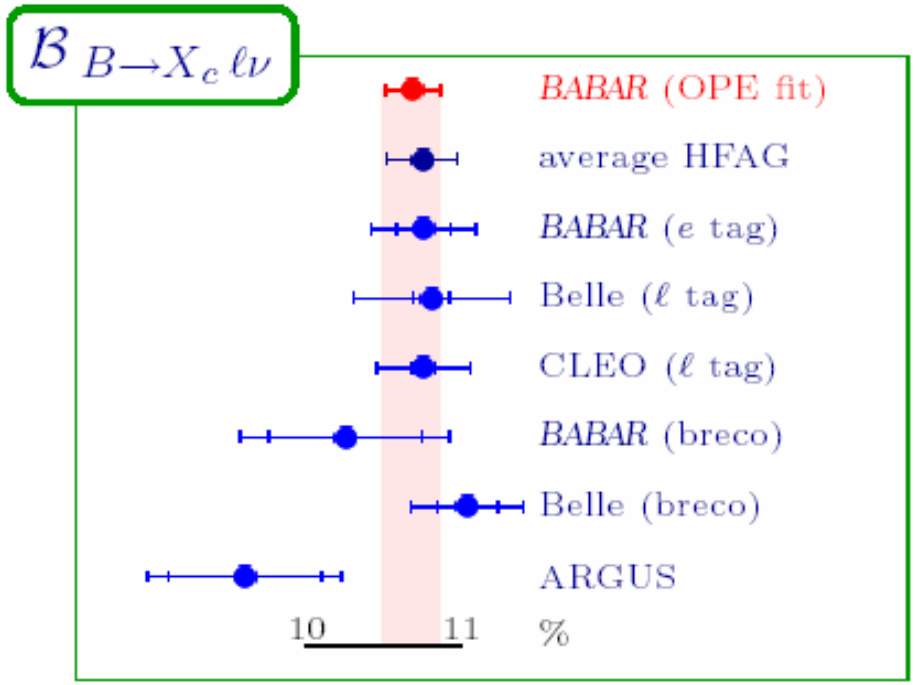

**2D projections of the fit result:**

$\Delta\chi^2=1$ ellipses of separate fits to lepton or hadron moments are consistent

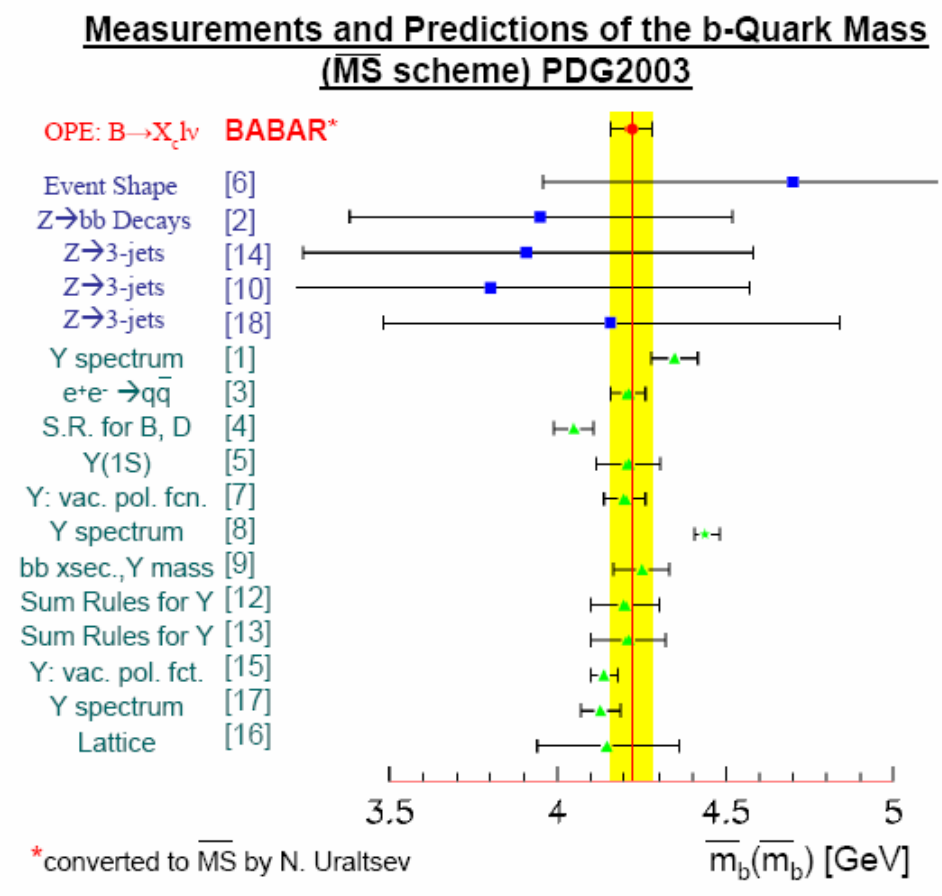
# Comparison with previous Determinations

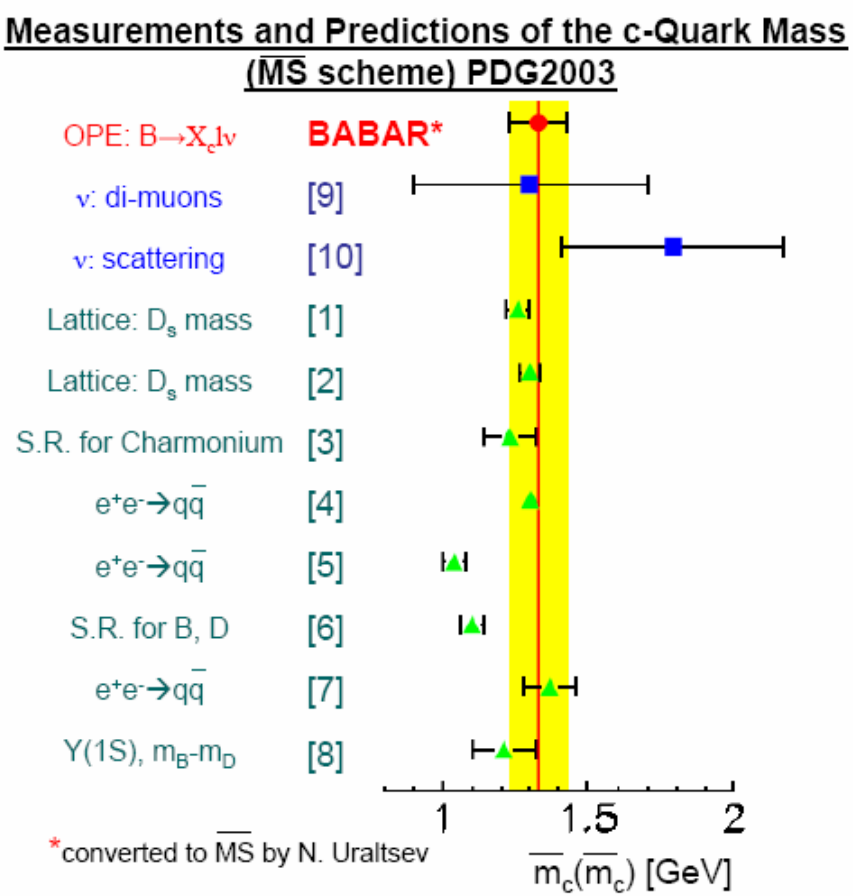
First measurement with all parameters floating to order $1/m_b^3$



# 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

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

$$
\begin{aligned}
|V_{cb}| &= (41.4 \pm 0.4_{\text{exp}} \pm 0.4_{\text{HQE}} \pm 0.2_{\alpha_s} \pm 0.6_{\Gamma_{SL}}) \times 10^{-3} \\
Br(B \to X_c e \nu) &= (10.61 \pm 0.16_{\text{exp}} \pm 0.06_{\text{HQE}})\% \\
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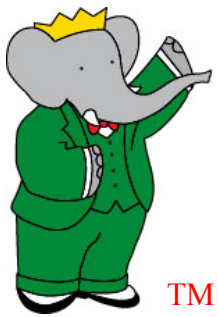
m_b(1\,GeV) - m_c(1\,GeV) &= (3.44 \pm 0.03_{\text{exp}} \pm 0.02_{\text{HQE}} \pm 0.01_{\alpha_s})\,GeV
\end{aligned}
$$



TM

## 2% error on $|V_{cb}|$ from BaBar

submitted to Phys. Rev. Lett.
hep-ex/0404017