Physikalisches Institut

Ruprecht-Karls-Universität Heidelberg

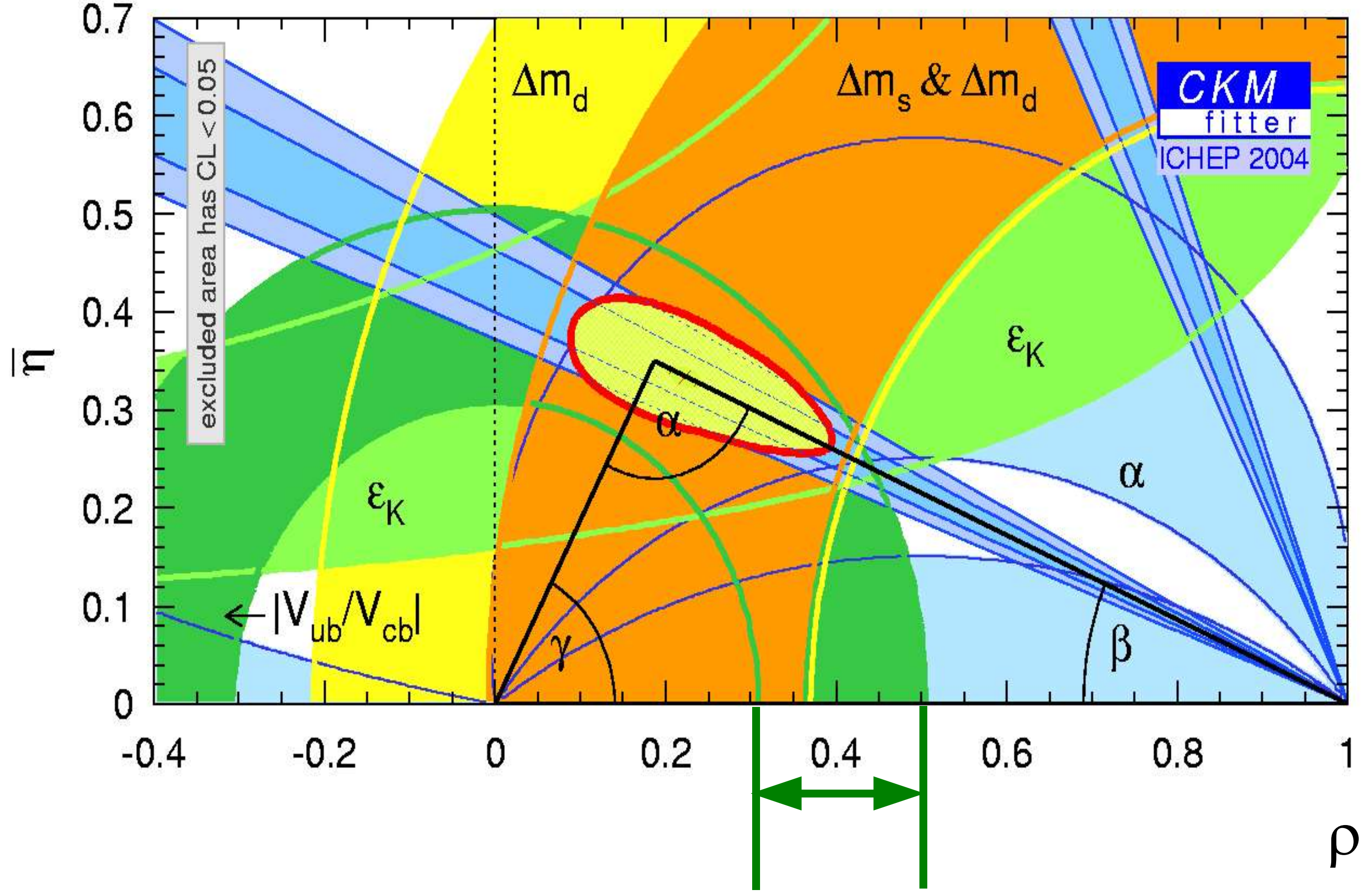
Measurement of $|V_{ub}|$ and $|V_{cb}|$ at BABAR

Rolf Dubitzky
University of Heidelberg

Overview

- **Introduction**
- **$|V_{cb}|$ from inclusive measurments**
  - Electron energy and hadronic mass moments
  - Combined Fit with Operator Product Expansion
- **$|V_{ub}|$**
  - Electron energy endpoint
  - E_l versus q^2
  - m_X
  - m_X versus q^2
  - moments from unfolded m_X spectrum

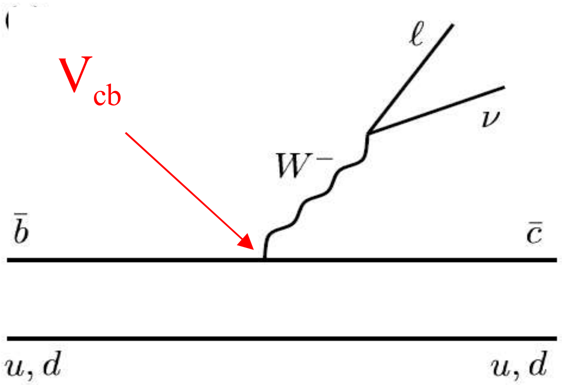
Motivation



Measurements of $|V_{ub}|$ and $|V_{cb}|$ provide **stringent and redundant consistency tests** of the unitarity triangle (UT)

Need to measure $|V_{ub}|/|V_{cb}|$ to better than 10% to limit unitarity tests

Challenge for semileptonic decays

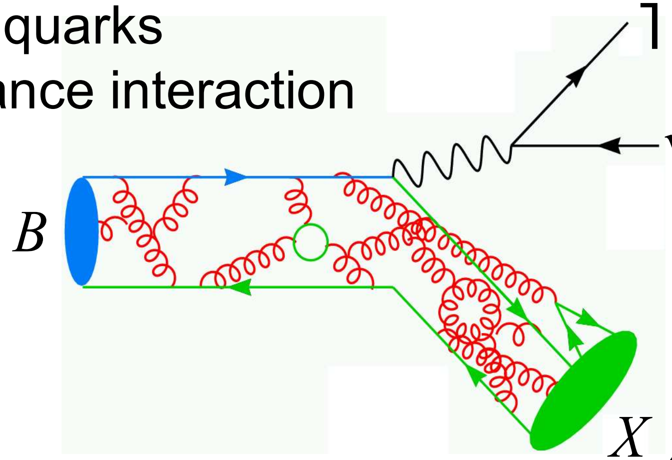


- Semileptonic B decays provide the best method to measure |Vcb| and |Vub|
  - relatively easy to calculate on parton level
  - rates depend on CKM matrix elements and quark masses:

$$\Gamma_u \equiv \Gamma(b \to u l \nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5$$

$$\Gamma_c \equiv \Gamma(b \to c l \nu) = \frac{G_F^2}{192\pi^2} |V_{cb}|^2 m_b^2 (m_b - m_c)^3$$

- **BUT:** sensitive to QCD phenomenology of heavy quarks
  - Higher order QCD (α_s^n) corrections to short distance interaction
  - long distance QCD interaction
- Evaluate in theoretical framework of **HQE / OPE**



Heavy Quark Expansion

- Evalute in theoretical framework of **HQE / OPE**
  - expand matrix element in powers of $1/m_b$ in terms of local operators
  - expectation values are properties of the b quark within the B meson
  - ✔ can calculate perturbative corrections (α_s)
  - ✔ can factorize long distance corrections ($1/m_b^n$) into measurable quantities

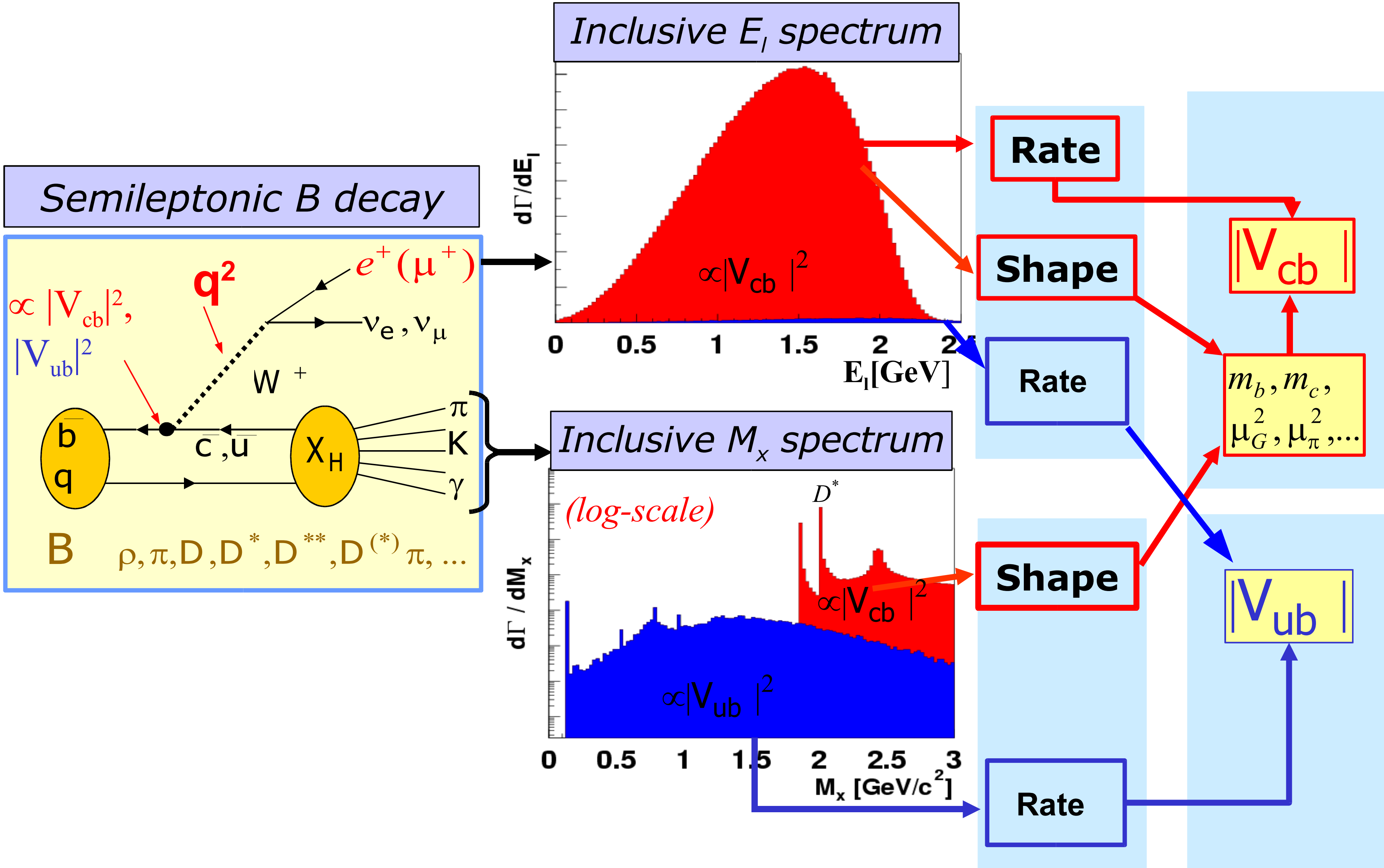
$$\Gamma_{clv} = \frac{G_F m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{ew}) A_{pert} A_{nonpert} \cong |V_{cb}|^2 f_{OPE}(m_b, m_c, a_i)$$

  - ✔ when summing over all final states ("**inclusive**") problems with properties of the final state cancel out

➔ **measure rate and shape of inclusive spectra**, e.g. Lepton energy moments are defined:

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

Overview of techniques



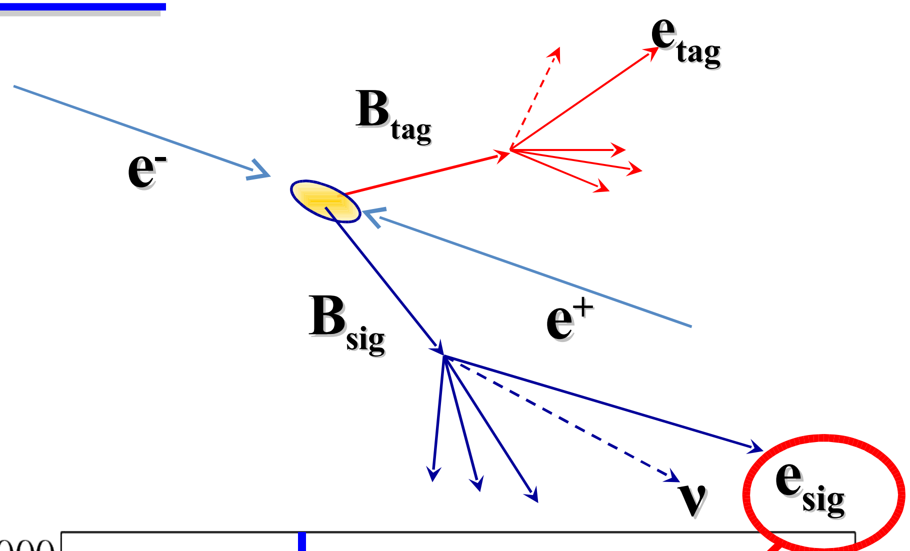
|Vcb| - Electron Energy Moments

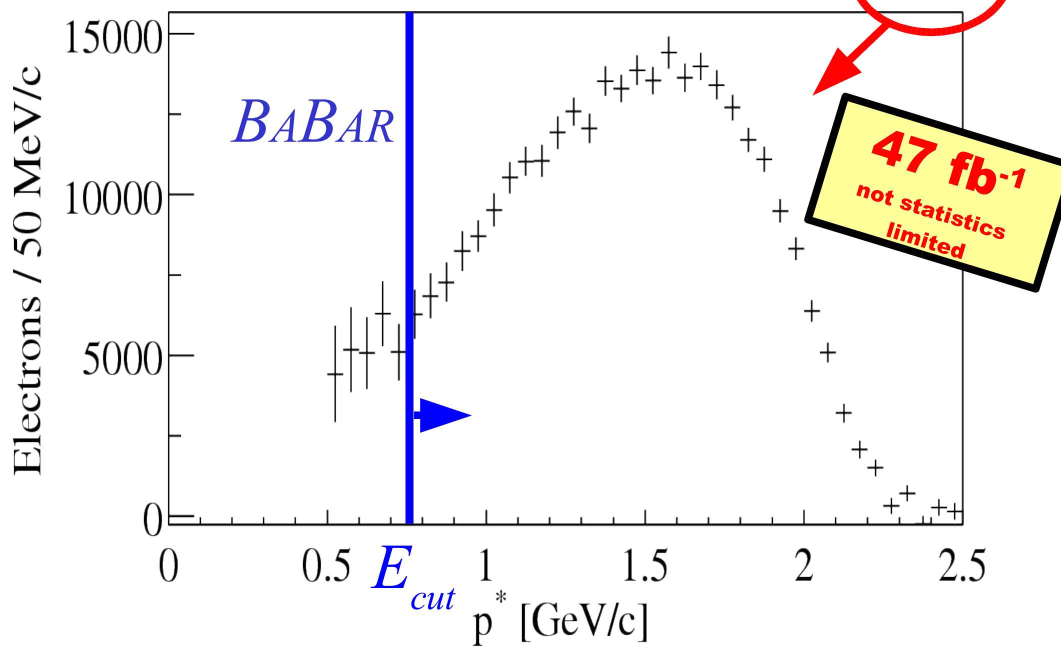
PRD69:111104

- Select events with 2 electrons
  - One electron to "tag" a B event (1.4 < p* < 2.3 GeV in CMS)
  - Measure the energy spectrum of the other ("signal") electron
  - ✔ Correct for efficiency, B^0 mixing, non-prompt electrons, and detector effects (e.g. Bremsstrahlung)
  - ✔ Subtract $B \to X_u \, l \, \nu$ background
- Calculate first four moments for various lower cuts in E_l:

$$E_{cut} = 0.6 \;....\; 1.5 \text{ GeV}$$

➔ Results are input to OPE fit





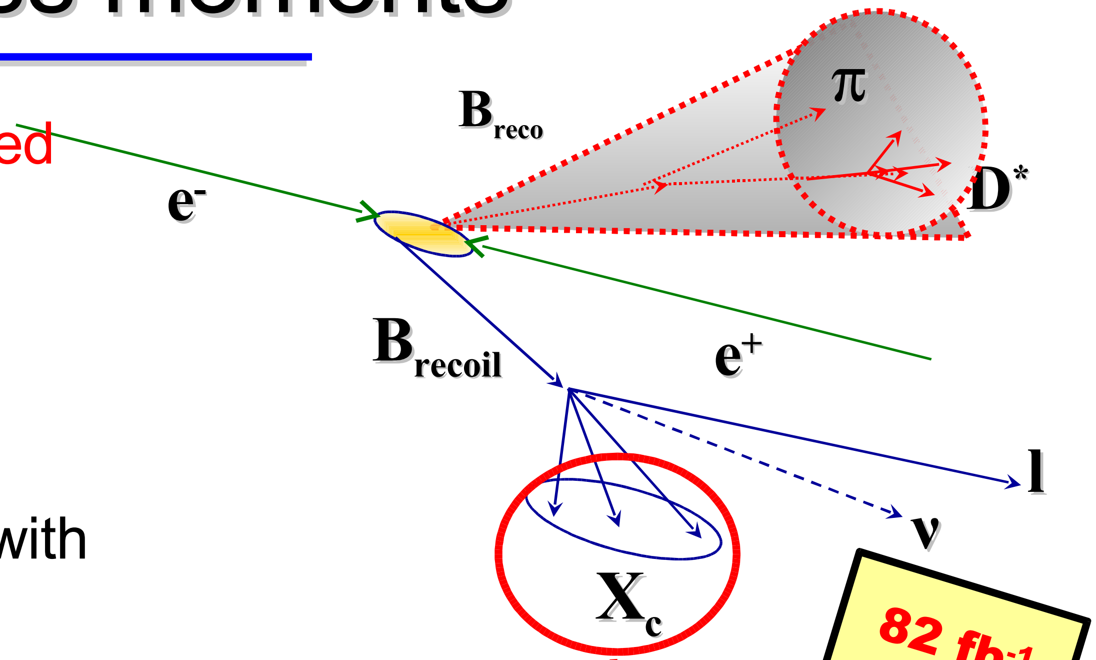
|Vcb| - Hadronic mass moments

PRD69:111103

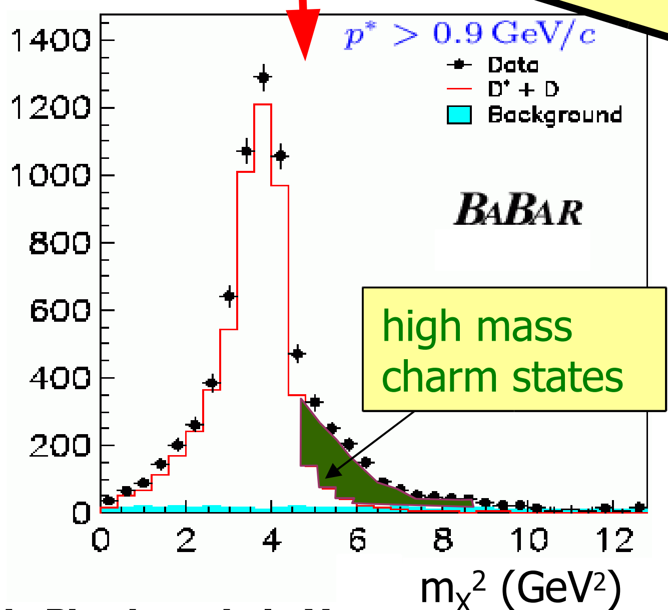
- Select events with fully-reconstructed B mesons
- Measure hadronic mass (m_X) of X_c
  - Select lepton l with $E_l > E_{cut}$
  - Require lepton charge consistent with fully reconstructed B meson
  - Use Breco momentum to calculate m_X
- Calculate first four moments for various lower cuts in E_l:

$$E_{cut} = 0.9 \;....\; 1.6\ \text{GeV}$$

➔Results are input to OPE fit



82 fb-1



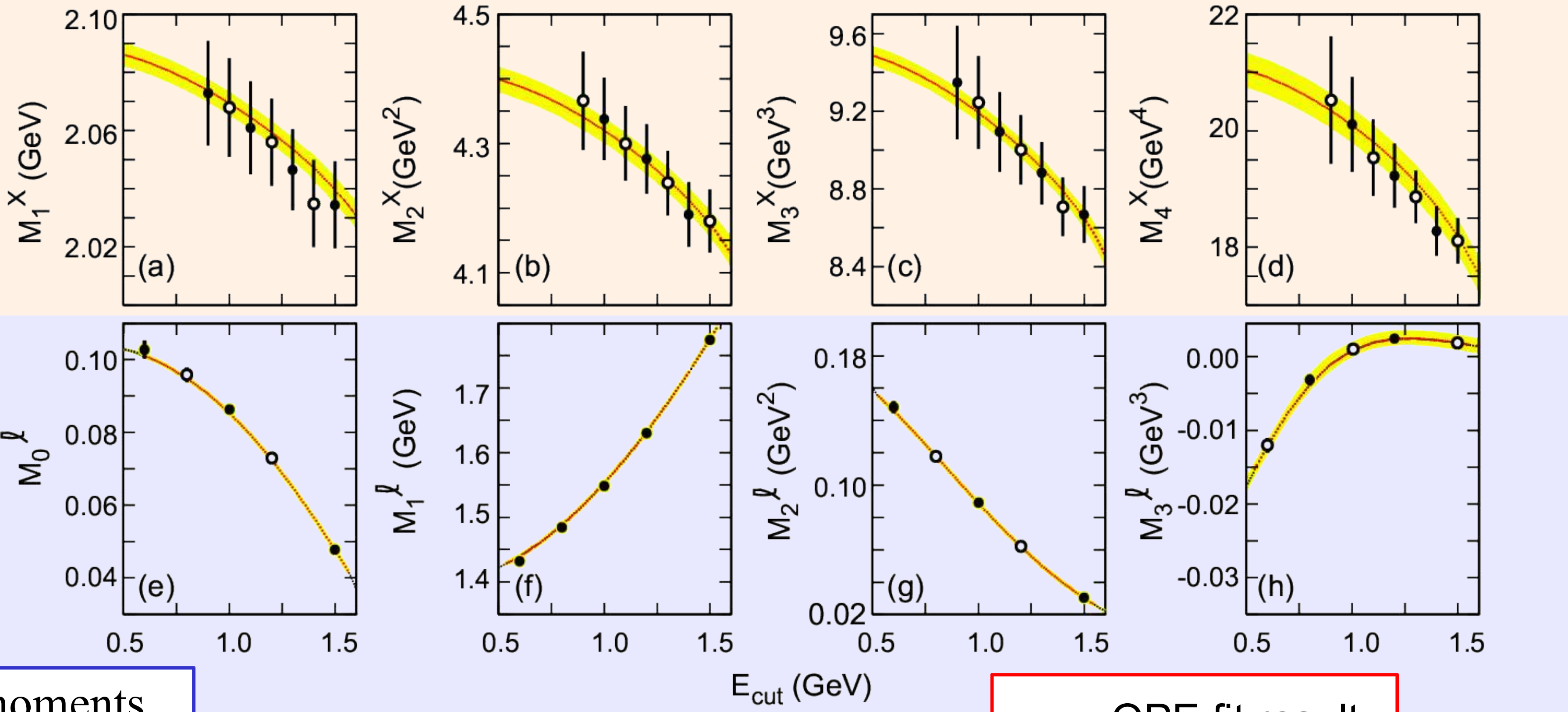
|Vcb| - Combined OPE fit

PRL 93:011803

● = used in fit
○ = not used in fit
(cross check: switch ●↔○)

m_X moments

$\chi^2/\mathrm{ndf} = 15/20$



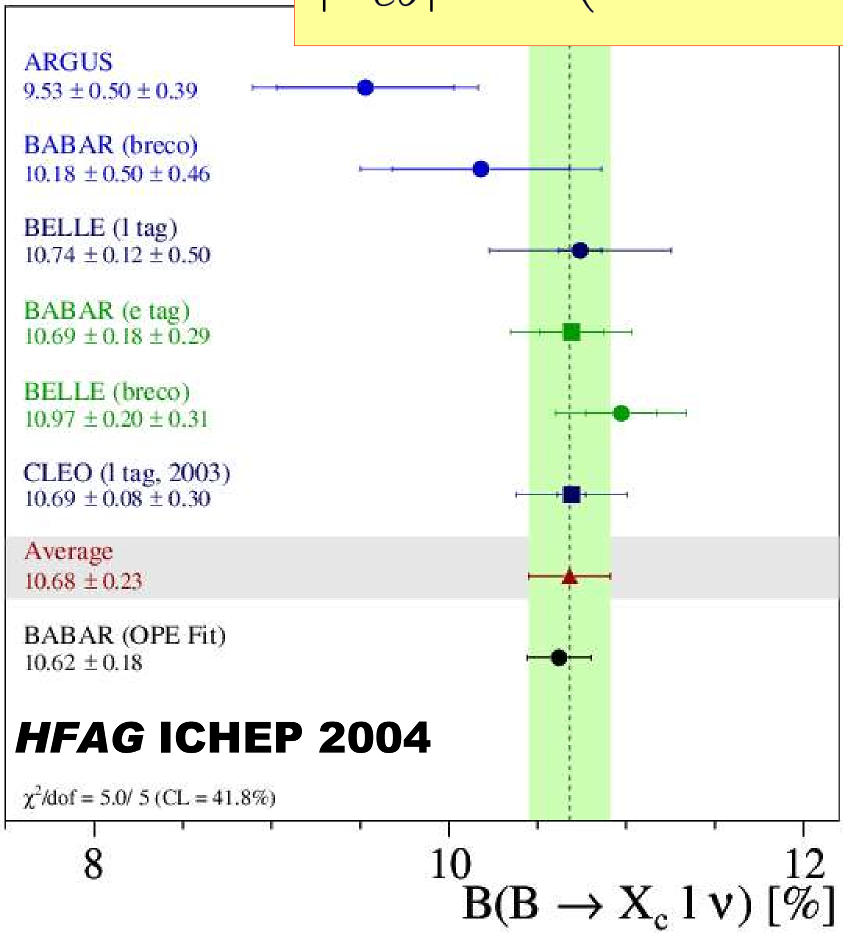
E_ℓ moments

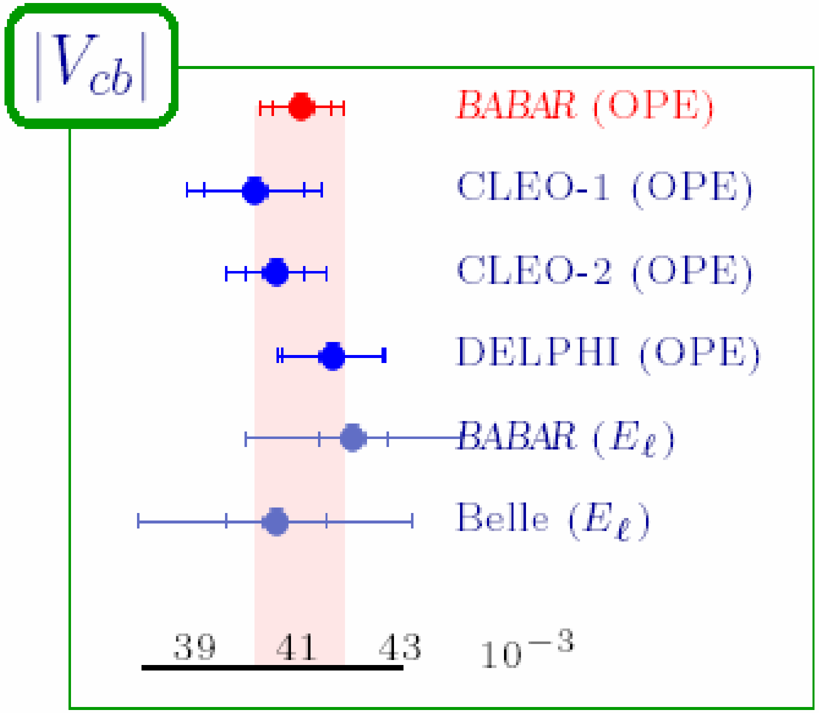
= OPE fit result
= theory errors

Inclusive |Vcb| Results

|Vcb| is measured up to ±2%:

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





$b \rightarrow u\, l\, \nu$ decays and $|V_{ub}|$

Challenging, because:

- $B \rightarrow X_c\, l\, \nu$ background 50 times higher
- signal can only by analyzed in limited region of phase space
- need theory to extrapolate to full rate or calculate partial rate

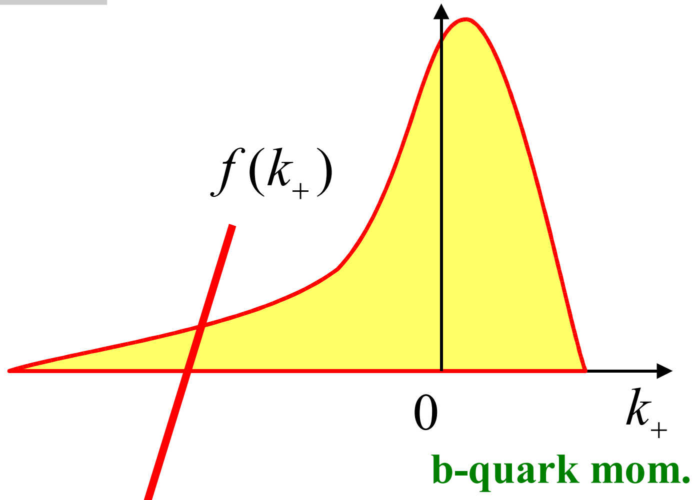
BABAR can present a set of internally consistent analyses,
using different approaches to reduce uncertainties and check consistency:

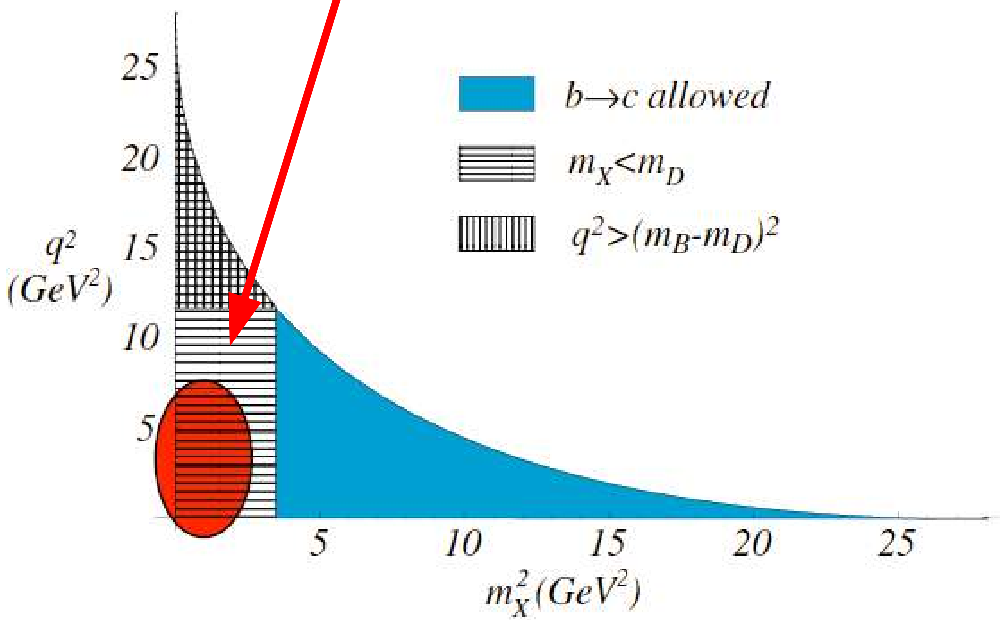
• Lepton endpoint, E_l	inclusive, untagged
• E_l vs q^2	add "neutrino reconstruction"
• m_X	tag with fully-reconstructed B mesons
• m_X vs q^2	dito, reduce uncertainties in theory
• hadronic moments	unfold detector response and calculate M_1, M_2'

Non-perturbative Effects (aka. Shape Function)

- OPE doesn't hold everywhere in the phase space
  - Fermi motion of b quark inside B meson
  - shape functions $f(k_+)$ (SF) describe non-perturbative effects
  - Problems:
    - need to parameterize SF
    - need to measure parameters
    - sub-leading shape functions
  - parameters can be measured from the moments of the photon energy spectrum in $b \to s\gamma$ decays

    BELLE: (exponential SF)
    - Λ^{SF} = 0.66 GeV
    - λ_1^{SF} = 0.40 GeV^2

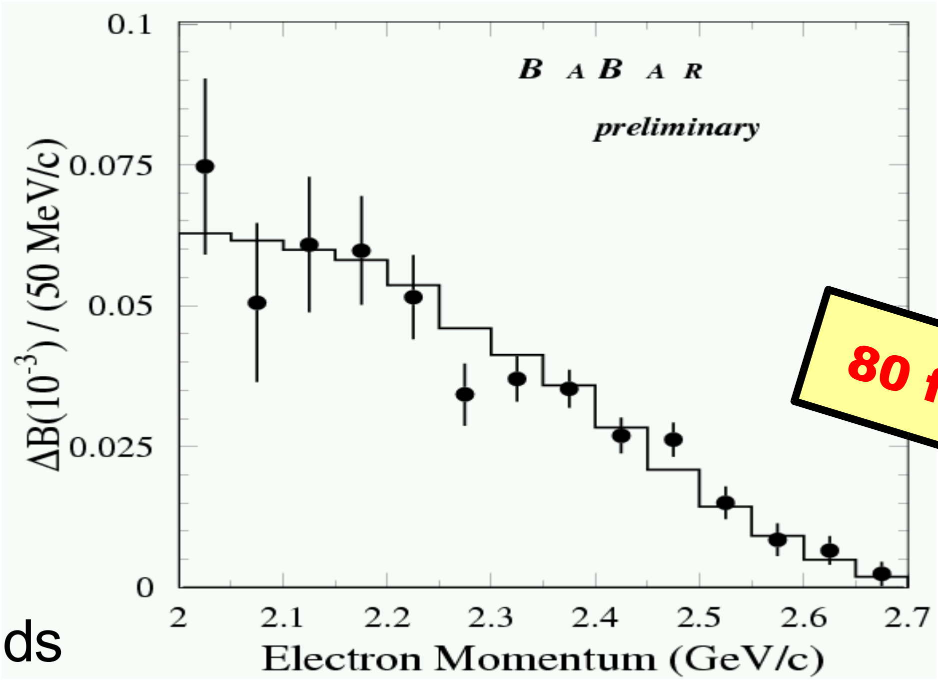




$|V_{ub}|$ - Lepton endpoint

hep-ex/0408075

- Electrons in energy range
  $2.0 < E_l < 2.6$GeV
- cut on
  - event shapes
  - missing momentum
  - subtract continuum using
    - off-peak data
    - on-peak for $E_l > 2.8$GeV



80 fb^{-1}

- Fit E_l spectrum with BBbar backgrounds from charm ($De\nu$, $D^*e\nu$, $D^{**}e\nu$, $D^{(*)}\pi e\nu$, non-resonant, and $X_u e\nu$)

partial BF = $(4.85 \pm 0.29_{(stat)} \pm 0.53_{(syst)}) \times 10^{-4}$

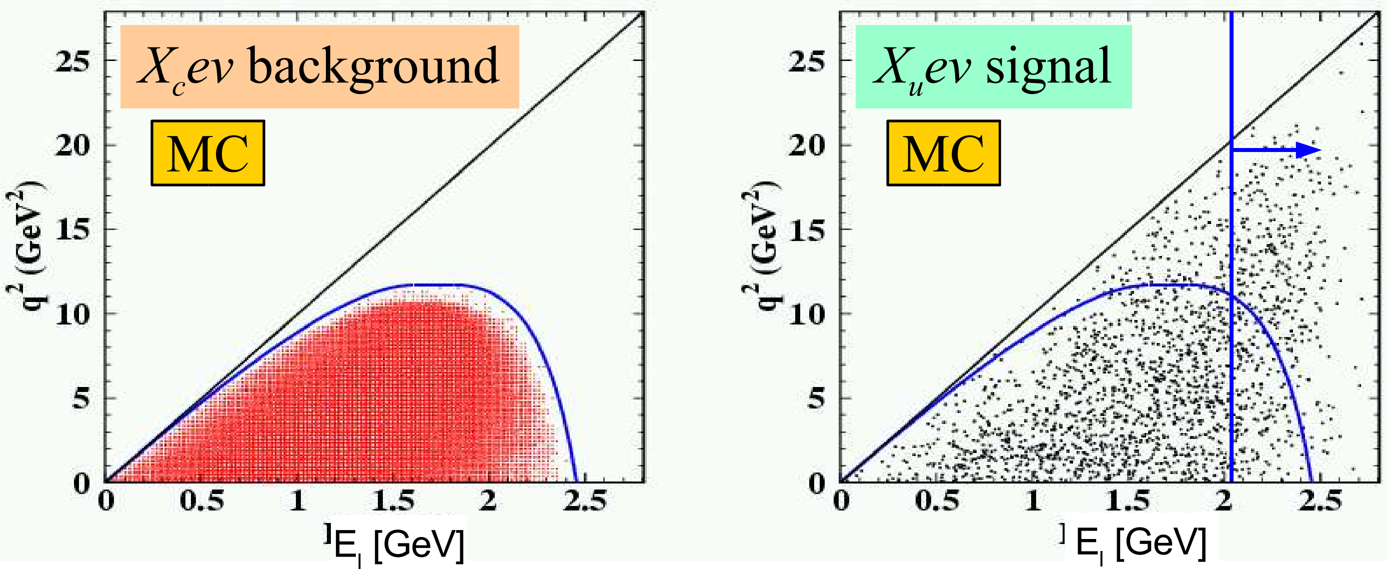
$|Vub| = (4.40 \pm 0.13_{(stat)} \pm 0.25_{(syst)} \pm 0.38_{(theo)}) \times 10^{-3}$

$|V_{ub}|$ - E_l versus q^2

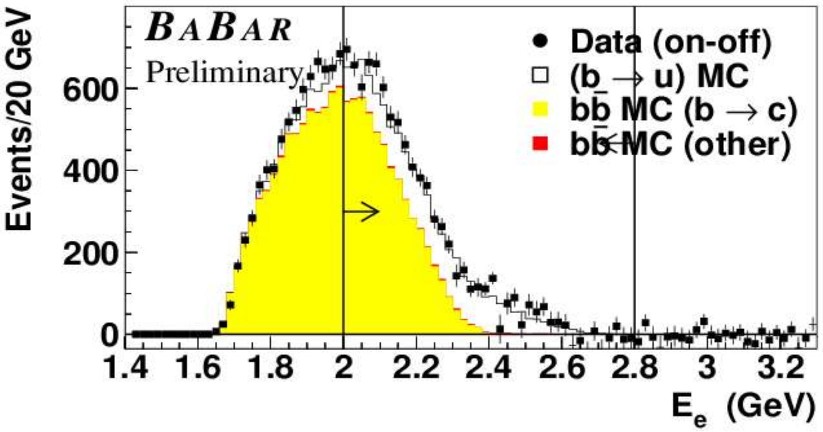
hep-ex/0408045

$$s_h^{max} = m_B^2 + q^2 - 2m_B E_e \sqrt{\frac{1 \mp \beta}{1 \pm \beta}} - 2m_B \left(\frac{q^2}{4E_e}\right)\sqrt{\frac{1 \pm \beta}{1 \mp \beta}}$$

with boost β=0.06



80 fb^{-1}

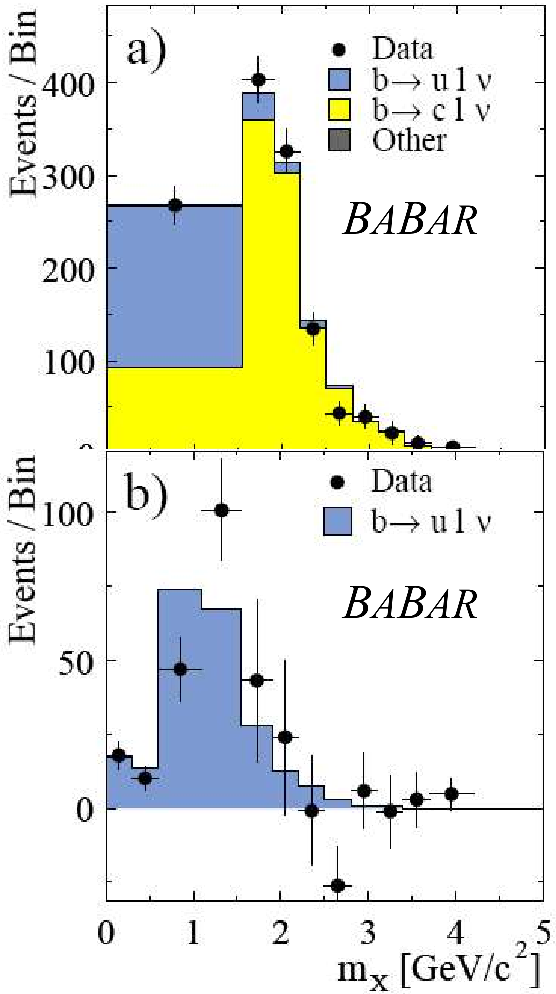


$$B = (2.76 \pm 0.26_{stat} \pm 0.50_{syst}{}^{+0.21}_{-0.26 SF}) \times 10^{-3}$$

$$|V_{ub}| = (4.99 \pm 0.48_{exp}{}^{+0.18}_{-0.23 SF} \pm 0.22_{OPE}) \times 10^{-3}$$

$|V_{ub}|$ - m_X spectrum

hep-ex/0408068



- Use fully-reconstructed B events
- reconstruct m_X of the recoil system analog to $b \to c l \nu$
- Background modelling from simulation
- Fit m_X signal+background to data
- Integrate background subtracted m_X-spectrum up to m_X = 1.55GeV
- Extract |Vub| following the DeFazio-Neubert[1] approach

80 fb^{-1}

$$\mathcal{B}(B \to X_u l \nu) = (2.81 \pm 0.32_{stat} \pm 0.31_{sys} {}^{+0.23}_{-0.21}{}_{theo}) \times 10^{-3}$$

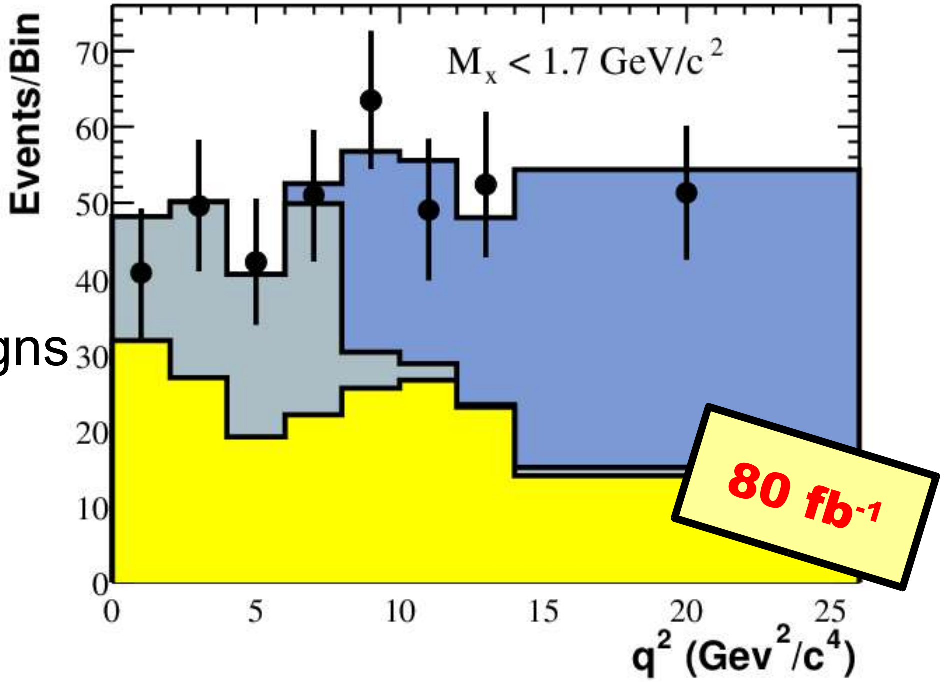
$$|V_{ub}| = (5.22 \pm 0.30_{stat} \pm 0.31_{syst} \pm 0.43_{theo}) \times 10^{-3}$$

[1] DeF. N. JHEP 06, 017 (1999)

$|V_{ub}|$ - m_X versus q^2

hep-ex/0408068

- Ansatz analog to E_l versus q^2
  - this aproach has a potentially smaller theoretic uncertainty
  - avoids phase space region where SF reigns
- Experimental technique similar to previous analysis (m_X)
  - but: need to determine partial branching fraction as function of q^2
- Extract |Vub| following the aproach of Bauer, Ligeti, Luke (BLL hep-ph/0111387):



$$|V_{ub}| = \sqrt{\frac{192\pi^3}{\tau_B G_F^2 m_b^5} \frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})}{G}}$$

$$\Delta BF = (0.90 \pm 0.14_{(stat)} \pm 0.14_{(syst)} \pm 0.02_{(theo)}) \times 10^{-3}$$

$$|Vub| = (4.98 \pm 0.4_{(stat)} \pm 0.39_{(syst)} \pm 0.47_{(theo)}) \times 10^{-3}$$

$|V_{ub}|$ - Unfolding the m_X spectrum

hep-ex/0408068

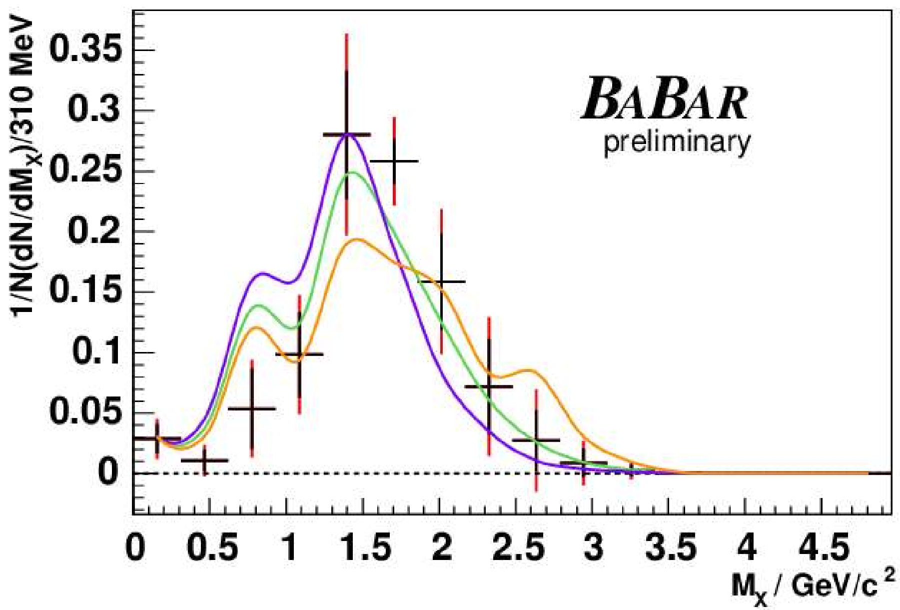
In order to turn the measured m_X spectrum into an observable which can be

- compared to other experiments, and
- used to extract spectral moments

it is necessary to unfold the detector response.

80 fb^{-1}

	M_{max}	value
M_1	<1.86	1.355 ± 0.084
M_2'	<1.86	0.147 ± 0.034
M_1	<5.0	1.584 ± 0.233
M_2'	<5.0	0.270 ± 0.099



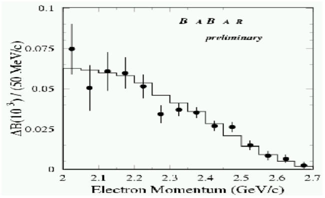
With more statistics:

→ crosscheck OPE fit results

→ check consistency with SF parameterization

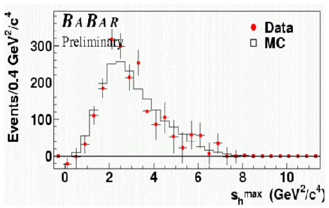
Summary

|Vub|



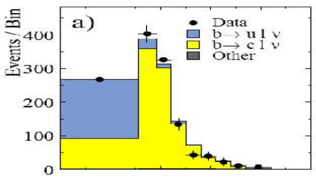
Lepton Endpoint

$4.40 \pm 0.28_{(exp)} \pm 0.38_{(theo)}$



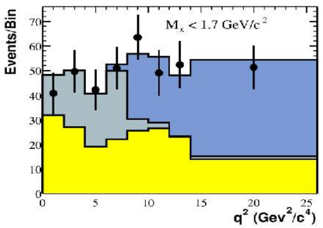
E_l vs. q^2

$4.99 \pm 0.48_{(exp)} \pm 0.32_{(theo)}$



m_X spectrum

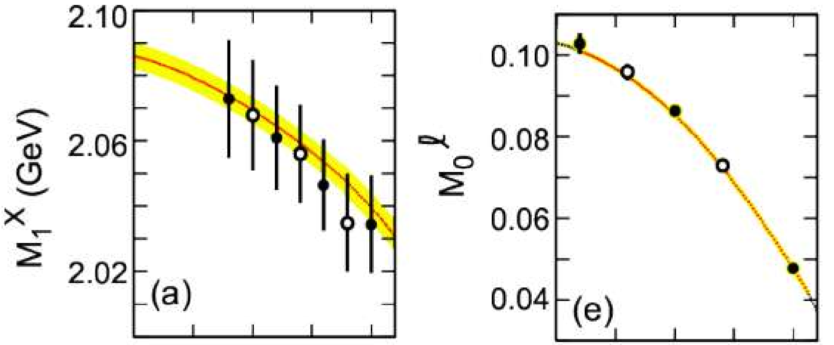
$5.22 \pm 0.42_{(exp)} \pm 0.43_{(theo)}$



m_X vs. q^2

$4.98 \pm 0.54_{(exp)} \pm 0.47_{(theo)}$

|Vcb|



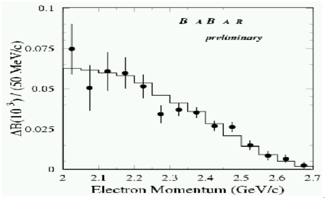
OPE fit to E_l and m_X moments:

$|Vcb| =$

$(41.4 \pm 0.4_{exp} \pm 0.4_{HQE} \pm 0.6_{theo}) \times 10^{-3}$

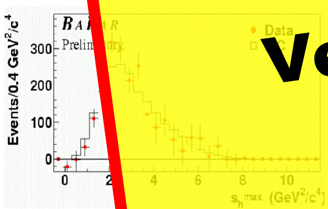
Summary

|Vub|



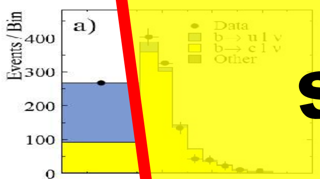
Lepton Endpoint

$4.40 \pm 0.28_{(exp)} \pm 0.38_{(theo)}$



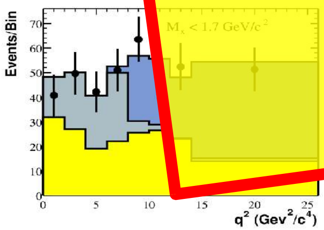
E_l vs. q^2

… $0.46_{(exp)} \pm 0.32_{(theo)}$



m_X spectrum

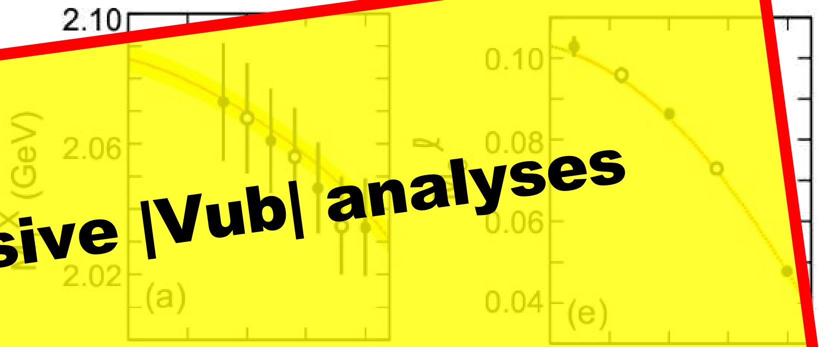
$5.22 \pm 0.42_{(exp)}$ … $_{(theo)}$



m_X vs. q^2

$4.98 \pm 0.54_{(exp)} \pm 0.47_{(theo)}$

|Vcb|



OPE fit to E_l and m_X moments:

$|V_{cb}| =$

$(41.4 \pm 0.4_{exp} \pm 0.4_{HQE} \pm 0.6_{theo}) \times 10^{-3}$

Very soon:
new / updated exclusive |Vub| analyses

Soon:
new results with b→sγ from BABAR

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

Gambino & Uraltsev hep-ph/0401063 & 0403166

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

$$B_{cl\nu} = (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\%$$

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

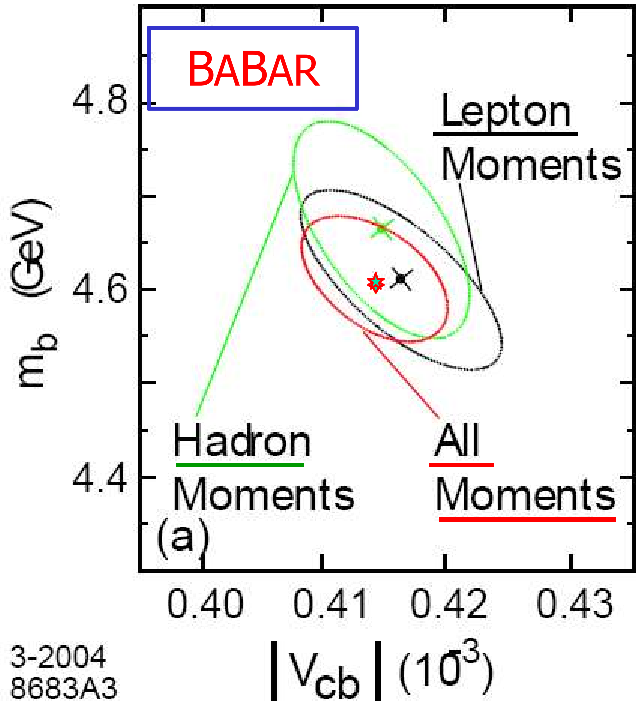
$$m_c = (1.18 \pm 0.07_{exp} \pm 0.06_{HQE} \pm 0.02_{\alpha_s})\,GeV$$

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

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

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

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



- 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