Semileptonic B Decays and Determination of CKM parameters $|V_{ub}|$ and $|V_{cb}|$

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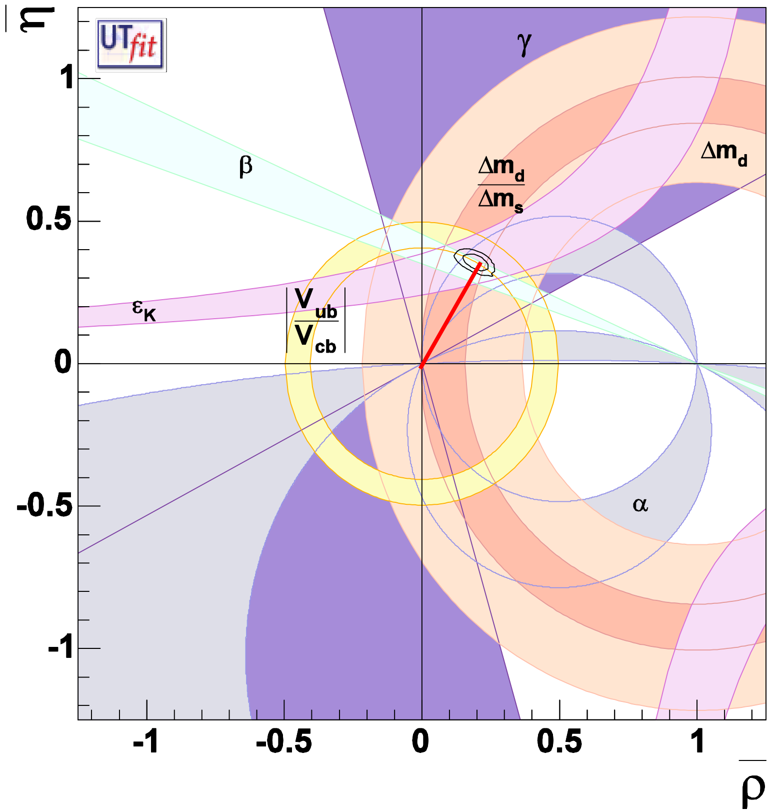
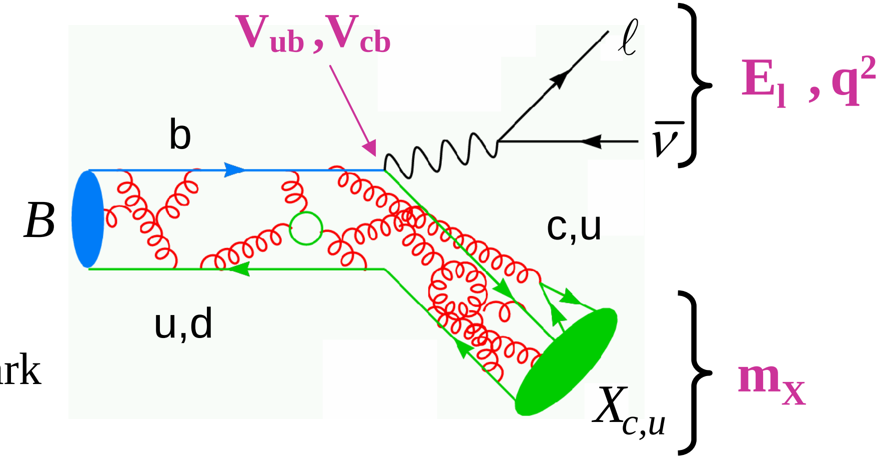
Pascos 06 , September 10-15 2006

Semileptonic B decays: why are they interesting

$|V_{ub}/V_{cb}|$ complements $\sin 2\beta$ to test (in)completeness of the SM

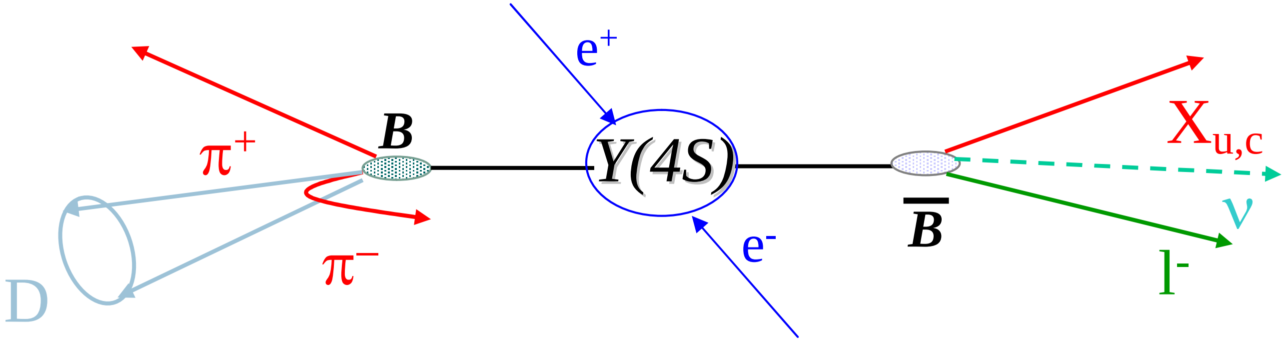


- Leptonic and hadronic currents factorize
- Sensitive to strong interactions in B mesons
  - Study structure of B meson
  - Allow test of e.g. Lattice QCD
- Two experimental approaches:
  - Inclusive: select lepton and look at the rest of the event inclusively
  - Exclusive : reconstruct hadronic final states X
  - Theoretical uncertainties complementary



- Semileptonic B decays provide the best method to measure $|V_{ub}|$ and $|V_{cb}|$
  - Simple theoretical description at parton level
  - Rates depend on CKM matrix element and quark masses

Experimental approaches to measuring $B \to X l \nu$



technique	pros/cons
untagged • no constraint on 'other' B meson • fully reconstruct signal side (ν reco)	• high statistics • high background
semileptonic tag • reconstruct $B \to D^{(*)} l \nu$ on the tag-side • tag-B kinematics incomplete → 2 ν	• improved purity compared to untagged
hadronic tag • fully reconstruct hadronic decay $B \to D^{(*)} Y$ (many modes) on the tag-side • known kinematics of signal B	• maximum purity • low efficiency

$b \rightarrow cl\nu$ decays and $|V_{cb}|$

$|V_{cb}|$ from $B \to D^* l \nu$ decays

$B \to D^* l \nu$ decay rate is given by

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} (F(w))^2 G(w)$$

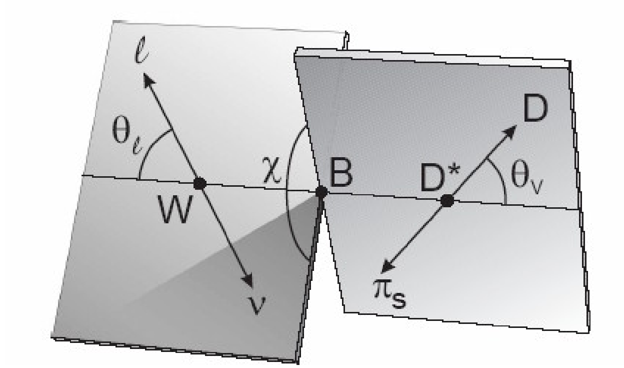
form factor

phase space

D^* boost in the B rest frame

- decay can be experimentally characterized by 4 kinematic variables: $\theta_\ell \;\; \theta_V \;\; \chi \;\; w$

- characterize the Form Factors by measuring their ratios $R_1(w)$ and $R_2(w)$ and slope at $w=1$ ρ^2



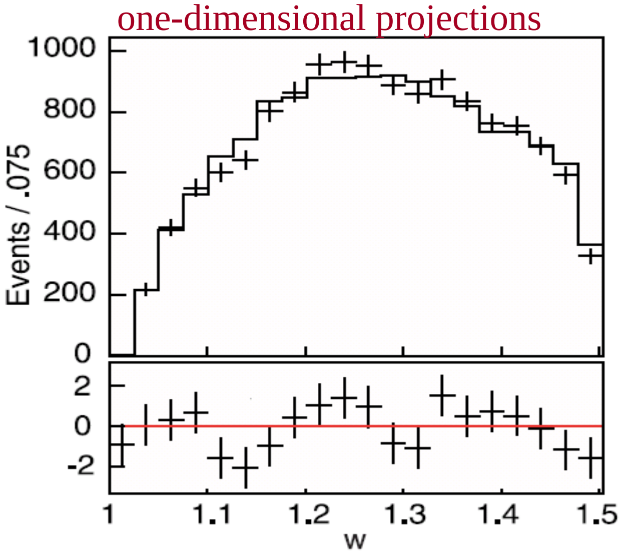
Extract R_1, R_2 and ρ^2 from multi-dimensional fit to differential decay rate

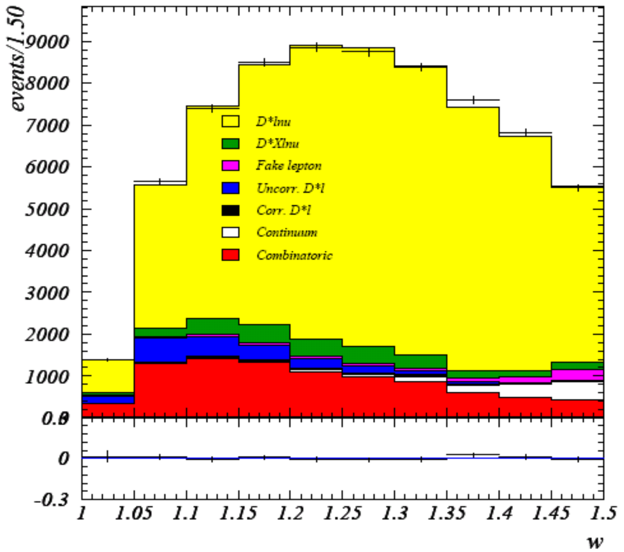
$B^0 \to D^{*-} l^+ \nu$ Form Factors measurement

79 fb^{-1}

- select $D^{*-}e^+\nu$ events ($D^{*-} \to D^0\pi^-$, $D^0 \to K\pi$)
- combinatoric background from $\Delta m = m(D^0\pi) - m(D)$ fit
- reduce D** model dependence by estimating D** background fraction by fitting $\cos\theta_{BY}$ on data
- fit to the four-dimensional decay distribution

BABAR-CONF-05/05 hep-ex/0602023





- select $D^{*-}l^+\nu$ events ($D^{*-} \to D^0\pi^-$, $D^0 \to K\pi$, $K\pi\,\pi^0$, $K\pi\pi\pi$)
- selection criteria and background estimation as in the previous analysis
- simultaneous χ^2 fit to one-dimensional projections

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Form Factors and $|V_{cb}|$ results combination

combination of two different analyses of the decay $B^0 \rightarrow D^{*-} l^+ \nu$

statistical overlap between the two analyses is small

our combinations :

$$\mathcal{B}(B^0 \rightarrow D^{*-}\ell^+\nu_\ell) = (4.77 \pm 0.04 \pm 0.39)\%$$

R_1= 1.417 ± 0.061 ± 0.044

R_2= 0.836 ± 0.037 ± 0.022

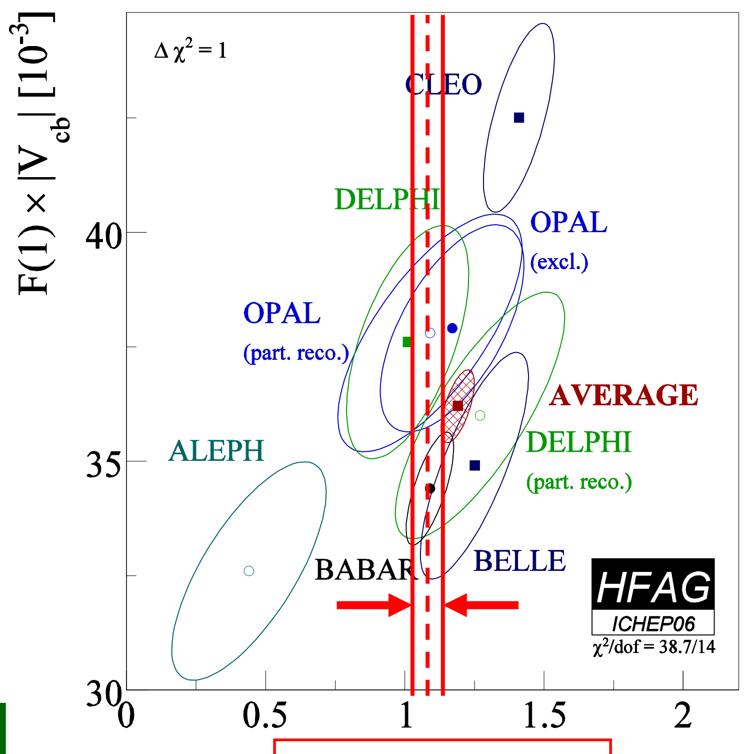
ρ^2= 1.179 ± 0.048 ± 0.028

factor ~5 improvement wrt CLEO result (PRL 76 (1996) 3898)

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$$

from lattice calculation

$$|V_{cb}| = (37.47 \pm 0.35_{stat} \pm 1.25_{syst} {}^{+1.23}_{-1.44}{}_{theo}) \times 10^{-3}$$

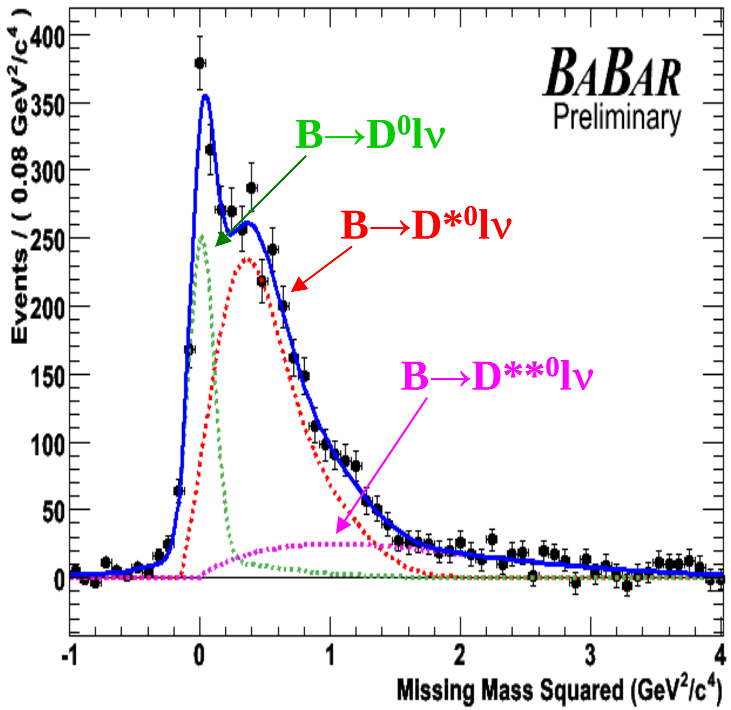


New BABAR FF

$\Gamma(B^- \to D^{(*,**)}l\nu)/\Gamma(B^- \to DXl\nu)$ measurement

211 fb^{-1}

- measure simultaneously D, D* and D** components in the $B^- \to DXl\nu$ sample
- hadronic data
- global χ^2 fit to : missing mass squared, lepton momentum, additional charged track multiplicity
- PDF to fit $B^- \to DXl\nu$ built from exclusive $B^- \to D^{(*,**)}l\nu$ distributions on data



$$\Gamma(B^- \to D^0 l\nu)/\Gamma(B^- \to DXl\nu) = 0.210 \pm 0.017 \pm 0.021$$

$$\Gamma(B^- \to D^{*0} l\nu)/\Gamma(B^- \to DXl\nu) = 0.611 \pm 0.022 \pm 0.027$$

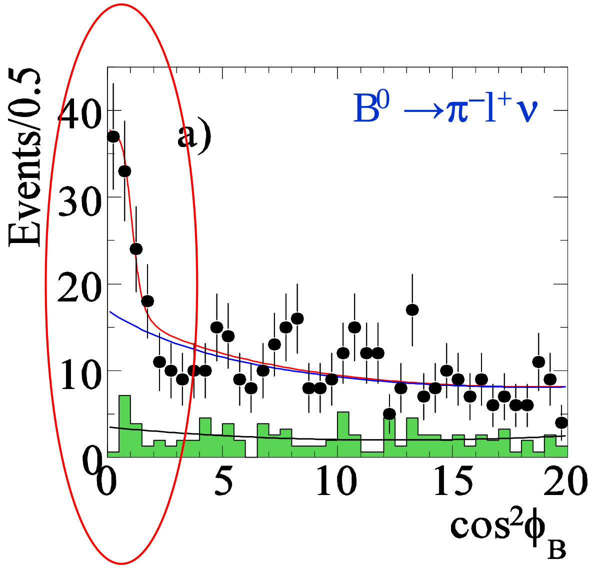
$$\Gamma(B^- \to D^{**0} l\nu)/\Gamma(B^- \to DXl\nu) = 0.173 \pm 0.017 \pm 0.021$$

- first BaBar measurement
- highest precision

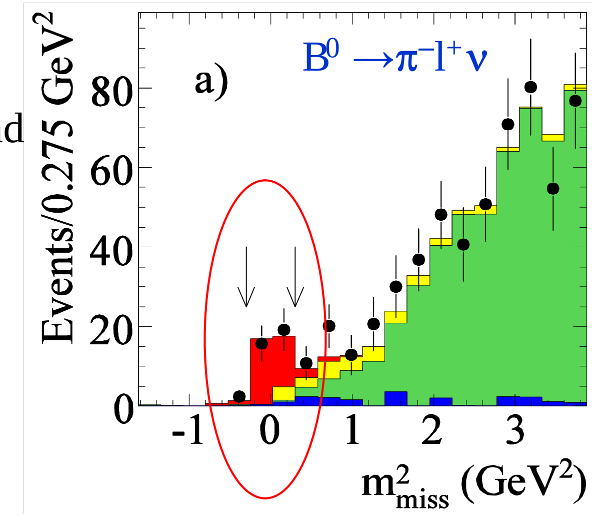
$b \to u l \nu$ decays and $|V_{ub}|$

$B \to \pi l \nu$: semileptonic + hadronic tags

211 fb^{-1}



- use semileptonic or hadronic tagged B
- identify a signal lepton (right charge) and search for a pion among the remaining particles
- no additional tracks and (low) neutral energy
- fit to to the $\cos^2\phi_B$ or the missing mass squared distribution



Extract the signal in q^2 bins to measure Form Factor shape and reduce model dependence

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 \, p_\pi^3 \, |f_+(q^2)|^2$$

Needs to combine 4 measurements: $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \pi^0 l^+ \nu$ using hadronic and semileptonic tags assuming isospin symmetry $\Gamma(B^0 \to \pi^- l \nu) = 2 \times \Gamma(B^+ \to \pi^0 l \nu)$:

- statistical errors are uncorrelated
- most systematic errors fully correlated

BABAR-CONF-06/015
hep-ex/0607060

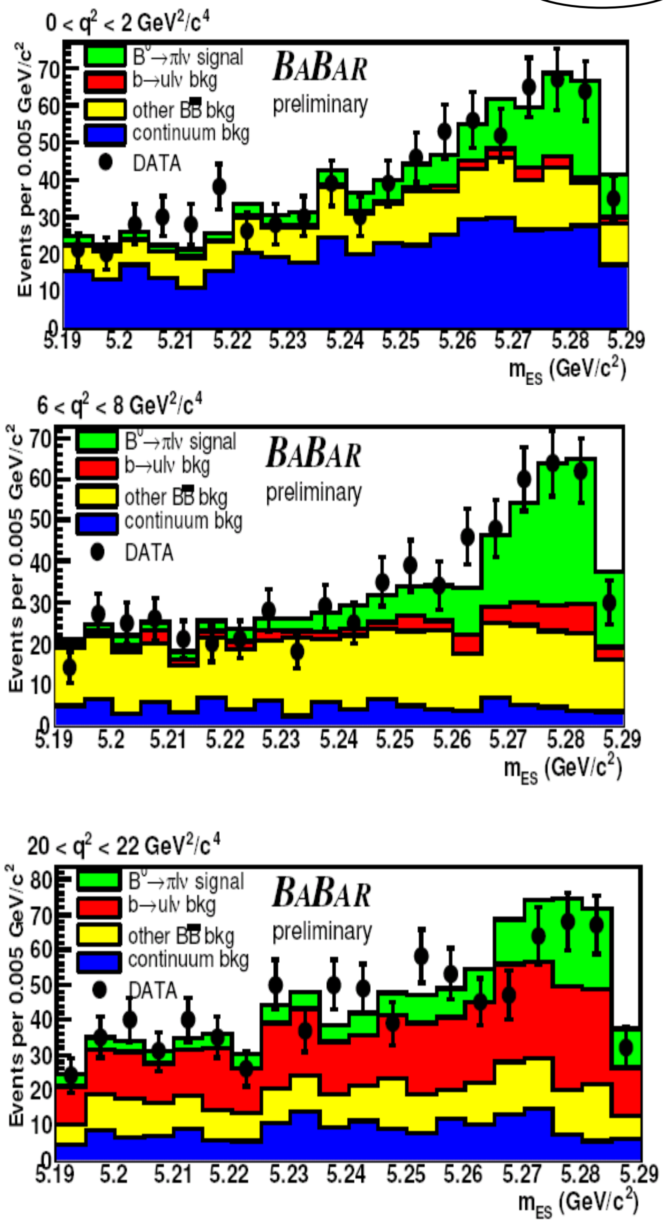
$B \to \pi l \nu$: untagged

206 fb^{-1}

- need for ν reconstruction from full event

compared with previous untagged analysis(PRD72, 051102) what is new in this approach:

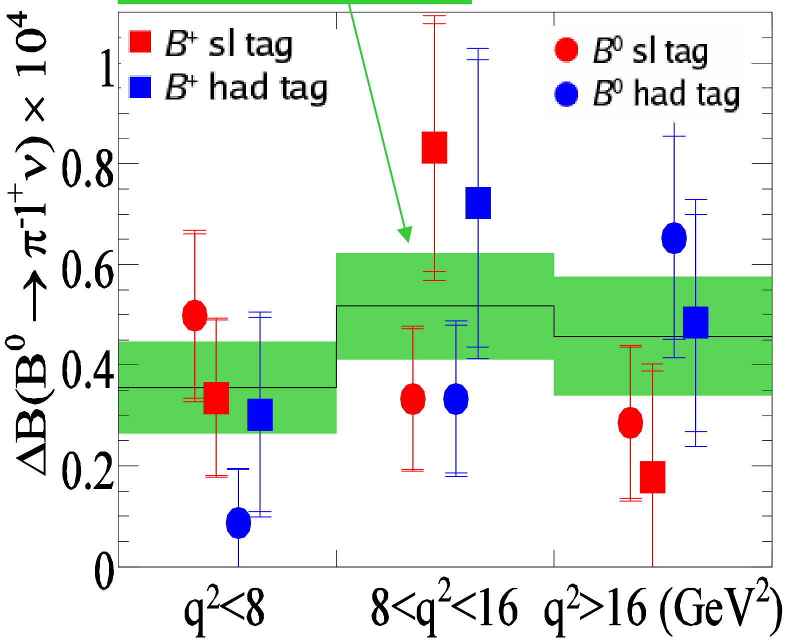
- no 'neutrino quality' cuts :
  - increased signal efficiency : 5 → 25 signal ev./fb^{-1} , somewhat higher background
  - use $q^2 = (p_B - p_\pi)^2$ instead of $q^2 = (p_l + p_\nu)^2$
- fit signal+background in $\Delta E - m_{ES}$ on 12 signal bins of q^2

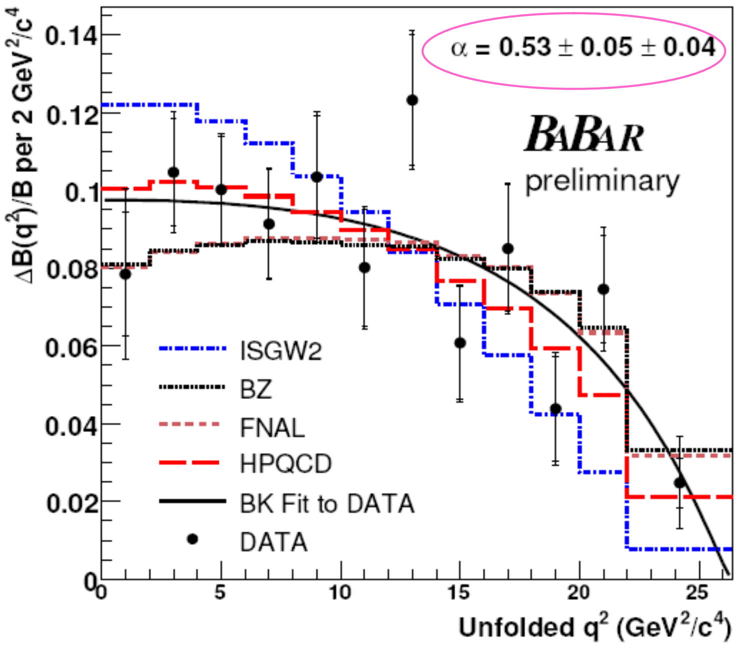


BABAR-CONF-06/015 hep-ex/0607060
PRD73, 012006 (2006)

$B \to \pi l \nu$ and $|V_{ub}|$: results

combination + errors





$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.33 \pm 0.17_{stat} \pm 0.11_{syst}) \times 10^{-4}$$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.44 \pm 0.08_{stat} \pm 0.10_{syst}) \times 10^{-4}$$

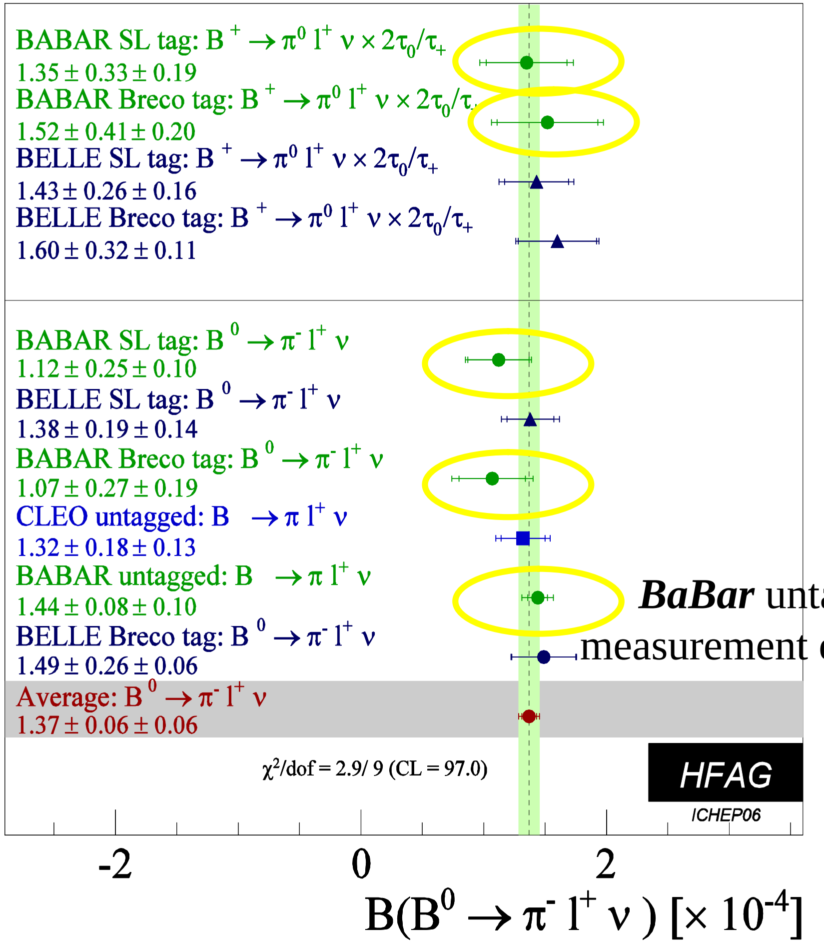
compare shape with theo. predictions

	q^2 (GeV^2/c^4)	$\lvert V_{ub}\rvert$ (10^{-3}) (tagged)	$\lvert V_{ub}\rvert$ (10^{-3}) (untagged)
Ball-Zwicky [6]	< 16	$3.2 \pm 0.2 \pm 0.1^{+0.5}_{-0.4}$	$3.6 \pm 0.1 \pm 0.1^{+0.6}_{-0.4}$
HPQCD [3]	> 16	$4.5 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$	$4.1 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}$
FNAL [4]	> 16	$4.0 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$	$3.6 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}$
APE [5]	> 16	$4.1 \pm 0.5 \pm 0.3^{+1.6}_{-0.7}$	$3.7 \pm 0.2 \pm 0.2^{+1.4}_{-0.7}$

tagged **untagged**

QCD calculation	stat+syst errors χ^2	$Prob(\chi^2)$ (%)	
ISGW2 [7]	34.1	0.07	incomp.
Ball-Zwicky [6]	13.0	37.2	good agreement
FNAL [4]	12.5	41.0	good agreement
HPQCD [3]	10.2	60.2	good agreement

exclusive $|V_{ub}|$: summary



BaBar untagged measurement dominant

$$\mathrm{BR}(B^0 \to \pi^- \ell^+ \nu) = (1.37 \pm 0.06 \ \pm 0.06\ )\times 10^{-4}$$

World average

exclusive $|V_{ub}|$: averages from HFAG

HPQCD , $q^2 > 16$ GeV^2

$$|V_{ub}| = (3.93 \pm 0.26_{\exp}{}^{+0.59}_{-0.41\,theo(FF)})\times 10^{-3}$$

Ball-Zwicky , $q^2 < 16$ GeV^2

$$|V_{ub}| = (3.38 \pm 0.12_{\exp}{}^{+0.56}_{-0.37\,theo(FF)})\times 10^{-3}$$

errors for exclusive $|V_{ub}|$ dominated by FF uncertainty

BABAR-CONF-06/026
hep-ex/0607066

B→ηlν and B→η'lν with hadronic tag

315 fb^{-1}

Independent measurements of various B → X_u l ν decay modes important to further constraint theoretical models

- hadronic tag
- reconstruction of recoil :
  - Lepton momentum in the B_{recoil} rest frame: p*> 0.5 GeV/c for electrons and p*> 0.8 GeV/c for muons
  - meson reconstructed in

$\eta \to \gamma\gamma$

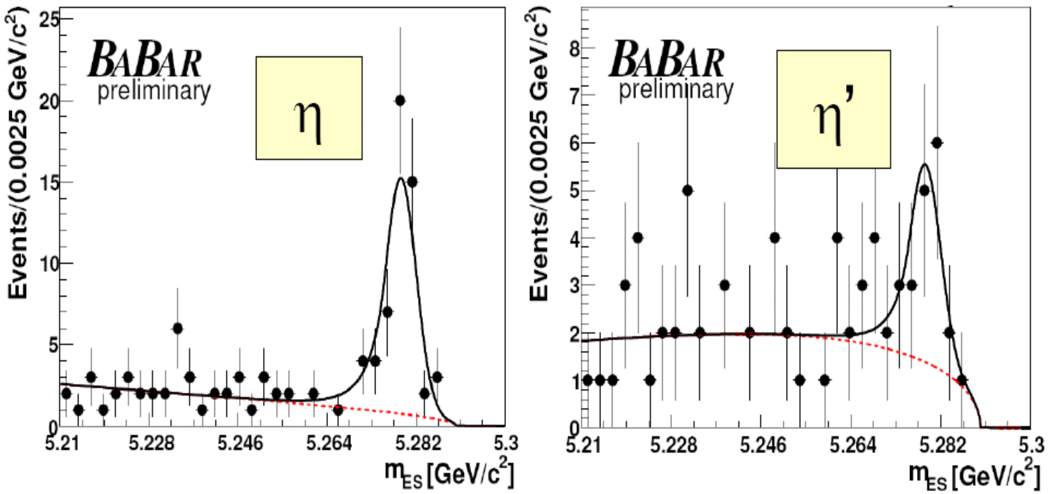
$\eta \to \pi^+\pi^-\pi^0$

$\eta \to \pi^0\pi^0\pi^0$

$\eta' \to \rho\gamma$

$\eta' \to \eta\pi^+\pi^-$

- fit to m_{ES} distributions to extract signal yields



$\mathcal{BR}(B^+ \to \eta\, l^+\nu) < 1.4 * 10^{-4}$ (90% *CL*)

$\mathcal{BR}(B^+ \to \eta l^+\nu) = (0.84 \pm 0.27_{stat} \pm 0.21_{syst}) * 10^{-4}$

$\mathcal{BR}(B^+ \to \eta'\, l^+\nu) < 1.3 * 10^{-4}$ (90% *CL*)

still limited by statistics

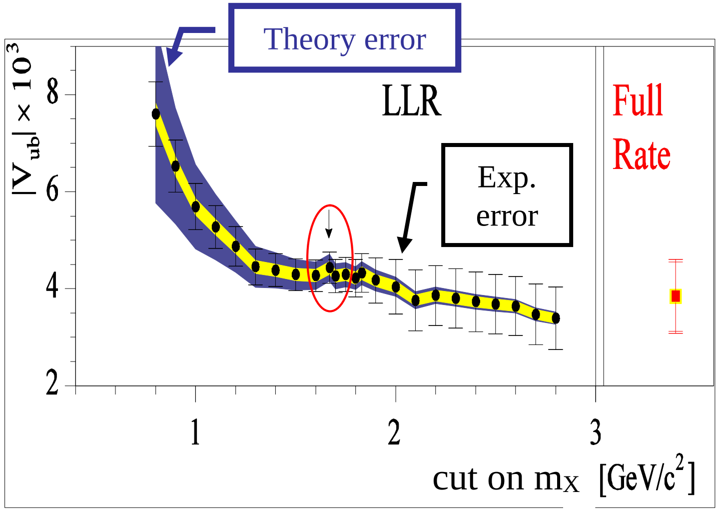
80 fb^{-1}

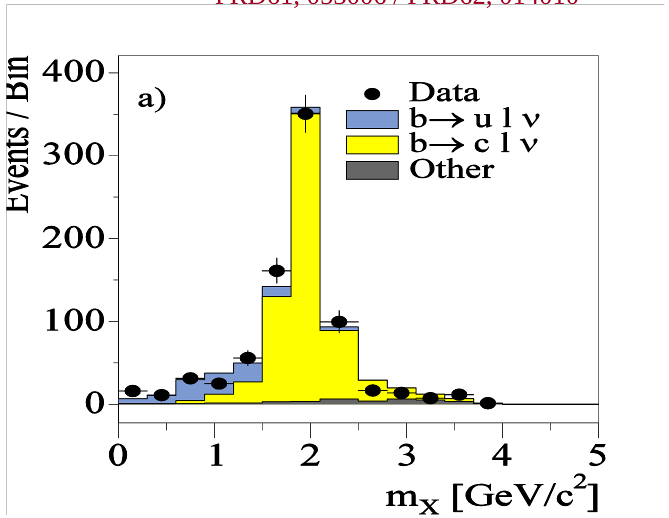
Inclusive $|V_{ub}|$ with reduced Shape Function dependence

previous inclusive |Vub| results had large uncertainties due to Shape Function parameters (b quark motion inside B meson) measured in $b \to s\gamma$ and $b \to cl\nu$ decays

- measure m_X spectrum; use two approaches to reduce Shape Function dependence
  - Relating $b \to ul\nu$ to $b \to s\gamma$ using weight functions
  - Measure full rate

Leibovich,Low and Rothstein:
PRD61, 053006 / PRD62, 014010





LLR : $M_X < 1.67$ GeV:

$$|V_{ub}| = (4.43 \pm 0.38_{stat} \pm 0.25_{syst} \pm 0.29_{theo}) \times 10^{-3}$$

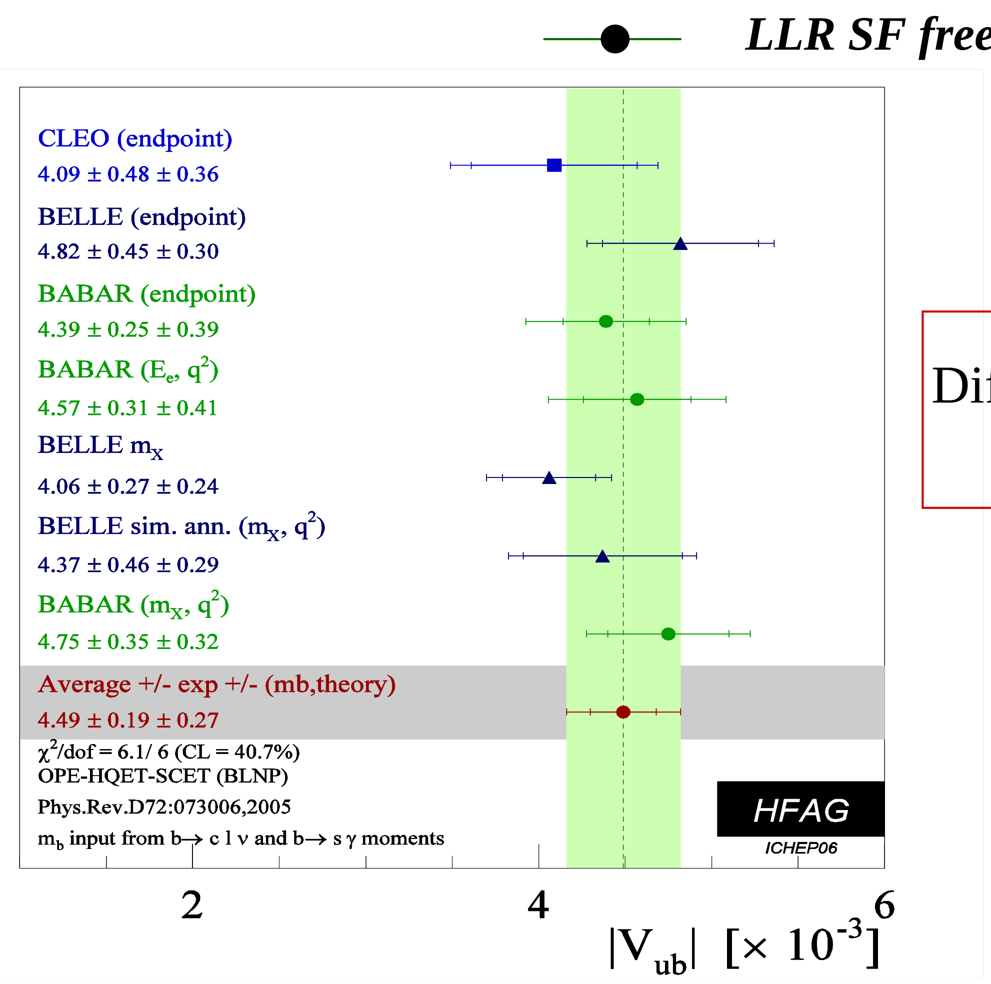
HQE : $M_X < 2.50$ GeV:

$$|V_{ub}| = (3.84 \pm 0.70_{stat} \pm 0.30_{syst} \pm 0.10_{theo}) \times 10^{-3}$$

Standard local HQE for full rate:
Uraltsev hep-ph/9905520
Hoang,Ligeti, Manohar
PRD 59, 074017 (1999)

reduced theory error as no extrapolation to full rate necessary

inclusive $|V_{ub}|$: summary



Different theoretical approaches (BNLP, DGE, LLR) give consistent results

inclusive $|V_{ub}|$ world average

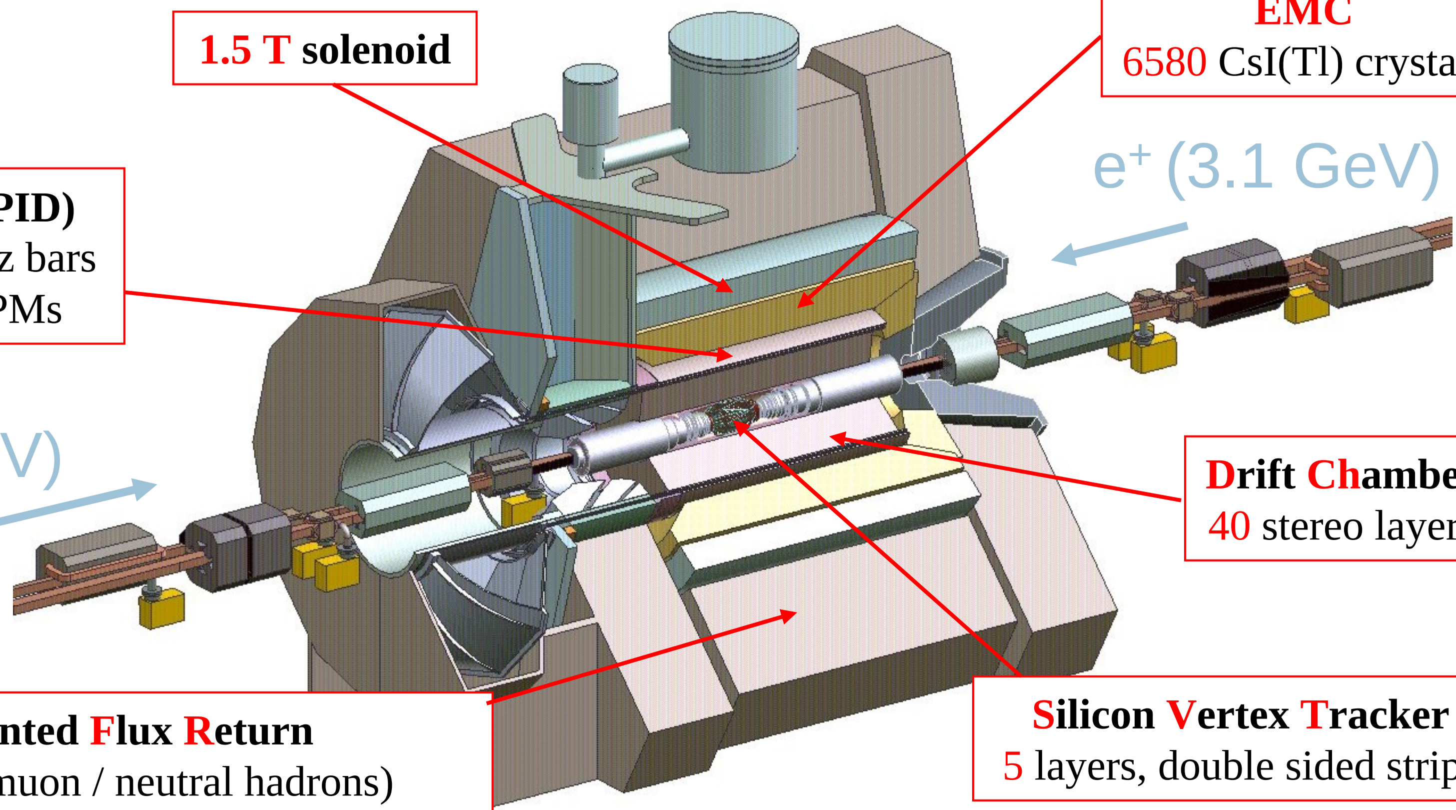
using BNLP and SF from b→clν and b→sγ

Summary

- new BaBar $B \to D^* l\nu$ form factors and improved $|V_{cb}|$ measurements
- first direct BaBar measurements of $\Gamma(B^- \to D^{(***)} l\nu) / \Gamma(B^- \to DXl\nu)$: currently most precise
- new exclusive $|V_{ub}|$ determination :
    - tag analysis : combined results comparable precision as published untagged measurement
    - new untagged ν reco analysis : most precise measurement for $BR(B \to \pi\, l\, \nu)$ to date and dominate the current world average
- new inclusive $|V_{ub}|$ determination : results consistent with previous measurements
    - Shape Function ‘independent’ $|V_{ub}|$ extraction

Backup Slides

The BaBar Detector



exclusive SL decays: theory

Theory must predict form factors to describe hadronization process

$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2\, p_\pi^3 \left|f_+(q^2)\right|^2$$

<u>Theoretical models</u>:

✓Light Cone Sum Rules (Phys. Rev. **D71**, 014015(2005))

  ✓valid for $q^2 < 14$ GeV^2

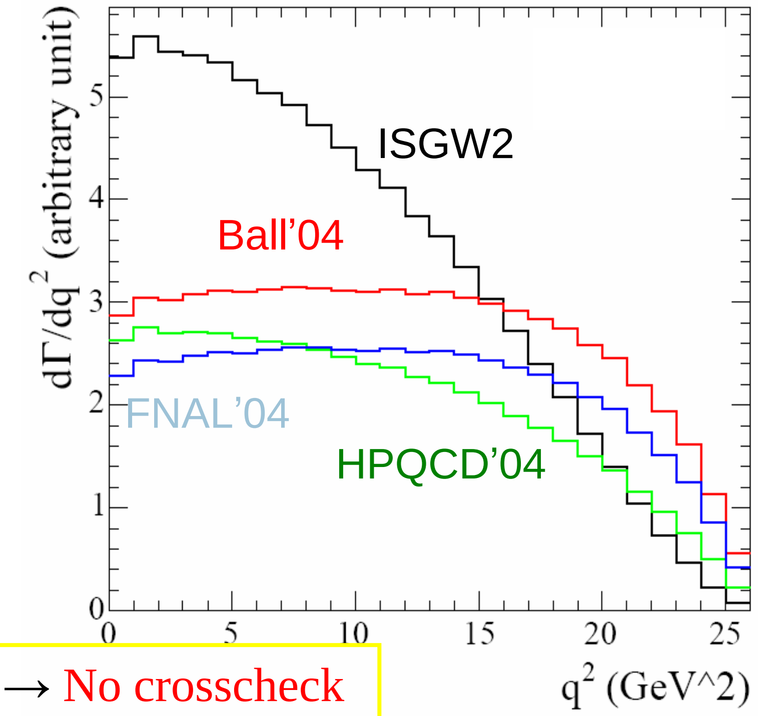
✓Lattice QCD

  ✓<u>unquenced</u> calculation by HPQCD (hep-lat/0408019), FNAL (hep-lat/0409116)

  ✓valid for $q^2 > 15$ GeV^2

✓Use parametrizations (e.g. Becirevic-Kaidalov) to extrapolate to full q^2 range

✓Quark models : ISGW II (Phys. Rev. **D52**, (1995)2783) (no error quoted)



LQCD and LCSR valid in different q^2 ranges → No crosscheck
important to measure differential decay rate as function of q^2

exclusive SL decays : Theory and Uncertainties

Theo. Form Factor uncertainties enter twice in measurement :

- FF shape → acceptance

Measure with data to reduce dependence on theoretical predictions

- FF normalization → extraction of V_{ub} from partial BRs

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to \pi\ell\nu)}{\Gamma_{th} \cdot \tau_{B^0}}},$$

10-13% error for LCSR and LQCD in their respective validity ranges

15-17% error for full q^2 range

Understanding inclusive SL decays

- theory must predict signal spectra (Operator Product Expansion, Soft Collinear Effective Theory)
- total $B \to X_u\, l\, \nu$ decay rate from OPE (theory error ~5%)

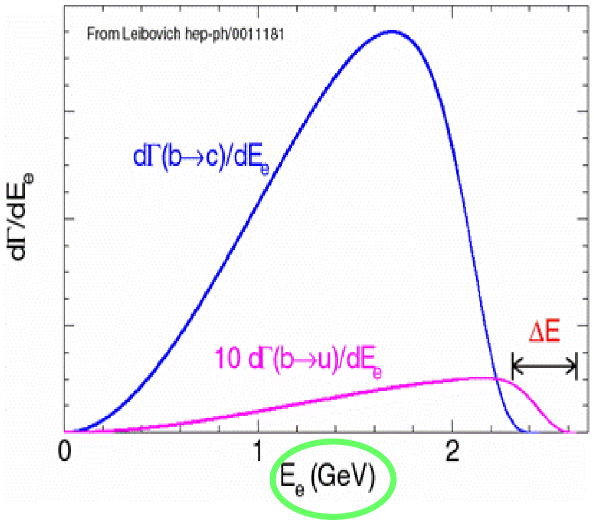
$$\Gamma\left(\bar{B} \to X_u l \bar{\nu}\right) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2 \times \left\{1 + O(\alpha_S) + O\left(\frac{1}{m_b^2}\right)\right\}$$

- but…inclusive decay width cannot be directly measured
  - experiments measure partial widths in limited region of phase space that are free from the $B \to X_c l \nu$ background
  - cuts on E_l, M_X, q^2 to suppress charm ($\Gamma_c = 50 \times \Gamma_u$)
- non-perturbative Shape Function (SF) must be used to calculate partial rates
  - SF depends on 2 parameters related to the mass and kinetic energy of the b-quark: Λ or m_b and λ_1 or μ_π^2
  - SF cannot be computed and must be determined experimentally:
    - from the photon energy spectrum in $b \to s\gamma$
    - from leptonic/hadronic spectra in $b \to c\, l\, \nu$

V_{ub} from partial $B \rightarrow X_u l\nu$ decay rates : experimental approaches

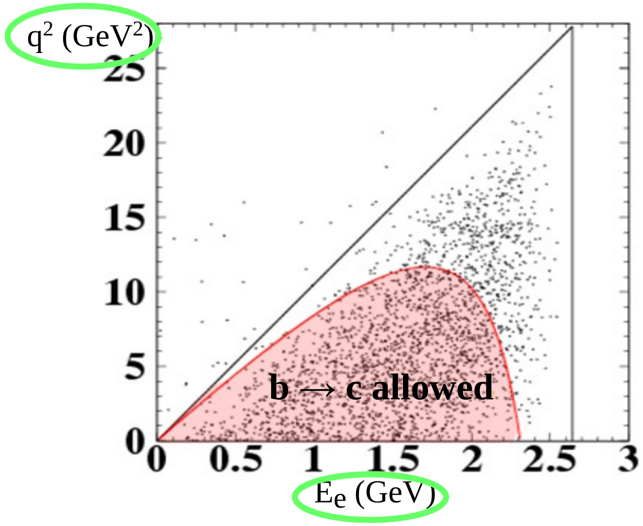
$\Gamma_c = 50 \times \Gamma_u$: use difference in kinematics to separate $ul\nu$ and $cl\nu$

Different types of partial decay rate measurements:

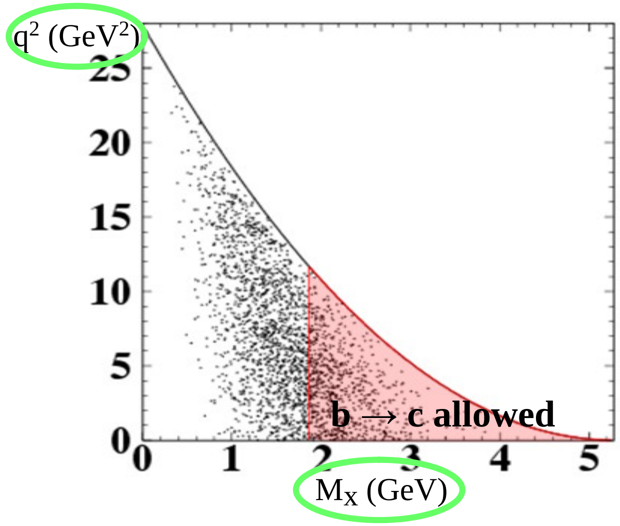


electron endpoint

hep-ex/0509040



E_e and q^2 regions
with ν reconstruction

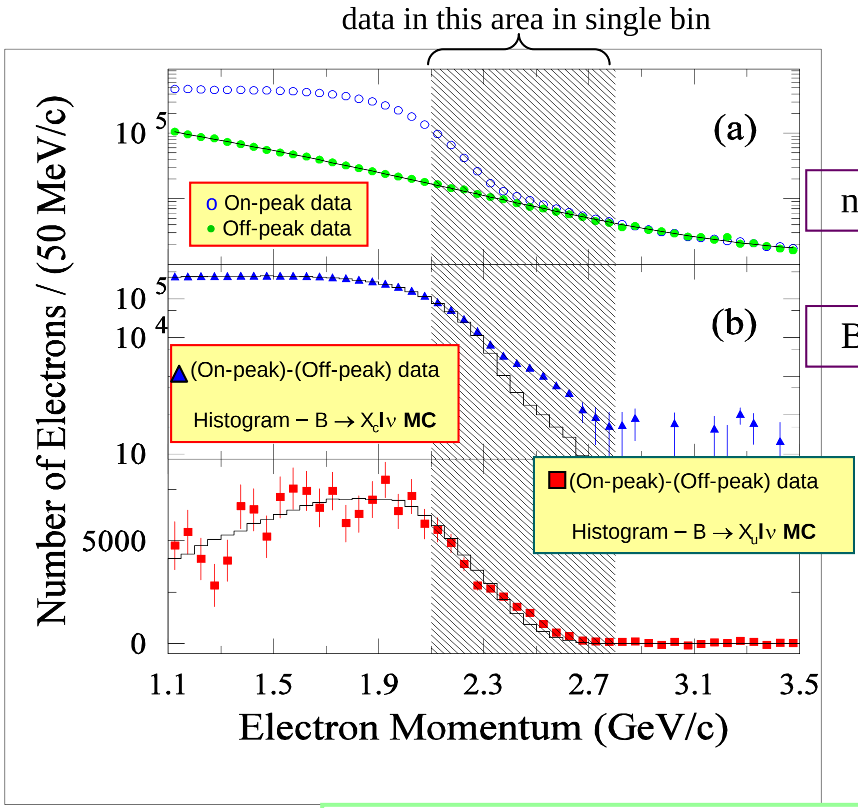


M_X and q^2 regions
with Breco tag

$|V_{ub}|$ from inclusive $B \to X_u l\nu$ endpoint spectrum

80 fb^{-1}

accurate model of bkg is crucial : S/N ~ 1/14



$2.0 < E_e < 2.6$ GeV

non BB bkg subtracted using off-peak data

$B \to D^{*(*)} l \nu$ from MC

- electrons energy range : $2.0 < E_e < 2.6$ GeV
- fully correct spectrum (efficiency,resolution,final state radiation,etc..)

$$\Delta B\ (B \to X_u\, l\, \nu) = (0.572 \pm 0.041_{stat} \pm 0.065_{syst}) \times 10\text{-}3$$

$$|V_{ub}| = (4.44 \pm 0.25_{exp}\ {}^{+0.42}_{-0.38}{}_{SF} \pm 0.22_{th\text{-}BLNP}) \times 10^{-3}$$

$b \to s\gamma$, $b \to cl\nu$ moments (from BaBar) combined fit