Semileptonic *B* Decays at BABAR

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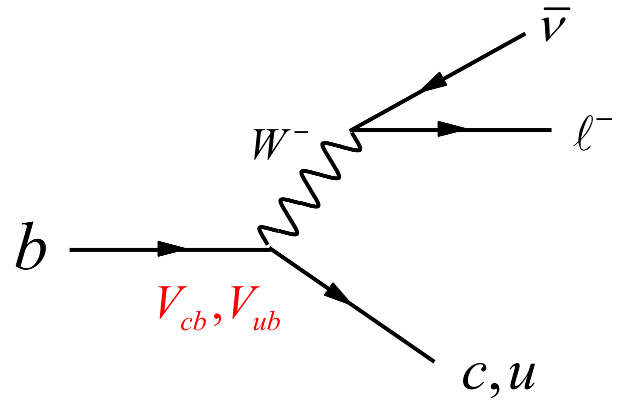
Semileptonic *B* Decays – Why are they Interesting

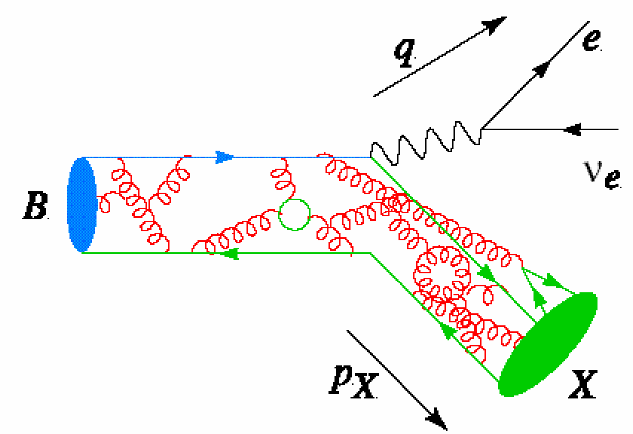
$$\Gamma(b \to c \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{cb}|^2 \, m_b^2 (m_b - m_c)^3 \qquad \Gamma(b \to u \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 \, m_b^5$$

- Semileptonic decays
  - theoretically simple at parton level
  - rate depends on CKM elements $|V_{cb}|$ and $|V_{ub}|$, the quark masses m_b and m_c
  - the leptonic current factors out cleanly,

    thus one can probe strong interactions in B mesons
  - sensitive to QCD corrections, OPE
- A precise determination of $|V_{cb}|$ and $|V_{ub}|$ with reliable errors

  important for
  - understanding B decay rates
  - testing of the unitarity of the CKM matrix and predictions of CP violation in B mesons





Semileptonic *B* decay studies at BABAR

	Inclusive decays	Exclusive decay modes
$b \to c\ell\nu$	$B \to X_c \ell \nu$ $\|V_{cb}\|$, total decay rate, HQE parameters	$B \to D^* \ell \nu$, $B \to D \ell \nu$,... Branching fractions, decay form factors, $\|V_{cb}\|$
$b \to u\ell\nu$	$B \to X_u \ell \nu$ $\|V_{ub}\|$, total decay rate, lepton momentum and hadron mass spectra	$B \to \pi \ell \nu$, $B \to \rho \ell \nu$,... Branching fractions, decay form factors, $\|V_{ub}\|$

2-nd B tagging: untagged, lepton tag, hadronic tag

Inclusive $B \to X_c \ell \nu$ decays: HQE Expansions

- Heavy Quark Expansions, tool to correct for QCD effects
  - 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 parameters cannot be calculated
- We choose calculation by Gambino & Uraltsev **hep-ph/0401063 & 0403166**
  - Kinetic mass scheme to $O(1/m_b^3)$
  - E_ℓ moments $O(\alpha_s^2)$
  - m_X moments $O(\alpha_s)$
- 8 parameters to be fitted

$$|V_{cb}| \quad m_b \quad m_c \quad \mathcal{B}(B \to X_c \ell \nu) \quad \mu_\pi^2 \quad \mu_G^2 \quad \rho_D^3 \quad \rho_{LS}^3$$

μ_π^2: kinetic, μ_G^2: chromomagnetic — $O(1/m_b^2)$

ρ_{LS}^3: spin-orbit, ρ_D^3: Darwin — $O(1/m_b^3)$

- Measure 8 moments, each as a function of minimum lepton energy E_ℓ

Measurement of Electron Energy Moments

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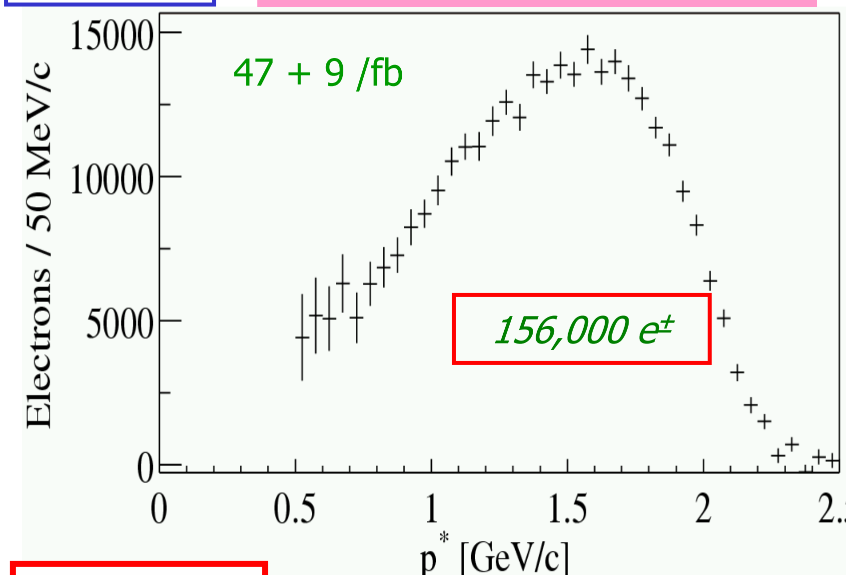
Albert *et al.* Phys.Rev. D **69**, 111104 (2004)

- Inclusive $e^{\pm}$ spectrum in 3×10^6 electron-tagged ($1.4<p^*<2.3$GeV/c) $B\bar{B}$ events
  - *Corrected for detector effects*
  - *Corrected for non-prompt electrons – lepton charge correlation and MC*
  - *Corrected for $B^0 - \bar{B}^0$ mixing*
- Moments for $E_{cut} = 0.6 \ldots 1.5$ GeV
  - *Corrected for the final state radiation*
  - *Translated to B rest frame*
  - *Subtracted $B \to X_u \ell \nu$ decays*



$$M_0^\ell = \frac{\int_{E_{cut}}^{\infty} d\Gamma}{\Gamma_B}$$

Partial BF

$$M_1^\ell = \frac{\int_{E_{cut}}^{\infty} E_\ell d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}$$

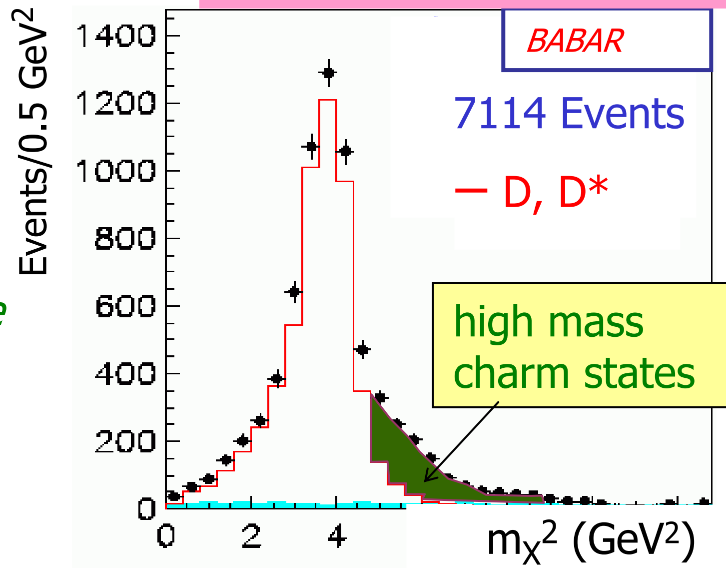
$$M_n^\ell = \frac{\int_{E_{cut}}^{\infty} (E_\ell - M_1^\ell)^n d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}, \ (n=2,3)$$

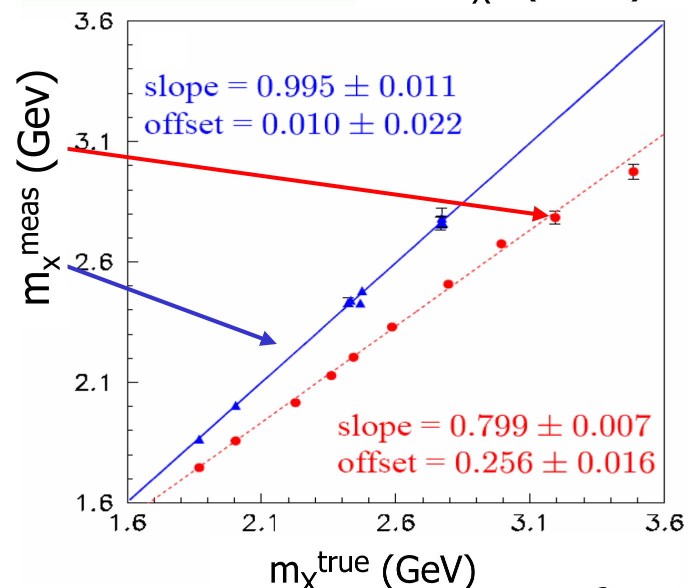
Lepton Energy Moments

Measurement of Hadron Mass Moments

Aubert *et al.* Phys.Rev. D **69**, 111103 (2004)

- $B\bar{B}$ events tagged by a fully reconstructed hadronic B decays
  - *$e^{\pm}$ or $\mu^{\pm}$ with $E_\ell > E_{cut}$ (0.9…1.6 GeV/c)*
  - *Lepton charge – B flavor correlation*
  - *Improve m_X measurement by kinematic fit to whole event, resolution ~350 MeV*
- To eliminate dependence of moments on uncertain BF and unknown masses of high mass charm mesons we calibrate m_X measurement
- Calibrate m_X based on MC simulation
  - *Linear relation between m_X^{meas} and m_X^{true}*
  - *Validate calibration with excl. $B \to D^{(*)} \ell \nu$*
- Moments corrected for detector effects and bkg





$$M_n^X = \frac{\int\limits_{E>E_{cut}} m_X^n \, d\Gamma}{\int\limits_{E_{cut}}^{\infty} d\Gamma}, (n = 1, 2, 3, 4)$$

Hadron mass moments

HQE Fits to Hadron Mass and Lepton Energy Moments

Aubert *et al.* Phys.Rev.Lett. **93**, 011803 (2004)

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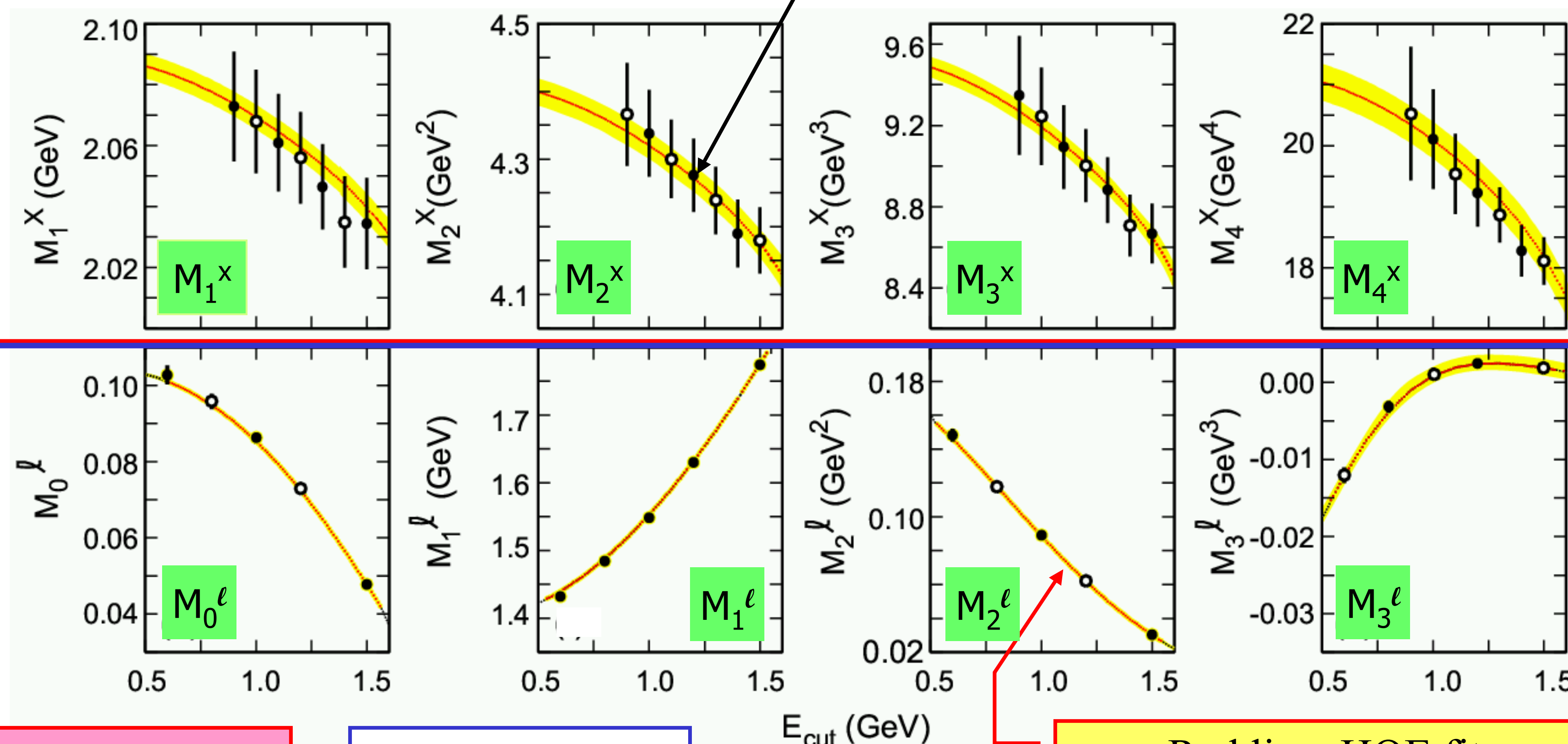
M_X moments

● = used, ○ = unused in the nominal fit



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

E_ℓ moments

Red line: HQE fit
Yellow band: theory errors

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

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

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

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

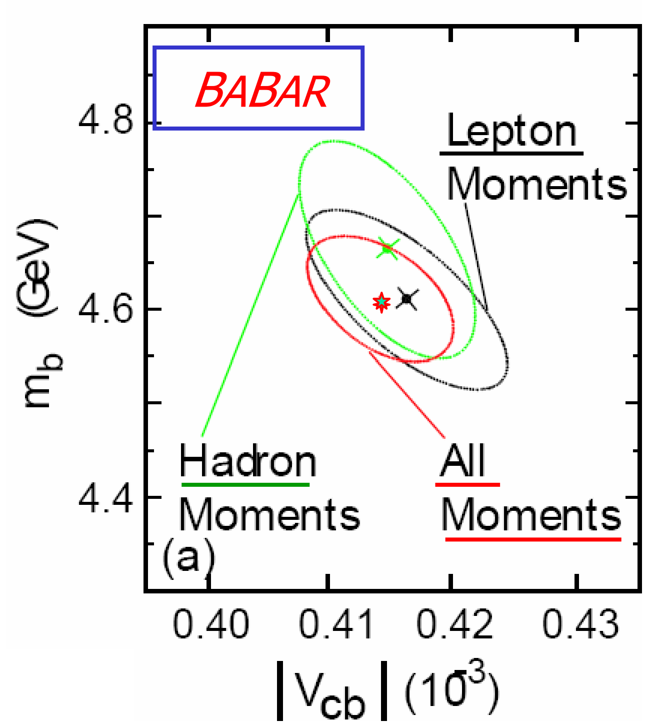
$$m_c = (1.18 \pm 0.07_{\rm exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\,\mathrm{GeV}$$

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

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

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

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



- 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 $B_{c\ell\nu}$ (1.6%) and quark masses, as well as HQE parameters

|Vub| from total $B \to X_u \ell \nu$ decay rate

- Total $b \to u \ell \nu$ decay rate from OPE:

$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2 \left\{ A_0 \left(1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_b^2} \right) - 2\frac{\mu_G^2}{m_b^2} + O\left(\frac{1}{m_b^3}\right) \right\}$$

- $|V_{ub}|$ from inclusive BF($B \to X_u l \nu$) (theory error ~5%):

$$|V_{ub}| = 0.00424 \left(\frac{\mathcal{B}(\overline{B} \to X_u \ell \overline{\nu})}{0.002} \frac{1.604ps}{\tau_B} \right)^{1/2} \times (1.0 \pm 0.048(\mathrm{OPE} + \mathrm{m_b})).$$

- Experimentally challenging due to charmed semileptonic background:

$$\frac{\Gamma(b \to u \ell \overline{\nu})}{\Gamma(b \to c \ell \overline{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$

$|V_{ub}|$ from partial $B \rightarrow X_u \ell \nu$ decay rates

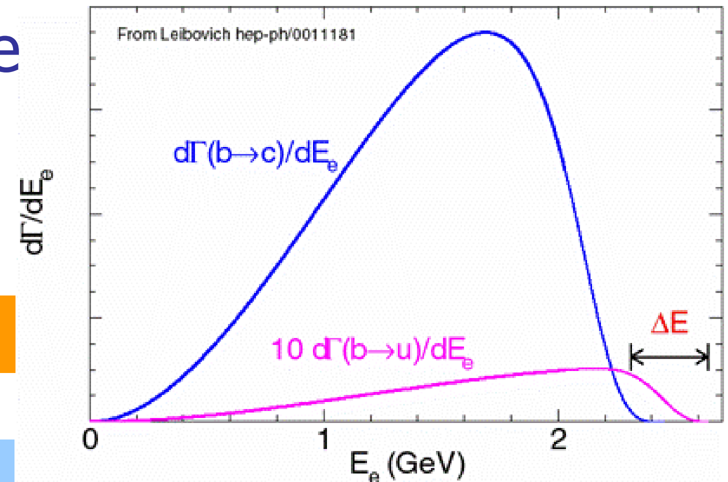
- Charmed semileptonic background can be controlled
in limited regions of phase space

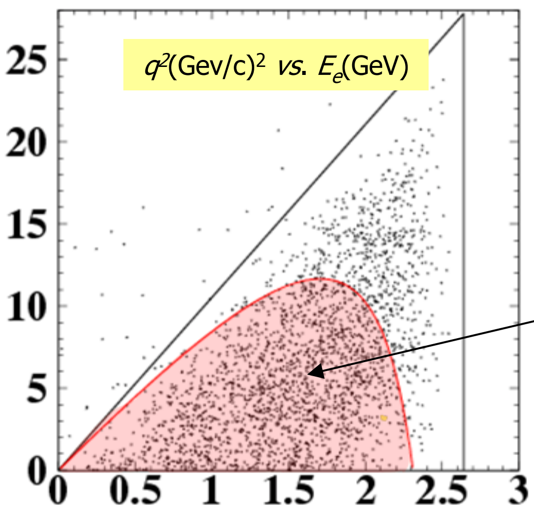
- Non-perturbative Shape Functions are used to extract $|V_{ub}|$ from partial branching fractions. The SF parameters are extracted from $b \rightarrow sg$ photon spectrum

- New approach to $|V_{ub}|$ extraction:
  - **Differential decay rate parametrization from BLNP**
    Bosch, Lange, Neubert, and Paz, Nucl. Phys. B 699, 335 (2004); Lange, Neubert, and Paz, hep-ph/0504071
  - **New source of information on SF parameters – moments of the $b \rightarrow c\, \ell\, \nu$ lepton spectrum**
    Neubert, Phys.Lett. B 612, 13 (2005)

$|V_{ub}|$ from partial $B \to X_u \ell \nu$ decay rates

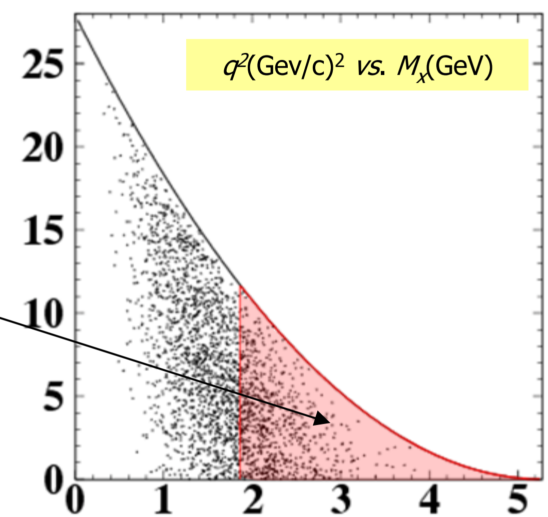
- Different types of partial decay rate measurements:
  - electron endpoint — hep-ex/0408075
  - E_e and q^2 regions with neutrino reconstruction — hep-ex/0506036
  - M_x and q^2 regions — hep-ex/0408068



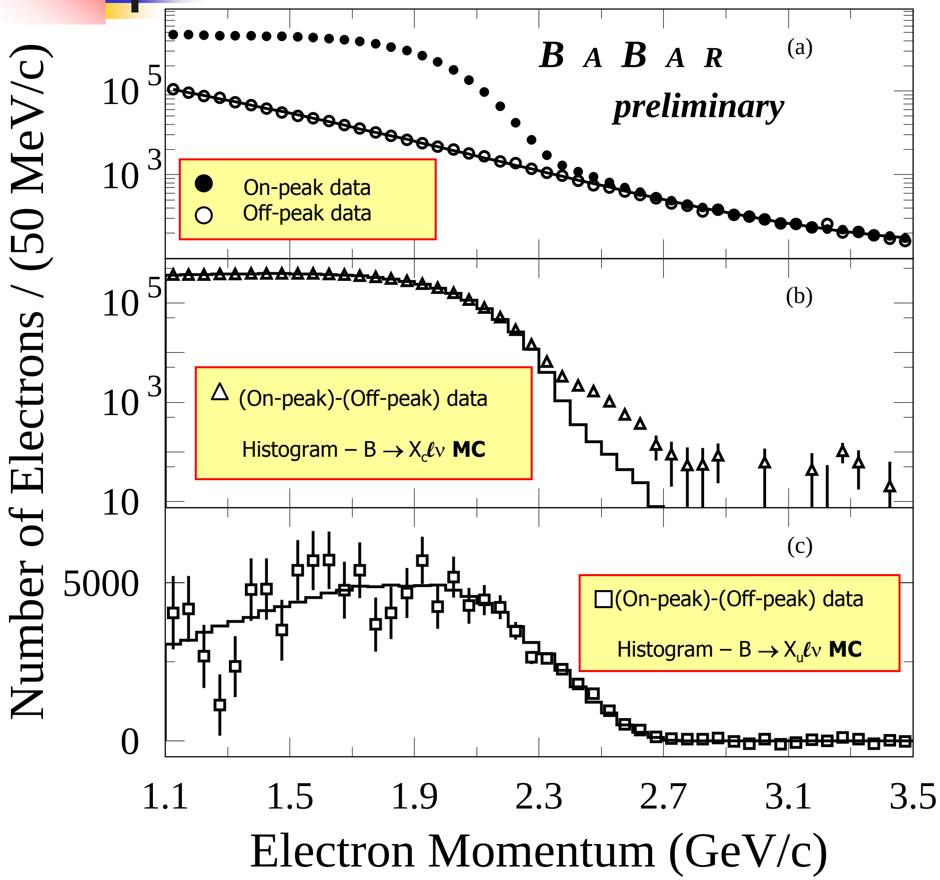


$$q^2=(p_\ell+p_\nu)^2$$

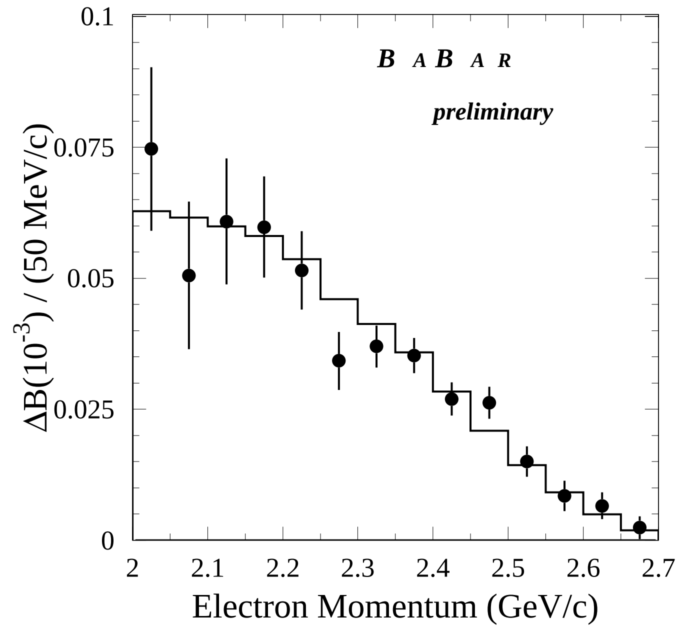
Kinematic regions of $B \to X_c \ell \nu$ decays



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



Signal extraction: subtraction of BB and continuum background



Differential $B \to X_u e \nu$ branching fraction as a function of electron momentum, corrected for detector effects and final-state radiation

● (On-peak)−(Off-peak) data
Histogram – $B \to X_u \ell \nu$ **MC**

Endpoint spectrum analysis: |Vub| extraction

- Determination of ΔBr for $p_e > p_{min}$
- Extrapolation to total charmless semileptonic decay Br using shape function parameters from $B \to X_s \gamma$ spectrum and calculations of DeFazio-Neubert(*) and Kagan-Neubert(**)
- Extraction of $|V_{ub}|$ using the OPE relation.
- BABAR preliminary results, based on BELLE shape function parameters and DFN approach (hep-ex/0408075):

  $\Delta Br(p_e > 2.0 GeV/c) = (0.531 \pm 0.032_{stat} \pm 0.049_{syst}) \times 10^{-3}$

  $Br = (2.16 \pm 0.24_{exp} \pm 0.27_{SF}) \times 10^{-3}$

  $|V_{ub}| = (4.40 \pm 0.24_{exp} \pm 0.28_{SF} \pm 0.21_{OPE+mb}) \times 10^{-3}$
- Analysis based on BLNP calculation is being completed

(*) F.De Fazio and M.Neubert, JHEP 9906, **017** (1999)

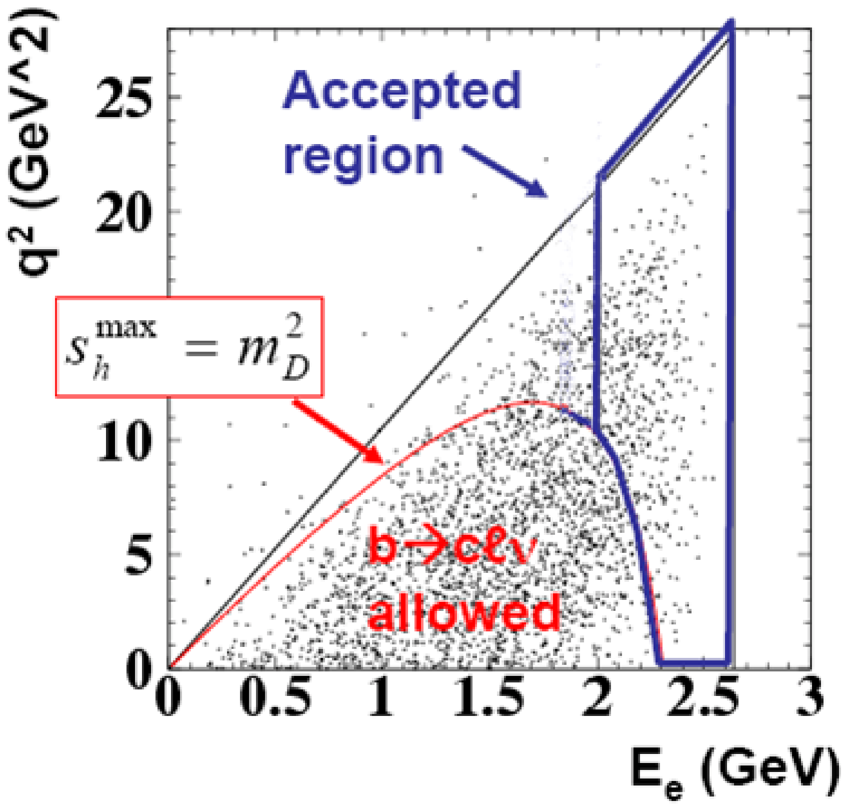
(**) A.L.Kagan and M.Neubert, Eur.Phys.J. C **7**, 5 (1999)

$q^2 - E_e$ analysis with neutrino reconstruction

- Event selection:
- High energy electron Ee>2GeV
- Missing momentum used for neutrino parameters estimation
- Cuts on missing momentum magnitude and direction, and event shape
- Suppression of b→ceν by $s^h_{max}=m^2_D$:

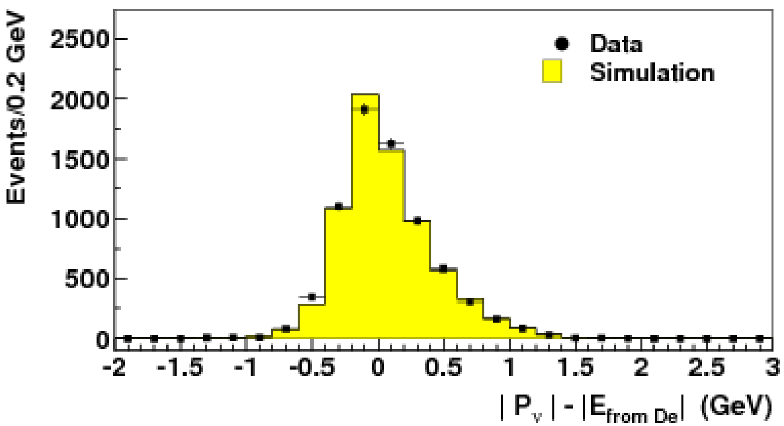
$$s_h^{\max} = m_B^2 + q^2 - 2m_B\left(E_e + \frac{q^2}{4E_e}\right),$$

(slightly modified for *B*-meson motion in the Υ(4S) rest frame)

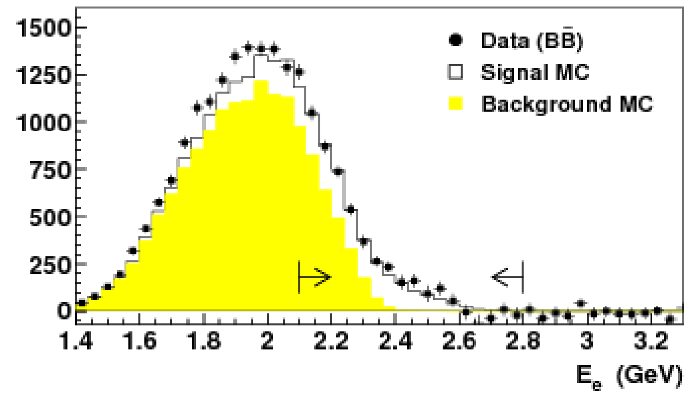


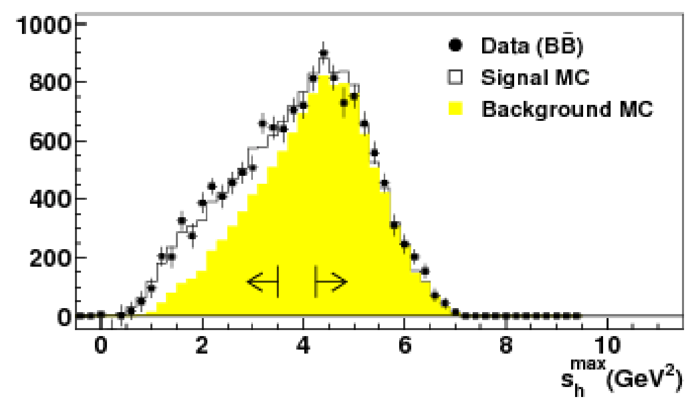
Acceptance ~ 14%, signal/bkg.~0.6

$q^2 - E_e$ analysis results



Test of neutrino energy resolution using pure control sample of $B \to D^{(*)} e\nu$ events





Signal extraction for E_e>2.0 GeV and s_h<3.5 GeV^2,
BB background normalization for s_h>4.25 GeV^2,

ΔBr(E_e>2.0GeV, s_h<3.5GeV^2)=(3.54±0.33 ±0.34) $\times 10^{-4}$

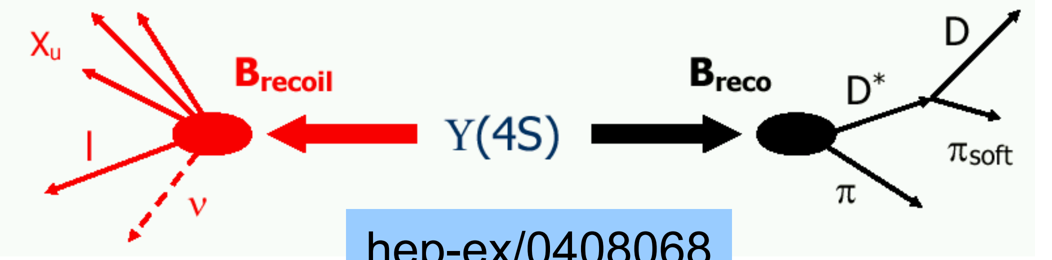
$$|V_{ub}| = \sqrt{\Delta B / (\Delta\zeta \times \tau_B)},\ \Delta\zeta \text{ - normalized partial rate }^{(*)},\ \tau_B = 1.604 \pm 0.023\text{ps}$$

$$|V_{ub}| = (3.95 \pm 0.18 \pm 0.19^{+0.58}_{-0.42} \pm 0.25) \times 10^{-3}$$

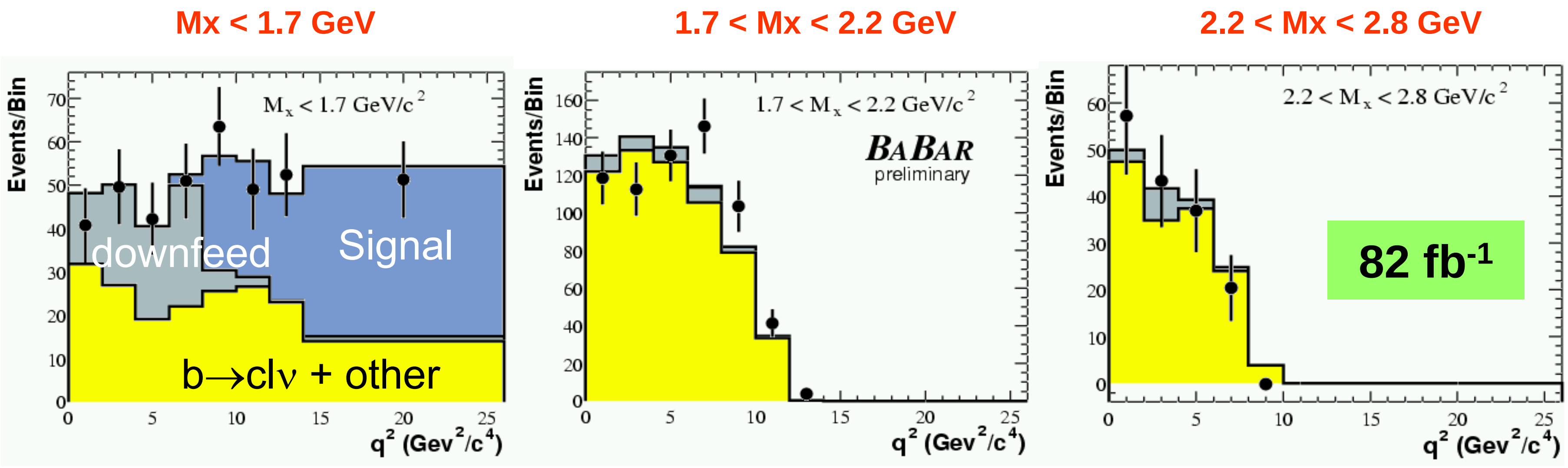
(*) B.O.Lange, M.Neubert and G.Paz, hep-ph/0504071

$M_X - q^2$ analysis

- Select events with a fully reconstructed B → D(*)X decay (B_{reco})
- Study charmless semileptonic decay of B recoiling against B_{reco}
  - require lepton with p^*_{lep} > 1 GeV
- 2D fit to measure partial BF
  in [M_x<1.7 GeV, q^2>8 GeV^2]



hep-ex/0408068



$M_X - q^2$ analysis: the results

BABAR preliminary (CKM 2005)

- M_x spectrum unfolding and fitting:

$$|V_{ub}| = (5.22 \pm 0.30_{\text{stat}} \pm 0.31_{\text{exp.syst}} \pm 0.21_{\text{fu}} \pm 0.25_{\text{OPE}}) \times 10^{-3} \text{ (DFN}^{*}\text{)}$$

- $M_x - q^2$ 2-dimentional fit:

$$\Delta Br(M_X < 1.7\text{GeV}, q^2 > 8\text{GeV}^2) = (8.96 \pm 1.43_{\text{stat}} \pm 1.44_{\text{syst}}) \times 10^{-4}$$

$$|V_{ub}| = (5.18 \pm 0.41_{\text{stat}} \pm 0.40_{\text{exp.syst}} \pm 0.22_{\text{fu}} \pm 0.25_{\text{OPE}}) \times 10^{-3} \quad \text{(DFN}^{*}\text{)}$$

$$|V_{ub}| = (4.98 \pm 0.40_{\text{stat}} \pm 0.39_{\text{exp.syst}} \pm 0.47_{\text{fu+OPE}}) \times 10^{-3} \quad \text{(BLL}^{**}\text{)}$$

(*) F.De Fazio and M.Neubert, JHEP 9906, **017** (1999)
(**) Bauer, Ligeti and Luke, hep-ph/0111387

Inclusive $B \rightarrow X_u \ell \nu$ decay summary

BABAR preliminary

Technique	$\lvert V_{ub} \rvert \times 10^3$
$E_\ell > 2$GeV (ICHEP2004)	$4.40 \pm 0.13_{stat} \pm 0.25_{exp.syst} \pm 0.28_{fu} \pm 0.21_{OPE}$
E_ℓ *vs.* q^2 (NEW)	$3.95 \pm 0.18_{stat} \pm 0.19_{exp.syst} + \left({}^{+0.58}_{-0.42}\right)_{SF} \pm 0.25_{theo}$
Mx *vs.* q^2 (CKM 2005)	$5.18 \pm 0.41_{stat} \pm 0.40_{exp.syst} \pm 0.22_{fu} \pm 0.25_{OPE}$
Average (using the procedure of HFAG)	$4.22 \pm 0.57 \quad CL = 0.45$

|Vub| from exclusive $B \to X_u \ell \nu$ decays

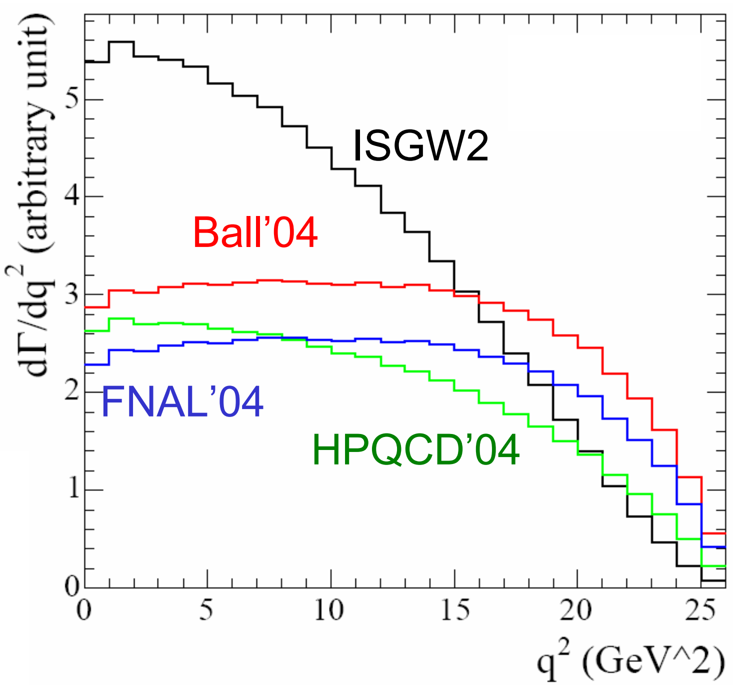
Strong nonperturbative effects included in form factors

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

$$|V_{ub}| = \sqrt{\frac{B(B \to \pi \ell \nu)}{x \tau_B}}$$

$$x = \frac{G_F^2}{48\pi^3} \int |\boldsymbol{k}_\pi|^3 |f_+(q^2)|^2 \, dq^2$$

$q^2 = (p_{lep} + p_\nu)^2$



Calculations

- Light-Cone Sum Rules: **Ball**,Zwicky (hep-ph/0406232)
- Unquenched Lattice QCD: **HPQCD** (hep-lat/0408019) and **FNAL** (hep-lat/0409116)
- **ISGW2**: quark model

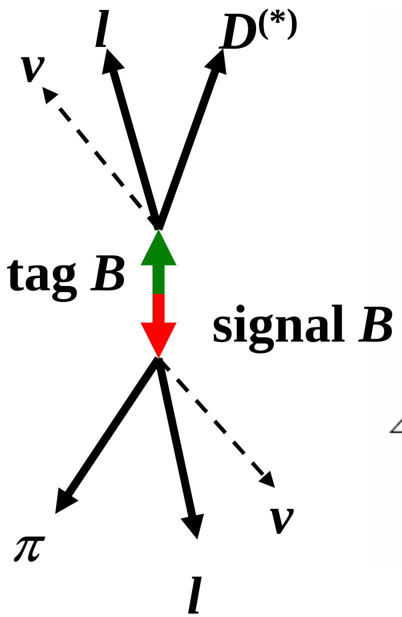
Exclusive decays, experimental techniques

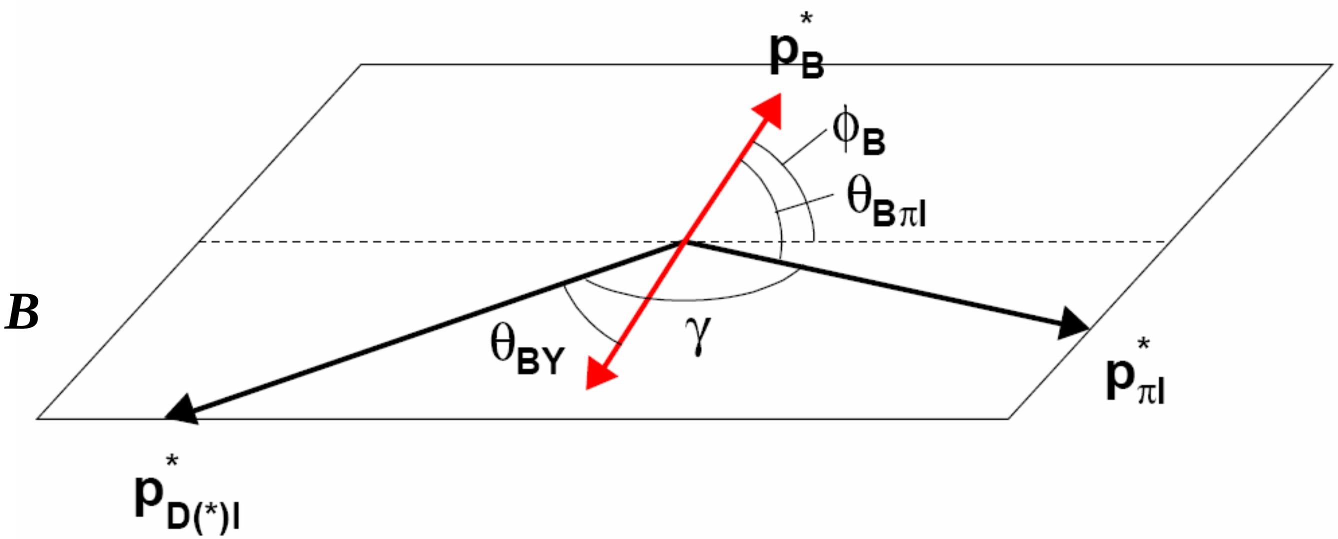
- Different experimental approaches to measure BF:

Untagged analysis	**Neutrino reconstruction** $B \to \pi \ell \nu$, $B \to \rho \ell \nu$	
Semileptonic Tags	**Recoil of $B \to D^{(*)} \ell \nu$** $B \to \pi \ell \nu$	
Hadronic Tags	**Recoil of $B \to D^{(*)}X$** 9 channels $(\pi,\rho,\omega,\eta,\eta',a_0)$	

PURITY ↓ **EFFICIENCY** ↑

Exclusive $B \rightarrow \pi \ell \nu$ decays, tagged analysis





- Use $B \rightarrow D^{(*)} \ell \nu$ decays of opposite B to “tag” event
- Use events with $B \rightarrow D^{(*)} \ell \nu$ decays on both sides to check tagging efficiency
- Measure ΔB($B^0 \rightarrow \pi^- \ell^+ \nu$) in bins of q^2
- BF for $B^+ \rightarrow \pi^0 \ell^+ \nu$

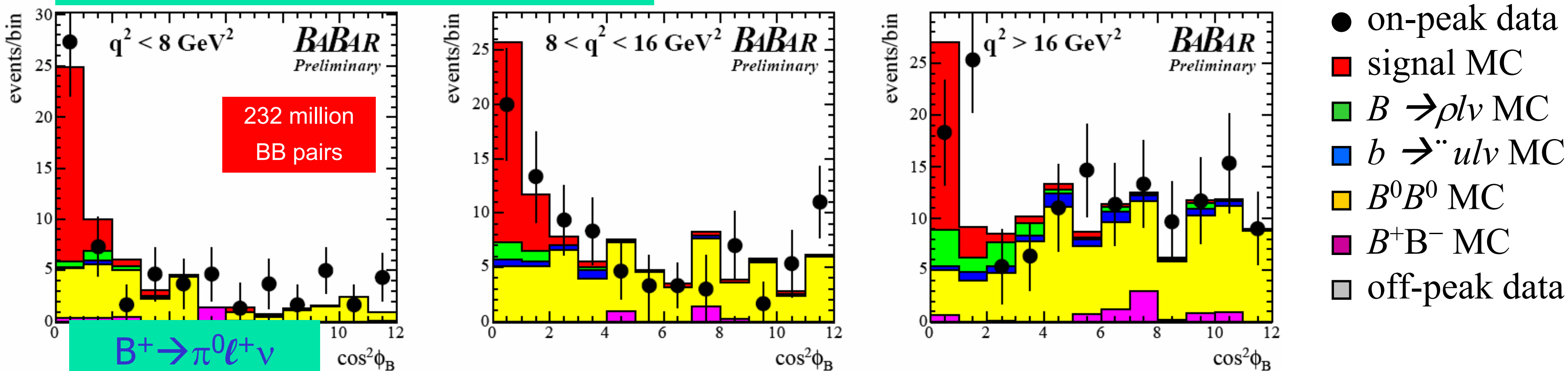
Discriminating Variables

- $B^0 \rightarrow \pi^- \ell^+ \nu$: angle between the B momentum and the plane defined by the $D^{(*)}\ell$ and $\pi\ell$ momenta: $\cos^2\phi_B$
- $B^+ \rightarrow \pi^0 \ell^+ \nu$: angle between B and $\pi^0 \ell$ system: $\cos\theta_{B\text{-}\pi l}$

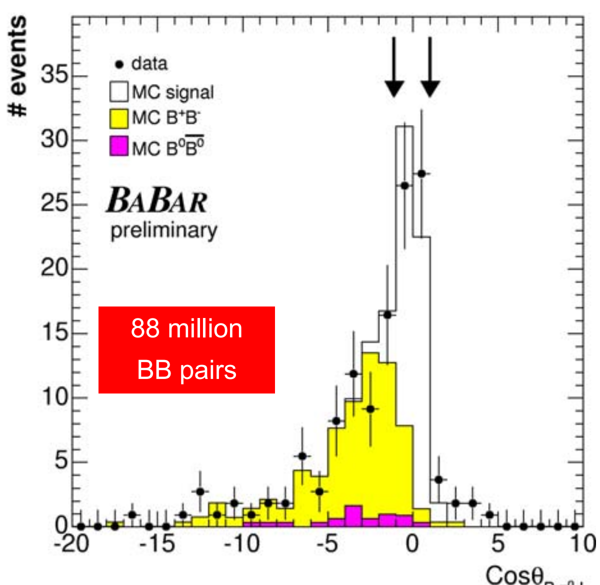
$B \to \pi \ell \nu$ tagged analysis: the results

BABAR
preliminary
(CKM 2005)

$B^0 \to \pi^- \ell^+ \nu$



$B^+ \to \pi^0 \ell^+ \nu$



Branching Fraction Results

$$B(B^0 \to \pi^- \ell^+ \nu) = (1.03 \pm 0.25_{stat} \pm 0.13_{syst}) \times 10^{-4}$$

in 3 bins of q^2

$$B(B^+ \to \pi^0 \ell^+ \nu) = (1.80 \pm 0.37_{stat} \pm 0.23_{syst}) \times 10^{-4}$$

Exclusive $B \to \pi(\rho)\, \ell\, \nu$ decays, untagged analysis

- Reconstruct neutrino from full event + ensure good reconstruction quality

$$(\vec{p}_{\rm miss}, E_{\rm miss}) = (\vec{p}_{\rm beams}, E_{\rm beams}) - (\sum_i \vec{p}_i \,, \sum_i E_i)$$

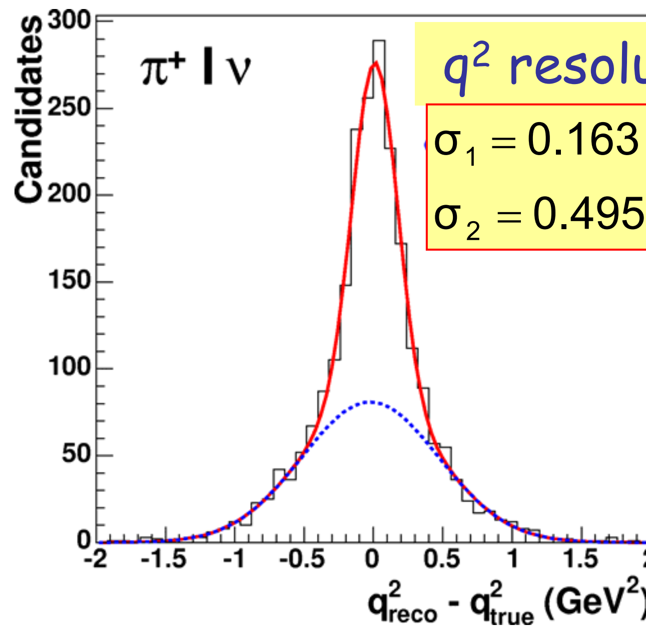
- Signal yield extracted from common fit to ΔE and m_{ES} in 5 q^2 bins for $\pi^+\ell\nu$, and 3 bins for $\rho^-\ell\nu$ and $\rho^0\ell\nu$ each

$$m_{ES} = \sqrt{s/4 - |\vec{p}_B^{\,*}|^2}$$

$$\Delta E = E_B^* - \sqrt{s}/2$$

$$q^2 = (p_l + p_\nu)^2$$

neutrino momentum scaled so ΔE=0 $\to$ improved q^2 resolution



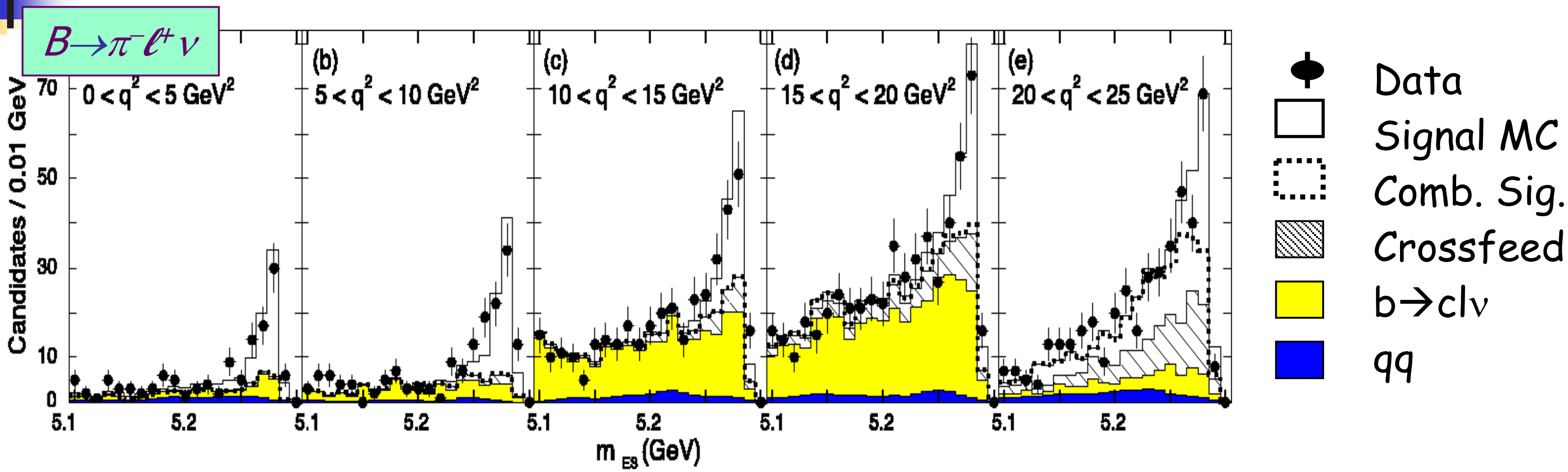
q^2 resolution

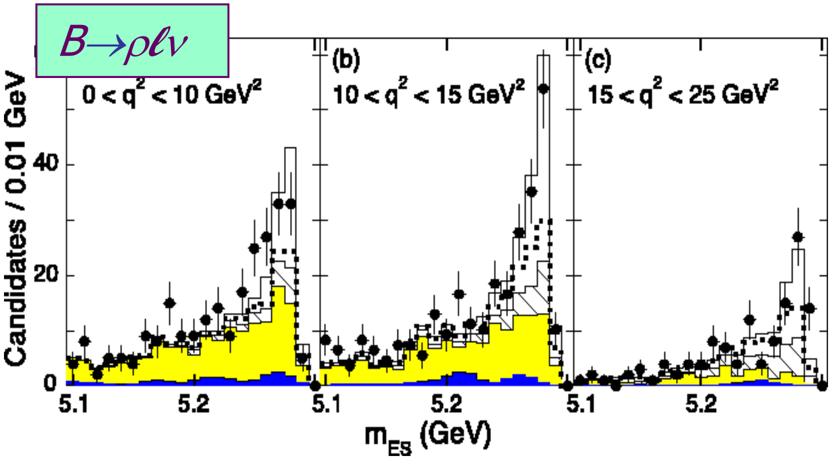
$\sigma_1 = 0.163$ GeV^2

$\sigma_2 = 0.495$ GeV^2

Untagged $B\to \pi(\rho)\,\ell\,\nu$, signal extraction

BABAR preliminary





Branching Fraction Results

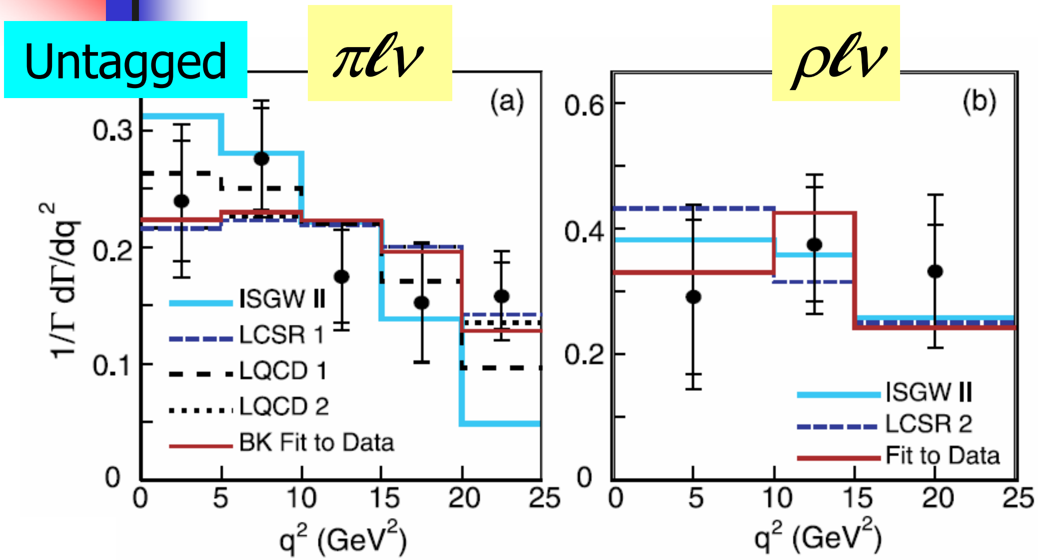
$$B(B^0 \to \pi^- \ell^+ \nu) =$$
$$(1.38 \pm 0.10_{stat} \pm 0.18_{syst} \pm 0.08_{FF}) \times 10^{-4}$$

$$B(B^0 \to \rho^- \ell^+ \nu) =$$
$$(2.14 \pm 0.21_{stat} \pm 0.53_{syst} \pm 0.28_{FF}) \times 10^{-4}$$

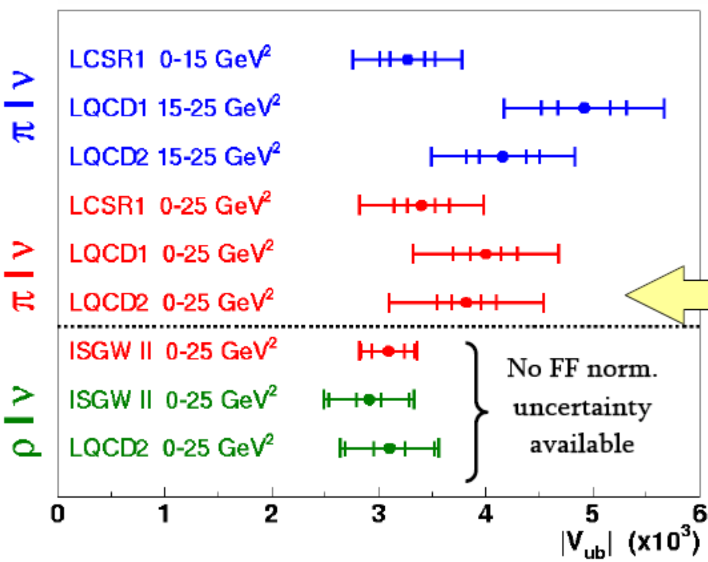
83 million
BB pairs

Form factor fits and $|V_{ub}|$ extraction

BABAR
preliminary
(CKM 2005)



- The $\pi\ell\nu$ untagged sample begins to distinguish among FF calculations: ISGW II is disfavored: Prob(χ^2) = 3%
- Other FF calculations tested are compatible with data



Quote LQCD2 as representative

Extraction of $|V_{ub}|$

LCSR $q^2 < 15$ GeV², LQCD $q^2 > 15$ GeV²
or extrapolation to whole q^2 range

Summary

- HQE fits to moments hadronic mass and lepton energy moments:
  Based on 80 fb^{-1}, ~30% of the current BABAR data, we have made significant advances in the analysis of semileptonic B decays.

  $|V_{cb}| = (41.4 \pm 0.4_{\exp} \pm 0.4_{HQE} \pm 0.6_{theory}) \times 10^{-3}$ $Br(B \to X_c \ell \nu) = (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\%$

  High precision measurement of m_b and m_c, and exp. determination of HQE parameters.

- Inclusive $B \to X_u \ell \nu$ decays, three different approaches:
  The most precise determination of $|V_{ub}|$
  Measurement of partial semileptonic branching fractions for different kinematic regions

- Exclusive $B \to \pi(\rho) \ell \nu$ decay modes in tagged and untagged samples:
  Determination of $|V_{ub}|$
  Begin to test decay form factor calculations

The analyses will be repeated for larger data samples and more precise shape function parameters derived from from $B \to X_s \gamma$ photon spectrum