Measurements of V_{ub} and V_{cb} at BABAR

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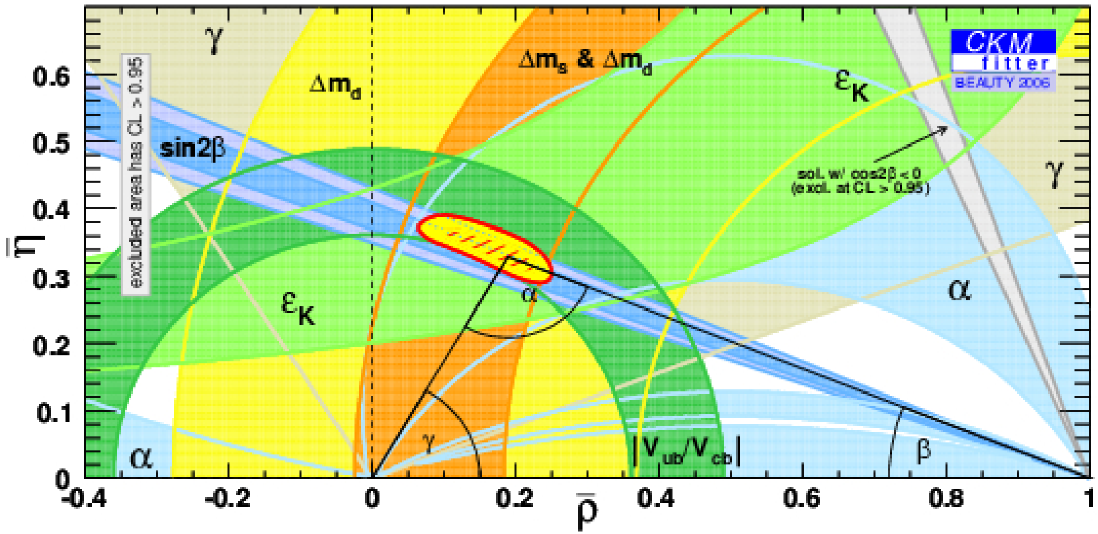
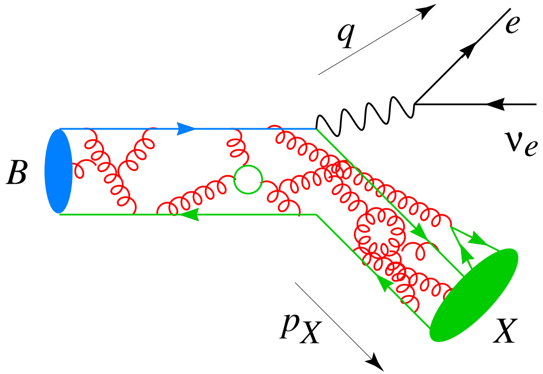
$|V_{ub}|$ and $|V_{cb}|$ in Flavor Physics

- Overconstraining SM flavor sector (CKM matrix) constrains New Physics
- $|V_{qb}|$ extracted from $b \to q\ell\nu$
- $|V_{ub}/V_{cb}|$ determines side opposite β
  - Hint of tension ($\sim 2\sigma$) between $|V_{ub}|$ (tree-level, NP insensitive) and $\sin 2\beta$ (loop process, NP sensitive)
- $|V_{qb}|$ measurements will be legacy of B-factories



★ Rate factorizes into hadronic and leptonic subprocesses

$$\Gamma = G_F^2 |V_{qb}|^2 m_b^5 |L_\mu|^2 |\langle X | J_L^\mu | B \rangle|^2$$



Two complementary approaches

Exclusive	Inclusive
Reconstruct specific final state ($X_q = D^{(*)}, \pi, \rho, ...$)	Any X_q
Parametrize $\langle D^* \| J_L^\mu \| B \rangle$, $\langle \pi \| J_L^\mu \| B \rangle$, ...	Perform OPE in $1/m_b$
Different form factors (FF) $f_i(q^2)$: Lattice QCD, QCD sum rules, Measurements	Universal nonpert. parameters: Measure in $B \to X_c \ell \nu$ and $B \to X_s \gamma$

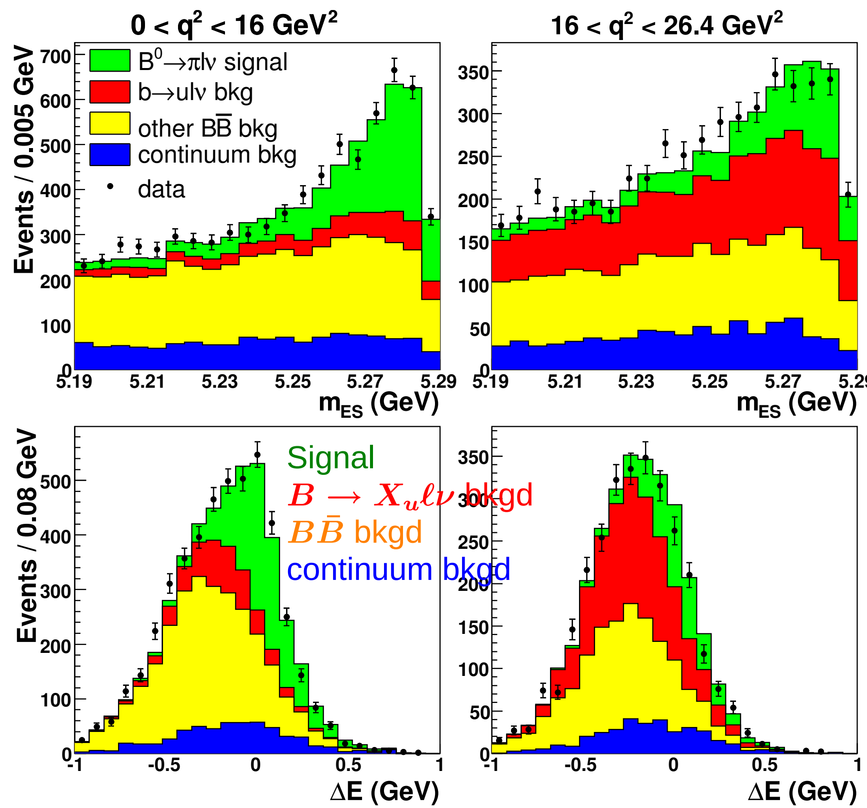
$B^0 \to \pi^- \ell^+ \nu$ Untagged

$$m_{ES} = \sqrt{E_{\rm beam}^2 - \vec{p}_B^{\,2}}$$

$$\Delta E = E_B - E_{\rm beam}$$

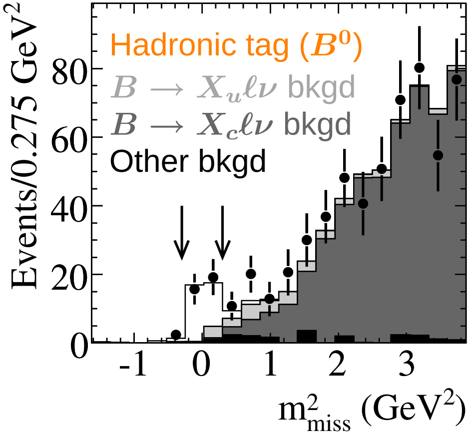
- Loose ν selection
  - Reconstruct ν for kinematic constraint
  - High signal efficiency
  - Low purity
- Signal yield: 5072 ± 251
- Constrain FF shape: 12 bins in $q^2 \equiv (p_\ell + p_\nu)^2$ $= (p_B - p_\pi)^2$

227M $B\bar{B}$ [hep-ex/0612020]

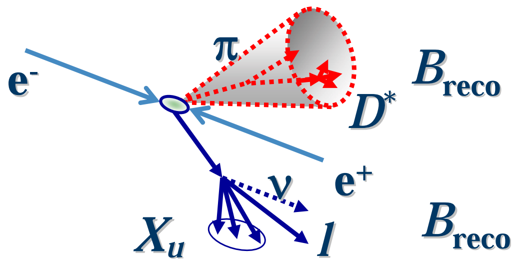


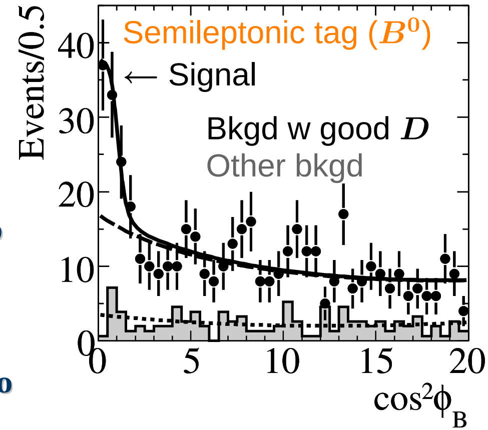
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.46 \pm 0.07_{[\rm stat]} \pm 0.08_{[\rm syst]}) \times 10^{-4}$$

$B \to \pi \ell \nu$ Tagged



232M $B\bar{B}$ [hep-ex/0607089]





- ⋆ Tag $B \to D^{(*)}Y$: high purity, small efficiency, kinematically constrained

- ⋆ $Y = n\,K + m\,\pi$
- ⋆ Use missing mass to select signal
- ⋆ Yield: $31 \pm 7\ (B^0)$, $26 \pm 7\ (B^+)$
- ⋆ $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)/10^{-4}$

B^0: $1.07 \pm 0.27_{[\text{stat}]} \pm 0.15_{[\text{syst}]}$

B^+: $1.52 \pm 0.41_{[\text{stat}]} \pm 0.20_{[\text{syst}]}$

(isospin)

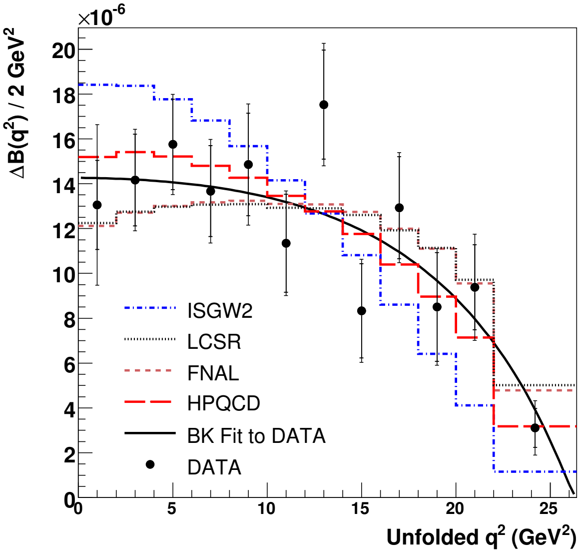
- ⋆ $Y = \ell \nu$
- ⋆ Fit to $\cos^2 \phi_B$ to select signal (⟶ kinematic consistency of event)
- ⋆ Yield $57^{+13}_{-12}\ (B^0)$, $92^{+26}_{-24}\ (B^+)$

B^0: $1.12 \pm 0.25_{[\text{stat}]} \pm 0.10_{[\text{syst}]}$

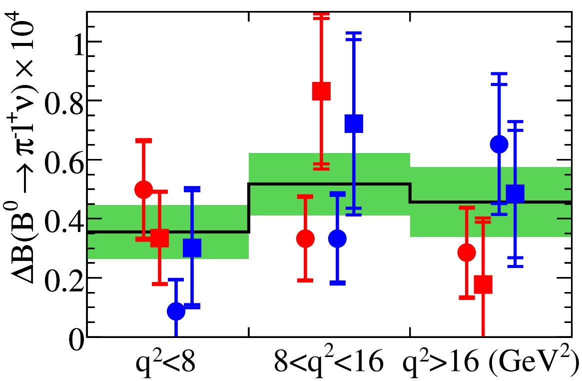
B^+: $1.36 \pm 0.33_{[\text{stat}]} \pm 0.15_{[\text{syst}]}$

(isospin)

$|V_{ub}|$ from $B \to \pi \ell \nu$

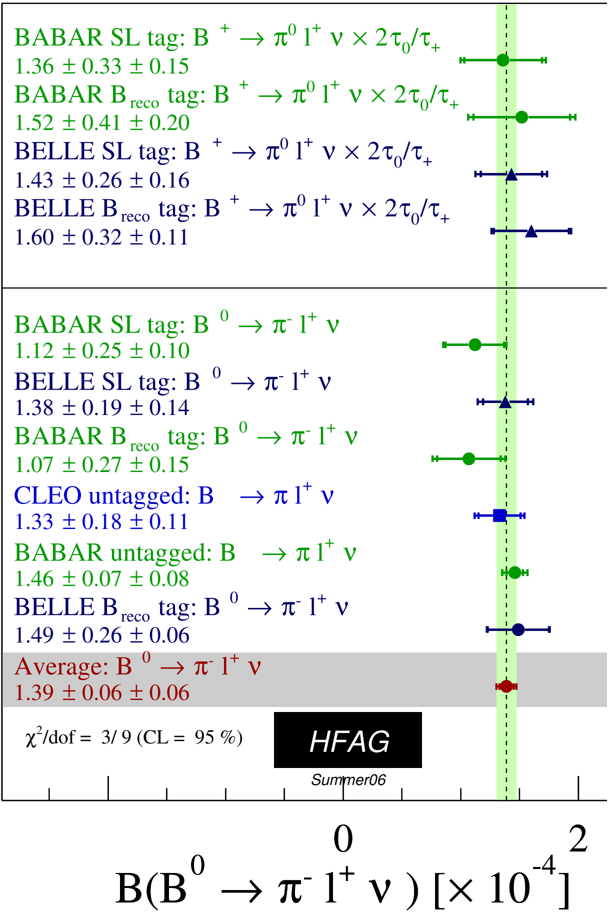


- Compare q^2 dependence to form factor predictions
  - Small q^2: QCD sum rules
  - Large q^2: Unquenched Lattice QCD (HPQCD, FNAL)
  - Start distinguishing between models
- $|V_{ub}| = \sqrt{\Delta\mathcal{B}(q^2)/(\tau_B \Delta\zeta)}$
  - Get $\Delta\zeta$ from Lattice QCD calculation of FF for $q^2 > 16\,\mathrm{GeV}^2$
    - Largest uncertainty on $|V_{ub}|$



- ● B^0, hadronic tag
- ■ B^+, hadronic tag
- ● B^0, semileptonic tag
- ■ B^+, semileptonic tag

Summary of $B \to \pi \ell \nu$



$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)/10^{-4}$

untagged: $1.46 \pm 0.07_{[\text{stat}]} \pm 0.08_{[\text{syst}]}$

avg. tagged: $1.33 \pm 0.17_{[\text{stat}]} \pm 0.11_{[\text{syst}]}$

$|V_{ub}|/10^{-3}$ from $q^2 > 16\,\text{GeV}^2$

untagged: $4.1 \pm 0.2_{[\text{stat}]} \pm 0.2_{[\text{syst}]}\,{}^{+0.6}_{-0.4}{}_{[\text{FF}]}$

avg. tagged: $4.5 \pm 0.5_{[\text{stat}]} \pm 0.3_{[\text{syst}]}\,{}^{+0.7}_{-0.5}{}_{[\text{FF}]}$

[HPQCD, PRD73, 074502 (2006)]

- ⋆ Kinematic cuts required to suppress $B \to X_c \ell \nu$

$$\frac{\mathcal{B}(B \to X_u \ell \nu)}{\mathcal{B}(B \to X_c \ell \nu)} \sim 0.02$$

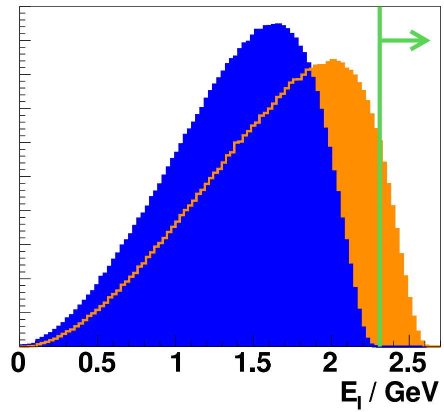
  - ⋆ Control of $B \to X_c \ell \nu$ background important

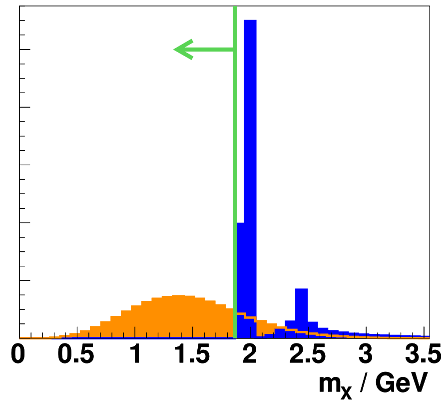
- ⋆ OPE breaks down in endpoint region, requires nonperturbative shape function ($\longrightarrow$ b quark motion in B $\longrightarrow$ smears kinematics)

- ⋆ $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\tau_B \Delta\zeta)}$

  To get $\Delta\zeta$

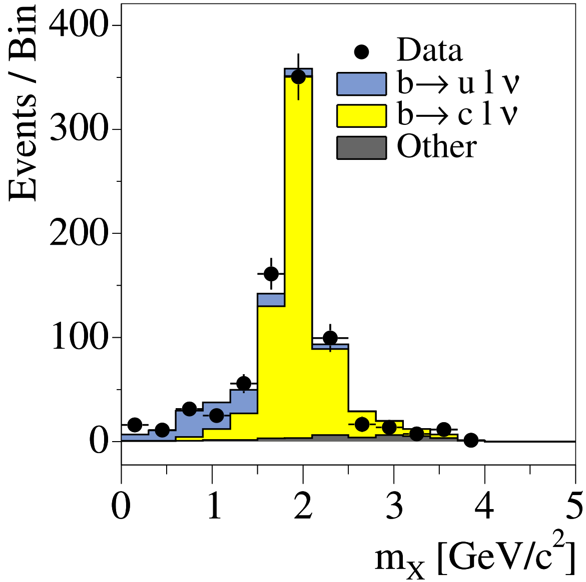
  - ⋆ Assume shape function model, extract model parameters from $B \to X_c \ell \nu$ and $B \to X_s \gamma$
  - ⋆ Use weighted integrals of $B \to X_s \gamma$ spectrum
  - ⋆ Push deep enough into $B \to X_c \ell \nu$ to use OPE





(Ideal resolution)

Inclusive $B \to X_u \ell \nu$, Hadronic Tag



88.9M $B\bar{B}$ [hep-ex/060146]

- ⋆ Hadronic tag provides well understood kinematics
- ⋆ Reduce dependence on shape function (uncertainties)
- ⋆ Trade-off between experimental and theoretical uncertainties

⋆ $|V_{ub}|/10^{-3}$ with cut on m_X

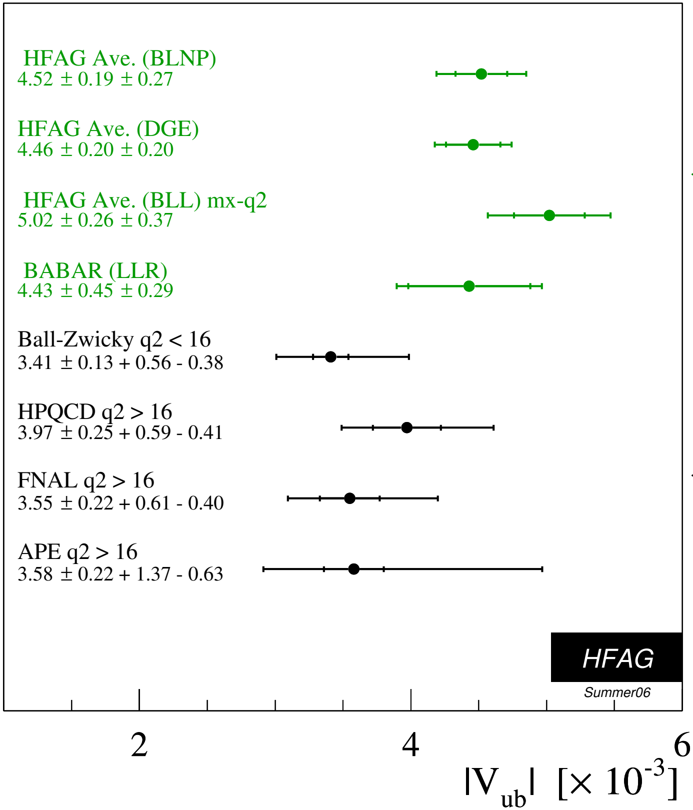
$m_X < 1.67\,\mathrm{GeV}$: $4.43 \pm 0.38_{[\mathrm{stat}]} \pm 0.25_{[\mathrm{syst}]} \pm 0.29_{[\mathrm{theo}]}$ (LLR)

Use BABAR $B \to X_s \gamma$ spectrum [PRD72 052004 (2005)]

$m_X < 2.50\,\mathrm{GeV}$: $3.84 \pm 0.7_{[\mathrm{stat}]} \pm 0.3_{[\mathrm{syst}]} \pm 0.1_{[\mathrm{theo}]}$ (full rate)

[LLR = Leibovich, Low, Rothstein, PRD61 053006 (2000), PLB486 86 (2000)]

HFAG Average of $|V_{ub}|$



⟵ Averages inclusive $|V_{ub}|$

Total uncertainty $7-8\%$

⟵ Averages exclusive $|V_{ub}|$

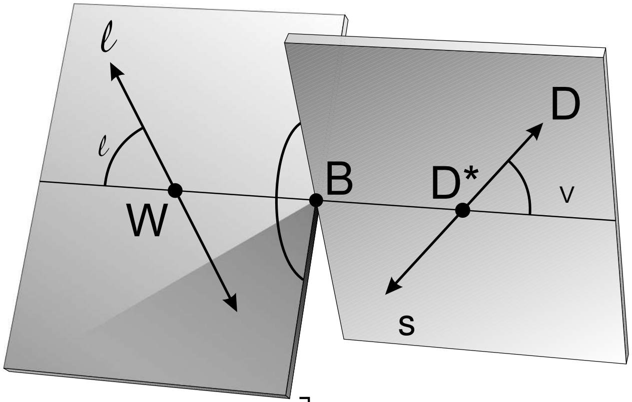
Total uncertainty 14%

- ★ Exclusive $|V_{ub}|$ averages appear systematically lower
  - ★ In better agreement with $\sin 2\beta$

$|V_{cb}|$ and FF in $B \to D^*\ell\nu$

$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw\,d\cos\theta_l\,d\cos\theta_V\,d\chi} = \frac{G_F^2|V_{cb}|^2}{48\pi^3}\mathcal{M}^2(w,\theta_\ell,\theta_V,\chi)\mathcal{G}(w) \quad (w = v_B \cdot v_{D^*})$$

- ⋆ $\mathcal{G}(w) \sim \sqrt{w^2-1}$ (phase space)
- ⋆ $\mathcal{M}(w,\theta_\ell,\theta_V,\chi)$ expressed in terms of D^* helicity amplitudes $H_{0,\pm}(w)$
- ⋆ Parametrize $H_{0,\pm}$ in terms of FF ratios $R_1(w)$, $R_2(w)$ and $h_{A_1}(w)$



$$h_{A_1}(w) = h_{A_1}(1)\left[1 - \rho^2(w-1) + \cdots\right]$$

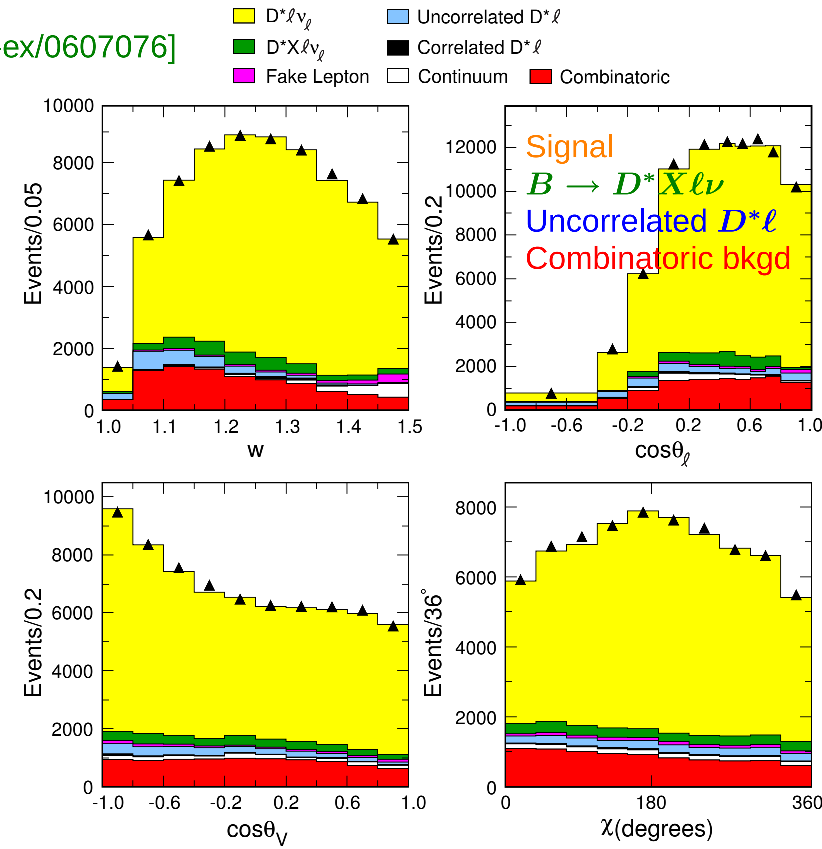
$$\mathcal{F}^2(w) = \int \mathcal{M}^2(w,\theta_l,\theta_V,w)\,d\theta_l\,d\theta_V\,d\chi$$

- ⋆ $\mathcal{F}(w=1) = 1$ in limit $m_{b,c} \to \infty$ but $\mathcal{G}(w \to 1) \to 0$

$\Rightarrow$ Extrapolate $\left.\frac{1}{\mathcal{G}(w)}\frac{d\Gamma}{dw}\right|_{w\to 1} = \frac{G_F^2|V_{cb}|^2}{48\pi^3}\mathcal{F}^2(w=1)$ to extract $|V_{cb}|$

$|V_{cb}|$ and FF in $B \to D^*\ell\nu$ (II)

88M $B\bar{B}$ [hep-ex/0607076]



★ χ^2 fit to three 1D distributions in w, $\cos\theta_V$, $\cos\theta_\ell$

★ Results

[combined with PRD74 092004 (2006)]

$$R_1(1) = 1.417 \pm 0.061 \pm 0.044$$

$$R_2(1) = 0.836 \pm 0.037 \pm 0.022$$

$$\rho^2 = 1.179 \pm 0.048 \pm 0.028$$

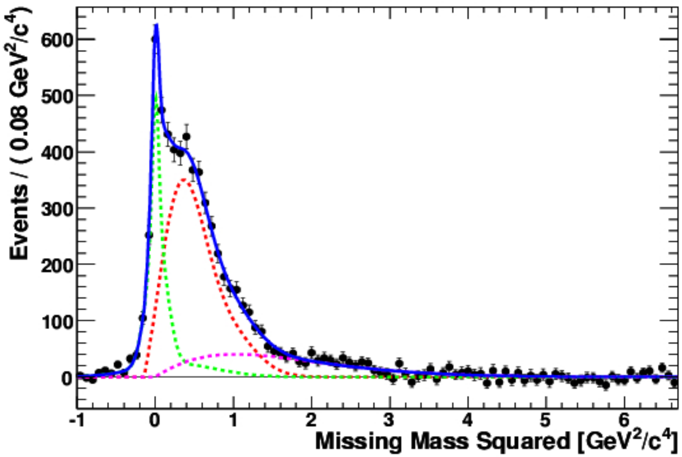
★ Use $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ from Lattice QCD to get

[Hashimoto et al., PRD66 014503 (2002)]

$$|V_{cb}| = (37.73 \pm 0.35_{[\text{stat}]} \pm 1.25_{[\text{syst}]}\ {}^{+1.23}_{-1.44}{}_{[\text{theo}]}) \times 10^{-3}$$

Composition of $B \to X_c \ell \nu$

362M $B\bar{B}$ [hep-ex/0703027]



- ⋆ Understanding composition of $B \to X_c \ell \nu$ important for $|V_{ub}|$, $|V_{cb}|$
- ⋆ Reconstruct D, ℓ and non-overlapping hadronic tag
- ⋆ Fit to missing mass, lepton momentum and charged track multiplicity to determine D, D^*, D^{**} components
- ⋆ D^{**} includes nonresonant decays

Ratio	B^- (%)	$\bar{B}^0$ (%)
$\frac{\Gamma(\bar{B} \to D \ell^- \bar{\nu}_\ell)}{\Gamma(\bar{B} \to D X \ell^- \bar{\nu}_\ell)}$	$22.7 \pm 1.4 \pm 1.6$	$21.5 \pm 1.6 \pm 1.3$
$\frac{\Gamma(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)}{\Gamma(\bar{B} \to D X \ell^- \bar{\nu}_\ell)}$	$58.2 \pm 1.8 \pm 3.0$	$53.7 \pm 3.1 \pm 3.6$
$\frac{\Gamma(\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell)}{\Gamma(\bar{B} \to D X \ell^- \bar{\nu}_\ell)}$	$19.1 \pm 1.3 \pm 1.9$	$24.8 \pm 3.2 \pm 3.0$

- ⋆ PDFs build on exclusive data samples
- ⋆ Comparable precision to current world average

Composition of $B \to X_c \ell \nu$ (II)

★ $\mathcal{B}(B \to D^{**}\ell\nu)/10^{-3}$

D_1^-: $3.64 \pm 0.32_{[\text{stat}]} \pm 0.49_{[\text{syst}]}$

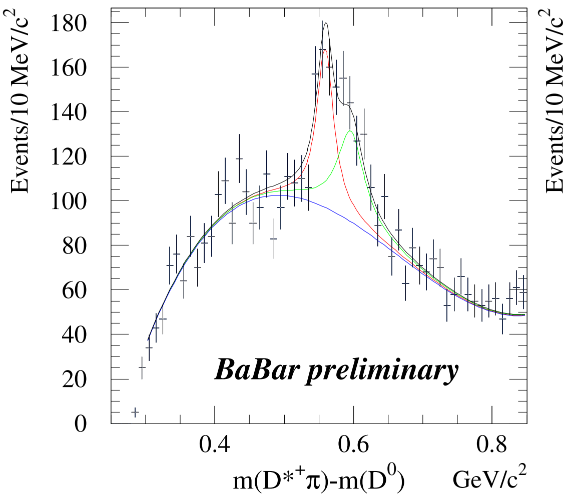
D_2^{*-}: $2.70 \pm 0.35_{[\text{stat}]} \pm 0.43_{[\text{syst}]}$

D_1^0: $4.48 \pm 0.26_{[\text{stat}]} \pm 0.35_{[\text{syst}]}$

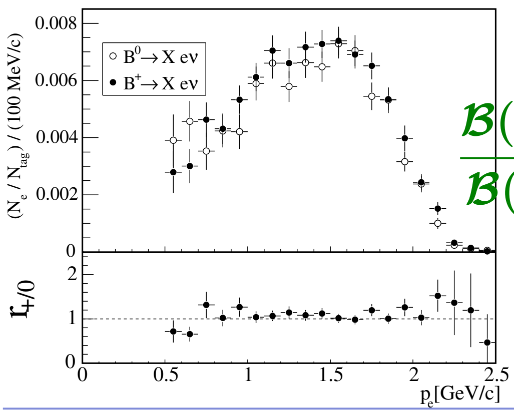
D_2^{*0}: $3.54 \pm 0.32_{[\text{stat}]} \pm 0.54_{[\text{syst}]}$

★ $\mathcal{B}(B \to D_2^*\ell\nu)/\mathcal{B}(B \to D_1\ell\nu)$ tests theoretical models

230M $B\bar{B}$



231M $B\bar{B}$ [hep-ex/0607111]



★ Good control of inclusive measurements important for inclusive extraction of $|V_{cb}|$

$$\frac{\mathcal{B}(B^+ \to Xe\nu)}{\mathcal{B}(B^0 \to Xe\nu)} = 1.084 \pm 0.041_{[\text{stat}]} \pm 0.025_{[\text{syst}]}$$

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.071 \pm 0.009$$ [PDG 2006]

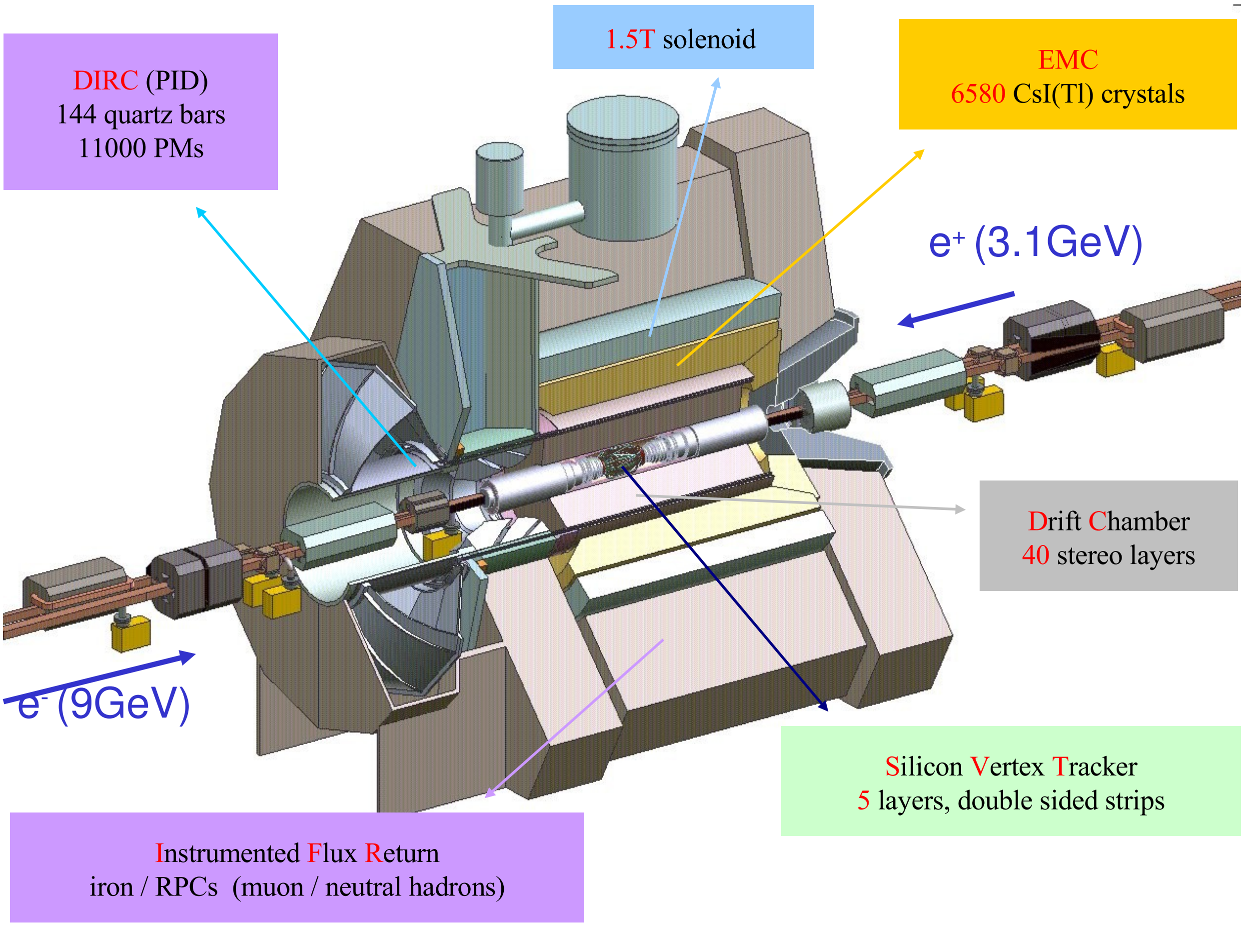
★ Consistent with equal semileptonic widths

Summary

- $|V_{ub}|$ from exclusive $B \to \pi\ell\nu$
  - Currently limited by Lattice QCD FF uncertainties (untagged)
  - Tagged analyses will benefit from increased statistics
- $|V_{ub}|$ from inclusive $B \to X_u\ell\nu$
  - First measurement directly using $B \to X_s\gamma$ spectrum
- $|V_{cb}|$ and FF in $B \to D^*\ell\nu$
  - Limited by FF uncertainties
- Currently higher precision from inclusive determinations
  - $|V_{cb}|$: 2% vs. 4% $|V_{ub}|$: 8% vs. 14%
- Understanding composition of $B \to X_q\ell\nu$ important for $|V_{ub}|$ and $|V_{cb}|$
- Active experimental and theoretical efforts to improve precision of $|V_{qb}|$

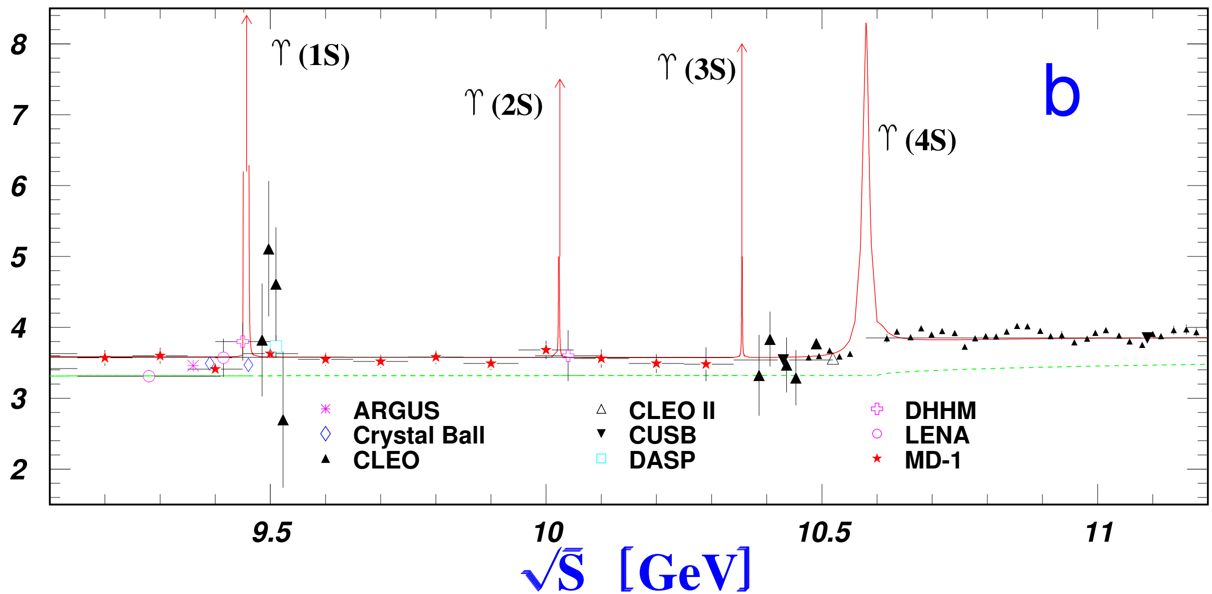
Backup Slides

The BABAR Detector

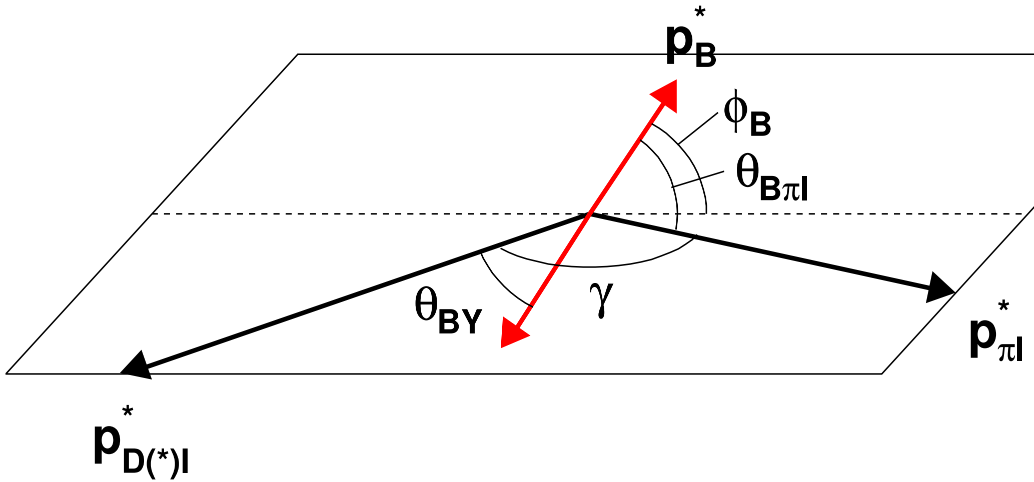


*B*A*B*A*R* and PEP-II

- PEP-II is "asymmetric B-factory":
  - $e^-(9\,\mathrm{GeV})e^+(3.1\,\mathrm{GeV}) \to \Upsilon(4S) \to B\bar{B}$
  - Collected $\sim 400\,\mathrm{fb}^{-1}$ (440 million $B\bar{B}$) between 1999 and now



Definition of ϕ_B



ϕ_B = angle between the direction of the B momenta $\vec{p}_B$ and the plane defined by the $D^{(*)}\ell_{\rm tag}$ and $\pi\ell_{\rm sig}$ momenta, $\vec{p}_{D^{(*)}\ell}$ and $\vec{p}_{\pi\ell}$

$|V_{cb}|$ and FF in $B \to D^*\ell\nu$ (II)

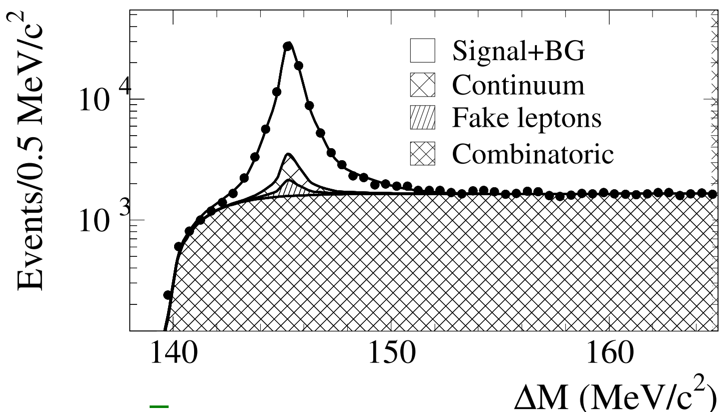
★ Select leptons with $p_\ell > 1.2\,\mathrm{GeV}$

★ Reconstruct $D^* \to D^0\pi$, $D^0 \to (K\pi$, $K\pi\pi^0$, $K\pi\pi\pi)$

Estimate backgrounds

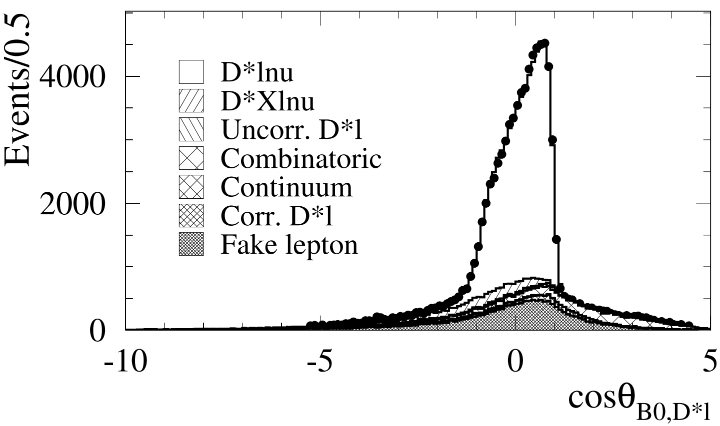
★ Combinatoric background

$$\Delta M = m(D^0\pi) - m(D^0)$$



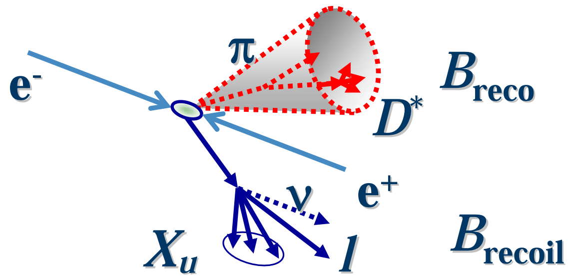
★ Other ($b \to c\ell\nu$) background

$$\cos\theta(B, D^*\ell)$$

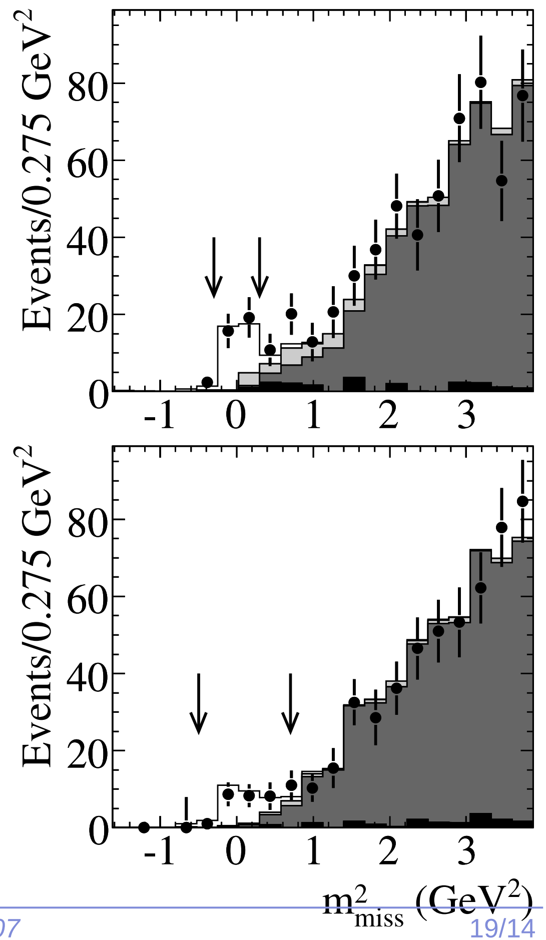


88M $B\bar{B}$ [hep-ex/0607076]

$B \to \pi\ell\nu$ Hadronic Tag



232M $B\bar{B}$ [hep-ex/0607089]



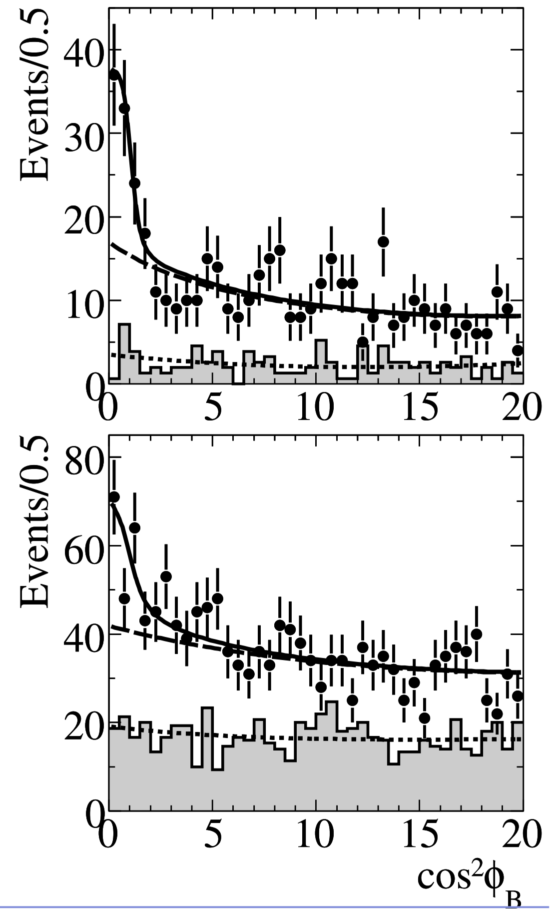
- Tag $B \to D^{(*)}Y$ with $Y = n\,K + m\,\pi$ ($\sim 0.4\%$ efficiency)
  - High purity
  - Signal yields $31 \pm 7\ (B^0)$, $26 \pm 7\ (B^+)$
- Use missing mass to select signal
- Normalize to $B \to X\ell\nu$ (3 bins of q^2)
- $\mathcal{B}(B^0 \to \pi^-\ell^+\nu)/10^{-4}$

  B^0: $1.07 \pm 0.27_{[\text{stat}]} \pm 0.15_{[\text{syst}]}$

  B^+: $1.52 \pm 0.41_{[\text{stat}]} \pm 0.20_{[\text{syst}]}$ (isospin)

$B \to \pi\ell\nu$ Semileptonic Tag

232M $B\bar{B}$ [hep-ex/0607089]



- Tag $B \to D^{(*)}\ell\nu$
  - High purity, but small efficiency
  - Signal yields 57^{+13}_{-12} (B^0), 92^{+26}_{-24} (B^+)
- Fit to $\cos^2\phi_B$ to select signal (angle between B momenta and $D^*\ell - \pi\ell$ plane)
- Measure $\mathcal{B}(B \to \pi\ell\nu)$ in 3 bins of q^2
- $\mathcal{B}(B^0 \to \pi^-\ell^+\nu)/10^{-4}$

  B^0: $1.12 \pm 0.25_{[\text{stat}]} \pm 0.10_{[\text{syst}]}$

  B^+: $1.36 \pm 0.33_{[\text{stat}]} \pm 0.15_{[\text{syst}]}$ (isospin)