Measurements of $|V_{ub}|$ at *BABAR*

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overview

1) Measurement of the Inclusive Electron Spectrum in Charmless Semileptonic B Decays Near the Kinematic Endpoint and Determination of $|V_{ub}|$

   BABAR Collaboration, B. Aubert & al, Phys. Rev. **D73**, 012006 (2006).

2) Determinations of $|V_{ub}|$ from Inclusive Semileptonic B Decays with Reduced Model Dependence

   BABAR Collaboration, B. Aubert & al, Phys. Rev. Lett. **96**, 221801 (2006).

3) Measurement of the $B^0 \to \pi^- l^+ \nu$ Form Factor Shape and Branching Fraction, and Determination of $|V_{ub}|$ with a Loose Neutrino Reconstruction Technique

   ICHEP 2006 (`hep-ex/0607060`).

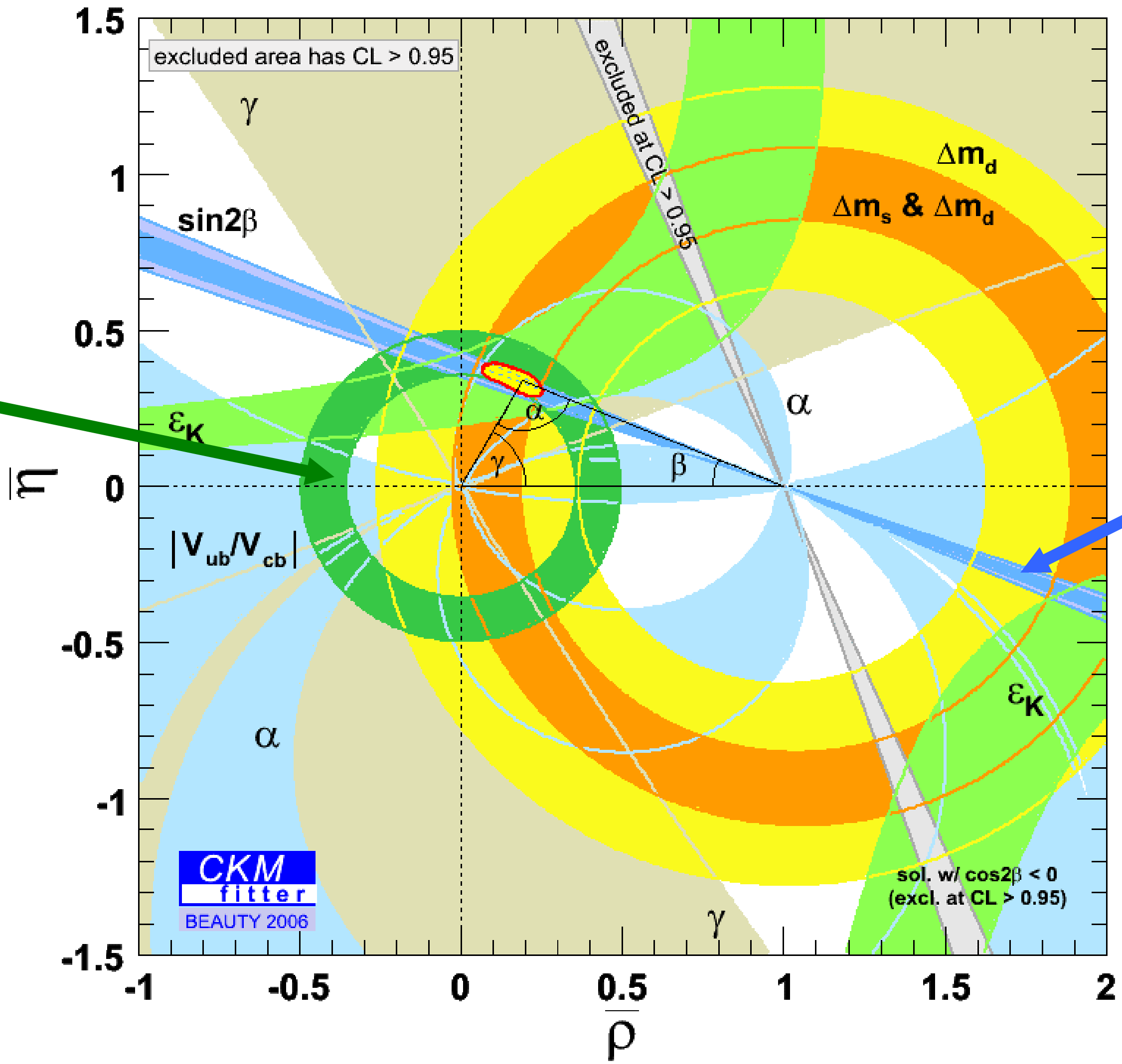
4) Measurement of the $B \to \pi l \nu$ Branching Fraction and Determination of $|V_{ub}|$ with Tagged B Mesons

   Accepted by Phys. Rev. Lett. (`hep-ex/0607089`).

5) Measurement of the $B^+ \to \eta l^+ \nu$ and $B^+ \to \eta' l^+ \nu$ Branching Fractions using $\Upsilon(4S) \to B\bar{B}$ Events Tagged by a Fully Reconstructed B Meson

   ICHEP 2006 (`hep-ex/0607066`).

$|V_{ub}|$

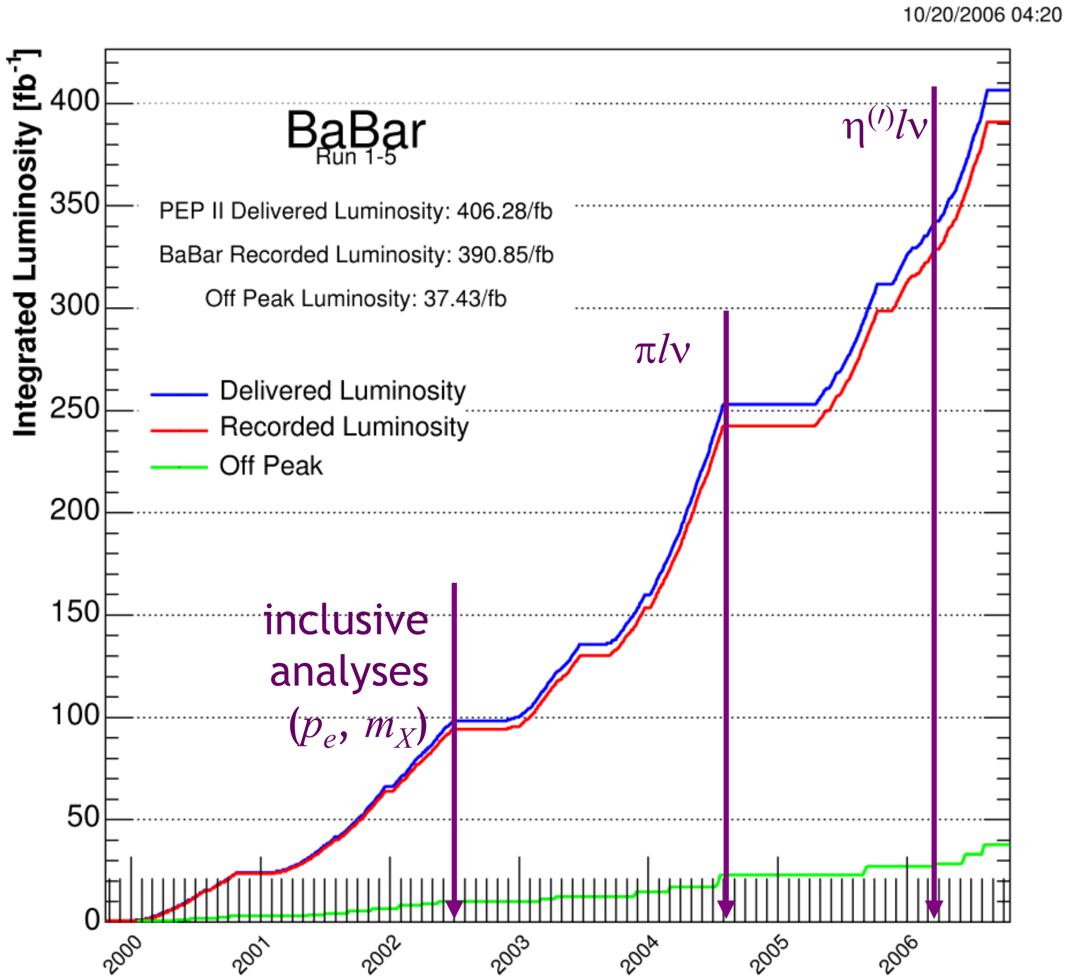


sin2β,
e.g., $B \to J/\psi K_S$

BaBar / PEP-II

9.0 GeV e^- HER,
3.1 GeV e^+ LER
$\Downarrow$
$\sqrt{s} = 10.58$ GeV
$(\beta\gamma)_{\Upsilon(4S)} = 0.56$

$$\int \mathcal{L}\, dt = 390.85\ \text{fb}^{-1}$$
$$\approx 430\text{M}\ B\bar{B}$$

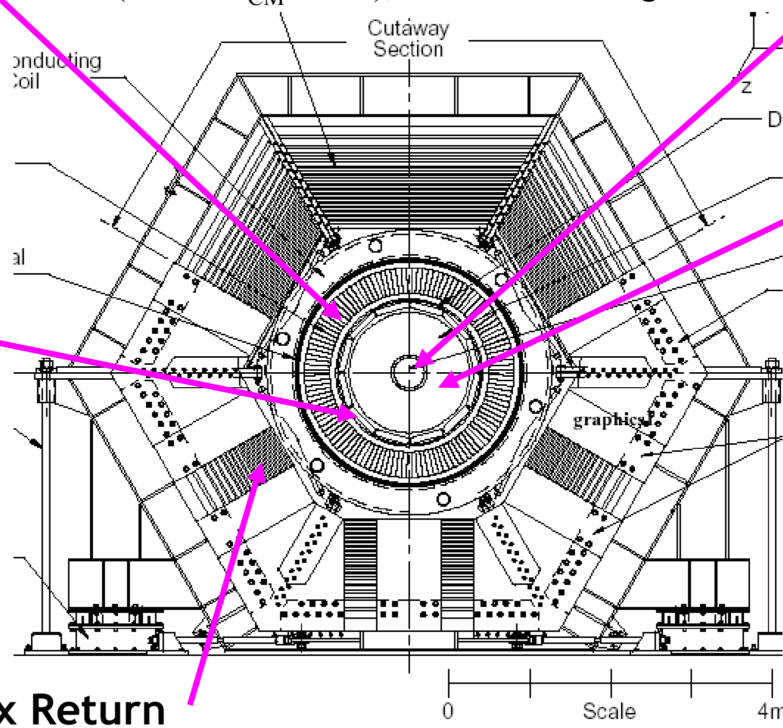


BABAR / BABAR

ElectroMagnetic Calorimeter
6580 CsI(Tl) crystals measuring EM showers
$\sigma_{m_{\pi 0}} = 6.9$ MeV

$-50^\circ < \lambda_{\mathrm{lab}} < 70^\circ$ latitudinal coverage
($-65^\circ < \lambda_{\mathrm{CM}} < 65^\circ$), $\sim 91\%$ solid angle

Silicon Vertex Tracker
5 layer double-sided Si strip detector in 1.5T



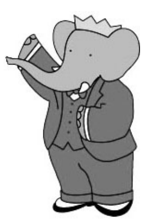
Drift CHamber
40 layers hexagonal cells
80 He : 20 *i*-butane

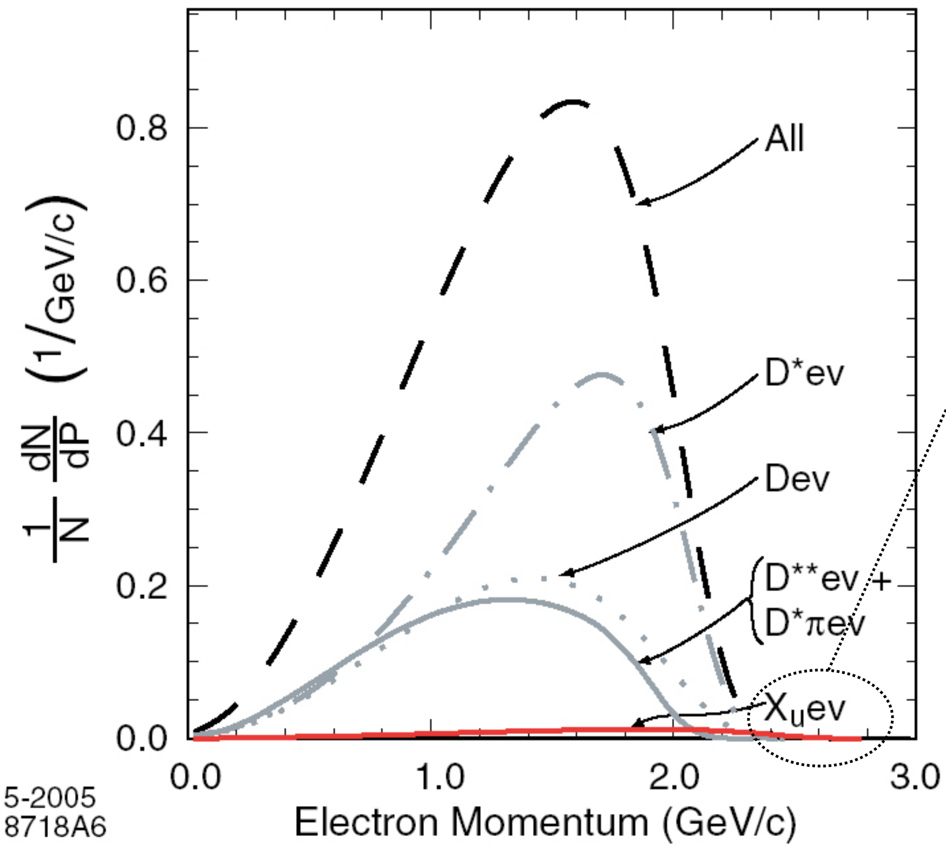
Detector of Internally Reflected Čerenkov light
12×12 synthetic silica ($n = 1.479$) bars
K eff. $\approx 96\%$
π misID $\approx 2\%$

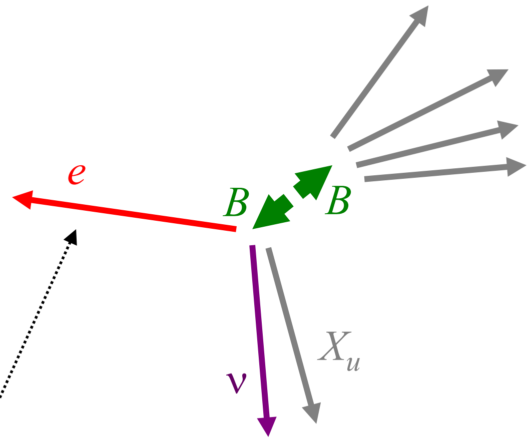
combined SVT, DCH:
$\sigma_{d_0} = 23\ \mu$m
$\sigma_{\phi_0} = 0.43$ mrad
$\sigma_{z_0} = 29\ \mu$m
$\sigma_{\tan\lambda} = 0.53 \times 10^{-3}$
PID below 700 MeV/c

Instrumented Flux Return
18-19 layers RPCs interleaved with magnetic flux return steel
μ eff. $\approx 90\%$
K_{L} eff. $\sim 64\%$

The BABAR detector has been described in detail elsewhere. [1]



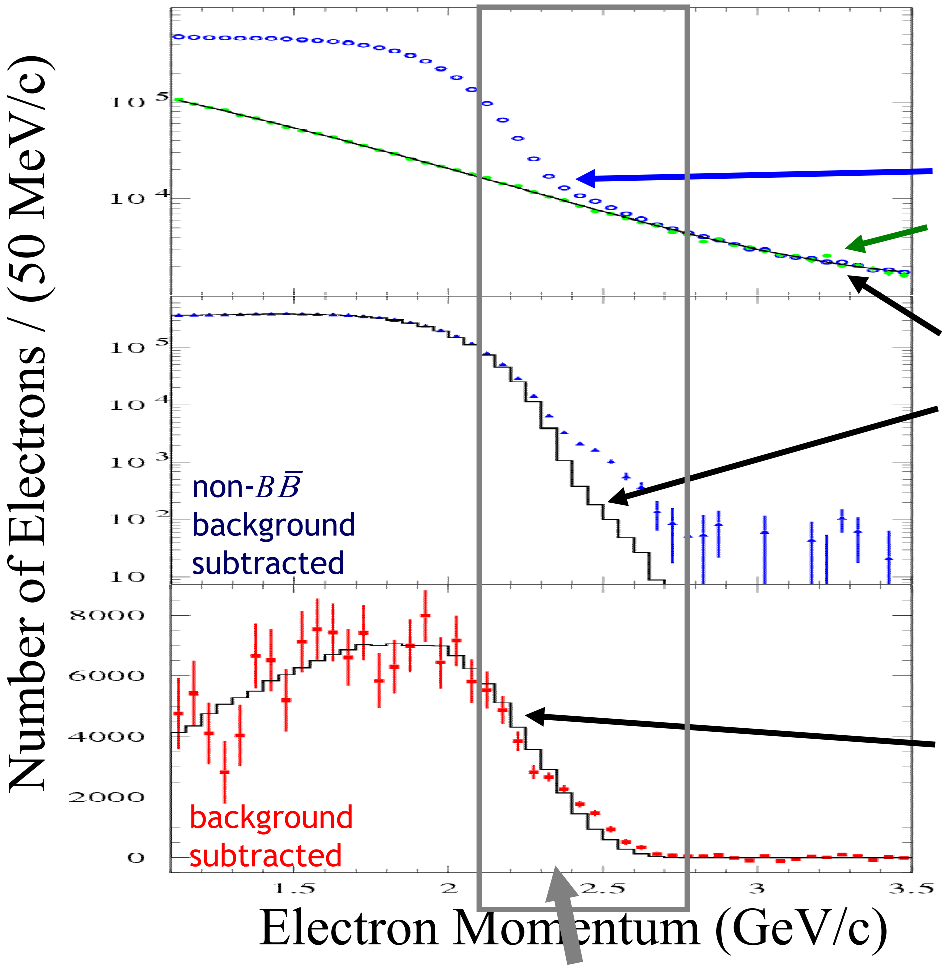




Note: $\frac{\mathcal{B}(b \to c l \nu)}{\mathcal{B}(b \to u l \nu)} \sim 50$

- $p_e > 1.1$ GeV/c, vetoing J/ψ
- $p_\nu > .5$ GeV/c, fiducial
- $\cos(\theta_{e\nu}) < 0.4$
- ≥ 4 charged tracks

overall signal efficiency: 35-50% (depends on p_e)



Electron momentum spectrum, (momentum scaled) off-peak data are simultaneously (χ^2) fit to:

- non-$B\bar{B}$ background (exponential),
- $B\bar{B}$ background (MC), separately:
  - $B \to De\nu$
  - $B \to D^*e\nu$
  - $B \to D^{**}e\nu$
  - $B \to D^{(*)}\pi e\nu$
  - other
- $B \to X_u e\nu$ (MC).

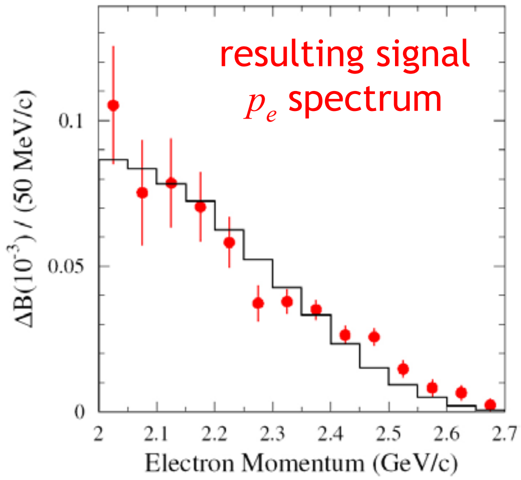
$\Rightarrow \chi^2 = 96/73$ d.o.f.

This region is combined into single bin to reduce input shape dependence.

Using

- $2.0 < p_e < 2.6$ GeV/c,
- Bosch, Lange, Neubert, Paz differential decay rate calculation [2], and
- shape function parameters (non-perturbative QCD corrections) from combined fit to *BaBar* moments [3],

we extract:



$$\mathcal{B}(B \to X_u e\nu) = (2.27 \pm 0.26_{\text{exp}}{}^{+0.33}_{-0.28}{}_{\text{SF}} \pm 0.17_{\text{theory}}) \times 10^{-3},$$

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

(for 88M $B\overline{B}$).

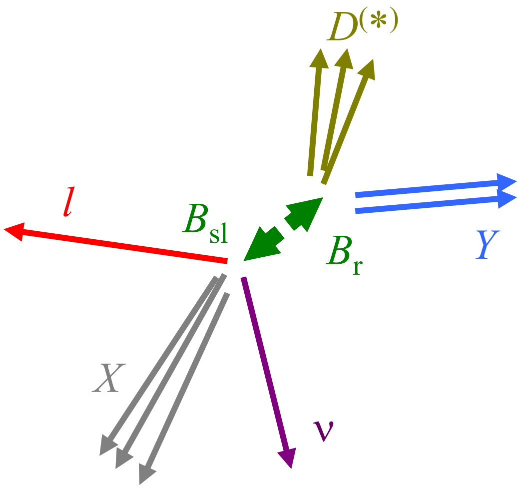
- The dominant experimental error is from event selection efficiency (sensitivity to cuts).
- We get comparable results when using smaller momentum range and/or other differential decay rate calculations and/or different shape function inputs.

m_X

hadronically reconstructed $B_\mathrm{r} \to D^{(*)}Y$

- reconstruct D hadronically, $D^* \to D\pi$, $D\pi^0$, $D\gamma$
- $q_Y = \pm 1$, some combination of $\pi^\pm$, $K^\pm$, π^0, $K_\mathrm{S}{}^0$
- select on $\Delta E \equiv E_B - \sqrt{s}/2$

$\varepsilon_{\mathrm{B0}} = 0.3\%$, $\varepsilon_{\mathrm{B}\pm} = 0.5\%$



for B_sl, require:

- hard ($p_l^* > 1$ GeV/c) lepton ($\{e, \mu\}$)
- $Q_\mathrm{total} = 0$
- consistent with ν hypothesis:

  $-1.0 < m^2_\mathrm{miss} < 0.5\ \mathrm{GeV}^2/c^4$, $|\mathbf{p}_\mathrm{miss}| > 0.3$ GeV/c

  $|\cos\theta_\mathrm{miss}| < 0.95$

reject events with $K^\pm$, $K_\mathrm{S}{}^0$ ($\to \pi^+\pi^-$) in X (suppresses $X = X_c$)

m_X is calculated with full kinematic fit

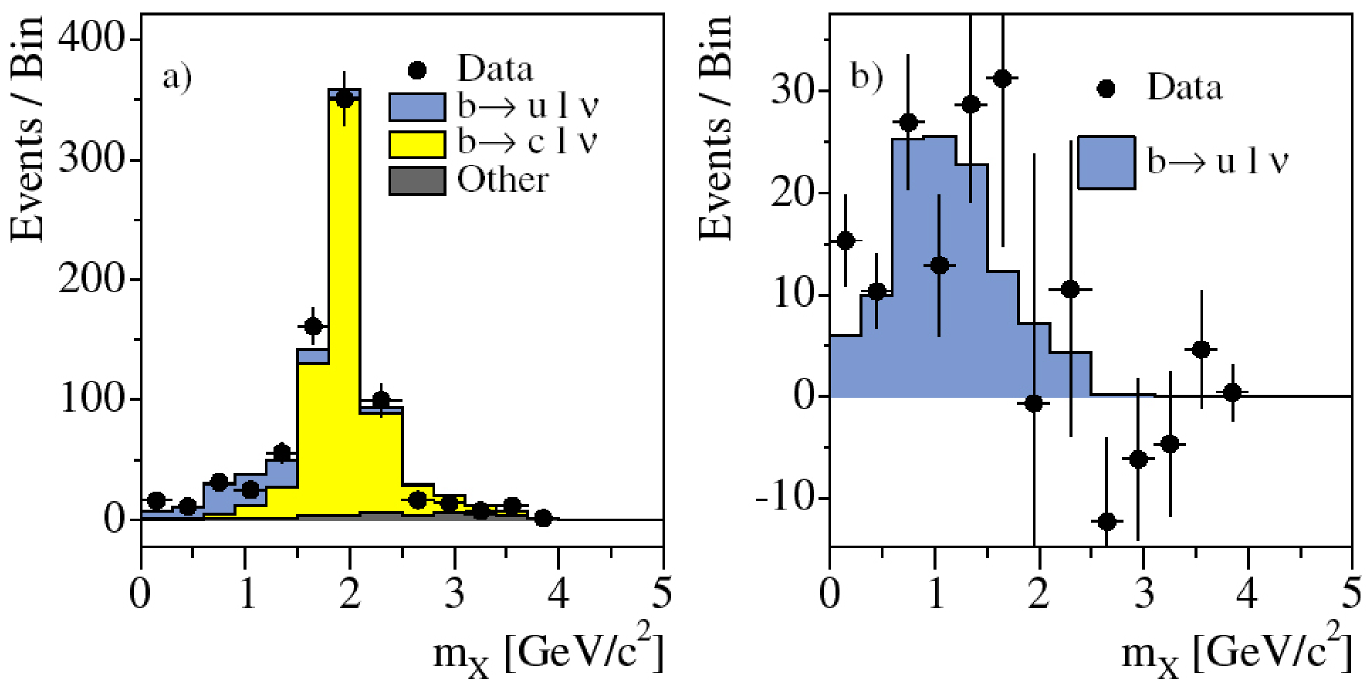
$\sigma_{mX} \sim 250\ \mathrm{MeV}/c^2$

m_X

From data and MC components ($X = X_u$, $X = X_c$, "other"),

combinatorial (5-25%) background is removed via UML $m_{ES} \equiv \sqrt{(s/4 - |\mathbf{p}_B|^2)}$ fit (separately for each m_X bin (300 MeV/c^2)).

Yield is extracted via binned χ^2 fit (sum of MC components to data) on m_X:



experimental errors (on $|V_{ub}|$):

	$|V_{ub}|$ extraction method	
	LLR†	full rate‡
statistical	7.7%	18.2%
detector systematics	3.3%	3.6%
dominated by combinatoric subtraction		
background simulation	1.0%	3.8%
dominated by uncertainty on $B \to D^* l \nu X$, $B \to D^{**} l \nu X$ branching fractions		
signal simulation	3.9%	5.6%

† See p13.
‡ See p12.

Using the full $B \to X_u l\nu$ rate

($0 < m_X < 2.50$ GeV/c^2 (~96%)),

for 88.9M $B\bar{B}$,

we extract [4]:

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

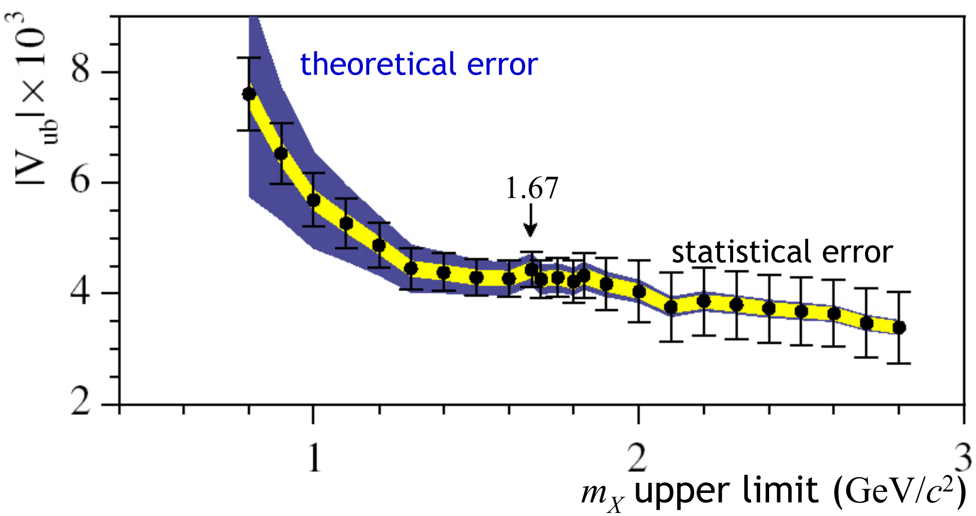
2.6%

Note that:

$$\Gamma(B \to X_u l\nu) = \frac{G_F^2 |V_{ub}|^2}{192\pi^3} m_b^5 \times \left[1 - \frac{9\lambda_2 - \lambda_1}{2m_b^2} + \cdots - \mathcal{O}(\frac{\alpha_s}{\pi})\right].$$

alternate $|V_{ub}|$ extraction (due to Leibovich, Low & Rothstein [5]):

$|V_{ub}|$ in terms of γ, l spectra from $B \to X_s\gamma$, $B \to X_u l\nu$ (B structure function independent)

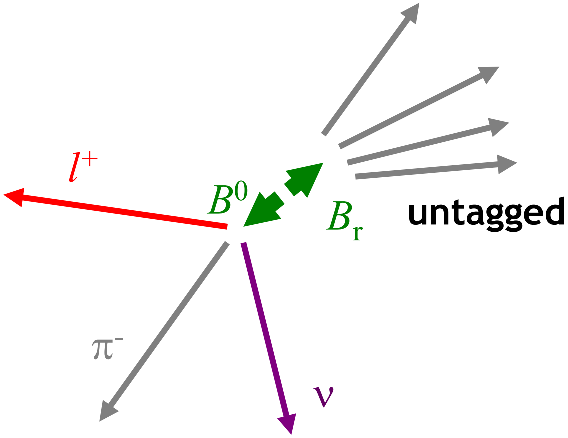


$$|V_{ub}| = (4.43 \pm 0.38_{\text{stat}} \pm 0.25_{\text{syst}} \pm 0.29_{\text{theo}}) \times 10^{-3}$$

includes statistical error from $B \to X_s\gamma$ [6]
(BABAR measurement of over $88.9M\ B\bar{B}$;
p_γ in B rest frame)

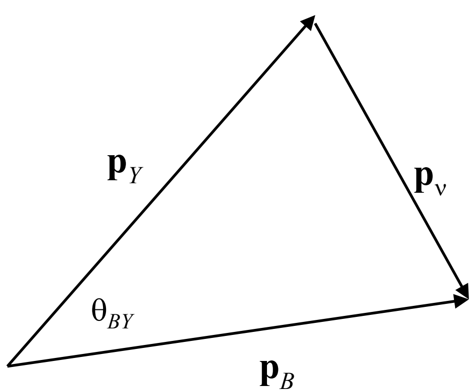
require $l^{\pm}$ ($p_e > 0.5$ GeV/c, $p_\mu > 0.8$ GeV/c), $\pi^{\mp}$

- tight PID
- vertex χ^2 probability > 0.01
- $|\cos\theta_{BY}| < 1$



suppress non-$B\bar{B}$ backgrounds:

- require $\geq$4 tracks
- cut on event shape variables
- explicitly reject radiative Bhabha, γ conversion



Where $P_Y \equiv P_l + P_\pi$, using nominal p_B and assuming $m_\nu = 0$,

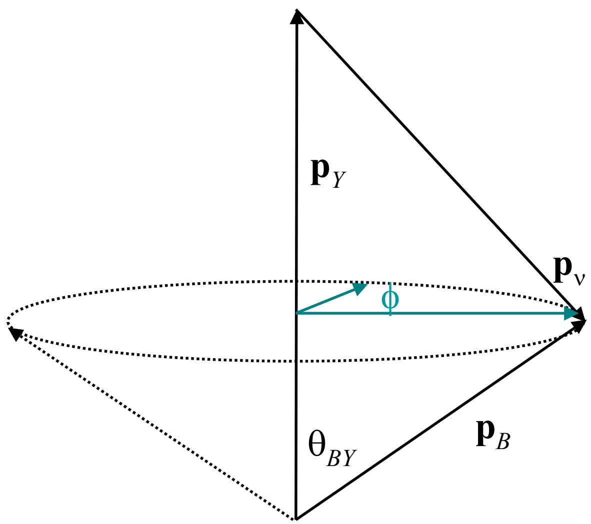
$$\cos(\theta_{BY}) = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y}.$$

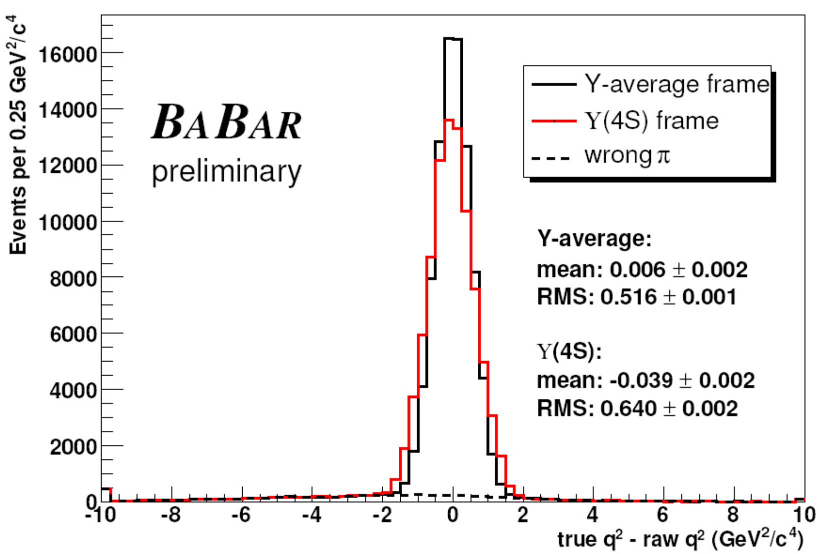
Looser ν quality cuts increase acceptance.

Rather than assume $P_\nu = P_{\text{miss}}$, $\bar{q}^2$ ("raw" q^2) is calculated via:

$$\bar{q}^2 \equiv (P_B - P_\pi)^2$$

in "Y-average frame"
(average over arbitrary azimuth ϕ, $\phi + 90°$, $\phi + 180°$, $\phi + 270°$).





$B\bar{B}$-background rejection

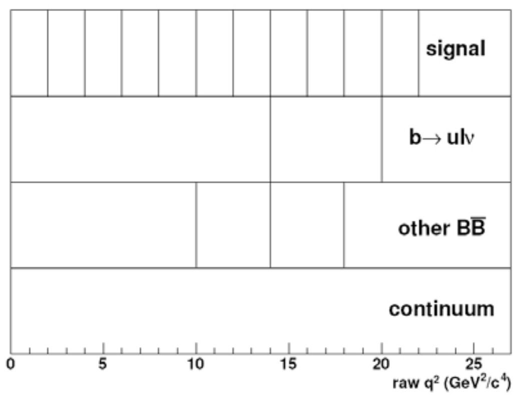
- reject $J/\psi \to \mu\mu$ ($3.07 < m_Y < 3.13$ GeV/c^2)
- $\vec{q}^2$-dependent cuts (to maximize $S/\sqrt{(S+B)}$) on W helicity angle (θ_l); angle between Y, event thrust axes (θ_{thrust}); missing mass; missing energy direction
- $|\Delta E| < 1.0$ GeV
- $m_{ES} > 5.19$ GeV/c^2

In events with multiple candidates, the one with smallest $|\cos \theta_l|$ is taken.

overall signal efficiency: 6.6 – 9.7%

three-dimensional (ΔE-m_{ES}, $\tilde{q}^2$) extended binned ML fit of PDFs (MC) to data

$\tilde{q}^2$ binning



over 227.4M $B\bar{B}$:

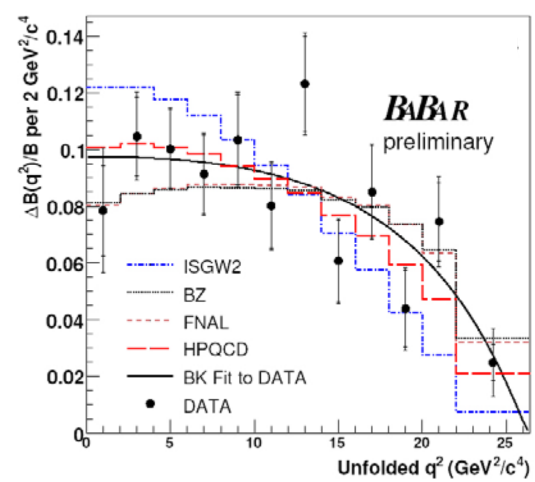
signal yield (events): 5047 ± 251
$b \to ul\nu$: 10015 ± 548
other $B\bar{B}$ background: 32788 ± 445
continuum: 9801 ± 467

$\chi^2 = 428 / 388$ d.o.f.

After $\tilde{q}^2 \Rightarrow q^2$ unfolding, $f^+(q^2)$ is evaluated from normalized spectrum $\Delta\mathcal{B}(q^2)/\mathcal{B}$.

E.g., we do fit to Becirevic-Kaidolov $f^+(q^2,\alpha)$ parameterization [7]:

$$f^+(q^2,\alpha) = \frac{f_0}{(1 - q^2/m^2_{B^*})(1 - \alpha q^2/m^2_{B^*})}.$$



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

Partial $\Delta\mathcal{B}(B^0 \to \pi^- \ell^+ \nu, q^2)$ and total $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ ($\times 10^7$) and their errors ($\times 10^7$) from all sources.

q^2 intervals (GeV^2/c^4)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-26.4	Total	q^2<16	q^2>16
fitted BF	113.2	151.1	144.6	131.8	149.3	115.7	177.8	87.7	122.7	63.3	107.6	78.7	1443.6	1071.2	372.4
fitted yield stat err	22.9	20.0	19.9	20.1	22.8	21.5	24.3	20.8	23.4	19.5	20.0	20.1	83.4	63.3	44.1
trk eff	14.7	1.5	6.1	3.3	3.7	3.4	4.4	4.0	2.4	4.6	1.3	4.4	40.3	39.7	4.5
γ eff	15.2	1.0	5.3	7.0	3.3	9.0	7.3	4.3	3.2	4.0	2.8	1.9	56.9	50.9	6.7
K_L^0 eff & E	1.6	1.0	1.1	1.4	1.5	0.8	2.2	1.6	1.7	1.5	1.2	1.8	7.1	5.2	3.7
Y PID & trk eff	2.3	2.9	2.1	2.8	2.3	1.7	3.4	1.5	2.3	0.9	1.9	1.8	22.1	15.8	6.5
continuum yield	3.2	0.6	0.4	0.1	0.1	0.2	0.2	0.6	0.6	1.3	0.8	2.1	4.2	2.2	4.6
continuum $\tilde{q}^2$	12.9	2.3	1.8	1.2	1.5	1.3	1.1	2.0	2.2	3.6	3.9	8.4	8.8	8.8	12.4
continuum m_{ES}	6.1	0.6	0.4	0.1	0.9	0.6	0.1	0.7	0.5	1.1	1.2	2.0	12.4	7.7	4.7
continuum ΔE	2.6	2.2	0.6	1.4	2.4	0.5	0.4	1.0	0.7	1.4	3.4	3.3	17.8	9.2	8.6
$D \to K_L^0$ BF	8.1	6.3	8.2	3.3	3.9	4.5	3.4	4.6	5.5	4.9	4.3	4.5	51.6	34.2	17.5
$b \to c\ell\nu$ BF	3.0	2.6	1.5	2.8	6.2	1.2	4.3	2.0	1.7	2.7	1.5	1.6	17.0	13.2	5.0
$b \to u\ell\nu$ BF	1.7	1.8	1.1	1.0	1.6	1.6	2.0	1.5	1.7	2.9	7.9	7.5	16.6	9.6	11.5
$\Upsilon(4S) \to B^0\bar{B}^0$ BF	2.3	3.3	2.3	2.0	2.1	1.9	2.9	1.1	2.0	0.8	2.4	1.4	23.9	17.7	6.3
$B \to D^*\ell\nu$ FF	1.7	1.3	0.2	2.0	4.0	1.0	2.6	0.9	1.0	0.8	0.8	2.5	12.5	10.2	2.7
$B \to \rho\ell\nu$ FF	4.0	1.2	3.4	1.7	1.1	1.7	2.6	3.9	1.3	1.9	1.6	3.5	18.3	14.4	5.7
$B^0 \to \pi^-\ell^+\nu$ FF	-1.2	-0.0	0.3	0.1	0.3	0.0	0.7	-0.3	-0.2	-1.3	1.6	4.5	4.7	0.0	4.7
signal MC stat error	1.8	2.6	2.4	2.6	2.4	2.3	2.6	1.5	1.7	1.1	1.3	1.1	5.5	5.1	2.2
B counting	1.2	1.7	1.6	1.5	1.6	1.3	2.0	1.0	1.4	0.7	1.2	0.9	15.9	11.8	4.1
total syst error	28.0	9.8	13.1	10.6	11.3	11.7	12.5	9.7	8.8	10.3	11.8	15.6	102.7	83.0	31.3
total error	36.2	22.3	23.8	22.7	25.5	24.5	27.3	23.0	25.1	22.1	23.3	25.4	132.3	104.4	54.1

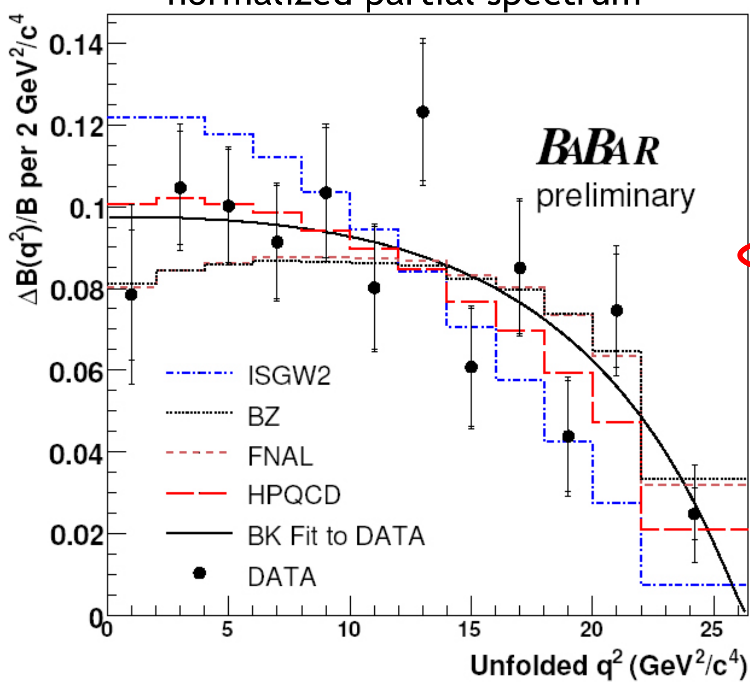
Errors from background BFs/FFs are suppressed by q^2 fit procedure.

We obtain, e.g.,

$$\mathcal{B}(B^0 \to \pi^- l^+ \nu) = (1.44 \pm 0.08_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}) \times 10^{-4},$$
$$|V_{ub}| = (4.1 \pm 0.2_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}{}^{+0.6}_{-0.4}{}_{\mathrm{FF}}) \times 10^{-3}$$

($|V_{ub}|$ using the most recent LQCD calculation [8], $q^2 > 16\ \mathrm{GeV}^2/c^4$).

normalized partial spectrum



Probabilities for QCD calculations (12 d.o.f.):

	χ^2	Prob(χ^2)
ISGW2 [9]	34.1	0.07%
Ball-Zwicky [10]	13.0	37.2%
FNAL [11]	12.5	41.0%
HPQCD [8]	10.2	60.2%

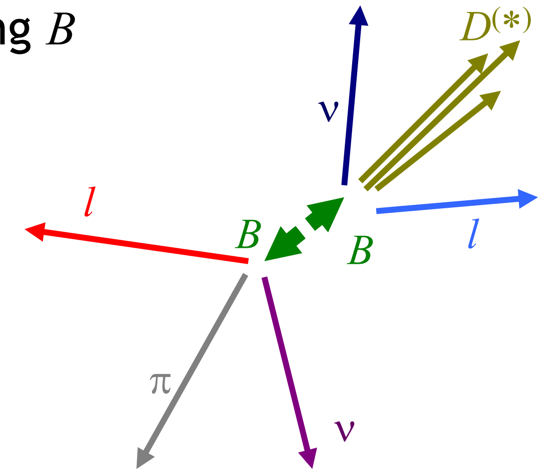
For Becirevic-Kaidalov parameterization, $\alpha_{BK} = 0.53 \pm 0.05_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$.

$B \to \pi l \nu$

$B \to \pi l \nu$ in the recoil of a semileptonically decaying B

- reconstruct D hadronically, $D^* \to D\pi, D\pi^0, D\gamma$
- look for decay products consistent with Dl, πl

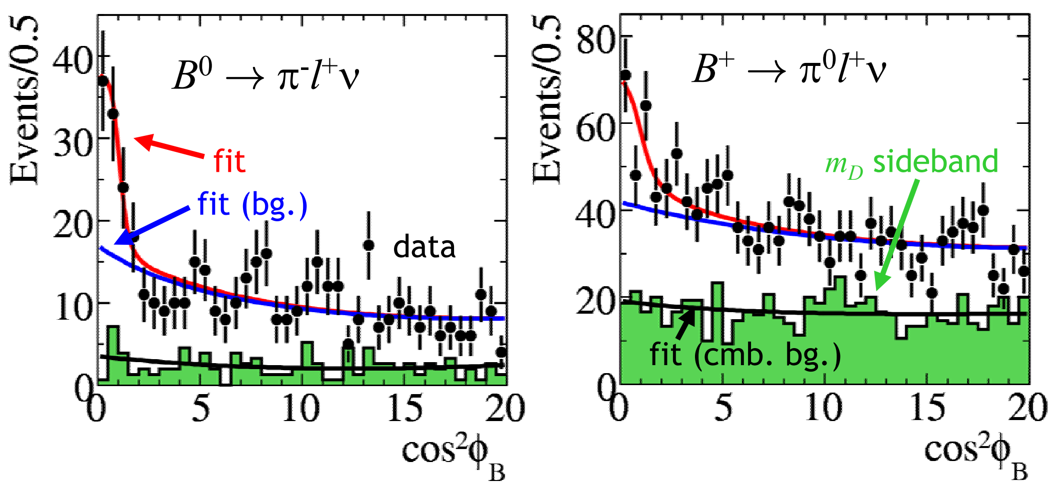
$\varepsilon_{B0} = 1.1 \times 10^{-3}$, $\varepsilon_{B\pm} = 3.0 \times 10^{-3}$



yield extracted via $\cos\phi_B$ fit:

ϕ_B is the angle between a p_B and the Dl-πl plane.

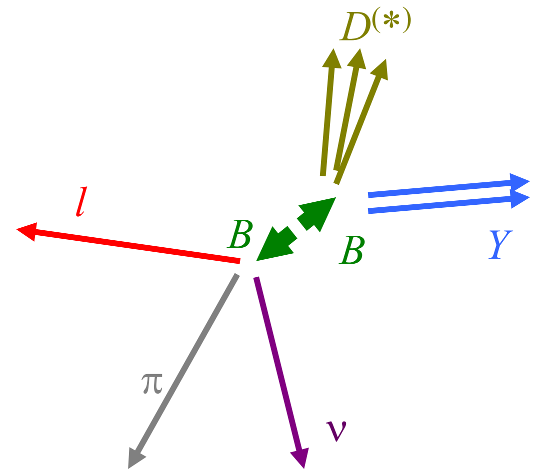
$\cos^2\phi_B \leq 1$ for signal



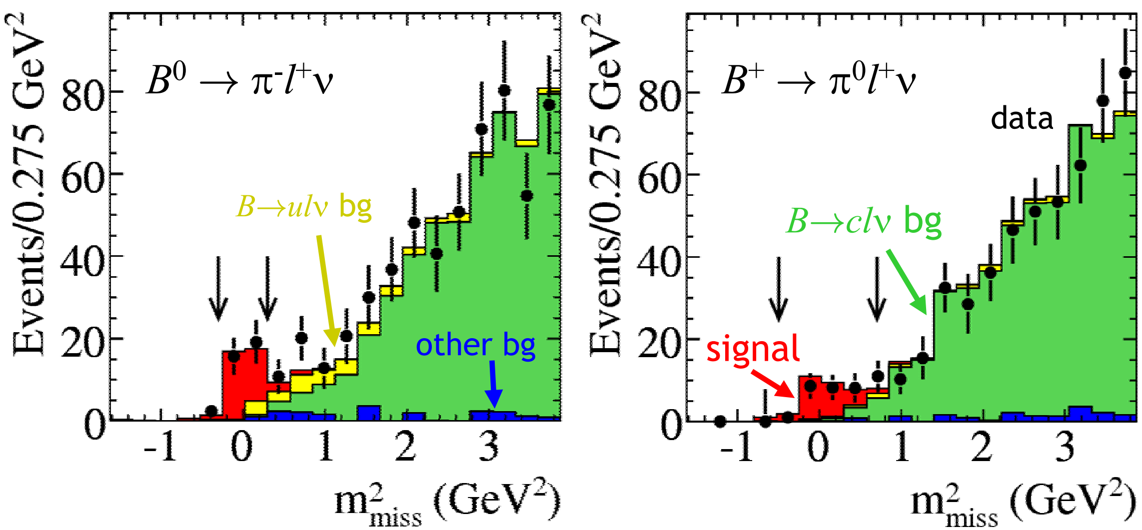
† Charge conjugates are implied throughout this talk.

$B \to \pi l \nu$

$B \to \pi l \nu$ in the recoil of a hadronically decaying B
- hadronic reconstruction of B (cp. m_X analysis)
- look for decay products consistent with πl



fully reconstructed ν:



For m^2_{miss} signal region, UML fit on m_{ES}.

Peaking backgrounds are subtracted via MC normalized to m^2_{miss} sideband.

Yield normalized to $B \to X l \nu$ decays.

$B \to \pi l \nu$

$B \to \pi l \nu$ analyses are done on $\sim$232M $B\bar{B}$, divided into $q^2 \equiv (P_l + P_\nu)^2$ (GeV$^2/c^4$) bins, yielding the branching fractions (10^{-4}):

		$q^2 < 8$	$8 < q^2 < 16$	$q^2 > 16$	$q^2 < 16$	Total
B^0	Semileptonic	$0.50 \pm 0.16 \pm 0.05$	$0.33 \pm 0.14 \pm 0.04$	$0.29 \pm 0.15 \pm 0.04$	$0.83 \pm 0.22 \pm 0.08$	$1.12 \pm 0.25 \pm 0.10$
	Hadronic	$0.09 \pm 0.10 \pm 0.02$	$0.33 \pm 0.15 \pm 0.05$	$0.65 \pm 0.20 \pm 0.13$	$0.42 \pm 0.18 \pm 0.05$	$1.07 \pm 0.27 \pm 0.15$
	Average	$0.38 \pm 0.12 \pm 0.04$	$0.33 \pm 0.10 \pm 0.03$	$0.47 \pm 0.13 \pm 0.06$	$0.72 \pm 0.16 \pm 0.06$	$1.19 \pm 0.20 \pm 0.10$
B^+	Semileptonic	$0.18 \pm 0.08 \pm 0.02$	$0.45 \pm 0.13 \pm 0.05$	$0.10 \pm 0.12 \pm 0.04$	$0.63 \pm 0.16 \pm 0.06$	$0.73 \pm 0.18 \pm 0.10$
	Hadronic	$0.16 \pm 0.11 \pm 0.03$	$0.39 \pm 0.16 \pm 0.06$	$0.26 \pm 0.12 \pm 0.06$	$0.56 \pm 0.19 \pm 0.08$	$0.82 \pm 0.22 \pm 0.11$
	Average	$0.18 \pm 0.07 \pm 0.02$	$0.43 \pm 0.10 \pm 0.04$	$0.22 \pm 0.09 \pm 0.05$	$0.61 \pm 0.12 \pm 0.05$	$0.82 \pm 0.15 \pm 0.09$
Combined		$0.36 \pm 0.09 \pm 0.03$	$0.52 \pm 0.10 \pm 0.04$	$0.46 \pm 0.10 \pm 0.06$	$0.87 \pm 0.13 \pm 0.06$	$1.33 \pm 0.17 \pm 0.11$

(Assuming isospin relation $\Gamma(B^0 \to \pi^- l^+ \nu) = 2\Gamma(B^+ \to \pi^0 l^+ \nu)$; "Combined" expressed as $\mathcal{B}(B^0 \to \pi^- l^+ \nu)$.)

e.g.:

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

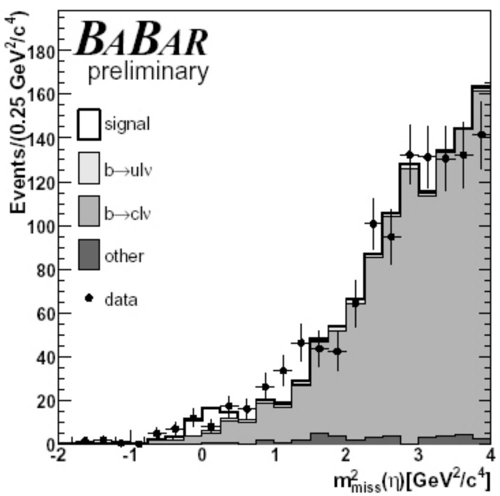
$$|V_{ub}| = (4.5 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}}{}^{+0.7}_{-0.5}{}_{\text{FF}}) \times 10^{-3}$$

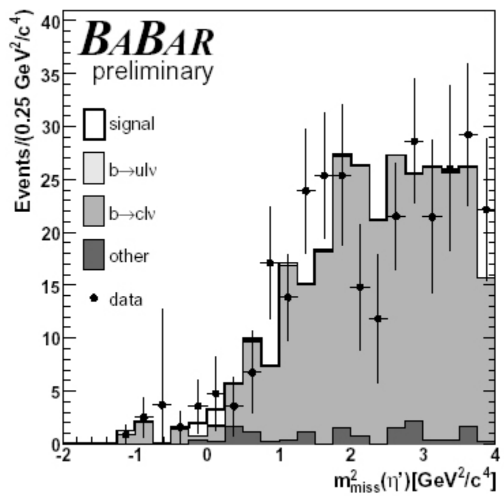
extracting $|V_{ub}|$ via lattice QCD [8], $q^2 > 16$ GeV$^2/c^4$.

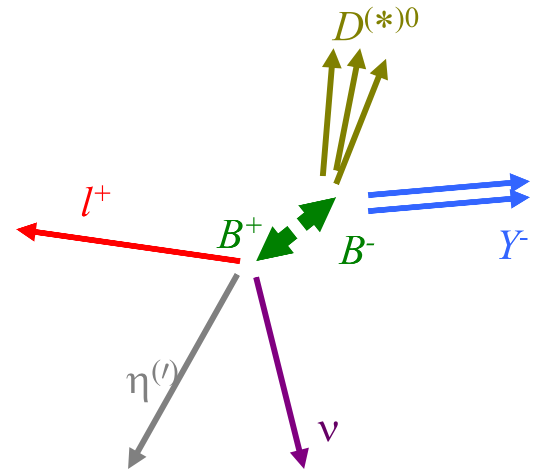
$B^+ \to \eta^{(\prime)} l^+ \nu$

largely analogous to $B \to \pi l \nu$ (hadronic B recoil)

- $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$
- $\eta' \to \rho^0\gamma$ ($\rho^0 \to \pi^+\pi^-$), $\eta\pi^+\pi^-$







With 347M $B\bar{B}$, we get:

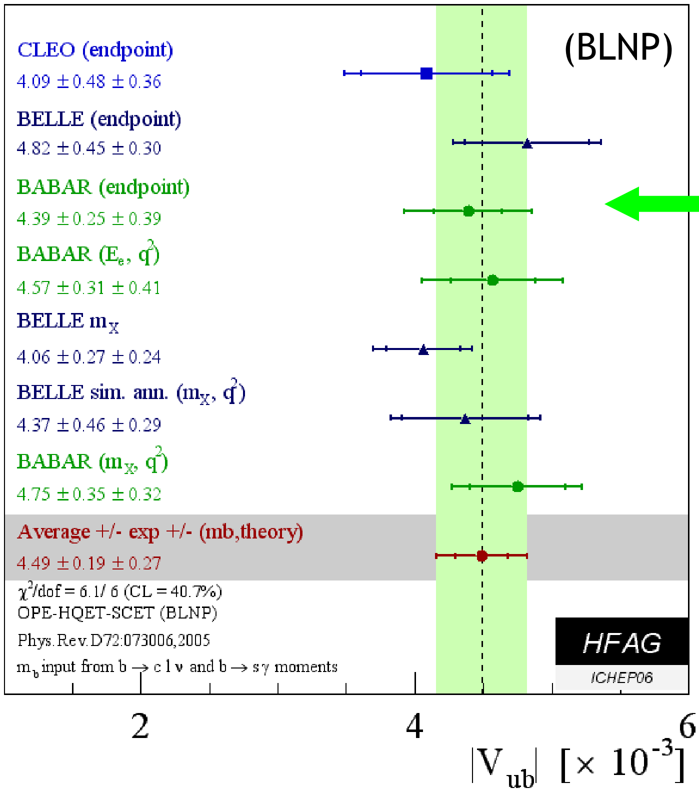
$$\mathcal{B}(B^+ \to \eta l^+ \nu) = (0.84 \pm 0.27_{\text{stat}} \pm 0.21_{\text{syst}}) \times 10^{-4},$$
$$\mathcal{B}(B^+ \to \eta' l^+ \nu) = (0.33 \pm 0.60_{\text{stat}} \pm 0.30_{\text{syst}}) \times 10^{-4},$$

or:

$$\mathcal{B}(B^+ \to \eta l^+ \nu) < 1.4 \times 10^{-4} (90\%\text{CL}),$$
$$\mathcal{B}(B^+ \to \eta' l^+ \nu) < 1.3 \times 10^{-4} (90\%\text{CL}).$$

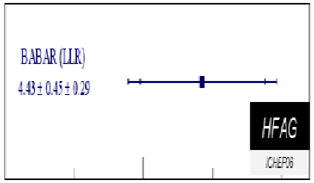
summary

inclusive $|V_{ub}|$ measurements



(1) electron endpoint spectrum: $(4.39 \pm 0.25 \pm 0.39) \times 10^{-3}$

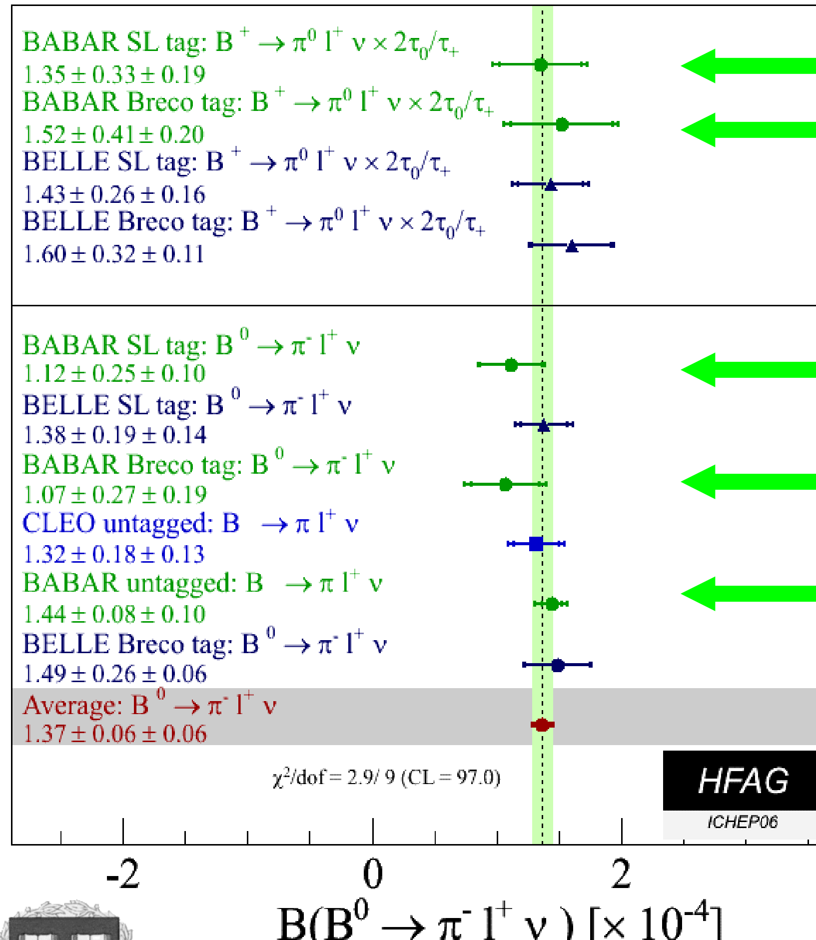
world average (not including (2)): $(4.49 \pm 0.19 \pm 0.27) \times 10^{-3}$



(2) m_X with reduced model dependence: $(4.43 \pm 0.45 \pm 0.29) \times 10^{-3}$

summary

exclusive $b \to u l \nu$ measurements



(4) π^0, semileptonic tag:
$(1.35 \pm 0.33 \pm 0.19) \times 10^{-4}$

π^0, hadronic tag:
$(1.52 \pm 0.41 \pm 0.20) \times 10^{-4}$

$\pi^\pm$, semileptonic tag:
$(1.12 \pm 0.25 \pm 0.10) \times 10^{-4}$

$\pi^\pm$, hadronic tag:
$(1.35 \pm 0.33 \pm 0.19) \times 10^{-4}$

(3) $\pi^\pm$, loose ν:
$(1.44 \pm 0.08 \pm 0.10) \times 10^{-4}$

world average:
$(1.37 \pm 0.06 \pm 0.06) \times 10^{-4}$

$\Downarrow$ [8]

$$|V_{ub}| = (3.93 \pm 0.26^{+0.56}_{-0.37}) \times 10^{-3}$$

We also (3) give $\Delta\mathcal{B}(B^0 \to \pi^- l^+ \nu, q^2)$.

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