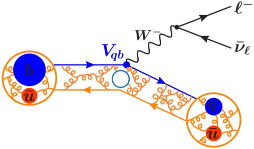
Recent results on semileptonic B-meson decays – at BABAR



Florian Bernlochner

on behalf of the BABAR collaboration

University of Victoria, Canada

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EPSHEP 2013

Stockholm, Sweden

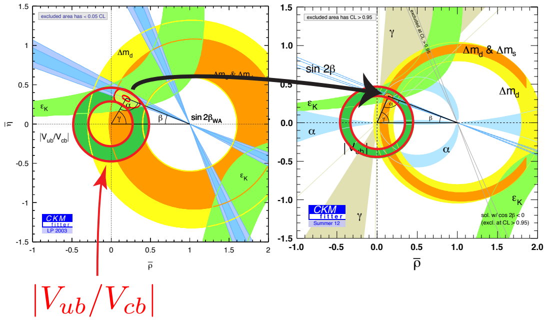
University of Victoria

- Semileptonic decays ⇔ Cabibbo-Kobayashi-Maskawa (CKM) matrix

Complex phase of CKM matrix source of SM *CP* violation.

Semileptonic decays: good exp. sensitivity and theoretical understanding to measure $|V_{qb}|$

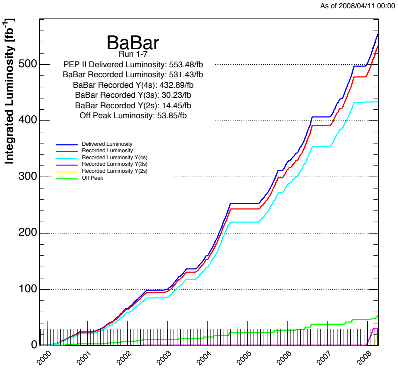
- SM CKM Matrix: *unitary* 3×3 matrix ⇒ unitarity represented as triangle
- Immense progress over the last decade in measuring CKM properties:

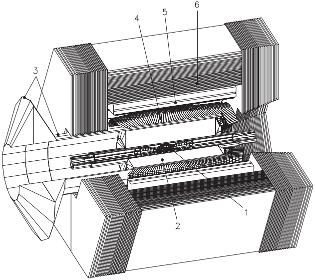


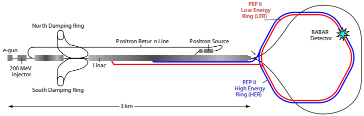
The unitarity triangle is shown, based on the triangel equation of $V_{ud}V_{ub}^* + V_{td}V_{tb}^* + V_{cd}V_{cb}^* = 0$. The result from CKM Fitter for 2003 (left) and 2012 (right) are shown.

The *BaBar* detector & Pep-II

- *BaBar* was a multipurpose detector: focus *CP* violation, τ physics, ISR, *b* and *c*.



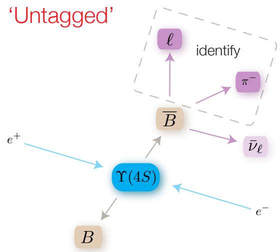


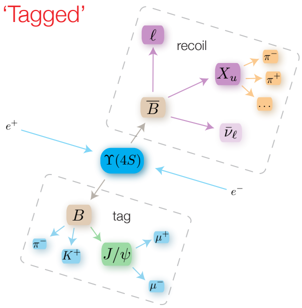


- (1) Silicon vertex tracker; (2) Drift chamber; (3) Cherenkov light detector; (4) Electromagnetic calorimeter; (5) superconducting coil; (6) Flux return & Muon detection
- Operated at the **Pep-II** *B*-**Factory** at the $\Upsilon(4S)$ resonance of $\sqrt{s} = 10.58$ GeV; also at $\sqrt{s} = 10.54$ GeV for background studies and for scans of $\Upsilon(3S-5S)$.
- Optimized trigger system to recognize $\Upsilon(4S) \to b\bar{b}$ with an efficiency of $> 99\%$. Main backgrounds from *off-resonance* $e^+e^- \to f\bar{f}$

Experimental techniques at B-Factories

- Several techniques to select and analyze B-**mesons** from $\Upsilon(4S) \to b\bar{b}$
  - Identify *lepton* or *exclusive* final state; use rest of the event to reconstruct *neutrino*
  - Completely reconstruct one B meson; infer full kinematics of recoiling B from this 'tag'





High efficiency – low Purity

Low efficiency – high Purity

Energy and momentum from initial states completely determined due to properties of $e^+ e^-$ system.

$|V_{ub}|$ from $q^2 - E_e$ measurement (1/3)

- New *untagged* measurement of $|V_{ub}|$ using the full BABAR data set.

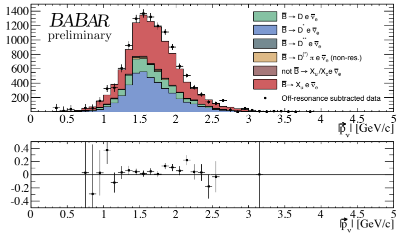
  to be submitted to PRD

- Select events with high energy electrons: $\mathbf{E_e > 1.4}$ GeV; several 'event cleaning' cuts to suppress *off-resonance* and other backgrounds.

Neutrino kinematics inferred from rest of event:

$$p_{\text{miss}} = p_{\Upsilon(4S)} - \sum_i^{N_{\text{chg}}} p^i_{\text{chg}} - \sum_i^{N_{\text{neut}}} p^i_{\text{neut}} \quad \Rightarrow \quad p_\nu = (F(|\vec{p}_{\text{miss}}|), \vec{p}_{\text{miss}})$$

F is a calibration function that maximizes the resolution.



Neutrino 3-momentum after final selection

- Simulated $\bar{B} \to X_u\, e\, \bar{\nu}_e$ signal
- Simulated $\bar{B} \to D\, e\, \bar{\nu}_e$, $\bar{B} \to D^*\, e\, \bar{\nu}_e$ backgrounds

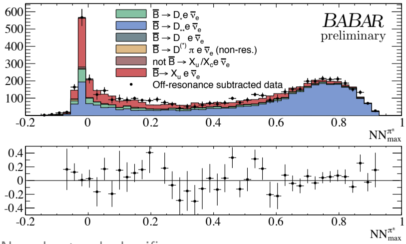
q^2 reconstruction

Four-momentum transfer of the B-meson to the X_u system, q^2, can be obtained by combining the neutrino and Lepton information:

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

$|V_{ub}|$ from $q^2 - E_e$ measurement (2/3)

- $\bar{B} \to D^*(\hookrightarrow D\pi)\, e\, \bar{\nu}_e$ background suppressed via *neural network*



Neural network classifier

- Reconstruct slow pion from D^* decay; use its kinematics to infer D^* kinematics

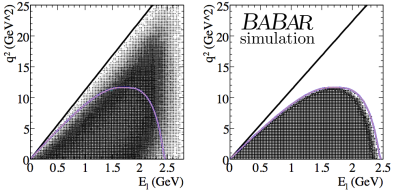
NN classifier input

$|\vec{p}_\pi|$; $\cos\theta_{B,D^* e}$; $\cos\theta_{D^*,e}$;

$m^2_{\text{miss}} = (p_B - p_{D^*} - p_e)^2$

- Simulated $\bar{B} \to X_u\, e\, \bar{\nu}_e$ signal
- Simulated $\bar{B} \to D^*\, e\, \bar{\nu}_e$ backgrounds

- The s_h^{max} cut: *Limits the mass of the hadronic X_u system to reject X_c*



$q^2 - E_e$ for $\bar{B} \to X_u\, e\, \bar{\nu}_e$ (left) and $\bar{B} \to X_c\, e\, \bar{\nu}_e$ (right)

- Invariant mass of the X_u system:

$$s_h^{max} = (p_B - (p_e + p_\nu))^2$$

$$= m_B^2 + q^2 - 2m_B\left(\eta_\mp E_\ell - \eta_\pm \frac{q^2}{4E_\ell}\right)$$

The second line expresses the invariant mass in terms of the measured electron energy in the $\Upsilon(4S)$ system.

- Impose $s_h^{max} < 3.52\ \text{GeV}^2$, corresponding to $X = D$, the lightest charm system.

$|V_{ub}|$ from $q^2 - E_e$ measurement (3/3)

- Signal efficiency ε_{sig} corrected using $\bar{B} \to D^0 X e \bar{\nu}_e$ control sample.
- Background yields corrected using s_h^{max} side band , which is enriched in $\bar{B} \to X_c e \bar{\nu}_e$ background.

$\bar{B} \to X_u e \bar{\nu}_e$ partial branching fraction extracted as:

$$\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}_\ell) = \frac{N_{\text{cand}}^{\text{data}} - F_{\text{SB}}^{\text{corr}} \cdot N_{\text{bkg}}^{\text{MC}}}{2N_{B\bar{B}} F_{D^0 e\bar{\nu}_e}^{\text{corr}} \cdot \varepsilon_{\text{sig}}} \times \left\{ 1 + \left(\frac{1}{f_u} - 1 \right) \frac{\overline{\varepsilon_{\text{sig}}}}{\varepsilon_{\text{sig}}} \right\}^{-1}$$

$F_{D^0 e\bar{\nu}_e}^{\text{corr}}$ is the ratio of MC and Data efficiency in the $\bar{B} \to D^0 X e \bar{\nu}_e$, determined using the pre-selection and the final-selection; $F_{\text{SB}}^{\text{corr}}$ is the ratio of $N_{\text{SB}}^{\text{MC}}$ and $N_{\text{SB}}^{\text{Data}}$ in the side band.

Results for $\Delta\mathcal{B}$ and $|V_{ub}|$: $\Delta\mathcal{B}$ unfolded from efficiency and resolution effects

- Extract $|V_{ub}|$ in the B rest frame using 3 QCD calculations for the decay rate $\Delta\zeta$:

From ΔB to $|V_{ub}|$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\bar{B} \to X_u e \bar{\nu}_e)}{\tau_B \Delta\zeta}}$$

- Estimated full set of experimental systematics.
- Result will supersede [Phys.Rev.Lett.95, 2005]

	$\Delta\mathcal{B}(\bar{B} \to X_u e \bar{\nu}_e) \cdot 10^4$ $E_e^* > 2.0\,\text{GeV}$ $s_h^{\max *} < 3.5\,\text{GeV}^2$	$\Delta\mathcal{B}(\bar{B} \to X_u e \bar{\nu}_e) \cdot 10^4$ $E_e^* > 1.9\,\text{GeV}$ $s_h^{\max *} < 3.5\,\text{GeV}^2$
	$3.98 \pm 0.22\,^{+0.27}_{-0.20}\,^{+0.17}_{-0.05}$	$4.48 \pm 0.24\,^{+0.31}_{-0.22}\,^{+0.29}_{-0.12}$
	$\lvert V_{ub}\rvert \cdot 10^3$	$\lvert V_{ub}\rvert \cdot 10^3$
BLNP	$4.44\,^{+0.16}_{-0.22}\,^{+0.30}_{-0.35}$	$4.35\,^{+0.28}_{-0.45}\,^{+0.27}_{-0.31}$
DGE	$4.11\,^{+0.15}_{-0.20}\,^{+0.23}_{-0.27}$	$4.11\,^{+0.16}_{-0.23}\,^{+0.26}_{-0.25}$
ADFR	$3.62\,^{+0.13}_{-0.18}\,^{+0.17}_{-0.17}$	$3.66\,^{+0.15}_{-0.20}\,^{+0.17}_{-0.17}$

$|V_{ub}|$ from exclusive $\bar{B} \to X_u \ell \bar{\nu}_\ell$ (1/3)

ø *untagged* measurement of $|V_{ub}|$ using the full BABAR data set.

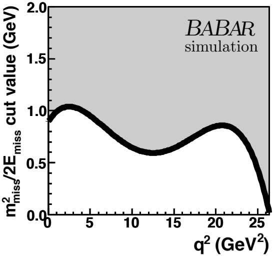
[Phys. Rev. D 86, 092004 (2012)]

- Select events with high energy electrons and muons with $\mathbf{E_e} > \mathbf{0.5}$ GeV and $\mathbf{E}_\mu > \mathbf{1.0}$ GeV. Reconstruct exclusive hadronic final state of interest: $X_u = \{\pi, \eta, \eta', \omega\}$.

Neutrino kinematics inferred from rest of event:

$$p_{\mathrm{miss}} = p_{\Upsilon(4S)} - \sum_i^{N_{\mathrm{chg}}} p^i_{\mathrm{chg}} - \sum_i^{N_{\mathrm{neut}}} p^i_{\mathrm{neut}} \quad \Rightarrow \quad m^2_{\mathrm{miss}} = p^2_{\mathrm{miss}}$$

- Neutrino kinematics used to suppress background, e.g. for $m^2_{\mathrm{miss}}/(2E_{\mathrm{miss}})$



q^2 reconstruction

Four-momentum transfer of the B-meson to the $X_u = h$ system, q^2, can be obtained by combining the B and light meson information:

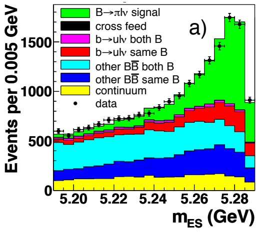
$$q^2 = (p_B - p_h)^2$$

$\vec{p}_B$ from average over 4 directions.

$|V_{ub}|$ from exclusive $\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$ (2/3)

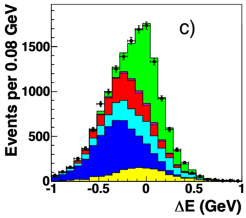
- Number of signal events extracted as a function of q^2 with 2D fits to *beam constrained mass* and *energy*:

m_{ES}



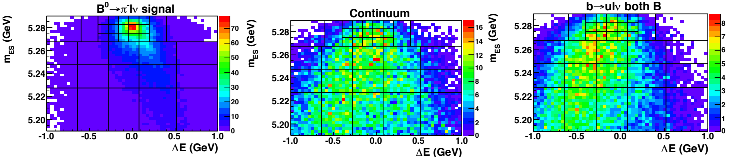
$$m_{ES} = \sqrt{(s/2 + \vec{p}_B \cdot \vec{p}_{beams})^2 / E_{beams} - \vec{p}_B^{\,2}}$$

ΔE



$$\Delta E = (p_B \cdot p_{beams} - s/2) / \sqrt{s}$$

- It is $p_B = p_h + p_\ell + p_\nu$ with $p_\nu = (|\vec{p}_{miss}|\,,\, p_{miss})$
- 2D distributions for signal $h = \pi$, off-resonance background, and X_u background.



$|V_{ub}|$ from exclusive $\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$ (3/3)

- Unfold q^2 distributions from detector effects and resolution, and use form factor predictions for $\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell$ and $\bar{B} \to \omega \, \ell \, \bar{\nu}_\ell$ to obtain $|V_{ub}|$.
- $\Delta\zeta$: Lattice (HPQCD, FNAL/MILC) valid in high q^2 , Light-Cone sum rule (LCSR) in low q^2 regime

Combined Data + Lattice fits

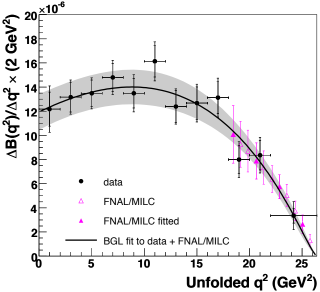
Lattice input can be used along with data to determine the form factor parameters. This is done by minimizing a global $\chi^2 = \chi^2_{\text{data}} + \chi^2_{\text{theory}}$ using the BGL Parametrization and the FNAL/MILC lattice points. [Phys. Rev. D80, 034026] [Phys. Rev. D56, 303 (1997)]

From ΔB to $|V_{ub}|$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\bar{B} \to X_u \, e \, \bar{\nu}_e)}{\tau_B \Delta\zeta}}$$

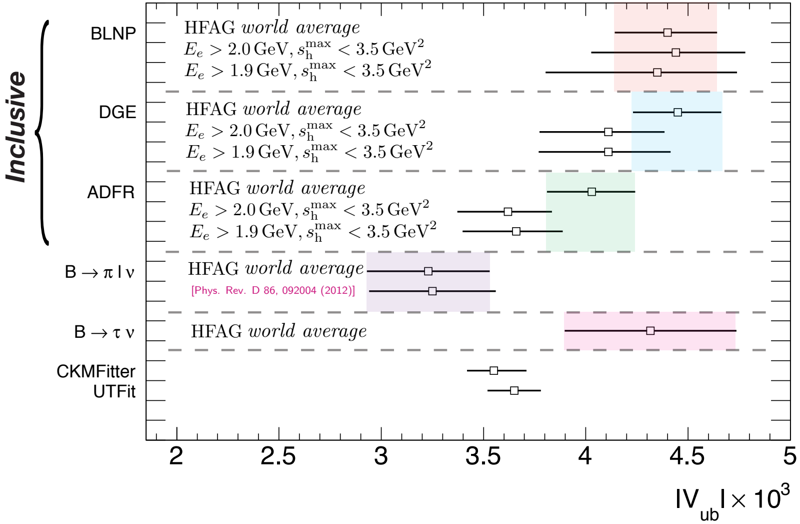
$$|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3}$$

- Unfolded q^2 distribution for $\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell$: (top right) $|V_{ub}|$ from combined data+lattice fit; (bottom right) $|V_{ub}|$ from lattice or LCSR.



	q^2 (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
$B \to \pi\ell^+\nu$				
HPQCD [5]	$16-26.4$	$0.37 \pm 0.02 \pm 0.02$	2.02 ± 0.55	$3.47 \pm 0.10 \pm 0.08^{+0.60}_{-0.39}$
FNAL [6]	$16-26.4$	$0.37 \pm 0.02 \pm 0.02$	$2.21^{+0.47}_{-0.42}$	$3.31 \pm 0.09 \pm 0.07^{+0.37}_{-0.30}$
LCSR [3]	$0-12$	$0.83 \pm 0.03 \pm 0.04$	$4.59^{+1.00}_{-0.85}$	$3.46 \pm 0.06 \pm 0.08^{+0.37}_{-0.32}$
LCSR2 [34]	0			$3.34 \pm 0.10 \pm 0.05^{+0.29}_{-0.26}$
$B^+ \to \omega\ell^+\nu$				
LCSR3 [18]	$0-20.2$	$1.19 \pm 0.16 \pm 0.09$	14.2 ± 3.3	$3.20 \pm 0.21 \pm 0.12^{+0.45}_{-0.32}$

Summary for $|V_{ub}|$



For $\bar{B} \to \tau\bar{\nu}$ the B meson decay constant of [arXiv:1302.2644], $f_B = 0.186(4)$ GeV, was used along with the preliminary HFAG average. CKMFitter and UTFitter are the FPCP 2013 and the Moriond 2013 results.

Outlook

- Expect to finalize preliminary $|V_{ub}|$ result using s_h^{max} cut soon.
- Several other semileptonic *BaBar* analyses are being worked on:

tagged
- $\bar{B} \to D^{(*)}\,\tau\bar{\nu}_\tau$
- $\bar{B} \to D^*\,\ell\,\bar{\nu}_\ell$ for $|V_{cb}|$
- $\bar{B} \to D^{**}\,\ell\,\bar{\nu}_\ell$
- $\bar{B} \to \rho\,\ell\,\bar{\nu}_\ell$

untagged
- $\bar{B} \to D/D^*/D^{**}\,\ell\,\bar{\nu}_\ell$ for global fit for $|V_{cb}|$

- All of them address aspects with poor understanding and tensions; analyses with *BaBar* data remain interesting until Belle II goes online and has a sufficient large data sample to overtake the past B-Factory experiments.

Thank you!