Recent $|Vub|$ *results from semi-leptonic* B *decays at* BABAR

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on behalf of the *BABAR* Collaboration

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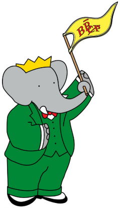
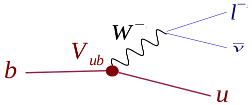


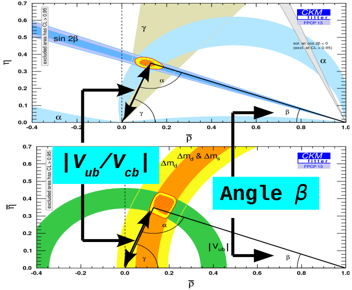
THE CKM MATRIX AND THE ROLE OF $|V_{ub}|$

$$V_{\text{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- In the SM, CKM matrix ⇒ flavor-mixing
- $|V_{ub}|$ is one of the smallest and most difficult elements to measure
- Semi-leptonic (SL) $b \to u\ell\overline{\nu}_\ell$ transition ⇒ $|V_{ub}|$

- Unitarity triangle: side opposite to angle β is $\propto |V_{ub}|/|V_{cb}|$
- Both β and $|V_{cb}|$ known to better than 3%
- Measurement of $|V_{ub}|$ places strong constraints on CKM framework



SEMI-LEPTONIC B DECAYS

- Cleanest source of $B\bar{B}$ pairs for studying SL B decays:

$$e^+e^- \to \Upsilon(4S) \stackrel{>96\%}{\to} B\bar{B}, \sqrt{s} = 10.58 \text{ GeV}$$

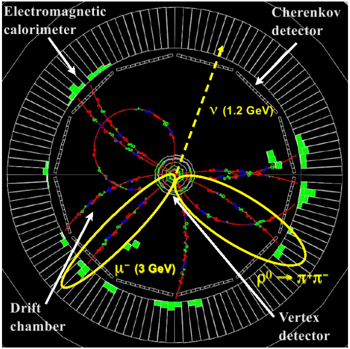
- PEP-II collider and BABAR detector: asymmetric e^+e^- B-factory at SLAC.

- Full "on-peak" dataset: $\sim$ 470 M $B\bar{B}$
- Inital 4-momentum fully known. Tag the "other" B, to reconstruct B_{sig}
- Two discriminating variables:

$$\Delta E = E_B^* - \sqrt{s}/2 \ (\sim 0 \text{ for signal})$$

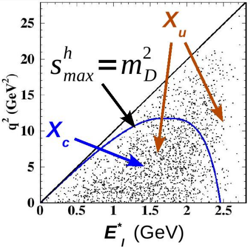
$$m_{\text{ES}} = \sqrt{s/4 - |\vec{p}_B^{\,*}|^2} \ (\sim m_B \text{ for signal})$$

$B^- \to \rho^0(\to \pi^+\pi^-)\mu^-\nu_{\text{miss}}$:



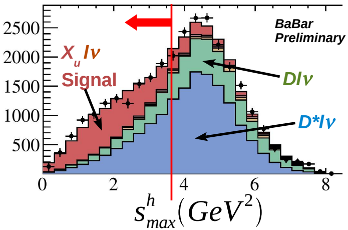
Inclusive $B \to X_u \ell \nu$ with s_h^{max} cut (untagged)

- Challenge: $50\times$ larger $B \to X_c \ell \nu$ background
- $\sqrt{q^2} \Rightarrow W^*(\ell \overline{\nu}_\ell)$ mass; $E_\ell \Rightarrow$ lepton energy
- $s_h^{max} \equiv m_X^2 < 3.52$ GeV^2: remove dominant charm background in $m_X > m_D$



- Update on PRL **95** 111801 (2005): full dataset, improved $D^*\ell\nu$ suppression (neural net cut) and systematics
- For $E_e^* > 2$ GeV, $s_h^{max*} < 3.5$ GeV^2:

$$\Delta\mathcal{B} = \left(3.98 \pm 0.22\Big|_{\rm stat} {}^{+0.27}_{-0.20}\Big|_{\rm sys} {}^{+0.17}_{-0.05}\Big|_{\rm th}\right) \times 10^{-4}$$



Extraction of $|V_{ub}|$

- To get $|V_{ub}|$ from partial BF: $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\tau_B \Delta\Gamma_{\text{theory}})}$
- Several QCD calculations available for $d\Gamma/(dE_\ell^* dq^2 dm_X)$:

BLNP (NPB 699,335 (2004))

DGE (JHEP 0601,096 (2006))

GGOU (JHEP 0710,058 (2007))

ADFR (EPJC 59,831 (2009))

Measurement	$\lvert V_{ub}\rvert$ (10^{-3})			
	BLNP	GGOU	DGE	ADFR
BABAR untagged (E_e^*, s_h^{max})(2005)	$4.66 \pm 0.31^{+0.31}_{-0.36}$	–	$4.32 \pm 0.29^{+0.24}_{-0.29}$	$3.82 \pm 0.26^{+0.17}_{-0.18}$
BABAR untagged (E_e^*, s_h^{max}) (2013)	$4.44^{+0.16}_{-0.21} \pm 0.31$	–	$4.11^{+0.15+0.23}_{-0.20-0.27}$	$3.62^{+0.13}_{-0.18} \pm 0.17$
BABAR tagged (m_X, q^2) (2012)	$4.28 \pm 0.24^{+0.09}_{-0.11}$	$4.35 \pm 0.24^{+0.09}_{-0.11}$	$4.40 \pm 0.24^{+0.12}_{-0.13}$	$4.29 \pm 0.24^{+0.18}_{-0.19}$
Belle tagged (m_X, q^2) (2010)	$4.47 \pm 0.27^{+0.19}_{-0.21}$	$4.54 \pm 0.27^{+0.10}_{-0.11}$	$4.60 \pm 0.27^{+0.11}_{-0.13}$	$4.48 \pm 0.30^{+0.19}_{-0.19}$

- New BABAR untagged E_e-s_h^{max} results to be submitted to PRD
- Consistent with hadronic tagged ($p_\ell^* > 1$ GeV, 2-D fit in (m_X, q^2))

INCLUSIVE $|V_{ub}|$ SUMMARY

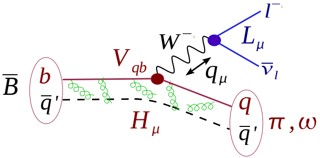
- Best measurements (Belle and BABAR) from hadronic tag
- Arithmetic average over 4 QCD calculations:

$$|V_{ub}|_{\text{incl}} = (4.41 \pm 0.15_{\text{exp}} \pm 0.17_{\text{th}}) \times 10^{-4}$$

- Systematic errors mostly from $B \to X_u \ell \nu$ and background Monte Carlo simulations

Exclusive $B \to \{\pi, \omega\}\ell\nu$ and form-factors

- Leptonic (L_μ) and hadronic (H_μ) sides factorize

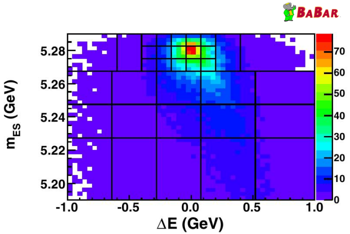


- Vector-meson: 3 helicity amplitudes $H_{\{0,\pm\}}$ and 3 form-factors (A_1, A_2, V)
- Pseudo-scalars: single H_0 amplitude, 1 FF (f_+)
- Theory predictions of FF's based on: quark models, light cone sum rules (LCSR), lattice calculations, with different q^2 regions of validity.
- Model-independent series expansions from dispersion relations $\Rightarrow$ data-driven way to fix q^2 dependence

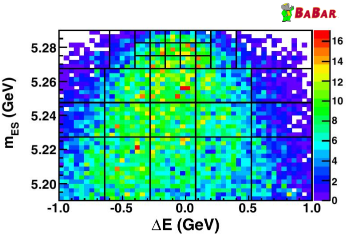
UNTAGGED $B \to \pi\ell\nu$ PRD **86**, 092004 (2012)

- Update on PRD **83**, 052011 (2011): full dataset, improvement at high q^2
- $Y \equiv (\pi\ell)$ and c.m. frame variable: $\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$
- Loose ν reconstruction: $|\cos\theta_{BY}| \leq 1$;
- Combined fit to π^+ and π^0 samples assuming isospin relations
- m_{ES}-ΔE-q^2 fits using signal + 5 background categories of PDF's from MC

Signal $\pi\ell\nu$:

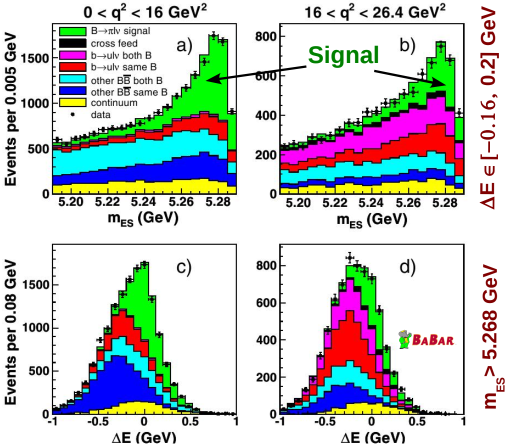


$e^+e^- \to q\bar{q}(\gamma)$ Continuum:



Untagged $B \to \pi\ell\nu$ PRD **86**, 092004 (2012) (cntd.)

- π^+/π^0 combined fit projections:



- Isospin-constrained: $\mathcal{B}(B \to \pi\ell\nu) = (1.45 \pm 0.04_{\text{stat}} \pm 0.06_{\text{sys}}) \times 10^{-4}$

BCL expansion fit

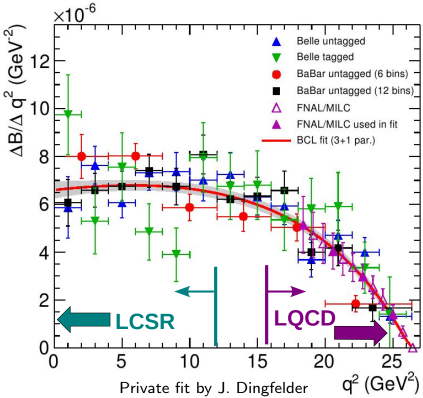
BABAR PRD **83**, 032007 (2011) Belle PRD **83**, 071101 (2011)
BABAR PRD **86**, 092004 (2012) Belle arXiv:1306.2781 (2013)

- BCL (Bourrely *et al.*, PRD **79**, 013008 (2009)) simple pole form:

$$f_+(q^2) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_k^{k_{max}} \tilde{a}_k z^k(q^2)$$

- Measured data ⇒ shape. Normalization towards q^2_{max} from LQCD (only 4/12 points)

$$|V_{ub}|_{fit} = (3.28 \pm 0.29) \times 10^{-3}$$



Private fit by J. Dingfelder

- Compare $f_+(0)_{fit} = 0.28 \pm 0.03$ with $f_+(0)_{LCSR} = 0.28 \pm 0.02$

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

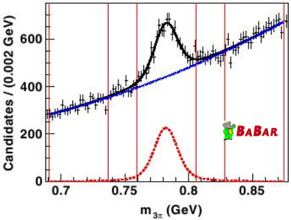
- Form-factor calculations
  1. LCSR, Khodjamirian *et al.*, PRD **83**, 094031 (2011)
  2. HPQCD (lattice), PRD **73** 074502 (2005)
  3. FNAL/MILC (lattice), PRD **79**, 054507 (2009)

Measurement	LCSR[1] $q^2 \in [0, 12]$ GeV^2	HPQCD[2] $q^2 \in [16, 26.4]$ GeV^2	FNAL/MILC[3] fit $q^2 \in [16, 26.4]$ GeV^2
	$\lvert V_{ub}\rvert$ (10^{-3})		
BABAR 6 q^2-bins (2011)	$3.54 \pm 0.12^{+0.38}_{-0.33}$	$3.22 \pm 0.15^{+0.55}_{-0.37}$	2.98 ± 0.31
BABAR 12 q^2-bins (2011)	$3.46 \pm 0.10^{+0.37}_{-0.32}$	$3.26 \pm 0.19^{+0.56}_{-0.37}$	3.22 ± 0.31
BABAR 12 q^2-bins (2012)	$3.46 \pm 0.10^{+0.37}_{-0.32}$	$3.47 \pm 0.13^{+0.60}_{-0.39}$	3.25 ± 0.31
Belle 13 q^2-bins (2011)	$3.44 \pm 0.10^{+0.37}_{-0.32}$	$3.60 \pm 0.13^{+0.61}_{-0.41}$	3.43 ± 0.33
Avg. untagged	$3.47 \pm 0.06^{+0.37}_{-0.32}$	$3.43 \pm 0.09^{+0.59}_{-0.39}$	3.21 ± 0.31
Belle hadronic tag (2013)	$3.40 \pm 0.16^{+0.37}_{-0.32}$	$3.81 \pm 0.24^{+0.66}_{-0.43}$	3.52 ± 0.29

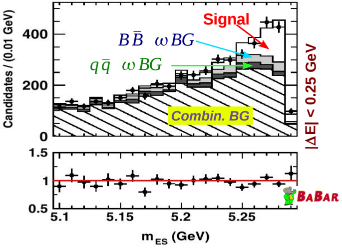
- Untagged $B \to \pi\ell\nu$ measurements still the most precise for exclusive $|V_{ub}|$. Error dominated by theory uncertainties.

UNTAGGED $B \to \omega\ell\nu$ PRD **87**, 032004 (2013)

- New untagged on full *BABAR* dataset, with $-1.2 < \cos\theta_{\rm BY} < 1.1$
- Neural network based selection for $q\bar{q}$ and $B \to X_c\ell\nu$ suppression
- Binned LH fit in 5 q^2 and 20 ΔE-$m_{\rm ES}$ bins
- Combinatoric BG *fixed* using $m_{3\pi}$ sidebands in Data

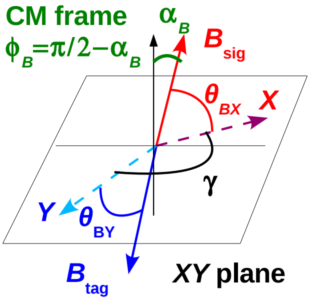


- Sample $m_{\rm ES}$ fit projection:



$$\mathcal{B}(B \to \omega\ell\nu) = (1.21 \pm 0.14_{\rm stat} \pm 0.08_{\rm sys}) \times 10^{-4}$$

SEMI-LEPTONICALLY TAGGED $B \to \omega\ell\nu$ (NEW!)



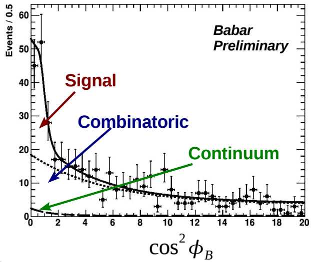
- Both B's decay semi-leptonically:

$B_{\text{tag}} \to Y\nu,\ Y \equiv D^{(*)}\ell;\ B_{\text{sig}} \to X\nu,\ X \equiv \omega\ell$

- θ_{BY} and θ_{BX} known in CM frame
- Back-to-back B_{tag} and B_{sig} fixes the B direction wrt the XY plane ($\equiv \phi_B$) upto sign

- $\mathcal{B}(B \to D^{(*)}\nu) \sim 8\% \Rightarrow$ tag efficiency $\sim$ 4.4% is higher than hadronic tags.
- Binned LH fits to $\cos^2\phi_B$ shape

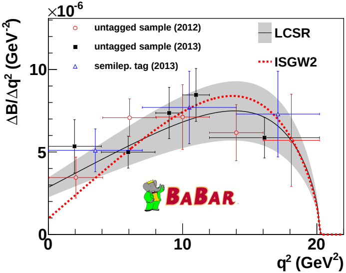
$$\mathcal{B}(B \to \omega\ell\nu) = (1.35 \pm 0.21_{\text{stat}} \pm 0.11_{\text{sys}}) \times 10^{-4}$$



$|V_{ub}|$ FROM $B \to \omega\ell\nu$

- References:

  PRD **86**, 092004 (2012)
  PRD **87**, 032004 (2013)
  arXiv:1308.2589 (2013)



- $\frac{d\mathcal{B}}{dq^2}$ compared to form-factor models:

  LCSR valid at $q^2 \to 0$
  HQE based ISGW2 valid at $q^2 \to q^2_{\max}$

Measurement	$\lvert V_{ub}\rvert$ (10^{-3}) LCSR $q^2 \in [0,12]$	LCSR $q^2 \in [0,21]$	ISGW2 $q^2 \in [0,21]$
BABAR untag. 2012		$3.22 \pm 0.24^{+0.45}_{-0.27}$	
BABAR untag. 2013	$3.37 \pm 0.23 \pm 0.38$	$3.23 \pm 0.22 \pm 0.38$	3.25 ± 0.22
BABAR SL tag. 2013		$3.41 \pm 0.31 \pm 0.38$	3.43 ± 0.31
BABAR avg.	$3.37 \pm 0.23 \pm 0.38$	$3.27 \pm 0.18 \pm 0.38$	3.3 ± 0.18
Belle had. tag (2013)	$3.08 \pm 0.31^{+0.44}_{-0.31}$		3.03 ± 0.26

Summary and inclusive/exclusive "tension"

- Several new BABAR measurements, both inclusive and exclusive. Results fully consistent with previous measurements.
- Current world averages for $|V_{ub}|$:

$$|V_{ub}|_{\text{incl.}} = (4.37 \pm 0.20_{\text{exp}} \pm 0.15_{\text{th}}) \times 10^{-4}$$

$$|V_{ub}|_{\text{excl.}} = (3.21 \pm 0.17_{\text{exp}} \pm 0.26_{\text{th}}) \times 10^{-4}$$

$\sim 2.9\sigma$ tension

- Inclusive: latest BABAR/Belle (q^2, m_X) tagged. Sum over 4 QCD calculations.
- Exclusive: only untagged $\pi\ell\nu$ and 4 LQCD points.
- Uncertainties have been reduced, but tension persists.
- Smaller, but non-zero tension in $|V_{cb}|$ as well

Future improvements

- Better understanding of BG composition/dynamics of incl. $X_{\{c,u\}}\ell\nu$ and $q\bar{q}$
- MVA-based (instead of cut-based) hadronic tagging algorithms, with larger ($40\times$ data) MC samples to study efficiencies of tag-modes with small BF's
- Full angular-fit for exclusive $B \to V\ell\nu$ to make use of correlations
- Improved QCD calculations with wider q^2 coverage for exclusive
- Global fits to m_X moments in $B \to X_u\ell\nu$ and E_γ spectrum in $B \to X_s\gamma$ to extract shape-function parameters and $|V_{ub}|$
- If tension is not due to measurements, ... New Physics? – RH currents, additional scalar and tensor terms in the effective Lagrangian