Semileptonic B Meson Decays At The B Factories

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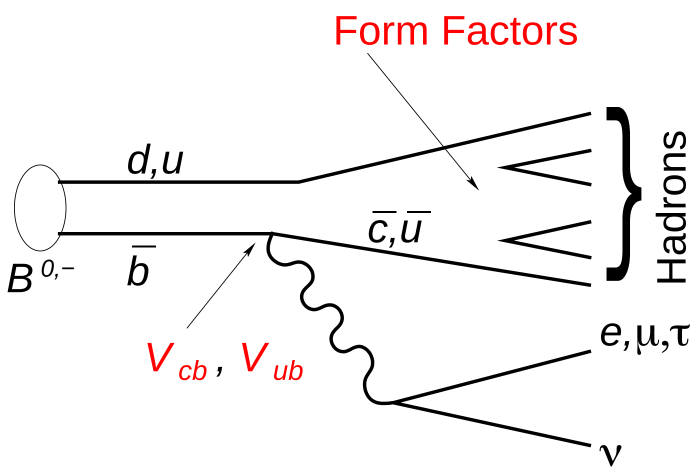
Semileptonic B Decays



Tree-level decays

Isolate hadronic vs. weak-decay effects

Inclusive or exclusive final states

Many kinematic variables available

m_X : mass of hadronic system
q^2 : mass of $\ell + \nu$
$p_{\rm miss}$: 4-vector of "neutrino"

Access to many features of hadronic physics

- CKM matrix elements $|V_{ub}|$, $|V_{cb}|$
- Non-perturbative QCD, form factors
- B meson properties: lifetimes, mixing

New approaches, new results

Semileptonic B decays have been a fertile field for two decades.

B-Factories have fed an explosion of results since 1999.

Far too many to be both comprehensive and coherent.
$\Longrightarrow$ Focus on few results since Summer 2005:

- $|V_{ub}|$ from $b \to u$ decays
- $|V_{cb}|$ and $B \to D^*$ form factors
- B^0 lifetime and mixing

For comprehensive background, see Richman & Burchat's 1995 review (RMP **67** (893); hep-ex/9508250).

$B \to X_u \ell \nu$: $|V_{ub}|$

See M. Rotondo's talk at 19.10 for BaBar results

Several complementary approaches

Exclusive final states ($X_u = \pi,\ \rho,\ \omega$, etc.)

- Large kinematic range; form-factor dependence
- Tagged (reconstructed B) or untagged methods
- Trade-off efficiency vs. purity

Inclusive lepton momentum spectrum

- High purity when tagged with reconstructed B
- Full event ID allows ν kinematics from $p_{\rm miss}, E_{\rm miss}$
- Large backgrounds from $b \to c$: restricts p_l
- V_{ub} extraction exploits $B \to s\gamma$ spectrum and QCD

Discrepancy? between $|V_{ub}|$ from inclusive and exclusive

$$(4.38 \pm 0.19 \pm 0.27) \times 10^{-3}[\text{incl}] \text{ vs. } \left(3.76 \pm 0.16\,^{+0.87}_{-0.51}\right) \times 10^{-3}[\text{excl}]$$

HFAG EPS 2005 summary

Exclusive $B \to X_u \ell \nu$: BaBar

See M. Rotondo's talk at 19.10

Select $B^{0,\pm} \to \pi\ell\nu$ and $\rho\ell\nu$ without reconstructing other B

- Well-identified lepton matched with $\pi^\pm$, $\pi^0(\gamma\gamma)$, $\rho^0(\pi^+\pi^-)$, $\rho^\pm(\pi^\pm\pi^0)$
- Remaining tracks/neutrals constrain missing E, p to ν

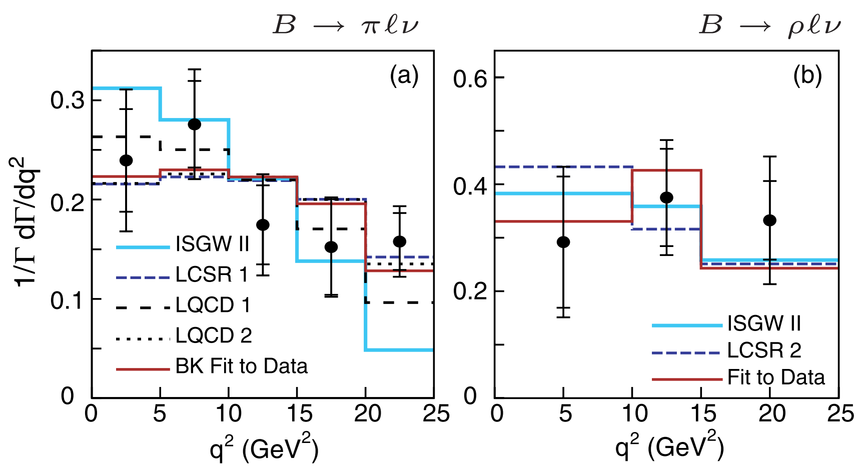
Five q^2 bins with partial BFs
Simultaneous fit for all modes

Compare form-factor models

$\Rightarrow$ LCSR, $q^2 < 16$ GeV

$\Rightarrow$ LQCD, $q^2 > 16$ GeV

Can also fit directly to data



$$f_+(q^2) = \frac{c_B(1-\alpha)}{(1-q^2/m^2_{B^*})(1-\alpha q^2/m^2_{B^*})}$$ (Becirevic-Kaidalov)

$$|V_{ub}| = \left(3.82 \pm 0.14 \pm 0.22 \pm 0.11\,^{+0.88}_{-0.52}\right) \times 10^{-3}$$

$|V_{ub}| = \left(3.76 \pm 0.16\,^{+0.87}_{-0.51}\right) \times 10^{-3}$ (HFAG)

Phys.Rev. **D72**(051102), hep-ex/0507003

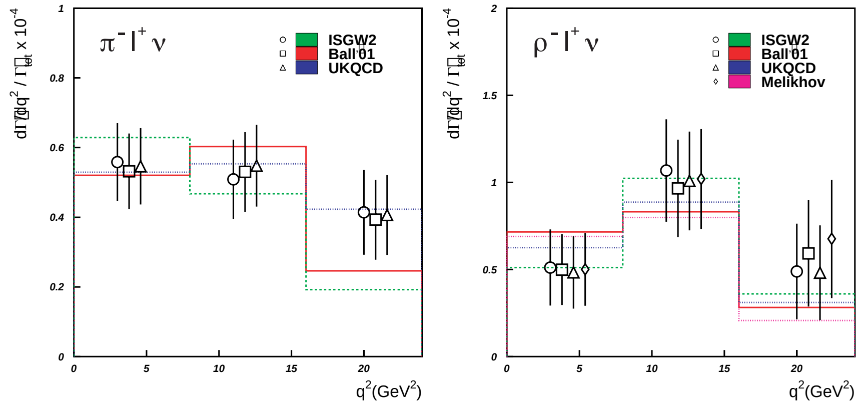
Exclusive $B \to X_u \ell \nu$: Belle

Select $B \to D^* \ell \nu$ events, look for lepton (e, μ) and π or ρ in recoil, with matching charge to tag.

Similar to BaBar analysis.

Partial rates for each channel in bins of q^2.

Compare with form-factor models.



Average $B^0 \to \pi^+ \ell \overline{\nu}$ and $B^- \to \pi^0 \ell \overline{\nu}$, use LQCD calculations to extract $|V_{ub}|$

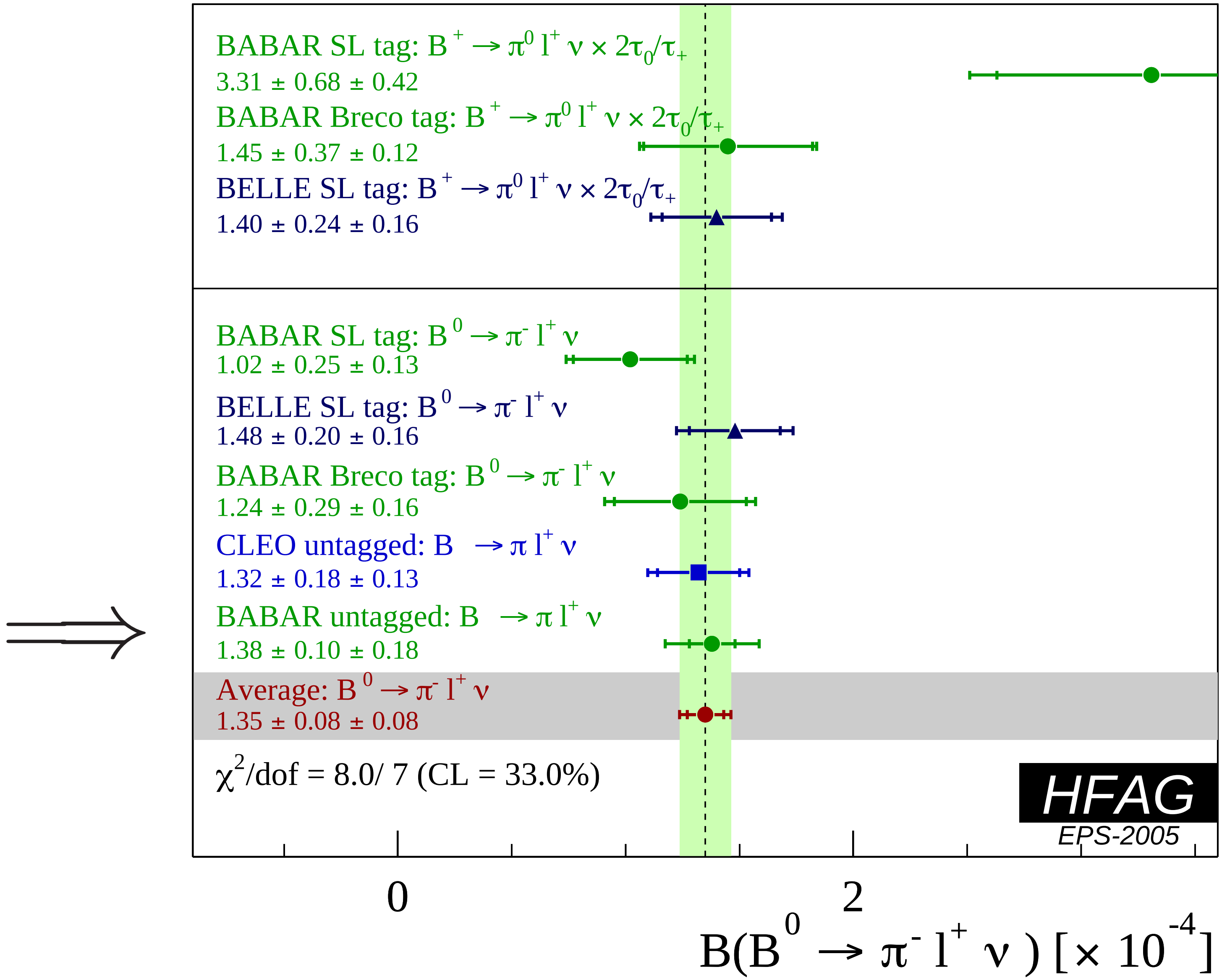
$$|V_{ub}| = \left(4.50 \pm 0.52 \pm 0.27\,^{+0.70}_{-0.48}\right) \times 10^{-3} \quad \text{(HPQCD)}$$

$$|V_{ub}| = \left(3.81 \pm 0.44 \pm 0.23\,^{+0.66}_{-0.43}\right) \times 10^{-3} \quad \text{(FNAL)}$$

$|V_{ub}| = \left(3.76 \pm 0.16\,^{+0.87}_{-0.51}\right) \times 10^{-3}$ (HFAG)

EPS 2005 Proceedings, hep-ex/0508018

Exclusive $B \to X_u \ell \nu$: HFAG



Inclusive $B \to X_u \ell \nu$: BaBar

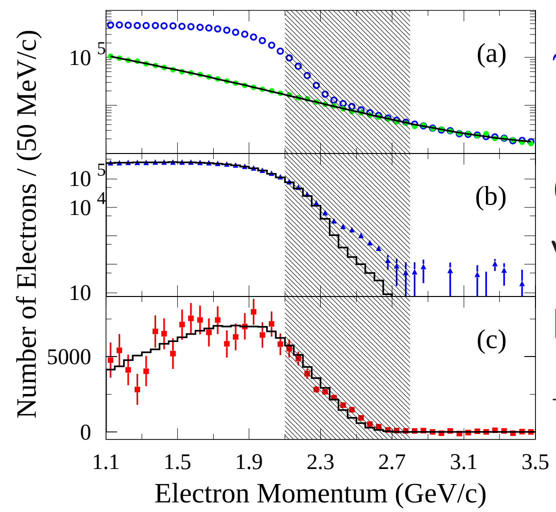
See M. Rotondo's talk at 19.10

Select "fast" electron ($p_e > 1.1$ GeV) in "$B\overline{B}$-like" events

- high multiplicity
- spherical ($\mathcal{R}_2 < 0.5$)
- high $p_{\rm miss}$ away from e

Subtract backgrounds

- data below $\Upsilon(4S)$
- events with $p_e > 2.8$ GeV/c
- Fit $B \to X_c \ell \nu$ composition in bkg subtraction



$\Upsilon(4S)$, off-res

(a) subtracted vs. $B\overline{B}$ bkg

Bkg-subtracted $B \to X_u e \nu$

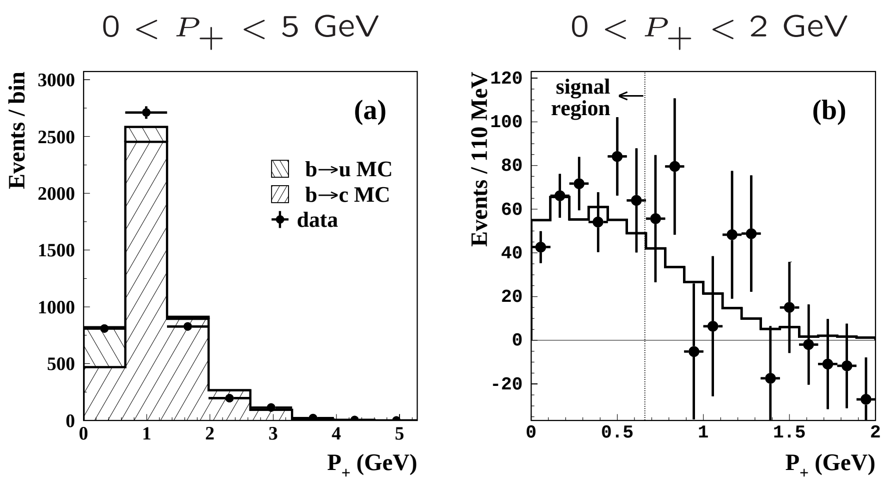
Combine partial rate with shape function parameters, moments from $B \to s\gamma$ spectrum, hadron mass & energy moments from $B \to X_c \ell \nu$

$$|V_{ub}| = \left(4.44 \pm 0.25 \,^{+0.42}_{-0.38} \pm 0.22\right) \times 10^{-3}$$

$|V_{ub}| = (4.38 \pm 0.19 \pm 0.27) \times 10^{-3}$ (HFAG)

Phys.Rev. **D73**(012006), hep-ex/0509040

Inclusive $B \to X_u \ell \nu$: Belle



Compute $P_+ \equiv E_X - |\vec{p}_X|$

$\Rightarrow$ non-B tag, non-lepton tracks and neutrals in event

Subtract $b \to c\ell\nu$ via simulation

$|V_{ub}|^2 \propto \Delta\Gamma_{b\to u\ell\nu}$ in region(s) with low $b \to c$ background

$P_+ < 0.66$ GeV/c(quoted result)
$M_X < 1.7$ GeV/c^2
$M_X < 1.7$ GeV/$c^2 \oplus q^2 > 8$ GeV$^2/c^2$

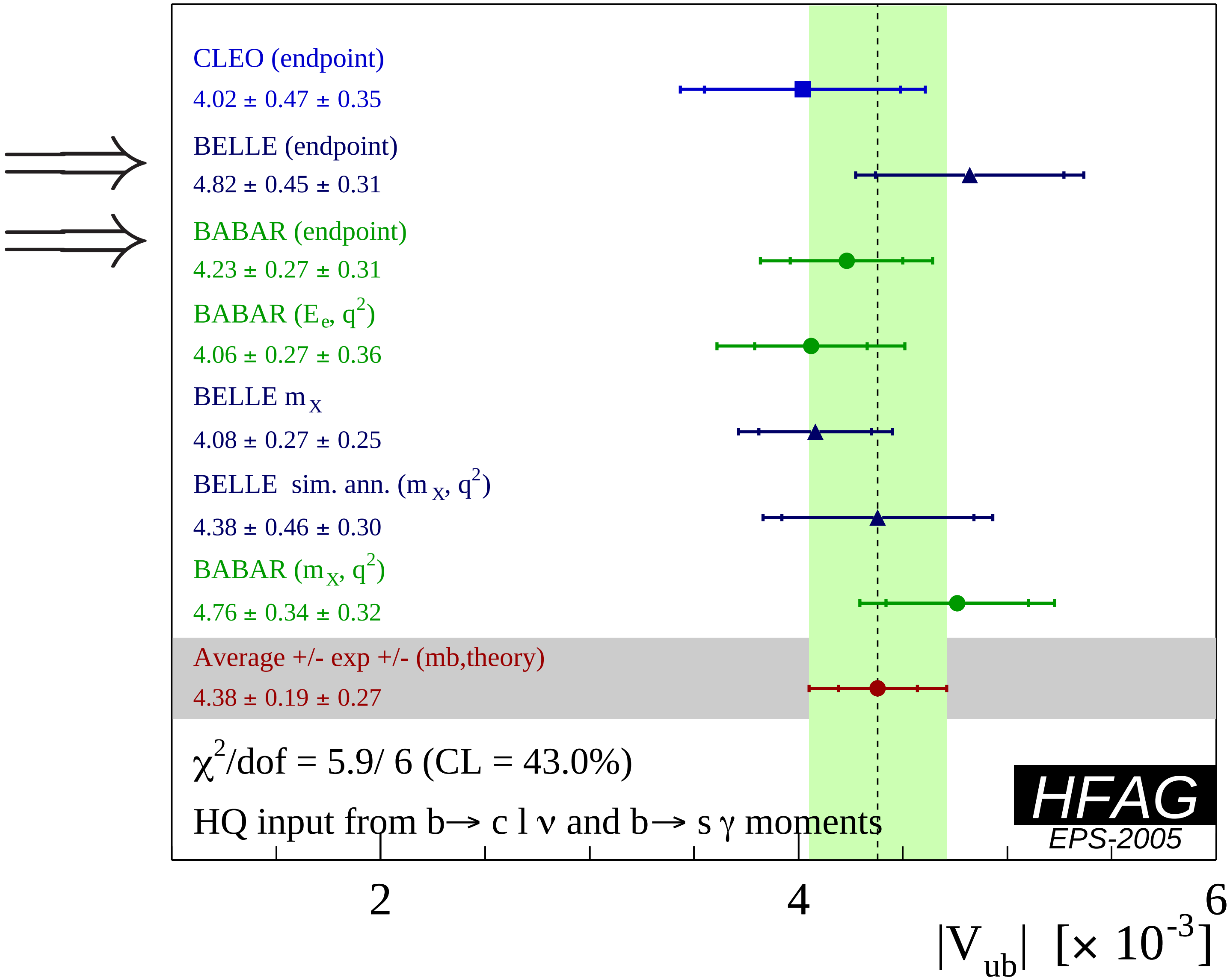
} All consistent

$$|V_{ub}| = \left(4.09 \pm 0.19 \pm 0.20\,^{+0.14}_{-0.15} \pm 0.18\right) \times 10^{-3}$$

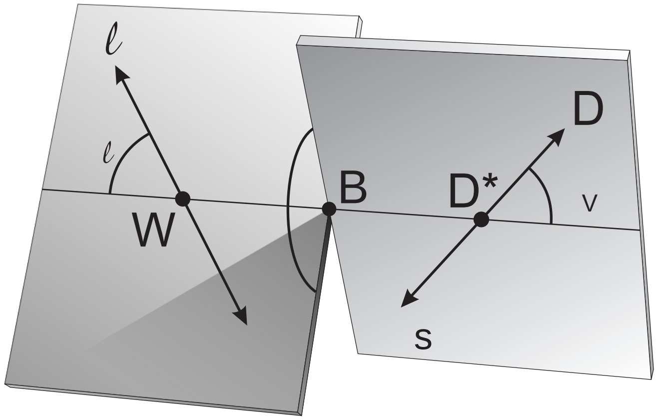
$|V_{ub}| = (4.38 \pm 0.19 \pm 0.27) \times 10^{-3}$ (HFAG)

Phys.Rev.Lett. **95**(241801), hep-ex/0505088

Inclusive $|V_{ub}|$: HFAG



$B \to D^* \ell \nu$ Form Factors : BaBar



Reconstruct $\overline{B}^0 \to D^{*+} e \overline{\nu}_e$

$D^{*+} \to D^0(\to K^- \pi^+) \pi^+$

No reconstruction of recoil B

Fit fully differential decay rate $\frac{d\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi}$

- $w = \frac{M_B^2 + M_{D^*}^2 - q^2}{2 M_B M_{D^*}} = E_{D^*}^{(B)} / M_{D^*}$
- θ_ℓ : lepton angle in "W frame" vs. W in B frame
- θ_V : D angle in D^* frame vs. D^* in B frame
- χ : angle between "D–D^*" and "W–ℓ" planes

Fn. of helicity amplitudes H_-, H_+, H_0 ($\sim D^*$ polarization)

$B \to D^* \ell \nu$ Form Factors : BaBar

Helicity amplitudes ⇒ three form factors A_1, A_2, V

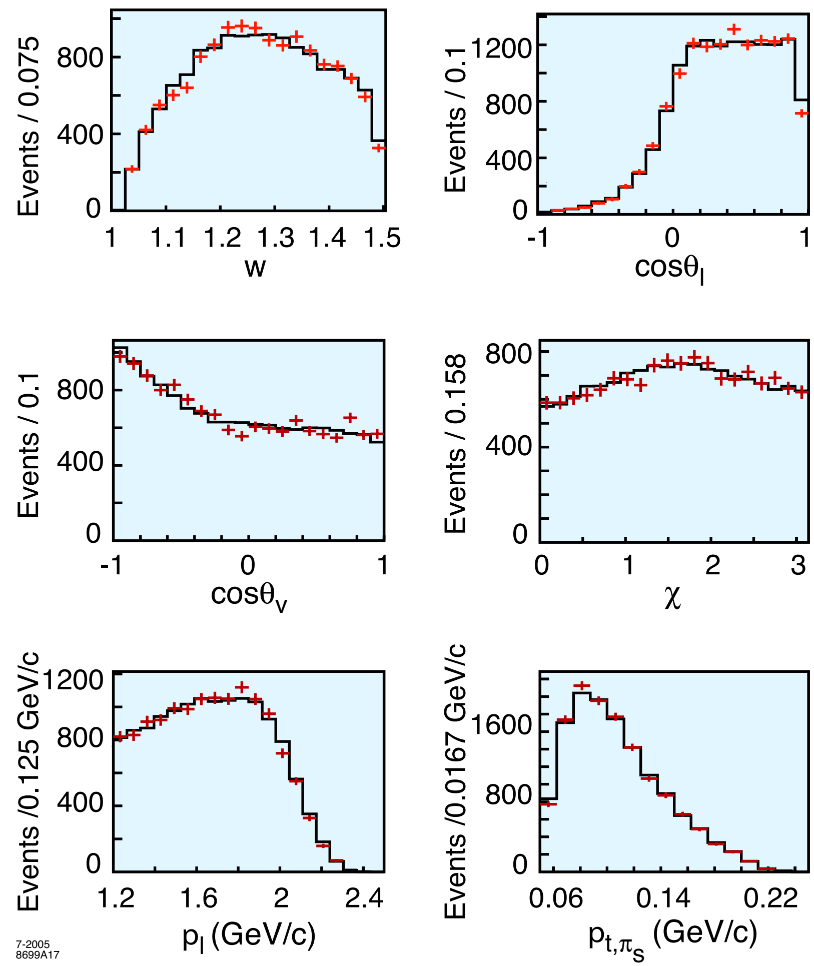
$$A_2(w) = \frac{R_2}{R^{*2}} \frac{2}{w+1} A_1(w)$$

$$V(w) = \frac{R_1}{R^{*2}} \frac{2}{w+1} A_1(w)$$

$$h_{A1}(w) = \frac{1}{R^*} \frac{2}{w+1} A_1(w)$$

$$h_{A1}(z) \propto \left[1 - 8\rho^2 z + (53\rho^2 - 15) z^2 - (231\rho^2 - 91) z^3\right]$$

$$z \equiv \frac{(\sqrt{w+1} - \sqrt{2})}{(\sqrt{w+1} + \sqrt{2})}$$



Data vs. MC generated with fitted form-factors

$B \to D^*\ell\nu$ Form Factors : BaBar

Sufficient data to fit for constant R_1, R_2 parameters.

$$\begin{aligned} R_1 &= 1.396 \pm 0.060 \pm 0.035 \pm 0.027 \\ R_2 &= 0.885 \pm 0.040 \pm 0.022 \pm 0.013 \\ \rho^2 &= 1.145 \pm 0.059 \pm 0.030 \pm 0.035 \end{aligned}$$

Different theoretical ansaetze result in 1–2σ variation

Using new FF parameters with previous BaBar technique

(Phys.Rev. **D71**(051502), hep-ex/0408027)

$$|V_{cb}| = \left(37.6 \pm 0.3 \pm 1.3\,^{+1.5}_{-1.3}\right) \times 10^{-3}$$

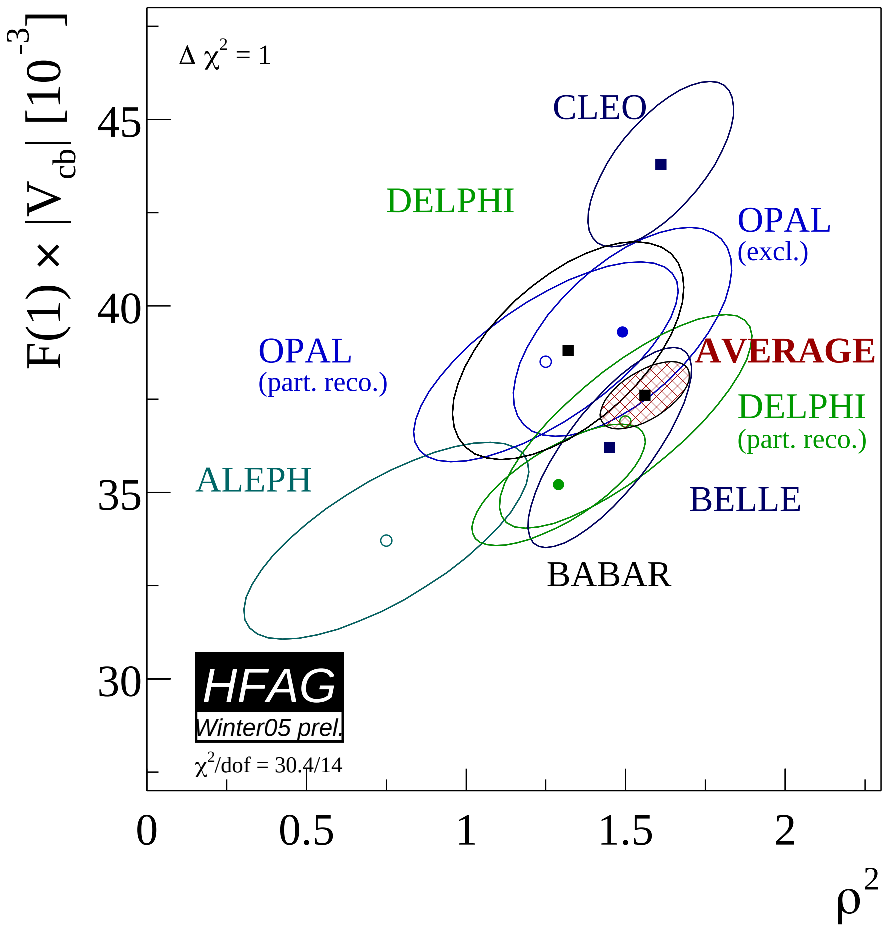
$\sim 2\sigma$ difference vs. average $|V_{cb}|$ from inclusive $b \to c\ell\nu, b \to s\gamma$

$(42.0 \pm 0.2 \pm 0.4 \pm 0.6) \times 10^{-3}$ (hep-ph/0507253)

$R_1 = 1.18 \pm 0.32$, $R_2 = 0.71 \pm 0.23$ (CLEO,1996)
$\rho^2 = 1.56 \pm 0.14$, $\mathcal{F}(1) = 0.92 \pm 0.04$
$|V_{cb}| = (40.9 \pm 1.8) \times 10^{-3}$ (HFAG)

Submitted to Phys.Rev.D, hep-ex/0602023

HFAG : $|V_{cb}|$, Form Factors



Existing results and average use 1996 CLEO fit of R_1, R_2 [PRL **76**(3898)] to set $\mathcal{F}(w)$.

BaBar's new result affects extraction of $|V_{cb}|$ from BFs (value and systematics).

Work underway within HFAG to incorporate result with existing and future analyses.

Summary and Outlook

Semileptonic B decays continue to be fruitful and exciting

- Many new measurements improving $|V_{ub}|$
- Differences between inclusive and exclusive $|V_{ub}|$ narrowing?

$$\begin{array}{c} \left(4.44 \pm 0.25\,^{+0.47}_{-0.44}\right) \times 10^{-3} \\ \left(4.09 \pm 0.19\,^{+0.30}_{-0.31}\right) \times 10^{-3} \end{array} \quad \text{vs.} \quad \left(3.82 \pm 0.14\,^{+0.91}_{-0.58}\right) \times 10^{-3}$$

  Statistically precise (<6%); consistent within uncertainties

- $B \to D^* \ell \nu$ form factor fit is first update in ten years. Results will affect exclusive $|V_{cb}|$ (central value and reduced systematics).
- Inclusive and exclusive $|V_{cb}|$ still seem different at $\sim 2\sigma$ level.

$$(42.0 \pm 0.2 \pm 0.7) \times 10^{-3} \quad \text{vs.} \quad \left(37.6 \pm 0.3\,^{+2.0}_{-1.8}\right) \times 10^{-3}$$

  Interesting? or not?

- Single-experiment precisions comparable to previous world averages

Expect more high-precision results, confronting theoretical models and S.M. predictions, over next few years!

The B Factories

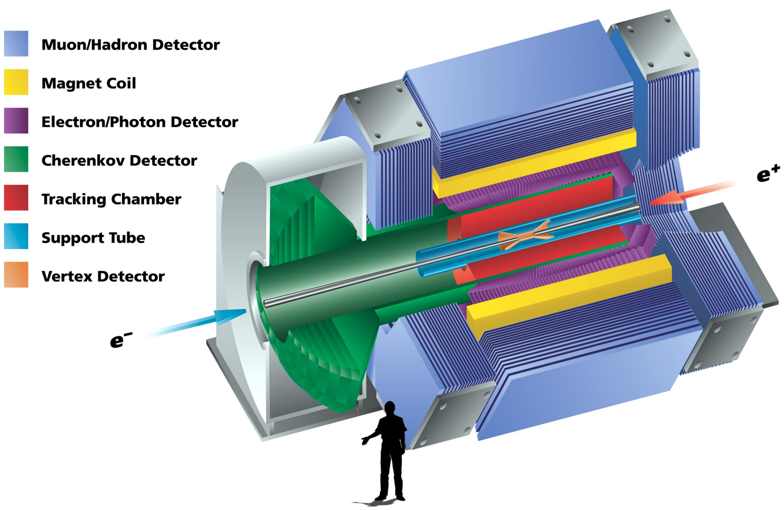
Asymmetric-energy collisions $e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0, B^+B^-$

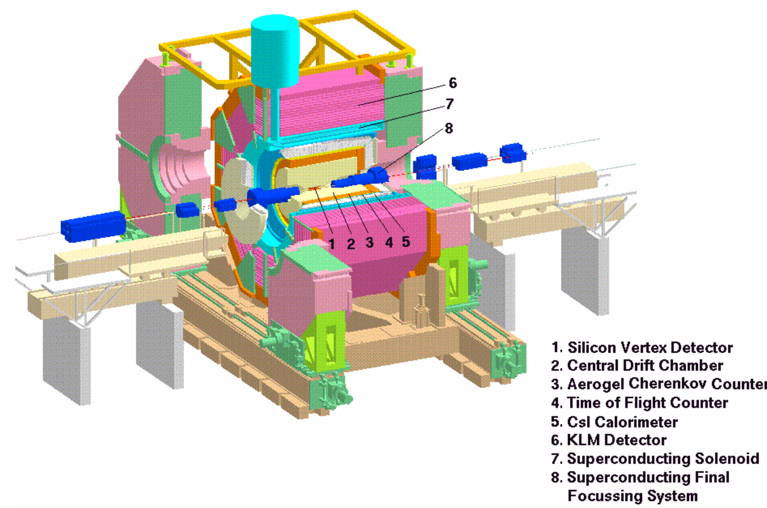
Babar at PEP-II

9 GeV e^-, 3.1 GeV e^+

Belle at KEK-B

8 GeV e^-, 3.5 GeV e^+





$\mathcal{L}_{peak} \lesssim 10^{34}$ **cm^{-2} s^{-1}**

$\mathcal{L}_{peak} \gtrsim 1.6 \times 10^{34}$ **cm^{-2} s^{-1}**

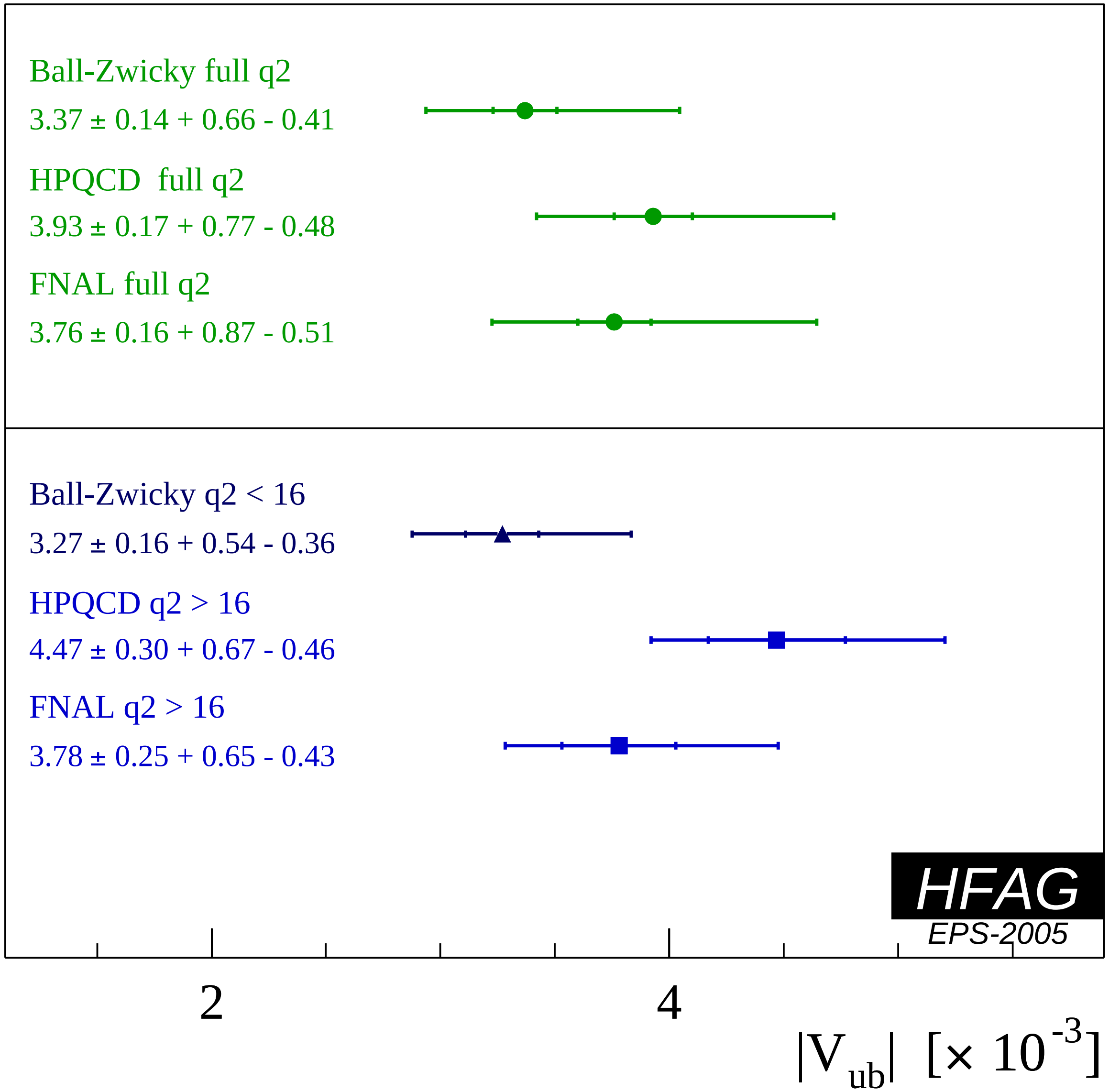
1999 to 2008/2009, $\sim$ 1 ab^{-1} (billion $B\overline{B}$) each

Advantages of B Factories

- Very high statistics: few $B\overline{B}$ per second
- Specific production states: at threshold for B^0, $B^\pm$
- Full event reconstruction: 5–20 tracks per event
- Resolve B decay times ($\beta\gamma \sim 0.5 \Rightarrow \Delta z \sim 250\ \mu$m)
- Low backgrounds, open (unbiased) trigger system

Exclusive $B \to X_u \ell \nu, |V_{ub}|$: HFAG

$\Longrightarrow$



Inclusive $B \to X_u \ell \nu$: BaBar

See M. Rotondo's talk at 19.10

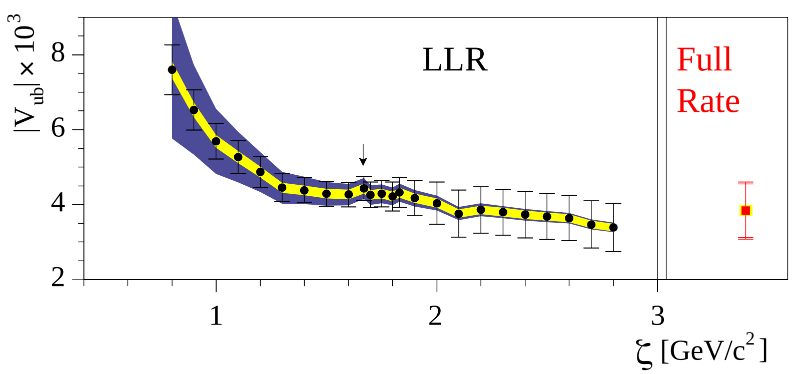
Mass of X_u from reconstructed B, lepton, "neutrino"

Partial rates in bins of $m_X \leq \zeta$, corrected for efficiencies

Avoid dependence on shape function (LLR, Neubert)

$$\frac{|V_{ub}|}{|V_{ts}|} = \sqrt{\frac{6\alpha\left(1 + H^{\gamma}_{\text{mix}}\right)\left[C_7^{(0)}\right]^2}{\pi\left[I_0(\zeta) + I_+(\zeta)\right]} \times \delta\Gamma(\zeta)}$$

$$\delta\Gamma(\zeta) = \frac{N_{b\to u}(\zeta)\mathcal{B}(\overline{B} \to X\ell\nu)}{N_{B\to X\ell\nu} \times \varepsilon(b \to u)} \times \textit{efficiencies}$$



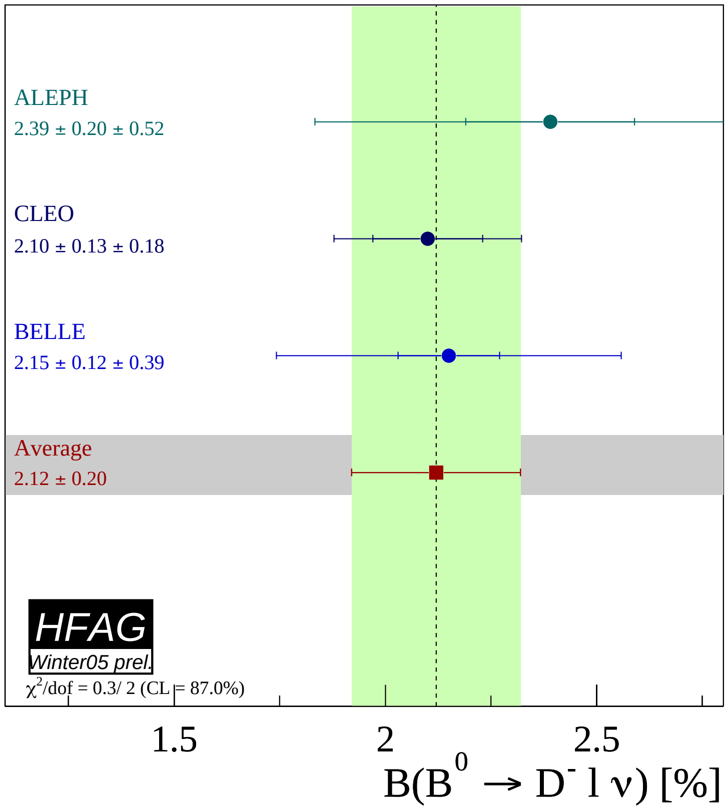
I_0, I_+ weighted integrals of $B \to s\gamma$ spectrum

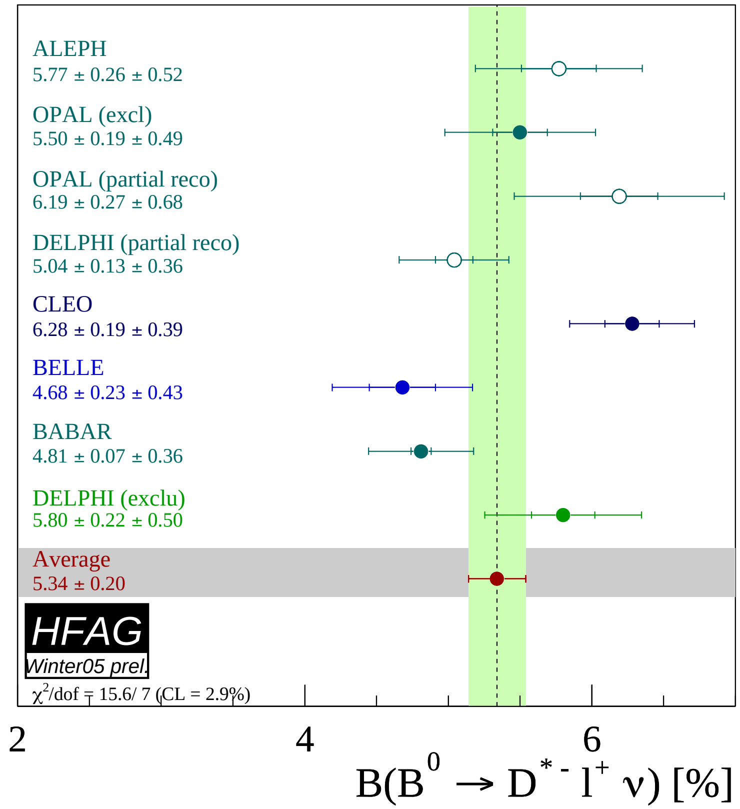
$$|V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \times 10^{-3}$$

$|V_{ub}| = (4.38 \pm 0.19 \pm 0.27) \times 10^{-3}$ (HFAG)

Submitted to Phys.Rev.Lett., hep-ex/0601046

HFAG : $B \to D\ell\nu, D^*\ell\nu$





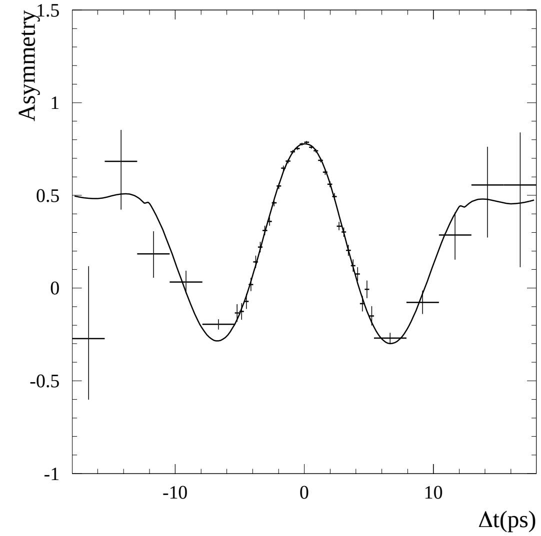
B^0 Properties : BaBar

$\overline{B}^0 \to D^{*+}\ell\overline{\nu}, D^{*+} \to \pi^+ D^0$

Lepton and "slow" pion only, not D^0

Recoil B identified from lepton only.

Fit $\Delta\tau \sim \Delta z$ using ℓ-π vertex, beam-spot, $\ell_{\rm recoil}$–beam-axis constraints.



$B^0\overline{B}^0$ mixing: $\dfrac{N_{\ell^\pm\ell^\pm} - N_{\ell^+\ell^-}}{N_{\ell^\pm\ell^\pm} + N_{\ell^+\ell^-}}$

$$\tau(B^0) = 1.504 \pm 0.013\,^{+0.018}_{-0.013}\ \text{ps}$$
$$\Delta(m_d) = 0.511 \pm 0.007\,^{+0.007}_{-0.006}\ \text{ps}^{-1}$$

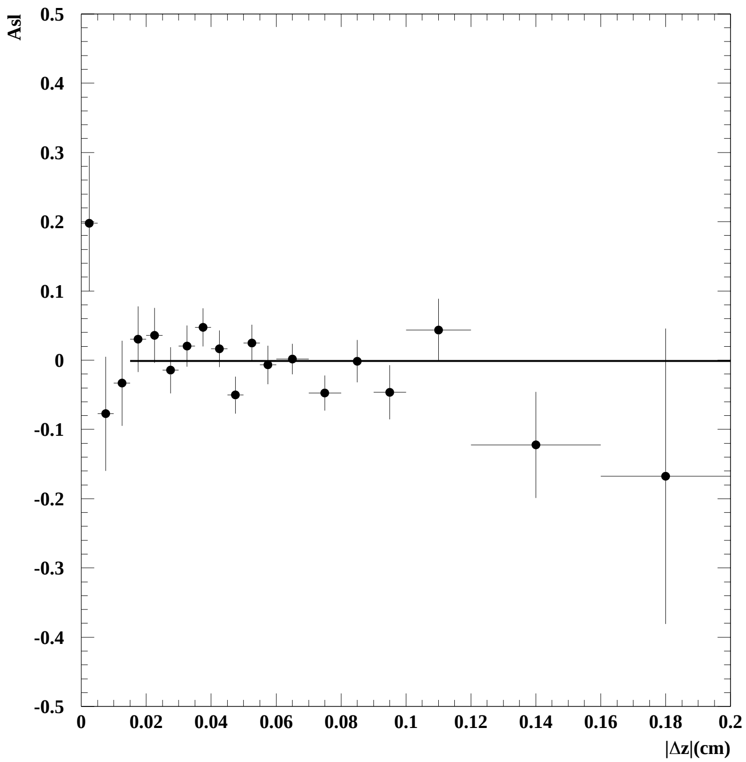
Phys.Rev. **D73**(012004), hep-ex/0507054

B^0 Mixing : Belle

Search for charge asymmetry in $B^0\overline{B}^0$ mixing.

Reconstruct events with pairs of leptons. Identify same-sign vs. opposite-sign events.

Look for difference in $\ell^+\ell^+$ compared to $\ell^-\ell^-$ (excluding known detector effects)



$$A_{\rm sl} = \frac{N_{\ell^+\ell^+} - N_{\ell^-\ell^-}}{N_{\ell^+\ell^+} + N_{\ell^-\ell^-}} = (-1.1 \pm 7.9 \pm 7.0) \times 10^{-3}$$

Submitted to Phys.Rev.D, hep-ex/0505017