Recent results on charmless semileptonic decays at \textit{BaBar}

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Overview

I. Why explore the Flavor sector of the Standard Model in the first place?

II. Inclusive measurement of $B \rightarrow X_u \ell \bar{\nu}_\ell$
   [arXiv:1112.0702]

III. Exclusive measurements for $B \rightarrow h \ell \bar{\nu}_\ell$ with $h = \pi, \omega, \rho, \eta, \eta'$
   [PRD:83032007], [arXiv:1205.6245], 2× [to be submitted]

IV. $|V_{ub}|$ from both approaches

V. The status of charmless semileptonic decays at $BABAR$
I.a Motivation

Why explore the Flavor sector of the Standard Model (SM) and measure charmless semileptonic decays?
[cf. Backup A.a for a slightly longer introduction]

I. Charmless semileptonic decay rate allows determination of $|V_{ub}|$

II. $|V_{ub}|$ important input for global CKM fits.
   a. What are the contributions from the Flavor sector to CP violation in the Universe?
   b. Violation of CKM unitarity $\Leftrightarrow$ new physics

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

III. Inclusive vs Exclusive measurements:
   a. Fairly independent experimental and theoretical methods
   b. Probe our understanding of non-perturbative and perturbative QCD
I.b Semileptonic decays

Semileptonic \( b \to u \) decays are characterized by

a \( q^2 = (p_B - p_X)^2 = (p_\ell + p_\nu)^2 \)

b \( \theta \): Angular variables (helicity, ...)

c \( m_X \): Invariant hadronic mass

\[ \mathcal{B}(B \to X_u \ell \nu_\ell) \propto |V_{ub}|^2 \times \text{'Something we can predict from Theory'} \]

a Challenges:

⇒ Much more abundant \( b \to c \ell \nu_\ell \) decays:
   Force e.g. inclusive measurements into regions with larger theory uncertainties. Orbital or other modes poorly known.

⇒ Very low signal yields

b Experimental techniques:

⇒ Neutrino reconstruction:
   \( (E_{\text{miss}}, \vec{p}_{\text{miss}}) = (E_{\text{beam}}, \vec{p}_{\text{beam}}) - \sum_i (E_i, \vec{p}_i) \)
   Missing mass squared: \( MM^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2 \)

⇒ Beam constraints: \( \Delta E \) and \( m_{ES} \)
   \( (E_B^*, \vec{p}_B^*^2) = p_X + p_\ell + p_{\text{miss}} \) or inferred from the tag side if present; \( * \) = in \( \Upsilon(4S) \) rest frame; \( E_{\text{beam}}^* \) beam energy

\[ \Delta E = E_B^* - E_{\text{beam}}^* / 2 \]

\[ m_{ES} = \sqrt{E_{\text{beam}}^2 / 4 - \vec{p}_B^*^2} \]
**BABAR** charmless overview:

- New result [to be submitted]
- Shown last ICHEP [PRD:83032007]
- New result [arXiv:1205.6245], [to be submitted]

**b→u Mass Spectrum**  
\(\pi, \eta, \eta', \rho, \omega\)  
Inclusive  

**Arbitrary Units**

**mx [GeV]**
II. New inclusive measurement

At a glance:

- Full $\bar{B}B$AR dataset of $467.8 \times 10^6$ $B\bar{B}$
- Inclusive $B \rightarrow X_u \ell \bar{\nu}_\ell$ using hadronic tags to reconstruct $p_B$, require lepton
- $p_X = \sum_i p_i^{\text{tracks}} + \sum_j p_j^{\text{calo}}$
  The sum excludes the lepton and all tracks and calor clusters associated with the tagged $B$
- Cut based Bkg suppression, e.g. $MM^2$, total charge, $D^*$ veto based on partial reco.
- $q^2 = (p_B - p_X)^2$; $m_X^2 = p_X^2$; $p_\ell$:
  $P_+ = E_X - |\vec{p}_X|$

  tag Unbinned LH Fit in $m_{ES}$ for comb. & continuum Bkg (→ top plot)

recoil $\chi^2$ Fit (→ List) for signal and $B\bar{B}$ Bkg

  Step 1  Fit # of $B \rightarrow X_u \ell \bar{\nu}_\ell$ evts. in given bins
  Step 2  Determine # of $B \rightarrow X \ell \bar{\nu}_\ell$ evts. in reco sample

⇒ Measure ratio $\Delta \mathcal{B}(B \rightarrow X_u \ell \bar{\nu}_\ell)/\mathcal{B}(B \rightarrow X \ell \bar{\nu}_\ell)$ (→ many systematics cancel)
II. New inclusive measurement

[aXiv:1112.0702]
II. New inclusive measurement

- $|V_{ub}| = \sqrt{\frac{\Delta B}{\tau_B \Delta \Gamma_{\text{theory}}}}$ with $\Delta \Gamma_{\text{theory}}$ from
  ADFR [EPJC:59;831], BLNP [NPB:699;335], DGE [JHEP:0601097],
  GGOU [JHEP:0710:058]

- $m_X - q^2$, $p_\ell^* > 1.0$ GeV vs $p_\ell^* > 1.0$ GeV
  Events overlap completely; Very nice agreement between theory
  predictions and signal regions $\rightarrow$ large region of phase space, very
  reduced sensitivity to non-pert. corrections (\(\hat{=} \text{shape function}\))

- $m_X - q^2$, $p_\ell^* > 1.0$ GeV vs $m_X < 1.7$ GeV
  Large overlap, cut on $m_X$ increases sensitivity to non-pert.
  corrections (\(\hat{=} \text{shape function}\))

| $|V_{ub}| \times 10^3$ | $p_\ell^* > 1.0$ GeV | $m_X - q^2$ | $m_X < 1.7$ GeV |
|----------------------|---------------------|-------------|-----------------|
| ADFR                 | 4.3 $\pm$ 0.3 +0.2 -0.2 | 4.3 $\pm$ 0.2 +0.2 -0.2 | 3.7 $\pm$ 0.2 +0.2 -0.2 |
| BLNP                 | 4.3 $\pm$ 0.3 +0.2 -0.2 | 4.3 $\pm$ 0.2 +0.2 -0.2 | 4.0 $\pm$ 0.2 +0.2 -0.2 |
| DGE                  | 4.4 $\pm$ 0.3 +0.1 -0.1 | 4.4 $\pm$ 0.2 +0.1 -0.1 | 4.2 $\pm$ 0.2 +0.3 -0.3 |
| GGOU                 | 4.4 $\pm$ 0.3 +0.1 -0.1 | 4.4 $\pm$ 0.2 +0.1 -0.1 | 3.9 $\pm$ 0.2 +0.2 -0.2 |

The apex of the UT from the Moriond 2012 CKMFitter result is compared to the constraints from the new
BABAR inclusive measurement as determined by the QCD calculation from [JHEP:0710:058], $A = 0.812 \pm 0.022$,
and $\lambda = 0.22543 \pm 0.00095$. $\rightarrow$ other calculations in Backup
**BABAR** charmless overview:

- New result [to be submitted]
- Shown last ICHEP [PRD:83032007]
- New result [arXiv:1205.6245], [to be submitted]
- New result [arXiv:1112.0702]

**b → u Mass Spectrum**

- $\pi$, $\eta$, $\eta'$, $\rho$, $\omega$
- Inclusive

Arbitrary Units

$m_X$ [GeV]
III.a New $B \to h \ell \bar{\nu}_\ell$ measurement

At a glance:

- Full $BABAR$ dataset of $467.8 \times 10^6 B \bar{B}$
- $B \to h \ell \bar{\nu}_\ell$ with $h = \pi, \eta, \eta', \omega$
- Un tagged; loose neutrino reconstruction
- $q^2 = (p_B - p_h)^2$, $p_B$ from average over directions; resolution unfolded
- $q^2$ dependent selection $\rightarrow$ Figure
- Binned LH Fit in $\Delta E - m_{ES} - q^2$

$h = \pi$: Signal in 12 bins of $q^2$; Bkg in two bins of $q^2$
$h = \omega$: Signal in 5 bins of $q^2$; Bkg in one $q^2$ bin
$h = \eta$: Signal in 5 bins of $q^2$; fixed or in one $q^2$ bin
$h = \eta'$: Signal in 1 bins of $q^2$; Bkg fixed

$\Delta E - m_{ES}$ Signal & Background PDFs:

... have been applied, in the case of the $B^0 \to \pi^- \ell^+\nu$ decay channel. Also shown is the binning used in this particular case.
III.b New $B \to h \ell \bar{\nu}_\ell$ measurement

$$\Delta B(B \to \pi \ell \bar{\nu}_\ell)/\Delta q^2; \quad \Delta B(B \to \omega \ell \bar{\nu}_\ell)/\Delta q^2; \quad \Delta B(B \to \eta \ell \bar{\nu}_\ell)/\Delta q^2$$

$|V_{ub}|$ from $B \to \pi \ell \bar{\nu}_\ell$ two methods:

a) Sum rule or lattice based QCD prediction of decay rate:

$$
\begin{array}{lrr}
q^2/\text{GeV}^2 & |V_{ub}| \times 10^3 \\
\text{[PRD:73074502]} & > 16 & 3.47 \pm 0.13^{+0.60}_{-0.39} \\
\text{[PRD:830904021]} & < 12 & 3.46 \pm 0.10^{+0.37}_{-0.32} \\
\text{[arXiv:1203.1359]} & 0 & 3.34 \pm 0.11^{+0.29}_{-0.26} \\
\end{array}
$$

b) Combined lattice and data fit of whole $q^2$ range with model independent form factor parametrization:

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

[PRD:56303], [PRD:80034026], [PRD:79054507]
**BABAR charmless overview:**

![Diagram showing the mass spectrum of inclusive \( \Pi, \eta, \eta', \rho, \omega \) particles.]
III.c New $B \to \omega \ell \bar{\nu}_\ell$ measurement

At a glance:

- Full $B_{ABAR}$ dataset of $467.8 \times 10^6 \ B\bar{B}$
- Untagged $B \to \omega \ell \bar{\nu}_\ell$; loose neutrino reconstruction.
- $q^2 = (p_\ell + p_{miss})^2$
- Neural Network based selection to suppress continuum and $B \to X_c \ell \bar{\nu}_\ell$
- $B\bar{B}$ comb. Bkg from $\omega$-mass sideband

- Binned LH Fit in $\Delta E - m_{ES} - q^2$ (→ Plot)

| $q^2/\text{GeV}^2$ | $|V_{ub}| \times 10^3$ |
|-------------------|-------------------|
| [PRD:71014029]    | $< 12$            |
|                   | $3.41 \pm 0.28 \pm 0.38$ |

Signal in 5 bins of $q^2$; $B\bar{B}$ Bkg with true $\omega$ in 5 bins of $q^2$
At a glance:

- **Full** $B_{ABAR}$ dataset of $467.8 \times 10^6$ $B\bar{B}$
- **Tagged** measurement of $B \rightarrow \omega \ell \bar{\nu}_\ell$
- Partial reconstruction of secondary $B$ meson kinematic via $B \rightarrow D(*) \ell \bar{\nu}_\ell$
- Kinematics of $B$-mesons inferred from beam constraints + $D(*) \ell$ and $\omega \ell$ candidates
- $q^2 = (p_B - p_\omega)^2$, meas. in $B$ rest frame.
- Binned LH fit in $\cos \phi_B - q^2$:

$\cos \phi_B$: angle of tag $B$ 3-momentum and the plane spanned by the $D(*)(n \pi) \ell$ and $\omega \ell$ 3-momenta

| $q^2$/GeV$^2$ | $|V_{ub}| \times 10^3$ |
|--------------|----------------------|
| [PRD:71014029] Full | $3.39 \pm 0.32 \pm 0.65$ |

Fitted $\cos \phi_B$ and $q^2$ spectrum
IV. Comparison of $|V_{ub}|$ from both approaches

I. Good agreement between $|V_{ub}|$ from different exclusive measurements.

Unquenched Lattice predictions for form factors for $B \to \omega \ell \bar{\nu}_\ell$ and $B \to \rho \ell \bar{\nu}_\ell$ highly desirable, considerable width of $\rho$ might make the $\omega$ easier target.

II. Tension between exclusive vs inclusive $|V_{ub}|$

Many ideas floating in the room: poorly understood QCD ($\to$ SIMBA), new physics (e.g. right-handed currents), poorly understood backgrounds (e.g. $B \to X_c \ell \bar{\nu}_\ell$ which has its own mysteries), experimental uncertainties underestimated, etc.

$|V_{ub}|$ from the combined data-lattice fit from page X for $B \to \pi \ell \bar{\nu}_\ell$ is compared to the values for $B \to \omega \ell \bar{\nu}_\ell$ and $B \to \rho \ell \bar{\nu}_\ell$ determined using the Sum rule calculation of [PRD:71014029]; The right-hand side shows the inclusive result from page Y for two phase-space regions and using the QCD calculation from [JHEP:0710:058].
V. Summary: The status of charmless decays and $|V_{ub}|$

I. Measurements using the full $B_{ABAR}$ dataset for 4 exclusive modes

Understand what makes up $\approx 44\%$ of the inclusive $B \to X_u \ell \bar{\nu}_\ell$ spectra for $m_X < 1.55$ GeV

II. Inclusive $b \to u \ell \bar{\nu}_\ell$ measurement using the full $B_{ABAR}$ dataset

Tension between inclusive and exclusive values of $|V_{ub}|$ remain:

![Mass Spectrum](image1)

Inclusive $|V_{ub}|$ from [arXiv:1112.0702] from GGOU with $q^2 - m_X$ fit with $E^*_l > 1.0$ GeV is compared with the combined $B \to \pi \ell \bar{\nu}_\ell$ data-lattice fit from slide 10. The CKMFitter result is from Moriond 2012 result.

Future plans at $B_{ABAR}$: tagged $B \to \rho \ell \bar{\nu}_\ell$; $B \to h h \ell \bar{\nu}_\ell$ with $h = p, K, pi, ...$

Studies for a better understanding of exclusive $b \to c \ell \bar{\nu}_\ell$ background.
Backup
Flavor sector of Standard Model (SM):

\[ \mathcal{L} = \frac{g_2}{\sqrt{2}} W^+ \bar{u}'_L \gamma^\mu V_{\text{CKM}} d'_L + \text{h.c.} \]

\( V_{\text{CKM}} \) couples Weak and Mass eigenstates

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\( V_{\text{CKM}} V_{\text{CKM}}^\dagger = 1 \to 6 \) triangle equations, e.g.

Unitary triangle: \( V_{ud} V_{ub}^* + V_{td} V_{tb}^* + V_{cd} V_{cb}^* = 0 \)

Semileptonic \( b \to q \) decays:

Characterized by:

\[ q^2 = (p_B - p_X)^2 = (p_\ell + p_\bar{\nu}_\ell)^2 \]

\( m_X \): Invariant hadronic mass

\( \theta \): Angular variables

Decay rate for \( b \to u \ell \bar{\nu}_\ell \):

\[ d\Gamma \propto |V_{ub}|^2 \times |A(q^2, \theta)|^2 \ dq^2 \ d\theta \ (d m_X) \]

\( \Rightarrow '\text{Hybrid}' \) simulation of \( b \to u \ell \bar{\nu}_\ell \)

\( \Rightarrow \) Amplitudes can be predicted using QCD; fairly independent approaches for Inclusive vs Exclusive states
Reconstruction of $q^2$:

$$q^2 = (p_B - p_X)^2 = (p_\ell + p_{miss})^2$$

→ **Tagged**: full or partial reconstruct second $B$-meson:

$$p_B = (E_{B_{tag}}, -\bar{p}_{B_{tag}})$$

Incl.: $p_X$ from $\sum$ over recoil side particles
Excl.: $p_X = p_h$ from $h = \pi, \ldots$ candidate

→ **Untagged**: average over unknown direction of $B$-meson using beam constraints

or $p_\ell$ + missing 4-momentum $p_{miss}$ of event.

Loose neutrino reconstruction:

(used in untagged)

Infer neutrino kinematics from missing 4-momentum:

$$(E_{miss}, \bar{p}_{miss}) = (E_{beam}, \bar{p}_{beam}) - \sum_i (E_i, \bar{p}_i)$$

sum runs over reconstructed particles from all charged tracks and unmatched calorimeter clusters in event.

Missing mass squared $MM^2 = E_{miss}^2 - |\bar{p}_{miss}|^2$

$\rightarrow MM^2/(2E_{miss})$ has better resolution

$\rightarrow$ Multivariate techniques (NN); cut; or cut($q^2$)

Isolation of signal decays:

$$\Delta E = E_B^* - E_{beam}$$

$$m_{ES} = \sqrt{E_{beam}^2 - \bar{p}_B^*^2}$$

(a)

(b)

Other Backgrounds

$e^+ e^- \rightarrow q\bar{q}$ cuts or NN; validation with off-resonance

$e^+ e^- \rightarrow b\bar{b}$ cuts or NN; validation with sidebands

→ **Semileptonic** $b \rightarrow c \ell \bar{\nu}_\ell$

$50 - 500 \times$ more abundant than signal decays

$m_X > 1.85$; lower lepton energy endpoint

Measurements in phase space regions where $b \rightarrow c$ strongly suppressed or forbidden

→ inclusive decays: model dependence due to unknown parton distribution function
B.a New inclusive $|V_{ub}|$ gallery

$|V_{ub}|$ Inclusive

- ADFR
- BLNP
- DGE
- GGOU

$\rho$ $\eta$

$q^2 - M_X; E_l > 1$ GeV

$M_X < 1.70$ GeV