BABAR Results on Leptonic and Radiative $B$ and Charm Decays

Brad Wray
The University of Texas at Austin
(For the BABAR Collaboration)

DPF 2011-Brown University
August 10, 2011
Outline

- Radiative and Leptonic Decays
- The BABAR Detector and Dataset
- $A_{CP}(B \rightarrow X_{s+d} \gamma)$
- $B \rightarrow K \nu \bar{\nu}$
- $B^+ \rightarrow \tau^+ \nu_\tau$
- $D_s^- \rightarrow \ell^- \bar{\nu}_\ell$
- Summary
Radiative and Leptonic Decays

- Radiative Decays
  - Lowest order SM contributions often involve loops ($B \rightarrow X_s \gamma$, $B \rightarrow X_d \gamma$)
  - Sensitive to new, heavy virtual particles in loops
  - BFs typically $\sim 10^{-4}$ or less
- Leptonic Decays
  - Clean probe of theoretical quantities
  - BFs $\sim 10^{-4}$ ($10^{-2}$ for charm) or less due to helicity suppression and CKM factors
  - Offer precision tests of Standard Model predictions
  - Any large deviation from SM prediction could be an indication of New Physics
  - Low energy indirect NP searches are complimentary to direct searches at high energy machines like LHC and Tevatron

(Haisch, arXiv:0805.2141)
The **BABAR** Detector & Dataset

- Asymmetric energy
  - $E_{\text{cms}} = 10.58$ GeV
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Wide range of flavor physics results in $B$, charm, and $\tau$ sectors

**BABAR** Detector & Dataset

- **1.5 T solenoid**
- **Si vertex tracker (SVT)**: 5 layers double-sided silicon
- **Drift chamber (DCH)**: 40 layers, tracking & dE/dx
- **Electromagnetic Calorimeter (EMC)**: 6580 CsI(Th) crystals, $e^+$ ID, $\pi^0$ and $\gamma$ reco
- **Cherenkov detector (DIRC)**: 144 quartz bars, $K$, $\pi$, $p$ ID
- **Instrumented Flux Return (IFR)**: 19 layers of RPCs or LSTs, $\mu/K\ell$ ID

**Total dataset**: $\sim 430$ fb$^{-1}$ at $\Upsilon(4S)$

<table>
<thead>
<tr>
<th>Type</th>
<th>N ($\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\bar{B}$</td>
<td>470</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>690</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>500</td>
</tr>
</tbody>
</table>

**PEP II Delivered Luminosity**: 553.48 fb$^{-1}$
**BABAR Recorded Luminosity**: 531.43 fb$^{-1}$
**BABAR Recorded $\Upsilon(4S)$**: 432.89 fb$^{-1}$
**BABAR Recorded $\Upsilon(3S)$**: 30.23 fb$^{-1}$
**BABAR Recorded $\Upsilon(2S)$**: 14.45 fb$^{-1}$
**Off Peak Luminosity**: 53.85 fb$^{-1}$

**As of 2008/11/11 00:00**

**DPF 2011 - August 10, 2011**  
**BABAR Results on Radiative & Leptonic Decays - B. Wray**
$A_{CP}(B \rightarrow X_{s+d} \gamma)$
$A_{CP}(B \rightarrow X_{s+d} \gamma)$: Background and Predictions

- LO contribution electroweak penguin

- Measurable inclusive rate equal within a few % of partonic rate

- New Physics may enter at same order as SM

- Sizable deviations from SM predictions (BF & $A_{CP}$)

- SM $\mathcal{B}(B \rightarrow X_{s} \gamma)$ at NNLO ($E_{\gamma} > 1.6$ GeV)

- $\hat{\mathcal{B}}(B \rightarrow X_{s} \gamma) = (3.15 \pm 0.23) \times 10^{-4}$ [1]

- Direct $CP$ asymmetry [2]

$$A_{CP} = \frac{\Gamma(b \rightarrow s \gamma + b \rightarrow d \gamma) - \Gamma(\bar{b} \rightarrow \bar{s} \gamma + \bar{b} \rightarrow \bar{d} \gamma)}{\Gamma(b \rightarrow s \gamma + b \rightarrow d \gamma) + \Gamma(b \rightarrow \bar{s} \gamma + b \rightarrow \bar{d} \gamma)}$$

- $A_{CP}(B \rightarrow X_{s+d} \gamma) \approx 10^{-6}$

- Photon spectrum moments

- Can be used to extract HQE parameters $m_b$ and $\mu_\pi^2$

**ACP(B→X_{s+d}γ): Analysis Strategy**

- Measurement uses 347 fb\(^{-1}\)
- High energy photon: 1.5 < \(E^{*}_{γ} \) < 3.5 GeV
- Veto \(π^{0}/η\) decays
- Continuum background
  - Leptonic tag
    - \(e/μ\) candidate with \(p^{*}_{t} > 1.05\) GeV/c
    - \(\cos θ^{*}_{γt} > -0.7\)
    - \(E^{*}_{\text{miss}} > 0.7\) GeV
  - Neural network exploiting jet-like topology
  - Remaining background subtracted using scaled off-resonance data
- \(B\bar{B}\) background
  - Subtracted using data corrected MC

* indicates \(\Upsilon(4S)\) frame

After selection, signal eff. of \(\approx 2.5\%\) while only \(0.0005\%\) of continuum and \(0.013\%\) of \(B\bar{B}\) background remain

**Full Selection**

**High Energy Photon Selection**

**continuum control region**

[Diagram showing distribution of events in \(E^{*}_{γ}\) with signal and background regions identified.]

DPF 2011 - August 10, 2011  BABAR Results on Radiative & Leptonic Decays - B. Wray
$A_{CP}(B \rightarrow X_{s+d} \gamma)$: Results

- Continuum region ($2.9 < E^*_{\gamma} < 3.5$ GeV)
  - $-100 \pm 138$ (stat.) events
- $B\bar{B}$ region ($1.53 < E^*_{\gamma} < 1.8$ GeV)
  - $1252 \pm 272$ (stat.) $\pm 841$ (syst.) events
- $CP$ asymmetry
  - Lepton charge gives $B$ flavor
  - Correct for mis-tag rate, $w$
  - Insensitive to photon energy cut
  - Optimized for $2.1 < E^*_{\gamma} < 2.8$ GeV
- Common systematics cancel in ratio

$$A_{CP} = \frac{A_{meas}}{1-2w} + \Delta A_{CP}$$

- $-0.004 \pm 0.013$ ($A_{CP}$ bkg)

$$0.131 \pm 0.0064$$ ($B^0$ oscillations)

Differs from null by 1.4\(\sigma\) but assumes no signal, when 100-400 signal events expected.
Search for

\[ B \rightarrow K \nu \bar{\nu} \]

**$B \to K\nu\bar{\nu}$: Analysis Strategy**

- FCNC in SM $\Rightarrow$ must proceed through loops
  - $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \approx 3.8 \times 10^{-6}$
  - Sensitive to new heavy particles appearing in loops $\Rightarrow$ may increase $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ 10x SM value
- Presence of two neutrinos $\Rightarrow$ few kinematic handles available for reconstruction of signal $B$
  - Reconstruct “other $B$” in event in $B \to D(\ast)\ell\nu$ mode (larger efficiency than hadronic tag)
  - Look for signal decay among remaining particles in event

**Charm meson modes reconstructed in semileptonic tagging**

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

**Full BABAR dataset**

$\sim 418$ fb$^{-1}$

---

DPF 2011 - August 10, 2011  
*BABAR* Results on Radiative & Leptonic Decays - B. Wray
**B→Kν̅ν**: Analysis Strategy

- Suppress large remaining background using ensemble of Bagged Decision Trees (BDT)
  - Trained on simulated signal and background events
  - Ensembles use 26 ($K^+$) or 38 ($K^0_s$) variables relating to:
    - missing four-momentum
    - overall event properties
    - signal kinematics
    - Tag $B$ reconstruction quality
- Selection chosen to optimize signal significance: $s/(s+b)^{1/2}$
**$B \rightarrow K \nu \bar{\nu}$: Results**

No significant signal observed. Best upper limits to date.

---

### Expected events

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\epsilon$ (in %)</th>
<th>$N_{\text{sgnl}}$</th>
<th>$N_{\text{bkgd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>0.16</td>
<td>$2.9 \pm 0.4$</td>
<td>$17.6 \pm 2.6 \pm 0.9$</td>
</tr>
<tr>
<td>$K_s^0$</td>
<td>0.06</td>
<td>$0.5 \pm 0.1$</td>
<td>$3.9 \pm 1.3 \pm 0.4$</td>
</tr>
<tr>
<td>low-$q^2 K^+$</td>
<td>0.24</td>
<td>$2.9 \pm 0.4$</td>
<td>$17.6 \pm 2.6 \pm 0.9$</td>
</tr>
<tr>
<td>high-$q^2 K^+$</td>
<td>0.28</td>
<td>$2.1 \pm 0.3$</td>
<td>$187 \pm 10 \pm 46$</td>
</tr>
</tbody>
</table>

### Observed events

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{excess}}$</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>$19.4^{+4.4}_{-4.4}$</td>
<td>$1.8^{+6.2}_{-5.1}$</td>
<td>38%</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$6.1^{+4.0}_{-2.2}$</td>
<td>$2.2^{+4.1}_{-2.8}$</td>
<td>23%</td>
</tr>
<tr>
<td>low-$q^2 K^+$</td>
<td>$19.4^{+4.4}_{-4.4}$</td>
<td>$1.8^{+6.2}_{-5.1}$</td>
<td>38%</td>
</tr>
<tr>
<td>high-$q^2 K^+$</td>
<td>$164^{+13}_{-13}$</td>
<td>$-23^{+49}_{-48}$</td>
<td>33%</td>
</tr>
</tbody>
</table>

### Upper limits

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\text{BF}$</th>
<th>90% CL</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\times 10^{-5}$</td>
<td>$\times 10^{-5}$</td>
<td>$\times 10^{-5}$</td>
</tr>
<tr>
<td>$K^+$</td>
<td>$0.2^{+0.8}_{-0.7}$</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$1.7^{+3.1}_{-2.1}$</td>
<td>5.6</td>
<td>6.7</td>
</tr>
<tr>
<td>Comb. $K^+, K^0$</td>
<td>$0.5^{+0.7}_{-0.7}$</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Low-$q^2 K^+$</td>
<td>$0.2^{+0.6}_{-0.5}$</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>High-$q^2 K^+$</td>
<td>$-1.8^{+3.8}_{-3.8}$</td>
<td>3.1</td>
<td>4.6</td>
</tr>
</tbody>
</table>

---

$B^+ \rightarrow \tau^+ \, \nu_\tau$
$B^+ \rightarrow \tau^+ \nu_\tau$: Background & Predictions

**Standard Model**

\[ \mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left( 1 - \frac{m_\ell^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+} \]

- Test SM and search for New Physics
- Sensitive to product $f_B |V_{ub}|$
- Two-Higgs doublet model can be mediated by charged Higgs [3]

**Inputs**

$|V_{ub}| = (3.89 \pm 0.44) \times 10^{-3}$ [1]

$f_B = (190 \pm 13) \text{ MeV}$ [2]

$\tau_{B^+} = 1.638 \text{ ps}$

**Helicity suppression term**

$e: \mu: \tau \sim 10^{-7}: 5 \times 10^{-3}: 1$

**Sensitive to** $f_B |V_{ub}|$

**Errors on** $|V_{ub}|$ and $f_B$

**dominant uncertainty on theoretical prediction.**

**New Physics**

\[ \mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{2HDM} = \mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{SM} \left( 1 - \tan^2 \beta \frac{m_B^2}{m_H^2} \right)^2 \]

[1] K. Nakamura *et al.* (Particle Data Group), Journal of Physics G37, 075021


**B⁺ → τ⁺ντ**: Analysis strategy

- Few kinematic handles to reconstruct signal \( B \)
- Fully reconstruct “other \( B \)” (tag \( B \))
  - Remove many tracks and clusters from further consideration
  - Only consider decay modes with >10% purity
  - Reconstruct signal from remaining clusters and tracks
- Look for a single charged track in rest of event
  - Reconstruct four \( τ \) decay modes: \( e^+νν, μ^+νν, π^+ν, ρ^+ν \) (~70% total BF)
- Reject background using likelihood ratio
  - \( D^{(*)0} / J/ψ \) momentum in CM
  - Magnitude of tag \( B \) thrust
  - Cosine of angle between tag \( B \) thrust and thrust of rest of the event

---

**Hadronic Tag \( B \)**

**Signal \( B \)**

\( B^- \rightarrow M^0 X^- \)

\[ M^0 = \]

\[ D^0 \rightarrow K^-π^+, K^-π^+π^0, K^-π^+π^-π^+, \]
\[ K^0_S π^0, K^0_S π^+π^-, K^0_S π^+π^0, \]
\[ K^+K^-, π^+π^- \]

\[ D^{*0} \rightarrow D^0 π^0, D^0 γ \]

\[ J/ψ \rightarrow e^+e^-, μ^+μ^- \]

\( X^- = nπ^± + mK + pπ^0 + qK^0 \)

\( n + m \leq 5, \quad m, p, q \leq 2 \)
**B^+ → τ^+ ν_τ**: Results

- Most powerful discriminating variable: \(E_{\text{extra}}\) (sum of neutral cluster energy not associated w/ tag \(B\) or \(\pi^0\) from \(\rho^+\) decay)

- Optimize for smallest statistical + systematic uncertainty

- Unbinned extended maximum likelihood fit to \(E_{\text{extra}}\)

  - Simultaneously fit 4 \(\tau\) decay modes
  - Signal PDF from MC
  - Combinatorial PDF from \(m_{ES}\) side band
  - Peaking PDF from \(B^+B^-\) MC

### Systematics

<table>
<thead>
<tr>
<th>Source of systematics</th>
<th>BF uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B) counting</td>
<td>0.5</td>
</tr>
<tr>
<td>Tag (B) efficiency</td>
<td>5.0</td>
</tr>
<tr>
<td>Background PDF</td>
<td>12</td>
</tr>
<tr>
<td>Signal PDF</td>
<td>1.7</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.8</td>
</tr>
<tr>
<td>Electron identification</td>
<td>2.6</td>
</tr>
<tr>
<td>Muon identification</td>
<td>4.7</td>
</tr>
<tr>
<td>Kaon identification</td>
<td>0.4</td>
</tr>
<tr>
<td>Tracking</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14</strong></td>
</tr>
</tbody>
</table>

**Fit Results**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>(\epsilon \times 10^{-4})</th>
<th>Branching Fraction ((\times 10^{-4}))</th>
<th>Significance (\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau^+ → e^+ν_ν)</td>
<td>2.73</td>
<td>0.39(^{+0.89}_{-0.79})</td>
<td>0.5</td>
</tr>
<tr>
<td>(\tau^+ → μ^+ν_ν)</td>
<td>2.92</td>
<td>1.23(^{+0.80}_{-0.80})</td>
<td>1.6</td>
</tr>
<tr>
<td>(\tau^+ → π^+ν)</td>
<td>1.55</td>
<td>4.0(^{+1.5}_{-1.3})</td>
<td>3.3</td>
</tr>
<tr>
<td>(\tau^+ → ρ^+ν)</td>
<td>0.85</td>
<td>4.3(^{+1.2}_{-1.0})</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>combined</strong></td>
<td><strong>8.05</strong></td>
<td><strong>1.80(^{+0.57}_{-0.54})</strong></td>
<td><strong>3.6</strong></td>
</tr>
</tbody>
</table>

**B(\(B^+ → τ^+ ν_τ\)) = (1.80^{+0.57}_{-0.54} ± 0.26) \times 10^{-4}**

Combine with statistically independent measurement from \(BABAR\) [1]

\(B(\(B^+ → τ^+ ν_τ\)) = (1.79 ± 0.49) \times 10^{-4}\)

$D_s^{-} \rightarrow \ell^{-} \bar{\nu}$

$D_s^\rightarrow \ell^- \bar{\nu}$: Background

- Clean probe of $f_{D_s}$
- Compare with SM prediction from LQCD
- Previously, tension between measured value of $f_{D_s}$ and LQCD prediction of $\sim3\sigma$ [1]
- Possible sign of New Physics

Leptonic branching fraction

$$\mathcal{B}(D_s^- \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s} m_{D_s} m_{\ell}^2 \left(1 - \frac{m_{\ell}^2}{m_{D_s}^2}\right)^2$$


Charged Higgs

Leptoquarks

J. Libby, CKM 2008
$D_s^- \rightarrow \ell^- \bar{\nu}$: Analysis Strategy

Reconstruct

$e^+e^- \rightarrow c\bar{c} \rightarrow D K X D_s^{*-}, \ D_s^{*-} \rightarrow D_s^- \gamma$

$D$ is $D^0, D^+, D^*, \Lambda_{c^+}$

$K$ is $K^+$ or $K_0^s$

$X$ is system of up to three pions

- Inclusive sample of $D_s$ by reconstructing mass recoiling against $D K X \gamma$ system

$$m_{D_s}^2 = [p_{e+} + p_{e-} - (p_D + p_K + p_X + p_\gamma)]^2$$

- Yield determined from 2d fit to mass recoiling against $D K X \gamma$ system and number of pions reconstructed in $X$ system $n_X^R$
  - Inclusive $D_s$ yield: $N_{D_s} = (67.2 \pm 1.5) \times 10^3$

- Reconstruct $D_s$ decays in four decay modes

  - $D_s^- \rightarrow e^-/\mu^- \nu$
  - $D_s^- \rightarrow \tau \bar{\nu}_\tau, \ \tau \rightarrow e^-/\mu^- \nu \bar{\nu}_\tau$

---

DPF 2011 - August 10, 2011  BABAR Results on Radiative & Leptonic Decays - B. Wray
\( D_s^- \rightarrow l^- \bar{\nu} \): Analysis Strategy

- \( D_s^- \rightarrow e^-/\mu^- \nu \)
  - Only one charged track remaining in event (ID as lepton)
  - Kinematic fit for neutrino mass
    - Mass recoiling against \( DKX\gamma \) constrained to PDG mass of \( D_s^+ \)
  - Binned maximum likelihood fit to mass recoiling against \( DKX\gamma e/\mu \) system squared to extract yield

- \( D_s^- \rightarrow \tau^- \nu\tau, \tau \rightarrow e^-/\mu^- \nu \nu\tau \)
  - Only one charged track remaining in event (ID as lepton)
  - Multiple neutrinos in event
  - Binned maximum likelihood fit to \( E_{\text{extra}} \) (sum of EMC energy not associated with \( DKX\gamma \) or \( D_s^- \))
    - Peaks near zero for signal
# $D_s^- \rightarrow \ell^- \bar{\nu}$: Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>$B (10^{-3})$</th>
<th>$f_{D_s}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s^- \rightarrow e^- \bar{\nu}_e$</td>
<td>6.1 ± 2.2 ± 5.2</td>
<td>&lt; 0.23 (90% C.L.)</td>
<td>-</td>
</tr>
<tr>
<td>$D_s^- \rightarrow \mu^- \bar{\nu}_\mu$</td>
<td>275 ± 17</td>
<td>6.02 ± 0.38 ± 0.34</td>
<td>265.7 ± 8.4 ± 7.7</td>
</tr>
<tr>
<td>$D_s^- \rightarrow \tau^- e\nu \bar{\nu}_\tau$</td>
<td>408 ± 42</td>
<td>50.7 ± 5.2 ± 6.8</td>
<td>247 ± 13 ± 17</td>
</tr>
<tr>
<td>$D_s^- \rightarrow \tau^- \mu\nu \bar{\nu}_\tau$</td>
<td>340 ± 32</td>
<td>49.1 ± 4.7 ± 5.4</td>
<td>243 ± 12 ± 14</td>
</tr>
</tbody>
</table>

- $f_{Ds}$ error-weighted average
  - Full BABAR dataset 521 fb$^{-1}$
  - New HFAG average 1.6σ from HPQCD value
- Analysis cross-checked with $D_s^- \rightarrow K^- K^+ \pi^-$
  - Consistent with previous CLEO-c result

**BABAR average**

$$f_{Ds} = (258.6 \pm 6.4 \pm 7.5) \text{ MeV}$$

**LQCD**

$$f_{Ds} = (248 \pm 2.5) \text{ MeV}$$

**BF ± stat. ± syst.**

- **BABAR**
  - (5.78 ± 0.20 ± 0.30)%
- **CLEO-c**
  - (5.50 ± 0.20 ± 0.30)% [1]


C. Davis et al., PRD 82, 114504 (2010)
Summary

• Radiative and leptonic $B$ and charm decays provide precision tests of Standard Model predictions

• Excellent environment to search for physics beyond SM and to constrain parameter space of New Physics models

• All results presented are consistent with SM expectations

• We look forward to interesting flavor results coming from LHCb and, in the more distant future, Belle-2 and SuperB.