Inclusive Semileptonic B Decays at BABAR

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for the BABAR collaboration
Overview

- Introduction: Heavy Quark Expansion (HQE) and moments of inclusive distributions
- Measurement of moments of the hadronic-mass distribution in inclusive decays $B \rightarrow X_{c} l \nu$
- Measurement of moments of the combined hadronic mass-and-energy spectrum:
- Measurement of the unfolded hadronic mass spectrum and its moments in decays $B \rightarrow X_{u} l \nu$
- HQE-fit: Extraction of $|V_{cb}|$, $m_{b}$, $m_{c}$, $B(B \rightarrow X_{c} l \nu)$, and the leading non-perturbative HQE-parameters

SLAC-PUB-13036
Inclusive Semileptonic B Decays

- Study of semileptonic $B \rightarrow X_{c/u} l \nu$ decays offers laboratory for studying the $b$ quark in the $B$ meson
- Single hadronic current gives better control over theoretical uncertainties
- $\Gamma_{sl}$ described by Heavy Quark Expansion (HQE) in $1/m_b \alpha_s$
  - First non-pert. correction at $O(1/m_b^2)$
  - $\mu_{\pi}^2$: kinetic energy of the $b$-quark, $\mu_G^2$: chromomagnetic moment

$$\Gamma_{sl}(B \rightarrow X_{c/u} l \nu) = \frac{G_F^2 m_b^5}{192 \pi^3} |V_{xb}|^2 \left(1 + A_{ew}\right) A^{\text{pert}} A^{\text{nonpert}}$$

Non-perturbative effects and quark masses need to be measured for a reliable extractions of $|V_{cb}|$ and $|V_{ub}|$
Moments of Inclusive Distributions

- Measure moments of inclusive distributions over wide range of phase space to avoid problems with quark-hadron duality
  - Moments depend only on quark masses and same set of universal non-perturbative parameters

\[ \langle E_{l}^{n} \rangle = N_{\text{norm}} \int (E_{l} - \langle E_{l} \rangle)^{n} \left( \frac{d \Gamma_{c,u}}{d E_{l}} \right) d E_{l} \]

\[ \langle m_{X}^{n} \rangle = N_{\text{norm}} \int m_{X}^{n} \left( \frac{d \Gamma_{c,u}}{d m_{X}} \right) d m_{X} \]


- Combined fit: experimental determination of quark masses and non-perturbative parameters

- Determination of $|V_{ub}|$ needs precise measurement of $m_{b}$
  - $b \rightarrow c lv$: sensitive to $m_{b}-m_{c}$, high statistics measurement
  - $b \rightarrow u lv$: sensitive to $m_{b}$, experimentally challenging, large $b \rightarrow c lv$ background, same mode in which $|V_{ub}|$ is extracted
Moments of the \textit{Hadronic Mass} and the Combined Hadronic Mass-and-Energy Distributions in Decays $B \rightarrow X_{c} l \nu$
Analysis Strategy

- **Dataset**: 230 million decays $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- **On the “recoil”** of fully-reconstructed $B_{\text{reco}}$
  - flavor and four-momentum of recoiling $B_{\text{SL}}$ known
  - $m_{ES} = \sqrt{\frac{s}{4} - \vec{p}_B^2}$ used to subtract combinatorial background
- **Measure one recoiling lepton** with $p^*_l > 0.8 \text{GeV}$ in the $B_{\text{SL}}$ restframe
- **Remaining particles** form the inclusive hadronic $X_c$-system
- **Missing mass and energy** consistent with unmeasured neutrino
- **Improve resolution** with kinematic fit
Reconstructed Spectra

- **Background contributions:**
  - mis-reconstructed $B_{\text{reco}}$ -mesons (combinatorial background)
  - non-$B\bar{B}$ decays: $e^+e^- \rightarrow qq \rightarrow "B_{\text{reco}}" + \ell$
  - secondary decays: $B^{0,+} \rightarrow D^{(*)0,+}X \rightarrow Y l^+\nu$, $B^{0,+} \rightarrow J/\psi$, $\psi (2S) \rightarrow l^+l^-$, ...
  - semileptonic decays to charmless hadronic final states: $B \rightarrow X_u l \nu$
  - $B\bar{B}$ oscillations

- **19212 events**
  - **21% background**

- **12888 events**
  - **22% background**
Calibration Method

- Unmeasured/missing particles bias hadronic system: 5-16% effect for $<m_X>$
  - Linear correction functions for moments (applied event-by-event):
    \[
    \langle m_{X,\text{true}}^n \rangle \leftrightarrow \langle m_{X,\text{reco}}^n \rangle, \quad \langle n_{X,\text{true}}^n \rangle \leftrightarrow \langle n_{X,\text{reco}}^n \rangle
    \]
  - Determined and tested in simulation
- Measure moments $<m_X^n>$ and $<n_X^n>$ as function of minimum lepton momentum

\[n_X^2 = m_X^2 - 2\Lambda E_{XB} + \Lambda^2, \text{ with } \Lambda = 0.65 \text{ GeV}\]

[Gambino and Uraltsev, hep-ph/0401063]

- Systematic uncertainties:
  - Low dependence on simulation model
  - Main systematics: calibration method, photon selection efficiency, background subtraction

\begin{center}
\begin{tikzpicture}
\begin{axis}[
grid style={dashed, draw=gray!30},
axis line style={draw=black}
]
\addplot [only marks, mark=*, darkred, mark size=3pt] coordinates {
(0.2, 2)
(0.4, 4)
(0.6, 6)
(0.8, 8)
(1.0, 10)
(1.2, 12)
(1.4, 14)
(1.6, 16)
};
\addplot [only marks, mark=o, darkblue, mark size=3pt] coordinates {
(1.4, 2)
(1.6, 4)
(1.8, 6)
(2.0, 8)
(2.2, 10)
(2.4, 12)
(2.6, 14)
(2.8, 16)
};
\addplot [only marks, mark=*, darkgreen, mark size=3pt] coordinates {
(1.6, 2)
(1.8, 4)
(2.0, 6)
(2.2, 8)
(2.4, 10)
(2.6, 12)
(2.8, 14)
(3.0, 16)
};
\addplot [only marks, mark=*, darkblue, mark size=3pt] coordinates {
(2.0, 2)
(2.2, 4)
(2.4, 6)
(2.6, 8)
(2.8, 10)
(3.0, 12)
(3.2, 14)
(3.4, 16)
};
\end{axis}
\end{tikzpicture}
\end{center}

\begin{align*}
0.2 &\leq E_{\text{miss}} - c|\vec{p}_{\text{miss}}| < 0.5 \text{ GeV} \\
6 &\leq N_{X_c} \leq 7
\end{align*}
Measurement of the unfolded hadronic mass spectrum and its moments in decays $B \rightarrow X_u \nu$
Inclusive Semileptonic B Decays at BABAR

Mass Spectrum and Moments

- 383 million decays $\Upsilon (4S) \rightarrow B \bar{B}$
- Measured on the recoil of fully reconstructed B mesons
- Select lepton with $E_\ell > 1\text{GeV}$
- Large background $B \rightarrow X_c l \nu$
- Veto events with $K^\pm$, $K_S$, and partially reconstructed $D^{*\pm}$
- Unfold spectrum for detector acceptance, efficiency, and resolution

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1027 ± 176 signal events
Moments and Interpretation

• Calculated moments from unfolded spectrum:
  (highly correlated: $\rho_{12}=0.99$, $\rho_{23}=0.94$, $\rho_{13}=0.88$)
  
  \begin{align*}
  \langle m_X^2 \rangle &= (1.96 \pm 0.34\text{ (stat) } \pm 0.53\text{ (syst)}) \text{ GeV}^2 \\
  \langle (m_X^2)^2 - \langle m_X^2 \rangle^2 \rangle &= (1.92 \pm 0.59\text{ (stat) } \pm 0.87\text{ (syst)}) \text{ GeV}^4 \\
  \langle (m_X^2)^3 - \langle m_X^2 \rangle^3 \rangle &= (1.79 \pm 0.62\text{ (stat) } \pm 0.78\text{ (syst)}) \text{ GeV}^6 
  \end{align*}

• HQE-fit to these moments in the kinetic scheme:
  
  $m_b = (4.604 \pm 0.250) \text{ GeV}$
  $\mu_{\pi}^2 = (0.398 \pm 0.240) \text{ GeV}^2$

  [Gambino et al., JHEP 0509, 010 (2005)]

  [hep-ex/0707.2670;
  Phys. Rev. D69,111104;
  Phys. Rev. D72,052004;
  Phys. Rev. Lett. 97 171803]
HQE-fit: Extraction of $|V_{cb}|$, $m_b$, $m_c$, $B(B \to X_c \ell \nu )$, and the leading non-perturbative HQE-parameters.
Combined HQE-Fits to BABAR Measurements

• Two combined $\chi^2$-fits in the *kinetic* scheme:
  - Fit only subsets of measurements to reduce correlations
  - Uneven mass/mixed moments not used
    (reduced accuracy of the expansion)
  - 12 mass moments *or* 12 mixed moments measured in $B \rightarrow X_c \ell \nu$
  - 13 electron energy moments measured in $B \rightarrow X_c \ell \nu$
    [Phys. Rev. D69, 111104 (with updated background BFs)]
  - 9 photon-energy moments measured in $B \rightarrow X_s \gamma$

• 8 fit parameters:
  \[ |V_{cb}|, B(B \rightarrow X_c \ell \nu), m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3 \]

• Additional inputs:
  - B-meson lifetime: \( \tau_B = (1.585 \pm 0.007) \) ps
  - Constraints: \( \mu_G^2 = (0.35 \pm 0.07) \) GeV$^2$
    \( \rho_{LS}^3 = (-0.15 \pm 0.10) \) GeV$^3$
HQE Predictions (Mass Moments)


Moments highly correlated

\[ \chi^2 \text{ (ndf)} = 11 \text{ (28)} \]
HQE Predictions (Mixed Moments)

\[ \chi^2 (\text{ndf}) = 8 (28) \]

## Fit Results and Comparison

(kinetic scheme with $\mu=1$)

|                      | $|V_{cb}| \times 10^3$ | $m_b$ [GeV]     | $m_c$ [GeV]     | $\mu_{\pi}^2$ [GeV$^2$] |
|----------------------|------------------------|-----------------|-----------------|--------------------------|
| mass moments         | $42.05\pm0.83$         | $4.549\pm0.049$ | $1.077\pm0.074$ | $0.476\pm0.063$         |
| mixed moments        | $41.91\pm0.85$         | $4.566\pm0.053$ | $1.101\pm0.078$ | $0.452\pm0.069$         |
| $B\to X_u\, l\nu$ moments |                        |                  |                 |                          |
| HFAG (Winter 2009)*  | $41.54\pm0.73$         | $4.620\pm0.035$ | $1.190\pm0.052$ | $0.424\pm0.042$         |
| BELLE 2008 [Phys.Rev. D78,032016] | $41.58\pm0.90$ | $4.543\pm0.075$ | $1.055\pm0.118$ | $0.539\pm0.079$         |

(* combined result includes published moments $B\to X_c\, l\nu$ and $B\to X_s \gamma$ measured by BaBar, BELLE, CDF, CLEO, and DELPHI)

- Agreement with other measurements and combined HFAG results
- Good agreement of $B\to X_u\, l\nu$ and $B\to X_c \, l\nu$ results
  - $m_b$ and $\mu_{\pi}^2$ extracted in different decay modes compatible
- Good agreement of results of mixed and mass moments
  - Indicating that higher order corrections have been treated correctly for the calculation of the mass moments
Comparison of Fits

Good agreement of different fits

\begin{align*}
\mu^2_{\pi} [\text{GeV}^2] \\
|V_{cb}| \times 10^3
\end{align*}

- combined fit (mass moments)
- combined fit (mixed moments)
- semileptonic B-decays
- hadronic-mass moments
Summary

- Measurement of the first six moments of the hadronic mass spectrum in semileptonic B-meson decays $B \rightarrow X_c \ell \nu$
  - Good agreement with previous measurements
- First measurement of the mixed moments $<(n_X^2)^k>$, $k=1...3$

- Measurement of the unfolded mass spectrum and its moments in $B \rightarrow X_u \ell \nu$

- Extraction of $|V_{cb}|$, $m_b$ and $m_c$, semileptonic branching fraction $B(B\rightarrow X_c \ell \nu)$, and non-perturbative HQE-parameter in the kinetic scheme
  - In agreement with other measurements

$m_b = (4.604 \pm 0.250) \text{ GeV}$
$\mu_\pi^2 = (0.398 \pm 0.240) \text{ GeV}^2$

$|V_{cb}| = (42.05 \pm 0.85) \times 10^{-3}$
$m_b = (4.549 \pm 0.049) \text{ GeV}$
$m_b - m_c = (3.472 \pm 0.032) \text{ GeV}$
$B(B\rightarrow X_c \ell \nu) = (10.64 \pm 0.18)\%$
Verification with MC-Simulations of Exclusive Modes

- Calibration curves constructed using a mixture of different exclusive hadronic final states
- Calibration applied to different simulated exclusive signal decays reproduces true underlying moments

\[
\langle m_X, \text{calib} \rangle = \langle m_X, \text{true} \rangle
\]

\[
\langle m_X, \text{calib} \rangle \text{ reco} \rangle = \langle m_X, \text{true} \rangle
\]

\[
\langle n_X, \text{calib} \rangle = \langle n_X, \text{true} \rangle
\]

before
after calibration
HQE Fit Predictions (Mass Moments)

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EPS'09, Krakow, 17.07.2009
HQE Fit Predictions (Mass Moments)

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HQE Fit Predictions (Mixed Moments)

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EPS'09, Krakow, 17.07.2009
HQE Fit Predictions (Mixed Moments)
**HQE Fit Results**

- Fits in good agreement with each other and previous measurements

**Fit 1 (mass moments)**

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<td>Results</td>
<td>42.05</td>
<td>4.549</td>
<td>1.077</td>
<td>0.476</td>
<td>0.300</td>
<td>0.203</td>
<td>-0.144</td>
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<td>$\Delta_{exp}$</td>
<td>0.45</td>
<td>0.031</td>
<td>0.041</td>
<td>0.0165</td>
<td>0.021</td>
<td>0.044</td>
<td>0.017</td>
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<tr>
<td>$\Delta_{theo}$</td>
<td>0.37</td>
<td>0.038</td>
<td>0.062</td>
<td>0.063</td>
<td>0.059</td>
<td>0.038</td>
<td>0.027</td>
</tr>
<tr>
<td>$\Delta_{\Gamma_{SL}}$</td>
<td>0.59</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$\Delta_{tot}$</td>
<td>0.83</td>
<td>0.049</td>
<td>0.074</td>
<td>0.176</td>
<td>0.063</td>
<td>0.058</td>
<td>0.032</td>
</tr>
</tbody>
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1.4% theoretical uncertainty on the semileptonic rate

**Fit 2 (mixed hadronic moments)**

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<tbody>
<tr>
<td>Results</td>
<td>41.91</td>
<td>4.566</td>
<td>1.101</td>
<td>0.452</td>
<td>0.304</td>
<td>0.190</td>
<td>-0.156</td>
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<tr>
<td>$\Delta_{exp}$</td>
<td>0.48</td>
<td>0.034</td>
<td>0.045</td>
<td>0.166</td>
<td>0.023</td>
<td>0.047</td>
<td>0.013</td>
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<tr>
<td>$\Delta_{theo}$</td>
<td>0.38</td>
<td>0.041</td>
<td>0.064</td>
<td>0.061</td>
<td>0.065</td>
<td>0.039</td>
<td>0.031</td>
</tr>
<tr>
<td>$\Delta_{\Gamma_{SL}}$</td>
<td>0.59</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\Delta_{tot}$</td>
<td>0.85</td>
<td>0.053</td>
<td>0.078</td>
<td>0.176</td>
<td>0.069</td>
<td>0.061</td>
<td>0.034</td>
</tr>
</tbody>
</table>

2.0%  1.1%  6.5% (kinetic scheme with $\mu = 1$ GeV)