SEMILEPTONIC DECAYS AT LHCb

BRIAN HAMILTON
UNIVERSITY OF MARYLAND
(ON BEHALF OF THE LHCb COLLABORATION)

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The LHCb Detector

Single-arm spectrometer – 2 ≤ η ≤ 5

• Single arm spectrometer optimized for beauty and charm physics at large η:
  
  • Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  
  • Tracking: σ_p/p ~ 0.4%–0.6% (p from 5 GeV to 100 GeV), σ_IP < 20 μm
  
  • Vertexing: στ ~ 45 fs for B_s→J/ψφ
  
  • PID: 97% μ ID for 1-3% π→μ misID
  
  • Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

b$b$ production dominantly at lower p_T:
parton CM frame highly boosted

At 7 TeV:
σ_{inel} ~ 70 mb
σ_{c\bar{c}} ~ 6 mb
σ_{b\bar{b}} ~ 280 μb
Semileptonic Decays at LHCb

- Semileptonic decays are a nice target at LHCb
  - High trigger efficiency and large branching fractions
    - high statistics samples: flexibility to select only the best candidate events
  - Final state high IP, high $p_T$ muon means clean samples “out of the box” without sophisticated event selections
  - LHCb has access to all ground state b hadrons, including $B^0_s, \Lambda_b^0, B^+_c$

- Challenge: missing neutrino in final state means analyses are inclusive. No possibility to account for everything in the event (e.g. B-factory hadronic $B_{tag}$), and no way to be sure only a neutrino is missing
Multivariate Isolation Technique

- Hadron collisions produce $b\bar{b} + MPI + showering + (pileup) + \cdots$
- Instead of accounting for full event, make use of superb tracking system
  - Scan over every reconstructed track with loose preselection (including stubs in VELO) and compare against $b$ hadron vertex
    - Check for vertex quality with PV and SV, change in displacement of SV, $p_T$, angular alignment with candidate
    - BDT trained on simulated extra charged particles from simulated partially-reconstructed backgrounds (signal tracks for BDT) vs rest of event (background tracks for BDT)
- Technique can be used to select isolated signal sample as well as anti-isolated background-enriched control samples
$|V_{ub}|$
Testing the Standard Model with $V_{ub}$

- $V_{ub} + \sin(2\beta)$ together give powerful test of CKM unitarity
- Extraction of $|V_{ub}|$ from measurements of inclusive vs exclusive semileptonic decays have shown consistent and puzzling tension ($\sim 3\sigma$)
  - Gap can be explained with new right handed charged current interactions pulling SL decays to pseudoscalar and vector hadrons in different directions
- At LHCb: can probe $V_{ub}$ with high statistics via the $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$ decay
  - Proton+muon signature has small background from underlying event
  - Unique spin structure can further constrain RH currents

Bernlocker, Ligeti, Turczyk
Phys. Rev. D 90, 094003 (2014)
Measurement Procedure

- Ratio \( \frac{N(\Lambda_b^0 \rightarrow p\mu\nu)}{N(\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow pK\pi)\mu\nu)} \) is proportional to \( \frac{|V_{ub}|^2}{|V_{cb}|^2} \)

- Fit for both yields in high-\(q^2\) regions avoiding extrapolated region of lattice predictions

  \[ q^2 = \left( p_{\Lambda_b} - \frac{p_{\Lambda_c}}{p}\right)^2 = (p_\ell + p_{\nu})^2 \]

  - Knowledge of \(p_T^{\nu}\) allows reconstruction of \(\nu\) kinematics up to 2-fold ambiguity
    - \(p_T^{\nu} = \nu\) momentum transverse to \(\Lambda_b^0\) candidate

  - Require that both solutions be above \(q^2_{min}\)
    - Reduced efficiency in exchange for minimizing feed-up from low \(q^2\) region
Fit

- Fit variable is corrected mass = $\sqrt{m_{reco}^2 + (p_T^\gamma)^2 + |p_T^\gamma|}$
  - Peaks at $b$ hadron mass for single missing neutrino. Select only events for which resolution on corrected mass is small

- Normalization of partially-reconstructed backgrounds controlled by using isolation MVA to fully reconstruct key components
  - E.g. $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow pK_S^0)\mu\nu$ sets size of $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow p + neutral)\mu\nu$ in fit
- Combinatoric/misID templates from data
Results

- Result after correcting for all efficiencies is
  \[ |V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{lattice}) \pm 0.06(V_{cb})) \times 10^{-3} \]
  - Excellent agreement with PDG2014 $B \to \pi \ell \nu$ results: disfavors RH current solution
    - Recent lattice updates may pull the exclusive results upward
  - Dominant systematics are $B(\Lambda_c^+ \to p K^+ \pi^-)$ and trigger efficiencies
    - Possible avenues of improvement for future measurements
$\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$
Context: New Physics in tauonic B decays

- NP contributions to semileptonic B decays may still be large if coupled dominantly to 3rd generation (e.g. charged Higgs-like bosons)
  - Can constrain very large areas of parameter space independently of direct searches

- Quantity of interest is $R(D^{(*)}) \equiv \frac{B(B \rightarrow D^{(*)}\tau\nu)}{B(B \rightarrow D^{(*)}\mu, e\nu)}$
  - Theory: form factor uncertainties largely cancel in ratio
  - Experiment: accessible directly by reconstructing $D^{(*)}\mu X$ final state

- Previous measurements from BABAR show 2.0 and 2.7σ tension with Standard Model, other measurements also uniformly high
Technique at LHCb

- Using the known B flight direction, approximate the B momentum using $\gamma\beta_{z,\text{vis}} = \gamma\beta_{z,B}$:
  - Estimate gives ~ 18% resolution on B momentum, but preserves shapes of already-broad distributions of to $m_{\text{miss}}^2$, $E_\mu^*$ and $q^2$
  - 3d MC-template based binned fit to $m_{\text{miss}}^2$ vs $E_\mu^*$ in coarse $q^2$ bins
Backgrounds

- Backgrounds can be divided into three categories:
  - Semileptonic backgrounds to excited charm
    - Shapes constrained by $D^{*+}\pi^-\mu$ and $D^{*+}\pi^-\pi^+\mu$ control samples in data
    - Includes fixed $B \to D^{**}\tau\nu$ fraction
  - $B$ meson decay to $B \to D^{**}H_c(\to \mu\nu X)X$, where $H_c$ is any charm meson
    - Simulation cocktail with corrections taken from $D^{**}K^+\mu$ control sample in data
    - Includes $B \to D^{**}D_s(\to \tau\nu)X$
  - Other backgrounds
    - Includes combinatoric and misidentified muon components all estimated from and constrained by data

\[ \bar{B}^0 \to D_1^+ (2420) \mu^- \bar{\nu}_\mu \text{ vs } \bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau \]
\[ \bar{B}^0 \to D^{*\pm}H_c(\to \mu^\mp\nu X)X \text{ vs } \bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau \]
\[ \text{Misidentified } \mu \text{ background vs } \bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau \]
Fit Result

- Shown above: signal fit to “signal” data passing isolation selection
- Result \( \frac{N_T}{N_{\mu}} = (4.32 \pm 0.37) \times 10^{-2}, R(D^*) = 0.336 \pm 0.027 \pm 0.030 \)
- \( N(\bar{B}^0 \rightarrow D^{**}\mu^-\bar{\nu}_\mu) = 363,000 \pm 1600 \)
Result

- Full result: 
  \[ R(D^*) = 0.336 \pm 0.027 \pm 0.030 \]

- Excellent agreement with BaBar result
  - Precision lower despite 10 × selected \( D^{*+}\mu^-\bar{\nu}_\mu \): boils down to higher backgrounds

- 2.1\( \sigma \) from SM. Not significant alone, but tantalizing given history of high results in this channel

- Dominant sources of systematic uncertainty are template statistical uncertainties and unfolding involved in misidentified muon background
  - Clear path for improvement, other systematics will scale down with control sample statistics

### Diagram

- Belle 2010
  - 657\( \times \)10^6 BB
  - (Inclusive Tag)
- BaBar 2012 (Full)
  - 471\( \times \)10^6 BB
  - (Hadronic Tag)
- Belle 2015
  - 772\( \times \)10^6 BB
  - (Hadronic Tag)
- LHCb Run1 preliminary
  - 3.0 fb^-1
  - \( \tau \rightarrow \mu \bar{\nu}_\mu \)

( Presented at FPCP)
Summary

• LHCb Run 1 dataset continues to provide an opportunity to study semileptonic b hadron decays cleanly with very high statistics
  • Excellent detector performance and new ideas allow for study of more “traditional” semileptonic observables which were once the exclusive domain of the B-factories
  • Other interesting results not shown today: $B^0, B_s^0$ mixing parameters, $a_{sl}^s, a_{sl}^d$ CP asymmetries

• A new measurement of $|V_{ub}|$ using the unique $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decay has been made which puts constraints on any new physics explanation for the inclusive-exclusive tension in this parameter
  • Already systematically limited: improvement possible, but requires improved external inputs

• LHCb has produced a competitive measurement of the semitauonic decay rate to $\bar{B}^0 \to D^{*+}\tau\nu$ which is in good agreement with previous results, all above the rate predicted within the SM
  • $\bar{B}^0 \to D^{*+}\tau^- (\to \pi^+\pi^-\pi^+\nu_\tau)\bar{\nu}_\tau$ in progress
  • Clear path for near term improvement and combined $R(D)$ and $R(D^*)$ fit
  • Most systematics will scale down with control sample statistics: excellent Run 2 prospects
Backup
## Vub systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)$</td>
<td>+4.7</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2</td>
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<tr>
<td>Tracking</td>
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</tr>
<tr>
<td>$\Lambda_c^+$ selection efficiency</td>
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</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu$ shapes</td>
<td>2.3</td>
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<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5</td>
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<tr>
<td>Isolation</td>
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<tr>
<td>Form factor</td>
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<tr>
<td>$\Lambda_b^0$ kinematics</td>
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<tr>
<td>$q^2$ migration</td>
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<tr>
<td>PID</td>
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<tr>
<td><strong>Total</strong></td>
<td>+7.8</td>
</tr>
<tr>
<td></td>
<td>-8.2</td>
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</table>
Fit to $D^{*+}(\pi^-)\mu^-$ sample

- $B \to D^{**} \to D^{*+}\pi^-\mu^-\bar{\nu}_\mu$ form factors constrained by this sample

- Low $q^2$
  - $m^2_{miss}$
  - $E_\mu^*$

- High $q^2$
  - $m^2_{miss}$
  - $E_\mu^*$

![Graphs showing $m^2_{miss}$ and $E_\mu^*$ distributions for different $q^2$ regions]

- Data
- $B \to D^*\tau\nu$
- $B \to D^*H_c (\to l\nu X')X$
- $B \to D^{**}\nu$
- $B \to D^*\mu\nu$
- Combinatoric
- Misidentified $\mu$
Fit to $D^{*+}(\pi^+\pi^-)\mu^-$ sample

Low $q^2$

$\mathbf{m^2_{miss}}$  

$\mathbf{E^*_\mu}$

High $q^2$

$\mathbf{m^2_{miss}}$  

$\mathbf{E^*_\mu}$

- Correction to shape of $\bar{B} \to D^{**}(\to D^{*+}\pi\pi)\mu^- \bar{\nu}_\mu$ template determined from this fit
Fit to $D^{*+} K^{\pm} \mu^-$ sample

Low $q^2$

$m_{miss}^2$  $E_{\mu}^*$

High $q^2$

$m_{miss}^2$  $E_{\mu}^*$

- Correction to shape of $B \rightarrow D^{*+} H_c (\rightarrow \mu \nu X') X$
template determined from this fit
Table 1: Systematic uncertainties in the extraction of $R(D^*)$.

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Size ($\times 10^{-2}$)</th>
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</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
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<tr>
<td>Misidentified $\mu$ template shape</td>
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<tr>
<td>$D^*$ form factors</td>
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<tr>
<td>$B \rightarrow D^*DX$ shape</td>
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<tr>
<td>$B(B \rightarrow D^{<strong>}\tau\nu)/B(B \rightarrow D^{</strong>}\mu\nu)$</td>
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<td>$B \rightarrow [D^*\pi\pi]\mu\nu$ shape</td>
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<td>Corrections to simulation</td>
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<td>Combinatoric background shape</td>
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<tr>
<td>$D^{**}$ form factors</td>
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<td><strong>Total model uncertainty</strong></td>
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<table>
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<tr>
<th>Multiplicative uncertainties</th>
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<td>Simulated sample size</td>
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<td>Hardware trigger efficiency</td>
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<tr>
<td>Particle identification efficiencies</td>
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<td>Form-factors</td>
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<tr>
<td>$B(\tau \rightarrow \mu\nu$</td>
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<td><strong>Total multiplicative uncertainty</strong></td>
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<td><strong>Total systematic uncertainty</strong></td>
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