Charm semileptonic decays at LHCb

A prospects talk

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On behalf of the LHCb Collaboration

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In the most general form, the decay rate of the $D$ meson can be written as

$$
\frac{d\Gamma^{(\ell)}}{dq^2} = (\text{Constants}) \times |V_{q_i q_j}|^2 \times (\text{F’n of form factors}(q^2, m_\ell))
$$

Things we can do:

1. Assuming known form factor dependence, measure $|V_{q_i q_j}|$
2. Measure $B$ dependence on $q^2$, use known CKM elements to understand form factors
3. Something completely different

In any case, dependence on $q^2$ is a key ingredient
LHCb acceptance: $2 < \eta < 5$

Reconstructed 1.8 billion charm hadron decays in 2011-2016
LHCb acceptance: $2 < \eta < 5$

Reconstructed 1.8 billion charm hadron decays in 2011-2016

\[ \text{Candidates per 19 keV/c} \times 10^6 \]

\[ K^+ \pi^+ \text{ mass [MeV/c}^2] \]

Signal: 789 million
LHCb acceptance: $2 < \eta < 5$

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LHCb

- LHCb acceptance: $2 < \eta < 5$
- Reconstructed 1.8 billion charm hadron decays in 2011-2016

\[ \frac{\text{Candidates per 19 keV/c}^2}{\times 10^6} \]

\[ \text{K}^+ \pi^+ \text{ mass [MeV/c}^2] \]

RICH: $K/\pi$ Separation

VELO: 20 $\mu$m IP resolution

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Charm semileptonic decays at LHCb
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LHCb acceptance: \( 2 < \eta < 5 \)

- Reconstructed 1.8 billion charm hadron decays in 2011-2016

\[ \text{Candidates per 19 keV/c} \times 10^6 \]

**VELO:**
- 20 \( \mu \)m IP resolution

**Dipole Magnet:**
- Reversible Polarity

**RICH:**
- \( K/\pi \) Separation

**TT & T Stations:**
- \( \Delta p/p = 0.4\% - 0.6\% \)
  - for 5 – 100 GeV Tracks

**HCAL/ECAL:**
- \( e/\gamma \) separation, Hadron ID

**Muon Stations:**
- Detection of \( \mu^\pm \)

**LHCb Preliminary:**
- Run I+2015+2016 data
- \( \phi \rightarrow K^+ \pi^- \)
- Signal: 789 million

\[ K^+ \pi^+ \text{ mass [MeV/c}^2\text{]} \]

LHCb

- LHCb acceptance: $2 < \eta < 5$
- Reconstructed 1.8 billion charm hadron decays in 2011-2016
LHCb acceptance: $2 < \eta < 5$

Reconstructed 1.8 billion charm hadron decays in 2011-2016

### Diagram
- **RICH:** $K/\pi$ Separation
- **Dipole Magnet:** Reversible Polarity
- **HCAL/ECAL:** $e/\gamma$ separation, Hadron ID
- **Muon Stations:** Detection of $\mu^\pm$
- **TT & T Stations:** $\Delta p/p = 0.4\% - 0.6\%$ for 5 – 100 GeV Tracks
- **VELO:** 20 $\mu$m IP resolution

### Graph
- **Candidates per 19 keV/c²**
- **K$\pi^+$ mass [MeV/c$^2$]**

### Text

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Charm semileptonic decays at LHCb
The Trigger

- Selection of hardware and software triggers requires care
- Depending on the physics analysis, one may be more optimal than another
- Software trigger for charm has both exclusive selections, and inclusive based on MVA trainings
Neutrino Reconstruction

- Challenge: Only partially reconstructed final state
- For $e^+ e^-$ machines, use the other side of the event and beam energy to constrain neutrino momentum

Not possible at a hadron collider
Neutrino Reconstruction

- Use flight direction of the $D$ to constrain $p'_T$
- Leaves two-fold ambiguity for total neutrino momentum
- Relies on $D$ mass constraint
- Solutions can be imaginary due to detector effects
- Choosing a solution will bias $q^2$ distributions
- Many methods of dealing with this already exist:
  - $k$ factor: $p_{true} = p(K\ell)/k$
  - If only missing one massless particle, can use
    $$M_{corr} = \sqrt{m(K\ell)^2 + p_T^2 + p'_T}$$
- Using $D^{*+} \rightarrow D^0 \pi_s^+$ decays can break this two fold ambiguity by using $D^*$ mass constraint (Cone Closure)
Experimental Strategies

- Topology choices are key
  - Prompt $D^*$ decay is most similar to what has been previously used

**Prompt**

- Can use hadronic $B$ decay with SL $D$ decay

**Secondary**

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Charm semileptonic decays at LHCb
Experimental Challenges

- Lots of places to induce bias (trigger, $\nu$ reconstruction, selection)
- Fits will be templated
  - Production/detection efficiencies requires carefully chosen control channels
    $$N_{\text{measured}} = N_{\text{physics}} \times \epsilon_{\text{trigger}} \times \epsilon_{\text{reconstruction}} \times \epsilon_{\text{PID}} \times \epsilon_{\text{selection}}$$
- Some, but not all, of these can be measured in a data driven way
- $q^2$ resolution: Depends heavily on decay kinematics, final state, and statistics
- Muons are good, electrons are a bit more difficult
An example measurement

- Measure

\[
\frac{|V_{cs}|^2}{|V_{cd}|^2} \text{ using } \frac{\mathcal{B}(D \rightarrow K\mu\nu)}{\mathcal{B}(D \rightarrow \pi\mu\nu)}
\]

- Analogous to measurement of \(|V_{ub}|\) from \(\Lambda_b \rightarrow p\mu\nu\) (Nature Physics 10 (2015) 1038)

- Experimental advantages:
  - Use \(D^{*+} \rightarrow D^0 \pi^+_s \rightarrow \) gives access to \(\Delta m\) for background rejection, \(q^2\) constraint
  - \(\mu, \pi_s\) detection efficiencies cancel in ratio
  - \(K, \pi\) detection efficiencies known well from CP measurements
  - \(\mu\) easily detectable
  - Use \(M_{corr}\) to reduce multibody/neutral backgrounds

- The hard parts
  - Trigger on the inclusive \(D\) event \(\rightarrow\) possible biases vs \(q^2\) depending on data-taking conditions
  - MC statistics will be a limiting factor
  - \(f^K_+(q^2), f^\pi_+(q^2)\) knowledge will play a large role in the extraction
But I want some numbers

\[ B(D_0 \rightarrow K^– \mu^+ \nu) \]

From Run I CPV/mixing (PRL 111, 251801 (2013)), \( \sim 50M D_0 \rightarrow K^– \pi^+ \text{events} \)

Use inclusive \( D^* \) trigger, lose 60% of statistics (\( \sim 20M \) (2012 only, 2/3 of year))

Assuming remaining reconstruction, selection efficiencies are \( \sim 20\% \), end with \( \sim 4.4M \) signal candidates

This gives \( 5 \times 10^{-4} \) fractional uncertainty on \( B(D_0 \rightarrow K^– \mu^+ \nu) \)

\[ B(D_0 \rightarrow \pi^– \mu^+ \nu) / B(D_0 \rightarrow K^– 0^+ \nu) = 0.2\% \] relative uncertainty

On ratio 10 bins of \( q^2 \) still leaves about 0.5% relative uncertainty

Using values from CKM Fitter, \( q^2 \) integrated would be at the same level as world average
But I want some numbers

\[ B(D^0 \rightarrow K^- \mu^+ \nu) \simeq B(D^0 \rightarrow K^- \pi^+) \]
But I want some numbers

- $B(D^0 \to K^- \mu^+ \nu) \approx B(D^0 \to K^- \pi^+)$
- From Run I CPV/mixing ([PRL 111, 251801 (2013)]), \(\sim 50\)M $D^0 \to K^- \pi^+$ events
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But I want some numbers

- \( B(D^0 \rightarrow K^- \mu^+ \nu) \approx B(D^0 \rightarrow K^- \pi^+) \)
- From Run I CPV/mixing (PRL 111, 251801 (2013)), \( \sim 50 \text{M} \) \( D^0 \rightarrow K^- \pi^+ \) events
- Use inclusive \( D^* \) trigger, lose 60% of statistics (\( \sim 20 \text{M} \)) (2012 only, 2/3 of year)
- Assuming remaining reconstruction, selection efficiencies are \( \sim 20\% \), end with \( \sim 4.4 \text{M} \) signal candidates
- This gives \( 5 \times 10^{-4} \) fractional uncertainty on \( B(D \rightarrow K \mu \nu) \)

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But I want some numbers

- $B(D^0 \rightarrow K^−μ^+ν) \approx B(D^0 \rightarrow K^−π^+)$
- From Run I CPV/mixing\(^{\text{(PRL 111, 251801 (2013))}}\), ~50M $D^0 \rightarrow K^−π^+$ events
- Use inclusive $D^*$ trigger, lose 60% of statistics (~20M) (2012 only, 2/3 of year)
- Assuming remaining reconstruction, selection efficiencies are ~20%, end with ~4.4M signal candidates
- This gives $5 \times 10^{-4}$ fractional uncertainty on $B(D \rightarrow K_μν)$
- $B(D \rightarrow π_μν) \approx 1/15 B(D^0 \rightarrow K_μν) \rightarrow 0.2\%$ relative uncertainty on ratio
- 10 bins of $q^2$ still leaves about 0.5% relative uncertainty
- Using values from CKM Fitter, $q^2$ integrated would be at the same level as world average
How close did we come?

- Back of the envelope calculation gives $\sim 4.4M$ signal $D \rightarrow K\mu\nu$ candidates
- $a_s^{sl}(PRL \ 117, \ 061803 \ (2016))$, used $D^* \rightarrow D^0\pi_s$, $D^0 \rightarrow K\mu\nu$ to cross check detection efficiencies.
- Triggering on the $\mu$ at L0, and further on the $K$ candidate gives $\sim 5M$ signal candidates
- Todo: understand the $q^2$ resolution and biases therein
- Run II will only bring more statistics
### Other measurements we could think about

<table>
<thead>
<tr>
<th>D^0</th>
<th>D^0 → πµν</th>
<th>(B = 0.238 ± 0.024%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D^0 → Kµν</td>
<td>(B = 3.3 ± 0.13%)</td>
</tr>
<tr>
<td></td>
<td>D^0 → K^+(892)^- µν</td>
<td>(B = 1.92 ± 0.25%)</td>
</tr>
<tr>
<td>D^+</td>
<td>D^+ → Kπµν</td>
<td>(B = 3.9 ± 0.4%)</td>
</tr>
<tr>
<td></td>
<td>D^+ → K^0 µν</td>
<td>(B = 9.3 ± 0.7%)</td>
</tr>
<tr>
<td></td>
<td>D^+ → K^*0 µν</td>
<td>(B = 5.3 ± 0.15%)</td>
</tr>
<tr>
<td></td>
<td>D^+ → ηµν</td>
<td>(B =~ 1%)</td>
</tr>
<tr>
<td>D_s</td>
<td>D_s^+ → φµν</td>
<td>(B =~ 2%)</td>
</tr>
<tr>
<td></td>
<td>D_s^+ → K^0 µν</td>
<td>(B =~ 0.3%)</td>
</tr>
<tr>
<td></td>
<td>D_s^+ → η(′) µν</td>
<td>(B =~ 3%)</td>
</tr>
</tbody>
</table>

- Items in red are unlikely
- Considerations: need a control channel for each
- Resonant vs non-resonant will be challenging
- \( D_{(s)}^+ \) would be possible from \( B \) decay first
- \( η(′) \rightarrow π^+π^−γ \) is a possibility (see LHCb-PAPER-2016-041 (in prep.), presented at CHARM 2016)
- \( Λ_c ? \) lifetime \( \sim 0.5τ(D^0) \), final state neutrons are a no-go
And now for something completely different
Measurements of $B \rightarrow D^{*}\tau\nu$

- Why am I even showing you this?
LNU in $D \to h\ell\nu_\ell$  

- Make ratio of individual branching fractions in $D$ system from PDG
Expectations and Experimental Concerns

- Theoretically clean: form factors cancel to a large degree
- Expect $> 1M \, D \rightarrow K\ell\nu_\ell$ events in Run I
- Stat error: $< 0.1\%$, would reduce error on the ratio by an order of magnitude
- Systematic uncertainties are harder to project
- Efficiencies which do not cancel in the ratio are then $\epsilon_\mu/\epsilon_e$
- Bremsstrahlung recovery is difficult, but not impossible, e.g. $B \rightarrow K^* ee$, (JHEP04(2015)064) $D^0 \rightarrow e\mu$ (PLB 754 (2016) 167)
- Neutral background rejection: use $\Delta m, M_{corr}$
- Use cone closure to solve for $p(\nu)$
- Run II is already bringing more statistics
Conclusions

- LHCb is a charm factory just as much as a $b$ factory
- Muon ID gives a good foothold into CKM element measurements and form factor measurements
- Downsides: Neutrino reconstruction, MC statistics
- $q^2$ resolution and understanding of biases will always be key
- LNU measurements are a new field in charm. LHCb is pursuing this and we hope others will as well
- Take home point: We should measure
  - $\mathcal{B}(D^0 \rightarrow h\mu\nu)$, CKM elements, $q^2$ dependence
  - LNU in charm, using $K$, $\pi$ and $K^*$
The future

- 2016 $pp$ run has just finished
- LHCb has collected $\sim 1.67 \text{ fb}^{-1}$
- 2017 running to resume $pp$ collisions $\sim$May (fingers crossed)
- The fun is just beginning
Backup Slides
Cone Closure

\[ \mu, (\text{cone}) D, \nu_{(\text{cone})}, \pi, K \]

from Johns, FERMILAB-THESIS-1995-05, UMI-96-02371