Semileptonic b decays and asymmetries

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Outline

- Semileptonic asymmetries
- SL decays with muons
- LFU tests with SL decays
Semileptonic asymmetries

\[
\alpha_{\text{sl}} \equiv \frac{\Gamma(\overline{B} \to B \to f') - \Gamma(B \to \overline{B} \to f')}{\Gamma(\overline{B} \to B \to f') + \Gamma(B \to \overline{B} \to f')} \approx \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right)
\]

**SM predictions**\(^1,2\)

\[
\alpha_{\text{sl}}^s = (2.22 \pm 0.27) \times 10^{-5}
\]

\[
\alpha_{\text{sl}}^d = (-4.7 \pm 0.6) \times 10^{-4}
\]

1. Lenz & Nierste, JHEP 06 (2007) 072. 0612167
2. Artuso, Borissov & Lenz, RMP 88 (2016) no.4, 045002 1511.09466
Landscape without LHCb

Note that the D0 dimuon asymmetry really sits in a 3D space of $a_{s_{l}}^{s}$, $a_{s_{l}}^{d}$ and $\Delta \Gamma_{d}/\Gamma_{d}$.

10.1103/PhysRevD.87.074020, PRD 89, 012002 (2014) (U. Nierste pointed out (CKM 2014) that the $\Delta \Gamma_{d}$ correction was overestimated).
Complications

This observable requires flavour tagging:

\[ a_{s1} = \frac{\Gamma(\bar{B} \to B \to f) - \Gamma(B \to \bar{B} \to \bar{f})}{\Gamma(\bar{B} \to B \to f) + \Gamma(B \to \bar{B} \to \bar{f})} \]

Luckily we don’t actually need tagging:

\[ \frac{N(B, t) - N(\bar{B}, t)}{N(B, t) + N(\bar{B}, t)} = a_{s1} \cdot \left[ \frac{1 - \cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}} \right] \]
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Luckily we don’t actually need tagging:

\[
\frac{N(B, t) - N(\bar{B}, t)}{N(B, t) + N(\bar{B}, t)} = \frac{a_{s1}}{2} \cdot \left[ 1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}} \right]
\]

\[ = \frac{a_{s1}}{2} - \left[ a_P + \frac{a_{s1}}{2} \right] \cdot \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}} \]

Accounting for the production asymmetry.
Complications

Simulation of $B_d$ case

\[
\frac{N(B, t) - N(\bar{B}, t)}{N(B, t) + N(\bar{B}, t)} = \frac{a_{sl}}{2} - \left[ a_P + \frac{a_{sl}}{2} \right] \cdot \frac{\cos \frac{\Delta M t}{2}}{\cosh \frac{\Delta \Gamma t}{2}}
\]

Accounting for the production asymmetry.
A simplification

The fast $B_s$ oscillations permit a simple untagged time-integrated approach for $a_{s1}^s$.

$$\frac{\int N(B, t) - \int N(\bar{B}, t)}{\int N(B, t) + \int N(\bar{B}, t)} \approx \frac{a_{s1}}{2}$$

![Graph showing decay time vs. candidates per 0.1 ps with fit curves for tagged mixed, tagged unmixed, fit mixed, and fit unmixed data.](LHCb)
Detection asymmetries

Detector misalignments*

Nuclear interactions

\[
\frac{\sigma(K^-N)}{\sigma(K^+N)} \sim 1.3
\]

*The ability to reverse our magnet field is crucial in controlling the systematic uncertainties associated to this source.

LHCb-PUB-2014-006
The kaon asymmetry

Method using combination of CF charm decays:

Still the single largest source of uncertainty for $a_{sl}^d$. The specific limitation is our yield of $D^+ \rightarrow K_s\pi^+$ decays.

Completely new method in the pipeline for Run-II.
Backgrounds

Measurement of $a_{sl}^s$ based on $B_s \rightarrow D_s \mu \nu X$. 

Straightforward to count $D_s \rightarrow KK\pi$ decays...

However, many sources of $D_s \mu X$, e.g: DDX, $D_s KX$ etc…

<table>
<thead>
<tr>
<th>Background fraction</th>
<th>$(18 \pm 6)%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction to $a_{sl}^s$</td>
<td>$(-0.04 \pm 0.06) \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Corrected mass
Corrected mass

\[ M_{\text{corr}} = \sqrt{m_{\text{vis}}^2 + p_{\perp}^2 + p_{\perp}} \]
Corrected mass

Future analyses could fit this distribution to subtract these backgrounds directly…
The LHCb Run-I results

\[ a^{d}_{sl} = (-0.02 \pm 0.19 \pm 0.30)\% \quad a^{s}_{sl} = (0.39 \pm 0.26 \pm 0.20)\% \]

PRL 117, 061803 (2016)  
PRL 114, 041601 (2015)

For measurements with Run-II and beyond, it is possible that we can scale statistically without hitting any systematic limit if we develop more sophisticated treatment of the (i) backgrounds and (ii) detection asymmetries.
After LHCb Run-I

\[ A_{SL}(B^0_S) \]

\[ \Delta \chi^2 = 1 \]

LHCb \[ B^0_{(s)} \rightarrow D^{(*)}_{(s)} \mu X \]

Theory \times 10

World average

HFLAV

Summer 2017

B \rightarrow \mu X

D\(\phi\) muons

\[ \text{D\(\phi\) average} \]

B factory average

\[ \text{World average} \]

\[ \text{Theory \times 10} \]

\[ \Delta \chi^2 = 1 \]

\[ \text{LHCb} \]

\[ B^0_{(s)} \rightarrow D^{(*)}_{(s)} \mu X \]

\[ \text{D\(\phi\) average} \]

\[ \text{B factory average} \]

\[ \text{World average} \]

\[ \text{Theory \times 10} \]
The true b factory

While we can’t easily disentangle production and decay, we can measure decay rate ratios and/or shapes.
First exploitation

Measure the ratio

\[ \frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF} \]

Lattice inputs for $R_{FF}$, e.g. for the $V_{ub}$ mode:

Our favourite variable

\[
\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^−\bar{\nu}_\mu)_{q^2>15\text{ GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7\text{ GeV}^2/c^4}} = (1.00 \pm 0.04\text{(stat)} \pm 0.08\text{(syst)}) \times 10^{-2}
\]
Impact of $\Lambda_b$ analysis

\[
\left| \frac{V_{ub}}{V_{cb}} \right| = 0.083 \pm 0.004\text{(expt)} \pm 0.004\text{(lattice)}
\]

Precision already comparable with $B$ meson based exclusive determinations, and complementary parametric dependence on different operators, e.g. RH currents.
Exclusive $\Lambda_b \rightarrow \Lambda_c \mu \nu$ study

First ever with high precision!

Consistent with predictions of HQET, sum rules, and relativistic quark model.
$|V_{cb}|$ itself.. surely not?

A possible strategy is to measure the ratio:

$$\mathcal{R} = \frac{BF(\Lambda_b \to \Lambda_c \mu \nu)}{BF(\Lambda_b \to [\Lambda_c X, D^0 p X, ...] \mu \nu)}$$

Isn’t there a $|V_{cb}|$ in numerator and denominator?

Relate the denominator to the measured lifetimes of the $\Lambda_b$ and $B$, and the measured SL decay width of the $B$, and assume the equality of SL decay widths of all $b$ species. E.g., Bigi et al., 1105.4574
Other SL decays with muons

Great prospects for $|V_{ub}|/|V_{cb}|$ determination with $B_s \rightarrow (K/D_s)\mu\nu$

From: UKQCD/RBC PRD 91, 074510 (15)

More challenging than $\Lambda_b \rightarrow p\mu\nu$, but we’re working hard on it, so stay tuned.

Endless possibilities, e.g. $b \rightarrow \mu\mu\nu$, $b \rightarrow \phi\mu\nu$, $b \rightarrow l\nu KK X$, $b \rightarrow p\mu\nu$, various $B_c$ decays…, other $b$ baryons…
How differential?

For decays with a single missing particle, we get a quadratic equation for the $b$ momentum. Can we do better than a random choice of solutions?

Simple unbiased regression approach based only on flight information.

Once luminosity/statistics allows, we can roughly double the number of bins in $q^2$ for the same bin purity!
Tree-level LFU tests

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau \nu)}{\mathcal{B}(B \to D^{(*)}\mu \nu)} \]

**SM predictions**\(^1,2\)

\[ R(D) = 0.300 \pm 0.008 \]
\[ R(D^*) = 0.252 \pm 0.003 \]

**Experiment**

\[ R(D^*) \to 6\% \text{ precision} \]

[BaBar, Belle, LHCb] combined \([R(D), R(D^*)]\) is 4\(\sigma\) from the SM.

1. Fajfer, Kamenik, Nisandzic, PRD85 (12) 094025
2. Bigi, Gambino, PRD94 (16)
At LHCb

Leptonic
PRL 115, 111803 (2015)

Three-prong hadronic
1708.08856 (2017)

τ BF ~ 18%

τ BF ~ 10%
First ever analysis of this mode!

These signals are abundant, but they have soft signatures that are subject to huge backgrounds. Common strategies: kinematics, isolation, (and τ flight).
Muonic analysis

Fit in 4 coarse $q^2$ bins, $m^2_{\text{miss}}$, and $E_\mu$.

Here is the $m^2_{\text{miss}}$ projection in the highest purity $q^2$ bin:
Three-prong analysis

The signal

$\nu_\tau$ $\pi$ $\pi$ $\pi$ $\nu$

$B^0 \rightarrow \bar{b} q \bar{c} \ell \nu_\tau \pi \pi \pi \nu$

$D^{(*)}$
Three-prong analysis

The first background

B/S ~ 100
Three-prong analysis

$D^*3\pi X$ almost entirely eliminated by harsh requirement on $\tau$ flight signature.

The signal again
Three-prong analysis

“Charm carrier” mimics the $\tau$ flight, but B/S ~ 10 at this stage...

“Double charm”
Taming the double charm

First we must control the $D_s \rightarrow 3\pi X$ modelling...

![Graph showing LHCb data and various decay channels](image)
Then the $B \rightarrow D^* D_s X$ modelling..
Three-prong fit

3D fit in $q^2$, $\tau$ lifetime, and a MVA discriminant.
Three-prong fit

\[ \mathcal{R}(D^{*-}) = 0.285 \pm 0.019 \text{ (stat)} \pm 0.025 \text{ (syst)} \pm 0.013 \text{ (ext)} \]
Status and prospects

In the pipeline from LHCb: $R(D^*)$, $R(D^+,0)$, $R(D_s^{(*)})$, $R(\Lambda^{(*)}_c)$, $R(J/\psi)$, $R(pp)$, $R(p)$, etc…
Tree-level e-μ tests

From Greljo, Isidori, Marzocca 1506.01705

Charged currents. The \( b \rightarrow c(u)\tau\nu \) charged currents should exhibit a universal enhancement (independent of the hadronic final state). This implies, in particular, \( R_{B\tau\nu} = R_D^{\tau/\mu} = R_D^{\tau/\mu} \). LFU violations between \( b \rightarrow c(u)\mu\nu \) and \( b \rightarrow c(u)e\nu \) can be as large as \( O(1\%) \). The inclusive \( |V_{cb}| \) and \( |V_{ub}| \) determinations are enhanced over the exclusive ones because of the \( \tau \) contamination in the corresponding samples.

Belle\(^1\): \( R_{e\mu} = 0.995 \pm 0.022_{\text{stat}} \pm 0.039_{\text{syst}} \)

Proposed approach at LHCb:

\[
R_{e\mu} = \frac{B \rightarrow D^{(*)} e\nu}{D^0 \rightarrow K e\nu} / \frac{B \rightarrow D^{(*)} \mu\nu}{D^0 \rightarrow K \mu\nu}
\]

Tentative goal with Run-I data: \( \delta R_{e\mu} \approx \text{few} \times 10^{-3} \)

l.Belle, 1510.03657 (2015)
Conclusions

Many interesting and unique LHCb results with semileptonic decays, and plenty more to look forward to!
Backup slides start here...
# Three-prong R(D*) systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R(D^{<em>-})/R(D^{</em>-})[%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td>Signal decay model</td>
<td>1.8</td>
</tr>
<tr>
<td>$D^{<strong>}\tau\nu$ and $D^{</strong>}\tau\nu$ feeddowns</td>
<td>2.7</td>
</tr>
<tr>
<td>$D^{s+}_s \rightarrow 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$B \rightarrow D^{<em>-}D^{s+}_s X$, $B \rightarrow D^{</em>-}D^{+}X$, $B \rightarrow D^{*-}D^{0}X$ backgrounds</td>
<td>3.9</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.7</td>
</tr>
<tr>
<td>$B \rightarrow D^{*-}3\pi X$ background</td>
<td>2.8</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>3.9</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Idea is to reconstruct the decay without requiring a full “long” track for one \( D^0 \) child. The kinematics can be fixed if this track has a direction determination from the VELO. We can then probe the detection asymmetries for the remainder of the tracking system. Method also works with K3pi decays. The 2 body D mode required new dedicated HLT lines which were introduced for Run-II.