Rare B decays in the HL-LHC era

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on behalf of the LHCb, ATLAS and CMS collaborations

Heavy flavour in the HL-LHC era

31/08/16
Assumptions

• The beauty cross-section doubles at 14TeV c.f. run I.

• Trigger/selection performance identical unless detailed studies say otherwise (e.g. CMS $B_s \rightarrow \mu\mu$ note).

• CMS/ATLAS collect $3ab^{-1}$.

• LHCb either
  
  • collects $50fb^{-1}$ up until run 4
  
  • collects $300fb^{-1}$ until run 5 (under consideration).
Rare B decays

Sensitive to NP heavier than machine energy.

- As they are rare, less likely to hit systematic and/or theoretical uncertainties. Excellent opportunities with the HL-LHC.
- Many observables have very precise SM predictions.
$B(s) \rightarrow \mu\mu$

- Very rare decay:

$\mathcal{B}_{SM}(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$\mathcal{B}_{SM}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[PRl 112 (2014) 101801]
B(s)\rightarrow\mu\mu - projections

- Detailed study in CMS PAS FTR-14-015 for CMS

- Assuming fs/fd uncertainty 5%, B(B+-\rightarrow J/\psi K) 3%.

With 3ab-1: \sigma(B_s) = 11%
\sigma(B_d) = 18%
R_{s/d} = 21%

Yield comparison

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>LHCb (50fb-1)</th>
<th>LHCb (300fb-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(B_d)</td>
<td>271</td>
<td>40</td>
<td>240</td>
</tr>
<tr>
<td>N(B_s)</td>
<td>2250</td>
<td>400</td>
<td>2400</td>
</tr>
</tbody>
</table>

Limiting systematics

• For the $B_s$ mode, expect to be limited by systematic uncertainties.

• Most likely limiting one is $fs/fd$.

Correlated uncertainties between two LHCb methods (LHCb-CONF-2013-011)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(D^- \to K^+\pi^-\pi^-)$</td>
<td>2.2</td>
</tr>
<tr>
<td>$\mathcal{B}(D_s^- \to K^+K^-\pi^-)$</td>
<td>2.5</td>
</tr>
<tr>
<td>Lifetime ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Other uncertainties include SU(3) breaking (had) and SL branching fractions.

• BES III can help push these charm branching fractions down.
Other limiting systematics

• $B(B^+\rightarrow J/\psi K^+)$ uncertainty currently 4%.

• Ambiguities related to isospin asymmetry at $Y(4S)$ need to be resolved (see M. Jung, arXiv:1510.03423), and should be by Belle 2.

• Other systematics related to semileptonic backgrounds (e.g. $B\rightarrow \pi \mu \nu$) should reduce with updated lattice calculations.

• Mis-ID background should be always controlled with data, but need to keep good $h\rightarrow \mu$ rejection in HL-LHC era.
Theoretical uncertainty

- Theo uncertainty dominated by CKM matrix elements and B decay constants.

- Both expected to decrease with lattice improvements.

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<table>
<thead>
<tr>
<th>Source</th>
<th>$f_{B_q}$</th>
<th>CKM</th>
<th>$\tau^H$</th>
<th>$M_t$</th>
<th>$\alpha_s$</th>
<th>Other param.</th>
<th>Non-param.</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}_{s\ell}$</td>
<td>4.0%</td>
<td>4.3%</td>
<td>1.3%</td>
<td>1.6%</td>
<td>0.1%</td>
<td>&lt; 0.1%</td>
<td>1.5%</td>
<td>6.4%</td>
</tr>
<tr>
<td>$\bar{B}_{d\ell}$</td>
<td>4.5%</td>
<td>6.9%</td>
<td>0.5%</td>
<td>1.6%</td>
<td>0.1%</td>
<td>&lt; 0.1%</td>
<td>1.5%</td>
<td>8.5%</td>
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</table>

**TABLE II**: Relative uncertainties from various sources in $\bar{B}_{s\ell}$ and $\bar{B}_{d\ell}$. In the last column they are added in quadrature.

Don’t expect expt uncertainty to ever reach theoretical.
$B_s \rightarrow \mu \mu$ effective lifetime

- The branching fraction cannot differentiate between scalar (S) and pseudo-scalar (vector) (P) contributions.

- Fortunately, can probe these as the P amplitude results in a 20% longer lifetime than the S amplitude.


A lifetime 5% uncertainty is estimated with 50fb$^{-1}$ for LHCb, essential to have 300fb$^{-1}$ to get down to 2%.
$B_s \rightarrow \mu \mu$ time dependent CP asymmetry

- Reminder: In 300fb-1 scenario, get 2.4K $B_s \rightarrow \mu \mu$ candidates

- With 4% tagging power, corresponds to 100 perfectly tagged candidates for measuring the time dependent CP asymmetry, $S_{\mu \mu}$.

- Estimate of possible sensitivity found by comparing with measurement of $A_{KK}$ (JHEP 10 (2013) 183)

  - With 14K candidates, get $A_{KK}$ uncertainty of 0.12
  - Could expect uncertainty on $S_{\mu \mu}$ 0.3 with 300fb-1.

Many assumptions made here!
Moving to a semi-leptonic decay, more freedom - now sensitive to vector and electromagnetic operators.

Well-documented discrepancy in the vector coupling, C9.

Experimental uncertainties expected to be dominated by statistics for many years - most limiting systematics come from theory side.
B-$\to$K*-\(\mu\mu\) projections

- Assuming trigger/selection efficiency the same as run 1.

- Project number of B-$\to$K*-\(\mu\mu\) in 1<\(q^2\)<6 GeV region.

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 1-3(4)</th>
<th>Run 1-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>600</td>
<td>20,000</td>
<td>120,000*</td>
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<tr>
<td>CMS</td>
<td>300</td>
<td>10,000</td>
<td>100,000</td>
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</table>

- Looking forward to run 1 results from ATLAS

* Assuming LHCb gets 300fb$^{-1}$. 
**B→K*μμ and charmonium**

- Interference with charmonium resonances (dominated by B→J/psiK*) has impact on SM predictions.
- With more q^2 bins (more data), can differentiate between charm and NP.
- Can also measure phase of charmonium contribution directly.
- Constraints on C_{10} not affected by this.
- We need K*mm to break degeneracy in B_s→μμ
  \[ B(B_s→μμ) \propto (C_{10} - C_{10}')^2 \]

Plot from K. Petridis’ talk [here].
Form factors

- Improvements to form factors are essential for reducing theoretical uncertainties to experimental ones in HL-LHC era.

- Here we can profit from advances in the lattice community.

- Here $\pi\pi$ scattering shows potential for $B \rightarrow K\pi$ form factors - could be available by HL-LHC timescale.

Other observables

- Easy to forget that there many $B \to K^* \mu \mu$ observables which are very theoretically clean.

\[ A_9 \]

\[ q^2 \text{ [GeV]} \]

\[ C_\text{NP} = -1.2 + 1.0i \]

\[ C_9 = 1.0 - 1.0i \]

\[ C_\text{NP} = -0.1 + 0.1i \]

\[ C_9 = -0.1 - 0.1i \]

\[ C_\text{NP} = 2 \pm 2i \]

\[ C_9 = 0.5 \pm 1i \]

\[ 0 \]

\[ 0.5 \]

\[ 0 \]

\[ 0.5 \]

\[ LHCb \]

\[ JHEP 02 (2016) 104 \]

\[ q^2 \text{ [GeV}^2/c^4]\]

\[ 0 \]

\[ 5 \]

\[ 10 \]

\[ 15 \]

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\[ 10 \]

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B—>K*ee

- The decay B—>K*ee gives the most constraints on the imaginary (RH) part of the Wilson Coefficient, C₇

With 3fb-1, LHCb’s K*ee is already most constraining on RH plot.
Belle 2 will have 50 times more data - with 300fb-1, LHCb would have 200 times more.
- Going to 300fb-1 would significantly improve constraints if can keep electron reconstruction/trigger efficiency.

A. Paul, D Straub, arXiv:1608.02556
LFU tests

LFU tests also very sensitive to NP.

R(X) stat uncertainties (my own projections based on muon BF uncertainties)

<table>
<thead>
<tr>
<th>Decay</th>
<th>Run 1</th>
<th>Run 2</th>
<th>50 fb⁻¹</th>
<th>300 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+\mu^+\mu^-$</td>
<td>11%</td>
<td>5%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0\mu^+\mu^-$</td>
<td>18%</td>
<td>8%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi\mu^+\mu^-$</td>
<td>36%</td>
<td>15%</td>
<td>8%</td>
<td>3%</td>
</tr>
</tbody>
</table>

- Will be mostly systematics limited by 50fb⁻¹.
- If $R_K$ discrepancy holds up, will want to test with b—>d transitions.
- Will need lots of data for this.
LFV searches

Signals for $B \rightarrow K \ell'^\mp$ implied if we see non-LFU.

<table>
<thead>
<tr>
<th>Exp:</th>
<th>$B^+ \rightarrow K^+ \mu^\pm \tau^\mp$</th>
<th>$B^+ \rightarrow K^+ e^\pm \tau^\mp$</th>
<th>$B^+ \rightarrow K^+ e^\pm \mu^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.14 \times 10^{-8}$</td>
<td>$3.84 \times 10^{-10}$</td>
<td>$0.52 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$&lt; 4.8 \times 10^{-5}$</td>
<td>$&lt; 3.0 \times 10^{-5}$</td>
<td>$&lt; 9.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exp:</th>
<th>$B_s \rightarrow \mu^\pm \tau^\mp$</th>
<th>$B_s \rightarrow e^\pm \tau^\mp$</th>
<th>$B_s \rightarrow e^\pm \mu^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.37 \times 10^{-8}$</td>
<td>$4.57 \times 10^{-10}$</td>
<td>$1.73 \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>$&lt; 1.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Taken from D. Guadagnoli’s [talk], based on Phys. Rev. Lett. 114, 091801 (2015)

- No public expt numbers available yet, but with 50 (300) fb-1 could expect to reach interesting regions.
Summary

• Many rare B decay observables will be interesting even with a factor 10 smaller uncertainties.

• HL-LHC period will significantly improve key observables such as.
  • Bs->µµ BF, lifetime and CP observable, Bd/Bs ratio.
  • Observables in K*µµ/ee.
  • Deeper probes in LFV decays.
  • Extend reach in phase-space for exotics.
Direct searches

- B decays excellent places to probe dark sector.
- Large top mass enhances coupling to models which mix with the Higgs boson.

Search in the dimuon mass distribution of $B \rightarrow K^* \mu \mu$ decays with 3fb-1 ruled out large parameter space for several hidden sector models.

Dark photon searches.


Important feature is ability to trigger on soft dimuons.

Mis-ID a key background.

Expect limits to get better by factor 5 with 300fb-1 for LHCb and a factor 3 for ATLAS/CMS with 3ab-1.
Majorana neutrinos

- Majorana neutrinos can be produced in rare B decays, such as $B^+ \rightarrow \pi^- \mu^+ \mu^+$

LHCb result (see Phys. Rev. Lett. 112, 131802) based on 3fb-1.

Limit dependent on model assumptions (see arXiv:1607.04258).

Could drastically improve limit with 300fb-1, and a more inclusive approach similar to what is proposed for the dark photon.

- Expected 40 $B_s$ signal and 4 $B^0$ with 3fb-1.
- Assuming 30% of signal has good B/S (similar to CMS projections).
  - Get 400 $B_s$ signal and 40 $B^0$ with 50fb-1 in this B/S region.
- If LHCb collects 300fb-1, expect 2.4K $B_s$ and 240 $B^0$.
  - Will vastly improve MFV ratio uncertainty in 300fb-1 scenario.
Rare B decays

Indirect - sensitive to NP heavier than machine energy.

Direct - sensitive to very weak couplings.

- As they are rare, less likely to hit systematic and/or theoretical uncertainties. Excellent opportunities with the HL-LHC.

- Many observables have very precise SM predictions.