Rare decays in $b$ hadrons

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13.3.2016
Indirect searches for New Physics

• High energy:
  “real” new particles can be produced and discovered via their decays
  – Discovery of the Higgs boson at the LHC → completion of the SM
  – Tested scale: <10\,\text{TeV}

• High precision:
  “virtual” new particles can be seen in quantum loops
  – Higher mass scale reachable (up to \sim 100\,\text{TeV})

Direct and indirect searches are both needed, both equally important, and complement each other
Searches for New Physics in $b \rightarrow s \ell^+\ell^-$

Rare B decays:

- SM: Flavour changing neutral currents only at loop-level
- $b \rightarrow s \ell^+\ell^-$ give a unique glimpse to higher scales: experimentally and theoretically clean
b → s ℓ+ℓ− as test bench for high scales

- b → s ℓ+ℓ− decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory, allows to extract potential New Physics amplitudes

\[
H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right]
\]

- Menu for this talk:
  - Purely leptonic decays: \( B_s \rightarrow \mu^+\mu^- \)
    \( \rightarrow \) sensitive to \( C_{S,P} \) and \( C_{10} \)
  - Recent measurements of \( b \rightarrow s \ell^+\ell^- \), dominantly \( B^0 \rightarrow K^* \mu^+\mu^- \)
    \( \rightarrow \) sensitive to \( C_{7,9} \) and \( C_{10} \)
  - Lepton flavour universality
    \( \rightarrow \) sensitive to \( C^e \) vs \( C^\mu \)
First observation of $B_s \rightarrow \mu^+\mu^-$

$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$

SM: $3.66 \pm 0.23 \times 10^{-9}$

6.2σ significance $\rightarrow$ first observation
- compatible with SM at 1.2σ

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$

SM: $1.06 \pm 0.09 \times 10^{-10}$

3.0σ significance $\rightarrow$ first evidence
- compatible with SM at 2.2σ

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \bigg|_P = \frac{9}{32\pi} \left[ \frac{3}{4} \left( 1 - F_L \right) \sin^2 \theta_K + F_L \cos^2 \theta_K + \right. \\
\left. + \frac{1}{4} \left( 1 - F_L \right) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_8 \sin 2\theta_K \sin \theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]

Observables depend on $B \rightarrow K^*$ form factors and on short distance physics.

fraction of longitudinal polarisation of the $K^*$

forward-backward asymmetry of the dilepton system
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- LHCb published the first full angular analysis of the decay
  - Unbinned maximum likelihood fit to $K\pi\mu\mu$ mass and three decay angles
  - Simultaneously fit $K\pi$ mass to constrain s-wave configuration
  - Efficiency modelled in four dimensions
  - Binned in $q^2 = m_{\mu\mu}^2$

Example fit projections in low $q^2$ bin

Results

- Full angular fit allows to extract:
  - CP-averaged terms and their correlations
  - CP asymmetries

- Standard Model predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
Results

- New results for $A_{FB}$ and $F_L$ last year from LHCb [JHEP 02 (2016) 104], CMS [PLB 753 (2016) 424] and BaBar [arXiv:1508.07960].

References:
LHCb [JHEP 02 (2016) 104],
CMS [PLB 753 (2016) 424],
BaBar [arXiv:1508.07960],
CDF [PRL 108 (2012) 081807],
Belle [PRL 103 (2009) 171801].
Results


• SM predictions based on [Altmannshofer & Straub, arXiv:1411.3161]!

References:
Results

- Determine zero crossing points by parameterizing the angular distribution with $q^2$ dependent decay amplitudes

$$q_0^2(S_5) \in [2.49, 3.95] \text{ GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$

$$q_0^2(A_{FB}) \in [3.40, 4.87] \text{ GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$

$$q_0^2(S_4) < 2.65 \text{ GeV}^2/c^4 \text{ at } 95\% \text{ C.L.}$$

SM: $q_0^2(A_{FB}) \sim 3.9-4.4 \text{ GeV}^2/c^4$

Form-factor “free” observables

• In QCD factorization/SCET there are only two form factors
  – One associated with $A_0$ and the other with $A_{||}$ and $A_{\perp}$

• Create ratios of observables with minimal dependence on
  form-factors, eg

\[ P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}} \]

• 2013: deviation in $P'_5$ seen with 1fb$^{-1}$ of data

• Full Run 1 analysis confirms effect

• If the observed anomalies are real, expect discrepancies in
  other $b \rightarrow s$ decays ..
### Branching fractions of $b \rightarrow s \mu^+\mu^-$

- **Analysis of large class of $b \rightarrow s \mu^+\mu^-$ decays**
  - Several tensions seen, but individual significance is moderate
  - Perform global analysis

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**Table 3**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Measurement</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+\mu^-$</td>
<td></td>
<td></td>
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<tr>
<td>$B_s \rightarrow \phi \mu^+\mu^-$</td>
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</tr>
</tbody>
</table>

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**SM predictions based on**

- [Altmannshofer & Straub, arXiv:1411.3161]
- [Lattice prediction from Horgan et al. arXiv:1310.3722]
Combine all $b \rightarrow s$ data in global fit

Effective Hamiltonian:

$$H = \sum_i \left( C_i^{SM} + C_i^{NP} \right) O_i$$

- Global fit to all $b \rightarrow s$ data prefers a deviation from the Standard Model in a vector-like interaction

Branching fractions

Angular variables

Altmannshofer & Straub, 1503.06199
Combine all $b \rightarrow s$ data in global fit

Effective Hamiltonian:

$$H = \sum_i \left( C_{i}^{SM} + C_{i}^{NP} \right) O_i$$

- Global fit to all $b \rightarrow s$ data prefers a deviation from the Standard Model in a vector-like interaction
- Interpretation:
  - “clearly New Physics”, or ..
  - Not well understood QCD contribution

$\Rightarrow$ Understanding needs more data and theoretical work
Lepton universality

- In the SM, leptons couple universal to $W^\pm$ and $Z^0$ → test this in ratios of semileptonic decays

\[ R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} \]

\[ R_{D^*} = \frac{BR(B^0 \rightarrow D^{*+} \tau^- \bar{\nu})}{BR(B^0 \rightarrow D^{*+} \mu^- \bar{\nu})} \]

- Ratios differ from unity only by phase space → hadronic uncertainties cancel in the ratio
LFU: electron vs. muon ($R_k$)

LHCb measures with 3fb$^{-1}$

$$R_k = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} = 0.745 \pm 0.074$$

(SM: $R_k = 1.00$, consistent at 2.6σ)

![Graph showing $R_k$ vs. $q^2$]
\[ R(D^*) = \frac{BR(B^0 \rightarrow D^{*+} \tau^- \nu)}{BR(B^0 \rightarrow D^{*+} \mu^- \nu)} \]

**Belle**

\[ R(D) = 0.375 \pm 0.064 \pm 0.026 \]
\[ R(D^*) = 0.293 \pm 0.038 \pm 0.015 \]

**LHCb**

\[ R(D^*) = 0.336 \pm 0.027 \pm 0.030 \]

PRL 115(2015)111803

- Combination is 3.9\(\sigma\) from the SM expectation:
  \[ R(D^*) = 0.252 \pm 0.003 \]

The Standard Model is tested in a variety of channels
- many measurements consistent with predictions
- significant deviations in of $b \rightarrow s \ell^+\ell^-$ channels
- need for data to conclude

Interesting flavour data coming soon
- LHCb Run 2 → tripling the dataset
- LHCb Upgrade – record data with „Trigger-less Readout“
## List of papers (Total of 303 papers)

<table>
<thead>
<tr>
<th>TITLE</th>
<th>DOCUMENT NUMBER</th>
<th>JOURNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of the $B_0^0 \rightarrow D_3^{(<em>)}+D_3^{(</em>)}-$ branching fractions</td>
<td>PAPER-2015-053</td>
<td>PRD</td>
</tr>
<tr>
<td>A new algorithm for identifying the flavour of $B^0_{s}$ mesons at LHCb</td>
<td>PAPER-2015-056</td>
<td>JINST</td>
</tr>
<tr>
<td>First observation of $D^{0} - \bar{D}^{0}$ oscillations in $D^{0} \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{-}$ decays and measurement of the associated coherence parameters</td>
<td>PAPER-2015-057</td>
<td>PRL</td>
</tr>
<tr>
<td>Constraints on the unitarity triangle angle $\gamma$ from Dalitz plot analysis of $B^{0} \rightarrow D K^{+}\pi^{-}$ decays</td>
<td>PAPER-2015-059</td>
<td>PRL</td>
</tr>
<tr>
<td>Measurement of the difference of time-integrated CP asymmetries in $D^{0} \rightarrow K^{-}K^{+}$ and $D^{0} \rightarrow \pi^{-}\pi^{+}$ decays</td>
<td>PAPER-2015-055</td>
<td>PRL</td>
</tr>
<tr>
<td>Study of $\psi(2S)$ production and cold nuclear matter effects in $pPb$ collisions at $\sqrt{s_{NN}} = 5$ TeV</td>
<td>PAPER-2015-058</td>
<td>JHEP</td>
</tr>
<tr>
<td>Observation of the $B_{s}^{0} \rightarrow J/\psi\phi\phi$ decay</td>
<td>PAPER-2015-033</td>
<td>JHEP</td>
</tr>
</tbody>
</table>
• Can also determine the angular observables using principal moments of the angular distribution:
  ✓ Robust estimator even for small datasets (allows us to bin more finely in \(q^2\)).
  ✗ Statistically less precise than the result of the maximum likelihood fit.

• SM predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
## LHCb Upgrade Projections

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb (5 fb(^{-1}))</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluonic penguin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S(B_s \to \phi\phi))</td>
<td>-</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>(S(B_s \to K^{*0}\bar{K}^{*0}))</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>(S(B^0 \to \phi K_S^0))</td>
<td>0.17</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>(B_s) mixing</td>
<td>(2\beta_s (B_s \to J/\psi\phi))</td>
<td>0.35</td>
<td>0.019</td>
<td>0.006</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S(B_s \to \phi\gamma))</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>(\Delta\Gamma_s (B_s \to \phi\gamma))</td>
<td>-</td>
<td>0.14</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>E/W penguin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A^{(2)}_T(B^0 \to K^{*0}\mu^+\mu^-))</td>
<td>-</td>
<td>0.14</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>(s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-))</td>
<td>-</td>
<td>4%</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B(B_s \to \mu^+\mu^-))</td>
<td>-</td>
<td>30%</td>
<td>8%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>(A_{FB}(B^0 \to \mu^+\mu^-))</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(\sim 35%)</td>
</tr>
<tr>
<td>(A_{FB}(B_s \to \mu^+\mu^-))</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma (B \to D^{(<em>)}\bar{D}^{(</em>)}))</td>
<td>(\sim 20^\circ)</td>
<td>(\sim 4^\circ)</td>
<td>0.9%</td>
<td>negligible</td>
</tr>
<tr>
<td>(\gamma (B_s \to D_s\bar{K}))</td>
<td>-</td>
<td>(\sim 7^\circ)</td>
<td>1.5%</td>
<td>negligible</td>
</tr>
<tr>
<td>(\beta (B^0 \to J/\psi K^0))</td>
<td>1%</td>
<td>0.5%</td>
<td>0.2%</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CPV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A_T)</td>
<td>(2.5 \times 10^{-3})</td>
<td>(2 \times 10^{-4})</td>
<td>(4 \times 10^{-5})</td>
<td></td>
</tr>
<tr>
<td>(A_{CP}(K\bar{K}) - A_{CP}(\pi\pi))</td>
<td>(4.3 \times 10^{-3})</td>
<td>(4 \times 10^{-4})</td>
<td>(8 \times 10^{-5})</td>
<td>-</td>
</tr>
</tbody>
</table>
**Experimental overview of** $b \rightarrow s \ (d) \ \ell^+\ell^-$

- FCNC decays $b \rightarrow s \ (d) \ \ell^+\ell^-$: large variety of final states
  - Allows detailed test of the structure of the underlying interaction
  - Effects in one decay can be cross checked in others

### # of events | BaBar 433fb^{-1} | Belle 605fb^{-1} | CDF 9.6fb^{-1} | LHCb 1 / 3 fb^{-1} | ATLAS 5fb^{-1} | CMS 5fb^{-1}
---|---|---|---|---|---|---
$B^0 \rightarrow K^*0 \ \ell^+\ell^-$ | 137±44* | 247±54* | 288±20 | 2361±56 | 466±34 | 415±29
$B^+ \rightarrow K^{*+} \ \ell^+\ell^-$ | | | 24±6 | 162±16 | | |
$B^+ \rightarrow K^+ \ \ell^+\ell^-$ | 153±41* | 162±38* | 319±23 | 4746±81 | | |
$B^0 \rightarrow K^0_s \ \ell^+\ell^-$ | | | 32±8 | 176±17 | | |
$B_s \rightarrow \phi \ \ell^+\ell^-$ | | | 62±9 | 174±15 | | |
$\Lambda_b \rightarrow \Lambda \ \ell^+\ell^-$ | | | 51±7 | 78±12 | | |
$B^+ \rightarrow \pi^+ \ \ell^+\ell^-$ | | | limit | | 25±7 | |

*B*mixture of $B^0$ and $B^\pm$ and $\ell = e, \mu$ only

other experiments: $\ell = \mu$ only

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Babar arXiv:1204.3933
Belle arXiv:0904.0770
ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]
LHCb arxiv:1403.8044 +1305.2168 +1306.2577 +JHEP12(2012)125
Complementarity LHCb – Belle 2

• B_s System
  CPV in J/ψφ, φφ,
  CPV in Mixing
• B → μμ
• CKM phase γ in B→DK
• CPV in B_d
• B→X_s ll (exclusive)
• B→X_γ (exclusive)
• Charm physics
• Semi-leptonic B decays
• τ - physics: LFV
  B→D, D* τν
• B→X_s ll (inclusive)
• B→X_γ (inclusive)
• B→τν, μν
• B→K*νν, B→ νν

“B_s & charged tracks”

Important cross checks

“inclusive & neutrals ”
The LHCb experiment

VErtex LOcator
\( \sigma_{IP} \sim 20 \, \mu m \)
for high-\( p_T \) tracks

RICH detectors
\( \varepsilon(K \rightarrow K) \sim 95 \% \)
for 5 % \( \pi \rightarrow K \) mis-id

Muon system
\( \varepsilon(\mu \rightarrow \mu) \sim 97 \% \)
for 1-3 % \( \mu \rightarrow \pi \) mis-id

Tracking system
\( \Delta p/p = 0.4 \% @ 5 \, \text{GeV}/c \) to
\( 0.6 \% @ 100 \, \text{GeV}/c \)

Calorimeters
ECAL: \( \frac{\sigma_E}{E} \sim 1 \% \otimes 10 \% / \sqrt{E} \, (\text{GeV}) \)

[JINST 3 (2008) S08005]