Search for New Physics in Heavy Quark Decays at LHCb

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On behalf of the LHCb collaboration
Outline

• Introduction to indirect searches for New Physics.
• LHCb and first recorded $B$ decays.
• Performance and outlook to key measurements from present run.
  • Mixing-induced CP violation in $B_s \rightarrow J/\psi \phi$.
  • Search for $B_s \rightarrow \mu^+\mu^-$
  • Asymmetries in $B_d \rightarrow \mu^+\mu^-K^*$ decays.
  • CKM angle $\gamma$ from tree-level $B$ decays.
• Charm Physics

Other LHCb talks:
Sebastian Bachmann: *LHCb status and minimum bias physics*
Matthew Charles: *Studies of open charm and charmonium production at LHCb*
**Indirect measurements of New Physics**

- New particles can appear as *virtual* particles in loop and penguin diagrams.
- Indirect searches can have a *higher sensitivity* to effects from new particles.
  - See NP effects before the direct searches.
  - Indirect measurements can access higher scales.
- Good chance to see NP appear first in loop or penguin diagrams
- Possible to measure the phases of the new couplings
  - Gives access to the flavour structure of NP.

→ Complementary to direct searches.
Two approaches for NP searches in heavy flavour decays

1. Transitions involving flavour-changing, neutral currents (FCNC).
   - Forbidden at tree level in SM: can be easily modified by New Physics.
     - Especially in $b \rightarrow s$ transitions (not so much constrained by current data).
   - Some NP models predict large deviations in FCNC transitions.
     - Add new long-distance operators.
     - Modify short-distance to Wilson coefficients.
   - Exploring rare $B$ and $D$ decays. For instance:
     - Branching ratio of $B_s \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow \mu^+\mu^-$. 
     - Helicity structure of $B_d \rightarrow \mu^+\mu^-K^-$ decays.
Two approaches for NP searches in heavy flavour decays

2. Metrology of the CKM matrix
   • Improve precision on current constraints
     • Current measurements consistent, but still open to $O(10-20\%)$ corrections.
   • Compare measurements which may or may not have NP contributions.
     • Explore CKM matrix in many different ways and search for inconsistencies.
   • Unitarity triangle not so much constrained from tree decays.
     • Tree decays not affected by New Physics.
     • E.g., a NP free measurement of $\gamma$ to nail down SM & gain sensitivity to NP.
LHCb made for Heavy Flavour physics

- Good vertex resolution
  - Time-dependent measurements.
  - Suppress background from prompt decays.
- Good particle identification
  - Important for trigger, flavour tagging
  - Suppress background.
- Good momentum resolution
  - Mass resolution of heavy flavours.
  - Suppress background.

LHCb can reach its design luminosity very early.

→ See talk of Sebastian Bachmann for a nice overview of LHCb.
Integrated luminosity

Recorded now: 0.014 pb$^{-1}$
Expected this year: 200 pb$^{-1}$
Expected end of 2010-11 run: 1000 pb$^{-1}$ (1 fb$^{-1}$)
First signs of $B$ hadrons

(Pseudo-) lifetime $J/\psi \rightarrow \mu^+ \mu^-$

Fingerprints from long-lived $B$ decays

Impact parameter $D^0 \rightarrow K\pi$

LHCb Preliminary
$\sqrt{s} = 7$ TeV Data

MC shape from $B \rightarrow D$ component

See talks from M. Charles and S. Bachmann.
First exclusive $B$ candidate

$B^+ \rightarrow J/\psi K^+$ candidate with good secondary vertex, clearly displaced from primary vertex.
• Measures $B_s$ mixing phase through $b \to c \overline{c}s$ decay
  • Mixing phase: $\varphi_s^{\text{SM}} = -2\beta_s$
  • Small penguin pollution.
  • $B_s$ counterpart of $B_d \to J/\psi K^0$.
• Mixing phase small in SM: $2\beta_s = 0.036 \pm 0.002$
  • New particles in box diagrams can modify measured phase $\varphi_s = \varphi_s^{\text{SM}} + \varphi_s^{\text{NP}}$

Experimental challenges:
• Requires flavour tagging:
  • Mistag rate: $\omega \sim 33\%$, tagging power $\varepsilon \sim 6\%$.
• Requires accurate measurement of decay time (to resolve oscillations).
  • Time dependent fit with resolution $\sim 40$ fs.
• Requires angular analysis
  • See next slide.
Angular analysis

$P \to VV$ decay: requires angular analysis to disentangle CP-even and CP-odd final states.

Use control channels to check angular acceptance description:
- $B^+ \to J/\psi K^+$
- $B \to J/\psi K^*$

In addition, include pure CP eigenmodes (e.g. $B_s \to J/\psi f_0, \eta, \eta'$) as cross-check. → No angular analysis needed.
Mixing-induced $\mathcal{CP}$ in $B_s \rightarrow J/\psi \phi$

$J/\psi \rightarrow \mu^+\mu^-$ from real data

$LHCb$ Preliminary
$\sqrt{s} = 7$ TeV Data

$N_{Signal} = 2242 \pm 72.1$
$B/S = 0.426 \pm 0.033$
$m_b = 3089.4 \pm 0.44$ MeV/c$^2$
$\sigma_{CB} = 15.4 \pm 0.43$ MeV/c$^2$

$\phi \rightarrow K^+K^-$ from real data

$LHCb$ Preliminary
$\sqrt{s} = 7$ TeV Data

$m_b = 1019.42 \pm 0.05$ MeV
$\sigma_{Gauss} = 1.46 \pm 0.6$ MeV
$N_{Signal} = 10,378.1 \pm 57.9.3$

Next step: the first $B_s \rightarrow J/\psi \phi$ candidate...
Promising measurement in presence of New Physics.

Expect 50k events in 1 fb⁻¹

LHCb’s sensitivity

- \( \sigma(\phi_s) \) with 0.2 fb⁻¹: 0.14
- \( \sigma(\phi_s) \) with 1.0 fb⁻¹: 0.07

Note that sensitivity from \( B_s \rightarrow J/\psi f_0(980) \) could be similar, depending on BR.

Current CDF sensitivity:
\[ \sigma(\phi_s) = 0.5 \text{ for } 5.2 \text{ fb}^{-1} \text{ (FPCP 2010)} \]

CDF+D0, 8fb⁻¹ EACH

LHCb 3.5+3.5TeV; \( \sigma(b\bar{b}) = 219 \mu b \)

Uncertainties on \( \sigma(b\bar{b}) \) and \( \text{BRvis}(B_s^0 \rightarrow J/\psi f_0) \)

\[ 2\beta_s \text{ SM value} \]
Search for $B_s \rightarrow \mu^+ \mu^-$

- Very rare decay. Prediction in SM: $\text{BR} = (3.35 \pm 0.32) \times 10^{-9}$ [hep-ph/0604057v5]
- Sensitive to New Physics:
  - E.g. branching ratio in MSSM enhanced by sixth power of $\tan \beta$:
    \[
    \text{BR}(B_s \rightarrow \mu^+ \mu^-) = 5 \times 10^{-7} \left( \frac{\tan \beta}{50} \right)^6 \left( \frac{300 \text{GeV}}{M_A} \right)^4
    \]
- Present limit from CDF (3.7 fb$^{-1}$):
  $\text{BR} < 3.6 \times 10^{-8}$ (90% CL).

The decay $B_s \rightarrow \mu^+ \mu^-$ provides sensitive probe for New Physics.

[arXiv:0907.5568v1]
Search for $B_s \rightarrow \mu^+\mu^-$

**Selection strategy**

- Select signal in a 3D-box of
  - Invariant mass
  - Geometrical likelihood
  - PID likelihood
→ Uncorrelated variables with different control samples

→ **Invariant mass**
- Detailed studies done with $K_s$ and $J/\psi$:

<table>
<thead>
<tr>
<th></th>
<th>$K_s \rightarrow \pi \pi$</th>
<th>$J/\psi \rightarrow \mu \mu$</th>
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</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>3.47 0.13 MeV</td>
<td>15.4 0.43 MeV</td>
</tr>
<tr>
<td><strong>MC</strong></td>
<td>3.31 0.12 MeV</td>
<td>13.12 0.05 MeV</td>
</tr>
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- Dominated by opening angle
- Dominated by momentum of daughters
- Ultimately, use kinematically similar decays $B_s \rightarrow K^+K^-$ (and $K\pi$, $\pi\pi$).
  - $B_s$ mass resolution from MC $\sim 20$ MeV

**Points:**
- **MC $B_s \rightarrow \mu^+\mu^-$ mass**
- **Red curve:** from $B_s \rightarrow K^+K^-$
- **Blue curve:** from $B_s \rightarrow K^+K^-$ (with correction for PID)
Search for $B_s \rightarrow \mu^+ \mu^-$

**Muon identification**

- Offline muon efficiency
  - Tag-and-probe method $p>3$ GeV using $J/\psi$'s

- Pion misidentification
  - $\pi \rightarrow \mu$ dominated by decays in flight
  - Data: $(2.38 \pm 0.02)\%$
  - MC: $(2.34 \pm 0.02)\%$

- Proton misidentification
  - $p \rightarrow \mu$ dominated by combinatorics in muon stations
  - Data: $(0.18 \pm 0.02)\%$
  - MC: $(0.21 \pm 0.04)\%$
Search for $B_s \rightarrow \mu^+\mu^-$

- All studies on data so far indicate that sensitivity from MC is realistic.
- Use known channels to determine BR from event yield
  - $B \rightarrow K\pi$ and $B^+ \rightarrow J/\psi K^+$
  - $BR(B_s \rightarrow \mu^+\mu^-)$ can be calculated as:

$$BR_{cal} \times \frac{\epsilon_{cal}^{REC, SEL}}{\epsilon_{sig}^{SEL}} \times \frac{\epsilon_{cal}^{TRIG, SEL}}{\epsilon_{sig}^{SEL}} \times \frac{f_{cal}}{f_{B_s^0}} \times \frac{N_{B_s^0 \rightarrow \mu^+\mu^-}}{N_{cal}}$$

Determine these ratio’s from data

Production ratio known to 13%. Extract ratio from data using $B_s \rightarrow D_s\pi$ and $B \rightarrow D^+K^-$

0.2 fb$^{-1}$ → improve on expected Tevatron limit.
1.0 fb$^{-1}$ → exclude BR down to $7 \times 10^{-9}$
  or observe 5$\sigma$ signal if BR = $3.5 \times$ SM.
  (Need 10 fb$^{-1}$ at 14 TeV to observe 5$\sigma$ signal if BR = SM)

Exclusion limit at 90% CL at $\sqrt{s}$=7 TeV

CDF (3.7 fb$^{-1}$)

CDF+D0 (8 fb$^{-1}$)

SM prediction

Exclusion limit @90% C.L.
• $B_d \rightarrow \mu^+ \mu^- K^*$ rare decay in the SM.
  • BR ($B_d \rightarrow \mu^+ \mu^- K^*$) $\sim 1.0 \times 10^{-6}$
• SM diagrams (can be easily modified in presence of NP):

  • Angular distributions contain a lot of information.
    • Many observables sensitive to NP
  • For first data focus on forward-backward asymmetry: $A_{FB}(q^2)$.
  • Zero crossing point of $A_{FB}$ well predicted in SM (minimize hadronic uncertainties).
    • Measures ratio Wilson coefficients $C_9/C_7$.
  • Sensitive to SUSY, graviton exchanges, extra dimensions…
Asymmetries in $B_d \rightarrow \mu^+\mu^-K^*$

Estimated error on $A_{FB}$: in most sensitive bin (1−6 GeV$^2$):
0.1 fb$^{-1}$: $\sigma(A_{FB})=0.20$

SM prediction
Belle
BaBar
LHCb (projection)
at 0.1 fb$^{-1}$

140 events expected
Asymmetries in $B_d \to \mu^+\mu^- K^*$

Estimated error on $A_{FB}$: in most sensitive bin (1–6 GeV$^2$):
- 0.1 fb$^{-1}$: $\sigma(A_{FB})=0.20$
- 0.3 fb$^{-1}$: $\sigma(A_{FB})=0.12$
- 1.0 fb$^{-1}$: $\sigma(A_{FB})=0.07$ (end of 2011)

SM exclusion assuming central value from Belle in most sensitive bin

SM prediction
- Belle
- BaBar
- LHCb (projection) at 1.0 fb$^{-1}$

1400 events expected
CKM angle $\gamma$ from tree $B$ decays

Current experimental status:
- From direct measurements with $B \to DK$ decays: $\gamma = (73^{+22}_{-25})$ ([BaBar] and [Belle])
- From SM fit using only indirect measurements: $\gamma = (67.7^{+4.5}_{-3.7})$ [CKMfitter Beauty09]

- Diagrams with $b \to c$ and $b \to u$ transitions → sensitive to $\gamma$.
- Use only tree diagrams to allow clean (NP free) extraction of $\gamma$.

\[ B^{+/0} \to D^0 K^{+/0} \]
- Measures $\gamma$ directly through interference between B and subsequent D decay.
- Counting experiment. Measure relative decay rates.
  - ADS+GLW method ($D^0 \to K\pi, KK, \pi\pi, K\pi\pi\pi$)
  - GGSZ (Dalitz) method ($D^0 \to K_s\pi\pi$)

\[ B_s \to D_s K \]
- Measures $\gamma - 2\beta_s$ through interference between mixing and decay.
  - Mixing phase $2\beta_s$ from $B_s \to J/\psi \phi$
  - Golden mode, but requires flavour tagging and time-dependent analysis.
**CKM angle $\gamma$ from tree $B$ decays**

- **$\gamma$** is the least well-known CKM angle

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    - Mixing phase $2\beta_s$ from $B_s \to J/\psi \phi$
    - Golden mode, but requires flavour tagging and time-dependent analysis.
First two channels of the $B \to DX$ family observed.

Signal by combining $B^0 \to D^+ \pi^-$ and $B^+ \to D^0 \pi^+$

Expect soon
- $B_s \to D_s \pi^-$
- $B \to DK$ (Cabibbo favoured)
LHCb has excellent potential for charm physics

- Dedicated HLT trigger line for $D^{*+} \rightarrow D^0(hh')\pi^+$
  - Yield of $O(10^8)$ events per fb$^{-1}$
  - Flavour tag from charge of pion.
- $D^0$ time resolution $\sim 0.040$ ps (from MC).

→ See talk of Matthew Charles on open charm and charmonium in LHCb
Mixing parameters and possible CP violation effects.

- CP violation would indicate New Physics.
- Lifetime ratio CP mixed and CP even decays ($y_{CP}$).
  - Expect $17 \times 10^6 (D \rightarrow K \pi; \text{CP mixed})$ and $1.3 \times 10^6 (D \rightarrow KK; \text{CP even})$ in 0.1 fb$^{-1}$.
- Measurement of oscillation in wrong sign $D \rightarrow K \pi$.
  - Expect $60 \times 10^3$ in 0.1 fb$^{-1}$

Direct CPV in single-Cabibbo-suppressed decays.

- Dalitz analysis with $D^+ \rightarrow K^+ K^- \pi^+$
  - Model independent
  - Not sensitive to production asymmetries.
  - Expect several millions of events in 0.1 fb$^{-1}$

Search for rare decay of $D^0 \rightarrow \mu^+ \mu^-$.

- Highly suppressed in SM: BR~$3 \times 10^{-13}$
- Can be significantly enhanced by NP.
- Current experimental limit BR $< 1.4 \times 10^{-7}$ @ 90% CL [Belle]
- Similar analysis as $B_s \rightarrow \mu^+ \mu^-$
- Expected limit LHCb for 0.1 fb$^{-1}$: BR $< 4 \times 10^{-8}$ @ 90% CL.
Conclusion

- LHCb is well on track for its heavy flavour programme.
- First B decays have been recorded.
- Performance for key measurements as expected.
- Increase our sensitivity to New Physics as data comes in.
- Expected performance:
  - 0.2 fb$^{-1}$ (2010): improve on current NP constraints.
  - 1.0 fb$^{-1}$ (2011): find NP or narrow down allowed region.
- Exciting times lies ahead of us and has already started!

No time to mention:
- $B_s \to \phi \gamma$ and other radiative $B$ decays.
- Charmless 2-body $B$ decays.
- Semileptonic $B$ decays
- Electroweak physics.
- Higgs and exotica.
- LFV tau decays
- And much, much more…