LHC results on tree-level beauty decays

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On behalf of the LHCb collaboration
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Topics covered with more detail in talks of
Concezio Bozzi *Recent results from LHCb on semileptonic decays of b-hadrons*
Donal Hill *Measurements of the CKM angle gamma at LHCb*
Tree-level decays
Tree-level decays

Outline:

Semileptonic decays
- b baryon $V_{ub}$ and $V_{cb}$ decays, and future LHCb prospects
- LHCb results on $R(D^*)$

Hadronic decays
- LHCb updates on $\gamma$
Tree-level decays

Outline:

Semileptonic decays
  • $b$ baryon $V_{ub}$ and $V_{cb}$ decays, and future LHCb prospects
  • LHCb results on $R(D^*)$

Hadronic decays
  • LHCb updates on $\gamma$

More details to follow in talks of

Concezio Bozzi

Donal Hill
CKM unitarity

The only source of quark flavour violation and CP violation?
Loops

\[ \sin 2\beta \]

\[ \Delta m_d \text{ & } \Delta m_s \]

\[ \frac{V_{td} V^*_{tb}}{V_{cd} V^*_{cb}} \]

excluded area has CL > 0.95

sol. w/ cos 2\(\beta\) < 0
(excl. at CL > 0.95)

\[ |\eta| \]

\[ \alpha \]

\[ \gamma \]

\[ \beta \]

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Trees

\[ V_{ud} V_{ub}^* / V_{cd} V_{cb}^* \]

Excluded area has CL > 0.95
Inclusive-exclusive puzzle

![Graph showing the relationship between |V_{cb}| and |V_{ub}| with various shaded regions indicating different exclusive and inclusive measurements. The graph includes the Indirect (HFAG) line and the ratio V_{ub}/V_{cb} N_b line.]
Inclusive-exclusive puzzle

Very recent progress, e.g. Grinstein, Kobach, PLB771 (17) 359-364, Bigi, Gambino, Schacht, PLB 769 (17) 441-445

In any case, it will be invaluable to complement the $B$ meson based measurements with those from other $b$ species.
LHC: access to all $b$ hadrons

We measure product of the $b$ cross section, fragmentation fraction, and branching fractions.

Focus on measurements of ratios or shapes of decay rates.

*Similar arguments apply to CP asymmetries — measure differences.*
$V_{ub}$ suppressed baryon decay

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:
Detmold, Lehner, Meinel, PRD 92, 034503 (15)
**V_{ub}** suppressed baryon decay

The corrected mass variable exploits the measured flight direction to better resolve the kinematics of the different signals and backgrounds.

\[ \mathcal{B}(\Lambda_b \rightarrow p\mu^+\bar{\nu}_\mu)_{q^2>15\text{ GeV}^2/c^4} / \mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7\text{ GeV}^2/c^4} = (1.00 \pm 0.04\text{ (stat)} \pm 0.08\text{ (syst)}) \times 10^{-2} \]
$V_{ub}$ suppressed baryon decay

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\text{(expt)} \pm 0.004\text{(lattice)}$$

Precision already comparable with $B$ meson based exclusive determinations.
**V\text{ub}** suppressed baryon decay

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

Complementarity of spin-\(\frac{1}{2}\) nature — already very powerful in testing RH-current hypothesis\(^1\) for incl./excl. puzzle.

\(^1\) Bernlochner, Ligeti, Turczyk, PRD90 094003 (2014)
$V_{ub}$ suppressed baryon decay

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \text{(expt)} \pm 0.004 \text{(lattice)}$$

The lattice predictions for $\Lambda_b \rightarrow \Lambda_c \mu \nu$

Detmold, Lehner, Meinel, PRD 92, 034503 (15)
Favoured baryon decay

Measure the *shape* of the $d\Gamma/dq^2$ spectrum of $\Lambda_b \rightarrow \Lambda_c \mu \nu$

![Graph showing the distribution of $dN/dq^2$ with $q^2_{gen}$]
Favoured baryon decay

\[ \frac{dN_{corr}}{dw} K(w) \]

\[ \xi_B(w) = 1 - \rho^2 (w-1) + 0.5\sigma^2 (w-1)^2 \]

Similar measurements possible with other b species and decay modes!
Prospects with $B_s$ mesons

Great prospects for $|V_{ub}|/|V_{cb}|$ determination with $B_s \to K\mu\nu$

Same lattice data give $\sim2x$ better precision than $B \to \pi\mu\nu$

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

Experimentally more challenging than $\Lambda_b \to p\mu\nu$, but we’re working hard on a measurement of $B_s \to K\mu\nu/B_s \to D_s\mu\nu$ — Stay tuned!
Prospects with $B_s$ mesons

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This is just one example of a rapidly expanding LHCb program with semileptonic $b$ decays.

E.g., $B \rightarrow \mu\mu\mu\nu$, $hhh\nu$, $\Phi\mu\nu$, $pp\mu\nu$, various $B_s$, $B_c$, etc…

Experimentally more challenging than $\Lambda_b \rightarrow p\mu\nu$, but we’re working hard on a measurement of $B_s \rightarrow K\mu\nu/B_s \rightarrow D_s\mu\nu$ — Stay tuned!
Tree LFU tests

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

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

(Very precise and well scrutinised/trusted by the community)

Experiment:
\[ R(D^*) \rightarrow 6\% \text{ precision} \]
Tree LFU tests

Combined $R(D,D^*)$ is now $\sim 4\sigma$ from SM
Tree LFU tests

If this is due to BSM physics, two observables aren’t enough to characterise it.

In the pipeline from LHCb:

- $B \rightarrow D^{*+} \tau \nu$
- $B \rightarrow D^{+,0} \tau \nu$
- $B_s \rightarrow D_s \tau \nu$
- $\Lambda_b \rightarrow \Lambda^{(*)}_{c} \tau \nu$
- $B_c \rightarrow J/\psi \tau \nu$
- $\Lambda_b \rightarrow p \tau \nu$
- $B \rightarrow pp \tau \nu$
- etc..

$P(\chi^2) = 67.4\%$
Tree LFU tests

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In the pipeline from LHCb:
- \(B \rightarrow D^{*,+}\tau\nu\)
- \(B \rightarrow D^{+,0}\tau\nu\)
- \(B_s \rightarrow D_s\tau\nu\)
- \(\Lambda_b \rightarrow \Lambda^{(*)}_c\tau\nu\)
- \(B_c \rightarrow J/\psi\tau\nu\)

For now:
- \(R(D^*)\) with \(\tau \rightarrow \mu\nu^\circ\nu\)
- \(R(D^*)\) with \(\tau \rightarrow \pi\pi\pi\nu\)

Very recent:

- \(B \rightarrow D^{*,+}\tau\nu\)
- \(B \rightarrow D^{+,0}\tau\nu\)
- \(B_s \rightarrow D_s\tau\nu\)
- \(\Lambda_b \rightarrow \Lambda^{(*)}_c\tau\nu\)
- \(B_c \rightarrow J/\psi\tau\nu\)

BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, arXiv:1612.00529

Average

\(\chi_\Delta R(D)=0.300(8)\) HPQCD (2015)
\(R(D)=0.299(11)\) FNAL/MILC (2015)
\(R(D^*)=0.252(3)\) S. Fajfer et al. (2012)

\(\chi^2\) = 67.4%
Fit in bins of $q^2, m^2_{\text{miss}}$, and $E_\mu$.

Here is the $m^2_{\text{miss}}$ projection in the highest purity $q^2$ bin:
LHCb hadronic $R(D^*)$

We actually measure

$$\frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

And use external measurements of $B(B \to D^{*}3\pi)$ and $B(B \to D^{*}\mu\nu)$ to get $R(D^*)$.

This required a new (2016) measurement of $B(B \to D^{*}3\pi)$ from BaBar. PRD 94 091101 (2016)

$$B(B \to D^{*}3\pi) = (0.726 \pm 0.011 \pm 0.031) \times 10^{-2}$$
LHCb hadronic $R(D^*)$
Different challenges, but expect the better constrained kinematics to allow very higher purity…
LHCb hadronic $R(D^*)$

First measurement with this decay mode!
And look forward to:
- $R(D^{*+})$, $R(D^{+}, 0)$, $R(D_s^{(*)})$
- $R(\Lambda^{(*)}_c)$, $R(J/\psi)$
- $R(pp)$, $R(p)$, etc...

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Hadronic tree decays
Hadronic tree decays

E.g. if the $D^0$ decays to a CP eigenstate, these two interfere.
leads to a CP-violating asymmetry that depends on; the amplitude ratio, and relative weak ($\gamma$) and strong phases.

Various methods with different decays. E.g. GLW (above example), ADS, GLS, GGSZ.
# LHCb $\gamma$ combination

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Status since last combination [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[2]</td>
<td>Updated to Run 2</td>
</tr>
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<td>$B^+ \to DK^+$</td>
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<td>ADS</td>
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</tr>
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<td>GLW/ADS</td>
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<tr>
<td>$B^+ \to DK^+$</td>
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<td>GLW/ADS</td>
<td>[20]</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K_s^0h^-h^-$</td>
<td>GGSZ</td>
<td>[21]</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K_s^0K^+\pi^-$</td>
<td>GLS</td>
<td>[22]</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \to D^*K^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[2]</td>
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<td>$B^0 \to DK^{*0}$</td>
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<td>GLW-Dalitz</td>
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<td>$B_s^0 \to D_s^\mp K^\pm$</td>
<td>$D_s^\mp \to h^+h^-\pi^+$</td>
<td>TD</td>
<td>[4]</td>
<td>Updated to 3 fb$^{-1}$</td>
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**W.r.t. JHEP 12 (2016) 087**

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Example new mode

CP asymmetries of main $B \rightarrow D^0 h$ peaks are related to $\gamma$ in well known GLW method.

5 fb$^{-1}$

LHCb preliminary

$B^- \rightarrow [\pi^+\pi^-]_b K^-$

LHCb preliminary

$B^+ \rightarrow [\pi^+\pi^-]_b K^+$

LHCb preliminary

$B^- \rightarrow [\pi^+\pi^-]_b \pi^-$

LHCb preliminary

$B^+ \rightarrow [\pi^+\pi^-]_b \pi^+$

m($Dh^\pm$) [MeV/c$^2$]
**Example new mode**

CP asymmetries of main $B \to D^0 h$ peaks are related to $\gamma$ in well known GLW method.

Can measure $B \to D^* h$ equivalents without actually reconstructing the full $D^*$ decays!
LHCb γ combination

Nov 2016  JHEP 12 (16) 087

- $B^+ \rightarrow DK^+, D \rightarrow h3\pi/hh'\pi^0$
- $B^+ \rightarrow DK^+, D \rightarrow K_s^0 hh$
- $B^+ \rightarrow DK^+, D \rightarrow KK/K\pi/\pi\pi$

- All $B^+$ modes
- Full LHCb Combination

NEW

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LHCb-CONF-2017-004 (in preparation)
LHCb $\gamma$ combination

Jul 2017 CONF-2017-004

- $B^+ \rightarrow D^{+} K, D \rightarrow h3\pi/hh' \pi^0$
- $B^+ \rightarrow D^{+} K, D \rightarrow K_s^0 hh$
- $B^+ \rightarrow D^{+} K, D \rightarrow KK/K\pi/\pi\pi$
- All $B^+$ modes
- Full LHCb Combination

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Already a 30% improvement, with many more Run-II updates and channels expected soon.

Dominant contributor to new HFLAV average\textsuperscript{1} \( \gamma = (76.2^{+4.7}_{-5.0})^\circ \)

\textsuperscript{1} http://www.slac.stanford.edu/xorg/hflav/triangle/summer2017/index.shtml#gamma_comb
Conclusions

Tree-level $b$ decays play a crucial role in testing CKM unitarity.

LHCb has a rapidly expanding program of studying semileptonic decays, making particular exploitation of $b$ species that are only accessible at hadron colliders.

LHCb has competitive precision on $R(D^*)$ with first attempt using hadronic $\tau$ decays.

A new LHCb $\gamma$ combination reaches $\sim 5^\circ$ precision.
Backup slides start here...
LHCb $\gamma$ combination

$1-\text{CL}$

$LHCb$

Preliminary

76.8$^{+5.1}_{-5.7}$

68.3%

95.5%
LHCb $\gamma$ combination

![Graph showing 1-CL vs $\gamma$]

- $B_s^0$ decays (Orange)
- $B^0$ decays (Yellow)
- $B^+$ decays (Blue)
- Combination (Green)

**Confidence Levels**
- $68.3\%$
- $95.5\%$
LHCb $\gamma$ combination

![Graph showing the $\gamma$ distribution with different categories: GGSZ, GLW/ADS, Others, and Combination. The graph indicates 68.3% and 95.5% confidence levels.]
\( \mathbf{B}^\pm \to (D^{*0} \to D^0 \pi^0) h^{\pm} \)
\( B^0 \to (D^{*\mp} \to D^0 \pi^{\mp}) h^{\pm} \)
\( B^\pm \to (D^{*0} \to D^0 \gamma) h^{\pm} \)
\( B^\pm \to D^0 h^{\pm} \pi^0 \)
\( B \to D^* h^{\pm} \pi \)
\( B^\pm \to D^0 h^{\pm} \pi \)
\( B^\pm \to D \pi^\pm \)
\( B^\pm \to D K^{\pm} \)
\( \Lambda_b \to \Lambda_c h^{\pm} \)
\( \text{Part. reco. mis-ID} \)
\( \text{Combinatorial} \)

\( m(Dh^\pm) [\text{MeV}/c^2] \)

Events / (10 MeV/c^2)

LHCb preliminary

\( B^- \to [\pi^+ \pi^-]_D K^- \)

\( B^+ \to [\pi^+ \pi^-]_D K^+ \)

\( B^- \to [\pi^+ \pi^-]_D \pi^- \)

\( B^+ \to [\pi^+ \pi^-]_D \pi^+ \)
New HFLAV $\gamma$ average