CP violation in b-hadrons

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on behalf of the LHCb collaboration
Moriond Electroweak 2016
Overview of CP violation in $b$-decays
- Measurements of $B$ meson mixing
- Quantification of penguin pollution

New physics searches in loop decays

Searches and CP violation studies in $b$-baryon decays

New result $\Lambda_b \rightarrow \Lambda \phi$ exclusive search, arXiv:1603.02870

New result $\Lambda_b(\Xi_b) \rightarrow \Lambda hh'$ inclusive searches, arXiv:1603.00413 - see dedicated talk by Daniel O’Hanlon on Monday.
LHCb Detector

- LHCb is a forward arm spectrometer (pseudo-rapidity range: $2 < \eta < 5$),
- Precise resolutions through vertex locator and tracking stations ($\Delta p/p \approx 0.4\%$, $\sigma(IP) \approx 20\mu m$),
- Accurate particle ID provided by RICH detectors,
- High muon identification efficiency from muon stations.
Note on tracks in LHCb

- For long-lived particles such as Λ and $K_s$ hadrons, a large fraction decay outside the vertex detector, and are then reconstructed as downstream.

- Due to different efficiencies and resolutions, so-called long and downstream datasets are treated separately.
Current picture

- Wide array of results from LHCb testing CP violation in b-hadron decays in Run 1:
  - Vast programme to measure the CKM angle $\gamma$ - see the talk of Malcolm John today.
  - So far the SM stands up amazingly (at least in terms of CP violation).

Picture from CKMfitter:

- LHCb is making important contributions, even in places we were not expected to, i.e. $|V_{ub}|$ - see the talk of Jeroen Van Tilburg today.
**B_d mixing**

- LHCb is able to provide input to the CP-violating phase in B_d mixing, defined as

\[
\phi_d \equiv 2\beta = 2 \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)
\]

- At LHCb, measured through the time-dependent CP asymmetry in B_d→K_S J/ψ

\[
A(t) = \frac{\Gamma(B^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(B^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} = \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2)} + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)
\]

- where

\[
S = 2\sin\phi_d/(1+|\lambda|^2)
\]

\[
C = (1-|\lambda|^2)/(1+|\lambda|^2)
\]

\[
A_{\Delta \Gamma} = -2\cos\phi_d/(1+|\lambda|^2)
\]

- LHCb measurement of

\[
S = \sin 2\beta = 0.731 \pm 0.035 \pm 0.020
\]

is approaching the precision of the B-factories.
**B_s mixing**

- An important measurement for LHCb is that of CP violation in B_s mixing, tested with tree-dominated b→cčs decays.

\[ \phi_s = -2 \beta_s = -2 \arg \left( -\frac{V_{cb} V_{cs}^*}{V_{tb} V_{ts}^*} \right) \]

- Experimentally very complex due to mixture of CP eigenstates in the B_s→J/ψKK transition
- CP eigenstates disentangled with an angular analysis
- Require excellent knowledge of the initial B meson flavour and B decay time resolution.
B_{s} mixing

PRL 114 (2015) 041801

96k candidates

S-wave

CP-even

CP-odd

Result combined with 27k $B_{s} \to J/\psi \pi \pi$ candidates
Bs mixing

- LHCb measurement of $-10\pm39$ mrad dominates the global fit PRL 114 (2015) 041801

- Constraining power of the measurement will increase as LHCb accumulates more data.

- Attention turns more to control of penguin pollution...

$$\phi_{s,i} = -2\beta_s + \phi^{BSM}_s + \Delta \phi^{J/\psi\phi}_{s,i} (a'_i, \theta'_i)$$

De Bruyn & Fleischer, arXiv:1412.6834
Penguin pollution

- LHCb can measure $\Delta \phi_{\text{penguin}}$ in decays that do not have the penguin amplitude suppressed.

\[
A \left( B^0_s \to (J/\psi K^{*0})_i \right) = -\lambda A_i \left[ 1 - a_i e^{i\theta_i} e^{i\gamma} \right]
\]

\[
A \left( B^0_s \to (J/\psi \phi)_i \right) = \left( 1 - \frac{\lambda^2}{2} \right) A'_i \left[ 1 + a'_i e^{i\theta'_i} e^{i\gamma} \right]
\]

- Assuming SU(3) symmetry, $a_i = a'_i$ and $\theta_i = \theta'_i$.

- $a$ and $\theta$ can be determined from the data with a modified least squares fit to CP asymmetries and branching fraction information.

- In combination with an equivalent study using $B_d \to J/\psi \phi$ decays (Phys. Lett. B742 (2015) 38-49), penguin pollution can be evaluated as:

\[
\Delta \phi^{J/\psi \phi}_{s,0} = 0.000^{+0.009}_{-0.011} \text{ (stat)} \pm 0.004 \text{ (syst)} \text{ rad}
\]

\[
\Delta \phi^{J/\psi \phi}_{s,\parallel} = 0.001^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad}
\]

\[
\Delta \phi^{J/\psi \phi}_{s,\perp} = 0.003^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad}
\]

Conclusion: penguin contamination is small

Can parameterise penguin and tree contributions to each polarisation amplitude

Detailed relations between \{a,\theta\} $\Leftrightarrow$ \{A_{CP,H}\} given in the backup
Penguin measurements - $B_s \to \phi \phi$

- Not all penguins are bad news...
- SM predictions of the CP violating phase in $b \to s\bar{s}s$ penguin decays (arXiv:0810.0249, arXiv:0910.5237) predict values close to 0.
- Amplitude analysis to disentangle the CP components of the $B_s \to \phi \phi$ decay.
- 4000 candidates from $3\text{fb}^{-1}$ of Run 1 data.
- LHCb measures the CP-violating phase to be (arXiv:1407.2222)
  \[-0.17\pm0.15\pm0.03 \text{ rad}.\]

Low systematic contributions, very interesting with Run 2 dataset sizes.
Penguin measurements - $B_s \to K^*K^*$

- Analysis a pure $b \to s\bar{d}$ transition.
- Mixture of CP eigenstates, so requires an angular amplitude analysis

\[
\begin{array}{c|c}
\text{Parameter} & \text{Value} \\
\hline
f_L & 0.201 \pm 0.057 \pm 0.040 \\
|A^+_s|^2 & 0.215 \pm 0.046 \pm 0.015 \\
|A^-_s|^2 & 0.114 \pm 0.037 \pm 0.023 \\
|A^0_{ss}|^2 & 0.485 \pm 0.051 \pm 0.019 \\
\delta_{||} & 0.066 \pm 0.022 \pm 0.007 \\
\delta & 5.31 \pm 0.24 \pm 0.14 \\
\delta - \delta_s^+ & 1.95 \pm 0.21 \pm 0.04 \\
\delta_s^- & 1.79 \pm 0.19 \pm 0.19 \\
\delta_{ss} & 1.06 \pm 0.27 \pm 0.23 \\
\end{array}
\]

- Low value of $f_L$ confirmed
- Large S-wave

1 fb$^{-1}$ of Run 1 data yields \(~700\ events

\[P \to VV\]
\[P \to SV, VS, SS\]
\[Re(A^+_0A^+_s)\]
Penguin measurements - $B_S \rightarrow K^*K^*$

Triple products measured through asymmetries of angular observables - Gronau & Rosner arXiv:1506.01346

\[
A_T^3 = \frac{\Gamma((\cos \theta_1 + \cos \theta_2) \sin \varphi > 0) - \Gamma((\cos \theta_1 + \cos \theta_2) \sin \varphi < 0)}{\Gamma((\cos \theta_1 + \cos \theta_2) \sin \varphi > 0) + \Gamma((\cos \theta_1 + \cos \theta_2) \sin \varphi < 0)}
\]

\[
= \frac{32}{5\pi \sqrt{3}} \frac{1}{D} \int \mathcal{M} \left( (A_\perp A_s^{*-} - \bar{A}_\perp \bar{A}_s^{*-}) M_1(m) M_0^*(m) \right) dm
\]

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_T^1$</td>
<td>0.003 ± 0.041 ± 0.009</td>
</tr>
<tr>
<td>$A_T^2$</td>
<td>0.009 ± 0.041 ± 0.009</td>
</tr>
<tr>
<td>$A_T^3$</td>
<td>0.019 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>$A_T^4$</td>
<td>-0.040 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>$A_D^1$</td>
<td>-0.061 ± 0.041 ± 0.012</td>
</tr>
<tr>
<td>$A_D^2$</td>
<td>0.081 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>$A_D^3$</td>
<td>-0.079 ± 0.041 ± 0.023</td>
</tr>
<tr>
<td>$A_D^4$</td>
<td>-0.081 ± 0.041 ± 0.010</td>
</tr>
</tbody>
</table>

4 CP-even polarisations give rise to 4 triple product asymmetries and 4 direct asymmetries

\[
\bar{A}_T^{i} \propto \text{Im}(A_f^* A_\perp - \bar{A}_f^* \bar{A}_\perp)
\]

\[
\bar{A}_D^{i} \propto \text{Re}(A_f^* A_s^{+} - \bar{A}_f^* \bar{A}_s^{+})
\]

CP-even: $f = 0, \parallel, s^-, ss$

CP-odd: $\perp, s^+$
Observation of the $\Lambda_b \rightarrow \Lambda \phi$ decay,

arXiv:1603.02870

- Submitted to Phys. Lett. B.
- Based on 3fb$^{-1}$ of Run 1 data.

- Baryonic version of the $B_s \rightarrow \phi \phi$ decay.

- $B_d \rightarrow K_s \phi$ control mode used for BF measurement.

- As for B decays, polarisation structure of $\Lambda_b \rightarrow \Lambda V$ decays gives rise to $T$-odd observables.
  - Allow access to CP violation without the use of a control mode.

- Measurements probe the decay directly without the presence of mixing.
Observation of the $\Lambda_b \rightarrow \Lambda \phi$ decay, arXiv:1603.02870

- 3D fit performed in the $KKp\pi$, KK, $p\pi$ dimensions.

- Decay observed with 6.5$\sigma$ statistical significance (5.9$\sigma$ including systematic uncertainties).

89±13 combined signal yield

$B(\Lambda_b^0 \rightarrow \Lambda \phi)/10^{-6} = 5.18 \pm 1.04 \text{(stat)} \pm 0.35 \text{(syst)} \pm 0.50 \text{ (syst)} \pm 0.43 (B(B^0 \rightarrow K_s^0 \phi)) \pm 0.44 (f_d/f_{\Lambda_b})$
Observation of the $\Lambda_b \rightarrow \Lambda \phi$ decay, arXiv:1603.02870

- With a large enough dataset, a full angular analysis may be performed as has been done for $\Lambda_b \rightarrow \Lambda J/\psi$ - arXiv:1302.5578
- $T$-odd observables are accessible without a full angular analysis.
- Use convention of Leitner and Ajaltouni - hep-ph/0610189

$$\cos \Phi_{n_i} = \vec{e}_Y \cdot \vec{u}_i$$
$$\sin \Phi_{n_i} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i)$$

$$\vec{u}_i = \frac{\vec{e}_Z \times \hat{n}_i}{|\vec{e}_Z \times \hat{n}_i|}$$

$A_A^c = -0.22 \pm 0.12$ (stat) $\pm 0.06$ (syst)
$A_A = 0.13 \pm 0.12$ (stat) $\pm 0.05$ (syst)
$A_\phi^c = -0.01 \pm 0.12$ (stat) $\pm 0.03$ (syst)
$A_\phi = -0.07 \pm 0.12$ (stat) $\pm 0.01$ (syst)

Asymmetries consistent with zero
\( \Lambda_b(\Xi_b) \rightarrow \Lambda h h' \) inclusive searches, arXiv:1603.00413

See talk of Daniel O’Hanlon tomorrow in YSF

Evidence for \( \Lambda_b \rightarrow \Lambda \pi \pi \)

First observations reported of \( \Lambda_b \rightarrow \Lambda K K \) and \( \Lambda_b \rightarrow \Lambda K \pi \)

Plots show long and downstream combined

Measurements of branching fractions and CP asymmetries relative to the \( \Lambda_b \rightarrow \Lambda c \pi \) control mode

\[
A_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-) = -0.53 \pm 0.23 \pm 0.11 \\
A_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+ K^-) = -0.28 \pm 0.10 \pm 0.07
\]

CP asymmetries measured for observed decays, which are interesting though consistent with zero
• Wide programme at LHCb for tests of the SM.
• Precision is everything:
  • SM is holding up pretty well at current levels of precision.
    - $2\beta$ - PRL 115 (2015) 031601
    - $2\beta_s$ - PRL 114 (2015) 041801
  • Experimental measurements used to determine affect of penguin pollution on CP violation measurements.
    - $B_s \rightarrow J/\psi K^*$ - JHEP 11 (2015) 082
  • Penguin modes themselves are important searches for physics beyond the SM.
    - $b \rightarrow s d \bar{d}$ - JHEP 07 (2015) 166
    - $b \rightarrow s \bar{s} s$ - Phys.Rev. D90 (2014) 5, 052011
• First exploratory studies undertaken of new baryonic modes:
  - $\Lambda_b \rightarrow \Lambda \phi$ - arXiv:1603.02870
  - $\Lambda_b \rightarrow \Lambda h h$ - arXiv:1603.00413

Run 2 of the LHC will mean the SM will be tested in flavour observables to new levels. Stay tuned...
Backup
Backup: SU(3) breaking

\[ a'_i = \xi \times a_i, \quad \theta'_i = \theta_i + \delta \]
\[ \tan(\Delta \phi_{s,i}^{J/\psi \phi}) = \frac{2\epsilon a_i' \cos \theta_i' \sin \gamma + \epsilon^2 a_i'^2 \sin(2\gamma)}{1 + 2\epsilon a_i' \cos \theta_i' \cos \gamma + \epsilon^2 a_i'^2 \cos(2\gamma)} \]

\[ A_i^{CP} = - \frac{2a_i \sin \theta_i \sin \gamma}{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2} \]

\[ H_i \equiv 1 - \frac{1}{\epsilon} \left| \frac{A_i'}{A_i} \right|^2 \Phi \left( \frac{m_{J/\psi}}{m_{B_s^0}}, \frac{m_{\phi}}{m_{B_s^0}} \right) \frac{B(B_s^0 \to J/\psi K^{*0})_{\text{theo}}}{B(B_s^0 \to J/\psi \phi)_{\text{theo}}} f_i' f_i \]

\[ = \frac{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}{1 + 2\epsilon a_i' \cos \theta_i' \cos \gamma + \epsilon^2 a_i'^2} , \]
Backup: $B_s \to K^* K^* PDF$

<table>
<thead>
<tr>
<th>$n$</th>
<th>$K_n$</th>
<th>$F_n$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>$\frac{1}{\Gamma_L}</td>
<td>A_0</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{\Gamma_L}</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{\Gamma_L}</td>
<td>A_\perp</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{1}{\Gamma_L}</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$-\frac{1}{2\sqrt{2}} \sin 2\theta_1 \sin 2\theta_2 \sin \varphi$</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>$-\frac{1}{2} \sin^2 \theta_1 \sin^2 \theta_2 \sin 2\varphi$</td>
</tr>
<tr>
<td>7</td>
<td>$\frac{1}{2} \left( \frac{</td>
<td>A_{s+}^+</td>
</tr>
<tr>
<td>8</td>
<td>$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L}</td>
<td>A_{s-}^-</td>
</tr>
<tr>
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</tr>
<tr>
<td>21</td>
<td>0</td>
<td>$\frac{1}{3\sqrt{2}} \sin \theta_1 \sin \theta_2 \sin \varphi$</td>
</tr>
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</table>
Backup: $B \rightarrow K_s \phi$ projections

Figure 3: Fit projections to the $\pi^+ \pi^- K^+ K^-$ invariant mass in the (a) long and (b) downstream datasets, the $K^+ K^-$ invariant mass in the (c) long and (d) downstream datasets, and the $\pi^+ \pi^-$ invariant mass in the (e) long and (f) downstream datasets. The total fit projection is given by the blue solid line. The green and blue dotted lines represent the combinatorial and $K_0 S$ random fit components, respectively. The red and magenta dashed lines represent the $B^0 \rightarrow K_0 S$ signal and the $B^0 \rightarrow K_0 S K^+ K^-$ non-resonant components, respectively. Black points represent the data. Data uncertainties are Poisson 68% confidence intervals. Data-driven corrections applied to simulated data along with the mass model used to determine the signal yields. Signal mismodelling is accounted for using a one-dimensional kernel estimate for the description of the simulated mass distributions [36]. Background mismodelling is accounted for using a linear function. The kernel estimate is used in both the signal and control channels to describe the $\pi^0 b$, $B^0$, $K_0 S$, and $\pi^0$ line shapes. In order to determine the systematic uncertainties, 1000 pseudoexperiments are generated with the alternative model and are subsequently fitted with the nominal model. The average difference between the generated and fitted yield values is taken as the systematic uncertainty. This leads to uncertainties of 3.0% and 0.6% for the signal and control mode yields, respectively. Systematic uncertainties associated with the efficiency corrections from simulated datasets are considered. The limited size of the simulated sample gives rise to an uncertainty of 2.2%. The main uncertainties in the tracking and vertexing correction factors arise...