Experimental status of lifetimes, mixing and CP violation

Durham 5th September 2017
Outline

• CP violation in $B_s$ mixing and $\phi_s$
• Intermezzo: Lifetimes
• $\sin 2\beta$
• $\Delta \Gamma_d / \Gamma_d$
• Thoughts for the future

Interesting things not covered:

$B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$ (LHCb-CONF-2016-018)
$\sin 2\beta_{\text{eff}}$ with $B \rightarrow DD$ (PRL 117 (2016) 261801)
$\Gamma_D$ (EPJC 76 (2016) 412)
CP violation in $B_s$ mixing
**B_s mixing**

\[ i \frac{\partial}{\partial t} \left( \frac{|B_s^0(t)\rangle}{|B_s^0(t)\rangle} \right) = \left( M - i \frac{\Gamma}{2} \right) \left( \frac{|B_s^0(t)\rangle}{|B_s^0(t)\rangle} \right) \]

- Flavour eigenstates mix to give physical states (see e.g. arxiv: 1306.6474)
- Interference between decays with/without mixing gives measurable phase

Excellent vertex detector needed to resolve fast B_s oscillations

\[ \Delta m_s = 17.757 \pm 0.021 \text{ ps}^{-1} \]

cf SM 18.3 +/- 2.7
CP violation in $B_s$ mixing

\[ \phi_s = \text{arg} \left( -\frac{M_{12}}{\Gamma_{12}} \right) \]

\[ \Delta \Gamma_s = \Gamma_L - \Gamma_H \]

\[ \Delta m_s = M_H - M_L \]

- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\Phi_D$
- In the Standard Model expected to be small $\phi_s = -0.04$ radian
- Larger values possible in models of New Physics

Golden mode used by all LHC experiments $B_s \rightarrow J/\psi \phi$
- LHCb also studied $B_s \rightarrow J/\psi K^+K^-$, $B_s \rightarrow J/\psi \pi^+\pi^-$, $B_s \rightarrow \psi(2s)\phi$, $B_s \rightarrow D_s^+D_s^-$

![Graphical representation of CP violation in $B_s$ mixing](image)
Measuring $\phi_s$

Mass distribution

Unbinned maximum likelihood fit to mass, time and angles

Resolution model from prompt $J/\psi$ Peak. Resolution $\sim 50$ fs

Time acceptance due to cuts in the trigger + reconstruction effects

Angular acceptance for signal from simulation

Mistag rate measured using $B^+ \rightarrow J/\psi K^+$ calibration channel
**Abstract**

A measurement of the $B_s^0$ decay parameters in the $B_s^0 \rightarrow J/\psi \phi$ channel using an integrated luminosity of 14.3 fb$^{-1}$ collected by the ATLAS detector from 8 TeV $pp$ collisions at the LHC is presented. The measured parameters include the $CP$-violating phase $\phi_s$, the decay width $\Gamma_s$ and the width difference between the mass eigenstates $\Delta \Gamma_s$. The values measured for the physical parameters are statistically combined with those from 4.9 fb$^{-1}$ of 7 TeV data, leading to the following:

$$\phi_s = -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad}$$

$$\Delta \Gamma_s = 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}$$

In the analysis the parameter $\phi_s$ is constrained to be positive. Results for $\phi_s$ and $\Delta \Gamma_s$ are also presented as 68% and 95% likelihood contours in the $\phi_s$–$\Delta \Gamma_s$ plane. Also measured in this decay channel are the transversity amplitudes and corresponding strong phases. All measurements are in agreement with the Standard Model predictions.

**Transversity angles**
\[ \phi_s = -0.075 \pm 0.097 \text{ (stat)} \pm 0.031 \text{ (syst) rad}, \]
\[ \Delta \Gamma_s = 0.095 \pm 0.013 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}. \]
$\phi_s$: LHCb

$B_s \rightarrow J/\psi \phi$

Helicity angles

Background subtracted using sweight technique

CP Even
CP Odd
S-wave
\( \phi_s \): LHCb

\( B_s \rightarrow J/\psi \pi^+ \pi^- \) contributes to overall LHCb sensitivity

\[
\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}
\]

\[
\Delta m_s = 17.711^{+0.055}_{-0.057} \pm 0.011 \text{ ps}^{-1}
\]

\[
\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}
\]

\[
\Delta \Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}
\]

\[
|\lambda| = 0.964 \pm 0.019 \pm 0.007
\]

\[
\phi_s = 75 \pm 67 \pm 8 \text{ mrad.} \quad B_s \rightarrow J/\psi \pi^+ \pi^-
\]

Combined

\[
\phi_s = -0.010 \pm 0.039 \text{ rad}
\]
LHCb: High mass KK

LHCb has studied CP violation using J/ψKK events above φ resonance

\[ \phi_s = 119 \pm 107 \pm 34 \text{ mrad}, \]
\[ |\lambda| = 0.994 \pm 0.018 \pm 0.006, \]
\[ \Gamma_s = 0.650 \pm 0.006 \pm 0.004 \text{ ps}^{-1}, \]
\[ \Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010 \text{ ps}^{-1}. \]
Summary of $\phi_s$

http://www.slac.stanford.edu/xorg/hflav/

$\Delta \Gamma_s = 0.085 \pm 0.06 \text{ps}^{-1}$

$\phi_s = -0.021 \pm 0.031 \text{rad}$
Summary of $\phi_s$

No sign of NP 😃
Still room for New Physics amplitude at level of 10 % in $B_s$ mixing (Similar story in $B_d$ sector) 😊

Updates to come with Run 2 data
Precision at <0.02 rad level by end of Run II

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$
Penguin contribution could mimic NP effects

Study using other modes related by SU(3) symmetry to limit size using data
e.g. B_s \rightarrow J/\psi K^*, B^0 \rightarrow J/\psi \rho

\[
A \left( B_s^0 \rightarrow (J/\psi \bar{K}^0)_{i} \right) = -\lambda A_i [1 - a_i e^{i\theta_i} e^{i\gamma}]
\]

Penguin contributions could mimic NP effects

JHEP 11 (2015) 082
Phys Lett B742 (2015) 38
The longitudinal (top), parallel (middle) and perpendicular (bottom) polarisations are shown.

B derived from the $\theta^\ast$ to $\psi^\ast$ decay. Superimposed are the confidence level contours obtained from a fit to CP observables + polarization amplitudes in $B_\ast \rightarrow J/\psi K^*$, $B_0 \rightarrow J/\psi \rho$.

JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

$\Delta \phi_{J/\psi \phi}^{B_0} = 0.000^{+0.009}_{-0.011} \text{ (stat)} \pm 0.004 \text{ (syst) rad}$, $\Delta \phi_{J/\psi \phi}^{B_\ast} = 0.001^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst) rad}$, $\Delta \phi_{J/\psi \phi}^{B_0} = 0.003^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst) rad}$.

Effect of penguins bounded to be less than current uncertainties.
LHCb: and charmless...

Can also look for CP violation in $B_s$ mixing in loop diagrams

$$B_s^0 \rightarrow \phi\phi$$

Run 1

$$\phi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst) rad}$$

Run 2 update soon

Other modes to study with Run 1/Run 2

$$B_s^0 \rightarrow K^*\bar{K}^*$$

$$B_s^0 \rightarrow \phi\pi^+\pi^-$$

SM predicts ~zero for $B_s \rightarrow \phi_L\phi_L$
Lifetime Measurements
Lifetime Measurements

As Alex just told lifetimes provide important test of Heavy Quark effective theory and duality assumptions

Challenging both to theory and experiment

Long saga of $\Lambda_b$ lifetime

Ratio of $B_s$ and $B_d$ lifetimes should be 1 to good precision [versus experiment 0.994 +/- 0.004]

$\tau(\Lambda_b^0)/\tau(B^0)_{\text{HQE2014}} = 0.935 \pm 0.054$
Lifetime Measurements

Two experimental approaches to understand decay time acceptance

**Direct measurements**

- Trigger/selection cuts
- Model + correct acceptance

Use of data driven techniques/unbiased triggers where possible

**Relative measurements**

- Use control channel with similar kinematics/trigger to signal to make relative measurement

\[ B_s^0 \rightarrow J/\psi \eta \]
\( B_s \rightarrow J/\psi \eta \) lifetime

\[ B_s^0 \rightarrow J/\psi \eta X \]

Measurement statistically limited

3021 +/- 73 candidates in Run 1 data

\[ \tau_{\text{eff}} = 1.479 \pm 0.034 \text{ (stat)} \pm 0.011 \text{ (syst) ps} \]
Baryons: e.g $\Xi_b^0$ lifetime

$$\frac{N_{cor}(\Xi_b^0)}{N_{cor}(\Lambda_b)} \approx e^{\beta t}$$

$$\frac{1}{\beta} = \frac{1}{\tau_{\Lambda_b}} - \frac{1}{\tau_{\Xi_b^0}}$$

$$\tau(\Xi_b^0) = 1.006 \pm 0.018 \pm 0.01$$

$\Xi_b^0$ and $\Lambda_b$ lifetime consistent to 2% as Expected from HQE

Statistics dominate
A lot more to come!

$\Xi_b$, CDF, PRD 89, 072014, 2014

$\Xi_b$, LHCb, arXiv:1405.1543

$\Xi_b^0$, LHCb-PAPER-2014-021
Semileptonic decays

LHCb has also measured with $B_s$Lifetime with semileptonic decays

Large statistics, worse resolution

Complementary measurements

$$\tau_{B_s}^{\text{fs}} = 1.547 \pm 0.013 \text{ (stat)} \pm 0.010 \text{ (syst)} \pm 0.004 \text{ (\tau_B) ps}$$
CMS lifetime results

CMS recently presented preliminary results on b-hadron hadron lifetimes

### CMS lifetime results

#### CMS-PAS-BPH-13-008

<table>
<thead>
<tr>
<th>Source</th>
<th>± (stat)</th>
<th>± (syst)</th>
<th>± (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(_0^0)</td>
<td>453.0 ± 1.6</td>
<td>± 1.5</td>
<td>0.1</td>
</tr>
<tr>
<td>B(_0^0)</td>
<td>457.8 ± 2.7</td>
<td>± 2.7</td>
<td>0.1</td>
</tr>
<tr>
<td>B(_0^0)</td>
<td>504.3 ± 10.5</td>
<td>± 3.7</td>
<td>0.1</td>
</tr>
<tr>
<td>B(_0^0)</td>
<td>443.9 ± 2.0</td>
<td>± 1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>(\Lambda_b^0)</td>
<td>443.1 ± 8.2</td>
<td>± 2.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\(c \tau\) in \(\mu\text{m}\)

CMS recently presented preliminary results on b-hadron hadron lifetimes.
B\(_s\) lifetime summary

Contours of \(\Delta(\log L) = 0.5\)

- \(B^{0}_s \rightarrow D_s D_s, J/\psi \eta\)
- \(B^{0}_s \rightarrow J/\psi \pi \pi, J/\psi f_0\)
- \(B^{0}_s \rightarrow c \bar{c} KK\)
- Combined

Contours of \(\Delta(\log L) = 0.5\)

- \(B^{0}_s \rightarrow J/\psi \pi \pi, J/\psi f_0\)
- Combined
- Theory
- \(B^{0}_s \rightarrow D_s D_s, J/\psi \eta\)

Does not include LHCb semileptonics or CMS results
$\sin 2\beta$
LHCb has measured $\sin 2\beta$ using Run 1 data.

Result reduces tension between direct + indirect determinations from global fit.

New LHCb Run 1 results using $\psi(2S)$ and electron modes

\[
\sin(2\beta) \equiv \sin(2\phi_1)
\]
C(B^0 \to J/\psi(e^+e^-)K_s^0) = 0.12^{+0.07}_{-0.07} \text{ (stat) } \pm 0.02 \text{ (syst)}

S(B^0 \to J/\psi(e^+e^-)K_s^0) = 0.83^{+0.08}_{-0.06} \text{ (stat) } \pm 0.01 \text{ (syst)}

C(B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0) = -0.05^{+0.10}_{-0.10} \text{ (stat) } \pm 0.01 \text{ (syst)}

S(B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0) = 0.84^{+0.10}_{-0.10} \text{ (stat) } \pm 0.01 \text{ (syst)}

LHCb uncertainty reduced by 20 %

C(B^0 \to [c\bar{c}]K_s^0) = -0.017 \pm 0.029

S(B^0 \to [c\bar{c}]K_s^0) = 0.760 \pm 0.034
$\Delta \Gamma_d$
Discrepancy of D0 result to SM led to suggestion that it could be due to New Physics in $\Delta\Gamma_d$ as this is relatively poorly constrained (arXiv:1404.2531).

Recent ATLAS measurement

Compare lifetimes in $B \rightarrow J/\psi K^*$ and $B \rightarrow J/\psi K_s$.

arXiv:1605.07485
\[ \Delta \Gamma_d \]

Fit yields of the channels in bins of decay length

\[ R_{i,\text{uncor}} = \frac{N_i(J/\psi K_S)}{N_i(J/\psi K^{*0})} \]

Correct for detector efficiency

\[ R_{i,\text{cor}} = \frac{R_{i,\text{uncor}}}{R_{i,\text{eff}}} \]

Takes proper account of production asymmetry

\[ \Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-2} \]
ΔΓ_d

ATLAS result consistent with SM + previous measurements

ΔΓ_d/Γ_d (SM) = (0.42 ± 0.08) × 10^{-2}

Value needed to explain D0 result

LHCb result is only with fraction of Run 1 dataset
Thoughts
Thoughts

The Run 1 era is ending

A lot was achieved 😊, close to pre-LHC expectations

Some things were not in the pre-LHC program: e.g. high J/ψ KK, J/ψππ 😊

Some things were so far not exploited: electrons for φs, CP even eigenstates 😓

Run 2 analyses will come soon

LHCb 2015+2016 dataset comparable in size to Run 1, adding 2017 will double in size

Measurements especially lifetimes will be increasingly systematics limited

Avoid monoculture: supporting and complementary measurements are important since NP small, e.g. lifetimes in Bs → J/ψη
Thoughts

The upgrade era is starting

ATLAS IBL, new CMS pixel detector are in LHCb upgrade after LS2 in ~2020

LHC upgrade era $\phi_s$ will be measured to 0.2°

Limit New Physics amplitude to the % level

arxiv:1309.2293
Thoughts

The upgrade era is around the corner

Early days of LHCb upgrade provides many interesting opportunities

Lifetimes, $\Delta m_s$ ideal first measurements to demonstrate new detector capabilities (as was case in 2010)

Bonus: New pixel detector with better performance very different systematic uncertainties

Since systematics are important mandatory to cross-check results with different modes, techniques and experiments

Run 2 and Run 3 provide opportunity to make precision measurement of $b$ baryon/hadron lifetimes, testing HQET
Summary

B_s mixing parameters known with precision after Run 1

- No sign of New Physics 😞

Run 2 results expected soon: improved precision

- Both tree-level and with charmless decays

Important to exploit precision by controlling theoretical uncertainties and exploiting data driven approaches to this

- Ensure that less headline impact supporting measurements and cross-checks get done

Run 3: will give even larger datasets, with new and more precision detectors
Backup
\( \text{B}_s \text{ mixing} \)

http://www.slac.stanford.edu/xorg/hflav/