CP violation, mixing and semi-leptonic decays of beauty at the LHC

Matthew Needham
University of Edinburgh
On behalf of the ATLAS, CMS and LHCb collaborations
Outline

Review measurements of B mixing parameters at the LHC

• B mixing
• $B_s$ mixing phase, $\phi_s$
• Semi-leptonic asymmetries: $a_{sl}$
• $\Delta \Gamma_d$ and $\Delta m_d$
• Summary

Huge number of Run 1 results
Impossible to present everything in 20 minutes. Focus on more recent results. Not covered $\sin2\beta$ and $\Delta m_s$
Neutral B meson mixing

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

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

\[ \Delta m_{d} \sim 0.5 \text{ ps}^{-1} \]

Slow B_d oscillations
Fast B_s oscillations
**B_s meson mixing**

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

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

\[ \Delta m_s = M_H - M_L \]

Physical states \( B_H \) and \( B_L \)

\( \tau_L \sim 1.4 \text{ ps}, \tau_H \sim 1.6 \text{ ps} \)

Observable phase

\[ \phi_s = -2\beta_s = \Phi_M - 2\Phi_D \]

In the Standard Model expected to be small \( \phi_s = -0.04 \text{ radian} \)

Larger values possible in models of New Physics such as Supersymmetry and Little Higgs
Measuring the $B_s$ mixing phase

- Golden mode to $\Phi$s measure is $B_s \rightarrow J/\psi \phi$
- Distinct experimental signature with low background
- But not CP eigenstate: Time dependent angular analysis needed

Polarization amplitudes
- $A(\text{perp})$ CP odd
- $A_0$ and $A(\text{para})$ CP even

Transversity angles
$\Omega = \theta, \phi, \psi$

CP eigenstate modes also studied by LHCb ($B_s \rightarrow J/\psi f^0$, $B_s \rightarrow D_s^+ D_s^-$). No angular analysis but lower yields
Measuring the $B_s$ mixing phase

Tagging of $b$ flavour at production

Asymmetry $\propto \sin 2\beta_s \times \sin \Delta m t$

For tagged $B_s$

[SM x 10 for visibility]

Good primary + secondary vertexing to measure proper time

Mass + pointing constraints to reduce background

Primary Vertex

Precision tracking crucial
Measuring the $B_s$ mixing phase

ATLAS, CMS, LHCb have all performed full angular analyses of $B_s \rightarrow J/\psi \phi$ using full Run 1 dataset.

[Graphs showing data from ATLAS, CMS, and LHCb]
Measuring the $B_s$ mixing phase

Unbinned maximum likelihood fit to mass, time and angles

Angular acceptance for signal from simulation

Mass sidebands or sWeight (arxiv: 0905.0724) technique to determine angular distribution of background

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

Decay time acceptance due to selection

Decay time Resolution model

Mass distribution

PRL 114 (2015) 041801

arXiv:1601.03297

PLB 757 (2016) 97
Measurement of the CP-violating phase $\phi_s$ and the $B_s \rightarrow J/\psi\phi$ meson decay width difference with $B_s \rightarrow J/\psi$ decays in ATLAS

The ATLAS Collaboration

Abstract

A measurement of the $B_s$ decay parameters in the $B_s \rightarrow J/\psi\phi$ 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 $s$ and the width difference between the mass eigenstates $s$. 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:

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

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

$$\Gamma_s = 0.677 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1}.$$
CMS: $B_s \to J/\psi \phi$

Using pp collision data collected by the CMS experiment at a centre-of-mass energy of 8 TeV and corresponding to an integrated luminosity of $19.7 \text{ fb}^{-1}$, $49,200 \, B_0^s \to J/\psi f(1020)$ signal candidates were used to measure the weak phase $f_s$ and the decay width difference $\Delta \Gamma_s$. The analysis was performed by using opposite-side lepton tagging of the $B_0^s$ flavour at the production time. Both muon and electron tags were used.

Transversity angles

$$\phi_s = -0.075 \pm 0.097 \text{ (stat)} \pm 0.031 \text{ (syst)} \text{ rad},$$

$$\Delta \Gamma_s = 0.095 \pm 0.013 \text{ (stat)} \pm 0.007 \text{ (syst)} \text{ ps}^{-1}.$$
LHCb: $B_s \rightarrow J/\psi \phi$

Helicity angles

Background subtracted using sweight technique

CP Even
CP Odd
S-wave
LHCb: $B_s \rightarrow J/\psi \pi^+ \pi^-$

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

$B_s \rightarrow J/\psi \phi$

\[ \phi_s = -0.058 \pm 0.049 \pm 0.006 \, \text{rad} \]
\[ \Delta m_s = 17.711 \pm 0.055 \pm 0.011 \, \text{ps}^{-1} \]
\[ \Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \, \text{ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \, \text{ps}^{-1} \]
\[ |\lambda| = 0.964 \pm 0.019 \pm 0.007 \]

$\phi_s = 75 \pm 67 \pm 8 \, \text{mrad}$.  

$B_s \rightarrow J/\psi \pi^+ \pi^-$

Combined

$\phi_s = -0.010 \pm 0.039 \, \text{rad}$
Results consistent with Standard Model
Still room for New Physics amplitude at level of 10% in $B_s$ mixing (Similar story in $B_d$ sector)

Can expect updates with Run 2 data

Precision at <0.02 rad level by end of Run II
Penguin pollution

Penguin contributions could mimic NP effects

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

\[
A ( B_s^0 \rightarrow (J/\psi K^{*0} )_i ) = -\lambda A_i [ 1 - a_i e^{i\theta_i} e^{i\gamma} ]
\]
The longitudinal (top), parallel (middle) and perpendicular (bottom) polarisations are shown.

B derived from the Figure 8: Limits on the penguin parameters. Superimposed are the confidence level contours obtained from a fit to CP observables + polarization amplitudes in $B_s \rightarrow J/\psi K^*$, $B^0 \rightarrow J/\psi \rho$

Effect of penguins bounded to be less than current uncertainties.

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

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

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

$\Delta \phi_{s,\perp}^{J/\psi \phi} = 0.003^{+0.010}_{-0.014}$ (stat) $\pm 0.008$ (syst) rad .
B$_s \rightarrow J/\psi \eta$ effective lifetime

$B_s \rightarrow J/\psi X$

Use $\eta \rightarrow \gamma\gamma$ decay mode

3021 +/- 73 signal candidates.
Extract Effective lifetime from 2-D fit to mass and lifetime distributions.
\[ \tau_{\text{eff}} = 1.479 \pm 0.034 \text{ (stat)} \pm 0.011 \text{ (syst)} \text{ ps} \]

Agrees with measurements in other modes and theory expectations
CP violation in B mixing

\[ \mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q) \]

\[ a_{sl} \equiv \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\bar{B} \to f) + \Gamma(B \to \bar{f})} \approx \frac{\Delta \Gamma}{\Delta m} \tan \phi_{12} \]

Probes with semileptonic decays (flavour specific)

\[ B_d^0 \to D^- \mu^+ \nu_\mu X \quad a_{sl}^d \]
\[ B_s^0 \to D_s^- \mu^+ \nu_\mu X \quad a_{sl}^s \]

SM values
Artuso, Borissov and Lenz
arXiv: 1511.09466
Story so far…

Status at start of this year….

![Graph showing CP violation](image)

- Known tension of D0 like sign dimuon measurement with SM

---

The graph shows the latest results from various experiments comparing to the Standard Model prediction. The horizontal axis represents the mixing-induced CP violation parameter $a_{sl}^d$, while the vertical axis shows the measurements in percentage deviation from the Standard Model prediction. The points represent the results from different experiments, including LHCb, D0, BaBar, and Belle. The latest result from HFAG Fall '14 is highlighted in yellow, showing a deviation from the expected SM prediction.
Untagged time integrated counting experiment

\[ A_{\text{raw}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)} \]

\[ a_{sl}^s = \frac{2}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_{\text{det}} - f_{\text{bkg}} A_{\text{bkg}}) \]

\( A_{\text{det}} \) is determined using data driven methods
Results

$\alpha_{sl}^s (0.39 \pm 0.26 \pm 0.20)\%$
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)

New measurement by ATLAS

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

arXiv:1605.07485
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

\begin{align*}
ΔΓ_d/Γ_d \text{ (SM)} &= (0.42 \pm 0.08) \times 10^{-2}
\end{align*}

- Delphi
- BaBar
- LHCb
- Belle
- ATLAS
- HFAG (Spring 2016)

Standard Model

LHCb result is only with fraction of Run 1 dataset

Value needed to explain D0 result
Δm_s now precisely known

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

Limitation on knowledge of UT sides from lattice (improving fast) and Δm_d

New LHCb measurement uses \( B^0 \rightarrow D(*) \mu \nu \) decays

LHCb Single most precise measurement

Δm_d = (505.0 \pm 2.1 \text{ (stat)} \pm 1.0 \text{ (syst)}) \text{ ns}^{-1}
Summary

• Measurements of all $B_s$ mixing parameters made during Run 1 of LHC

  • Not covered in this talk: $\Delta m_s$, $\sin 2\beta$

  • LHC experiments producing high precision results with low systematic uncertainties

• Run 1 measurements still coming out, e.g. $B_s \rightarrow J/\psi \eta$, $\tau_{\text{eff}}$

• Run 1 results consistent with Standard Model

  • But still room for new physics at 10 % level

• Significant improvement coming with Run II and beyond
Backup