Mixing and CP violation in the B^0 and B_s systems

G. Borissov,
Lancaster University, UK
On behalf of ATLAS Collaboration

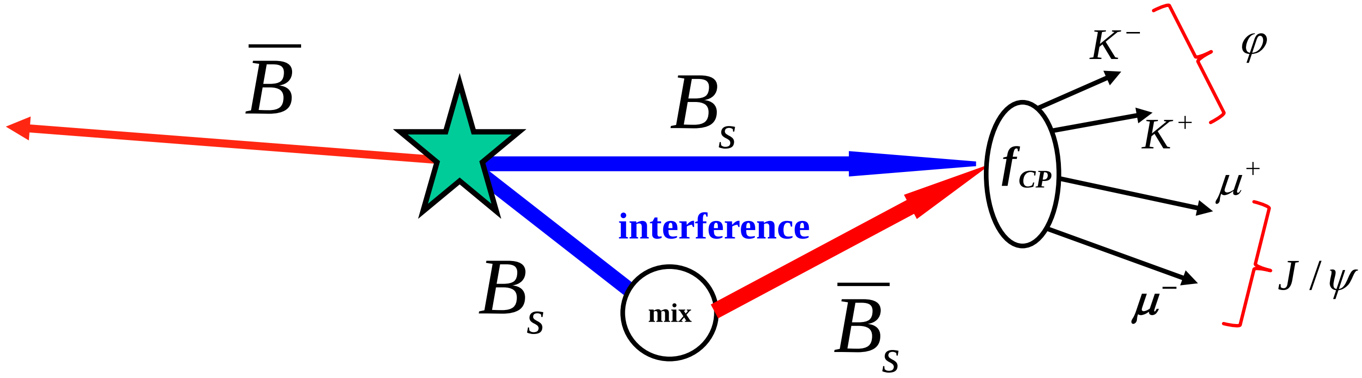
DIS-2016 conference
Hamburg, 12 April 2016

B physics in ATLAS

- ATLAS collaboration is very active in *B* physics
- In this talk, some of our recent results are presented
  - Study of CP violation in $B_s \to J/\psi\ \varphi$ decay
  - Measurement of the width difference of B^0 meson

CP-violation in $B_s \to J/\psi\ \varphi$ decay

- Interference of B_s decays with and without mixing to the final state accessible to both B_s and $\overline{B}_s$ results in CP violation

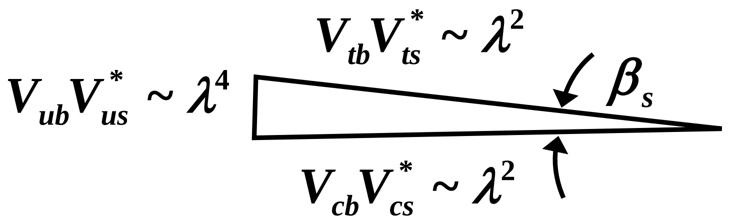


$$\Gamma(B_s(\to \overline{B}_s) \to f_{CP}) \neq \Gamma(\overline{B}_s(\to B_s) \to f_{CP})$$

CP violation in $B_s \to J/\psi\ \varphi$ decay

- CP asymmetry in $B_s \to J/\psi\varphi$ decay is described by the phase $\phi^{J/\psi\varphi}$
- Within the SM $\phi^{J/\psi\varphi}$ is related with the angle β_s of the (bs) unitarity triangle:

$$\phi^{J/\psi\varphi,SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = -0.0363^{+0.0016}_{-0.0015}$$



- $\phi^{J/\psi\varphi}$ can be modified by the new physics:

$$\phi^{J/\psi\varphi} = \phi^{J/\psi\varphi,SM} + \phi_s^{NP}$$

- This possibility explains elevated interest to this decay mode
- The precise measurements of $\phi^{J/\psi\varphi}$ by the LHC experiments considerably reduced the possible amount of new physics contribution
- Still, the precise measurement of $\phi^{J/\psi\varphi}$ is essential to test the SM and to study the possible new physics extensions

Analysis of ATLAS data

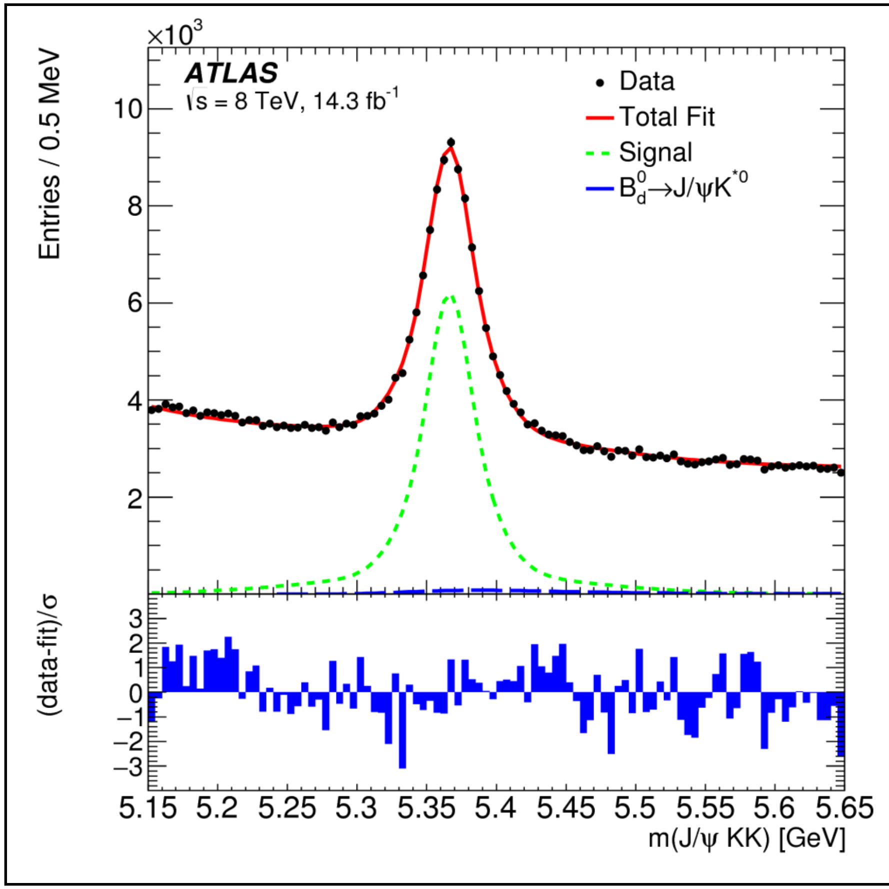
- Analysis of 2011 ($\sqrt{s}$ = 7 TeV) and 2012 ($\sqrt{s}$ = 8 TeV) data samples is completed
- Results obtained with 2011 data is published
  - Phys. Rev. D90 (2014), 052007

$$\phi^{J/\psi\varphi} = 0.12 \pm 0.25\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\,(\text{stat}) \pm 0.010\,(\text{syst})$$

- New result based on 2012 data is released recently
  - arXiv: 1601.03297
  - It is discussed in detail in this talk

Analysis of 2012 data

- Events are selected using dimuon triggers
  - Muon p_T threshold is either 4 or 6 GeV
- Lifetime-unbiased reconstruction
- In total 376K event candidates are selected with $5.15 < m(J/\psi\varphi) < 5.65$ GeV
  - About 75K signal events
  - About 3.5 times more signal events than in 2011 analysis

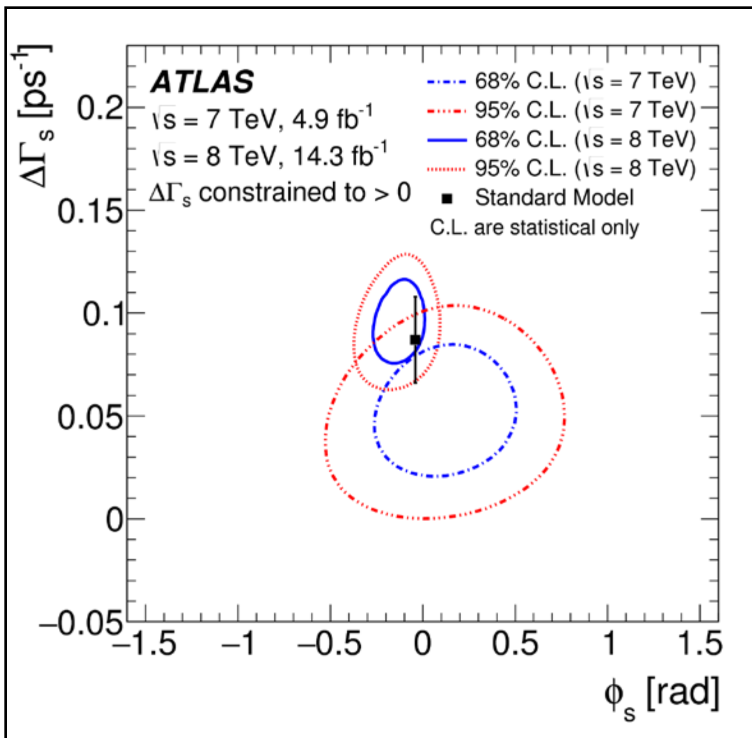


Results

- From the likelihood fit we obtain:

$$\phi^{J/\psi\varphi} = -0.123 \pm 0.089\,(\text{stat}) \pm 0.041\,(\text{syst})$$
$$\Delta\Gamma_s = 0.096 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})$$

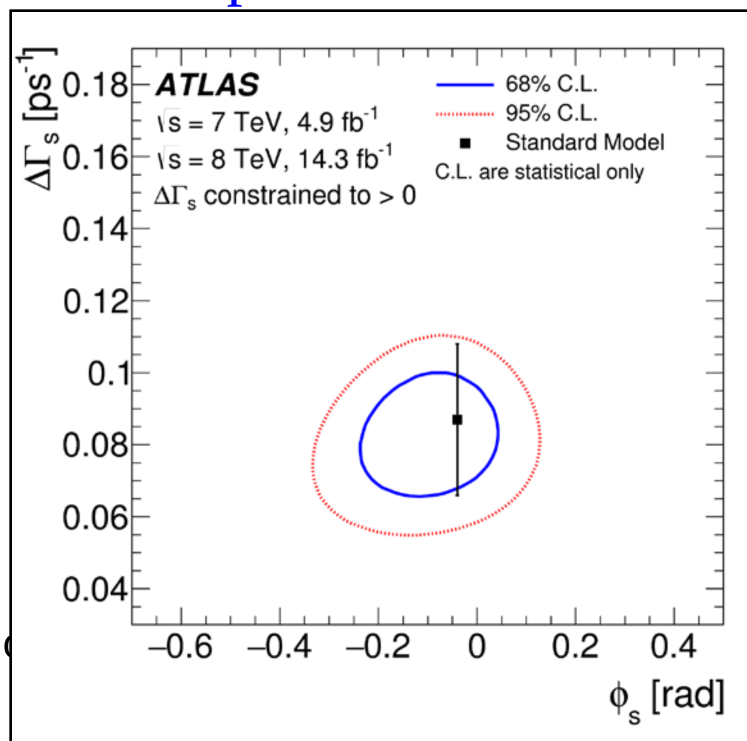
- Results of 2011 and 2012 are consistent



- Combination of 2011 and 2012 results gives:

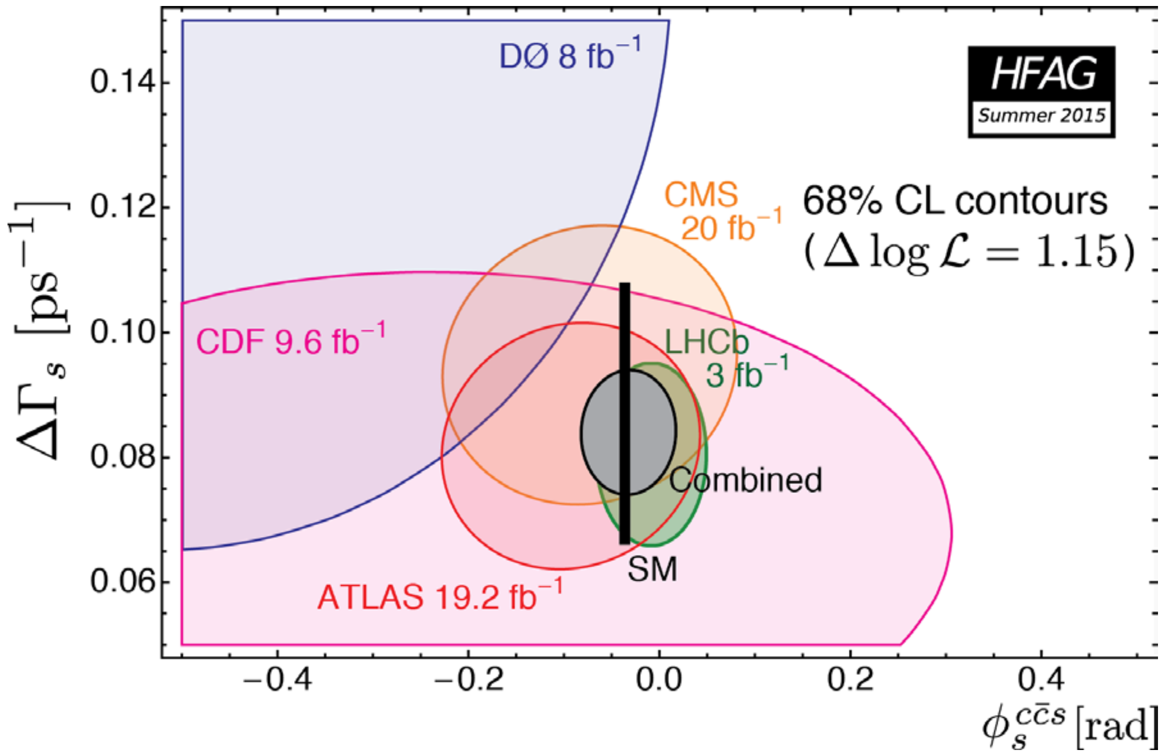
$$\phi^{J/\psi\varphi} = -0.098 \pm 0.084\,(\text{stat}) \pm 0.040\,(\text{syst})$$
$$\Delta\Gamma_s = 0.083 \pm 0.011\,(\text{stat}) \pm 0.007\,(\text{syst})$$

- Result agrees well with the SM expectation



Comparison with other experiments

- Results of ATLAS are consistent with other measurements of CP violation in this B_s decay



Width difference of B_d

- $\Delta\Gamma_d$ is one of the parameters describing the time evolution of the B_d system
- It is reliably predicted in the Standard Model

$$\Delta\Gamma_d = (0.42 \pm 0.08) \times 10^{-2} \text{ (SM)}$$

- Current experimental uncertainty is too large to allow a comparison with the SM prediction

$$\Delta\Gamma_d = (0.1 \pm 1.0) \times 10^{-2} \text{ (World Average)}$$

- Additional measurements are required to constrain this quantity and verify the SM prediction

Measurement method

- $\Delta\Gamma_d$ is obtained from the ratio of the proper decay time distributions of $B^0 \to J/\psi\, K_s$ and $B^0 \to J/\psi\, K^{*0}$ decays
- Decay time distribution of $B^0 \to J/\psi\, K_s$ depends on $\Delta\Gamma_d$:

$$\Gamma[t, J/\psi K_S] \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} + \cos(2\beta)\sinh\frac{\Delta\Gamma_d t}{2} - A_{\rm P}\sin(2\beta)\sin(\Delta m_d t)\right]$$

  - t is the proper decay time of B^0 meson
  - β is the angle of the unitarity triangle
  - $A_{\rm P}$ is the production asymmetry of B^0 meson
- Decay time distribution of $B^0 \to J/\psi\, K^{*0}$ is almost not sensitive to $\Delta\Gamma_d$:

$$\Gamma[t, J/\psi K^{*0}] \propto e^{-\Gamma_d t}\cosh\frac{\Delta\Gamma_d t}{2}$$

  - Decays $B^0 \to J/\psi\, K^{*0}$ and $\overline{B^0} \to J/\psi\, \overline{K^{*0}}$ are added together

Measurement method

- Using the ratio of the distributions of the two decay modes helps to reduce the systematic uncertainties of the measurement
  - The same number of charged particles in these two decay modes
  - Both decay modes are triggered by the same di-muon triggers and the other particles from B^0 decay are not used in the trigger
  - The factor $e^{-\Gamma_d t}$ is cancelled in the ratio increasing the sensitivity to $\Delta\Gamma_d$

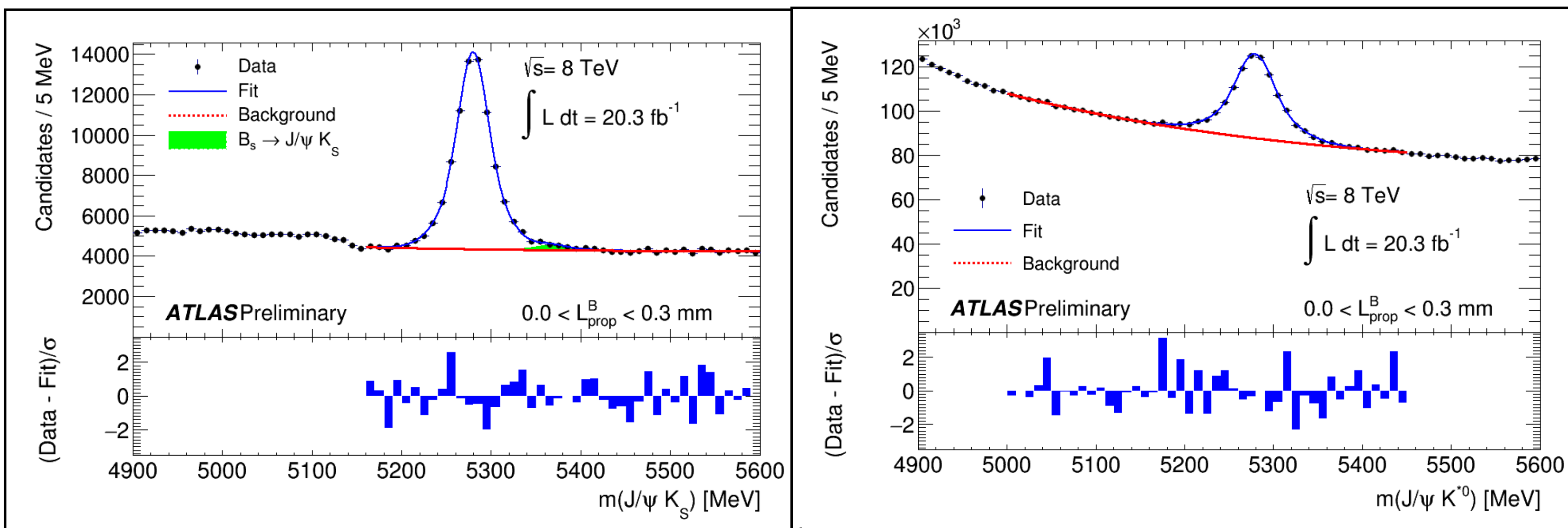
Essential ingredients of this measurement

- Measurement of the proper decay length (L_{prop}) distributions of $B^0 \to J/\psi\, K_s$ and $B^0 \to J/\psi\, K^{*0}$ decays
  - Proper decay length is equivalent to proper decay time: $L_{prop} = c\,t$
  - It is a three-dimensional decay length divided by γ-factor of B^0 meson
- Ratio of reconstruction efficiencies of $B^0 \to J/\psi\, K_s$ and $B^0 \to J/\psi\, K^{*0}$ decays
- Production asymmetry of B^0 meson

Proper decay length distributions

- The number of decays $B^0 \to J/\psi\, K_s$ and $B^0 \to J/\psi\, K^{*0}$ is measured in 10 intervals of the B^0 proper decay length (L_{prop})
  – The total range of L_{prop} is between −0.3 and 6 mm
  – The number of decay is obtained from the fit of the mass distributions
- Number of $B^0 \to J/\psi\, K_s$ and $B^0 \to J/\psi\, K^{*0}$ decays measured in each interval is used to obtain the ratio of the L_{prop} distributions of the two decay modes

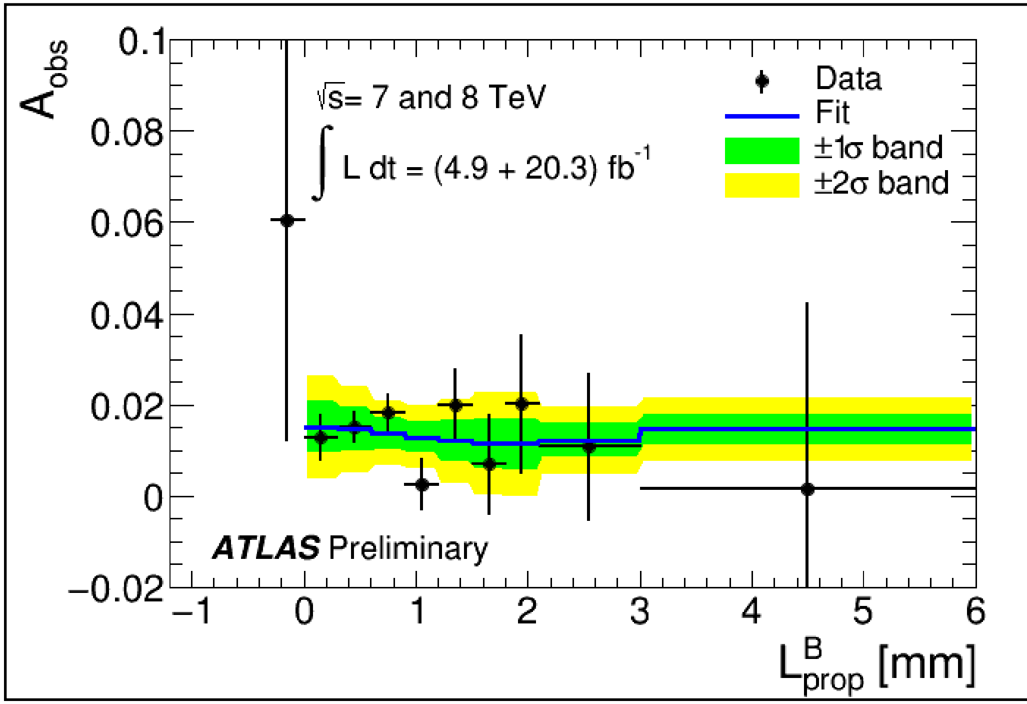
Example of the mass fit for $0 < L_{prop} < 0.3$ mm



B^0 production asymmetry

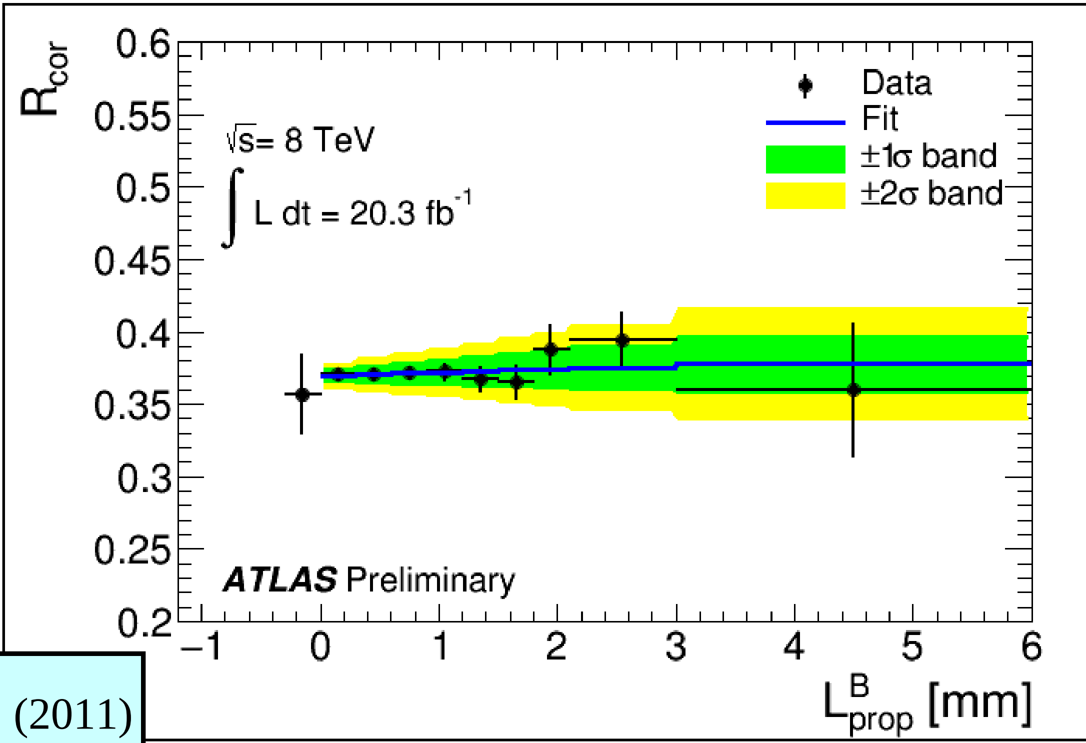
- B^0 production asymmetry (A_P) is expected to be ~1%
- It is measured using the dependence of the charge asymmetry of $B^0 \to J/\psi\, K^{*0}$ decay A_{obs} on L_{prop}
- This asymmetry should oscillate if there is a difference in the production rate between B^0 and $\overline{B}^0$
- ATLAS result:

$$A_P = (+0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$$



Measurement of $\Delta\Gamma_d$

- Ratio of L_{prop} distributions corrected by the ratio of reconstruction efficiencies is fitted to extract $\Delta\Gamma_d$
- Normalisation of the ratio is arbitrary
- Obtained result:



$$\frac{\Delta\Gamma_d}{\Gamma_d} = (-2.8 \pm 2.2(\text{stat}) \pm 1.7(\text{syst})) \times 10^{-2} \quad (2011)$$

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (+0.8 \pm 1.3(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-2} \quad (2012)$$

- Combination of these two measurements gives:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (-0.1 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-2}$$

Comparison with other experiments

- ATLAS result is consistent with other measurements of $\Delta\Gamma_d$

$$\Delta\Gamma_d / \Gamma_d = (-0.1 \pm 1.1 \pm 0.9) \times 10^{-2} \quad \text{(ATLAS)}$$

$$\Delta\Gamma_d / \Gamma_d = (-4.4 \pm 2.5 \pm 1.1) \times 10^{-2} \quad \text{(LHCb)}$$
$$\Delta\Gamma_d / \Gamma_d = (+1.7 \pm 1.8 \pm 1.1) \times 10^{-2} \quad \text{(Belle)}$$
$$\Delta\Gamma_d / \Gamma_d = (+0.8 \pm 3.7 \pm 1.8) \times 10^{-2} \quad \text{(Babar)}$$

- Currently, it is the most precise single measurement
- It is consistent with the SM prediction

$$\Delta\Gamma_d = (0.42 \pm 0.08) \times 10^{-2} \quad \text{(SM)}$$

Conclusions

- Analysis of Run I ATLAS data reveals no anomaly in $B_s \to J/\psi\varphi$ decay

$$\phi^{J/\psi\varphi} = -0.098 \pm 0.084\,(\text{stat}) \pm 0.040\,(\text{syst})$$
$$\Delta\Gamma_s = 0.083 \pm 0.011\,(\text{stat}) \pm 0.007\,(\text{syst})$$

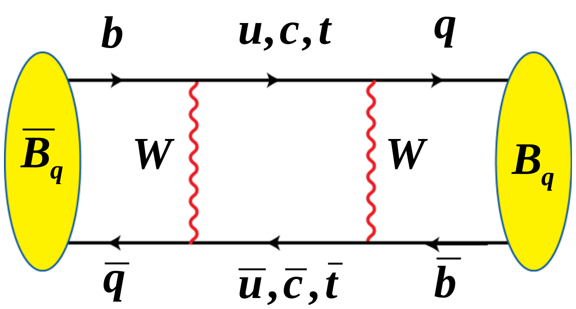
- ATLAS obtained the most precise single measurement of $\Delta\Gamma_d$:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (-0.1 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-2}$$

- Significant increase in statistics is expected in Rin II, and the precision of these measurements will be considerably improved

Backup slides

Neutral B_q system



- Dynamics of B_q meson ($q = d,s$) is described by 5 parameters:

$$m_q, \quad \Gamma_q, \quad \Delta m_q, \quad \Delta\Gamma_q, \quad \phi_q^{12}$$

- Δm_q and $\Delta\Gamma_q$ are the mass and width difference of two physical states B_q^H (heavy) and B_q^L (light)
  - With these definitions both Δm_q and $\Delta\Gamma_q$ positive in the SM
- m_q^{12} and Γ_q^{12} are non-diagonal elements of the **(m-*i*Γ/2)** matrix

$$\|\mathbf{m}_q\| = \begin{bmatrix} m_q & m_q^{12} \\ (m_q^{12})^* & m_q \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_q & \Gamma_q^{12} \\ (\Gamma_q^{12})^* & \Gamma_q \end{bmatrix}$$

$$\Delta m_q = m_{q,H} - m_{q,L} \approx 2\left|m_q^{12}\right|$$

$$\Delta\Gamma_q = \Gamma_{q,L} - \Gamma_{q,H} \approx 2\left|\Gamma_q^{12}\right| \cos\phi_q^{12}$$

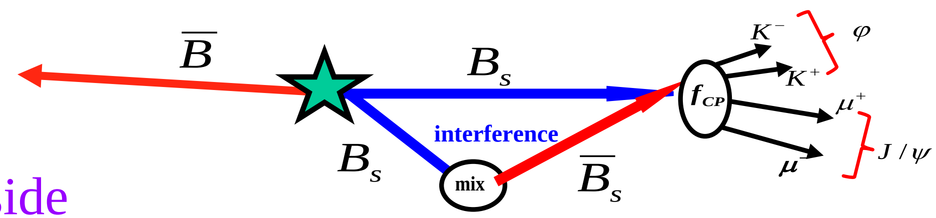
$$\phi_q^{12} = \arg\left(-\frac{m_q^{12}}{\Gamma_q^{12}}\right)$$

Initial state flavour tagging

- Tagging of the initial flavour (B_s or $\overline{B}_s$) is essential for CP violation study
  - We need to measure the difference between

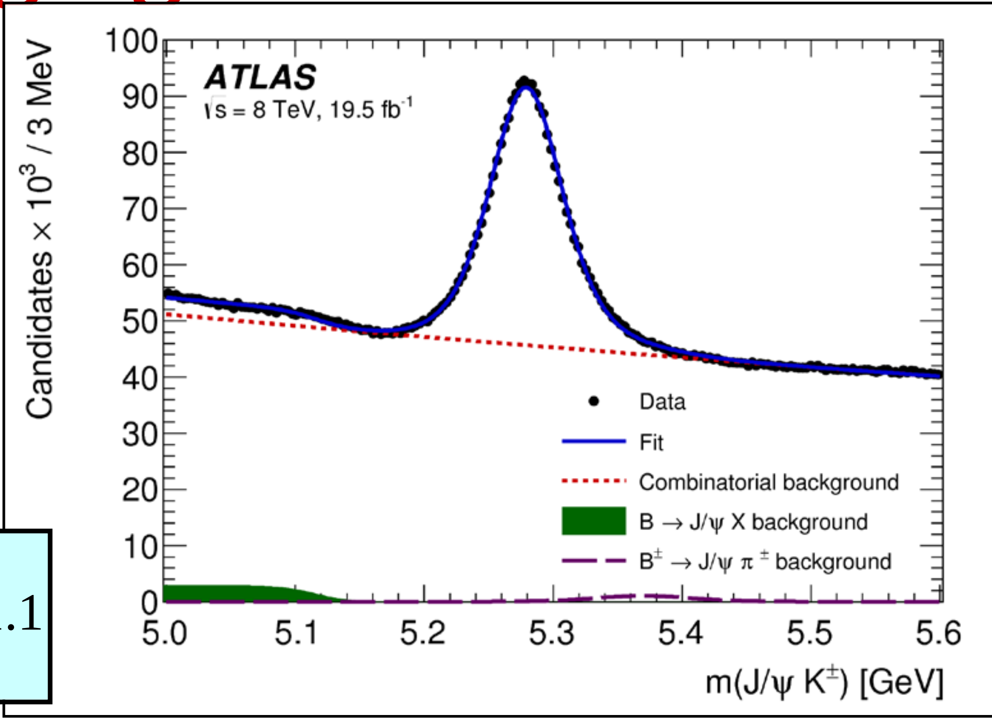
$$\Gamma(B_s(\to \overline{B}_s) \to f_{CP}) \text{ and } \Gamma(\overline{B}_s(\to B_s) \to f_{CP})$$

- In ATLAS the initial B_s flavour is determined by the flavour of the opposite B meson



- Several tagging methods are used
  - Muon or electron from the opposite side
  - Jet charge of the jet with maximal b-tagging value
    - Tracks forming B_s candidate are excluded from the jet charge measurement
- Achieved tagging power is (1.49±0.02)%
    - Tagging power shows the effective fraction of statistics with 100% correct initial flavour measurement

Flavour tagging: details



- Flavour tagging is calibrated using $B^{\pm} \to J/\psi\, K^{\pm}$ events
- Both for the muon charge and for the jet charge the tagger is computed as:

$$Q = \frac{\sum_i q^i (p_T^i)^k}{\sum_i (p_T^i)^k}; \quad k = 1.1$$

  - For muon the sum is taken over tracks in $\Delta R<0.5$ cone around the muon
  - For jet the sum is taken over all tracks in the jet

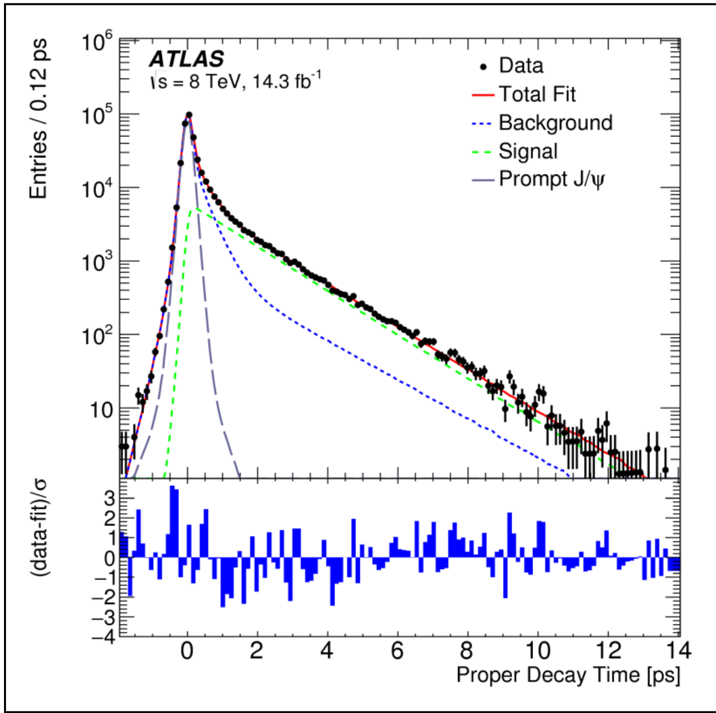
Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined μ	4.12 ± 0.02	47.4 ± 0.2	0.92 ± 0.02
Electron	1.19 ± 0.01	49.2 ± 0.3	0.29 ± 0.01
Segment-tagged μ	1.20 ± 0.01	28.6 ± 0.2	0.10 ± 0.01
Jet-charge	13.15 ± 0.03	11.85 ± 0.03	0.19 ± 0.01
Total	19.66 ± 0.04	27.56 ± 0.06	1.49 ± 0.02

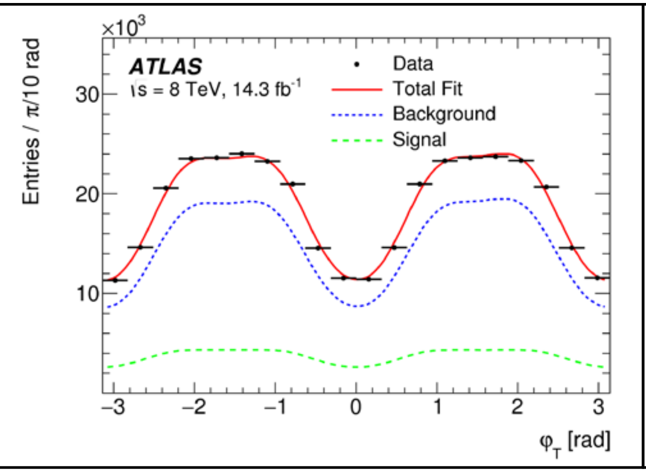
Unbinned maximum likelihood fit

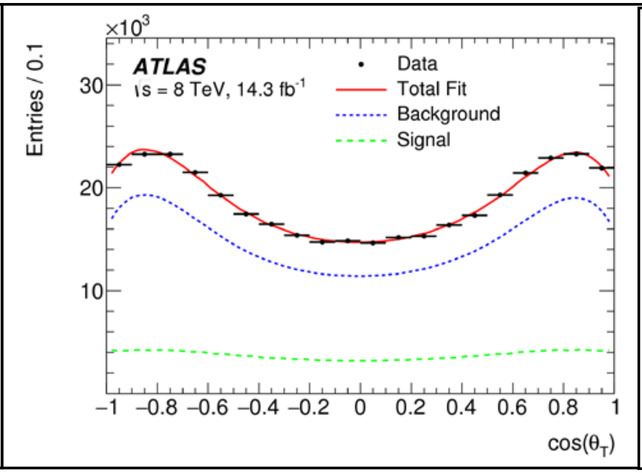
The properties of $B_s \rightarrow J/\psi\varphi$ decay are obtained from the unbinned maximum likelihood fit which includes:

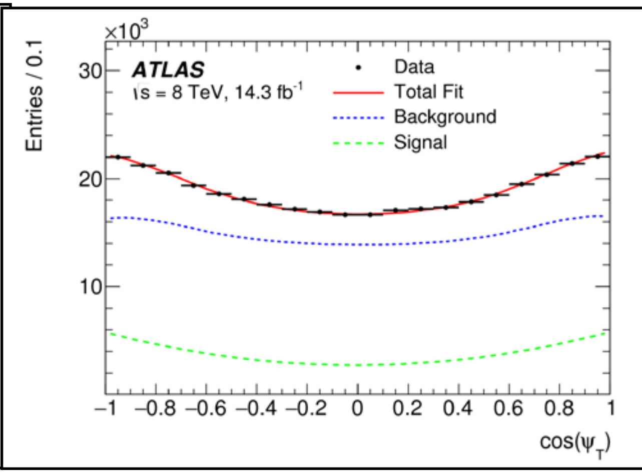
- Mass of $J/\psi\varphi$ system and its uncertainty
- p_T of B_s candidate
- Proper decay length and its uncertainty
- Angles describing the kinematics of B_s decay
- Flavour tagging

- Good quality of the fit is confirmed by the projection of the fit on all variables





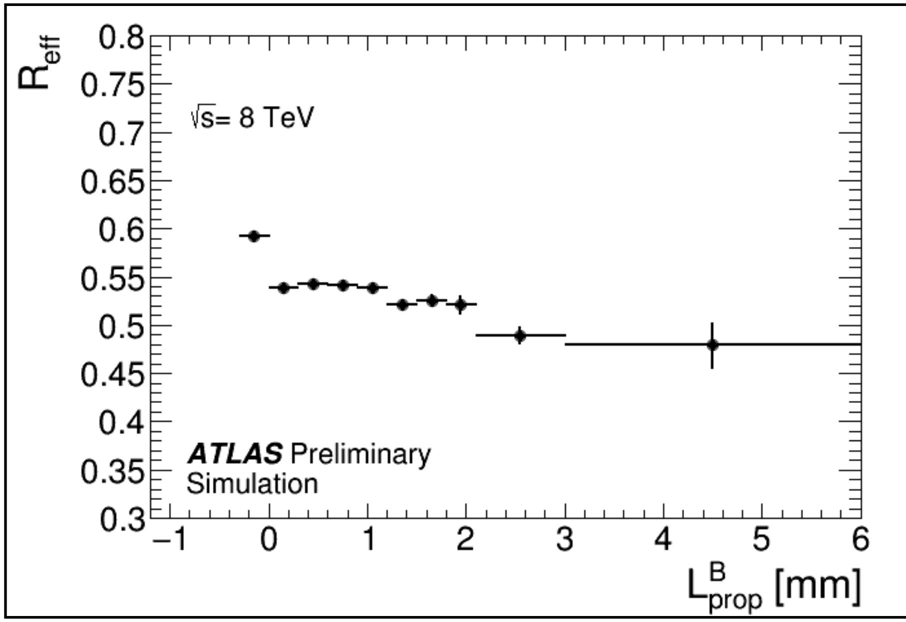




Ratio of reconstruction efficiencies

- The ratio of the L_{prop} distributions should be corrected by the ratio of the reconstruction efficiencies of the $B^0 \to J/\psi\ K_s$ and $B^0 \to J/\psi\ K^{*0}$ decays
- This ratio is obtained from MC
- In this ratio, many inefficiencies of two channels cancel
- The deviation of this ratio from the average value does not exceed 5% for L_{prop} < 2 mm

Ratio of reconstruction efficiencies of $B^0 \to J/\psi\ K_s$ and $B^0 \to J/\psi\ K^{*0}$ decays
Normalisation is arbitrary



Systematic uncertainties

- Systematic uncertainty has a large contribution from the available number of MC events
- Can be improved in the future

Source	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2011	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2012
K_S decay length	0.21×10^{-2}	0.16×10^{-2}
K_S pseudorapidity	0.14×10^{-2}	0.01×10^{-2}
$B^0 \to J/\psi K_S$ mass range	0.47×10^{-2}	0.59×10^{-2}
$B^0 \to J/\psi K^{*0}$ mass range	0.30×10^{-2}	0.15×10^{-2}
Background description	0.16×10^{-2}	0.09×10^{-2}
$B_s^0 \to J/\psi K_S$ contribution	0.11×10^{-2}	0.08×10^{-2}
$L_{\rm prop}^B$ resolution	0.29×10^{-2}	0.29×10^{-2}
Fit bias (Toy MC)	0.07×10^{-2}	0.07×10^{-2}
B^0 production asymmetry	0.01×10^{-2}	0.01×10^{-2}
MC sample	1.54×10^{-2}	0.45×10^{-2}
Total uncertainty	1.69×10^{-2}	0.84×10^{-2}