# CPV, oscillations and rare B-decays in RUN 1

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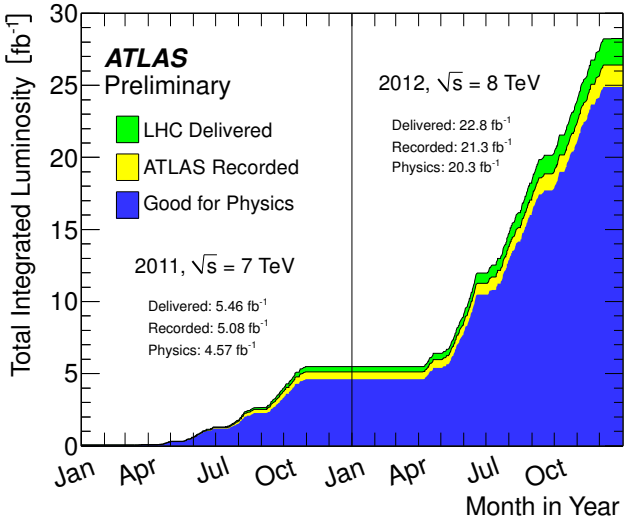
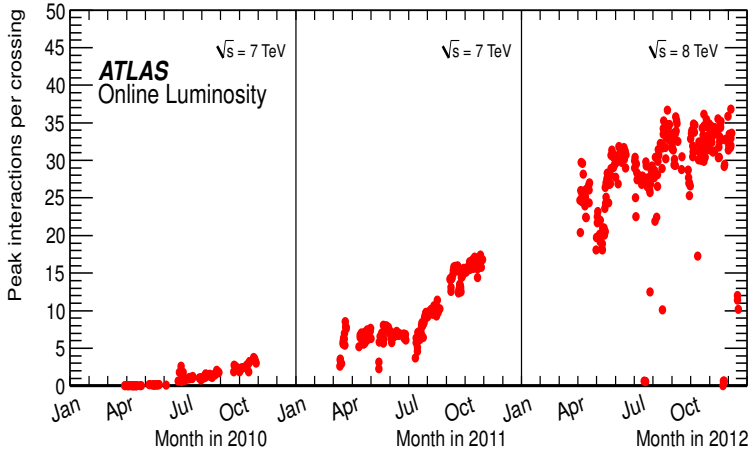
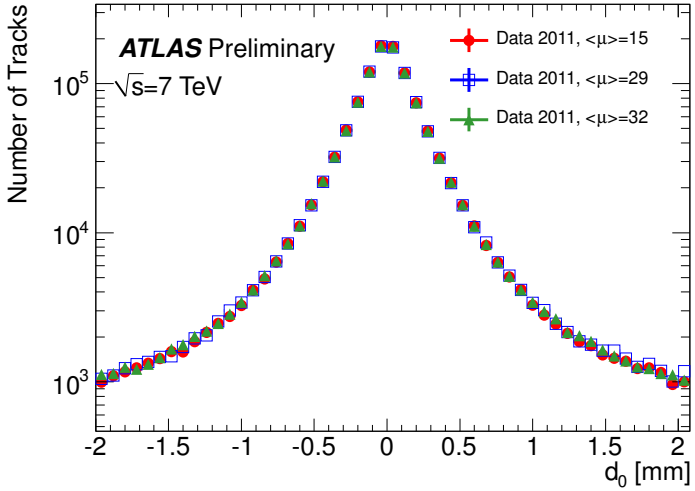
May 6, 2016

# Run1 data, ATLAS performance




- Precise tracking is essential for B-physics
- With increasing pileup, the quality of tracking, vertexing was improved to achieve stability
  - d0 resolution (the width of main peak) remained unchanged
  - tails are potentially sensitive to fakes: no increase in the fake rate observed

# $B_s^0 \to J/\psi\phi$ measurement of $\Delta\Gamma_s$ and the CPV Phase $\phi_s$

## Physics Motivation

- $B_s^0 \to J/\psi\phi$ expected to be sensitive to BSM physics
- CP-violation phase: $\phi_s$
  - *CPV* due to interference between:
    - Direct decay
    - Flavour oscillation
- SM Predictions:
  - $\phi_s = -0.0364 \pm 0.0016$ [rads]
  - Indirect determination via global fits
  - SM precision much smaller than experimental
  - Experimental measurement a viable BSM search

# Methodology - fit

## Time-Dependent Angular Analysis

- Observables:
  - Mass, lifetime, $p_T$, transversity angles, initial flavour
  - Per-candidate errors
- UMLF $\to$ Physics parameters:
  - $\phi_s$ $\Delta\Gamma_s$ $\Gamma_s$
  - transversity amplitudes: $|A_0(0)|^2$, $|A_{\|}(0)|^2$ , $|A_S(0)|^2$, $\delta_\perp$ , $\delta_{\|}$, $\delta_\perp - \delta_S$

# Methodology - tagging

## OST Tagging

- Detect decay of pair-produced b
  - $p_T$ weighted sum of charges from decay
- Per-event tagger/probability:
  - Muon, electron (2012), jet-charge
- Calibrated with $B^{\pm} \to J/\psi K^{\pm}$
- Tagging applied probabilistically in fit

| Tagger | Efficiency [%] | Dilution [%] | Tagging Power [%] |
|---|---|---|---|
| Combined muon | $4.12 \pm 0.02$ | $47.4 \pm 0.2$ | $0.92 \pm 0.02$ |
| Electrons | $1.19 \pm 0.01$ | $49.2 \pm 0.3$ | $0.29 \pm 0.01$ |
| Segment Tagged muon | $1.20 \pm 0.01$ | $28.6 \pm 0.2$ | $0.10 \pm 0.01$ |
| Jet charge | $13.15 \pm 0.03$ | $11.85 \pm 0.03$ | $0.19 \pm 0.01$ |
| Total | $19.7 \pm 0.04$ | $27.6 \pm 0.06$ | $1.49 \pm 0.02$ |

# Mass/Lifetime Fits

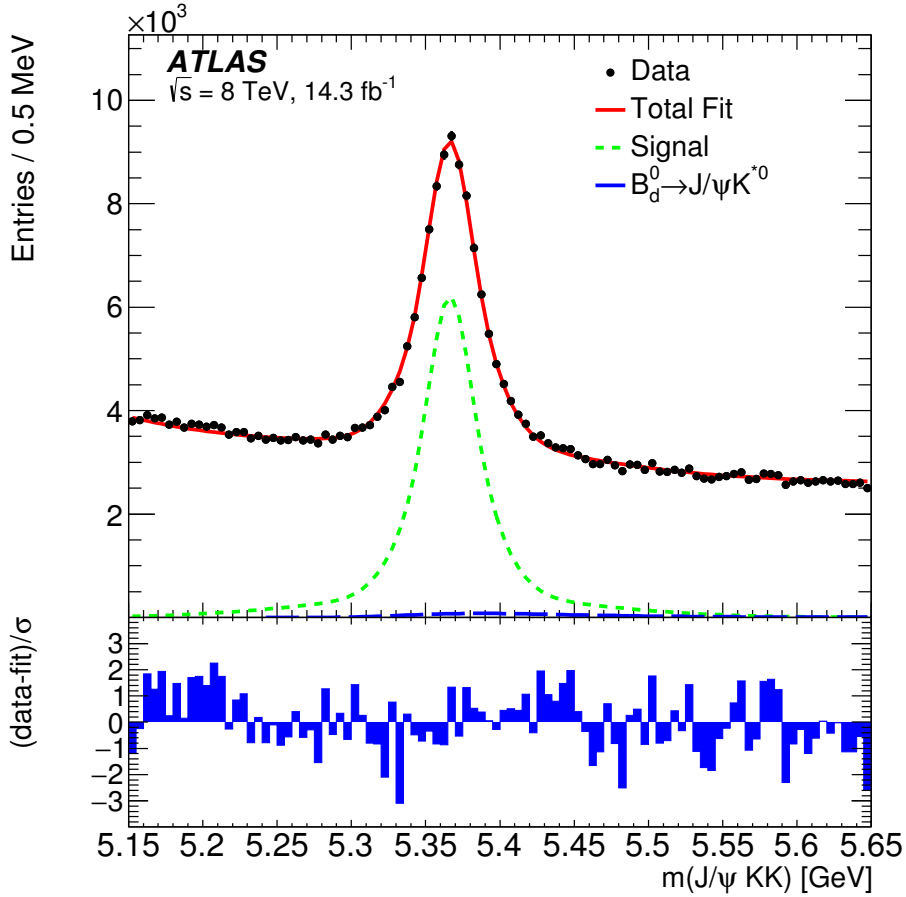



Figure: $B_s^0$ mass distribution (2012)

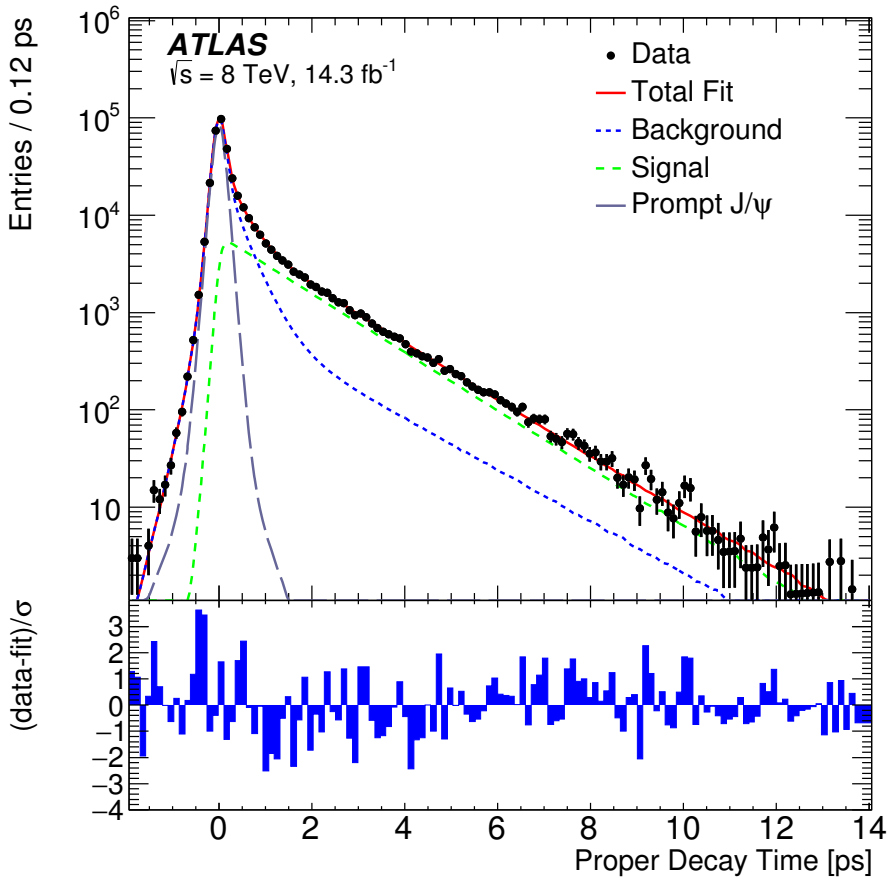



Figure: $B_s^0$ lifetime distribution (2012)

# Angular Projection Fits

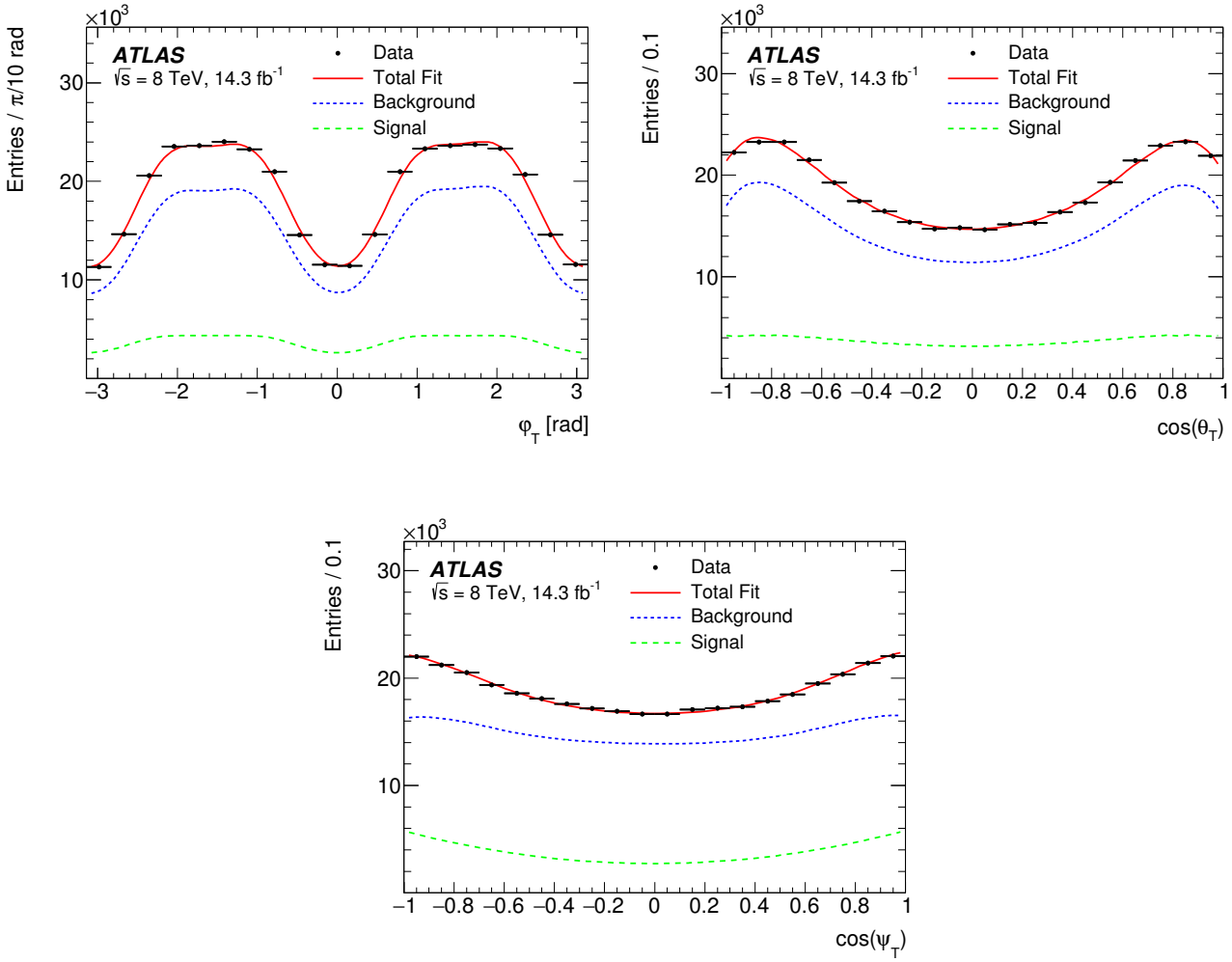



Figure: $B_s^0$ angular fit projections

# 2D Scans - $\phi_s$ v's $\Delta\Gamma_s$

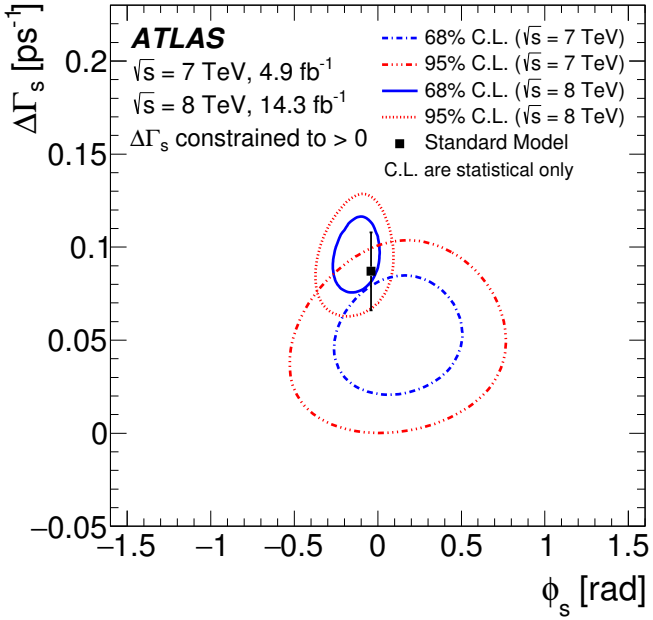



Figure: 2D scan (2011/2012)

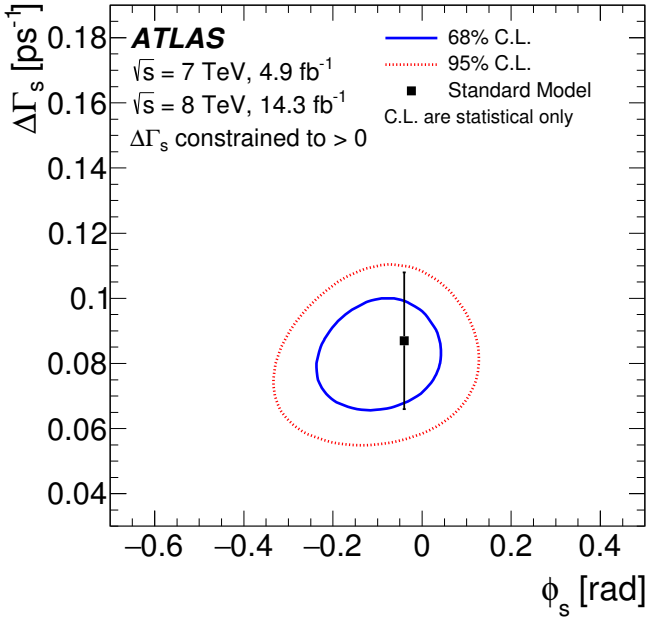


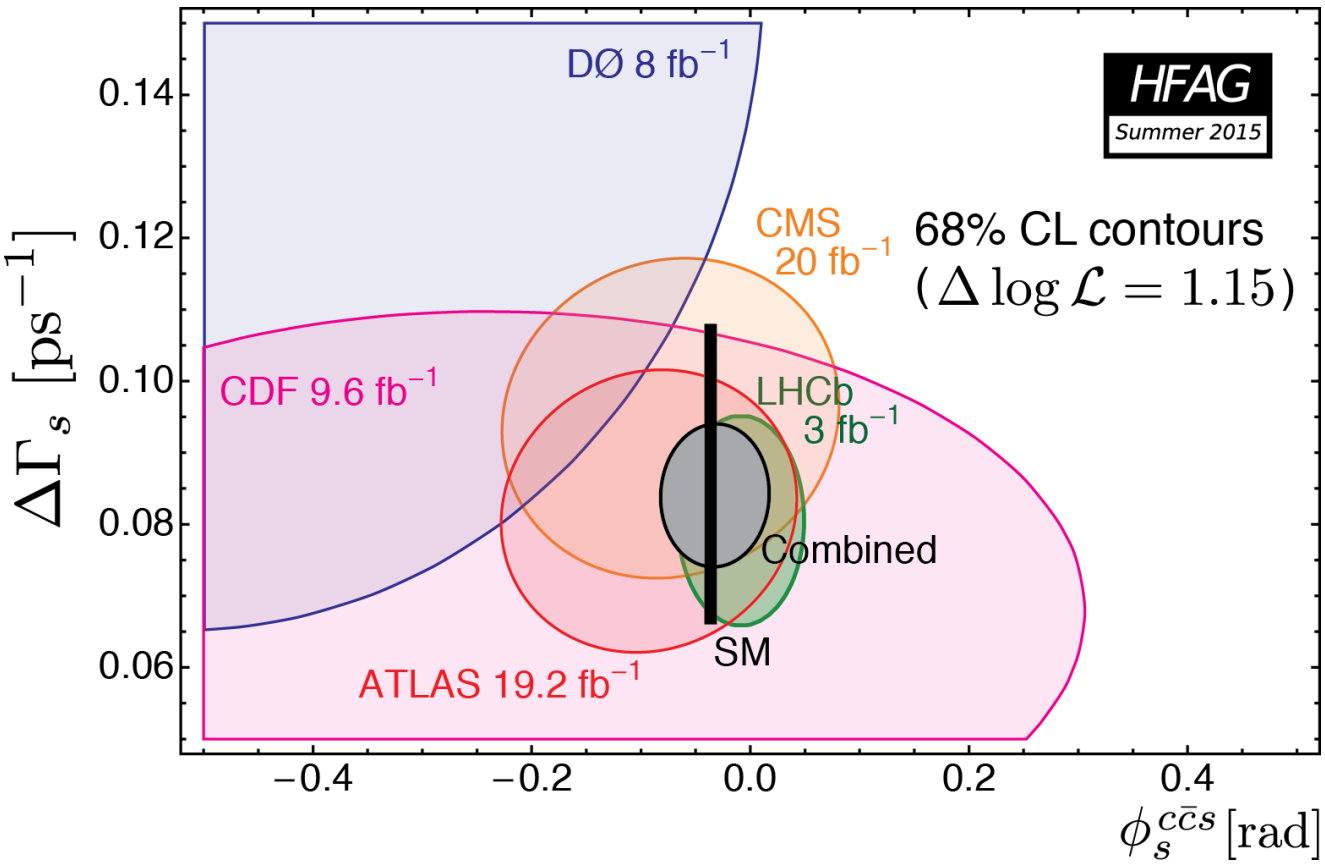

Figure: 2D scan (Run 1)

# $B_s^0 \to J/\psi\phi$ Run 1 Results

| Parameter | Value | Stat | Systematic |
|---|---|---|---|
| $\phi_s$ rad | - 0.098 | 0.084 | 0.040 |
| $\Delta\Gamma_s$ [ps$^{-1}$] | 0.083 | 0.011 | 0.007 |
| $\Gamma_s$ [ps$^{-1}$] | 0.677 | 0.003 | 0.003 |
| $\lvert A_0(0)\rvert^2$ | 0.514 | 0.004 | 0.003 |
| $\lvert A_\parallel(0)\rvert^2$ | 0.227 | 0.004 | 0.006 |
| $\lvert A_S(0)\rvert^2$ | 0.071 | 0.007 | 0.017 |
| $\delta_\perp$ [rad] | 4.13 | 0.33 | 0.16 |
| $\delta_\parallel$ [rad] | 3.15 | 0.13 | 0.05 |
| $\delta_\perp - \delta_S$ [rad] | - 0.08 | 0.04 | 0.01 |

Table: Run 1 result

# $B_s^0 \to J/\psi\phi$ Comparison, Conclusion




- All existing data consistent between each other and with the SM
  - HFAG used Preliminary ATLAS version, May 2015, ATLAS ArXive numbers - presented here - slightly differ
- Room for NP in CPV $\phi_s$, need Run2 and LHC upgrade

# Width difference of $B_d^0$

## Physics motivation

- $\Delta\Gamma_d$ is one of the parameters describing the time evolution of the $B_d^0$ system
- It is reliably predicted in the Standard Model

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

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

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

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

# $\Delta\Gamma_d$ measurement method

$\Delta\Gamma_d$ determined from ratio of proper decay time distributions of $B_d^0 \to J/\psi K_S^0$ and $B_d^0 \to J/\psi K^*$

- $B_d^0 \to J/\psi K_S^0$

$$\Gamma_d(t) \sim e^{-\Gamma t}(\cosh \frac{\Delta\Gamma_d}{2} t + \cos(2\beta) \sinh \frac{\Delta\Gamma_d}{2} t - A_p \sin(2\beta) \sin(\delta m t))$$

$\beta$ CKM angle, $A_p$ production asymmetry of $B_d^0$

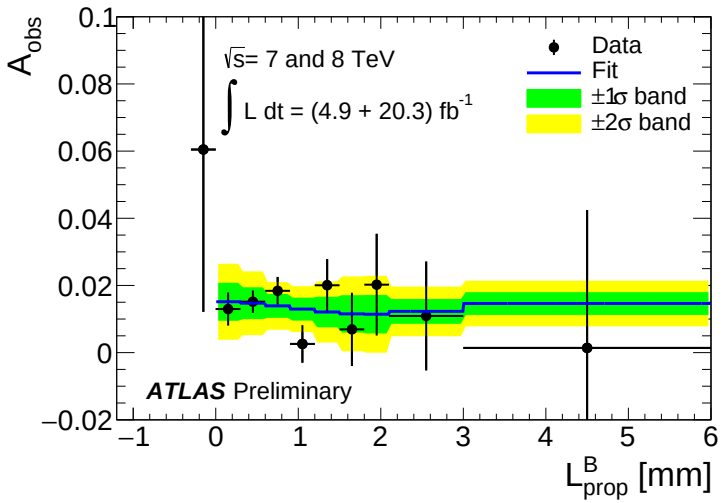
- $B_d^0 \to J/\psi K^*$ almost insensitive to $\Delta\Gamma_d$

$$\Gamma_d(t) \sim e^{-\Gamma t} \cosh \frac{\Delta\Gamma_d}{2} t$$

# $B_d^0$ production asymmetry

- $B_d^0$ production asymmetry $A_p$ measured from a charge asymmetry $A_{obs}$, from a difference between $B_d^0 \to J/\psi K^*$ and $\overline{B}_d^0 \to J/\psi \overline{K}^*$ decays as a function proper decay lengths $L_{prop}^B$
- $A_{obs}$ should oscillate if $A_p$ different from 0. Detector induced asymmetry included.

- ATLAS result $A_p = (0.25 \pm 0.48(stat) \pm 0.05(syst) \cdot 10^{-2}$



# $\Delta\Gamma_d$ result

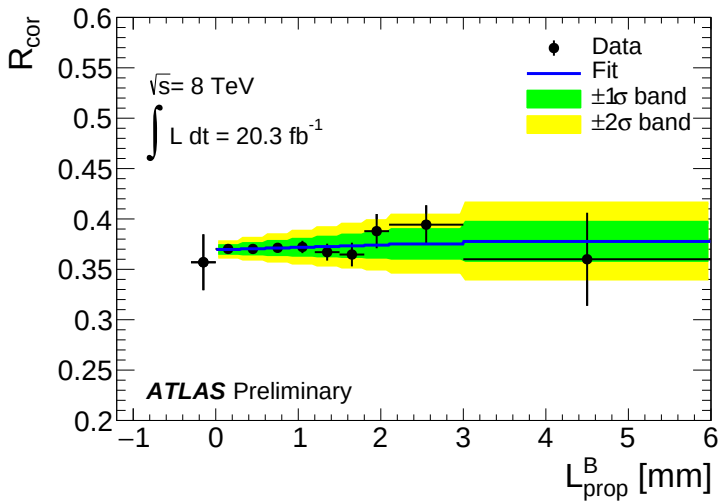



Figure: Ratio of $L^B_{prop}$ distributions of $B_d^0 \to J/\psi K_S^0$ and $B_d^0 \to J/\psi K^*$, fitted to extract $\Delta\Gamma_d$

## $\frac{\Delta\Gamma_d}{\Gamma_d}$ ATLAS Results

$$(-2.8 \pm 2.2(stat) \pm 1.7(syst)) \cdot 10^{-2} \text{ (7 TeV data)}$$

$$(0.8 \pm 1.3(stat) \pm 0.8(syst)) \cdot 10^{-2} \text{ (8 TeV data)}$$

$$(-0.1 \pm 1.1(stat) \pm 0.9(syst)) \cdot 10^{-2} \text{ (Combined)}$$

# $\Delta\Gamma_d$ Comparison, Conclusions

## $\frac{\Delta\Gamma_d}{\Gamma_d}$ Comparison

$$(-0.1 \pm 1.1(stat) \pm 0.9(syst)) \cdot 10^{-2} \text{ (ATLAS Run1)}$$

$$(-4.4 \pm 2.5(stat) \pm 1.1(syst)) \cdot 10^{-2} \text{ (LHCb)}$$

$$(1.7 \pm 1.8(stat) \pm 1.1(syst)) \cdot 10^{-2} \text{ (Belle)}$$

$$(0.8 \pm 3.7(stat) \pm 1.8(syst)) \cdot 10^{-2} \text{ (Belle)}$$

- ATLAS result is consistent with other measurements
- It is consistent with the SM prediction

$$(0.42 \pm 0.08) \cdot 10^{-2} \text{ (SM)}$$

# $B_s^0/B_d^0 \to \mu^+\mu^-$ Physics motivation

## Theory

- Flavour-changing neutral-current processes highly suppressed in SM
- $B_s^0/B_d^0 \to \mu^+\mu^-$ additional helicity suppression.
- SM prediction accurate:
  - Br ( $B_s^0 \to \mu^+\mu^-$ ) $= (3.65 \pm 0.23) \times 10^{-9}$
  - Br ( $B_d^0 \to \mu^+\mu^-$ ) $=(1.06 \pm 0.09) \times 10^{-10}$

## Experiment

- Experimental measurement a viable BSM search
- CMS and LHCb observation of $B_s^0 \to \mu^+\mu^-$ and evidence of $B_d^0 \to \mu^+\mu^-$:
- Br ( $B_s^0 \to \mu^+\mu^-$ ) $= (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- Br ( $B_d^0 \to \mu^+\mu^-$ ) $= (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

# Method

## Signal

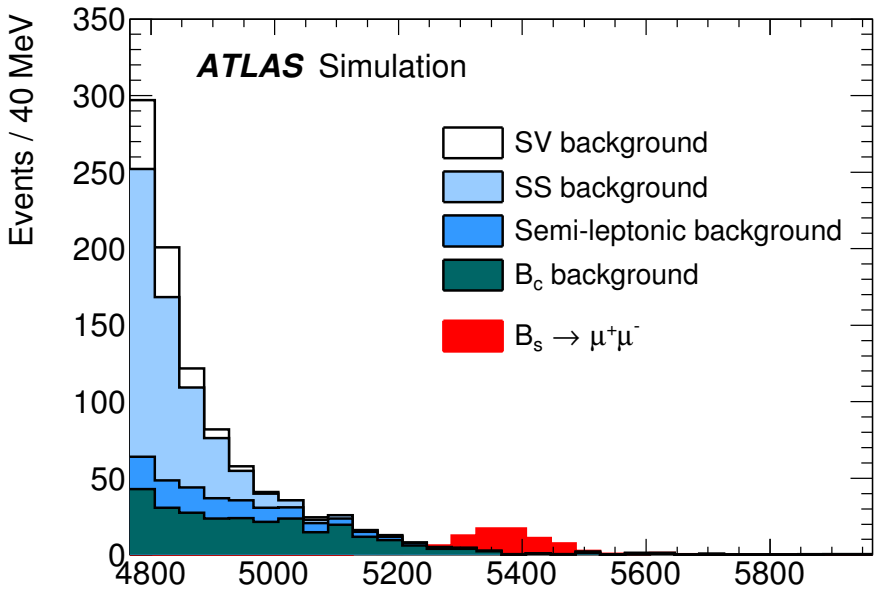
- Select signal di-muon events from data.
- Extract yield using an un-binned maximum- likelihood fit to the data.
- Use control samples to understand background suppression BDT and other cross checks.

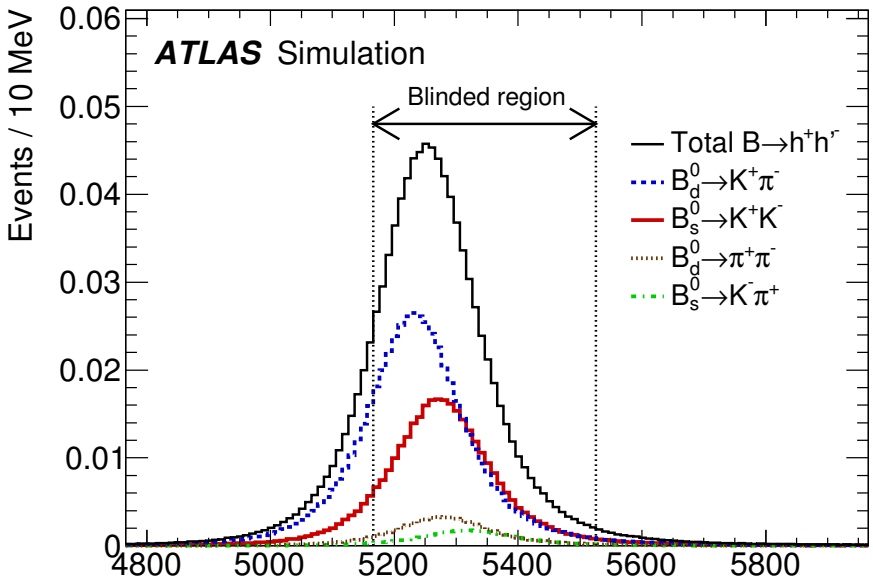
## Normalise signal to $B^{\mp} \to J/\psi K^{\pm}$

- Requires knowledge of hadronisation probabilities $f_u/f_s$ and $f_u/f_d$
- Use the ATLAS result for $f_s/f_d = 0.240 \pm 0.020$. ATLAS Coll, PRL 11(2015) 262001(arXiv:1507.08925) and assuming isospin symmetry $f_u/f_d$=1.

# Backgrounds

- Combinatorial Background - muons from b, $\overline{b}$ quarks
- Partially Reconstructed Decays:
  - Same Vertex (SV): $b \to s\mu^+ qJ/\psi$
  - Same Side (SS) cascades; e.g. $b \to c\mu\nu_\mu \to s(d)\mu\mu\nu_\mu\overline{\nu}_\mu$
- Fully reconstructed 2-body decays
- Background suppression use a boosted decision tree (BDT) using signal and background variables. Figures showing background before BDT.



# Result

Using 25 $fb^{-1}$ of 7 TeV and 8 TeV proton–proton collision data ATLAS obtains:

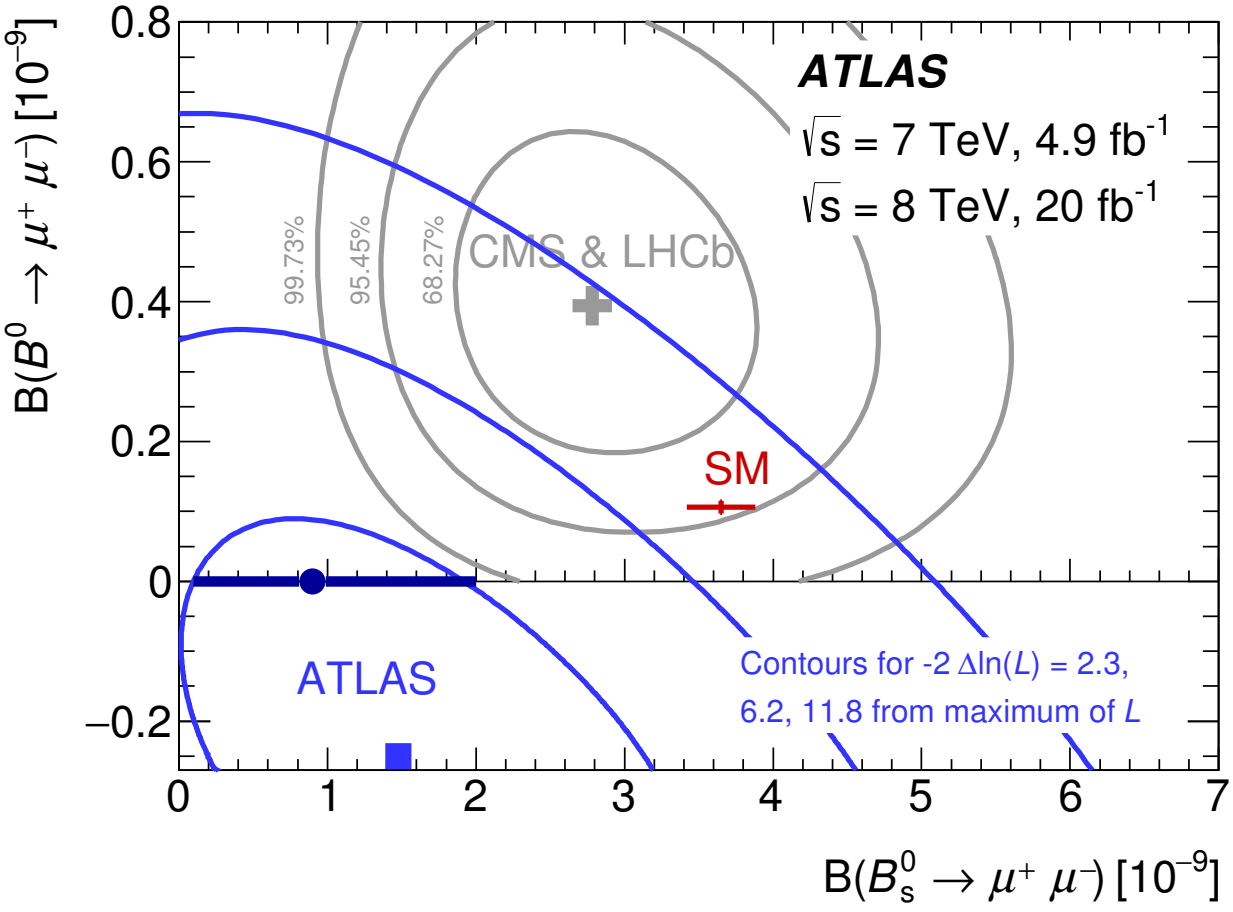
$$Br(B_d^0 \to \mu^+\mu^-) < 4.2 \cdot 10^{-10} \quad 95\% \ C.L.$$

$$Br(B_s^0 \to \mu^+\mu^-) < 3.0 \cdot 10^{-9} \quad 95\% C.L.$$

$$Br(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \cdot 10^{-9}$$

where the errors include both the statistical and systematic uncertainties.

# Comparison, conclusion




- ATLAS is consistent with the SM, LHCb and CMS
- Room for NP destructively interfering with the SM

# Summary

- Using Run1 LHC data ATLAS made important contributions to CPV, mixing and rare decays of B-hadrons
- Results are consistent with other experiments
- Consistency with SM in all presented cases
- Room for New Physics opened
- Run2 data expected to increase precisions

# Backup

Backup Slides