Beyond Standard Model searches in B decays with ATLAS

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on behalf of ATLAS Collaboration

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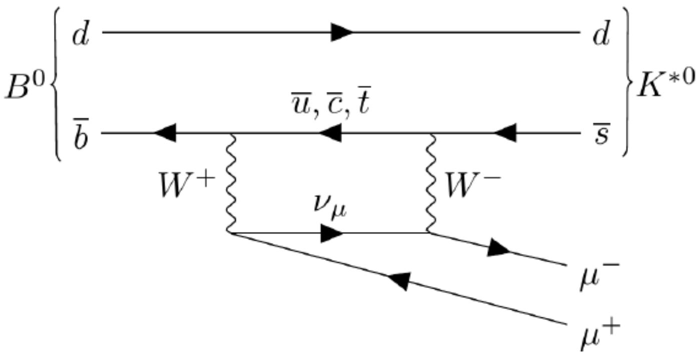
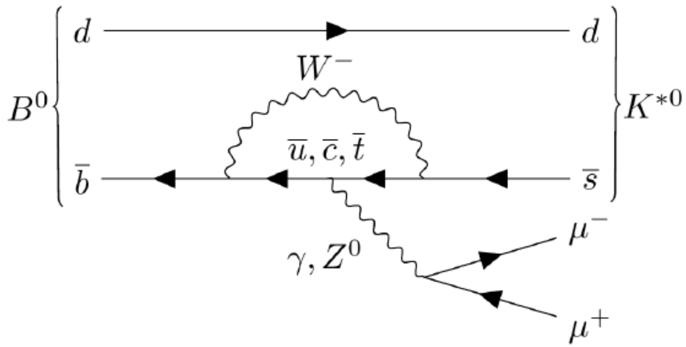
Introduction

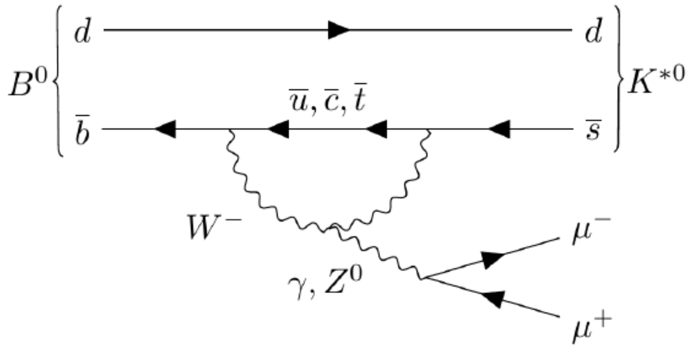
- Studying heavy flavour decays provides an opportunity for indirect search for BSM physics
  - $b \to s(d)ll$ transitions occur via FCNC processes
  - Forbidden in SM at tree level and thus sensitive to New Physics contributions in the loop diagrams
- In this talk
  - Angular analysis of $B^0 \to \mu^+\mu^- K^{*0}$ decay CERN-EP-2017-161, submitting to JHEP
    - Paper just released!
  - Measurement of the width difference in B^0-$\overline{B}^0$ system JHEP 06 (2016) 081, arXiv:1605.07485
  - (briefly) Studying rare decays $B^0_{(s)} \to \mu^+\mu^-$ EPJC 76 (2016) 513, arXiv:1604.04263

$B^0 \to \mu^+ \mu^- K^{*0}$ angular analysis

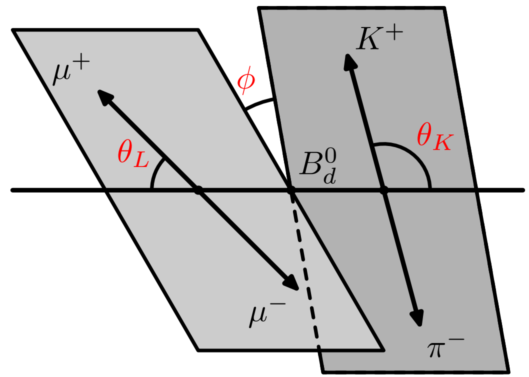
Introduction





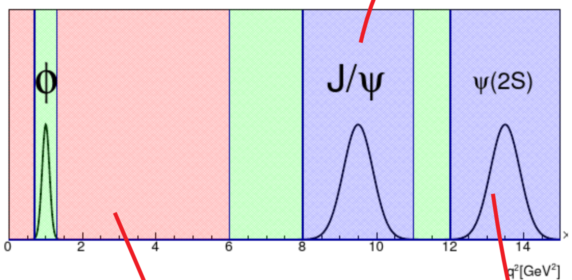


- The decay is forbidden in SM at tree level, occurs via suppressed loop diagrams
- BR($B^0 \rightarrow \mu^+\mu^- K^{*0}$) = $(1.03 \pm 0.06) \times 10^{-6}$ → allows differential decay rates measurement
  - **Measured parameters:** K^{*0} longitudinal polarization fraction F_L and angular parameters S_i, in bins of q^2 – dimuon mass squared
    - up to 3.4σ deviation in P_5' was reported earlier by LHCb
  - Extracted from the fit to distributions of $m_{K\pi\mu\mu}$, $\cos\theta_K$, $\cos\theta_L$, φ
- **Data:** 20.3 fb^{-1} collected by ATLAS at $\sqrt{s}$=8 TeV in 2012

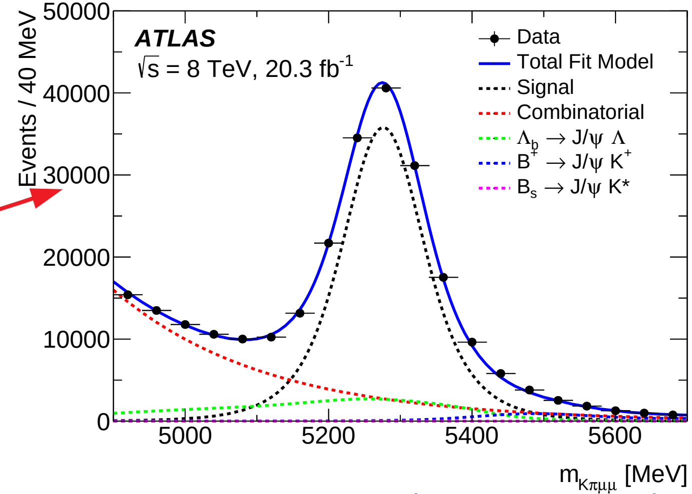


Event selection

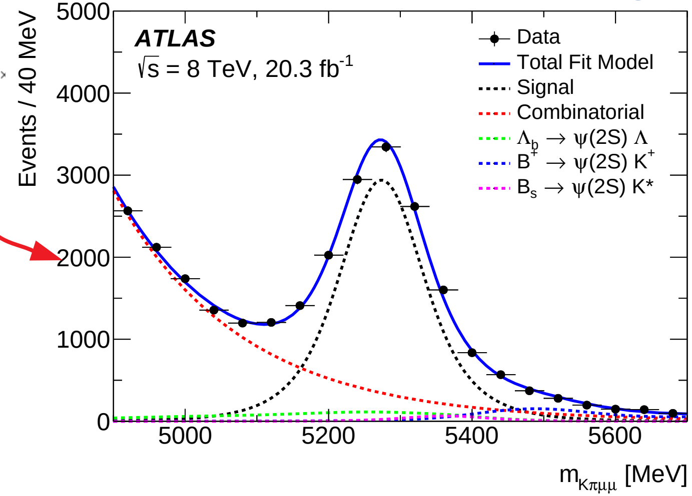
- Trigger: inclusive set of selections
  - single, di-, and tri-muon requirements
- Acceptance and mass cuts
  - $|\eta(\pi,K,\mu)| < 2.5$
  - $p_T(\pi,K) > 0.5$ GeV, $p_T(\mu) > 3.5$ GeV
  - $m(K\pi) \in [846,946]$ MeV
  - $m(K\pi\mu\mu) \in [5150,5700]$ MeV
- q^2 ranges studied
  - $q^2 \in [0.04, 6]\backslash[0.98, 1.1]$ GeV^2 – signal
  - $q^2 \in [8, 11]$ GeV^2 – control J/ψ
  - $q^2 \in [12, 15]$ GeV^2 – control $\psi(2S)$
- Background suppression cuts
  - $p_T(K^{*0}) > 3$ GeV
  - $\tau/\sigma_\tau > 12.75$
  - $\cos\theta > 0.999$
  - $\chi^2/\text{n.d.f.}(B^0) < 2$
- Multiple candidate treatment
  - choose best χ^2 candidate
  - smallest $|m(K\pi)-m_{PDG}(K^{*0})|/\sigma(m(K\pi))$ → residual mis-tag rate ~11%



787 signal events passed



Plots from charmonia control regions



Angular fit model

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]. \quad (1)$$

- Use optimized $P_i^{(\prime)}$ instead of S_i to reduce dependence on hadronic form factors

$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

- Statistics is not sufficient for fitting the full distribution (1)

- Use trigonometric "folding" to reduce the problem to 4 sets of fits for 3 parameters each: F_L, S_3 (P_1) and one of $S_{j=4,5,7,8}$ ($P_{j=4,5,6,8}{}'$)
- E.g. for F_L, S_3, S_4:

$$\begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

- F_L, S_3 can be extracted from any of the fits → use the one with the lowest systematics
- S_6 (A_{FB}) and S_9 cannot be extracted in this approach

Fitting procedure

- Extended ML fit with each of the fit variants in bins of q^2

$$\mathcal{L} = \frac{e^{-N}}{n!} \prod_{i=1}^{n} \sum_{j} n_j P_{ij}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \widehat{p}, \widehat{\theta}),$$

- j = 1, 2 for signal and combinatorial background PDFs
  - other exclusive sources of background are accounted for only for systematics
- Sequential fitting procedure

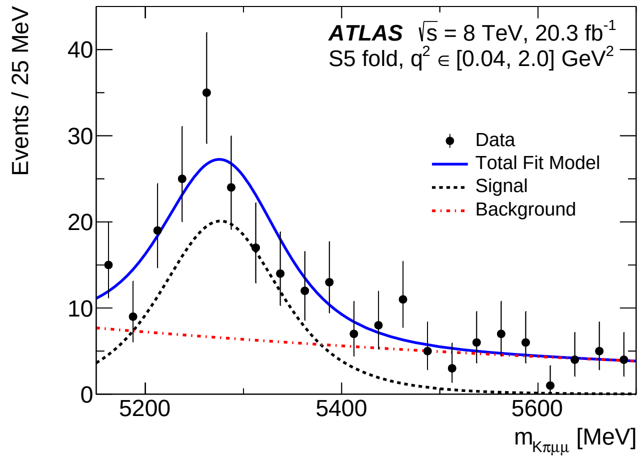
  0) Extract the mass and width parameters of B^0 from J/ψ control region → *fix them*

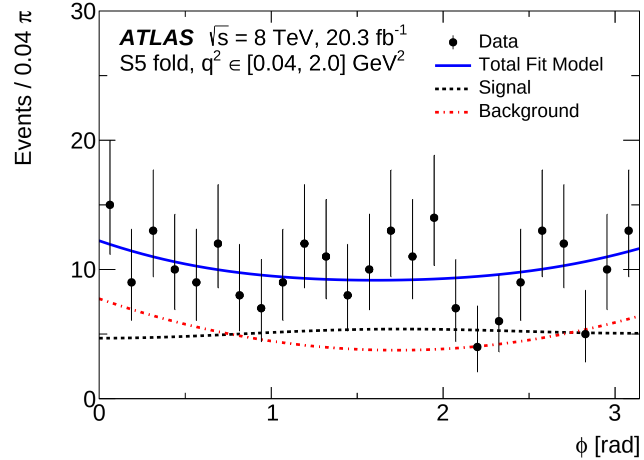
  1) Fit only the $m_{K\pi\mu\mu}$ to extract the nuisance parameters: signal and background yields, background mass shape → *fix them*

  2) Add the angular distributions and extract the parameters of interest F_L and S ($P^{(\prime)}$)
- The procedure extensively validated using toy MC
- Bins of q^2: [0.04, 2.0], [2.0, 4.0], [4.0, 6.0] GeV^2
  - Also fit in [0.04, 4.0], [1.1, 6.0], [0.04, 6.0] GeV^2 to facilitate comparisons to various predictions and experiments

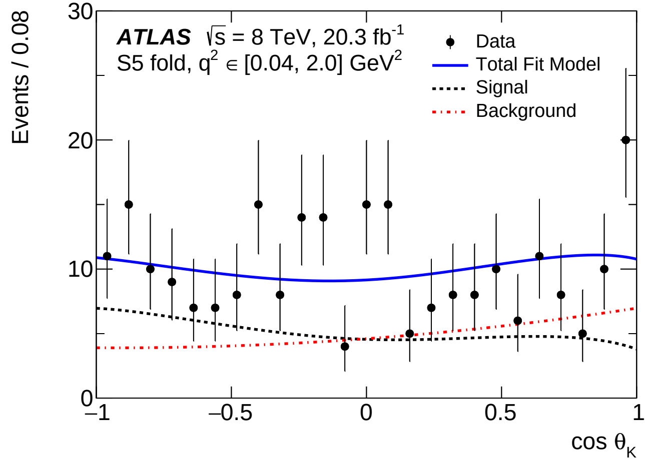
Fit projection

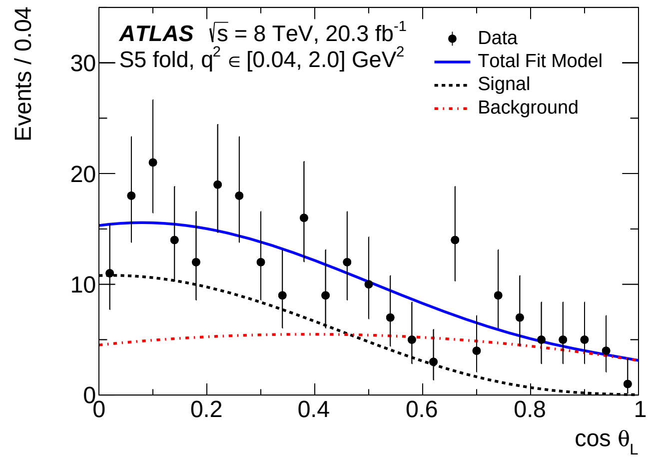
- Signal model:
  $P = \varepsilon(\cos\theta_K)\varepsilon(\cos\theta_L)\varepsilon(\varphi) \times$
  $g(\cos\theta_K, \cos\theta_L, \varphi) \times$
  $G(m_{K\pi\mu\mu})$
  - **Angular acceptance:** polynomials extracted from MC
  - **Differential decay rate**
  - **Mass shape:** Gaussian with per-candidate errors, fixed from $c\bar{c}$ control region
- Background model
  - **Mass shape**: exponential
  - **Angular shapes:** factorized into 1D terms – 2nd order Chebyshev polynomials





Fit in $q^2 \in$ [0.04, 2.0] GeV² for S_5 folding scheme is shown



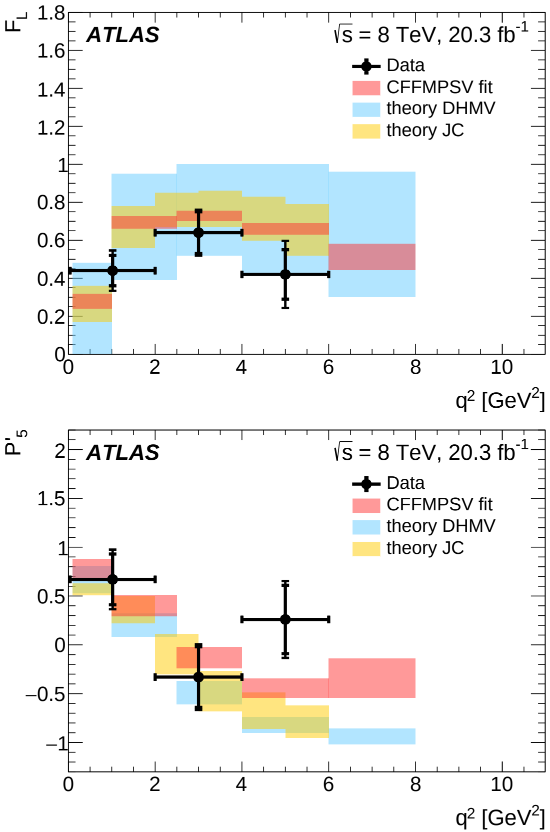


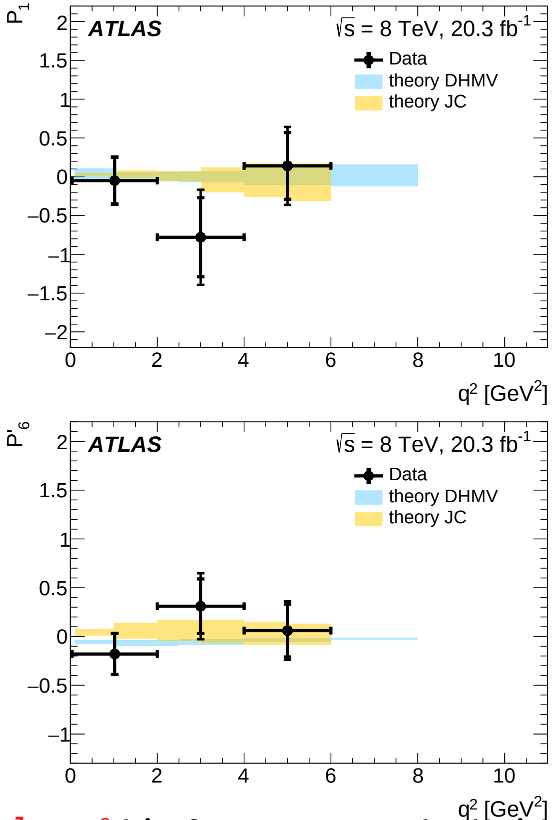
Results

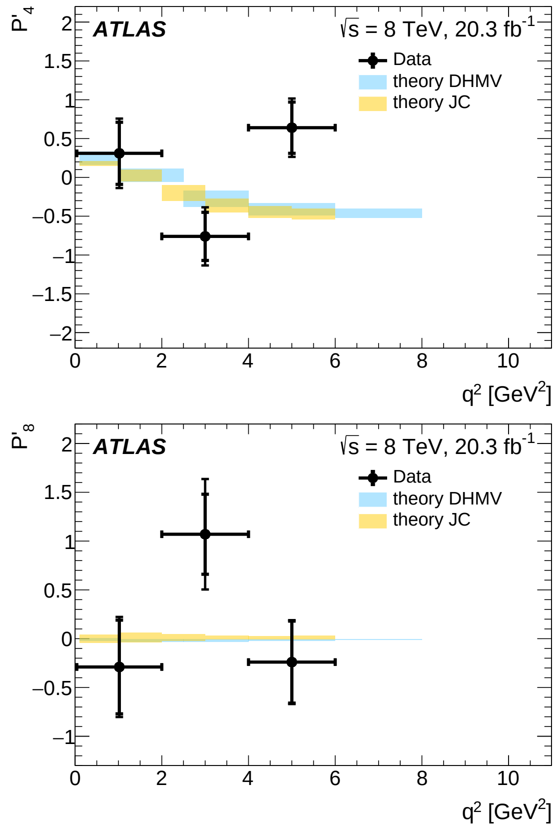
fit-based prediction using LHCb data **CFFMPSV**: Ciuchini et al. JHEP 06 (2016) 116, arXiv:1512.07157

QCD factorisation approaches **DHMV**: Descotes-Genon et al. JHEP 12 (2014) 125, arXiv:1407.8526

JC: Jäger and Camalich PRD 93 (2016) 014028, arXiv:1412.3183







- Deviations for P_4' and P_5' in $q^2 \in [4, 6]$ GeV^2 bin from DHMV calculation are 2.7σ
- Consistent with those reported by LHCb (comparison with experiments on backup)
- All measurements are within 3σ range covered by the predictions

Statistical uncertainty dominates

B^0-$\overline{B}^0$ system width difference

Introduction

- Standard model prediction for the width difference $\Delta\Gamma_d = \Gamma^L{}_d - \Gamma^H{}_d$:
  - $\Delta\Gamma_d = (0.45 \pm 0.08) \times 10^{-2}$
- World average before (BaBar, Belle, LHCb):
  - $\Delta\Gamma_d = (0.1 \pm 1.0) \times 10^{-2}$
- Other independent measurements do not constrain $\Delta\Gamma_d$
  - It was shown that relatively large variations due to NP contributions would not break other SM tests
- Good independent test complementary to other measurements

- **Data:** 25.2 fb^{-1} of $\sqrt{s}$ = 7 and 8 TeV collected by ATLAS in 2011-2012
- **Method:** measuring the lifetime-dependent ratio of $B^0{}_d$ decays rates to $J/\psi K^{*0}$ and $J/\psi K^0{}_S$

Analysis strategy

- Time-dependent B→f decay rate

$$\begin{aligned}\Gamma[t,f] &\equiv \sigma(B_q^0)\Gamma(B_q^0(t)\to f)+\sigma(\bar{B}_q^0)\Gamma(\bar{B}_q^0(t)\to f)\\ &\propto e^{-\Gamma_q t}\left[\cosh\frac{\Delta\Gamma_q t}{2}+A_{\mathrm{P}}A_{\mathrm{CP}}^{\mathrm{dir}}\cos(\Delta m_q t)+A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma_q t}{2}+A_{\mathrm{P}}A_{\mathrm{CP}}^{\mathrm{mix}}\sin(\Delta m_q t)\right]\end{aligned}$$

- A_P is B/$\overline{\text{B}}$ production asymmetry (due to presence of valence light quark)
- A_{CP}^{dir}, $A_{\Delta\Gamma}$, and A_{CP}^{mix} are well defined for either CP- or flavour-specific states:
  - $J/\psi K^0_S$ – CP state: $A_{CP}^{dir} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A_{CP}^{mix} = -\sin 2\beta$
  - $J/\psi K^{*0}$ – flavour state: $A_{CP}^{dir} = 1$, $A_{\Delta\Gamma} = 0$, $A_{CP}^{mix} = 0$
- For $J/\psi K^0_S$:

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

  - used to extract the $\Delta\Gamma_d$
  - A_p can be also extracted from data
- For $J/\psi K^{*0}$ + $J/\psi \overline{K}^{*0}$:

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

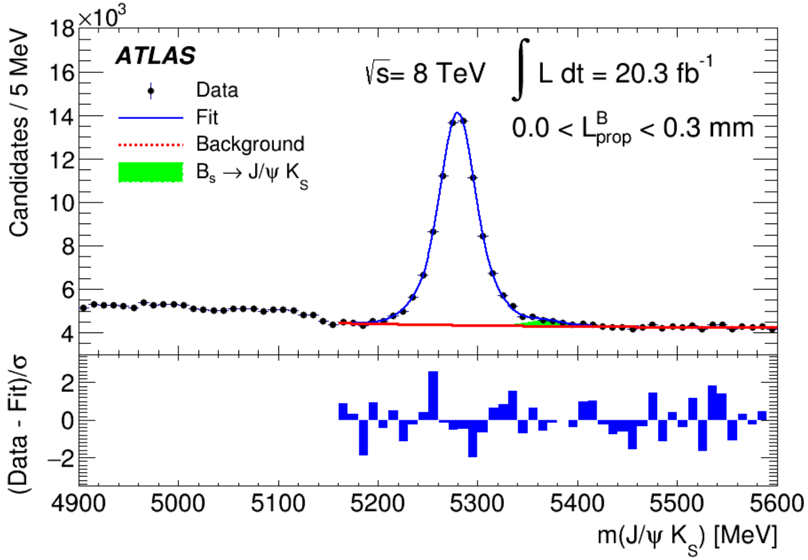
  - provides normalization of the above to reduce the systematics uncertainties
  - terms corresponding to production asymmetry and CPV in mixing are ~10^{-3}-10^{-4} and neglected

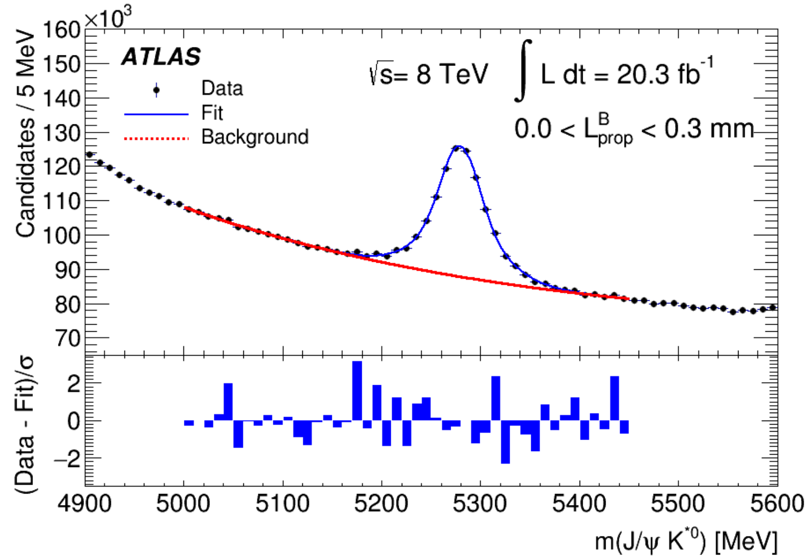
Extraction of signal yields

- Both decay channel signal yields are extracted in bins of proper decay length (in transverse plane)

Bin number	1	2	3	4	5	6	7	8	9	10
Lower edge [mm]	−0.3	0.0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	3.0
Upper edge [mm]	0.0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	3.0	6.0

- Using fits to mass of reconstructed $J/\psi K^{*0}$ and $J/\psi K^0_S$ candidates
- Per-bin detector acceptances are further accounted for in the measurement



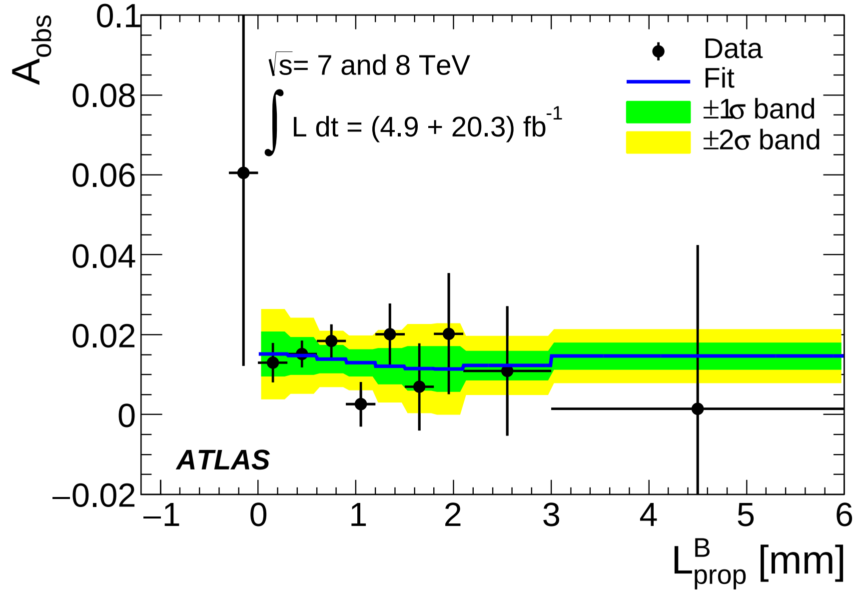


Production asymmetry determination

- Production asymmetry is derived from time-dependent asymmetry between $J/\psi K^{*0}$ + $J/\psi \bar{K}^{*0}$:

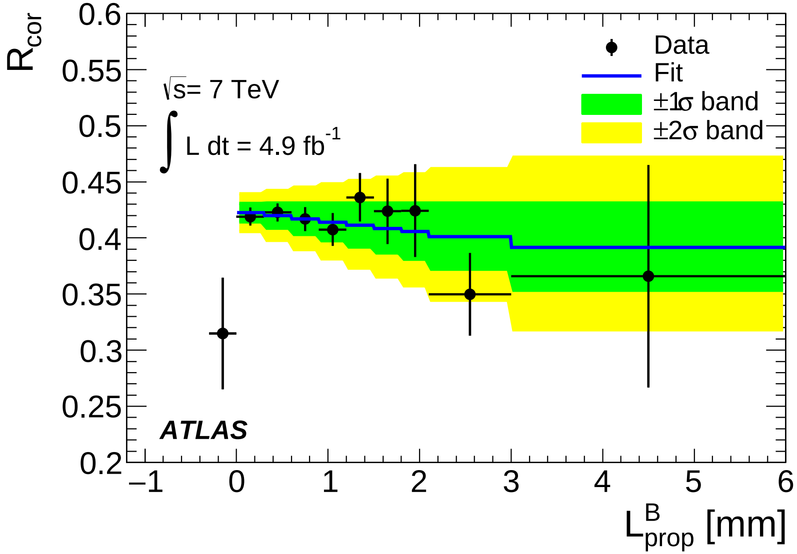
$$\Gamma[t, B^0(\bar{B}^0) \to J/\psi K^{*0}/\bar{K}^{*0}] = e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} +(-) A_p \cos\Delta m_d t\right]$$

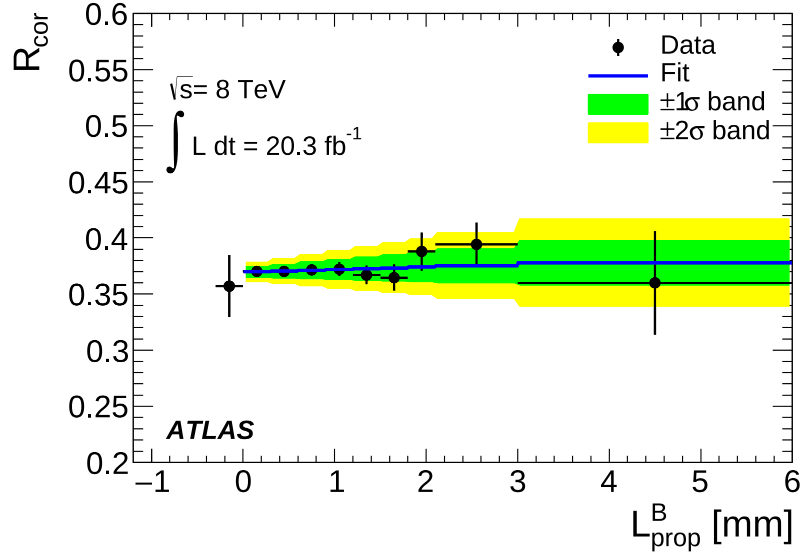
  - Neglect CPV in mixing term
- Observed charge asymmetry $\mathbf{A_{i,obs}}$ is fitted with $\mathbf{A_{i,exp} = (A_{det} + A_{i,osc})(1-2W)}$
- $W = 0.12 \pm 0.02$ – K/π mis-tag fraction
  - from simulation
- A_{det} - detector asymmetry for K^+/K^- reconstruction
- Fit results
  - $A_{det} = (1.33 \pm 0.24 \pm 0.30)\times10^{-2}$
    - agrees with simulation
  - $\mathbf{A_p = (0.25 \pm 0.48 \pm 0.05)\times10^{-2}}$
  - χ^2/n.d.f. = 6.50/7
  - Systematics dominated by the W uncertainty and deviation of $|q/p|$ from unity
- The $\mathbf{A_p}$ value consistent with LHCb
  - the first measurement at LHC in central region



Extraction of $\Delta\Gamma_d$

- Extract yields of $J/\psi K^{*0}$ and $J/\psi K^0_S$ in bins of proper decay length
- Fit the efficiency-corrected ratio $R_{i,\mathrm{cor}} = \frac{N_i(J/\psi K^0_S)}{N_i(J/\psi K^{*0})} \frac{\epsilon_i(B^0 \to J/\psi K^{*0})}{\epsilon_i(B^0 \to J/\psi K^0_S)}$ leaving $\Delta\Gamma_d/\Gamma_d$ the only free parameter



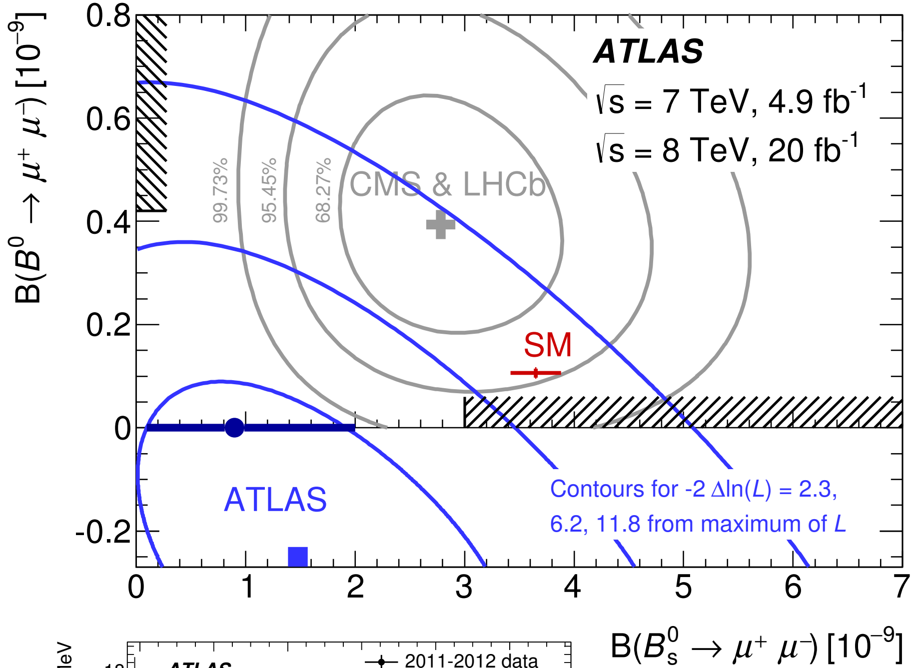


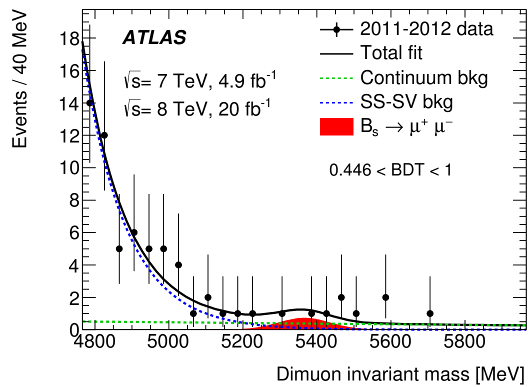
- Consistent between 7 and 8 TeV datasets; combined result: **$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.0(\mathrm{stat.}) \pm 0.9(\mathrm{syst.}))\times 10^{-2}$**
  - Statistically dominated measurement; largest systematics comes from the signal yield fits and MC statistics
- Most precise single measurement to date
  - PDG 2016 including this result: **$\Delta\Gamma_d/\Gamma_d = (-0.2 \pm 1.0)\times 10^{-2}$**

$B^0_{(s)} \rightarrow \mu^+ \mu^-$ rare decays

$B^0_{(s)} \to \mu^+\mu^-$ results

- No significant signals observed:
  - Observed: **N_s = 11, N_d = 0**
    (N_s = 16 ± 12, N_d = −11 ± 9 if not positively constrained)
  - Expected: **N_s = 41, N_d = 5**
- Measured BR:
  - $BR(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$
- 95% C.L. limits are set:
  - $BR(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$
  - $BR(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$
- Compatibility of the simultaneous fit with the SM:
  - p = 4.8% (2.0σ)





- ATLAS result is compatible with CMS and LHCb Run-1 measurements and the Run-2 LHCb measurement (PRL 118 (2017) 191801, arXiv:1703.05747)
- ATLAS analysis on Run-2 data is on-going

Summary

- Three NP-sensitive B-physics analyses were presented:
- Angular analysis of $B^0 \to \mu^+\mu^- K^{*0}$ decay
  - Uses Run-1 $\sqrt{s}$ = 8 TeV data, 20.3 fb^{-1}
  - Results are compatible with theoretical predictions and other experiments
- Measurement the B^0-$\overline{B}^0$ width difference
  - Full Run-1 data statistics, 25.2 fb^{-1}
  - First measurement of the central production asymmetry, consistent with LHCb (and with 0)
  - Most precise single measurement of $\Delta\Gamma_d/\Gamma_d$
  - Still far from the SM precision
- Both measurements statistically limited → repeating them on Run-2 data
- $B^0_{(s)} \to \mu^+\mu^-$ rare decays study was done only on full Run-1 so far
  - Expected precision comparable to that of CMS or LHCb, but suffer from “under-fluctuation” of signal yield
  - Run-2 (2015+2016) analysis results to come soon
- **Keep in touch for new results!**

Backup slides

Results – comparison to other experiments

fit-based prediction using LHCb data CFFMPSV: Ciuchini et al. JHEP 06 (2016) 116, arXiv:1512.07157
QCD factorisation approaches DHMV: Descotes-Genon et al. JHEP 12 (2014) 125, arXiv:1407.8526
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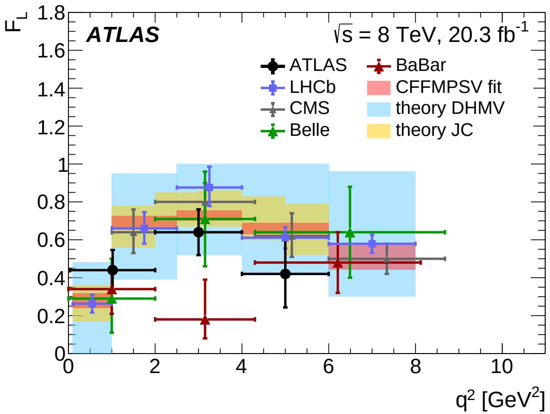

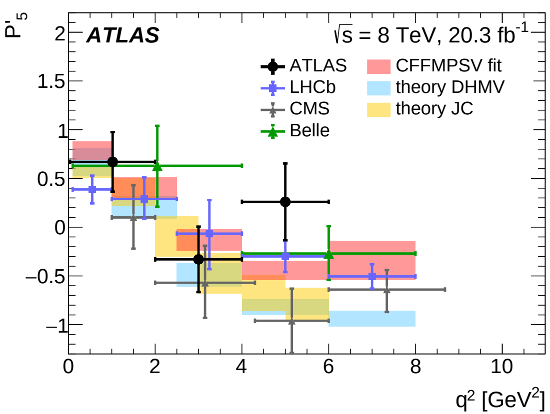

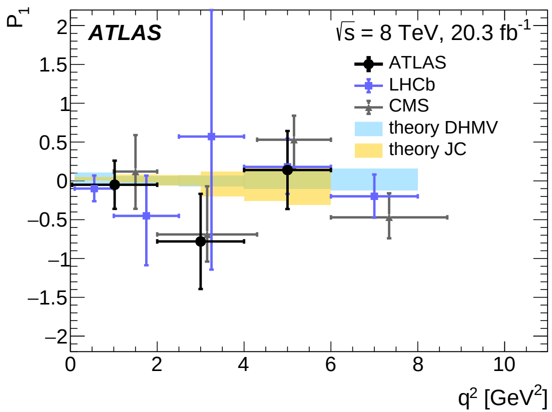

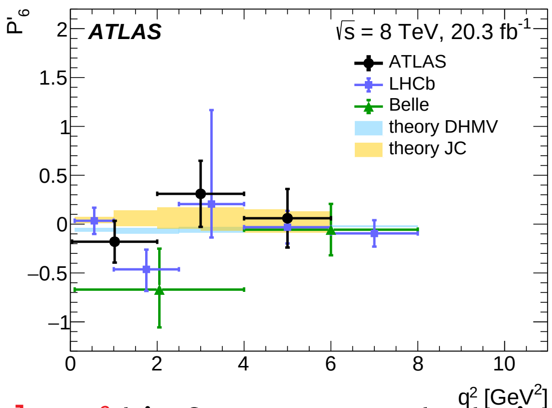

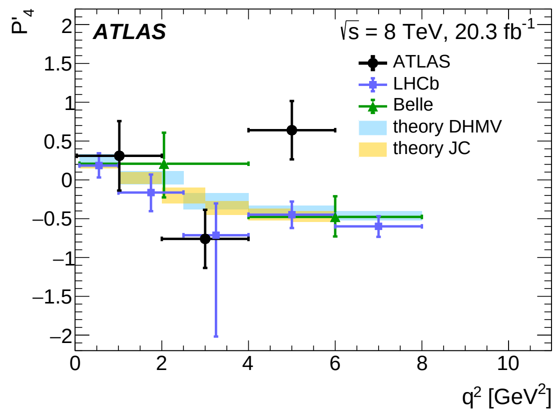

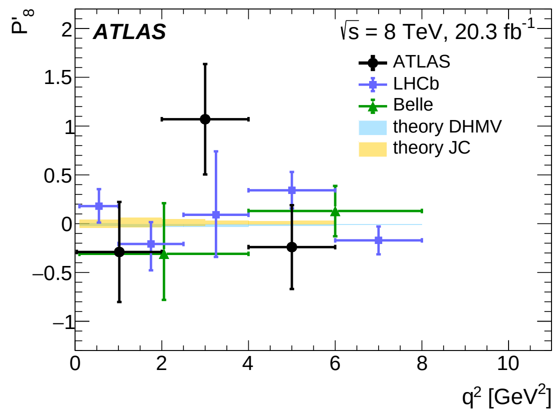

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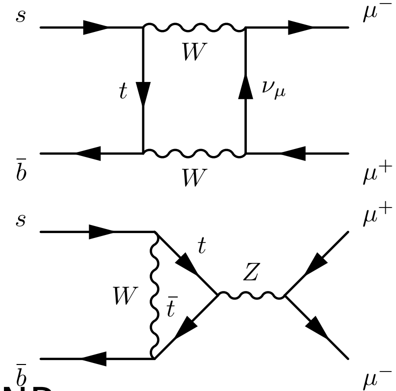
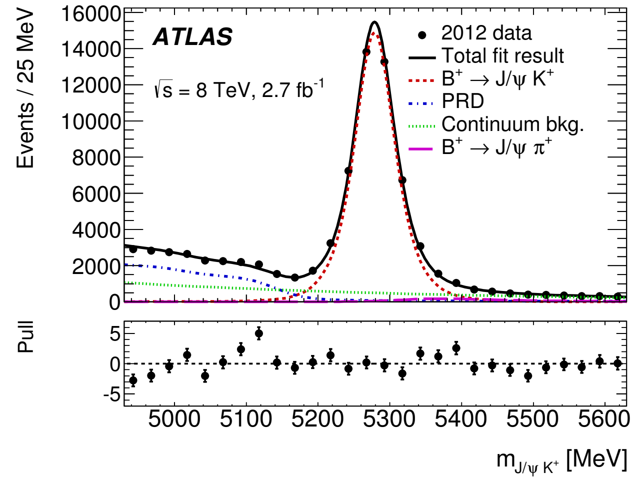
- Consistent with those reported by LHCb
- All measurements are within 3σ range covered by the predictions

$B^0_{(s)} \rightarrow \mu^+ \mu^-$ rare decays

Analysis strategy

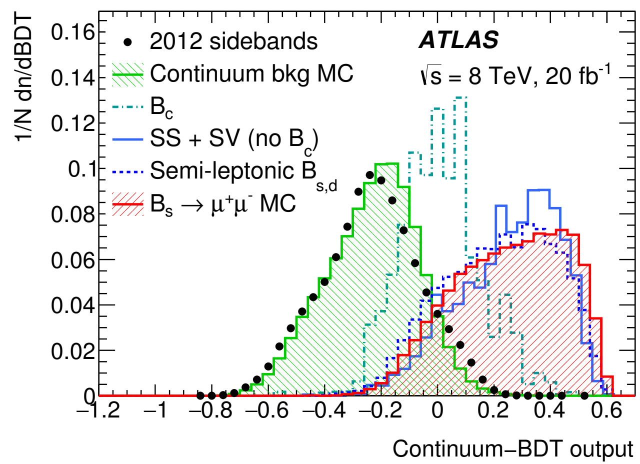




- FCNC process, CKM and helicity suppressed
- SM predictions:
  - $Br(B^0_s \to \mu^+\mu^-) = (3.65\pm0.23)\times10^{-9}$
  - $Br(B^0 \to \mu^+\mu^-) = (1.06\pm0.09)\times10^{-10}$
- Experimentally very clear signature sensitive to NP
- ATLAS analysis uses full Run-1 data of 25 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV
- Signal decay Br measured w.r.t. reference mode $B^+ \to J/\psi(\mu^+\mu^-)K^+$

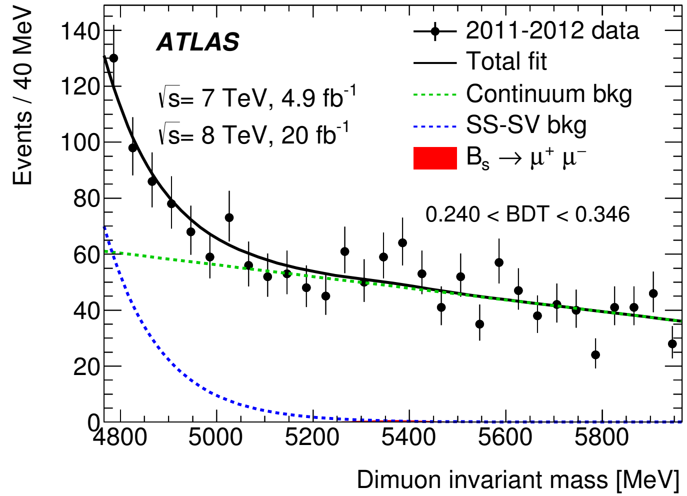
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

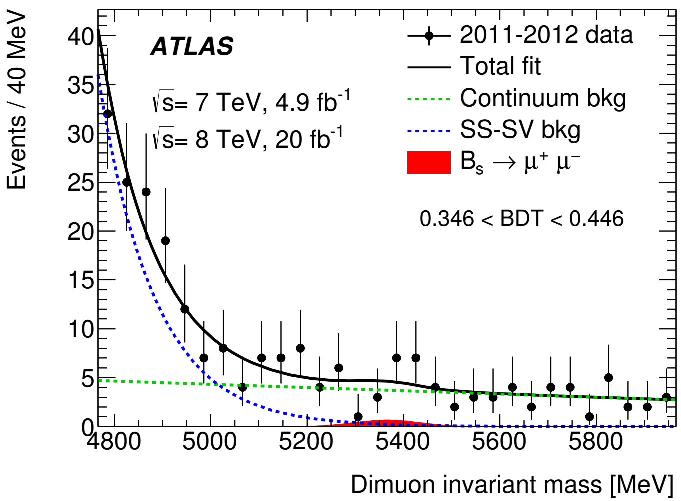
  - Many uncertainties reduced
- Complicated multi-variate event selection
  - *"Continuum-BDT"* to suppress combinatorial muon pairs
  - *"Fake-BDT"* for mis-identified muons suppression (e.g. from $B^0 \to \pi K$ decays)

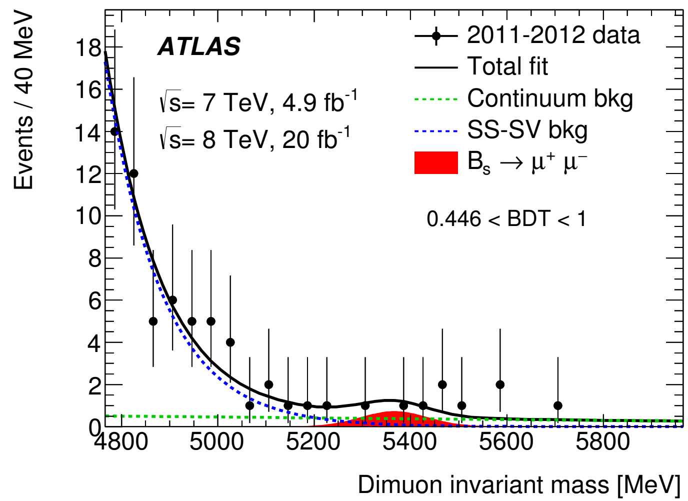


Signal fits

- ML fit in 3 bins of *continuum-BDT* with with equal 18% signal efficiency
- If yields positively constrained
  - **$N_s = 11, N_d = 0$**
- No constraints:
  - **$N_s = 16 \pm 12, N_d = -11 \pm 9$**
- SM expectation:
  - **$N_s = 41, N_d = 5$**

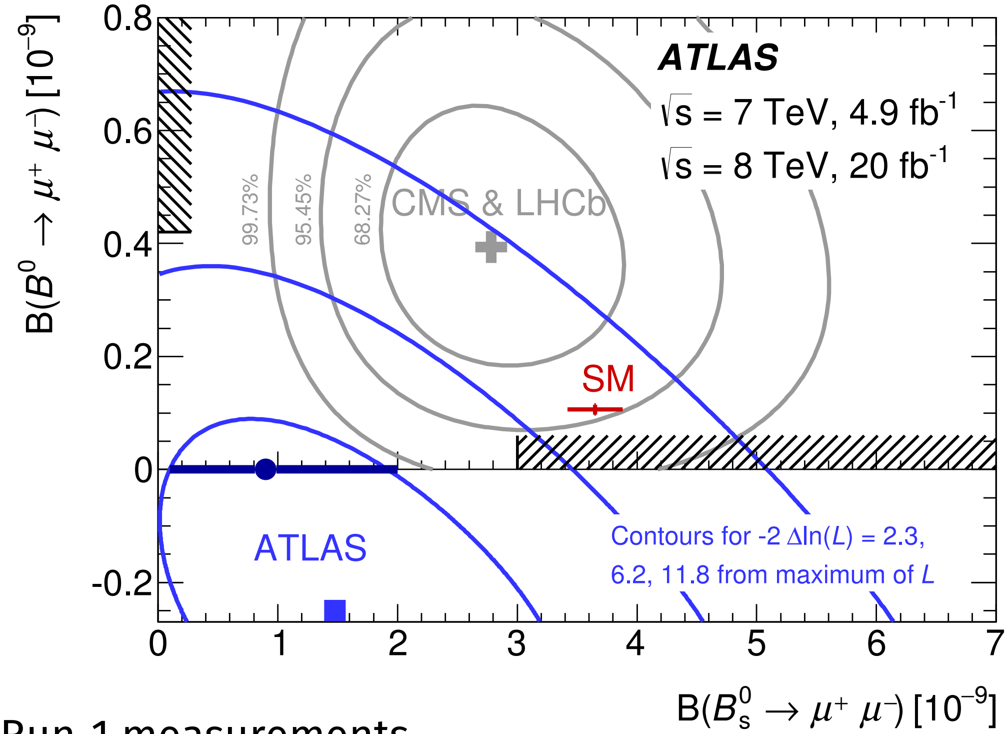






Results

- Measured BR:
  - $BR(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8})\times 10^{-9}$
- 95% C.L. limits are set:
  - $BR(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$
  - $BR(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$
- Compatibility of the simultaneous fit with the SM:
  - p = 4.8% (2.0σ)



- ATLAS result is compatible with CMS and LHCb Run-1 measurements
- Tension in B^0 is reduced with the Run-2 LHCb measurement (PRL 118 (2017) 191801, arXiv:1703.05747)
  - LHCb Run-2: $BR(B^0 \to \mu^+\mu^-) < 3.4\times 10^{-10}$ @ 95% C.L.
- ATLAS analysis on Run-2 data is on-going