B-physics in ATLAS: decays

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Outline

- Time dependent flavour-tagged ϕ_s and $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\phi$ in Run1; JHEP **1608**, 147 (2016)
- Measurement of the relative width difference of the $B^0 - \bar{B}^0$ system; JHEP **1606**, 081 (2016)
- Measurement of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi\Lambda^0$; Phys. Rev. D **89**, no. 9, 092009 (2014)
- Branching ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$; Phys. Lett. B **751**, 63 (2015)
- Search for tetraquark states $X(4140,...) \to J/\psi\phi$.

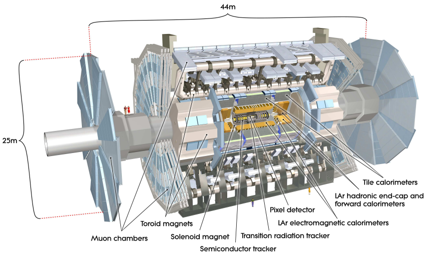
ATLAS detector and trigger system

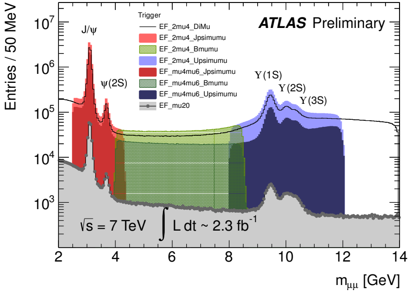
ATLAS: general purpose detector:

- Subsystems essential for B-physics: Inner detector and Muon spectrometer,
- Inner detector: tracking, momentum and vertexing, $|\eta| < 2.5$, d_0 resolution $\sim 10\mu m$,
- Muon spectrometer: trigger and muon identification,
- J/ψ mass resolution ~ 60 MeV, $\Upsilon(1S) \sim 120$ MeV,
- ATLAS trigger system: hardware *Level-1 trigger* and two-level software *High-Level Trigger*

Trigger selection for heavy flavour studies is mostly based on di-muon signature:

- muon p_T threshold (4 or 6 GeV)
- di-muon vertex reconstruction
- invariant mass window

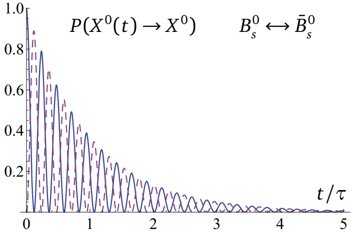




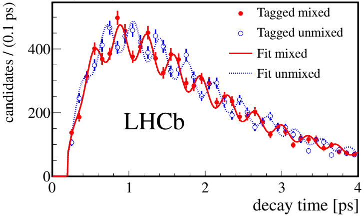
Time dependent flavour-tagged ϕ_s and $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\phi$

Mixing in $B_s^0 - \bar{B}_s^0$ system

- Meson mixing is a phenomenon that only occurs for the weakly-decaying, open flavor neutral K, D, and $B_{d,s}^0$ mesons.
- The oscillation frequency of B_s^0 meson mixing is characterized by the mass difference Δm_s of the heavy B_H and light B_L mass eigenstates; it is known with relative precisions of 0.12%.
- The heavy state B_H is expected to have a smaller decay width than that of the light state B_L. Hence, $\Delta\Gamma_s^{\text{SM}} = \Gamma_L - \Gamma_H = (0.087 \pm 0.021)\,\text{ps}^{-1}$ is expected to be positive in the Standard Model.
- The non-zero decay width difference in the $B_s^0 - \bar{B}_s^0$ is well established, with a relative difference of $\Delta\Gamma_s/\Gamma_s = (13.5 \pm 0.8)\%$, meaning that the heavy state B_H lives $\sim 14\%$ longer than the light state B_L.



LHCb: $B_s^0 \to D_s^- \pi^+$, New J. Phys. 15, 053021 (2013)



CP violation in $B_s^0 \to J/\psi\phi$ decay

- CP violation in the $B_s^0 \to J/\psi\phi$ decay occurs due to interference between direct decays and decays with $B_s^0 - \bar{B}_s^0$ mixing.
- The CP violating phase ϕ_s is defined as the weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude.
- In the absence of CP violation, the B_H state would correspond to the CP-odd state and the B_L to the CP-even state.
- In Standard Model the phase $\phi_s^{b\to c\bar{c}s}$ is small and can be related to Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix elements $\phi_s^{b\to c\bar{c}s} = -2\beta_s = -2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = -0.0370 \pm 0.0006$
- The phase $\phi_s^{b\to c\bar{c}s}$ is expected to be very sensitive to New Physics.

Analysis details

B-flavor tagging

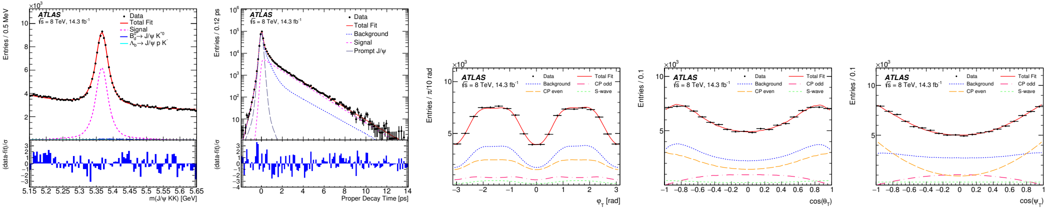
- Knowledge of $B_s/\bar{B}_s$ flavor at production significantly increases signal PDF sensitivity to ϕ_s
- Opposite-side tagging: the initial flavour of a neutral B_s meson can be inferred using information from the opposite-side B meson that contains the other pair-produced b-quark in the event.
- Three taggers: muon, electron, b-tagged jet.
- Key variable Q: charge of p_T-weighted tracks in a cone around the opposite side primary object (μ, e, b-jet), used to build per-candidates tag probability $p(B|Q)$:
- $B^+ \to J/\psi K^+$ decays are used to study and calibrate OST methods.

Measured variables:

- B_s mass
- B_s proper decay time t and its uncertainty σ_t
- 3 angles $\Omega = \{\theta_T, \phi_T, \psi_T\}$ to separate CP states
- B_s momentum p_T
- B_s tag probability $p(B|Q)$

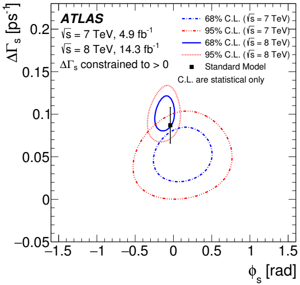
Signal decay main parameters:

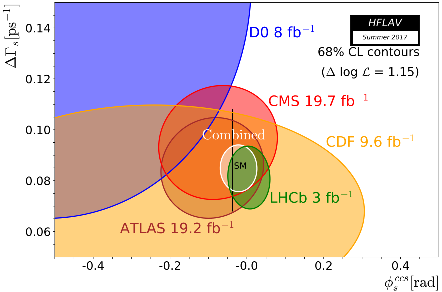
- Δm_s is fixed to 17.77 ps^{-1}
- B_s mean mass
- decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$
- decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ is constrained to be positive
- CP state amplitudes $|A_0(0)|^2$ and $|A_\parallel(0)|^2$
- strong phases $\delta_\parallel$ and $\delta_\perp$
- S-wave amplitude $|A_S(0)|^2$ and phase δ_S

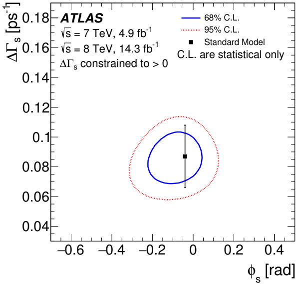


Results of the CP violation $B_s^0 \to J/\psi\phi$

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.110	0.082	0.042
$\Delta\Gamma_s$[ps^{-1}]	0.101	0.013	0.007
Γ_s[ps^{-1}]	0.676	0.004	0.004
$\lvert A_\parallel(0)\rvert^2$	0.230	0.005	0.006
$\lvert A_0(0)\rvert^2$	0.520	0.004	0.007
$\lvert A_S(0)\rvert^2$	0.097	0.008	0.022
$\delta_\perp$ [rad]	4.50	0.45	0.30
$\delta_\parallel$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.03	0.01







Measurement of the relative width difference $\Delta\Gamma_d/\Gamma_d$ of the $B^0-\bar{B}^0$ system

Relative width difference $\Delta\Gamma_d/\Gamma_d$ in $B^0 - \bar{B}^0$ system

- Standard Model prediction $\Delta\Gamma_d^{\text{SM}}/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2}$
- Experimental sensitivity still below SM predictions
- Measured through relative ratio of B_d^0 to $J/\psi K_S^0$ vs $J/\psi K^*(892)^0$

Method

The untagged timedependent decay rate $\Gamma(B_q(t) \to f)$ to a final state f:

$$\Gamma(B_q(t) \to f) \propto \mathrm{e}^{-\Gamma_q t}\left[\cosh\frac{\Delta\Gamma_q t}{2} + A_\mathrm{P} A_\mathrm{CP}^\mathrm{dir}\cos(\Delta m_q t) + A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma_q t}{2} + A_\mathrm{P} A_\mathrm{CP}^\mathrm{mix}\sin(\Delta m_q t)\right]$$

- A_P is the particle/antiparticle production assymmetry (excess of $B^0(\bar{b}d)$ mesons over $\bar{B}^0(b\bar{d})$ mesons due to the presence of valence d quark)
- $A_\mathrm{CP}^\mathrm{dir}$, $A_\mathrm{CP}^\mathrm{dir}$ and $A_{\Delta\Gamma}$ are theoretically well defined for flavour-specific final states and CP eigenstates
- CP eigenstates $J/\psi K_S^0$: $A_\mathrm{CP}^\mathrm{dir} = 0$, $A_\mathrm{CP}^\mathrm{mix} = -\sin(2\beta)$, $A_{\Delta\Gamma} = \cos(2\beta)$, where $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$
- flavour-specific eigenstates $J/\psi K^*(892)^0$: $A_\mathrm{CP}^\mathrm{dir} = 1$, $A_\mathrm{CP}^\mathrm{mix} = 0$, $A_{\Delta\Gamma} = 0$

Fit the ratio of CP/flavour eigenstates to determine $\Delta\Gamma_d$:

$$\frac{\Gamma[\psi K_S^0, t]}{\Gamma[\psi K^*, t]} = \frac{\cosh\frac{\Delta\Gamma_q t}{2} + \cos 2\beta\,\sinh\frac{\Delta\Gamma_q t}{2} - A_\mathrm{P}\sin(\Delta m_q t)}{\cosh\frac{\Delta\Gamma_q t}{2} + A_\mathrm{P}\cos(\Delta m_q t)}$$

- using the ratio eliminates the dominant factor $e^{-\Gamma_q t}$ and leads to improved precision for $\Delta\Gamma_d$
- production assymmetry A_P can be determined from data

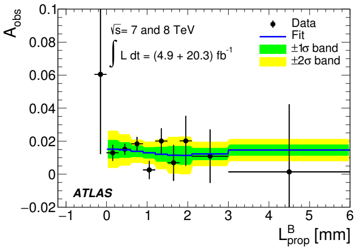
Determination of production assymmetry A_{P}

Production asymmetry derived from observed time-dependent asymmetry of $B_d \to J/\psi K^*(892)$ candidates (omitting CP violating mixing terms):

$$\Gamma[B/\bar{B} \to J/\psi K^*, t] \propto \mathrm{e}^{-\Gamma_q t}\left[\cosh\frac{\Delta\Gamma_q t}{2} \pm A_{\text{P}}\cos(\Delta m_q t)\right]$$

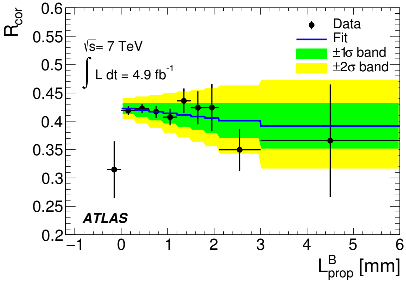
Observed charge asymmetry $A_{i,\text{obs}} = (K^* - \bar{K}^*)/(K^* + \bar{K}^*)$ is fitted with $A_{i,\text{exp}} = (A_{\text{det}} + A_{i,\text{osc}})(1 - 2W)$

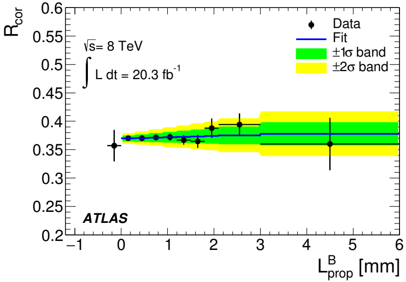
- A_{det} is detector-related asymmetry due to differences in the reconstruction of positive and negative particles;
- $W = 0.12 \pm 0.02$ mistag fraction than the decay $K^* \to K^+\pi^-$ is identified as $\bar{K}^* \to K^-\pi^+$, is determined from MC;
- $A_{i,\text{osc}} = A_{\text{P}}\cos(\Delta m_q t)/\cosh\frac{\Delta\Gamma_q t}{2}$
- $A_{\text{det}} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$ is consistent with MC
- $A_{\text{P}} = (0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$ is consistent with LHCb
- First LHC measurement of production asymmetry in central region



Determination of $\Delta\Gamma_d$

- Extract ct-dependent yields for K^* and K_S decays
- Fit ct-dependency leaving $\Delta\Gamma_d/\Gamma_d$ as the only free parameter





- Consistent result for the two datasets:

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

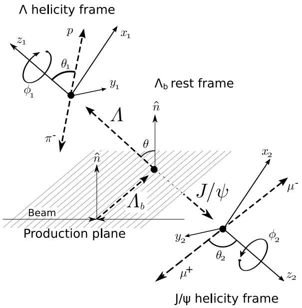
- Currently, this is the most precise single measurement. It agrees with the Standard Model prediction and the measurements by other experiments.

Λ_b^0 decays

Λ_b^0 polarization: exact properties

V. V. Abramov, Spin physics in high-energy hadron interactions, Phys. Atom. Nucl. **68**, 385 (2005) [Yad. Fiz. **68**, 414 (2005)]:

- In strong interactions, secondary particles C originating from reactions of the type $\boldsymbol{A+B \to C^{\uparrow}+X}$ cannot have a longitudinal polarization P_L. The presence of a longitudinal polarization would violate the parity-conservation law.
- For collisions of identical unpolarized particles, $P_T(-x_F) = -P_T(x_F)$, by virtue of invariance under the rotation of the coordinate system through an angle of 180° about the normal $\boldsymbol{n}$ to the reaction plane. As a consequence, we have $P_T(x_F = 0) = 0$ $(x_F = 2p_L(\Lambda_b^0)/\sqrt{s})$.



- *$\boldsymbol{\theta}$ is the polar decay angle of $\boldsymbol{\Lambda}^0$ with respect to the normal direction $\hat{\boldsymbol{n}}$ in $\boldsymbol{\Lambda_b^0}$ rest frame;*
- *$\boldsymbol{\theta}_1$ and $\boldsymbol{\phi}_1$ are the polar and azimuthal angles of proton in $\boldsymbol{\Lambda}^0$ rest frame with respect to the $\boldsymbol{\Lambda}^0$ direction in $\boldsymbol{\Lambda_b^0}$ rest frame;*
- *$\boldsymbol{\theta}_2$ and $\boldsymbol{\phi}_2$ are the polar and azimuthal angles of $\boldsymbol{\mu}^+$ in $\boldsymbol{J/\psi}$ rest frame with respect to the $\boldsymbol{J/\psi}$ direction in $\boldsymbol{\Lambda_b^0}$ rest frame.*

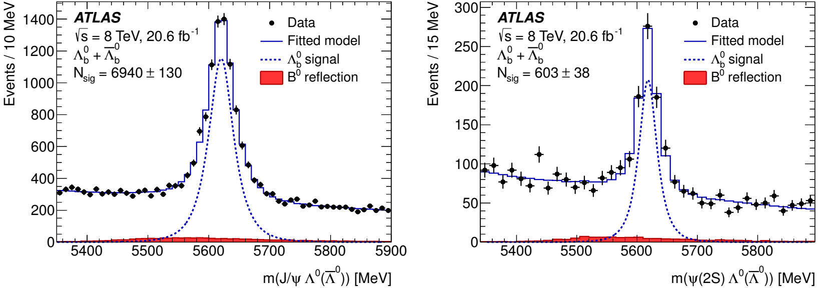
Helicity amplitudes of $\Lambda_b^0 \to J/\psi \Lambda^0$

$\boldsymbol{H}^{\Lambda_b^0 \to \Lambda^\star \psi}_{\lambda_{\Lambda^\star}, \lambda_\psi}$ helicity amplitudes measured by ATLAS and LHCb for $\Lambda_b^0 \to \Lambda^0 J/\psi$ with theory prediction by T. Gutsche *et al.*, Phys. Rev. D 88, 114018 (2013):

	$\Lambda_b^0 \to \Lambda^0 J/\psi$			$\Lambda_b^0 \to \Lambda^0 \psi(2S)$	
	theory	LHCb	ATLAS	theory	experiment
$\lvert\widehat{H}_{+1/2,+1}\rvert^2$	$0.31 \cdot 10^{-2}$	$-0.06 \pm 0.04 \pm 0.03$	$(0.08^{+0.13}_{-0.08} \pm 0.06)^2$	$0.12 \cdot 10^{-1}$	?
$\lvert\widehat{H}_{+1/2,0}\rvert^2$	$0.46 \cdot 10^{-3}$	$-0.01 \pm 0.04 \pm 0.03$	$(0.17^{+0.12}_{-0.17} \pm 0.09)^2$	$0.32 \cdot 10^{-2}$	?
$\lvert\widehat{H}_{-1/2,0}\rvert^2$	0.53	$0.58 \pm 0.06 \pm 0.03$	$(0.59^{+0.06}_{-0.07} \pm 0.03)^2$	0.45	?
$\lvert\widehat{H}_{-1/2,-1}\rvert^2$	0.47	$0.49 \pm 0.05 \pm 0.02$	$(0.79^{+0.04}_{-0.05} \pm 0.02)^2$	0.54	?
α_b	-0.07	$0.04 \pm 0.17 \pm 0.07$	$0.30 \pm 0.16 \pm 0.06$	0.09	?

- $\alpha_b = \lvert\widehat{H}_{+1/2,0}\rvert^2 - \lvert\widehat{H}_{-1/2,0}\rvert^2 + \widehat{H}_{-1/2,-1}\rvert^2 - \lvert\widehat{H}_{+1/2,+1}\rvert^2$
- $\widehat{W}(\cos\theta) = \frac{1}{2}\left(1 + P\alpha_b \cos\theta\right)$

Observation of $\Lambda_b^0 \to \psi(2S)\Lambda^0$



- $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0) = 0.501 \pm 0.033(\text{stat}) \pm 0.019(\text{syst})$
- The only available theoretical expectation for the branching ratio is 0.8 ± 0.1 exceeds the measured value

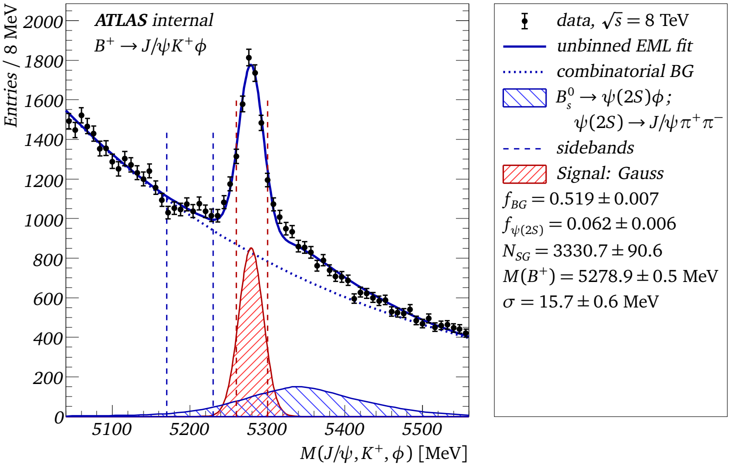
Search for tetraquark states $X(4140, \ldots) \to J/\psi\,\phi$

Search for tetraquark states $X(4140,...) \to J/\psi\phi$

- **CDF 2008:** first evidence for a narrow near-threshold $X(4140) \to J/\psi\phi$ mass peak in $B^+ \to J/\psi\phi K^+$ decay;
- $X(4140)$ does not fit conventional expectations for a charmonium state; it is well above the threshold for open charm decays, so a $c\bar{c}$ charmonium meson with this mass would be expected to decay into an open charm pair dominantly and to have a tiny branching fraction into $J/\psi\phi$;
- $X(4140)$ structure could be a molecular state, a tetraquark state, a hybrid state or a rescattering effect;

- $B^+ \to J/\psi K^+\phi$
  - large signal yield
  - lack of particle identification, large backround from pions
  - peaking background from $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$
- $B^0 \to J/\psi K_S^0\phi$
  - moderate signal yield
  - K_S^0 identified like V^0 decay, contamination from Λ^0 is negligible
  - 41 ± 7 candidates from BaBar: Phys. Rev. D **91**, no. 1, 012003 (2015)
- $\Lambda_b^0 \to J/\psi\Lambda^0\phi$
  - small signal yield
  - possible contamination from K_S^0 can be suppressed
  - this decay channel has not yet been observed
  - hidden charm pentaquark state with strangeness $S = -1$ in $(J/\psi, \Lambda^0)$ system

ATLAS: $B^+ \to J/\psi K^+ \phi$

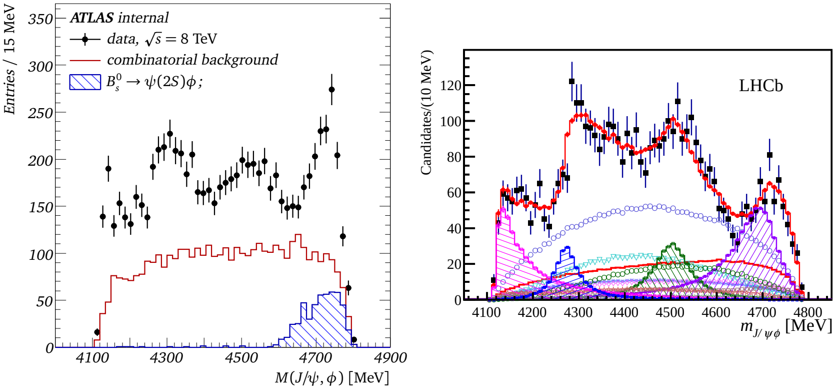


- selection criteria are very preliminary
- BG contamination from $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ is moderate

ATLAS: $(J/\psi, \phi)$ mass spectrum from $B^+ \to J/\psi K^+ \phi$

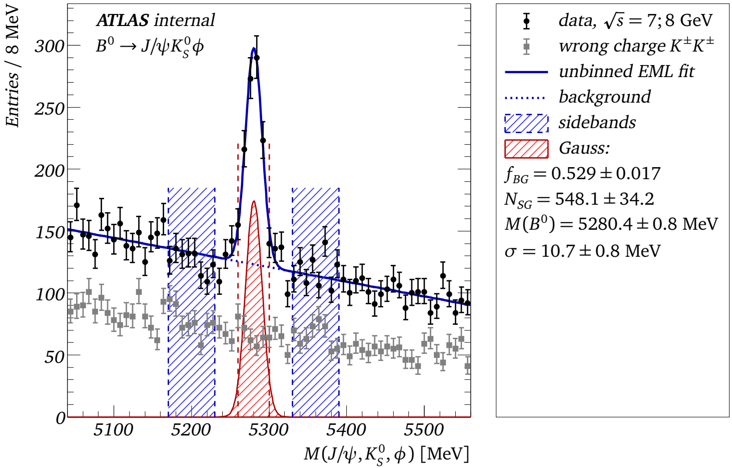
ATLAS: $M(J/\psi, \phi)$ from $B^+ \to J/\psi K^+ \phi$

LHCb: $M(J/\psi, \phi)$ from $B^+ \to J/\psi K^+ \phi$



- peaks from $X(4274)$ and $X(4500)$ are clearly seen
- $X(4140)$ is near threshold, accurate amplitude analysis is needed to determine its natural width
- the contamination from B_s^0 is large at high mass; the measurement of $X(4700)$ state is not starightforward

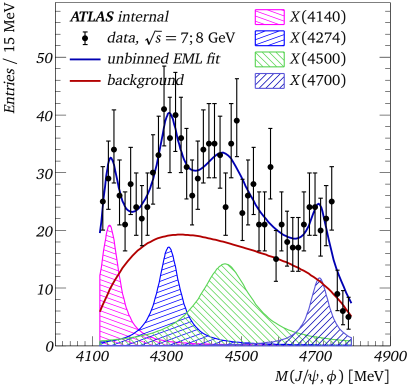
ATLAS: $B^0 \to J/\psi K_S^0 \phi$



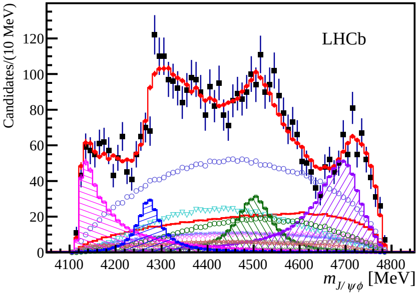
- no peaking background
- small statistics at RunI

ATLAS: $(J/\psi, \phi)$ mass spectrum from $B^0 \to J/\psi K_S^0 \phi$

ATLAS: $M(J/\psi, \phi)$ from $B^0 \to J/\psi K_S^0 \phi$



LHCb: $M(J/\psi, \phi)$ from $B^+ \to J/\psi K^+ \phi$



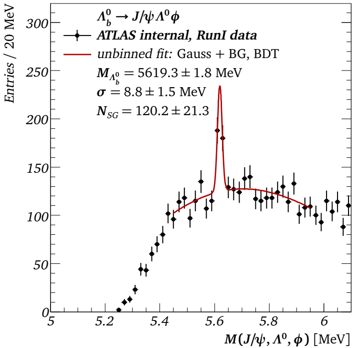
- same structure in $(J/\psi, \phi)$ mass spectrum as in $B^+ \to J/\psi K^+ \phi$ decay chain
- toy fit model, no interference between X states

ATLAS: $\Lambda_b^0 \to J/\psi \Lambda^0 \phi$

variables:

- $\chi^2(\Lambda_b^0)$, $\chi^2(J/\psi + \Lambda^0)$
- $p_T(\Lambda^0)$, $p_T(K^+)$, $p_T(K^-)$
- $p_T(\Lambda_b^0)/p_T^{\mathrm{vtx}}$
- proper decay time ct

ATLAS RunI data, TMWA BDT



- strong evidence for signal
- this decay chain has not yet been observed by any experiment

Summary

- ATLAS has produced impressive and competitive results in beauty and charm physics:
- CP violation induced by $B_s^0 - \bar{B}_s^0$ mixing in $b \to c\bar{c}s$ transitions has not yet been observed either, with an uncertainty on the $\phi_s^{b \to c\bar{c}s}$ phase of 31 mrad;
- Most precise single-experiment measurement for $\Delta\Gamma_d/\Gamma_d$
- All results discussed are statistics-limited: very encouraging perspectives with Run 2
- More public results can be found on ATLAS B-physics TWiki page