B-physics in ATLAS

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On behalf of the ATLAS collaboration

LHC Days 2012

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Outline

1. The ATLAS detector, data, and triggers
2. Heavy flavour production and properties (lifetimes)
3. Observation of $\chi_b(3P)$
4. Rare B Decays: $B_{(s)} \to \mu^+\mu^-$
5. ϕ_s and $\Delta\Gamma_s$ from $B_s \to J/\Psi\phi$
6. Conclusions and Outlook

The ATLAS detector

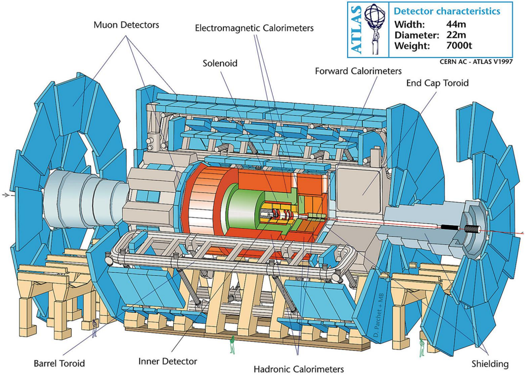
General purpose detector

Tracking:

- Silicon (Pixel + SemiConductor Tracker) and Transition Radiation Tracker
- 2T solenoidal field

Muon Spectrometer:

- Dedicated tracking chambers
- 0.5-2T toroidal field



Tracking performances:

- $10\mu m$ impact parameter resolution
- $\frac{\sigma_{p_T}}{p_T} \sim 0.05\% p_T \oplus 1.5\%$
- $\sigma_m(J/\psi - \Upsilon) \sim 60 - 120$ MeV (ID dominated)

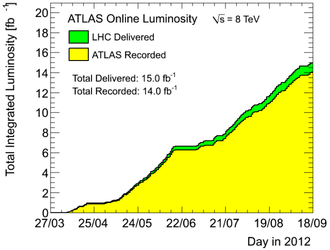
ATLAS Data Taking

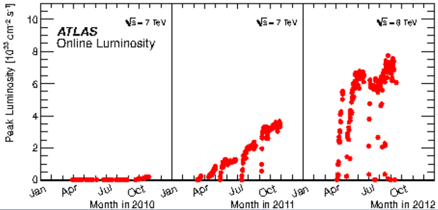
2011:

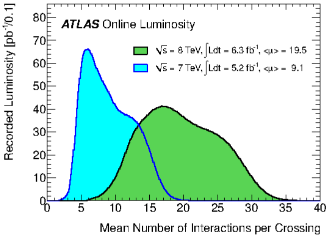
- $> 5fb^{-1}$ recorded in 2011
- Instantaneous luminosity and pile-up steadily increasing

2012:

- $> 14fb^{-1}$ recorded (so far)
- Flatter instantaneous luminosity profile
- Harsher pile-up conditions!

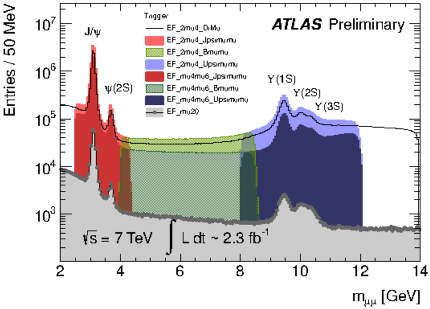






ATLAS Triggers

- Di-muon triggers are our main tool, but also have single-muon triggers (higher p_T)
- Ran with constant trigger thresholds for di-muons all across 2011
- As luminosity increases $\rightarrow$ more stringent selection
  - Higher p_T thresholds
  - Specific di-muon selections with barrel/endcap logic (more central decays)
  - Specific resonances
  - Tighter quality cuts



B-physics data collected with the above triggers all across 2011 and most of 2012

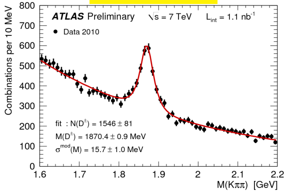
The ATLAS Heavy Flavour Program

- Production, polarization and spectroscopy: → QCD predictions
  - Charm ($D^0, D^+, D_s, D^*, \ldots$)
  - Onia ($\Upsilon_{1,2,3}, J/\psi, \psi^{'}, \ldots$)
  - B mesons (B^0, B^+, B_s, B_c)
  - b-baryons (Λ, Θ, χ)
- Lifetimes → QCD, HQET
- Rare decays → CKM, SM, NP
- CP violation → CKM, SM, NP

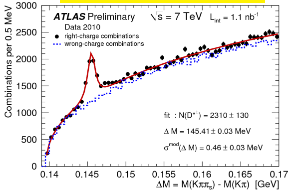
I will focus on new physics-related studies,
and new states searches within the SM itself

Open Charm and Onia

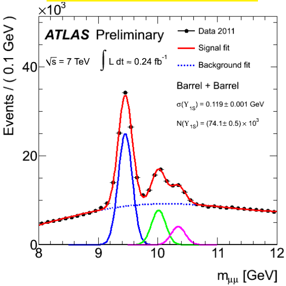
$D^+ \to K\pi\pi$



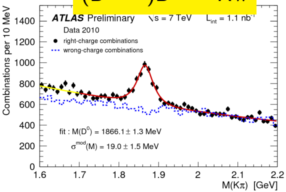
$D^* \to \pi_s D^0 (\to K\pi)$



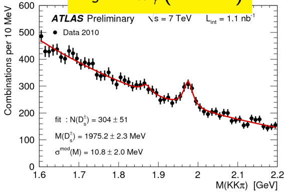
$\Upsilon(1S,2S,3S) \to \mu\mu$



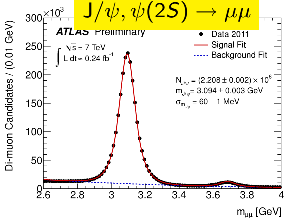
$(D^* \to) D^0 \to K\pi$



$D_s \to \pi\phi(\to KK)$



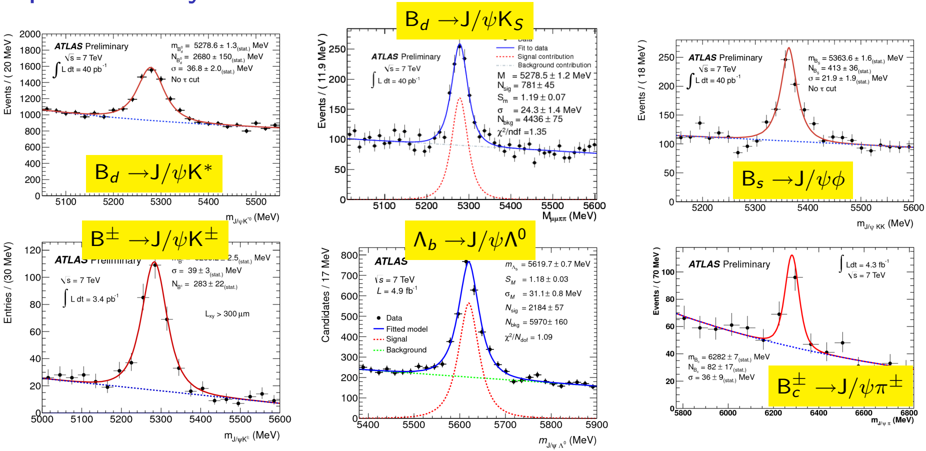
$J/\psi, \psi(2S) \to \mu\mu$



All masses consistent with PDG!

Widths consistent with expectations from detector simulations!

Open Beauty Production

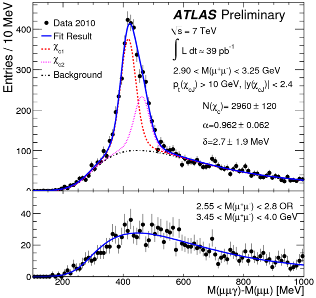


- Latest updates using 2011 data
- Masses of all B-hadrons measured in exclusive decays with J/ψ
- **All** masses consistent with PDG!
  Widths consistent with expectations from detector simulations!

Charm, B and Onia Production

- Observation of D, J/ψ, $\psi(2S)$ and Υ with ATLAS
  ATLAS-CONF-2010-034, ATLAS-CONF-2010-045
- $D^{\pm}$, D^{*}, D_s differential and integrated cross sections
  ATLAS-CONF-2011-017
- J/ψ differential cross section, and prompt/non-prompt separation
  Nucl.Phys.B, Vol. 850, issue 3, 27/09/2011, pp. 387-444
- Υ production cross-section
  Phys.Lett.B, Vol. 703, issues 1-2, 3/11/2011, pp. 428-446
- Observation of χ_c states through $J/\psi\gamma$ transitions
  ATLAS-CONF-2011-136
- B-hadron differential production cross-section
  Nucl.Phys.B, Vol. 864, issue 3, 21/11/2012, pp. 341-381

$\chi_c \rightarrow J/\psi\gamma$

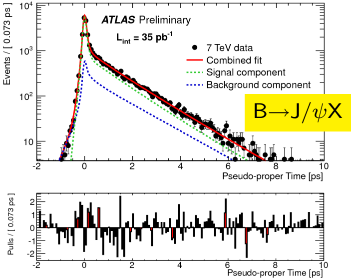


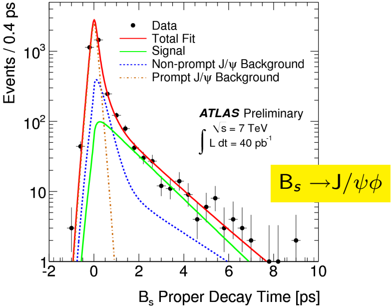
All x-sections and ratios consistent with latest QCD predictions!

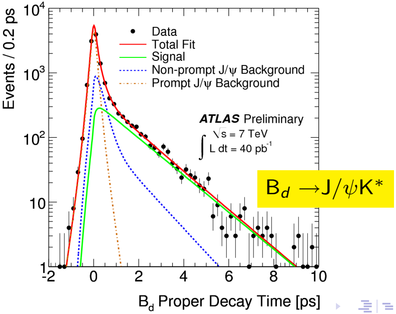
Lifetimes

- Lifetime measurements are the foundation for more complex measurements and selections (oscillations, mixing, $\Delta\Gamma_s$, β_s, rare decays, etc.)
- All lifetimes (inclusive and exclusive) consistent with PDG!

ATLAS-CONF-2011-092 (B_d, B_s)
ATLAS-CONF-2011-145 (B)

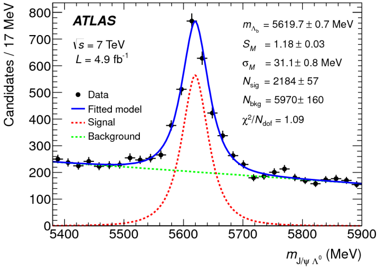


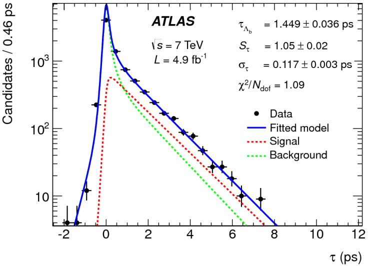




Λ_b Mass and Lifetime

arXiv:1207.2284





$\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$

- 4.9fb^{-1} of 2011 data, $\sqrt{s} = 7\,TeV$
- $\tau = \frac{L_{xy} \cdot m^{PDG}}{p_T}$
- Simultaneous mass and decay time maximum likelihood fit

  $\tau_{\Lambda_b} = 1.449 \pm 0.036(\text{stat.}) \pm 0.017(\text{syst.})$ ps

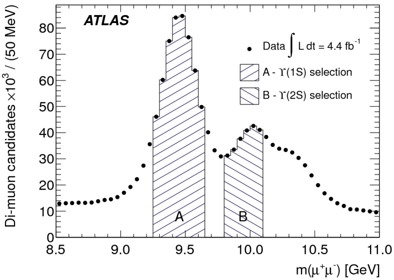
  $m_{\Lambda_b} = 5619.7 \pm 0.7(\text{stat.}) \pm 1.1(\text{syst.})$ MeV

Best single-experiment measurement of τ_{Λ_b}!

Observation of $\chi_b(3P)$

- 4.4fb^{-1} of 2011 data collected at $\sqrt{s} = 7\text{TeV}$
- $\chi_b(nP)$ observed through radiative decays to Υ
  - Υ identified through di-muon decay
  - Reconstruct either converted (e^+e^-) or un-converted photons originating from di-muon vertex

Phys.Rev.Lett.108 (2012) 152001



Observation of $\chi_b(3P)$

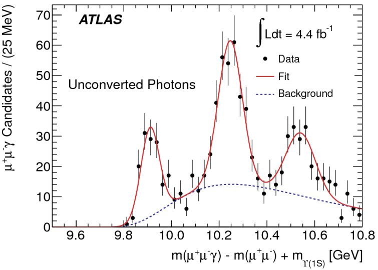
Phys.Rev.Lett.108 (2012) 152001

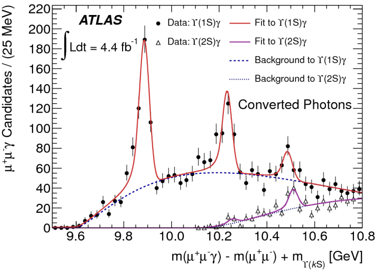
- $\chi_b \to \Upsilon(1S, 2S)\gamma$
  - Measure m(χ)-m(Υ)
  - 1P (9.90 GeV) and 2P (10.26 GeV) states clearly visible
  - Masses consistent with pdg
- Additional structure at 10.5 GeV seen with both converted and un-converted photons

$m(\chi_b(3P)) = 10.530 \pm 0.005(\text{stat.}) \pm 0.009(\text{syst.})$ GeV

Consistent with theoretical predictions!

First new resonance discovered at the LHC!

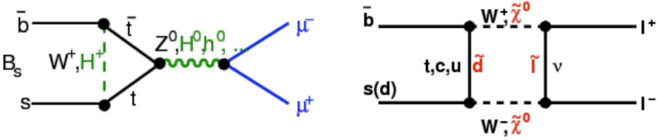




Search for Rare B Decays: $B_s \to \mu^+\mu^-$

Phys.Lett. B713 (2012) 387

- Flavour Changing Neutral Currents (FCNC) are highly suppressed in the Standard Model (SM)
  - Expected $B_s \to \mu\mu$ branching fraction is
    $(3.2 \pm 0.2) \times 10^{-9}$ Buras et al., Phys.Lett. B694 (2011) 402
    $(3.5 \pm 0.3) \times 10^{-9}$ UTfit prediction



- $B \to \mu\mu$ branching ratio may be significantly enhanced by couplings to non-SM particles
  - SM well understood $\to$ this channel provides a powerful method to peek into NP!

Analysis Strategy

- $2.4 fb^{-1}$ of data collected April-August 2011 at $\sqrt{s} = 7 TeV$
  → Update expected soon!
- Aim at cancellations of uncertainties through measurement wrt a reference decay: $B^{\pm} \to J/\psi K^{\pm}$
- Limit placed using standard CLs method
- Analysis is blind! Signal region (±300MeV around B_s mass) is blinded

$$BR(B_s \to \mu^+\mu^-) = N_{\mu^+\mu^-} \left[\frac{1}{N_{J/\psi K^{\pm}}} \frac{A_{J/\psi K^{\pm}}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^{\pm}}}{\epsilon_{\mu^+\mu^-}} \frac{f_u}{f_s} BR(B^{\pm} \to J/\psi K^{\pm} \to \mu^+\mu^- K^{\pm}) \right]$$

- Signal extraction
  - Event count in “signal” region
  - “subtraction” of sidebands: interpolation from 50% of sidebands (even events)
- Signal-background discrimination
  - 14 variables combined with multivariate tools (BDT)
  - 50% of sidebands used to model background (odd events)

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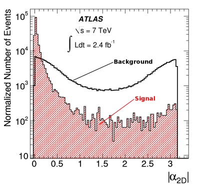
- Efficiencies and acceptances
  - Derived from MC ("calibrated" on data)
    $\epsilon \cdot A = \#$(reconstructed and selected events)/$\#$(generated events)
  - Reference channel selected with cuts as similar as possible to signal
- BR of the reference channel and relative production rate $\frac{f_u}{f_s}$
  - Taken from PDG and the latest LHCb results

Backgrounds and Discriminants

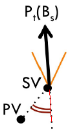


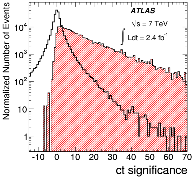
Dominant: continuum background

- $bb \to \mu\mu X$
- Smoothly varying with di-muon mass
- Interpolated from sidebands into the signal region

Resonant backgrounds

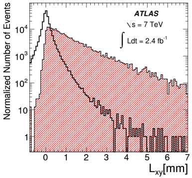
- $B \to hh$, with hadrons mis-identified as muons (0.2-0.4%)
- Similar decay topology as signal $\to$ hard to suppress
- Contribution estimated from MC: 0.24 events in total





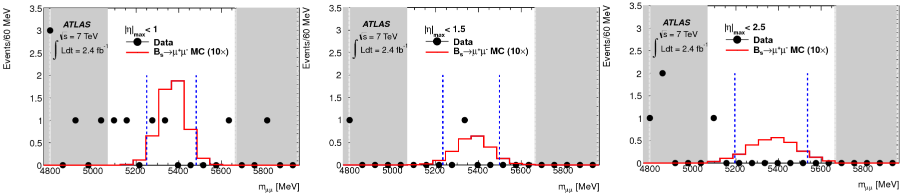
Discriminating variables picked to exploit:

- PV-SV separation (L_{xy}, ct significance)
- Symmetry of final state (pointing angle, d_0, ...)
- Full reconstruction (pointing angle, D_{min}, ...)
- B hadronization features (isolation, p_T of B, ...)



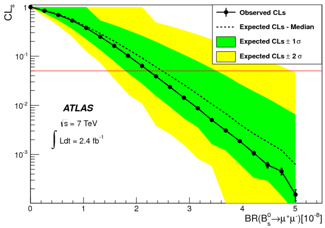
Box Opening

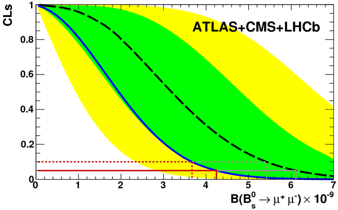
	$\lvert\eta\rvert < 1.0$	$1.0 < \lvert\eta\rvert < 1.5$	$1.5 < \lvert\eta\rvert < 2.5$
Even events in sidebands	5	0	2
Expected continuum background in SR	3.86	0	2.28
Expected resonant background in SR	0.1	0.06	0.08
Observed events in SR	2	1	0



- Grey areas: sideband regions
- Dotted blue lines: optimized search windows
- Red curves: enhanced MC signal peaks (x10)

Upper Limit





ATLAS-CONF-2012-061

ATLAS (2.4fb^{-1}) limit

- Upper limit extracted with modified frequentist (CLs) approach
- Median expected limit: 2.3×10^{-8} @ 95% CL
- Observed limit: 2.2×10^{-8} @ 95% CL

LHC wide combination

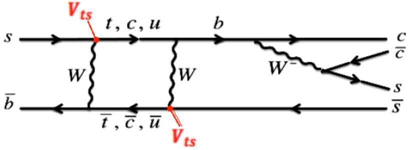
- Combined limit: 4.2×10^{-9} **@ 95% CL**
- Close to SM prediction: 3.2×10^{-9}
- Compatible with bkg+SM sig: $(1 - CL_{S+B}) = 84\%$
- Less compatible with bkg-only: $(1 - CL_B) = 5\%$

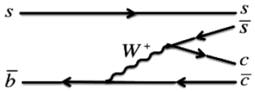
Mode	Limit	ATLAS	CMS	LHCb 2010	LHCb 2011	Combined
$B_s^0 \to \mu^+\mu^-$ (10^{-9})	Bkg Only	23	(3.6)	65	3.4	2.3
	Bkg+SM		8.4		7.2	6.1
	Obs	22	7.7 (7.2)	56	4.5	4.2

ϕ_s and $\Delta\Gamma_s$ from $B_s \to J/\Psi\phi$

arXiv:1208.0572

- The time evolution of the B_s and $\bar{B}_s$ is described by the superposition of the B_L and B_H states, with masses $m_s \pm \frac{\Delta m_s}{2}$ and lifetimes $\Gamma_s \pm \frac{\Delta\Gamma_s}{2}$
- The mass eigenstates deviate from the CP eigenstates $\to$ described in the SM by the mixing phase ϕ_s ($\phi_s = \arg[V_{ts}^2] = -2\beta_s$)
- SM predictions: $\phi_s = -0.0368 \pm 0.0018$ rad
  $\Delta\Gamma_s = 0.082 \pm 0.021$ ps^{-1}
- New physics can contribute to ϕ_s and change the ratio $\Delta\Gamma_s/\Delta m_s$





ϕ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\Psi\phi$

Data

- $4.9fb^{-1}$, $\sqrt{s} = 7\,TeV$

Selection

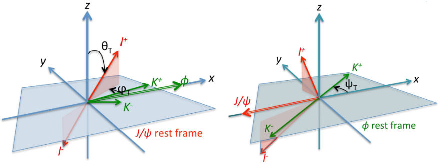
- η-dependent J/ψ mass window (varying resolution)
- ϕ required to be within 22MeV of the PDG mass
- χ^2(B decay vertex fit)/$\#dof < 3$
- No flavour tagging used to distinguish between initial B_s and $\bar{B}_s$ states

Efficiency

- Data-driven procedures (e.g. J/ψ tag & probe studies)

Angular analysis

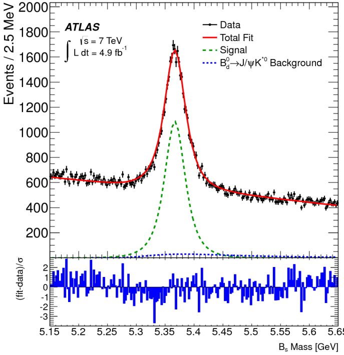
- $B_s \to J/\psi\phi$
  - Vector-Vector decay
  - $L = 0, 2 \to$ CP-even
  - $L = 1 \to$ CP-odd
- CP eigenstates are distinguished statistically through the time-dependence of the decay and angular correlations amongst the final-state particles

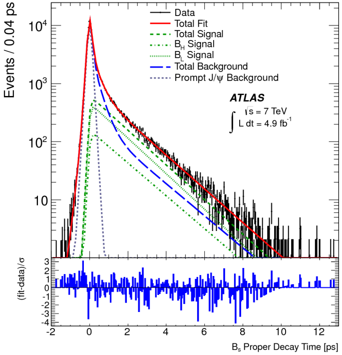


- Measurement uses "transversity basis":
  - Suitable angular parameterization to disentangle angular distributions
    - x-axis - direction of decay
    - xy-plane - ϕ decay plane
    - ψ_T - K^+ angle wrt x-axis
    - θ_T, ϕ_T - polar and azimuthal coordinates of μ^+
    - All angles and orientations defined in the parents' decay frame
  - Triplet of angular coordinates $\Omega = (\psi_T, \theta_T, \phi_T)$ uniquely identifies the decays angular signature
  - Can define 3 decay amplitudes, $A_0, A_\perp \text{and} A_\parallel$ that correspond to S-, P-, and D-wave transitions respectively
- Signal extracted from an unbinned maximum likelihood fit in (m, proper-time, Ω)

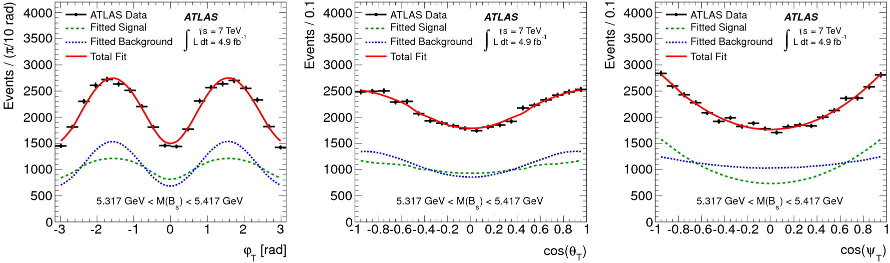
Fit Results: Mass and Proper Time

- Time dependence of untagged rate does not depend on Δm_s
  $\to \Gamma_L$ and Γ_H can be determined from data sample of untagged B_s mesons (Extraction of Δm_s requires tagging)
- Separation of Γ_L and Γ_H $\to$ can determine the lifetime difference between CP-even (B_s^L) and CP-odd (B_s^H) states





Fit Results: Transversity Angles



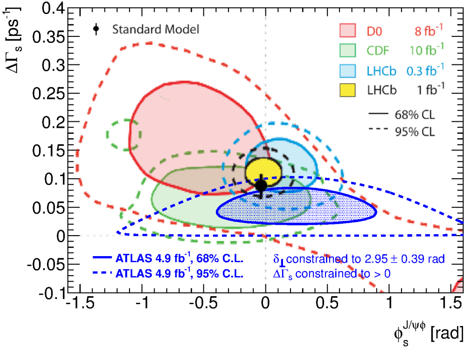
Allows to disentangle the amplitudes of the projections on the transversity basis: $A_0, A_{||}, A_\perp$, and A_S

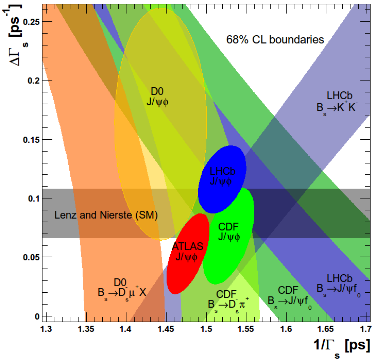
Fit Result: Summary

- In an untagged analysis ATLAS is not sensitive to $\delta_\perp$ $\rightarrow$ Constrain to 2.95 ± 0.39 rad [LHCb]
- So, with $4.9 fb^{-1}$ of ATLAS 2011 data, without flavour tagging, and assuming $\delta_\perp = 2.95 \pm 0.39$ rad and $\Delta\Gamma_s$ positive

$$
\begin{aligned}
\phi_s &= 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad} \\
\Delta\Gamma_s &= 0.053 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (syst.) ps}^{-1} \\
\Gamma_s &= 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1} \\
|A_0(0)|^2 &= 0.528 \pm 0.006 \text{ (stat.)} \pm 0.009 \text{ (syst.)} \\
|A_\parallel(0)|^2 &= 0.220 \pm 0.008 \text{ (stat.)} \pm 0.007 \text{ (syst.)}
\end{aligned}
$$

Likelihood ($\phi, \Delta\Gamma$) Contour and Comparison





Consistent with SM and other experiments!

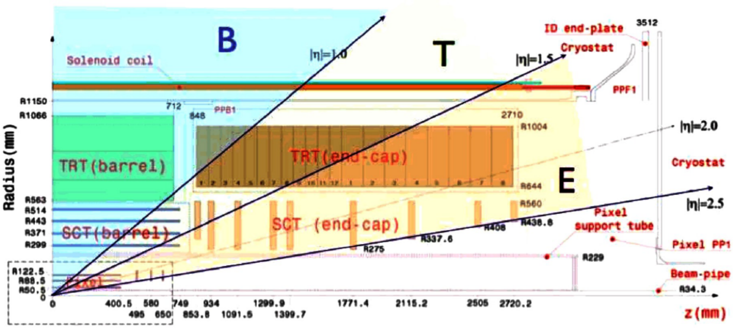
Conclusions

- ATLAS B physics program very successfull
- Consistent data-collection strategy for 2011 and 2012 data taking periods, with good signal collection efficiencies
- We discovered the first new particle at the LHC!
- First iterations on the pillars of our NP related program:
  - ϕ_s from $B_s \rightarrow J/\psi\phi$
  - Rare B decays
- New analyses, and updated results with higher integrated luminosities and improved analysis techniques in the pipeline

Backup

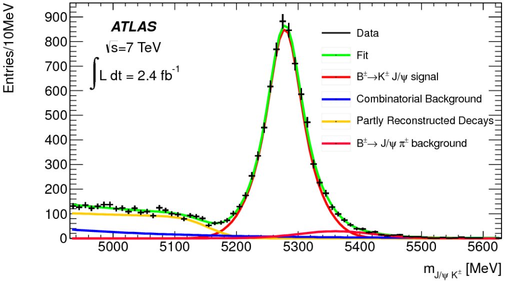
Separation in B Mass Resolution

- Signal candidates are split in 3 $|\eta_{max}|$ regions: Barrel, Transition, Endcap $\rightarrow$ (51%,24%,25%)
- Mass resolution gets worse with increasing $|\eta|$: (60MeV, 80MeV, 110MeV)



Reference Channel Yield

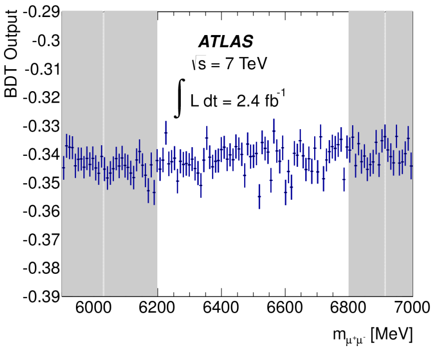
- BDT trained for B_s used also for B^+ in order to minimize selection systematics
- Inclusion of per-event mass resolution in the fit
- Yield uncertainties
  - Statistical
  - Systematic
    - Vary binning
    - Signal/ background models
    - Binned/un-binned fit

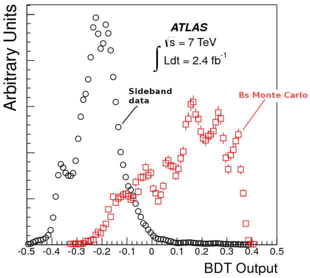


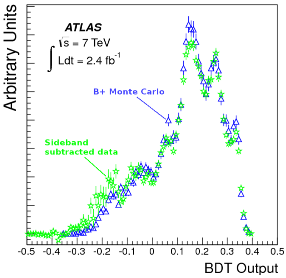
$\lvert\eta_{max}\rvert$ Range	0-1.0	1.0-1.5	1.5-2.5
$B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm$	4300	1410	1130
statistical uncertainty	±1.6%	±2.8%	±3.0%
systematic uncertainty	±2.9%	±7.4%	±14.1%

Boosted Decision Tree

- Combine 14 discriminants in 1 variable
- Trained and optimized on $B_s \to \mu\mu$ MC and odd sideband events
- Mass independence checked with training on higher masses (6.5GeV signal mass)







Ingredients for the Limit Extraction

$\lvert\eta\rvert_{\max}$ Range	0–1.0	1.0–1.5	1.5–2.5
$B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm$	4300	1410	1130
statistical uncertainty	±1.6%	±2.8%	±3.0%
systematic uncertainty	±2.9%	±7.4%	±14.1%

$\lvert\eta_{max}\rvert$ Range	$R^i_{A\epsilon}$	Δ % Stat.	Δ % Syst.
0-1.0	0.274	3.1	3.1
1.0-1.5	0.202	4.8	5.5
1.5-2.5	0.143	5.3	5.9

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu} \frac{1}{N_{B^\pm\to J/\psi K^\pm}} BR(B^\pm \to J/\psi K^\pm) \frac{f_u}{f_s} \frac{\epsilon_{B^\pm\to J/\psi K^\pm}}{\epsilon_{B_s\to\mu\mu}} \frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}$$

$1/(4.45\pm0.38)\times10^3$

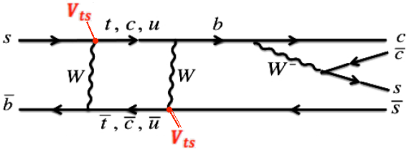
[PDG + LHCb]

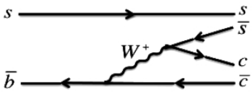
Additional sources of systematics:

- vertex reconstruction efficiency in data/MC
- absolute $K^\pm$ reconstruction efficiency
- asymmetry in detector response to K^+/K^-

ϕ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\Psi\phi$

- In general, the decay to a final state that is coupled to B_s and/or $\bar{B}_s$, exhibits fast oscillations driven by Δm_s. Interference between amplitudes for both states generates CP violation, and conveys information on ϕ_s





- If $\bar{B}/B$ flavour at production is not determined (not tagged), the fast oscillations cannot be observed, but interference terms remain if the final state is described by a superposition of amplitudes of different CP values

Systematic Uncertainties & Results

Several techniques used to derive systematics:

- Variation in detector simulation (e.g. alignment)
- Data-driven studies (e.g. efficiency)
- Monte Carlo "toy studies" (e.g. mass models, background angles)
- Variations in analysis methods and assumptions

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.22	0.41	0.10
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.008
Γ_s(ps^{-1})	0.677	0.007	0.004
$\|A_0(0)\|^2$	0.528	0.006	0.009
$\|A_\parallel(0)\|^2$	0.220	0.008	0.007
$\|A_S(0)\|^2$	0.02	0.02	0.02

Systematic Uncertainty	ϕ_s(rad)	$\Delta\Gamma_s$(ps^{-1})	Γ_s(ps^{-1})	$\|A_\parallel(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$
Inner Detector alignment	0.04	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Trigger efficiency	< 0.01	< 0.001	0.002	< 0.001	< 0.001	< 0.01
Signal mass model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background mass model	0.03	0.001	< 0.001	0.001	< 0.001	< 0.01
Resolution model	0.05	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Background lifetime model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background angles model	0.05	0.007	0.003	0.007	0.008	0.02
B^0 contribution	0.05	< 0.001	< 0.001	< 0.001	0.005	< 0.01
Total	0.10	0.008	0.004	0.007	0.009	0.02

Symmetries of the Likelihood Function

The PDF describing the $B_s \to J/\psi\phi$ decay is invariant under the following simultaneous transformations:

$$\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S \to \pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S$$

In the absence of initial state flavour tagging the PDF is also invariant under

$$\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S \to -\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S$$

leading to a fourfold ambiguity.

The value for the Gaussian constraint on $\delta_\perp$ is taken from the LHCb measurement [arXiv:1112.3183] $\to$ two of the four minima fitted in the present non-flavour tagged analysis are excluded from the results presented here.

Additionally a solution with negative $\Delta\Gamma_s$ is excluded following the LHCb measurement [arXiv:1202.4717]