Recent B physics results from ATLAS

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on behalf of the ATLAS Collaboration

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Recent B physics results from ATLAS

**Outline**

- ATLAS data, detector and triggers
- Heavy flavour production and decay
- Indirect new physics searches
- Conclusions
**ATLAS**

- **Tracking**
  - Silicon (Pixel+Semiconductor tracker) and Transition Radiation Tracker
  - 2T solenoidal field

- **Muon identification:**
  - Dedicated tracking chambers
  - 0.5-2 T toroidal field

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**LLWI 2015**

- **Tracking**
  - Silicon (Pixel+Semiconductor tracker) and Transition Radiation Tracker
  - 2T solenoidal field

- **Muon identification:**
  - Dedicated tracking chambers
  - 0.5-2 T toroidal field

**>25 fb⁻¹ recorded in Run1**

**ATLAS Preliminary**

- **2012, √s = 8 TeV**
  - Delivered: 22.8 fb⁻¹
  - Recorded: 21.3 fb⁻¹
  - Physics: 20.3 fb⁻¹

- **2011, √s = 7 TeV**
  - Delivered: 5.46 fb⁻¹
  - Recorded: 5.08 fb⁻¹
  - Physics: 4.57 fb⁻¹

**di-muon triggers are our main tool**

- constant trigger thresholds for di-muons all across 2011: 4+4 GeV p_T

**in 2012 specific di-muon selections with Barrel/Endcap logic**

- new dedicated μμX trigger
- 4+4 p_T and 4+6 GeV p_T thresholds

**Several results still based on 2011 data only:**

\[ \mathcal{L} = 4.9 \text{ fb}^{-1} \text{ at } \sqrt{s}=7 \text{ TeV} \]
Production cross-section of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

$\chi_c$ production

W$+\psi$ and Z$+\psi$ Productions

Search for the $X_b$ beauty state in the $\pi^+\pi^-\Upsilon(1S)$ channel

Observation of an excited $B_c$ meson state
Heavy Flavour production:

Ideal probes of hadron formation (QCD), but production is not yet understood

- **Colour Singlet Model:**
  produced directly as colour-neutral $q\bar{q}$ pairs

- **NRQCD factorization:**
  also produced as coloured $q\bar{q}$ pairs of any possible quantum numbers

Onia production occurs through:

- **Prompt production:** direct production or feed-down from higher quarkonium states.
- **Non-prompt production:** from B hadron decays (only charmonium).

Distinguished through different proper-time distributions
Recent B physics results from ATLAS

Heavy quarkonium physics

cc family

- \( \Psi(2S) \)
- \( \chi_{c0}(1P) \)
- \( \chi_{c1}(1P) \)
- \( \chi_{c2}(1P) \)

- \( J/\psi(1S) \)

- direct produced
- \( J/\psi \) in CDF data

bb family

- \( \Upsilon(3S) \)
- \( \chi_{b0}(2P) \)
- \( \chi_{b1}(2P) \)
- \( \chi_{b2}(2P) \)

- \( \Upsilon(2S) \)
- \( \chi_{b0}(1P) \)
- \( \chi_{b1}(1P) \)
- \( \chi_{b2}(1P) \)

- \( \Upsilon(1S) \)

- direct produced
- \( \Upsilon(1S) \) in CDF data

- from \( \Upsilon(2S) + \Upsilon(3S) \)
- from \( \chi_{b1}(2P) + \chi_{b2}(2P) \)
- from \( \chi_{b1}(1P) + \chi_{b2}(1P) \)

- non-prompt (b-hadrons)
Production cross-section of $\psi(2S) \to J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

Measurements of the prompt and non-prompt production cross-sections for $\psi(2S)$ mesons

\[
\frac{d^2\sigma(pp \rightarrow Q + X)}{dp_T dy} \cdot B_r(Q \rightarrow \mu\mu) = \frac{N_{corr}^{Q \rightarrow \mu\mu}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}
\]

- $N_{corr}^{Q \rightarrow \mu\mu}$: signal yield corrected for efficiency and acceptance
- $\mathcal{L}$: integrated luminosity corresponding to the sample
- $\Delta p_T(y)$: interval bin of the differential variable

Signal yield: unbinned maximum likelihood fits on mass and proper time $\Rightarrow \sigma$ stat ~ few %

$p_T$ and $\eta$ efficiency maps $\Rightarrow$ data driven methods (tag & probe)

acceptance corrections $\Rightarrow$ from simulation

2.1 fb$^{-1}$ of 2011 data

JHEP 09 (2014) 079
Production cross-section of $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$

prompt production cross-sections for $\psi(2S)$ mesons

- Good agreement with CMS and LHCb
- Sensitivity to the new high $p_T$ regime

2.1 fb$^{-1}$ of 2011 data

**JHEP 09 (2014) 079**
Recent B physics results from ATLAS

**Production cross-section of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$**

- Good agreement with CMS and LHCb
- Sensitivity to the new high $p_T$ regime

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**Non-prompt production cross-sections for $\psi(2S)$ mesons**

- Good agreement with predictions @ all $p_T$

2.1 $fb^{-1}$ of 2011 data

**JHEP 09 (2014) 079**
Measurement of $\chi_{c1}$ and $\chi_{c2}$ production

- Radiative decay $\chi_c \to J/\psi \gamma$
  with $J/\psi \to \mu^+\mu^-$
  with converted photons.

- Mass difference to distinguish the $\chi_{c1}$ and $\chi_{c2}$ states: partial cancellations give improved overall mass resolution.

- Non-prompt $\chi_c$ produced in the decays of $b$-hadrons distinguished from prompt $\chi_c$ candidates (produced in the primary pp interaction) with the pseudo-proper decay time distribution

4.5 fb$^{-1}$ of 2011 data

JHEP 07 (2014) 154
Measurement of $\chi_{c1}$ and $\chi_{c2}$ production

- Prompt $\chi_c$ cross sections combined with prompt $J/\psi$ production to obtain the fraction of prompt $J/\psi$ produced in feed-down from $\chi_c$ decays

- $\chi_{c2}$ production rate relative to $\chi_{c1}$ prompt and non-prompt $\chi_{c2}$ function of $J/\psi$ transverse momentum.
Associated W/Z+J/ψ Production

Studies of production of prompt (and non-prompt) J/ψ in association with W or Z bosons:

- observation of associated quarkonia production
- cross-section measurements
- study of the double/single parton scattering contributions
  fully reconstructed quarkonia → experimentally cleaner than alternatives methods

Two possible production modes

- single parton scattering (SPS): objects from same diagrams,
  can be resonant or non-resonant
  - sensitive to different matrix elements: to test/develop theoretical models
  - possibility of resonant production from Higgs or New Physics

- double parton scattering (DPS): each object from a separate hard scatter within the same proton collision:
  - difficult to address theoretically but often invoked
    to explain (e.g.) rates of multiple heavy-flavour production

JHEP 04 (2014) 172
arXiv:1412.6428
Recent B physics results from ATLAS

**Associated W+J/ψ Production**

**UML fit to J/ψ mass and lifetime**

- gives ~30 prompt J/ψ with a W±
- includes 1.8 ± 0.2 from pile-up and
- 10.8 ± 4.2 from double parton scattering (DPS)

**14.8 M inclusive W±**

(W + J/ψ) to inclusive W±: ratio of cross-section

- ATLAS, √s = 7 TeV, ∫L dt = 4.5 fb⁻¹
- BR(J/ψ→μμ)/σ(W) × 1/d²σ(W+J/ψ)/dy dp⁺

- Data
- Total fit
- W + prompt combinatorics
- W + non-prompt combinatorics

- pp→ prompt J/ψ + W : pp→ W

- 4.5 fb⁻¹ of 2011 data

Marcella Bona, QMUL
Associated Z+J/ψ Production

Same pattern is observed in the azimuthal opening angle with the W

Again the DPS band is an estimate

DPS dominates this bin

Yield extracted by first fitting weighted distributions of mass and lifetime of the J/ψ and then Z mass is fitted

Lower limit on estimated DPS effective cross-section

Yield extracted by first fitting weighted distributions of mass and lifetime of the J/ψ and then Z mass is fitted

Lower limit on estimated DPS effective cross-section

20.3 fb⁻¹ of 2012 data

arXiv:1412.6428
Associated Z+J/ψ Production

Lowest $p_T$ bin $\sim$ mostly DPS

SPS drops off less steeply with $p_T$ than DPS so highest bins are SPS dominated

Theory discrepancy gets more pronounced with increasing $p_T$

c.f. inclusive spectra, where NRQCD now does a reasonable job

20.3 fb$^{-1}$ of 2012 data

arXiv:1412.6428
Search for the $X_b$ beauty state in the $\pi^+\pi^-\Upsilon(1S)$ channel

Exotic state $X(3872)$ discovered in $J/\psi \pi\pi$: diquark-diantiquark or $D\bar{D}$ molecule
Search for a $bb/BB$ equivalent: $J^{PC} = 1^{++}$, narrow and produced in $pp$ collisions
- model-dependent mass predictions: $m = 10.561$ GeV for Swanson BB* molecule

- Test for signal every 10 MeV
- Binned simult. fit across 8 analysis bins

No evidence for any new states
- Upper limits of $\sigma \times BR / (\sigma \times BR)_{2S} = 0.8\% - 4.0\%$

$\Upsilon(3S)$: simult. fit to 8 analysis bins
$\Upsilon(2S)$ and $\Upsilon(3S)$: agreement with predictions in yields

16.2 fb$^{-1}$ of 2012 data
Observation of an excited $B_c$ meson state

- No excited states of $B_c^+$ reported previously
- Spectrum and properties of $B_c^+$ family predicted by NR potential models, perturbative QCD and lattice calculations
- State with mass $6842 \pm 4 \text{ (stat.)} \pm 5 \text{ (syst.) MeV}$, consistent with the predicted mass of $B_c^+(2S)$
- Significance includes “look elsewhere effect”

Combined significance: $5.2\sigma$
(local significance is $5.4\sigma$)

24.1 fb$^{-1}$ of 2011+2012 data
flavour observables and indirect searches for new physics

Parity violating asymmetry parameter $\alpha_b$ and helicity amplitudes for the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

search for rare decays: $B_s \rightarrow \mu\mu$

angular analysis of decays: $B_d \rightarrow K^*\mu\mu$

$\Delta \Gamma_s$ and $\phi_s$ measurement from $B_s \rightarrow J/\psi \phi$

PRD 89 (2014) 092009
ATLAS-CONF-2013-076
ATLAS-CONF-2013-038
PRD 90 (2014) 052007
Parity violation in decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

$$w(\cos \theta) = \frac{1}{2} (1 + \alpha_b \cdot P \cdot \cos \theta)$$

- Violation not maximal $\rightarrow |\alpha_b| < 1$
- Measure moments ($F_i$) of the angular distribution
- Result:
  $$\alpha_b = 0.30 \pm 0.16 \text{ (stat)} \pm 0.06 \text{ (syst)}$$
  - consistent with LHCb $\alpha_b = 0.05 \pm 0.17 \pm 0.07$
  - predictions: $\alpha_{\text{HQET}} = 0.78$ and $\alpha_{\text{pQCD}} = -(0.14 \div 0.17)$

![Graphs and diagrams showing data and results from ATLAS experiment, including event distributions and fitted models.]

**ATLAS**

- $\sqrt{s} = 7 \text{ TeV}, \int L \, dt = 4.6 \text{ fb}^{-1}$
- $\Lambda_b^0 + \bar{\Lambda}_b^0$

**$\chi^2_{\text{min}}$ value**

- $\sqrt{s} = 7 \text{ TeV}, \int L \, dt = 4.6 \text{ fb}^{-1}$
- $\Lambda_b + \bar{\Lambda}_b$
- $\alpha_b^{\text{best}} = 0.30$
- $\chi^2_{\text{min}}(\alpha_b^{\text{best}}) = 3.15$

4.6 fb$^{-1}$ of 2011 data

search for rare decays: $B_s \rightarrow \mu\mu$

- FCNC highly suppressed
- expected $B_s \rightarrow \mu\mu$ SM BR: $(3.65 \pm 0.23) \times 10^{-9}$
- result from CMS+LHCb: $(2.9 \pm 0.7) \times 10^{-9}$
- number of observed events: 6 wrt 6.75 exp.

$$\text{BR} < 1.5 \times 10^{-9} @ 95\%$$

Ongoing analysis on whole Run1:
many improvements: fake $\mu$ rejection, background characterisation and separation, signal extraction with mass fits

angular analysis of decays: $B_d \rightarrow K^*\mu\mu$

- FCNC:
  - BR $\sim 1.1 \times 10^{-6}$
  - angular analysis as function of di-muon mass $q^2$
  - $N\text{ sig} = 466 \pm 34$
  - $N\text{ bkg} = 1132 \pm 43$

ATLAS-CONF-2013-076
4.9 fb$^{-1}$ of 2011 data

ATLAS-CONF-2013-038
Recent B physics results from ATLAS

**ΔΓ_с and φ_с measurement from B_s → J/ψφ**

- **B_s** time-dependent analysis: sensitive to the mixing phase φ_с (φ_с = -2β_с),

  - **SM prediction (fit):** φ_с = -0.0368 ± 0.0018 rad and ΔΓ_с = 0.082 ± 0.021 ps⁻¹

  - New Physics can contribute to φ_с, and change the ratio ΔΓ_с /Δm_с.

- **B_s → J/ψφ → l⁺l⁻ K⁺K⁻** in angular amplitudes → CP = +1 or -1

  - need of an angular analysis: the “transversity angles” are used

- signal extracted from a ML fit: mass+lifetime+angular variables+initial B_s flavour

  - dominant systematic: uncorrelated description of background angle distributions

- **Likelihood profiles in the φ_с – ΔΓ_с plane**

  - uncertainty of φ_с improved by 40% compared to untagged analysis

**References:**

- PRD 90 (2014) 052007
- 4.9 fb⁻¹ of 2011 data
ΔΓ_s and φ_s measurement from B_s → J/ψφ in Run 2:

- New Inner Detector layouts IBL and ITK improve decay time resolution σ_t by 30% w.r.t. Run 1
- Higher p_T improves σ_t and signal purity at the expense of efficiency
- Slight σ_t (~14%) increase in Run 2 with number of PVs but stable for N(PV) > 40

- Triggers of p_T thresholds for dimuons:
  - Run 2-3: 6+6 GeV (nominal)
  - or 11+11 GeV (pessimistic) [7x less B_s]
- HL-LHC: 11+11 GeV
- Room for further improvements
- Developments of L1 topological trigger
- Take into account flavour tagging and fit improvements developed in analysis of 2012 data

ATL-PHYS-PUB-2013-010
conclusions

- ATLAS able to provide a rich heavy flavour programme:
  - heavy flavour production and decay
    - $\psi(2S)$ production prompt and non-prompt cross section
    - $\chi_c$, $\chi_b$, and associated $W/Z + J/\psi$ productions
    - searches for exotic state $X_b$
    - observation of an excited $B_c$ meson state
  - semirare, rare $B$ decays and CP phase measurements
    - $P$ violation in $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
    - search for the rare decay $B_s \rightarrow \mu\mu$
    - angular analysis of the decay $B^0 \rightarrow K^{0*}\mu\mu$
    - measurement of CP violating phase $\phi_s$ and the decay width difference $\Delta\Gamma_s$ in the decay $B_s \rightarrow J/\psi\phi$
  - all measurements are consistent with predictions from the SM
  - no sign for physics beyond the SM
  - all measurements are statistically limited
  - analyses including 2012 data (~20/fb) ongoing
  - plenty of possibilities for improvements
backup
search for rare decays: $B_s \rightarrow \mu\mu$

- FCNC highly suppressed
  - expected $B_s \rightarrow \mu\mu$ SM BR: $(3.65 \pm 0.23) \times 10^{-9}$
    - Bobeth et al
  - result from CMS+LHCb: $(2.9 \pm 0.7) \times 10^{-9}$
- indirect searches orthogonal to direct searches: can reach higher scales

- BR measured wrt $B^+ \rightarrow J/\psi K^+$ reference mode
- systematics dominated by reference channel BR and efficiency ratio
- number of expected bkg events: 6.75
- number of events observed: 6
- measured upper limit from the number of observed events
  $< 1.5 \times 10^{-9} \text{ @ 95%}$

Ongoing analysis on whole Run1:
- many improvements: fake $\mu$ rejection, background characterisation and separation, signal extraction with mass

**Recent B physics results from ATLAS**

**LLWI 2015**

**ATLAS**

**ATLAS-CONF-2013-076**
analysis strategy @ ATLAS:

- Integrated luminosity 4.9 fb$^{-1}$ used
- Relative BR measurement:
  - partial cancellation of uncertainties: on luminosity, cross-section, ..
  - reference channel ($B^\pm \rightarrow J/\psi K^\pm$, $J/\psi \rightarrow \mu^+\mu^-$)
  - blind analysis: signal region ± 300 MeV around $B_s$
  - limit placed using CLs method

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

- Signal extraction:
  - event count in “signal region”
  - “subtraction” of sidebands: interpolation from 50% of sidebands (even events)
- Background composition:
  - resonant: $B \rightarrow hh$, with hadrons misidentified as muons estimated from MC.
    Currently still negligible but included in the analysis
  - continuum: dominated by non-resonant $b\bar{b}$ production with $\mu\mu X$ final states.
    Contains real muons. Has a smooth shape in the di-muon mass.
analysis strategy @ ATLAS:

**Relative BR measurement:**
- partial cancellation of uncertainties: on luminosity, cross-section, ..
- reference channel ($B^\pm \rightarrow J/\psi K^\pm$, $J/\psi \rightarrow \mu^+ \mu^-$)
- blind analysis: signal region $\pm$ 300 MeV around $B_s$ mass blinded
- limit placed using CLs method

\[
BR(B_s \rightarrow \mu\mu) = \frac{N_{B_s \rightarrow \mu\mu}}{N_{B^\pm \rightarrow J/\psi K^\pm}} \frac{1}{BR(B^\pm \rightarrow J/\psi K^\pm)} \frac{f_u}{f_s} \frac{\varepsilon_{B^\pm \rightarrow J/\psi K^\pm} A_{B^\pm \rightarrow J/\psi K^\pm}}{\varepsilon_{B_s \rightarrow \mu\mu} A_{B_s \rightarrow \mu\mu}}
\]

**Efficiencies & acceptances**
- derived from simulation ("calibrated" on data)
  \[
  \varepsilon \cdot A = \frac{N_{\text{reconstructed and selected}}}{N_{\text{generated}}}
  \]
- reference channel ($B^\pm \rightarrow J/K^\pm$) selected with as-close-as-possible selection
- systematics taken from the data-MC discrepancies in signal distributions

**BR of the reference channel and relative production rate $f_u/f_s$**
- taken from PDG and the latest LHCb results
background discrimination

- **continuum:**
  - dominated by non-resonant $\bar{b}b$ production with $\mu\mu X$ final states → real muons
  - to discriminate against this background 13 discriminating variables used in a boosted decision tree (BDT) trained on simulated events
  - best BDT configuration and selection criteria optimised on half of the sideband data (odd events) and signal MC.
  - contamination to the signal region measured by interpolation from sideband data into the signal region

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**data-MC agreement for the continuum background in two of the most powerful variables**
background discrimination

- **continuum:**
  - dominated by non-resonant $\bar{b}b$ production with $\mu\mu X$ final states $\rightarrow$ real muons
  - to discriminate against this background 13 discriminating variables used in a boosted decision tree (BDT) trained on simulated events
  - best BDT configuration and selection criteria optimised on half of the sideband data (odd events) and signal MC.
  - contamination to the signal region measured by interpolation from sideband data into the signal region
background composition

- **continuum:**
  - dominated by non-resonant bb production with $\mu\mu X$ final states
  - real muons
  - smooth shape in the di-muon mass
  - limited MC statistics available in ATLAS
  - measured by interpolation from sideband data into the signal region

- **resonant:**
  - $B \rightarrow hh$, with hadrons misidentified as muons
  - mainly $B \rightarrow K^+\pi^-/\pi^+\pi^-$ decays
  - $BR \times$ (fake rate) $\approx 10^{-9}$
    - close to the SM $B_s$ to $\mu\mu$ BR
  - similar decay topology $\rightarrow$ hard to suppress
  - contribution estimated from MC currently still quite small

\[ B_s \rightarrow \mu\mu \]
reconstruction and event selection

- 2, 3 or 4 prong vertex constraint depending on decay topology
- Primary Vertex selection:
  - the closest in z to the B candidate
  - Re-fit excluding B daughters
- Tracks:
  - At least 1 pixel, 6 SCT and 9 TRT hits *(good tracks)*
  - $|\eta| < 2.5$ and $p_T > 4$ (2.5) GeV for muons (kaons)
  - tracks from the tracking systems matched to muon spectrometer tracks
- B candidates: $p_T > 8$ GeV and $|\eta|<2.5$

- select events based on their decay topology
- discriminating variables to distinguish between B and continuum events
- 14 variables identified and used in a boosted decision tree (BDT):
  - not correlated with invariant mass
  - highest discriminating power
  - highly correlated variables excluded

$$B_s \rightarrow \mu \mu$$
discriminating variables

Exploit:
- Primary Vertex-Secondary Vertex separation: $L_{xy}$, $c\tau$ significance
- Symmetry of final state: pointing angle, $d_0$...
- Full reconstruction: pointing angle, $D_{\text{min}}$...
- B hadronization features: Isolation, $p_T$ of the B...

$\mathbf{B}_s \rightarrow \mu\mu$
angular analysis of decays: \( B_d \rightarrow K^*\mu\mu \)

- another way to look at FCNC: \( \text{BR} \sim 1.1 \times 10^{-6} \)
- angular distribution of the 4 particles
  in the final state sensitive to new physics
  for the interference of NP and SM diagrams
- decay described by three angles \( (\theta_L, \theta_K, \phi) \) and the di-muon mass \( q^2 \)
- Measure forward-backward asymmetry \( (A_{FB}) \) and longitudinal polarization fraction \( (F_L) \) with unbinned ML fit in \( q^2 \) bins
- \( N \text{ sig} = 466\pm34, N \text{ bkg} = 1132\pm43 \)

\[ \text{vetoed } J/\psi \text{ and } \psi(ns) \rightarrow \mu\mu(\gamma) \]

\[ \begin{align*}
A_{FB} & \\
F_L & 
\end{align*} \]
Binning in $q^2$

Bins are identical to those used by Belle

- $0.04 < q^2 < 2.00$ GeV$^2$ (no angular analysis performed due to low statistics)
- $2.00 < q^2 < 4.30$ GeV$^2$
- $4.30 < q^2 < 8.68$ GeV$^2$
- $8.68 < q^2 < 10.09$ GeV$^2$ (J/$\psi$ mass region, excluded)
- $10.09 < q^2 < 12.86$ GeV$^2$
- $12.86 < q^2 < 14.18$ GeV$^2$ ($\psi(2S)$ mass region, excluded)
- $14.18 < q^2 < 16.00$ GeV$^2$
- $16.00 < q^2 < 19.00$ GeV$^2$
- $1.00 < q^2 < 6.00$ GeV$^2$
Fit strategy

Extended unbinned maximum likelihood fit in each $q^2$ bin
Sequential fit: first fit $m(K\pi\mu\mu)$ distribution, then the angular distributions with mass term parameters fixed.

The procedure checked to give same results as single-step fit except the lowest $q^2$ bin (included in systematics there).

- Mass fit (*in each* $q^2$ *bin*):

$$\mathcal{L} = \prod_{i=1}^{N} [N_{\text{sig}} \cdot \mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) + N_{\text{bckg}} \cdot \mathcal{M}_{\text{bckg}}(m_i)]$$

- Signal mass PDF – gaussian with per-candidate errors:

$$\mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) = \frac{1}{\sqrt{2\pi s_m \delta_{m_i}}} \exp \left( \frac{-(m_i - m_{B_d}^0)^2}{2(s_m \delta_{m_i})^2} \right)$$

- Background mass PDF – exponential

$$\mathcal{M}_{\text{bckg}}(m_i) = e^{-\lambda \cdot m_i}$$
Fit strategy (2)

- Angular fit *(in each $q^2$ bin)*:

$$\mathcal{L} = \prod_{i=1}^{N} \left[ N_{\text{sig}}^{\text{fix}} \cdot \mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}|\text{fixed}) \cdot \mathcal{A}_{L,\text{sig}}(\cos \theta_{L,i}) \cdot \alpha_{L}(\cos \theta_{L,i}) \cdot \mathcal{A}_{K,\text{sig}}(\cos \theta_{K,i}) \cdot \alpha_{K}(\cos \theta_{K,i}) + N_{\text{bckg}}^{\text{fix}} \cdot \mathcal{M}_{\text{bckg}}(m_i|\text{fixed}) \cdot \mathcal{A}_{L,\text{bckg}}(\cos \theta_{L,i}) \cdot \mathcal{A}_{K,\text{bckg}}(\cos \theta_{K,i}) \right]$$

- Signal PDFs:

$$\mathcal{A}_{L,\text{sig}}(\cos \theta_{L,i}) = \frac{3}{4} F_L(q^2) (1 - \cos^2 \theta_{L,i}) + \frac{3}{8} (1 - F_L(q^2)) (1 + \cos^2 \theta_{L,i}) + A_{FB}(q^2) \cos \theta_{L,i}$$

$$\mathcal{A}_{K,\text{sig}}(\cos \theta_{K,i}) = \frac{3}{2} F_L(q^2) \cos^2 \theta_{K,i} + \frac{3}{4} (1 - F_L(q^2)) (1 - \cos^2 \theta_{K,i})$$

- Background PDF – linear combination of Chebyshev polynomials up to $2^{nd}$ order:

$$\mathcal{A}_{L(K),\text{bckg}} = 1 + p_{1L(K)} \cos \theta_{L(K),i} + p_{2L(K)} \left( 2 \cos^2 \theta_{L(K),i} - 1 \right)$$

- $\alpha_{L}(\cos \theta_{L,i}), \alpha_{K}(\cos \theta_{K,i})$ – acceptance functions taking into account detector and selection effect on the angular shapes
Systematic uncertainties

Ranges of the mass fit region
Differ in $q^2$ bins due to $\Delta M$ cut effect

Angular background shapes
Varied between 2nd and 3rd Chebyshev polynomials

Contribution of $B^\pm \rightarrow \mu^+\mu^-K^\pm$ events
Estimated by removing potential $B^\pm \rightarrow \mu^+\mu^-K^\pm$ candidates

Angular acceptance effects
Mainly from limited MC statistics
Various signal angular shapes tested

Sequential fitting approach
Non-negligible effect only in $2.00 < q^2 < 4.30$ GeV$^2$ bin
due to low statistics

Following sources found to be negligible
Contribution from S-wave ($B_d^0 \rightarrow \mu^+\mu^-K^+\pi^-$ decays)
Contribution from $B_s \rightarrow \phi \rightarrow K^+K^- \mu^+\mu^-$ events
Background mass shape
Possible bias due to angular fit approach (neglecting correlation)
Recent B physics results from ATLAS

**signal observation**

- **ATLAS Preliminary**
  - $0.04 \text{ GeV}^2 < q^2 < 19.00 \text{ GeV}^2$
  - $\sqrt{s} = 7 \text{ TeV}$
  - $Ldt = 4.9 \text{ fb}^{-1}$

- **mass fit** with Gaussian shape for the signal including the per-candidate error and exponential shape for the background

- **full di-muon mass range** with $J/\psi$ and $\psi(2S)$ regions excluded

- **signal yield**: $N_{\text{sig}} = 466 \pm 34$
measurements of $A_{FB}$ and $F_L$

- $A_{FB}$ and $F_L$ in different regions of $q^2$:
  - 8 bins used defined à la Belle
- use unbinned maximum likelihood fit
- sequential fit approach applied
- use mass to separate signal and background contributions
- angular fit with yields fixed to the results from the mass fit

$4.30 < q^2 < 8.68 \text{ GeV}^2$
Recent B physics results from ATLAS

Theoretical prediction from C. Bobeth et al.
arXiv:1105.2659

<table>
<thead>
<tr>
<th>$q^2$ range (GeV$^2$)</th>
<th>$N_{sig}$</th>
<th>$A_{FB}$</th>
<th>$F_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00 &lt; $q^2$ &lt; 4.30</td>
<td>19 ± 8</td>
<td>0.22 ± 0.28 ± 0.14</td>
<td>0.26 ± 0.18 ± 0.06</td>
</tr>
<tr>
<td>4.30 &lt; $q^2$ &lt; 8.68</td>
<td>88 ± 17</td>
<td>0.24 ± 0.13 ± 0.01</td>
<td>0.37 ± 0.11 ± 0.02</td>
</tr>
<tr>
<td>10.09 &lt; $q^2$ &lt; 12.86</td>
<td>138 ± 31</td>
<td>0.09 ± 0.09 ± 0.03</td>
<td>0.50 ± 0.09 ± 0.04</td>
</tr>
<tr>
<td>14.18 &lt; $q^2$ &lt; 16.00</td>
<td>32 ± 14</td>
<td>0.48 ± 0.19 ± 0.05</td>
<td>0.28 ± 0.16 ± 0.03</td>
</tr>
<tr>
<td>16.00 &lt; $q^2$ &lt; 19.00</td>
<td>149 ± 24</td>
<td>0.16 ± 0.10 ± 0.03</td>
<td>0.35 ± 0.08 ± 0.02</td>
</tr>
<tr>
<td>1.00 &lt; $q^2$ &lt; 6.00</td>
<td>42 ± 11</td>
<td>0.07 ± 0.20 ± 0.07</td>
<td>0.18 ± 0.15 ± 0.03</td>
</tr>
</tbody>
</table>

- statistically limited uncertainty
- measurement consistent with the SM prediction
Recent B physics results from ATLAS

**angular analysis in** \( B_s \rightarrow J/\psi \phi \)**

- In the decay \( \bar{B}_s(B_s) \rightarrow J/\psi \phi \rightarrow l^+l^- K^+K^- \)
different components in the angular-distributions amplitudes correspond to CP = +1 or −1.

- The “transversity angles” are used to describe the angular distributions.

- Analysis using data collected in 2011, corresponding to 4.9 fb\(^{-1}\)


- Signal extracted from a maximum likelihood fit:

\[
\ln \mathcal{L} = \sum_{i=1}^{N} \left\{ w_i \cdot \ln \left( f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i) \right) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) \right. \\
\left. + \left( 1 - f_s \cdot (1 + f_{B^0}) \right) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i) \right\} + \ln P(\delta_\perp)
\]

- The prompt and non-prompt combinatorial background described with empirical angular distribution. (No K-\( \pi \) discrimination.)

- \( w_i \) describes a small trigger inefficiency (~1%).

- The background due to \( B^0 \rightarrow J/\psi K^* \)

- And \( B^0 \rightarrow J/\psi K\pi \) with amplitude \( f_{B^0} \)
flavour tagging

- determine flavour eigenstate of $B_s$ meson at production
- opposite side flavour tagging used

**Muon Tagger**
- Identify the muon from semileptonic decay
- Calculate muon cone charge $Q_\mu$

**Jet Charge Tagger**
- Identify jet originating from same primary vertex
- Calculate jet charge $Q_{jet}$

Two different methods applied in hierarchy of performance
flavour tagging

- Determine probability that signal decay contains $\bar{b}$ as function of $Q_\mu$ and $Q_{\text{jet}}$ using calibration sample $B^+ \rightarrow J/\psi K^+$

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<tr>
<th>Tagger</th>
<th>Efficiency [%]</th>
<th>Dilution [%]</th>
<th>Tagging Power [%]</th>
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<tr>
<td>Segment Tagged muon</td>
<td>1.08 ± 0.02</td>
<td>36.7 ± 0.7</td>
<td>0.15 ± 0.02</td>
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<tr>
<td>Combined muon</td>
<td>3.37 ± 0.04</td>
<td>50.6 ± 0.5</td>
<td>0.86 ± 0.04</td>
</tr>
<tr>
<td>Jet charge</td>
<td>27.7 ± 0.1</td>
<td>12.68 ± 0.06</td>
<td>0.45 ± 0.03</td>
</tr>
<tr>
<td>Total</td>
<td>32.1 ± 0.1</td>
<td>21.3 ± 0.08</td>
<td>1.45 ± 0.05</td>
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Efficiency $\varepsilon$: fraction of successfully tagged candidates
Dilution D: 1-2w (where w is the wrong-tag fraction)
Tagging power: $\varepsilon D^2 = \sum_i \varepsilon_i D_i^2$

Combined Muon: a muon with inner detector and muon spectrometer track information
Segment Tagged Muon: muons with only muon spectrometer track information
flavour tagging

- determine probability that signal decay contains $\bar{b}$ as function of $Q_\mu$ and $Q_{\text{jet}}$ using calibration sample $B^+ \rightarrow J/\psi K^+$

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- In the likelihood fit to $B_s$ data, the per-candidate probability and probability distributions are considered. $P=0.5$ in absence of tagging information.
results of the fit

observables: mass, proper decay time and their errors, three transversity angles and the tagging probability

projection on $B_s$ mass and proper decay time: $22,670 \pm 150$ signal events from fit.
recent results of the fit

observables: mass, proper decay time and their errors, three transversity angles and the tagging probability

projections on the three transversity angles: $\phi_T$, $\cos(\theta_T)$ and $\cos(\psi_T)$
Recent B physics results from ATLAS

**Agreement with the SM prediction**

**Likelihood profiles in the $\phi_S - \Delta \Gamma_S$ plane**

- **$\phi_S$** improved by 40% compared to untagged analysis
- $\Delta \Gamma_S$ central value and uncertainty unchanged
- also the strong phase $\delta_\perp$ can now be determined
- dominant systematic uncertainty: uncorrelated description of background angle distributions

**Results for $\phi_S$ and $\Delta \Gamma_S$ in $B_s \rightarrow J/\psi\phi$**

- $\phi_S = 0.12 \pm 0.25$ (stat.) $\pm 0.11$ (syst.) rad
- $\Delta \Gamma_S = 0.053 \pm 0.021$ (stat.) $\pm 0.009$ (syst.) $\text{ps}^{-1}$
- $\Gamma_s = 0.677 \pm 0.007$ (stat.) $\pm 0.003$ (syst.) $\text{ps}^{-1}$
- $|A_0(0)|^2 = 0.529 \pm 0.006$ (stat.) $\pm 0.011$ (syst.)
- $|A_\parallel(0)|^2 = 0.220 \pm 0.008$ (stat.) $\pm 0.009$ (syst.)
- $\delta_\perp = 3.89 \pm 0.46$ (stat.) $\pm 0.13$ (syst.) rad

*ATLAS* Preliminary

$\sqrt{s} = 7$ TeV

L $dt = 4.9$ fb$^{-1}$

(Statistical errors only)

Agreement with the SM prediction
results for $\phi_S$ and $\Delta \Gamma_S$ in $B_s \to J/\psi \phi$

- uncertainty of $\phi_S$ improved by 40% compared to untagged analysis
- $\Delta \Gamma_S$ central value and uncertainty unchanged

Likelihood profiles in the $\phi_S - \Delta \Gamma_S$ plane

ATLAS Preliminary

$\int s = 7$ TeV

L $dt = 4.9$ fb$^{-1}$

$\Delta \Gamma_S$ constrained to $> 0$

68% C.L.

90% C.L.

95% C.L.

Standard Model

$\Delta \Gamma_S = 2|\Gamma_{12}| \cos(\phi_S)$

(Statistical errors only)

Agreement with the SM prediction