Beauty in ATLAS: New physics searches, spectroscopy and decay properties of *B*-hadrons

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On behalf of the ATLAS collaboration

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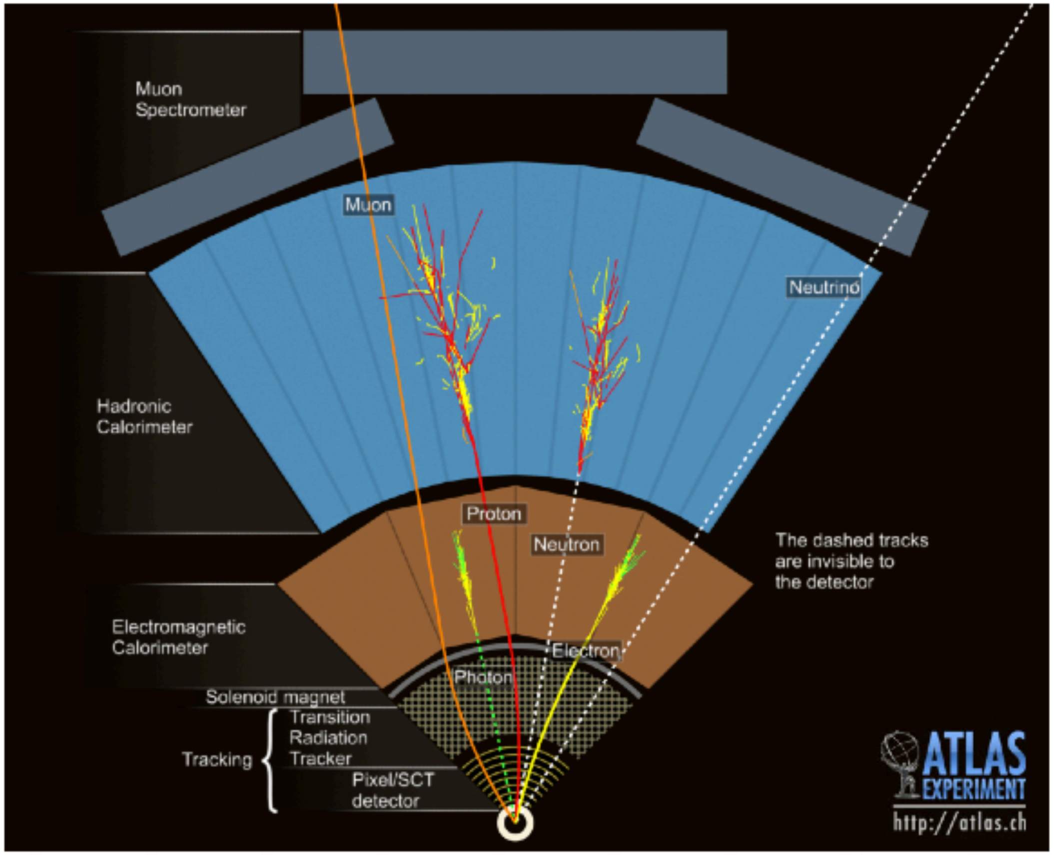
Outline

- *B*-physics in a nutshell
- The ATLAS experiment at LHC
- Parity violation in the decay $\Lambda_b^0 \to J/\psi\ \Lambda^0$
- *CP* violation in $B_s^0 \to J/\psi\ \phi$ (Brief summary)
- Rare decay of $B_s^0 \to \mu^+ \mu^-$ (Brief summary)
- Summary and outlook

B-physics in a nutshell

- *B*-physics investigates physics of mesons and baryons containing at least one bottom quark
- *B*-physics at ATLAS:
  - Large beauty production cross section and high luminosity provide high sensitivity to *B*-hadrons
  - Focus on competitive topics:
    - Testing *CP* Violation through decay parameters that influence CKM matrix elements
    - Studying heavy flavor meson and baryon production and decay properties, e.g. cross section, lifetime, etc
    - Testing predictions of heavy quark interaction models, e.g. HQET, factorization, heavy quark expansion, etc
    - New physics searches through rare and very rare decays which are highly suppressed in SM

ATLAS detector overview



Muon Spectrometer

Hadronic Calorimeters

EM Calorimeters

Inner Detector

Tracking system (Pixel, SCT & TRT) reconstruct trajectories and momenta of charged particles; **crucial for identifying the *b* decay products**

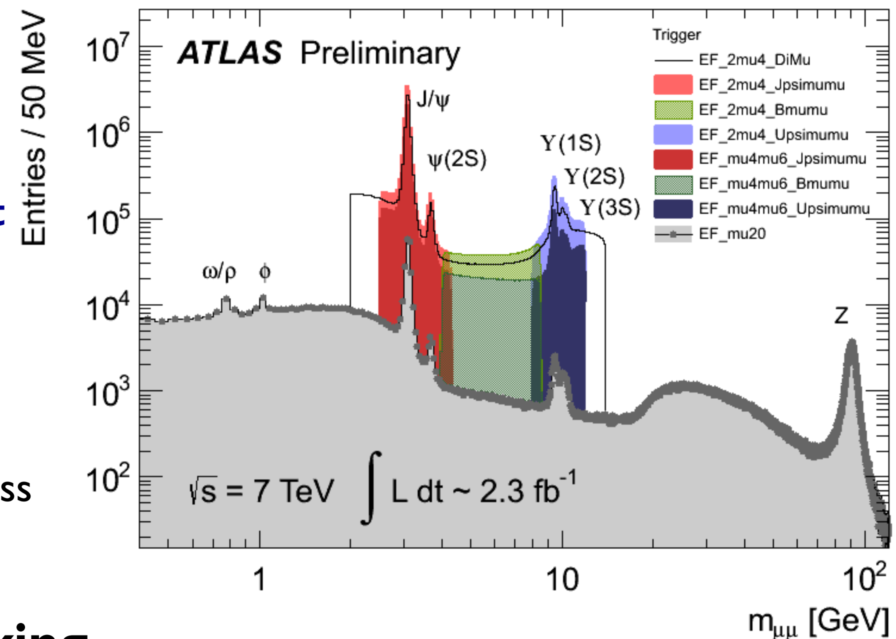
EM/hadronic calorimeters energy deposition of particles and missing energy

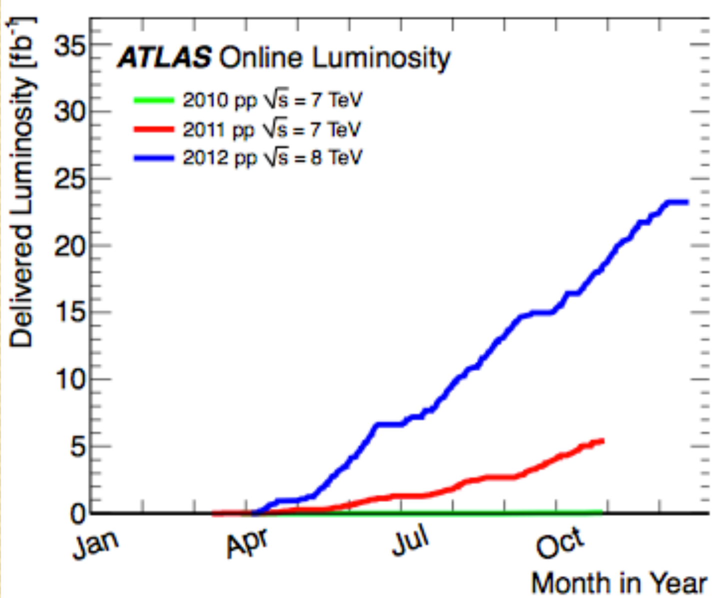
Muon spectrometer precise tracking and momentum measurement of muons; **for study of *b*-jets containing J/ψ** (final products are a muon pair)

Triggers & data taking at ATLAS

Triggers for *B*-physics

- Reduce huge collision data rate from ~40MHz to ~500Hz
- **Most *B*-physics channels studied at ATLAS have di-muon signature ($B \to J/\psi(\mu\mu)X$, $B \to \mu\mu$, etc.)**
- Main *B*-physics triggers in ATLAS
  - **single or di-muon triggers**
  - **topological triggers** (invariant mass window for J/ψ, B_s, Upsilon(Υ), etc)



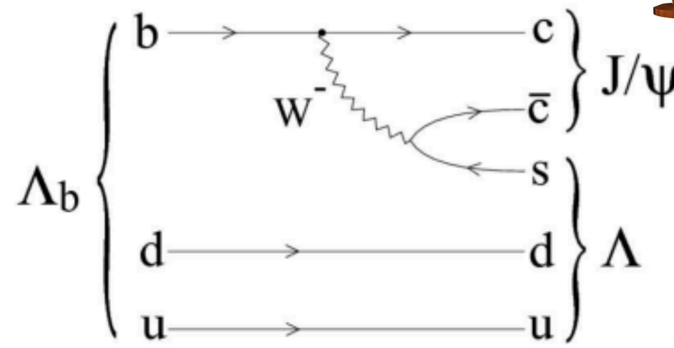


Data taking

- Run 1(2010-2012) ended. Upgrades and preparation for Run 2 in 2015 are ongoing
- Data recorded for *pp*-collisions:
  - **45 pb^{-1} in 2010** ($\sqrt{s}$ = 7 TeV, max lumi **2.1×10^{32}** $cm^{-2}s^{-1}$)
  - **5.1 fb^{-1} in 2011** ($\sqrt{s}$ = 7 TeV, max lumi **3.6×10^{33}** $cm^{-2}s^{-1}$)
  - **21.3 fb^{-1} in 2012** ($\sqrt{s}$ = 8 TeV, max lumi **7.7×10^{33}** $cm^{-2}s^{-1}$)
- Excellent acquisition efficiency (>90%) and detector performance
- More suitable triggers for heavy quark physics in **2010** and **2011** data due to **lower thresholds**. Updates of analyses using 2012 data are ongoing

Parity violation in the decay $\Lambda_b^0 \to J/\psi\ \Lambda^0$

- Parity violation is a well-known feature of weak interactions. It is **not maximal in decays of hadrons** due to the presence of **strongly coupled spectator quarks**
- Results of parity violation measurement can be used to test predictions made by different **quark interaction models**



Four possible helicity amplitudes:

Amplitude	$\lambda_{J/\psi}$	λ_Λ
a_+	0	1/2
a_-	0	-1/2
b_+	-1	-1/2
b_-	1	1/2

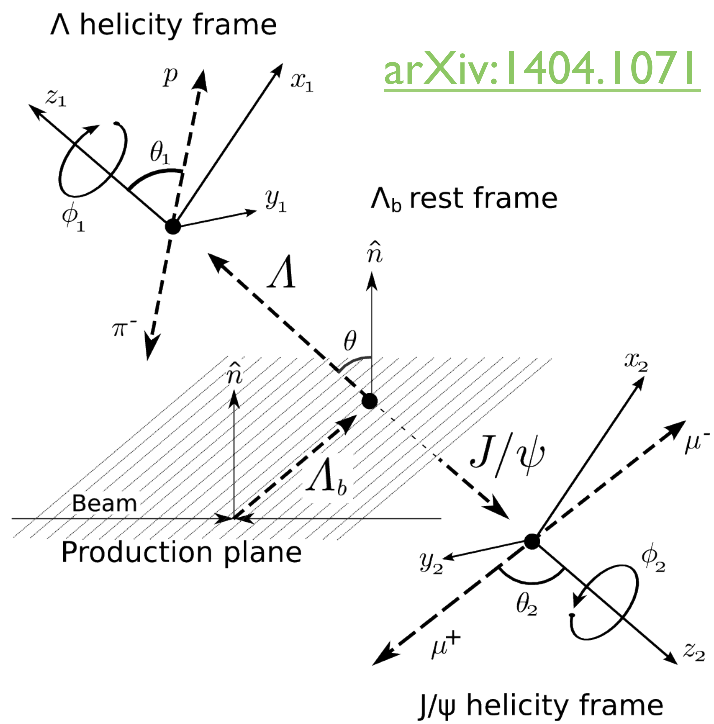
Normalization condition

$$|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1.$$

Parity violating asymmetry parameter

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$

arXiv:1404.1071

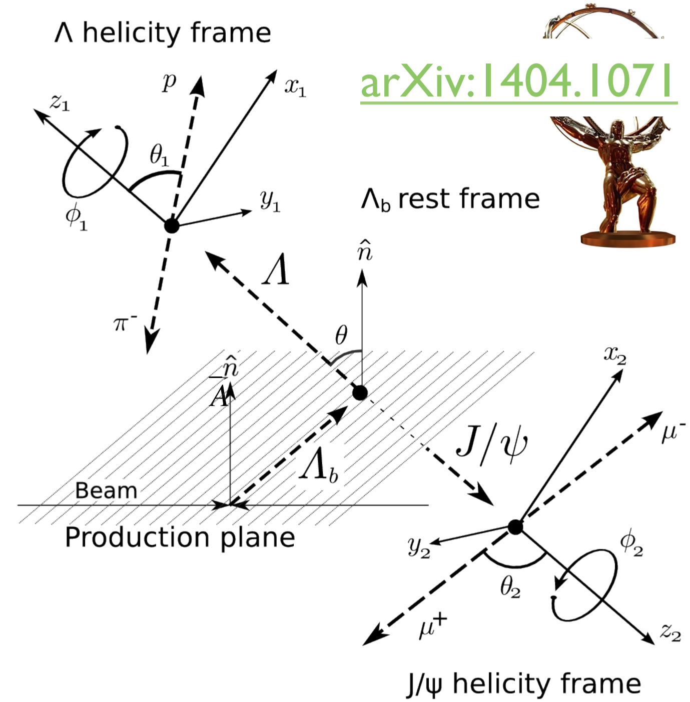


arXiv:1404.1071

Full angular PDF[1,2,3] :

$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

f_{1i} : bilinear functions of the four helicity amplitudes $\vec{A}$
f_{2i} : functions of polarization P of Λ_b and decay parameter α_Λ of Λ, where $\alpha_\Lambda = 0.642 \pm 0.013$
F_i : functions of decay angles $\Omega(\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$



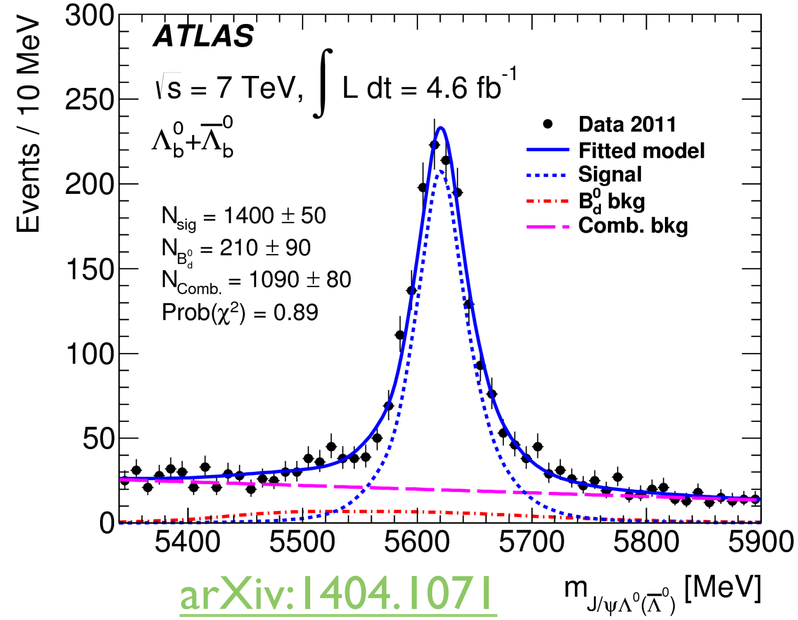
i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
2	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	α_Λ	$\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
6	$-a_+a_+^* + a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
18	$3/\sqrt{2}\, Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1 \sin\theta_2 \cos\theta_2 \cos(\phi_1 + \phi_2)$
19	$-3/\sqrt{2}\, Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1 \sin\theta_2 \cos\theta_2 \sin(\phi_1 + \phi_2)$

1: J. Phys. G **21**, 629 (1995), arXiv:hep-ph/9405231
2: Sov. J. Nucl. Phys. **43**, 817 (1986)
3: Z. Phys. C **57** 115 (1993)

Parity violation in the decay $\Lambda_b^0 \to J/\psi\ \Lambda^0$

- 4.9 fb^{-1} of 2011 data at $\sqrt{s}$ = 7 TeV collected with **topological J/ψ trigger**
- Λ_b^0 reconstructed through cascade decay topology $\Lambda^0_b \to J/\psi\ \Lambda^0$ fit (with $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$)
- **Selection results**

Parameter	[5340, 5900] MeV	[5560, 5680] MeV
N_{sig}	1400 ± 50	1240 ± 40
N_{Comb}	1090 ± 80	234 ± 16
$N_{B_d^0}$	210 ± 90	73 ± 30



arXiv:1404.1071

- **Parameter extraction**

α_b and helicity amplitude parameters can be found by solving:

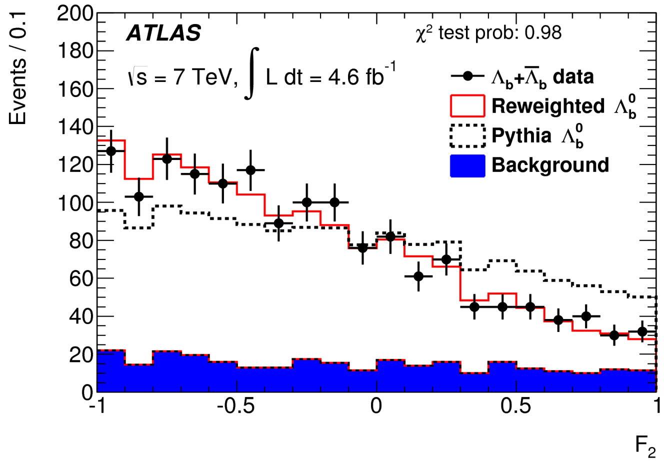
$$\langle F_i \rangle^{\text{expected}} = \langle F_i \rangle, \quad \text{for } i = 2, 4, 6, 18, \text{ and } 19$$

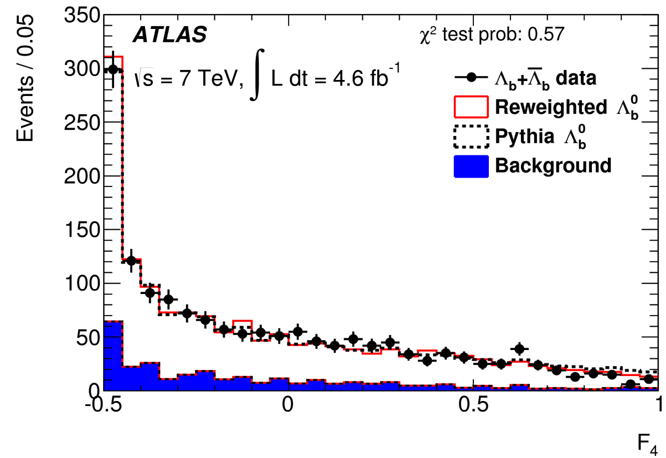
Imaginary exact solutions were found. χ^2 minimization fit is used to constraint the helicity amplitude parameters to real values that are statistically closest to the exact solution:

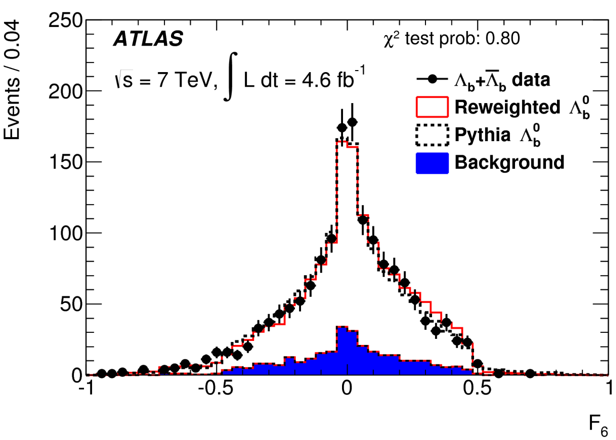
$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\exp} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\exp} - \langle F_j \rangle), \qquad \text{for } i, j = 2,4,6,18,19$$

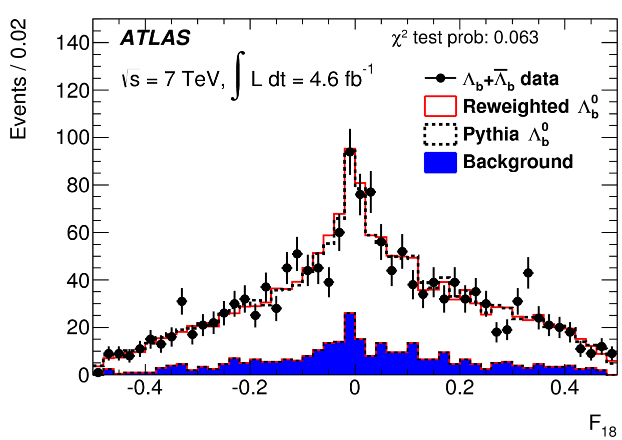
where V_{ij} is the covariance matrix of measured $\langle F_i \rangle$, and $\langle F_i \rangle^{exp}$ is evaluated from models including detector effects

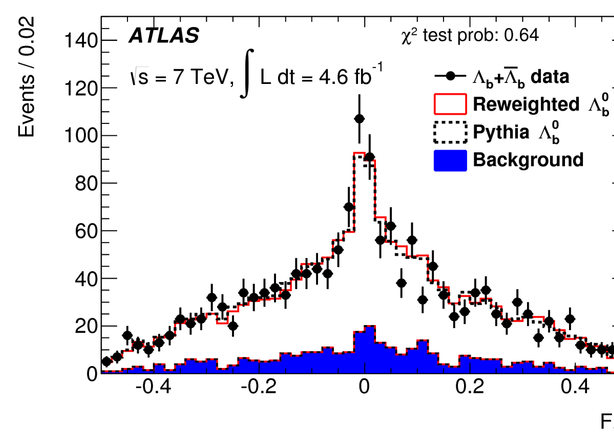
Fit results [arXiv:1404.1071]











- The weighted MC and the background distributions of F_i variables are added and compared with data
- The background is estimated by adding the left and right sidebands
- Main systematics came from detector effect estimation & background contribution

Parity violation in decay $\Lambda_b^0 \rightarrow J/\psi\ \Lambda^0$

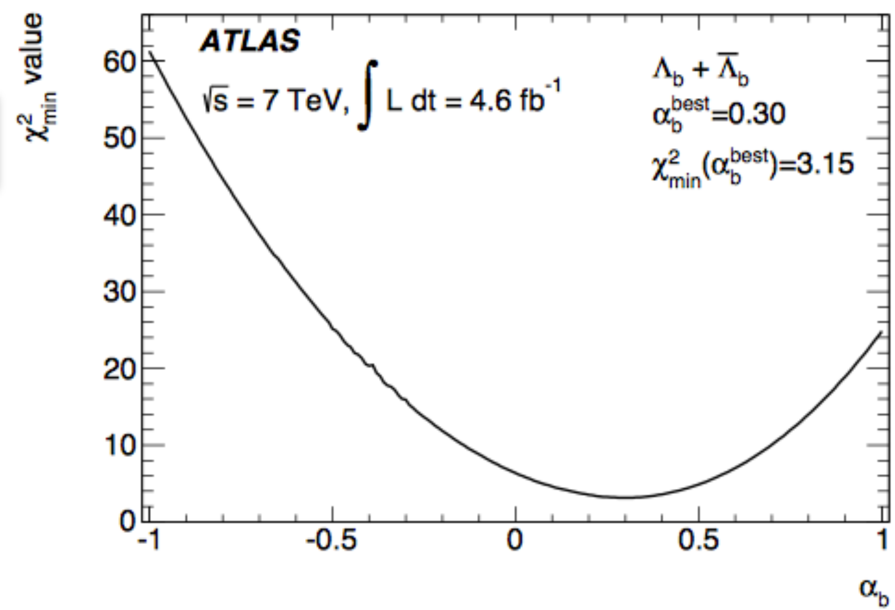
arXiv:1404.1071

Results

$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}),$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}),$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}),$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}).$$

Λ^0 hyperons are more likely to carry a negative helicity



Consistent with the latest LHCb result[1]

$$\alpha_b = 0.05 \pm 0.17 \pm 0.07$$

Results deviated from two theoretical predictions

pQCD[2]: -(0.14~0.17) at 2.6 s.d.
HQET[3,4]: 0.78 at 2.8 s.d.

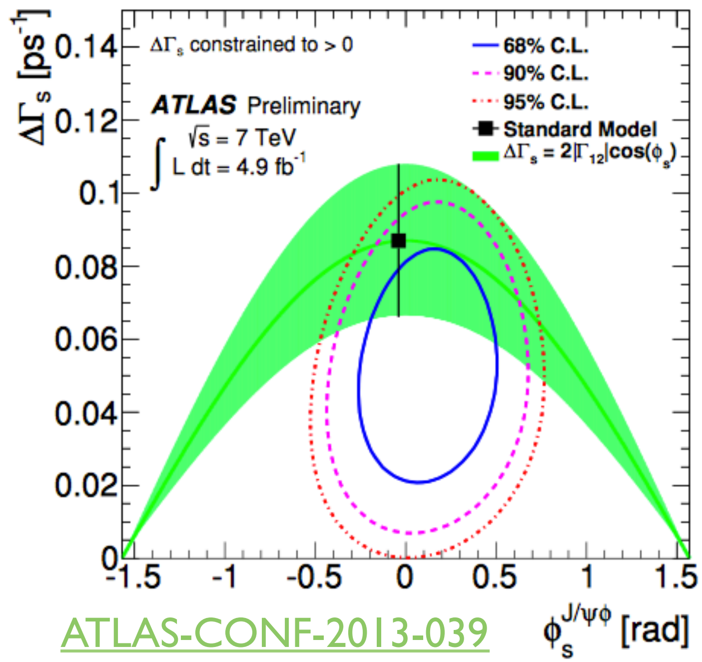
Analysis using 2012 data is ongoing

1: Phys. Lett. B 724 (2013) 27
2: Phys. Rev. D **65**, 074030, arXiv:hep-ph/0112145
3: Nucl. Phys. **A755**, 435 (2005), arXiv:hep-ph/0412131
4: Phys. Lett. B **614**, 165 (2005), arXiv:hep-ph/0412116

CP violation in $B_s^0 \to J/\psi\ \phi$ (Brief summary)

- Small theoretical uncertainty → well predicted in the SM
- New particles can contribute to B_s-B_s box diagrams and significantly modify the SM prediction

- Update to previous measurement using **flavor tagging**
- 4.9 fb^{-1} data collected in 2011 with **topological J/ψ trigger** is used
  - Signal region defined to retain 99.8% of J/ψ candidates (see backup slides)
  - An unbinned maximum likelihood fit (MLF) is performed on the selected events to extract decay parameters
  - Tag information is used in the MLF



ATLAS-CONF-2013-039

SM prediction[1]

$\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018$ rad

where $\beta_s = \arg[-(V_{ts}V^*_{tb})/(V_{cs}V^*_{cb})]$

$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.087 \pm 0.021\ ps^{-1}$

Results (see backup slides for more details)

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$

Results are consistent with CDF[2], D0[3] and LHCb[4]

1: Phys.Rev.Lett. **97** (2006) 151803, arXiv:hep-ph/0605213
2: Phys. Rev. **D85** (2012) 072002, arXiv:1112.1726
3: Phys. Rev. **D85** (2012) 032006, arXiv:1109.3166
4: Phys. Rev. Lett. **108** (2012) 101803, arXiv:1112.3183

Rare decay of $B_s^0 \rightarrow \mu^+\mu^-$ (Brief summary)

- Flavor changing neutral current highly suppressed in SM
- Of particular interest in **search of new physics**, complementary to direct search for physics beyond the SM
  - 4.9 fb^{-1} data collected in 2011 by the ATLAS detector is used
  - Update to previous result using 2.4 fb^{-1} data
    - μ: p_T > 4 GeV and $|\eta|$<2.5 B_s: p_T > 8 GeV and $|\eta|$<2.5
    - μμ: 4.0<m(μμ)<8.5 GeV and $\chi 2$/n.d.f.<2.0
    - Signal Region: [5.066, 5.666] GeV
    - Sidebands: [4.766, 5.066] or [4.766, 5.066] GeV
    - **390K Bs candidates were selected**
  - Decay $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm$ used as **reference channel** for normalization of integrated luminosity, acceptance and efficiency

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-}}$$

  - Main systematics came from **PDG branching fractions** and **acceptance x efficiency ratio** between the rare decay and reference channel

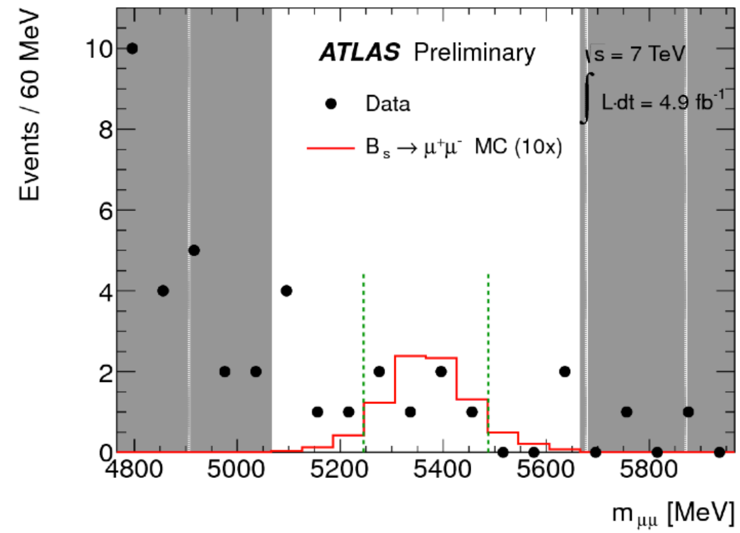
Rare decay of $B_s^0 \rightarrow \mu^+\mu^-$ (Brief summary)

Main backgrounds:

- Combinatorial bkg b antib->$\mu^+\mu^- X$
- Resonant bkg due to *B*-hadron decay with 1 or 2 hadrons misidentified as muon

Signal selection optimization:

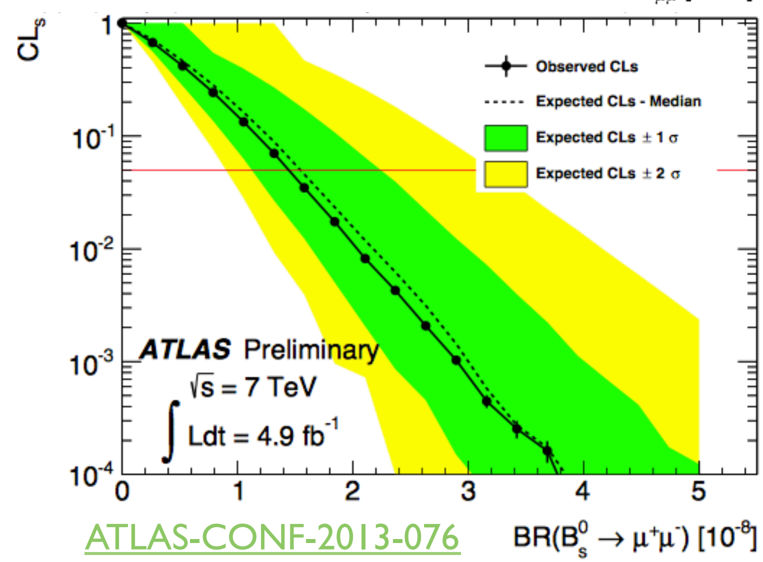
- Performed to select best performing BDTs and final selection cuts in the BDT output variables and invariant mass window for best sensitivity to the signal
- By maximizing estimator of separation power: $\mathbf{P} = \varepsilon/(1+\sqrt{B})$, where ε is the signal efficiency and B is the number of bkg events



$BR(B^0_s \rightarrow \mu^+\mu^-)$ branching fraction
SM prediction[1] $(3.56 \pm 0.30) \times 10^{-9}$
LHCb result[2] $(2.9 \pm 1.1) \times 10^{-9}$
CMS result[3] $(3.0 \pm 1.0)\ 10^{-9}$

Results

Observed limit is set to be
$< 15 \times 10^{-9}$ at 95% CL
compatible with expected limits at
$< 16 \pm 7 \times 10^{-9}$ at 95% CL



ATLAS-CONF-2013-076

1: Eur. Phys. J. C72 (2012) 2172, arXiv:1208.0934.
2: Phys.Rev.Lett. **110** (2013) 101805, arXiv:1307.5024v2
3: arXiv:1307.5025.

Summary and outlook

- Excellent muon identification and measurement allow ATLAS to study a wide range of *B*-physics topics at high energy which are out of reach of *B* factories
- **Parity violation** in decay $\Lambda_b^0 \rightarrow J/\psi\,\Lambda^0$ result **consistent with LHCb result**, which lies between two theoretical predictions (pQCD & HQET). Updates with 2012 data ongoing
- **Update on *CP* violation** measurement in $B_s \rightarrow J/\psi\,\phi$ with flavor tagging **consistent with SM predictions**
- **Improved upper limits set on rare decay** $B_s^0 \rightarrow \mu^+\mu^-$ **consistent with expected values**. Update with 2012 data needed to obtain a comparable result with other experiments
- More public results available on ATLAS B-physics twiki page
- More results from dedicated analyses using 2012 data are ongoing

More *B*-physics public results…

ATLAS EXPERIMENT - Public Results

B-physics public results

- Publications
- CONF notes
- PUB notes
- Stand-alone plots
- CSC B-physics chapter
- Daily updated table...

Publications

Publications appearing in or submitted to peer-reviewed journals are listed below.

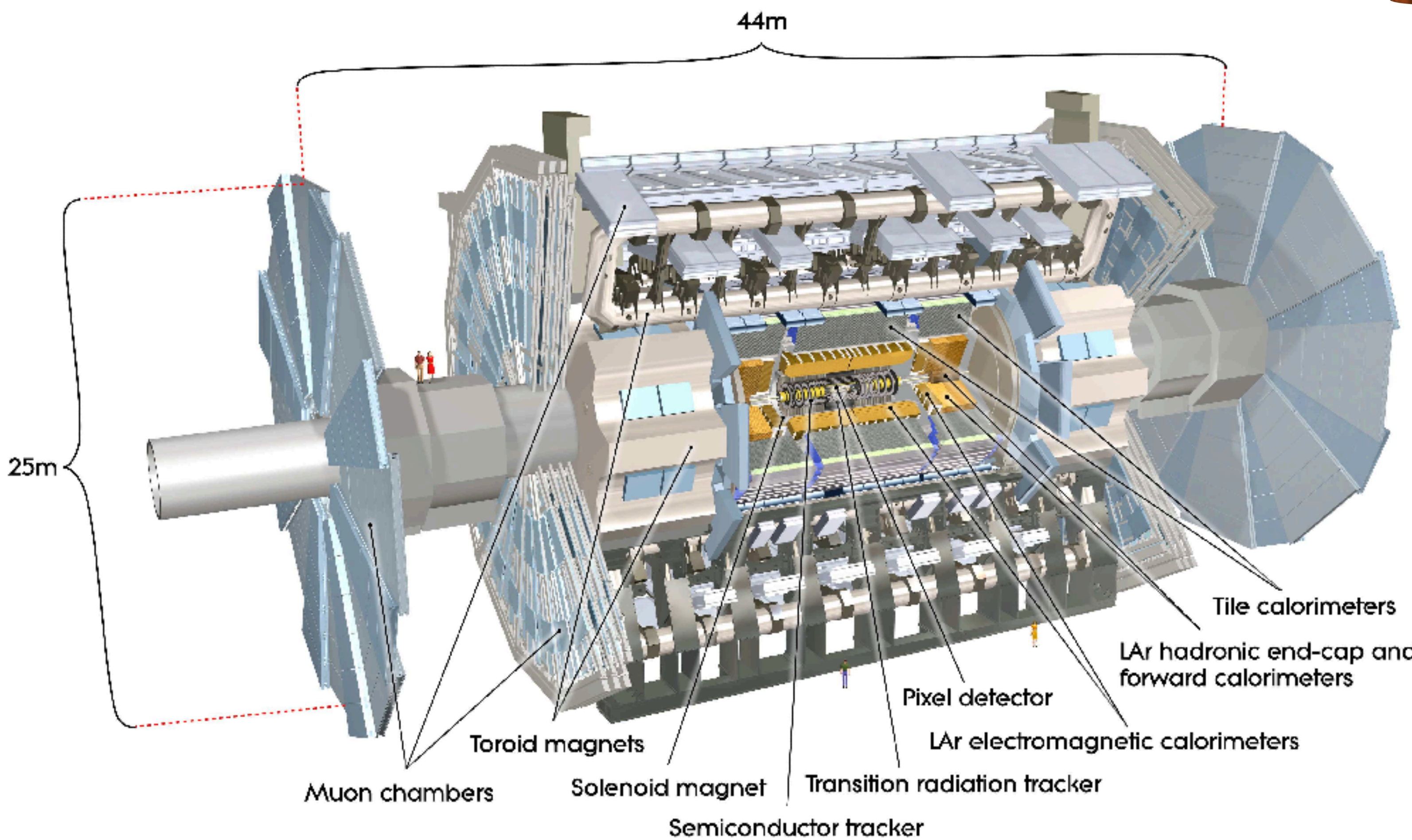
Short Title	Int L	Journal	Preprint	Plots
NEW Associated production of prompt J/ψ mesons and W boson in at $\sqrt{s}$ = 7TeV	4.6 fb^{-1}	To be submitted to JHEP	arXiv:1401.2831	Link
NEW Production cross section of B^+ at $\sqrt{s}$ = 7TeV	2.4 fb^{-1}	JHEP 10 (2013) 042	arXiv:1307.0126v2	Link
Inclusive Υ(nS) differential cross sections and ratios	1.8 fb^{-1}	Phys. Rev. D 87 (2013) 052004	arXiv:1211.7255	Link
φ_s and $\Delta\Gamma_s$ from time dependent angular analysis of $B^0_s \to J/\psi\,\phi$	4.9 fb^{-1}	JHEP 12 (2012) 072	arXiv:1208.0572	Link
Measurement of the Λ_b lifetime and mass	4.9 fb^{-1}	Phys. Rev. D 87 (2013) 032002	arXiv:1207.2284	Link
b-hadron production cross-section from $D^*\mu X$ final states	3.3 pb^{-1}	Nucl. Phys. B864 (2012) 341-381	arXiv:1206.3122	Link
Search for the decay $B^0_s \to \mu\mu$	2.4 fb^{-1}	Phys. Lett. B713 (2012) 180-196	arXiv:1204.0735	Link
Observation of a new χ_b state in radiative transitions to Υ(1S) and Υ(2S)	4.4 fb^{-1}	Phys. Rev. Lett. 108 (2012) 152001	arXiv:1112.5154	Link
Υ(1S) Fiducial Production Cross-Section	1.1 pb^{-1}	Phys. Lett. B703 (2011) 428-446	arXiv:1106.5325	Link
Differential cross-sections of inclusive, prompt and non-prompt J/ψ production	2.3 pb^{-1}	Nucl. Phys. B 850 (2011) 387-344	arXiv:1104.3038	Link
Analyses performed within other ATLAS Physics Groups:				
$D^{*+/-}$ production in jets	0.3 pb^{-1}	Phys. Rev. D 85, 052005 (2012)	arXiv:1112.4432	Link
Inclusive production of electrons and muons (b/c cross section)	35 pb^{-1}	Phys. Lett. B 707 (2012) 438-458	arXiv:1109.0525	Link
Centrality dependence of J/ψ production in heavy ions collisions	6.7 μb^{-1}	Phys. Lett. B 697 (2011) 294-312	arXiv:1012.5419	Link

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

THANK YOU

BACK UP SLIDES

The ATLAS experiment at LHC



ATLAS is a general purpose detector, designed for a wide range of physics scenario (SM, Higgs, SUSY, BSM, etc.)

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$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

arXiv:1404.1071

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P\,\alpha_\Lambda$	$\cos\theta\ \cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P	$\frac{1}{2}(3\cos^2\theta_2 - 1)\ \cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\ \cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P\,\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\ \cos\theta\cos\theta_1$
8	$-3Re(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \cos\phi_1$
9	$3Im(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \sin\phi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \cos(\phi_1 + 2\phi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \sin(\phi_1 + 2\phi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \cos\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos\phi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \cos\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin\phi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\ \sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos(\phi_1 + \phi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\ \sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\phi_1 + \phi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\ \sin\theta_2\ \cos\theta_2\ \cos\phi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\ \sin\theta_2\ \cos\theta_2\ \sin\phi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\phi_1 + \phi_2)$

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

Event selection

- $J/\psi \rightarrow \mu^+ \mu^-$ candidates
  - at least one pair of oppositely charged muon candidates
  - pair of muon tracks refitted to a common vertex
  - χ^2/d.o.f. <10
  - $2.959 < m(\mu^+ \mu^-) < 3.229$ GeV for both muons with |eta| < 1.05
  - $2.913 < m(\mu^+ \mu^-) < 3.273$ GeV for one muon with 1.05 < |eta| < 2.5
  - $2.852 < m(\mu^+ \mu^-) < 3.332$ GeV for both muons with 1.05 < |eta| < 2.5
- $\phi \rightarrow K^+K^-$ candidates
  - reconstructed from oppositely charged tracks not identified as muon
    - p_T > 0.5 GeV
    - |eta| < 2.5
- $B_s^0 \rightarrow J/\psi\ \phi$ candidates
  - reconstructed by fitting four tracks each with
    - at least 1 hit in pixel detector
    - at least 4 hits silicon strip detector
    - χ^2/d.o.f. < 3
    - fitted $p_T(K^+/K^-)$ > 1 GeV
    - $1.0085 < m(K^+K^-) < 1.0305$ GeV

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Likelihood function

An unbinned maximum likelihood fit is performed on the selected events to extract the parameters of the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay. The fit uses information about the reconstructed mass m, the measured proper decay time t, the measured mass and proper decay time uncertainties σ_m and σ_t, the tag probability, and the transversity angles Ω of each $B_s^0 \to J/\psi\phi$ decay candidate. There are three transversity angles; $\Omega = (\theta_T, \psi_T, \phi_T)$ and these are defined in section 5.1.

The likelihood function is defined as a combination of the signal and background probability density functions as follows:

$$\ln \mathscr{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathscr{F}_s(m_i, t_i, \Omega_i) + f_s \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i, t_i, \Omega_i) + (1 - f_s \cdot (1 + f_{B^0}))\mathscr{F}_{\text{bkg}}(m_i, t_i, \Omega_i)) \} \quad (3)$$

where N is the number of selected candidates, w_i is a weighting factor to account for the trigger efficiency, f_s is the fraction of signal candidates, f_{B^0} is the fraction of peaking B^0 meson background events calculated relative to the number of signal events; this parameter is fixed in the likelihood fit. The mass m_i, the proper decay time t_i and the decay angles Ω_i are the values measured from the data for each event i. $\mathscr{F}_s$, $\mathscr{F}_{B^0}$ and $\mathscr{F}_{\text{bkg}}$ are the probability density functions (PDF) modelling the signal, the specific B^0 background and the other background distributions, respectively. A detailed description of the

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Full results:

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

Table 7: Summary of systematic uncertainties assigned to parameters of interest.

	ϕ_s (rad)	$\Delta\Gamma_s$ (ps^{-1})	Γ_s (ps^{-1})	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\perp}$ (rad)	$\delta_{\parallel}$ (rad)	$\delta_{\perp} - \delta_S$ (rad)
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$< 10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B_d^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.10	0.001	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.002	0.05	$<10^{-2}$	$<10^{-2}$
Models:									
default fit	$<10^{-2}$	0.002	$<10^{-3}$	0.003	0.002	0.006	0.07	0.01	0.01
signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.11	0.009	0.003	0.009	0.011	0.028	0.13	0.09	0.04

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Rare decay of $B_s^0 \rightarrow \mu^+ \mu^-$

Discriminative variables

Variable	Description	Rank
L_{xy}	Scalar product in the transverse plane of vectors	1
$I_{0.7}$ isolation	Ratio of |~*pB*T| to the sum of |~*pB*T| and the transverse momenta of all tracks with isolation $p_T > 0.5$ GeV within a cone $R < 0.7$ from the *B* direction, excluding *B* decay prod.	2
$\|\alpha_{2d}\|$	Absolute value of the angle in the transverse plane between vectors ~*x* and ~*pB*	3
$p_{L\,min}$	Minimum momentum of the two muon candidates along the B direction	4
pTB	*B* transverse momentum	5
ct significance	Proper decay length divided by its uncertainty	6
χ^2_z , χ^2_{xy}	Significance of the separation between production (PV) and decay vertex (SV)	7
|*D*xy|min, |*D*z|min	Absolute values of the minimum distance of closest approach in the xy plane or along z of tracks in the event to the B vertex	8
ΔR	R-parameter in two dimensions, $R=\sqrt{\Delta\eta^2+\Delta\phi^2}$	9
|*d*0|max, |*d*0|min	Absolute values of the maximum and minimum impact parameter of B-decay products in the transverse plane	10

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