B hadron production and decay at ATLAS

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On behalf of the ATLAS collaboration

BEACH2014, Birmingham, UK, June 21st - 27th, 2014

Topics

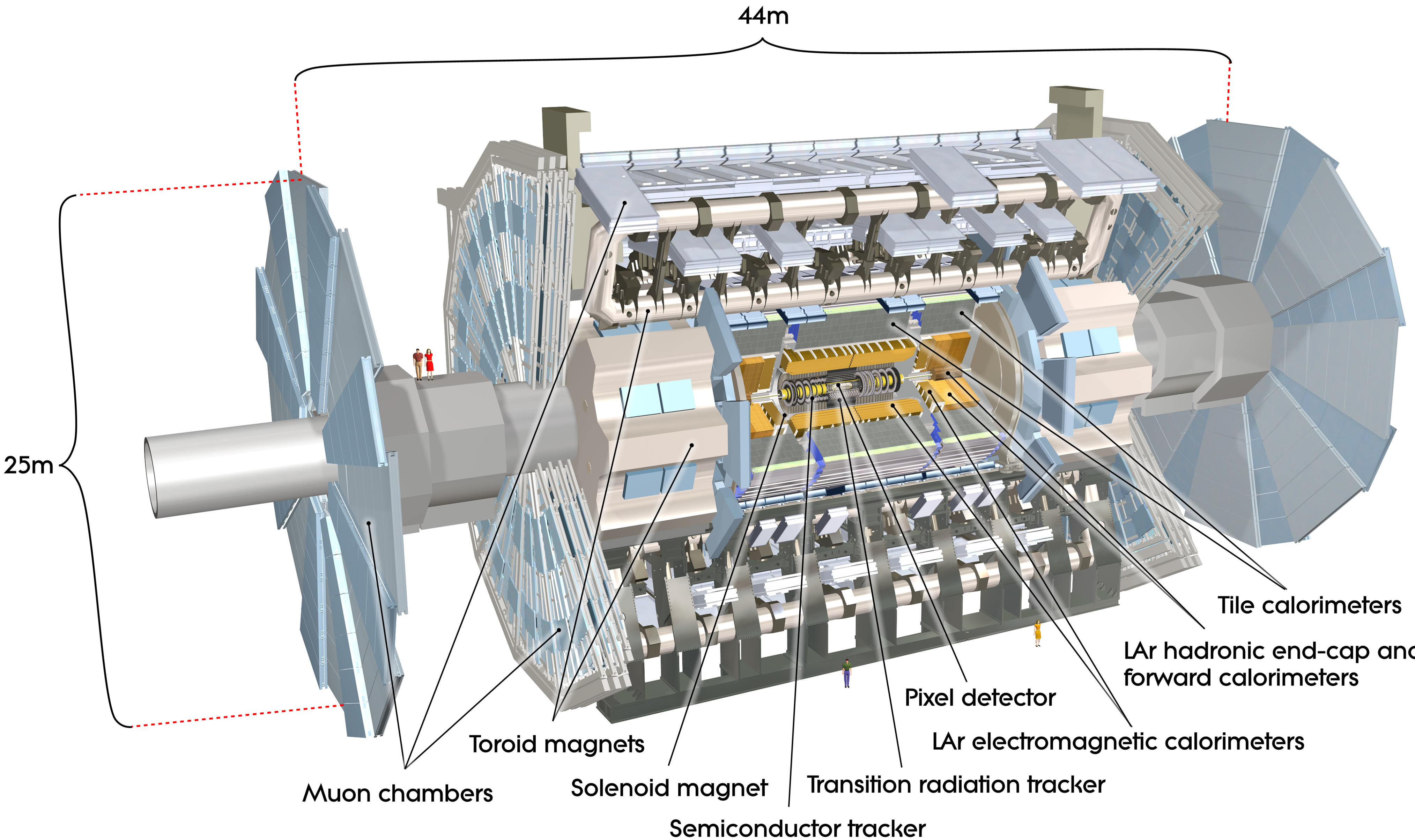
Parity violation and helicity amplitudes in $\Lambda_b^0 \to J/\psi \Lambda^0$

PRD 89, 092009 (2014)

Observation of an excited $B_c^{\pm}$ meson state

arXiv:1407.1032, Submitted to PRL

The ATLAS Detector



Muon Spectrometer:
$|\eta| < 2.7$
air core toroids(average 0.5T)
gas-based muon chambers
Muon trigger and reconstruction
Momentum resolution < 10%
$up\ to\ E(\mu) \sim 1\ TeV$

3-level trigger, reducing the rate from 40 MHz to ~200 Hz

EM Calorimeter:
Pb-LAr accordion
e/γ trigger, identification and measurement
Resolution:
$\sigma/E \sim 10\%/\sqrt{E}$

Inner Detector:
Si Pixels, Si Strips, TRT straws
Precise tracking and vertexing
pT resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4}\ p_T(GeV) \oplus 0.015$
$|\eta| < 2.5,\ \ B = 2T$

HAD Calorimetry:
$|\eta| < 5$
Fe/scintillator tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and MET
Resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Parity violation and helicity amplitudes in $\Lambda_b^0 \to J/\psi \Lambda^0$

parity violation in hadron weak decays not maximal $(\alpha_{\Lambda^0 \to p\pi^-} \approx 0.6)$

for heavy baryons theoretical predictions are possible (pQCD and FA, HQET)

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + P\alpha_b \cos\theta)$$

In ATLAS the average polarisation P = 0 (symmetric interval in pseudorapidity)

use the information of subsequent decays of J/ψ and Λ^0

Helicity amplitudes: $A(\lambda_\Lambda, \lambda_{J/\psi})$

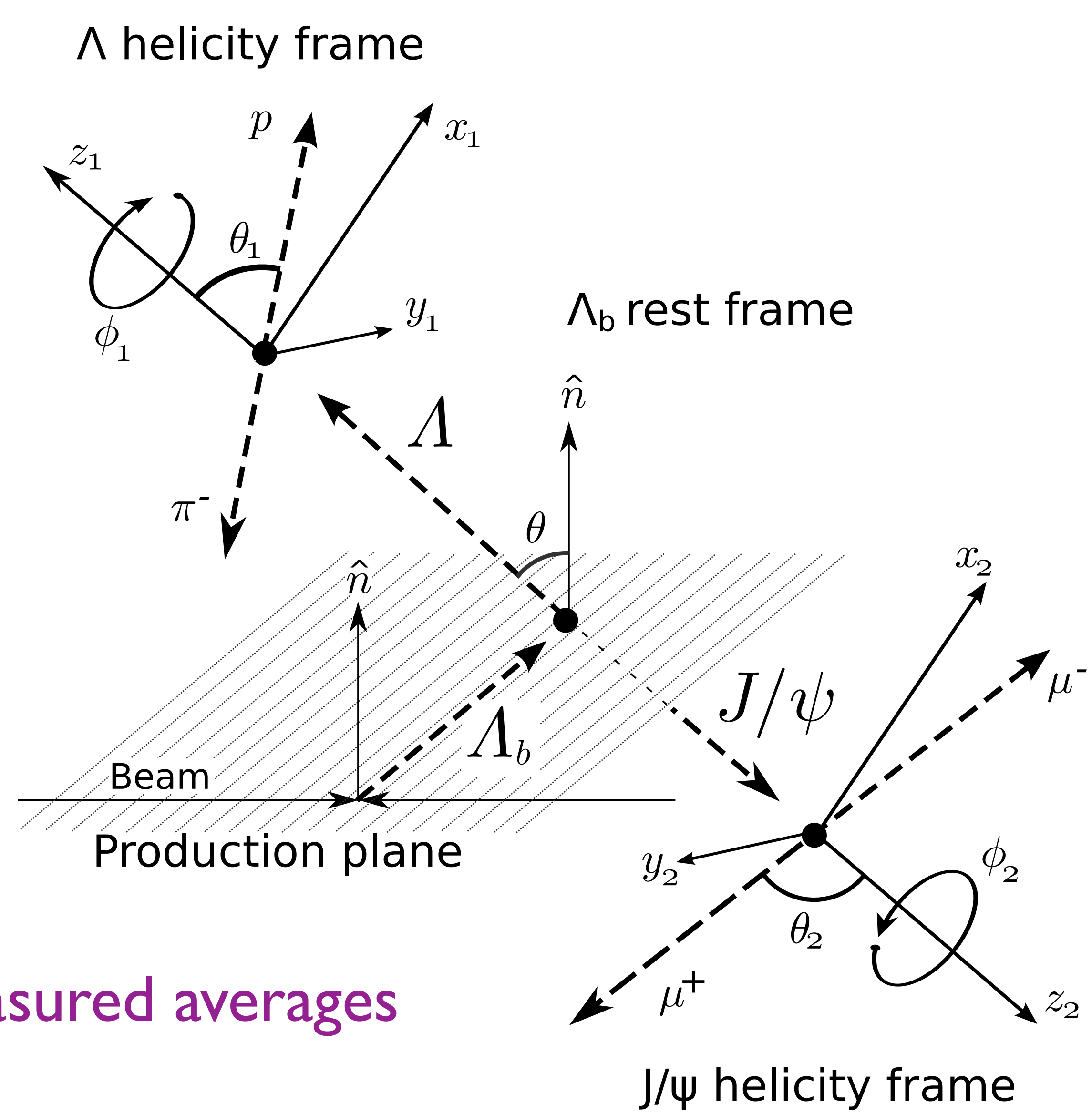
(normalised to unity)

$$a_+ \equiv A(\frac{1}{2}, 0), \quad a_- \equiv A(-\frac{1}{2}, 0)$$

$$b_+ \equiv A(-\frac{1}{2}, -1), \quad b_- \equiv A(\frac{1}{2}, 1)$$

Parameters (A): $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$,

$$k_+ = \frac{|a_+|}{\sqrt{|a_+|^2 + |b_+|^2}}, \quad k_- = \frac{|a_-|}{\sqrt{|a_-|^2 + |b_-|^2}}, \quad \Delta_+, \quad \Delta_-$$



Full PDF of $\Omega = (\cos\theta, \phi, \cos\theta_1, \phi_1, \cos\theta_2, \phi_2)$:

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

$F_i(\Omega)$ orthogonal functions of the decay angles

only i = 0, 2, 4, 6, 18 and 19 remain

$\alpha_\Lambda = -0.642 \pm 0.013$

CP conservation assumed

analysis extracts α_b and helicity amplitudes from measured averages

$$< F_i > = \frac{1}{N^{data}} \sum_{n=1}^{N^{data}} F_i(\Omega)$$ with a least square fit

ATLAS: PRD 89, 092009 (2014)

Λ_b Reconstruction

1400 Λ_b^0 and $\bar{\Lambda}_b^0$ baryons in $\mathcal{L} = 4.6\ fb^{-1}$ 7 TeV data recorded in 2011

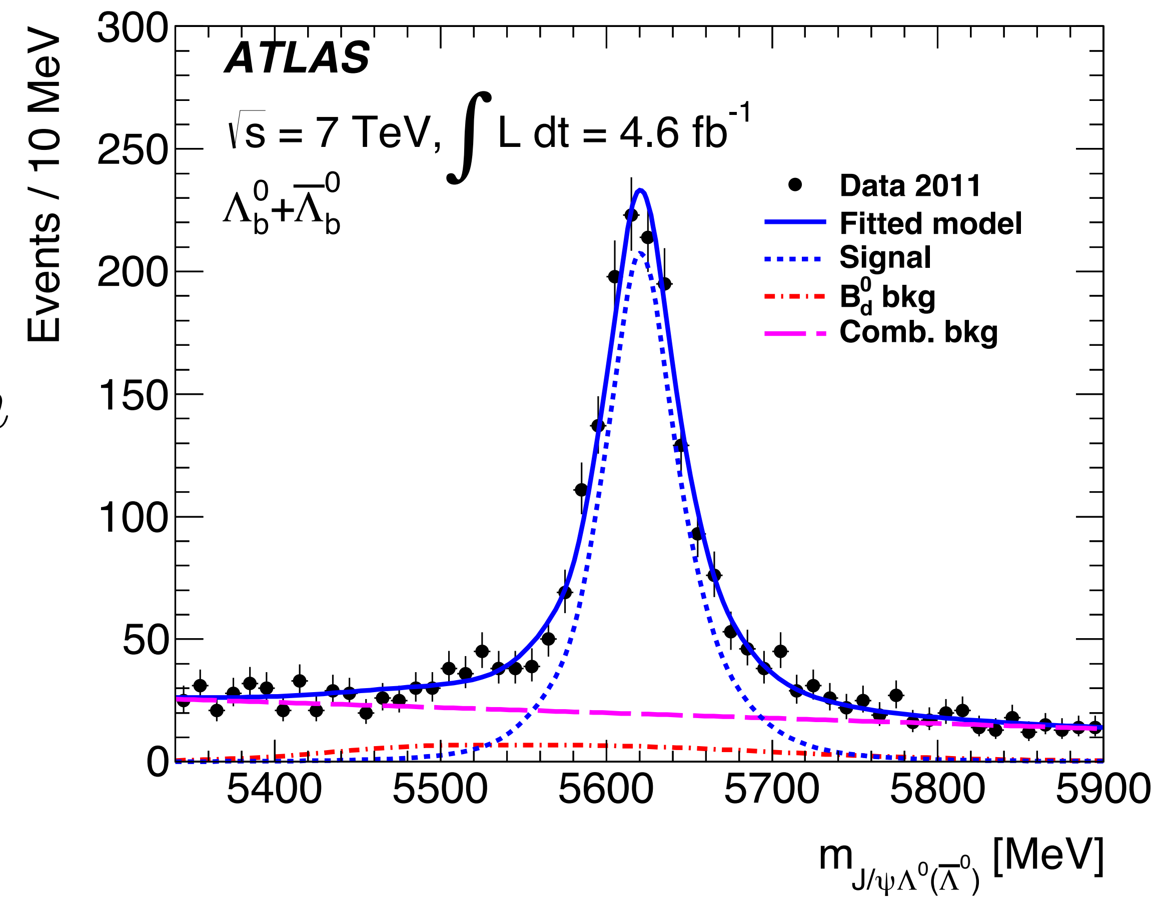
single-muon and $J/\psi \to \mu\mu$ triggers

$2.8 < m_{\mu\mu} < 3.4\ GeV$ $1.08 < m_{p\pi} < 1.15\ GeV$

mass constrained cascade fit:

$\chi^2/N_{dof} < 3,\ p_T^{\Lambda^0} > 3.5\ GeV,\ L_{xy}^{\Lambda^0} > 10\ mm$

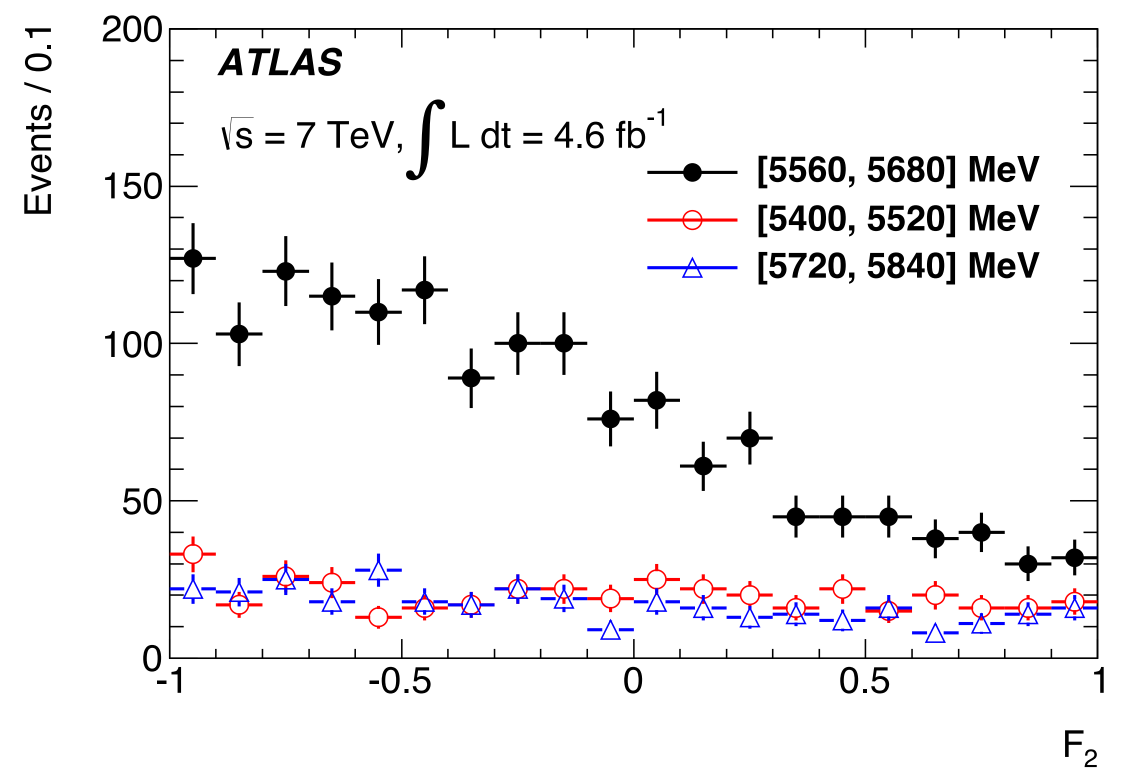
$\tau > 0.35\ ps$, loose B_d^0 veto: $\mathcal{P}_{\Lambda_b^0} > \mathcal{P}_{B_d^0}$



extended binned maximum likelihood fit

Λ_b^0 and B_d^0 shapes modelled using one-dimensional Gaussian-kernel estimation PDFs (MC templates)
combinatorial background: first-order polynomial

background subtraction: average of two sidebands:
[5400, 5520] MeV and [5720, 5840] MeV



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

Parameter Extraction

Least square fit:

$$\chi^2 = \sum_i \sum_j (< F_i >^{exp} - < F_i >) \, V_{ij}^{-1} \, (< F_j >^{exp} - < F_j >)$$

V_{ij} is the covariance matrix of the measured $< F_i >$ values

expected values of $< F_i >$ $\quad < F_i >^{exp} = \sum_j f_{1j}(A) f_{2j}(\alpha_\Lambda) C_{ij}$

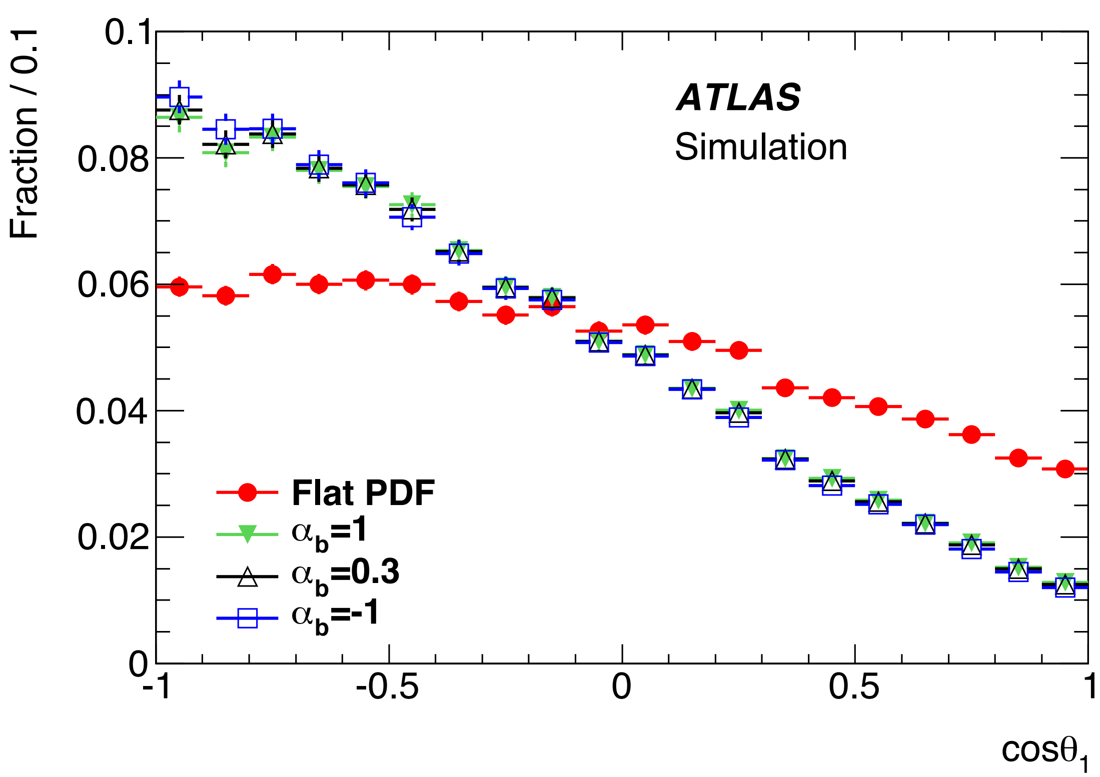
where $C_{ij} = \frac{1}{(4\pi)^3} \iint F_i(\Omega') T(\Omega', \Omega) F_j(\Omega) d\Omega' d\Omega$

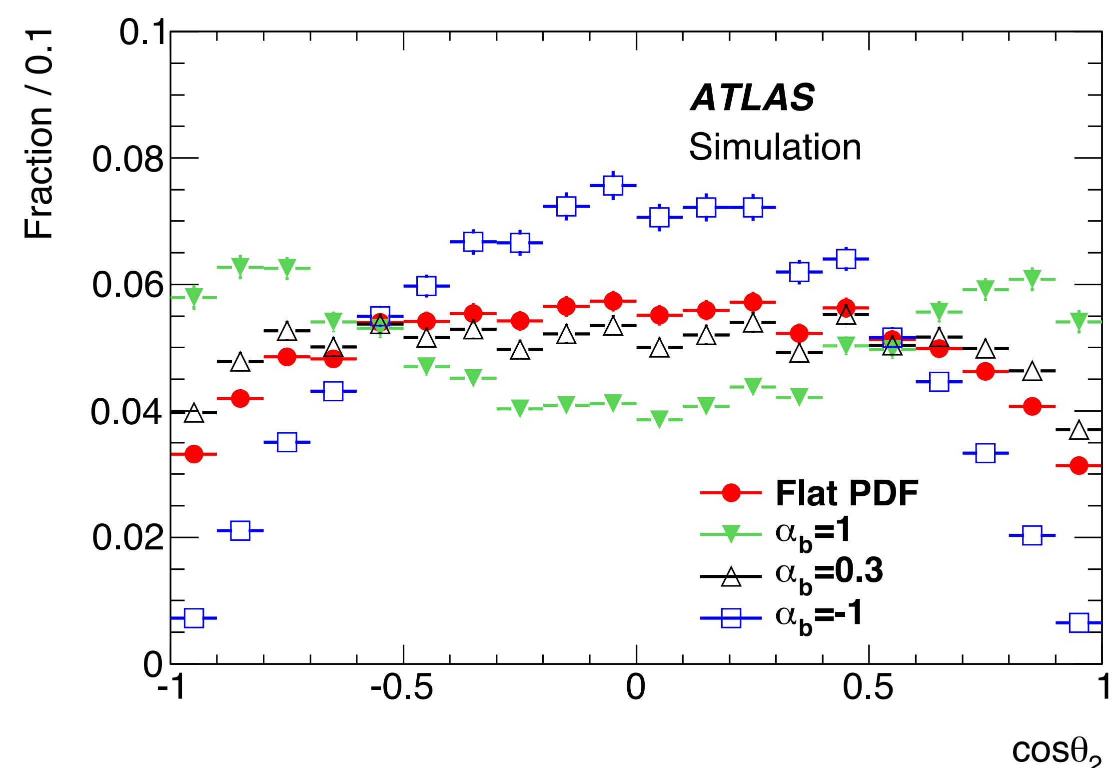
$$\approx \frac{\epsilon_T}{N^{MC}} \sum_{n=1}^{N^{MC}} F_i(\Omega'_n) F_j(\Omega_n)$$

$T(\Omega', \Omega)$ detector effects (acceptance, efficiency and resolution)

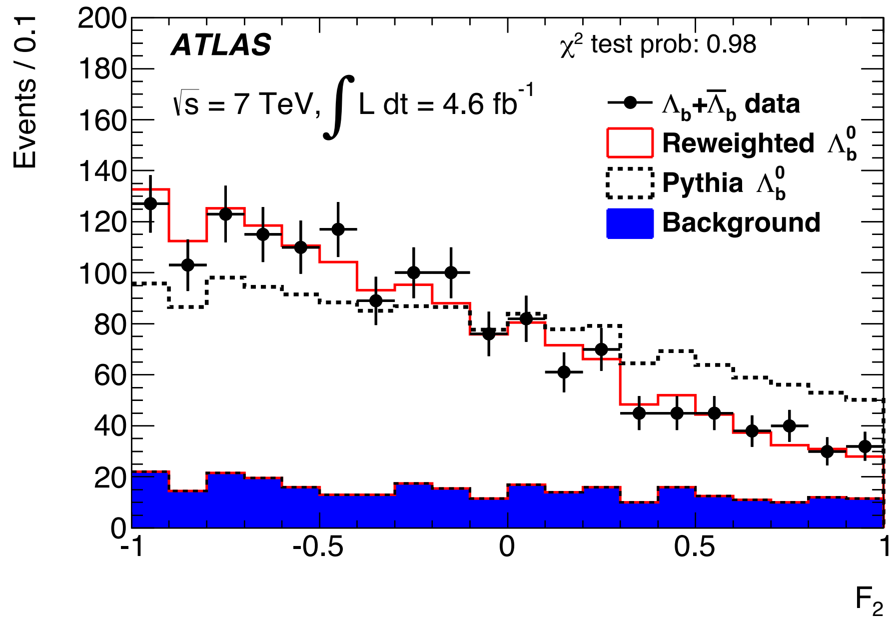
ϵ_T determined from $< F_0 >^{exp} \equiv 1$

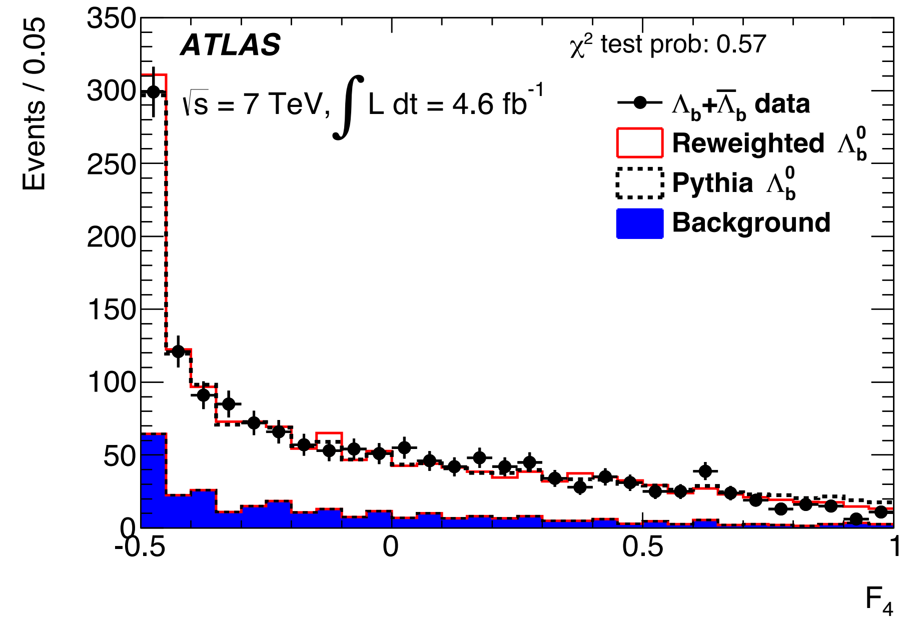
trigger and kinematic (p_T, η) weights applied to MC events

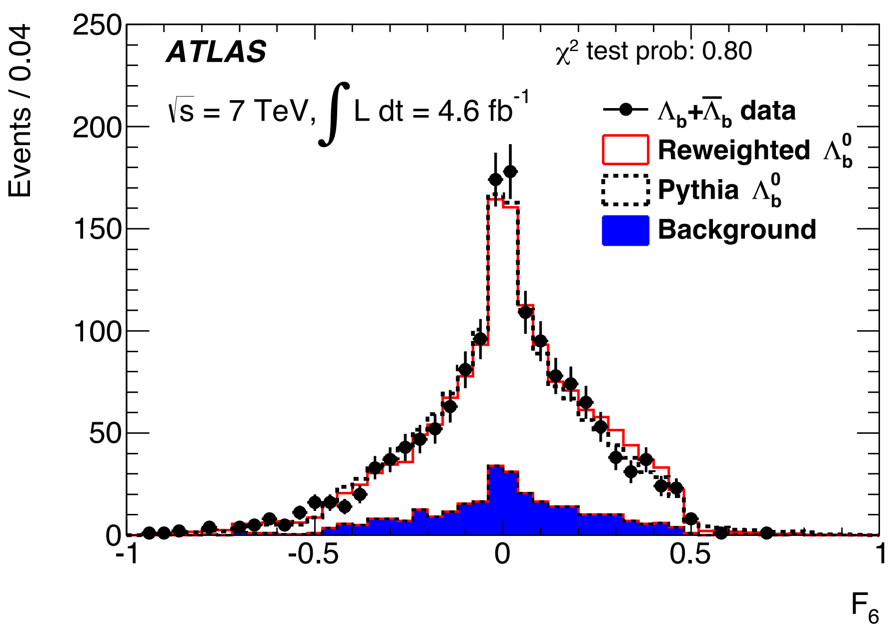


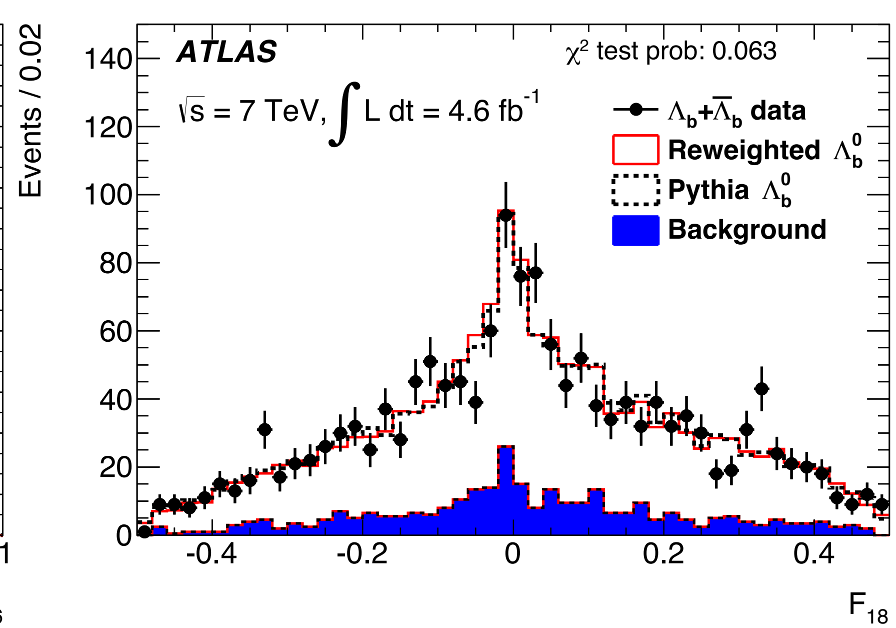


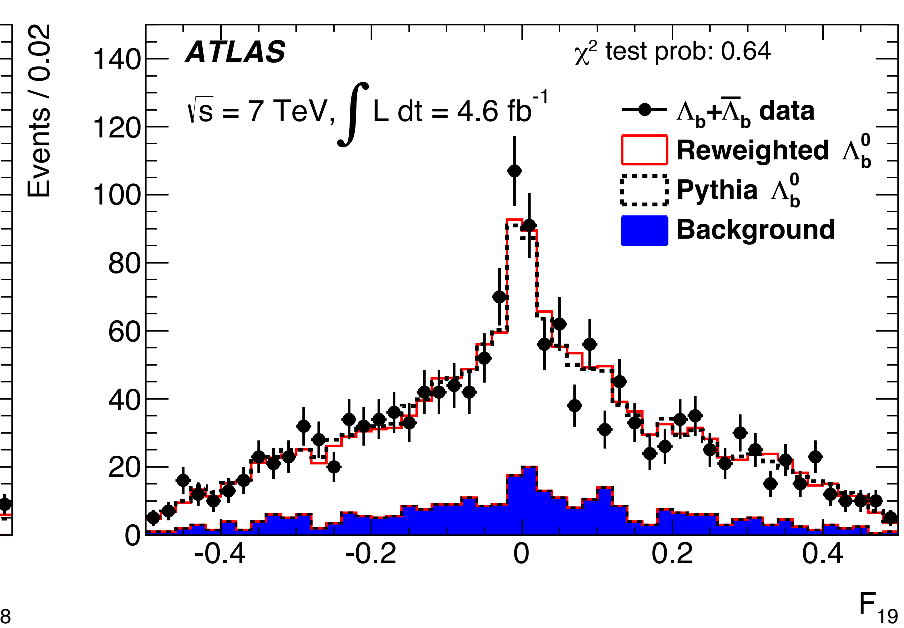
MC re-weighted distributions using the measured parameters











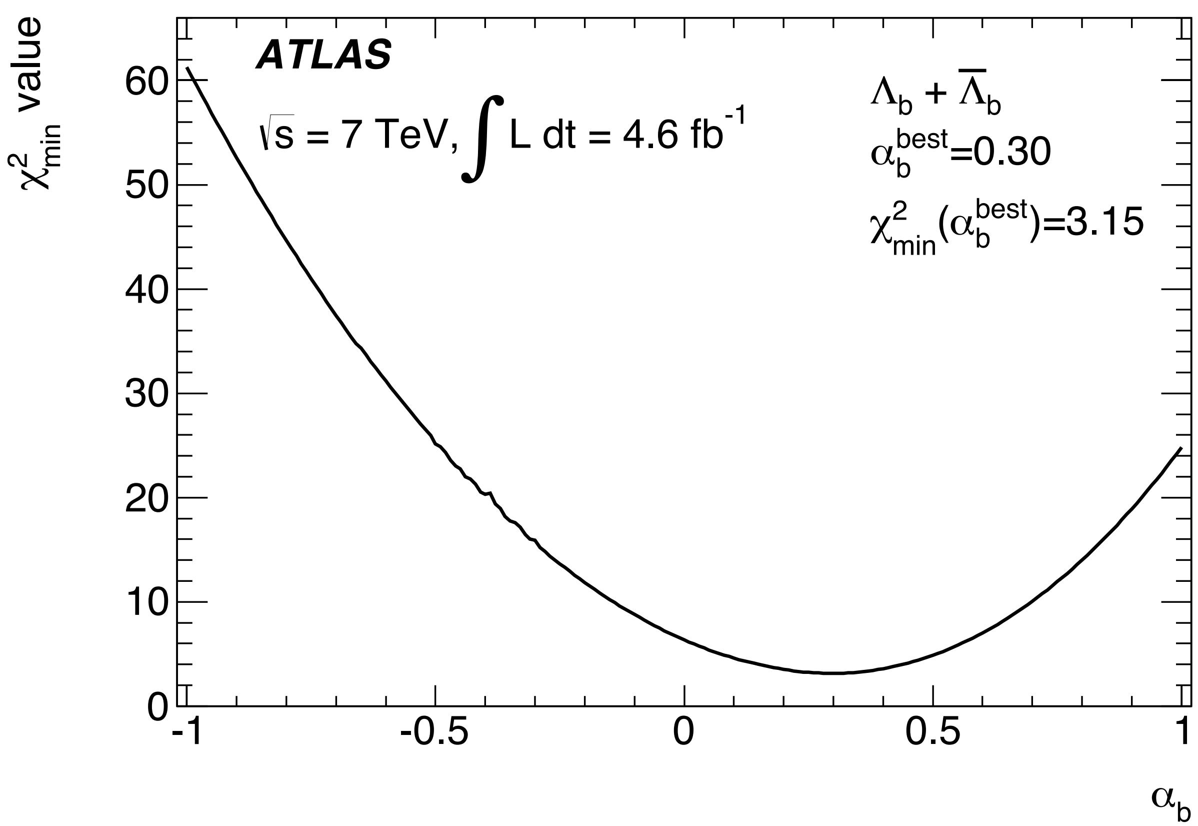
Results

$$
\begin{aligned}
< F_2 > &= -0.282 \pm 0.021, \\
< F_4 > &= -0.044 \pm 0.017, \\
< F_6 > &= 0.001 \pm 0.010, \\
< F_{18} > &= 0.019 \pm 0.009, \\
< F_{19} > &= -0.002 \pm 0.009.
\end{aligned}
$$

Main systematic uncertainties:

MC statistics

Background shape modelling



Fit results

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

$$k_+ = 0.21^{+0.14}_{-0.21}(stat) \pm 0.13(syst)$$

$$k_- = 0.13^{+0.20}_{-0.13}(stat) \pm 0.15(syst)$$

corresponding to

$$|a_+| = 0.17^{+0.12}_{-0.17}(stat) \pm 0.09(syst)$$

$$|a_-| = 0.59^{+0.06}_{-0.07}(stat) \pm 0.03(syst)$$

$$|b_+| = 0.79^{+0.04}_{-0.05}(stat) \pm 0.02(syst)$$

$$|b_-| = 0.08^{+0.13}_{-0.08}(stat) \pm 0.06(syst)$$

α_b value consistent with LHCb:

0.05 ± 0.17(stat) ± 0.07(syst)

(PLB 724 (2013) 27)

intermediate between pQCD (-0.17 to -0.14) and HQET (0.78) predictions

(PRD 65, 074030 (2002), NPA755, 435 (2005), PLB 614, 165 (2005))

large $|a_-|$ and $|b_+|$ suggest negative helicity for Λ^0

Observation of an excited $B_c^{\pm}$ meson state

$B_c^{\pm}$ first observed at the Tevatron, now by the LHC experiments

spectrum and properties predicted by non-relativistic potential models, pQCD and lattice calculations

$m_{B_c(2S)} \sim 6835 \div 6917\ MeV$

width $\sim 50\ keV$

$m_{B_c(2S)} - m_{B_c(1S)} \sim 600\ MeV$

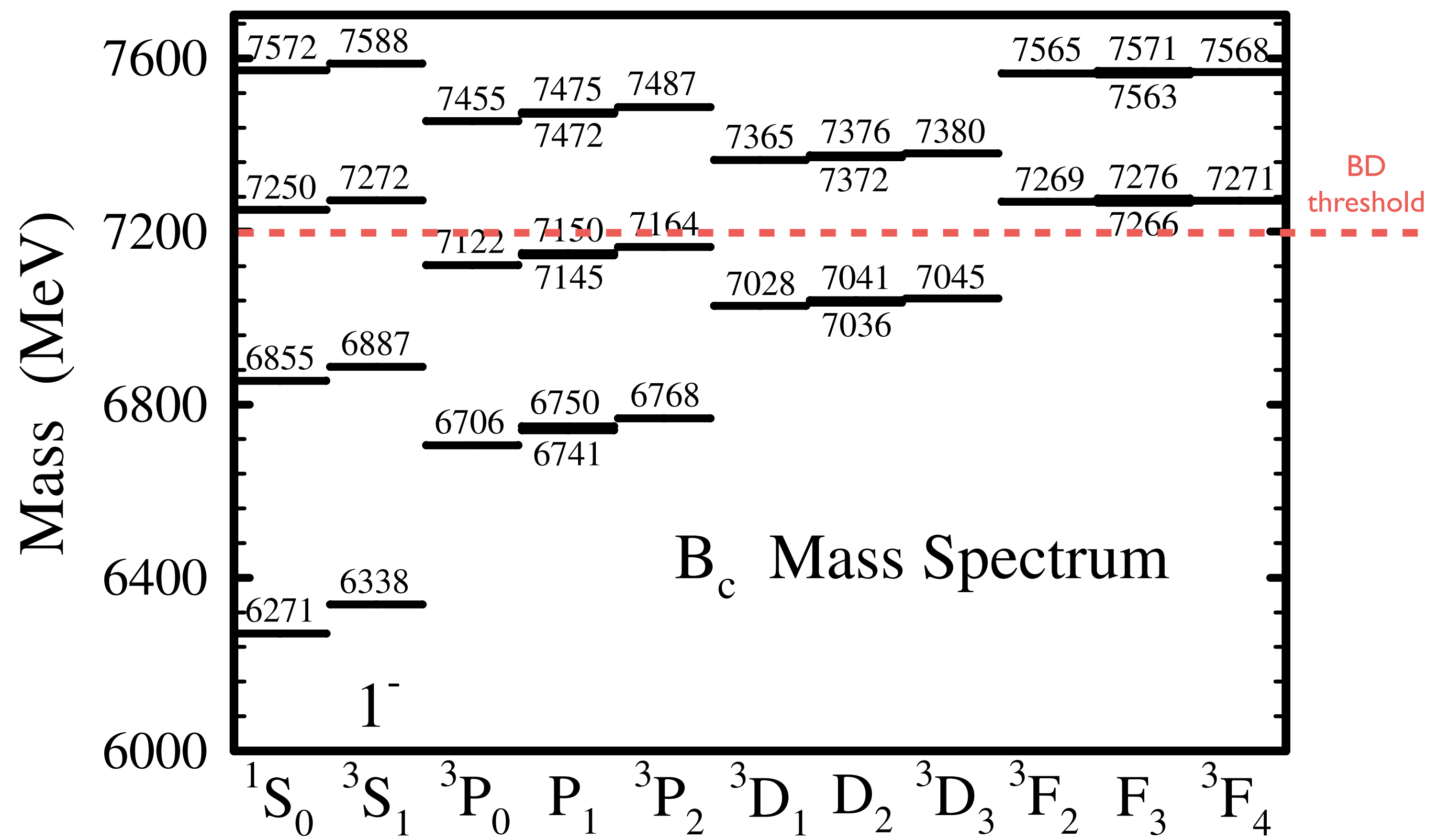
$B_c(2S_0) \rightarrow B_c(1S_0)\,\pi\pi$

$B_c(2S_1) \rightarrow B_c(1S_1)\,\pi\pi$

$\hookrightarrow B_c(1S_0)\,\gamma$ (invisible)

$m_{2S_1} - m_{2S_0} \sim 20 \div 50\ MeV$

cannot be separated by this analysis



DOI: http://dx.doi.org/10.1103/PhysRevD.70.054017

Peak observed in the mass difference distribution

$$Q = m(B_c^{\pm}\pi\pi) - m(B_c^{\pm}) - 2m(\pi^{\pm})$$

ground state channel: $B_c^{\pm} \rightarrow J/\psi(\mu^+\mu^-)\pi^{\pm}$

CDF: PRL 81 (1998) 2432, PRL 96 (2006) 082002, PRL 1000 (2008) 182002

D0: PRL 101 (2008) 012001

LHCb: PRL 108 (2012) 251802, PRD 87 (2013) 071103 and 112012, JHEP 09 (2013) 075, JHEP 11 (2013) 094, PRL 111 (2013) 181801

ATLAS: ATLAS-CONF-2012-028

CMS: CMS-PAS-BPH-11-003

Data selection and reconstruction

$\mathcal{L} = 4.9\ fb^{-1}$ 7 TeV data and $\mathcal{L} = 19.2\ fb^{-1}$ 8 TeV data recorded in 2011/2 $J/\psi \to \mu\mu$ trigger

J/ψ reconstruction: $p_T^{\mu_{high}} > 6\, GeV$ $p_T^{\mu_{low}} > 4\, GeV$ mass window: $\pm 3\,\sigma$, σ : $40 \div 90\ MeV$

$B_c^{\pm}$ reconstruction: $p_T^{\pi} > 4\, GeV$ mass constrained vertex fit

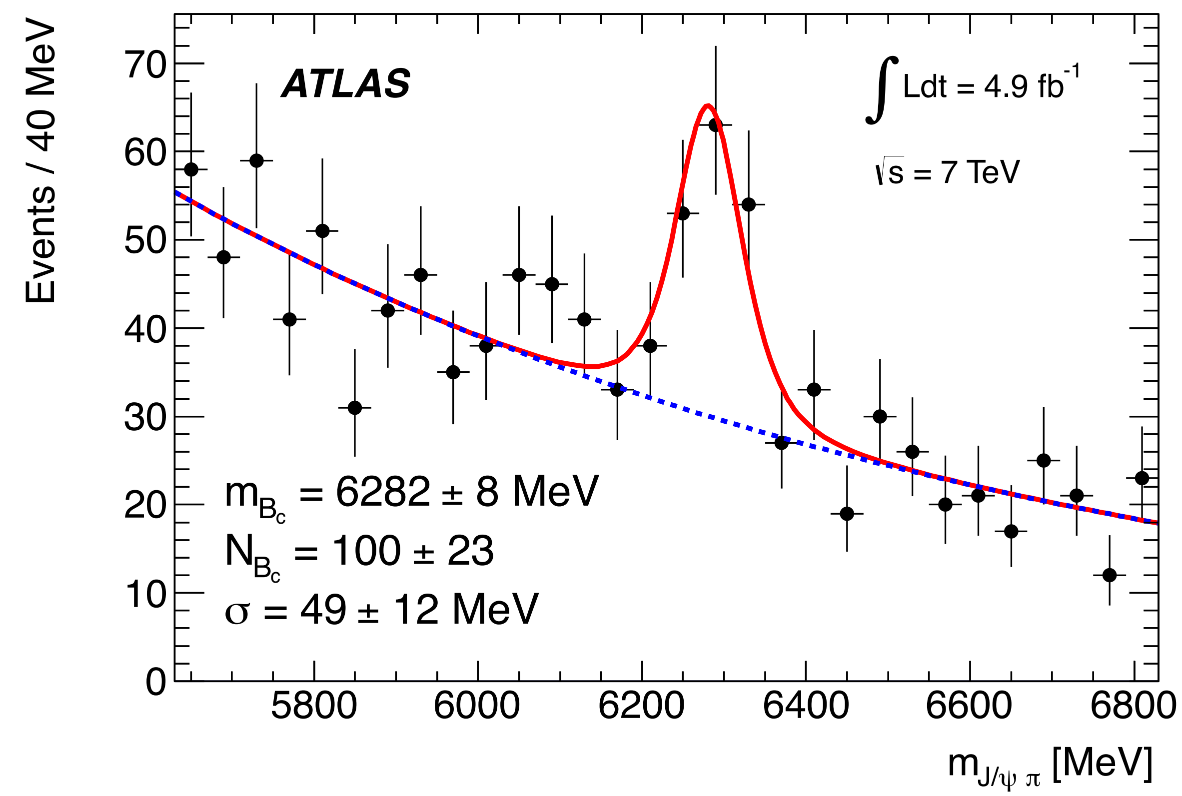
combinatorial background reduced using IP cut

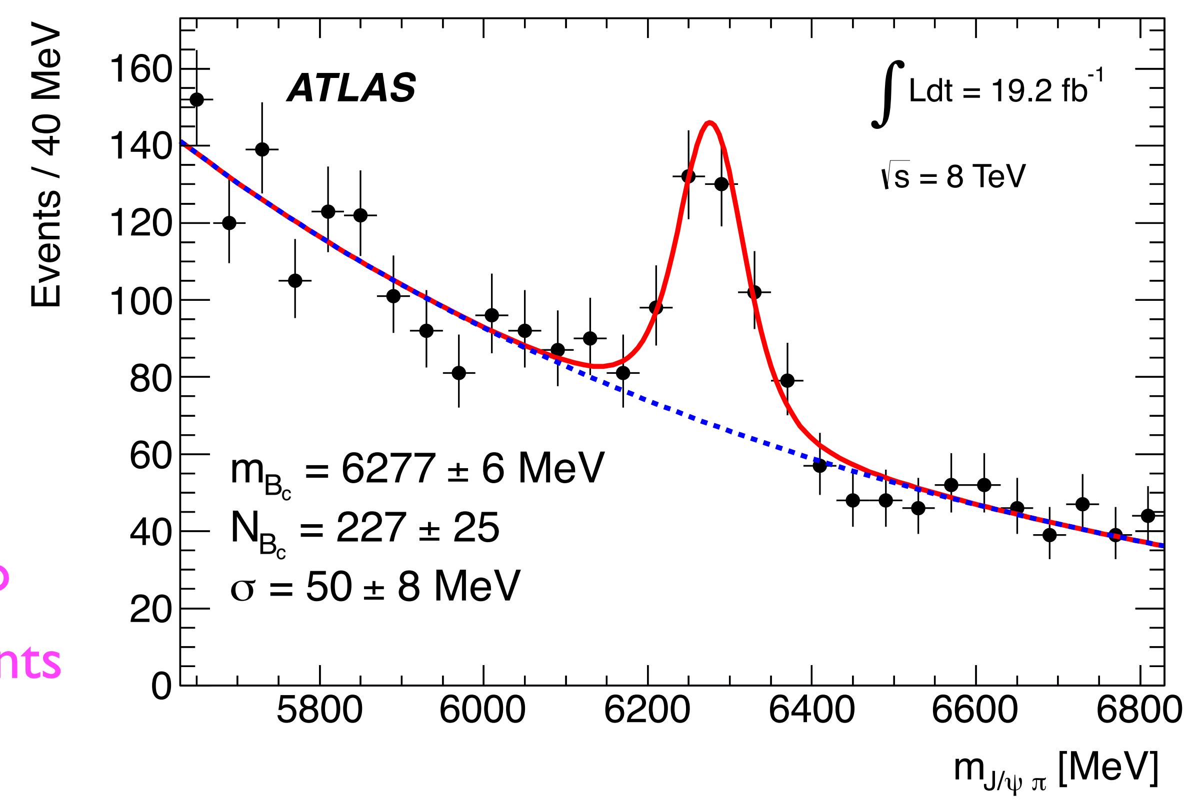
d_0 defined w.r.t primary vertex PV

7 TeV PV: highest sum of p_T^2 of tracks in vertex

8 TeV PV: vertex closest to $B_c^{\pm}$ vertex in 3D

cut		7 TeV	8 TeV
$d_0/\sigma(d_0)$	$>$	5	4.5
χ^2/N_{dof}	$<$	2	1.5
$p_T(B_c^{\pm})$	$>$	15	18 (GeV)





extended unbinned maximum likelihood fit

signal: Gaussian function, background: exponential

fitted mass consistent with the world average

stability of the $B_c^{\pm}$ yield checked through its normalisation to $B^{\pm} \to J/\psi K^{\pm}$ decays reconstructed with similar requirements

$B_c(2S)$ Reconstruction

$B_c^{\pm}$ candidates within $\pm 3\sigma$ of the fitted mass combined with 2 tracks from the corresponding PV,

$p_T^{\pi} > 400\ MeV$

cascade fit: J/ψ mass constraint,

$B_c^{\pm}$ pointing to $B_c(2S)$ vertex

best χ^2 candidate kept

unbinned maximum likelihood fit to right-charge combinations

signal: Gaussian function, background: third-order polynomial

background shape consistent with wrong-charge combinations

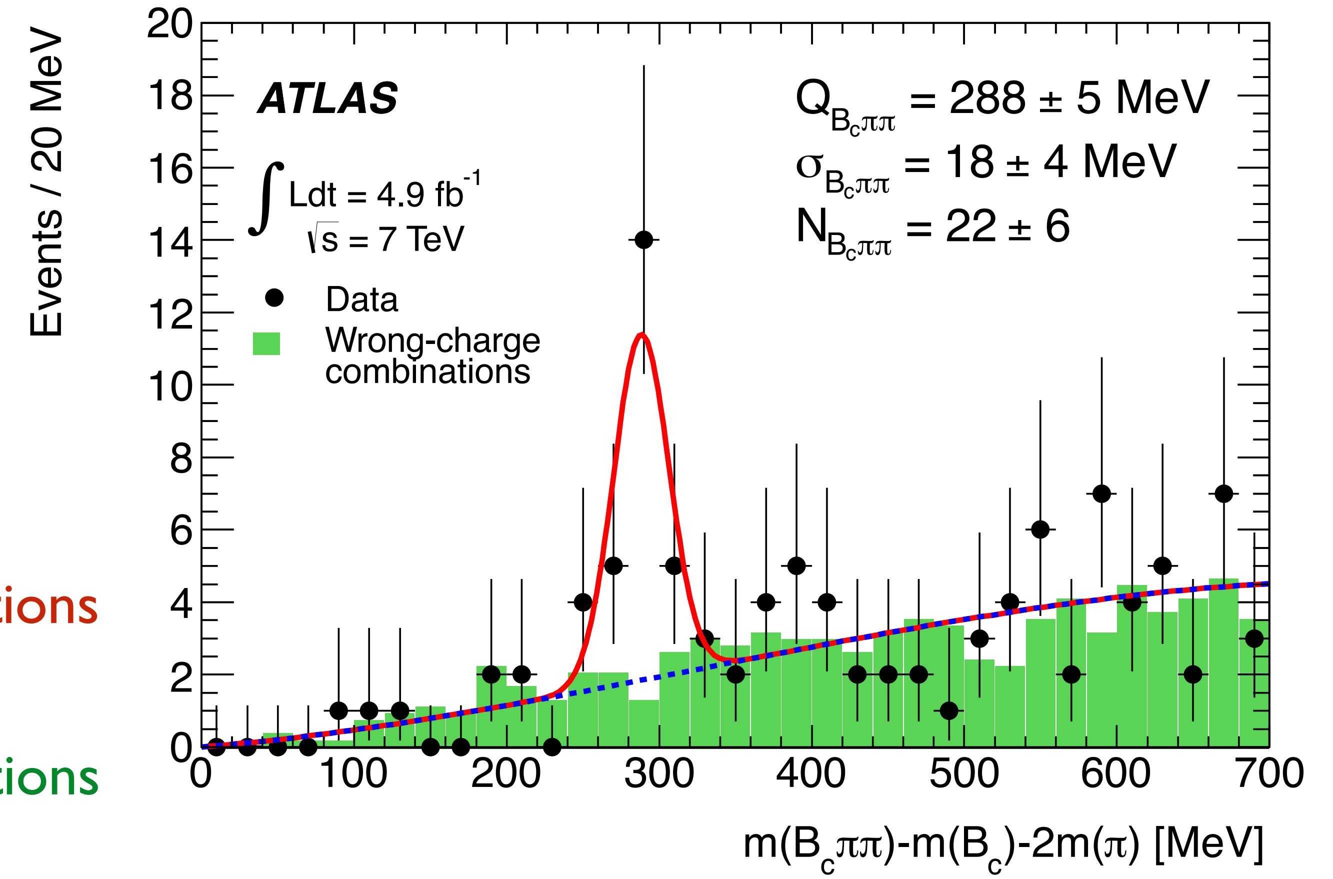
	7 TeV	8 TeV
mass (MeV)	288.2 ± 5.1	288.4 ± 4.8
width (MeV)	18.2 ± 3.8	17.6 ± 4.0

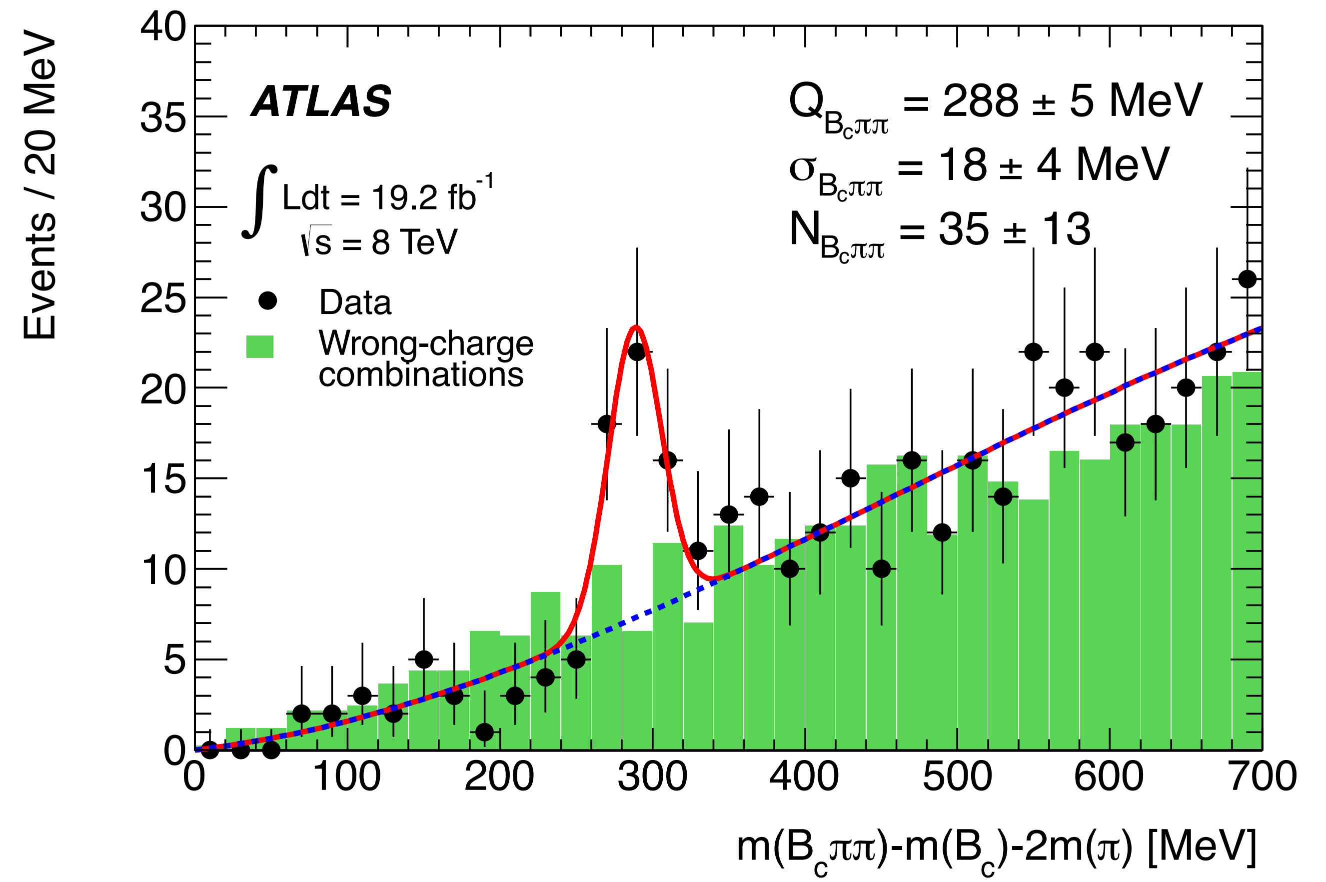
(statistical uncertainties only)

the relative $B_c^{\pm}(2S)/B_c^{\pm}$ yield ratio statistically consistent between 7 TeV and 8 TeV data

systematic uncertainties: uncertainty on the mass of the ground state, pion momentum scale, signal and background models, selection of best candidate

total averaged systematic uncertainty: 4.1 MeV





Results

the significance of the new structure evaluated with pseudo-experiments using the parameters from the fit

the mean mass value of the signal contribution is not constrained within the theoretically motivated range to account for a "look elsewhere effect"

significance: calculated as the fraction of the pseudo-experiments in which the difference of the logarithms of the fit likelihoods $\Delta \ln L$ with and without signal is larger than in the data

7 TeV: 3.7σ 8 TeV: 4.5σ

Combined: $5.2\,\sigma$

local significance (fixing the mean value of the signal component): $5.4\,\sigma$

A new state observed in the ATLAS detector with
$\mathcal{L} = 4.9\, fb^{-1}$ 7 TeV data and $\mathcal{L} = 19.2\, fb^{-1}$ 8 TeV data

error weighted mean mass of the observed structure: $Q \;=\; 288.3 \pm 3.5(stat) \pm 4.1(syst)$

corresponding to a mass of $6841 \pm 4(stat) \pm 5(syst)\; MeV$

consistent with the predicted mass: $m_{B_c(2S)} \sim 6835 \div 6917\; MeV$

Summary

The parity-violating decay asymmetry parameter and the helicity amplitudes in $\Lambda_b^0 \to J/\psi \Lambda^0$ decays have been measured by ATLAS

$$\alpha_b \;=\; 0.30 \pm 0.16(stat) \pm 0.06(syst)$$

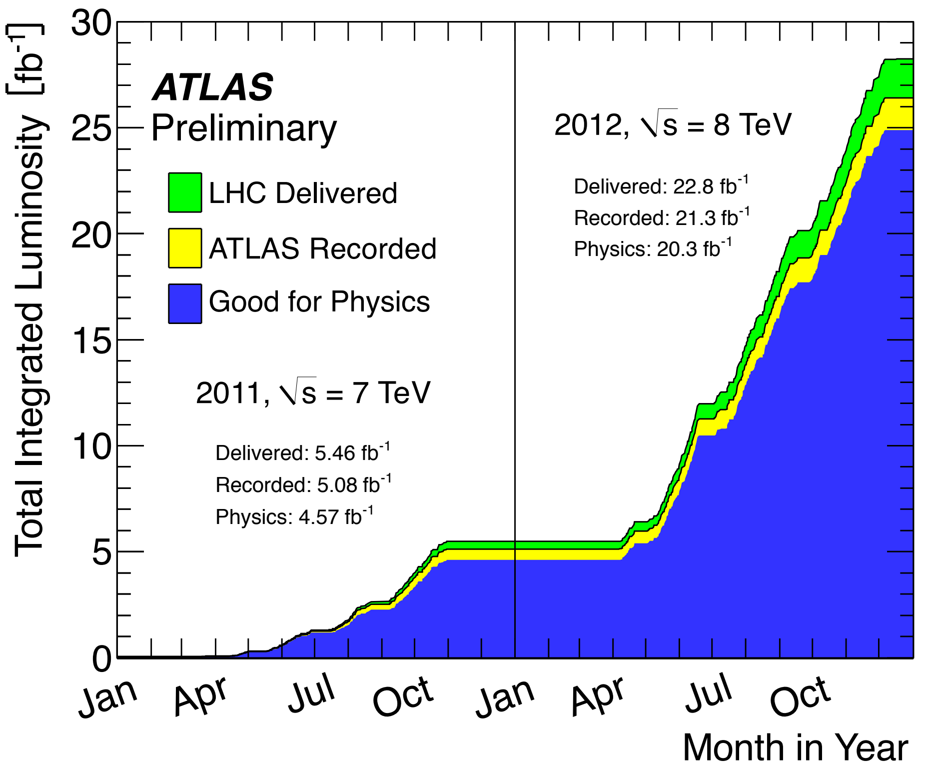
A new state has been observed in the ATLAS detector with a mass

$$6841 \pm 4(stat) \pm 5(syst)\ MeV$$

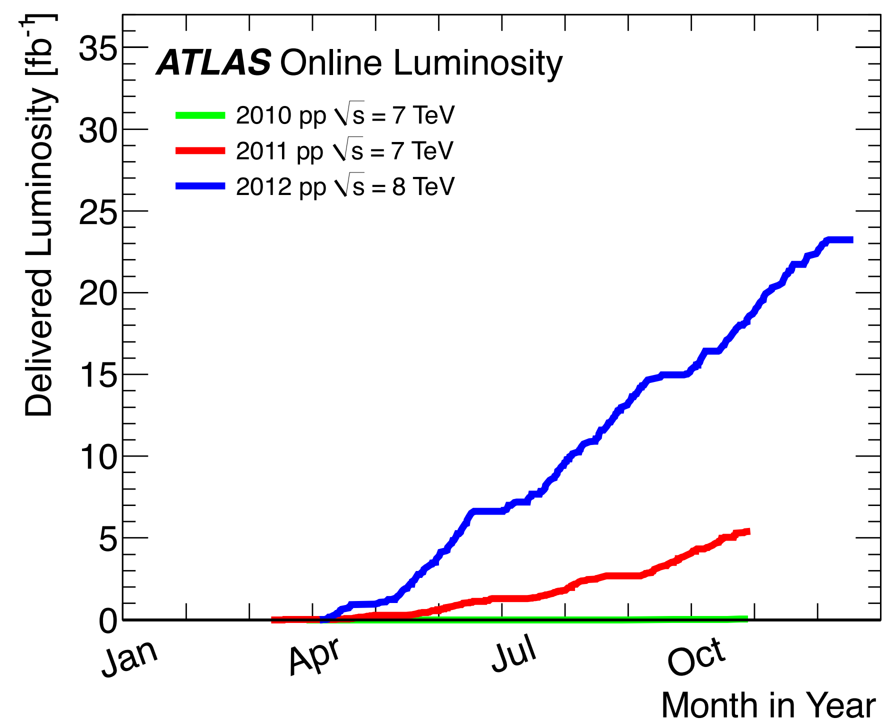
consistent with $B_c(2S)$ predicted as: $m_{B_c(2S)} \sim 6835 \div 6917\ MeV$

Backup slides

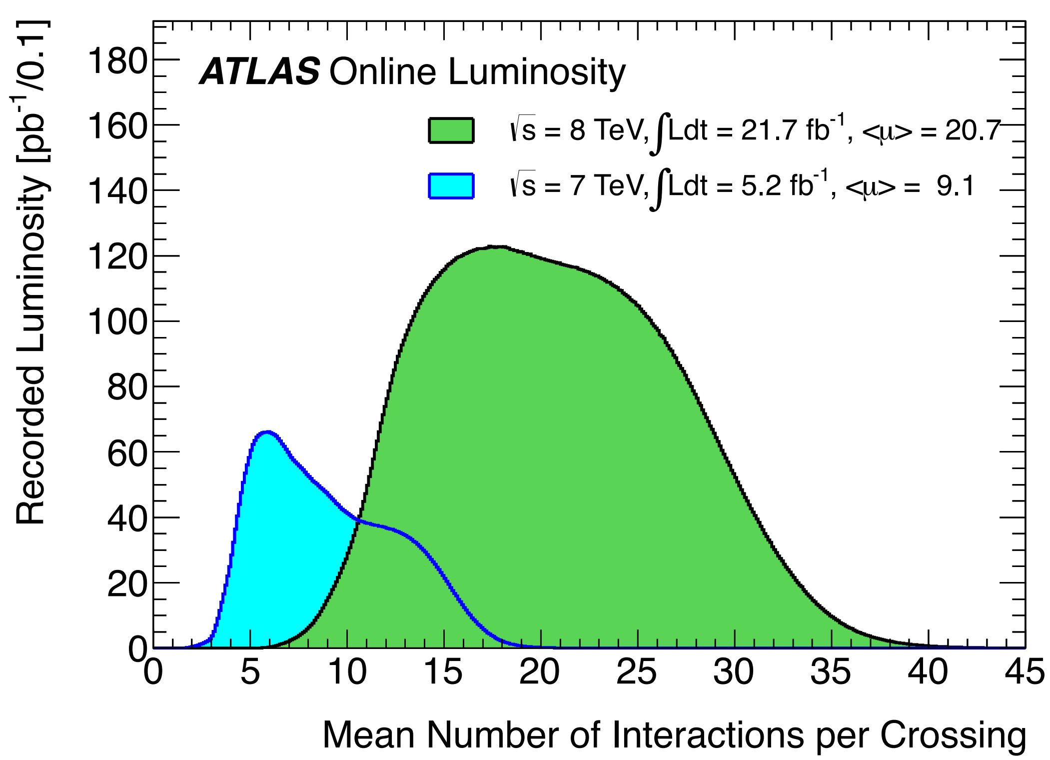
Luminosity



ATLAS
Preliminary
LHC Delivered
ATLAS Recorded
Good for Physics
2011, √s = 7 TeV
Delivered: 5.46 fb^{-1}
Recorded: 5.08 fb^{-1}
Physics: 4.57 fb^{-1}
2012, √s = 8 TeV
Delivered: 22.8 fb^{-1}
Recorded: 21.3 fb^{-1}
Physics: 20.3 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
Jan Apr Jul Oct Jan Apr Jul Oct
Month in Year



ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb^{-1}]
Jan Apr Jul Oct
Month in Year



ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb^{-1}, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb^{-1}, <μ> = 9.1
Recorded Luminosity [pb^{-1}/0.1]
Mean Number of Interactions per Crossing

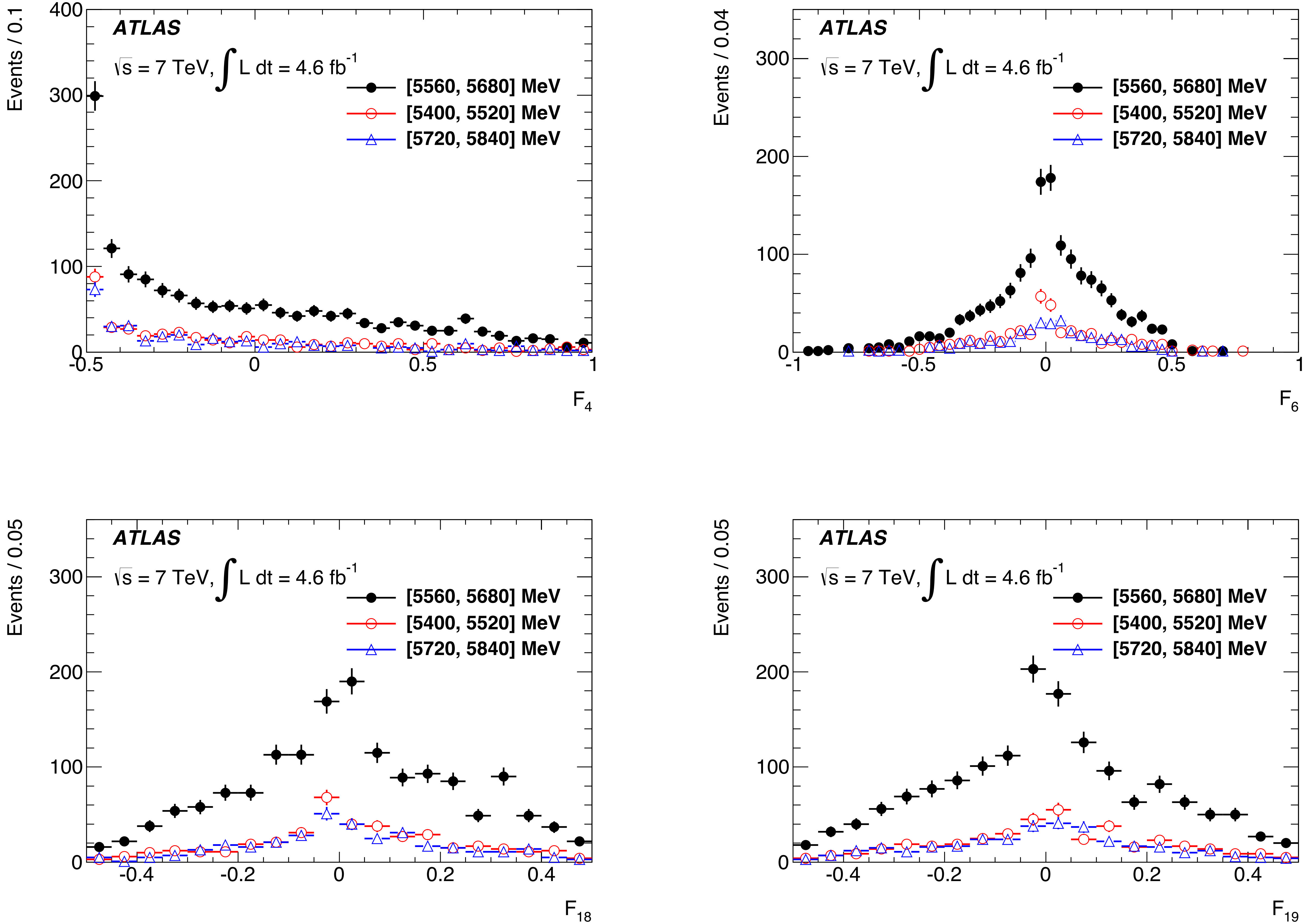
$$a_+ \equiv A(\frac{1}{2},0), \quad a_- \equiv A(-\frac{1}{2},0) \qquad a_+ = |a_+|e^{i\rho_+} \qquad b_+ = |b_+|e^{i\omega_+}$$

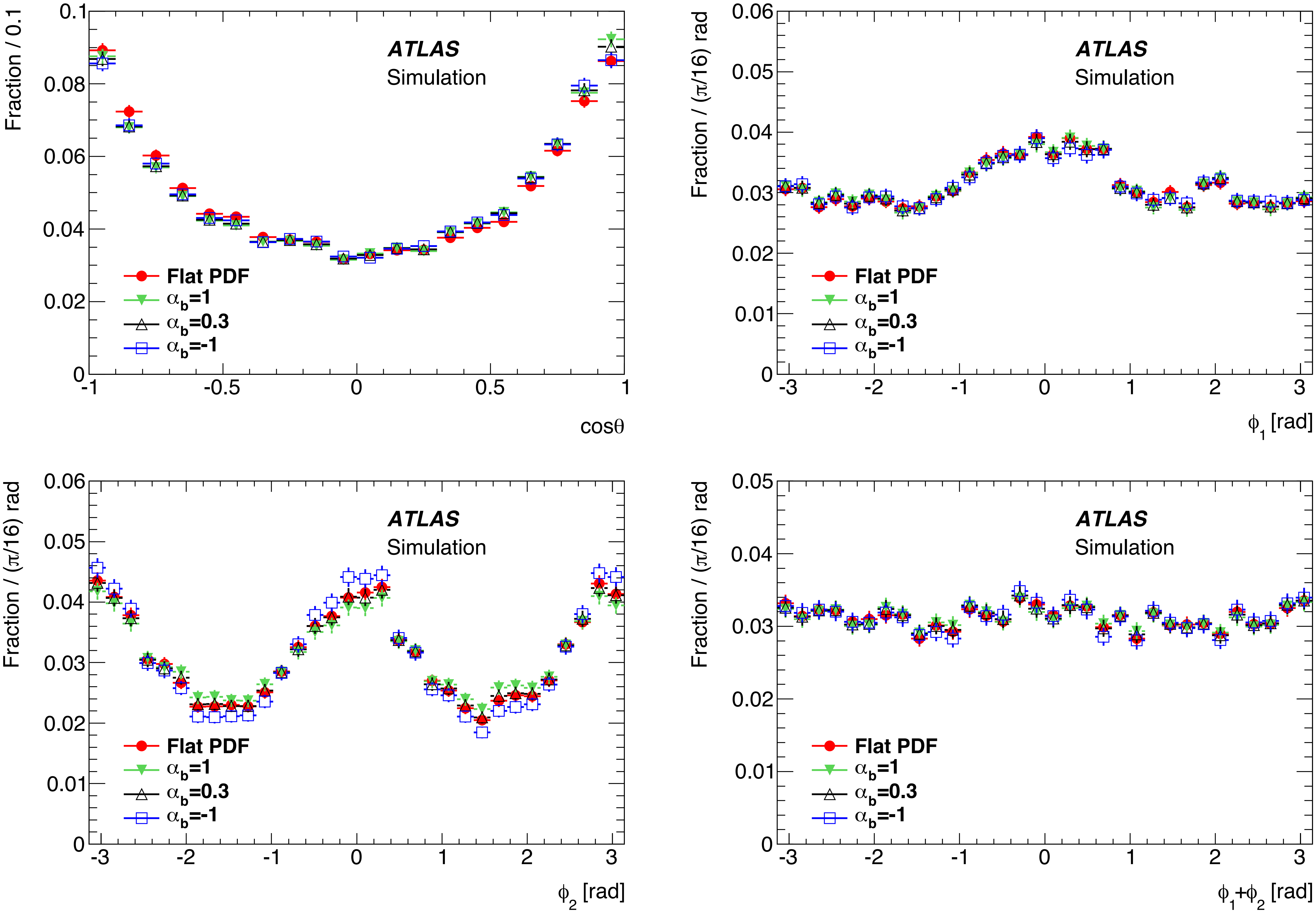
$$b_+ \equiv A(-\frac{1}{2},-1), \quad b_- \equiv A(\frac{1}{2},1) \qquad a_- = |a_-|e^{i\rho_-} \qquad b_- = |b_-|e^{i\omega_-}$$

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	$-3\mathrm{Re}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos\phi_1$
9	$3\mathrm{Im}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin\phi_1$
10	$-\frac{3}{2}\mathrm{Re}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos(\phi_1 + 2\,\phi_2)$
11	$\frac{3}{2}\mathrm{Im}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin(\phi_1 + 2\,\phi_2)$
12	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
13	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
15	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$
16	$\frac{3}{\sqrt{2}}\mathrm{Re}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}\mathrm{Im}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
18	$\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$

i	f_{1i}
0	1
2	$(k_+^2 + k_-^2 - 1) + \alpha_b(k_+^2 - k_-^2)$
4	$\frac{1}{4}[(3k_-^2 - 3k_+^2 - 1) + 3\alpha_b(1 - k_-^2 - k_+^2)]$
6	$-\frac{1}{4}[(k_+^2 + k_-^2 - 1) + \alpha_b(3 + k_+^2 - k_-^2)]$
18	$\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\cos(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\cos(\Delta_+)]$
19	$-\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\sin(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\sin(\Delta_+)]$

$$
\begin{aligned}
\alpha_b &= |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2, \\
k_+ &= \frac{|a_+|}{\sqrt{|a_+|^2 + |b_+|^2}}, \\
k_- &= \frac{|b_-|}{\sqrt{|a_-|^2 + |b_-|^2}}, \\
\Delta_+ &= \rho_+ - \omega_+, \\
\Delta_- &= \rho_- - \omega_-.
\end{aligned}
$$


ATLAS
√s = 7 TeV, ∫ L dt = 4.6 fb-1
[5560, 5680] MeV
[5400, 5520] MeV
[5720, 5840] MeV
Events / 0.1
F4
Events / 0.04
F6
Events / 0.05
F18
F19


ATLAS
Simulation
Fraction / 0.1
cosθ
Flat PDF
α_b=1
α_b=0.3
α_b=-1
Fraction / (π/16) rad
ϕ_1 [rad]
ϕ_2 [rad]
ϕ_1+ϕ_2 [rad]