MPP Colloquium
17 September 2013

B-Physics Results from the ATLAS Experiment

Pavel Řezníček
Excellence Cluster Univers, LMU Munich

Outline

- ATLAS experiment at the Large Hadron Collider
- Physics of B-hadrons at ATLAS
- B-physics trigger
- CP violation in the $B_s \rightarrow J/\psi\phi$ decay
- Angular analysis of rare $B_d \rightarrow K^*\mu\mu$ decay
- Limit on very rare $B_s \rightarrow \mu\mu$ branching ratio
- Rare/new B-hadrons observations
- Angular analysis of $\Lambda_b \rightarrow \Lambda\mu\mu$ decay
- B-production x-sections measurements
- Summary

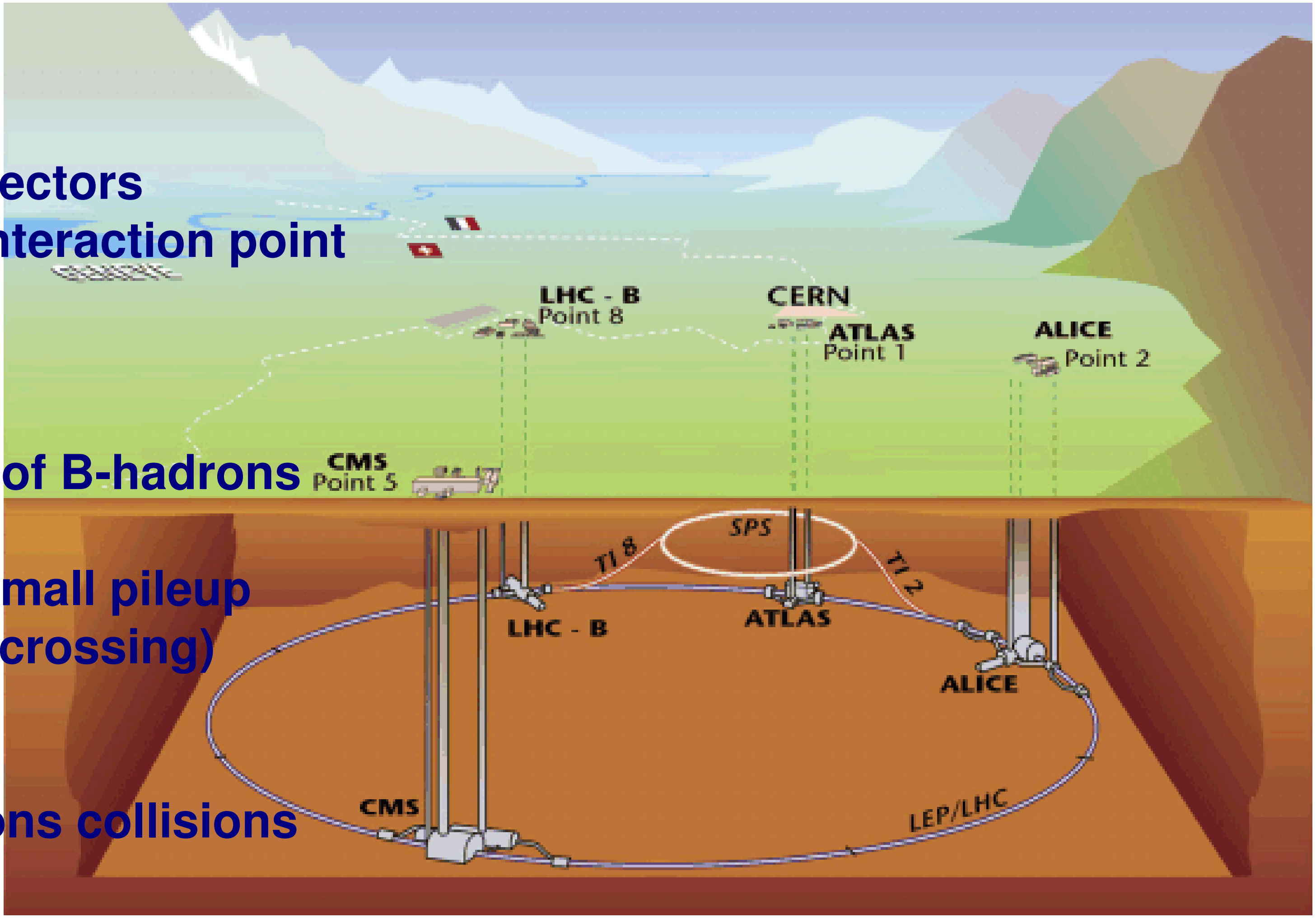
Large Hadron Collider

- Design parameters: $\sqrt{s}$ = 7+7 TeV, L = 10^{34} $cm^{-2}s^{-1}$, ~23 pp interactions per bunch crossing
- Achieved in 2011: $\sqrt{s}$ = 7 TeV, L_{max} ~ 3.5×10^{33} $cm^{-2}s^{-1}$, ~12 pp interactions per bunch crossing
- Achieved in 2012: $\sqrt{s}$ = 8 TeV, L_{max} ~ 7.7×10^{33} $cm^{-2}s^{-1}$, ~24 pp interactions per bunch crossing

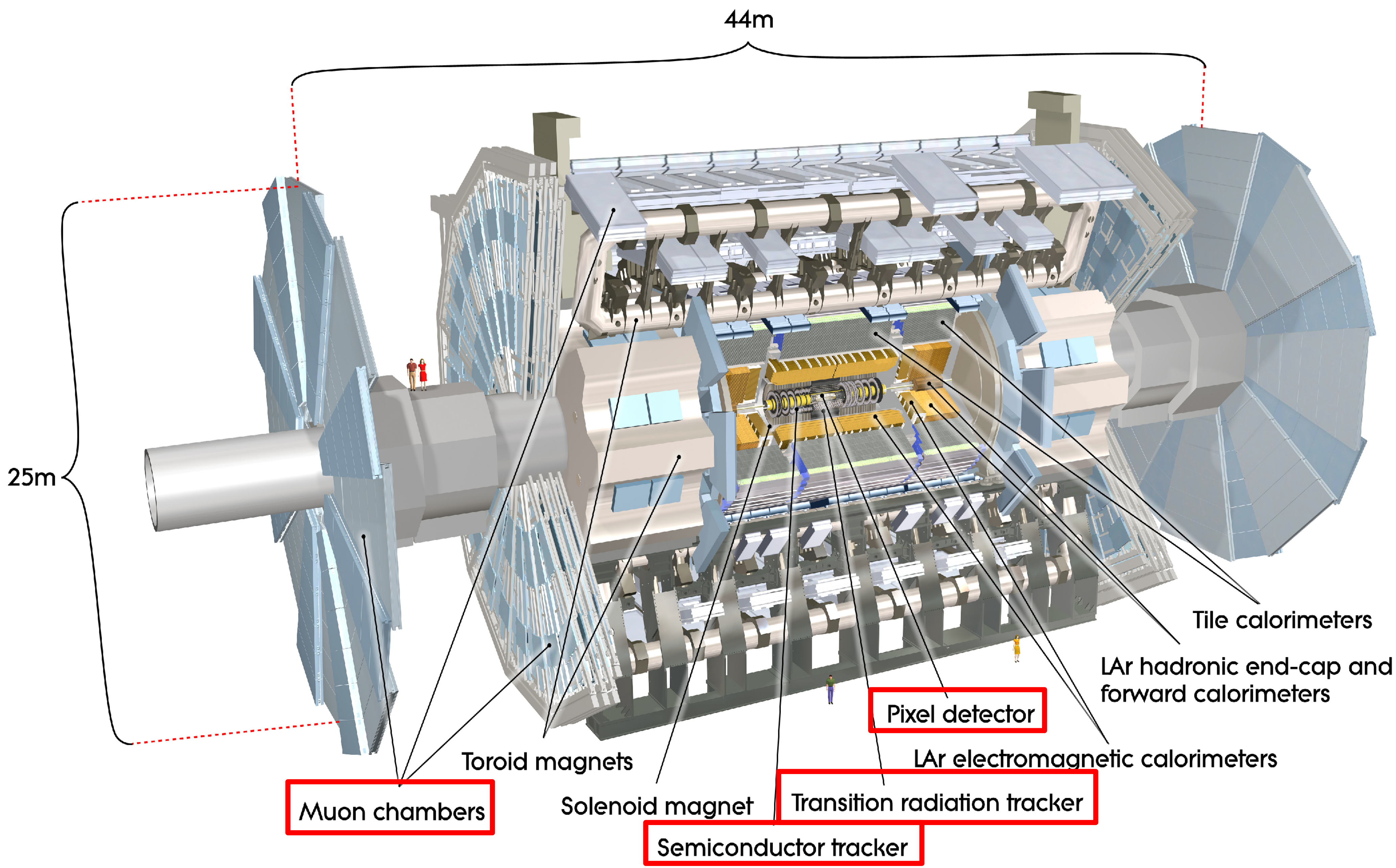
ATLAS/CMS
- **general purpose detectors**
- **symmetric around interaction point**
- **maximal luminosity**

LHCb
- **focused on physics of B-hadrons**
- **forward geometry**
- **limited luminosity, small pileup (pp interactions per crossing)**

ALICE
- **focused on Heavy Ions collisions**



The ATLAS Detector

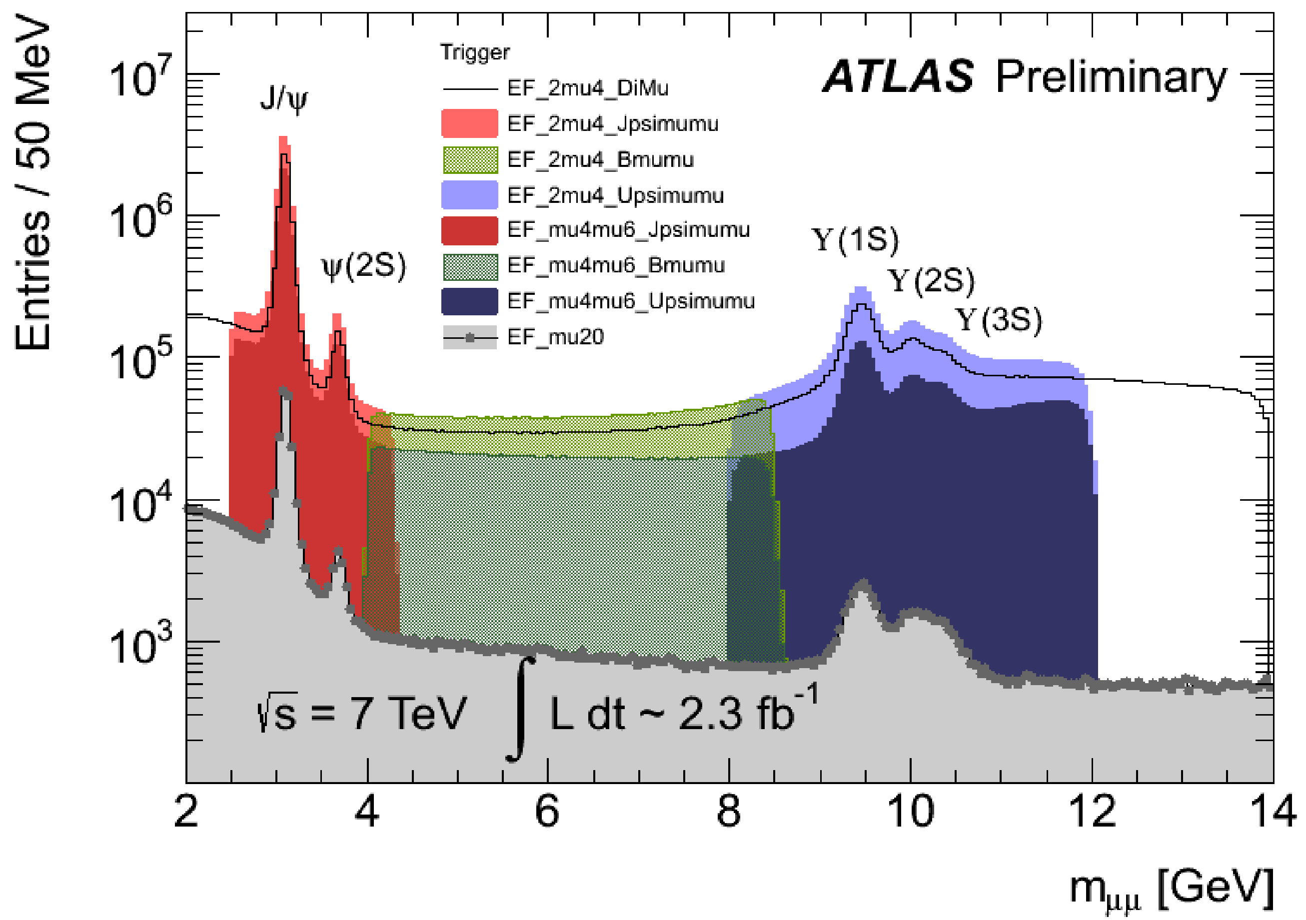


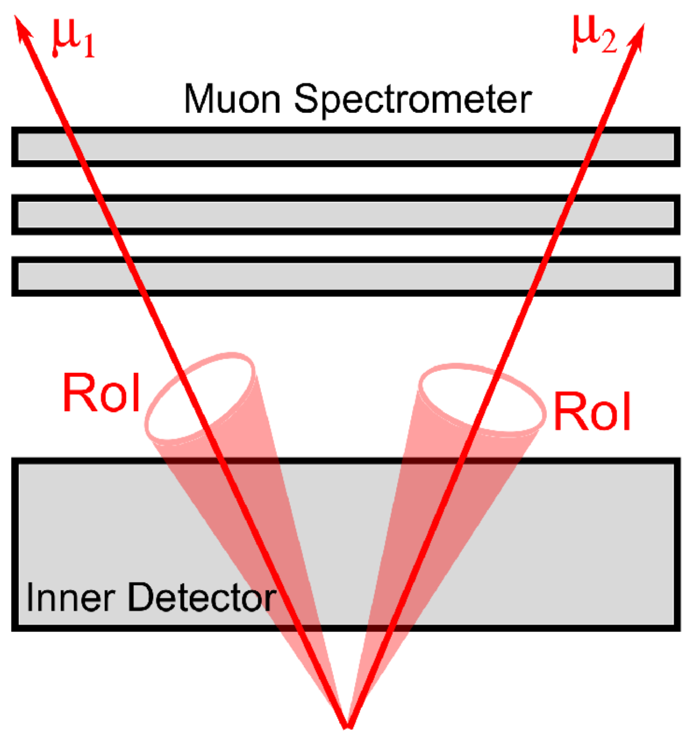
ATLAS B-Physics Program

- Two ways to search for physics beyond Standard Model: **direct** (resonances observation) or **indirect** through anomalies in known decays
- ATLAS B-physics focused on the beyond-SM effects in the B-hadron decays
- Analyses thus include precision measurements and rare processes in decays that can be fully reconstructed by the detector (all final state particles are charged):
  - quarkonia production
  - b-production x-section
  - rare decays $B_s \to \mu\mu$ and $b \to s\mu\mu$
  - angular, lifetime and mass measurements: $B_s \to J/\psi\phi$, $\Lambda_b \to \Lambda\mu\mu$
  - observation of rare/new b-hadrons: B_c, χ_b
- Despite ~0.5×10^9 B^0-pairs expected in 2011 data, all ATLAS B-physics measurements are statistically limited (room for improvemet with 2012 data and beyond)

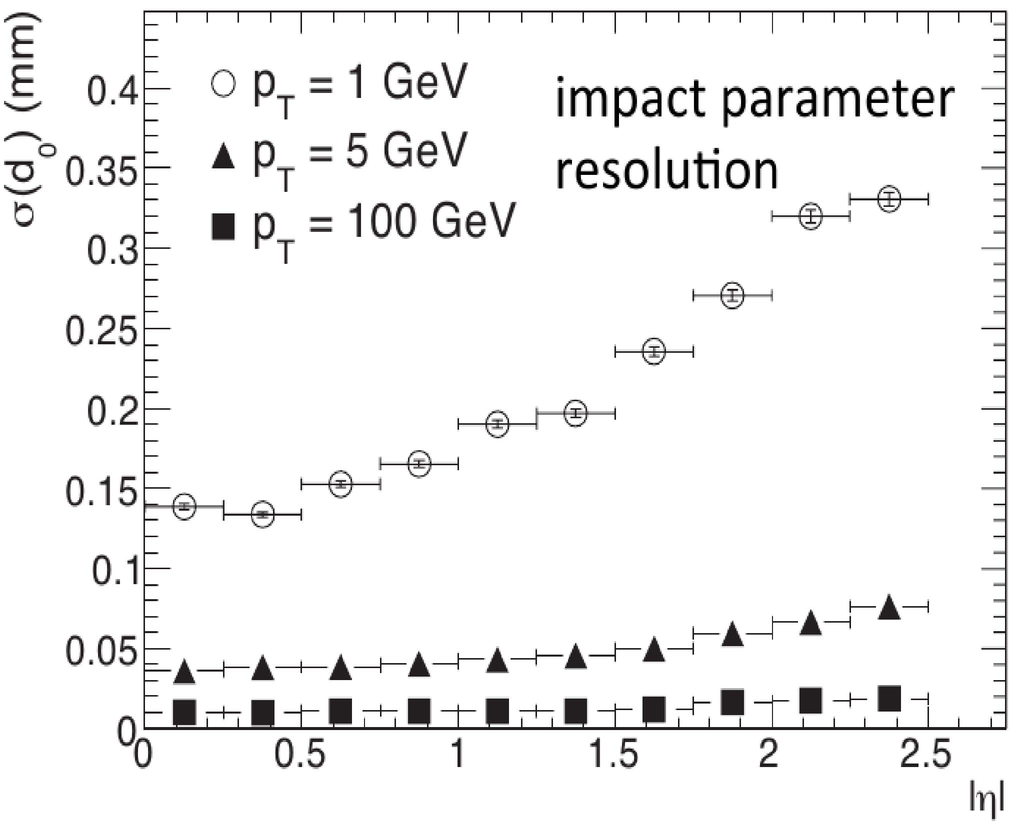
B-Physics Trigger

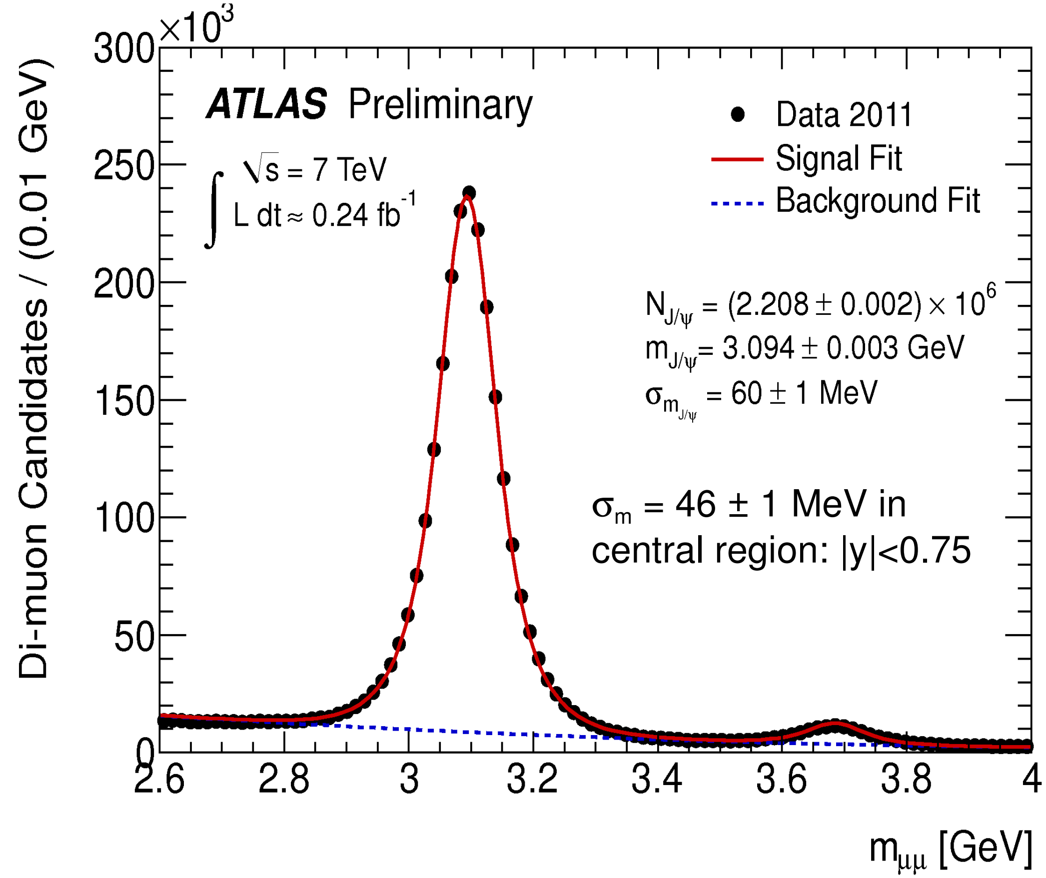
- Based on di-muon signature (e/γ or hadronic B-decays lost in background)
- Whole trigger chain 3-level based:
  - L1 – HW based, fast muon detectors, di-muons with $p_T > 4$ GeV
  - L2/EF – SW based, precise confirmation of the muons by Inner Detector tracks reconstruction, di-muon vertex construction (inv. mass cut), eventuall search for other hadronic tracks of requested B-decays





Performance of the ATLAS Detector





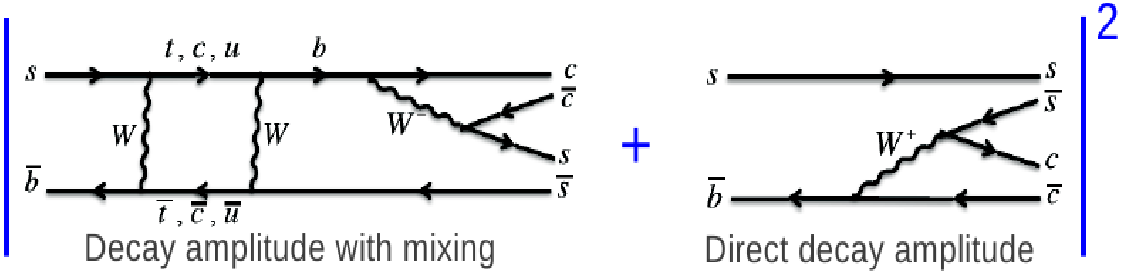
- Good impact parameter (reconstructed tracks deviation from real vertex in the transverse plane) resolution needed for good secondary B-hadron decay vertex separation
  - proper decay time resolution ~ 0.1 ps, typical B-hadron lifetime 1.5 ps
- Excellent mass resolution for good S/B performance
- No K/π separation ability → higher combinatorial background

CP violation in the $B_s \rightarrow J/\psi\phi$ decay (extraction of $\Delta\Gamma_s$ and ϕ_s)

CP Violation in $B_s \to J/\psi\phi$ Decay

- CP violation in $B_s \to J/\psi\phi$ occurs through the interference in mixing and decay

Decay rate ~

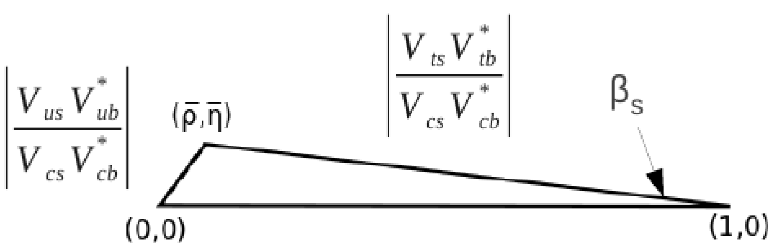


B_s mixing:
- Mass difference $\Delta m = m_H - m_L$
- Mixing phase ϕ_s
- Decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$

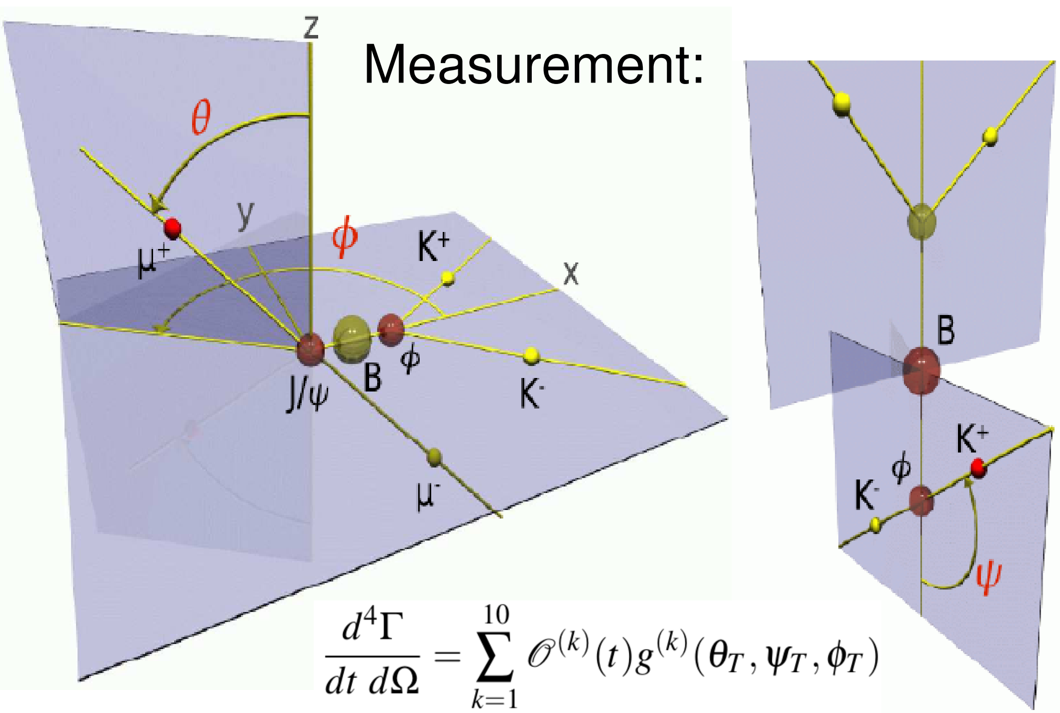
- Time evolution of flavour tagged $B_s \to J/\psi\phi$ very sensitive to New physics
- 9 physics parameters to describe $B_s \to J/\psi\phi$ decay

Γ_s, $\Delta\Gamma_s$	decay with and decay width difference
ϕ_s ($\approx 2\beta_s$)	CP violating phase
$\lvert A_0\rvert^2$, $\lvert A_\parallel\rvert^2$	CP state amplitudes
$\delta_\parallel$, $\delta_\perp$	Strong phases
$\lvert A_S\rvert^2$, δ_S	S-wave parameters



ϕ_s small in SM, clear to see potential excess from NP

Measurement:



$$\frac{d^4\Gamma}{dt\,d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T)$$

$B_s \to J/\psi\phi$ Decay Rate

- **Experimental challenges:** $J/\psi\phi$ not pure CP eigenstate → statistical separation, good vertex resolution for time information, S/B ratio without K/π identification, initial B-flavour charge tagging

k	$\mathscr{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2 \left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2 \left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_\parallel$ $\left[(1+\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1-\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$-\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t)-\cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t)-\cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2 \left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}(1-\sin\theta_T\cos^2\phi_T)$
8	$\lvert A_S\rvert\lvert A_\parallel(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{L}^{(s)}t}-e^{-\Gamma_\mathrm{H}^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t)-\sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\lvert A_S\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)e^{-\Gamma_\mathrm{L}^{(s)}t}+(1+\cos\phi_s)e^{-\Gamma_\mathrm{H}^{(s)}t}\mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_\mathrm{H}^{(s)}t}-e^{-\Gamma_\mathrm{L}^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t)+\sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$

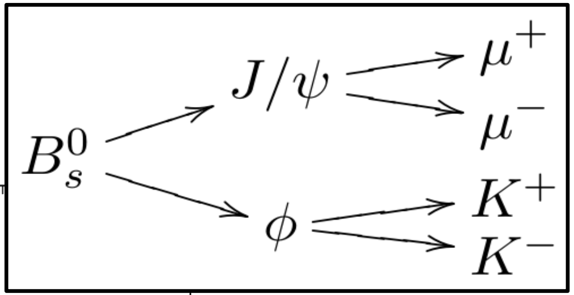
Symmetries in the formulas:

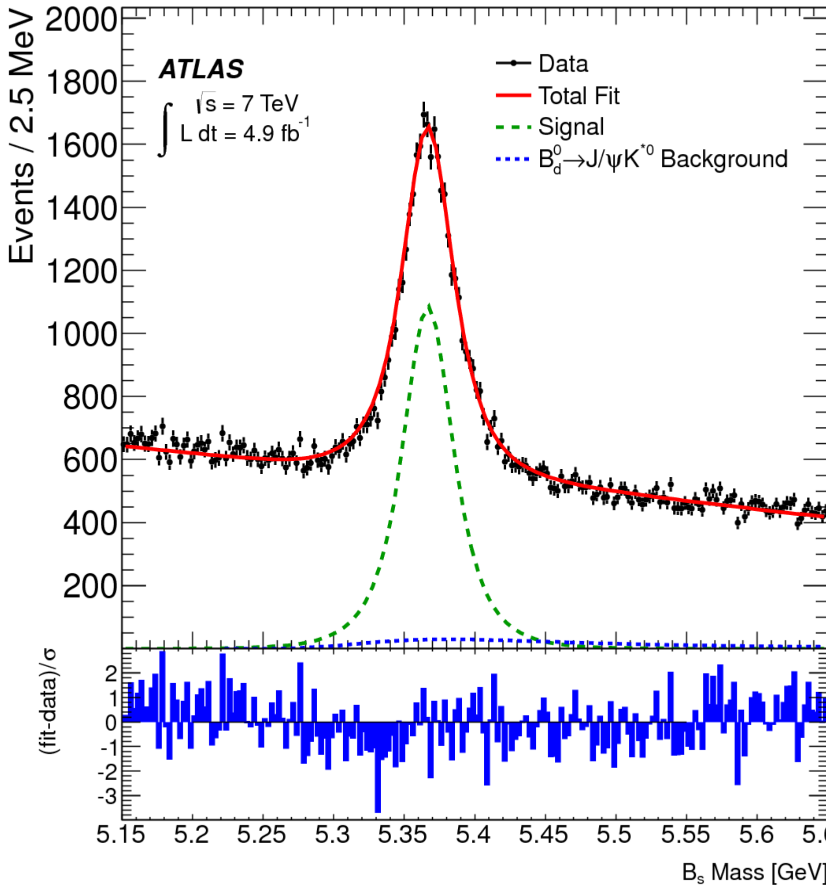
$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{\pi-\phi_s, -\Delta\Gamma_s, \pi-\delta_\perp, -\delta_\parallel, -\delta_S\}$$

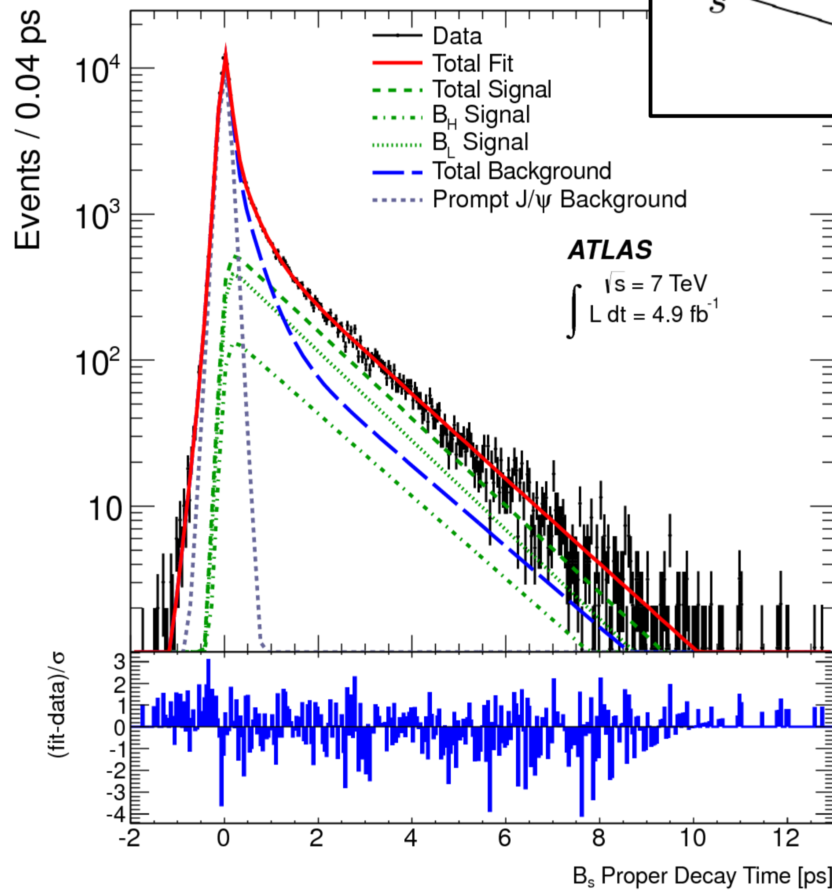
~~$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{-\phi_s, \Delta\Gamma_s, \pi-\delta_\perp, -\delta_\parallel, -\delta_S\}$~~

$B_s \to J/\psi\phi$ Events Selection

- $J/\psi(\mu\mu)$ trigger, reconstruction of 4-tracks vertex: $B_s \to J/\psi\phi$
  - cuts on vertex quality, tracks p_T, invariant mass of J/ψ and ϕ







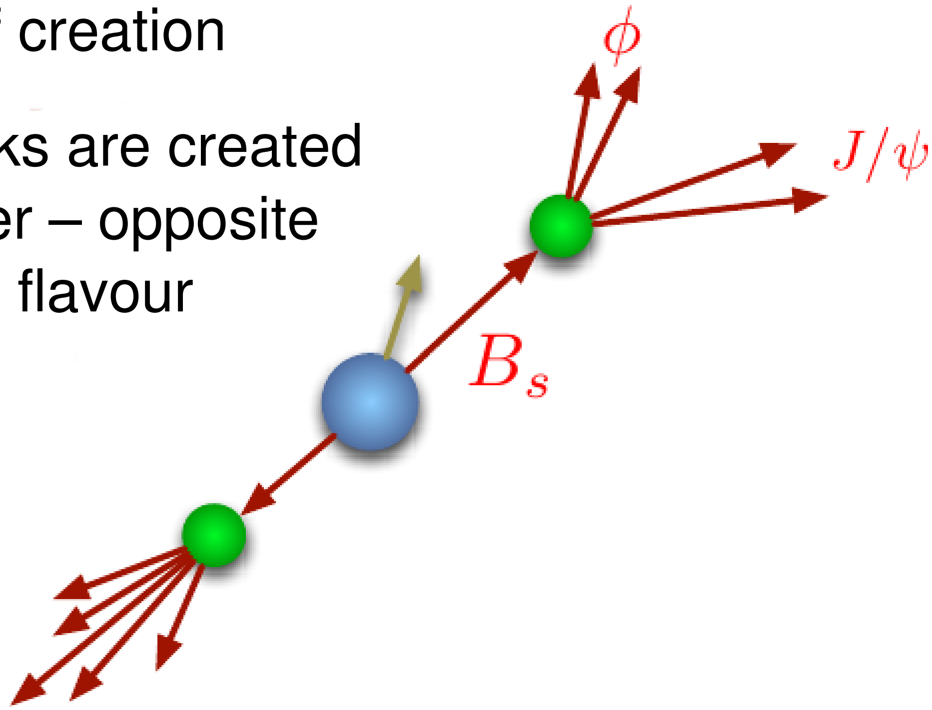
- Extraction of the decay angles from the fully reconstructed topology, Bs proper decay time calculated in transverse plane:

$$t = \frac{L_{xy}\, M_B}{c\, p_{T_B}}$$

- Important selection of correct primary vertex (by pointing of B_s momentum)

Initial B_s Charge Flavour Tagging

- Find the B_s-charge flavour at the time of creation
- Method is based on the fact that b-quarks are created in $b\bar{b}$ pairs → by reconstructing the other – opposite side – B-hadron, one can determine the flavour of the signal $B_s \rightarrow J/\psi\phi$
- Two methods of determination of the opposite B-hadron charge flavour:



Muon tagger:

- Identify muon from semileptonic B-decay
- Calculated charge of cone around the muon: Q_μ

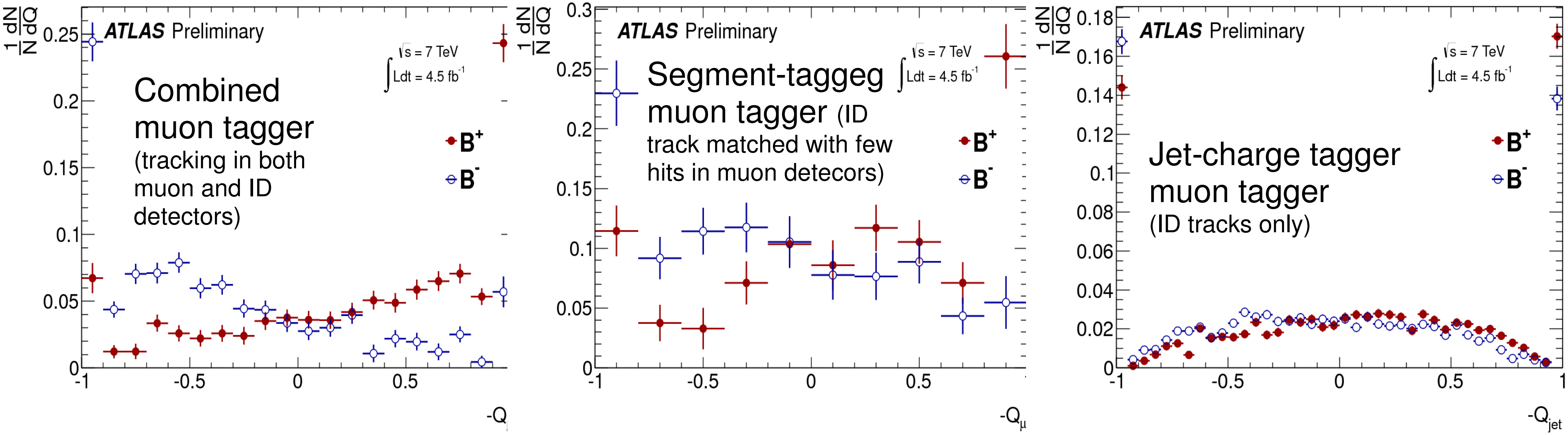
$$Q_\mu = \frac{\sum_i^{N\ \text{tracks}} q^i \cdot (p_T^i)^\kappa}{\sum_i^{N\ \text{tracks}} (p_T^i)^\kappa}$$

Jet-charge tagger:

- Reconstruct a jet coming from the same primary vertex
- Calculate charge of the jet (made of Innder Detector tracks): Q_{jet}

Initial B_s Charge Flavour Tagging - Results

- The method is calibrated on self-tagging data sample of $B^+ \rightarrow J/\psi K^+$



- Determine probability that signal decay contains $\bar{b}$ as a function of the muon cone or jet charge Q_μ or Q_{jet}

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

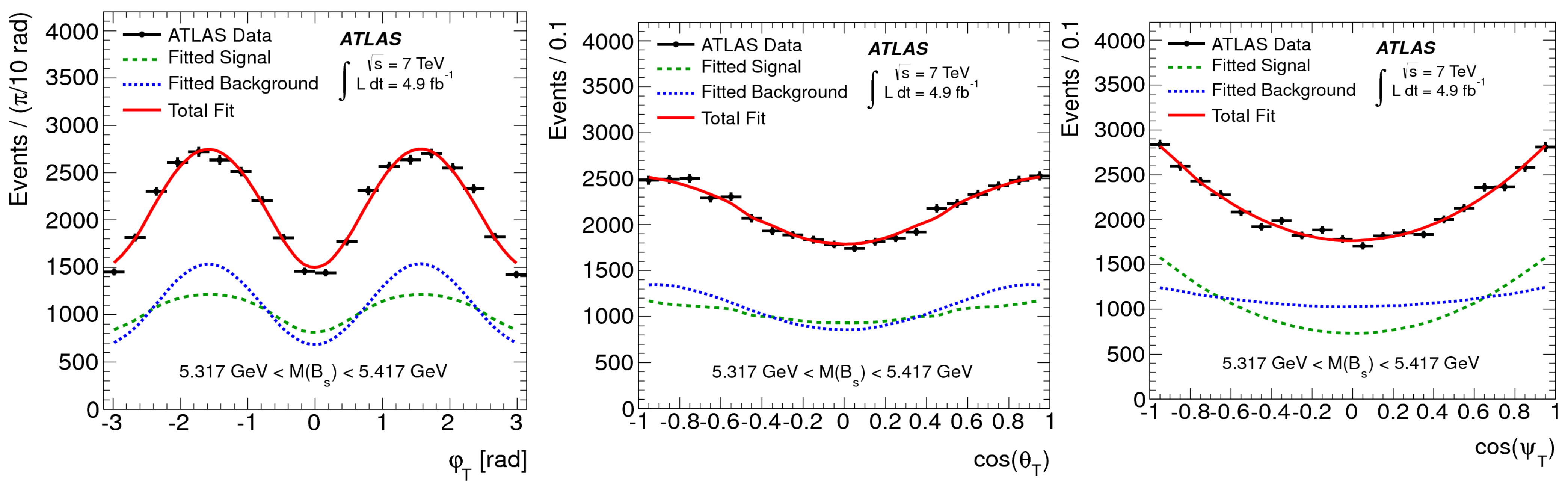
Measurement of $\Delta\Gamma_s$ and ϕ_s

- Running unbinned maximum likelihood fit (acounts for event-by-event resolutions):

$$\mathcal{L} \sim \prod_{1}^{N} w_i \cdot [f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) + (1 - f_s - f_s \cdot f_{B^0}) \cdot \mathcal{F}_{bck}(m_i, t_i, \Omega_i)]$$

- Non-resonant contribution for $B_s \to J/\psi K^+K^-$ included in the signal

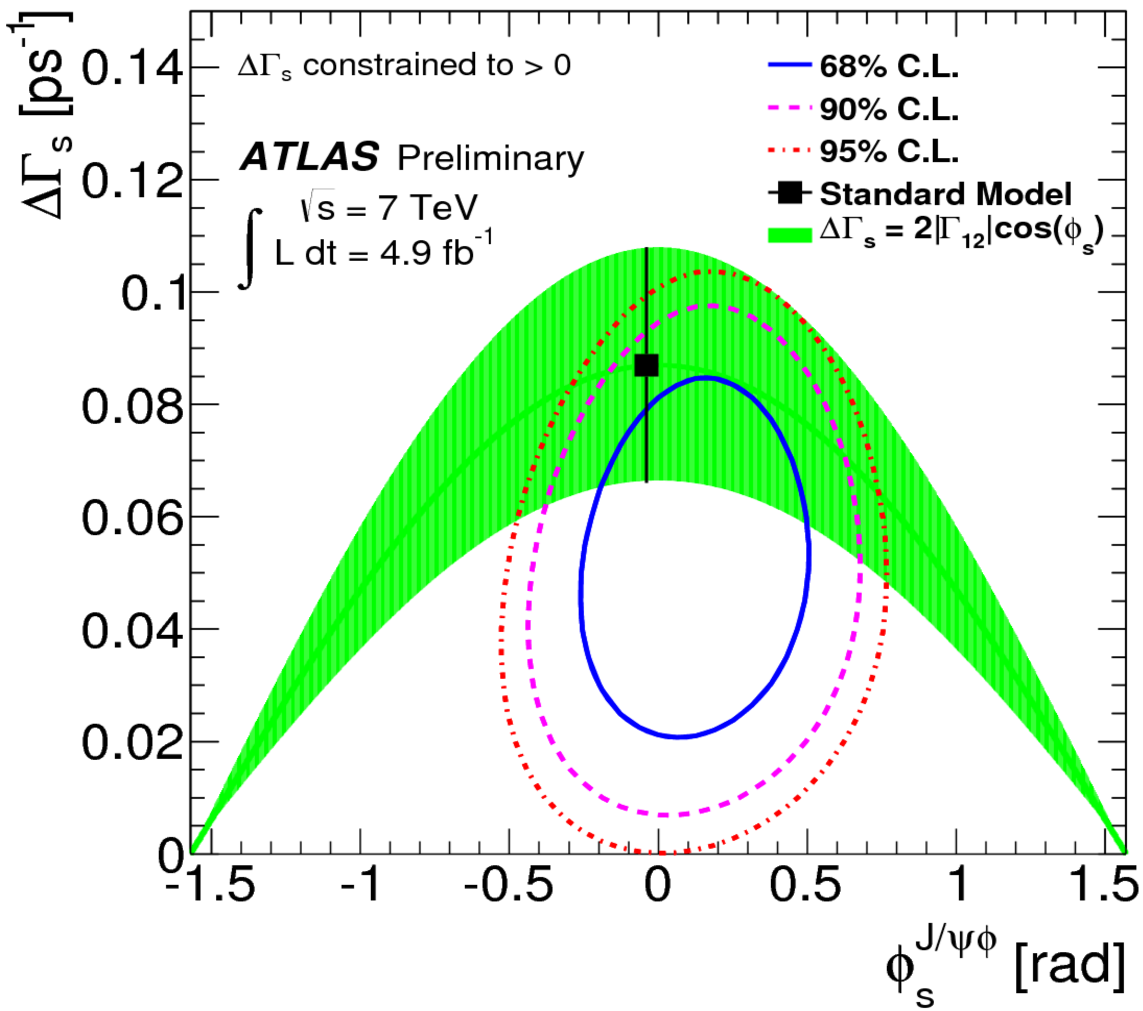
- Dedicated functions to describe background from $B_d \to J/\psi K^*$ (6.5%) and $B_d \to J/\psi K\pi$ (4.5%). Enters signal B_s-mass region due to different mass hypothesis on the hadronic tracks.



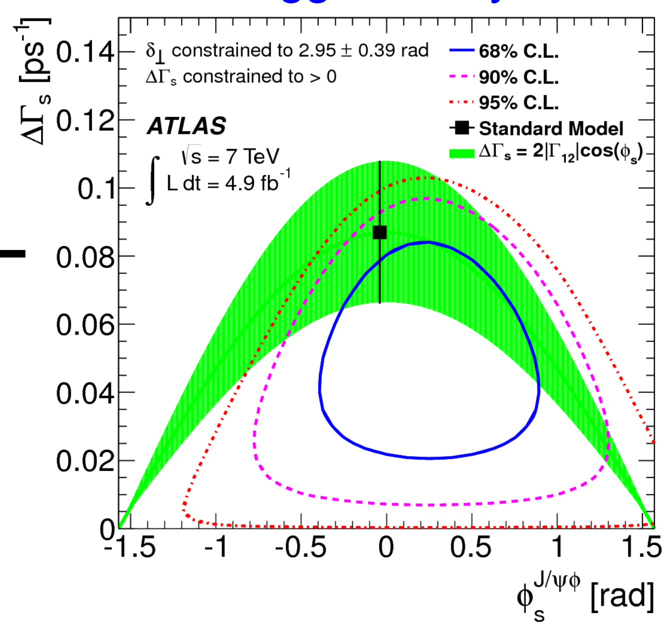
Results: Measurement of $\Delta\Gamma_s$ and ϕ_s

- Measurement still statistically dominated (2012 analysis in progress)
- Uncertainty due to initial B-charge flavour tagging improved by 40%
- Largest systematics from uncorrelated background description (to be improved in 2012 analysis)

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



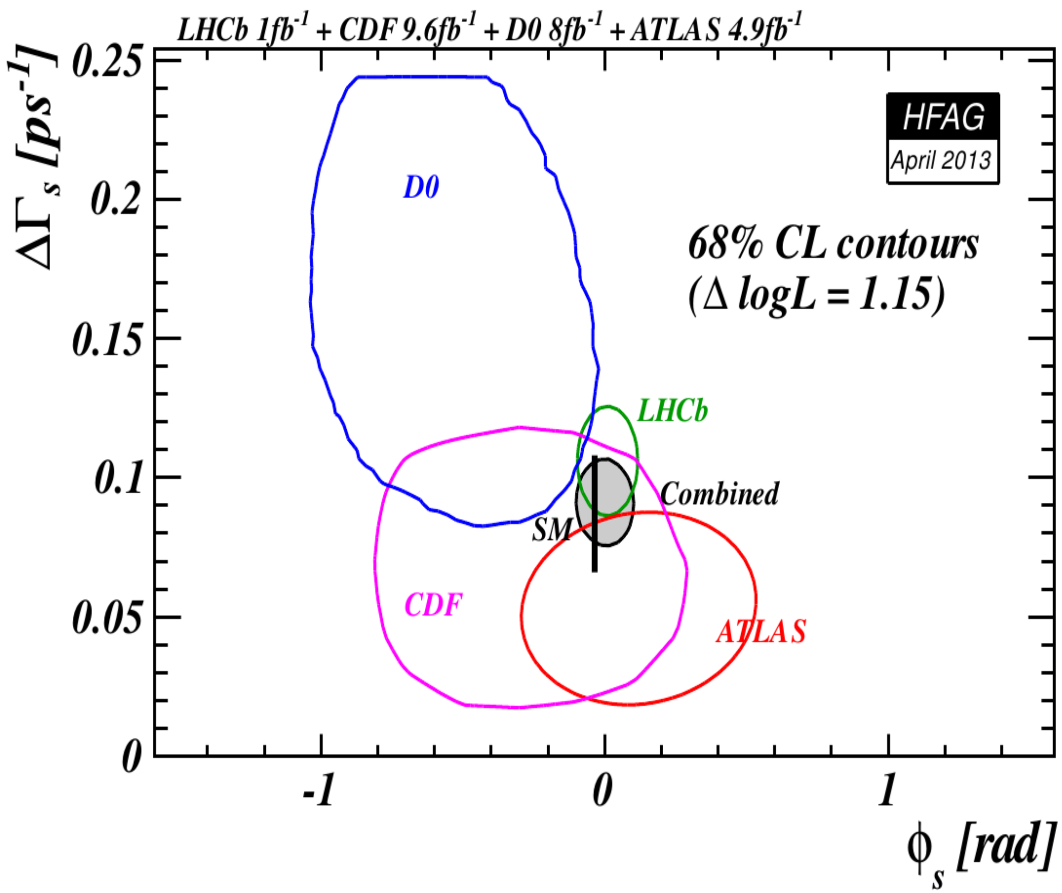
untagged analysis



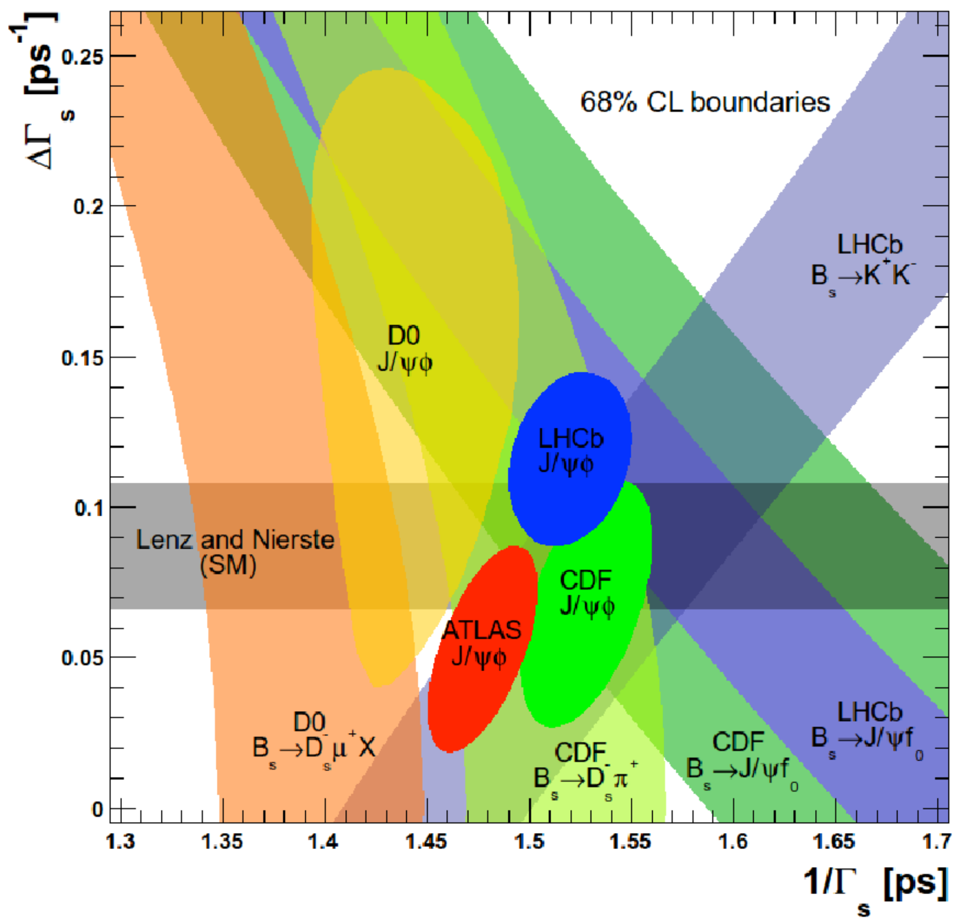
$B_s \rightarrow J/\psi\phi$ Results Among Experiments

- ATLAS can provide similar precision in $\Delta\Gamma_s$ measurement as LHCb; ϕ_s precision is connected with lifetime resolution which LHCb has >2x better

early 2013 status



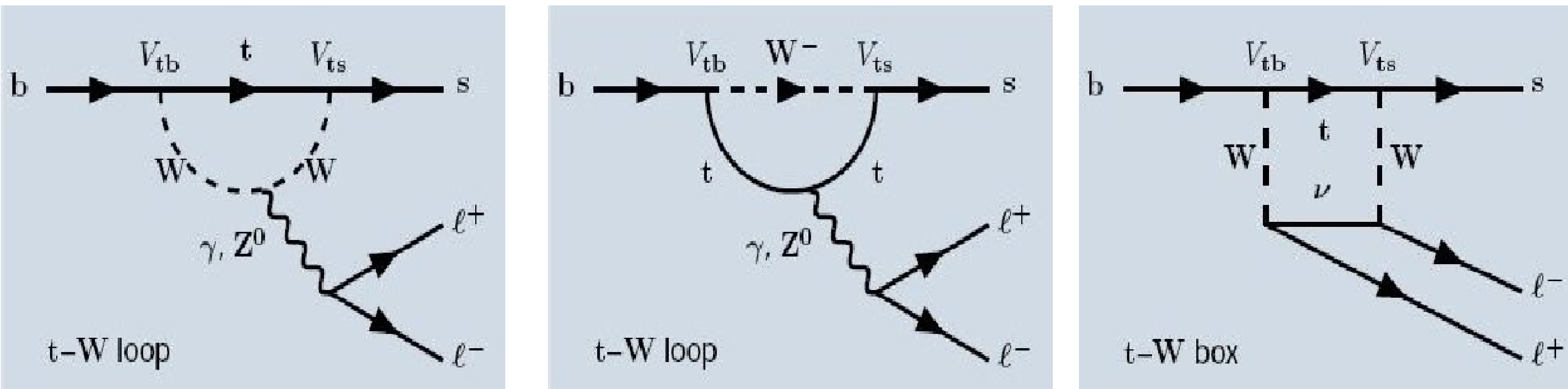
2012 status



Angular analysis of semileptonic rare decay $B_d \rightarrow K^{*0}\mu\mu$ decay (extraction of A_{FB} and F_L)

Angular Analysis of $B_d \rightarrow K^{*0}\mu\mu$ Decay

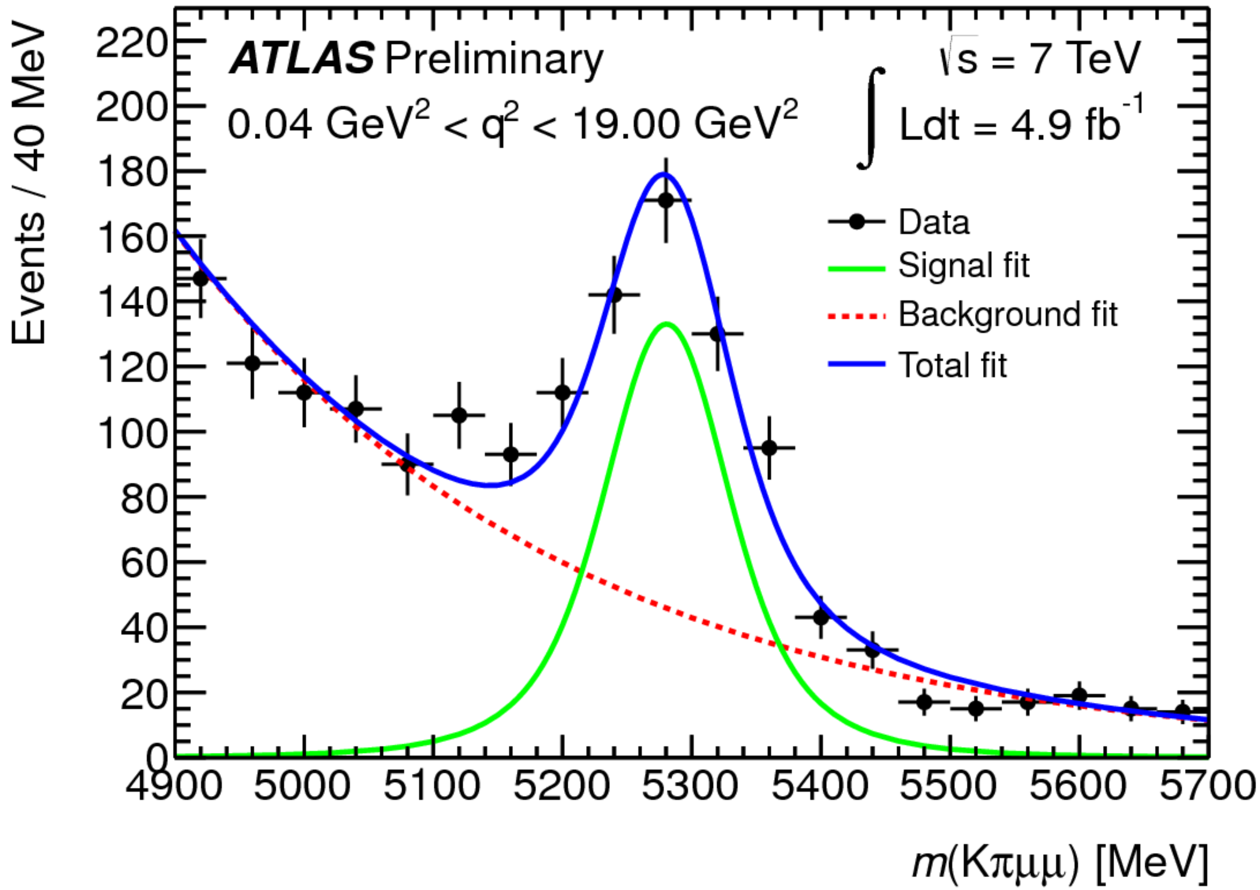
- $b \rightarrow s\mu\mu$ FCNC transitions in SM do not occur at tree level, but only with loops
  - small branching ratio ~ 10-6
  - great sensitivity to eventual non-SM particles in the loops



- Measure the differential decay rate – angular distributions at different q^2 areas (square of invariant mass of the muon pair)

$B_d \rightarrow K^{*0}\mu\mu$ Observation

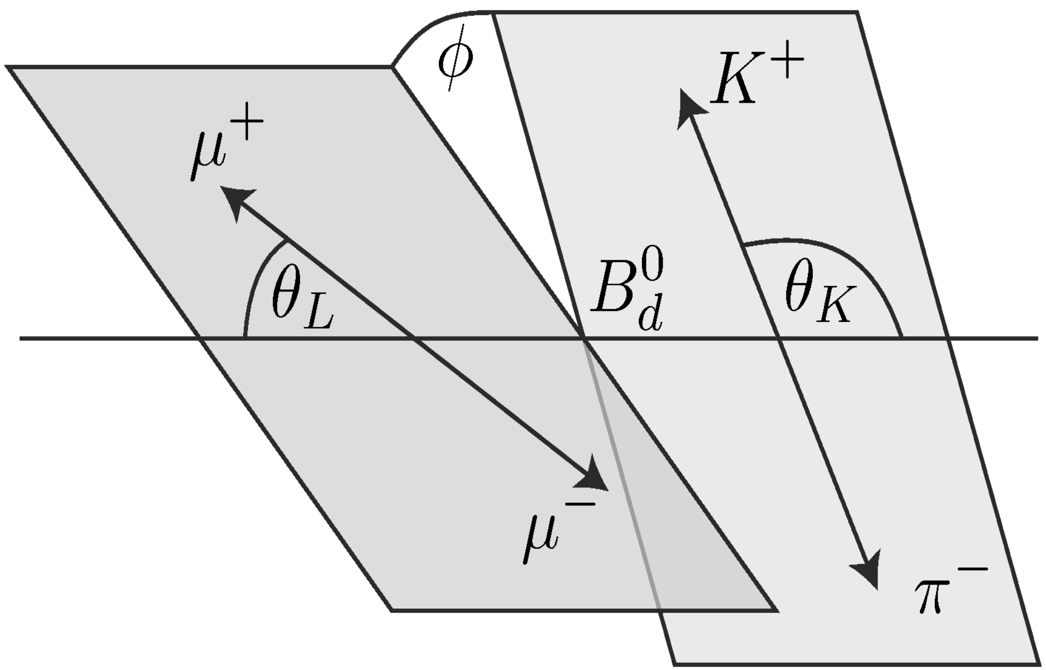
- Events are collected with di-muon and single-muon triggers (di-muon triggers are limited in μμ-invariant mass, single-muon trigger with 2nd muon reconstructed offline helps collecting events)
- Cut based analysis; cuts optimized on MC for full $q^2 = M(\mu\mu)^2$ region
- Full range of di-muon mass, but excluded $c\bar{c}$-resonances



- Observed 446 ± 34 signal events over 1132 ± 43 background (extracted from fit to the mass distributions with per-event gaussian signal and polynomial background)

Angular Analysis of $B_d \to K^{*0}\mu\mu$

- Reconstructed $B_d \to K^*\mu\mu$ decay candidate characterized by 3 angles and di-muon invariant mass (q^2)



- Due to low number of signal events:
  - datasample divided into just six q^2 bins (Belle definition; to be comparable with other experiments)
  - in each q^2 bin simultaneously fitting two 1D angular distributions (integrated over the other two angles):

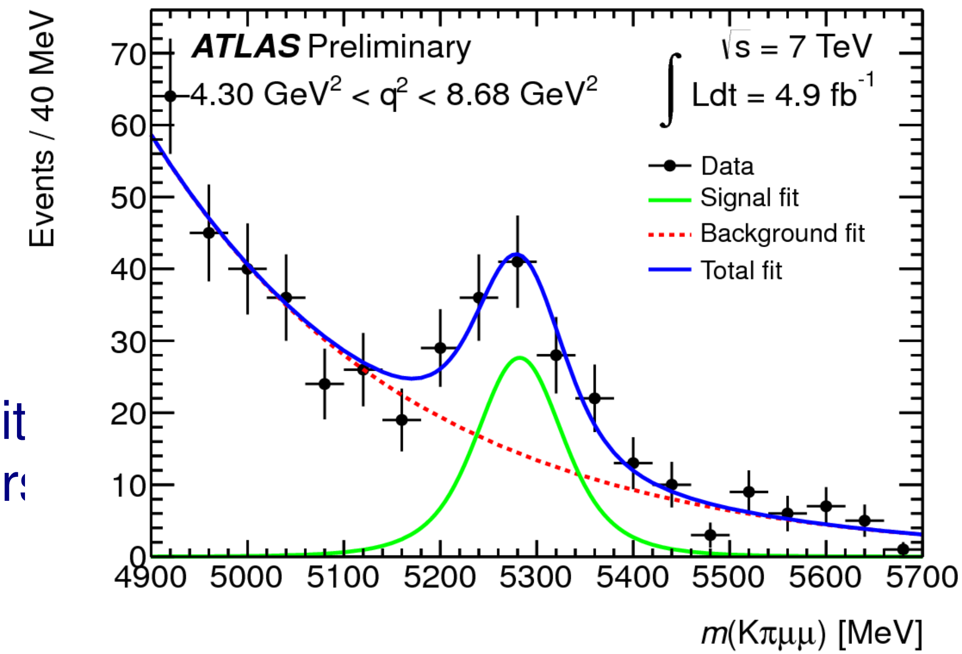
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_L} = \frac{3}{4}F_L(q^2)\left(1-\cos^2\theta_L\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_L\right) + A_{FB}(q^2)\cos\theta_L$$

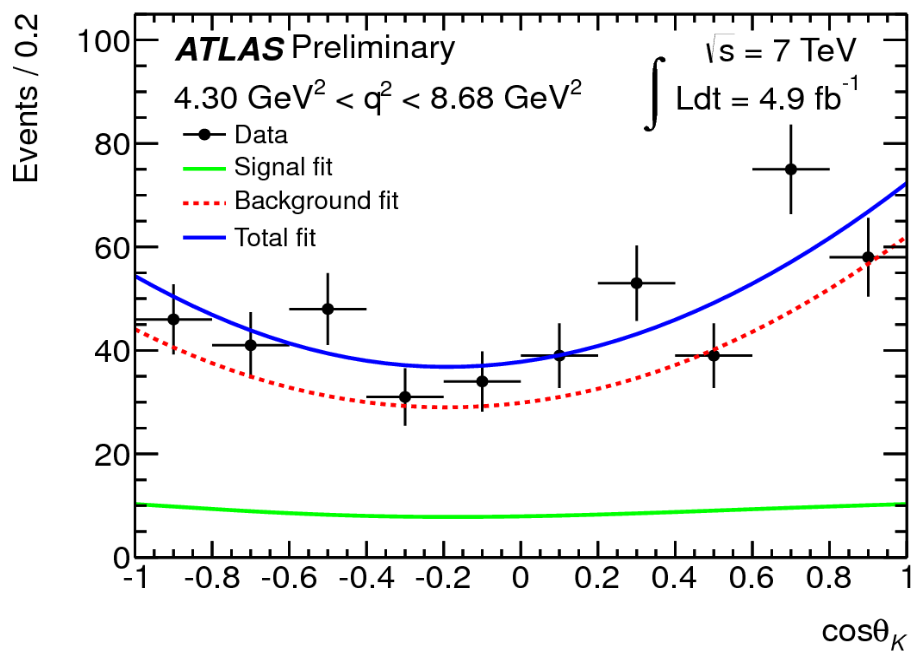
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right)$$

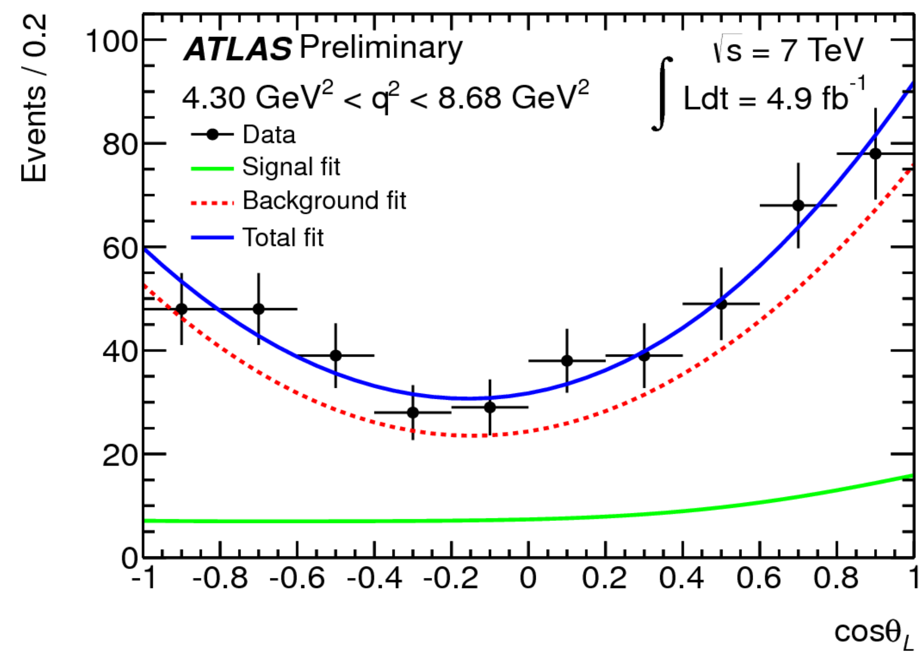
  - **only two angular observables remain:**
    - A_{FB} – forward-backward asymmetry of the μ^+ direction w.r.t. B
    - F_L – K* longitudinal polarization fraction

Measurement of the A_{FB} and F_L

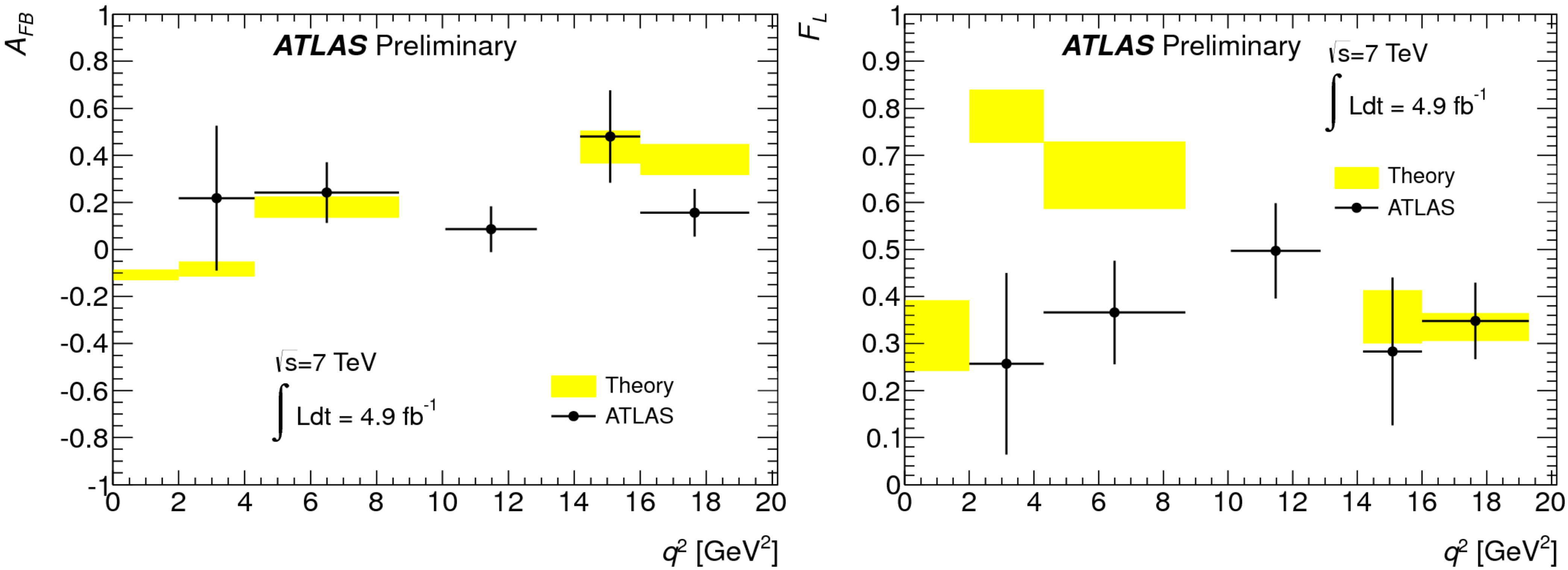
- Running unbinned maximum likelihood fit (in each q^2 region) to B-mass and and the two angular distributions:
  - B-mass distribution to separate signal
  - sequential fit approach → firstly B-mass distribution is fitted, then mass-angular fit is run with the B-mass related parameters fixed







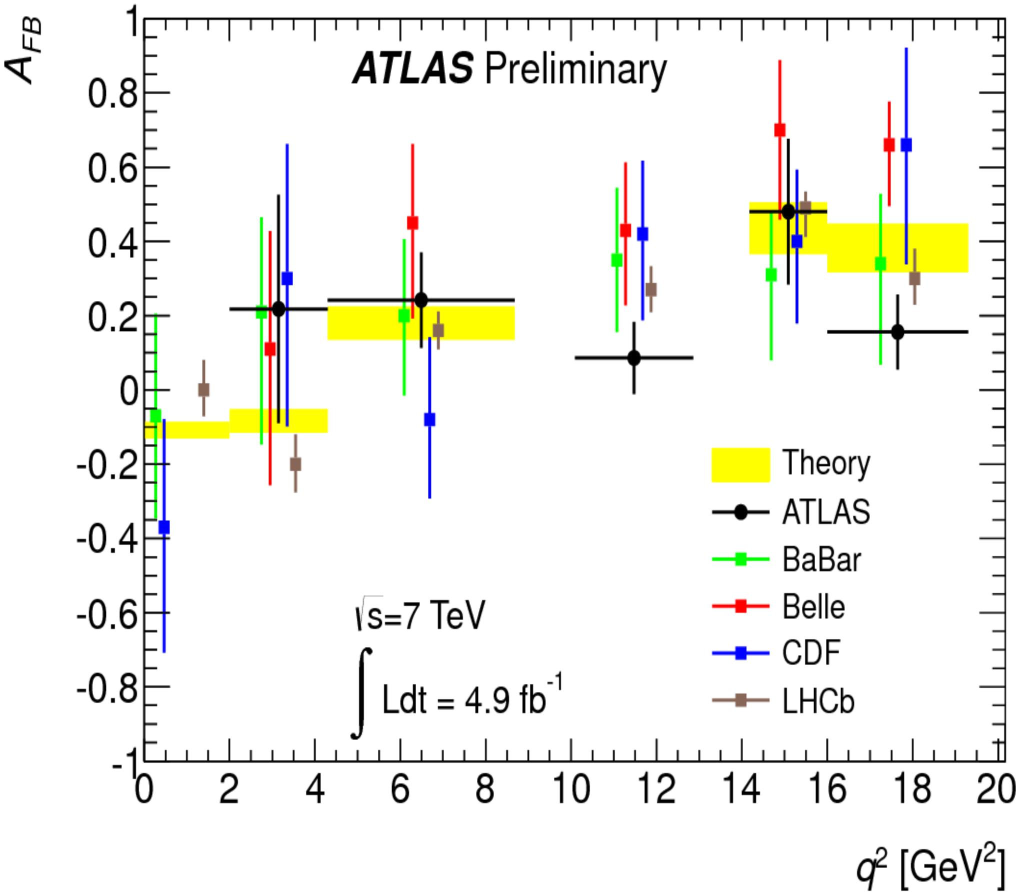
Fits Results

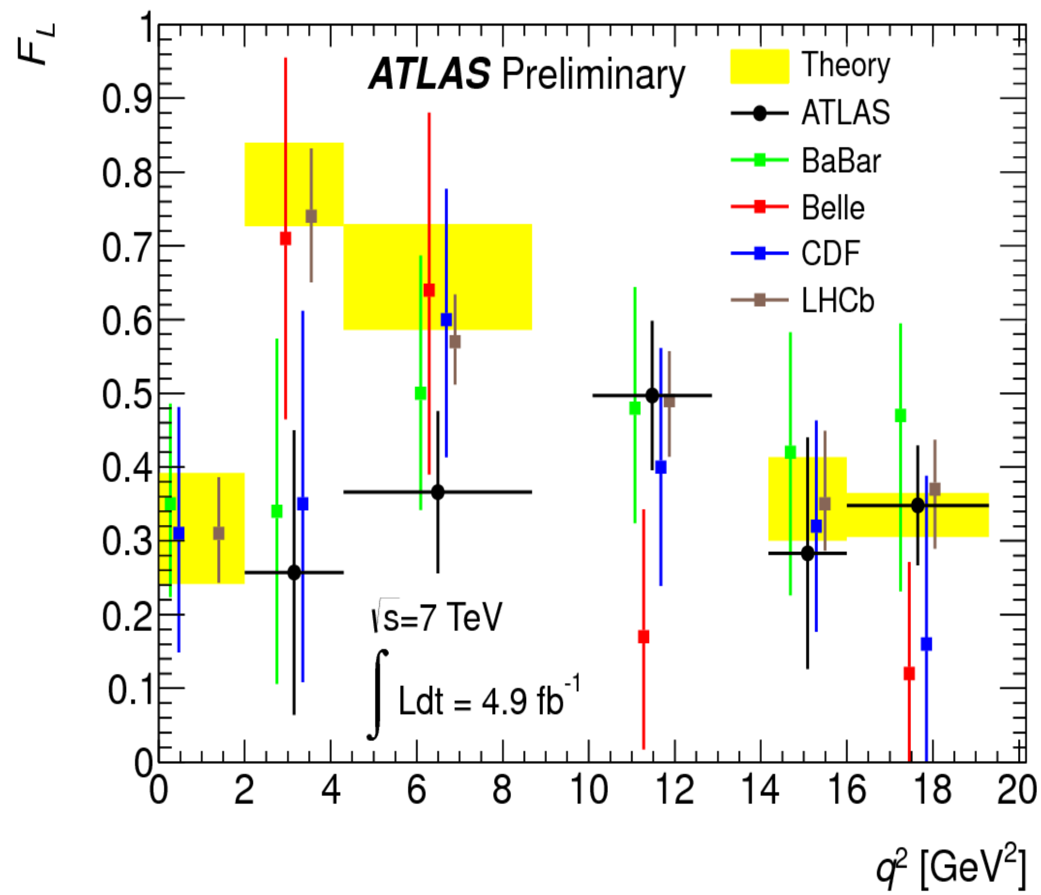


- Uncertainty statistically dominated
- Measurements consistent with SM prediction

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

Comparison to Other Experiments



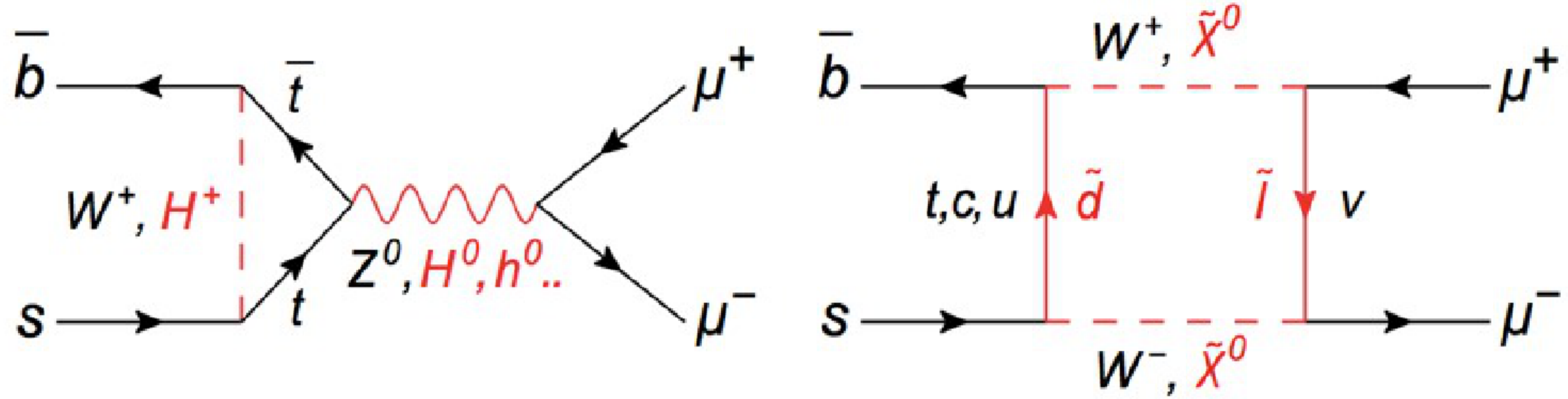


- Can provide competitive precision at high-q^2 region
- Relative yields in low-q^2 bins should improve with 2012 data (better trigger for these decays)
- Full angular analysis planned with 2012 data

Measurement of branching ratio of very rare decay $B_s \rightarrow \mu\mu$

$B_s \rightarrow \mu\mu$ Branching Ratio Measurement

- $B_s \rightarrow \mu\mu$: Flavor Changing Neutral Current (FCNC)
  - strongly suppressed in the SM, BR(theo) = $(3.5 \pm 0.2) \times 10^{-9}$
  - can be enhanced by new physics



- First measurement of the BR by LHCb is:
  $BR(B_s \rightarrow \mu\mu) = (3.2\ ^{+1.5}_{-1.2}) \times 10^{-9}$
  Phys. Rev. Lett. **110**, 021801 (2013), LHCb-TALK-2012-306

- Sufficient precise measurement of the BR can allow to claim the new physics
  => combination of ATLAS, CMS and LHCb

Analysis Outline

- Analysis relative to reference channel B+ → J/ψ(μμ)K+

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

- Analysis of full 2011 dataset (latest update)
- Blind signal region in the whole datasample (although 1/2 was already analyzed in previous paper)
- Use MC for continuum background modeling
- J/ψ polarization correction applied to MC of the reference channel
- Signal extraction via event count in the signal region
- Estimate of expected background – use 50% of the sidebands
- Cuts optimization on the other 50%

Background Modeling

- 14 discriminating variables explored to distinguish signal from continuum backround

L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x} \cdot \vec{p}^B)/\lvert\vec{p}_T^B\rvert$	1
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}_T^B\rvert$ to the sum of $\lvert\vec{p}_T^B\rvert$ and the transverse momenta of all tracks with $p_T > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products	2
$\lvert\alpha_{2D}\rvert$	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^B$	3
p_L^{min}	Minimum momentum of the two muon candidates along the B direction	4
p_T^B	B transverse momentum	5
ct significance	Proper decay length $ct = L_{xy} \times m_B/p_T^B$ divided by its uncertainty	6
χ_z^2, χ_{xy}^2	Significance of the separation between production (PV) and decay vertex (SV) $\Delta\vec{x}^T \cdot \left(\sigma^2_{\Delta\vec{x}}\right)^{-1} \cdot \Delta\vec{x}$, in z and (x, y), respectively	7, 13
$\lvert D_{xy}\rvert^{min}, \lvert D_z\rvert^{min}$	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, 11
ΔR	Angle $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between $\Delta\vec{x}$ and $\vec{p}^B$	9
$\lvert d_0\rvert^{max}, \lvert d_0\rvert^{min}$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex	10, 12

- Peaking backrounds (fake rates from p and K) estimated from MC + latest branching ratios → 0.3 ev contribution in signal region

MC Reweighting

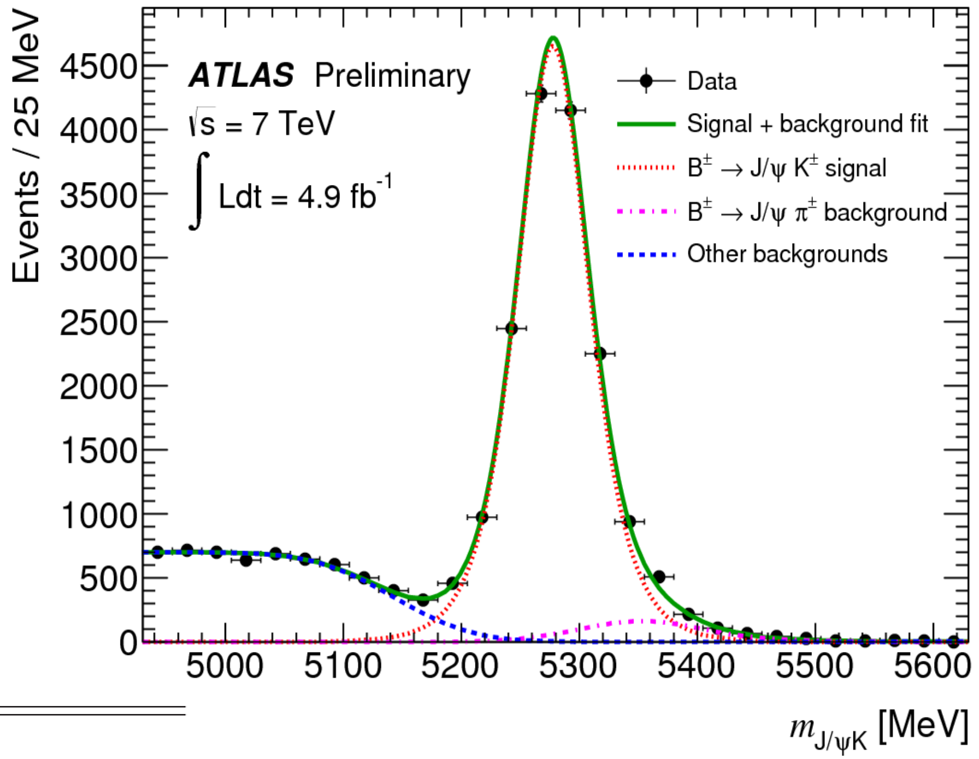
- All distribution used in the cuts are confronted between data and MC and eventually reweighted
  - for signal the reference channel is used for comparisons
  - for continuum background the data sidebands and inclusive MC are compared
- Correction for J/ψ polariztion in the reference channel
- Correction for cut of at low-p_T events during MC production
- Reweight B-p_T and pseudorapidity distribution to match data
  - extract weights from half of $B+ \rightarrow J/\psi K+$ and $Bs \rightarrow J/\psi\phi$ data to be applied to MC
  - to be used in the selection training (BDT) and calculation and efficiencies for signal and the reference channel

Final Optimization, Acceptance and Efficiency

- Optimization runs at half of sidebands data and reweighted signal MC
- Optimizing selection and signal region width
- Optimization based on maximization of punzi estimator: (signal MC efficiency, background from sidebands)

$$\mathcal{P} = \frac{\epsilon}{1 + \sqrt{B}}$$

- Same final selection applied to the reference channel:



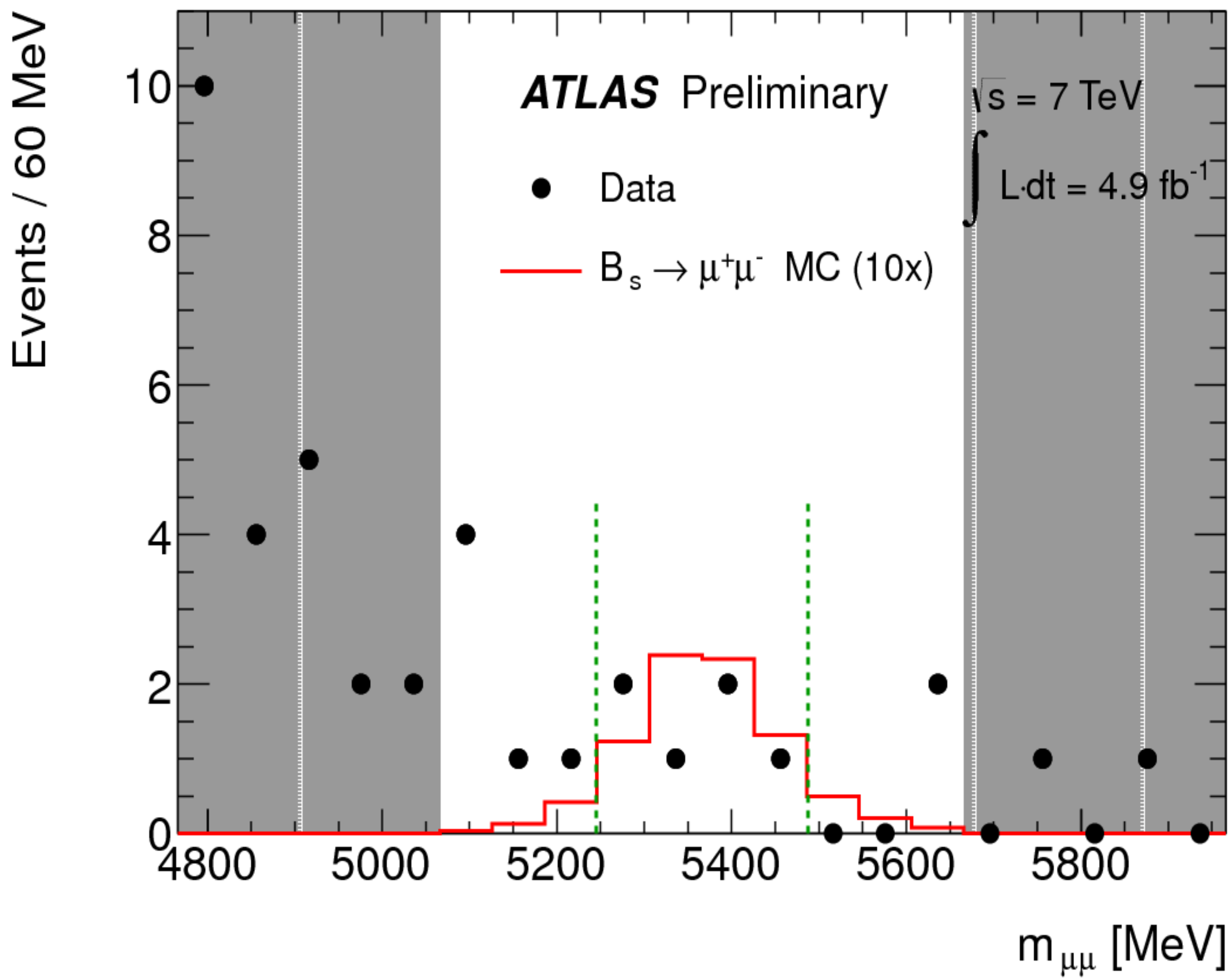
Acceptance and efficiency:

- Ratio between reference and signal channel
- Extracted from the rewerighted MC samples

Channel	$A \times \epsilon$	$R_{A\epsilon}$
B^+	$1.317 \pm 0.008\%\,(stat)$	$0.267 \pm 1.8\%\,(stat) \pm 6.9\%\,(syst)$
B^0_s	$4.929 \pm 0.084\%\,(stat)$	

Opening the Blinded Region

- Extrapolation of the number of background events into the signal region yields 6.75 events
- After unblinding 6 events observed



Extracted Upper Limit on BR($B_s \to \mu\mu$)

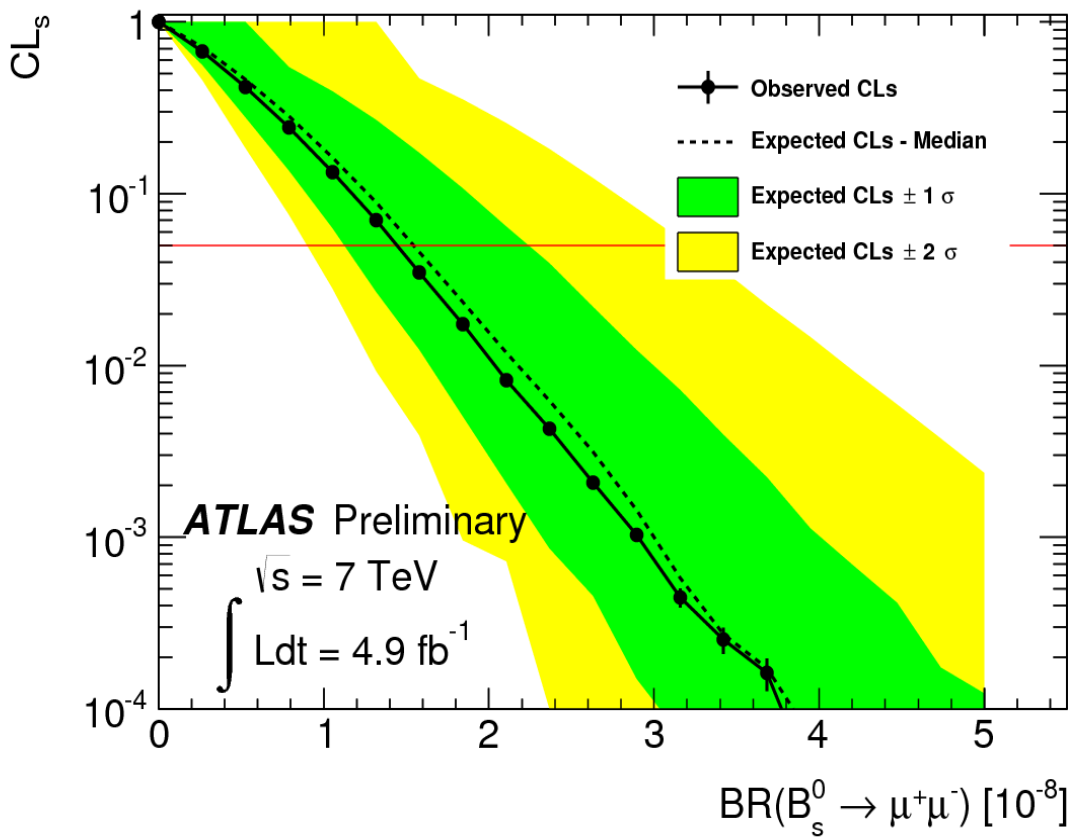
- Use CLs method with profile likelohood ratio:

signal region — sidebands

$$\mathcal{L} = \text{Poisson}(N^{obs}_{SR}|\epsilon\,\mathcal{B} + N_{bkg} + N_{B\to hh})\,\text{Poisson}(N^{obs}_{bkg,SB}|R_{bkg}\,N_{bkg}) \times \text{Gauss}(\epsilon^{obs}|\epsilon,\sigma_\epsilon)\,\text{Gauss}(R^{obs}_{bkg}|R_{bkg},\sigma_{R_{bkg}})$$

1/SES constraint — $R=\Delta_{sb}/\Delta_{sr}$ constraint

with $\varepsilon = ses^{-1}$



upper limit (10^{-8})	at 95% CL	at 90% CL
observed limit	1.5	1.2
expected limit	$1.6^{+0.7}_{-0.4}$	$1.3^{+0.7}_{-0.4}$

(limit from half of 2011 data: 2.2 x 10^{-8} (95% C.L.)

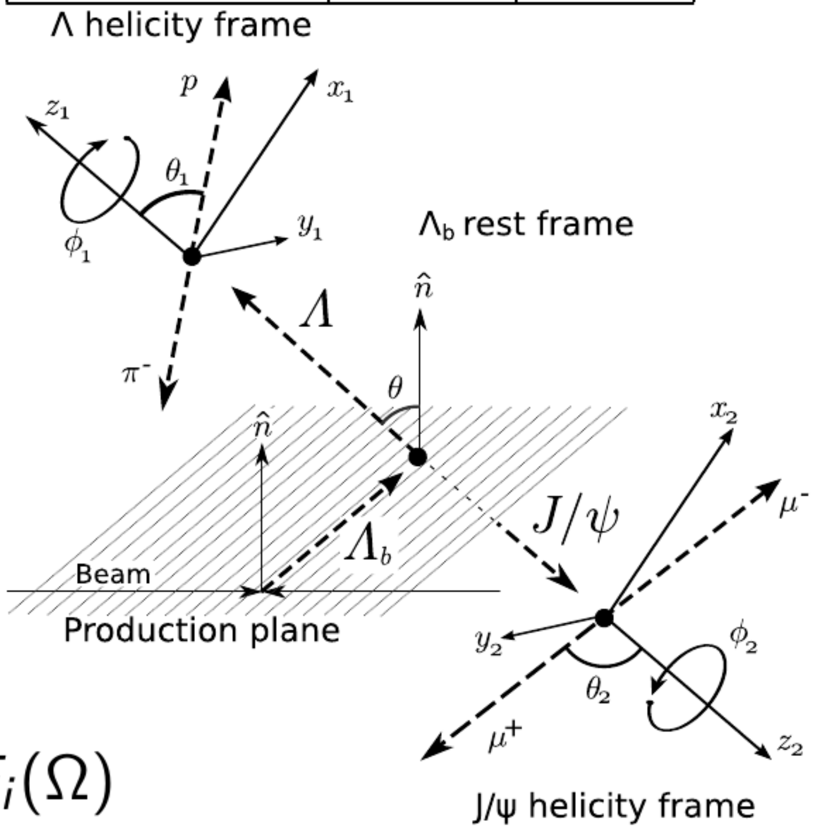
Measurement of parity violating asymmetry parameter α_b and the helicity amplitudes in decay $\Lambda_b \to J/\psi\Lambda$

$\Lambda_b \to \Lambda J/\psi$ - Motivation

- The Λ^0 and J/ψ decay are well studied.
- Little is known about Λ_b^0 decay
- PDF of the decay angle

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

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



- Four possible Helicity combinations

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

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

- The full decay angular PDF

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

Full Decay Angular PDF

- Can be reduced constraining normalization of the helicity amplitudes, arbitrary overall phase and considering ATLAS detector symmetry

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	$-3Re(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \cos\varphi_1$
9	$3Im(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \sin\varphi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \cos(\varphi_1 + 2\varphi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \sin\theta_1\ \sin^2\theta_2\ \sin(\varphi_1 + 2\varphi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \cos\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos\varphi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\ \cos\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin\varphi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\ \sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos(\varphi_1 + \varphi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\ \sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\varphi_1 + \varphi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\ \sin\theta_2\ \cos\theta_2\ \cos\varphi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\ \sin\theta_2\ \cos\theta_2\ \sin\varphi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos(\varphi_1 + \varphi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\varphi_1 + \varphi_2)$

$$\alpha_{\mathrm{b}} = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$

$$k_0 = \frac{|a_+|}{\sqrt{|a_+|^2 + |b_+|^2}}$$

$$k_1 = \frac{|b_-|}{\sqrt{|a_-|^2 + |b_-|^2}}$$

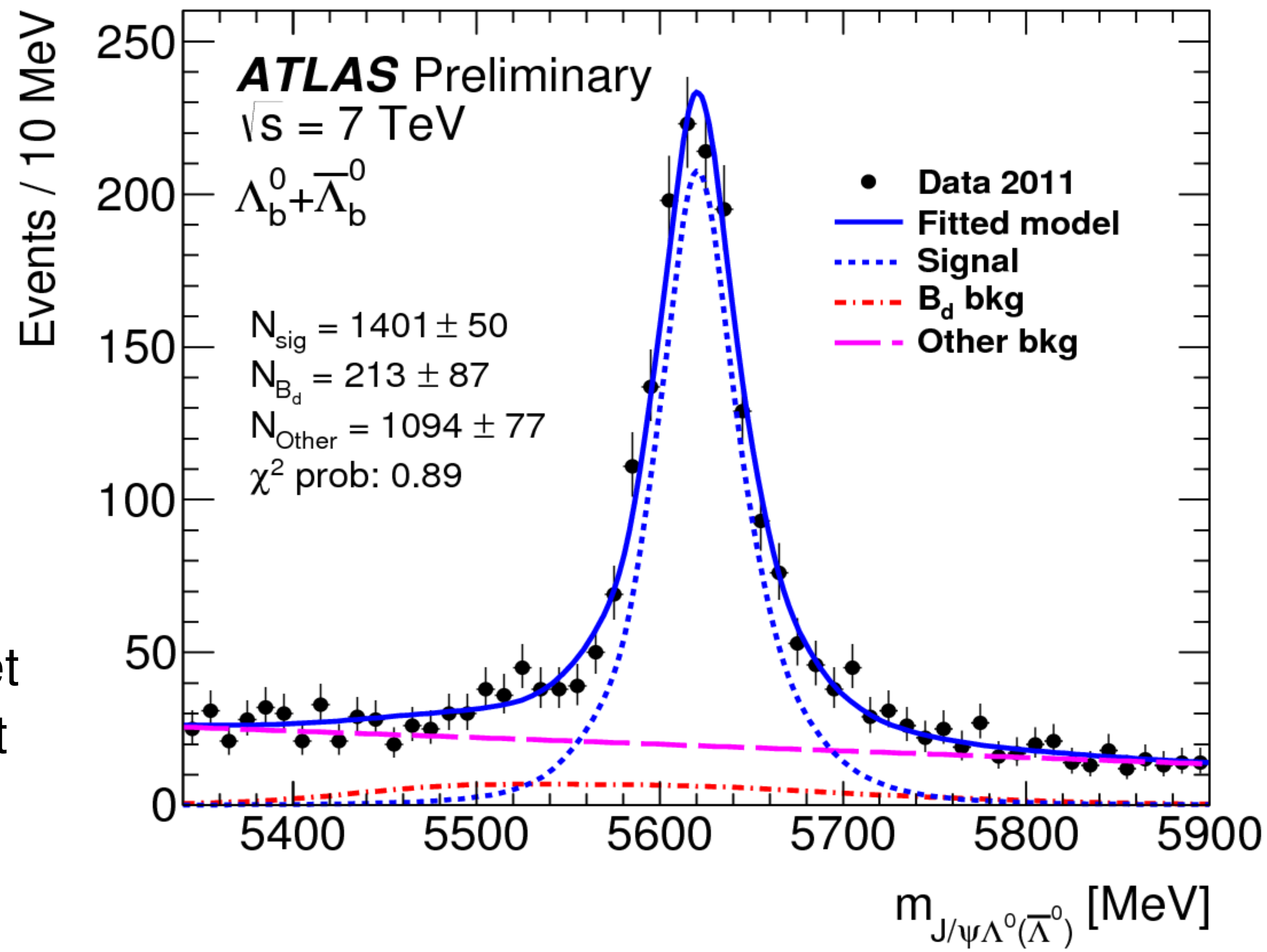
$$\Delta_+ = \rho_+ - \omega_+$$

$$\Delta_- = \rho_- - \omega_-$$

i	f_{1i}	f_{2i}	F_i
0	1	1	1
2	$(k_0^2 + k_1^2 - 1) + \alpha_{\mathrm{b}}(k_0^2 - k_1^2)$	α_Λ	$\cos\theta_1$
4	$\frac{1}{4}[(3k_1^2 - 3k_0^2 - 1) + 3\alpha_{\mathrm{b}}(1 - k_1^2 - k_0^2)]$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
6	$-\frac{1}{4}[(k_0^2 + k_1^2 - 1) + \alpha_{\mathrm{b}}(3 + k_0^2 - k_1^2)]$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\ \cos\theta_1$
18	$\frac{3}{\sqrt{2}}[\frac{1-\alpha_{\mathrm{b}}}{2}\sqrt{k_1^2(1 - k_1^2)}\cos(-\Delta_-) - \frac{1+\alpha_{\mathrm{b}}}{2}\sqrt{k_0^2(1 - k_0^2)}\cos(\Delta_+)]$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \cos(\varphi_1 + \varphi_2)$
19	$-\frac{3}{\sqrt{2}}[\frac{1-\alpha_{\mathrm{b}}}{2}\sqrt{k_1^2(1 - k_1^2)}\sin(-\Delta_-) - \frac{1+\alpha_{\mathrm{b}}}{2}\sqrt{k_0^2(1 - k_0^2)}\sin(\Delta_+)]$	α_Λ	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\varphi_1 + \varphi_2)$

Selected Events

- Combination of di-muon and single muon triggers is used (to collect as large as possible signal yield)
- $\Lambda_b \rightarrow J/\psi(\mu\mu)\ \Lambda(p\pi)$ decay is fully reconstructed with appropriate vertexing constraints
- Extraction of signal events considers among combinatorial background also peaking background from $B_d \rightarrow J/\psi(\mu\mu)\ K^0_s(\pi\pi)$ decays
- Cross-checked that dataset of Λ_b and $\overline{\Lambda}_b$ are consistent



Fit and Results

- Least square fit:
  - calculate average <Fi> moments (consider detector acceptance and fraction of $B_d \to J/\psi(\mu\mu)\ K^0_s(\pi\pi)$ bacground, perform sidebands substraction for the combinatorial backround)

$$\chi^2 = \sum_{i=1}^{5}\sum_{i=1}^{5}(\langle F_i\rangle^{\text{expected}} - \langle F_i\rangle)V_{ij}^{-1}(\langle F_j\rangle^{\text{expected}} - \langle F_j\rangle)$$

- Fit results:

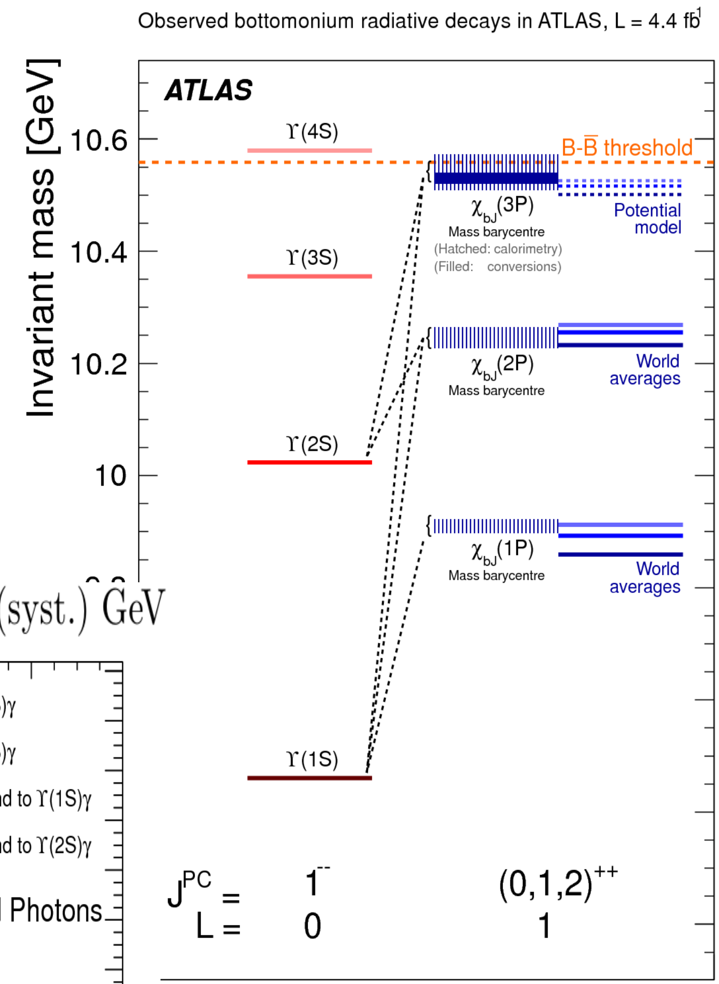
$$\alpha_b = 0.28 \pm 0.16 \pm 0.06$$
$$|a_+| = 0.17^{+0.12}_{-0.17} \pm 0.06$$
$$|a_-| = 0.59^{+0.06}_{-0.07} \pm 0.04$$
$$|b_+| = 0.79^{+0.04}_{-0.05} \pm 0.02$$
$$|b_-| = 0.08^{+0.13}_{-0.08} \pm 0.05.$$

- consistent at ~1σ with LHCb measurement
- deviates by 2.5σ resp. 2.9σ from theory predictions by pQCD and HQET
- 2012 data analysis ongoing

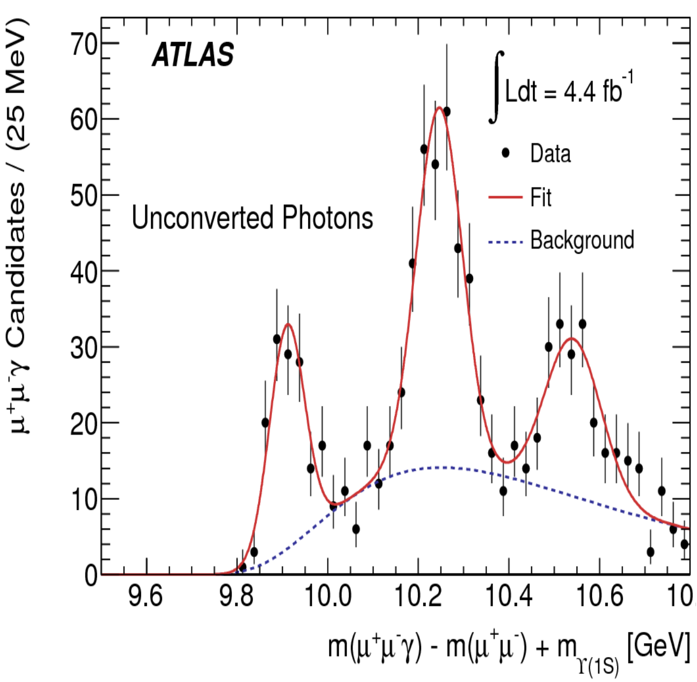
Observations of rare/new B-hadrons (B_c, χ_b)

First Observation of $\chi_b(3P)$ State

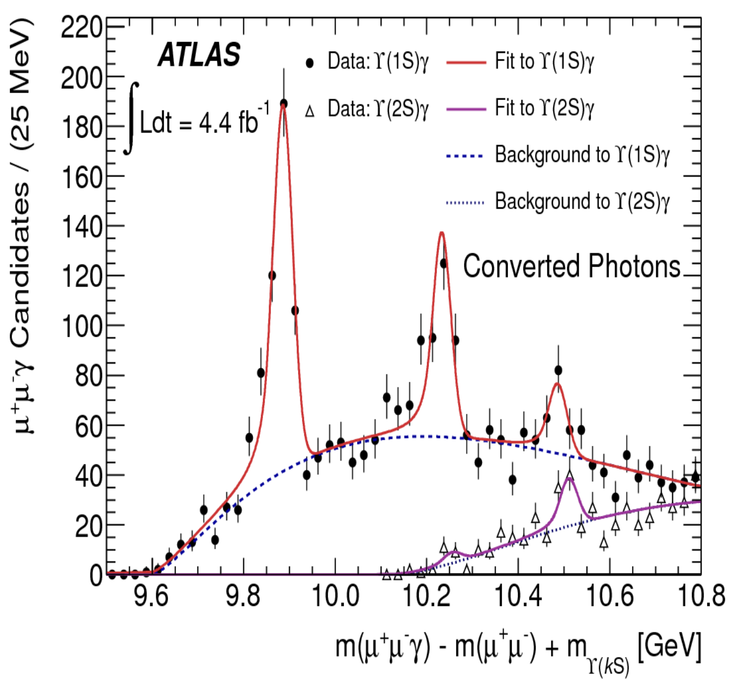
- Understanding underlying structure in recently observed quarkonium-like states (can be 4-quark, cc-gluon etc. states)
- New peak observation interpreted as:
  $\chi_b(3P) \rightarrow \Upsilon(1S) + \gamma$, $\chi_b(3P) \rightarrow \Upsilon(2S) + \gamma$
- γ reconstructed from both conversions and EM calorimeter (higher p_T => $\Upsilon(2S) + \gamma$ only)



$$\overline{m}_3 = 10.541 \pm 0.011\ (\text{stat.}) \pm 0.030\ (\text{syst.})\ \text{GeV}$$



$$\overline{m}_3 = 10.530 \pm 0.005\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{GeV}$$

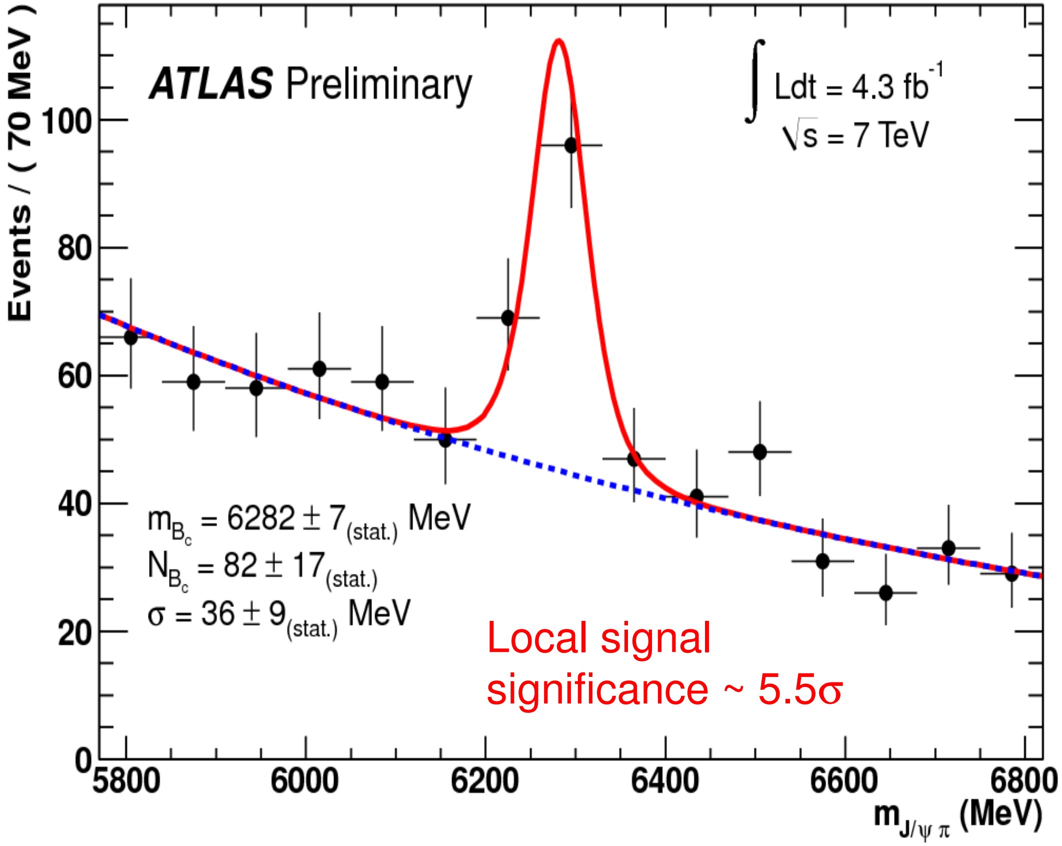


$\chi_b(3P)$ also expected below $B\overline{B}$ threshold, predicted CoG mass 10,525 GeV

B_c^+ Observation

- Two different heavy flavours → study heavy quark production dynamics
- B_c Lifetime measurement → test B_c decay model (**b** and **c** quark decays compete)
- First observed by CDF in 1998, lifetime measured by CDF (2006) and DØ (2009) in semileptonic decay channel including neutrino; LHCb measured relative x-section to B^+

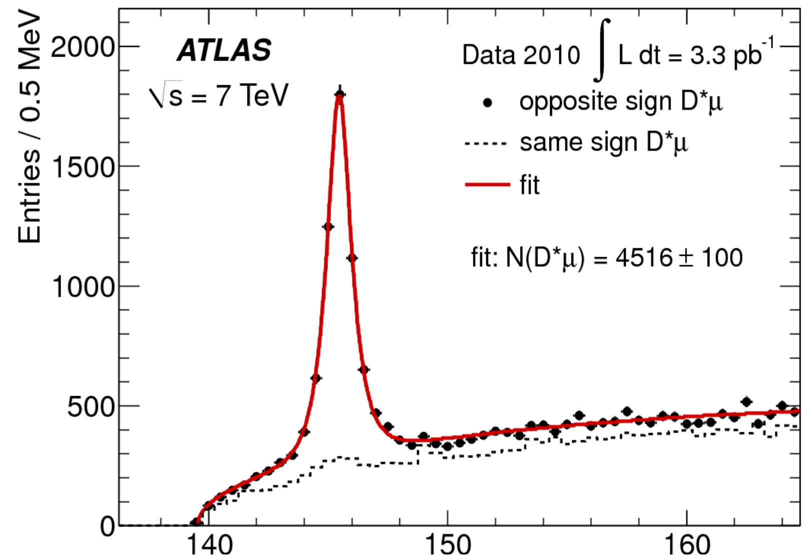
- ATLAS observation in $B_c^+ \to J/\psi\pi^+$ decay channel
- Di-muon J/ψ decay (trigger)
- Main selection:
  - B_c^+ vertex quality,
  - π track d_0 significance

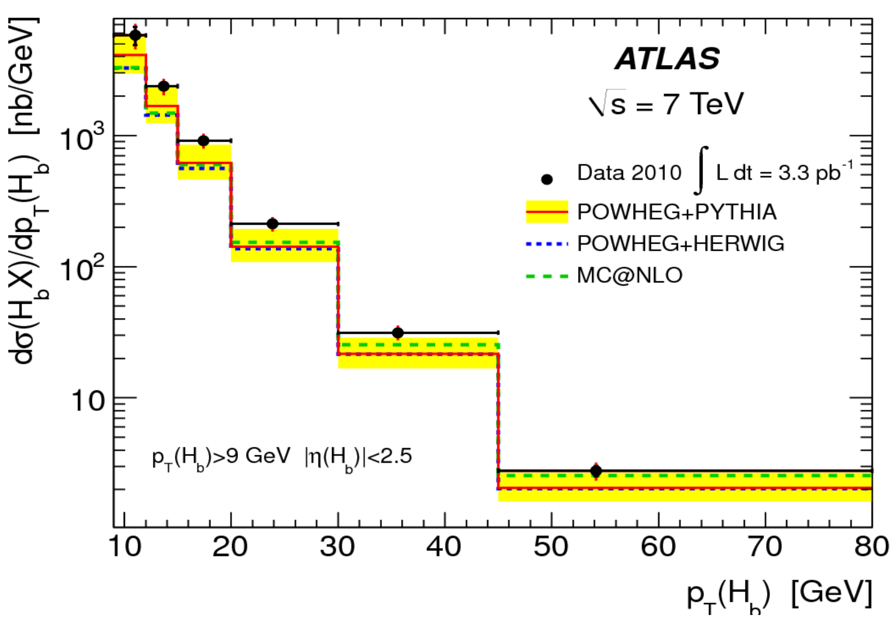


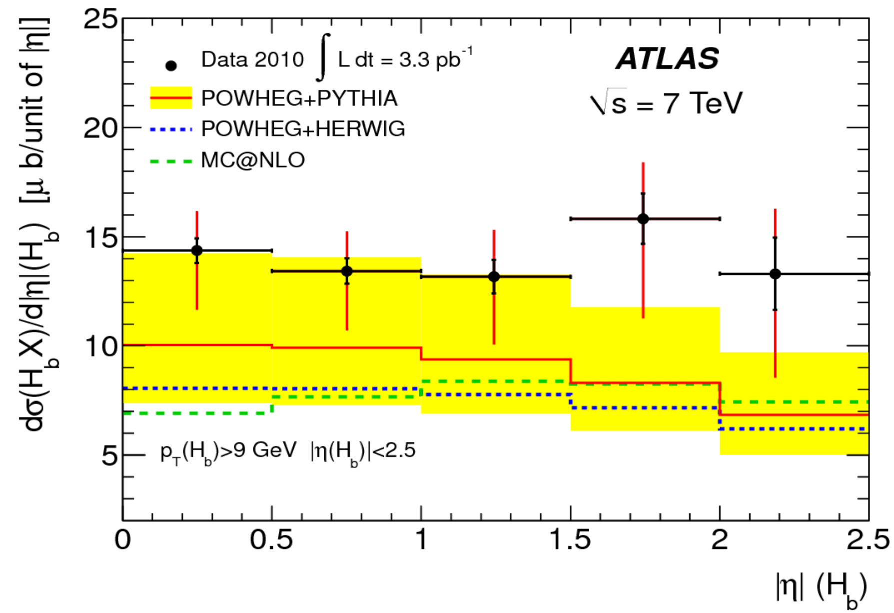
Production cross-section measurements

B-hadron Production in D*μX

- Aim: differential x-section for open beauty production in pp collisions
- Decay mode: $B \rightarrow D^{*\pm}\mu X$; $D^{*\pm} \rightarrow D^0\pi^\pm$; $D^0 \rightarrow \pi K$
  - the muon act as a trigger
  - the decay is fully reconstructable in ATLAS detector
- Unfolding procedure to obtain differential x-section as a function of B-hadron η/p_T; and detector acceptance to define the fiducial volume in the B-hadron η/p_T space







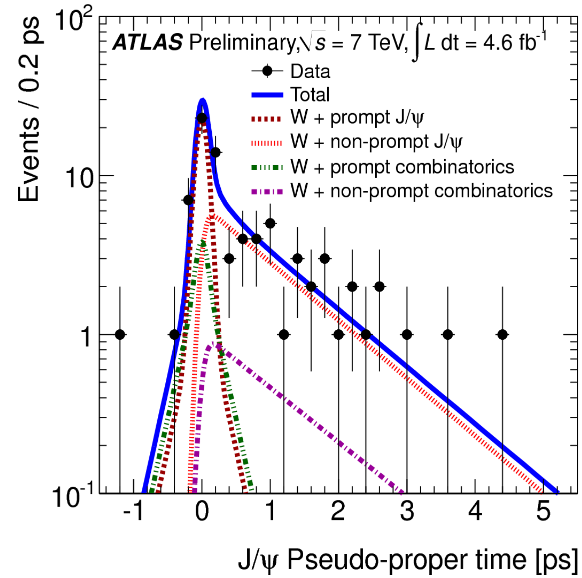
$$\sigma(pp \rightarrow H_b X) = 32.7 \pm 0.8\ (\text{stat.}) \pm 3.1\ (\text{syst.})^{+2.1}_{-5.6}(\alpha) \pm 2.3(\mathscr{B}) \pm 1.1(\mathscr{L})\ \mu b$$

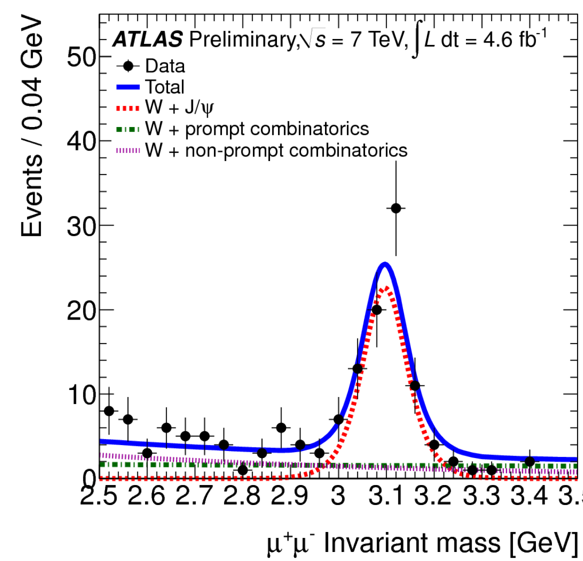
Associated Production of Prompt J/ψ and W±

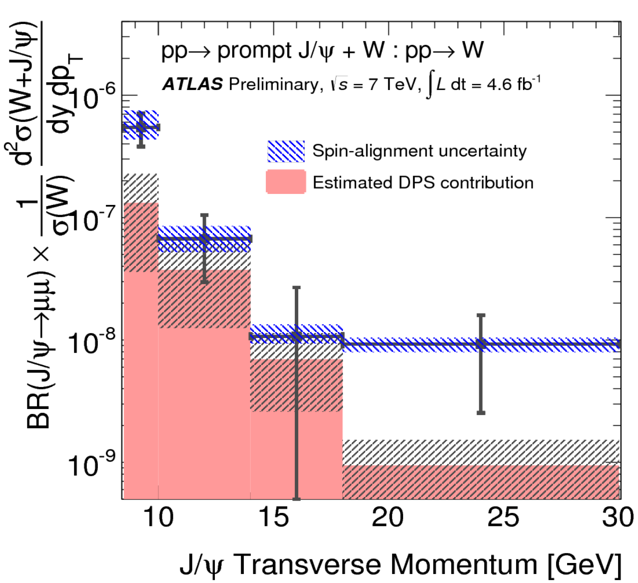
- Probes quarkonium production mechanis; Sensitive to multiple parton interactions
- Final state: W(→μν) + J/ψ (→ μμ)
- Unbinned maximum likelihood fit to get prompt J/ψ yield;
  W selection pratically backround-free; → ~29 candidates
- Assumption for probability of W and J/ψ originate from different parton interaction in the same pp collision (DPS):

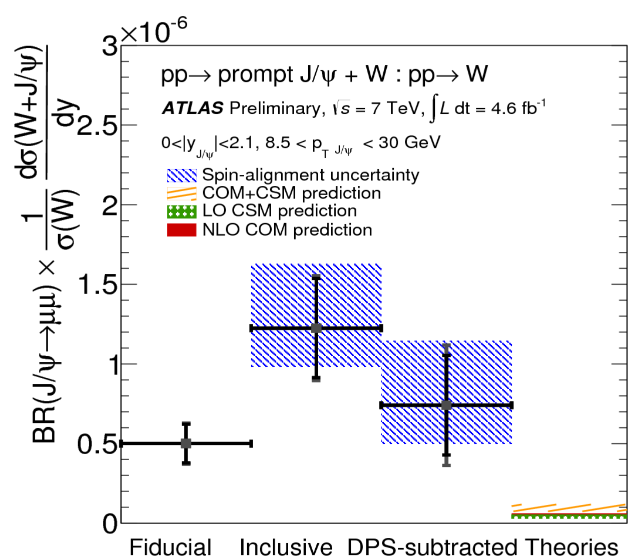
$$d\sigma_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{Eff}}$$

- Ratio to W+J/ψ to W production order of magnitude above theory prediction









Other Production X-Section Measurements

- B^+ production x-section in $B^+ \rightarrow J/\psi K^+$ channel
  - large theory uncertainties, measurement in good agreement within the uncernt.

Quarkonia production:

- test mechanism of production at low-energy scale for heavy quarks in bound state
- Inclusive / prompt and non-promp J/ψ production
  - range: $p_T(J/\psi)$ (1-70) GeV, $|y| < 2.4$
- $\psi(2S) \rightarrow J/\psi(\mu\mu)\pi\pi$ production
  - range: $p_T(\psi)$ (10-100) GeV, $|y| < 2.0$
- Upsilon fiducial x-section measurement
  - range: $p_T(\Upsilon) < 70$ GeV, $|y| < 2.25$
  - observed saturation of the production of higher Υ states relative to $\Upsilon(1S)$ at ~ p_T = (30-40) GeV
- $\chi_{c1,2} \rightarrow J/\psi(\mu\mu)\gamma$ production; branching fraction of $B^+ \rightarrow \chi_{c1,2}K^+$
  - range: $p_T(J/\psi)$ (10-30) GeV, $|y| < 0.75$

Summary

- ATLAS can do B-physics measurements in some areas competitive with (or at least providing cross-checks to) dedicated experiments
  - rare decays $B \to \mu\mu$, $b \to s\mu\mu$,
  - CPV in $B_s \to J/\psi\phi$, Λ_b polarization
  - rare/excited B-hadrons (decays) observations/searches
- Cross-section measurements at complement other experiments in measuring b-production at >7 TeV in different p_T and rapidity regions
- Currently mostly 2011 dataset analyzed, more to come soon with 2012 data (~4× larger data sample)
- ATLAS B-physics plans to continue also in next LHC phases and related detector updates; up to now no studies shown limits from larger pile-up

Backup

ATLAS B-Physics Results

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

Publications

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

Short Title	Int L	Journal	Preprint	Plots
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
$\Upsilon(1S)$ Fiducial Production Cross-Section	1.1 pb^{-1}	Phys. Lett. B703 (2011) 428-446	arXiv:1106.5325	Link
Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$	4.4 fb^{-1}	Phys. Rev. Lett. 108 (2012) 152001	arXiv:1112.5154	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
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
Measurement of the Λ_b lifetime and mass	4.9 fb^{-1}	Phys. Rev. D 87 (2013) 032002	arXiv:1207.2284	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
Inclusive $\Upsilon(nS)$ differential cross sections and ratios	1.8 fb^{-1}	Phys. Rev. D 87 (2013) 052004	arXiv:1211.7255	Link
NEW Production cross section of B^+ at $\sqrt{s}$ = 7TeV	2.4 fb^{-1}	To appear on JHEP	arXiv:1307.0126	Link
Analyses performed within other ATLAS Physics Groups:				
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
Inclusive production of electrons and muons (b/c cross section)	35 pb^{-1}	Phys. Lett. B 707 (2012) 438-458	arXiv:1109.0525	Link
$D^{*+/-}$ production in jets	0.3 pb^{-1}	Phys. Rev. D 85, 052005 (2012)	arXiv:1112.4432	Link

ATLAS B-Physics Results

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

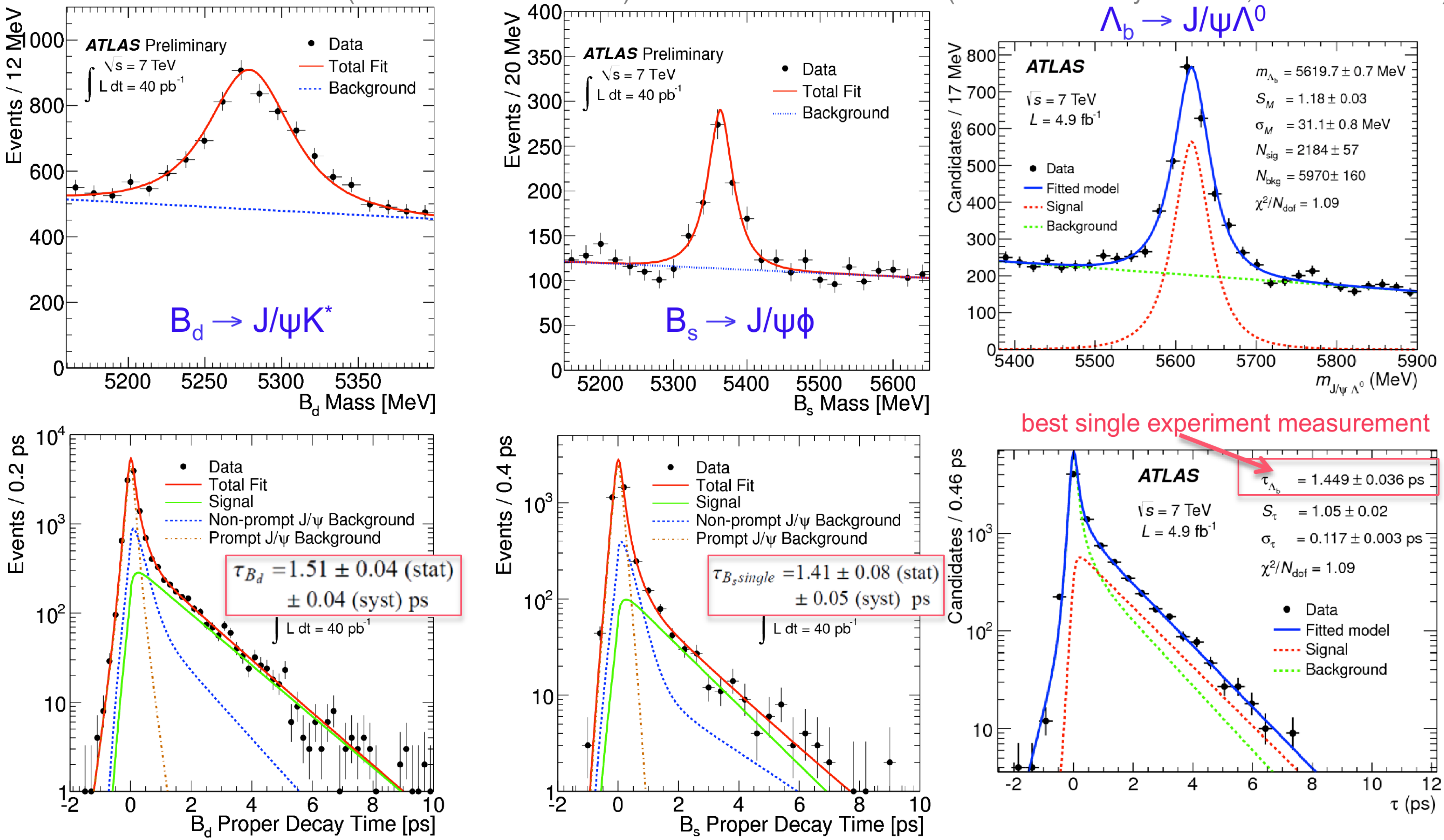
CONF notes

Notes containing preliminary or unpublished results based on data, the contents of which may be used in conference talks, are listed below.

Short Title	Int L	Ref./link to ATLAS public pages
D(*) mesons reconstruction in pp collisions at $\sqrt{s}$ = 7TeV	0.37 nb^{-1}	ATLAS-CONF-2010-034
Observation of the $J/\psi \to \mu\mu$ resonance	6.4 nb^{-1}	ATLAS-CONF-2010-045
(Preliminary) Measurement of the $J/\psi \to \mu\mu$ differential cross section and fraction from B decays	19.5 nb^{-1}	ATLAS-CONF-2010-062
Observation of the B± meson in the decay $B\pm \to J/\psi(\mu+\mu-) K\pm$	3.4 pb^{-1}	ATLAS-CONF-2010-098
Measurement of D* and D+ meson production cross sections at $\sqrt{s}$ = 7TeV	1.1 nb^{-1}	ATLAS-CONF-2011-017
Observation of the B^o_d and B^o_s mesons in the decays $B^o_d \to J/\psi K^{*o}$ and $B^o_s \to J/\psi \phi$	40 pb^{-1}	ATLAS-CONF-2011-050
Measurement of the B^o_d and B^o_s lifetimes in the decays $B^o_d \to J/\psi K^{*o}$ and $B^o_s \to J/\psi \phi$	40 pb^{-1}	ATLAS-CONF-2011-092
Observation of the decay $B^o_d \to J/\psi K_S$	40 pb^{-1}	ATLAS-CONF-2011-105
Observation of χ_c states through $J/\psi \gamma$ transitions	40 pb^{-1}	ATLAS-CONF-2011-136
Observation of the decay $\Lambda_b \to J/\psi(\mu\mu) \Lambda$	1.2 fb^{-1}	ATLAS-CONF-2011-124
Measurement of the average B lifetime in inclusive $B \to J/\psi X \to \mu+\mu- X$ decays	35 pb^{-1}	ATLAS-CONF-2011-145
Observation of the $B^{\pm}_c$ meson in the decay $B^{\pm}_c \to J/\psi(\mu^+\mu^-) \pi^{\pm}$	4.3 fb^{-1}	ATLAS-CONF-2012-028
Combined LHC limit to the decay $B^o_s \to \mu\mu$ (ATLAS-CMS-LHCb note)	2.4-5-1.0 fb^{-1}	ATLAS-CONF-2012-061
Angular analysis of $B^0_d \to K^{*0}\mu^+\mu^-$	4.9 fb^{-1}	ATLAS-CONF-2013-038
φ_s and $\Delta\Gamma_s$ from flavor-tagged time-dependent angular analysis of $B^o_s \to J/\psi \phi$	4.9 fb^{-1}	ATLAS-CONF-2013-039
NEW Associated production of prompt J/ψ mesons and W boson in at $\sqrt{s}$ = 7TeV	4.6 fb^{-1}	ATLAS-CONF-2013-042
NEW Measurement of the parity violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi \Lambda^0$	4.6 fb^{-1}	ATLAS-CONF-2013-071
NEW Limit on $B^o_s \to \mu\mu$ branching fraction based on 4.9 fb^{-1} of integrated luminosity	4.9 fb^{-1}	ATLAS-CONF-2013-076
NEW Cross-section measurement of $\psi(2S) \to J/\psi (\to \mu^+\mu^-) \pi^+\pi^-$ at $\sqrt{s}$ = 7TeV	2.1 fb^{-1}	ATLAS-CONF-2013-094
NEW Measurement of χ_{c1} and χ_{c2} production with $\sqrt{s}$ = 7TeV *pp* collisions	4.5 fb^{-1}	ATLAS-CONF-2013-095

Early Measurements: B-Hadrons Mass & Lifetime

(ATLAS-CONF-2011-092) (Submitted to Phys. Rev. D, arXiv:1207.2284)



All masses and lifetimes consistent with PDG ⇒ well prepared for CPV measurement