New physics searches with B mesons at the ATLAS experiment

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on behalf of the ATLAS collaboration

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Outline

- Introduction
- $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$
- $B^0_s \rightarrow \mu^+ \mu^-$
- $B^0_s \rightarrow J/\psi\ \varphi$
- Summary

Introduction

- The Standard Model (SM) has explained all experimental observations for decades.
- But is an incomplete model.
- Many possible improvements postulated.
- Two approaches to find new physics:

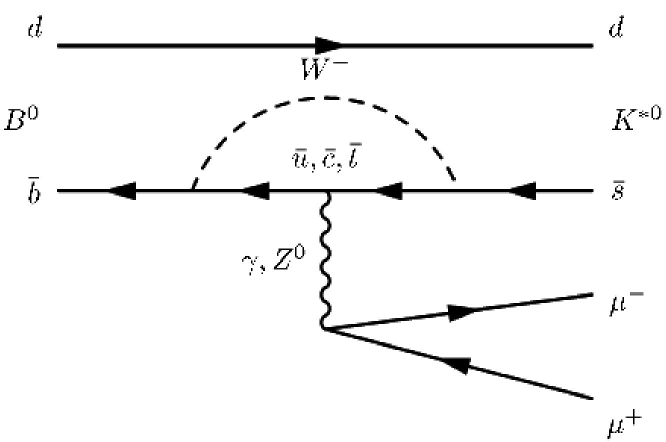
➔ Direct.

➔ Indirect: ***rare decays.***

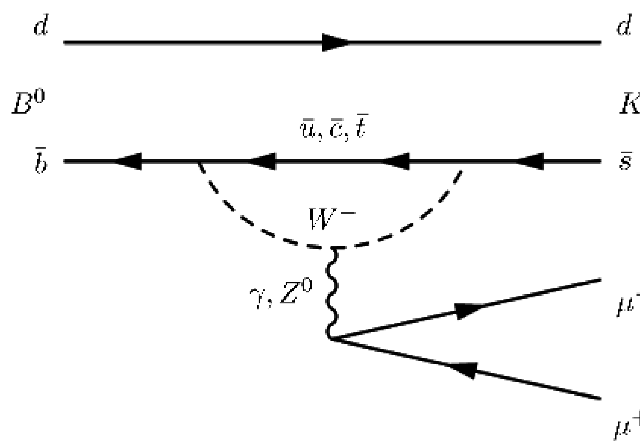
Angular Analysis of $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$

Why $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$?

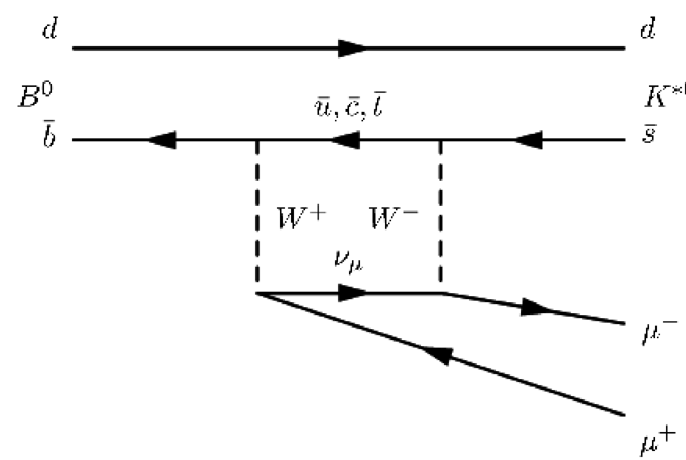
- The (semi-)rare decay $B^0_d \rightarrow K^{*0} \mu^+\mu^-$ is a FCNC decay and thus proceeds via several competing loop diagrams in the SM, allowing for substantial ***new physics*** contributions.



SM electromagnetic penguin diagram.



SM weak penguin diagram.



SM box diagram.

➔ Able to test the SM (QCD, effective theories etc.)

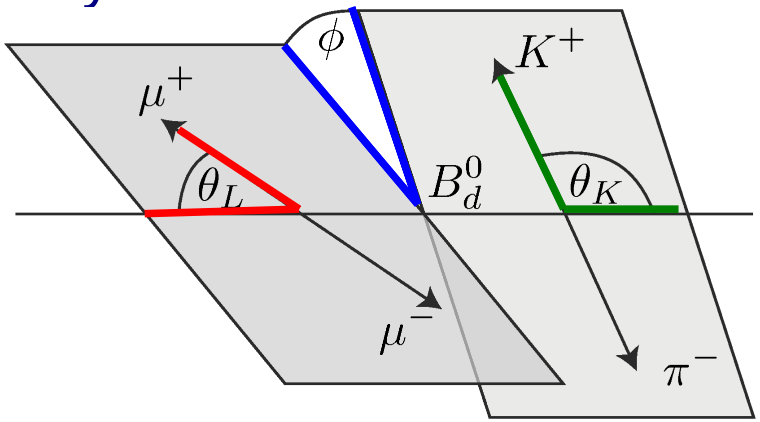
➔ We can indirectly search for new physics at scales beyond the reach of the LHC.

➔ Heightened interest from P'_5 discrepancy. [LHCb-CONF-2015-002]

What Are We Measuring?

- The decay $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$, where $K^{*0} \rightarrow K^+ \pi^-$, is described by **four** kinematic variables:

1) The invariant mass squared $\mathbf{q^2}$ of the dimuon system.



2) θ_L
3) θ_K
4) Φ

} Three angles describing the geometrical configuration of the final state as shown.

- The angular distribution is factorised in terms of the helicity angle distributions according to a chosen **angular PDF** and any **observables** of interest are extracted.

2011 Formalism

- At a given q^2 the integration of the differential decay rate over θ_K and φ gives:

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_\ell dq^2} = \frac{3}{4}\boxed{F_L(q^2)}(1-\cos^2\theta_\ell) + \frac{3}{8}(1-\boxed{F_L(q^2)})(1+\cos^2\theta_\ell) + \boxed{A_{FB}(q^2)}\cos\theta_\ell,$$

and over θ_L and φ gives:

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

$F_L(q^2)$ is the longitudinal polarisation of the K^{*0}.
$A_{FB}(q^2)$ is the forward-backward asymmetry of the muons.

- We fit $f(\cos\theta_L)f(\cos\theta_K)$ to improve the precision on F_L, but also introduces a small bias on that quantity.

Analysis Strategy

- **Trigger:**
  Two muon candidates with opposite charge.

- **Background:**
  Combinatorial from $b\bar{b} \rightarrow \mu^+ \mu^- X$, $c\bar{c} \rightarrow \mu^+ \mu^- X$, Drell Yan.
  Resonant from exclusive decay channels.
  Remove radiative charmonium decays from B decays:
  $B^0_d \rightarrow K^{*0} J/\psi$ and $B^0_d \rightarrow K^{*0} \psi(2S)$

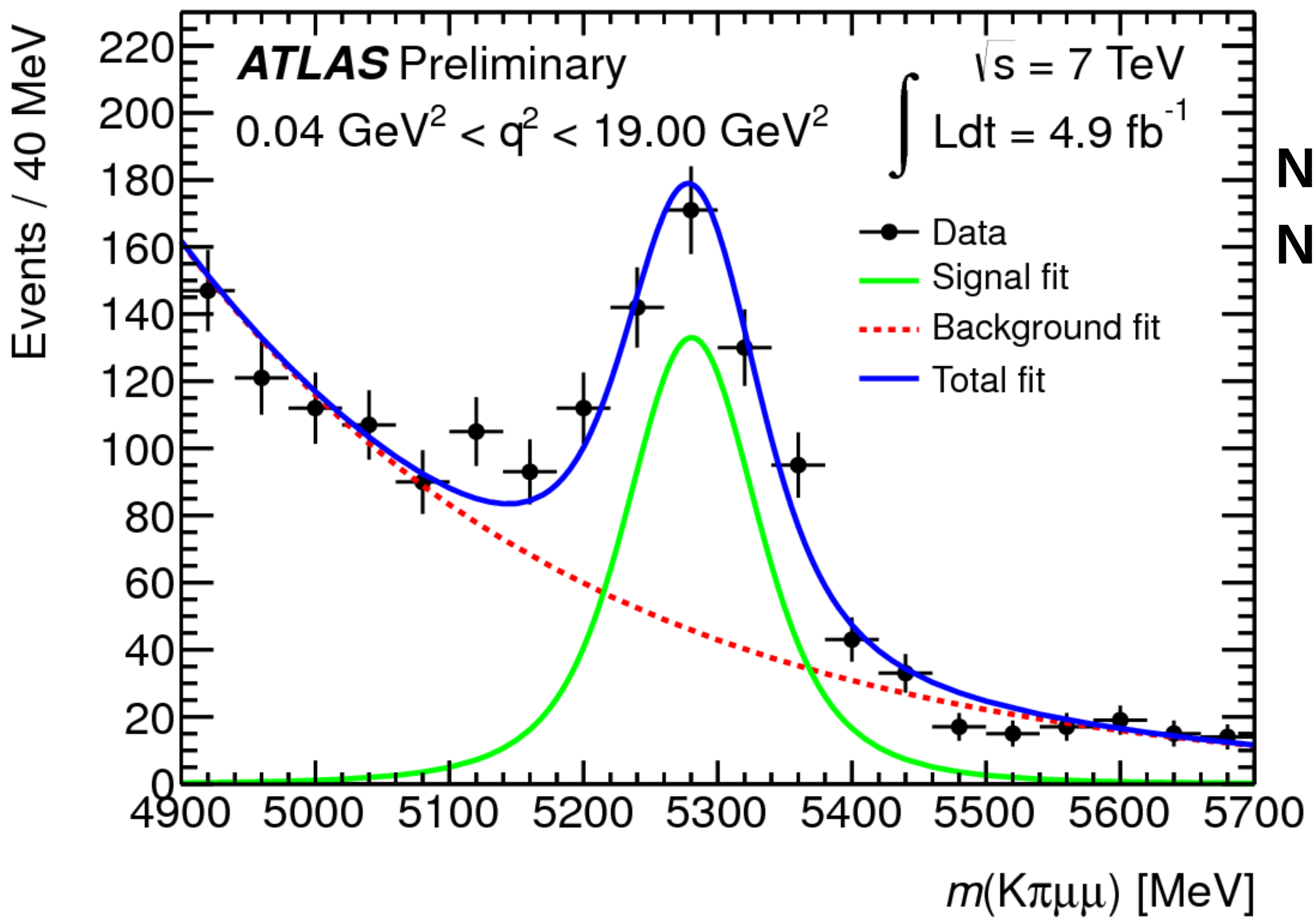
- **Cuts:**
  Optimised by maximising the estimator:
  $$P(N_{sig}, N_{bckg}) = N_{sig} / \sqrt{(N_{sig} + N_{bckg})}$$

- **Mass region:**
  $4600 \text{ MeV} < m(K\pi\mu\mu) < 5900 \text{ MeV}$

➔ 4466 candidates in the full q^2 range, after the optimised selection.

ATLAS 2011 Results

- Invariant mass distribution of $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$ candidates after full signal selection using 4.9 fb^{-1} of data:



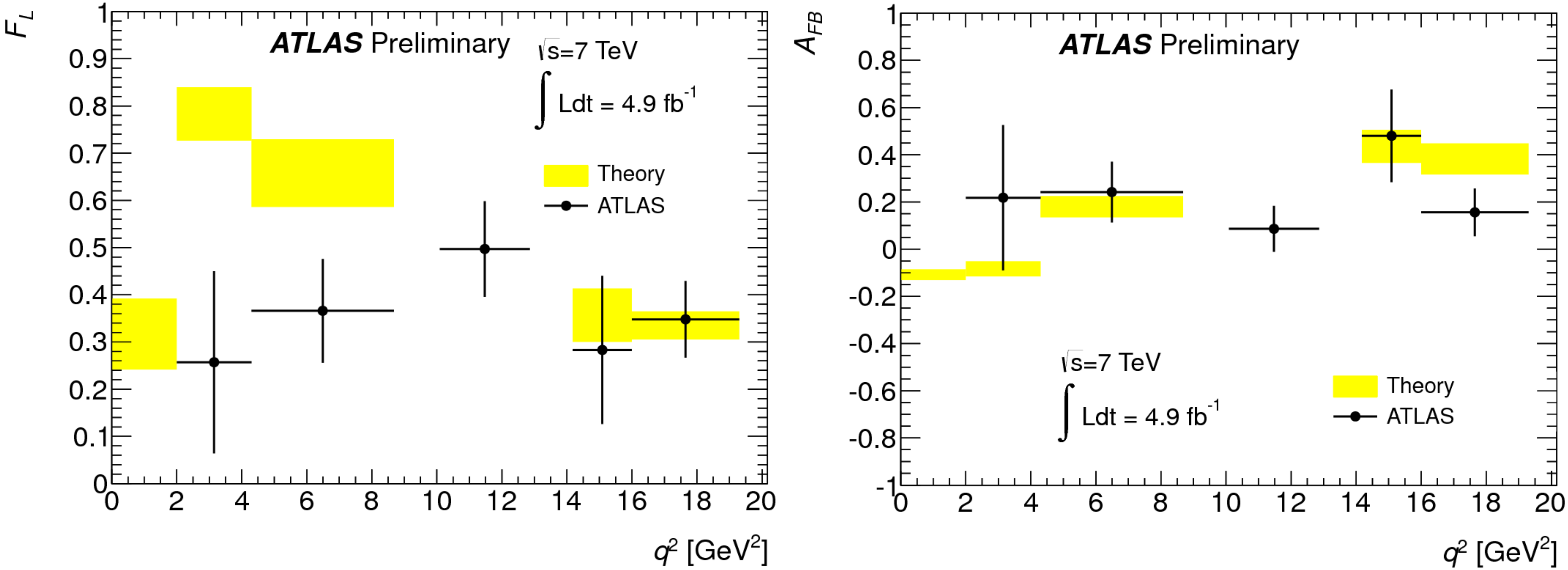
N_{sig} = 466 ± 34

N_{bkgd} = 1132 ± 43

ATLAS 2011 Results

- Total signal event yield of 454.
- The angular observables are are consistent with the SM.
  [C. Bobeth et al. arXiv:1105.2659].

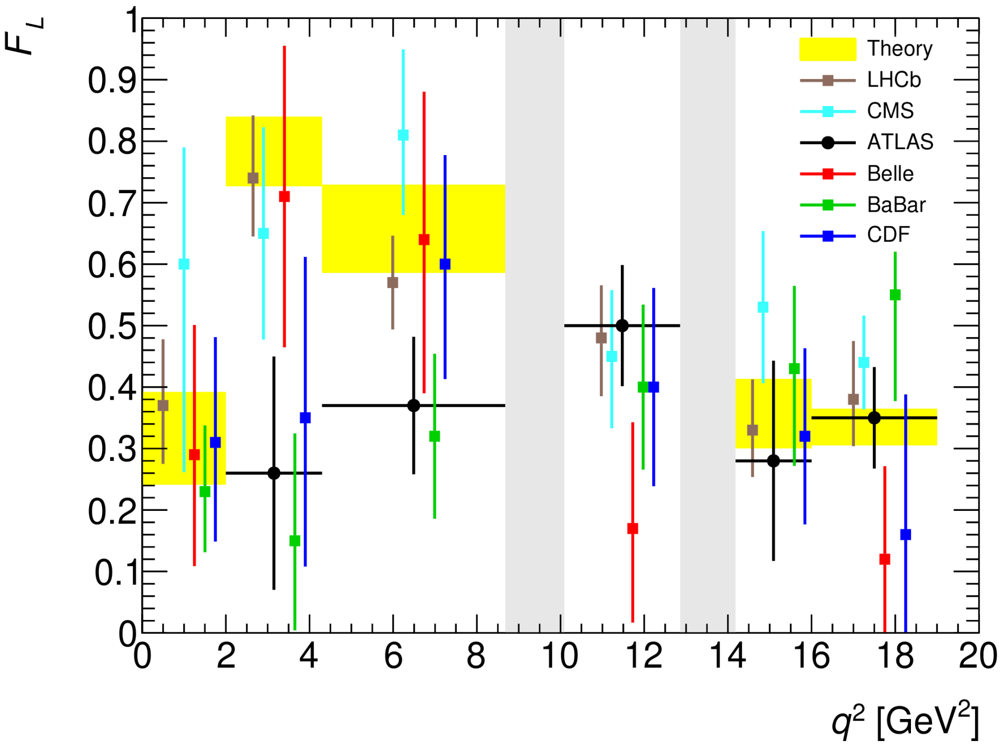
q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	19 ± 8	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88 ± 17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138 ± 31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	32 ± 14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

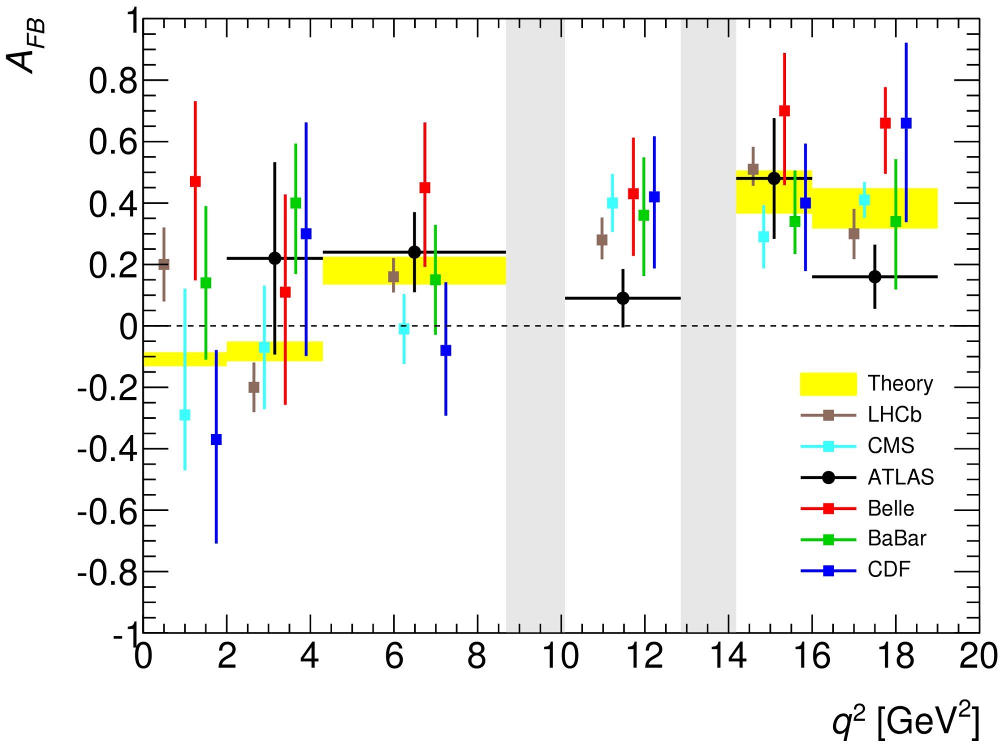


$B^0_d \to K^{*0} \mu^+ \mu^-$

2011 Results

- F_L and A_{FB} as a function of q^2 measured by ATLAS (black dots) with the results of other experiments shown in conjunction.





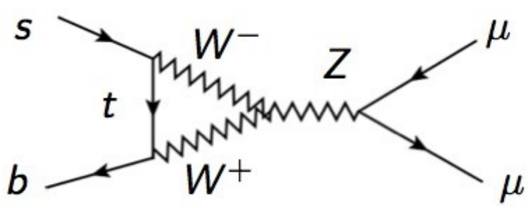
Theory [Phys. Rev. D 87 (2013) 034016]
LHCb [JHEP 1308 (2013) 131]
BaBar [arXiv:1301.1700v1]
CDF [Phys. Rev. Lett., 108 (2012) 081807]

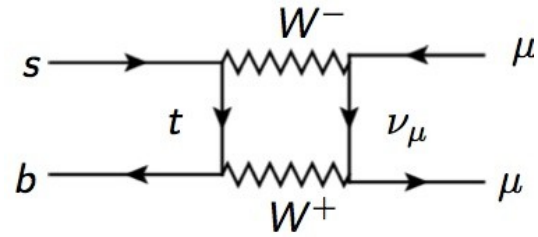
ATLAS [ATLAS-CONF-2013-038]
CMS [Phys. Lett. B, 727 (2013) 77-100]
Belle [Phys. Rev. Lett., 103 (2009) 171801]

Search for $B^0_s \rightarrow \mu^+ \mu^-$ decay

Why $B^0_s \to \mu^+ \mu^-$?

- FCNC, highly suppressed in the SM.



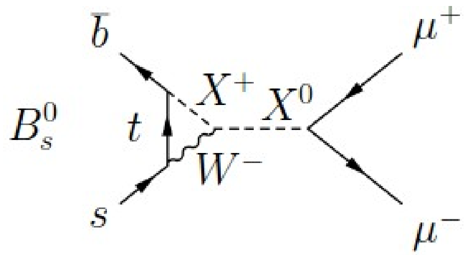


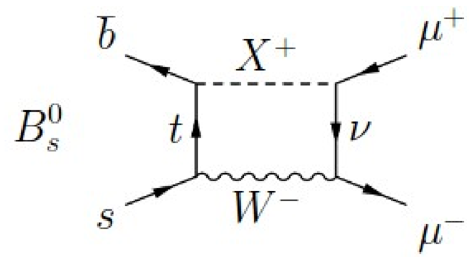
- Very precise SM branching ratio predictions:

  $\mathcal{B}$ **($B_s^0 \to \mu^+ \mu^-$) = (3.66 ± 0.23) x 10^{-9}**, compatible at 1.2σ.

- Coupling to non-SM particles in competing diagrams can affect the branching ratio.

[Bobeth et al., PRL 112 (2014) 101801]





- Combined CMS and LHCb dataset:

  $\mathcal{B}$ **($B_s^0 \to \mu^+ \mu^-$) = ($2.79^{+0.66+0.26}_{-0.60-0.19}$) x 10^{-9}**, 6.2σ observed (7.6σ expected)

[arxiv:1411.4413]

$B^0_s \to \mu^+ \mu^-$ 2011 Measurement

- The branching fraction ($\mathcal{B}$) can be written as:

[LHCb: JHEP 1304 (2013) 001]

$$\mathcal{B}(B_S \to \mu^+\mu^-) = \mathcal{B}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \cdot \frac{f_u}{f_s} \cdot \frac{\epsilon_{J/\psi K^\pm} . A_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-} . A_{\mu^+\mu^-}} \cdot \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}}$$

[PDG 2012]

Data-calibrated MC

$\varepsilon . A = N_{rec+sel}/N_{gen}$

- Reference channel $B^\pm \to J/\psi\ (\mu^+\mu^-)\ K^\pm$ (which introduces partial cancelation of systematic errors.)

Channel	Signal region	Sideband regions
$B^0_s \to \mu^+\mu^-$	[5066, 5666] MeV	[4766, 5066] MeV
		[5666, 5966] MeV
$B^\pm \to J/\psi K^\pm$	[5180, 5380] MeV	[4930, 5130] MeV
		[5430, 5630] MeV

- Blind analysis → invariant mass region ± 300 MeV around B^0_s mass.

- Count events $N_{\mu+\mu-}$ in signal region.

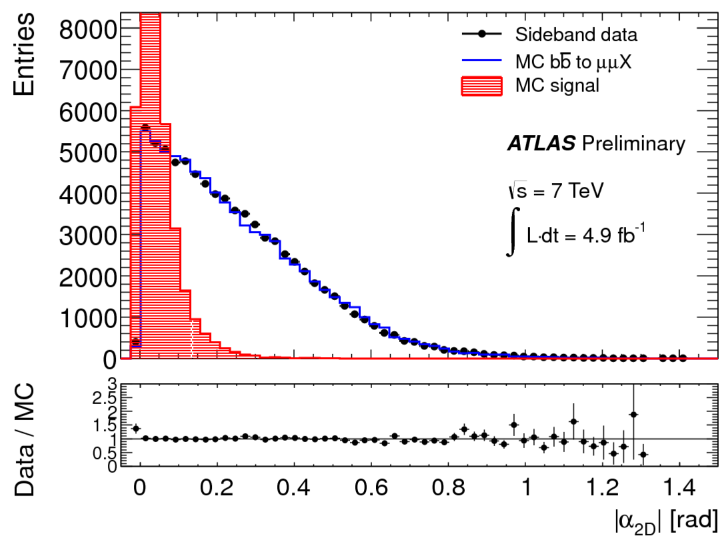
Analysis Strategy

Background discrimination

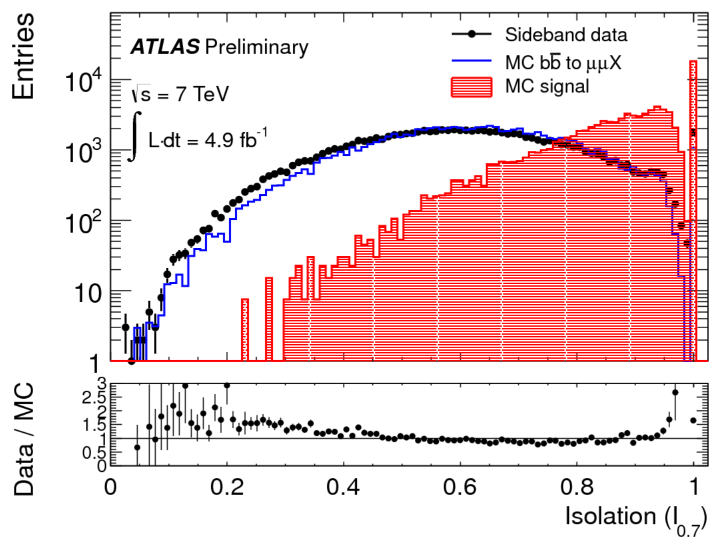
ATLAS-CONF-2013-076

- Boosted Decision Tree (BDT) used (13 discriminating variables).
- Continiuum dominated by $b\bar{b} \rightarrow \mu^+ \mu^- X$.
- Resonant background due to fake muons, dominated by B → hh.
- Odd numbered events from sidebands used for BDT cut optimisation.
- Even numbered events from sidebands used for interpolation.

Pointing angle



Isolation



BDT selection

Analysis Strategy

Background discrimination

ATLAS-CONF-2013-076

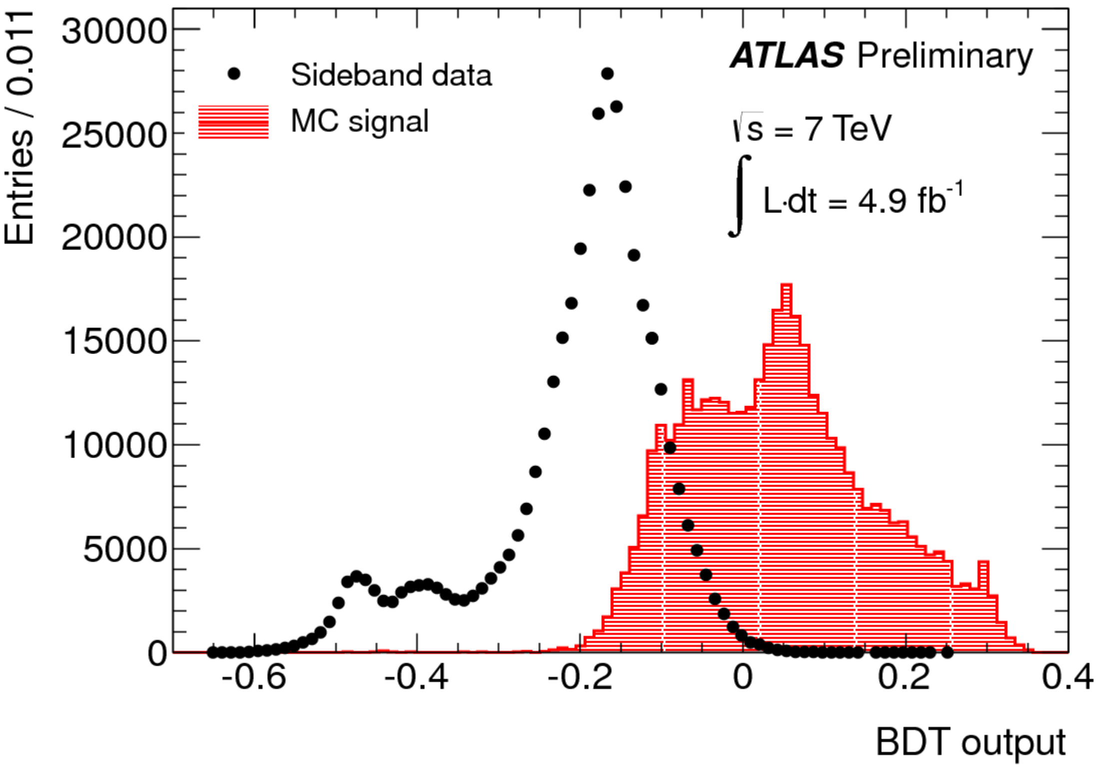
BDT selection

- Selection optimisation:
q: BDT event classifier
Δm: signal mass window width

- Maximise estimator:

$$P(\Delta m, q) = \frac{\epsilon_{sig}}{1+\sqrt{N_{bkg}}}$$

- P_{max} = 0.0145. Corresponding to final selection cuts:
  q > 0.118
  Δm = 121 MeV



$B^0_s \rightarrow \mu^+ \mu^-$

$B^0_s \rightarrow \mu^+ \mu^-$ 2011 Result

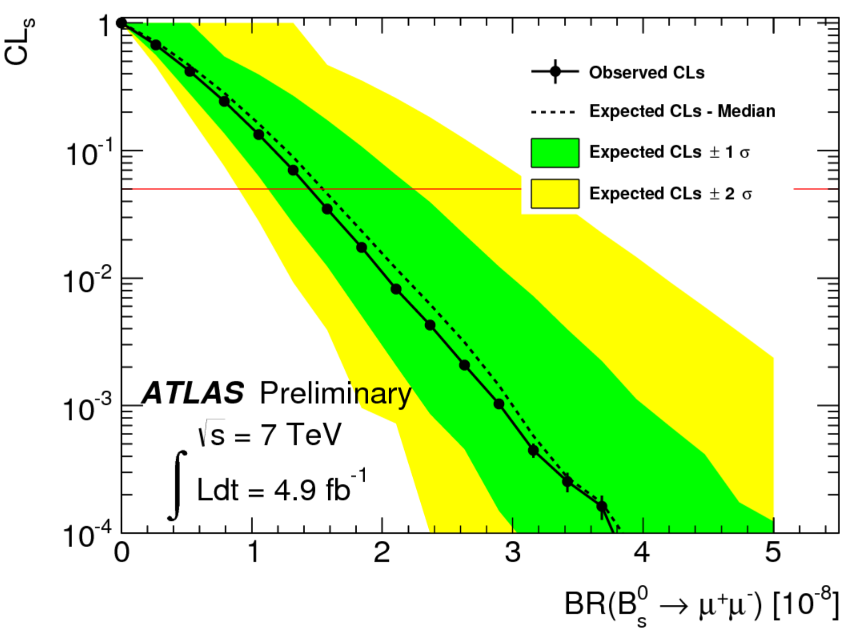
- Single-event-sensitivity (SES) defined as the $\mathcal{B}$ given by 1 observed event:

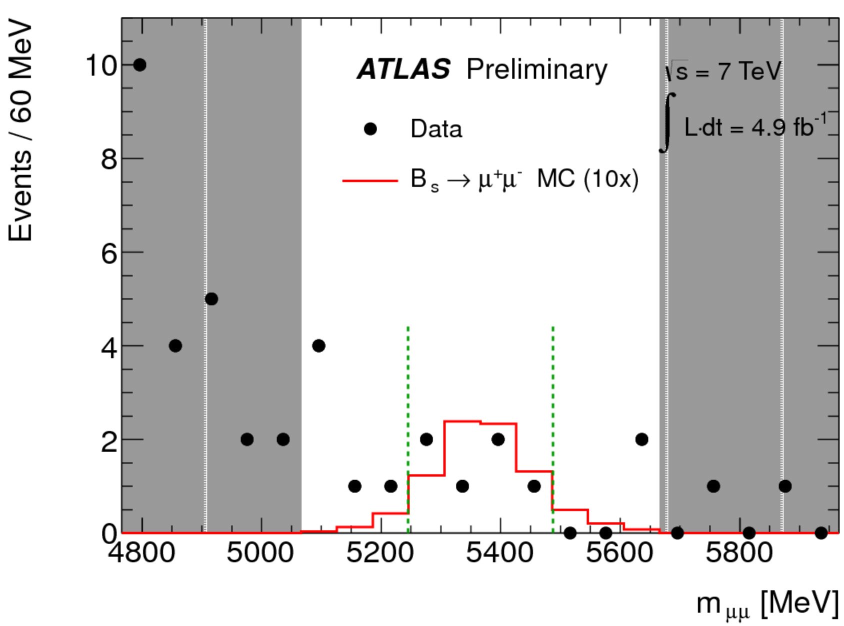
$$\text{SES} = \mathcal{B}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm).\frac{f_u}{f_s}.\frac{\epsilon_{J/\psi K^\pm}.A_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-}.A_{\mu^+\mu^-}}.\frac{1}{N_{J/\psi K^\pm}} = (2.07 \pm 0.26) \cdot 10^{-9}$$

- SES systematic = 12.5 % (dominated by reference channel $\mathcal{B}$, f_u/f_s & A·ε)

$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) < 1.5\ (1.2) \times 10^{-8}$ at 95% (90%) CL

ATLAS-CONF-2013-076





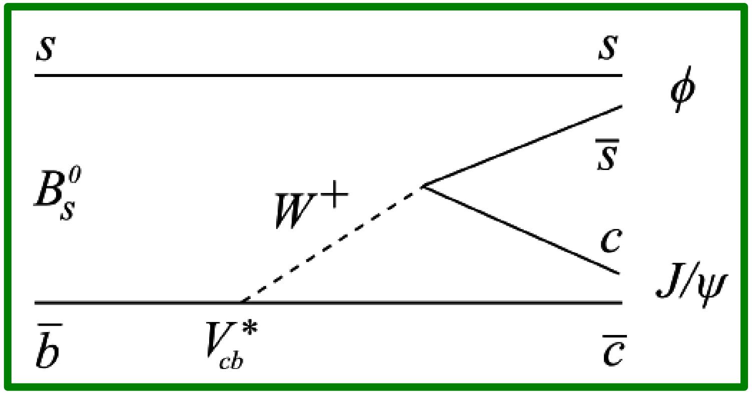
$N_{expBkg} = 6.7$

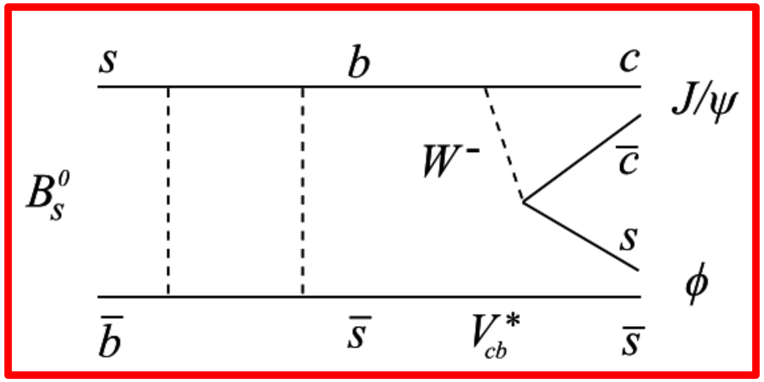
$N_{\mu+\mu-} = 6$

Flavour tagged time-dependent angular analysis of $B^0_s \to J/\psi\ \phi$

Why $B^0_s \rightarrow J/\psi\ \phi$?

- Expected to be a sensitive to BSM physics.
- CP violation occurs due to interference between direct decays and decays with $B^0_s - \overline{B}^0_s$ mixing (oscillation frequency charactersied by Δm_s between B_H and B_L).





- CP-violating weak phase difference φ_s is precisely predicted in SM:

  $\varphi_s = -0.037 \pm 0.002$ rad [Phys. Rev. Lett. 97,151803 (2006).]

- SM also predicts decay width difference:

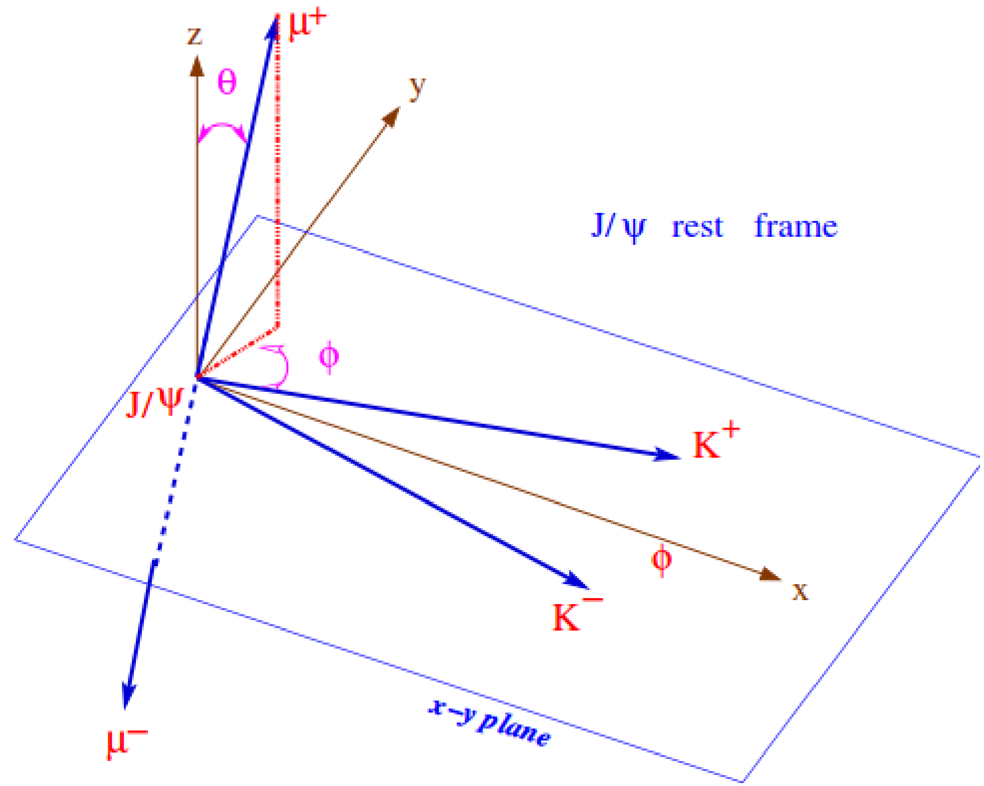
  $\Delta\Gamma_s = 0.087 \pm 0.021\ ps^{-1}$ [arXiv:1102.4274]

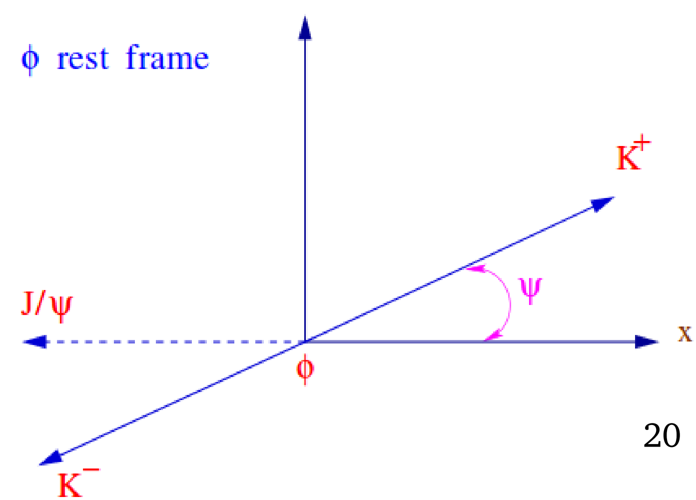
Measurement

- Pseudoscalar → vector vector decay.
- Admixture of CP odd (L = 1) and CP even (L = 0,2) states.
- Flavor tagging is used to distinguish between the initial B^0_s and $\overline{B}^0_s$ states.
- Time-dependent angular analysis to resolve CP eigenstates.

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

- Unbinned maximum likelihood fit performed on selected events.





B^0_s → J/ψ φ

Analysis Strategy

PHYSICAL REVIEW D 90, 052007 (2014)

- Triggers on $J/\psi \rightarrow \mu^+ \mu^-$ decay.
- Opposite side tagging (OST) used to determine initial flavour of neutral B meson (calibrated using $B^\pm \rightarrow J/\psi\, K^\pm$).

Tagger	Efficiency (%)	Dilution (%)	Tagging power (%)
Combined μ	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Segment tagged μ	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
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

→ 131513 B^0_s candidates within a mass range of 5.15 GeV < $m(B^0_s)$ < 5.65 GeV

- Two B^0_d background channels: $B^0_d \rightarrow J/\psi(\mu^+ \mu^-)\, K^+ \pi^-$
  $B^0_d \rightarrow J/\psi(\mu^+ \mu^-)\, K^{*0} (K^+ \pi^-)$
- Combinatorial background
- $B^0_s \rightarrow J/\psi(\mu^+ \mu^-)\, \varphi(K^+ K^-)$ signal PDF extracted, $f(m, t, \Omega, P(B|Q))$
- Two S-wave signal channels:
  non-resonant $B^0_s \rightarrow J/\psi(\mu^+ \mu^-)\, K^+ K^-$
  resonant $B^0_s \rightarrow J/\psi(\mu^+ \mu^-)\, f_0(K^+ K^-)$

$B^0_s \rightarrow J/\psi\, \varphi$

ATLAS 2011 Result

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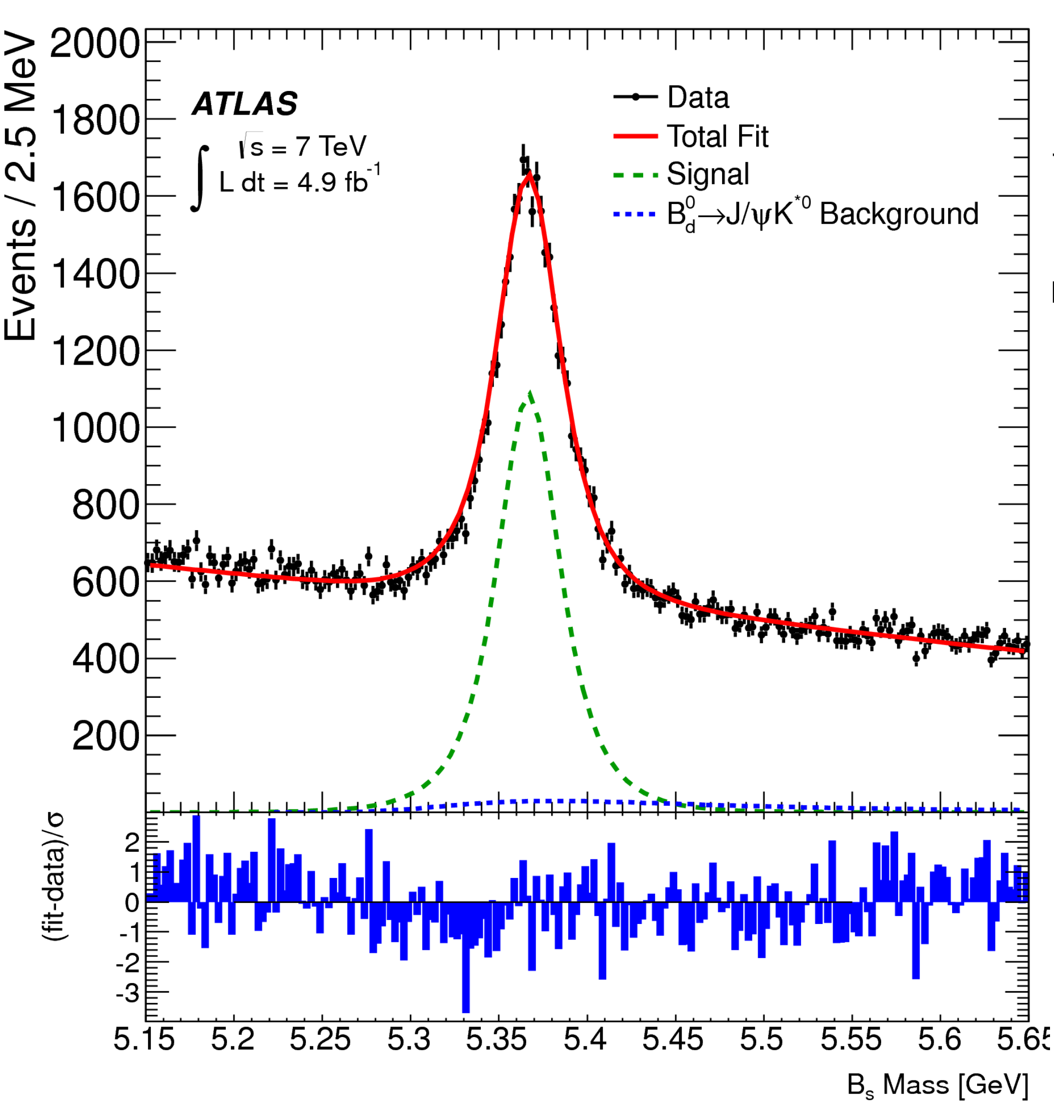

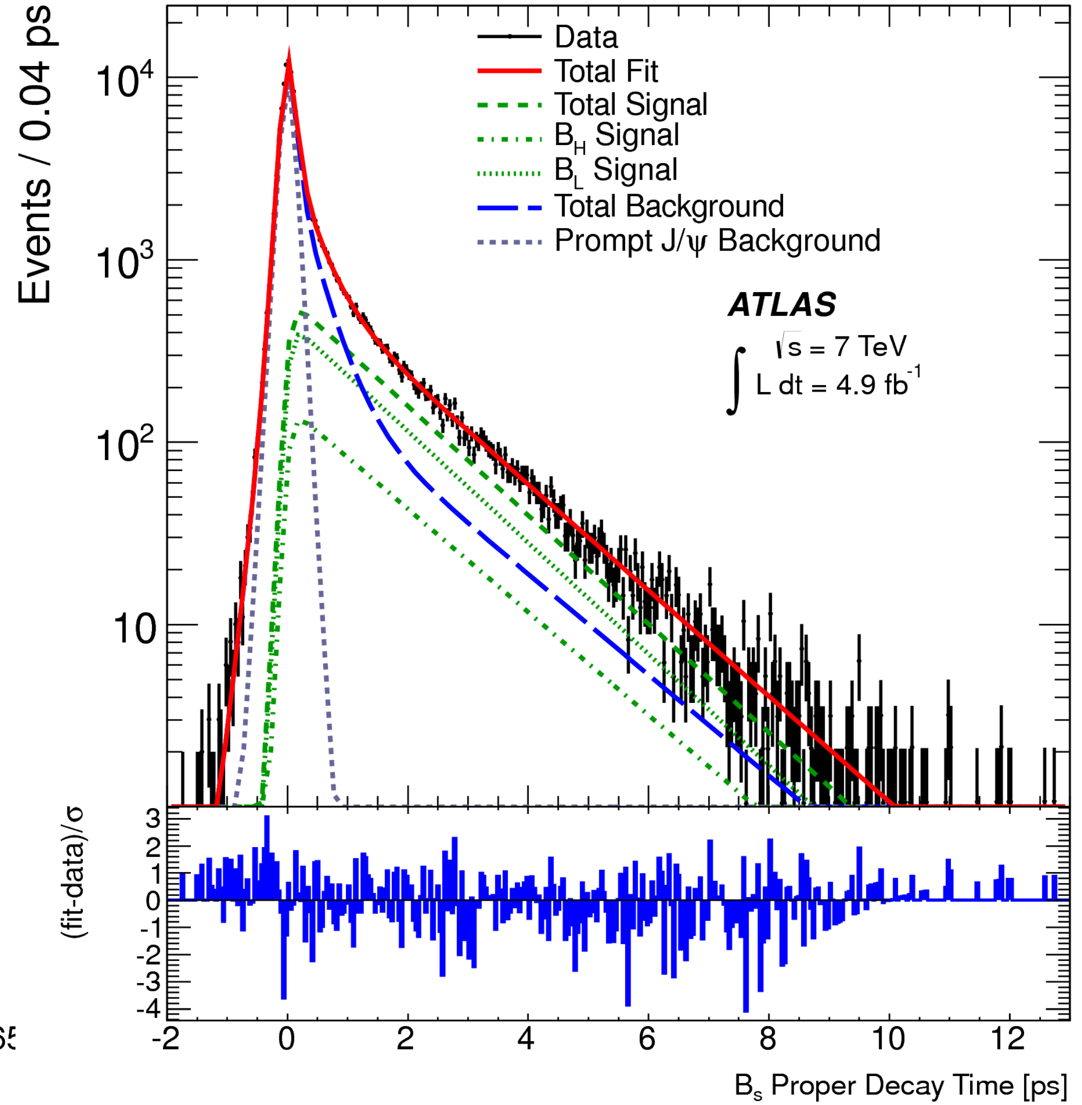

$B^0_s \to J/\psi\ \varphi$

ATLAS 2011 Result

- Fitted $B^0_s \to J/\psi\, \varphi$ decay parameters and their uncertainties using 4.9 fb^{-1} of data:

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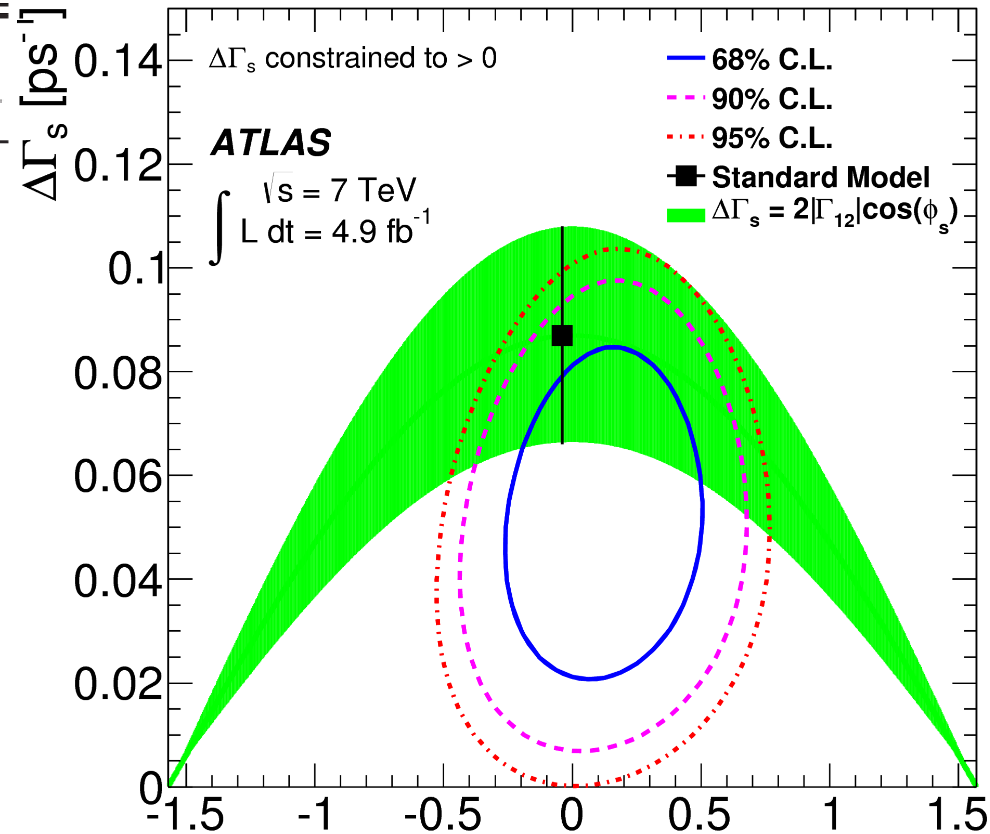
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	0.12	0.25	0.05
$\Delta\Gamma_s$[ps^{-1}]	0.053	0.021	0.010
Γ_s [ps^{-1}]	0.677	0.007	0.004
$\lvert A_\parallel(0)\rvert^2$	0.220	0.008	0.009
$\lvert A_0(0)\rvert^2$	0.529	0.006	0.012
$\lvert A_S(0)\rvert^2$	0.024	0.014	0.028
$\delta_\perp$	3.89	0.47	0.11
$\delta_\parallel$	[3.04, 3.23]		0.09
$\delta_\perp - \delta_S$	[3.02, 3.25]		0.04

Transversity amplitudes

Strong phases (68% CL)



- 22670 ± 150 signal B^0_s meson candidates extracted from fits.
- Consistent with values obtained in untagged analysis.
- Consistent with the values predicted in the SM.

Summary

- **$B^0_d \to K^{*0} \mu^+ \mu^-$**
  - Measurement of F_L and A_{FB} using 4.9 fb^{-1} of data presented.
  - Mostly consistent with SM.
  - 2012 analysis ongoing.
  - Plan to move towards an optimised observable parameterisation.

- **$B^0_s \to \mu^+ \mu^-$**
  - Upper limit on branching fraction set, using 4.9fb^{-1} of data.
  - Consistent with SM.
  - 2012 analysis ongoing, expect to unblind soon.

- **$B^0_s \to J/\psi\ \varphi$**
  - Flavour-tagging analysis performed on 4.9fb^{-1} of data.
  - Decay parameters including φ_s and $\Delta\Gamma_s$ presented.
  - Results consistent with SM expectations.
  - Expect updated analysis using 2012 data to be out soon.

Back Up

$B^0_d \rightarrow K^{*0} \mu^+ \mu^-$ Back Up

Traditional Angular Analysis

- Traditional full angular analysis of the data using:

$$\frac{1}{\Gamma}\frac{d^5\Gamma}{d\cos\theta_l d\cos\theta_K d\phi dq^2} = \frac{9}{16\pi}\Bigg\{\Bigg(\frac{2F_S(q^2)}{3} + \frac{4A_S(q^2)\cos\theta_K}{3}(1-\cos^2\theta_L)$$
$$+ (1-F_S(q'^2))\Bigg[2F_L(q^2)\cos^2\theta_K(1-\cos^2\theta_L) + \frac{1-F_L(q^2)}{2}(1-\cos^2\theta_K)(1+\cos^2\theta_L)$$
$$+ \frac{1-F_L(q^2)}{2}A_T^2(q^2)(1-\cos^2\theta_K)(1-\cos^2\theta_L)\cos 2\phi$$
$$+ \frac{4A_{FB}(q^2)}{3}(1-\cos^2\theta_K)\cos\theta_L$$
$$+ A_{Im}(q^2)(1-\cos^2\theta_K)(1-\cos^2\theta_L)\sin 2\phi\Bigg]\Bigg\}$$

- Can add a scalar component to the fit introducing two new parameters.
- The full distribution introduces two additional parameters to extract.
- 6 observables of interest are: F_L, A_{FB}, F_S, A_S, A_T, A_{im}.

✔ **Complete information.**
✗ **FF dependent observables at leading order.**

Optimised Observable Analysis

- FF independent analysis:

$$\frac{1}{(\Gamma+\overline{\Gamma})}\frac{d^4(\Gamma+\overline{\Gamma})}{d\cos\theta_l d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l$$
$$+ S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_l\cos\phi + S_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

- In addition to F_L, we can measure the FF independent parameters.

$$P_i'^{(s,c)} = \frac{S_i^{(s,c)}}{\sqrt{F_L(1-F_L)}}$$

➔ 9 observables to measure in total.

- Can reduce the number of observables directly by **folding** the differential decay rate and exploiting the symmetries in the angular expressions, e.g.:

$$\begin{aligned}\phi &\rightarrow -\phi \quad \text{if } \phi<0\\ \theta_\ell &\rightarrow \pi-\theta_\ell \quad \text{if } \theta_\ell>\frac{\pi}{2}\end{aligned}$$

Optimised Observable Analysis

- We will perform a FF independent analysis:

$$\frac{1}{(\Gamma+\overline{\Gamma})}\frac{d^4(\Gamma+\overline{\Gamma})}{d\cos\theta_l d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l$$
$$+S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_l\cos\phi + S_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

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$$P_i^{\prime(s,c)} = \frac{S_i^{(s,c)}}{\sqrt{F_L(1-F_L)}}$$

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- Can reduce the number of observables directly by **folding** the differential decay rate and exploiting the symmetries in the angular expressions, e.g.:

$$\begin{aligned}\phi &\rightarrow -\phi \quad \text{if } \phi < 0\\ \theta_\ell &\rightarrow \pi - \theta_\ell \quad \text{if } \theta_\ell > \frac{\pi}{2}\end{aligned}$$

✔Complete information.
✔ FF independent observables at LO

CP Asymmetry

- The CP asymmetry, A_{CP}, for $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ is defined as:

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

- The data gives us: $N_{obs} = (1-\omega)N + \overline{\omega}\overline{N}$ and $\overline{N}_{obs} = (1-\overline{\omega})\overline{N} + \omega N$

- Hence:

$$A_{CP} = \frac{(1-\Delta\omega)\overline{N}_{obs} - (1+\Delta\omega)N_{obs}}{(1-\overline{\omega}-\omega)(\overline{N}_{obs} + N_{obs})}$$

- A_{CP} is predicted to be of the order $<10^{-2}$ in the SM. [Christoph Bobeth et al JHEP07(2008)106]

- The measurement is sensitive to physics beyond the SM.

$B^0_s \rightarrow \mu^+ \mu^-$ Back Up

$B^0_s \to \mu^+ \mu^-$ Discriminating Variables

- Variables are listed in order of relevance as ranked by the multivariate classifier used in the final signal/background separation.

Variable	Description	Ranking
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x} \cdot \vec{p}^B)/\lvert\vec{p}^B_T\rvert$	1
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}^B_T\rvert$ to the sum of $\lvert\vec{p}^B_T\rvert$ 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^{min}_L	Minimum momentum of the two muon candidates along the B direction	4
p^B_T	B transverse momentum	5
ct significance	Proper decay length $ct = L_{xy} \times m_B / p^B_T$ divided by its uncertainty	6
χ^2_z, χ^2_{xy}	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

$B^0_s \rightarrow J/\psi\ \phi$ Back Up

Time-dependent amplitudes

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

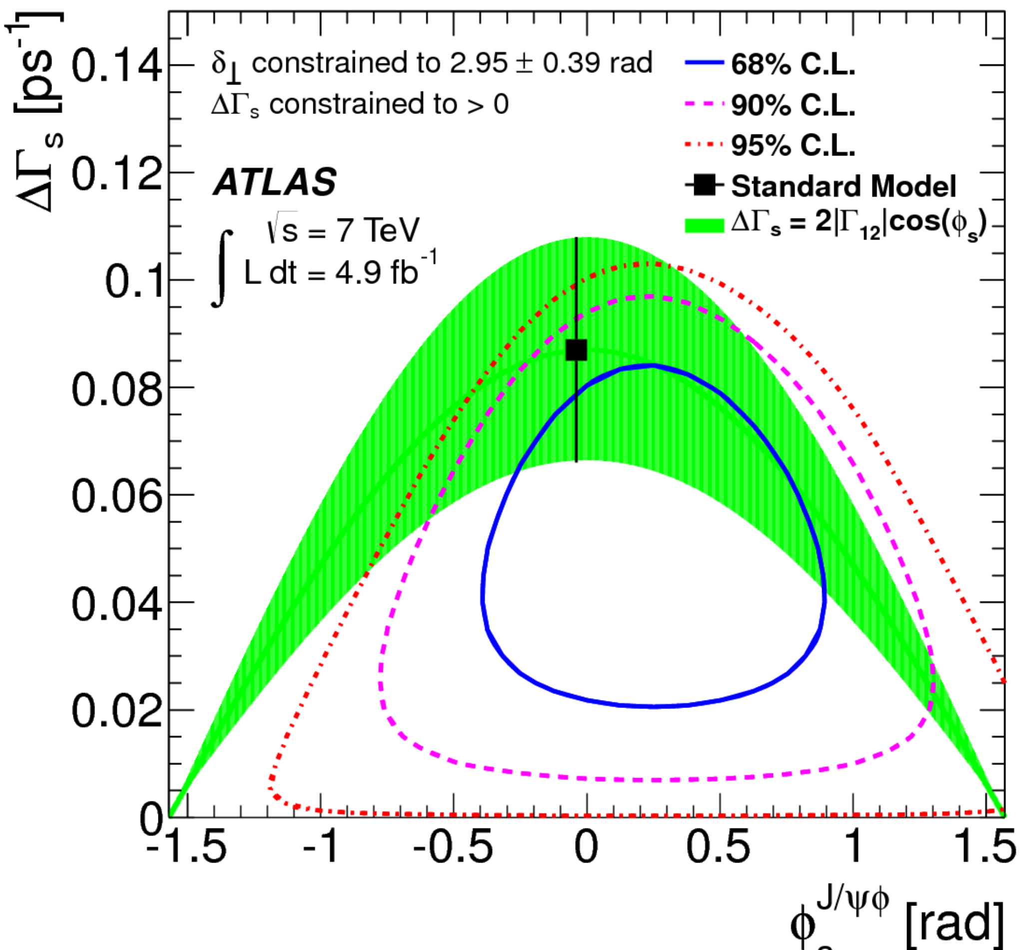
Systematic Uncertainties

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\|A_\parallel(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_\perp$ [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^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.03	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.04	$<10^{-2}$	$<10^{-2}$
Acceptance	0.02	0.004	0.002	0.002	0.004	...	...	$<10^{-2}$	...
Models:									
Default fit	$<10^{-2}$	0.003	$<10^{-3}$	0.001	0.001	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	0.05	0.010	0.004	0.009	0.012	0.028	0.11	0.09	0.04

Tagged and untagged 2011 analysis

Untagged

[JHEP 1212 (2012) 072]

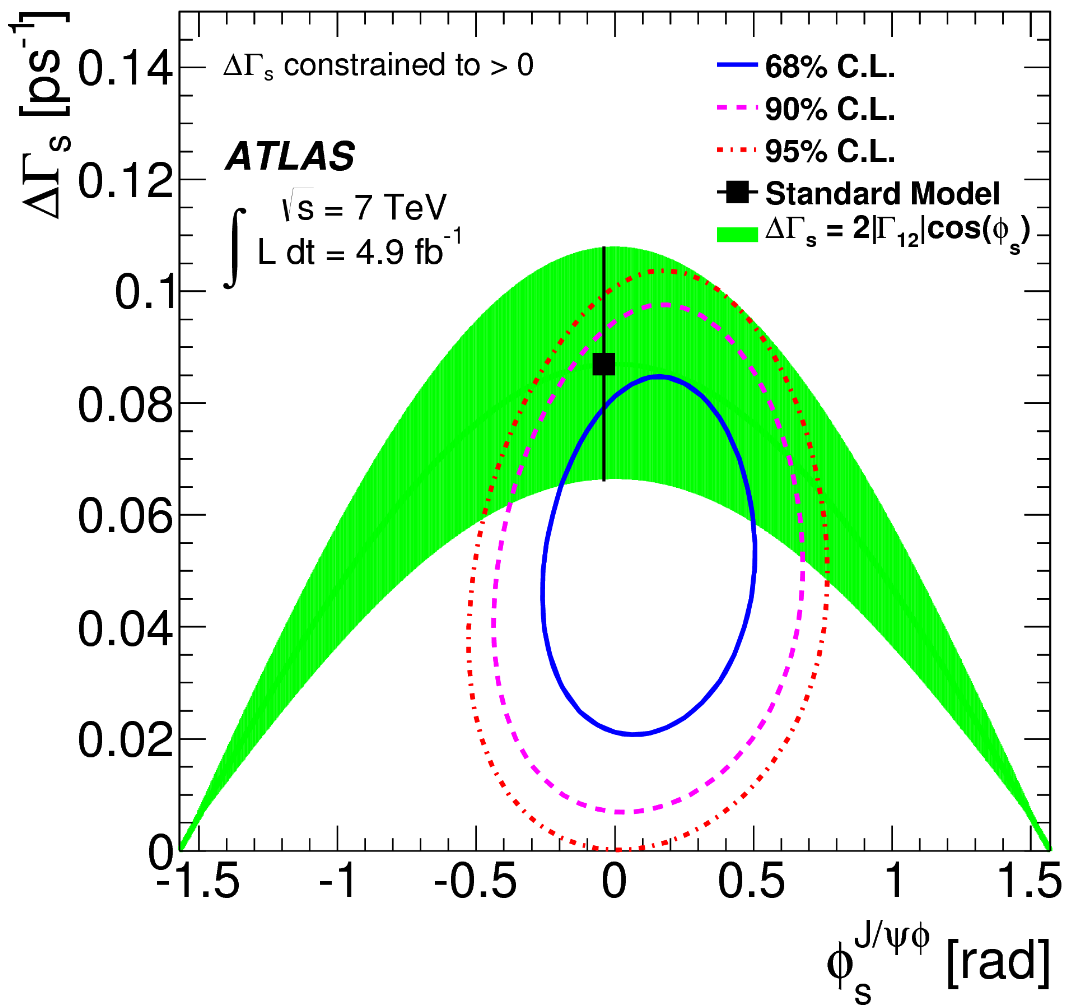


Tagged

[JHEP 1212 (2012) 072]

40% better φ_s stat. error,

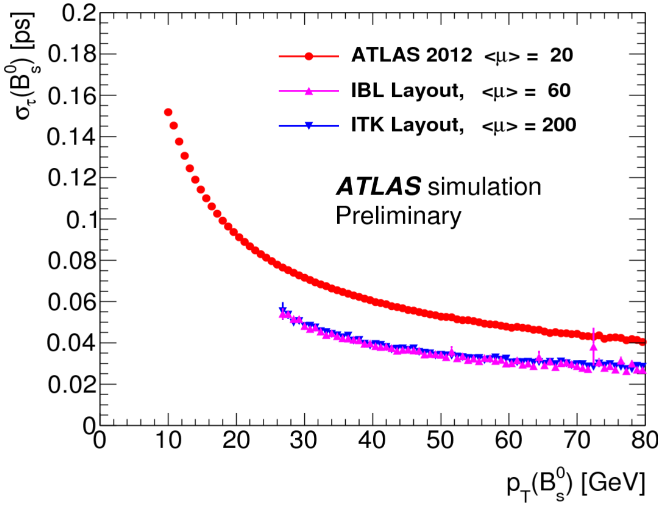
$\Delta\Gamma_s$ error unchanged

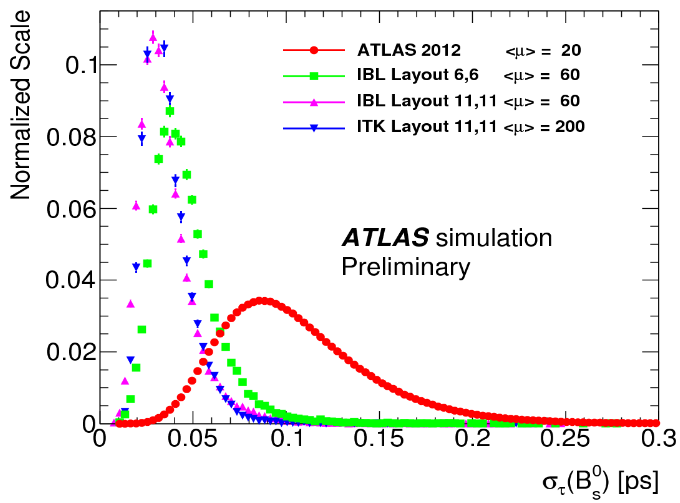


Case Study – CPV in $B_s \to J/\psi\ \varphi$ at ATLAS

ATLAS-PHYS-PUB-2013-010

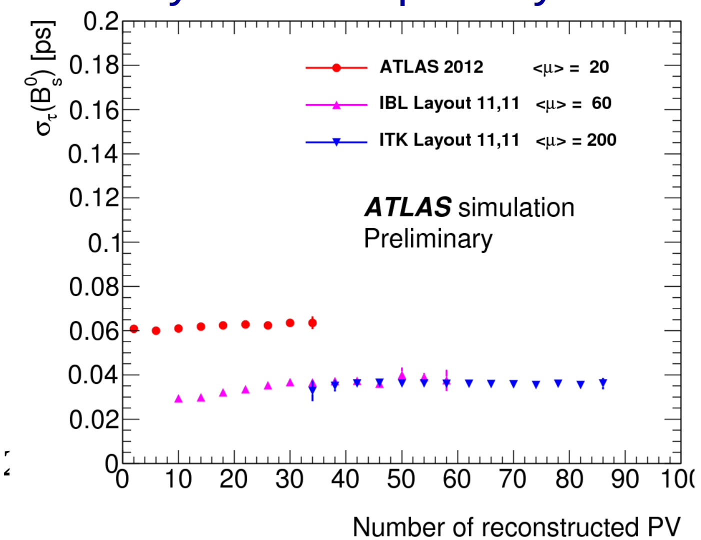
- Time-dependent angular analysis of the $B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$ decays
- Key factors: # of signal candidates, lifetime precision, performance stability in high pileup
- Lifetime precisions:

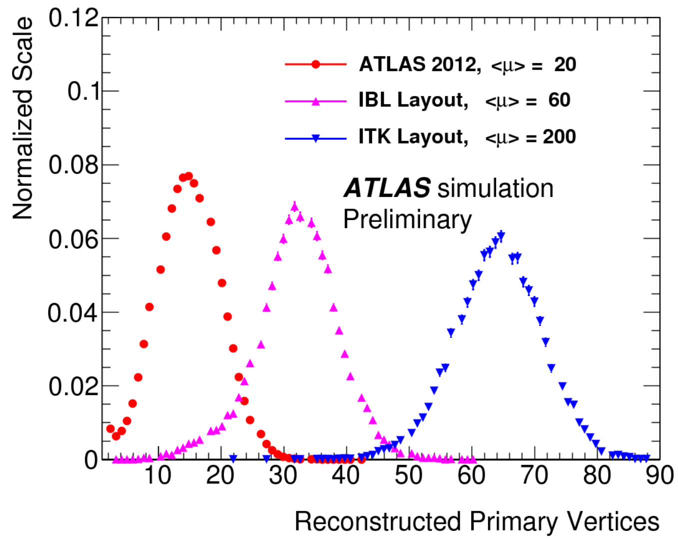




- New ID layouts IBL and ITK **improve** proper decay time resolution **σ_τ by 30%** w.r.t. Run-1
- Higher p_T improves σ_τ and signal purity on the account of lower efficiency

- Stability with # of primary vertices:





- Resolution σ_τ (secondary vertex displacement from PV) may deteoriate with increasing #PV (select correct PV based on Bs-momentum direction)
- σ_τ stable in Run-1 (low-p_T, dominated by material)
- Slight σ_τ (~14%) increase in Run-2 with #PV, **stable** at #PV > 40

Case Study – CPV in $B_s \rightarrow J/\psi\phi$ at ATLAS

- Trigger scenario: di-muon with the muon p_T threholds:
  - **Run-2/3**: 6+6 GeV (nominal, assuming basic L1-topo usage) or 11+11 GeV (pessimistic)
  - **Hl-LHC**: 11+11 GeV

	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- Toy-MC prediction based on 2011 analysis, 2012 sidebands data and fully simulated signal at Run-2/3/HL-LHC conditions
- Potential in Runs-2/3 will strongly depend on the trigger thresholds: ~7x less B_s events in the pessimistic 11+11 GeV $p_T(\mu^{\pm})$ trigger configuration
- Results prepared for ECFA 2013 (ATL-PHYS-PUB-2013-010), considered conservative:
  - Further development of the L1-topological usage => part of the Run-2 data expected to be collected by triggers with lower muon p_T thresholds: 4-6 GeV
  - (Not considered flavour tagging and fit improvements developed in analysis of 8 TeV data of 2012)